SUPERCONDUCTING MAGNETS FOR A SUPER LHC

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Abstract

Feasibility studies underway for the upgrade of luminosity and energy of the LHC indicate the need for intensifying the R&D on long, accelerator-type magnets that target the highest possible fields. The major technological aspects of such magnets will be presented, together with the expected physical limits, some envisaged solutions and open questions. Ongoing programmes to reach for the maximum practical operational fields will be reviewed. The report will conclude with a tentative analysis of the cost issues related to the use of proposed new materials and technologies.

1 INTRODUCTION

What is a Super LHC? After about 5 years of running at the maximum luminosity achievable with the LHC, it can be foreseen that upgrades will be sought to increase the machine's luminosity, *L*, and energy, *E,* and thereby extend the physics reach. It is therefore proposed to make a staged upgrade of the LHC and its injectors, compatible with established accelerator design criteria and fundamental limitations of hardware. This is aimed initially at a target luminosity of up to 10^{35} $cm^{-2}s^{-1}$ in the two high luminosity experiments, to be followed by an increase in proton beam energy from 7 TeV to approaching 14 TeV. All upgrades beyond baseline LHC performance, including the "ultimate" $L = 2.3\ 10^{34}$ $cm^{-2}s^{-1}$, are considered, the Super LHC (S-LHC) being the final goal. The idea is to proceed by seeking maximum performance in each of 3 main phases:

- Baseline (Phase 0): with no hardware changes
- Phase 1: with hardware changes outside the arcs
- Phase 2: with major hardware changes throughout

A CERN Task Force was set up in July 2001 to study the feasibility of these upgrades, and scenarios were sketched for upgrades of both *L* and *E.* Unsurprisingly, the study revealed the magnet system as being a major limitation [1].

The baseline LHC machine pushes the demands on superconducting technology to the utmost limit that can be obtained from the industry-standard niobium titanium alloy (NbTi). It has taken many years of R&D to get where we are today with this material, and even a relatively modest upgrade of the machine will call for magnets with coils that have to carry heavy currents in the presence of significantly higher magnetic fields. This will require the use of different superconducting materials. All candidate materials are brittle and much more difficult to incorporate into engineered magnet designs than NbTi.

As a direct follow up to the Task Force study, last March a collaboration meeting was held to address the most likely first step in upgrading the machine, namely that of the interaction regions (IR). Replacement of the IR magnets, which represent current state-of-the-art in superconducting magnet technology, with a higher performance design will constitute the major feature of this upgrade [2].

Although the initial completion of the baseline machine is still some years away, it must be understood that the development of the magnets and others systems that will be required, first for an upgraded IR and later for the arcs, will take many years. The purpose of this report is to give an idea of the magnitude and urgency of this enterprise.

2 REQUIREMENTS & CONSTRAINTS

Nominal LHC performance is already very challenging, and is limited be several fundamental effects:

- Dynamic aperture - determined by the quality of the magnetic field and corrector schemes, which limit the emittance at injection, and by the crossing angle
- The single beam intensity - determined by collective and electron cloud effects, cryogenic load, etc.
- Peak luminosity - determined by non-linear interactions
- Luminosity lifetime - determined by transverse blow-up
- Integrated luminosity - determined by operations
- Energy - determined by the maximum bending field

Phase 1. For a luminosity upgrade, scaling laws indicate:

- 1) Reduce β^* (from nominal 0.5 m to 0.25 m, say)
- 2) Increase crossing angle (by a factor of about $\sqrt{2}$)
- 3) Increase protons/bunch up to ultimate intensity $\Rightarrow L = 3.3\ 10^{34}$ $cm^{-2}s^{-1}$ (not beam-beam limited)
- 4) Halve bunch length $\Rightarrow L = 4.7\ 10^{34}$ $cm^{-2}s^{-1}$
- 5) Double number of bunches $\Rightarrow L = 9.4\ 10^{34}$ $cm^{-2}s^{-1}$
- 6) Reduce longitudinal emittance

Note that 1) and 2) require new low-β insertions, 4) requires a higher order harmonic system, and 5) is excluded according to the present understanding of the electron cloud effect. Upgrades in intensity and brilliance are viable options, but require larger crossing angles, implying larger quadrupoles.

Three different layout options are under discussion for the new IRs: (i) to maintain the same basic layout and optics as the existing IRs, but with new quadrupoles; (ii) to reverse the order of beam separation dipoles and inner triplet; and (iii) to reduce the distance from the interaction point (IP) to the first insertion magnet. The first idea is the most straightforward technologically, is minimally disruptive to the matching section, and results in only about a factor 2 increase in β_{max} for 50% reduction in β^*.

