

**The Impacts of Large Research Infrastructures
on
Economic Innovation and on Society:
Case Studies at CERN**



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The Forum's reports are available at www.oecd.org/sti/gsf. The GSF staff are based at OECD headquarters in Paris, and can be contacted at gsforum@oecd.org.

FOREWORD

Since the creation of the OECD Megascience Forum in 1992, which was renamed the Global Science Forum (GSF) in 1999 after the broadening of its mandate, research infrastructures have been a major topic for analysis and discussion at the Organisation for Economic Co-operation and Development.

Following a publication on “[Large Research Infrastructures](#)”, which dealt with the challenges associated with launching and managing large single-site facilities, this new report addresses the potential economic and societal impacts of international research facilities, using case studies from one of the largest global research infrastructures: the European Organisation for Nuclear Research (CERN).

The GSF undertook this study following an initial approach by CERN, which was interested in having an external perspective that could serve as a basis for further optimising the organisation’s policies and procedures as well as being of value to CERN’s member states. The GSF approach, although based on the analysis of CERN’s achievements and policies, aimed to shed light on generic issues that could be applicable more broadly to international research infrastructures.

This report is based on case studies that were carried out using two sources of information: papers/articles and interviews, which were carried out by Dr Stefan Michalowski from the GSF Secretariat with nearly fifty key individuals. These included staff at CERN, experts from outside of CERN and current or former employees of companies that manufactured some of CERN’s major equipment.

The GSF’s objective was not to carry out an exhaustive analysis but rather to derive useful lessons and practices for administrators, funding agencies and policymakers, who are faced with challenging decisions about implementing new infrastructure projects and programmes (or about upgrading or terminating existing ones). We hope that this report will be informative and useful and we would be interested in receiving comments from readers. The GSF staff can be reached at gsforum@oecd.org.

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EXECUTIVE SUMMARY

This report of the OECD Global Science Forum (GSF) is an examination of some of the economic and societal impacts of a well-known international research facility: the European Organisation for Nuclear Research (CERN). Via a few case studies, this report aims to shed light on generic questions that could be applicable to any number of potential future international research infrastructures.

Among the beneficiaries of the study will be government officials who seek to understand all of the ways in which the outcomes of publicly-funded research can benefit national economies and can affect the lives of citizens in general. Similarly, facility administrators are always interested in optimising their organisational structures, procedures and internal policies to better manage useful secondary outcomes, and to maximise social/economic impacts without detracting from primary research objectives. Scientific leaders who are exploring the prospects of future new facilities will benefit from the results of this OECD study as well, by being able to anticipate relevant opportunities and challenges, and perhaps incorporating the findings of the study into future governance structures as they are being designed.

In this study, four impact categories were analysed, related to (i) innovations needed for major CERN component development; (ii) innovations unrelated to the facility needs; (iii) software applications; (iv) education and public outreach.

- i. The ability of CERN to carry out internally major technological innovation efforts associated with the design, development and fabrication of essential components of its research infrastructure, such as the dipole magnets of the Large Hadron Collider, was linked to a number of practical features:
 - Its size, which allows CERN to accommodate the various early stages of a project without detracting from its on-going authorised and funded projects.
 - Its internal staff, who have advanced knowledge of the various design and engineering possibilities of equipment, have access to extensive international networks, and have the capacity to develop long-range plans besides their primary work assignment.
 - Its degree of flexibility in the management and internal accounting procedures.

The decision to develop internally such technological effort is largely associated with risk management strategies and constraints. In the case of large equipment possessing unique technological characteristics, a number of challenges have to be met:

- Respond to time, schedule and cost constraints for unique and highly innovative equipment.
- Avoid potential legal proceedings with under-performing contractors.
- Avoid risks related to *juste retour* mechanisms.

Internal development of these challenging new technological components requires a number of features:

- The capacity to set up strong control and oversight of its partners. Because CERN's budget is provided by cash contributions from its Member States, it is free to specify the degree of control it wishes in its call for tenders, which may not be the case for projects based on in-kind contributions.
 - The capacity to call for external expertise and contribution from affiliated and associated research institutions when in-house knowledge and experience is insufficient (CERN is one of the central nodes of the research community and organisations in physics).
 - Close collaboration with a network of trusted industrial contractors.
 - The capacity to maintain internal efforts in a broad range of technologies besides carrying out theoretical research projects, which may be called for when technological challenges emerge.
- ii. The case of the hadron cancer therapy in CERN represents an innovation development that was not part of the laboratory's principal scientific objectives, but illustrates how a major research infrastructure can generate impacts beneficial to society without detriment to its main mission. The capacity of CERN to enable such innovation was linked to a number of factors:
- A capacity to attract staff of very high quality who can serve as a resource when new prospective projects are introduced.
 - Management flexibility that allows experts to contribute in an *ad-hoc* manner to new projects, and the capacity of CERN to assign resources to such projects.
 - A catalysing role of CERN, allowing staff from different background to exchange ideas on new initiatives, which can later develop in spin-off projects outside CERN.
 - A work culture of the institution, that allows staff to work outside normal hours on new/exploratory concepts with CERN resources (within reasonable limits), and communicate freely up and down the chain of authority.
 - A capacity to foster bottom up projects, even outside the mainstream mission of CERN, the institution acting as an incubator for projects that are ultimately destined to be implemented at national level, but that require an established and supportive environment in their initial phase.
- iii. Countless software applications have been developed at CERN, to respond to specific requirements that could not be fulfilled by commercial products. In some instances, software was developed for applications that were sufficiently generic and of wide potential utility that it became worthwhile to make it available to a wider community. This was, for instance, the case for two products, "INVENIO" and "INDICO", which can be used to create digital web-based document repositories and to design and convene lectures, meetings or conferences.

Transforming in-house software into a generic product requires considerable effort from the institution: it has to be reliable, provide attractive and intuitive graphic user interfaces, and offer documentation and support services (although not comparable to commercial products in terms of packaging, advertising, extensive warranty and user support). However, such examples illustrate how a research facility can generate positive impacts by providing useful products in a no-fee, open source mode, without detracting from the main scientific goal of the laboratory.

- iv. Education and outreach activities have been developed in CERN for the last 15 years, to connect a very theoretical and high-level research infrastructure to a broader audience.

Two types of programmes have been developed: one centrally delivered at CERN for High-School teachers; and national teacher programmes delivered in member countries. In both cases, the content is created by scientists, members of CERN staff or members of the experimental teams. Although the actual impact of these programmes is difficult to evaluate, they benefited over a thousand teachers in 2012.

In parallel, CERN has makes substantial efforts to communicate with the general public and welcomes about 80 000 visitors each year. The importance of such outreach activities led to the establishment of a foundation that operates “The Globe”, a visitor centre designed to improve public understanding of high-energy physics.

More generally, technology and knowledge transfer are important considerations for any research infrastructure, for many technological advances have the potential to lead to commercial products. While national research or funding organisations have often developed incentives and mechanisms to facilitate transfer to the commercial sector, the issue is more complicated for international structures. In the CERN case, such transfer also has to be compatible with paragraph 2 of Article II of its Convention, which highlights the fundamental character of the research carried out by the Organisation.

The stance at CERN, however, is that the text of this Article is not incompatible with the assertion of Intellectual Property Rights (IPR) based on ideas developed at CERN. A Knowledge Transfer Office (KTO) was thus established to manage a portfolio of about 40 patents, and this has led to around one hundred licence agreements. However, research infrastructures should not overestimate potential gains from their IPR, and should think about developing effective incentives to maximise returns on investment. In the case of CERN, the KTO involves about a dozen staff members, but license agreements only generate about two million Swiss francs per year (about 0.1 % of its annual budget). CERN owns the IPR and any royalties are split between the employee’s Department, the Section and the KTO, with no financial reward for the inventor. However, even if CERN rules allowed performance-based monetary bonuses to be awarded to staff members, this would not necessarily ensure that staff would be motivated to pursue commercial applications.

Section A. Rationale, background and objectives

This report is an examination of some of the economic and societal impacts of a well-known international high-energy physics infrastructure: the European Organisation for Nuclear Research, CERN, with special emphasis on its latest and most prominent scientific installation, the Large Hadron Collider (LHC). While both CERN and the LHC are, to a large extent, unique among research infrastructures, it is hoped that the case studies, analyses and conclusions in this report will make a useful contribution to the wider debate concerning the impacts of investments in large basic research facilities. Specifically, an enumeration and analysis of the pertinent issues and options should be a useful resource for persons who are contemplating the establishment of any major new international collaboration.

Through four specific case studies, this report aims to shed light on generic questions that could be applicable to any number of potential future international research infrastructures. Over the years, CERN leaders have developed their own answers to these questions, based on the specific challenges and opportunities that they have encountered. No claim is made that the CERN answers are universally valid, but the solutions described in this report could be useful for interested parties. Among the questions are:

- When, in the course of its scientific mission, the infrastructure needs to acquire equipment whose technological parameters exceed the state of the art, what are the pros and cons of various innovation strategies, for example, in-house R&D versus external procurement? What are good strategies for optimising cost, schedule and technology transfer to commercial partners? What are possible strategies for reducing risks during the process of technological innovation?
- When procuring new equipment, how can the international infrastructure's pursuit of the highest quality of R&D and manufacturing be reconciled with the requirements of *juste retour* when selecting national partners (academic, industrial) for co-operation?
- When an entirely new research capability is to be created, what are the advantages and disadvantages of developing it within an existing international research structure, versus an existing national entity, or an entirely new organisation? What special considerations apply to an organisation like CERN that is based on an inter-governmental treaty, is financed chiefly via cash contributions, and has a unique, custom-designed governance and administrated structure?
- To what extent, and how, can an infrastructure pursue societally beneficial goals that are separate from its main scientific missions, without detriment to those missions? What are the advantageous ways to proceed whenever such opportunities emerge spontaneously during the pursuit of the main scientific mission? If the exploration of the separate goals is deemed desirable, how can the communication, authorisation/accountability and governance structures be optimised for achieving positive outcomes? Is it possible, within defined limits, to use the infrastructure's budgetary (or other) resources to pursue the separate goals? What are good practices for ensuring efficient and accurate communication among all levels of the governance structure: from technicians, engineers and scientists, to the various management levels, and to the oversight body that represents the international partners?
- When research that may have practical/commercial applications is being carried out, how can the requirements of commercial confidentiality (notably, assertion of intellectual property rights) be reconciled with the culture of openness that is a hallmark of scientific research? Can the infrastructure itself develop marketable products based on spin-offs from its own research programmes?
- Can an infrastructure serve its national members as a general-purpose source of new technology and/or expertise? If so, how can the interests of the members be balanced?

- What are some good practices for establishing a Technology (or Knowledge) Transfer Office within the infrastructure, and which principles/procedures can best be applied, especially for managing financial and international issues? What is the extent to which staff members can undertake new activities based on their own initiative, going beyond those to which they have been assigned?

Questions such as these are being asked more and more as the importance of large research infrastructures continues to grow. In some research domains, the imperatives of the science itself require the creation of large infrastructures: that is, there is simply no other way to conduct the needed experiments, observations or computations. In addition, policymakers are confronted with daunting global-scale challenges that demand innovative, science-based solutions in areas such as health, energy, environmental protection, or food security. All components of the research enterprise, even those that are devoted to advanced cutting-edge research, are being solicited to address such global-scale challenges, sometimes with efforts that are on the same vast scale as the challenges themselves.

Given the high cost of state-of-the-art research infrastructures, policy makers and officials of funding agencies are increasingly relying on formal, systematic procedures for making key decisions about implementing new projects and programmes (or about upgrading or even terminating existing ones). Furthermore, in an effort to reduce costs, to share expertise, to optimise the global inventory of research resources (i.e. to avoid unnecessary duplication), scientists and policy makers are turning to the *internationalisation* of infrastructure projects. Hence, there is a demand for credible principles, methodologies, metrics, procedures, and good practices for assessing infrastructures of many different kinds.

For over 20 years, the OECD Global Science Forum¹ has performed analyses and developed recommendations concerning the planning, establishment and operation of large basic research infrastructures. The GSF's work has addressed generic issues (for example, access policies, roadmapping) and issues specific to individual scientific disciplines, namely (in chronological order) neutron sources, radio astronomy, high-intensity proton accelerators, nuclear physics, condensed matter research, high-energy physics, high-intensity lasers, structural genomics, astronomy and astrophysics, and astroparticle physics. This report, on the impacts of large international infrastructures, is thus a logical extension of past work.

The term “research infrastructure” needs to be used with some precision, since various definitions are in use in the international science policy arena.² The Global Science Forum uses the following taxonomy (with examples provided in *italics*):

¹ The OECD body was established as the Megascience Forum in 1992, and adopted its current name in 1999. Basic information about the Global Science Forum is provided in Appendix F.

² As an example of the diversity of definitions, the European Commission favours the following useful formulation: “... facilities, resources and related services that are used by the scientific community to conduct research in their respective fields and covers major scientific equipment and sets of instruments; knowledge-based resources such as collections, archives or structures for scientific information; enabling Information and Communication Technology-based infrastructures such as grid, computing, software and communication, or any other entity of a unique nature essential for achieving excellence in research. Such infrastructures may be ‘single-sited’ or ‘distributed’ (and organised network of resources).”

1. Facilities

- “Facility-scale Experiments”, for example: *CERN, LHC, ITER, JET, Pierre Auger Observatory*.
- User facilities for a small number of users, for example: *ALMA, SKA, big telescopes in general*.
- User facilities for a large number of users, for example: *ESRF, ILL, XFEL, FAIR, ESS, LSST*.

2. Distributed infrastructures (“Association or network of geographically-separated, distinct entities from more than one country that agree to jointly perform or sponsor basic research.”)

- Scientific measurement using multiple facilities:
 - Combining signals from a set of independent instruments, for example: *EVN, LIGO/VIRGO*.
 - Subdividing a large task among distinct institutions, for example: *AGRP, ICGC*.
- Co-ordination/integration of research based on a common scientific theme:
 - Co-ordination of a set of large infrastructures, for example: *ELI, GEOSS, ELIXIR*.
 - Co-ordination/integration of diverse projects/programmes, for example: *SIOS, GEM*.
 - Provision of resources/services, for example: *CLARIN, EMMA*.

iii. E-infrastructures

- Federation, storage, curation of large data sets: *GBIF, INCF, CESSDA, Lifewatch*.
- High performance computing and networking: *GÉANT, PRACE*.

Section B. Methodology

CERN leaders approached the OECD, an organisation that has an extensive track record of assessing publicly-funded activities, with the suggestion that OECD might analyse the laboratory’s impact(s) on the economy and society. They wanted a study and a report that reflected an external perspective, would not be seen as self-serving, and could serve as basis for further optimising the organisation’s policies and procedures. Such a report should also be of value to CERN Member States, allowing them to understand better the full range of outcomes that are enabled via their support for research at the laboratory.

The Global Science Forum agreed to undertake the study as an empirical, pragmatic exercise that would be of use to policymakers and research administrators, with no claims being made of universality, nor adherence to the standards of any particular academic school of thought, regarding the chosen methodology.

This study is qualitative rather than quantitative. Attempts have been made elsewhere to develop analytical methods, and to gather appropriate data, in order to derive statements of the form “X currency units invested by governments in fundamental research generates Y currency units in additional GDP (or jobs, or increases in quality of life indices)”. But these attempts (and results) have been criticised on

methodological grounds, and the Global Science Forum decided not pursue a quantitative study of this type.

When attempting to measure the outcomes of investments in basic research, it is not uncommon to express the results in terms of the number PhDs granted, and the number of peer-reviewed scientific publications.³ While these outcomes have the virtue of being relatively easy to measure, they do not always meet the practical needs of policy makers. Unless a research system has fundamental flaws or inefficiencies, the number of graduates and/or papers will rise monotonically with increases in resources (funding). The magnitude of the increase can be used to compare different systems (for example, across countries or regions) and can thus serve as a tool for assessing policy instruments (for example, various reforms of university systems), but it is not a powerful way of gauging the degree and variety of impacts. For this reason, such a metric is not used in this OECD study.

For the specific case of CERN, six impact categories are identified and briefly described in this report (Section C). In four of these categories, focussed data-gathering and analysis, in the form of case studies, were undertaken (Section D). The case studies were carried out using two sources of information: papers/articles (listed in the References) and notes from confidential telephone and face-to-face interviews with key individuals at CERN, with non-CERN experts and, for the study of the LHC main ring magnets, with current or former employees of the companies that manufactured the magnets.⁴ Typical telephone interviews lasted between one and two hours, while the face-to-face discussions were often much longer. A significant amount of valuable information was obtained from these interviews, much of it not available elsewhere. The 47 interviewees are listed in Appendix B.

Section C. Impact categories

As mentioned in Section A, an important goal of this study is to produce information and advice that can be useful in the establishment and optimisation of the organisational, managerial and governance mechanisms of large international research infrastructures. With this in mind, six impact categories have been empirically defined, grouped into two broad classes, based on the extent to which the impacts/outcomes are produced by researchers and happen “naturally” (being at the core of the facility’s mission), versus the extent to which their occurrence is merely a potentiality whose realisation is a function of needs, decisions and actions by managers/administrators, either at the laboratory or in the national agencies that fund the laboratory and participate in its governance at the highest level.

The first group – Categories I through Va – consists of non-discretionary outcomes. The second – Categories Vb through VI – consists of discretionary outcomes. The separation of impact categories into non-discretionary and discretionary is central to this study, the second group being of greater interest because the relevant impacts will not be realised unless managers/administrators positively desire them and allocate the required resources. Most of the information that was accumulated in the course of this OECD study, and most of the text of this report, concerns Categories V and VI. This is not to imply that impacts in Categories I through IV happen automatically or without effort.

³ For laboratories that are closer to applied research and that have more industrial users (e.g. photon and neutron sources), the number of patents obtained can be tracked as well.

⁴ The review of documents and the interviews were conducted by the Global Science Forum’s Executive Secretary, Stefan Michalowski, who also drafted this report.

Category I	Purely scientific results, intended to advance fundamental knowledge.	<i>Non-discretionary</i>
Category II	Direct impact of spending for construction and operation of the laboratory.	
Category III	Training of scientists, engineers, administrators, and other professionals.	
Category IV	Achieving national, regional and global goals; strengthening international scientific co-operation.	
Category V	Developing and diffusing technological innovations while pursuing the scientific mission.	
	Va Innovations needed for major component development / procurement, with both high-energy physics (HEP) and non-HEP impacts.	<i>Discretionary</i>
	Vb Non-HEP Innovations that can become external impacts with only minor modifications.	
	Vc Non-HEP Innovations that can become external impacts with major additional efforts.	
Category VI	Education (of teachers and/or students), and various forms of public outreach.	

Category I. Purely scientific results, intended to advance fundamental knowledge

This is the most visible impact category, given the main mission and activities of a laboratory. In practice, impacts of this type are achieved via measurements as well as associated theoretical investigations (which can be computational, analytic, or both), and they are embodied in peer-reviewed publications, pre-prints, theses and presentations. Short-term impacts can range from spectacular (in the case of a dramatic, unexpected finding or if a long-awaited result is finally obtained) to incremental (making a contribution to a systematic programme of exploration based on the time-tested method of validating or disproving theories via an accumulation of experimental evidence).

Long-term impacts on science, the economy and society are, typically, difficult to forecast and to assess. They can even be difficult to evaluate retrospectively, since science typically advances over a broad front, with many separate but interlinked discoveries producing overall societal change. The impact of any particular scientific result is hard to separate cleanly from that of many others. In addition, it is widely acknowledged that scientific and technological progress are closely intertwined, such that certain fundamental problems cannot be tackled unless technology (even commercial technology) is sufficiently advanced.

Scientists who undertake basic research may not be motivated by a desire to achieve concrete societal benefits. In some cases the emergence of benefits is a long-term and highly indirect process, such as when advances in understanding provoke a “scientific crisis” that then becomes a driver for breakthrough discoveries. These, in turn, can lead to large economic impacts many years later. Thus, for example, some one hundred years ago, the adoption of the atomic theory of matter led to a baffling prediction that the physical world should be unstable, i.e. the electrons of an atom ought to fall into its nucleus, causing all of ordinary matter to implode on a timescale of less than one second. Obviously, that theory needed a major revision. With time, the quantum revolution, which radically altered the atomic

theory, led to the development of semiconductors which enabled all of modern electronics, computing and communications.

This study and report were not designed to consider this category via case studies. The impact of progress in high-energy physics on society and the economy is a potentially fascinating topic, given the very esoteric nature of research in the field, and the intriguing linkages to other areas of advanced research. Impacts could occur in such areas as energy generation, communication or computation. But this type of prospective forecasting is not part of the current OECD effort.

From a purely scientific perspective, there is no question that the CERN laboratory has, during the past half-century, been one of the top institutions in its field. Even a cursory census of major discoveries illustrates this. As described in Appendix C, the Standard Model of Particles and Fields posits that there are a mere seventeen species of elementary particles, which, via various combinations and interactions, make up the entire physical Universe. Of these, seven could be considered as previously “known”, or “grandfathered” into the theory, without the attribution of a discoverer.⁵ Of the remaining ten, four were discovered at Fermilab⁶ (US), three at CERN,⁷ two at SLAC⁸ (US) and one at DESY⁹ (Germany).

Category II. The direct and indirect impacts of spending for building and operating the laboratory

Public funds are used to purchase equipment and utility services, to remunerate staff, and for many other purposes, including R&D for high-technology equipment. These funds then diffuse throughout the local (and, to a lesser extent, the more distant) economy, into such enterprises as manufacturing, construction, transportation, wholesale and retail trade, insurance, real estate, the tax base, etc.

When a major new high-energy physics (HEP) infrastructure is built, the funds are disbursed across a very wide spectrum of categories, from moving large quantities of earth and pouring vast amounts of concrete, to procuring unique high-technology components such as superconducting magnets and accelerating cavities. To a first approximation, the impact of many of these expenditures is short-lived and local. Looking more closely, long-term benefits, widely distributed, can occur from an overall increase in the prosperity of the community that surrounds the laboratory (for example, because of an increase of the local tax base). Other second-order benefits for the community can be linked to the influx of highly educated/skilled professionals (scientists, engineers, technicians, administrators, graduate students).¹⁰

This impact category assumes special importance during the course of planning and negotiations for implementing any new large international research infrastructure, because it is relevant to the challenging issues of site selection and agreeing on a “host premium”. The host country can be expected to derive greater benefits than the non-host partners, especially if those partners make their contributions in cash,

⁵ The up, down and strange quarks, the electron and its neutrino, the muon, and the photon.

⁶ The top and bottom quarks, and the muon and tau neutrinos.

⁷ The Z, W, and Higgs bosons.

⁸ The tau lepton and charm quark (the latter co-discovered at the Brookhaven National Laboratory).

⁹ The gluons.

¹⁰ An example of a quantitative investigation into this impact category is a study whose results were published in August 2011: “The Economic Impact of the Fermi National Accelerator Laboratory”, commissioned by the University of Chicago, prepared by consultants Caroline Sallee, Scott Watkins and Alex Rosaen. <http://www.uchicago.edu/research/economic-impact.shtml>.

but even when the contributions are made in kind. The importance of this effect can decrease somewhat if the international facility is exempted from local taxes for major purchases.

To a large extent, the direct economic impact category simply represents a transfer (via the laboratory) of public funds into the local economy. This category is not being considered in the present OECD study, although it would be interesting to inquire about the extent to which the “multiplier effect” of an investment in a basic research facility is greater or smaller than that for a more conventional large infrastructure such as an airport or a hospital.

In the case of CERN, and from a science and innovation policy perspective, a more interesting phenomenon is the indirect impact of spending, especially the medium- and long-term impact of procurement (i.e. a subset of total financial transactions) on firms that do business with the laboratory. This impact does not have to be local; indeed, the procurement process is designed to spread benefits among the Member States. An interesting study, covering the years 1973-1987, attempts to measure the “Economic Utility Resulting from CERN Contracts”.¹¹ Economic Utility is defined as the sum of increased turnover (sales) and cost savings. Turnover could be increased via development of new products, new marketing techniques and strategies, or improvements in the quality of existing products. Cost savings usually result from learning by company engineers, based on interactions with CERN staff. Only high-technology suppliers were considered in the study. There were deemed to be 519 of these out of a total of approximately 6 000. The authors of the study interviewed managers of 160 firms, asking them to provide quantitative estimates of the impacts of the CERN procurement contracts. The results are summarised thus: “The corrected utility/sales ratio is 3.0 which means that one Swiss franc spent by CERN in high technology generated three Swiss francs in Economic Utility. The overall cost of the Organisation during 1973-1982 was 6 945 million Swiss francs, which gives a value of about 0.6 for the ratio of corrected utility to total CERN cost. It may therefore be stated that, by 1987, CERN’s high technology purchases made during 1973-1982 will have generated Economic Utility amounting to about 60% of the overall cost of CERN during the same period.” Two figures from the report are shown below: breakdowns by industrial sector, and the evolution of sales and utility over time (including a five-year extrapolation).

