In most cases digital optical links were selected because of their high bandwidth and very low material mass (optical fibres are by far lighter than copper links). It required the radiation hardness qualification of optical devices (edge emitting lasers and PIN diodes), the development of low-mass packages and for the CMS tracker the development of an analogue optical link. A high-speed radiation-hard serializer able to feed an optical link at 1.6 gigabit per second has also been developed and extensively used. The installed density of optical links is unique: 20 000 are installed in ATLAS and more than 100 000 in CMS.

The power dissipated by the front-end electronics required special attention because it occurs in confined places; bringing power inside the detector requires thick copper cables. The total power consumption of the front-end electronics is ~ 350 kW for each ATLAS and CMS. Operated at low voltages, tens of kA are needed. In order to reduce the size of the cables penetrating the detector volume, DC-DC converters located at places with low magnetic field in the experimental caverns, followed by linear voltage regulators in the detector volume are used. This again required the development, often in collaboration with industry, of radiation tolerant devices that could be installed in the experimental caverns.

The development and deployment of this signal processing system with its large number of radiation-hard ASICs (1.5 million ASICs have been installed in ATLAS and CMS) represents a unique achievement, even more so, considering the radiation levels, to which the readout electronics of the inner detectors are exposed.

This success, unique in so many ways, is a tribute to a world-wide collaboration of dedicated physics, engineering institutes and industry, with CERN assuming a substantial load and the coordination of these activities.

8.12 Giant Magnets for Giant Detectors

Alain Hervé, Peter Jenni and Thomas Taylor

All four major experiments, ALICE, ATLAS, CMS, and LHCb, feature large spectrometer magnets [47]. These devices are the costliest single components of the detectors, and many of the other components rely on their structure for support. In contrast with LEP, where 3 of the 4 detectors were assembled in a “garage position”, the LHC experiments were installed in their final position on the beam. When the detectors are fully assembled the magnets are difficult to access; it follows that any significant repair would require a long shutdown, affecting the entire machine. This gave rise to two important constraints: (i) all the magnets had to be delivered and installed on time, and (ii) the magnet systems had to be designed for utmost reliability. Although the magnets were to be designed, manufactured, tested and installed under the technical and financial responsibility of the collaborations, they also had to satisfy constraints imposed by CERN: powering, cooling, cryogenics and controls would be supplied and maintained by the laboratory. For reasons of economy this infrastructure had to be standardized. Common safety standards also had to be applied. CERN therefore allocated experienced technical staff to the collaborations to help with the magnet projects, to ensure compatibility with the interfaces and to provide the essential leadership for ensuring success (Chapter 11).

Following the experience with LEP, CERN was already associated with studies for the LHC detector magnets before the collaborations gelled and the magnet designs were frozen. It was realized that the major detectors would require larger superconducting magnets than had been made before, and that they would have to run at higher current, probably around 20 kA. The architecture of the conductors for magnets for experiments — cabled Nb-Ti stabilized with pure aluminium — was well established in previous work (at CEA, Saclay, CERN, INFN, KEK and RAL), but only for currents of up to about 5 kA. The superconducting cable could be similar to that developed for the LHC dipole magnets [Highlight 8.2], but co-extrusion of the cable with the aluminium stabilizer would call for gaining access to very large extrusion presses, and extensive testing to verify that the superconductor was not degraded by overheating during the process. It was also essential to ensure good bonding between the cable and the high purity aluminium, and to be able to control the quality of the bond on production lengths. Collaborations were set up with ETH Zürich and CEA Saclay to develop and validate such conductor for use in windings for a practical magnet [48].

For the winding being envisaged for the powerful CMS magnet, designed for operation at 4 T, the high-purity Al used to stabilize the superconductor was not sufficiently strong to withstand the stress on the conductor when the magnet was excited to full field (4 T). One solution proposed was to surround the pure Al/Nb-Ti insert described above with aluminium alloy, to be co-extruded simultaneously [49]. This was found to be impractical as it required heating to > 500°C causing massive degradation to the superconductor. The alternative was to solder or weld Al alloy flanges to the pre-extruded insert — a process that became the subject of another development in collaboration with ETHZ. Working together with industry it was found that by using electron-beam welding the process was both feasible and practical and resulted in a superconductor degradation of less than 5%.