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The principal attractions of the "dipoles first" scheme are that long-range beam-beam collisions are reduced by about 50%, the beams pass through the centres of the quadrupoles allowing better correction of field errors, and these can be corrected independently for each beam. Disadvantages are an increase in β_{max} for the same β^* relative to the baseline, a greater number of magnetic elements that must be changed, difficulty in dealing with the power deposited by collision debris in the first dipole, and even more difficult magnets. The short length available for dispersion suppressers and matching sections is a severe constraint that posed problems for the baseline layout. It is therefore likely that the more straightforward upgrade (i) will be applied to Phase 1, while other options may be combined with the second upgrade of the IRs, required to match the energy upgrade of Phase 2.

Phase 2. For the energy upgrade:

- Increase strength (B_{nom}) of all magnets
- Increase cooling power (to absorb heat due to SR)
- Increase injection energy (E_{inj}) (add a ring in the SPS and/or include an injector in the LHC tunnel)

Here we note that the bending radius is a fixed constraint, as the idea is to reuse the LHC tunnel, the local terrain being such as to make a new tunnel prohibitively expensive. Given the recent advances in high-field dipole R&D, the Task Force concluded that a B_{nom} of up to 15 T (+ ~ 2 T margin) may be a viable option within about ten years, provided the necessary preparatory work is done. The injection energy should be increased in order to limit the dynamic range of the collider. This must be limited for two reasons: the required aperture scales as the inverse of the energy (a problem, as aperture is costly), and persistent currents adversely affect low field quality. The dynamic range of the baseline machine (16) is already uncomfortable. In fact an increase in E_{inj} would also yield an increase in luminosity in the machine with the baseline arc magnets, and this could be considered as a useful intermediate step.

At the IP the angular beam size ~ a/d, where $a \sim 6\sigma$ beam envelope and $d = \sqrt{(\beta^*\beta_{max})}$. In order to increase this parameter, we can increase a (larger aperture quadrupoles) and/or decrease d (move quadrupoles closer to the IP). It is expected that with the general rearrangement of the ring (and the experiments) the matching sections and low-β insertions could also be rearranged, reducing the distance (l^*, presently 23 m) from the IP to the first quadrupole (or dipole). This is the classical way to reducing β^*. We should envisage quadrupoles and/or dipoles embedded in the experiment.

Three main categories of magnet will thus be required:

- Large aperture high gradient quadrupoles for Phase 1
- Very low cost medium field magnets for a new injector
- Low cost high performance magnets for Phase 2 lattice

Given the small number of units involved, the magnets of the IR upgrades could employ techniques that should be avoided for magnets that have to be produced in long series.

The cryogenics to accompany these upgrades would appear to be feasible, accepting some basic constraints. The cryogenic distribution line (QRL) is at maximum cross-section in the arc tunnel, so for Phase 1 changes are only possible in the straight sections. Moreover, as beam screens cannot be changed in the arcs, the maximum power that can be extracted is limited (due to the size of the cooling tube), even if the cooling power is increased. To increase the cooling power the possibilities are (i) to add cryoplants for inner triplets at IP1 and IP5, and (ii) to double cryoplants for cooling each half octant. The second option requires space outside the CERN domain to house new equipment.

The 4.6 - 20 K load, 1.7 W/m in nominal conditions, becomes 15 W/m for a luminosity upgrade to 10^{35} cm^{-2}s^{-1}. The pressure in header C will have to be increased from 3 to 6 bar to cope with the beam screen heat load. The QRL can handle this, but due to reduced efficiency the cryoplants would need modifying. Upgrades with bunched beams aiming for $L > 5\ 10^{34}$ cm^{-2}s^{-1}, as well as energy upgrades, will require additional cryoplants at the existing points.

3 A NEW GENERATION OF SUPERCONDUCTING MAGNETS

Why are superconducting magnets for accelerators such a problem? The requirement is have reliable, high quality bending and focusing fields in a long aperture, a. To attain higher energies, field or bending radius has to be increased. For constant radius $E \sim B_{nom}$. The difficulty in making the magnet scales with the Lorentz forces and the stored energy. The forces on the conductors in the windings that provide the magnetic field scale as B_{nom}^2, and the stored energy of the magnet system of length Λ scales as $\Lambda a^2 B_{nom}^2$. Having to work with a fixed radius strongly limits the potential.

