ENERGY DEPOSITION PATTERNS IN THE LHC INNER TRIPLET AND THEIR IMPACT ON THE PHASE II LUMINOSITY UPGRADE

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Abstract

Recent studies show that the energy deposition for the LHC Phase I luminosity upgrade, aiming at a peak luminosity 2.5×10^{34} $cm^{-2}s^{-1}$, can be handled by appropriate shielding. The Phase II upgrade aims at a further increase of peak luminosity by a factor 4, possibly using Nb_3Sn quadrupoles. This paper describes how the main features of the triplet layout, such as quadrupole lengths, gaps between magnets, and aperture, affect the energy deposition in the insertion. We demonstrate how the energy deposition patterns depend on the triplet layout. An additional variable which is taken into account is the choice of conductor, i.e. solutions with Nb-Ti and Nb_3Sn are compared. Nb_3Sn technology gives possibilities for increasing the magnet apertures and space for new shielding solutions. Our studies give an indication on the possibility of managing energy deposition for the Phase II upgrade.

MOTIVATION

The present lay-out of the magnets around the interaction regions of the Large Hadron Collider [1] consists of a triplet of quadrupoles followed by a separation dipole. These quadrupoles are needed to squeeze the beam in the interaction point down to β^*=0.55 m. Proposals for reaching a higher luminosity rely on increasing the beam current and/or the focusing in the interaction point [2,3].

The increased focusing relies on the optics, i.e., further decreasing β^* from the nominal values of 0.55 m to 0.25 m, or less if possible. The triplet aperture of 70 mm does not allow a further squeeze since the beam would become too large in the triplet.

A further squeeze of β^* with respect to the nominal value requires a larger aperture, that scales with the inverse of the square root of β^*, plus an offset due to tolerances. On the other hand, the quadrupole gradient is independent of β^*, since it is determined only by the distance of the triplet from the IP and by its length. There is a way to reach the further squeeze without a change of technology (for instance, still using Nb-Ti in the quadrupole coils) by making the triplet longer: a longer triplet requires a lower gradient and the lower gradient enables larger apertures. It is true that the beta function in the triplet increases with the triplet length, but the gain in aperture largely wins over the resulting increase in the beam size. Therefore, with Nb-Ti one can build an optics reaching arbitrarily small β^* with very long triplets [4]. The limitation of having a stronger and stronger focusing then comes from the correction of the linear chromaticity, which is proportional to the maximum beta function in the triplet, to its length, and to the gradient.

The LHC upgrade is split in two phases, the first, "Phase I", relying on the Nb-Ti technology, to increase the luminosity by a factor 2.5, value used in our studies, with respect to nominal luminosity. Part of this increase is due to a further squeeze of the beam from $\beta^* \sim 0.55$ m to $\beta^* \sim 0.30$ m. The present lay-out of Phase I, with 120 mm aperture quadrupoles, is pretty close to the limit of Nb-Ti technology as minimal β^* [5,6].

A second phase, "Phase II", aims at reaching 10^{35} cm^{-2} s^{-1} [1-3]. The Nb_3Sn technology offers two advantages: first, the larger material performance in terms of peak field can be translated to larger and stronger magnets: the ultimate limit to squeeze is about $\beta^* \sim 0.15$ m [2,4], i.e., a factor two w.r.t. the present phase I. Second, it can tolerate a factor three larger heat deposition [7].

The above considerations lead us to explore, during the phase one upgrade work, the dependence on the energy deposition of the triplet length and aperture for Nb-Ti quadrupoles [8]. In this paper we extend this study to the case of Nb_3Sn. Previous works showed that the patterns of the energy deposition versus the longitudinal coordinate are far from being uniform, the peaks being very sharp, and determining the need for shielding [9]. Here, we try to better understand the influence of the gaps-lengths between magnets on the peak energy deposition.

INTERACTION REGION LAYOUTS FOR PHASE I AND PHASE II

The parametric exploration has been instrumental for the conceptual design of the phase one upgrade of LHC. The combination of quadrupole lengths and gradients making it possible to design optics that can be matched to the LHC arcs is listed in Table I. Phase I is with Nb-Ti conductor, and Phase II with Nb_3Sn.

Table 1: Main Parameters For The Analysed Triplet Layouts

Aperture (mm) Phase I	Aperture (mm) Phase II	Gradient (T/m)	L(Q1,Q3) (m)	L(Q2a,b) (m)	Length (m)
90	130	156	8.69	7.46	36.2
115	166	124	9.98	8.42	40.7
130	186	111	10.81	9.04	43.6
140	200	102	11.41	9.49	45.7

A 20% operational margin has been considered in all cases. This corresponds to a temperature margin at 1.9 K of about ~2 K for Nb-Ti and of ~5 K for Nb_3Sn. A typical cross-section of a quadrupole is shown in Fig. 1.

