Advanced Accelerator Magnets for Upgrading the LHC

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***Abstract*—The Large Hadron Collider is working at about half its design value, limited by the defective splices of the magnet interconnections. While the full energy will be attained after the splice consolidation in 2014, CERN is preparing a plan for a Luminosity upgrade (High Luminosity LHC) around 2020 and has launched a pre-study for exploring an Energy upgrade (High Energy LHC) around 2030. Both upgrades strongly rely on advanced accelerator magnet technology, requiring dipoles and quadrupoles of accelerator quality and operating fields in the 11–13 T range for the luminosity upgrade and 16–20 T range for the energy upgrade. The paper will review the last ten year of $\mathrm{Nb_3Sn}$ accelerator magnet R&D and compare it to the needs of the upgrades and will critically assess the results of the $\mathrm{Nb_3Sn}$ and HTS technology and the planned R&D programs also based on the inputs of first year of LHC operation.**

***Index Terms*—Accelerator magnets, large Hadron collider, large-scale systems, superconducting magnets.**

I. Introduction

THE LHC is the largest scientific instrument ever built [1], [2] and its performance critically relies upon its 1700 large superconducting magnets [3]. After the brilliant start-up of 10 September 2008 and the severe setback due to the incident of 19 September 2008 [4], it has resumed operation on 22 November 2009. From 30 March 2010 LHC is regularly working [5], producing particle collisions at energy of 3.5 TeV/beam, which is half its design value. Indeed the consequences of the incident are such that the main dipoles are operated at 4.15 T, which is half of the design field, exceeded by all magnets during acceptance test. The physics run will continue also in the next year before a long shutdown in 2013-14, scheduled to fix all bad electrical splices in the magnet interconnects.

Despite the setback of operating at reduced energy, LHC is exploring new territory and first important results are approaching. The machine is beating all records for hadron accelerators in terms not only of energy (3.5 times the Tevatron of Fermilab) but also in term of luminosity, an important parameters proportional to the rate of particle collision. Actually we are not far from the design luminosity, $\mathrm{L} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$, considering that luminosity scales linearly with energy. The magnetic system is performing very well, with an excellent reliability and with a field accuracy even better than the design target [6], very much due to the strict Quality Assurance and analysis during construction and test [7], [8]. The magnetic model of the machine [9], incorporating all superconductivity effects, like persistent currents, decay, snap backs, as well as iron yoke saturation and hysteretic effects, is also performing very well, allowing LHC operators to forget—almost—that the machine requires the adjustment of some 80 magnetic circuits, a good part of them needing to be precise in term of field at better than 10^{-4}.

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II. The CERN Magnet Upgrade Program

Meanwhile the LHC will continue improving and producing new physics, CERN has defined a few projects requiring the use of SC accelerator magnets beyond 10 T:

- Upgrade of the background field of the 30 kA current test station, FRESCA; the station is based on a 10 T@1.9 K–80 mm aperture dipole about 1 m long. The upgrade aims at a dipole capable to produce 13 T in a 100 mm useful aperture dipole [10]. The magnet, called FRESCA2, will have a coil aperture of 120 mm, therefore the jump in energy and forces beyond the present magnet is considerable.
- A new 11 T dipole for improving the beam collimation system, capable to generate a bending strength equal to LHC main dipoles: $8.4\ \mathrm{T} \times 14.2\ \mathrm{m} \approx 120\ \mathrm{Tm}$, with a 3 m shorter length, i.e., 11 T × 11 m [11]. Despite that its field is 30% higher, this dipoles must respect many constraints imposed by their use as LHC main dipole: i) minimum 56 mm aperture, 570 mm yoke outer diameter; ii) transfer function in Tm/A equal to the main dipole; iii) field harmonic content very near (within few 10^{-4}) to the LHC main dipoles despite the very different iron saturation behavior. The number of such magnets is between 10 and 20 units, on the horizon 2017–2021, according to various scenarios for collimation upgrade.
- New magnets for upgrading the Interaction Regions (IRs) around the two high luminosity insertions (ATLAS and CMS experiments). The most important change will concerns sixteen low-β quadrupoles that govern luminosity [12]. They will have all main parameters strongly enhanced over the present ones: peak field of 13 T (+60%), aperture 120–150 mm (+100%), 8–10 m of length (+30%): the jump in forces and stored energy is striking. Other sixteen new magnets, with higher field and/or larger apertures, are requested by the IRs upgrade: two types of dipoles and two types of quadrupoles, some of them requiring probably A15 conductors. All will have to cope with an increased radiation environment and must be ready by 2020 at latest.

