PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Large Hadron Collider project: organizational and financial matters (of physics at the terascale)

Jos Engelen

Phil. Trans. R. Soc. A 2012 **370**, 978-985
doi: 10.1098/rsta.2011.0466

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2012) **370**, 978–985
doi:10.1098/rsta.2011.0466

Review

The Large Hadron Collider project: organizational and financial matters (of physics at the terascale)

By Jos Engelen*

Netherlands Organisation for Scientific Research (NWO), P.O. Box 93138, 2509 AC The Hague, The Netherlands, and Faculty of Science, University of Amsterdam, NIKHEF, Science Park 105, 1098 XG Amsterdam, The Netherlands

In this paper, I present a view of organizational and financial matters relevant for the successful construction and operation of the experimental set-ups at the Large Hadron Collider of CERN, the European Laboratory for Particle Physics in Geneva. Construction of these experiments was particularly challenging: new detector technologies had to be developed; experimental set-ups that are larger and more complex than ever before had to be constructed; and larger collaborations than ever before had to be organized. Fundamental to the success were: the 'reference' provided by CERN, peer review, signed memoranda of understanding, well-organized resources review boards as an interface to the national funding agencies and collegial, but solidly organized, experimental collaborations.

Keywords: finance; Large Hadron Collider; organization

1. Introduction

The outline of the Large Hadron Collider (LHC) project gradually became visible during various workshops in the 1990s, after the initial ideas had been launched in the 1980s. A description of the project and some of its history can be found in Evans [1].

A workshop in Evian, in 1992, marked an important moment in the initial discussions about the experimental programme at the LHC. The questions we were facing can be summarized as follows. How does one:

— organize 2000 scientists to collaborate and create a huge system of detectors, requiring beyond the frontier of state-of-the-art technology,
— build the most advanced experimental set-ups ever, and do this for four detectors in parallel,

*j.engelen@nwo.nl

One contribution of 15 to a Discussion Meeting Issue 'Physics at the high-energy frontier: the Large Hadron Collider project'.

— effectively coordinate, monitor and control the hundreds of sub-projects involved in each detector,

while, at the same time, constructing the most advanced colliding beam accelerator in the world?

Various branches of the CERN (Conseil Européen pour la Recherche Nucléaire) organization were concerned with these questions. I served as Scientific Director in 2004–2008, the period of construction, installation and commissioning of the LHC and the detectors, and as such had the responsibility for coordinating the construction of the detectors. Although the schedule and budgets were not kept exactly, they remained within very reasonable margins.

Today, the LHC and the experiments are working marvellously well, as has been beautifully illustrated in the presentations at this meeting.

2. CERN

Key to the success of the LHC accelerator and detectors was and is the organization and quality reference provided by CERN. This is exemplified by the quality of its accelerator physicists and engineers. Let me open a parenthesis here: Many national funding organizations fund research projects based on selection in a competitive process that includes peer review. The engineering sciences often complain that such a process disadvantages them because peer review traditionally includes a quality measure based on publications and citations. They make a plea for including an assessment of 'artefacts' resulting from their work, in the peer-review process. In this approach, the p–pbar collider, Large Electron–Positron collider (LEP) and now the LHC should be considered convincing proof of the quality of the accelerator scientists and engineers at CERN. This should provide the basis of trust to grant CERN new projects in the future, provided, of course, that CERN maintains an open and transparent recruitment process, with quality as the only criterion.

The high-energy physics community 'self-organized' itself in a remarkable way from the early days of the LHC project. Statements heard in those early days could be summarized as follows: 'The next step (after LEP) for high-energy physics would ideally be a linear electron–positron collider, but nobody can build it. The alternative is to build a hadron collider, but nobody can build a detector for it.' From these two 'impossible' choices, the community opted for the second one, and after ground-breaking R&D, succeeded brilliantly. R&D on a linear electron–positron collider is ongoing, so that the other possibility should not be excluded forever on technical grounds.

