Superconducting Magnet Development for the LHC Upgrades

Lucio Rossi

Abstract

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Superconducting Magnet Development for the LHC Upgrades

Lucio ROSSI*

Synopsis: LHC is now delivering proton and heavy ion collisions at the highest energy. Upgrading the LHC beyond its design performance is a long term program that started during the LHC construction, with some fundamental R&D programs. The upgrade program is based on a vigorous superconductor and magnet R&D, aimed at increasing the field in accelerator magnets from 8 T to 12 T for the luminosity upgrade, with the scope of increasing the collider luminosity by a factor 5 to 10 from 2022. The upgrade program might continue with the LHC energy upgrade, which would require magnets producing field in the range of 16-20 T. The results obtained so far and the future challenges are discussed together with the possible plan to reach the goals.

Keywords: accelerators, high energy colliders, high field superconductors, large scale superconductivity, superconducting magnets

(Some figures in this article may appear in colour only in the electronic version)

1. Introduction

Since December 2009, the Large Hadron Collider 1,2) is the accelerator that explores the energy frontier of particle physics, delivering high intensity colliding beams (mainly protons but also ions) to four experiments. The LHC is based on the use of superconducting (SC) magnets 3), the performance of which determines beam energy and, among other parameters, collider luminosity. After collision energy, luminosity (proportional to the collision rate) is the principal indicator of collider performance.

Whatever the results on the Higgs search and on Physics beyond the Standard Model, the main goals of the present LHC, there is a general consensus that after ten years of operation the machine will require an upgrade in luminosity to increase the measurement precision of rare events. It is expected that the upgraded machine (called High Luminosity LHC, HL-LHC) will then continue to run well into the 2030s.

On a more distant horizon, an upgrade in energy of LHC (also called High Energy LHC, HE-LHC) should be considered. For example, a possibility would be to double the energy of LHC collisions, which would require magnets producing fields in excess of 16 T, to provide an alternative to (or – more probably – complementary to) a high energy lepton collider such as ILC or CLIC.

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* CERN, European Organization for Nuclear Research
1211 Geneva 23, Switzerland
E-mail: lucio.rossi@cern.ch

2. LHC Accelerator Upgrade Plan

The main parameter of a High Energy Physics particle beam is its energy, measured in Tera-electron-Volt (TeV) and for a relativistic circular accelerator of a given diameter is proportional to the magnetic field of the main dipoles. The 1232 15m–long LHC main dipoles are presently operated at 4.16 tesla, resulting in a beam collision energy of 7 TeV (3.5x2 TeV). In 2012 it is foreseen to increase the field to 4.76 tesla, to reach a collision energy 8 TeV. In 2013-14 there will be a long shutdown to repair defective electrical splices of the connections between superconducting magnets 4). This consolidation will enable approaching the full energy of 14 TeV by pushing the main dipoles to close to their design field of 8.3 T. While all dipoles passed acceptance tests at 8.3 T (most reached 9 T), magnet re-training has proved to be long towards 8 T 5), so collision energy may be slightly lower than the nominal 14 TeV. The beam luminosity reached so far is 0.35L0, L0 being the nominal design luminosity of the LHC machine: L0 = 1035 cm-2 s-1. This is a very good result at such an early stage. Even more important is the value of integrated luminosity (proportional to the total number of collisions), which today amounts to 5.5 fb-1 (inverse femtobarns). After the 2013-2014 shutdown we expect to reach the nominal design luminosity L0 and then to saturate at a value not far from 2L0.

2.1 Luminosity upgrade plans and magnet needs

In Fig. 1 is reported the long term plan for the LHC operation, indicating the long shutdowns (LS). During
The project appears to be feasible. The critical issue is LHC has been recently considered in dedicated workshop. A detailed plan of the HL-LHC can be found in Ref. 8. In order to insert an insertion will be upgraded, resulting in a significant technology. Many other devices near the experimental coil of about 12 T; again, we’ll beyond the reach of Nb-Ti technology must be used for such magnets.