TABLE I
MAGNETS FOR LHC UPGRADES

Magnet type	Name	Scope	Quantity	Peak Field (T)	Coil bore (mm)	Length (m)	Energy (MJ)	F_x (MN/m)	Deadline (year)
Race track	SMC	R&D	~10	12.5	=	0.4	0.35	2	=
Dipole	FRESCA 2	Ic Test station	1-2	13	120	1.5	3.6	15	2013
Twin dipole	LHC	=	=	8.3	56	14.3	7	3.4	=
Twin Dipole	11T	HL-LHC DS	10-20	11	60	11 (2×5.5)	11	7.3	2017-2020
Quad	Low-β Q1-Q3	HL-LHC IR	16	12	120-150	8-10	12	=	2018-2020
Dipole	D1	HL-LHC IR	4	6-8	120-150	5	6	7	2019
Two-in-One Dipole	D2	HL-LHC IR	4	3-5	100	5-10	=	=	2019
Twin Quad	Q4	HL-LHC IR	4	8	85	4.5	1.2	=	2019
Twin Quad	Q5	HL-LHC IR	4	8	70	4.5	0.6	=	2019
Dipole	LHC2D	HE-LHC **demo**	1	20	40	1-2 m	5	20	2016
Twin Dipole	LHC2T	HE-LHC **demo**	1	20	40	1-2 m	10	20	2017

- A new twin aperture 20 T dipole for a future possible upgrade in energy of the LHC. A preliminary study indicated that 20 T is close to the maximum compatible with the boundary imposed by the LHC tunnel [13]. The challenge of such a magnet are multiple: superconductors (not yet available), multiple grading by use of Nb-Ti, Nb_3Sn and HTS sections independently powered, very large forces and inductances, huge stored energy with severe protection issues. The mass production, eventually 20 km of twin dipoles, demands also an affordable cost, especially for the Nb_3Sn and HTS superconductors. A design and possibly a prototype must be ready on the horizon 2016-17.

All these studies and projects has been regrouped under the project called *High Luminosity LHC* (HL-LHC), recently formed at CERN with the scope to study and to implement the necessary changes in the LHC to increase its luminosity by a factor five around 2022. The program, which counts on the participation of many EU partners, includes a basic R&D on Nb_3Sn superconductor initiated in 2004 [14] and on high field magnet technology, initiated in 2007 and then delayed by two years because of the LHC incident [4].

The magnet program for the LHC upgrade is more advanced in the USA, thanks to the long term program LARP (Lhc Accelerator Research Program) [15], [16] and the basic programs of the various DOE laboratories. In Fig. 1 the historic of superconducting magnets for hadron accelerators is traced showing the objectives for the High Luminosity and the High Energy upgrades of the LHC, while in Table I a summary of the new magnets, of their main parameters and installation time is reported.

The list of Table I deserve some comments since it is rather inhomogeneous, comprising both R&D prototypes and magnets that have to operate in the accelerators:

- All magnets for HL-LHC must have the quality to operate in the accelerator. The tolerance to deviation from specification is almost zero; their reliability must be as high as the LHC magnets to avoid downgrading performance.
- The current density is almost the same for all type of magnets, around 400 $\mathrm{A/mm^2}$ at their operational field and 1.9 K. This feature is intrinsic in the optimization of the accelerator magnets when pushed toward their limit and when practical conditions and cost are taken into account.

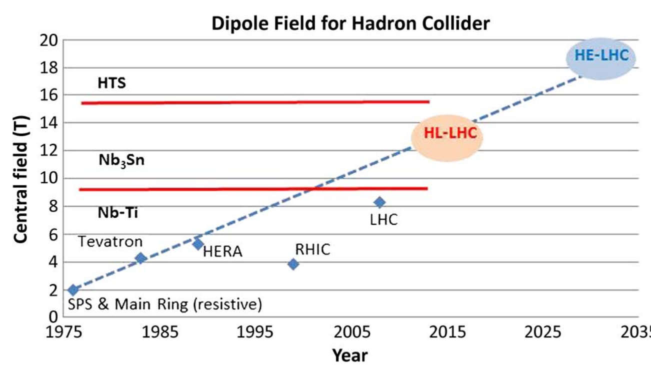


Fig. 1. Field progress for main dipoles used for large colliders and the region of interest for the next CERN projects. Main Ring and Tevatron are at Fermilab (USA), HERA at Desy (D) RHIC at Brookhaven (USA), SPS and LHC at CERN, Geneva (CH). For LHC the date of September 2008 is considered, since all magnets passed nominal field, however the accelerator will operate at maximum field after 2014.

- For the HE-LHC for the next years we will focus on prototypes: the issue for the cost however is critical since, eventually, some 1200 15 m-long dipoles and about 500 4 m-long quadrupoles will be needed for the project. Cost issues are much more important for the Energy upgrade than for the Luminosity upgrade.

In addition to the list of Table I, a number of corrector magnets, which might also be in Nb_3Sn, will be needed to be designed and integrated in the main magnet cold mass.

The ambitious program of Table I is complemented by two more programs in similar domain:

1) The construction of HTS round cables capable of 100–200 kA@5kV d.c.; this project is mainly driven by the HL-LHC and aims to remove the power converters feeding the magnets in the IRs or other high radiation zone from the 100 m deep tunnel up to the surface [17]; each cables is 300–600 m long and will be cooled by He gas at 4–20 K. About 3 km of cable will be needed starting from 2014 until 2021.

