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Design Studies for the Low-beta Quadrupoles for the LHC Luminosity Upgrade

Ezio Todesco¹, Herve Allain¹, Giorgio Ambrosio², Franck Borgnolutti³, Francesco Cerutti¹,
Dan Dietderich³, Luigi Esposito¹, Helene Felice³, Paolo Ferracin¹, Gianluca Sabbi³,
Peter Wanderer⁴, Rob Van Weelderen¹

1 CERN, Geneva, Switzerland

2 Fermilab, Batavia, IL, USA

3 Lawrence Berkeley National Laboratory, Berkeley, CA, USA

4 Brookhaven National Laboratory, Upton, NY, USA

In this paper we outline the present status of the design studies for the high luminosity LHC, focusing on the choice of the aperture of the inner triplet quadrupoles. After reviewing some critical aspects of the design as energy deposition, shielding, heat load and protection, we present the main tentative parameters for building a 150 mm aperture Nb₃Sn quadrupole, based on the experience gathered by the LARP program in the past several years.

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Abstract—In this paper we outline the present status of the design studies for the high luminosity LHC, focusing on the choice of the aperture of the inner triplet quadrupoles. After reviewing some critical aspects of the design as energy deposition, shielding, heat load and protection, we present the main tentative parameters for building a 150 mm aperture Nb₃Sn quadrupole, based on the experience gathered by the LARP program in the past several years.

Index Terms— Colliding beam accelerator, superconducting magnets, superconducting materials

I. INTRODUCTION

THE LARGE HADRON COLLIDER (LHC) has been operated at 4 TeV per beam and 70% of nominal luminosity in 2012. After the consolidation of the accelerator, it will provide $\sim 300\text{--}500\text{ fb}^{-1}$ of integrated luminosity at 6.5–7 TeV per beam within 2021. After this date, CERN is planning to have a luminosity upgrade (High Luminosity, or HL-LHC) to get 3000 fb^{-1} in the following 10 years [1]. Part of the upgrade relies on halving the beam sizes in the Interaction Points (IPs), thanks to an improved optics. To reach this ambitious goal one has to double the aperture of the present triplets [2],[3]. The baseline is the Nb₃Sn technology, which allows a more compact layout and $\sim 30\%$ higher performance. This technology applied to the high luminosity LHC has been studied during the past several years by the LARP collaboration [4]. First studies focused on a 1-m-long 90-mm-aperture quadrupole (TQ) [5]. The quest for performance has pushed to larger apertures, and a series of 120-mm-aperture model has been developed (HQ) [6]. At the same time, the TQ short model has been scaled up to 3.4 m (LQ) to explore for the first time the challenges related to long Nb₃Sn magnets [7]. In 2011, a design study has been launched to prepare a technical design report of the upgraded LHC layout by 2015. The initial part of the study has been focused on the selection of the triplet aperture. This decision also affects the aperture of other magnets to be replaced in the LHC such as separation/recombination dipoles, and large aperture two-in-one quadrupole Q4. Here we review the main

challenges for the superconducting technology applied to this project, and the solutions envisaged to cope with them.

II. LAYOUTS

The aperture is one of the key parameters of the inner triplet (denoted by Q1, Q2 and Q3) of quadrupoles. In the LHC baseline [2],[3] a ‘symmetric’ layout is adopted, with Q1 and Q3 of equal lengths, and Q2 about twice in length as Q1. The same layout is kept for the upgrade, with longer magnets. The aperture of the baseline is 70 mm, and since the target of the HL-LHC project is to halve the beam size in the IP, one has to roughly double the magnet aperture to ~ 140 mm. This was the starting point of our analysis, where we considered two 140-mm-aperture lay-outs, the first one with the Nb₃Sn technology (MQXF) and a back-up with Nb-Ti (MQXD). Both cases are a scaling of existing 120-mm-aperture short models, one in Nb₃Sn (HQ, a 0.8-m-long model built by LARP and tested in several versions [6]), and one in Nb-Ti (MQXC, 1.8-m-long model built at CERN and recently tested [8]). Since HQ and MQXC are in an advanced stage of development, and present many of the technological features needed for this application, we also considered two lay-outs based on this aperture.

We assumed a Nb₃Sn current density of 1400 A/mm^2 at 15 T and 4.2 K (without self-field correction), stepping back by $\sim 20\%$ from the highest level reached in the US conductor program. For the gradient we assumed a $\sim 20\%$ margin on the loadline (see Table I). For the 140 mm Nb₃Sn version we use the HQ strand but we increase the number of strand from 35 to 40, to compensate for the aperture increase from 120 to 140 mm. A larger cable allows higher gradient (for a fixed margin), and lower current density. Lower current density means lower stress and easier protection – which are two critical aspects for HQ, as we will see in the next section.