After the run of 2019-2021, it is foreseen to stop the LHC for another long shutdown, both because the luminosity will start to saturate and because the accumulated dose in the magnets near the collision will reach damage level (see Fig. 2). In this 2022-23 shutdown we will carry out the luminosity upgrade, which requires to strongly increase the aperture of the (low-beta) quadrupoles adjacent to the experiments. The aperture of the new low-beta quadrupoles (~140 mm, vs. 70 mm for the present NbTi magnets) implies a peak field on the coil of about 12 T; again well beyond the reach of Nb-Ti technology. Many other devices near the experimental insertion will be upgraded, resulting in a significant modification of about 1 km of the accelerator. In order to meet this deadline all equipment must be built and tested in the period 2015-2020. A detailed plan of the HL-LHC project can be found in Ref. 8.

2.2 Energy upgrade plans

The possibility of increasing the beam energy of the LHC has been recently considered in dedicated workshop. The project appears to be feasible. The critical issue is the maximum field attainable by the main dipoles.

The minimum goal of HE-LHC is to double the present LHC design energy: however, the target has been set at 33 TeV centre-of-mass (collision) energy, implying the use of main dipoles operating at 20 T. In order to operate safely at this level, magnets have to be designed with a short baseline limit (nominal theoretical maximum) at around 25 T. This is a huge jump beyond the present state-of-art, as can be seen in the plot of historical evolution of the dipole field for hadron colliders shown in Fig. 3, where the range of interest for HL-LHC and HE-LHC is indicated.
3. Magnet R&D

All the SC magnet types related to the LHC upgrades are listed with their main characteristics in Table 1\(^{10}\). Attention is drawn to the following comments:

- All magnets for HL-LHC must have field quality and reliability required for operation in the accelerator. The tolerance on deviation from specification is almost zero; their reliability must be as high as that of the magnets already installed in the LHC;
- The current density is similar for all types of magnet, i.e. about 400 A/mm\(^2\) at nominal field and 1.9 K;
- For the HE-LHC for the next years we will focus on prototypes. While the cost of a single magnet is not an issue, developing low cost technology is crucial since, eventually, some 1200 15 m-long dipoles and about 500 4 m-long quadrupoles will be needed for the project. Cost issues are far more important for the Energy upgrade than for the Luminosity upgrade.

In addition to the main magnet units indicated above, several thousand new corrector magnets, which may also need to use Nb\(_3\)Sn, will be required for the HE-LHC.

Before discussing in details the magnets of Table 1, it is worth noting that the LHC upgrade program includes three other projects relying on superconductivity:

a. The design and construction of superconducting links between the magnets in the tunnel and the remote power supplies. These links rely on round HTS cables, capable of feeding multiple circuits with an integrated current of 100-200 kA@5 kV d.c., 300 m long and with 100 m elevation\(^{11}\). They are required on the time-scale of HL-LHC.

b. The construction of a small prototype of a Fast Cycling Magnet (FCM) with a hollow Nb-Ti cable in super-ferric configuration to yield about 2 T with a continuous field ramp of \(\pm 2\) T/s\(^{12}\). This dipole could be the prototype for a renovation of the 600 m long PS accelerator, in view of its upgrade for the HE-LHC. In parallel with this, another type of FCM magnet, with field of 4.5 T and ramp rate of 1 T/s, that could serve for the SPS accelerator upgrade (also needed for HE-LHC) has been manufactured by the INFN-GSI collaboration\(^{13}\) for the FAIR project.

c. The development and construction of Superconducting Crab Cavities\(^{14}\), special RF devices that deflect and rotate, rather than accelerate, bunches of the beam. This equipment is required to achieve the performance goal of the HL-LHC.

3.1 11 T dipole for LHC

Because of the need to improve the collimation system on a relatively short scale, this type of magnet is likely to house the first Nb\(_3\)Sn coil to be used in an accelerator. Fermilab has been pursuing a 10 to 11 T dipole program for some time\(^{15}\) and has developed design capabilities, tooling, and technologies suitable for this type of magnet. Fermilab and CERN collaborate closely on this project.

The dipole must be powered in series with the other LHC main dipoles and be practically identical in bending.
strength and harmonic content, which is a severe constraint. A coil layout has been found that gives the target field of 11 T at 80% of the short sample value along the load line. The design is based on cable built using 0.7 mm strand with 108/127 layout from OST, with a current density of 2750 A/mm² at 12 T in the virgin state (we allow for a degradation of up to 10% from virgin to conductor in the coil). The nominal copper content is 53% and the effective filament diameter is 45-50 μm.