2) The construction of a small prototype of a Fast Cycling Magnet (FCM). This small prototype [18] employs a hollow Nb-Ti cable and is used in super-ferric configuration to yield about 2 T with a continuous field ramp of ± 2 T/s. This dipole might be the prototype for a renovation of the PS accelerator in view of its upgrade for the HE-LHC, while a magnet that could serve for the SPS accelerator upgrade has been manufactured by the INFN-GSI collaboration [19] for the FAIR project.

III. Superconductor Development

The timely availability of a superconductor with high current density in the targeted field range (10–15 T and above), precise and stable geometry (2 $\mu\mathrm{m}$ tolerance), tolerance to mechanical stress and strain (150 MPa pressure), controlled magnetization in DC and AC conditions (smaller than 100 kA/m at 1 T), and, last but not least, acceptable cost, is a necessary condition for the success of the magnet R&D with the ambitious targets described above. Therefore a large effort, has been allocated to the development of $\mathrm{Nb_3Sn}$ for high field magnets in the range of 15 T, while in future we intend to dedicate a similar effort also to HTS development for magnets targeting the 20 T. Apart for the inherent difference among the two technologies, the level of maturity of $\mathrm{Nb_3Sn}$ is higher than for HTS materials. For this reason the conductor program unfolds in two directions: i) in the case of $\mathrm{Nb_3Sn}$ the aim is to demonstrate that the technology is sufficiently mature for its first application as a main optics element in a running accelerator, including issues of beam control, reliability and long term operation; ii) for HTS materials the aim of the conductor program is to explore the technology options and verify the feasibility for accelerator application.

Although both LTS and HTS technologies have great challenges, the program is naturally biased towards industrial procurement of $\mathrm{Nb_3Sn}$. Overall, the conductor development and procurement for the high-field magnet program is expected to require approximately 25 tons of $\mathrm{Nb_3Sn}$ and funding at the level of 20 M euros. For HTS conductors it is too early to provide a forecast. For this reason, below we focus on the work on $\mathrm{Nb_3Sn}$. The main activities of CERN on HTS materials are summarized elsewhere [17].

At present, HL-LHC program is capitalizing on the achievements of the development in US (DOE Conductor Development Program (CDP) and on EU-FP6 program NED [14].

The US CDP, complemented by basic program of the various DOE labs, has managed to raise the critical current density in the non-copper cross section to values well in excess of 3000 $\mathrm{A/mm^2}$ on usable piece lengths (1 km and longer) of wires with a diameter in the range of 0.7 to 1 mm. To date, these high $\mathrm{J_C}$ wires have filament diameter of 50 $\mu\mathrm{m}$ at 0.7 mm strand diameter, or 75 $\mu\mathrm{m}$ at 1 mm strand diameter [latest OST]. The NED wire R&D culminated in the best performance PIT 1.25 mm strand that achieved a critical current density of 1500 $\mathrm{A/mm^2}$ at 15 T and 4.2 K, corresponding to 2700 $\mathrm{A/mm^2}$ at 12 T and 4.2 K. This was achieved at a moderate reaction temperature (625°C) that maximizes the final fraction of fine-grained $\mathrm{Nb_3Sn}$ in the initial Nb tube. This wire has a geometric filament diameter of 50 $\mu\mathrm{m}$, and an RRR of 200 [20].

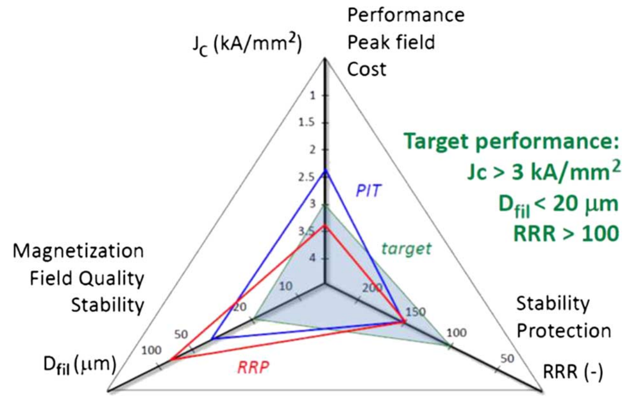


Fig. 2. The performance parameter space for $\mathrm{Nb_3Sn}$.

The spectacular increase of $\mathrm{J_C}$ achieved over the past 10 years is a great success, but has also brought a number of riddles. In some cases, magnet performance was found to be below expectations, affected by instabilities that could be reproduced in single strands and cables both experimentally and theoretically [21], [22]. The basic explanation lies in the well-known effect of flux jumps and self-field instability. Indeed, very high $\mathrm{J_C}$ is only accessible in strands of modest diameter (typically 1 mm and smaller) if the filament diameter is small (typically below 50 $\mu\mathrm{m}$) and the RRR is large (typically above 100). Achieving simultaneously high $\mathrm{J_C}$ with small filaments and high RRR is challenging for any of the leading wire manufacturing routes, see Fig. 2.

