ACCELERATOR MAGNETS R&D PROGRAMME AT CERN

D. Tommasini, L.Bottura, G.de Rijk, L. Rossi, CERN, Geneva, Switzerland

Abstract

The exploitation and evolution of the CERN accelerator complex pose a continuous challenge for magnet engineers. Superconducting and resistive magnets have a comparable share. The overall mass of either is approximately 50,000 tons, spread over 3 major machines (PS, SPS and LHC), two large experimental area, and a number of smaller experiments and accelerator rings. On the short term (2012-2014) the CERN plan is to upgrade its injection chain (Linac4) and experimental area (HIE-Isolde, ELENA) that require mostly a multitude of resistive magnets. The medium-term plan for the evolution of the LHC complex (2015-2021), also referred to as High-Luminosity LHC, foresees interventions on about 1 km of the machine, with magnets to be substituted with higher field, larger aperture, or both. On the long term (2025-2035) we are exploring the technological challenges of very high field magnets, at the verge of 20 T for a High Energy LHC (HE-LHC), which would also call for fast cycled SC magnets in a revamped injector, and we are studying extremely stable high gradient quadrupoles for the Compact Linear Collider (CLIC).

INTRODUCTION

Magnet R&D at CERN is pursed in almost any domain relevant to accelerators magnet technology.

Specifically treated in this paper are the developments required for new accelerators or the upgrade of the existing ones, ranging from resistive magnets that generate low but extremely reproducible fields, to magnets that aim at record field levels in accelerator configurations. For reasons of space we will not treat developments on magnets made with Nb-Ti Rutherford cables, though in certain cases, for example for the MQXC large aperture quadrupoles for LHC interaction regions upgrade, they are rich of innovative features [1].

The complexity and size of the accelerator complex also require a continuous evolution of diagnostic tools and maintenance plans, together with the development of specific technologies to improve reliability of the present machines: these aspects are covered elsewhere [2,3].

LOW FIELD MAGNETS

LEP already made extensive use of low-field bending magnets [4], with 3280 “steel-concrete” cores of 5.75 m of length, operating between 21 mT Gauss at the injection beam energy of 20 GeV and 110 mT at a collision energy of 100 GeV. The choice of spacing low-carbon steel laminations and embedding them in a cement mortar was not only economical, but also to allow the iron to work at a higher magnetic field density providing a better magnetic reproducibility in particular at injection level.

The need for a new generation of compact low field bending magnets arose recently in the frame of the design study of the ring-ring variant of the Large Hadron electron Collider (LHeC). These dipoles have a nominal operating range of 13 mT to 76 mT with challenging demands on homogeneity and reproducibility. At this level of excitation the field quality and reproducibility depend strongly on iron material properties (remanence, coercive field and permeability), and the homogeneity of industrial production may not be sufficient to guarantee the required performance. For this reason the magnetic design must include features to compensate for the material variability, such as the dipole design reported in [5], for which tests performed on prototypes have shown excellent reproducibility, better than 1 unit (1 unit=10^{-4} of the main field), for a variety of yoke materials and grades.

Another example of low field magnets concepts is the study for dipoles of the CLIC Beam Delivery System. These magnets are 206 with fields ranging from 2 mT to 12 mT and lengths between 1.5 m and 11.3 m to be designed and built with relative field precision and jitter better than 10^{-4}.

Both above programs are presently being carried out at a minimum exploratory level to support the conceptual studies of the relevant accelerators: it is not planned in a short or medium term to perform a massive work on these subjects.

PERMANENT AND HYBRID MAGNETS

An advanced activity on permanent magnets has been initiated recently, with different motivations depending on the specific application. For Linac 4 the use of permanent magnets for the intertank quadrupoles [6] allows to respect stringent space constraints, in certain beamlines for experiments permanent magnets provide reliability and ease of installation as they do not require a specific infrastructure (powering and cooling), for the CLIC study they allow to provide large gradients in compact size [7]: for the large number of magnets required for the linac-ring variant of the LHeC, permanent magnets would represent a reliable and economically advantageous alternative to conventional water-cooled electro-magnets.

Issues of permanent magnets, besides the obvious limitation of operating at a constant field unless sophisticated remotely controlled structures are used, are the trimming of magnetic field quality, the temperature stability and, for large magnets, an investment cost that may be much higher than for conventional magnets.