For the Nb-Ti back-ups we use the LHC dipole cable. Among these four layouts, analysis efforts have been focused on the most promising option in terms of performance, i.e., the 140 mm aperture Nb₃Sn quadrupole MQXF.

TABLE I
GRADIENTS, LENGTHS, APERTURES AND MATERIALS OF THE FOUR OPTIONS

Technology		Nb-Ti	Nb-Ti	Nb3Sn	Nb3Sn
Aperture	(mm)	140	120	140	120
Name		MQXD	MQXC	MQXF	MQXE
Gradient	(T/m)	100	118	150	170
Q1-Q3 length	(m)	10.6	9.5	7.7	7.2
Q2 length	(m)	8.7	8.0	6.6	6.2
Total length	(m)	38.6	34.9	28.5	26.8
Current	(kA)	12.5	12.9	15.4	14.7
Triplet differential inductance	(mH)	225	167	251	190
Triplet stored energy	(MJ)	19.4	14.4	34.8	26.4

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E. Todesco, Herve Allain, Francesco Cerutti, Luigi Salvatore Esposito, Paolo Ferracin, Rob Van Weelderen are with CERN, CH-1211 Geneva e-mail: ezio.todesco@cern.ch.

Giorgio Ambrosio is with Fermilab, Batavia, IL

Franck Borgnolutti, Dan Dietrich, Helene Felice, Gianluca Sabbi, are with Lawrence Berkeley National Berkeley Laboratory, Berkeley, CA

Peter Wanderer is with Brookhaven national Laboratory, Upton, NY

III. THE Nb₃Sn 140 MM APERTURE CASE

A. Challenges stemming from energy deposition

The HL-LHC challenging target of 3000 fb⁻¹ integrated luminosity should be achieved with a peak luminosity of 5×10^{34} cm⁻² s⁻¹, i.e., five times higher than the nominal LHC. The high peak luminosity induces an intense shower of debris from the IP on the magnet coils, producing high heat loads and radiation damage in the magnet components. Appropriate shielding is therefore required to bring coil heating and radiation damage within targets. Shielding can be effective, but takes space. An estimate of the heat load and of the radiation damage is essential to select the shielding materials and to design the magnet coil and structure.

Previous quench limits assumed in the literature for Nb₃Sn are 12 mW/cm³ power deposition in continuous regime (embedding a safety factor of 3) [9]. For the peak radiation dose we set a tentative target at 50 MGy. This is a rather challenging value, since this dose can damage many resins and insulation materials. This is a starting point for our analysis, and could be further lowered to 20 MGy.

First FLUKA [10],[11] simulations for the MQXF case included only the structural element of a stainless steel beam tube, 3.7 mm thick, needed to contain the helium and to resist to pressure increase during a quench. In this case, the peak power on the coil (averaged over the radial cable thickness) is 20 mW/cm³, whereas the peak dose exceeds 300 MGy (see Fig. 1). Both levels are well beyond the target values.

Fig. 1. Peak dose/power profile along the triplet, averaged over a 3 mm thickness in the innermost layer of the coil: case with 3.7 mm cold bore (black circles) and with additional 2 mm beam screen plus 6 mm W inserts (red triangles). When averaging over the whole radial thickness of the cable, as relevant for quench risk evaluation purposes, the maximum power deposition turns out to be roughly halved. Power is normalized to 5×10^{34} cm⁻² s⁻¹ instantaneous luminosity and dose to 3000 fb⁻¹ integrated luminosity, assuming 85 mb proton-proton cross section (including inelastic and diffractive processes).

The distribution of power density has a strong dependence on the angle, see Fig. 2, since it is driven by the magnetic field of the quadrupoles and by the crossing angle [9],[12]. Therefore one has to shield mainly along the horizontal and vertical axes. A proposal of shielding, based on the concepts developed for the phase-I project [13], is shown in Fig. 3: within the beam tube one has a beam screen holding four 6-mm-thick tungsten absorbers placed at midplanes. With this shielding, the peak dose is reduced below 60 MGy. The

corresponding value for the peak heat load on the coil is 4 mW/cm³. These values can be considered as a good starting point for our optimization.

Further performance margin can be obtained by using a thicker shielding in the initial part of the triplet (Q1 and in first half of Q2, where the load is larger) since the beam is smaller and aperture requirements are less stringent.

Fig. 2. Angular distribution of dose (averaged over a 3 mm thickness in the innermost layer of the coil) at the Q1 end longitudinal maximum, case with shielding (see Fig. 1).

Fig. 3. Magnet coils, poles, cold bore, and beam screen with W absorbers.