In particular, the demand of high $\mathrm{J_C}$ implies that the filament cross section must be reacted almost completely, with the risk of a Sn leak in the stabilizer matrix and a catastrophic drop of RRR. In practice, a fixed thickness of Nb barrier is left unreacted (a few $\mu\mathrm{m}$), which is essentially a lost percentage of the filament cross section. A demand for high RRR hence limits the maximum achievable $\mathrm{J_C}$. Similarly, reducing the filament diameter while maintaining the thickness of unreacted barrier, also reduces the *real estate* available for reaction, and causes a reduction of the final $\mathrm{J_C}$. In summary, critical current density $\mathrm{J_C}$, effective filament diameter and RRR have a simple but very delicate interplay, that requires a careful compromise in the cable design.

The above elements were instrumental in determining the target specifications for the CERN HFM strands. Two strands are presently on the palette, namely a large diameter strand (1 mm) for the production of the high current cable for FRESCA2 [10], and a moderate diameter strand (0.7 mm) for the 11 T Twin dipole (see next sections). The strand for FRESCA2 is an evolution of the NED strand, with smaller diameter (1 mm vs. 1.25 mm) and reduced critical current density (1250 $\mathrm{A/mm^2}$ vs. 1500 $\mathrm{A/mm^2}$ at 15 T and 4.2 K), to limit the risk of self-field instability. For the strand of the 11 T dipole, a smaller diameter is mandatory to satisfy the constraints on available space and operating current. The reduced filament diameter (30 $\mu\mathrm{m}$) in this case is beneficial as it brings better field quality at injection. For both strands we relaxed the NED specifications on RRR in view of the recent experimental and analytical results indicating that a lower limit of 100 is appropriate [23].

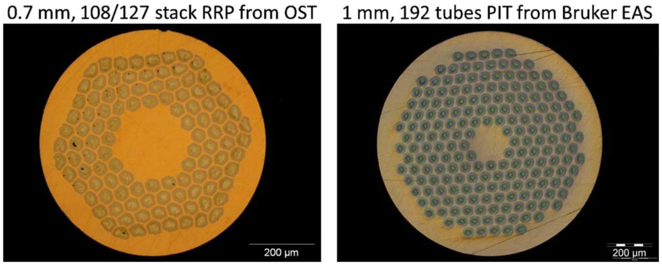


Fig. 3. Nb_3Sn layouts from leading ITD Nb_3Sn manufacturers.

Both leading manufacturing routes are considered for the HFM strands, i.e. the RRP of Oxford OST, and the PIT of Bruker-EAS. A cross section of two samples from wires procured recently is shown in Fig. 3. The RRP wire used at present is identical to the wire developed within the scope of US-LARP, i.e. 108 superconducting sub-elements in a 127 stack arrangement (108/127). A new architecture is in production, based on a 169 stack arrangement that will reduce the sub-element dimension to approximately 50 μm at a strand diameter of 1 mm and 35 μm at a strand diameter of 0.7 mm. The 1 mm PIT strand procured has 192 tubes of 48 μm diameter. A 0.7 mm version of PIT is presently in R&D phase, with qualification for production expected by early 2012.

At present, three types of Nb_3Sn Ruhterford cables are being manufactured at CERN, using the cabling machine inherited by the LHC project: the large size FRESCA2 rectangular cable made of 40 strands of 1 mm diameter, its sub-scale prototype for the SMC program, made of 18 strands of the same diameter, and a keystoned cable of 40 strands of 0.7 mm diameter for the MB-DS program.

The HEP-grade strands described above are delicate material, as a general rule the cable compaction should be kept in the range of 85% to avoid excessive deformation and shear of the sub-elements at the cable edges. This is much lower than the 90% compaction typically used for Nb-Ti Rutherford cables and we count on a maximum cabling degradation of 10% of the virgin strand I_c. In practice, the cabling degradations observed on the SMC and 11 T dipole cables are around 3% on average, which is a very good result. Larger degradation is presently obtained in the FRESCA2 cable (around 18% on average) which is why we are still exploring the range of cabling parameters to reduce this undesired effect.

IV. HFM R&D AT CERN AND FRESCA2 DESIGN

The aim of CERN High Field Magnet R&D program is to develop the HFM technology for the magnets needed for the LHC upgrade and future machines. In a first phase (2004–2012) we focused on the development of Nb_3Sn conductor suitable for accelerator, base magnet construction technology, and training of the personnel. Then in a second phase (2009–2014) we aim at upgrading the cable test facility to 13 T (FRESCA2), see Fig. 4, and we also aim working on design concepts for magnets in the 15 T–20 T domain. In this second phase we also put the ground for design and construction of models and later of prototypes for 11 T dipole and 13 T quadrupole necessary for the upgrade (see next sections).

