Chapter 11

Managing the Laboratory and Large Projects

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11.1 The CERN Approach: Change and Continuity

The role and governance of CERN

The principal mission of CERN is to provide large-scale facilities for performing and analysing experiments related to high energy particle physics. This European laboratory was founded in 1954 to foster collaboration and rebuild confidence between scientists who until ten years earlier had been confronted in a devastating war. From the beginning CERN was to have the ambition to provide world-class facilities that would allow European scientists to engage in fundamental research on a par with the opportunities existing outside Europe, particularly in the USA. The scale of the accelerators and infrastructure, and the personnel and financial effort required for this kind of research had reached such a level that the nations of Europe had to pool resources to build them and thus remain internationally competitive. The CERN Convention, signed in 1953 between 12 founding member states, entered into force in September 1954. This remarkable and visionary 32-page document, sets out the rules for the governance and the purpose of the Organization [1]: "… to provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published and otherwise made generally available."

The governing body of the Organization is the CERN Council, consisting of two delegates from each member state. The Council is assisted by the Finance Committee (FC) dealing with all issues of personnel and material budgets, and the Scientific Policy Committee (SPC) advising the Organization on the research agenda. Council allocates the annual budget, with funds provided by the member states in proportion to their Net National Income (capped for any one member state, via a formula, to be less than 25% of the total budget). In order to provide a stable funding profile, to enable planning of the medium and long-term scientific programme as well as the day-to day running of the laboratory, a system of five-year rolling forecasts ("Bannier procedure") is applied. Each year the budget for the following year is established, together with firm estimates for the following two years, and provisional estimates for the subsequent two years. While the delegates are briefed by their ministries to hold a certain line, the CERN Council has maintained the authority to negotiate and take decisions in the interest of the Organization, largely without permanent consultation with the governments.

In order to make the best use of worldwide resources, the CERN programme is harmonized with that of other laboratories. The CERN Council is kept informed by the European Committee for Future Accelerators (ECFA) and the International Committee for Future Accelerators (ICFA) concerning the scientific merit and advisability of undertaking new large projects. Along with the FC and the SPC, these entities are independent of CERN.

The astounding swiftness of the implementation of CERN and the visionary scope set out by its founders still remains, 60 years on, a remarkable achievement.

The CERN Organization

The Laboratory is organized today in four sectors and a number of units, as shown in Fig. 11.1. The Accelerators and Technology, Research and Computing, Finance and Human Resources sectors are structured into departments; the fourth sector covers International Relations. The Beams (BE), Technical (TE) and Engineering (EN) departments provide the particle beams for the experiments; they are centres of excellence that work together to design, build, operate, maintain and develop the accelerator complex, including R&D for new facilities. These departments report to the director of Accelerators and Technology; projects are coordinated via the director's office (DO). The Theory (TH), Experimental Physics (EP) and Information Technology (IT) departments are also mutually beneficial centres of excellence in their respective fields, and through which CERN assists visiting physicists; CERN physicists also collaborate in experiments on an equal footing with the external partners. The departments that handle these activities report to the director of Research and Computing. Finance, human resources and general services are provided by departments reporting to the director of Administration, and provide the regulatory environment for all activities. Certain activities are shared: the main workshops are used by the accelerator/technical and research sector; the information and communication technologies department addresses the needs of the entire laboratory, including users. Regulations on health, safety and environment are applied by an independent unit reporting to the director-general.

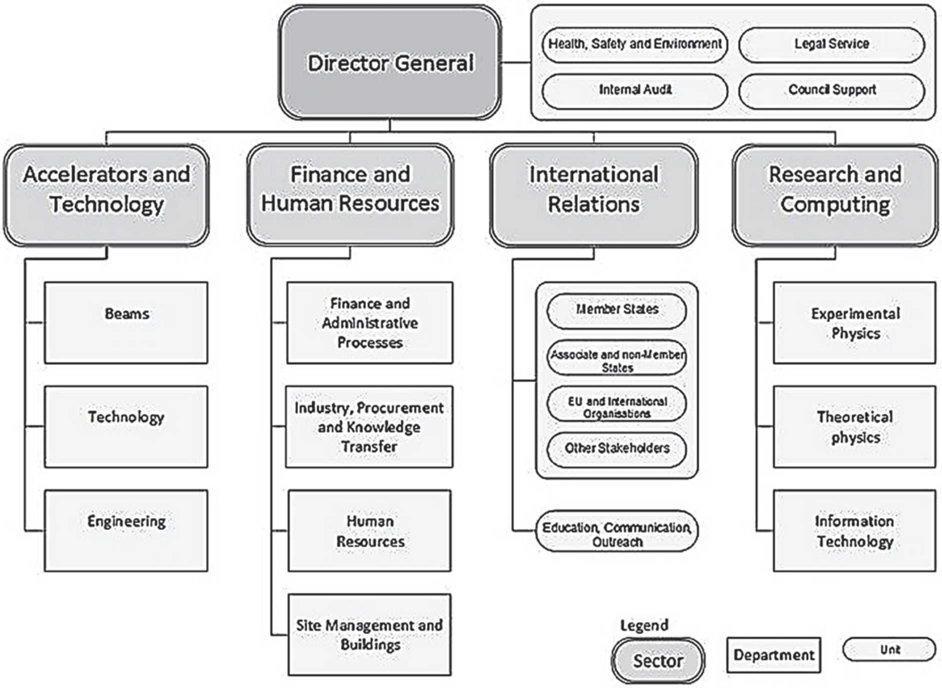

Fig. 11.1. Functional organigramme of CERN in 2016.

Directors, department heads and the director-general, who leads the laboratory, are appointed by the CERN Council. Further information regarding the organization of the laboratory can be found on the CERN web pages [2].

The overall organization of the laboratory has evolved over time; the recent addition of a sector devoted to International Relations reflects CERN's gradual evolution from a solely European entity to a broadening stature in the world. Until the 1980s all projects were administered by the departments (previously called divisions); starting with the LEP project, large accelerator and experimental facility projects are headed by project leaders responsible to the directorate. Until the early 2000s the particle beam facilities (accelerators and colliders) required for the experiments were provided by the respective divisions; subsequently it was decided to group the activities across the different accelerator divisions, to operate all the accelerators from a single control centre, and to assemble the specialists in groups in three divisions (renamed departments in 2004): Beams (BE), Accelerator Technology (TE), and Engineering (EN). Control is accomplished by a system of line management with mainly large groups (~ 100 staff) specialized in the various domains (operations, vacuum, radio-frequency, magnets, cryogenics, etc.). Most sub-projects can be handled within groups, simplifying control and avoiding the perils of matrix management, with essentially self-governing cross-group teams being formed to tackle very large projects. In the research sector the experiments are proposed, and largely staffed, by teams of researchers from external laboratories and universities. CERN groups participate in the experiment collaborations and, coupled with a few technical groups, cover particular needs and do the bulk of interfacing with the CERN infrastructure. The research sector has seen an explosion in the number of users, and the accelerator sector an increase in the complexity of the machines, obviously influencing their evolution. The technical and research sectors benefit from a collaborative administrative sector whose work has also become more complex with time.

CERN is an international organization, with staff drawn mostly far from their countries of origin. This has reinforced the international atmosphere of the laboratory and helped the users to integrate. Importantly, since the beginning, the staff has been motivated by the desire to achieve a common goal, in a constructive and non-bureaucratic collaboration between the sectors, building on their strengths and with a shared commitment to the Organization.