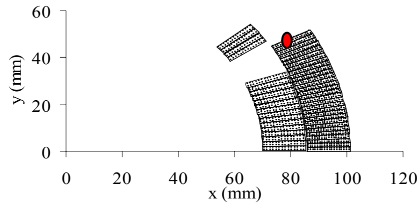

Figure 1: A possible cross-section of the 140 mm aperture quadrupole. The red dot indicates the spot where the coil reaches the short sample limit.

As we have pointed out in the introduction, Nb_3Sn allows to have larger apertures or more compact triplets, and to reach a β^* of 0.15 m (ultimate limit due to the correction of linear chromaticity). Moreover, the larger temperature margin of Nb_3Sn gives a factor three larger quench limit in energy deposition: 12.3 mW/cm^3 for Nb_3Sn to be compared with 4.3 mW/cm^3 for Nb-Ti [7]. Both values include a factor 3 of safety, to take into account errors in the simulations of energy deposition, coming from modelling and statistical errors.

This increase in quench limit for Nb_3Sn is nearly enough to compensate the increase of luminosity of a factor four from “Phase I” to “Phase II”. Indeed, previous papers [9] show that the Phase II luminosity could be tolerated with appropriate shielding. However, the impact of different triplet geometry (lengths, aperture, and gradient) has to be carefully analysed.

To see the influence of larger apertures on energy deposition in the magnets and on the load on the cryogenic system, we consider the same symmetric lay-outs as analysed for Phase I, i.e. the same gradients and lengths, see Table 1 and Ref. [8]. Assuming the present performance of high current density cables (3000 A/mm^2 at 12 T and 4.2 K), one can build Nb_3Sn quadrupoles with a ~50% larger aperture and with the same operational gradient w.r.t Nb-Ti. Also in this case, we assume a 20% operational margin, i.e., the magnets work at 80% of the loadline.

We have included a cold bore tube and a beam screen (BS) of minimum dimensions that are mechanically acceptable for the different apertures [8]. The half crossing angle at the interaction point is 220 μrad in this study. Since the energy deposition has large peaks along the magnet axis, which are always close to the magnet ends (see Fig. 2) we first study the dependence of energy deposition on the gaps between magnets.

GAPS BETWEEN MAGNETS

We compare the case with gaps between magnets of 1.3 m and the hypothetical case where we have no gaps. For the case without gaps, the lengths of the quadrupoles are slightly increased: the length of Q1 and Q3 is 11.15 m and the two Q2 magnets are 9.59 m long. The luminosity is 2.5×10^{34} cm^{-2} s^{-1}, and the cable properties the same.

The simulations by FLUKA [10,11] show that the pattern of peak power deposition becomes continuous for the case without gaps, and that the peaks at the beginning of Q2, Q3 and Q4 are due to the presence of gaps (see Fig. 2). Avoiding the gaps, the largest peak is reduced by 30%! We conclude that either the gaps between magnets should be made as small as possible, or a shielding of the interconnection should be considered. Both options allow avoiding the build up of these sharp local maxima.

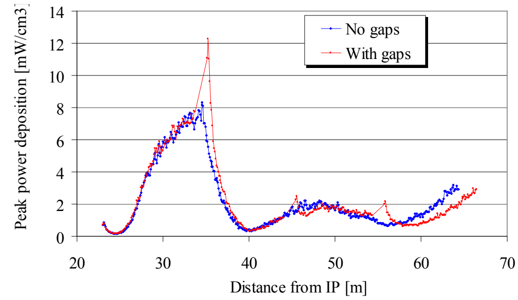

Figure 2: Peak power deposition in the coil: lay-out with gaps and lay-out without gaps, 130 mm aperture.

DEPENDENCE ON APERTURE

We first assume the luminosity 2.5×10^{34} cm^{-2} s^{-1} and the same cable composition; we consider only the change in the triplet geometry between “Phase I” and “Phase II”. This is done to explore the influence of larger apertures on energy deposition. Results are shown in Fig. 3 for the more compact case, and in Fig. 4 for the longer one. One observes that in both cases ~50% larger apertures, obtainable with Nb_3Sn, for the same triplet lay-out, reduce the peak energy deposition by about 1/3 on the first and the second quadrupole. No significant improvement is observed on Q2 and Q3, which are anyway not critical.

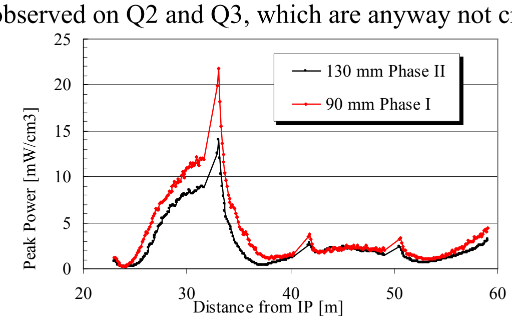

Figure 3: Peak power deposition in the coil for the 36 m long triplet, the case with a 90 mm Nb-Ti quad, and the case with 130 mm Nb_3Sn quad, both cases without shielding for a peak luminosity of 2.5×10^{34} cm^{-2} s^{-1}.

