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Challenges of the LHC: the accelerator challenge

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The LHC is a project that faces – or has faced – challenges at each stage. Here I would like to focus on particular challenges in the three phases of approval, construction and operation.

1 The challenge of project approval

It is generally considered that the starting point for the LHC was an ECFA meeting in Lausanne in March 1984 [1], although many of us had begun work on the design of the machine in 1981. It took a very long time – 10 years – between then and project approval. During most of this time Giorgio Brianti led the LHC project study. However we should not forget the enormous debt we have to Carlo Rubbia in the second half of that decade, in holding the community together – the particle physics community and the accelerator community – 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, which would have been a terrible thing to do, but at that point we had no alternative. However, after a major crisis in 1996, where CERN had a rather severe budget cut, at least the constraints on borrowing were relaxed, and a single-stage machine was approved. The first operation of the LHC is now foreseen for spring 2007. It has been a very long road indeed.

2 The challenge of project construction

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It is very clear that building the LHC is a very challenging project [2]. It is based on 1232 double aperture superconducting dipole magnets – equivalent to 2464 single dipoles – which have to be capable of operating at up to 9 T. 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 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 “2-in-1” superconducting quadrupole magnets operating at more than 250 T/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, below the lambda point of helium.

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 an enriching experience.

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, which has now reached its required plateau. The final schedule for machine startup in spring 2007 was fixed once

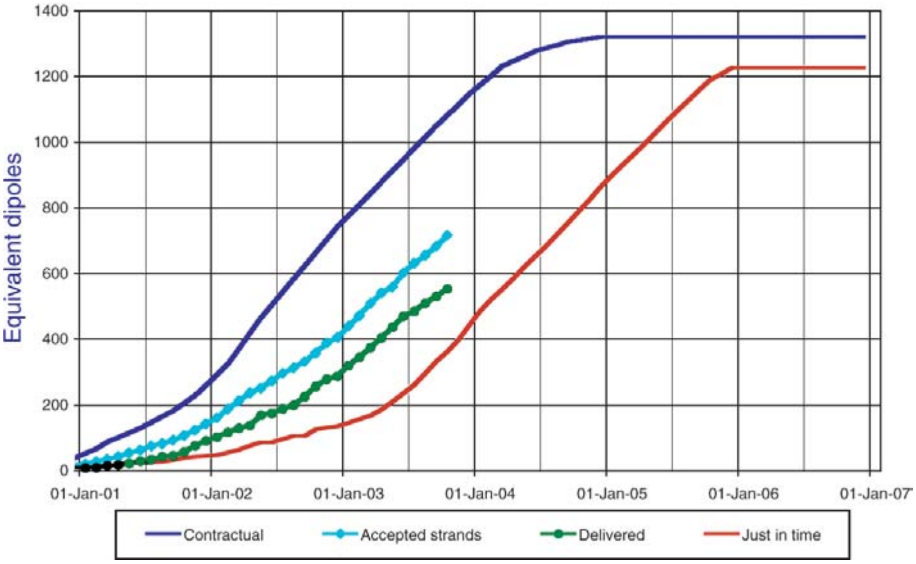

Fig. 1. The production of cable for LHC superconducting magnets

we were confident in reaching this plateau. This schedule is also well matched to the construction of the detectors.

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 collared coils are assembled into the cold masses, which are delivered to CERN where they are installed in their cryostats, tested and stored. More than 100 dipole cold masses are now at CERN, and we are confident that we will be very close to the final date for installation.

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 installation of the cryoline, to provide the liquid helium refrigeration. This must be finished by the end of 2003 so that we can begin installing dipoles in January. We are now looking forward to as smooth a passage as possible from installation into commissioning.

3 The challenges of operation

The LHC is a very complicated machine, and there are many challenges in its operation. The most fundamental ones concern the beam–beam interaction and collimation. In designing a particle accelerator, we try to make sure that the magnets have as little non-linearity 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). But we always make sure that we do not introduce any harmonics. 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 [3]. This produces very important effects, as 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 Interesting 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!)

Figures 2a and b show 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. At small amplitudes there is harmonic oscillation, but because of the beam–beam non-linearity the frequency varies with amplitude, and at some amplitude higher order non-linear resonances appear. Figure 2a shows the ten "islands" of a 10th order resonance. The situation is further complicated by synchrotron motion. This produces synchro-betatron resonances, which in turn create a side-band island structure, with much higher order resonances, again visible in Fig. 2a. This, then, is the complicated phase space in the presence of the beam–beam in-