An example of development focussed to overcome one of the above issues is the collaboration with the Swiss Federal Bureau of Metrology (METAS) on an ultra-stable permanent magnet for the Swiss Watt Balance [8]. The design is based on the use of a Gd stabilized SmCo material [9], complementd by a shunt made in a low-

Curie temperature NiFe alloy which limits the magnetic field variations due to temperature to a few ppm/°C.

FAST CYCLED MAGNETS

The CERN work in the field of energy efficient, superconducting, fast-cycled magnets is limited to the possible energy upgrade of the LHC injectors.

The *Fast Cycled Magnet* (FCM) programme [10], started as an alternative to the resistive design of a PS2 [11], is devoted to the demonstration of a low-loss super-ferric dipole magnet design with a large bore (70 mm gap) operating continuously in trapezoidal cycles of 1.8 T peak field and 1.5 T/s field ramp-rate. The magnet concept contains a number of interesting features, such as the internally cooled cable, the use of a warm iron yoke, a separately cooled structure, and an optimized support in the cryostat. The demonstrator magnet is fully assembled (Fig. 1) and is now being cold tested.

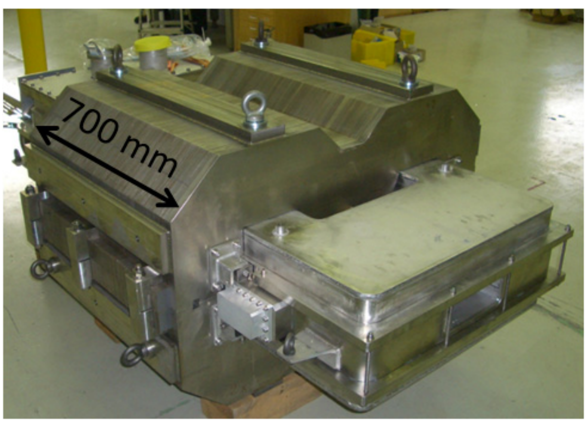

Figure 1: The FCM demonstrator magnet.

The second line of activity in the field of fast cycled magnets is the participation to the procurement of a low-loss cable, and its insulation, for the production of a prototype of a dipole magnet for the SIS-300 storage ring at FAIR [12]. This work is performed within the WP5 of the CRISP EU-FP7 programme and represents a follow-up of the DISCORAP programme [13], approaching completion at INFN, where a dipole with a 100 mm diameter aperture, 4.5 T bore field and maximum ramp-rate of 1 T/s is also ready for test. These parameters are comparable to those that would be of interest for a superconducting SPS, accelerating protons up to an energy of 1 TeV.

Both FCM and CRISP are not high priority in the magnet R&D work. Nonetheless, they address key technological issues in a long term perspective.

HIGH FIELD MAGNETS

While the full energy of the LHC will be attained after the splice consolidation in 2013-2014, CERN is preparing a plan for a Luminosity Upgrade (High Luminosity LHC), requiring dipoles and quadrupoles of accelerator quality and operating fields in the range of 11 T to 13 T, well beyond the established capability of Nb-Ti.

In this frame CERN is engaged in a *High Field Magnet* (HFM) R&D program, counting on the participation of many EU partners involved since 2004 in the NED program [14] and synergic to the US-LARP program [15,16]. The program is articulated in different projects: the main ones consist on the *Fresca-2* dipole, the *SMC* and *RMC* model coils, the *11-T* dipole. Technology R&D for the *IR-Quadrupoles* for the LHC Insertion Regions is presently covered by the US-LARP program [17]. On this last project no model activity is on-going at present at CERN, though in the course of 2012 it is planned to start active work on wire and cable procurement, targeting design options for large aperture (140 mm).

FRESCA-2

FReSCa [18] is the 30 kA current test station based on a 1 m long, 80 mm aperture dipole made with Nb-Ti superconductor operating at 1.9 K. Its upgrade, FRESCA-2 , will be based on a Nb_3Sn block-coils dipole, with a useful bore of 100 mm, operating field of 13 T and short sample limit at 4.2 K of approximately 15.5 T [19]. The magnet is based on the bladder-and-key technology invented at LBNL [20], and is a main deliverable of the FP7-EuCARD project built as a joint venture between CERN and CEA, with technical contributions from several other laboratories [21].

