

The challenges of the LHC

The Large Hadron Collider project has had to overcome challenges at every stage.

Lyn Evans focuses on the three phases of approval, construction and operation.

It is generally considered that the starting point for the Large Hadron Collider (LHC) was an ECFA meeting in Lausanne in March 1984, although many of us had begun work on the design of the machine in 1981. It took a very long time – 10 years – from this starting point for the project to be approved. During most of this time Giorgio Brianti led the LHC project study. However, we should not forget the enormous debt we owe to Carlo Rubbia in the second half of that decade for holding the community together behind the LHC against all the odds.

The first project approval came in December 1994, although under such severe financial constraints that we were obliged to make a proposal for building the machine in two stages. This would have been a terrible thing to do, but at that point we had no alternative. However, after a major crisis in 1996, when CERN had a rather severe budget cut, at least the constraints on borrowing were relaxed and a single-stage machine was approved (p24).

It is clear that building the LHC is a very challenging project. It is based on 1232 double-aperture superconducting dipole magnets – equivalent to 2664 single dipoles – which have to be capable of operating at up to 9T. We were doing R&D on these magnets in parallel with constructing the machine and the experimental areas. This was not just a question of building a 1 m scale model with the very skilled people here at CERN, but of being able to build the magnets by mass production, in an industrial environment, at an acceptable price. This is something we believe we have achieved.

The machine also incorporates more than 500 “two-in-one” superconducting quadrupole magnets operating at more than 250T/m. Here, our colleagues at Saclay have taken on a big role in designing and prototyping the quadrupoles very successfully. There are also more than 4000 superconducting corrector magnets of many types. Moreover, operating the machine will involve cooling 40 000 tonnes of material to 1.9 K, when helium becomes superfluid. An additional challenge has been to build the machine in an international collaboration. Although usual for detectors, this was a first for the accelerator community, and it has proved to be an enriching experience.

The production of the superconducting cable for the dipoles has driven the final schedule for the LHC, because we have to supply the cable to the magnet manufacturers. We could not risk starting magnet production too early when we were not sure that we could follow it with cable production. Figure 1 shows the ramp-up of cable production in 2002–2003.

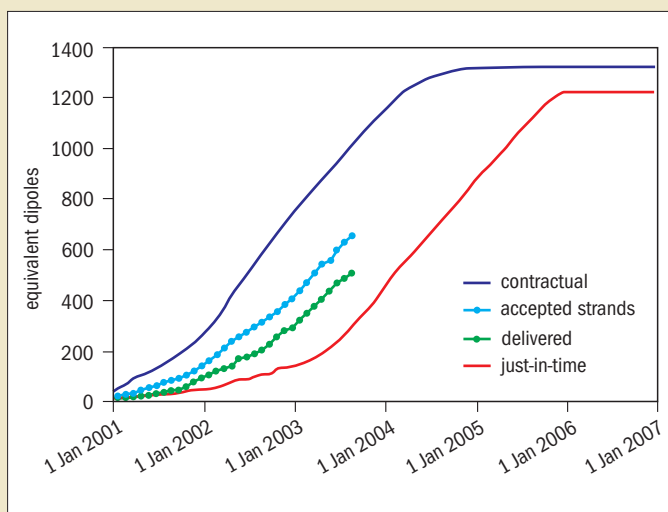
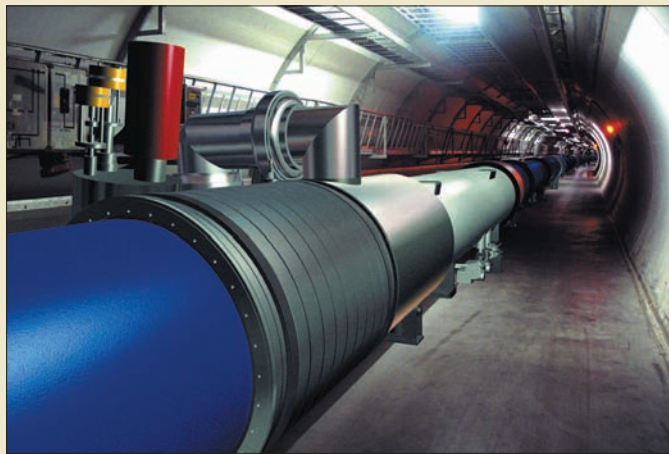


Fig. 1. The delivery of the superconducting cable for the LHC comfortably above the “just-in-time” line in 2003.