Style of Management

CERN has earned a reputation for developing state-of-the-art technology, the result of the collaboration of creative people in technology and research, covering a large spectrum of competence and coming with different cultural backgrounds. To "lead" and "manage" this staff requires certain talents: done properly it encourages efficiency, and includes the ability to judge when to stop "improving". Leaders and spokespersons are chosen from those who have earned the respect of colleagues, based on their scientific and personal standing or their technical achievements. In fact, in both the accelerator and research sectors the real motivation is provided by agreeing on a common goal, which can essentially always be achieved by rational discussion on scientific and technical grounds (notwithstanding shows of emotion and passion in certain circumstances!). Thus CERN's managerial decision model can be qualified as being one of "bounded rationality", a concept developed by Nobel laureate Herbert Simon [3]. Many of the ideas discussed in this book originated from scientists[a] and technicians actually doing the work, not their hierarchical leaders. Obviously, large accelerator projects and experiments must have a certain level of coordination, but for this to be efficient it must be done by staff respected for their technical competence, and their ability to recognize viable ideas when proposed. In the accelerator sector the

[a]At CERN, professional engineers and research, experimental and applied physicists, enjoy equal status and are referred to as scientific staff.

practice has been to vest group leaders with the necessary authority, and for them to hold the agreed budgets, and bear the responsibility for group activity. It has been found to be important to avoid appointing purely administrative group leaders, unable to provide respected technical leadership. The effective management structure is remarkably flat (especially in the research sector).

A further important aspect is responsible procurement of technical equipment, i.e. aimed at procuring at minimal cost to the Organization while balancing industrial returns to its Member States. How has this been done? The method has consisted of (i) performing a comprehensive cost/performance analysis of all projects, (ii) defining and applying a set of simple, fair and transparent purchasing rules, and (iii) empowering competent individuals or small teams to define goals consistent with the planning of the laboratory, and allowing them to achieve those goals with minimal bureaucracy and cost.[b]

By far the most important element in an organisation such as CERN is the quality of the staff, and this in turn depends on the ability to recruit and retain appropriate personnel, and to provide them with professional perspective. Thanks to its reputation and relatively competitive employment conditions, CERN is able to recruit and retain highly qualified staff.

Evolution of management in the accelerator sector

The management of CERN sectors has evolved over the years to take into account the continuous enlargement of the accelerator complex, and constraints on recruitment following a series of reviews of the Organization by external committees appointed by Council. Similar to other organizations, the staff complement increased rapidly in the period 1955–1970, peaking at about 3600 in 1979. Then, following the recommendations of the external committees, recruitment virtually stopped and numbers were steadily reduced, stabilising around the present complement of 2500. Almost no new staff was recruited for the LEP project, requiring a major redeployment of personnel both within the accelerator sector (closure of the ISR), and from the research sector (Experimental Facilities division) to the accelerator sector (with a consequent reduction in the service for the experiments). Towards the end of the 1980s new recruitment was authorized for about one in three of the posts liberated by an early departure scheme. This had become sorely needed with the appearance of the LHC project, but the approval of the construction of this machine was assorted with a further directive to reduce staff numbers. To face this challenge the accelerator sector

[b]In line with this approach CERN has pioneered since the 1990s the electronic issue and handling of administrative documents, aiming at a paperless administration.

underwent a major reorganisation, from being machine-centred to being activity-centred — e.g. having a single vacuum group, instead of separate vacuum groups for the PS, SPS, LEP etc. Similarly, the operation of all accelerators was grouped in a single control centre. This evolution was justified from the standpoint of classical management practice, and necessary for the groups responsible for operation and maintenance, which requires a sufficient pool of staff to provide round-the-clock service. It also purports to ensure perennial expertise within the technical groups in spite of repeated redeployment of personnel to projects. However, the LHC had started, like LEP, with an LHC division that assumed the responsibility for providing the main systems (magnets, vacuum and cryogenics), and despite being later renamed "Accelerator Technology Department" it continued to manage the work via a classical structure, with the department head taking responsibility as *de facto* the technical coordinator/team leader for major LHC work, in addition to providing the services for the other machines. In this way the pitfalls of matrix organization were avoided, and the staff working on the LHC did so as a team of groups, much as the teams on the large experiments, working towards a well-defined common goal. However, whereas for previous accelerator projects those who had participated in the construction continued to work for the machine they had built, taking an interest in its operation (an arrangement that often led to the acquisition of new competencies and the development of improved equipment), operation is now squarely in the hands of the operations team, and contact with the equipment groups is looser and more in the nature of a service. Today, the medium-size project to upgrade LHC luminosity is being handled as if it were a very large future accelerator project, with many collaborations, and in addition has adopted features of matrix-style organization. Time will tell whether this evolution is good for CERN.

Unlike large corporations, CERN is not free to hire and fire. This requires that staff remain flexible in supporting the goals of the organization and adapting to changing requirements. And change there was! The number of user scientists passed from hundreds in the 1970s to thousands in the 1990s and now stands at about 12 000. In parallel the number and complexity of the accelerators also grew: the increase in size, from the 6 m diameter synchrocyclotron to the 8.5 km diameter of LEP/LHC is impressive, but does not do justice to the true magnitude of the evolution. A corporation might have increased staff numbers, but CERN had to respond differently. It developed collaborations with outside laboratories for building accelerators, as was done (on a much larger scale) for the experiments. For the LHC, about 15% of the value of machine hardware was delivered via such collaborations (compared with about 80% in the case of the large experiments). This included the beam transfer magnets (BINP, Russia), the development and production follow-up of main ring superconducting quadrupoles (CEA, France) and cryostats (CNRS, France), the final focus quadrupoles and cryostats (Fermilab, USA, and KEK, Japan) and superconducting corrector magnets (DAE, India). CERN also benefited from the work of contingents of scientists and technicians from DAE, India (to staff the round-the-clock magnetic measurement campaign), and IFJ PAN, Kraków, Poland (to help with the installation and commissioning of the magnet protection system). CERN provided close expert oversight for such work, to ensure timely delivery of quality equipment and conformity to standards. Such arrangements rely heavily on the availability of core competence at the host laboratory and the strong motivation to achieve the goal, be it a working accelerator or working experiment.

In-kind contributions of equipment

The preferred way of acquiring equipment is via competitive tender from industry, using a detailed technical specification, if necessary based on model and prototype work done previously at CERN [Highlight 11.2]. In recent years supply via in-kind contributions from external institutes or laboratories have become more frequent, especially in the research sector, but also in the accelerator sector, as cited above. Although the in-kind supply may be free of charge to CERN it is not "free" for the project: it requires additional coordination, and reduces the degree of control CERN may deem necessary — a risk it has had to learn to take.

Additional monetary contributions from non-member states can be especially efficient, as they allow CERN to enlarge the tendering process. As an example, following Japan's special contribution to the LHC, firms there bid successfully for crucial advanced-technology equipment such as cold hydrodynamic helium compressors, high performance superconductors, and special steel.

While the LHC has so far only produced a few percent of the total number of collisions foreseen, options are starting to be discussed for a next large accelerator project. Such machines would cost much more than the LHC, and would almost certainly require truly worldwide funding. Could the model of the LHC experiments, which were funded at only 20% via the CERN budget, be adopted for financing a new accelerator?

In contrast with the experiments, a major fraction of the cost of a collider is (i) the civil engineering, and (ii) multiple units of a single sophisticated component. The quantities are such that they have to be produced in industry. This reasoning has led the proponents of the International Linear Collider (ILC) to consider in-kind contributions from designated regions that are possibly of a different design but "plug-compatible", bought from regional industry and controlled by regional "hub" laboratories. This ought to be possible, but would rely on there being a strong, competent central group, probably based at the host laboratory. It is generally understood that the civil engineering would be donated by the host region; together with the necessary oversight and central coordination, and procuring some key equipment, the minimum cost to the host region is plausibly close to 50% of the total. This is the starting assumption for discussions on how to fund the ILC; for ITER, hosted in France, the EU is contributing about 45% of the total cost, with the other six regional parties contributing about 9% each [4]. It would arguably be less risky and more economical to manage the funds for building a large new accelerator through the host laboratory, placing contracts worldwide via competitive tender, eventually featuring a degree of fair return on their expenditure. This is discussed in more detail below.