3. The Large Hadron Collider Committee

Although self-organization is an important first step, it is not sufficient. The LHC Committee (LHCC), a peer-review committee consisting of independent scientists, played an essential role in shaping the experimental LHC programme and in guaranteeing and controlling its quality. The committee was and is essential for the legitimacy of the LHC programme. It reports to the CERN Directorate, and through that to the Scientific Policy Committee and the CERN Council, the highest governing body of CERN.

Let me give you a few examples of the issues that were discussed. On the basis of letters of intent, two 'general-purpose' experiments were selected: ATLAS (the result of the merger between two original proposals, ASCOT and EAGLE) and CMS (Compact Muon Solenoid). For the specialized study of proton–proton interactions resulting in mesons and baryons containing the bottom quark (which are considered to be very important), various concepts were initially postulated, but the colliding beam option—the most audacious but also the most promising one—was recommended. This experiment is called LHCb. To complete the suite of the four large-scale experiments was ALICE, a detector designed to study the collisions between heavy ions, e.g. lead–lead interactions.

Although the LHCC reports to the CERN Directorate, it also interacts closely with the experiments in reaching its recommendations. In general, its advice is accepted by the collaborations. There have been a few instances where its advice was not followed by the collaboration in question. For example, a debate on the preferred technology for the ATLAS muon chambers resulted in a recommendation that was not accepted by the collaboration, but even in this case the quality of the final choice profited from the debate held in the LHCC. Another example of the role of the LHCC is the discussion that arose when CMS opted for an 'all-silicon' tracker against the earlier decision to base a large part of this device on microstrip gas chamber technology. An in-depth debate in the LHCC and the subsequent support for this choice was very important for the collaboration. It is remarkable and very encouraging that these and other difficult choices, through the quality of the process, did not lead to major conflicts in the collaborations and certainly not to disruptions of the joint effort. There are also many examples where the discussions with the LHCC led the collaborations to base their choices on more robust arguments.

The LHCC also advised (and advises) on the progress of the experiments and on the credibility of their schedules. When Roger Cashmore was Scientific Director of CERN, he felt strongly, and rightly so, that taking responsibility for CERN's LHC programme implied that a tool was needed for measuring progress in an objective manner, and this is very difficult. The LHC accelerator itself was monitored through a methodology called 'earned value management' [2], which is suitable for large complex projects that are centrally funded and managed. For the detectors, constructed in a distributed manner under central (but also to a certain extent distributed local) management, such a system was not practicable. Therefore, the detector collaborations were asked to define rather detailed milestones and a plot was invented where the number of milestones to be achieved in order to complete the project on time was plotted against time. On the same plot, the number of milestones actually achieved was also plotted against time, in a different colour. As a management tool, this methodology will never make it into textbooks on project management, and it could of course only have been invented by a physicist. The plot became known as the Cashmore plot. Attempts have been made to replace this plot by something more sophisticated (that might then have become known as the Engelen plot!). But in spite of a few attempts, this failed. A Cashmore plot is shown in figure 1. It illustrates that the divergence observed between achieved and planned milestones leads to 're-baselining' and to