A computer-generated image of the Large Hadron Collider.

The next step is the series production of the dipoles, with installation in the tunnel starting in January 2004 and finishing in summer/autumn 2006. The “collared coils” – more than half the work on the dipoles – are now being made at the rate we need. These are assembled into the cold masses, which are delivered to CERN where they are installed in their cryostats, tested and stored.

At the same time the infrastructure of the tunnel is being prepared for the installation of the superconducting magnets. Sector 7-8, the first sector to be instrumented, now has its piping and cabling installed. The next step is the installation of the cryoline, to provide the liquid-helium refrigeration. We are now looking forward to as smooth a passage as possible from installation into commissioning.

The LHC is a very complicated machine, and its operation presents many challenges. The most fundamental concern is >

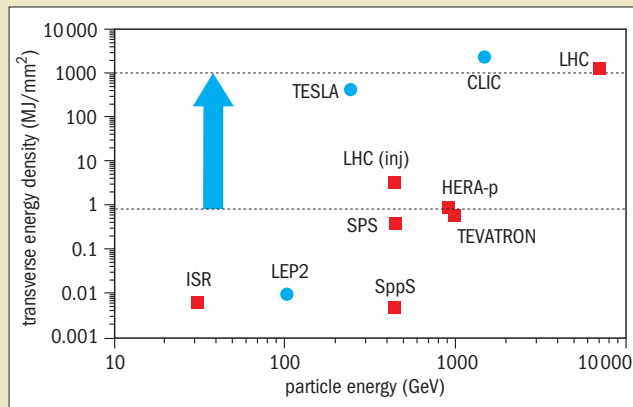
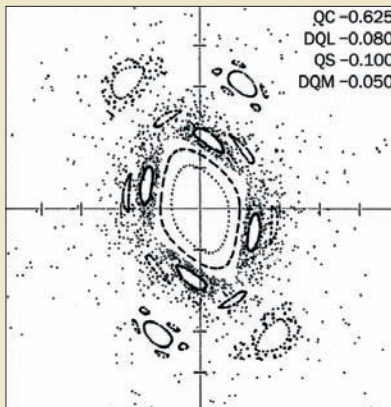


Fig. 2 (left). Simulation showing the chaotic effect of the beam-beam interaction on the position-velocity space of a particle in one of the beams. Fig. 3 (right). At less than 1% of nominal intensity the collimation system enters new territory. The collimators must survive under very punishing conditions.

the beam-beam interaction and collimation. In designing a particle accelerator, we try to make sure that the magnets have as little nonlinearity as possible: that is, they have pure dipole and quadrupole fields. We then introduce controlled non-linearities – sextupoles to control chromatic aberrations and octupoles to give beam stability (Landau damping). We want smooth, distributed non-linearity, not a “lumped” linearity at one point in the ring. So we take a great deal of care, but then we are stuck with what we absolutely do not want – the beam-beam interaction itself. When the beams are brought into collision, a particle in one beam sees the Coulomb field of the other beam, which is strongly non-linear and is lumped – in every revolution the particle sees the beam-beam interaction at the same place. This produces very important effects, which I shall describe.

First, however, I should mention that the conversion of the Super Proton Synchrotron (SPS) into a proton-antiproton collider was a vital step in understanding this phenomenon. Indeed, it is not generally known what a step into the unknown we took with the collider. In this machine the strength of the beam-beam interaction, which we call the beam-beam “tune shift”, was very large, much larger than at the Intersecting Storage Rings (ISR). The collider was to operate in a domain where only electron-positron machines had worked, and these machines have the enormous advantage of strong synchrotron-radiation damping: particles that go through large amplitudes are “damped” into the core of the beam again. So we were going to operate a machine with no damping and a strong beam-beam effect. (Indeed, tests at SPEAR at lower and lower energies with reduced damping showed catastrophic effects, which when extrapolated indicated that the proton-antiproton collider could never work!)