In-kind supply of qualified technical assistance

The testing, installation and quality control of equipment for a large accelerator project involves peaks of activity that call for more personnel than CERN can possibly provide. An efficient in-kind contribution is that of competent staff on secondment for a limited period during these peaks of activity — provided qualified technical supervision is available. This approach was adopted for the LHC magnet testing and the electrical circuit quality assurance referred to earlier.

Collaborations

In the accelerator sector, outside laboratories collaborate increasingly in design and prototyping work. This is clearly important when laboratories have specific expertise in domains not well covered at CERN. In this approach, (i) the collaborative sub-projects have to match the competence and infrastructure of the external laboratory; (ii) there must be effective liaison, recognizing the usual iterative design process; however, (iii) by concentrating on coordination, CERN technical staff is increasingly engaged in dispatching work to others. This has to be balanced with the need to maintain and develop core technical competence [5].

A collaborative response to requests for the transfer of know-how in core activities to external laboratories is part of the mandate of CERN. Occasional secondment of staff to work on projects elsewhere is also part of CERN's mission, and serves to enhance its visibility.

Over the last decade, CERN has become increasingly involved in the EU Framework Programmes (FP) such as CARE (Coordinated Accelerator Research in Europe) and EuCARD (European Cooperation for Accelerator Research and Development) together with a large number of laboratories. The EU FP are an excellent initiative, encouraging small teams to enter into cross-border scientific collaborations, with the possibility of attaining critical mass for specific R&D. There is also a clear sociological dimension. But with it comes a different style of control and reporting, typical of the EU programmes. CERN has shown in the past that it is capable of adapting to changing conditions: one has to be confident that it is able to absorb the additional constraints for the small fraction of activity addressed via EU-funded programmes. For most activities within the accelerator sector CERN can continue to apply the method proven successful over the years, namely to take advantage of in-house technical competence for design and model work, to purchase series equipment through contracts via normal competitive tender, and to transfer technology via close technical follow-up of manufacture.

Coordination

Coordination of large projects is obviously necessary. It is generally recognized that this is best left to those having the technical expertise and leadership ability. In the case of CERN, big projects, such as a new accelerator, are broken down into sub-projects, the leaders of which coordinate the sub-projects, resolve technical issues, and ensure respect of interfaces. Indeed, once the sub-projects have been allocated to competent and responsible technical groups, the remaining problems show up at the interfaces. It is the role of the project leader to organize structured meetings on a regular basis to track progress and manage changes at the interfaces. Between competent staff this goes smoothly with a minimum of meetings and reviews, thanks to a clear definition of the agreed goal.

In contrast with accelerator projects, the role of coordination is somewhat different for large experiments, built up from many collaborating institutes, and where decision-making is essentially via consensus. This requires clearly spelled-out management procedures, enshrined in the "Constitution of the Collaboration". After an initial learning phase this "management by consensus" has proved its worth, witness the swiftness and quality with which the LHC experiment collaboration have produced their scientific results.

Reviews

The use of reviews to examine technical choices and monitor progress of the major accelerator projects started with LEP, i.e. when the control of such projects passed nominally from the divisions to the directorate. However, reviewing the many sub-projects of the main project has only recently been adopted in the accelerator sector. The function was previously within the purview of the machine advisory committees, which reviewed on a regular basis the whole project, including sub-projects. CERN also had to participate in the process through collaborations with US laboratories, where frequent reviews are imposed. While reviews are useful — even essential, oversight does occur. Two instances of failure to detect problems at the LHC come to mind: the cryostats for the high luminosity insertions, and the magnet interconnects. In the first case a design flaw of the support system was not detected in the reviews. It was revealed during commissioning and was corrected (with some difficulty), but did not delay the start-up of the machine. In the second case the inherent weakness of the electrical splice was not pinpointed in the design review, with the well-publicized consequence of the September 2008 incident [6]. Problems may be averted by advice from reviews, but there is a real danger that they dilute responsibility. Reviews do not replace due diligence of project leaders.

The research sector has been accustomed to reviews for several decades. For the LHC experiments, the LHC Committee (LHCC) was established. With members external to CERN and the experiments, it served the important function of monitoring and providing advice, following progress and requesting remedial action if delays were incurred. This committee shares major credit for the remarkable operation of the experiments and the quality of the research results.

Patents

Most of the ideas that were conceived and developed at CERN, some of which even led to the award of Nobel prizes, have been published to make them available as common intellectual property, and not patented. Several studies [7–9] have shown that this policy has led to significant indirect added value, beyond direct commercial interest, for companies involved in producing material for CERN, as well as for society at large. The most dramatic example was the decision of CERN to put the WWW in the public domain. However, there is increasing pressure on publicly financed laboratories to protect technology from being patented commercially, and to provide a measure of their usefulness to society at large. At CERN, while this is still mainly achieved through publication as stipulated in the Convention, the approach with regard to patents is evolving (see Chapter 10).

One should bear in mind that the concept of patenting can itself be questioned, its net utility to society not being so evident [10]. It is well known that the vast majority of ideas develop into usable technology via interaction between members of a team, and for that to happen individuals should not be tempted to keep their ideas to themselves, with the hope of eventual personal profit from a patent taken out by CERN. Added to which it is generally recognized that for institutions like CERN the effort managing a patent portfolio might be such that the cost exceeds the benefit. CERN is vigilant as to the pitfalls of patenting.

Evolution of management in the research sector

The research sector during the "learning years"

Up to about the time of the p–p̄ collider, CERN provided a large fraction of the experimental equipment. At the same time, however, many university institutes acquired the competence to develop, build and operate experimental equipment. Importantly, this helped to establish a base and visibility of particle physics in

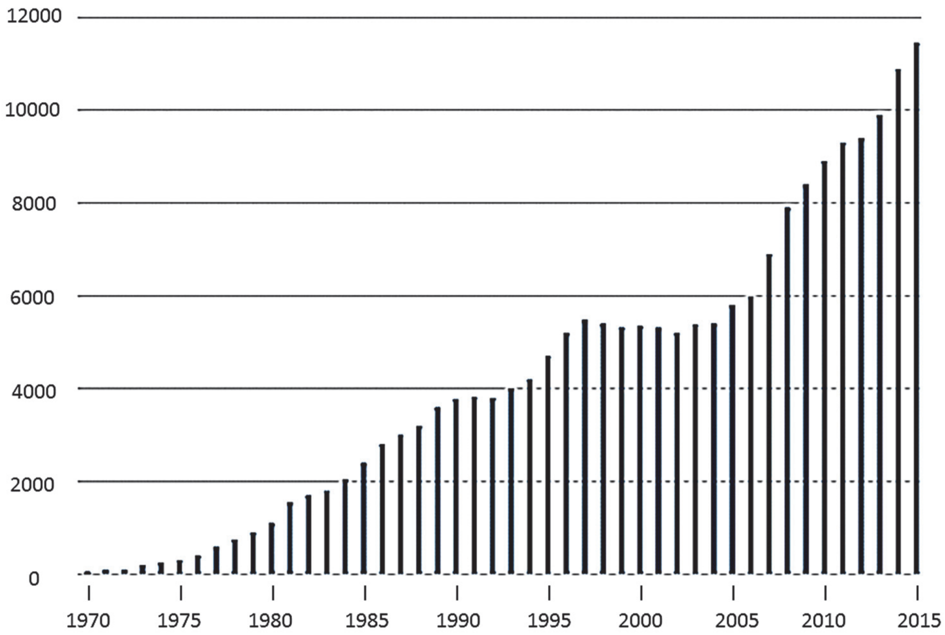

Fig 11.2. Number of CERN users vs. time.

academia. Starting with the p–p̄ collider era, experiments became large collaborative efforts with external institutions taking on a major share in providing, maintaining and operating equipment. This ever-larger involvement of the community is seen dramatically in the rising number of CERN users (Fig. 11.2).

The years to maturity

The four LEP experiments were each a collaboration of about 400 scientists, involving around 50 institutions, with CERN technical coordination and infrastructure. The evolution continued: for the LHC experiments CERN contributed only about 20% to the equipment value of the detectors, with the rest provided by the participating institutes and universities. These new conditions called for fresh ways to design, construct and operate the experiments.