The coil is double-layer, like the LHC dipole, but without superconductor grading, which would have required smaller strands for the outer layer cable: there is presently no high Jc strand in Nb3Sn of diameter less than 0.7 mm so this would have required dedicated and possibly long R&D. Furthermore, by using the same cable a back-wound double pancake technique can be used, thus avoiding a dangerous splice in the high field region (today almost all accelerator Nb3Sn coils are wound as double pancakes for this reason). The electromagnetic design is further complicated by two issues: 1) the superconducting persistent current magnetization, due to high Jc and relatively large filament size, which is large enough to generate a b1 harmonic of 44 units (10⁻⁴ of the main field) at flat bottom field, almost ten times the one of the LHC main dipole; 2) the 30% higher field in the same iron yoke geometry as for the LHC dipoles, make b1 unacceptably high at flat top field, 6.6 units being generated by iron saturation.

Reduction of the persistent current sextupole will be obtained by means of passive magnetic shims near or inside the coils, and by a special powering cycle which should bring residual effect to within the acceptable range of 10 units. The saturation effects are strongly reduced by shaping of the internal iron profile and by a set of three holes (see Fig. 4). The mechanical design to withstand the forces, ~70% higher than in the LHC dipole, relies on clamping by austenitic steel collars and by a line-to-line fit between collars and iron yoke: the iron yoke and outer shell are assembled with interference, a procedure that avoids excessive stress during collaring but requires that very tight tolerances and careful assembly. In this way the transverse stress, a constant concern with fragile Nb3Sn, is kept below 150 MPa while the pole-coil interface remains always under compressive stress.

We plan to manufacture the 11 m long dipole by joining in the same cryostat two straight magnets of length 5.5 m. The inner diameter is 60 mm, 4 mm larger than that of the LHC dipoles.

In a preparatory stage two short (~2 m) single bore dipoles with full cross section are being manufactured in 2012: the test of the first of these is foreseen in April. Two different approaches for the coil-collar interface are being explored in this R&D phase, and they will be eventually assembled in one Two-In-One magnet model that should validate the superconductor and the basic design. A full size prototype should be ready in 2014.

3.2 Low-beta Quadrupoles for IRs

The keyword for the magnets needed for the HL-LHC is one: large aperture. The goal is to be able to further squeeze the beam in the interaction regions from the 55 cm design value of the betatron function at the Interaction Point (IP), the so-called β*. The beta function in the triplet is proportional to the inverse of β*. The plan is to reduce β* by a factor of four down to about 15 cm, so the aperture of the quadrupoles has to double from 70 mm to ~140 mm (beam size being proportional to β½).

The baseline option is to have Nb3Sn quadrupoles. The technology is not yet fully validated for use in an accelerator, but we rely heavily on the 10-year-long LARP effort through which several 90 mm aperture and one – in multiple variants – 120 mm aperture quadrupoles have been built and tested. The program is based on the long term Nb3Sn program of the US DOE (see next section on Superconductor R&D), and has enabled the R&D to be well structured. In the first R&D phase, dealing with 1-m long model magnets, two different mechanical designs have been pursued and evaluated: the classical collar-type structure and the so-called shell-bladder structure. The shell-bladder structure, first proposed and developed by LBNL, basically consists in pre-compressing the coils against an external restraining cylinder. With respect to the classical collar system, in the shell-bladder concept stress is