The strong conductor issue was approached in a different way for the ATLAS central solenoid (CS). A doped pure aluminium [50], sufficiently strong but with low resistivity was developed for this magnet (an in-kind contribution of Japan).

The conductors for the CMS and ATLAS magnets are shown in Fig. 8.27.

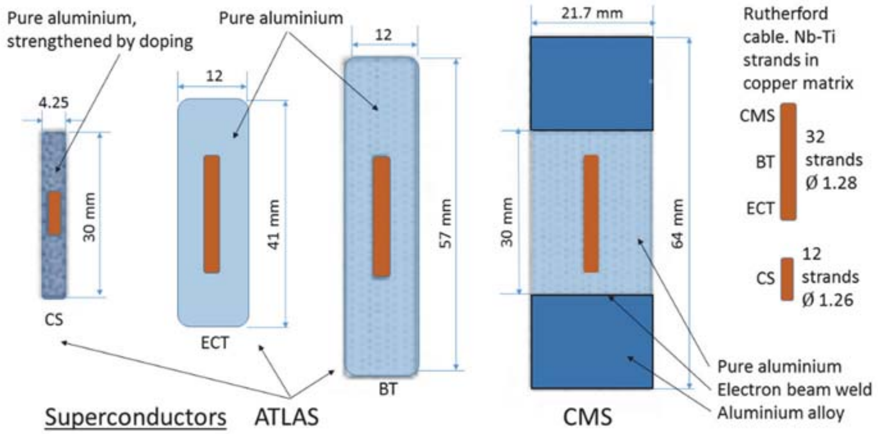

Fig. 8.27. Comparison of the superconductors used for ATLAS and CMS.

CMS magnet

The CMS magnet (Fig. 8.28) consists of a 6 m diameter, 12.5 m long solenoid coil surrounded by a steel yoke [51]. The coil is special in that unlike previous magnets of this type that featured single layer coils, it has four layers. For ease of manufacture (and transport) it is divided into five sub-units; the coils are wound on the inside of the support cylinder [52]. The 12 000 t yoke is made of plates between which detectors are installed to track muons emanating from the interaction. The steel, which serves as a general supporting structure for the detector, carries the return flux and is magnetized, so the tracks are curved and momentum can be determined. The coils are cooled by liquid helium in parallel tubes between manifolds top and bottom, forming a thermo-siphon configuration, following that of the ALEPH magnet at LEP. The magnet was designed for 4 T, up to which field it was tested, but it is run at 3.8 T to prolong its lifetime. Besides being presently the single magnet having the largest stored energy (2.6 GJ) in the world, it also features a record ratio of stored energy to cold mass (about 12 kJ/kg) for this type of magnet. This is tolerable due the inductive heating of the external mandrel if a quench should occur, rapidly spreading the quench to the whole winding. In normal circumstances half the energy is extracted in case of a quench.

The magnet was assembled and tested in the surface building above the cavern at LHC point 5, and lowered into position in the cavern in eleven pieces of mass between 600 and 2000 t. This procedure was based on the experience gained with lowering the support tube for the L3 experiment at LEP [Highlight 7.10]. The magnet itself has been working flawlessly since its installation in 2008, but some auxiliary equipment has had to be repaired.

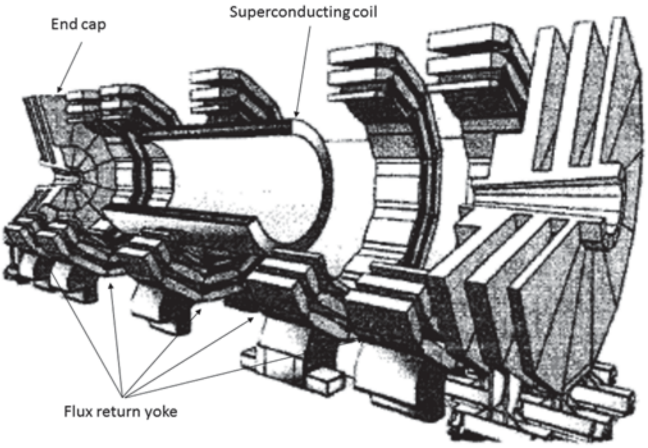

Fig. 8.28. Schematic exploded view of the CMS solenoid magnet.