CERN provided for each experiment, in addition to the infrastructure, the technical coordination, interfacing and integration, and financial control. An LHC experiment hosts up to 4000 collaborators coming from over 100 institutions. The funding of the collaborating institutions is provided by the national funding agencies in various forms and sometimes on an annual basis. It was impractical, if not impossible, to draw up legally binding contracts. Instead, the collaborations were (and are) held together via Memoranda of Understanding (MoUs). These are "best effort" agreements between stakeholders to supply selected items of equipment, cash (into a common fund) and associated personnel. Surprising as it may seem, it has worked remarkably well! The strong common interest of the stakeholders to reach the goal, and their ability to motivate and mobilize the experienced scientists, post-docs and students, were certainly important factors, but it should be stressed that the organizational framework and structure provided by CERN, the LHCC, the Resources Review Boards (RRB), and their sub-committees, have been crucial to the success of the LHC experiment projects [11].

Research at the global scale

The LHC experiments are represented by an elected spokesperson and "coordinated" (significantly the terms "managed" and "led" are avoided) by the spokesperson, aided by a technical coordinator (a recognized technical expert who takes responsibility for technical coordination and interfaces), a resource manager (who concentrates attention on funding issues), and elected scientists designated to coordinate the activities that are spread over the many collaborating institutes. The technical coordinators and resource managers are CERN staff. While it is only natural that there can be disagreements, the system is basically self-governing where governance is provided by the consensus derived from rational discussion among stakeholders, and crucially held together by the overriding desire to achieve the common goal of building a working experiment.

Apart from the experimental cavern, which is CERN-supplied infrastructure, the largest single-cost item of a detector is the experimental magnet, representing typically 30% of the value of the experiment. Up to the time of LEP these magnets had been designed and procured by CERN in much the same way as accelerator equipment. For LEP the design and fabrication of the two superconducting solenoids was outsourced (to CEA, France and to RAL, U.K.), with some CERN oversight. The normal-conducting solenoids were built at CERN. For the LHC an attempt was made to completely outsource the design and follow-up of the supply of the magnets. This turned out to be problematic for the magnets of all four major experiments, and closer control and collaboration of CERN was re-established.

In-kind contributions

The detectors of the experiments are complex but can mostly be sliced into packages of reasonable size; most of the equipment was developed and assembled in university laboratories, but sometimes it, was purchased by the institutes from industry. For the LHC, the framework for the tendering process via the common funds was provided by CERN, which often helped the collaborating institutes in this respect. Interfacing and integration was assured by the CERN group, and thanks to the effort (both technical and managerial) of the technical coordinators, the endeavour turned out to be successful. As the sources of both funding and manpower were widely dispersed, the experiments were subjected to regular scrutiny by the various committees to keep them on track with respect to technical performance, budget and schedule.

The volume of data generated by the experiments would have been impossible to handle using the computers available at the time the experiments were proposed. Decisions on data-handling equipment were therefore delayed until the last minute in order to take advantage of improving capacity (and decreasing cost), betting on the continuing validity of Moore's Law. The backbone for the data management was provided by CERN through the development of the Computing GRID, a software driven network of sharing the data and using the computing capacities of the collaborating institutes, distributed around the globe [Highlight 9.7].

Externalities

While the single-minded determination to succeed in the design, assembly and running of the very large experiments was essential, the congenial and fertile environment provided by the long-established infrastructure at CERN, its prescient Convention, the constructive support of the CERN Council and the national funding agencies, CERN's status as a leading research institution, and its location in an internationally-oriented city, have also been important factors. This should not be forgotten when trying to apply the successful formula elsewhere.

11.2 Building Large Accelerators with Industry: Lessons from the LHC

Philippe Lebrun

High energy particle accelerators are among the largest scientific instruments built by man. From their invention as table-top physics instruments a century ago — the cathode-ray tube with which J.J. Thomson discovered the electron in 1896 rested on a laboratory bench and the beam chamber of the first cyclotron built by E.O. Lawrence and S. Livingston in Berkeley in 1930 fitted in the palm of a hand — they have developed over the years in size, performance and complexity to become large technological systems, installed in multi-kilometre underground tunnels, federating the work of thousands of physicists, engineers and technicians for their construction, operation and maintenance, and relying on the series production by industry of advanced components that meet demanding specifications at market prices. Sustaining such a development over many orders

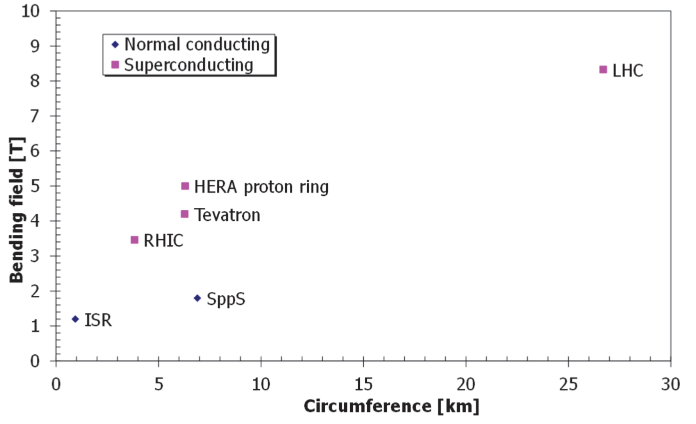

Fig. 11.3. Circumference and bending field of hadron colliders.

of magnitude in performance at affordable cost could only be achieved by a combination of larger size and more advanced technology (Fig. 11.3), leading to a continuous decrease in specific cost (Fig. 11.4) — a trend which could, fortunately, be maintained up to the largest and most advanced machine to-date, the Large Hadron Collider (LHC) at CERN. With more than one hundred major procurement contracts in advanced-technology industry, the LHC constitutes a comprehensive reference in the domain of industrialization and industrial procurement of components and systems for a large accelerator [12, 13]. To draw lessons from this experience can be instructive in the way to involve industry in large scientific projects and to ensure both scientific and industrial success of future endeavours.

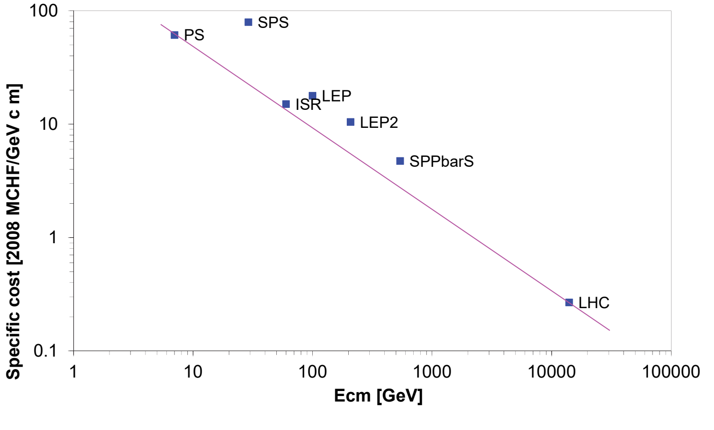

Fig. 11.4. Specific cost vs centre-of-mass energy of CERN accelerators.