![Fig. 4 Cross section and axonometric view of the 11 T Two-in-One dipole for LHC, courtesy of M. Karppinen and B. Auchmann (CERN).](image-url)
directly controlled, rather than resulting from the interference between collar and coil. The pre-stress is thus less sensitive to the actual size and rigidity of the coil. In addition since the cylinder is in aluminum, there is the benefit of additional strain during cool down due to the difference in thermal contraction. The latter effect is in principle also obtainable via the use of aluminum collars (as in HERA and the early LHC design), but so far designers have considered impractical the use of aluminum collars for high field magnets. The shell-bladder design has been so successful that in 2008 it was selected by the LARP collaboration as the baseline structure for the successive phase, the manufacturing of a long – 3.6 m – magnet. In these two phases the coil apertures were 90 mm, based on a early evaluation of LARP and CERN \cite{21} that later proved to be too small for the needs of the upgrade. The results of the 3.6 m long quadrupole can be found in Ref. 18. In 2010 the third phase of the LARP study took off with the construction of HQ: a 1-m long model with a large coil aperture, 120 mm – very near to the final requirement. This quadrupole poses formidable challenges given the jump in stresses and in stored energy per unit length. The design of HQ also addresses the problem of assuring alignment accuracy for an accelerator-like magnet. HQ has successfully passed 80% of the short sample critical current, a threshold that is critical for qualifying for operation. However some issue of reliability of insulation and repeatability of results are not yet fully solved. A review of the LARP results is in Ref. 22. For the conductor the two high current options (RRP from OST-USA, and PIT from Bruker-EAS-Germany) are both viable, targeting a $J_c$ in the range of 1500 A/mm$^2$ at 15 T, and a filament size of less of 50 μm or less. The main issues that still have to be resolved and on which the community is making an R&D effort are:  
- **Performance**: magnets still have to fully prove reliable operation at 80% of short sample. In some cases, most of which have been understood, long training and/or insufficient performance has been observed. The 10% gain that should derive from reducing operating temperature from 4.2 K to 1.9 K \cite{23} is impeded by conductor instability.  
- **Field quality**: we still have no statistics to prove the reproducibility of the coil geometry, which is related to the random component of the field harmonics. A cored cable is almost certainly needed to avoid ramp rate effects due to the low inter-strand resistance. Up to now there is a very limited, but positive experience \cite{24}, however the next generation of HQ will make use of a cored cable, to gain experience in this issue, which is also relevant for the 11 T dipole project previously described.  
- **Radiation resistance**: all materials have to withstand an extremely high radiation load - to reach the final target of 3000 fb$^{-1}$ one has an accumulated dose of 100-150 MGy. A systematic program has been launched by CERN in collaboration with a few European Institutes, and KEK and J-PARC in Japan.  
- **Length**: with 140 mm aperture magnets providing 150 T/m operational gradient, one needs 8-m-long magnets. So far, Nb$_3$Sn dipoles and quadrupoles exist as 1-m-long models, and a few 3.4-m-long quadrupoles. All problems related to differential thermal contraction of the components and to cable quality become more critical with longer lengths. The impact on performance of replacing 8-m long magnets with two 4-m units is being evaluated. A demonstrator satisfying these issues is required for 2014/2015 so that the layout of the upgrade can be fixed. If the Nb$_3$Sn technology is not shown to be viable, a back-up solution using Nb-Ti conductor will be adopted. The attendant loss in peak luminosity is estimated to be at least 25%, and the stability margin would be reduced. **3.3 Other magnets for IRs** The aperture requirements stemming from the smaller $\beta^*$ also affect the separation and recombination dipoles. Today the beam are separated by a normal conducting dipole (D1) consisting of six 3.4-m-long modules and providing 1.28 T in a 60 mm aperture. The foreseen aperture for the upgrade is of the order of 150 mm; superconducting technology is considered viable with appropriate shielding, allowing to shrink the beam recombination length and make room in the lattice for other elements (longer triplets, crab cavities). A large operational margin with nominal current at 66% along the load-line has been selected; moreover a large coil width of 30 mm (as in the LHC dipoles) allows to further reduce the high stresses due to the large aperture \cite{25}. For Nb-Ti these constraints lead to an operational field of 6.5 T, so one 4-m-long magnet will be sufficient to provide a bending power of 26 Tm, which is the present baseline. KEK is exploring with CERN various design options. Although the above-mentioned Nb-Ti design is the baseline, an interesting alternative for this range of field-apertures is the Nb$_3$Al conductor: its $J_c$ behavior vs. strain could possibly allow reacting first and then winding the coil, making use of classical technology for insulation.
and coil assembly. A 30 mm-thick coil would give 8.5 T with the same 33% margin, which would make it even shorter and with better heat deposition characteristics ($T_c \approx 18$ K). A further alternative giving a lot of current and stability margin is to use available, relatively cheap, Nb$_3$Sn strands from ITER production. While it is far less performant than the Nb$_3$Sn for HEP in terms of $J_c$, it is superior to Nb-Ti in this region of parameter space. But despite its possible advantages, the extra cost and complication of Wind&React technology required by Nb$_3$Sn strongly favor the Nb-Ti option.

3.4 High field dipoles

The race toward the highest fields is of course one of the most exciting adventures of magnet technology.

