



**PARAMETRIC STUDY OF ENERGY DEPOSITION
IN THE LHC INNER TRIPLET FOR THE PHASE 1 UPGRADE**

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Abstract

To be able to make a global parametric analysis and to have some basic understanding of the influence of critical parameters, scaling laws may be of help. For the design of the LHC insertion regions triplets, among the critical parameters the energy deposited in the superconducting triplet plays a fundamental role in avoiding magnet quench, too heavy load on the cryogenic system, and degradation of the materials due to radiation. The influence on energy deposition of the lay-out key parameters, such as the magnet apertures, the magnet lengths and positions, has been studied for $\beta^* = 0.25$ m.

INTRODUCTION

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 (see Fig. 1). These quadrupoles are needed to squeeze the beam in the interaction point down to $\beta^* = 0.55$ m. Proposals for reaching a higher luminosity rely on increasing the beam current and/or the focusing in the interaction point [2,3]. Unfortunately, the triplet aperture of 70 mm does not allow a further squeeze since the beam would become too large in the triplet.

ATLAS

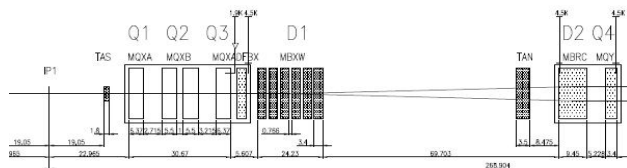


Figure 1: Lay-out of the LHC insertion region

The present quadrupoles, built as a special contribution of US and Japan, provide a gradient of 215 T/m at the nominal collision energy of 7 TeV [4]. Their coil lay-outs are optimized to provide the largest possible aperture for that nominal gradient using a Nb-Ti cable. A larger aperture providing the same gradient can be obtained only by a change of superconductor, i.e. using a material tolerating a larger peak field, such as Nb₃Sn [5]. On the other hand, making a longer triplet one can decrease the gradient, and providing a larger aperture and a smaller β^* using the same superconductor cable [6,7,8,9]. The drawback of the triplet lengthening is a larger β function in the triplet, and a larger chromaticity. The linear chromaticity correction sets today an ultimate limit to the smallest β^* that can be achieved with a Nb-Ti triplet, which is ~ 0.19 m [8,9].

A longer and larger triplet also affects the energy deposition in the magnets due to the debris coming from the interaction point. It has been shown that an appropriate shielding can considerably reduce the energy deposited in the superconducting coils [10,11]. Indeed, it is important to understand how a longer and larger triplet, made of magnets fully exploiting the performances of the same superconductor, affects the peak energy deposition in the coil and in the total load for the cryogenics. Previous parametric studies on the LHC interaction region analysed the impact of a rigid shift of the triplet structure towards the IP to find out the dependence of energy deposition on the distance to the IP [12]. Here we fix the distance to the IP and we explore four lay-outs with increasing length and aperture, compatible with a full exploitation of the Nb-Ti cable. Increasing the length implies also a change in the ratio of the magnet lengths to be able to match the optics requirements.

This parametric exploration of the phase space aims at understanding whether the energy deposition sets limits to longer and larger triplets. This information can be relevant for the conceptual design of the phase I upgrade, which aims at gaining up to a factor 2.5 in luminosity using a larger triplet based on Nb-Ti coils [11].

INTERACTION REGION LAY-OUTS

The parameter space of the triplet has several dimensions, namely the type of triplet, its aperture, its lengths, and its gradients. We keep the distance of Q1 to the IP to 23 m as in the baseline, and we fix the gaps between magnets to the minimum value of 1.3 m. Following the approach outlined in [8,9,13], we select a “symmetric” triplet, i.e. a triplet where the quadrupoles have the same aperture and the same gradient, and two different lengths. Q1 and Q3 have the same length, and Q2, which is split in two cold masses Q2a and Q2b, a different one. We select the ratio between the lengths of Q1-Q3 and Q2 to have the same maximum of the beta functions in the two planes. Then, the quadrupole gradient is determined from the length of the quadrupoles in order to have an approximated matching.

Quadrupole lay-outs are based on a two-layer $\cos\theta$ design, using the inner and outer layer of the LHC main dipoles respectively (see Fig. 2). This constraint allows a considerable saving in time and money, since a large stock of this cable is available. This determines the aperture, given the quadrupole gradient. In this way we get a one-parameter family of solutions whose independent variable can be either the aperture, or the gradient, or the total length of the triplet. Starting from

the present baseline of 70 mm aperture, we increased the aperture by successive steps. The last step has been chosen to be 140 mm since the LHC dipole cable is not long enough to wind larger aperture quadrupoles of the needed length, i.e. one should have split the cold mass in two parts, thus considerably increasing the costs. The list of parameters relative to the four lay-outs is given in Table I.