The superconducting state is lost if the conductor is warmed above its critical temperature, causing the magnet to quench. If this occurs the stored energy of the system has to be rapidly extracted and/or dissipated uniformly in the system to avoid burn out of the quenching magnet. Quenching will inevitably happen, so there must be a reliable and redundant quench protection system. At liquid helium temperature the specific heat of the conductors is low, and movements of the order of a μm can cause the local temperature to climb to above critical and provoking a quench. This places additional demands on the design of the structure require to support the forces. Another essential attribute is the purity of the field and the uniformity of the magnets throughout the production such that errors that are unavoidable are identified and can be more easily corrected. The magnets must also be cheap to produce, of course…

In the quarter century of application of superconductivity to accelerators, a standard approach to making magnets satisfying these constraints has been established. Flat keystoned cable of superconducting strands is positioned in blocks around a circular bore to approximate a cosine current distribution. The cable is insulated with polyimide film and the coils are pre-stressed azimuthally by applying radial pressure such that they remain in compression at all levels of excitation. Positional accuracy of the conductors is ensured by control of the cable thickness and by the use of collars made of accurately stamped laminations to provide the rigid cavity in which the coils are held. The superconducting strands consist of fine filaments (~6 µm) of niobium titanium alloy (NbTi) in a copper matrix with a volume Cu:SC ratio of about 1.5. To avoid reduction of transport current and field errors due to trapped currents, the cable is fully transposed by twisting the strands and by the subsequent cabling process. The conductor is both strong and ductile, which facilitates the manufacturing process.

Why can't we simply extend this technology to higher fields? The problem is that superconductors only have zero resistance when used below the critical surface in the plot of field and current density against temperature. The critical temperature (T_c) and critical field of NbTi are relatively low, at 10 K and 12 T respectively. It is only by sub-cooling the baseline LHC to 1.9 K, at which temperature the working field can be increased by 3 T with respect to its level at 4.2 K, that NbTi can be used. There is obviously little to be gained by further reductions in temperature.

Fortunately there are other superconductors having better electrical characteristics. These are the A15 compounds and the newer high temperature superconductors (HTS). The most commonly used A15 compound is Nb_3Sn, for which $T_c = 18$ K. This material will carry useful levels of current in fields of up to 17 T. Some other materials, e.g. Nb_3Al and Nb_3Ge have slightly better characteristics, but are more difficult to produce. The HTS materials have very high critical field when used below 25 K, and may become interesting contenders when their current carrying capacity is increased. Unfortunately, when reacted, all these materials are brittle, so that much of the design and manufacturing experience gained on working with NbTi cannot be applied directly. The designers of high field solenoids and Tokamaks face the same problem, but as their constraints are quite different, that experience is only of limited use. In particular we require much higher current density in order to make the magnets compact and affordable on a large scale, and it is also for this reason that the HTS materials need further targeted development before they become competitive candidates for accelerator magnets. The major thrust of current commercial R&D on HTS is for working at 77 K in low magnetic fields, and is only partially applicable.

4 GENERIC STUDIES THAT IMPACT ON THE MAGNET DESIGNS

4.1 *Accelerator physics*

There has been a resurgence of interest in quasi-DC colliders employing superbunches [3,4]. A major benefit of such a mode of operation is that the electron cloud problem disappears. This may impact on magnet design choices.

Studies in the past have shown that there could be some interest in combining the functions of the machine For Phase 2 it would be worth reviewing this option. It would be unwise to decide on the Phase 2 optics before understanding the baseline LHC machine, but conversely, with that understanding one could take advantage of a reduction of the flexibility built into the baseline machine.

4.2 *Radiation issues*

In the baseline case the contact dose rate on the triplet vacuum vessel outer wall will already reach 0.1 mSv/h, and 100 mSv/h in the Q1-2 region. Radiation will definitely be an issue to contend with for any upgrade [5].

In the simplest upgrade case, using 200 T/m 90 mm bore quadrupoles in the triplet, for $L = 2.5\ 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ the peak power deposit due to cascading in the coils is up by a full factor of 2.5, and it may be necessary to close the collimator jaws slightly to allow smaller TAS aperture.

Basic studies have yet to be made on both radiation and collimation for the energy upgrade.