¹¹ “Economic Utility Resulting from CERN Contracts” by M. Bianchi-Streit, N. Blackburne, R. Budde, H. Reitz, B. Sagnell, H. Schmied and B. Scorr. Publication CERN 84-14, December 1994. The findings and results of the report are extrapolated through 1987.

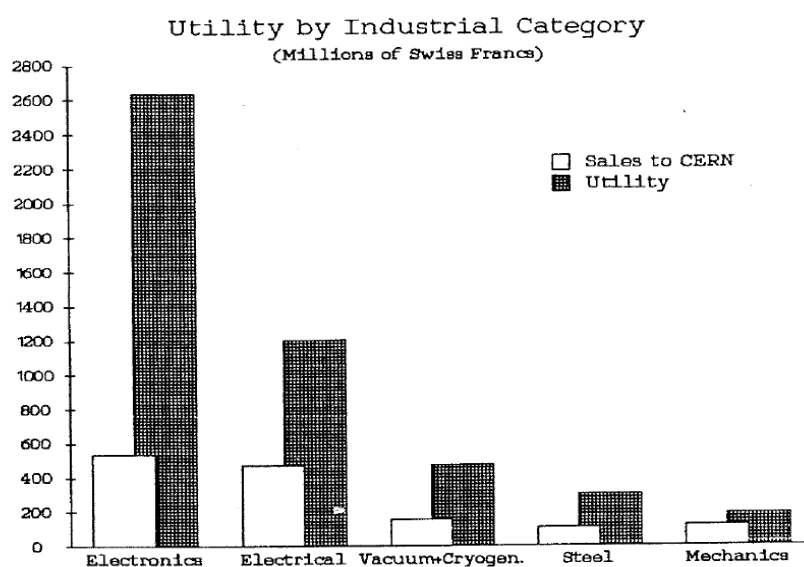


Figure 4: Total sales and total utilities from 519 high technology suppliers, broken down by industrial category.

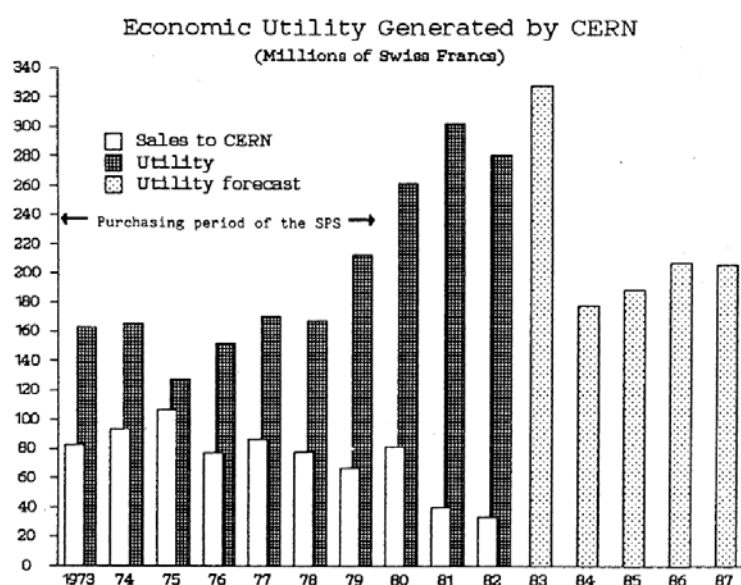


Figure 2: Yearly sales and yearly utilities from 160 firms interviewed.

Category III. Training for scientists, engineers, technicians, administrators and other professionals

The intellectual environment at high-energy physics laboratories is exceptional, and is probably comparable to that of the most innovative high-technology companies. This is particularly true during those phases of a laboratory's history when a new capability has just been realised; for example, when a new accelerator is being designed, when it begins operations, or when there is a major increase in performance (e.g. energy or luminosity). There is a constant interchange of ideas and information; an untiring pursuit of excellence; determination to produce results in a speedy manner; a casual acceptance of the most exacting scientific and technological standards (accuracy, reliability, safety, documentation, etc.); an ever-shifting pattern of personal contacts and spontaneous collaborations; an indifference to the conventional trappings of status; and a low tolerance for complacency or mediocrity. Personal ambition, drive, and academic or institutional stature are important for success, but the prevailing standard of achievement is merit, measured by concrete results.

This meritocratic environment is a favourable one for career development, both in terms of the absorption of knowledge and expertise, and for learning how to work collaboratively towards the achievement of common goals. Very few of the scientists, engineers and technicians at a HEP laboratory work in isolation. This is especially – and increasingly – true of the physicists who are members of the large detector collaborations.

The above advantages accrue to all who spend a few months or more at a HEP laboratory including, importantly, the significant number of people who move on to other employment opportunities in the field, or even other careers. At CERN, the staff policy of the organisation promotes mobility by offering fixed-term contracts to new staff. These can later be converted to indefinite contracts for the most valuable employees.

For academic researchers, the highly collaborative nature of large HEP experiments builds and reinforces many useful skills, but it does so at the expense of some qualities that characterised the field during some of its most productive years. A number of persons interviewed for this project expressed reservations about the emergence, however inevitable, of huge detector collaborations, and compared them unfavourably with the small- and medium-sized fixed-target experiments of the 1960s–1980s. In those earlier times, graduate students, post-doctoral fellows and even senior researchers would actively participate in all of the phases of the experiment, from designing, building and testing of the apparatus, to taking data, analysing it, performing the needed theoretical calculations, and preparing manuscripts for publication. A complete experiment could be performed in two or three years, whereas the lifetime of today's large detector collaborations can span decades. Indeed, it is possible for a graduate student to take part in only a single phase of an experiment (for example, testing and certifying a subcomponent of the large detector, or analysing data from a remote site on another continent).¹² The emergence of “mega-collaborations” involves, at least in some cases, a trade-off between the development of collaborative skills, and the reinforcement of other desirable attributes: creativity, flexibility, independence. Another shift in the structure of scientific careers has been the gradual decline in the number of experimental physicists who are also experts in accelerator theory and design. Some of the great pioneering figures in the field (e.g. Ernest Lawrence or Robert R. Wilson) were intellectual leaders in all aspects of experimental and theoretical physics. Arguably, there are fewer such polymaths in the field today.

¹² The degree to which careers of high-energy physicists have evolved towards the “big detector” model should not be exaggerated. All HEP facilities maintain small- to medium-sized experimental programmes. The development of some of the components of the big detectors (e.g. central tracker, calorimeter, muon chambers) follows more closely the complete, integrated student career model, combining exposure to work on hardware, software, theory and computation. This more traditional approach also applies to the development of many of the sub-systems of the accelerator complex.

For the purposes of this OECD study, little more needs to be said about this impact category, chiefly because it is bound to occur at any well-run research institution that is active at the frontier of knowledge in a highly visible, competitive, and prestigious scientific field. Explicit actions by funding agency programme managers and senior laboratory administrators play a lesser role in this category than in some of the others.

Category IV. Achieving national, regional and global goals; strengthening international scientific co-operation

When individual countries, or groups of nations, combine their resources to implement a large research infrastructure, they usually have a variety of motivations and goals, of which advancing scientific knowledge is only one. Among the non-scientific considerations may be economic, technological or industrial development, as well as political integration.

In the case of CERN, the ratification of its Convention by 12 West European countries in 1954 is widely recognised as a major milestone in the post-World War II recovery/reconstruction process. The creation of CERN sent a strong geopolitical signal regarding the desire of a group of former wartime adversaries to play a major independent role in the bi-polar Cold War configuration that had emerged on the continent. Over the years, however, CERN (and other high-energy physics laboratories on both sides of the Iron Curtain) took on yet another role: a venue where scientists from the major political/economic/military blocks could collaborate peacefully and constructively in pursuit of a common universal goal.

Today (2013) the global geopolitical landscape bears scant resemblance to the one in which CERN was established. Collectively, Europe is the world's largest economic block, and the process of European integration – economic, political, and scientific – is very far advanced. (For example, one-half of the CERN Member States have adopted the euro). In the realm of science, there exists a corpus of world-class *inherently international* research organisations, consortia and institutions, among them the European Southern Observatory (ESO), the European Space Agency (ESA), the European Molecular Biology Laboratory (EMBL), the Joint European Torus (JET). Europeans participate, both individually and collectively, in numerous large scientific and technological undertakings, such as the International Space Station, the International Thermonuclear Experimental Reactor (ITER), the Atacama Millimetre Array (ALMA), and the Square Kilometre Array (SKA). In the domain of science policy (i.e. planning, prioritising, designing, managing and assessing research projects) remarkable progress has been made via such mechanisms as the European Strategic Forum on Research Infrastructures (ESFRI), as well as the various roadmaps and joint initiatives in fields such as astronomy, astroparticle physics and nuclear physics. Increasingly, the European Commission has assumed a role in planning and implementing international research on the continent. Even though only some 4% of actual research funding in Europe passes through the EC (primarily via its successive Framework Programmes), the actual weight of the Commission's activities is much higher,¹³ given its co-ordinating and integrative functions, its ability to foster the development of co-operative mechanisms such as the European Research Infrastructure Consortium (ERIC), and the vital “seed funding” it provides to scientific initiatives during their very early, formative stages, when motivated groups of scientists need money for inexpensive but critical activities such as meetings, workshops and feasibility studies.

¹³ The EC's contributions are not always entirely visible. Thus, although ESFRI is not itself an EC activity, it has from the beginning been staffed by Commission personnel.

Categories V and VI. These categories are treated in detail in Section D.

Section D. Case studies of selected CERN impacts

The case studies bring together information about four impact-generating CERN activities. In accordance with the adopted procedure for the study and report, credible inferences were expected to result from an accumulation of a fairly significant amount of detailed material, gleaned from numerous documents and interviews. To emphasise the link between the methodology and the conclusions, the detailed material is included in the main text and footnotes, with only one portion of the text relegated to an appendix (“Introduction to the scientific rationale of the LHC project”).

Section D.1 Case study: LHC main ring dipole magnets

Section D.1.a Rationale for this case study

This case study pertains to Impact Category Va: “Innovations needed for major component development / procurement, with both HEP and non-HEP impacts”.

Scientists at high-energy physics laboratories perform experiments at the cutting edge of science. To reveal the most fundamental properties of the Universe, they create and manipulate the tiny sub-atomic constituents of matter – elementary particles – while subjecting these particles to extreme energies. It is hardly surprising therefore that the laboratories are users of some of the most advanced technology that is available in the commercial or academic sectors. At a laboratory such as CERN, it is not unusual to encounter the use of the fastest computers linked via the most sophisticated networks. The highest vacuums, the purest alloys, the densest arrays of detectors, enormous voltages and powerful electro-magnetic fields – all of these are staples of HEP research.

The requirements of such research sometimes go beyond the current state of the art, and the laboratory’s researchers need to create a new, original technological solution; in a word, to *innovate*. This section presents a case study of one such instance, when the CERN laboratory took the lead in designing and manufacturing a large number of big superconducting dipole magnets for the Large Hadron Collider (LHC). These magnets (of which there are 1 232, each 14 metres long and weighing 35 tonnes) bend the trajectories of the LHC’s two counter-circulating proton beams, so that the particles remain inside the evacuated beam pipes, and return to the interaction regions again and again.

Whether in industry, academia, or research institutions, technological innovation at the cutting edge is inherently difficult, costly, time consuming and risky. The objectives of this case study are to clarify the motivations for pursuing innovation, to explain the principles, strategies and mechanisms (both existing and new) that were invoked to cope with the challenges that emerged during this process, and to highlight the role of external entities that CERN turned to for support at critical moments. Concerning the last objective, the interaction with *industrial partners* needs to be highlighted, because these are entities that can serve to transfer the results of the innovation process to the non-HEP environment, potentially resulting in lasting benefits to the companies and, ultimately, to society.

The LHC dipoles are the natural choice for a case study that is focussed on technological innovation. In every major respect, these magnets are the dominant element of the entire LHC accelerator complex.¹⁴ Alternative case studies could have been the LHC’s cryogenic or vacuum system, but these,

¹⁴ This argument does not take into account the four large LHC detectors (ATLAS, CMS, LHCb and ALICE). The research, design and construction of these is the responsibility of CERN’s external collaborators (chiefly universities and national research institutions), with the laboratory making a contribution at the level of 20% of the total effort and cost.

while presenting numerous interesting challenges, were not characterised by the same degree of novelty and risk. Before LHC, no accelerator had ever used dipole magnets of comparable size and magnetic field strength. Moreover, contracts for the magnets constituted 50% of all LHC contract expenditures.¹⁵

It should be noted that accelerator main ring dipole magnets do not always present a major technological challenge. Thus, the LEP electron-positron collider, which had occupied the same 8.6-kilometre diameter tunnel at CERN, used dipoles with a mere 3% of the field strength of those of the LHC.¹⁶ The conventional (i.e. not superconducting) LEP dipoles were relatively “low tech”, although some ingenuity was needed to distribute the magnetic field in a uniform way along the particle trajectory.¹⁷ In the case of LEP, it was not magnets but the *accelerating cavities* that required the most R&D effort (especially for the upgrade to “LEP2”, using superconducting cavities that doubled the energy of the collider). Obviously, HEP laboratories do not engage in technological innovation for its own sake; they do it selectively, when needed, in order to achieve specific, ambitious scientific objectives, as shown below.

Section D.1.b Background and incentives for technological innovation

To understand why LHC proponents took on the demanding and risky task of designing and building a new, high-performance type of magnet, it is necessary to comprehend the rationale for the LHC project itself. This, in turn, requires an appreciation of both the scientific and political realities of the early 1980s. During that time, elementary particle physicists were strongly motivated to elaborate and, if possible, to validate the Standard Model of Particles and Fields – a single theoretical framework that was meant to describe and explain all (or nearly all) sub-atomic phenomena. A non-technical, greatly simplified description of the Standard Model is provided in Appendix C.

Computations based on the Standard Model were a basis for many theoretical predictions of phenomena that would be experimentally observed. The most conspicuous of these predictions was the existence of two new elementary particles: the top quark and the Higgs boson. The expectation was that both would be very massive particles, so that new powerful accelerators would be needed to produce them.

As physicists contemplated the prospects for new large facilities they naturally turned to the question of how to secure the needed large investments. Historically, public investments in the field were motivated not only by the search for scientific truth, but were linked to the intense rivalry between the

¹⁵ The other contract categories were: civil engineering (16%), cryogenic equipment (15%), technical services infrastructure (11%), other accelerator components (6%), and transfer lines, beam injector& dump (2%).

¹⁶ For particles of unit charge (such as electrons, positrons and protons) a simple expression links the magnetic field (B , in Tesla), the bending radius (R , in metres), and the energy of the particles (E , in GeV):

LEP collided electrons and positrons with energies up to 130 GeV, whereas the LHC is designed to collide protons at 7 000 GEV in the same tunnel as LEP, hence the need for a much higher magnetic field. Some care is needed when applying the above formula to any specific accelerator, because bending magnets do not fill up the entire circumference of the ring.

¹⁷ The ingenuity consisted, within each 5.75-metre long magnet, in separating the 1 000 low-carbon steel laminations (which were 1.5 mm thick) with 4 mm of poured concrete. During design and testing, it was found that embedding the laminations in a concrete matrix would not unduly affect their magnetic properties, but this result did not hold up when the magnets were manufactured and prepared for installation. A crash programme had to be organised: all 3 392 LEP magnets were subjected to a carefully controlled process of bashing with a hydraulic ram, thus relieving the internal stresses in the concrete and restoring the magnetic properties of the iron laminations. In the event, this unforeseen crisis did not delay the LEP schedule, but it illustrates the pitfalls and limitations of even the most thorough R&D programme. The LHC was not immune to these risks, as witnessed by the serious accident that damaged a significant part of the collider shortly after it was turned on in 2009. It resulted from flaws in the design and testing of the high-current electrical connections between neighbouring dipoles.

world's principal geopolitical entities as well. In the years following World War II, elementary particle physics enjoyed enormous prestige linked, in part, to its position at the apex of the entire scientific enterprise but also because of its perceived links to critical applications such as nuclear power and nuclear weapons. For many years, the two great Cold War rivals, the United States and the Soviet Union, competed via a series of ever-more-powerful accelerators. With time, they were joined by Japan, and by the nations of Western Europe, both individually (via national accelerator-based laboratories in France, the United Kingdom, Germany and Italy) and collectively through CERN.

For promoting and accelerating scientific discovery, the inter-regional rivalries had some distinct advantages. They acted as a driving force, inspiring scientists and engineers to work harder and to be more creative, so as to avoid being upstaged by their rivals. In addition, duplication is a traditional hallmark of the scientific method, providing a means of confirming results whose validity could be questioned on statistical or interpretational grounds.¹⁸

The discovery of the Z and W bosons (essential components of the Standard Model) at CERN in 1983 generated great excitement in the HEP community. Scientists were strongly motivated to study these particles in detail, thereby refining the Standard Model in many ways. Two electron-positron colliders, whose construction was already under way, would be able to produce the (neutral) Z boson, but the (charged) W particles would require significantly higher energies.¹⁹ The first machine to become operational was the Stanford Linear Collider (SLC). It made use of an existing linear electron accelerator, with the addition of an ingenious set of components that allowed the simultaneous production and acceleration of positrons, leading to collisions in a single large detector. Data-taking at Stanford commenced in 1989.²⁰

Beginning in 1976, studies at CERN had been under way, aiming to build the ultimate circular electron-positron collider, with a per-beam energy of up to 150 GeV, and an underground tunnel circumference of 25 kilometres or more. Such an accelerator would operate near the limit of performance: any effort to increase the energy of the electron (or positron) beams would be futile, since any added energy would be lost immediately via “synchrotron radiation”, that is, the emission of X-ray photons by the circulating electrons.²¹ Multiple design studies were carried out, optimising performance

¹⁸ Duplication is often practiced even at individual accelerator laboratories, especially in the case of circular colliders, where the counter-rotating beams of particles can be made to intersect at several locations. On more than one occasion, important results have been announced simultaneously by researchers from multiple detectors at the same laboratory.

¹⁹ In electron-positron collisions, charged particles have to be produced in oppositely-charged pairs, since the initial state is neutral overall, and charge must be conserved. Neutral particles can be produced individually in such collisions. The Z and W were discovered at the CERN proton/antiproton collider, with measured masses of 91 GeV/c and 80 GeV/c respectively. Thus, Ws are harder to produce than Zs in electron-positron colliders, even though they have lower mass. An electron-positron collider with an energy of 45.5 GeV per beam can produce neutral Zs, but it must achieve 80 GeV per beam to create pairs of charged Ws.

²⁰ SLC was explicitly designed to produce huge numbers of the neutral Z particles. No attempt was ever made to increase the energy for producing Ws. Mention should be made of the TRISTAN circular electron-positron collider at the KEK laboratory in Japan (1986–1996). Unfortunately, because of its limited size, its energy reach was below the threshold for producing Zs.

²¹ Electron-positron colliders with energies higher than 150 GeV per beam are eminently feasible but, to escape the limits imposed by synchrotron radiation, they must be linear, not circular. An international effort to design such a collider is currently (2013) in an advanced state.

The amount of synchrotron radiation that particles emit as they circulate in an accelerator depends very strongly on the rest mass of the particles, being many orders of magnitude smaller for protons than for electrons.

Synchrotron radiation has become an extremely useful tool for the study of condensed matter at the atomic level, including biological systems. Nearly all of the atomic-scale structures of proteins have been determined via X-ray crystallography at any of a large number of dedicated synchrotron light sources worldwide.

of this collider (dubbed LEP) based on stringent cost limitations imposed by CERN's Member States. Within these limitations the diameter and the length of the tunnel were chosen to allow for the future installation of a proton-proton collider, as proposed by the ECFA-LEP working group in 1979. When LEP construction was approved in 1981, it was decided that the collider would have an initial energy of 50 GeV per beam, allowing detailed study of the Z bosons. At the same time, a technology development programme for more powerful superconducting accelerating structures would be pursued, so that the energy of LEP could be raised to 100 GeV per beam or more. With such an upgrade (designated LEP2), the W particle production threshold would be reached. It was hoped that the top quark and the Higgs boson could be found as well.

In the late 1970s, some influential members of the US particle physics community began to worry that they were losing ground to their European rivals. In 1983, the discovery of the Z and W at CERN, and the cancellation of the ISABELLE collider project at Brookhaven National Laboratory (it was to be a proton-proton collider with beams of 250 GeV) only heightened their concerns. As a result, in that same year, an extremely ambitious plan was adopted to build a proton-proton collider that would eclipse any rivals for the foreseeable future and would become *the* focal point for HEP research, attracting the top scientists worldwide. This Superconducting Super Collider (SSC) was to be installed in an approximately circular 87-kilometre tunnel in Waxahachie, a suburb of Dallas, Texas. It was to collide proton beams of 20 000 GeV each – nearly ten times higher than ISABELLE.

The Europeans were hard-pressed to be internationally competitive with respect to an initiative conceived on such a vast scale. They explored the possibility of becoming partners in the SSC project but, according to their accounts, they were rebuffed by the Americans who were willing to accept donations of equipment (or even cash), and welcomed European participation in the experimental programme, but would not allow any role in the planning and administration of the project. So an opportunity for a truly global-scale collaborative project was lost.

Given the SSC challenge, a group of European physicists had in mind an audacious scheme that, if successful, would result in the Europeans reaping the first harvest of new physics results, using a smaller and less expensive proton-proton collider, to be installed in the existing LEP tunnel.²² It would be known as the Large Hadron Collider. The Europeans argued as follows:

- Based on existing data, and theoretical considerations, there was a good chance of making major discoveries (notably, the top quark, the Higgs boson and, possibly, the lowest mass supersymmetric particles) at energies just above those of the existing accelerators. For these discoveries, the very highest energy scales of the SSC would not be needed. A proton-proton collider with per-beam energies of 5 000 GeV or 10 000 GeV would be sufficient to skim off the most exciting results.
- According to the Standard Model, protons are composite objects: each is made of three quarks. The quarks continually exchange numerous gluons. Although, in everyday speech, SSC and LHC would be referred to as “proton colliders”, the collisions that actually matter and produce interesting results (for example, the creation of new particles) occur between the elementary constituents, i.e. the quarks and gluons. They, in turn, move back and forth inside the protons with very high speeds, so that the effective energy of some collisions is higher than if the

²² The first complete description of a proton-proton collider for the LEP tunnel is contained in an internal CERN publication (LEP Note 440) by Stephen Myers and Wolfgang Schnell, dated April 1983.

constituents were stationary inside the proton.²³ This complicates the analysis of the individual events, because the initial energy of the colliding entities is not known, but it means that the energy range of any proton collider is effectively extended upwards.²⁴ The exceptionally high-energy collisions are rare, since the momentum distribution of the constituents trails off at very high values. To take advantage of this effect, and to be competitive with the SSC, the LHC had to be endowed with a very high luminosity, that is, a higher rate of proton-proton collisions. It was hoped that this could be achieved at CERN via various ingenious manipulations of the beams.

- A collider that is designed with high luminosity to extend effective energy coverage will produce huge numbers of collisions that are of no scientific interest, but that send vast quantities of particles into the detectors, potentially overwhelming them with spurious signals. The LHC proponents were confident that advances in detector technology, electronics, and computational science could be used to overcome this difficulty.
- As an established accelerator laboratory, CERN had some inherent and important advantages over the SSC, which was going to be built on an empty (“green field”) site on the outskirts of Dallas:
 - The already-existing LEP tunnel with caverns in the interaction regions.²⁵
 - An existing accelerator complex for creating proton beams that would be injected into the new machine.
 - Experienced teams of scientists, engineers, technicians and administrators, working within a mature, time-tested governance structure.
 - Physical infrastructures such as buildings, power distribution stations, cooling towers, roads, dormitories, cafeterias, computers, test equipment, etc.
 - Strong, long-standing links to academic and research institutions, industrial contractors, and other HEP laboratories.

In a remarkable instance of long-term foresight and planning, leading scientists and managers at CERN began exploring the feasibility of installing a proton-proton collider in the LEP tunnel, and they did so *even before* the final configuration for LEP was chosen. Indeed, the prospect of installing *two* colliders (each with two counter-rotating beams) was considered carefully when the final LEP parameters were set.²⁶ Vigorous debates took place regarding this hadron collider option, with a special

²³ This internal motion of the constituent quarks and gluons is a very significant effect. Indeed, the mass of an ordinary proton at rest is several hundred times higher than the sum of the masses of the three quarks of which it is made, while the gluons are massless. The mass of the proton derives primarily from the enormous binding energy contained in the gluon field or, in other words, from the extreme motions of the quarks that are captured by the powerful strong interaction field that confines them inside the tiny volume of the proton. This energy manifests itself as mass according to the famous expression $E = mc^2$.