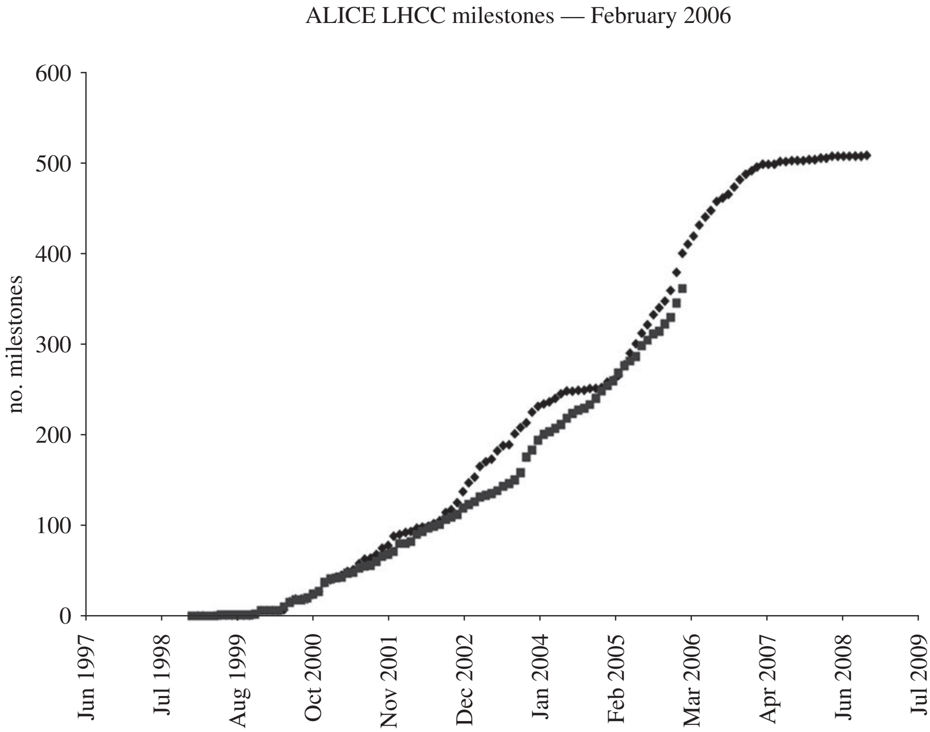

Figure 1. A Cashmore plot: milestone completion with respect to plan (further details are provided in the text). Diamonds, new baseline; squares, passed.

ever better-understood planning. (It should of course be emphasized that the detailed schedules underlying these plots were indeed the real tools to plan and monitor these complex projects, but these were not suited for 'high-level' status reports.)

Obviously, some milestones were harder to pass than others and some were more crucial than others. For a more detailed understanding of the status of the various projects, the 'LHCC comprehensive reviews' were invented. These were particularly useful, for management of both CERN itself and the individual experiments. These reviews lasted almost a week, including the (parallel) pre-meetings, and were very labour-intensive. This way of working and the competence and dedication of the LHCC members (by definition, not involved in the LHC experiments) was crucial for the success of the programme.

Scientific and technical, critical peer review is an absolutely essential ingredient for reaching excellence.

4. Memoranda of understanding

A very important tool for providing a foundation to the collaborations are the so-called memoranda of understanding (MoUs). Although not legally binding, these documents, signed between CERN and the collaborating institutes, were very important in agreeing on the contributions and long-term commitments from each of the institutes, including CERN, and then for monitoring that the various partners were actually living up to their promises.

The MoUs were also essential for organizing the worldwide LHC Computing Grid (wLCG). It was not until relatively late after LHC approval that it was realized that the computing effort required for processing the LHC data would need a very innovative approach, which turned out to be the Grid, and would also require very substantial investment, both at CERN and worldwide. In a very complex but successful operation, we managed to get the wLCG organized.

The actual drafting of the MoUs was carried out by David Jacobs from CERN (working with the experiments' managements) with the help of CERN's legal department. These MoUs were particularly important as a way of communicating with the national funding agencies supporting the collaborating institutes and institutions. It is of course important that these MoUs be signed by persons who have the mandate to do so and it is therefore important to verify the credentials of the signatories.

5. Resources review boards

Resources review boards (RRBs) were set up for each experiment. The membership of these consisted of one representative from each funding agency with the experiment's management in attendance and was chaired by the CERN Director of Research.

These provided the interface between the experiments, the national funding agencies and CERN. During the period of construction of the experiments, the RRBs were particularly crucial in securing adequate and continuing funding. The RRBs will continue throughout the lifetime of the experiments.

The RRBs monitored progress in the light of available (or pledged) resources. For the large general-purpose experiments, ATLAS and CMS, a ceiling of 475 MCHF (million swiss francs) for each was agreed, in fact imposed by the CERN Directorate, as the maximum investment costs. Although this may look somewhat artificial, it actually proved to be a great incentive for the experimental collaborations to be as resourceful and realistic as possible. The famous word 'descoping' was invented, referring to the process of giving up some (redundant) functionality in order to save costs.

Certain additional costs were however sometimes unavoidable. A clear, detailed and well-motivated overview of the costs was presented at the RRBs along with the progress made. On the basis of this and of the discussions in the RRB, agreements were reached on additional pledges from the funding agencies and from CERN. These agreements also included schemes for postponing certain investments that were less urgent than others.