Project governance, funding and procurement rules

In view of application to future projects, the feedback from experience referred to above should however be taken *cum grano salis*, due to possible differences between the technical, organizational and institutional context of such projects and those of the LHC. Although it was globalized through special contributions from CERN non-member states — Canada, India, Japan, Russia and the USA — the LHC accelerator remained a CERN laboratory-centred project. It was to a large extent (about 85%) funded by the CERN yearly budget and as such, subject to the regulatory framework and procurement rules and practices of the CERN Organization, focusing on its European member states. Most important, the project team had direct control — within the regulatory framework — over the largest fraction of the budget. In contrast, it is likely that industrial procurement for future large accelerator projects will occur on a worldwide basis, possibly with a major proportion of in-kind contributions arranged by regional funding agencies and handled through regional "hub laboratories", according to something resembling the so-called "ITER model" [14]. A critical issue is then to estimate the value of the in-kind contributions from the different partner agencies in a way that reflects their worth to the project, without departing too much from industrial market prices which will eventually have to be paid by these agencies upon procurement of their contributions. This can only be achieved provided the procurement rules and the conditions of commercial competition are known: lowest price or best-value-for-money, world market or imposed national/regional returns, wide open and perennial market versus monopole/oligopole or monopsone/oligopsone (one-of/limited market). Even when this is settled, differentials between the estimated value and the real price of the in-kind contributions may still appear in the execution of the contracts, due to scope and interface changes as well as technical, commercial or organizational difficulties. In any case, a process has to be established and agreed among the partner agencies and the project governance to manage these differentials. Maintaining a sufficient common fund with the project governance to handle such contingencies must be part of the process.

Aiming at the right level of technology

The history of particle accelerators has shown that adopting more advanced technology is the best way to sustain their development in performance while containing increase in size and cost. For each type of supply, the main technical decision is that which aims at the "right" level of technology, i.e. bold enough to break through and achieve performance at minimal cost, and conservative enough to be compatible with large industrial production and acceptable risk to the project.

A typical example of this is the choice of Nb-Ti superconducting alloy operating in superfluid helium for the LHC magnets, an alternative to magnets made of Nb_3Sn operating in "conventional" liquid helium at normal boiling temperature. This decision was considered conservative enough to warrant industrial feasibility and acceptable cost for series production of superconducting magnets, while requiring novel developments in cryogenic refrigeration and cooling schemes. Although both types of superconductors exist since the early 1960s and model magnets using both technologies were built in the early years of R&D for the LHC, only Nb-Ti was an industrial product, manufactured and commercialized at market prices by several companies in Europe, America and Asia at the time of project approval. Industrialization of superfluid helium cryogenics [Highlight 8.3] was deemed easier to achieve than that of Nb_3Sn superconducting magnets, a decision which proved the correct one *a posteriori*: twenty years after the approval of LHC construction, there is still no example of a Nb_3Sn magnet operating in a particle accelerator, and this technology is now still under development for future projects, including LHC upgrades [15]. Conversely, high-temperature superconductors, discovered only a decade before the LHC project was approved, bore the promise of so large benefits for reducing cryogenic heat loads in electrical current feedthroughs that CERN launched a vigorous — and successful — development and construction programme which culminated in the installation of more than 1100 such components in the machine (Fig. 11.5), where they have been smoothly operating ever since [Highlight 8.4], saving the capital expenditure of an additional large helium cryogenic plant and several MW electrical power in operation.

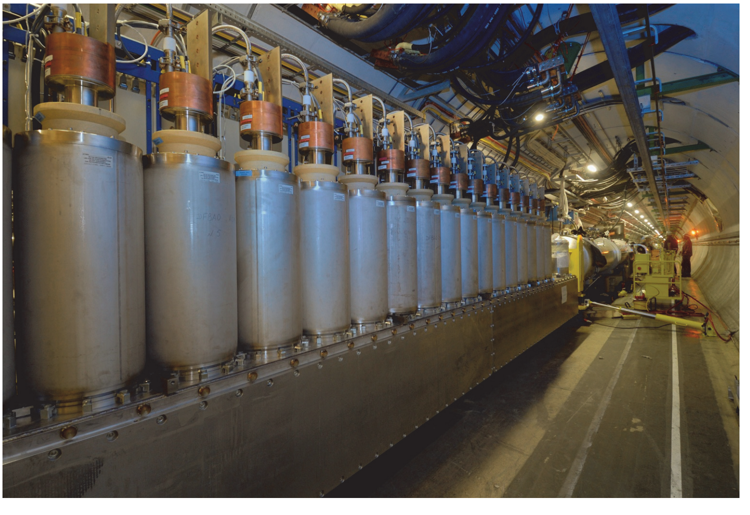

Fig. 11.5. High-temperature superconductor current feedthroughs in the LHC tunnel.

Fig. 11.6. Modular switch-mode 12 kA, 8 V power converter for the LHC.

The benefits of technological developments may also come from existing industrial products which can be adapted to the specific needs of the project, as shown in the following example. Powering superconducting magnet circuits in a particle accelerator requires high-current, moderate-voltage power converters operating with high precision, controlled at the part-per-million (ppm) level. These current and voltage ranges are characteristic of those used for arc welding, which however requires much less precision. Many of the LHC power converters were procured — for the power part — from companies manufacturing modular arc welding systems, complemented by high-precision measurement and control of the delivered current provided by CERN (Fig. 11.6), resulting in a win-win situation: technical performance was as specified, final cost to the project very competitive, and the companies could learn and assume leading positions in novel markets.

Defining an industrial procurement strategy

The basic decision for procuring technical components is whether to go to industry or start a production line in the laboratory: in this respect, CERN policy has been to go to industry whenever possible, and to foster industry's interest through incentive actions in marginal cases. Only in a limited number of specific cases — absence of industrial competence, lack of interest by companies, impossibility of specifying a supply or forming a price, difficulty of defining or managing interfaces, or failure of a contractor — did CERN undertake industrial-type series activities. One such case was the construction of a cryogenic test station for the series superconducting magnets of the LHC [16], which was gradually designed and constructed by CERN from components procured from industry, integrating feedback from experience with prototype test benches and building up testing capacity from two to 12 benches running in parallel. An essential tool for quality and performance control of the 1250 main dipole and 400 main quadrupole magnets upon delivery from industry, this station operated round-the-clock for several years and remains today a unique facility (Fig. 11.7).

Even when technical constraints favoured or imposed construction activities to take place on its premises, CERN specified and outsourced the work to industrial companies that came and operated in the laboratory. This was the case of the assembly of the LHC superconducting magnets into their cryostats [17]: once assembled, road transport of delicate and expensive 15 m long, 37 t cryo-magnets across Europe would have constituted a technical and financial risk to the project. After designing the cryo-magnets, developing their assembly methods and procuring components and specific tooling, CERN entrusted an industrial contractor to perform the task — with a total volume of 425 person-years — in a dedicated on-site assembly hall (Fig. 11.8).

Fig. 11.7. Cryogenic test station for reception tests of LHC main magnets.

Fig. 11.8. Assembly of LHC superconducting magnets into their cryostats.

Another clear-cut case of on-site industrial contract involving advanced technology is that of the electrical and cryogenic interconnection of the cryo-magnets after installation in the accelerator tunnel [18]. Again the methods and specific tooling, driven by the technical requirements, were developed, validated and specified by CERN and implemented by the contractor. Induction-furnace soldering and ultrasonic welding were used for the 65 000 electrical interconnections which require very low residual resistance (down to below one nΩ) and ground insulation at the kV level, while TIG orbital welding was retained for performing the 40 000 helium-tight cryogenic pipe junctions. In all cases, the processes were rendered as automatic as possible to ensure repeatability in the field and achieve reproducible quality. Still, in spite of several lines of defence implemented against quality drifts — process validation, operator training, process tracking by means of periodic checks of witness samples and equipment reproducibility, quality audits — a few electrical interconnections were outside tolerances, leading in particular to the incident of 19 September 2008 in which powering at high current resulted in destruction of such an interconnection, electrical arcing and damaging of some 50 cryo-magnets which had to be removed from the tunnel for inspection and repair [6].

Once the decision to go to industry for a given supply has been made, comes the choice of single or multiple sourcing. While the desire to procure at the lowest bid price on a competitive market, to benefit from economy of scale in large series and to ease contract follow-up tend to favour single sourcing, multiple sourcing may well be the only solution to obtain adequate consolidated production capacity; it also brings other important benefits such as security of supply and leverage on balancing returns to different regions/countries, an important consideration for an international project. For all these reasons, the LHC project generally practised multiple sourcing, e.g. for the procurement of superconductors from seven companies in Europe, the USA and Japan and for production of the main dipole magnets, contracted to three companies or consortia in France, Germany and Italy [Highlight 8.2]. A few cases of single sourcing, driven by circumstances such as a single lowest bid from a company aiming at obtaining the whole production, have met diverse levels of success in execution, making it difficult to draw general recommendations.