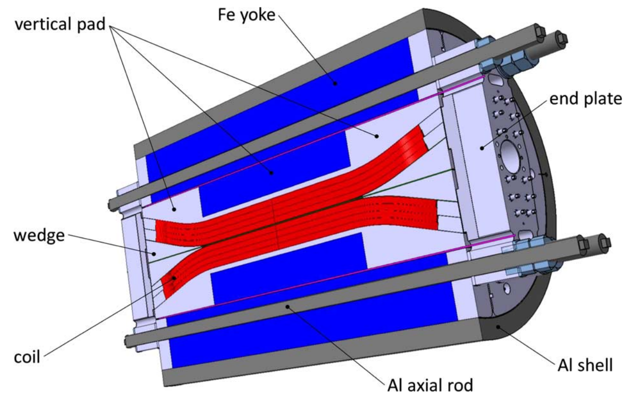


Fig. 4. Side section of the 13 T–100 mm bore FRESCA2 dipole.

The European FP6-CARE-NED joint research activity (2004–2008) [14], with a budget by Europe of less than 1 M euros, and more than 2 M euros provided as matching funds by the collaborating Institutes, hosted the first phase, in which we developed a 1.25 mm diameter Nb_3Sn strand with European industry, described in the previous section. In the frame of NED design concepts for high field accelerator magnets and insulation schemes were studied.

Beyond the official NED program, CEA-CERN-RAL-LBNL, formed a collaboration to design small magnet with racetrack coils: the so called "Short Model Coil", SMC. The main scope was to test the NED cable and provide a "fast turnaround" test bed to qualify SC cables of new types and new strands. The SMC program, which relies strongly on the expertise in the US and in particular of LBNL, has already produced 2 small magnets; the second one has been recently tested with great success, confirming the good performance for the NED cable. The SMC reached the design field on the coil [24].

The second phase of the CERN high field magnet program is carried out in the framework of the FP7-EuCARD project [10]. The development of HFM technology is the subject of EuCARD work-package 7 (WP7) shared by 12 partner institutes. It runs from 1st April 2009 for 4 years with a total budget of 6.4 M euros from which 2.0 M euros will be contributed by the EC. Beside the technological development, the main tasks of the WP7 is the design and construction of a 1.5 m long 13 T dipole with an aperture of 100 mm and the development of an High Temperature Superconductor insert with a flux density contribution of $\Delta B = 6\ T$ to be used inside the 13 T dipole. The 13 T dipole, intended to upgrade the CERN cable test facility to higher fields (FRESCA2), features a coil block layout, rather than a $\cos\vartheta$ one. Block layout helps to limit the stress build up, however it requires more conductor and requires the development of flare ends, see Fig. 4.

The radiation hardness of the Nb_3Sn superconductor itself is being assessed by CERN. Irradiation of samples with different particle types is on-going or planned at the Atominstitut in Vienna and the Kurchatov institute in Moscou. In parallel a task in EuCARD is investigating the radiation resistance of the coil insulation, aiming to produce a list of candidate radiation resistant insulation schemes for the LHC upgrade magnets.

As a successor to EuCARD insert, the first step towards 20 T magnets, a new FP7 program is in preparation (EuCARD2) planning to build a 5 T HTS dipole. The aim is to build a magnet with full accelerator quality. This comprises: development of a 5 kA–10 kA HTS compact cable (targeting the 85% compaction factor of the $\mathrm{Nb_3Sn}$ Rutherford cables), achieving the geometric field quality and the ability to ramp the magnet in $\sim$500 s with an acceptable dynamic field quality. The magnetization properties also have to be controlled, with the goal of filament size in the 50 $\mu\mathrm{m}$ region. Both YBCO tape and BSCO strand will be investigated. At a later stage this magnet should be tested as in insert in one of the large aperture high field dipoles.

V. Magnets for HL-LHC

A. 11 T Two-in-One Dipole

Because of the need to improve the collimation system on a relatively short scale, this type of magnet has a fairly good chance to be the first $\mathrm{Nb_3Sn}$ coil to be used in an accelerator. The decision to start this project has been taken in October 2010, and from then Fermilab and CERN are closely collaborating. Fermilab has been pursuing a 10–11 T dipole field program for long time as part of its basic R&D program [25] and has developed design capabilities, tooling, and technologies that well fits the needs of this project.

As previously mentioned the fact that it must be series powered with the other LHC main dipoles and identical to them in bending strengths and harmonic content is a severe constraint. A coil lay-out has been found to reach the target field of 11 T at 80% of the short sample value on the load line. The design is based on 108/127 lay out 0.7 mm strand, by OST, with a current density of 2750 A/mm2 at 12 T in virgin state, (we expect a 10% degradation from virgin to conductor in the coil). The nominal copper content is 53% and the effective filament diameter is 45–50 $\mu\mathrm{m}$.

The coil is of course double-layer, like LHC dipole, however there is no superconductor grading, which would have required a smaller strands for the outer layer cable. Furthermore, by using the same cable a double pancake technique can be used, avoiding dangerous splice in the high field region (today almost all accelerator $\mathrm{Nb_3Sn}$ coils are wound in double pancake for this reason). The electromagnetic design is further complicated by two issues: 1) the filament size generates a $\mathrm{b_3}$ 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 and the same iron geometry as for the LHC dipoles, make the sextupole component, due to saturation effect at high field, unacceptable high: 6.6 units.