Table 1 provides an illustration meant to convey that the financing of the experiments is by no means trivial or straightforward, and this table is obviously an oversimplified representation of the underlying 'costbook'. The table shows: the nations (funding agencies) involved in this particular project (column 1); the number of scientists holding a PhD (a measure for the expected contribution; column 2); the initially agreed contribution to the total investment (adding up to a little more than 450 MCHF in this example; column 3); additional funding required as identified during construction in October 2002 and April

Table 1. Illustration of investment costs (MCHF) of the CMS experiment, including additional requirements and including a 'phased' approach to full performance (further details are given in the text).[a]

(1)	PhDs (2)	MoU funding 2002 (3)	CTC1 RRB15 Oct02 (4)	CTC2 RRB20 Apr05 (5)	constr. funding 2006 (6)	step 1 low lumi (constr.) (7)	step 2 DAQ (PhD) (8)	step 3 rest (PhD) (9)	total design lumi (10)
Austria	11	3900	600	275	4775	211	45	171	427
Belgium	27	5000	870	300	6170	272	111	420	803
Brazil	9				0	0	37	140	177
Bulgaria	5	600	0	0	600	26	21	78	125
CERN	72	85 200	13 500	4800	103 500	4569	297	1119	5984
China	13	4315	500	300	5115	*in kind, resistive plate chambers*			
Croatia	7	280	49	20	349	15	29	109	153
Cyprus	3	600	106	0	706	31	12	47	90
Estonia	2	90	16	6	112	5	8	31	44
Finland	12	5000	870	300	6170	272	49	187	508
France CEA	14	5600	1687	445	7732	341	58	218	617
France IN2P3	38	19 700	2000	2000	23 700		*2000*	0	*2000 pledged*
Germany BMBF	41	17 000	2709	1100	20 809	919	169	637	1725
Germany DESY	5				0	0	*2000*	0	*2000 new collab.*
Greece	17	5000		0	5000	221	70	264	555
Hungary	6	1000	58	0	1058	47	25	93	165
India	26	4400	300	500	5200	*in kind, resistive plate chambers*			
Iran	3	510	700	0	1210	*in kind, resistive plate chambers*			
Ireland	1				0	0	4	16	20
Italy	181	55 000	8927	4000	67 927	2998	746	2813	6557
Korea	12	1315	500	147	1962	*in kind, resistive plate chambers*			
Mexico	5				0	0	21	78	98
New Zealand	3				0	0	12	47	59
Pakistan	3	2445	230	149	2824	*in kind, resistive plate chambers*			
Poland	12	3000		0	3000	132	49	187	368
Portugal	5	2000	300	140	2440	108	21	78	206
RDMS	72	18 862	2211	1657	22 730	1003	297	1119	2419
Serbia	3		450	0	450	20	12	47	79
Spain	34	6000	1350	450	7800	344	140	528	1013
Switzerland	30	86 500		200	86 700	0	124	466	590
Taipei	11	2330	410	0	2740	121	45	171	337
Turkey	18	1000	58	0	1058	47	74	280	401
UK	49	9100	918	3000	13 018	575	202	762	1538
USA	418	104 320	12 800	1868	118 988	5252	1722	6497	13 471
sum	**1618**	**450 067**	**52 119**	**21 657**	**523 843**	**17 530**	**8400**	**16 600**	**42 530**
requested			**63 000**	**32 000**					

[a]CTC, cost to completion; lumi, luminosity; DAQ, data acquisition; RDMS, Russia and Dubna member states.

2005 (columns 4 and 5); column 6 is the sum of the previous three columns; the following columns (steps 1, 2 and 3) indicate a phased approach to the funding of the final detector including some 'descoping'. The final column (10) is the sum of the previous three columns. It should also be noted that columns 4 and 5 include 'requested sums' that are larger than the actually required sums, in an attempt to obtain some contingency, but this was not granted.

Some of the financial difficulties, as already mentioned, arose because in some cases the signatories of the MoUs were not recognized as having the power to sign by their own funding authorities. However, this was rare and it was always possible to straighten it out with the help of CERN.