4.3 *Conductor*

High field magnet studies at Fermilab and BNL, as well as at LBNL feature cable being developed in the conductor section of the LBNL high field magnet group [6]. A major effort is being put into the development of strands of Nb_3Sn and BSCCO-2212, and into the cabling of these strands. The present target for Nb_3Sn of 2800 A/mm^2 @ 12 T and 4.2 K has been achieved on samples. An important quality of even the presently available grade of Nb_3Sn is a threefold increase in temperature margin over that of the baseline NbTi. Though at a less advanced stage of development, BSCCO-2212 is also a very promising material for use in magnets operating at up to 20 K, as it can be produced in round wires that can be fully transposed in flat Rutherford cable. The University of Twente, together with SMI, is pursuing the development of powder-in-tube (PIT) Nb_3Sn [7], which holds promise for J_c and small filaments. KEK and NIMS work on Nb_3Al, which could be promising because it is more strain resistant than Nb_3Sn [8].

Magnets using HTS have the potential of achieving very high fields, and HTS may constitute enabling technology for some designs. In addition to their high field capability, temperature margin is much better than any LTS. The best material to date can achieve 2 kA/mm^2 in the SC, out to 20 T @ 4.2 K, in 100 m lengths. If the engineering current density is conservatively based on the ratio Ag:HTS = 3:1, for currently available material (2200/2000 A/mm^2 for Nb_3Sn/HTS) a 12T Nb_3Sn dipole would achieve 5 T if replaced by HTS , but a 18 T Nb_3Sn dipole would achieve 19 T. For quadrupoles, higher gradient requires higher J_c, and a 230 T/m magnet with 90 mm bore cannot be envisaged today. But the material could be an alternative for use in Phase 2. The benefits of HTS for IR magnets are high field capability and temperature margin. A reasonable R&D effort could pave the way to making magnets with sufficiently high performance [9].

4.4 Insulation

Related to placing magnets closer to the IP is the question of electrical insulation. In the baseline design at 10^{34} cm^{-2}s^{-1} a coil replacing the front absorber (TAS) would have to withstand 15 mW/g and 100 MGy – which is only weeks of lifetime for polyimide film. Which insulation would survive? Another question concerns choice of insulation for magnets which are not subjected to such harsh operational conditions but which have to be reacted after winding [10].

4.5 Generic magnet R&D

Studies and tests are being made at LBL to simplify and shorten the complicated heat treatment, and hence improve the efficiency of the wind-and-react (W&R) procedure.

Accelerator magnets based on coils of cosθ geometry are necessarily W&R at present, due to the tight bending radius of the conductor at the coil end. For dipoles, the common coil geometry [9] allows us to consider using simple racetrack coils where the conductor could be reacted before winding. For a single aperture quadrupole magnet, it is also possible to use combinations of simple racetrack coils. These so-called block coils can be disposed to produce good field quality, but are intrinsically less efficient than the cosθ coils and are only viable if HTS conductor (for which the peak field is much less of an issue) can be used.

Common coil dipoles, built using both react-and-wind (R&W) and W&R procedures are being assembled and tested for evaluation. In particular a number of test coils have been wound using pre-reacted Nb_3Sn or HTS conductor to explore winding techniques and the use of different types of insulation, allowing to build up expertise in handling the materials. Recent measurements suggest that degradation can be avoided with both Nb_3Sn and BSCCO-2212 [9]. To be competitive the J_c of the HTS conductor will need to improve by a factor of 3 over what is possible today.

Another line being followed up is that of using thin strands of Nb_3Sn to make a flexible (round) cable that can be more easily made into coils after reaction. Such cables (but of NbTi) have been used at BNL for the slotted helical wiggler magnets for RHIC. If this technique could be extended to high field magnets and HTS it could lead to a breakthrough for R&W.

5 TODAY'S VIEW OF S-LHC MAGNETS

5.1 Magnets for Phase 1 low-beta insertions

An inner triplet using larger Cos2θ quadrupoles is favoured. A conceptual design has been made of a 90 mm aperture quadrupole having the same length and performance as the 70 mm bore magnets in the baseline machine [11]. It uses Nb_3Sn cable of the best quality that can be purchased today in long lengths (2200 A/mm^2 @ 12 T and 4.2 K). The 2-layer R&W coil is designed to give good harmonics. The magnetization effects associated with large filament diameters (~50 μm) are compensated by introducing iron strips on the wedges in the inner layer. To avoid degradation of the brittle Nb_3Sn the magnet is designed with a peak stress of less than 150 MPa. This magnet needs to be manufactured and tested to validate calculations of field quality and quench protection.

5.2 Magnets for a new energy boosting injector

These magnets need to provide about 4.5 T, which could be done using conventional NbTi conductor, or possibly using the recently discovered MgB_2 - which could work at a higher temperature and place less demands on the cryogenics. The challenge for this ring will be to make it cheap and reliable. Besides working at temperatures of up to 20 K, the MgB_2 conductor is potentially very cheap and is a serious contender for this application. It would be interesting to study a MgB_2 magnet with warm iron for this application.