Since the initial period where this research was led by BNL (before SSC time), the lead has been in the hands of LBNL. This laboratory has been continuously pursuing the route of higher and higher field for more than 20 years. Today the record in a small dipole-like structure is 16 T, obtained in 2003 $^{26}$ without bore and 13.8 T in 2010 in the 35 mm bore HD2. However the record in a dipole approaching accelerator quality is still the 50 mm aperture LBNL D20 dipole of 1997 with 13.4 T at 1.8 K $^{27}$.

In Europe the high field was pursued in the preliminary phase of the LHC project with the dipole CERN-ELIN, that produced the first dipole coils able to break the 10 T barrier (in mirror configuration) and the University of Twente – CERN dipole that in 1995 went beyond 11 T with almost no training. Research on high field dipole resumed in 2003 with the NED dipole design. However, as laboratories in Europe were busy with LHC construction, and as financial support was short, the NED venture was limited to conductor development $^{29}$. So it is only recently, after LHC completion that a program aimed at high field has been resumed via the EuCARD collaboration $^{29}$ and Europe is again in the business. EuCARD is pursuing a dipole magnet for upgrading the present cable test facility of CERN. Named Fresca2, the dipole has a large coil aperture (120 mm). However, the field quality is less important than that required for use in an accelerator. With a central field of 13 T and the large aperture, forces and stored energy are enormous making the project very challenging. A similar project, called LD1, is pursued by LBNL in the USA $^{30}$. Both projects are foreseen to be commissioned in 2013-14 and feature a layout where coils are shaped in rectangular blocks, rather than the conventional cos $\vartheta$ arrangement, and feature flared ends for access to the central field (see Fig. 5).

Small magnet programs

Most of the R&D in high field magnets is actually done by means of small coils, initiated in LBNL as SM (sub-scale model), and now called SMC (Small Coil Magnet) at CERN. These small coils have been designed, manufactured and tested to support the conductor development and to test insulation and various technologies, as well as to establish the process and train technicians and young researchers. These magnets make use of a moderate quantity of conductor, about 10 kg, rather than hundreds of kg like Fresca2, and allow also a fast turnaround: typically 1-1.5 years against 3-5 years for a full-size magnets. However, while the usefulness of this small size test magnet is now widely recognized, the passage from SMC (or SM) to real magnets still involves a number of risks due to effects linked to conductor quantity, size, weight, and complication of geometry that cannot be fully modeled on a small scale.

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**Fig. 5** Various cross section of the Fresca2 dipole. Courtesy of G. de Rijk (CERN) and P. Manil (CEA-Saclay, F).
Various coil layouts

Over the last year various studies were undertaken to determine the scaling laws relating the dependence of maximum field on material properties and coil thickness. The cos \( \theta \) coil layout is the most efficient, in term of field-current relation, however it generates high stress in the coil mid-plane, which for Nb3Sn may be dangerous. The practical alternatives have been the common coil design and the so called block-coil design, proposed for Nb3Sn by P. McIntyre with a particular feature called stress management. The block-coil is now the structure that is most pursued for dipoles. While very attractive, proof has yet to be provided that this structure is really more convenient than the cos \( \theta \) structure - proof that should come from projects HD2, Fresca2 and LD1.

While the subject of coil layout is highly controversial, there is a general consensus that for fields below 11-12 T cos \( \theta \) is the best and for fields above 15 T the block-coil looks more viable, while in the intermediate 12-15 T region the choice depends on the appreciation of the designer and on details of the structure. For quadrupoles where forces are lower and high current density is important, the cos 2\( \theta \) layout does not have competition.

Magnet Structure

Since the time of Tevatron magnets the collars have been the structure of preference for force retention. Other systems have been explored; the main alternative has been to use the yoke as “collar” pushed by a restraining cylinder around the yoke (which serve also as He vessel). LHC main dipole is based on a collar system, adapted for the twin structure; however the yoke contributes at very high field, around 8 T. For quadrupoles, the free-standing collar structure has been the choice of preference, however is worth noting the success of an alternative concept, developed in the early R&D for LHC by T. Taylor, where the pre-stress is given by the external cylinder via the yoke.

For the LHC upgrade the stresses are such that new routes have been explored, the one most successful is the shell-bladder concept previously mentioned. It can be applied to quadrupoles and dipoles, to cos \( \theta \) and to block-coil layouts. The fact that Nb3Sn coils have a very high modulus, more than 20 GPa rather than 5-10 GPa common for NbTi, makes it more difficult to control stress via collars and favors the shell-bladder. However this structure must still be shown to be viable for large production – and to provide the required field quality.