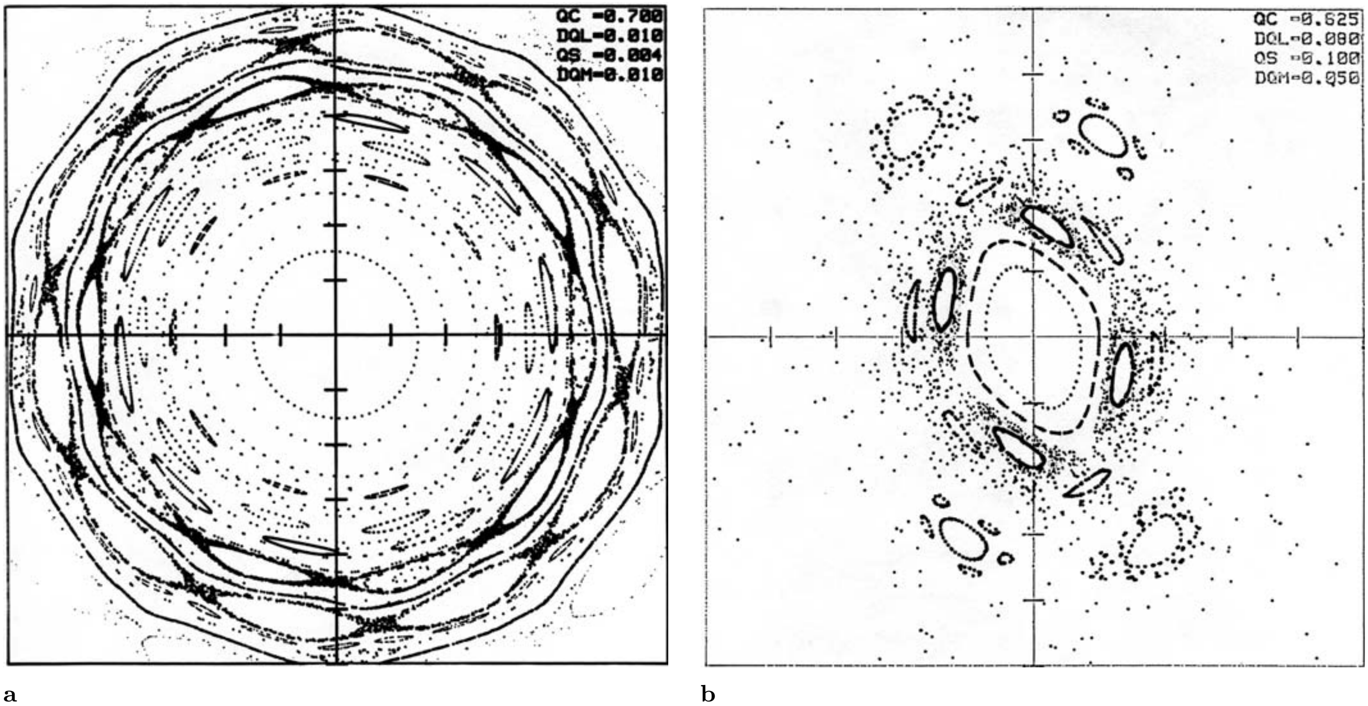

Fig. 2. **a** Simulation of position versus velocity of particle in a perfect LHC. The ten “islands” of a 10th order resonance. **b** Simulation of the chaotic motion created by beam–beam interaction at the LHC

teraction. As you increase the strength of the non-linearity the size of the islands expands and the logical question is what happens when they touch? Figure 2b shows the result – we get chaotic motion.

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. So we have designed the machine such that we are in a parameter space that we have already visited, although the beam–beam interaction will always be a fundamental limit. The tune shift is proportional to luminosity and there will always be a tendency to push it to the limit.

A second major challenge in operating the LHC concerns collimation [4], which is needed to remove halo particles from the beams, in order to avoid their touching the superconducting magnets, and to control the background in the detectors. We also need collimation to protect the

