# A Design Concept for the LHC Insertion Quadrupoles

W. Scandale and T. Taylor
CERN, CH-1211 Geneva 23, Switzerland

*Abstract*

The low-ß insertion optics imposes severe constraints on the desired characteristics of the local quadrupoles. In order to obtain the necessary degree of focusing at the LHC, triplets made up of four 250 T/m superconducting quadrupoles, about 6 to 7 m long, are presently envisaged. The large value of the betatron functions through these magnets is such that beside being the principal source of chromatic aberrations, errors in their gradient will also contribute significantly to the excitation of resonances in the circulating beams. The magnets should therefore provide a gradient field of very high quality. The relatively small number of quadrupoles involved means that the cost constraints are less binding on these than on the lattice magnets. Their single aperture also opens up the possibility of an approach different to that adopted for the regular twin-aperture quadrupoles. One of the design concepts being investigated involves the use of flat cable wound in rectangular blocks to approximate the required quadrupole producing current density. This could lead to better control of the azimuthal prestress produced by radial pressure. The characteristics of the magnet are described, as is the method of applying the required prestress to the winding.

## I. OPTICAL LAYOUT

For the LHC to achieve the high luminosity in excess of $10^{34}$ $cm^{-2}$ $s^{-1}$ necessary for useful physics experimentation in the 10 to 15 TeV center-of-mass frame, special low-ß insertions are proposed [1], the layout of which is shown schematically in Fig. 1. The most critical element of these insertions are the quadrupoles forming the final triplet. Along them the values of the ß-functions are large and vary rapidly, which leads to tight tolerances on the field quality, straightness and alignment of the magnets.

In the general purpose insertions for pp collisions there is a free space of ± 20 m around the interaction point for the experimental detectors and radiation shielding of the superconducting quadrupoles. To avoid unwanted collisions, a horizontal crossing angle of 200 µrad is chosen. In both sides of this section there are an inner triplet of tightly packed quadrupoles, Q1,Q2, Q3, an outer triplet of quadrupoles Q4, Q5, Q6, more largely spaced, and the dispersion suppressor, with the four quadrupoles Q7, Q8, Q9, Q10. Next to the inner triplet there is the separating doublet of dipoles D1, D2, spaced by a drift length of 29 m, at the outer end of which the beam centres are separated by 180 mm.

The inner triplet is made of single bore quadrupoles; Q1 and Q3 are 6.8 m long. Q2 consists of two 6.1 m long quadrupoles powered in series. In all of them the magnetic field has to be linear over a large radius, since the values of the ß functions are large in collision mode, and the beam trajectory is off-axis, due to the crossing angle. Multipolar corrections up to the dodecapole have thus to be included.

By varying the strengths of the ten quadrupole gradients Q1 to Q10 up to 250 T/m, the value of ß* can be continuously tuned from 0.5 to 15 m. The upper limit is set by the saturation of Q3. The lower limit is set to avoid values of the ß functions in excess of 4 km in the inner triplets. Values of ß* down to 0.35 m can be reached, and are associated with ß-peak values of 6.5 km. Unipolar power supplies can be used, since there is no crossing of zero along the ß* tuning path.

The peak-value of ß in the inner triplets is a decreasing function of ß*. At injection, the value of ß* is set to 8 m, and such that the envelope of the beam in the outer triplet is about the same as at high energy with collision optics, shown in Fig. 2.