ATLAS magnet system

ATLAS features a unique configuration of four large superconducting magnets [53]. Most imposing is the 26 m long air-cored barrel toroid (BT), presently the largest magnet in the world, consisting of eight rectangular superconducting coils, each enclosed in its own cryostat. The unusual architecture of this experiment makes it possible to decouple precise muon momentum measurements, made beyond the calorimeters, from momentum measurements in the inner tracking system. The toroidal configuration (Fig. 8.29), completed with two endcap toroids (ECT) [54], provides increasing field integral with decreasing forward angle, corresponding to nearly constant sensitivity in the measurement of transverse momentum over the angular momentum of particles from a proton collider. The low-mass superconducting air-cored solution provides high muon resolution thanks to minimal multiple scattering. A thin, 2 T superconducting solenoid (CS) [55], 5.8 m long, diameter 2.4 m, surrounds the inner tracking detector. Its insulating vacuum enclosure also serves the LAr electromagnetic calorimeter [Highlight 8.8] — a novel approach that minimizes material thickness. For the muons the two independent momentum measurements are combined to get the best resolution. The configuration and size of the system made this project challenging with regard to cost containment and installation. Major CERN contributions were the modification of the original design to simplify (to make more affordable) the BT coil casing of the barrel toroid, and changes to enable powering the three toroidal magnets in series, rather than separately. The stored energy of the BT is 1.1 GJ, and that of the ECTs is 0.5 GJ.

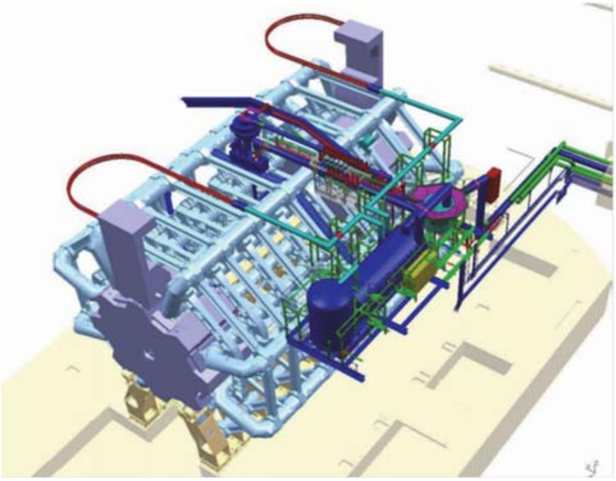

Fig. 8.29. Schematic view of the toroidal magnet system including services connections. The eight BT coils are visible with the two castellated ECTs inserted on both ends.

The three toroids are cooled by pumping supercritical helium through pipes attached to the coil casing, requiring a powerful pump. The dedicated refrigeration plant is located in a side-cavern.

The complete magnet system was commissioned in the cavern in 2008, and has worked reliably during all data taking periods. It is the largest and most complex superconducting magnet system ever built for a particle physics experiment.

LHCb magnet

Like ALICE, the LHCb detector also features a forward dipole. The first design of the magnet was based on the use of superconducting coils. However, at that stage the design was conceptual and the LHCC magnet advisory group (MAG) judged that it would be difficult to flesh out the design and build and test the magnet in the allotted time. Moreover, a quick study showed that sufficient performance could be obtained with resistive coils, avoiding the necessity of local cryogenics, by making a judicious adjustment to the steel yoke [56]. The idea was to maximize the integrated bending field by having sloping poles (Fig. 8.30), in a similar way to a previous magnet that had been designed at CERN for use at the ISR. The LHCC strongly urged the collaboration to pass to the resistive version, which they did. The magnet was designed at CERN and the coils were specified and purchased via competitive tender, with a strong technical follow-up by CERN. The total mass of the magnet is 1450 t; it consumes 4.2 MW when run at an excitation current of 5.85 kA to deliver an integrated field of 3.6 T m.

