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.

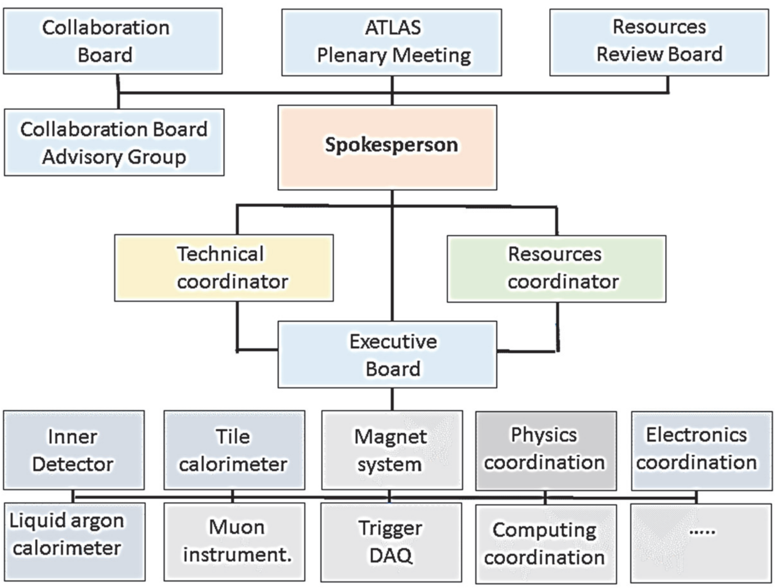

Fig. 11.12. ATLAS Organization during the construction period [21].

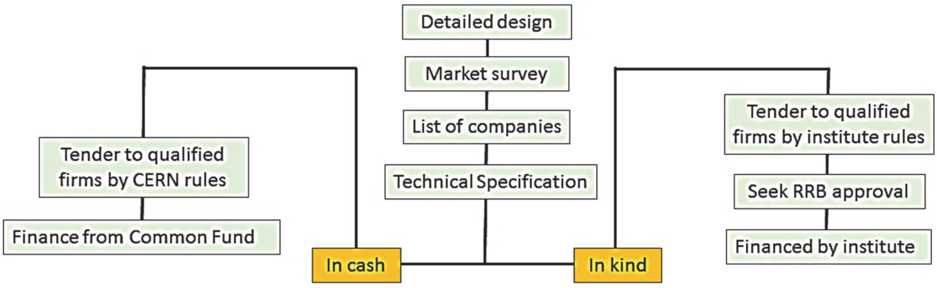

Fig. 11.13. Purchase of equipment via the Common Fund [21].

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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