The quest for a high field dipole is under way via three main programs: 1) LBNL, the leading lab. is pushing the limit of the HD structure. HD2 reached 13.8 T, about 78% of the \( J_c \), while HD3 with a larger bore has shown some problems (possibly not due to intrinsic limitations); 2) the LD1 program – Large Dipole 1 – is a 13 T dipole with large bore (>100 mm) for an upgraded USA cable test facility; 3) the EU program EuCARD, led by CERN, aimed at producing some 19 T with a small HTS race track (without bore) when inserted in the 13 T Fresca 2 dipole; 4) The EU program EuCARD-2 – in the application stage and not yet approved – aimed at developing a 10 kA-class HTS cable and the design and manufacture of a 5 T, 40 mm bore HTS dipole of accelerator quality. The scope is to eventually insert the 5 T HTS dipole in a large Nb3Sn dipole to prove that HTS can enhance the field to > 15 T with a useful bore.

3.5 HE-LHC considerations

The possibility of an energy upgrade of the LHC based on a dipole having an operating field of 24 T was put forward in 2006. This was based, however, on a current density of 800 A/mm² – still far from being achievable. Recently at CERN a study has been carried out, and the target field for the main dipoles, the main driver of the entire project, has now been set to 20 T (operational) in a 40 mm bore, which would enable HE-LHC to reach 33 TeV center-of-mass energy for proton collisions. A pre-study clearly identified the following critical points:

- The required margin is about 20%, measured along the load line, i.e., the short sample limit of the magnet needs to be 25 T. A lower margin does not guarantee operability of the accelerator.
- The overall current density of the coil should be around 400 A/mm², at the design field, as in all previous accelerator magnets. Lower current density means too large and expensive a magnet, and higher current density (if available!) would have to be diluted to avoid too high operational stress and too high temperature at the quench hot spot. One should also consider that insulation, voids and stress degradation concur to reduce the actual current density in the coils, so the engineering current density of the basic element, strand or tape \( J_o \), must anyway be substantially higher than the overall 400 A/mm² in the operating coil.
- The coil of this magnet is very thick, so it is not worth pushing for bore size much smaller than 40 mm. Despite the small bore the inter-aperture distance must be increased from the present 194 mm to 300 mm.
- The outer diameter of the iron flux return yoke must not exceed 800 mm (compared to 570 mm in the
present LHC dipoles) which is a tough constraint considering the amount of flux that needs to be intercepted.

Based on these constraints and hypotheses it is possible to make a very preliminary design using Nb-Ti, Nb$_3$Sn and HTS, without making any commitment in favor of Bi-2212 round wire or YBCO tape. The superconductor grading is done primarily for cost reduction, however it also allows us to make the best use of material. For the moment the reference design (see Fig. 6) is based on a block-coil rather than cos $\vartheta$ structure. To save coil volume and cost, the Nb$_3$Sn part is further subdivided into a high $J_c$ low field subsection and a low $J_c$, high field one.

In terms of design we are investigating the solution of powering the coil sections with different power supplies. Although this configuration complicates the circuitry and makes separate optimization of cable size and amperage for the three materials. Moreover, while Nb-Ti and Nb$_3$Sn can be manufactured in very large cables (15-20 kA), this is not at all is granted for HTS.

- Coil segmentation will favor magnet protection, a technique largely employed in the large solenoid magnets (working at ~1 kA rather than > 10 kA like accelerator magnets): the amount of energy and inductance is such that the usual technique, a single diode in parallel to the whole magnet, is insufficient.

- Dynamic compensation of the field harmonics. This is extremely important since it is very unlikely that Nb$_3$Sn and in HTS will feature the 5-7 $\mu$m filament size developed for the SSC and LHC Nb-Ti. We have to live with $\varphi_{th} = 25-50$ $\mu$m for Nb$_3$Sn and most probably > 50 $\mu$m for the HTS part, with sextuple components coming from persistent current of 50-100 units. Use of passive shims can mitigate but not fully compensate for these large effects. Separate powering, first proposed for SSC 37, facilitates compensation of these effects as well as other dynamic effects due for example to interstrand resistance that are difficult to control at the cable level.

