PERFORMANCE LIMITS AND IR DESIGN OF A POSSIBLE LHC LUMINOSITY UPGRADE BASED ON NbTi SC MAGNET TECHNOLOGY

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Abstract

We investigate the maximum LHC performance for a standard IR design based on classical NbTi insertion magnets. We include in our analysis a ternary Nb-based ductile alloy such as NbTi(Ta), a less developed but relatively cheap superconducting material which may allow to gain about 1 T in the peak field in the coils, and discuss the corresponding luminosity reach for a possible LHC upgrade compared to that based on Nb_3Sn magnets.

INTRODUCTION

Future LHC IR layouts can be broadly classified into two categories, *i.e.*, 'large bore' triplet quadrupoles (baseline: two beams go through) or 'small bore' triplet quadrupoles providing an independent magnetic channel for each beam. The small bore layout includes large crossing angles, with long superbunches or crab cavities, and the 'dipole-first' option [1]. The corresponding aperture requirements based on beam acceptance are presented in the next section. After discussing several aspects of magnet technology, including a scaling law for the maximum field gradient vs coil aperture, we show that an upgrade of the low-β quadrupoles based on classical NbTi technology may be compatible with $\beta^* = 0.25\,\mathrm{m}$ for a baseline 'large bore' configuration. This option requires individual triplet quadrupoles of optimized length and aperture, and deserves further investigation for the first phase of LHC upgrade or for an intermediate phase, should the need for reducing β^* be felt earlier than it is possible to complete the Nb_3Sn magnet R&D.

MAGNET APERTURE REQUIREMENTS

The aperture of the IR magnets for the baseline 'large bore' scheme must provide enough space for beam envelope ($9\,\sigma$ per beam), beam separation ($7.5\,\sigma$), β-beating (20%), peak orbit excursion (3 mm), mechanical tolerance (1.6 mm), and spurious dispersion orbit d (2.6 mm for nominal LHC conditions). The minimum magnet diameter is

$$D_{\min} > 1.1 \times (7.5 + 2 \times 9) \cdot \sigma + 2 \times (d + 3\,\mathrm{mm} + 1.6\,\mathrm{mm}).$$

The coil diameter has to be about 10 mm larger, to allow for beam screen, cold bore, and adequate coil cooling. The nominal LHC optics configuration with $\beta^* = 0.5\,\mathrm{m}$ corresponds to a maximum beam size $\sigma = 1.54\,\mathrm{mm}$ (at Q2) and the triplet diameter must satisfy $D_{\min} > 58\,\mathrm{mm}$, which is compatible with the current triplet coil aperture of 70 mm. This expression provides only an approximate estimate of the required magnet aperture; note that most of the long range beam-beam interactions occur in the drift space around the IP, where the minimum beam separation is larger than the $7.5\,\sigma$ quoted above (approximately $9.5\,\sigma$).

For a given maximum momentum deviation $\Delta p/p$, the spurious dispersive orbit $d(s)$ depends on the local betatron function $\beta(s)$, and thus on the value β^* at the IP, and on the full crossing angle θ

$$d(s) = (\Delta p/p)\left(0.3 \times 10.4\,\mathrm{m} + \frac{0.04\,\mathrm{mm}}{\theta}\right)\sqrt{\frac{\beta(s)}{4.877\,\mathrm{km}}}.$$

We estimate the local spurious dispersion from the arc dispersion invariant as $2\,\mathrm{m} \times \sqrt{4877/180} \simeq 10.4\,\mathrm{m}$ and assume that about 30% of it will not be corrected. For the nominal r.m.s. momentum spread $\sigma_p \simeq 1.13 \times 10^{-4}$, we obtain

$$(\Delta p/p) \sim 0.5 \times 10^{-3} + 3.2 \times \sigma_p \sim 0.86 \times 10^{-3},$$

including a margin on the momentum deviation to allow for classical dispersion measurements. The results for the baseline 'large bore' option are reported in Table 1.

The 'small bore' option requires a large crossing angle to let each beam pass through an independent quadrupole. The aperture requirements are less severe since the additional $7.5\,\sigma$ beam separation is not needed. Technological constraints impose a minimum inter-axial distance around 45 mm and thus a full crossing angle $\theta \simeq 2\,\mathrm{mrad}$ or possibly less, if we give up some margin for the first quadrupole, which may be conceived as a disposable magnet to be replaced every 1-2 years.