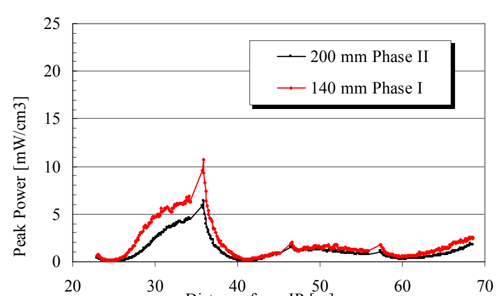

Figure 4: Peak power deposition in the coil for the 46 m long triplet, the case with a 140 mm Nb-Ti quad, and the case with 200 mm Nb_3Sn quad, both cases without shielding for a peak luminosity of 2.5×10^{34} cm^{-2} s^{-1}.

Fig. 5 displays the total heat load in all cold masses and the total load on the beam screen for the case with small apertures (Phase I layout) and with larger apertures (Phase II layout). The decrease of the total heat load, if larger apertures are chosen, is ~10 % for the cold mass and 50% for the beam screen: a larger aperture for the same layout and fields is beneficial to protect the magnet from the impact of the debris.

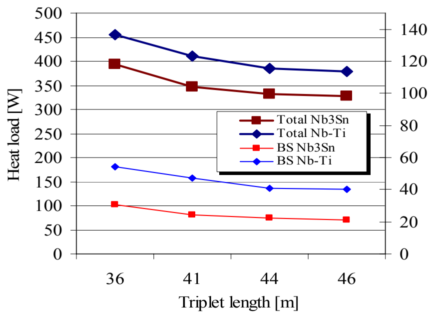

Figure 5: Total heat load on magnets, separating the contribution on the cold mass from the contribution on the beam screen, comparison between Nb-Ti and Nb_3Sn layouts.

We now scale the data from the large aperture layouts to the Phase II luminosity of 10^{35} cm^{-2} s^{-1} and take into account the composition of the Nb_3Sn cable, by density scaling on the coils (18%, including He in the cable that was not included in the simulations discussed above). The results for the peak power deposition for the four lay-outs are shown in Fig. 6. Considering a limit for Nb_3Sn of 12 mW/cm^3, we can see that shielding is needed in the two quadrupoles close to the interaction point, but that the values appear to be manageable.

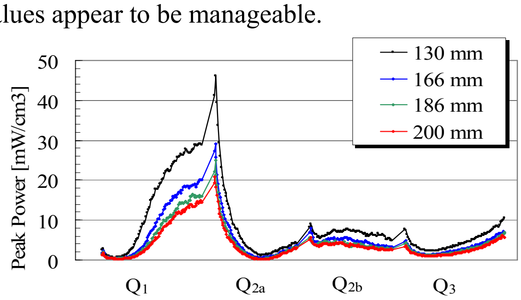

Figure 6: Peak power deposition in the coil for the four analysed lay-outs (Nb_3Sn) for the luminosity 10^{35} cm^{-2} s^{-1}, triplet length scaled to be the same for all layouts.

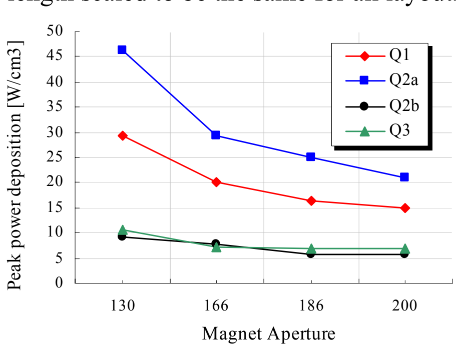

Figure 7: Maximum of the peak power deposition in the coil versus triplet aperture in Q1, Q2a, Q2b and Q3.

The maximum of the peak power deposition is shown in Fig. 7 and the total heat loads in Fig. 8. The deposited energy decreases with increasing lengths in a similar way as for the case with smaller apertures [8].

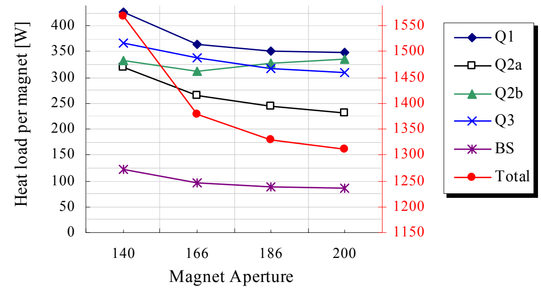

Figure 8: Heat load versus triplet aperture in Q1, Q2a, Q2b and Q3, beam screen and total load on magnets without beam screen.

CONCLUSION

Nb_3Sn tolerates a factor 3 larger energy deposition compared to NbTi. Using this technology for Phase II and a lay-out having larger apertures, giving an additional 30% reduction on the critical magnets, gives in total a factor 4 which is the increase of peak luminosity expected from phase I to phase II. For these reasons, we conclude that similar shielding as used in phase I should be considered. The interest of larger apertures is also that thicker liners could be inserted to further protect the magnets and give a possibility to insert thicker beam screens to take up the heat load at a higher temperature and giving increased coil protection.

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