²⁴ This effect does not exist in the case of electron-positron colliders such as LEP, since the colliding particles have no structure. When comparing the two types of colliders, a rule of thumb is that, in proton machines, the collisions of the fundamental constituents occur at an effective energy that is one-tenth of the energy of the protons.

²⁵ In the event, the two biggest LHC detectors (ATLAS and CMS) required the excavation of entirely new caverns.

²⁶ Having both electron and proton colliders operating simultaneously would also have allowed the study of electron-proton collisions. In the event, this option was never realised, although it did influence the layout of LEP in the tunnel (for example, the magnet ring was installed low to the ground, leaving free space for a second ring). At some stage during the R&D process, the idea of simultaneously operating LEP and the LHC was quietly abandoned. This may have been linked to a certain disappointment with quality of the scientific results that had been obtained at the German HERA electron-proton

urgency due to the international competition and rivalry.²⁷ In the end, it was decided to build a tunnel for LEP that was as big as financial constraints would allow, in order to be able, at some future date, to install the proton-proton collider. In this way, CERN took up the challenge of competing successfully with the bigger, more powerful SSC. The elements of the challenge were:

- *Energy and luminosity*: to achieve the scientific goals (and making educated guesses about the masses of the top quark and the Higgs boson), a per-beam energy of 10 000 GeV was desirable. To benefit from effects linked to the composite nature of the proton, the luminosity had to be a factor of ten higher than that of the SSC.
- *Cost*: A way had to be found to develop and build the new machine without increasing the annual CERN budget, and while completing and operating LEP.
- *Size*: The new collider had to fit into the free space above LEP or, if that was not feasible, in the existing tunnel then occupied (but to be vacated) by LEP.
- *Schedule*: The new collider had to begin operations at about the same time as the SSC, circa 1999.

Once the above constraining parameters were recognised, it became clear that only one major obstacle stood in the way of realising the LHC: there was no credible design or experience with the *dipole magnets* that would be needed to guide the counter-rotating beams of protons around the circumference of the collider. The required field strength was approximately 10 Tesla (T), so it was understood that the magnets would use superconducting coils to support the enormous electrical current requirements. The Superconducting Super Collider, being much bigger in circumference, could make do with a magnetic field of 6T, despite the higher energies of the beams. Other superconducting accelerators used even lower fields, as shown in Figure 1 and the Table.²⁸ All of these machines used coils manufactured from a superconducting alloy of niobium and titanium (NbTi), immersed in liquid helium at a temperature of 4.2 K (i.e. 4.2 degrees centigrade above absolute zero). Unfortunately, such magnets cannot reliably produce the magnetic field that would be needed for the LHC. CERN designers considered using coils made from the chemical compound niobium tin (Nb₃Sn) but this advanced material was deemed to be unsuitable for the LHC.²⁹ Instead they settled on NbTi in a bath of “superfluid” helium at a temperature of 1.9 K. This involved a series of trade-offs and serious design challenges.³⁰

collider, but also for practical reasons: it was simply deemed too difficult to fit both magnet rings in the tunnel, with their supporting structures and components. In the end, LEP was removed entirely before the installation of LHC began.

²⁷ A potential alternative to responding so directly to the challenge of the SSC would have been to make a major commitment to a very high energy *linear* electron-positron collider. In Europe, the DESY laboratory in Hamburg was the home of this initiative, which continued even after most of the European funds were committed to the LHC, and transformed itself into the XFEL project – a source of coherent ultra-high intensity X-rays for condensed matter research. XFEL is currently under construction. A linear collider has been of great interest to the HEP community for many years. The community agreed that design and R&D for the linear machine would be a globally-co-ordinated effort involving major laboratories (the leaders of this initiative were three laboratory Directors: Burton Richter (SLAC), Hirotaka Sugawara (KEK) and Bjorn Wiik (DESY). Today (2013) the design effort has been successfully concluded, but the major funding needed for construction has not been secured.

²⁸ Besides LHC, LEP and SSC, the table shows the parameters for other accelerators and colliders of interest, notably the contemporary Russian UNK machine, which was conceived as a “fixed target” machine, but could be converted to a proton-antiproton collider or, with the addition of a second ring of magnets, a proton-proton collider. The UNK magnet development programme was completed and a tunnel was excavated in Protvino near Moscow (interestingly, it had the biggest cross section – 7 metres – of any accelerator) but funding for the project was terminated before construction could be completed.

²⁹ CERN designers were familiar with the difficulties that had been encountered when an attempt was made earlier to develop Nb₃Sn magnets for ISABELLE at the Brookhaven laboratory. Nonetheless, they pursued an R&D effort, in collaboration

The space constraint was quite severe, especially if designers wanted to preserve the joint LEP/LHC option. In the case of the SSC, designers opted for two separate rings of magnets, one placed on top of the other (as shown in Figure 1).³¹ There was not enough room above the LEP ring for this configuration and, in addition, the cost of two sets of magnets would have been prohibitive. So the LHC dipoles were configured with a unique “2-in-1”, “twin-bore” design, with the coils and beam pipes for the two counter-rotating proton beams contained in a single evacuated insulated cryostat (Figure 2).³² The magnetic field that guides both beams is generated by all of the coils and forms a single integrated magnetic circuit. As can be seen in Figure 1, this innovative solution was not used for any other collider. There was scepticism (for example about the quality of the magnetic field) among some experts but, from the CERN perspective, the design resulted in considerable space and cost savings³³. European physicists were confident that their considerable experience with superconducting magnets would allow them to successfully meet the technological challenge.

with the Austrian company Elin, that resulted in a one-metre long, 10 Tesla, single bore prototype. This was an encouraging result, but it was felt that there were insufficient resources to continue with two parallel magnet R&D efforts, and the niobium tin work was halted in 1990. Among the reasons for this were doubts about the mass manufacturability of these magnets, whose coils become superconducting only after they are wound and heated to a high temperature. Even then, they tend to be quite fragile mechanically. Today (2013) after an interval of more than twenty years, niobium tin is being used in the very high-field magnets of the ITER fusion tokamak at Cadarache, France. Niobium tin magnets are also being considered as an option for a future energy upgrade of the LHC.

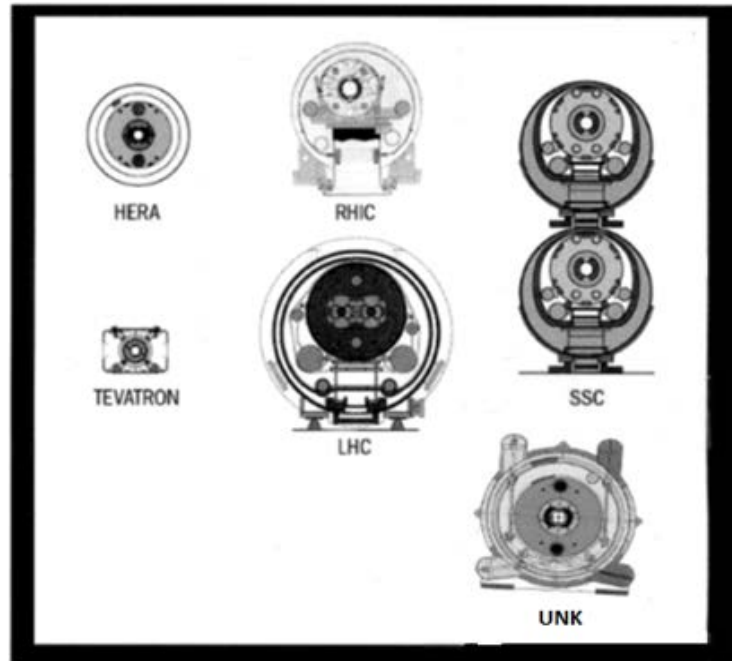
- ³⁰ On the positive side, NbTi coils at the lower temperature can maintain their zero-resistance (superconducting) properties in the presence of an enormous current load and high magnetic field, which they cannot do at the higher temperature. Also, superfluid helium has some remarkable and very desirable properties: zero viscosity (allowing it to flow freely in the tight spaces inside magnets without the need for pumps, thus cooling the coils more effectively), a very high specific heat, and very high thermal conductivity (so it can absorb lots of heat and rapidly move it away from the coils). On the negative side, the specific heat of the niobium titanium alloy is several times *lower* at 1.9 K, meaning that even small depositions of energy in the coil (caused, typically, by friction when the coils undergo small displacements in response to enormous magnetic forces) can raise the temperature to a point where the superconducting properties are lost: a phenomenon known as “quenching”. The resulting sudden release of the huge amount of energy stored in the magnetic field, if not properly managed, can damage the magnet.
- ³¹ It is sometimes claimed that this solution was not available to LHC planners because of the smaller cross section of the LEP tunnel (this tunnel thus being a “poison gift” for the LHC). But, in fact, the two tunnels were approximately the same size, about 5 metres in diameter.
- ³² According to some accounts, the details of this design were first studied in the 1960s at the Brookhaven National Laboratory by Hildred Blewett (1911-2004), one of the first women accelerator physicists of the 20th century. Based on the abbreviated description in this report, it should not be concluded that the final design that is shown in Figure 2 emerged at the very beginning of the R&D process. Several variants of the 2-in-1 approach were studied (analytically, computationally and, in a few cases, experimentally) before the design was finalised. In particular, the final design has no iron yoke material between the two bores (the collars are made of non-magnetic stainless steel). This was a money-saving but controversial choice and was only accepted following extensive analysis and testing.
- ³³ The persons interviewed for this report estimated that the cost savings from adopting the 2-in-1 design were approximately 15% - 20%, because of lower manufacturing costs, and lower costs for smaller quantities of certain materials and finished components (for example, a single cryostat, one magnetic yoke).

Table 1. Comparison of accelerator design parameters

	LHC	LEP2	Tevatron	SSC	UNK	HERA	RHIC
Colliding beams of	p, p	e^+, e^-	p, \bar{p}	p, p	Fixed tgt then p, p	p	p
Momentum at collisions, TeV/c	7	0.1	0.98	20	3	0.03	0.25
Peak luminosity, $\text{cm}^{-1} \text{s}^{-2}$	10^{34} (design)	10^{32}	4.3×10^{32}	10^{33}			
Dipole field at top energy [Tesla]	8.33	0.11	4.4	6.5	-3, +5	5.2	3.4
Fraction of energy lost in synchrotron. rad., per turn	10^{-9}	3%	10^{-11}				
Tunnel length [km]	27	27	6.3	87	21	6.3	3.8
Tunnel diameter [m]	4.3		1.00	13.8	3.3		
No of dipoles	1232	3368		7664/7944	2168	416	264
Dipole length [m]	14.2			15	5.8	8.8	9.7

Source: Expanded from Brüning et al, Progress in Particle and Nuclear Physics, 2012 (CERN-ATS-2012-064).

Figure 1. Accelerator dipole magnet cross-section, drawn to the same scale

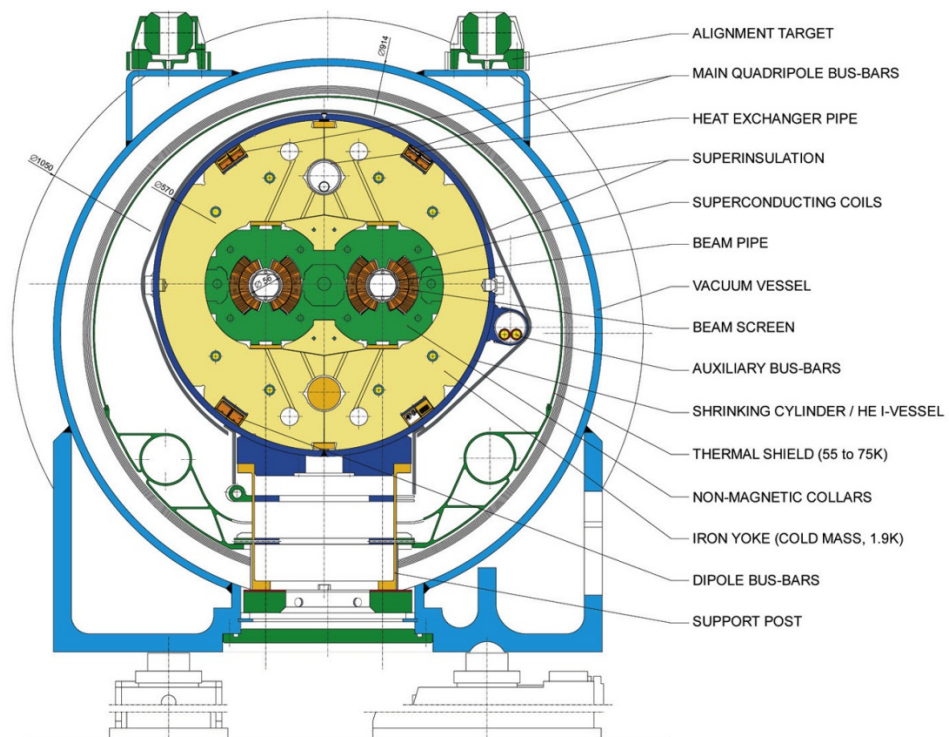


Source: Adapted from L. Rossi, CERN Courier, 25 October 2011.

Figure 2. LHC dipole magnet cross-section

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



Source: CERN.

Section D.1.c Dipole magnet research and development

The R&D process for the dipole magnets lasted from 1985 to 2001, when the call for tender was finally issued for serial industrial production of over 1 200 magnets. It is a complex story involving many individual and institutions, impossible to relate in detail in this report. The following are highlights that were derived from the interviews and from written materials. The chosen highlights are ones that allow the extraction of relevant conclusions (Section D.1.e).

- At the outset, there was very limited experience at CERN in designing and building superconducting magnets.³⁴ The R&D process was one of learning, chiefly from laboratories, institutions and companies with which CERN had already established close links over many years. Of greatest importance and utility were the two accelerator projects that were actually built and operated: the Tevatron at Fermilab (US) and the HERA³⁵ electron-proton collider at DESY (Germany).
- A basic proof-of-concept prototype magnet had to be made and tested first. CERN produced a design for a one-metre, single-bore magnet, but the laboratory had neither the facilities nor the funds to manufacture it. The Italian company Ansaldo offered to produce it *at no cost*, using superconducting cable provided by CERN. There had been a long-standing collaboration between the Italian Institute for Nuclear Physics and Ansaldo-Componenti, EM-LMI (Europa Metalli, later La Metalli Industriali) and E. Zanon for research, development and production of high-field superconducting magnets. As part of this programme, 242 superconducting dipoles³⁶ for HERA had been built, as an in-kind contribution to the project funded by the Italian Government. According to Ansaldo officials, the “gift” of the single-bore magnet to CERN was a sensible investment in the future, although the primary corporate focus at the time was on potential contracts for the SSC³⁷ rather than LHC, whose prospects were still regarded as uncertain. The company seconded an engineer and a draftsman to CERN for the duration of this prototyping project. The magnet was delivered in 1986. It was tested at CERN at 1.9 K, installed in a vertical cryostat that had been manufactured in Spain, funded in part by a large Spanish industry association. The test results were highly satisfactory. A field strength of 9T was achieved, vindicating the basic concept of a magnet with niobium titanium coils immersed in superfluid helium.
- The design and manufacturing of the NbTi *cables* for the LHC was an enormous challenge. There was already considerable experience with such cables, notably the pioneering work linked to the Fermilab Tevatron, but also for HERA, ISABELLE and the SSC. Physicists and engineers from these projects shared their ideas, experiences, and even material samples with their CERN colleagues. At least two of CERN’s major industrial contractors (Alstom-Jeumont and Ansaldo Supraconduttori) already had significant experience in using the type of cable that

³⁴ This experience included the “low-beta” insertion quadrupoles for the Intersecting Storage Rings, a small number of beam-steering magnets, and the large magnet for the Gargamelle bubble chamber. Little of this experience was directly relevant to the LHC dipoles.

³⁵ HERA collided 920 GeV protons with 28 GeV electrons. Only the proton ring magnets were superconducting. The collider was operational from 1990 to 2007.

³⁶ Strictly speaking, the company delivered “cold masses”, that is, assemblies consisting of coils, collars and yokes (plus other associated components) shown, for example. The cryostat and various other elements were produced elsewhere, and the final assembly and testing were performed at CERN. This was the case not just for the various prototypes described in this report, but for the final production runs by the main contractors as well.

³⁷ In fact, Ansaldo was a bidder (in partnership with the Grumman Corporation) for producing SSC dipoles.

would be used for the dipoles. But more R&D was needed because the LHC constraints called for higher magnetic fields, greater current densities, stronger internal forces, and lower operating temperatures. Furthermore, there were complications linked to the dynamics (i.e. the time-dependant characteristics) of the LHC. The magnetic field, and thus the current in the coils, has to increase as the injected beams are accelerated to the values at which collisions of the beams can be usefully studied. This produces undesirable transient effects that must be counteracted with special coatings, manufacturing techniques, etc. These effects appeared prominently during the implementation of the HERA dipoles, and the lessons learned were passed on to the CERN designers. Additional R&D was done at CERN, some of it quite late in the development process, well into the 1990s.

- The *mechanical properties* of the superconducting magnets had to be carefully analysed and accounted for in the design. The coils carry enormous currents. They are immersed in the strong magnetic field that they themselves generate, so the resulting mechanical forces are extremely large. Even the smallest resulting displacement can lead to a deposition of energy, a rise in local temperature, and a sudden loss of superconductivity that can quickly propagate to the entire magnet. This, in turn, results in a sudden release (and conversion into heat) of the enormous energy that is stored in the dipole magnetic field.³⁸ Since the coils are made of (relatively) soft metal, they must be carefully constrained by the collars and yokes. All the components must therefore be manufactured and assembled with very strict tolerances, taking into account the significant changes in the properties of the many disparate materials contained in the dipoles, and the changes in these properties as the magnets are cooled from room temperature to less than 2 degrees Kelvin above absolute zero.
- After the initial success, more one-metre prototypes, this time with two bores arranged in various configurations, were designed at CERN and manufactured, under contract, by companies in several European countries (Ansaldo, Jeumont Schneider, Elin, Holec). They were tested at CERN, using the Spanish cryostat and superfluid helium. Concurrently, design and prototyping began for full-length³⁹ (10-metre) twin-bore dipoles. Use was made of the coils that had been developed for HERA at DESY, even as research continued on the high-performance coils that would be needed for LHC. For lack of a large cryostat, early testing had to be performed in France, at the *Commissariat à l'énergie atomique* (CEA) research centre at Saclay near Paris, where components for a large scale-fusion experiment ("Tore Supra") had been tested. When funds became available, CERN purchased a full-sized cryostat (in 1993).
- With the acquisition of a large cryostat, CERN was ready to build and test a series of full-scale prototype dipoles, and to settle on a final design. But with the laboratory's budget nearly fully committed to the construction of LEP, research and development for the LHC could not proceed without assistance from outside entities. Luckily, CERN's French and Italian partners were able to offer timely help. The CEA Saclay centre was able to pick up the design, prototyping and manufacturing effort for the 392 superconducting twin-aperture *quadrupole* magnets that, together with the dipoles (and other smaller magnets such as sextupoles, octupoles, decapoles, etc.) make up the LHC ring. The quadrupoles share many design features

³⁸ The amount of energy stored in the LHC's dipoles is enormous: at the peak design field strength it totals eleven Gigajoules – the equivalent of the chemical explosive energy of over two metric tonnes of TNT.

³⁹ The final production LHC dipoles are actually 14.2 metres long. The increase in length lowered the total cost, since fewer magnets (each with complex, costly structures at both ends) needed to be produced. There was, of course, a trade-off: designers had to solve the problem of the finite curvature imposed by the 14-metre length, which could be ignored in the shorter models.

with the dipoles, and they are slightly easier to manufacture since the internal magnetic forces are lower during operation. Nonetheless, the contribution from CEA was especially helpful, since all of the finished quadrupoles (including the cryostats) constituted a supplementary in-kind contribution to CERN from France (where the cost was split by the CEA and CNRS/IN2P3 agencies).

- A major boost to the dipole R&D effort was provided by INFN, which ordered to and collaborated with Ansaldo Componenti, LMI and Zanon for two full-length prototypes.⁴⁰ This critical contribution by Italy was over and above its general financial contribution to CERN. Working through INFN, the Italian government wished to put the Italian companies in a strong position for winning the expected large future contract for dipole production. The magnets arrived at CERN in the spring of 1994 and were assembled into the first two-element “string”. Successful tests were carried out during the summer. The results were broadly positive and led directly to the final approval of the LHC by the CERN Council in December of 1994. CERN purchased more dipoles for the R&D and testing programme in 1995 (they were manufactured by Austrian, German and French companies) but the fundamental decision to go ahead with the LHC had already been made.
- As the CERN R&D programme was moving forward, the Superconducting Super Collider, whose projected cost kept rising, was losing the support of the United States Congress. The story of this demise is a complex one and, to this day, it evokes regret and some bitterness among American particle physicists. The project was definitively cancelled in the fall of 1993, after some 2 billion dollars had been spent.⁴¹ At CERN, the news was greeted without satisfaction, since the rivalry, though very real, had never been acrimonious. In any case, the Europeans felt that, with a more innovative accelerator, they were ahead in the race for the first physics results. Indirectly, the impact on the LHC project was positive, since, in subsequent years, the United States government made a major contribution to LHC in the form of 200 million dollars-worth of magnets (notably, superconducting quadrupoles) and related equipment for focussing the beams at the experimental interaction regions. Contributions from non-CERN countries had an important impact on the LHC schedule. Without them, the collider might have had to begin operations without a significant fraction of magnets installed and, hence, at a lower beam energy. In any case, with the cancelation of the SSC, LHC’s scientific *raison d’être* was secure, despite significant slippages in the LHC schedule.⁴² In the event, the first proton-proton collisions took place in November 2009, some ten years later than the earliest optimistic projections.

⁴⁰ Twenty years later, one of these prototype magnets is still in use. It is incorporated into the CAST experiment at CERN - a search for exotic, hypothetical axion particles that could be generated in the centre of the Sun. None has been found to date.

⁴¹ It might interest the reader to know that the creation of the OECD Megascience Forum (MSF, precursor of the Global Science Forum) in 1992 was linked to the abandonment of SSC. As the project encountered financial difficulties, U.S. officials unsuccessfully sought contributions from other countries. To avoid such situations for future projects, these officials then conceived the idea of a standing international committee of senior science policy officials who could consider the prospects for new large international collaborations in a timely way. They were able to persuade officials of OECD countries of the value of this idea, and thus the MSF was born in 1992.

⁴² This *raison d’être* necessarily changed, however, when the top quark was discovered in 1995 by two research teams at Fermilab’s Tevatron proton-antiproton collider. This time, no Nobel Prize was awarded to the experimentalists, although Makoto Kobayashi and Toshihide Masakawa did share the 2008 prize for developing, in the early 1970s, the relevant theoretical framework. Fermilab scientists worked hard to detect the Higgs boson, but were not successful. After LHC began operations, the Tevatron was shut down (September 2011). Later, analysis revealed a weak Higgs signal in the data.

Section D.1.d Procurement, manufacturing and testing

During the first years of post-WWII high-energy physics, it was not unusual for an individual laboratory to be the site of design, R&D and manufacturing of successive accelerators and detectors. Many particle physicists prided themselves on being accelerator experts and engineers as well. With time, and with the growing size and complexity of accelerators, increasing differentiation and specialisation took hold. “Accelerator physicists” and “particle physicists” became two separate groups. For some important accelerator components, certain tasks could be confided to industrial companies, some of which began to specialise in fulfilling contracts for research organisations. The tasks included manufacturing and, to some extent, R&D and testing. Still, for any individual accelerator project, there is a range of options available concerning distribution of roles and responsibilities among the principal actors: the accelerator laboratory, affiliated research institutions, and private companies.

Because CERN is an international inter-governmental organisation, Member States are free to define the procurement principles and procedures without having to conform to all of the requirements of the host (or any other) country. These principles and procedures are especially important to the organisation, since the Member States make their contributions to CERN *in cash*. They have an expectation that some significant fraction of this cash will return to them in the form of contracts to national companies for goods and services. But, alongside this desire for *juste retour*, there is an additional desideratum: conducting purchasing via open competitive calls and awarding contracts to the lowest bidder(s), regardless of nationality, provided that quality and performance requirements are met. There is an inherent tension between these requirements and, as a result, procurement rules and practices are constantly monitored. Occasionally, they are changed.