Figure 2 shows the effects in a simulation of the transverse phase space (the position-velocity space) of a particle in a perfect machine, apart from the beam-beam interaction. Because of the strong nonlinearity of the beam-beam interaction, particle motion can become chaotic and unstable at large amplitude. This was a real worry at the proton-antiproton collider, which proved to be an absolutely essential prototype for defining the parameters of the LHC. We have designed the LHC to beat this effect by sitting in a very small corner of “tune space” with very precise control in order to stay away from high-order resonances, although the beam-beam interaction will always be a fundamental limit.

A second major challenge of operating the LHC concerns collimation, which is needed to remove halo particles from the beams

to avoid their touching the superconducting magnets, and to control the background in the detectors. We also need collimation to protect against fault conditions – the stored energy in the nominal LHC beam is equivalent to 60 kg of TNT! If there is a fault the beam will be kicked out, and for that there is a 3 μ s hole in the bunch spacing to allow the field in the kicker magnets to rise. If there is a misfiring particles will be lost as the kickers rise, and the collimators can melt, so they have to be very carefully designed.

Already, at less than 1% of its nominal intensity, the LHC will enter new territory in terms of stored energy. It is two orders of magnitude more in stored beam energy, but the beam-energy density is three orders of magnitude higher (figure 3) because as the beam is accelerated it becomes very small. To cope with this we have designed a very sophisticated collimation system. At injection the beam will be big, so we will open up the collimators to an aperture of about 12 mm, while in physics conditions the aperture of the beam will be 3 mm – the size of the Iberian Peninsula on a €1 coin. The beam will be physically close to the collimator material and the collimators themselves are up to 1.2 m long.

We are now on the final stretch of this very long project. Although there are three-and-a-half years to go, they will be very exciting years as we install the machine and the detectors. It is going to be a big challenge both to reach the design luminosity and for the detectors to swallow it. However, we have a competent and experienced team, and we have put into the design 30 years of accumulated knowledge from previous projects at CERN, through the ISR and proton-antiproton collider. We are now looking forward to the challenge of commissioning the LHC.

● January/February 2004 p27 (abridged).

Based on a talk given at a symposium at CERN, published in *Prestigious Discoveries at CERN. 1973 Neutral Currents. 1983 W & Z Bosons* (Springer 2003).

Résumé

Le Grand collisionneur de hadrons a dû surmonter des obstacles à chaque étape de sa réalisation. Dans cet article, Lyn Evans, chef du projet LHC, examine les trois phases du projet – approbation, construction et exploitation – et, en particulier, les nombreux défis que représente l'exploitation d'une machine aussi complexe.

Lyn Evans, CERN.

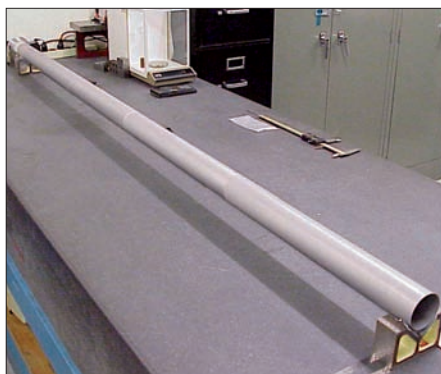
Beryllium beam pipes for ALICE, ATLAS and CMS

With the startup of the Large Hadron Collider (LHC), the ALICE, ATLAS and CMS experiments are also beginning. Brush Wellman Electrofusion Products (Fremont, California) played a crucial role in making all three of these projects a reality by supplying the beryllium beam pipes.