B. Coil components and radiation damage

A dose of few ten MGy can seriously affect some critical components of the magnet. While the superconductor itself is not expected to degrade at these dose levels [14], the most critical aspect is the epoxy used to impregnate the Nb₃Sn coils, coupled with the cable insulation. The dose limits for the system that is currently being used in Nb₃Sn model (CT101) should be characterized. Alternative resins as cyanate ester, used in ITER [15], show improved radiation resistance by about one order of magnitude and could be incorporated if CT101 does not provide adequate margin with respect to the expected radiation levels.

C. Coil design and heat loads

With an operating point at 80% margin of the conductor limit calculated along the loadline, the superconductor has a 4.8 K temperature margin. Using the heat load estimated for the shielding conditions shown in Fig. 3, one can compute the temperature in the coil in the stationary regime. This temperature profile depends on two aspects: the conduction properties of the impregnated Nb₃Sn coil, and the heat removal in the structure around the coil, which must be as permeable as possible, but able to keep electrical and

mechanical integrity. Most of the heat is removed through the annulus of helium, whose thickness has been dimensioned to 1.5 mm, between the cold bore and the coil (see Fig. 3, in yellow).

Assuming a completely permeable structure (i.e., the coil under the shower of debris in a bath of helium), the highest temperature in the coil is 2.25 K, i.e. 0.35 K larger than operational. On the other hand, using the present tentative structure, scaled from HQ, the peak temperature in the coil is 3.2 K, i.e. 1.3 K larger than operational (see Fig. 4). To further reduce this value, the following steps to improve the permeability of the structure can be envisaged: (i) remove the inner layer heaters, that block the heat transfer from the coil to the annulus of helium (ii) provide cooling channels covering about 4% of the coil pole surface to allow heat to reach the heat exchangers through collar laminations. With these steps, one can bring the peak coil temperature down to 2.4 K, i.e., 0.5 K warmer than the He bath: this is a good starting point for our design. The temperature margin is around 5 K, and we ask for the cooling transport to reduce it by not more than $\sim 10\%$. Further analysis will focus on the comparison between the temperature margin provided by the superconductor in each part of the coil with the temperature maps under heat load. The openings in the coil pole are new features that need to be developed and incorporated in the design of the models.

Fig. 4. Temperature in the magnet coils under the heat load from IP for HQ

D. Quench protection

Protection is another critical aspect. The total inductance of the triplet is of the order of 150 to 250 mH (see Table 1), depending on the powering scheme of the individual magnets (independently or in series). With currents of the order of 15 kA a dump resistor cannot be larger than 50 m Ω in order to limit the voltage, and time constants of the circuit - in absence of significant resistance of the magnet - range from 3 to 5 s. This means that (i) quench heaters have to be used to increase the resistance of the circuit, speed up the current decay and dissipate the energy in a larger coil volume, and (ii) the fraction of stored energy dissipated in the dump resistor is negligible (a dump resistor could be needed anyway to protect the busbars).

The protection strategy for LARP models was based on

dump resistor and quench heaters. The design included also inner layer quench heaters, (i.e., between the coil and the beam tube). This approach poses two main issues: the heaters constitute a barrier to heat flow, and since they are not supported on the inner side, they can detach with the thermal strains induced by quench and consequently lose their efficiency.

For these reasons, a special campaign of protection studies has been carried out on HQ to check the possibility of protection without dump resistor and without inner layer quench heaters (see [16] for more details). The results indicate that protection without inner layer heater and without dump resistor may be viable, but bringing the hot spot temperature at ~ 300 K. The conclusion is that protection parameters should not be made worse than in HQ, and possibly improved.

Additional margin for protection can be obtained by using more superconductor, roughly scaling the coil width with the aperture. A second option would be to increase the Cu/non-Cu ratio, but this affects the wire design and reduces gradient, and therefore the performance, so we keep it as back-up.

In Fig. 5 we give an outlook of the energy density in the strand and strand current density in some Nb₃Sn and Nb-Ti magnets. The first quantity is defined as the total stored energy in the magnet divided by the volume of the strand. An upper limit for the energy density is 0.5-0.6 J/mm³, which would bring locally each strand to room temperature, in the adiabatic approximation. We see that Nb₃Sn magnets have an energy density ranging between 0.10 and 0.15 J/mm³, well below this limit, but already twice what is usually found in Nb-Ti magnets. In the case of the MQXF we obtain a 140 mm aperture quadrupole with 150 T/m operational gradient and similar energy density in the strand of ~ 0.14 MJ/m³, but we lower the current density in the strand from 900 to 770 A/mm². This is done thanks to the larger strand diameter and to the larger number of strands per cable. One can see that w.r.t. other Nb₃Sn magnets, we are moving away from a dangerous zone of high current densities. This is a critical parameter since one can prove that the margin for protecting long magnets scales at first order with the inverse of the square of the current density [17].