Knowing the number of suppliers and factory sites, the delivery rates per production line can be calculated and the level of automation in the production techniques adapted to minimize overall costs. For large accelerators up to and including the LHC, the series numbers for most components were low enough (a few hundred to a few thousand, sometimes with a large number of variants) not to warrant automation in the workshop: only subcomponents produced in large numbers (e.g. punched laminations) called for automatic production (Fig. 11.9).

Such statements may however need to be revised for the next generation of high energy accelerators beyond the LHC: producing complex, high-precision accelerator devices in much larger series may well be achieved more efficiently, at higher quality and lower cost on automated production lines.

In the light of experience, it appears essential to decide on the industrial strategy prior to launching procurement for each type of component, based on technical criticality, maturity of design, series numbers to be produced, quality assurance requirements, market structure and production follow-up capabilities.

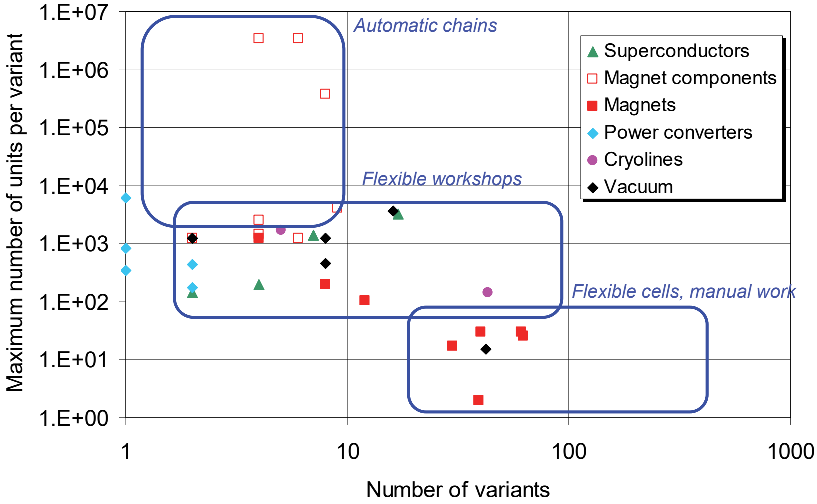

Fig. 11.9. Series numbers and production techniques of LHC components.

Involving industry efficiently and successfully

Once the policy lines are established, one can proceed to industrial procurement proper, starting with the identification and selection of companies. This is done in steps, starting with distribution of information about the requirement in terms of technology, quality, and schedule, as well as the applicable procurement rules and constraints [13]. Such information can be channelled via symposia explaining the main industrial stakes of the project to representatives of industry, summary documents to industrial liaison officers, and presentations to professional societies in the field of interest, all of which was used in the years preceding approval of LHC construction. Companies can then be pre-qualified on the basis of previous experience, capacity and declared interest, as expressed in their responses to market surveys: it is essential at this stage to ensure pre-qualification of a sufficient number of companies so as to maintain commercial competition at the time of the final invitation to tender, especially if one aims for multiple sourcing in the execution phase. A powerful tool in this phase is the best use of industrial models and prototypes, as a means not only to develop and validate technology and build know-how among potential future vendors, but also to foster partnerships, involve companies early and maintain their interest over preparatory periods which may appear very long by their standards [19]. This approach is exemplified in the successive periods of R&D, model building, prototyping and pre-series which led to the series production of the main dipole magnets for the LHC (Fig. 11.10).

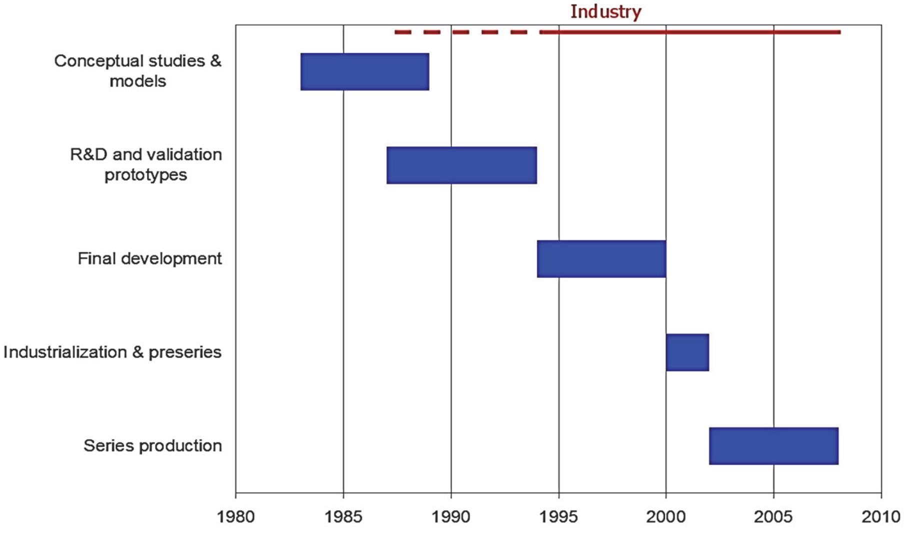

Fig. 11.10. History of LHC main dipole development and production.

Another interesting example of a project fostering industrial collaboration is provided by the cold hydrodynamic compressors providing power refrigeration at superfluid helium temperature for the LHC. The state-of-the-art previous to the project was based on a few small-capacity, lower-efficiency and high-cost machines developed by two vendors, in Europe and Japan. CERN stimulated a development programme, via design studies and the procurement of prototypes of different technologies, resulting in adoption of new technical solutions and enlargement of the industrial basis to six companies worldwide, some of them already working in cooperation. At the time of procurement, contracts for the 28 cold compressors of the LHC were placed with two groups of companies previously involved in prototyping, operating in a consortium or in contractor/subcontractor mode. For such components, which required specific development in order to meet the demands of the project, it was therefore important to start cooperating with industry from a very early stage, while ensuring that the conditions of commercial competition were maintained up to final procurement.

The technical specification remains the essential document for launching procurement: in the case of the LHC, they were of two different types, depending on the type of technology. Build-to-print specifications were used in cases where CERN owned the technology and the associated technical risk (e.g. superconducting magnets). Functional-&-interface specifications were used for components and systems normally available in industry. In all cases, the guiding principle was to ensure that the risk be taken by the party who is most knowledgeable: as an example, LHC magnets were specified to industry in terms of electro-technical equipment (mechanical tolerances, electrical continuity, ground and inter-turn insulation), while the specific risks of superconducting magnet technology, e.g. quench performance or field quality, were taken by CERN. On a different register, the use of performance incentives, e.g. bonus/malus on measured performance, can be an efficient way to stimulate technical progress. The functional-and-interface technical specification for the LHC cryogenic plants included an adjudication formula based on the sum of investment and operating costs integrated over ten years, thus favouring higher-efficiency designs; in order to make sure that real performance would be in accordance with quoted values and thus "close the loop", a shared bonus/malus was applied on the difference of effectively measured versus quoted performance. As a result, the plants not only show record efficiency, approaching 30% of the theoretical maximum (Carnot cycle), thus saving on operation costs, but they could also be built smaller for the same refrigeration output, resulting in savings on investment.

Another important question concerning series production is that of intermediate component supply: is this left to the main industrial suppliers, or does the project management also act as general contractor procuring these components centrally and providing them to the main suppliers? The latter solution brings the advantages of ensuring better technical control on quality and homogeneity of intermediate supply for critical components (e.g. magnetic and non-magnetic steels, superconducting wire and cable in the case of LHC), economy of scale (e.g. punched laminations), balanced industrial returns, and mutualization of supply logistics, at the cost and risk of having to follow more contracts, of handling, storing and dispatching more material, and of taking direct responsibility in the timely feeding of production chains and — conversely — in their accidental stoppage. During LHC construction, CERN thus ran a "component centre" with several storage sites and associated follow-up, quality control and logistics: with appropriate levels of resources and effort, no rupture of supply occurred and not a single day was lost in the downstream production lines.