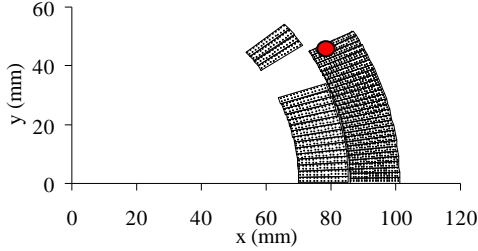


Figure 2: Cross-section of the 140 mm aperture quadrupole. The red dot indicated the coil area where the coil reaches the short sample limit at 100% of the loadline.

Aperture (mm)	Gradient (T/m)	L(Q1,Q3) (m)	L(Q2a,b) (m)	Total length (m)
90	156	8.69	7.46	36.2
115	124	9.98	8.42	40.7
130	111	10.81	9.04	43.6
140	102	11.41	9.49	45.7

The minimum thickness of the beam tube and of the beam screen inside the coil aperture required by mechanical constraints has been included: indeed, they both have a non negligible shielding effect. We assume in this study that the beam tube and the beam-screen extend continuously over the gap between the magnets.

The beam tube thickness is given by to (valid for stainless steel, buckling, pressure vessel code, 25 bar):

$$t = 0.0272D,$$

where t is the tube thickness and D is the outer diameter of the tube. The beam screen has been dimensioned according to the forces it has to support due to eddy currents from the change of magnet gradient during quench (Table 2). We have added one mm thickness to these calculations for the beam screen to be close to the values in the present triplet. There is electrical ground insulation of 0.5 mm between the coil and beam pipe. A tolerance for the insertion of the beam screen has been taken as 1.75 mm (radial) for all cases.

Aperture (mm)	BS thickness (mm)	BP thickness (mm)
90	2.0	2.36
115	2.0	3.03
130	2.0	3.44
140	2.0	3.72

POWER DEPOSITION IN THE TRIPLET

The evaluation of the power deposition depends on the size of the bin where quantities are integrated. The bin

size has been chosen as the cable transverse size times a longitudinal length of 10 cm, which is the twist pitch. This choice should correspond to the maximum volume of equilibrium for the heat transport. This bin size is crucial for the evaluation of the quench risk.

The following results, though affected by limited statistical errors (about 10% for peak power values and less than 1% for integral values), carry significant systematic uncertainties related to interaction/transport models, cross section extrapolation at the 14 TeV center of mass energy, geometry and material implementation, dramatic dependence on a tiny fraction of solid angle in the angular distribution of the reaction products. A proper safety margin is a factor of 3 on peak power values, neglecting uncertainties on quench limits.

The peak power deposition versus the distance from the IP computed with Fluka [14,15] is shown in Fig. 3 for the four cases. The results are scaled for a luminosity of $2.5 \cdot 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$. One observes that the peak power decreases for larger and longer triplets. Moreover the pattern of the power deposition along the longitudinal axis is preserved, i.e. the main peaks are at the end of Q1 and at the beginning of Q2a (see Fig. 4 and 5, where the same plot is given by reducing the magnets to the same length). The maximum of the peak power versus the triplet length and aperture is shown in Fig. 5. One observes a large dependence of the peak energy on the aperture: the 22 mW/cm³ peak in Q2a for the 90 mm aperture is reduced by a factor 2 for the 140 mm case. A 130 mm aperture gives about 25% less peak energy than the 115 mm one. The peaks are in the coil mid-plane, i.e., far from the zone where the coil reaches the short sample limit (see Fig. 2).

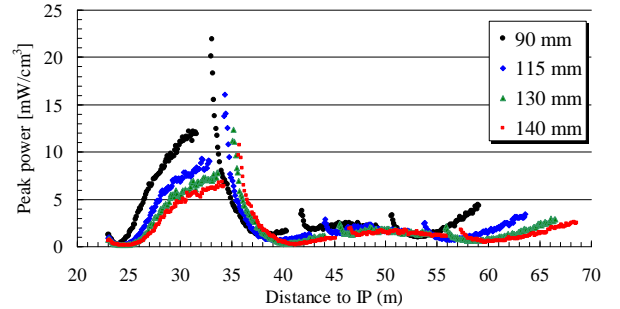


Figure 3: Peak power deposition in the coil versus distance from the IP.