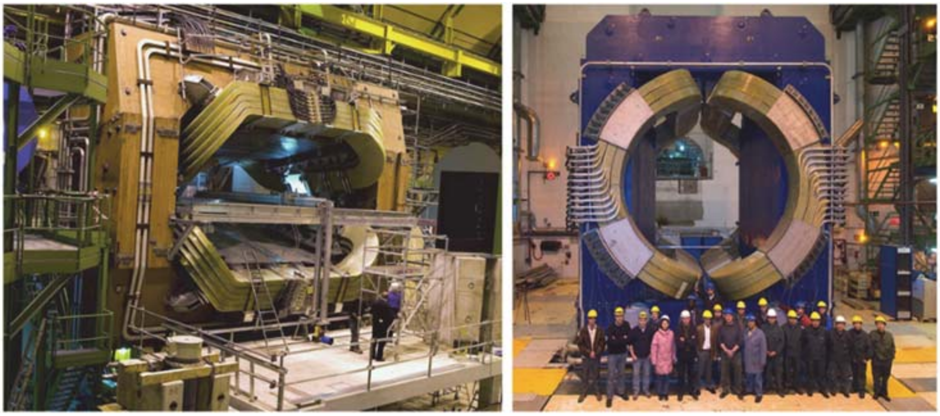

Fig. 8.30. The LHCb magnet (left) and the Alice dipole magnet (right) assembled, ready for testing.

ALICE solenoid and dipole magnet

This experiment uses the large solenoid designed and constructed at CERN for the LEP L3 experiment [57], complemented with a new large dipole magnet installed downstream for analysing particle (in particular di-muon) trajectories emerging at small angles [58]. The solenoid was overhauled and fitted with an improved water cooling system. The dipole magnet was designed by JINR (Dubna) in collaboration with CERN; steel for the yoke was an in-kind contribution from Russia. The coils were finish-designed at CERN and purchased via competitive tender. The delivery schedule was held thanks to strong technical follow-up and support by CERN (Fig. 8.30). The total mass of the magnet is 800 t; it consumes 5 MW at an excitation current of 6 kA, to deliver a bending strength of 3 T m.

References

1. L. Evans (ed.), *The Large Hadron Collider: a Marvel of Technology* (EPFL Press, 2009).
2. G. Brianti, The Large Hadron Collider project: historical account, *Phys. Rep.* **403–404** (2004).
3. M. Jacob (ed.), *ECFA-CERN Workshop on a Large Hadron Collider in the LEP Tunnel*, *Lausanne and Geneva*, CERN 84-10-V-1, ECFA-84-085-V-1 (CERN, Geneva, 1984). http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/16/034/16018264.pdf; M. Jacob (ed.), *ECFA-CERN Workshop on a Large Hadron Collider in the LEP Tunnel*, *Lausanne and Geneva*, CERN 84-10-V-2, ECFA-84-085-V-2 (CERN, Geneva, 1984). http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/16/034/16034963.pdf.
4. J.H. Mulvey (ed.), *Workshop on Physics at Future Accelerators*, *La Thuile*, *Italy*, CERN-1987-007 (CERN, Geneva, 1987). https://cds.cern.ch/record/179654?ln=en.
5. Report of the long-range planning committee, CERN/1658. August 1987, see CERN/1670 (1987).