5.3 Magnets for a new main ring

Magnets for the arcs. These must be aimed to provide around 15 T reliably and cheaply. From today's viewpoint the most likely design for these magnets is that of the common coil, based on simple racetrack coils, configured vertically side-by-side and connected to produce equal and opposite dipole fields in the two apertures, superimposed vertically [9]. This geometry should permit R&W construction, and could be based on LTS or HTS conductor. Innovative designs might include using thick, possibly profiled, conductor working at 50-100 kA. Warm iron is attractive, especially considering the small tunnel size.

Magnets for the insertions. In addition to providing performance corresponding to that of the new arc magnets, they will have to be radiation hard. The major advantages of HTS material - higher fields and larger temperature margin - should play in its favour for this application. While HTS technology may not be sufficiently mature for use in the magnets of the Phase 1 upgrade, its has certain potential for use in Phase 2.

6 COST

Recent optimizations for a "Next Hadron Collider" point to a large diameter ring with magnets having a field of less than 11.5 T [12]. The case of the S-LHC is different in that a larger tunnel is not an economic proposition in the local terrain, so we are constrained to use the LHC tunnel. The value of the laboratory infrastructure at the site is however considerably enhanced by its longstanding international dimension, and taking this into account yields a field of perhaps 12.5 T with present assumptions. Advances in conductor performance give ground for hope that higher fields will be achievable for little more investment, and the present ball-park estimate of material cost is $300M for Phase 1, and $3000M for Phase 2. The first figure includes the cost of most of the magnet R&D required for both phases. No credit is taken for associated technology transfer.

7 TECHNOLOGY TRANSFER POTENTIAL

While the primary motivation for the Super-LHC is surely pure Knowledge, Science and Education, the likelihood of useful technology spin-off from the magnet R&D is substantial. A parallel should be drawn between the R&D on NbTi that was stimulated by the European Committee for Future Accelerators (ECFA) in the late 1960s, and performed in the framework of the GESSS collaboration. The outcome of this work was modern NbTi superconductor of fine, twisted, filaments incorporated into stable magnet windings, without which the MRI scanner revolution would not have happened. It is quite possible that learning how to use brittle conductors which work at higher temperatures and fields will lead to similar breakthroughs, particularly when considered in conjunction with the new cryo-coolers.

8 CONCLUSION

It has been accepted from the outset that the LHC high luminosity insertions will be changed a few years after commissioning the baseline machine. One consequence of this assumption is that a design parameter of the present magnets is radiation hardness associated with 5-7 years of normal operation at nominal luminosity. It may be hard to achieve the baseline design luminosity, and the case for an upgrade enabling the reduction of β^* made earlier still.

CERN staff and facilities are taken for the baseline LHC, can only work on upgrades "at the margin". Nevertheless, the appointment of the Task Force last summer underscores a commitment to serious studies of upgrades. The motivational aspects of a credible upgrade programme are very important. We also benefit from collaborations with other laboratories on the baseline machine, and by extending these collaborations to an upgrade programme we can profit directly from high field magnet work being undertaken elsewhere. Work on the VLHC [12] is particularly relevant. Accelerator physics studies of key parameters must of course go hand in hand with the magnet development.

The small cross-section of the LHC tunnel is a major engineering constraint for any upgrade. The space for the long straight sections is also uncomfortably tight (even for the baseline). The most likely route to the luminosity upgrade will therefore be to replace the inner triplets with larger aperture magnets in a similar layout to that of the baseline. The possibility of decreasing the distance l^* from the IP to the first quadrupole should be addressed for the Phase 2 machine, and major changes to the sections matching to the inner triplets are unlikely in Phase 1 of the upgrade.

The cross-section of the cryoline around the arcs cannot be increased, but there is a technical path for a substantial increase in cooling power.

Both luminosity and energy upgrades will require the use of higher performance conductors, all of which present the serious drawback of being very sensitive to strain. The conductors have as yet only marginally sufficient current density. The engineering of magnets using these conductors is also at an early stage, as no model of more than 1 m in length has ever been built. These issues are being addressed in a number of laboratories, some of which are using likely LHC upgrade parameters as a target.

It is necessary to identify sufficient financial resources to carry through these programmes. The problem of how to distribute these resources to make the best use of available expertise in the different laboratories must also be addressed.

Based on the experience of NbTi for accelerator magnets, a major and sustained R&D effort will be required to arrive at being able to mass-produce reliable magnets based on the use of fundamentally different conductor. A start has been made, and the expertise is there - so let's get on with it!

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