As already described, the design, research and development phases for the main ring dipoles were carried out chiefly at CERN, albeit with important contributions from other research organisations and in collaboration with a small group of high-technology companies. When the time came to manufacture the approximately one thousand dipole magnets for the LHC ring, CERN managers decided to continue with a highly centralised strategy; that is, they retained direct responsibility, decision-making and control for the critical scheduling, purchasing, manufacturing, assembly and testing functions. Based on the interviews that were conducted for this study, it appears that their motives for this were threefold: (1) they wanted to *minimise risks* by being themselves responsible for quality control and for resolving any technical or organisational problems; (2) they needed to *control the schedule and costs* and felt that they could manage the complex manufacturing problem more cheaply in-house, and (3) there was *no realistic alternative* since there were no contractors who were able and willing to undertake the entire magnet manufacturing project.

By adopting the above strategy, CERN became both supplier and customer with respect to the various firms. During the R&D phase, CERN staff completed full design specifications not just for the components of the dipoles, but for the manufacturing and testing procedures as well, and even the one-of-a-kind tooling that would be needed. CERN engineers and administrators drew up all of the specifications, purchased raw materials, delivered them to selected manufacturers, and received the resulting components which they then provided to other contractors for further processing or assembly. For example, once the specifications for the all-important niobium titanium cables were finalised, CERN placed orders for the necessary raw materials (including the very special variety of copper which makes up a significant fraction of the cable mass), delivered them to the cable manufacturing company, and then provided the finished cable to the three main contractors who wound the coils and assembled the “cold masses” (coils+collars+yokes+numerous smaller magnet components) that were delivered to CERN. A similar procedure was used for the steel collars (which keep the coils in place) and the iron yokes (which shape the magnetic field).

In this way, CERN retained control, but it also incurred risks and responsibilities in case delivery schedules could not be met or if the designs did not meet requirements. In addition, this process involved a significant expansion of CERN's contracting bureaucracy.

The procurement contract for coil winding and the assembly of the dipole cold masses was the largest LHC contract and was closely scrutinised within the CERN governance structure, including the Council. The number of European companies that had the necessary expertise to credibly bid for the contract was necessarily very small, but still the procedure was not straightforward, and the rules had to be adjusted before success could be achieved. Initially, CERN put out a call for bids for one-eighth of the ring (160 cold masses), specifying a target price (and providing an incentive if the actual final cost was lower than the target, plus a penalty if the target price was exceeded). No acceptable bids were received, and the process had to be re-designed. Given the small number of potential bidders and the pressure to achieve *juste retour* goals, the competitive nature of the procurement was significantly reduced. In the end, identical fixed-price contracts were negotiated with three companies: Ansaldo Superconduttori (Italy), Alstom-Jeumont (France) and Babcock-Noell (Germany). Even these discussions were lengthy and difficult, given the very severe financial pressures at CERN and the unwillingness of the contractors to take on excessive degrees of risk.

During contract execution, CERN engineers and managers exercised strict oversight, and they enforced mechanisms whose goal was to ensure quality and uniformity of the assembled cold masses. Even though the three contractors were competitors in the high technology domain, they were asked to share techniques and good practices that they developed. A resident CERN engineer was present on the premises of each company, monitoring the assembly and supervising the testing programme. CERN experts had to take responsibility for proper testing, because the performance specifications did not originate with the contractors, whose engineers and technicians could not always be expected to understand all of the intricacies of the design. Thus, for example, various mechanical shims needed to be placed inside the assemblies in just the right way, so that the magnets would achieve the correct physical configuration after they had been cooled down to 1.9 degrees above absolute zero. But the low-temperature testing could only be performed after delivery to CERN, since no liquid helium was available at the contractor sites.

There were some limited opportunities for the contractors to make original contributions to the effort. Thus, coil-winding machines were developed separately by the three contractors. In the case of the collaring presses, Ansaldo used a device that was purchased by INFN, Alstom's was purchased by CERN from another company, whereas Babcock-Noell designed and built their own press. The welding presses were built at CERN and sent to all three assemblers. Generally speaking, however, the contractors did not have much leeway for achieving desired results with lower expenditures. Because almost all of the procedures were so precisely defined in advance, there was little margin for innovation during manufacturing and assembly – hence, few prospects for boosting profits, even though the volume of production was substantial. Although it is impossible to know with certainty, none of the companies seem to have lost money on the contracts. Still, their original motivation for seeking the CERN contracts went beyond short-term financial considerations. They viewed their work for CERN as an opportunity for technological learning in an area with – they hoped – high commercial potential.

During the late 1980s and early 1990s, low-temperature superconductivity, while by no means a new phenomenon,⁴³ was perceived as a potential source of very diverse (and lucrative) commercial applications, chiefly in the transportation and energy sectors. There were hopes for developing levitated trains, and propeller-less ships with magneto-hydrodynamic propulsion. High-capacity energy storage,

⁴³ It was discovered in 1911 in Leiden by Dutch physicist Heike Kamerlingh Onnes.

long-distance transmission lines, high-current switching equipment, transformers, generators for nuclear power plants, tokamak fusion reactors – all of these were seen as potential markets and sources of profits. Naturally, a publicly-financed project at the cutting edge of applied superconductivity was seen as an excellent source of expertise, especially since the CERN engineers were eager to share all of their know-how (and more tangible resources such as computer programmes) which would hardly have been the case for a contract offered by a private company. The contractors can hardly be faulted for not anticipating the gradual fading of the vision of a superconducting future.⁴⁴ To an extent, the vision was side-tracked by the emergence, in the late 1980s, of “high-temperature” (as opposed to liquid helium, cryogenic) superconductors, which lose electrical resistance at liquid nitrogen temperatures. While promising, these have yet to find wide-scale commercial applications. Two commercially-viable medical cryogenic applications have emerged: cyclotrons for hadron therapy, and magnetic resonance imaging (MRI) scanners. At least one of the three LHC magnet contractors is active in these areas.

Regarding the long-term impact on the three contractors of the magnet assembly contract, a mixed picture emerges. One of the companies is no longer involved in superconductivity at all, based on a decision by senior management to re-direct the company towards other markets. Another contractor has adopted a much more positive attitude and is very much present in the business of supporting high-tech research. It intends to compete for contracts that are on the horizon and that involve superconducting magnets of various kinds, but also other high-technology assemblies for experiments and facilities. There are research infrastructures with such potential needs in several domains (notably fusion and astroparticle physics). Not least among potential future customers are CERN and the LHC. Already, plans are being made to upgrade the luminosity of the collider (which would involve, *inter alia*, the development of new, very high-performance superconducting magnets) or even an energy upgrade (in which all of the dipoles would need to be replaced). However, these potential sources of contracts would be publicly funded, and the potential for a large “civilian” market opportunity (i.e. one that is not restricted to pure basic research) is perceived to be low.

All of the contractors’ representatives who were interviewed for this study judged the CERN experience to be a positive one. They praised the CERN staff who were generous in transferring knowledge and were responsive to each company’s concerns. The companies use their LHC connection in their advertising and feature it on their web sites.

Section D.1.e Conclusions concerning the dipole magnets

CERN as a generator of technological challenges and solutions

At the beginning of Section D, an implicit question was posed: why do HEP laboratories innovate? The LHC and, in particular, its dipole magnets, was an undertaking that required the creation of considerable intellectual added value. As explained above, there had been no previous experience with the large-scale deployment of magnets with the required performance characteristics. These requirements emerged when it became clear that they were needed to realise the next chapter in CERN’s history as a leading HEP laboratory. The scientific imperative for a large proton-proton collider was clear, given the need to test the predictions of the Standard Model. But the imperative for the LHC combined scientific motivations with those based on international rivalry in the field (chiefly, competition with the SSC) and

⁴⁴ Among the reasons for the relatively meagre spin-off potential of cryogenic superconductivity is that the lack of resistance to the flow of electric current applies only to steady currents, and tends to disappear when the currents are time-varying. This effect had to be carefully taken into account in the design of the NbTi cables for the LHC dipoles. The effect is more serious when the currents vary very rapidly (for example, in electrical generators). But it does not entirely preclude the use of low temperature superconductors: for example, radio frequency (RF) cavities, made with pure niobium, in particle accelerators such as LEP and LHC.

the desire to preserve the standing (perhaps even the existence) of CERN itself. Even in the face of severe constraints (a finite budget and a commitment to the LEP collider as the highest priority) it was concluded that CERN could still win the scientific race, and guarantee its future for several decades, but only by building a massive new accelerator and, necessarily, developing magnets with unprecedented performance characteristics. Thus, in this case, the source of technological innovation was international competition in basic research, and long-term strategic planning by an established, mature, prestigious international organisation. Although it is impossible to prove, it may be doubted whether, without CERN, European countries could have responded to the American challenge at the frontiers of particle physics. The perceived rejection of a partnership for implementing the SSC, involving Americans and Europeans on equal terms, inspired the latter to respond creatively on their own.

The ability of CERN to undertake a project with the scope of the LHC was made possible by its mandate, status, and history, but also some entirely practical factors. CERN was big enough to accommodate the various early stages of the project (conceptual design, examination of various options, preliminary R&D) without detracting from its on-going authorised and funded activities. In addition, CERN was the home of some of the top experts in accelerator design, who had advanced knowledge and access to extensive international networks, and who were equipped with the tools needed to develop an ambitious but realisable long-range plan, sometimes working in parallel with, and in addition to, their primary work assignments. The ability to innovate was linked to a certain degree of flexibility, and a certain amount of leeway, in the management and internal accounting procedures of the organisation. Creative, ambitious individuals are attracted to organisations of this type, such that (as in the other case studies described in this report) success breeds success in innovation.

The LHC initiative was, to some extent, a gamble: innovation and creative use of existing resources as a way of confronting a major external challenge. In proposing a risky strategy, CERN leaders could point to a successful precedent from the late 1970s: the conversion of the SPS proton accelerator to a proton-antiproton collider combined with the implementation of the highly innovative technique of stochastic cooling of the antiprotons. That venture had paid off handsomely with the Nobel-winning discoveries of the W and Z bosons. Thus, successful innovation inspires and generates the confidence that spurs further innovation.

Risk management and governance

In surveying the strategy chosen by CERN during the dipole magnet project, one striking characteristic emerges: almost all of the added value was produced at CERN. Early on, CERN experts decided on the unique technological characteristics of the magnets and then they systematically identified and solved the hundreds of challenges, great and small, that stood in the way of producing a design that could be handed off to industrial contractors for mass fabrication. It is true that the CERN experts benefitted from the knowledge, experience and concrete accomplishments of their many external partners, as described below. It is also the case that the results that they obtained were then made freely available to all interested parties. But almost everything that was truly new was produced at CERN and not contracted out to external entities. The rationale for this emerged clearly during the interviews: it was the only strategy that was compatible with adequate *risk management*. That is, given the demanding time, schedule and cost constraints, CERN staff could not transfer the responsibility to anyone else, at any price. While some of the companies that CERN worked with had already manufactured superconducting magnets for particle accelerators (most notably for the HERA collider at DESY) they did not have capabilities that would have allowed them to bid on a contract that included a sizeable amount of research and development.⁴⁵ Even if the companies had expressed interest in receiving such

⁴⁵ The case study concerns the dipoles, but a similar history – and conclusions – pertain to another critical LHC sub-system: the production and circulation of superfluid helium for the superconducting dipoles, quadrupoles, sextupoles and decapoles

contracts, and boosting their research capabilities accordingly, the costs would have been prohibitive, and CERN would not have accepted the associated risk.⁴⁶

A major priority for CERN administrators was to avoid any chance of being forced to engage in legal proceedings with under-performing contractors. Even if they were to obtain satisfaction in such proceedings, and a recovery of costs, the delays could have jeopardised their chances of achieving the overarching scientific goals. To prevent this, they maintained strict oversight, and were willing to devote internal CERN resources, when problems occurred during manufacturing (even when, strictly speaking, the resolution of the problems was a contractor responsibility).

Requirements for multiple vendors/contractors and for *juste retour* can be difficult to reconcile with optimal risk management. There may be situations in which *juste retour* requires the awarding of contracts to companies that would not be chosen if price, performance and minimisation of risk were the only selection criteria. Even if all the contractors were of equal quality, their multiplicity could generate risk, as CERN learned when one of the three main contractors became insolvent, having been acquired by another corporation. Luckily, the details of the contract were such that the problem could be resolved, but it did create temporary anxiety.

CERN's ability to manage risk by putting in place a system of strong control and oversight of its industrial partners is dependent on its status as a certain kind of international research institution: one based on annual *cash contributions* from its Member States. In its calls for tender, it is free to specify the degree of control that it wishes to exercise. If (as is, and has, been the case for other large international research undertakings) it was based on *in-kind contributions* of major components of the infrastructure, it would have had to delegate much of the oversight to the contributing partners. While there are potential benefits of an in-kind scheme (for example, each contributor is responsible for delivering components that function correctly, regardless of the cost and effort) there are risks as well. Not only is it difficult to deal with partners who don't deliver (in terms of quality, performance or schedule) according to their commitments, but there is a significant effort associated with on-site system integration of sub-assemblies that are manufactured elsewhere. History shows that, for in-kind projects, this effort tends to be underestimated and, hence, under-funded. It should be noted, however, that an in-kind strategy can succeed. Thus, the large LHC detectors were implemented this way, as was the HERA electron-proton collider at DESY (in Hamburg, Germany, operational from 1992 to 2007).

CERN's conservative risk-management strategy, based on generating almost all intellectual added value in-house, had a significant impact on the type of technological learning that was experienced by its contractors. Necessarily, it was more passive than it would have been had the contractors been presented with performance specifications for R&D, rather than detailed production-ready designs. To be sure, passive learning can be effective: engineers from one of the interviewed contractors asserted that they could now independently design and build a large superconducting magnet system. Through their

(the latter two types of magnets were needed to correct for undesired higher-order components in the fields of the main dipoles). There was no precedent, in either industrial or research environments, for the implementation of a superfluid distribution system on such a large scale. The challenges were formidable, and were linked to the very unusual properties of the liquid (e.g. zero viscosity).

⁴⁶ This approach can be usefully contrasted with that in the space and astronomy research sectors. CERN's equivalent in the former domain is the European Space Agency (ESA). Unlike CERN, it conducts no intramural R&D, but relies instead on a network of academic institutions and industrial firms. Among the latter are some that are experienced designers and manufacturers of satellite-based research infrastructures such as telescopes and sophisticated sensors of many kinds. On the other hand, the European Southern Observatory, which operates a number of world-class optical and radio telescope facilities, is much closer to CERN in its operating mode. Like CERN, ESA and ESO are formal international inter-governmental organisations.

interactions with CERN engineers, they had acquired not just the needed basic knowledge, but practical tools as well, such as computer programmes for modelling different magnet designs.

The role of external entities

A recurring theme of this study and report is how CERN makes use of its status as a long-established, high-profile international research institution. CERN is one of the central nodes in a world-wide network of research-oriented organisations (institutions, agencies and companies) that share and exchange knowledge, research tools and, at times, people. With an extensive history of designing, implementing and exploiting a series of accelerator-based facilities, CERN has made major contributions to this network and, more importantly for the purposes of this case study, benefitted extensively from the work of external entities.

When the ambitious performance parameters for the LHC dipoles were formulated, there was insufficient in-house knowledge and experience, so the subsequent external contributions were of great importance. These came from affiliated and associated research institutions (and their national funding agencies) and from companies that were candidates for contracts. In the former category, mention has already been made of how relevant know-how and information concerning high-field superconducting magnets was made available by engineers involved in Fermilab's Tevatron, the Superconducting Supercollider project, Brookhaven's ISABELLE, and DESY's HERA. The fact that some of these laboratories were CERN's rivals for global pre-eminence in experimental elementary particle physics did not impede the exchange.⁴⁷ During the magnet R&D phase, some of the benefits to CERN had a decidedly tangible character, most notably the undertaking by the CEA Saclay laboratory of (essentially) the entire superconducting quadrupole effort. There were numerous important contributions by Italy's INFN as well.

CERN's industrial contractors made useful contributions during both the R&D and procurement phases. Among the three main cold mass assemblers (who were, among other tasks, responsible for winding the coils using superconducting cables provided by CERN) there was considerable relevant experience from previous CERN and non-CERN projects (especially the large contract for manufacturing the HERA dipoles).

Several interviewed experts stressed the importance of maintaining a viable, globally-integrated effort in accelerator R&D, covering a broad range of relevant technologies, such as magnets of various kinds, accelerating structures, vacuum and cryogenic systems, beam diagnostics, as well as research into advanced accelerating concepts, going beyond the use of radio frequency cavities and with a potential for revolutionary advances in energy, intensity, size or energy efficiency. Maintaining a robust accelerator R&D programme, co-ordinated among the various national bodies that fund basic research, was seen by the interviewees as a wise long-term strategy, even during periods when it cannot be directly associated with a specific accelerator project.

⁴⁷ Interestingly, little information was shared between CERN and the Russian UNK project – a residue of the long-standing tensions, even as the Cold War was ending.

Section D.2 Case study: hadron cancer therapy

This Section pertains to Impact Category Vc: Non-HEP Innovations that can become external impacts with major additional efforts.

Section D.2.a Introduction to hadron therapy

Cancer is the third-leading cause of death worldwide,⁴⁸ with one person in three developing the disease in his/her lifetime. Cancer occurs when normal metabolic processes are disrupted in a single cell, causing it to multiply uncontrollably, often resulting in the appearance of a macroscopic tumour.⁴⁹ Some of the cancerous cells can then move to other parts of the body, giving rise to secondary tumours, a process known as metastasis – that can overwhelm the body, resulting in death.

There are four ways of treating cancer (often applied in combination): surgical removal, chemotherapy, targeted therapy,⁵⁰ and radiation therapy. This last method can involve the implantation of radioactive materials next to a tumour, or the destruction of malignant cells by exposing them to beams of elementary particles: photons (X-ray radiotherapy), electrons or hadrons.⁵¹ The hadrons, in turn, can be neutrons, protons or light nuclei. This case study describes CERN's contribution to an advanced, innovative form of radiation therapy: the destruction of tumours using beams of carbon ions.

When charged particles impinge on cells (whether healthy or diseased) they deposit energy via ionisation: that is the intense electromagnetic fields of the incident particles cause the ejection of electrons from molecules inside the cells – molecules such as water, proteins, carbohydrates, lipids, acids, etc. The ionised molecules may subsequently disintegrate, or may enter into various chemical reactions, some of them damaging to cells. These molecules, and the ejected electrons, can disrupt the DNA molecules inside cellular nuclei.⁵² While cells are able to repair DNA to some degree, a properly dosed quantity of radiation (especially one that can cause multiple breaks in a short stretch of DNA) makes it impossible for the irradiated cells to multiply further, and can even destroy tumour cells completely. However, the effectiveness of the method is limited by the extent of radiation damage to nearby healthy cells, especially when a tumour has formed in the vicinity of a vital organ (the eye, the liver, the brain, an artery, etc.).

To understand the advantages and limitations of different forms of radiation therapy, it is necessary to consider in some detail the effects of particle beams as they enter and propagate in living matter:⁵³ Figure 3 shows the dose delivered by various types of beams, as a function of the depth of penetration.

⁴⁸ The number one cause of death is cardiovascular diseases, followed by infectious and parasitic diseases.

⁴⁹ This description of cancer and of cancer therapy is necessarily highly simplified. There are many different forms of cancer, affecting various organs in diverse ways.

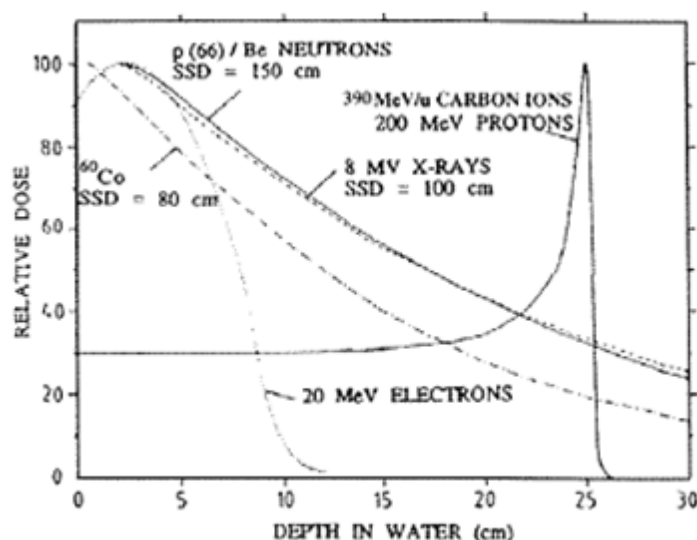
⁵⁰ Targeted therapy involves administering medications that interfere with specific biochemical processes in cancerous cells, as opposed to chemotherapy, in which drugs are used to impede rapid cell division throughout the body. Ideally, the specificity of targeted therapy produces fewer harmful side effects.

⁵¹ The term “hadrons” refers to elementary particles that are composed of quarks, held together via the exchange of gluons (the carriers of the strong, or nuclear, force). Protons and neutrons are “baryons”, each composed of three quarks. There are also “mesons” (for example, pions) that contain only two quarks. Accelerators can produce these two-quark particles, and their therapeutic properties have been studied, but the line of investigation has been abandoned.

⁵² Particle beams can also damage DNA molecules directly by “knocking” some atoms (or groups of atoms) out of the double helix, although this effect is important only at the very end of the hadron trajectory.

⁵³ The figure actually shows doses of radiation in *water*, not human tissue. Obviously, such measurements are easier to make. It is assumed that various amounts of energy deposited in water have an equivalent effect on DNA in living tissues.

Figure 2. Energy deposited by particle beams, as a function of depth



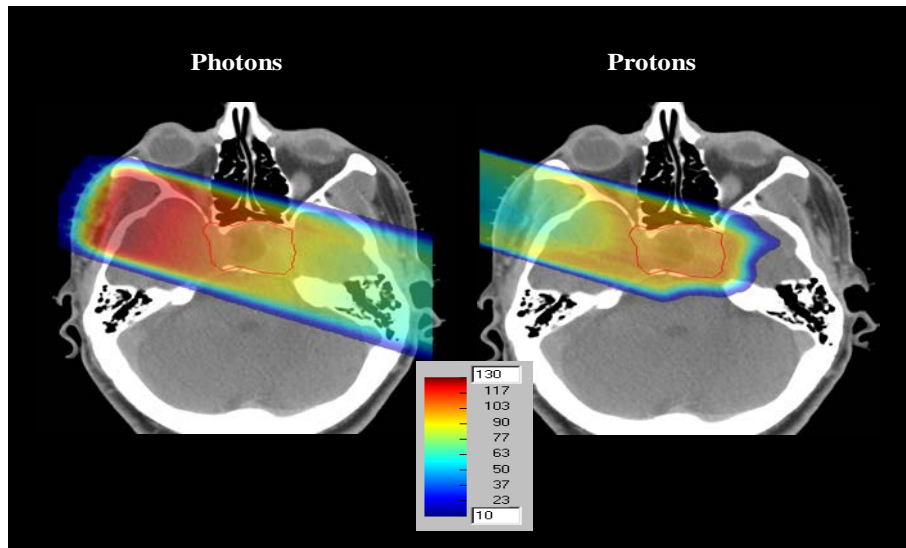
The conspicuous feature of this graph is that, in the case of protons and carbon ions, a significant fraction of the energy is deposited in a narrow depth range near the endpoint of the trajectory. This part of the energy-deposition curve is called the “Bragg peak”.⁵⁴ The depth of the maximum energy loss depends on the energy of the beam; in the case shown, it is approximately 25 centimetres at a beam energy of 200 Megaelectron-Volts (MeV) for protons or 390 Megaelectron-Volts per nucleon for carbon ions. Thus, by properly aiming and adjusting the energy of a hadron beam to correspond to the location (and the shape) of the tumour inside the body, damage to the tumour can be maximised while minimising the impacts on healthy tissues. In contrast, photons (X-rays) produce damage to tissue (both cancerous and healthy) all the way along the path of the beam (in the graph, their energy deposition curve is labelled ^{60}Co). The figure below shows the colour-coded intensity of energy deposition for X-rays (left) and protons (right) impinging on a human head, with a tumour located behind and in between the eyes. The advantage of using hadrons is clear: maximum energy deposition coincides with the tumour, whereas, in the case of X-rays, the maximum exposure occurs in healthy tissue at or near the surface of the skin.⁵⁵

⁵⁴ The existence of the Bragg peak for protons and ions, but not for photons, can be understood intuitively as follows: if the deposition of energy in a microscopic volume is proportional to the amount of time that the particle spends there, then protons and ions will deposit more and more energy as they slow down, until they stop. X-rays, being photons, do not slow down – they are constrained to move always at the speed of light.

The peak for hadrons is named after Sir William Henry Bragg (1862-1942), who discovered the effect in 1904. He shared the 1915 Nobel Prize in Physics with his son, Sir William Lawrence Bragg (then 25 years old, and the youngest laureate ever, even to this date).

⁵⁵ In actual practice, the source of X-rays rotates around the body. The beam impinges from different angles, thus decreasing the dose delivered to individual healthy tissues.