Mitigation measure for the persistent sextupole is to change the powering cycle, lowering the minimum current from 350 A down to 100 A, which reduces $\mathrm{b_3}$ down to the bearable value of 20 units. Further reduction will be obtained by means of passive magnetic shims near or inside the coils, which should bring residual effect in the range of 10 units. Although twice as high as the LHC, this residual effect is certainly tolerable because we will install only a few dipoles. The saturation effects are strongly reduced by a special profile of the internal iron shape and by special set of three holes, see Fig. 5 where a sketch of the coil and cold mass is shown. The mechanical design to keep the forces, $\sim$70% higher than in the LHC dipole, counts 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 system that avoids excessive stress during collaring but requires that very tight tolerances and assembly procedures. In this way the transverse stress, a constant concern with fragile $\mathrm{Nb_3Sn}$, is kept below 150 MPa while the interface pole-coil remains always under compressive stress.

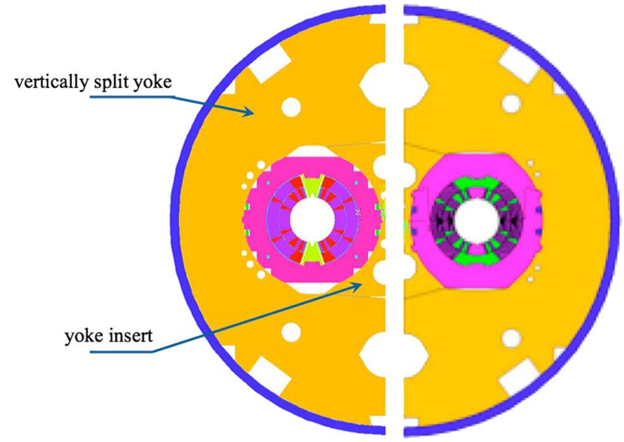


Fig. 5. Cross section of the cold mass of the 11 T dipoles. Left and right halves differs in the way the pole is fixed to the coil or it is insertable.

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

We intend to manufacture two single bore short ($\sim$2 m) full cross section dipoles by spring 2012, the first being already under construction and its test is foreseen in February 2012. Two different approaches are explored in this R&D phase for the coil-collar interface, 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.

B. The Low-β Quadrupole Triplet

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 betatronic function in the Interaction Point (IP), the so-called β^*. LHC is based on a quadrupole first optics, with a triplet of quadrupoles with alternating gradient, which are the magnets closest to the IP. The beta function in the triplet is proportional to the inverse of β^*. At zero order, the aperture is proportional to the square root of β^*: since the plan is to reduce β^* of a factor four down to 15 cm, the aperture of the quadrupoles has to double from 70 mm to $\sim$140 mm [26].

The baseline option is to have $\mathrm{Nb_3Sn}$ quadrupoles. The technology is not yet fully validated for the use in an accelerator, but we heavily rely on the 10-years-long LARP effort [15], which has built several 90 mm aperture [27] and one—in multiple variants—120 mm aperture [28] quadrupoles. For the conductor the two high current options (RRP from OST and PIT from Bruker-EAS) are both viable, targeting a j_c in the range of 1500

$\mathrm{A/mm^2}$ at 15 T, and a filament size of less of 50 $\mu\mathrm{m}$ or less. The main issues that have to be analysed are:

- Performance: magnets still have to fully prove to be able to operate at 80% of short sample—in some cases, most of which have been understood, long training and/or insufficient performance has been observed. Conductor instability is not yet fully solved and in particular it impedes the additional 10% gain of 1.9 K w. r. t. 4.2 K operation [22].
- 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. The control of the coil size is crucial, also to minimize the non-allowed harmonics. Moreover, a cored cable is needed to avoid ramp rate effects due to the low inter-strand resistance—up to now there is a very limited, but positive experience [29].
- Radiation resistance: all materials have to withstand an extremely high radiation load—to reach the final target of 3000 $\mathrm{fb^{-1}}$ one has an accumulated dose of 100–150 MGy.
- Length: with 140 mm aperture providing 145 T/m operational field, one needs 8-m-long magnets. $\mathrm{Nb_3Sn}$ dipoles and quadrupoles are all 1-m-long models, only one 3.4-m-long quad has been successfully built and tested, the LQ01 of LARP [27]. All problems related to different thermal contraction of the components and to cable quality become more critical with longer lengths. One option that will be explored is to have two 4-m-long magnets, with some limited losses in performance.

A demonstrator satisfying these issues should be ready for 2015 in order to be able to have a final lay-out of the upgrade.

If the $\mathrm{Nb_3Sn}$ technology were shown not to be viable, a Nb-Ti solution is an acceptable alternative. One has a loss in peak luminosity that can be estimated at about 25%, a less compact triplet, and a smaller energy margin. A 120 mm model with many innovative features to maximize the heat removal is being assembled and test is expected for end of 2011 [30].