6. *LHC Design Report. Vol. 1: The Main Ring*, CERN-2004-003 (CERN, Geneva, 2004). http://dx.doi.org/10.5170/CERN-2004-003-V-1.
7. P. Lebrun, Superfluid helium as technical coolant, *LHC Project Report 125,* (1997).
8. J.H. Mulvey (ed.), *The Feasibility of Experiments at High Luminosity at the Large Hadron Collider: report of the High-Luminosity Study Group to the CERN Long-Range Planning Committee,* CERN-1988-002 (CERN, Geneva, 1988). http://dx.doi.org/10.5170/CERN-1988-002.
9. ATLAS Collaboration, The ATLAS Experiment at the LHC, *JINST 3,* S08003 (2008).
10. CMS Collaboration, The CMS Experiment at the LHC, *JINST 3*, S08004 (2008).
11. LHCb Collaboration, The LHCb Detector at the LHC, *JINST 3*, S08005 (2008).
12. ALICE Collaboration, The ALICE Experiment at the LHC, *JINST 3*, S08002 (2008).
13. P. Jenni and T. S. Virdee, The discovery of the Higgs Boson at the LHC, in *60 Years of CERN Experiments*, ed. H. Schopper and L. Di Lella, (World Scientific, 2015) ISBN 978-9814644143.
14. R. Perin, Status of LHC programme and magnet development, *IEEE Trans. Appl. Supercond.* **5**, 189–195 (1995).
15. D. Leroy, R. Perin, G. de Rijk and W. Thomi, Design of a high-field twin-aperture superconducting dipole model, *IEEE Trans. Magnetics*, **24**, 1373–76 (1987).
16. R. Perin, pp. 71-92 in *Proc. CAS-CERN Accelerator School: Superconductivity in Particle Accelerators*, *Hamburg*, *Germany*, *May 1995*, S. Turner (ed.), CERN-1996-003 (CERN, Geneva, 1996). http://dx.doi.org/10.5170/CERN-1996-03.71.
17. P. Fessia *et al*., Selection of the cross-section design for the LHC main dipole, *IEEE Trans. Appl. Supercond*. **10** (2000).
18. A. Siemko, *Safeguarding superconducting magnets*, pp. 35–37, CERN Courier, September 2013.
19. F. Savary *et al*., Description of the main features of the series production of the LHC main dipole magnets*, IEEE Trans. Appl. Supercond.* **18**, No. 2, (2008).
20. V. Chohan, Operation for LHC cryomagnet tests: concerns, challenges & successful collaboration, *2007 Asian Particle Accelerator Conference (APAC)*, RRCAT, Indore, India, pp. 84–88 (2008).
21. J. Billan *et al.,* Twin Rotating Coils for Cold Magnetic Measurements of 15 m Long LHC Dipoles, *IEEE Trans. Appl. Supercond.* **10,** 1422–26 (2000).
22. D. Leroy, Review of the R&D and supply of the LHC superconducting cables, *IEEE Trans. Appl. Supercond*. **15**, 1454–60 (2006).
23. P. Lebrun, Cryogenics for the Large Hadron Collider, *IEEE Trans. Appl. Supercond.* **10**, 1500–06 (2000).
24. G. Claudet and R. Aymar, Tore Supra and helium II cooling of large high-field magnets, *Adv. Cryo. Eng*. **35A**, 55–57 (1990).
25. P. Lebrun and L. Tavian, pp. 453-476 in *Proc. CAS-CERN Accelerator School: Superconductivity for Accelerators*, *Erice*, *Italy*, *April 2013*, R. Bailey (ed.), CERN-2014-005 (CERN, Geneva, 2014). http://dx.doi.org/10.5170/CERN-2014-005.453.
26. P. Lebrun, L. Serio, L. Tavian and R. van Weelderen, Cooling strings of superconducting devices below 2 K: the helium II bayonet heat exchanger, *Adv. Cryo. Eng.* **43A**, 419–42 (1998).
27. V. Baglin, P. Lebrun, L. Tavian and R. van Weelderen, Cryogenic beam screens for high-energy particle accelerators, *Proc. ICEC24 – ICMC 2012*, Fukuoka (Cryogenics and Superconductivity Society of Japan, 2013) pp. 629–634.