Figure 3. Colour-coded doses of radiation deposited by X-rays and proton beams



Source: Paul Scherrer Institute.

The possibility of exploiting the Bragg peak for cancer therapy was first proposed in 1946 by one of the pioneers of experimental elementary particle physics and accelerator design, R. R. Wilson,⁵⁶ who was working at Harvard University, and at the Radiation Laboratory at the University of California, Berkeley.

The first clinical trials with patients were conducted at accelerator laboratories that were dedicated primarily to fundamental research in nuclear and particle physics. As the benefits of proton therapy for specific types of cancers became apparent, the first dedicated facilities were established, optimised for receiving patients and, typically, linked to large hospitals. Proton therapy is now readily available in industrialised countries. The tables in Appendices D and E are lists of facilities that are either operational or under construction.

While proton therapy is by far the most prevalent form of hadron therapy, the notion of using beams of heavier nuclei has been under consideration from the very beginnings of the field, including in R. R. Wilson's seminal paper of 1946. The potential advantage derives from the stronger electromagnetic field of a larger nucleus containing more protons, with greater resulting ionisation and, hence, more damage to malignant cells. But many complicating phenomena must be taken into account when weighing the pros and cons of ion therapy. Thus, for example, large nuclei can break apart as they traverse a patient's body, sending ionising fragments (some of them unstable, i.e. radioactive) into surrounding tissues. In addition, the beams can activate these tissues, inducing radioactivity that can, over many years, actually *add* to the risk of formation of a new cancer.⁵⁷ For these, and other, reasons, ion therapy is limited to using light nuclei. Among them, carbon appears to offer the greatest benefits, although its neighbours in the periodic table (boron, nitrogen, oxygen) may become ions of choice, depending on the results of future research.

⁵⁶ Robert Rathbun Wilson (1914-2000) was one of the most creative and dynamic particle physicists of the twentieth century. When he proposed exploiting the Bragg peak, particle beams had already been used for cancer therapy on an experimental basis for several years. Wilson's was the driving force behind the establishment of the US National Accelerator Laboratory (which was founded in 1967, and renamed "Fermilab" in 1974).

⁵⁷ When assessing the utility of radiation therapy, it must be borne in mind that DNA damage can kill tumour cells, but it can also make healthy cells cancerous. The trade-offs are the subject of much analysis, experimentation, and some disagreement among experts. These are complicated by the fact that the negative consequences of radiation sometimes only manifest themselves many years after the exposure.

From a medical perspective, there are differences between the therapeutic effects of protons and of ions, depending on the properties of the particles and the nature of the cancerous tissue. For example, the amount of oxygen in the tissue (linked to the presence of blood vessels surrounding the tumour) has an impact on the nature of the damage to DNA. It is impossible to do justice in this report to the complexities of the relative advantages and limitations of different types of radiation therapies for different types of cancer, taking also into account the effects on the patients (e.g. the duration and number of treatment sessions) and the costs of the treatments. It may simply be asserted that while some nine out of ten of all the patients treated today with X-rays can be treated via proton therapy (with the attendant benefit of sparing healthy tissues), about 5% of patients could benefit instead from a carbon ion treatment. These patients have so-called "radio-resistant" tumours which resist to both X-rays and protons, but can be controlled by the much greater ionization of a carbon ion beam. Many clinical trials have still to be performed to determine which tumours should be irradiated with what carbon ion doses.

Proton therapy facilities use cyclotrons to produce the beams, but to accelerate ions, a synchrotron is needed. As can be seen by examining Figures 5 and 6, the former tend to be simpler and more compact (and, hence, less expensive).⁵⁸ Medical cyclotrons are available from commercial vendors as complete "turnkey" installations, including subsystems for beam delivery, patient support and orientation, software for treatment planning and monitoring, maintenance and training. While basic cyclotron technology is mature, innovations are still being pursued. Thus, for example, the MEVION Corporation is marketing a very compact accelerator that is mounted on a robotic arm, allowing the source of the beam to impinge on the patient from many directions, reducing damage to healthy tissues. This superconducting accelerator is equipped with coils that are made from the compound niobium tin, mentioned already in Section D.1.b.

Worldwide, only a handful of treatment centres offer synchrotron-based carbon ion therapy. There are three in Japan (Chiba, Hyogo and Gunma), one in China (Lanzhou, with another under construction in Shanghai), and two in Europe (Heidelberg and Pavia, with a facility in Wiener Neustadt nearing completion). There are plans for developing ion therapy in the United States, Russia, Brazil and other countries. Bringing carbon therapy to Europe was a difficult and ambitious task, requiring major technological, political, organisational and financial efforts. The fact that CERN was able to play an essential role in this undertaking says much about the laboratory as a source of innovation in Europe.

Section D.2.b History of CERN's involvement in hadron therapy

CERN's involvement in hadron therapy began in 1986, when a multidisciplinary group of experts met at the laboratory to design a feasibility study for a light-ion accelerator-based medical facility. The chief proponent was accelerator physicist Pierre Mandrillon of the *Laboratoire du cyclotron* in Nice, France. Mandrillon had worked at CERN immediately after receiving his doctoral degree, and knew the laboratory well. His goal was to obtain funding from the Commission of the European Communities (today's European Commission) for a design effort that would consider the full range of relevant issues: accelerator and beam delivery design, theoretical and empirical studies of the cancer-fighting effectiveness of various ion species, patient treatment protocols, and the economics of hadron therapy within the European context (e.g. the number of patients that could benefit from hadron therapy,

⁵⁸ On the other end of the size spectrum, it is worth mentioning the existence of much larger, more powerful cyclotrons, used for fundamental research in nuclear physics. For reference, today's biggest machine is installed at the RIKEN Radioactive Ion Beam Facility near Tokyo. Equipped with superconducting magnets, with a diameter of 20 metres and a weight of 8 300 metric tons, this cyclotron can accelerate uranium ions to an energy of 350 MeV/nucleon. Very recently, physicists have begun exploring the prospects of developing very large, advanced cyclotrons for producing intense neutrino beams for research in fundamental elementary particle physics.

reimbursement of costs under national insurance schemes). Above all, Mandrillon wanted the feasibility study to go beyond the consideration of purely theoretical issues, and to produce a practical, economically-viable accelerator design that could subsequently be implemented by national or regional authorities.

As a result of the CERN meetings (followed by numerous consultations) a proposal was prepared, and funding was obtained from the CEC for a two-year project, dubbed EULIMA, that began in 1989. There were participants from several European laboratories, co-ordinated by a small group that was based in the Proton Synchrotron (PS) Division at CERN. Initially, the Division provided some free in-kind support to the project (e.g. the use of two offices). Once funding from Brussels became available, a formal arrangement was concluded to reimburse CERN for the use of various resources. The laboratory provided a supportive environment for EULIMA even before the project was funded, that is, during the critical and vulnerable phase when many worthwhile initiatives wither for lack of even modest resources. Senior CERN managers, including Directors-General Herwig Schopper and Carlo Rubbia, were fully briefed and supportive of CERN's contribution to EULIMA.

From the beginning, the key deliverable of EULIMA was to be an advanced design for an affordable light-ion accelerator, optimised for the medical application.⁵⁹ Going into the study, the preferred choice was a compact superconducting *cyclotron*. While this option was certainly explored, the fact that the project was based at CERN had a major impact on the final outcome. CERN has always been (and continues to be) a centre of expertise in *synchrotrons*.⁶⁰ Since 1982 CERN had been operating a relatively small synchrotron/storage ring, the Low Energy Antiproton Ring (LEAR) of approximately the right configuration for ions.⁶¹ Various CERN experts, notably Pierre Lefèvre (the chief designer of LEAR) contributed their knowledge and experience to the EULIMA analyses and deliberations. A critical technological contribution was the “slow extraction” of particles from the circulating beam – a necessity for delivering a proper, and carefully dosed, amount of radiation to patients. CERN experts had abundant experience in this domain, since fixed-target high energy physics experiments work best when particles arrive on target at a controlled, uniform rate. As a result, while the advantages and limitations of both fundamental designs were fully explored, the final report came squarely down on the side of the synchrotron, a result that was not greeted with universal satisfaction, especially among some of the originators of the project.

EULIMA ended rather abruptly in 1991 with the end of CEC funding. But, a short time later, hadron therapy appeared again as an explicit CERN activity. This time, the undertaking of this work was linked, at least in part, to the momentous political events that changed the face of Europe.

The term “Central Europe” is imprecise, but it corresponds roughly to the area within which the Iron Curtain was erected after World War II. With the end of the Cold War, a number of thoughtful persons began to speculate about restoring the economic, political and cultural importance of this region which, in the past, had played such an eminent role in European affairs. Specifically, scientists in Austria were able to persuade some leading political figures to support the establishment of a major scientific facility

⁵⁹ This is not to detract from the other results obtained by the EULIMA team, for example measurements (carried out at CERN, but also at GSI in Germany and GANIL in France) of the radiobiological effects of various light ions, or original contributions to the designs of the giant beam-delivering moving gantries.

⁶⁰ Technically speaking, all of CERN's main accelerators have been synchrotrons, including both fixed-target machines (PS, SPS) and the storage rings/colliders (ISR, SPSppbar, LEP, LHC).

⁶¹ Unlike most synchrotrons, LEAR, which was in use from 1982 to 1996, was designed to *decelerate* particles (anti-protons) for use in basic physics experiments. These particles were produced in collisions between high-energy protons from CERN's main accelerator, the Proton Synchrotron (PS), and a fixed target. In 1996, LEAR was converted into the Low Energy Ion Ring (LEIR) to provide beams of lead nuclei for injection, acceleration and collision in the LHC.

in that country, to provide a central, visible and prestigious venue for regional scientific activities. In the early days of this initiative, the exact nature of the facility was not specified, and various possibilities were brought forward by members of Austria's scientific community.⁶² Gradually, the plan that gathered the most support was the construction of a high-intensity neutron spallation source.⁶³

The concept of a Central European spallation source had special appeal due to the world-wide concern (in scientific and technological circles) about the threat of a “neutron drought”, brought about by the gradual shutting down of the first post-war generation of nuclear reactors, which had been the main producers of neutrons before spallation (accelerator-based) sources were invented.⁶⁴ Replacing these reactors with new ones was an increasingly dubious proposition, especially after the accident at Three Mile Island in 1979, and the Chernobyl disaster of 1986. Already, the European Spallation Source (ESS) initiative was under way, with many design and feasibility studies being conducted. The only (pulsed) spallation source in Europe was the ISIS facility in the United Kingdom. At the time, Europe was, arguably, the world leader in neutron-based research, but there was concern among the continent's scientists about maintaining this lead in view of plans for constructing very large spallation sources in the United States and in Japan.⁶⁵ Already, an association of neutron source proponents had been created in Central Europe, known as the “Pentagonale”.⁶⁶ It brought together neutron specialists from Austria, Italy, Yugoslavia, Hungary, and Czechoslovakia. This was the context within which the AUSTRON neutron source initiative was born. CERN was to play an important role during the emergence, development and demise of this initiative and, most importantly, in its remarkable transformation into MedAustron, a major new facility for hadron cancer therapy.

As Austrian officials debated the choice of the scientific initiative that they wished to champion in Central Europe, CERN Director General Carlo Rubbia emerged as an influential proponent of the neutron source option. Given the status and prestige of CERN in Europe, the opinion of any CERN D-G is bound to carry considerable weight, but Nobel laureate Carlo Rubbia was an especially effective advocate. He was known as a vigorous and highly knowledgeable supporter of powerful accelerator-based neutron sources for two (combined) critical applications: energy production and the treatment of radioactive nuclear wastes. In addition, he was strongly motivated to cement CERN's position in Central Europe, especially among the newly-independent states (Hungary, Poland, plus the Czech and Slovak Republics which came into existence on 1 January 1993). While it was difficult (for financial reasons) for these countries to become full members of CERN, various intermediate solutions (e.g. collective membership) were being envisaged. In addition, the continued support and adherence of the smaller Member States (for example, Austria) is a perennial priority for the CERN leadership: these countries tend to have small particle physics communities, and the national cash contribution to CERN is periodically questioned by researchers from other fields. Thus, there is a desire to take advantage of

⁶² Among the options considered were an electron-positron collider, a synchrotron light source, and a supercomputing centre. Somewhat later, a centre for crystallography was proposed as a serious alternative, and a major study by the European Science Foundation was convened to critically compare it with a spallation source. The latter project was judged to be superior.

⁶³ In such a facility, beams of neutrons are produced when a high-intensity proton beam (produced in a linear accelerator or a synchrotron) impinges on a heavy-metal target. The neutron beams can be used for a vast range of basic and applied research projects across a wide range of scientific and technological domains, from fundamental physics, materials studies, the life sciences, to even seemingly-remote fields such as archaeology and art history.

⁶⁴ The OECD Megascience Forum (precursor of the Global Science Forum) performed a study, and issued a report, on the issues and options related to the potential shortage of neutrons for research.

⁶⁵ These plans were indeed realised with the construction of the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, and the multi-purpose J-PARC facility in Tokai.

⁶⁶ Later, the association's name changed to “Hexagonale” when it was joined by Poland.

every opportunity of providing “value for money” to these countries – in this case, in the form of expertise and resources for developing a new and ambitious type of proton accelerator of very high intensity.

The Austrian government’s decision to support AUSTRON was influenced by the prospect of effective support from CERN, primarily in the form of expertise and the availability of facilities for R&D on critical components of the accelerator complex.⁶⁷ Indeed, the detailed design study (published in 1994) was done at CERN, funded in part by Austria. The study group was led by accelerator physicist Philip Bryant. CERN’s Director of the PS Division, Kurt Hubner (an Austrian) authorised Bryant to work on the spallation source project. A prominent Austrian physicist, Meinhard Regler, who had spent many years as a visiting researcher at CERN, became the principal advocate for CERN’s contribution to the Austrian initiative. All three individuals were to remain key protagonists in the unfolding story.

For a variety of reasons, the AUSTRON initiative was abandoned (definitively in 2003). The initiative did not generate enough support in Europe, given that the Austrian government was not in a position to fund more than one-third of the total cost of the facility. The larger ESS project also faltered and was shelved for several years. Today, the construction of the European Spallation Source is under way in Lund, Sweden, with full operations expected in 2025.

While the AUSTRON accelerator design was under way at CERN, the option of a proton therapy application was introduced into the overall design, taking advantage of the “slow extraction” technique that had figured prominently in the conclusions of the EULIMA study, and which constituted a major intellectual contribution from CERN to the EULIMA synchrotron design. The idea was that a tiny portion of the extremely intense circulating proton beam could be removed from the machine and diverted to a special-purpose medical facility. Philip Bryant and another CERN accelerator physicist, Horst Schonauer (an Austrian) led the effort to explore this option, but it was found to be unrealistic (among other reasons, because the energy of the main proton beam was too high). Rather than abandoning the idea, however, the leaders of the AUSTRON study decided to develop a medical application in parallel, with a newly-designed, dedicated synchrotron for cancer treatments. An important advantage of such a machine is that it could be used to explore the advantages of ion (not just proton) therapy.

Support for the AUSTRON neutron source waned and eventually vanished but, remarkably, the ion therapy initiative (dubbed MedAustrotron) survived thanks to the persistence of its proponents in Austria and at CERN, and because it was strengthened, at a critical moment, by combining forces with another project – one led by Italian elementary particle physicist Ugo Amaldi.

Amaldi was already a prominent member of the CERN community. He was one of the architects of the DELPHI collaboration that built one of the four very large detectors for the LEP collider. As the LEP experimental programme wound down and CERN’s main focus turned to the LHC, Amaldi decided to return to a subject that he had inspired him to take up physics as a young man: the effects of radiation on living organisms, and the potential medical applications. He immersed himself in the subject of hadron therapy, and became convinced of the great as-yet-unfulfilled potential of using ions to treat X-ray-resistant tumours. Based on his earlier work in the field (one of his contributions was a book on radiation physics) Amaldi had extensive contacts in Italy’s medical and physics communities. He succeeded in bringing together physicists, physicians and engineers, and, in the years that followed, pursued his goal with abundant energy and tenacity. Two complete designs for facilities were developed under his

⁶⁷ The word “complex” is used advisedly, since a synchrotron typically requires a linear accelerator (the “injector”) that provides an initial beam of low-energy particles for acceleration in the main circular structure.

leadership, with proposed locations in Novara and Milan, but neither project could be brought to fruition. In 1992, Amaldi established the TERA foundation hoping that it would serve as a focal point for developing the financial and political support that would be needed to establish a research and cancer treatment facility in Italy. He had already assembled a team of experts who had produced a large body of technical work and were eager to keep moving ahead, but there was still a need for an appropriate collaborative institutional environment. The breakthrough came in September of 1995 during a reception at CERN's "glass box" restaurant to celebrate the release of the AUSTRON design study. There, Amaldi and Regler⁶⁸ first conceived the idea of a CERN-based hadron therapy project, linking the Austrian and Italian initiatives and taking advantage of the results that had already been achieved by both groups.

Amaldi and Regler set about the task of convincing an initially sceptical Director-General (Christopher Llewellyn-Smith) of the merits of their idea, and in this they had two important allies within the CERN leadership: Kurt Hubner (Director of Accelerators) and Horst Wenninger (Research-Technical Director of the LHC project). They arranged a visit to CERN by Gerhardt Kraft – a prominent advocate for ion therapy in Europe, and head of a research team at the Gesellschaft für Schwerionenforschung (Institute for Heavy Ion Research, GSI) in Darmstadt, Germany. Kraft expressed support for a new CERN-based effort, focussed on the design of an optimised medical accelerator. Meanwhile, technical consultations continued under the auspices of TERA, and numerous small meetings were held throughout Europe. These efforts were crowned with success and, in April of 1996, CERN's PIMMS (Proton Ion Medical Machine Study) project was launched.

PIMMS was conceived as a collaboration between CERN and MedAustron, TERA, GSI and the foundation "Oncology 2000", based in the Czech Republic. CERN's contribution was the participation of a team of researchers, based in the Proton Synchrotron (PS) Division,⁶⁹ led by Philip Bryant, who became the full-time leader of the project. CERN accelerator expert Giorgio Brianti was head of the Project Advisory Committee (PAC). Office space would be provided, plus a small budget line for travel, computers and supplies. No significant hardware development was foreseen. The main objective was to develop a new design for a synchrotron that could produce both proton and ion beams.

As PIMMS began, it was acknowledged that the technical parameters of the medical ion accelerator would not be unusual in terms of the energy and intensity of the delivered beams. But the requirements for safety, reliability, maintainability and ease of use called for considerable ingenuity and effort. Safety had to be the primary concern, since radiation therapy involves delivering very significant doses of radiation needed to destroy tumours, while sparing nearby healthy tissues⁷⁰ as much as possible. The position, energy and intensity of the beam have to be precisely monitored and controlled at all times. In addition, the entire complex system has to be extremely robust, placing a premium on simplicity, accessibility and redundancy. Significant downtime periods have to be avoided at all costs, since treatments, which consist of multiple carefully time-staged sessions, cannot be interrupted without negative consequences for the medical outcome. The fact that there are so few ion therapy facilities means that each one has to be much more reliable than the typical research accelerator, where downtime is merely a nuisance.

⁶⁸ The two physicists knew one another well. Regler had been the Austrian member of the DELPHI Collaboration Board, of which Amaldi was the Head.

⁶⁹ This unit no longer exists at CERN. In January 2003, it was merged with the SPS + LEP (SL) Division to form the Accelerators and Beams (AB) Division. In 2009, the AB Division, the Accelerator Technology (AT) department and parts of Technical Services were combined in the Accelerators and Technology Directorate, which has three departments: Beams (BE), Technology (TE) and Engineering (EN).

⁷⁰ A typical course of radiation treatment can consist of twenty sessions, each delivering a dose of 2-3 Grays (Gy) to the tumour. For comparison, a single dose of 5Gy delivered uniformly to the entire body can be fatal.

Given the special requirements, a number of creative solutions were developed during the course of PIMMS. The injection and extraction of the ion beams were the subject a special effort. To ensure a uniform flow of particles out of the accelerator and into the treatment rooms, a special type of accelerating structure was developed, a modern version of a device – the “betatron” – whose origins go back to 1940, before synchrotrons were even known. A beam delivery system, including active scanning (varying the energy of the particles to control the depth of maximum energy deposition in the patient’s body, and rapidly displacing the beam vertically and horizontally across the projected outline of the tumour) plus a “gantry” (a set of magnets to transport the beam and to orient it vertically downwards at the patient in the treatment room), were to be included in the overall design.

The manpower contributions of CERN’s external partners to PIMMS have been estimated as follows:

25 person-years	TERA
10 person-years	MedAustron
2 person-years	Oncology 2000

The CERN experts made contributions, on a part-time basis, within their individual technical domains, for example, designing magnets of various kinds (including dipoles, quadrupoles, sextupoles and other specialised types), vacuum systems, acceleration and power supplies, beam monitoring, and others. Their contribution is estimated to represent about 20% of the overall effort – approximately 10 person-years. Besides providing intellectual added value, they carried out the critical task of training their outside collaborators, many of whom participated in the follow-on efforts as described below. It must be understood that these resources, while modest, were contributed during a period of the most intense activity at CERN, and very restricted budgets associated with the implementation of the Large Hadron Collider.

As the home base of PIMMS, CERN played a complex role: an organisational venue for the Italian and Austrian initiatives that needed support and credibility as they continued to seek support in their own countries, and a source of technical expertise, and an original contributor, to the overall goal of establishing dedicated ion treatment centres in Europe.

PIMMS ended in 1999 with the delivery of a complete accelerator system design, the technical details of which were published in two volumes. This design was subsequently adopted (with some modifications) by the two principal partners (Italian and Austrian) who, throughout the duration of PIMMS and beyond, conducted intense and, ultimately, successful efforts to find national support for building and operating treatment facilities. However, it is important to understand the exact nature of the CERN-based effort which, while it addressed and resolved all of the fundamental issues associated with designing a special-purpose medical synchrotron, did not advance to the stage where a set of blueprints and instructions could be handed off to contractors for manufacturing.

The PIMMS project was never intended to deliver a working accelerator for treating patients. The follow-on engineering, prototyping, fabrication, testing and certification were carried forward by the leaders of TERA who, following the conclusion of PIMMS, were successful in putting together, in 2001, an extensive new collaborative effort: the *Centro Nazionale di Adroterapia Oncologica* (National Centre for Oncological Hadron Therapy), CNAO. Members of the TERA staff transferred to CNAO, bringing with them (at no cost to the new foundation) a large quantity of technical materials (mechanical drawings, software, intellectual property, etc.). CNAO was created as a non-profit foundation under Italian law, governed by a Board representing its members: TERA, a university hospital in Pavia, two public hospitals in Milan, and a private cancer hospital in that city. The establishment of CNAO was the

key development in translating the results of PIMMS into actual therapeutic practice. It was made possible, in large part, by the support of Dr Umberto Veronesi, who served as Italy's Health Minister from April 2000 to June 2001.⁷¹

Under the aegis of CNAO, a complete cancer treatment facility was built in the city of Pavia, funded by the Italian government, the regional government, and private contributors. The total cost was approximately 125 million euros, of which about 40% was spent on the synchrotron and its support equipment. The facility was inaugurated in February 2010, began treating patients with protons in September 2011, and with carbon ions in November 2012. It is built around the synchrotron and its beam delivery systems, but it incorporates many additional sub-systems and resources for receiving patients, for treatment planning (including PET, CT and NMR imaging systems), for maintenance and support, plus various administrative services.

The Italian *Istituto Nazionale di Fisica Nucleare* (INFN) was CNAO's principal technical partner in the implementation of the synchrotron, including the magnets, accelerating structures, beam transport lines, and the control system. The Institute was eminently able to do this work, based on more than a half-century of experience in nuclear and particle physics research, carried out in more than twenty university departments and dedicated INFN laboratories (Gran Sasso, Frascati, Legnaro and Catania). CERN was a partner in the implementation of the CNAO facility. A formal agreement between the two organisations was signed in December 2004 (and extended in May 2008). Under its terms, certain technical services were provided by CERN, the complete costs being reimbursed by CNAO. Most notably, the big dipole ring magnets were sent directly from the manufacturer (Ansaldo in Genoa, Italy) to CERN, where the magnetic fields were measured with great precision before shipping and installation in Pavia. A second CERN/CNAO collaboration agreement was signed in 2011. It is not as specific as the first one, and defines a framework for further collaboration between the two organisations. CNAO treated its first patients at the end of 2011 and by the end of 2013 about 200 patients had been treated, half of them with protons and half with ions.

Software development was a major undertaking during the creation of the treatment centre from the PIMMS design. To maximally reduce any risk to patients, extensive hardware and software safeguards were implemented, incorporating principles such as redundancy and "fail safe" operations. In addition, a software system had to be devised that would allow clinicians to accurately monitor the progress of the treatment of each patient, incorporating extensive use of graphics and user-friendly interfaces.