The project presents immense challenges, the first one being to make available the necessary superconductors and make out of them the required conductors. The total quantity of superconductor is three times the LHC, i.e. about 3000 tonnes of finished strands (or tapes), containing about 40% of superconductor and 60% of stabilizer. We believe that in a few years the Nb$_3$Sn conductor will be technically available, thanks to the program for HL-LHC, and that industry, through production for ITER, will have acquired the knowledge to master such a large production. Therefore the biggest uncertainty concerns the HTS that is still far from being ready for this type of practical application. The candidates are Bi-2212 round wire and YBCO tape, the merits of which will be discussed in section 4.

The EuCARD2 program mentioned above will explore both routes, complementing the on-going program in the USA, more focused on Bi-2212. The basic R&D study on HTS for HE-LHC must be carried out in the next 4 to 5 years since by 2016 or 2017 a credible design must be available. Should HTS not meet the very demanding requirements of HE-LHC, closing the door to the 16-20 T region, the HE-LHC magnets will be based on Nb-Ti & Nb$_3$Sn technology, with the goal being a maximum operating field of 15.5 T, a figure that still enables a respectable 26 T center-of-mass (collision) energy.
4. Superconductor R&D

Both LTS and HTS technologies for the LHC upgrades present great challenges, however the program is naturally biased towards industrial procurement of Nb$_3$Sn, given the fact that HL-LHC is approaching the prototype phase. Overall, the conductor development and procurement for the CERN high-field magnet program is expected to require approximately 25 tons of Nb$_3$Sn and funding at the level of 20 M€. For HTS conductors it is too early to provide a forecast. For this reason, below we focus on the work on Nb$_3$Sn. The main activities of CERN on HTS materials are summarized elsewhere 11).

At present, the HL-LHC program is capitalizing on the achievements of the development in the US (DOE Conductor Development Program (CDP) and on EU-FP6 program NED 28). The US CDP, has managed to raise the critical current density in the non-copper cross section to values in excess of 3000 A/mm$^2$ at 12 T and 4.2 K on usable piece lengths (1 km and longer) of wires with diameter in the range 0.7 to 1 mm. To date, these high $J_c$ wires have a filament diameter of 50 μm for 0.7 mm, or 75 μm for 1 mm diameter strand. The NED wire R&D culminated in the best performance Powder-In-Tube (PIT) 1.25 mm strand, which achieved a critical current density of 1500 A/mm$^2$ at 15 T and 4.2 K, corresponding to 2700 A/mm$^2$ at 12 T and 4.2 K. This wire has a filament diameter of 50 μm, and an RRR of 200.

The spectacular increase of $J_c$ achieved over the past 10 years is a great success, but not all problems have been solved. For examples, instabilities whose explanation lies in the well-known effect of flux jumps and self-field instability. Because of this, very high $J_c$ is only accessible in strands of diameter $< 1$ mm, if the filament diameter is $\leq$50 (70) μm and the RRR is large – above 100. Achieving simultaneously high $J_c$ with small filaments and high RRR is challenging for any of the leading wire manufacturing routes 10).

Both leading manufacturing routes for Nb$_3$Sn are considered for the strands, namely the RRP of Oxford OST, and the PIT of Bruker-EAS. The HEP-grade strands are delicate. We count on a maximum cabling degradation of 10% of the $I_c$ of the virgin strand. In practice, the cabling degradation observed on the SMC and 11 T dipole cables are around 3% on average – a very good result. Larger degradation is presently obtained in the FRESCA2 cable (18% on average) and we are exploring the range of cabling parameters to reduce this undesired effect. In the LARP program, which makes use exclusively of RRP from OST, the degradation of RRP is typically 3%: clearly RRP has still a considerable advantage over PIT.

As concerns HTS, the studies are concentrated on Bi-2212 round wires and YBCO tapes. A recent summary of the performance of technical conductor at 4.2 K is shown in Fig. 7. It can be seen that HTS is advantageous
for fields above 15 T, i.e. the territory of HE-LHC. To take advantage of these material properties to provide an effective “usable conductor”, a vigorous R&D program is required. The main problems are 1) that the cost of HTS is presently very high, about ten times that of Nb$_3$Sn (or fifty times that of Nb-Ti), and 2) that the current density must increase by a factor of two. This and other technical issues will be faced in the previously mentioned EuCARD2, an EU development program coordinated with the various programs that are already pursuing HTS for accelerators in other regions, namely in the US (Very High Field Superconducting Magnet Collaboration – VHFSMC: many labs, sponsored by the DOE) and Japan (JST project on HTS, led by University of Kyoto, in close collaboration with KEK).