28. S. Claudet, P. Gayet and U. Wagner, Specification of four new large 4.5 K refrigerators for the LHC, *Adv. Cryo. Eng.* **45B**, 1269–1276 (2000).
29. S. Claudet *et al.*, Specification of eight 2400 W at 1.8 K refrigeration units for the LHC, Proc. ICEC 18 Mumbai (Narosa Publishing, 2000) pp. 215–221.
30. D. Delikaris *et al.*, Cryogenic operation methodology and cryogen management at CERN over the past 15 years, *Proc. ICEC 22 – ICMC 2008* (KIASC, Seoul 2009) pp. 33–38.
31. A. Ballarino, Large capacity current leads, *Physica C* **468**, 2143–2148 (2008).
32. J.G. Bednorz and K.A. Müller, Possible high Tc superconductivity in the Ba−La−Cu−O system, *Zeitschrift für Physik B Condensed Matter,* **64** (2), 189–193 (June 1986).
33. A. Ballarino, HTS current leads for the LHC magnet powering system, *Physica C* **372–376**, 1413–1418 (2002).
34. A. Ballarino, Operation of 1074 HTS current leads at the LHC: overview of three years of powering the accelerator, *IEEE Trans. Appl. Supercond.* **23** (3), 4801904 (2013).
35. P. Bauer *et al.*, R&D towards HTS current leads for ITER, *IEEE Trans. Appl. Supercond.* **19** (3), 1500–1503 (2009).
36. C. Benvenuti, Non-Evaporable getters: from pumping strips to thin film coatings, *Proc. EPAC 98* (1998) pp. 200–204.
37. C. Benvenuti, P. Chiggiato, F. Cicoira and Y. L'Aminot, Non-evaporable getter films for UHV applications, *J. Vac. Sci. Technol. A* **16** (1), 148 (1998).
38. L. Rossi, P. Fischer, T. Rohe and N. Wermes, *Pixel Detectors, From Fundamentals to Applications* (Springer, 2006).
39. CMS Collaboration, Alignment of the CMS tracker with LHC and cosmic ray data, *JINST* **9**, P06009 arXiv:1403.2286 (2004).
40. ATLAS Collaboration, Performance of the ATLAS inner detector track and vertex reconstruction in the high pile-up LHC environment, *ATLAS-conf-2012-042*, (2012). http://cdsweb.cern/record/1435196
41. CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *JINST* **9**, P10009 (2014).
42. E. Cerrón Zeballos *et al.*, A new type of resistive plate chamber: the multigap RPC, *Nucl. Instr. & Meth. A* **374**, 132 (1996).
43. M.C.S. Williams, Particle identification using time of flight (2012), *J. Phys. G: Nucl. Part. Phys.* **39** 123001 (2012).
44. R. Aaij *et al.*, (LHCb collaboration), Measurement of b-hadron branching fractions for two-body decays into charmless charged hadrons, *JHEP* **10**, 037 (2012).
45. M. Adinolfi *et al.*, The LHCb RICH Collaboration, *Eur Phys. J. C* **73**, 2431 (2013).
46. D. Green, *At the Leading Edge: The ATLAS and CMS LHC Experiments* (World Scientific, 2010).
47. T.M. Taylor, The magnets for the LHC experiments, *IEEE Trans. Appl. Supercond.* **10** 1, 342–346 (2000).
48. I.L. Horvarth *et al.*, The CMS conductor, *IEEE Trans. Appl. Supercond.* **10** 1, 395–398 (2000).
49. J.C. Lottin *et al.*, Conceptual design of the CMS 4 T solenoid, *Adv. in Cryo. Eng.* **41** 819–825 (1996).
50. K. Wada *et al.*, Development of high-strength and high RRR aluminium–stabilized superconductor for the ATLAS solenoid, *IEEE Trans. Appl. Supercond.* **10** 1, 373–376 (2000).
51. A. Herve, The CMS detector solenoid, *IEEE Trans. Appl. Supercond.* **10** 1, 389–394 (2000).

52. P. Fabbricatore *et al*., The construction of CMS superconducting coil, *IEEE Trans Appl. Supercond*. **14** 2, 552–555 (2004).
53. H.H.J. ten Kate, The superconducting magnet system for the ATLAS detector at CERN, *IEEE Trans. Appl. Supercond*. **10** 1, 347–352 (2000).
54. D.E. Baynham *et al*., ATLAS end cap toroid magnets cryostat design, manufacture and installation at CERN, *IEEE Trans. Appl. Supercond*. **14** 2, 522–525 (2004).
55. A. Yamamoto *et al*., The ATLAS central solenoid, *Nucl. Instr. & Meth. A* **584** 53–74 (2008).
56. M. Losasso *et al*., Test and field map of LHCb dipole magnet, *IEEE Trans. Appl. Supercond*. **16** 2, 1700–1703 (2006).
57. F. Wittgenstein *et al*., Construction of the L3 magnet, *Proc. 11th Int. Conf. on Magnet Tech. (MT-11)*, 130–135 (1989).
58. D. Swoboda *et al*., Status of the ALICE magnet system, *IEEE Trans. Appl. Supercond*. **12** 1, 432–437 (2002).