In Austria, a commitment for funding was made by the authorities of Lower Austria for implementing MedAustron, a facility that is under construction (as of 2013) and set to begin treating patients in the year 2015. Ultimately, 1 400 patients per year will undergo treatment at the facility, which is located some 50 kilometres south of Vienna. The design of the accelerator is essentially that of the CNAO machine; indeed, the complete documentation was purchased from the Italians for a sum of 3.2M€, a nominal price representing a very small portion of the actual R&D costs. This sum was allocated to CNAO, INFN and CERN according to the agreed fractions of the created intellectual property.

As mentioned earlier, the support of GSI's Gerhardt Kraft was instrumental for getting PIMMS established at CERN. But the relationship with the Darmstadt-based effort did not flourish during the course of PIMMS (it seemed to be limited to sporadic attendance at meetings) and it took a decidedly

⁷¹ Veronesi, who was born in 1925, had been associated with the CERN-based EULIMA project, and, in the year 2000, was one of Italy's best known and most respected surgeon/oncologists. He is famous, among other achievements, for devising innovative surgical procedures for breast cancer that are alternatives to radical intervention (mastectomy).

unexpected turn when it became clear that the CERN and GSI researchers had very different approaches to the issue of intellectual property. With the encouragement of German funding authorities, the GSI team was intent on bringing their work into the clinical environment as soon as possible, with the added desirable goal of ensuring the commercial viability of ion therapy. Specifically, they hoped that treatment centres could be implemented and operated by private entities. To this end, they established a co-operative venture with Siemens.

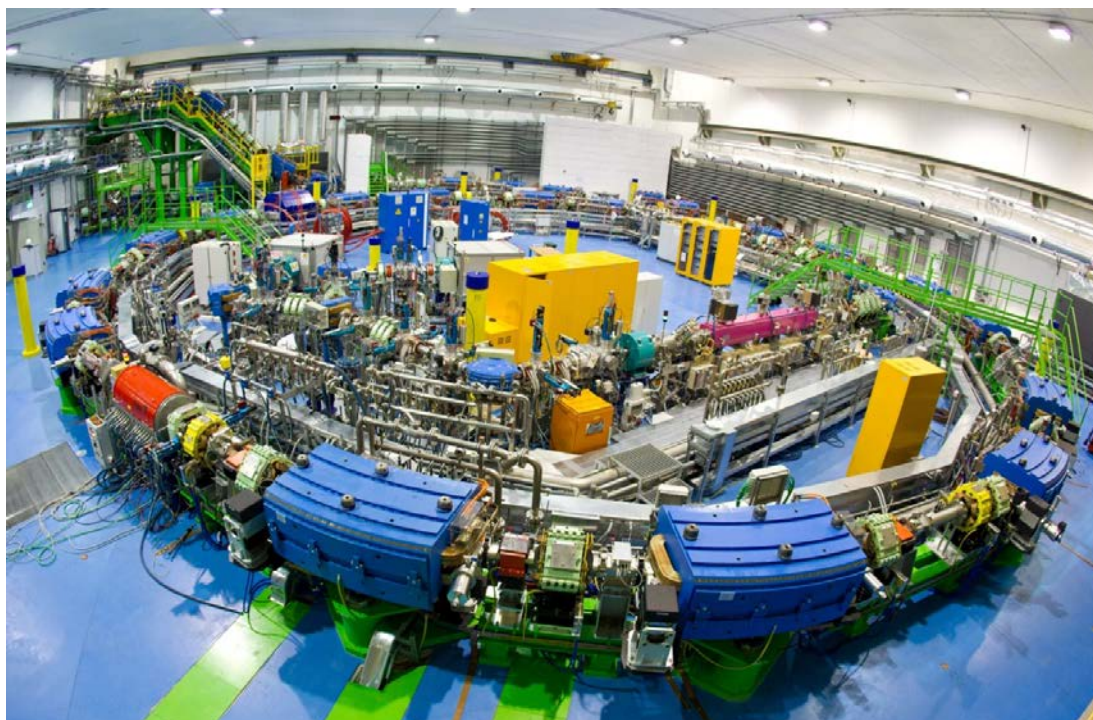
GSI researchers had developed their own synchrotron design and, together with Siemens, they applied for a number of European patents that would help to make the venture economically sound. However, certain members of the CERN staff, including senior researchers and administrators linked to PIMMS, concluded that some of the patent applications concerned generic accelerator techniques that were well-known in the community, and that patents could not be justified merely by that fact that the application domain (i.e. cancer therapy) was new. Acting on this conviction, they submitted a series of briefs to the European Patent Office, and they succeeded in blocking some of the German patent applications. The episode was regretted by all, but it left lingering bad feelings. It highlighted some of the difficulties associated with moving this particular set of technologies from the research environment into the real world of clinical practice.⁷² The economic constraints of the real world emerged as an important consideration, as evidenced by the subsequent history of the involvement of Siemens in ion therapy. The collaboration with GSI gave birth to the Heidelberg Ion Beam Therapy Centre (HIT) at the University of Heidelberg, which operates in both clinical and research modes.⁷³ The company also built a complete facility in Marburg, and another one in Kiel, where the intention was to treat 3 000 patients annually. However, the company subsequently withdrew from the radiation therapy field and from both facilities, whose future is now uncertain.⁷⁴ It appears that the projections concerning the economic viability, based on expected number of patients and the reimbursement of the costs of therapy via insurance, were not realistic. Liability was also a concern. According to one expert who was interviewed for this study, the German experience has been a “cold shower” for proponents of ion therapy, demonstrating the need for great rigour in preparing the economic underpinning for future initiatives.

⁷² The long-term fallout of this episode did not preclude further collaboration. Indeed, the CNAO synchrotron, while derived primarily from PIMMS, uses a linear accelerator whose design was adopted from that in use at GSI for injecting ions into that facility’s SIS synchrotron.

⁷³ HIT began operations in 2009. As of the end of 2011, 568 patients had been treated with protons and ions. Beginning in 2013, the facility hopes to treat 750 patients per year.

⁷⁴ Another Siemens-built ion facility, in Shanghai, China, is treating patients. As of late-2013, the Kiel facility has been definitively dismantled, while there is some prospect of activation of the one in Marburg.

Figure 4. The CNAO synchrotron. The diameter of the ring of magnets is approximately 25 metres. The ladder at the right-hand edge of the picture provides a sense of scale.



Source: CNAO

Figure 5. A commercial medical cyclotron, the Proteus 235 by Ion Beam Applications S.A. (IBA). It produces a proton beam with a fixed energy of 250 MeV. The diameter of the accelerator is 2.5 metres, one tenth the size of the CNAO synchrotron ring



Source: IBA.

Interestingly, the PIMMS design almost found a third European realisation. Since 1997, a group of physicists, engineers and physicians have been trying to establish an ion treatment facility in Lyon, France. Initially, the only (modest) funding that was forthcoming for exploratory work was from the regional government. In 2007, the French Ministry of Health authorised the establishment of the *Etoile* consortium, with the goal of creating an ion treatment facility that would be economically viable as a public-private partnership. The current plan (in 2013) is to implement financing using bank loans that would be repaid using future revenues (that would, in turn, come from reimbursement for treatment under various insurance arrangements). Originally, *Etoile* proponents planned to use the PIMMS design (as modified by TERA) but economic considerations have led them to adopt the system that was developed in Japan and is available commercially from AREVA/Mitsubishi.

CNAO and MedAustron are the tangible outcome of CERN's involvement in cancer therapy. Both facilities are just coming on line but, soon, their impact (and CERN's) will be measurable in a way that matters most: in numbers of patients treated, and numbers of lives saved.

Section D.2.c Recent developments and prospects for the future

With the conclusion of the PIMMS project, CERN's engagement in hadron therapy shifted away from a primary focus on accelerator design. While there were some discussions concerning the establishment of an actual research and treatment facility at the laboratory, the chosen new emphasis has been on networking and co-ordination among the European stakeholders: physicists, engineers, biologists and physicians. Using funding from the European Commission's Framework Programmes, the ENLIGHT network ("European Network for Light Ion Therapy") was established,⁷⁵ having for goal the promotion and co-ordination of research, communication, good practices and future planning across the spectrum of issues surrounding ion cancer therapy. Today, the co-ordinator of the network (and its components listed below) is Manjit Dosanjh, Deputy Group Leader of CERN's Knowledge Transfer Group. She is a molecular biologist who came to CERN in the year 2000 as an advisor for life sciences.

An overarching theme of ENLIGHT is interdisciplinarity. This theme, and the breadth of purpose of the whole project, is reflected in the four sub-programmes that are funded by the EC (for a total amount of 24 million euros):

- PARTNER ("Particle Training Network for European Radiotherapy") provides support for the training of young researchers, using funding from the EC's Marie Curie Training Programme. Among the ten collaborating institutes are many that figure in this report: CNAO, TERA, GSI, HIT, MedAustron, Siemens Medical and *Etoile*. Also involved are Ion Beam Applications, a Belgian company that sells turnkey hadron therapy systems, the University of Surrey, the Karolinska Institute in Stockholm, and IFIC – the Institute of Particle Physics at the University of Valencia in Spain. The young researchers are active in areas such as basic radiobiology, epidemiology, beam guiding, treatment planning, accelerator and beam line design.
- ULICE ("Union of Light Ion Centres in Europe") promotes access by researchers to ion therapy facilities (both currently-operating facilities HIT and CNAO, and future ones such as MedAustron and *Etoile*). Twenty research organisations participate in this activity. The research concerns topics such as new instruments, patient selection and treatment protocols, beam steering and delivery.

⁷⁵ The main proponents were Ugo Amaldi, Jean-Pierre Gérard, Richard Pötter and Hans Svensson.

- ENVISION (“European NoVel Imaging Systems for ION therapy”) is specifically focused on improving the delivery of ion beams to cancerous tissues in terms of spatial accuracy and precise control of radiation doses. Researchers are developing ways of detecting particles (photons and charged particles) that are emitted by the irradiated tissues, thus being able to monitor the treatment in real time, making adjustments to the beams as necessary. This work addresses the difficult generic problem (common to all forms of radiotherapy) of correcting for the motion of tumours and healthy organs (as a result, for example, of breathing). Seventeen European research organisations participate in this work.
- ENTENVISION (Research Training in 3D Digital Imaging for Cancer Radiation Therapy) concentrates on research in three-dimensional imaging that is critical for early detection and diagnosis, characterisation of tissues (recognising that only a fraction of cancers can be treated using ion therapy) and accurate positioning and dose delivery during treatment. This networking activity brings together ten academic institutions and two companies.

In February 2010, CERN organised a workshop (“Physics for Health”, PHE) on the general theme of applying physics to address human health issues, with a special focus on imaging (e.g. positron emission tomography), assuring supplies of radioisotopes, and hadron therapy. This was followed, in February/March 2012, by a follow-on event convened jointly with the International Conference on Translational Research in Radio-Oncology (ICTR). This event, which attracted over 600 participants from the major stakeholder communities, was an opportunity for CERN leaders to seek information and opinions regarding possible future activities of the laboratory in the hadron therapy domain.

Regarding possible future activities under the aegis of CERN, consultations are on-going among a number of experts but, because of their sensitive and preliminary nature, it would not be appropriate to describe them completely in this report. One potential new direction would involve more research on advanced accelerator concepts for light ion therapy (based, for example, on the Fixed-Field Alternating Gradient – FFAG – concept that combines features of both cyclotrons and synchrotrons). A related set of research topics concerns accurate beam transport, delivery and monitoring. Another intriguing possibility is the establishment of centre (presumably using supplementary funding outside the main CERN budget) that would be devoted to very basic research on hadron therapy. Some scientists believe that new techniques could be developed, and therapeutic outcomes could be improved, if there was a more complete understanding of how particle radiation interacts with living matter. In effect, at the level of individual biological molecules and of the cellular metabolic systems within which these molecules function, the interactions with different beams (protons and ions of various kinds) is only imperfectly understood, as is the behaviour of the beams themselves (e.g. fragmentation and scattering of the incident nuclei). To carry out the appropriate research, a dedicated facility is envisaged, providing well-calibrated beams incident on well-instrumented targets, and backed up with biological measurement and analysis equipment. A potential advantage of CERN could involve the availability of the Low Energy Ion Ring (LEIR)⁷⁶ accelerator, which is currently dedicated to injecting lead ions into the Large Hadron Collider. In August 2013, CERN appointed Stephen Myers (Director of Accelerators and Technology) as Head of CERN Medical Applications, with a broad mandate to promote further contributions in health and medicine.

⁷⁶ LEIR is the upgraded/converted LEAR accelerator, which played a role in the very earliest phase of CERN’s involvement in hadron therapy, in connection with the EULIMA project

Section D.2.d Conclusions concerning hadron therapy

CERN as an enabler of innovation

Provision of human, technological and infrastructure resources

CERN's status as a front-line particle physics laboratory allows it to attract and retain staff members of very high quality, including physicists, engineers, technicians and administrators. These can then serve as a resource when new prospective projects are introduced. In the case of hadron therapy, the expertise in accelerator design (which includes not just the basic domains of magnet lattice configuration, and RF acceleration techniques, but other relevant disciplines such as external beam transport/steering/monitoring, vacuum technology, cryogenics, radiation hardening, safety) not only made the laboratory a logical venue for the EULIMA and PIMMS projects, but had a major substantive impact on outcomes. Thus, for example, mastery of the critically-important "slow extraction" technique helped CERN participants steer the recommendation of the EULIMA study to the synchrotron as the preferred design for an ion therapy accelerator – a result that was not at all foreseen when the project began (a time when the cyclotron was the solution of choice).

The hadron therapy story demonstrates the important role of CERN's technical experts, especially the accelerator physicists and engineers (for example, Philip Bryant, Giorgio Brianti and Pierre Lefèvre). To the outside world, they are not as prominently visible as the physicists who are identified with the great scientific discoveries, but they are valued and influential within the councils of the laboratory. They, in turn, are supported by a strong contingent of electronic and mechanical designers, programmers and computer systems specialists, machinists, computer-aided design experts, and others. All of this constitutes a diverse, flexible, installed human and material infrastructure – a valuable resource for any project that is in an inherently exploratory mode and might need to investigate many technological pathways before converging on a favoured solution.

For the EULIMA and PIMMS projects, CERN management had the ability to assign some staff members, part-time and even full-time, despite the enormous demands on time and resources in connection with LEP and LHC. In addition, the laboratory's open and dynamic working atmosphere made it possible for many experts to contribute ideas in an ad-hoc manner, based only on personal interest and a desire to help.

CERN's reservoir of talent is not limited to the approximately 2 300 persons who are actual employees of the laboratory. Indeed, the latter are only a fraction of the total number of persons who spend significant amounts of time at CERN. Two of the principal initiators of CERN's involvement in hadron therapy – Pierre Mandrillon and Meinhard Regler – were, in fact, not CERN employees, but they had spent a great deal of time there, knew the laboratory well, and could communicate directly with senior administrators.

As described above, CERN's contribution to the full implementation of hadron therapy facilities was limited to solving fundamental conceptual and design problems, and went no further. In particular, it did not include the considerable engineering, testing and certification efforts that were required to create a working medical treatment facility. This work was left to the nationally-funded institutions and laboratories, a form of "subsidiarity" that has become a familiar concept in European science and innovation policy. Thus, CERN's special strengths were fully exploited, without getting the laboratory involved in time-consuming and costly work that could be done at the national level. This is in marked contrast to the development of the LHC dipole magnets, where CERN scientists and engineers were deeply involved, and responsible for, the entire cycle of innovation, with the exception of the serial manufacturing that was performed by the three contractors.

The physical layout of the laboratory is well-suited to undertaking new exploratory R&D. As any visitor to CERN knows, the facility has a sprawling, decentralised aspect – a legacy of its long and diverse history. Offices and laboratories are scattered throughout the complex of several dozen buildings. These buildings are sometimes re-configured when they are no longer needed for their original purpose, linked to one of the many past accelerators or experiments. This character of the site makes it more easily adaptable for hosting yet one more small project, for example, by moving some equipment and desks around to create an environment where newly-formed groups can pursue their common objectives without disturbing or displacing any on-going activities.

EULIMA and PIMMS were medium-scale projects, but CERN has catalysed many initiatives on even smaller scales. Over the years, senior administrators have gone out of their way to make the laboratory a general-purpose venue where highly diverse groups of individuals can meet, at little or no incremental expense to the laboratory, to pursue the very broad overall goal of harnessing physics (well beyond HEP) for the benefit of society. Numerous learned societies, associations, task forces and working groups have held meetings at CERN, taking advantage of the convenient location in the heart of Europe, the proximity to the Geneva airport, the inexpensive cafeteria and hostel, and the efficient security system for controlling access to the site.

Intangible factors in innovation

On a superficial level, it seems perplexing that an institution whose stated objective is to investigate the nature of the most fundamental constituents of the Universe can make a significant contribution to addressing an apparently unrelated challenge: the treatment of a fearsome human disease. It might be expected that the governance mechanisms of the institution would inhibit (or even prevent) such a major departure from the primary mission. The fact that it did indeed happen indicates that these mechanisms are characterised by a certain degree of flexibility. This study finds that this flexibility operates on several levels.

The open and meritocratic working environment enables staff members at all levels to explore, within reasonable limits that appear to be intuitively understood, ideas beyond the narrow scope of primary assigned responsibility. These ideas can be freely debated with colleagues and can be communicated up and down the chain of authority. It is not unusual for a technician or an engineer to share ideas and opinions with the head of a division, or even the Director-General. Most often, these ideas pertain to the laboratory's primary mission, but they can extend to other domains. The work culture of the institution is fully consistent with this phenomenon: the 40-hour work week is a concept that has little meaning for the scientists at CERN and for many of the engineers and technicians as well. Thus, an individual who wishes to develop a new concept (whether linked to HEP or not) can work late, on weekends, or during holidays, without having to make special arrangements.⁷⁷ Under the informal rules that pertain to this type of low-level activity, the individual can make modest, reasonable use of resources such as computers or office supplies. Typically, colleagues within the immediate professional sphere, even superiors, would be aware, perhaps even engaged, in such exploratory work.

⁷⁷ The type of working environment described here is certainly not unique to CERN. It characterises many front-rank research institutions in all fields of research, worldwide. Unrestricted working hours are probably a universal characteristic of research institutions, but the freedom to communicate up and down the chain of command is not.

Governance and operations

The above characteristics of the working environment do not completely explain the genesis of non-HEP initiatives at CERN. For any innovative concept to mature in a meaningful way, supervisors at all levels have to have some authority, however circumscribed, to support the development of new ideas. Ultimately, it is the senior administrators who must take responsibility for authorising (or not) any non-HEP activity that could have a measurable impact on how the laboratory's resources are used. This is a major responsibility, given that CERN, throughout its history, has operated under heavy budgetary pressure, always trying to do as much as possible using available resources, and always encountering unexpected technological difficulties that are inherent to the conduct of research at the frontiers of knowledge.

As evidenced by the work on hadron therapy, the Director-General, the Directors, and the Heads of Departments, form a network that is able to assign resources (for example those devoted to PIMMS), informing the CERN Council in an appropriate way. This freedom, in turn, is linked to CERN's legal status as an International Organisation which is (to a real extent, but one that is impossible to elaborate in this report) exempt from some formal requirements (as well as the labour laws) that apply to national laboratories in the Member States, including the host countries. The freedom is a prerogative of this particular institution that is, generally speaking, regarded as a showcase of European scientific and technological prowess or even, with the successful implementation of the LHC and the discovery of the Higgs boson, a measure of supremacy on the global scale. In other words, success legitimates the mechanisms and procedures (informal as well as formal) that produce it.

CERN's major contribution to ion therapy was not mandated "top down" from the highest governance levels. Rather, it grew and evolved gradually as a small fraction of the laboratory's work programme was shifted towards a new goal, based on the creativity, determination and idealism of a small number of staff members. Interestingly, these motivated persons occupied very different positions in the nominal institutional hierarchy. Thus, individuals who played essential roles in the hadron therapy story include (and this enumeration is not meant to be exhaustive) a Director-General (Carlo Rubbia), a senior administrator (Kurt Hubner), two senior physicists (Ugo Amaldi and Meinhard Regler) and an accelerator engineer (Pierre Mandrillon). This "telescoping" of the hierarchical structure of communication and authority appears to be an important characteristic of CERN. The prominence of key individuals in the story of CERN's involvement in hadron therapy highlights its serendipitous nature. After all, there are numerous non-HEP applications of particle accelerators,⁷⁸ and CERN's mandate is not to be a general-purpose accelerator-based technology development facility. The laboratory's ability to make a significant contribution to cancer therapy is, to some extent, based on a coincidence of the right topic, the right scale of the undertaking and, above all, the right people.

CERN's historic role in the process of European integration, and the scientific discoveries that it is identified with, allow it to be a venue for integration of multidisciplinary efforts to advance hadron therapy in Europe. As already described, this is the stated goal of the ENLIGHT network and its sub-programmes. It is a continuation of a major theme of CERN's involvement in hadron therapy, namely the necessity of involving clinicians and of always keeping in mind the demographics of cancer, and the economic aspects of any potential solutions.

⁷⁸ Among the existing and potential non-HEP applications are: synchrotron and linear accelerator-based photon sources, spallation neutron sources, hadron cancer therapy, treatment of flue gases in power plants, decontamination of water, development of radiation-resistant materials for fusion power generators, transmutation of radioactive nuclear wastes, cross-linking for industrial polymers, curing of inks and adhesives, pathogen destruction/sterilisation, surface hardening, ion implantation in semiconductors, multiple applications of mass spectrometry. This list is by no means exhaustive.

The history of the PIMMS study included a remarkable episode, when senior CERN staff submitted briefs to the European Patent Office objecting to certain patent applications by GSI and Siemens. Very likely, this situation was unprecedented: employees of an intergovernmental research organisation actively opposing patent applications submitted by a publicly-funded laboratory and a private company of a member country. The staff members were motivated by the explicit declaration in the CERN Convention (cited in Section E of this report), the long-established culture of openness and spontaneous communication, plus a deeply rooted distaste for isolating the research process behind walls of commercial secrecy. At the same time, they understood the motivations and constraints of their German colleagues who were, at least nominally, formally-established partners in PIMMS. While the episode now belongs to history, it is possible to discern its echo in the ways that the Knowledge Transfer Office defines and conducts its work.

CERN as a pan-European institution

One of the interviewees for this study pointed out that “national laboratories have one boss that they need to please (meaning the national funding agency) but CERN has twenty bosses (meaning the Member States)”. It is the perennial responsibility of the CERN leadership to successfully manage the individual priorities, constraints and concerns of these countries, all the while pursuing the main scientific mission, and managing a laboratory with 2 300 employees. One way of achieving this has been to configure the laboratory as a general-purpose European centre of excellence on matters having to do not just with elementary particle and nuclear physics, but with relevant applications as well. This auxiliary role must function within the correct limits, as illustrated by the case of CERN’s involvement in hadron therapy, and especially the origins and conduct of the PIMMS study. As described in the previous section of the report, the eminent physicist Carlo Rubbia advised the Austrian government on their ambitious plans for strengthening research capacity in Central Europe during a critical period in European history. He did so not simply on the strength of his reputation and recently-awarded Nobel Prize, but also as the Director-General of CERN. In throwing his support behind one particular research facility – a high-power accelerator-based spallation neutron source – he was able to offer the prospect of strong intellectual, substantive and infrastructure support from an institution with unquestioned expertise in accelerator design. Support provided to a “small” country is especially important, since they tend to have small scientific communities that may lack the critical mass for implementing/hosting a project on a regional scale.

In offering CERN as a resource for non-HEP applications in Member States, the Directors-General exercise discretion. Mindful of the general CERN principal of distributing benefits (e.g. contracts, staff positions) in an equitable manner among the contributing countries, they take care to not provide services to individual Member States in a disproportionate way. At the same time, they may use the prospect of substantive assistance to cement national support for CERN,⁷⁹ or to encourage non-member countries to strengthen their ties with CERN.

CERN’s role in the genesis and evolution of the MedAustron project deserves special attention. Initially, the medical application was to be a relatively small part of a much bigger undertaking – the AUSTRON spallation neutron source – whose main thrust was far removed from health applications. The fact that plans for a patient treatment centre survived when those for a condensed matter research facility did not, is a remarkable development, and was due in a significant part to the role played by CERN experts, with their detailed knowledge of accelerator design. In addition to scientific and technological expertise, however, it should be acknowledged that the national affiliation of key staff

⁷⁹ It appears that the organised support from the Austrian stakeholders in MedAustron had an impact on the government’s decision to continue its membership in CERN.

members played a role as well. Informal networks that are based on nationality form naturally among the staff of international organisations and, as long as they function openly and within proper limits, can play a constructive role in maximising the benefits of national membership in the organisations.