The main magnet components and tooling are being procured, and the magnet assembly is planned at CERN in 2013, for a delivery and test in 2014.

SMC and RMC

The Short Model Coil (SMC) program constitutes an ideal playground for engineers and technicians, and was soon recognized as a basic tool for the test of Nb_3Sn cable performance over lengths of the order of 100 m. The SMC [22] is largely inspired by the sub-scale magnets developed at LBNL [23]. It is a bore-less magnets made with racetrack, flat coils assembled with the bladder-and-key principle. So far, two SMC were built and tested (SMC1 and SMC3a), one is in construction (SMC3b). Best performance achieved so far was with SMC-3a, with a peak field of 12.7 T on the coil [24].

To test the quench performance of the full-size cables that will be used for the construction of FReSCa-2, or other magnets of similar stored magnetic energy density (e.g. large aperture IR quadrupoles) it has been decided to design an up-scaled version of the SMC, the Racetrack Model Coil (RMC) test magnet, which provides space for one or two large racetrack coils, with width of 250 mm and length 400 mm: the first assembly using the full-size FReSCa-2 cable is planned by end 2013.

11 T Dipole

Operating experience at the LHC, and dedicated beam collimation studies, show that the dispersion suppressor (DS) region may require additional protection from beam losses. To provide space for additional collimators one option [25] is to substitute at each location one LHC dipole with a shorter magnet producing an identical kick.

ISBN 978-3-95450-115-1

A suitable bore field target for such a double aperture dipole could be around 11 T, using available Nb_3Sn technology, resulting in a slot of approximately 4 m for the collimator. A demonstration program is running as a joint collaboration between FNAL and CERN [26,27]: a view of the magnet cross section, and a coil manufactured at FNAL is in Fig. 2.

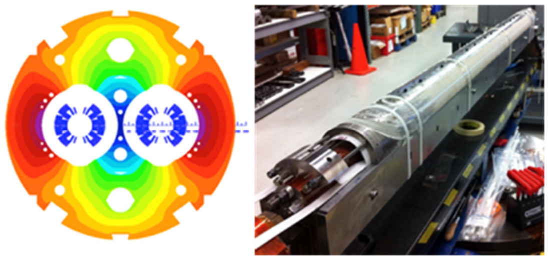

Figure 2: The twin-aperture, 11 T DS MB cross section (left), and the first coil of the FNAL demonstrator ready for heat treatment (right).

The FNAL/CERN collaboration is following an aggressive program of single and double aperture short models (2012-2013), followed by long prototypes (2014) and eventually the production of the first batch of cold masses (2015-2017) to enter the LHC during LS2.

VERY HIGH FIELD MAGNETS

A possible "higher energy" accelerator in the existing tunnel calls for magnets with significantly higher bore field than the LHC. Nb_3Sn would allow a factor of two increase with respect to NbTi, i.e. a dipole with a bore field in the range of 15-16 T. Any increase beyond this value requires the use of High Temperature Superconductors (HTS). These materials exhibit large critical fields (100 T and larger), and can hence be used at low temperature as high field superconductors. Finding a use for HTS in Very High Field Magnets (VHFM) for accelerators, whose range we place somewhat arbitrarily above 20 T, would have immense implications also for other applications such as solenoid magnets for NMR or power generation, storage and transmission.

CERN launched a worldwide collaboration aiming at producing a demonstrator magnet, built with a HTS cable, producing a field of 5 T in a 40 mm bore with sufficient field quality to be suitable for use in an accelerator [28]. This magnet would be used as a high field insert in a hybrid 20 T NbTi-Nb_3Sn-HTS magnet. At the same time, thanks to the large temperature margin, such a dipole could find applications in regions of high radiation or energy deposition, operating at intermediate temperature, above the liquid helium range.

ACKNOWLEDGMENT

Many Colleagues are involved in these activities in collaborating institutes, in CERN, and in private companies constituting a rich network, partly supported by Governmental, European and U.S.A. programs, providing enthusiastic and effective work.