Once the procurement contracts are in place, their execution needs to be carefully monitored from the point of view of production rate and quality. Industry will not let production lines roll until all series methods, procedures and tooling are in place and ready, which may lead to initial delays in production ramp-up (Fig. 11.11). The end of series production, including that of sufficient number of spares while the production lines are still running, also requires particular attention and sometimes careful negotiation with the contractors, anxious to redeploy the best operators to new projects.

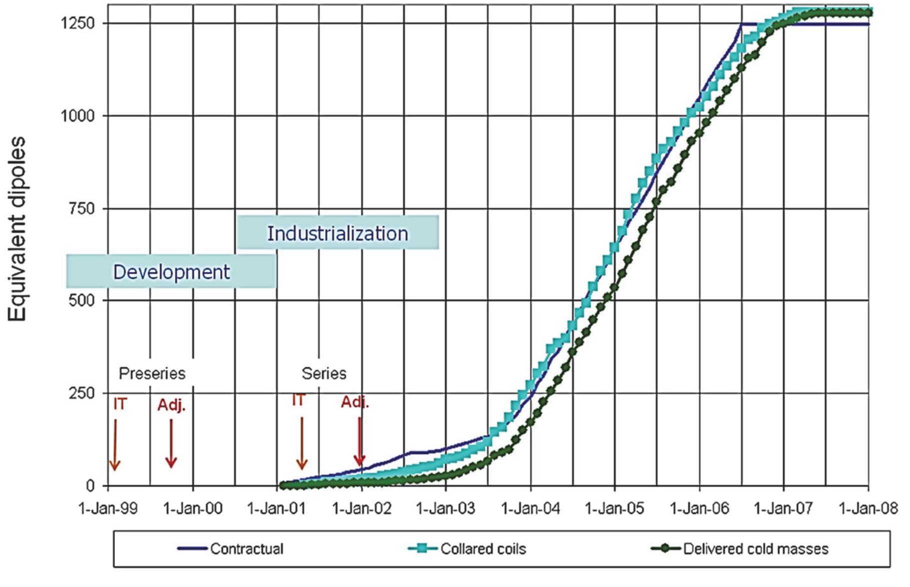

Fig. 11.11. History of the series production of the LHC main dipoles. IT: invitation to tender; Adj: contract adjudication.

Keeping quality under control starts with the project Quality Assurance Plan, which sets the formal framework in terms of procedures and documents. Each component must be accompanied by a Manufacturing and Test Folder containing all relevant data, and enabling to trace back the sources of non-conformities detected upon delivery and reception. In the case of the LHC, all such documents were informatics files in the project Engineering Data Management System, a unique repository of LHC project data kept up-to-date and permanently accessible via the World-Wide Web from any type of platform. Manufacturing and test data were in most cases transferred electronically from the production and testing sites, enabling swift detection of drifts, diagnostics and corrective action. Proper execution of the quality assurance procedures was monitored at production sites by resident and itinerant inspectors from a company, in support of staff from CERN and contributing laboratories. Formal quality audits were also conducted at intervals, or when drifts in production quality had been detected. CERN ensured that such actions were perceived as a help, and not a load by the contractors.

Finally, the best organized production is also subject to the hazards of the industrial world, be it technical (drift of quality, breach of the supply chain), organizational (company mergers), social (work stoppage) or financial (insolvencies and bankruptcies) which are bound to happen over the long time scale of large accelerator projects, and did happen in several instances throughout LHC construction. The project management must then be prepared to react through several types of actions, including — at worst — the taking over of tasks which were originally part of the contractors' duties; this can be done with limited impact on the project schedule provided a minimum amount of core technical resources are kept available, and can be rapidly redeployed in the host laboratory.

Building on capitalized expertise in the laboratory

The facts reported and argumentation developed in the preceding pages may give the impression that sound project management, resting on adequate organizational structure and making proper use of the competency, skill and production capacity of industry, are the keys to the success of large accelerator projects. An absolutely essential component is also the involvement of a numerous, experienced and dedicated personnel in the laboratory, at all professional levels, working in a spirit of collaboration towards a common goal. As an example, construction, installation and pre-operation of the LHC accelerator required some 7000 person-years activity of CERN staff over a period of 14 years, about 40% scientific/engineering and 60% technical. Beyond the bare numbers — and certainly even more important — is the expertise developed over the years by these physicists, engineers, technicians and administrators with the construction, operation and upgrade of previous accelerators. The success of the LHC also rests on the complex RF and beam manipulation techniques developed at the PS synchrotron, on the physics of colliding beams learnt at the ISR and SPS colliders, on the culture of very large projects stemming from the LEP collider, on the technology of superconducting magnets and RF cavities, large-capacity helium cryogenics, "cold" ultra-high vacuum, distributed computer controls, pioneered on previous CERN projects and made perennial through the expertise acquired by the personnel. In order to prepare for the future it is important for CERN to continue to provide the opportunities for staff to accumulate expertise through in-house development of existing and new technology, and thereby acquire the skills needed to interact credibly and efficiently with industrial partners.

11.3 Building LHC Detectors: Collaborations that Span the World

Markus Nordberg, Achille Petrilli and Thomas Taylor

The ATLAS, CMS, LHCb and ALICE experiments at the LHC show that large experimental facilities can be successfully designed, procured and assembled, in a timely manner and close to budget, by large collaborations of scientists. Key to this success was, and is, the quality reference provided by CERN [11].

The first discussions on the possible LHC and detectors took place in the mid-1980s. Possible designs of detectors, and associated R&D started in the early 1990s followed by consolidation of proposals with mergers and withdrawals, with the major experiments taking shape at the time of the demise of the SSC and the increasing likelihood of getting approval of the LHC. The technical proposals for the complete experiments were peer-reviewed and approved in 1994–95, followed by Technical Design Reports (TDRs) for each subsystem from 1997 onwards.

Each experiment formalized its collaboration by drawing up a Constitution stating the rights and obligations of participating institutes, and a Collaboration Board (CB) made up of their representatives — the "Parliament" of the experiment.

In 1997, in order to provide a level playing field the LHC Resources Review Board (RRB) set the budgets for each of the two large, general purpose experiments, ATLAS and CMS, at 475 MCHF (1995 value), called the CORE value.[c] The CORE value does not include the cost of home institute infrastructure, or salaries. The figure for the total CORE value came from careful estimation of expected expenditure, numerous discussions with collaborating institutes, and by paring down the original requests for around 500 MCHF to new agreed values.

[c]CORE refers to the LHC COst REview committee.

Where would the money come from? A system was drawn up that functioned as follows: Memoranda of Understanding (MoUs) were established between the experiment and collaborating institutes for the supply of components satisfying performance and interface specifications for an agreed budgetary cost. Though not legally binding, this arrangement by "best-effort agreement" is very much lighter from a bureaucratic point of view, and can work thanks to an intense and shared motivation to build the experiment with the objective of obtaining otherwise unobtainable scientific data — possibly leading to ground-breaking discoveries, and the mutual pressure on collaborations to strive to achieve the agreed goals (not to mention a degree of perceived competition with the other large experiment). No funds were included for institute manpower or contingency, which meant that funding agencies accustomed to including salaries, overheads and contingency in their estimates had to separate these out from their contribution to the CORE cost. By 2001 the estimated cost had increased to 515 MCHF, and the final cost when the accounts for the construction of the experiments were closed in 2009 was about 540 MCHF each for CMS and ATLAS, corresponding to the original estimated cost plus a notional intervening escalation of 2% per annum on uncommitted funds (2% was the figure applied for the accelerator). This result was possible thanks to continuous tight control, the absorption of some cost overrun by collaborating institutes, and the staging of less urgent and/or critical components.