Fig. 5. Current density versus operational peak field in the coil in Nb-Ti (dots) and Nb₃Sn (triangles) quadrupoles. Two markers are shown for MB and MQXC since they use a graded coil, with two different current densities.

IV. THE 150 MM APERTURE CHOICE

The analysis carried out in the previous sections shows that a ~10-mm-thick shielding (including beam screen, cold bore, and tungsten absorbers) is needed to protect the quadrupoles from the radiation damage, and that protection is critical for the HQ, but larger apertures are still feasible, provided that the coil width is correspondingly increased. Keeping this into account, a proposal to fix the quadrupole aperture to 150 mm was accepted in June 2012.

To create additional margin for protection, we propose to increase the strand diameter from the values used in previous LARP models, ranging between 0.7 and 0.8 mm, to 0.85 mm. A cable with 40 strands of 0.85 mm results in a bare width of the order of 18 mm. Compared to HQ, the aperture/cable width is approximately maintained, i.e. we have an homothetic rescaling (see Table II).

The cable will have a core to reduce the large ramp rate effects which have been observed in previous LARP models [18], and in the 11 T program [19]. Even though targets for field quality at injection are rather loose, dynamic effects resulting from eddy currents can be problematic for operation [6],[16]. In addition, the conductor needs to be optimized to limit flux jumps which can affect stability and protection [7].

LARP experience also showed that a more robust insulation system is required. Planned improvements include insulating coatings on metallic parts, additional layers of ground insulation and an increase of the cable insulation thickness from 0.1 to 0.15 mm to have a larger margin in the electrical integrity. Assuming conductor performance parameters typical of previous LARP models, and operation at the 80% level on the loadline, a design gradient of 140 T/m can be selected. One can see that even though the stored energy per meter is nearly doubled w.r.t. HQ, the energy density in the strand increases by 10% only, and the overall current density is reduced by 16% (see Fig. 5 and Table II).

TABLE II
MQXF 150 MM APERTURE DESIGN COMPARED TO 140 MM AND HQ

		HQ	MQXF_140	MQXF_150
Aperture	(mm)	120	140	150
Strand diameter	(mm)	0.778	0.800	0.850
# strands	(adim)	35	40	40
Insulation thickness	(mm)	0.10	0.10	0.15
Cable width	(mm)	15.150	17.314	18.273
Cable thickness inner	(mm)	1.338	1.338	1.396
Cable thickness outer	(mm)	1.536	1.536	1.604
Turns	(adim)	20+26	23+29	23+28
Gradient	(T/m)	170	150	140
Margin on loadline	%	18	20	20
Stored energy	(MJ/m)	0.85	1.22	1.41
Current	(kA)	15	15.4	16.7
Overall current density	(A/mm ²)	593	539	501
Energy density in the strand	(J/mm ³)	0.139	0.146	0.152
Midplane stress	(MPa)	95-122	103-130	113-122

The guidelines of the coil cross- section design are to follow the basic layout of HQ, which was optimized for stress distribution among layers and field quality. This is why the

first drafts for the coil lay-out have four blocks (see Fig. 6, left), with two layers having similar angles as HQ. We consider a thick midplane shim of 0.25 mm (from midplane to first insulated cable) to allow fine tuning of field quality.

The stress due to electromagnetic forces is at the same level of HQ. The structure is based on the bladder and key concept (see Fig. 7, right), with a 25-mm-thick aluminum shell. Alignment is given by spacers that proved to provide a good field quality in the HQ. Three additional features are:

- 80-mm-diameter holes for heat exchanger in the iron;
- Tiny holes in the pole to leave about 4% of space for helium transfer towards the heat exchanger;
- The quadrupole cold mass size has been increased from the current value of 570 mm to 630 mm for mechanical support, and to reduce fringe fields.

Fig. 6. A tentative cross-section of the 150 mm aperture MQXF

V. CONCLUSION

We described the status of the design study for the inner triplet large aperture quadrupoles needed for the LHC luminosity upgrade. The Nb₃Sn technology is considered as the baseline, allowing a better performance. Many of the issues related to the design and construction of these magnets have been addressed by the US-LARP. The main features that need further development derive from the strong radiation load coming from the collision debris of the LHC. A thick shielding is needed, and materials should target to withstand a dose of the order of few ten MGy. This may result in a need to replace the epoxy impregnation and insulation with materials having better properties. The thick shielding is the main motivation to go to a 150 mm aperture to preserve performance. Moreover, the coil and the structure should also be designed to allow an efficient heat removal, to limit the temperature increase in the coil w.r.t. helium bath of a few tenths of kelvin degree.

Previous experience on LARP quadrupoles shows that the quench protection is marginal for the case of long magnets as needed in the LHC. The design of the 150 mm quadrupole relies on a larger quantity of superconductor to increase the margin for protection. A cored cable will also be needed to minimize the ramp rate effects.

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