Table 1: 'Large bore' option: LHC beam parameters at 7 TeV and triplet aperture requirements (at Q2) for nominal β^* and baseline luminosity upgrade scenario with reduced β^*. The luminosity refers to nominal 25 ns bunch spacing and to nominal–ultimate LHC beam intensity.

symbol [units]	present IR layout	baseline upgrade
β^* [m]	0.5	0.25
θ_c [μrad]	315	445
$D_{\min}$ [mm]	58.0	79.4
σ [mm]	1.55	2.2
d [mm]	2.6	4.3
σ_z [cm]	7.55	3.78
σ_p [10^{-4}]	1.13	1.60
I_{av} [A]	0.58–0.86	0.58–0.86
L [$10^{34}/\mathrm{cm}^2\,\mathrm{s}$]	1–2.3	2–4.6

Assuming $\theta = 2$ mrad and $\beta^* = 0.25$ m, the spurious dispersion orbit at the first quadrupole is $d \simeq 1.7$ mm and the required quadrupole aperture $D_{\rm min} \simeq 33$ mm for nominal LHC bunch length and momentum spread: this option requires crab cavities to avoid a severe luminosity loss. For the same crossing angle and long super-bunches with $\sigma_p = 5.8 \times 10^{-4}$, the spurious dispersion orbit at the first quadrupole becomes $d \simeq 4.6$ mm and the required aperture is $D_{\rm min} \simeq 39$ mm. The above formulae can also be applied to the dipole-first option to derive the required D1 and D2 apertures of the different configurations.

ASPECTS OF MAGNET TECHNOLOGY

Several aspects of conductor development, magnet design and technology need to be taken into account for an LHC upgrade. The recent developments of Nb_3Sn conductors have shown impressive improvement in the critical current density J_c [2], but the effective filament diameter is too large (more than 100 μm) leading to instability of the wire and/or to large field errors. Material development programs aimed at mitigating this effect are under way both in the USA and in Europe [3]. For an LHC upgrade requiring about 10 t of SC cable, the cost of Nb_3Sn is not a critical issue.

Recently there has been a renewal of interest for SC magnets based on NbTi(Ta), an alloy that has mechanical characteristics similar to classical NbTi and a critical field about 1 T higher at 1.9 K. This material, which has been produced in the past but never commercialized, may be of interest for a project of the size of the LHC upgrade. The above mentioned gain in critical field has not yet been 'transformed' into a corresponding gain of critical current [3], however we assume that such a performance could be reached in the medium term. It should be noted that NbTi(Ta) has the same critical temperature as NbTi and that the temperature margin is essentially identical.

The possibilities in terms of gradient–coil aperture offered by the various superconductors are illustrated by the the scaling law plotted in Fig. 1. In this plot, J_c in NbTi is 5% higher than in the present LHC cable, a reasonable assumption when considering a specific optimization with larger filament size (15-20μm). As noted, NbTi(Ta) still needs to be developed, and Nb_3Sn of very high performance needs to be improved in filament size and to be demonstrated in large quantities.

As concerns magnet technology, important R&D work is under way in several labs, and a small 16 T proof-of-principle magnet has been successfully tested [4]. Clearly, Nb_3Sn-based conductors are the technology of predilection for accelerator magnets beyond 10 T.

The first phase of an LHC upgrade will certainly concern the low-β triplets, and possibly some other magnets in the high-luminosity insertions. Considering the limited extent of machine modifications, the price of magnet construction for this upgrade is a secondary issue. However, the fact that there is no experience with Nb_3Sn-magnets of

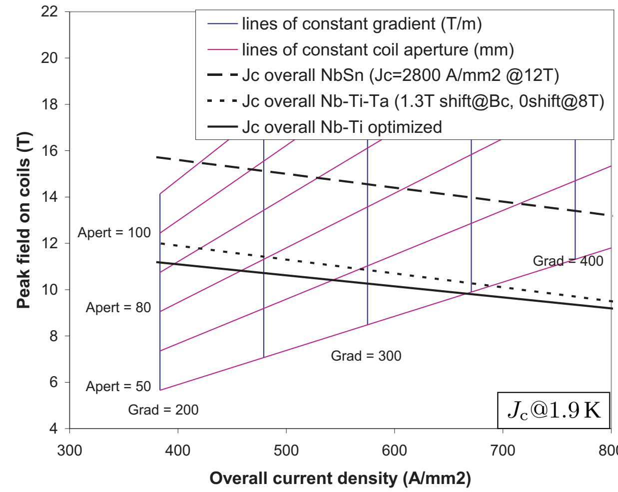

Figure 1: Scaling law for quadrupole design, based on a reference design of 250 T/m with 70 mm coil aperture, giving the maximum field versus the overall current density for an optimized magnet based on NbTi (solid curve), NbTi(Ta) (dotted curve), and Nb_3Sn (dashed curve).

length comparable to the present LHC low-β quadrupoles implies not only technical risk but may also require long and costly development and construction. The cost factor should therefore be considered within the time frame of an upgrade, expected to occur by 2012-2014.

On the other hand, more than a decade-long experience in building LHC magnets has shown that NbTi-based superconducting magnets cooled at 1.9 K is a mature technology, and that high-quality magnets operating in the range of 9 T can be constructed in lengths of the order of 15 m in reasonable time and cost. For these reasons, upgrade options based on proven magnet technology, although inherently less performing, need to be considered should an intermediate upgrade be required.