C. Separation and Recombination Dipoles

The aperture requirements stemming from the smaller β^* also affect the separation and recombination dipoles. Today the beam are separated by a D1 normal conducting dipole made of six 3.4-m-long modules providing 1.28 T in a 60 mm aperture. The foreseen aperture for the upgrade is of the order of 150 mm; a 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% of 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 given by the very large aperture [31]. For Nb-Ti this would give 6.5 T operational field, i.e., one 4-m-long magnet providing an integrated kick of 26 Tm, which is the present baseline. An interesting option for this range of field-apertures is the $\mathrm{Nb_3Al}$ conductor: its excellent (for an A15 compound) $\mathrm{J_c}$ behavior vs. strain would allow to react first and then to wind the coil, with a direct use of classical Nb-Ti technology for insulation and coil assembly. A 30 mm-thick coil would give 8.5 T with the same 33% margin, which will make it even shorter and with much better heat deposition characteristics ($\mathrm{T_c} \cong 18$ K).

Studies for the recombination dipoles D2 still have to start. This is a double-aperture magnet providing the same integrated field of 26 T m. Here the main challenge is to have a two-in-one structure with large aperture: today we have Nb-Ti magnets with a 10-mm-thick RHIC-like coil of 80 mm aperture. The plan is to keep the same technology and to increase the aperture.

D. Matching Section Quadrupoles

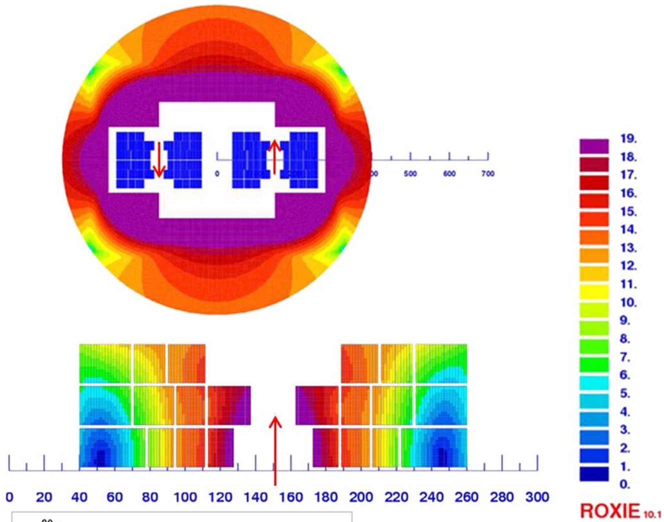
The larger beta functions induced by the smaller β^* propagate along the lattice, requiring larger aperture two-in-one quadrupoles. Today we have 70 mm aperture Nb-Ti quadrupoles (MQY) for the Q4 (i.e., the fourth quadrupole after the IP). Here the new aperture requirements are in the range of 85 mm, at the limit of what is do-able with a 192 mm beam separation. While a design is not yet done, it looks that Nb-Ti technology will be sufficient, integrating the new features to improve the heat transfer mentioned in [30]. The loss in gradient can be compensated by a longer magnet, MQY being only 3.4 m long.

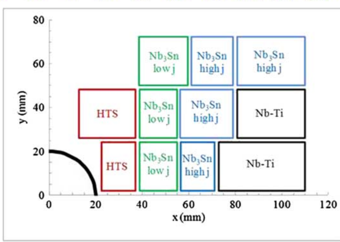
VI. Magnets Concept for the HE-LHC

The possibility of an energy upgrade of the LHC has been already mentioned in 2001 [32] and a few years later a proposal for a LHC tripler based on a 24 T operating field dipole was put forward in 2006 [33], however with a current density of 800 $\mathrm{A/mm^2}$, today not yet achievable. Recently at CERN a study have been carried out [34], [35]: the target field for the main dipoles, the main driver of the entire project, has been set to 20 T operative field in a 40 mm bore, which will enable the *High Energy LHC* (HE-LHC) to reach *33 TeV center-of-mass energy for proton collisions*. A pre-study clearly identified the following critical points:

1) The margin needed is about 20%, measured on the load line, i.e., we need a short sample magnet of 25 T. Lower margin does not guarantee operability of the accelerator. For the LHC it is probable that the 8.33 T nominal field, easily passed by all dipoles in stand-alone test, will not be reached in the accelerator, even after the repair of defective interconnect splice after 2014. Probably it will run at 7.7 T, 20% less than the short sample limit of 9.7 T
2) The overall current density should be around 400 $\mathrm{A/mm^2}$, at the design field, as in all previous accelerator magnets [36]. Lower current density means a too large and expensive magnet, higher current density (if available!) must be diluted to avoid too high stress and too high 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 $\mathrm{J_e}$, must be sensible higher than the overall 400 $\mathrm{A/mm^2}$ in the operating coil.
3) The coil of this magnet is very thick, so it is not worth to push for bore smaller than 40 mm, since it will make integration and alignment very difficult, with no real advantage.