REFERENCES

[1] S. Russenschuck et al., "Design challenges for a wide aperture insertion quadrupole magnet", IEEE Trans. Appl. Supercond. 21(3), June 2011.
[2] D.Tommasini et al., "Status of resistive magnets in the LHC injectors chain", MT-21, Hefei, China, 2010.
[3] J.Ph. Tock et al., "Consolidation of the LHC Superconducting Circuits", this conference.
[4] M. Giesch and J.P. Gourber, "The bending magnet system of LEP", MT-11, Tsukuba, Japan, 1989.
[5] D.Tommasini et al., "Dipole magnets for the LHeC Ring-Ring option", MT-22, Marseille, France, 2011.
[6] D.Tommasini et al., "Permanent quadrupole magnets for Linac4", MT-22, Marseille, France, 2011.
[7] M. Modena et al.,"Design, Assembly and Measurements of a Short Model for CLIC Final Focus Hybrid Quadrupole QD0", this conference.
[8] A. Eichenberger et al., "The METAS Watt Balance Mark II Experiment", CPEM 2012, Washington DC, USA.
[9] J.F. Liu and M.H. Walmer, "Thermal Stability and Performance Data for SmCo 2:17 High-Temperature Magnets", IEEE Trans. on Electronic Devices, May 2005.
[10] L. Bottura et al., "The Fast Cycled Superconducting Magnets (FCM) R&D Program at CERN", HHH-2008.
[11] M. Benedikt, B. Goddard, "Design Optimization of PS2", 1828-1832, PAC-09, Vancouver, Canada, 2009.
[12] P.J. Spiller et al., "Design Status of the FAIR Synchrotrons SIS100 and SIS300 and the High Energy Beam Transport System", EPAC08, Genoa, Italy, June 2008.
[13] P. Fabbricatore et al., "Development of a Curved Fast Ramped Dipole for FAIR SIS300", IEEE Trans. Appl. Supercond. 18(2), (2008) 232.
[14] A. Devred et al., "Overview of the Next European Dipole Joint Research Activity", Supercond. Sci. Technol., 2006.
[15] LARP proposal, May 2003. http://www.uslarp.org/
[16] G. Ambrosio et al., "Test Results of the First 3.7 m Long Nb3Sn Quadrupole by LARP and Future Plans", IEEE Trans. Appl. Supercond. 21(3), June 2011.
[17] G.L. Sabbi, "New Magnets for the IR", Proc. of the LHC Performance Workshop - Chamonix 2012.
[18] A.P. Verweij et al., "1.9 K Test Facility for the Reception of the SC for the LHC", IEEE Trans. Appl. Sup., 1999.
[19] A. Milanese et al., "Design of the EuCARD High-Field Model Dipole Magnet FRESCA2",MT-22,Marseille, 2011.
[20] S. Caspi et al., "The use of pressurized bladders for stress control of superc magnets", IEEE Trans. Appl. Sup., 2001.
[21] G. de Rijk et al., "The EuCARD High Field Magnet Project", MT-22, Marseille, Sept 2011.
[22] F. Regis et al., "Mechanical Design of the SMC Dipole Magnet", IEEE Trans. Appl. Sup., 20(3), 204-207, 2010.
[23] H. Felice et al., "Design and Test of a Nb3Sn Subscale Dipole Magnet", IEEE Trans. Appl. Sup., 17(2), 2007.
[24] J.C. Perez et al., "The SMC dipole: An R&D program for Nb3Sn accelerator magnets", IEEE Trans. Appl. Sup. 2012.
[25] G. de Rijk, A. Milanese, E. Todesco, "11 Tesla Nb3Sn dipoles for phase II collimation in the Large Hadron Collider", sLHC PN 0019, CERN, July 2010.
[26] M. Karppinen et al., "Design of 11 T Twin-Aperture Nb3Sn Dipole Model for LHC upgrades", CERN-ATS-2012-033, IEEE Trans. Appl. Sup. 2012.
[27] A.V. Zlobin et al., "Development of Nb3Sn 11 T Single Aperture Demonstrator Dipole for LHC Upgrades", Proc. of PAC 2011, New York, 1460-1462, 2011.
[28] L. Rossi, "Eucard 2: WP on Magnets for HE-LHC: a First Description", CERN-EDMS 1152224, July 2011.