One example of a cost overrun was the increase in cost of the lead tungstenate ($PbWO_4$) crystals used in the electromagnetic calorimeter of the CMS. After a long and intensive R&D programme, the successful production of crystals with adequate radiation hardness, light yield, homogeneity, temperature coefficient, etc. was achieved. The large majority of the crystals were going to be produced by a Russian company. A price was quoted of around two dollars per cubic centimetre (initially even less). The CMS collaboration needed 10 million cubic centimetres. The company, which was technically very competent, was making the transition from state-owned and state-run to a company with a business model based on standard commercial practice. One thing that was overlooked in the original calculation of the price was the cost of electricity. Not a small detail, since electrical ovens were needed for melting the raw material from which the $PbWO_4$ crystals are grown! In spite of the problems caused by the price hike, a solution was finally agreed upon and, in reaching a compromise, the help of the RRBs and of CERN was essential.

Another issue was the production capacity of these crystals. In order to increase this capacity—as required by the CMS schedule—additional crucibles, made out of platinum, were required. This platinum was provided as a loan by Union de Banques Suisses (UBS), negotiated by CERN. This was of course only possible on the basis of a long-term relationship of trust between CERN and UBS.

One other subject that is very important and needs to be discussed under this heading is the maintenance and operating (M&O) costs of the experiments. The considerable continuing M&O costs for the experiments were not readily accepted or even understood by some of the funding agencies. In order to make the cases as convincing as possible, a Scrutiny Group that reports to the RRBs was formed. The experiments provided detailed information on the costs incurred (retrospectively) and made estimates for the next year. After 'scrutiny', these costs were then shared between the participants. The discussions were often emotional. 'Users' are not used to paying for things at CERN. But the CERN budget is not meant for (and is certainly insufficient for) carrying the entire experimental programme in addition to the investments (and running costs) for its accelerator complex. The RRBs were successful in getting agreement as to the size and sharing between funding agencies of the necessary M&O costs.

6. Management structure of the experiments

The organizational framework and structure provided by CERN, the LHCC, the RRB and a number of their sub-committees have been crucial for the success of the LHC project. However, there is one other immensely important organizational structure and this is the experimental collaboration itself. These large collaborations, consisting of more than a thousand members, coming from dozens of different institutes, supported by dozens of funding agencies, organized themselves but adhered to a general structure, agreed with CERN. This structure consisted of a Spokesperson, a Technical Coordinator, a Resources Coordinator and a Collaboration Board at which each collaborating group was represented. The Spokesperson is elected by the Collaboration Board on the basis of qualities of scientific leadership and managerial competence. In passing, we also note that the technical expertise available at and through CERN has been essential for the collaborations.

7. Lessons learned and the future

For accelerator-based high-energy physics, a central laboratory with top engineers and top scientists is essential. The smooth interaction between this central accelerator laboratory and national and regional laboratories and universities lies at the heart of the success of the 'CERN model'. Standard peer-review processes for quality control and quality assurance are essential for reaching excellence.

For the future of this unique field of scientific research, it is vital to maintain and renew the relevant expertise continuously. In addition to the LHC, CERN therefore needs a vigorous and ambitious R&D programme both in-house and in the collaborating institutes.

8. Conclusions

We all hope that Nature has hidden some secrets at the TeV scale, allowing the LHC experiments to make ground-breaking discoveries, discoveries worth a Nobel Prize. And even if this prize can only be shared by three persons, I will be ready to make my nominations; I think I understand the LHC project sufficiently well to be able to do so. And, actually the Nobel Prize is only limited to three persons per year!

I thank the organizers for this very inspiring meeting and for the unique programme. It gives a complete and very high-quality overview of this wonderful project, the LHC and its experiments. I also thank Prof. George Kalmus for his help in writing this article.

References

1 L. Evans (ed.) 2009 *The Large Hadron Collider: a marvel of technology.* Lausanne, Switzerland: EPFL Press.

2 Ferguson, J. & Kissler, K. H. 2002 Earned value management. Report CERN-AS-2002-010. CERN.