   The inter-aperture distance must be increased form 194 mm of LHC up to 300 mm. This parameter is critical, since it determines the maximum field in the bore. The





	N. turns	%
Nb-Ti	41	27%
Nb_3Sn	85	57%
HTS	24	16%
Total	150	

Fig. 6. Cross section of the 20 T twin dipole for HE-LHC (top); coil expansion with field code (center); expansion of the coil blocks with material indicated (bottom) and table of the fraction of various superconductors.

outer diameter of the iron flux return yoke must not exceed 1 m (compared to 570 mm in the present LHC dipoles) which is not an easy task considering the amount of flux that need to be intercepted.

Based on these constraints and hypothesis, we have worked out a design using Nb-Ti, $\mathrm{Nb_3Sn}$ and HTS, without making any commitment in favor of Bi-2212 round wire or YBCO tape. This superconductor grading is done for cost, of course, but also to make the best use of material: for example $\mathrm{Nb_3Sn}$ suffers from flux jump instability at low field, and HTS critical current is lower at low field. The design, see Fig. 6, is based on coil block, rather than $\cos\vartheta$, a choice that based on stress consideration, too high in $\cos\vartheta$ lay-out for field higher than 13–15 T. However, this magnet typology, that will be used in FRESCA2 (see previous section) and that has been used for the 13.8 T record field, 35 mm bore HD2 short dipole [37], has to rely on flare ends, with bend in the non-easy direction, and must still give its definitive proof. To save coil volume and cost, the $\mathrm{Nb_3Sn}$ part is further subdivided into a high Jc low field subsection and a low J_c, high field one.

In term of design we will investigate the solution of powering the coil sections with different power supplies. This configuration will of course complicate the circuitry and the interconnections, but will buy us a few key advantages:

- It allows separate optimization of conductor for the three materials in a separate. This might be critical especially for HTS, since we assume that Nb-Ti and $\mathrm{Nb_3Sn}$ can be manufactured ion very large cable (15–20 kA), which not at all is granted for HTS.
- Coil segmentation will favor magnet protection, a technique largely employed in the large solenoidal magnets (working at $\sim$1 kA rather than $>$10 kA like accelerator magnets): inductance and stored energy are such that protection by a 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 $\mathrm{Nb_3Sn}$ and in HTS will feature the 5–7 $\mu\mathrm{m}$ filament size developed for the SSC and LHC Nb-Ti. We have to leave with 25–50 $\mu\mathrm{m}$ for $\mathrm{Nb_3Sn}$ and most probably $>$ 50 $\mu\mathrm{m}$ of HTS, with sextuple components coming from persistent current of 50–100 units! Use of passive shims can mitigate but not fully compensate for these big effects. Separate powering, first proposed for SSC [38], and then by P. McIntyre [39], allows compensation for these effects and also for any other dynamic effects due for example to interstrand resistance which will be very difficult to control at cable level. The LHC dipoles circuit is already segmented into eight sectors, tracking each other within 1 ppm: for the HE-LHC we will need to separate the dipoles into 3 $\times$ 8 circuits, something that seems feasible. Of course managing coupling between coils inside the same magnets and among the magnets of the circuits will need deep investigation.

The project has immense challenge, the first one is to make available the necessary superconductors and make of them the needed *conductors*. The total quantity of superconductor is three times the LHC, i.e. about 3000 tons of finished strands (or tapes), about 60% of stabilizer and 40% of superconducting fraction. We believe that in a few years the $\mathrm{Nb_3Sn}$ conductor will be technically available, thanks to the program for HL-LHC, and that Industry with ITER production will acquire the knowledge to master such a large production. The biggest uncertainty concerns the HTS: i) Bi-2212 is very suitable for classic Rutherford cabling, but needs to gain a factor two in critical current density and to overcome the problem of reaction and reliability. In addition the transverse strain sensitivity seems to be a real concerns since the coil will work at 130–150 MPa minimum stress. ii) YBCO is certainly more promising in term of current density and strain tolerance, however its texturing and the consequent anisotropy requires a magnet design aimed at reducing to a minimum the transverse field. In addition the tape shape is not suitable for high compact-high current cable. The future European program EuCARD2 mentioned in the High Field Magnets section will explore both routes, complementing the on going program in the USA. The basic R&D study on HTS for HE-LHC must be carried out in the next 4–5 years since by 2015 a credible design must be available. In case HTS will not meet the very demanding requirements of HE-LHC, closing the door to 16–20 T region, the HE-LHC magnets will be based on Nb-Ti & $\mathrm{Nb_3Sn}$ technology: the goal will be at maximum a 15.5 T operating field, a figure enabling *26 T c.o.m. collision energy*.

VII. CONCLUSION

At CERN a strong Superconducting Magnet program has been launched to seize the opportunity given by upgrades of the LHC. It is based on a consolidated collaboration among different laboratories in Europe, Japan and the US. The goal is to break the wall of 10 T, with the High Luminosity LHC upgrade, to test in operation advanced superconductive technologies under development. Such a step will pave the way to the High Energy upgrade a giant step toward a new frontier for science and technology where superconductivity will play, again, a fundament role.

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