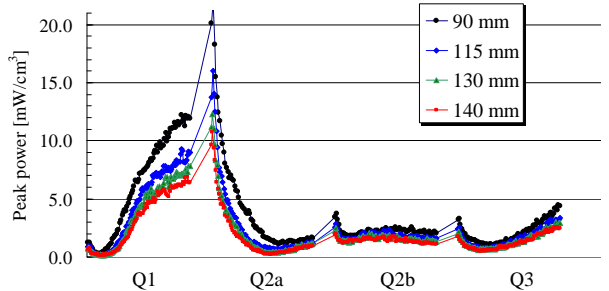


Figure 4: Peak power deposition in the coil for the four analysed lay-outs versus a rescaled longitudinal coordinate, making all magnets of the same length.

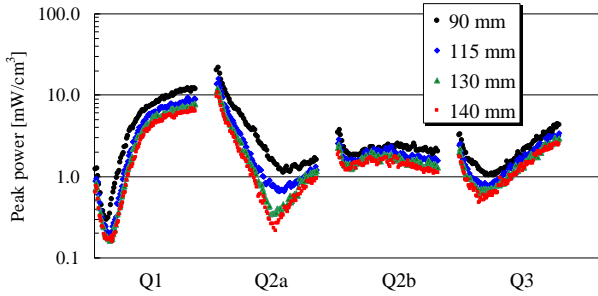


Figure 5: Same as Fig. 4, with peak power in log scale.

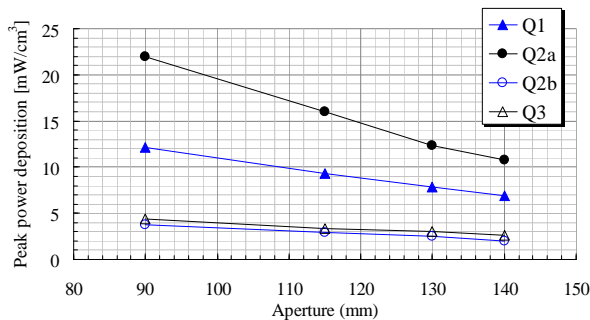


Figure 6: Maximum of the peak power deposition in the coil versus triplet aperture in Q1, Q2a, Q2b and Q3

The peaks and total heat load in the magnets (see Fig. 6 and 7) decreases with longer lengths and larger apertures. For instance, a 90 mm and 36.2 m long triplet has a heat load of about 505 W, whereas the 130 mm aperture and 43.6 m long has a heat load of 426 W, i.e. 16 % less, including the beam screen.

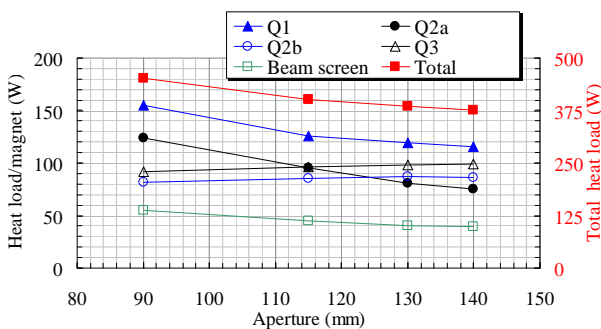


Figure 7: Heat load versus triplet aperture in Q1, Q2a, Q2b and Q3, beam screen and total load on magnets without beam screen.

CONCLUSIONS

In this paper we evaluated four lay-outs for the LHC interaction region triplets characterized by increasing quadrupole apertures (90 to 140 mm) that can be built using the available Nb-Ti cables used in the LHC main dipoles. The quadrupole gradients and their lengths are fixed according to the optics requirements. For each case the quadrupole cross-sections have been designed and an

energy deposition evaluation has been carried out. The final aim was to evaluate if longer and larger triplets will receive larger energy deposition.

The main result shows that longer and larger Nb-Ti triplets have a lower peak energy deposition. A 56% increase of the aperture from 90 to 140 mm reduces the peak energy of a factor two. An increase from 115 to 130 mm gives a 25% reduction. We also observe that the pattern of the peak energy along the magnets is invariant, i.e. for longer triplets the peak energy pattern is simply stretched on a larger length.

Longer and larger triplets do not give rise to larger heat loads: simulations show that there is a modest decrease of total heat load on the magnets. For instance, the heat load is reduced by 18 % by increasing the aperture from 90 mm to 140 mm.

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