The responsibilities were divided and delegated, with the nominated project leaders having to optimize funding and execution locally. Common funds (about 15% of the total for CMS, 44% for ATLAS) were established to cover projects that had to be controlled centrally: these were funded globally by the collaboration, with contributions being monetary or in-kind, and funds pooled for payment of specific contracts. Expenditure was monitored by the experiment oversight committee and the RRB.

This scheme of things is sometimes referred to as an "adhocracy", which works thanks to the sharing of a common goal and common scientific understanding: problems can be sorted out through rational discussion, and once a consensus is reached the different agents fall naturally into line and get on with the job. If the discussion gets too drawn out the spokesperson is called upon to arbitrate. For such a bottom-up approach to work it is nevertheless essential that those in charge are respected for their scientific/technical expertise and human qualities rather than theoretical management skills. Analysis has revealed that the management of these detector projects would probably not benefit from being approached from a more classical "professional" business viewpoint [20]. Rather the contrary, it could bring increased risk to schedule and cost overruns. Motivation is the essence.

The management of the finances of the large experiments, for which a major input was "in-kind", depended on the arrangements made with the suppliers, which ranged from a truly collaborative effort in which equipment is delivered regardless of the effort, to equipment supplied by institutes acting as commercial partners, which chalk up costs for changes and design oversight with little regard to the impact on the overall budget. This brought plenty of opportunities for creative intervention by spokespersons, technical coordinators and resource managers, needing to keep a cap on the cost. For example, while the possibility for the large experiments to tap into manpower reserves associated with collaborating institutes is a clear advantage, such labour comes at a financial cost to the experiment. However, overcoming the bureaucratic hurdles is made possible by the special status of CERN as an international organization, and the institutes could supply temporary specialized labour at more affordable rates than those applied locally (if indeed such qualified personnel could have been found), but attractive in the home locations. Without such arrangements budgets would have suffered.

To summarize, there are certain perceived advantages and disadvantages of the approach taken for the LHC to construct the large experiments [21]. The advantages of the approach are:

- Technical problems can be solved where the core competence resides;
- It enables collaborating institutes to utilize/maintain/develop skills;
- It involves students and provides a top level educational experience;
- Institutes share technical and financial risks;
- Outreach and economic returns are enhanced due to wide involvement;
- Light financial reporting (enabled by the CORE value arrangement).

But there are disadvantages:

- Management has little power to make collaborators follow decisions;
- Decision making is sometimes slow;
- There risks to be some duplication/waste of resources between institutes;
- The system is tributary to stable conditions of host state services.

Maintenance and Operation

From the outset it was made clear to the collaborations that they would have to continue to support the experiments while they were operating. There would have to be a flow of people (for data-taking) and money (for repairs and maintenance), in addition to funds required for likely upgrades. It was not readily understood by some of the funding agencies that, being dedicated to the investment and running costs of the accelerator complex, the CERN budget does not include a post for also carrying the entire experimental programme. A Scrutiny Group reporting to the RRBs was therefore set up to analyse the costs incurred and suggest how best to share the burden, thanks to which they came to agree as to the size (typically an annual 3% to 5% of the cost of the detector) and the sharing of this charge.

Typical organization of an experiment

The ATLAS organization during the construction phase is shown in Fig. 11.12. To provide stability during the construction phase, until March 2009 the spokesperson was elected, after consultation with the CERN management, for a term of 3 years, renewable with a 2/3 majority. Since then the mandate is for 2 years, also renewable with the same terms. Deputies, technical coordinator and resource coordinator are proposed by the spokesperson, endorsed by the executive board, and approved by the CERN management. For the duration of their mandates these officials are CERN staff.

About 60% of the construction capital was allocated to deliverables: institutes and their funding agencies committed to supply as "in-kind" with a recognized CORE value [20]. The nature of deliverables reflected the core competencies of the institutes providing them. The remaining 40% were defined as common items, shared in proportion to deliverables, and of which around 60% were provided as in-kind contributions. The mechanism for these purchases is shown in Fig. 11.13.

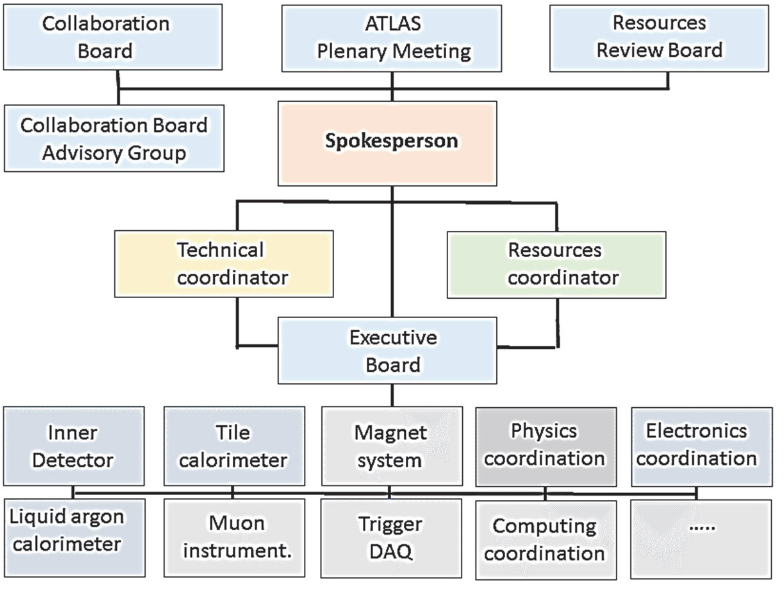

Fig. 11.12. ATLAS Organization during the construction period [21].

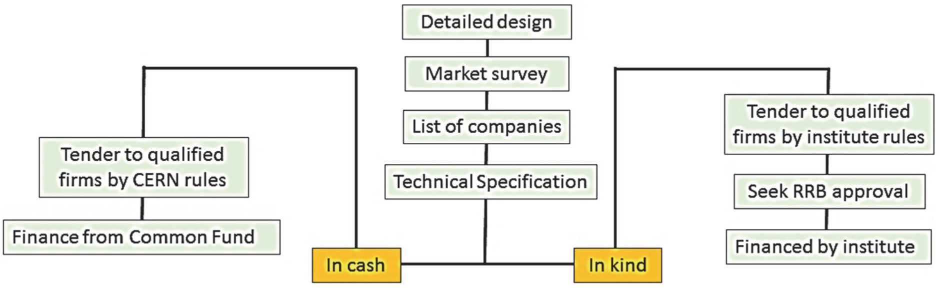

Fig. 11.13. Purchase of equipment via the Common Fund [21].

In the case of CMS, since the installation the spokesperson is elected for a 2-year non-renewable term. As for ATLAS, close assistants (technical coordinator, resource manager, etc.) are chosen by the spokesperson, to be endorsed by the collaboration board. The organizational charts are similar to those of ATLAS.

Concluding remarks

While the RRBs and the LHC Committee did provide a level playing field for the two very different large experiments with full solid-angle coverage, the approach to getting the equipment made and installed was sufficiently similar for observers to isolate plausible macroscopic reasons for the success of the projects:

- Setting up of simple rules and regulations (based on CERN experience);
- MoUs creating peer pressure between suppliers of sub-systems;
- Peer pressure between the experiments;
- The careful selection of competent technical coordinators;
- Problem solving based on technical realities, and a common value scale;
- The common goal of building a viable experiment to probe the unknown.

For accelerator-based high energy physics, a central laboratory staffed with top-level scientists, engineers and technicians is essential [11]. In order to ensure the optimization of complex systems, scientists must be prepared and willing to take a genuine interest in the detail of technical design and manufacturing issues. The smooth interaction between the central laboratory and other laboratories and universities, combined with peer reviews to ensure quality control, are key to the success of the "CERN model". To ensure continuity, it is vital to maintain enthusiasm, and to maintain and renew core expertise. This is best done via a vigorous and ambitious R&D programme.

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