The ALICE beam pipe is 4820 mm long, the CMS beam pipe is 6240 mm long and the ATLAS beam pipe is an impressive 7300 mm long. Although Electrofusion has been building beryllium beam pipes since 1973, these LHC projects demanded a much higher level of precision and more advanced techniques from Electrofusion than ever before. Unlike beam pipes used in other projects, these are buried deep within the LHC, surrounded by layer upon layer of detectors, thermal systems, cabling and structural supports. The resulting limited future accessibility meant that CERN engineers needed to do everything possible to minimize the possibility of failure.

As an example, previous to the LHC project, the beryllium portions of the beam pipes were joined to aluminium and stainless steel sections using an atmosphere brazing technique. However, due to materials introduced during the typical beam pipe brazing process, the risk of contamination or leaks during operation concerned the engineers at CERN. Electrofusion was therefore encouraged to investigate alternative joining processes for the LHC beam pipes. In response to this request, Electrofusion developed processes for joining beryllium to beryllium and beryllium to aluminium using electron beam welding. Joining beryllium to stainless steel was achieved by vacuum furnace brazing.

Although these improved joining techniques minimized contamination and leakage concerns, they brought with them a new challenge: how to predict and compensate for the distortion of beam pipe sections during the newly developed joining processes. The mechanical tolerance specifications were extremely challenging so Electrofusion developed sophisticated tooling coupled with complex theoretical calcu-



The ATLAS beam pipe, prior to final assembly.

lations to achieve the end result.

The beam pipes for ALICE and CMS had stainless steel extensions and flanges and the beam pipe for ATLAS had aluminium extensions and flanges, so Electrofusion repeated the tooling design and calculations for the different types of joints. An iterative design process also played a part in developing this difficult joining technique. After some test runs with the electron beam welding process, it was determined that the electron beam welding equipment needed to be reconfigured and upgraded. Even then, the first few welds of the "live" beam pipe sections did not meet Electrofusion's exacting standards. Tooling had to be modified, power settings had to be adjusted and the sections had to be remachined and re-welded. Through all of this, Electrofusion was able to expand its fundamental knowledge base of beryllium fabrication and joining.

The tight mechanical tolerances posed special challenges with the beryllium sections. The individual beryllium beam pipe sections were approximately 1 m long and required a typical wall thickness of only 800 μm . Machining beryllium into simple shapes is difficult, so something this complex required extra attention. First, rods of solid beryllium were gun-drilled to produce the final inside diameters of the pipes (58–60 mm). To arrive at the final shape profile, the gun-drilled beryllium pipes were subsequently precision machined on the exterior surfaces. Using solid rods reduced the need for longitudinal weld seams and helped to meet the extremely demanding vacuum leakage

specification of $2 \times 10^{-10} \text{ Pa} \cdot \text{m}^3/\text{sec}$.

The final installation of the beam pipes in the LHC required bake-out so part of the acceptance testing dictated that Electrofusion perform a qualification bake-out of each beam pipe prior to shipping. Electrofusion constructed a custom tube furnace to accommodate beam pipes up to 10 m long. The furnace needed uniform axial heating and accomplished this with sophisticated temperature monitoring and control.

As with all projects of this sophistication and magnitude, collaboration and communication between CERN and Electrofusion was essential. Gordon Simmons, the engineering manager at Electrofusion who oversaw the development of the three beam pipes, was in constant communication with CERN engineers throughout the fabrication period. Working together, they overcame manufacturing challenges and negotiated compromises to bridge the very demanding tolerance callouts specified by the project engineers and the limitations of precision manufacturing. They are looking forward to future modifications and improvements that will make LHC experiments even more productive.

In addition to beryllium beam pipes, Electrofusion has expertise in fabricating beryllium windows into a wide array of complex UHV chambers, flanges and custom frames. Electrofusion provides ultrahigh purity beryllium as well as very thin foils – as thin as 7.6 μm . Founded in 1966, Electrofusion Products became a subsidiary of Brush Wellman in 1990, gaining access to a broad spectrum of beryllium alloys and complementary metallurgical engineering resources.

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