The story of hadron therapy shows how CERN can serve as a temporary haven for projects that are ultimately destined to be implemented at the national level, but need an established, recognised and supportive environment where they can develop as they await the consolidation of national support. While a positive outcome is not by any means guaranteed (CNAO and MedAustron were realised, AUSTRON was not) it would be difficult to overestimate the importance of even very modest levels of intellectual, technical and infrastructure support for projects that are still in a conceptual phase. Proponents of such projects have, typically, little or no dedicated funding, but they need to hold meetings, to prepare and store documents, to make simple prototypes. They need such basic items as desks, telephones and computers.

When assessing the relationship between CERN and Italy and Austria, an interesting contrast can be observed. Italy has been especially pre-eminent in high-energy physics, with many accelerators having been designed and built there on a national basis, under the aegis of INFN. Considering only the technological challenges, the PIMMS design could surely have been implemented as a purely Italian project. A CERN-based activity was able to catalyse and enable the national efforts, bringing together, within an international organisation, the elements that were missing in individual countries.

Pan-European networks and research programmes, funded by the European Commission, are increasingly important components of the global scientific enterprise. CERN has been (and continues to be) a potential recipient of European research funding (such as for EULIMA from 1989 to 1991, and presently with the four components of the ENLIGHT network: PARTNER, ULICE, ENVISION and ENTERVISION).

Section D.3 Case study: software packages

This Section pertains to Impact Category Vb: non-HEP Innovations that can become external impacts with only minor modifications.

It would be difficult, perhaps impossible, to enumerate all of the software applications that have been developed at CERN during the LHC era. While ready-made commercial packages are used extensively, custom-written software had to be developed for numerous applications, the rationale being the same as that invoked in Section D.1.b: the CERN's special requirements could not always be met through the use of existing products. Accordingly, *software innovation* was undertaken, albeit on a smaller scale than the hardware innovation associated with superconducting dipole magnets.

Usually, the software produced was highly specialised and idiosyncratic: intended, for example, to monitor or control a particular elementary particle detector, or a specific accelerator sub-system (vacuum, cryogenics, radio frequency cavities, etc.). But in some instances, the software was developed for an application that was sufficiently generic, and was of sufficiently wide potential utility and benefit beyond CERN, that it became worthwhile to make it available to a wider community. In those cases, a decision had to be made about taking on additional efforts to make the software useable by persons who were not involved in its development and who, typically, would not have the motivation or skills to document, maintain, modify or debug it. Work of this type is routinely done by software companies (whether large enterprises such as Microsoft, or small entrepreneurial start-ups) whose motivation is obvious: they hope to sell their products for a profit. In the case of a physics laboratory, the motivation is necessarily different. Two concrete examples are presented here to illustrate how CERN can and does

generate a positive impact by providing useful products in a no-fee, open-source mode, and without detracting in any significant way from the main scientific goals of the laboratory.

In both of the cases examined here, CERN software developers started out by addressing very specific local needs: managing the large number of high-energy physics publications, and organising the numerous meetings of experts in the field.

The INSPIRE project was undertaken jointly by four major HEP laboratories: CERN, DESY (Germany), SLAC (United States) and Fermilab (United States). The goal was to provide a single integrated gateway to all of the scientific publications in the field, including not just preprints and journal articles, but also material from conferences and various media products. While INSPIRE was destined for the particle physics community, with time it was integrated into a more general-purpose software package – dubbed INVENIO – that can now be used to create a digital web-based document repository (i.e. a library in the broadest sense) in any field. INVENIO can be used to manage articles, books, images, video and even collections of physical objects. The contents are organised into “collections” which, in turn, are integrated into tree structures. There is provision for adding annotations to the individual records (for example, user comments and other types of metadata). A multi-featured, customisable user interface is included, featuring search tools that can handle up to two million records.

INVENIO development began at CERN, but became a joint project involving the INSPIRE partners and the *Ecole Polytechnique de Lausanne* (Switzerland). These institutions form the CERN Document Server Software Consortium. INVENIO is available for downloading by anyone without fee in open-source mode under the terms of the well-established GNU General Public License, and has been adopted by a diverse set of some thirty institutions world-wide. Among them are institutions closely linked to physics (for example the Italian National Institute of Nuclear Physics, INFN, and the TRIUMF laboratory in Vancouver, Canada, but also the International Labour Organisation (ILO) and the Himalayan Document Centre in Kathmandu, Nepal. INVENIO is a complex, multi-featured product. Users can benefit from (and contribute to) dedicated mailing lists and chatrooms. Questions and bugs can be submitted to the developers. In addition, CERN offers a yearly fee-based contract service for institutions, including installation, configuration, maintenance and support.

Another complete, powerful web-based software package that originated at CERN is *INDICO*. Available on the same terms as INVENIO, it allows users to design and convene almost any kind of lecture, meeting, workshop or conference. CERN’s partners in the development process were the University of Udine, the **Netherlands Organisation for Applied Scientific Research (TNO)**, the University of Amsterdam, and the International School for Advanced Studies (SISSA) in Trieste. Among INDICO’s features are: creating agendas, registration of participants and automatic notification of updates to the programme, online payment support, paper submissions (including calls for abstracts, reviewing), managing speakers and their presentations (uploading, archiving), finalising the proceedings, collecting evaluations. Various data formats are supported, including slides, audio recordings and videos. Many different display formats are available, both for the participants (external conference websites, agendas and timetables) and for the organisers. It is estimated that more than one hundred institutional entities make extensive use of INDICO (chiefly in the scientific research sector) although it is not possible to know for certain because the software can be downloaded and installed for free by anyone at any time.

A considerable effort has been made to “productise” INVENIO and INDICO, by making them reliable, by developing attractive and intuitive graphic user interfaces, by preparing documentation and providing support services. Still, the effort was not comparable to that which would be made for a purely

commercial operation dedicated to marketing a commercial product (including, for example, packaging, advertising, extensive warranty and user support).

Section D.4 Education and outreach (impact Category VI)

The visitor to CERN cannot fail to be struck by how deeply the scientists are immersed in their research, not just intellectually, but emotionally as well. Even in casual conversations, they do not hide their enthusiasm and their pride in being at the frontline of discovery. For some, the quest for scientific truth is a purely personal one, but many others are motivated to share with non-scientists the satisfaction that comes from gaining insight into the workings of nature, and to share as well the desire to probe ever deeper into the daunting mysteries that remain. It is no surprise, therefore, that CERN is home to extensive public outreach activities, aimed at spreading not just factual knowledge about elementary particle physics, but also the significance, excitement and even beauty of the field. In practical terms, the activities take two forms: education programmes, and activities aimed at the general public.

As is characteristic of CERN, educational activities emerged via a bottom-up process, based on the personal motivation of a small number of resident researchers. In 1998, John Ellis, a well-known theoretical physicist, began a small training programme for high school teachers, based on the assumption that it is much more efficient to train teachers than students. Thus, information imparted to one teacher can be transferred to hundreds of young people over many years. Even as the programme grew and evolved in subsequent years, that assumption did not change. The curriculum is designed specifically for high school physics teachers. No time devoted to mundane elementary topics and the immediate focus is on the cutting-edge research. But in addition to conveying knowledge about advanced topics, information and advice is provided about proven methods for making modern physics more accessible and attractive to students.

From the earliest days, the activity had the support of the Director-General (Robert Aymar who, in the early days, gave it an administrative home in his office). The CERN Council, while not taking formal action, has been supportive of the work; its individual members, when solicited, have helped to build links to relevant national projects. Today, an extensive teacher training programme is in place, supported by slightly less than one per cent of the CERN budget and staffed by 12 full-time employees. It has two components:

The **High School Teacher Programme** which features an intensive three-week summer session, funded primarily by CERN, but with some support in individual countries by other organisations. Stipends are provided for travel and living expenses, and on-site housing is provided. The programme accepts applications from individual teachers from CERN Member and Observer States, and there is some support for teachers from non-member states. Applicants are required to provide some evidence of their motivation. The curriculum – which is presented in English – focuses on particle physics, but with excursions into domains such as cosmology, and relevant applied topics such as medical applications and superconductivity.

The **National Teacher Programmes** are held in all the CERN member countries, with instruction in the local language. CERN provides all of the materials as well as administrative and technical support, with the individual countries being responsible for the travel and expenses of the teachers. Typically, instruction takes place over several days. It is noteworthy that much of the instructional content is created by scientists who are members of the CERN staff or of the experimental teams. In this way, CERN leverages its explicitly international character to provide added value to member countries at no incremental cost.

In 2012, 1 120 teachers participated in the above programmes. They came from 18 CERN member countries and 12 non-member countries (including Rwanda, Uganda, Kenya, Morocco, Algeria, Mozambique, South Africa and Thailand). Curriculum materials (presentations, videos, reference documents) are archived on the CERN website and are available to everyone.

Outreach to the general public is aimed at communicating with two populations: the approximately 80 000 people who visit CERN each year, and the large group that accesses the laboratory's internet site. Within CERN's administrative structure, educational and outreach activities are administered by the same unit, which is led by Rolf Landua, a physicist who purposely undertook a career change with the goal of promoting particle physics beyond the boundaries of CERN.

A main focal point for visitors to CERN is "The Globe" – a conspicuous spherical structure, some 40 metres in diameter and 27 metres tall, made almost entirely of wood. It was created for the Swiss national exhibit "Expo.02" and was subsequently donated to CERN, where it was inaugurated as a public space in 2004. It is located across the road from the main entrance of the laboratory, so large numbers of visitors can be accommodated without interfering with the research programme. On the ground floor, it hosts a permanent exhibit whose subject is the world of elementary particles and the research activities of CERN, while the upper floor features a domed auditorium seating 250. The Globe operates as a self-standing foundation, funded by donors and sponsors.⁸⁰

Figure 6. "The Globe", an educational and exhibition space for the general public, located near the main entrance to CERN.



Source: CERN.

⁸⁰ The Principal Donors are Rolex, the Meyrin Foundation for Cultural, Sports and Social Promotion, and the *Loterie Romande*. There are 35 Donors, chiefly local private companies.

CERN's website contains a wealth of information about the facility, presented in a mundane format that is likely to surprise anyone who knows that the World Wide Web was invented at CERN in 1989 by Timothy Berners-Lee. Efforts are currently under way to create a new WWW presence for CERN, using a variety of interactive and high-tech visualisation techniques.

Section E. Knowledge transfer

The case studies of Section D cover only a small fraction of CERN's many activities during the LHC era, but even this small sample highlights a question that, increasingly, preoccupies the administrators of large research infrastructures (and should preoccupy proponents of new facilities): what are the best strategies and practices for dealing with technological advances that are developed while carrying out the main scientific mission, and that could find applications in other areas? Of special interest are technological advances that could be realised as commercial products, to be produced, sold, and used for purposes that are unrelated to those of the infrastructure.

There is no single valid answer to the above question. Administrators of a facility that is devoted to fundamental research in nanotechnology or molecular biology generally need to pay more attention to the question than their counterparts at an astronomical observatory or a seismology centre. Modern industry increasingly incorporates very advanced devices and algorithms into its R&D activities, and into the resulting products themselves. Accordingly, the issue of *technology transfer* (or, as it is sometimes called, *knowledge transfer*) deserves the attention of scientists and policymakers who are engaged in planning or implementing large research infrastructures. It is instructive to examine the approach that CERN administrators have taken to dealing with this matter.

There are incentives for developing commercially successful and socially useful applications of discoveries that are made in the laboratory. National funding agencies endorse the application of publicly-funded knowledge and technology for the benefit of society. They especially value transfers to the private commercial sector, which lead, among other benefits, to rising employment and higher tax revenues. But there are complications, and even potential pitfalls. In particular, there is the possibility of the laboratory becoming side-tracked from its primary mission, delaying essential research work, losing ground to its international scientific competitors, and distracting the staff with prospects of lucrative ventures. In addition, technology transfer often requires the assertion of intellectual property rights (IPR), which can be contrary to the time-honoured open and spontaneous exchange of ideas, information and data in the research community. Obtaining and servicing patents is burdensome and expensive. If the patents generate royalties for the laboratory, these may be perceived as a substitute for vital (and traditional) public funding – a risky and financially dubious approach. But potential commercial partners strongly favour the assertion of IPR by the inventor: it is essential for protecting any investment they may make from encroachments by competitors.

At CERN, the assertion of intellectual property rights has always been a sensitive issue. In fact, openness is addressed explicitly in paragraph 2 of Article II of the Convention:

The Organisation shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organisation shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available.

This text has not been interpreted as being incompatible with asserting IPR based on ideas developed at CERN. Indeed, a Knowledge Transfer Office (KTO) has been established. It currently brings together approximately one dozen staff members, including experts in intellectual property law and in reviewing patents. Among its functions are the following:

- The office manages a portfolio of approximately 40 patents (as of mid-2012), mostly in the domains of electronics, particle detectors, vacuum systems and cryogenics. About one hundred license agreements have been made, generating an annual revenue of somewhat less than two million Swiss francs (i.e. on the order of one tenth of one per cent of the CERN budget). Only a dozen or so of the licenses make a significant contribution to this total.
- Currently, the invention that generates the most revenue is Medipix: a CMOS chip containing a large array of particle detectors (“pixels”) and associated digital electronics. Single particles can be detected with extremely low noise levels, and versions of the chip have been developed with enhanced timing and energy-measurement capabilities. Medipix technology was originally developed for detecting particles in the large LHC detectors, but it has now been used for X-ray diffraction, medical imaging (X-ray CT scanning, mammography) with potential applications in electron microscopy and general radiation monitoring.
- When a potentially patentable invention is brought to the attention of the KTO, the essential services are provided, including a search for “prior art”, which can entail a significant effort, including detailed reviews of existing patents and technical publications. The office can move quickly to obtain a patent (the typical costs being approximately 8 000 euros for attorney’s fees, and 4 000 euros to file).
- Inside the laboratory, the KTO staff endeavour to explain the principles and procedures that apply to exploring potential external applications of work done in connection with CERN’s main mission. But they find themselves hindered by the lack of an effective *incentive structure* for the employees. Nominally, all intellectual property rights belong to CERN (or are owned jointly with collaborating institutions) and any royalties from the licensing of patents would be split, in equal thirds, between the employee’s Department, the Section, and the KTO,⁸¹ with no financial reward for the inventor. CERN rules do allow for awarding a performance-based monetary bonus to a staff member, but this cannot consistently ensure the motivation for pursuing commercial applications.
- KTO staff can play a “matchmaking” role, linking CERN inventors with other researchers in the public or private domains, hoping to establish effective partnerships that can move inventions out of the laboratory. This is a vital function, since experience shows that, typically, many difficult, time-consuming and expensive steps are needed to transform an idea into a commercially-viable product, especially if the targeted application domain is far removed from elementary particle physics and the environment of a basic research laboratory. Specialised knowledge in the intended application domain is needed, plus the ability to address practical issues such as manufacturability, reliability and long-term durability, cost containment, safety, certification, documentation, user interface design and training.

KTO publishes lists and descriptions of technology projects that originated at CERN and are subsequently developed in collaboration with industry or external research organisations. An interesting example of a successful link to an external entity is the story of the application of CERN-developed vacuum technology, originally developed for the LEP collider, and modified for use in the LHC. The technology is “gettering”, which consists of using thin films of metal alloys to create a surface that captures and removes molecules of gas inside an evacuated

⁸¹ Royalties received do not fully cover the costs of operating the KTO, whose goal is to promote the economic and societal impacts of the lab, not to be a significant source of revenue for CERN.

volume.⁸² CERN engineer Christoforo Benvenuti conceived the idea of applying the technology to thermal solar panels, whose efficiency depends on reducing thermal conduction between the inner solar-heated element, and the transparent outside enclosure of the panel.⁸³ For cost reasons, the vacuum inside the panels cannot be maintained via active pumping. With support from the Director-General and the KTO office, flat solar panels with incorporated getters were developed, tested and patented at CERN. Private investment capital was arranged, and the panels are now being manufactured by a company (SRB Energy) that was established in 2005 specifically for manufacturing and marketing the panels. Serial manufacturing began in 2009. Among other installations, 282 of the solar collectors, with a combined surface area of 1 139 m², have been placed on the roof of the main terminal at the Geneva Airport, producing a high-temperature fluid that can be used to heat or cool the terminal as needed.

Section F. General observations

The OECD Global Science Forum study on CERN was undertaken with the goal of identifying characteristics of the laboratory that could be of interest to proponents of future large international scientific collaborations, specifically in terms of impacts on economic innovation and on society at large. It was anticipated that some of these characteristics could be deliberately incorporated into the legal/administrative/managerial structure of a new facility, or into its financial and operational procedures, or even its informal practices and workplace culture. The goal of the study was not to make an assessment (in the sense of praising or criticising work done at CERN), assign some kind of grade, or by some means quantify the economic or social return on the financial investment by the Member States.

To achieve the desired goal, the GSF Secretariat staff carried out a small number of case studies, relying principally on in-depth, confidential interviews with the persons most directly involved. Two of these investigations were especially detailed: the development of the superconducting dipole magnets for the Large Hadron Collider, and CERN's contribution to hadron cancer therapy using beams of carbon ions. It was anticipated that the sought-after key features of CERN would emerge by examining the actual real-life processes of planning, priority-setting, decision-making, confronting difficulties and, of course, conducting research and development. Even though the case studies had a narrow scientific and technological scope, it was found that a number of interesting themes emerged. It is likely that these can be seen as generic and more generally valid, thus fulfilling the goal of the study. To be sure, they necessarily pertain to a mature, long-standing, international regional infrastructure, but it is hoped that they will prove to be relevant to other types of projects and programmes as well. The observations are grouped under two headings, as follows:

Status of CERN as a European organisation

- As described in this report, the laboratory's leaders, administrators, engineers and technicians rose successfully to the scientific and technological challenge of the LHC. In this, they were continuing a tradition of continually focussing on the long-term future of the laboratory, and of

⁸² The basic technology is about one hundred years old, and was extensively used in vacuum tubes in the pre-transistor era. The requirements for an accelerator are much more stringent, especially for colliding-beam machines such as LEP or LHC, where the particles circulate inside evacuated chambers for many hours and can be disrupted by the presence of even very small quantities of gas. The residual pressure must be on the order of 10⁻¹¹ Torr – five orders of magnitude smaller than that of a vacuum tube!

⁸³ The effect of an insulating vacuum in a thermal solar panel can be quite dramatic. Tests conducted at CERN showed that, with no vacuum, an absorbing element coated with intensely black chromium dioxide can reach a temperature of 120 degrees C when exposed to the Sun. When it is insulated with a vacuum of 10⁻⁴ Torr, the temperature increases to 350 degrees! Even under daytime cloudy skies, a temperature of 250 degrees can be achieved.

assigning resources to exploring the potential implementation of ambitious new projects. The history of CERN features a succession of accelerators at the frontier of HEP, of which LEP and LHC are just the most recent. The launching of the LHC initiative was a bold move, but one that was deemed appropriate for this high-profile, high-status organisation.

CERN is part of a growing constellation of world-class European research facilities that reflect a major strength of the continent, with evident links to economic, political, educational and social advances of the past half-century. Although the commitment of the Member States to CERN is not taken for granted, and the degree of support from individual countries can wax and wane, the overall special status and prestige of the laboratory – which is based on an inter-governmental Convention, with a special legal standing and various immunities and privileges – have helped to ensure its survival during a period when many national laboratories (including some European ones) have terminated their HEP activities or face uncertain futures.

- The special status of CERN allows it to play a part in determining its own future. In particular, the European Strategy for Particle Physics has been prepared twice (in 2006 and 2013) under the auspices of CERN, but with the participation of other major stakeholders, including non-European ones. This systematic foresight and planning process provides a level of stability and security that can enable forward-looking, innovative activities, such as the ones described in the report.
- CERN derives numerous benefits from a well-developed network of links to national research agencies, institutions and laboratories in Europe (and beyond). In past years, when several countries maintained national HEP facilities, the relationship had elements of rivalry as well as co-operation but, even then, there were many productive exchanges of ideas, people, equipment and other research resources. The case studies of Section D document how CERN's network of institutional and personal contacts played a critical role in catalysing R&D, and in overcoming difficulties in meeting cost and schedule goals. To some extent, the network is there simply because of the passage of time (the institutions concerned have been interacting for sixty years). It is true, as well, that national research organisations receive their funds from the same agencies that finance CERN, so that the linkages emerge naturally during the elaboration of national science policies. But the richness and productivity of the network is also due to the open nature of the working environment of CERN.
- The longevity of CERN produces tangible consequences for enabling new scientific ventures. Existing installations (including accelerators, but also power supplies, buildings, laboratories, machine shops, etc.) can be adapted and put to new uses. As described in Section D.1, the installed infrastructure can constitute a significant advantage, allowing the allocation of scarce resources to the development of new technology and intellectual added value.
- This report describes the pro-active role that CERN was able to play in European affairs in matters that were significantly removed from pure research in elementary particle physics: supporting the revitalisation of Central Europe following the end of the Cold War, and promoting the development of an advanced, extremely sophisticated form of cancer therapy. In the latter case, CERN served as a unique refuge for projects that needed time to mature in their respective countries. CERN was able to play this role because it could bring important skills and resources to bear, but also because of the recognised stature and influence of the laboratory's leaders at the time.

- Today, CERN is intensifying its international outreach in high-energy physics and beyond. It seeks not only to add new national partners and collaborators, but also to strengthen connections with neighbouring scientific disciplines (for instance, the newly-revitalised field of astroparticle physics), to establish links to intergovernmental organisations (such as OECD and selected agencies of the United Nations), and to make contributions to initiatives that have both political and scientific goals, such as the education programmes described in Section D.4, or the SESAME project (which, after twenty years of effort, is on the verge of inaugurating a synchrotron light source in Amman, Jordan, hoping to bring together scientists from Israel and the Arab countries).

Operations and governance

- CERN's Member States make their annual contributions in cash although, at critical times, they have provided in-kind contributions as well (as illustrated, for example, in Sections D.1.b and D.1.c). The current annual budget is approximately 1.2 billion Swiss francs (about 1.3 billion USD, or one billion euros). Non-member countries have made major in-kind contributions as well (for instance, the United States provided equipment with a value of approximately one half-billion dollars for the LHC and its detectors).

Access to cash allows the laboratory to assume responsibility for a vast array of activities. As described in the report, this includes R&D on new accelerator technologies, plus large-scale interactions with industry and procurement. CERN also participates in the development and construction of the particle detectors, but only at the level of 20% of their cost.

CERN employs about 2 300 staff members, among them scientists, engineers and technicians. Normally, they are assigned to the many tasks that are associated with the laboratory's main HEP projects but, as detailed in this report, they can engage in exploratory work in other areas that are deemed to correspond to the laboratory's broader role as a source of technological expertise in Europe. This manpower reserve is a great asset for the organisation. It can be deployed in response to strategic "top down" decisions or, more intriguingly, in response to initiatives that arise in a "bottom up" mode. These secondary projects are only taken on under rare circumstances, and in consultation with the laboratory's leadership hierarchy and the Council (in the latter case, and for small projects, the consultation process may be informal). If a larger-scale effort is needed, for example, during the collaboration with MedAustron (Section D.2.b), a financial agreement can be reached whereby CERN provides technical services with full cost recovery.

As outlined in Section E, the exploration of non-HEP applications of CERN-developed technologies is a work in progress. The mandate and activities of the Knowledge Transfer Office have evolved in recent years, with the goal of enhancing the societal impacts of CERN, but without doing harm to the main scientific mission.

- The CERN community, like that of many leading scientific institutions, is uniquely suited to producing innovative solutions to challenging problems. The combination of the factors already cited in this section (high scientific and political standing, ambitious forward-looking research programme, independence as a supra-national organisation, cash-based finances) results in an ability to recruit and retain very competent staff. As an established international organisation that was founded in the 1950s, CERN is able to offer attractive employment conditions (salaries, pensions, etc.). The staff form an interacting community characterised by a vigorous exchange of ideas. At times, ideas emerge that can be transformed into innovative new

technologies, even commercial products. The most well-known instance of this is, of course, the invention of the World Wide Web by Timothy Berners-Lee at CERN in 1989-1990, but other examples could be cited, such as the early work of David Townsend at CERN, between 1970 and 1978, that eventually led to the development of the PET/CT (Positron Emission Tomography / Computed Tomography) scanner. Other examples are cited in Section E.

- All large research institutions are necessarily hierarchical organisations, with well-defined structures and procedures for ensuring responsibility, accountability and reporting. CERN's version of the hierarchy is relatively "flat", especially where it concerns communication and interaction across the vertical dimension of the hierarchy. It is not unusual for junior members of the staff, or researchers from collaborating institutions (even graduate students) to "buttonhole" the senior laboratory leaders in order to present original ideas or opinions. In part, this is a consequence of the inherently meritocratic nature of scientific research but, at CERN, it is reinforced by the special status of the laboratory that sets it apart from traditional institutions.