Thermal stability of the coils

The superconducting magnets closest to the experiments, e.g. the low-β triplets, are exposed to high radiation flux emanating from particle collisions which is directly proportional to the luminosity. As a result, in the case of nominal LHC luminosity of 10^{34} cm^{-2} s^{-1} and at 7 TeV, high local and integral heat depositions of the order of 0.4 mW/g and 5 W/m, respectively, are expected in the coils [7]. The coil design must guarantee that the conductor is efficiently cooled and that heat is extracted without large temperature gradients. These arguments favour superfluid helium cooling, irrespective of the properties of the superconductor.

The temperature margin of the coil depends on the load line of the magnet and properties of the superconductor, while the effective temperature rise in the coil depends on its heat transfer properties. Considerable work has been done in improving the helium porosity of the NbTi cable insulation at 1.9 K while preserving its electrical properties [5], and improvements in heat transfer of a factor of 5 have been achieved between polyimide insulated and epoxy impregnated coils. All high field Nb_3Sn-magnets to-date are fully impregnated. It is therefore reasonable to assume that with respect to NbTi-magnets, the temperature rise in Nb_3Sn coils is higher for a given power density.

For the first generation of LHC low-β quadrupoles a safety margin of about a factor of 3 has been assumed between the calculated peak power density of 0.4 mW/g and the quench limit. Although some improvement is expected in coil insulation [5, 6], in view of the uncertainties we assume that the power density in the magnets for the luminosity upgrade should not exceed the present value by more than a factor 2, retaining the same safety margin of 3. Clearly, experience with the LHC will give the best guideline for the safety margin required.

Coil aperture and heat deposition

Two main criteria need to be considered when defining the coil aperture. The first is based on beam acceptance arguments, described above. The other is the radiation acceptance of the coil. In both cases, the layout of the magnets and their operating field, but also the geometry of the crossing beams at the IP, play a dominant role. While the beam acceptance can be parameterized in terms of the β^*, expected orbit errors, parasitic dispersion, etc., there is no simple relation between the power density in the coils and the operating parameters of the magnets, or of the geometry of the crossing. An estimate of the radiation parameters of the magnets requires extensive simulations [7], based on detailed knowledge of material distribution around the beam from the interaction point to the magnets.

As a general rule, the peak power density scales for a given coil aperture with the length of the magnet and inversely with the field strength; the dependence on the integral field is expected to be weak. On the other hand, the power density grows linearly with the crossing angle, and increases by a factor of two when going from zero to the nominal crossing angle of 300 μrad. On the basis of the available estimates, it is therefore expected that for magnets operating at the limit of radiation acceptance, the choice of the coil aperture is driven more by the power density limit than by the beam acceptance.

BASELINE TRIPLET UPGRADE

We use the current LHC triplet layout and assume that each quadrupole can be individually optimized by chosing an appropriate length and aperture, compatible with the gradient limits of Fig. 1. In addition we assume a reduced distance of 22 m from the IP to the first quadrupole Q1 and a 0.3 m gap between each triplet quadrupole, including the two Q2 magnets; these two assumptions are not essential. In Table 2 we show the resulting quadrupole lengths and apertures for $\beta^* = 0.25$ m compatible with the NbTi gradient limit (93% of the peak field), based on the beam aperture requirements discussed above.

Table 2: 'Large bore' baseline option: triplet quadrupole lengths and apertures for $\beta^* = 0.25$ m compatible with the NbTi gradient limit (lower curve in Fig. 1).

quad	length m	gradient at 7 TeV T/m	coil aperture mm
Q1	6.0	275	53
Q2	7.4	197	85
Q3	7.8	196	82

Assuming the gradient limit for NbTi(Ta) or Nb_3Sn in Fig. 1, the coil diameter is increased by 8 mm or 38 mm, respectively. This corresponds to a minimum β^* value of $\beta^* \simeq 0.2$ m for NbTi(Ta) and $\beta^* \simeq 0.1$ m for Nb_3Sn. In all cases, limitations due to heat deposition are not taken into account and we still assume an r.m.s. momentum spread $\sigma_p = 1.6 \times 10^{-4}$.

CONCLUSIONS

For a baseline IR layout there is certainly room to improve the LHC luminosity performance by a factor of two acting on β^* alone. This can be accomplished by pushing to the limit the NbTi superconductor performance or its derivative NbTi(Ta), while limiting the cost and risk of magnet construction. For a more substantial improvement in luminosity, Nb_3Sn technology presently appears to be the only candidate and could open further upgrade scenarios, such as the 'dipole-first' option. Important issues related to the construction of long magnets with Nb_3Sn need to be addressed by vigorous R&D.

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