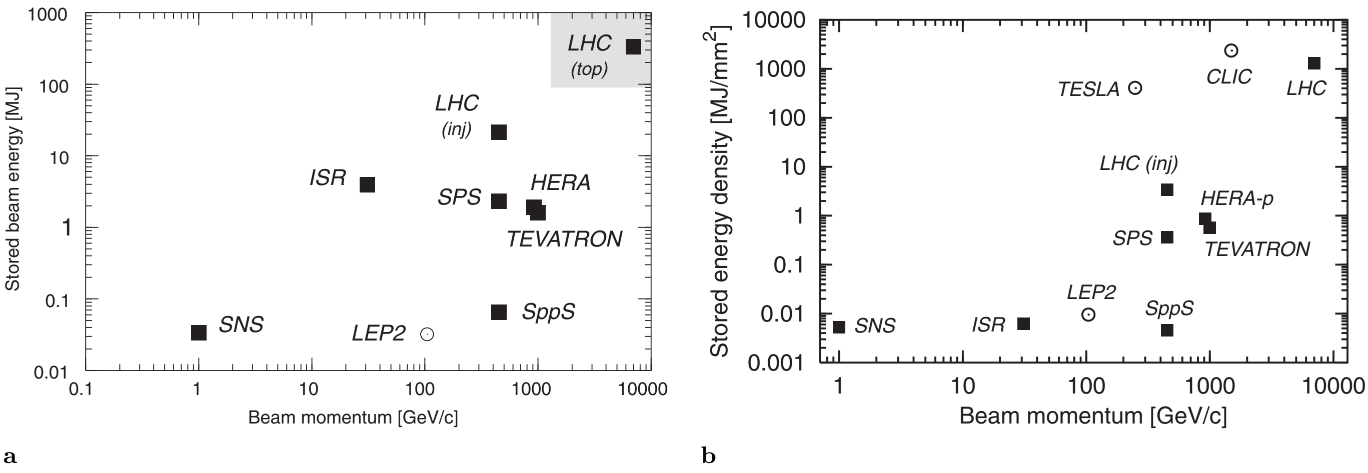

Fig. 3. **a** Energy stored in the accelerator beam, as a function of beam momentum. At less than 1% of nominal intensity LHC enters new territory. Machine damage (e.g. collimators) and quenches must be avoided. **b** Stored energy density as a function of beam momentum. Transverse energy density is a measure of damage potential and is proportional to luminosity! Collimators must survive expected beam losses

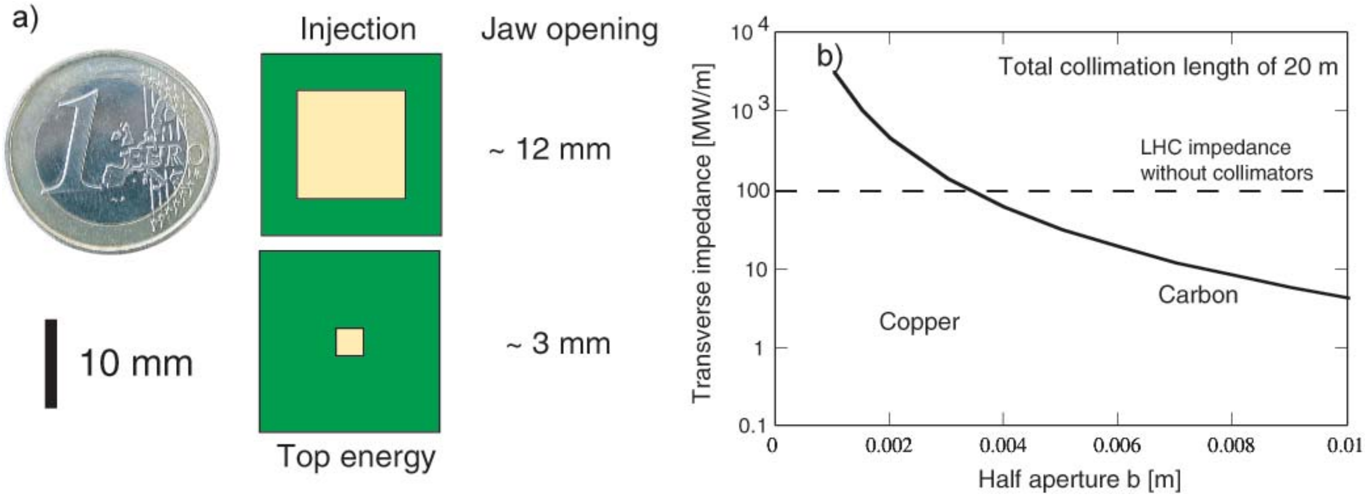

Fig. 4. Collimating with small gaps. **a** LHC beam will be physically quite close to collimator material and collimators are long (up to 1.2 m)! **b** The machine impedance increases while closing collimators (Carbon curve). LHC will operate at the impedance limit with collimators closed!

machine in the phenomenal intensity in the LHC, and to protect against fault conditions – the stored energy in the nominal LHC beam is equivalent 60 kg of TNT! If there is a fault the beam will be kicked out, and for that there is a 3 microsecond 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. As Fig. 3a shows, the LHC is two orders of magnitude more in stored beam energy. But the beam energy density is three orders of magnitude higher (Fig. 3b) because as it is accelerated the beam 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 one euro coin. The beam will be physically close to the collimator material, and the collimators themselves are up to 1.2 m long. As Fig. 4 shows the machine impedance increases while closing the collimators, and once the collimators are closed down, the LHC will operate at the impedance limit!

4 Conclusions

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 certainly going to be a big challenge both to reach the design luminosity and for the detectors to swallow it. However, we have on the project a competent and experienced team, and we have put into the machine 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. It will be there in spring 2007.

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