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APPENDIX A. Members of the International Experts Group, appointed by GSF Delegations

Australia	Herma Buttner	Australian Nuclear Science and Technology Organisation
European Commission	Zajzon Bodó	DG CNECT/C1 eInfrastructure
	Marco Weydert	DG Research and Innovation, Unit B.4
France	Jean-Pierre Caminade	Ministry of Higher Education and Research
Germany	Hans-Jürgen Donath	Federal Ministry of Education and Research DESY
Italy	Valerio Vercesi	Istituto Nazionale Di Fisica Nucleare (INFN), Sezione di Pavia
Japan	Yuko Ito	National Institute of Science and Technology Policy
Spain	Juan Fuster	Instituto di Fisica Corpuscular, Valencia
United Kingdom	Penny Woodman	Science and Technology Facilities Council (STFC) Innovations
United States	Michael Salamon	US Department of Energy Office of High Energy Physics

APPENDIX B. List of interviewed experts

(Regarding the affiliations that are shown, it should be noted that some of the persons have retired or otherwise departed from the indicated institutions, while others have additional affiliations that are not listed.)

- **LHC main ring dipole magnets:**

CERN

Stephen Myers
Maurizio Bona
Herwig Schopper
Kurt Hubner
Giorgio Brianti
Lyndon Evans
Romeo Perin
Lucio Ross
Theodor Tortschanoff
John Ellis
Frank Zimmermann

Dipole Magnet Contractors

Gérard Grunblatt (*Alstom*)
Daniel Bresson (*Alstom*)
Roberto Marabotto (*Ansaldo*)
Roberto Cappellini (*Ansaldo*)
Alessandra Secchi (*Ansaldo*)
Willi Gaertner (*Babcock Noell*)

Non-CERN

Burton Richter (*Stanford University*)
Maury Tigner (*Cornell University*)
Michael Peskin (*SLAC National Accelerator Laboratory*)
Keith Ellis (*Fermilab*)

- **Software packages:**

Frédéric Hemmer

- **Hadron cancer therapy:**

CERN

Herwig Schopper
Ugo Amaldi
Pierre Mandrillon
Philip Bryant
Horst Schonauer
Manjit Dosanjh

Non-CERN

Meinhard Regler
(*Austrian Academy of Sciences, Institute of HEP*)
Ken Peach
(*Oxford University Particle Therapy Cancer Research Institute*)
Gerhard Kraft
(*GSI Helmholtzzentrum für Schwerionenforschung*)
Martin Jermann (*Paul Scherrer Institute*)
Leonid Rivkin (*Paul Scherrer Institute*)
Sandro Rossi⁸⁴ (*CNAO*)
Bernd Moesslacher (*MedAustron*)

⁸⁴ Sandro Rossi is the General Director and Technical Manager at the *Centro Nazionale di Adroterapia Oncologica* (CNAO) in Pavia. He was the principal interlocutor during a visit by OECD staff at CNAO on 19-20 June 2013. Other participating experts were Valerio Vercesi (member of the OECD Experts Group), Umberto Dosselli, Claudio Sanelli, Antonio Zoccoli and Marco Pullia.

- ***Education and outreach:***

Rolf Landua

- ***Knowledge transfer:***

Jean-Marie Le Goff

Sigurd Lettow

Enrico Chesta

Javier Serrano

Giovanni Anelli

Cristoforo Benvenuti

François Fluckiger

- ***General:***

Rolf-Dieter Heuer

Maurizio Bona

Michel Spiro

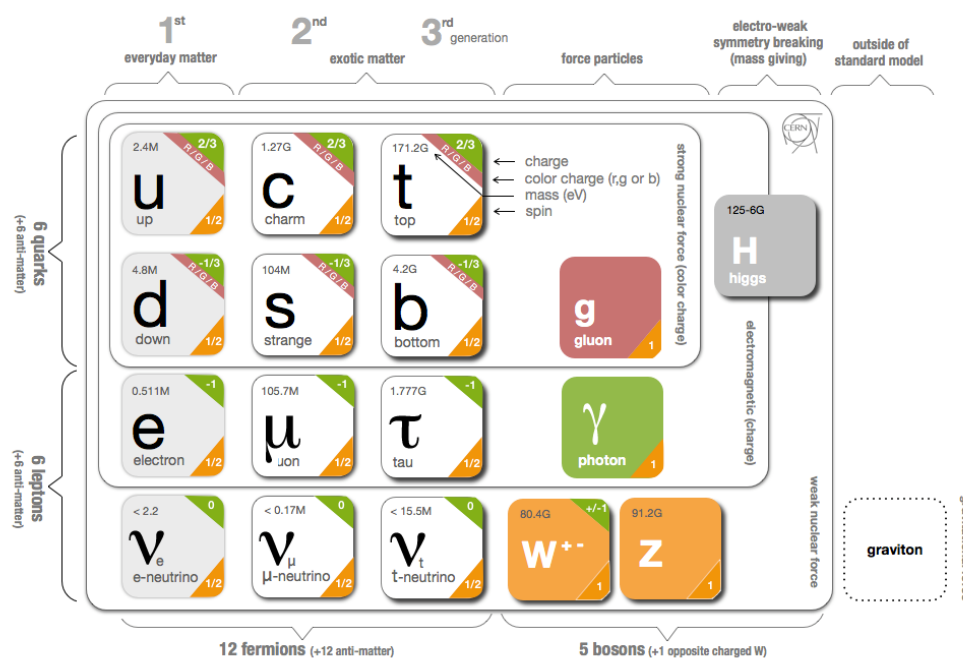
Jens Vigen

APPENDIX C. Introduction to the scientific rationale of the LHC Project

In this Appendix, a non-technical, highly simplified description of the scientific rationale for undertaking the LHC project is presented. It pertains to the state of understanding of fundamental physical phenomena as of approximately 1980 when, as described in Section D.1.b, CERN and other high-energy physics laboratories were scientific competitors in the race to confirm the Standard Model of Particles and Fields, and to discover the top quark and the Higgs boson.

In the traditional (reductionist) view of nature and of science, elementary particle physics occupies a special place: it seeks to identify the most elementary, most fundamental constituents of physical reality, and to explain their properties and their interactions. In principle (although the details are not at all well understood, to say the least) all other phenomena, from the properties of inert materials to the behaviour of living things, can be regarded as the inevitable results of the interactions of the fundamental constituents. Given the vast diversity and intricacy of the higher-level, macroscopic phenomena, it might be supposed that the world of the fundamental particles must also be one of overwhelming complexity but, to the great satisfaction of the physicists, the opposite appears to be the case. In fact, during the past half-century, particle theorists have developed a minimalist, compact, elegant theoretical framework, the *Standard Model of Particles and Fields* (usually called the “Standard Model”) that accounts for all – or very nearly all, as described below – of known phenomena at the atomic and subatomic scales. Moreover, like the best scientific theories, it has been a source of predictions about the results of experiments that were not yet performed when the theory was developed. These predictions have, to date, all been confirmed, sometimes with great precision.

Figure 7. Standard Model



Source: Produced at CERN webfest, 2012; see ISGTW, 15 August 2012.

The figure above lays out graphically that, according to the Standard Model, physical reality consists of combinations of a small set of generic point-like particles: quarks, leptons, and gauge bosons. In the theory, there are only six kinds of quarks, grouped in three pairs (up/down, charmed/strange, top/bottom) and three pairs of leptons (electron, muon, and tau, each with a distinct associated neutrino). Moreover, there are only two possible interactions among these particles: “strong” and “electroweak”. The former binds quarks into composite particles: mesons and baryons (such as protons and neutrons), and thus accounts for all of the known species and properties of nuclei.⁸⁵ The electroweak interaction encompasses nuclear radioactivity and, importantly, all of electromagnetism, including the motions of electrons surrounding nuclei. In this way, all atomic phenomena, all of chemistry (and, by extension, biology) is accounted for, at least in principle.

In the Standard Model, the two fundamental interactions (strong and electroweak) have the interesting property that each can be identified with a field (i.e. an entity that has a value at every point in space, like the classical gravitational field first conceived by Newton). But each interaction can, completely equivalently, be described as acting through the interchanges between the interacting particles of elementary, point-like particles called gauge bosons. These bosons are integral parts of the Standard Model, as shown in the figure. In the case of the strong interaction, the exchanged bosons are the gluons (there are several sub-species of these), whereas the electroweak interaction is mediated by three particles: W, Z and the familiar photon. In this way, and to summarise, everything that has or will ever exist is depicted as an interacting ensemble of only sixteen distinct types of elementary particles:⁸⁶ a startling picture, and a very bold claim indeed.

The Standard Model does much more than just enumerate an ensemble of fundamental particles. Its mathematical formalism, embodied in a set of complex but elegant mathematical equations, allows the computation of numerous experimentally measurable quantities, such as the masses (and other properties) of composite particles (e.g. hadrons and mesons), reaction rates, and decay modes.

One of the most gratifying developments in any scientific discipline occurs when a new insight into the nature of reality emerges solely from the examination of the mathematical formalism of a theory. In the case of the Standard Model, a new field (or, equivalently, a new interaction) was identified that could give completeness and coherence to the theoretical structure. In the real world, this field could be interpreted as that which endows particles with a very fundamental property: mass.⁸⁷ With this new insight, an intense search began to verify the existence of this new field (dubbed the Higgs field) and of the corresponding exchanged particle, the Higgs boson.

⁸⁵ The quarks and antiquarks of the first quark pair (“up” and “down”) make up all of the nuclei that we observe in the extended everyday world: ourselves, our immediate surroundings, our planet, the Solar System, and all of the stars and galaxies of the observable Universe. But the other two families of quarks really do exist (they have been created in accelerator-based experiments). Presumably, they played an important role in the first instants when the Universe was created in the Big Bang, and we would not be here if not for their fleeting existence, long ago.

⁸⁶ This simple calculus does not take into account the existence of *antimatter*. In the Standard Model – and, it appears, in nature – each quark and lepton is matched by an anti-particle (with the possible exception of the neutrinos – a question that is still under investigation). Very small amounts of antimatter can be detected in the everyday world, the result of radioactive decay, or the bombardment of the Earth by cosmic rays. Normally, antimatter combines quickly with matter, and disappears in a burst of electromagnetic radiation (photons). Accelerator experiments usually produce equal (albeit tiny) amounts of matter and antimatter, and many different species of composite particles have been created in this way. Thus, for example, those two fundamentals of physical reality, the neutron and the proton, are composed of quarks: one up quark and two down quarks make up the neutron, while two up quarks and one down quark form a proton. An antiproton is made of two up antiquarks and one down antiquark.

⁸⁷ Without this additional interaction, all of the particles in the theory (quarks, leptons, etc.) ought, theoretically, to be massless. But in reality, only photons and gluons have zero mass (and the neutrinos nearly so).

In the mid-1970s, the Standard Model was a new and exciting development, but it could not be considered to be fully verified by experiments. The up, down and strange quarks, constituents of “ordinary” matter, were standard elements of quark-based theories that emerged in the late 1960s and early 1970s. Their existence could be taken for granted. Then, in only a few years, the other, more exotic fundamental particles were produced in accelerator laboratories around the world. The discovery of the charm quark in 1974 (by Burton Richter⁸⁸ at the Stanford Linear Accelerator Centre [SLAC] and Samuel Ting at the Brookhaven National Laboratory) galvanised the world of physics. In that same year, the first indication of the existence of the Z boson (in the form of a “weak neutral current”) was announced by CERN researchers. Next, the tau lepton was detected in 1975 by Martin Perl’s group at SLAC. The discovery of the bottom quark was made by Leon Lederman at Fermilab in 1977,⁸⁹ and definitive evidence for the existence of gluons was obtained in 1978 at the DESY laboratory in Hamburg. The W and Z particles were directly detected at CERN in 1983, earning Simon van der Meer and Carlo Rubbia (CERN Director-General from 1989 to 1994) a Nobel Prize in 1984.⁹⁰

Thus, at that point, there were two major missing pieces of the Standard Model: *the top quark and the Higgs boson*. According to the theorists, and based on strong experimental evidence, these missing particles were to be very heavy, each with the mass of a good-sized nucleus. New, more powerful accelerators and detectors would therefore be needed to produce and study them.

Finding “the Higgs” and “the top”, and thus confirming the Standard Model, was to become a major motivating force in high-energy physics for three decades. But, during that time, scientists also explored new, more comprehensive theories. While the Standard Model is one of the greatest achievements of modern science, the attitude of some experts is reflected in a quip by physicist David Hertzog: “Physicists love the Standard Model, but they don’t like it”. In effect, the theory lacks some desirable features – features that would, presumably, be present in an even more elegant, more compact, more comprehensive theory. In the Standard Model, the two fundamental interactions – strong and electroweak – are separate (albeit linked) mathematical constructs, whereas purists would have more confidence in a completely unified formalism. In addition, a number of measurable properties of particles that would, ideally, have been predicted by the theory, have to be inserted into it instead, based on measurements.⁹¹ Also, the Standard Model does not naturally explain one of the most fundamental properties of the Universe: the overwhelming preponderance of matter over antimatter. And, finally, the Model has no place at all for two phenomena that play a central role in the composition, structure and evolution of the Universe: gravitation⁹² and dark matter. Already in the 1980s, the search for “physics beyond the Standard Model” – including such hypothetical phenomena as “supersymmetry” and “grand unification” – was to become a major priority, alongside completing and verifying the Model itself. That search continues to this day.

⁸⁸ In this report, the statement “... was discovered by X” usually means “... was discovered by an experimental group headed by X”.

⁸⁹ The bottom quark (or, more accurately, the Upsilon particle, which is a bound state of a bottom quark and a bottom antiquark) was discovered by researchers working on the E288 experiment at Fermilab. This discovery differed from the others mentioned in this paragraph in that it was made using protons incident on a stationary platinum target. The other particles were all produced and detected in collider-based experiments.

⁹⁰ Lederman, Richter, Perl and Ting all became Nobel laureates as well.

⁹¹ An example of this is provided by the Higgs mechanism. The theory consistently and logically explains how any particle’s mass is a manifestation of its interaction with the Higgs field, but it says nothing about the actual value of the mass (i.e. the strength of the interaction) which must be put into the theory “by hand” (artificially, based on measurements). Because of this, the huge differences between the masses of the fundamental particles (e.g. a top quark is 340 000 times more massive than an electron) remain unexplained.

⁹² Today (2013) *dark energy* should be added to the omissions in the Standard Model. It manifests itself as an extremely powerful force that accelerates the expansion of the entire Universe. It is closely linked to gravitation.

APPENDIX D. Operational hadron therapy facilities around the world

Proton therapy facilities in operation, including patient statistics:

Country	Centre	Began operations	Patients treated
Canada	TRIUMF, Vancouver	1995	170 (12/12)
China	WPTC, Zibo	2004	1078 (12/12)
Czech Republic	PTC Czech r.s.o., Prague	2012	1 (12/12)
England	Clatterbridge	1989	2297 (12/12)
France	Nice	1991	4692 (12/12)
	Orsay	1991	5949 (12/12)
Germany	HZB (HMI), Berlin	1998	2084 (12/12)
	RPTC, Munich	2009	1377 (12/12)
	HIT, Heidelberg	2009	252 (12/12)
Italy	INFN-LNS, Catania	2002	293 (11/12)
	CNAO, Pavia	2011	58 (03/13)
Japan	NCC, Kashiwa	1998	1226 (03/12)
	HIBMC, Hyogo	2001	3198 (12/11)
	PMRC(2), Tsukuba	2001	2156 (12/12)
	SCC, Shizuoka Cancer Centre	2003	1365 (12/12)
	STPTC, Koriyama-City	2008	1812 (12/12)
	Medipolis PTRC, Ibusuki	2011	490 (12/12)
Poland	IFJ PAN, Krakow	2011	15 (12/12)
Russia	ITEP, Moscow	1969	4246 (12/10)
	St. Petersburg	1975	1386 (12/12)
	Dubna	1999	922 (12/12)
South Africa	NRF, iThemba Labs	1993	521 (12/11)
South Korea	NCC, Ilsan	2007	1041 (12/12)
Sweden	Uppsala	1989	1267 (12/12)
Switzerland	PSI, Villigen	1996	1409 (12/12)

Country	Centre	Began operations	Patients treated
USA, CA.	Loma Linda	1990	16884 (12/12)
USA, CA.	UCSF	1994	1515 (12/12)
USA, IN.	IU Health PTC	2004	1688 (12/12)
USA, MA.	NPTC, MGH, Boston	2001	6550 (12/12)
USA, TX.	MD, Anderson Cancer Centre, Houston	2006	3909 (12/12)
USA, FL.	UFPTI, Jacksonville	2006	4272 (12/12)
USA, OK.	ProCure PTC, Oklahoma City	2009	1045 (12/12)
USA, PA.	UPenn, Philadelphia	2010	1100 (12/12)
USA, IL.	CDH Proton Centre, Warrenville	2010	840 (12/12)
USA, VA.	HUPTI, Hampton	2010	489 (12/12)
USA, NJ.	ProCure Proton Therapy Centre, Somerset	2012	137 (12/12)
USA, WA.	SCCA, Proton Therapy, a ProCure Centre, Seattle	2013	1 (03/12)

Carbon ion therapy facilities in operation, including patient statistics:

Country	Centre	Began operations	Patients treated
China	IMP-CAS, Lanzhou	2006	194 (12/12)
Germany	HIT, Heidelberg	2009	980 (12/12)
Italy	CNAO, Pavia	2012	22 (03/12)
Japan	HIMAC, Chiba	1994	7331 (01/12)
	HIBMC, Hyogo	2002	788 (12/11)
	GHMC, Gunma	2010	537 (12/12)

Source: Particle Therapy Co-operative Group (PTCoG), <http://ptcog.web.psi.ch/ptcentres.html>

APPENDIX E. Hadron therapy facilities around the world: under construction or planned

Country	Centre	Start of treatment planned
China	SJFH, Beijing	?
France	Centre Antoine Lacassagne, Nice	2014
Germany	Proton Therapy Centre, OncoRay, Dresden	2014
	WPE, Essen	2013
Italy	ATreP, Trento	2013
Japan	Fukui Prefectural Hospital PTC, Fukui City	2014 ?
	Aizawa Hospital, Proton Therapy Centre, Nagano	2014
	Nagoya Proton Therapy Centre, Nagoya City, Aichi	2013
Netherlands	Holland PTC, Delft	?
Poland	IF J PAN, Krakow	2014 ?
Russia	PMHPTC, Protvino	?
Saudi Arabia	King Fahad Medical City, Riyadh	2015 ?
Slovak Republic	CCSR, Bratislava	?
	CMHPTC, Ruzomberok	?
South Korea	Samsung Proton Centre, Seoul	2014
Sweden	Skandion Clinic, Uppsala	2014
Switzerland	PTC Zürichobersee, Galgenen	2016
Taiwan	Chang Gung Memorial Hospital, Taipei	2013 ?
USA, MI.	McLaren PTC, Flint	2013
USA, IL.	Northern Illinois PT Res. Institute, W. Chicago	2013 ?
USA, MO.	Barnes Jewish, St. Louis	2013
USA, CA.	Scripps Proton Therapy Centre, San Diego	2013
USA, NB.	Rober Wood, Johnson	2014
USA, OK.	Oklahoma University, Oklahoma City	2014

Country	Centre	Start of treatment planned
USA, FL.	MD Anderson, Orlando	2014
	First Cast Oncology, Jacksonville	2014
USA, TN.	Provision Centre for Proton Therapy, Knoxville	2014
USA, LA.	WK Proton Therapy Centre, Shreveport	2015
USA, MN.	Mayo Clinic Proton Beam Therapy Centre, Rochester	2015
USA, AZ.	Mayo Clinic Proton Beam Therapy Centre, Phoenix	2016
USA, NY	Proton Institute of New York, New York	2015

Source: Particle Therapy Co-operative Group (PTCoG), <http://ptcog.web.psi.ch/ptcentres.html>.

APPENDIX F. About the OECD Global Science Forum

For over twenty years, the Organisation for Economic Co-operation and Development (OECD) has hosted a committee of governmental science policy officials of its Member and Observer countries. It began as the Megascience Forum (MSF) in 1992. Its creation was based on necessity: increasingly, big research projects needed to be discussed internationally in a timely manner to ensure a globally-coherent response to recognized scientific priorities, to avoid unnecessary duplication and, when appropriate, to bring together funding and expertise for implementing joint research facilities, networks and programmes. The OECD was chosen as the venue for the Forum because of the organisation's commitment to sustainable economic and social innovation, and its acknowledgement of the vital role of basic and applied research for achieving these goals.

In 1999, a new mandate was adopted by the 30 participating countries. The newly-designated Global Science Forum (GSF) shifted its main focus away from the biggest research projects, to concrete challenges and opportunities in well-defined scientific domains, and also to generic cross-cutting issues that concern the planning, funding and managing of basic research. The GSF has now become a general-purpose inter-governmental science policy committee, able to address issues across the entire spectrum of physical, life, earth and social sciences.

The Global Science Forum works in a simple way: topics for specific activities are proposed by national delegations, and are reviewed at general meetings that take place every six months. When a proposal is accepted, interested delegations nominate national experts to collectively carry out the activity with assistance from the Forum's Secretariat. Depending on the subject area, meetings, workshops, surveys, consultant studies or other mechanisms may be employed over a period of time that ranges from one to three years. An activity always ends with the drafting of a concise (typically, twenty-five pages) policy-level report that contains a clear description of the challenge or problem or opportunity that led to the undertaking of the activity, relevant facts and findings and, most importantly, recommendations for actions by governments or by other entities, such as international scientific organisations. GSF Forum reports are always made available to the public.

On four occasions, the outcome of the GSF's work was the establishment of new international research collaborations that became fully independent of the OECD:

- The Global Biodiversity Information Facility (GBIF).
- The International Neuroinformatics Co-ordinating Facility (INCF).
- The Global Earthquake Model (GEM).
- Scientific Collections International (SciColl).

Since 1992, more than 50 activities have been carried out in this way. To provide a good notion of the range diversity of the GSF's work, the following are activities that are currently under way, or were completed in only the last 24 months:

- Promoting international collaboration and co-ordination of scientific research collections.
- Modelling of urban systems to address the challenges of climate change and biodiversity.
- Fostering the development and utilisation of data infrastructures for the social sciences.

- Global modelling of natural hazard risks.
- Opportunities, challenges and good practices in international research co-operation between developed and developing countries.
- International co-operation in astroparticle physics.
- Establishing and operating international distributed research infrastructures.
- Facilitating international co-operation on non-commercial clinical trials.
- Scoping a network for temperate agriculture research.
- Optimising scientific advice for governments.
- Case studies of the economic and societal impacts of large research infrastructures.

Throughout its twenty-two year history, the work of the MSF and GSF has been based on two fundamental principles:

Transparency and outreach to scientific communities. The member countries recognise that scientists initiate research projects via a “bottom-up” process, and while the Forum has always been an essentially inter-governmental body, scientists, scientific organisations, and major research institutions have routinely been invited to fully participate in the subsidiary activities, including the formulation of final findings and action recommendations. Thus, for example, when the GSF convened the Working Group on Astroparticle Physics, representatives of CERN and of PaNAGIC (the Particle and Nuclear Astrophysics and Gravitation International Committee of the International Union of Pure and Applied Physics, IUPAP) took part in all of the deliberations and in the preparation of final findings and recommendations. Indeed, the international physics community has often been involved in the work of the GSF. Three of IUPAP’s standing Working Groups were created in part as a result of OECD recommendations: International Committee on Ultrahigh Intensity Lasers, International Co-operation in Nuclear Physics, and the Astroparticle Physics International Committee.

Efficiency and responsiveness. When OECD countries created the Megascience Forum in 1992, one of their requirements was to avoid creating a large international bureaucracy. They wanted a lean, efficient, cost-effective operation that would serve them and would not, under any circumstances, insert itself, and its own institutional interests, into the substantive work of the committee. Accordingly, they agreed on a budget that would support a minimal secretariat: three full-time international civil servants (one of whom is a secretary/administrator) based at OECD headquarters in Paris. Two members of the secretariat have scientific backgrounds (high-energy physics and molecular biology) but they are not expected to have expert knowledge in the highly diverse topics that the Forum takes up. They play an enabling and facilitating role, so that substantive work is performed by experts designated by national delegations – chiefly senior programme managers of science funding agencies, and prominent scientists invited by the Forum. Operating this way, 6-8 activities are typically on-going in parallel.

The current five-year mandate of the GSF will expire at the end of 2014. Discussions are already under way on whether the work should continue beyond that date, possibly with a revised mandate or new operating procedures. To support that decision, an evaluation exercise will be conducted in 2014.