One characteristic of EuCARD2 is the aim at a real cable suitable for accelerator magnets, capable of carrying 10 kA. Making a cable is relatively easy for Bi-2212 which has the advantage of being in the form of round wire. However for Bi-2212 the big issue is the uniformity of properties when large quantities are involved, such as for a coil of 50-500 kg, and its vulnerability to transverse stress. The US program is addressing the issue of uniformity, with innovative ideas such as isostatic pressing. However, the problem of stress sensitivity in the 100-200 MPa range is difficult, resembling that of Nb$_3$Sn. In both cases a possible way out is stress mitigation at the level of magnet design.

YBCO tape is the material favored by a larger number of laboratories. The fact that an entire community is pursuing YBCO conductor for power applications gives it a clear advantage over Bi-2212. The key point for using YBCO is to develop a means of making compact multi-strand cable, analogous to the flat Rutherford cable that is built from round wires. For accelerator magnets a filling factor of 80-90% is required – compared with between 10 and 30% for energy transport or fusion applications. While tapes are not suitable for cabling in the style of Rutherford cable, a solution that is being explored is the Roebel cable. Recent results are encouraging, with length of few tens of meter and current of 10 kA at the first attempt in a test at CERN. However many issues need to be resolved – issues that do not appear to be insurmountable in principle, but clearly need to be addressed vigorously.

5. Conclusions

The LHC upgrade is a staged program, first luminosity and then energy, and offers a unique opportunity for a great leap forward in high field magnet technology. HL-LHC is a well-founded and motivated project requiring 30 to 40 magnets in the range of 11-12 T, for the 11 T dipole and the low-$\beta$ quadrupole magnets. The time scale is the end of the decade. It will prove Nb$_3$Sn technology on a moderate scale in a real accelerator.

Based on the expected success of HL-LHC magnets, a much larger project, HE-LHC is appearing at the horizon beyond 2030. For this project we need to carry out a basic R&D program in the next years, increasing the performance by a factor of more than two above LHC: 16-20 T. The push is really to explore the 20 T landscape, and to this scope various R&D programs on HTS in the three main areas, USA, Japan and Europe, are coordinating their effort. Making HTS suitable for accelerator is very challenging. However the large amount of SC involved, 3000 tonnes in total (with 3-400 t of HTS for the 20 T dipoles), as well as the physics goal fully justify this effort. The decision for HE-LHC is expected in the period 2018-2020: however a decision on whether or not to use HTS for the magnets, and if so which type of HTS to use (Bi-2212 or YBCO), should be taken around 2016. This early decision on HTS is necessary to allow fixing the ultimate goal in term of field and providing a sufficient number of long successful magnets as input for a correct decision on HE-LHC.

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References

2) L. Evans (ed.): Large Hadron Collider – A Marvel of Technology, EPFL Press, 2009
8) L. Rossi: “LHC upgrade plans: options and strategy,” Joint Accelerator Conferences Website (JACoW) IPAC11 (2011)
22) G. Sabbi: “Development of long Nb₃Sn quadrupoles by the US LHC accelerator research program,” Joint Accelerator Conferences Website (JACoW) PAC2011 (2011)
31) S. Caspi and P. Ferracin: “Limits of Nb₃Sn accelerator magnets,” Joint Accelerator Conferences Website (JACoW) PAC03 (2003)
32) R. Gupta: “A common coil design for high field 2-in-1 accelerator magnets,” Joint Accelerator Conferences Website (JACoW) PAC97 (1997) 3344-3346
35) P. McIntyre and A. Sattarov: “On the feasibility of a tripler upgrade for the LHC,” Joint Accelerator Conferences Website (JACoW) PAC05 (2005) 634

Lucio ROSSI
Lucio Rossi holds a doctorate in Plasma Physics at the University of Milan, where in 1992 became professor in experimental physics, developing accelerator and detector magnets and large scale superconductivity. He developed record \( J_c \) Nb₃Sn, (1998), as well as the first LHC dipole prototype (1994) and the superconductor and first coils for the ATLAS toroid (2000). In 2001 he joined CERN where he led the Superconductor and Magnet construction for LHC, the largest superconducting system ever built with more than 1600 large magnets. Since 2010 he is coordinator of the High Luminosity LHC Project, developing new high field magnets, SC cables and SCRF cavities.