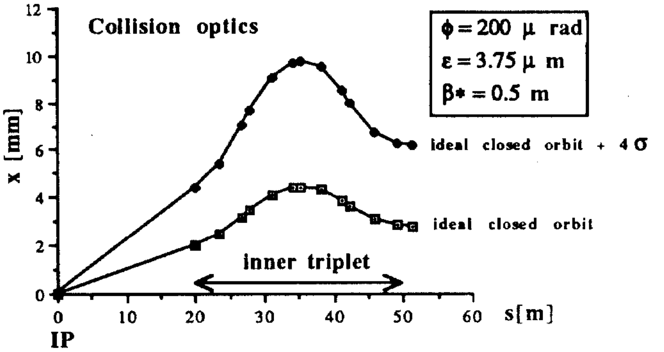

Fig. 2 Beam envelope of the general purpose insertion

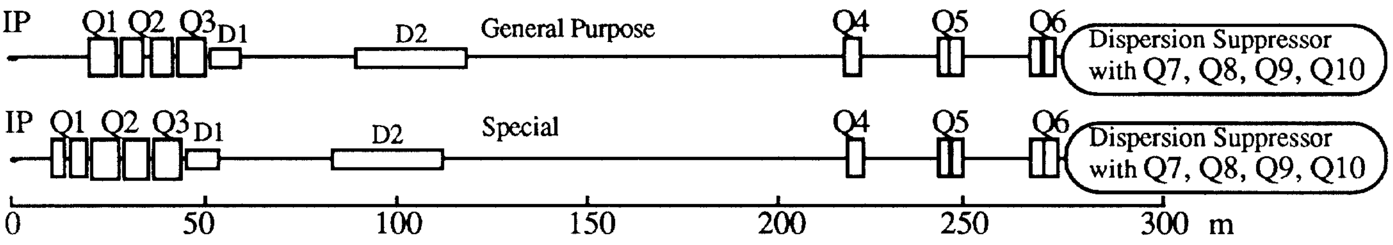

Fig. 1 Layout of the experimental insertions

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A special insertion for pp collisions has been designed for a single experiment at very high luminosity. Its layout is derived from that of the general purpose experimental insertion. There is a free space of ± 10 m around the interaction point for the detector and the radiation shielding. Because of this, the inner triplet has to be re-designed. Q1 is made of a pair of quadrupoles 4.4 m long, powered in series, Q2 is a pair of quadrupoles 6.6 m long, also powered in series, and Q3 is a 7.2 m quadrupole. The layout is shown in Fig. 1. The horizontal crossing angle is set to 230 μrad.

The values of ß* can be tuned from 0.3 to 11 m. As in the general purpose insertion, the upper limit is set by the saturation of Q3. The lower limit is set to limit the values of the ß functions to below 4.9 km in the inner triplets. The axial displacement of the beams is then about the same as in the general purpose insertion. Values of ß* down to 0.25 m can be reached, associated with values of ß-peak of 5.8 km. At injection, the value of ß* is set to 6 m, using the same criteria as the general purpose insertion. The quadrupole strengths do not cross zero in the ß* tuning process.

The effect of the imperfections of the inner triplet have been studied by tracking simulations [1]. With low-ß optics, the dynamic aperture of a single beam is determined by imperfections of the single bore quadrupoles, where the value of the ß-functions is maximum. In order to ensure sufficient aperture for the beam, values of the normal and skew multipole coefficients, at a reference radius of 1 cm, must not exceed $10^{-5}$ units up to dodecapole, and a few $10^{-6}$ units beyond. As concerns coupling, tilts of up to 1 mrad are correctable using the global skew quadrupole scheme.

## II. MAGNETS

It is clear from the above that special attention must be paid to the triplet quadrupoles. The magnets should have significantly better field quality than those used in the lattice. Moreover, they are situated in the potentially hostile environment close to the interaction points, where beam-beam created radiation may deposit up to 4 W per metre length into the windings. There are however relatively few of these units to be provided, and, in contrast to the arc magnets, they can also be considered as replaceable items as experience is gained in the understanding of the machine. For these reasons, the present strategy is to seek a magnet design which though more costly is likely to provide better accuracy in conductor placement, and, hence, a lower multipole content. This is the medium to long term goal. It is fully realized that this goal will not be easy to achieve; much effort is already put into getting the highest possible field quality in the lattice magnets, and for the triplets a factor of 2 to 3 better is required. The short term strategy is therefore to obtain the required accuracy by selection. Work is now in progress on a slight modification to the insertions which will allow them to be based on combinations of (low current) quadrupoles of two standard lengths for use up to QS5, i.e. for magnets which must be excited separately. This will provide a suitable stock from which the best units can be chosen for the insertion triplets. The selected units will be complemented by local individually tuned correction windings.

The approach being followed for the specific triplet quadrupoles in the longer term is to explore the possibility of using combinations of rectangular coil blocks, instead of cylindrical sectors azimuthally prestressed via external radial pressure. The advantages of this technique are clear from the point of view of winding accuracy; the coils can be wound using rectangular rather than wedge-shaped cable, against accurately machined planar formers. Independent investigations by Wenzel [2] have lead to proposals to explore a similar approach for the SSC magnets. It is interesting to consider an intersecting ellipse model of current density for this, rather than the $\cos 2\theta$ distribution; the geometry lends itself better to breaking up into rectangular constituent blocks. A disadvantage however is that more conductor is required to obtain the same gradient. For the purposes of the present study, a gradient of 250 $\text{Tm}^{-1}$ is required, and the inner radius of the coil is taken to be 30 mm. As shown in Fig. 3, prestress is applied to the coil (B) by a stainless steel shrinking cylinder (F), via locked iron laminations (E). These laminations are 5 mm thick fine-blanked components cut on the centre plane; the gap alternates from the vertical to the horizontal plane, from one set of laminations to the next, so that when the magnet is cooled they apply horizontally-oriented and vertically-oriented prestress respectively. Zinc alloy keys (D) control the prestress, and increase the amplification effect due to the lower coefficient of expansion of the iron sectors, which slide at the lamination interfaces. The forces are transmitted from the laminations to the coil via a load-spreading structure (C), and the inside of the coil presses against the reinforced vacuum tube support (A). The optimization of material and thickness of the various components is the subject of an on-going study.

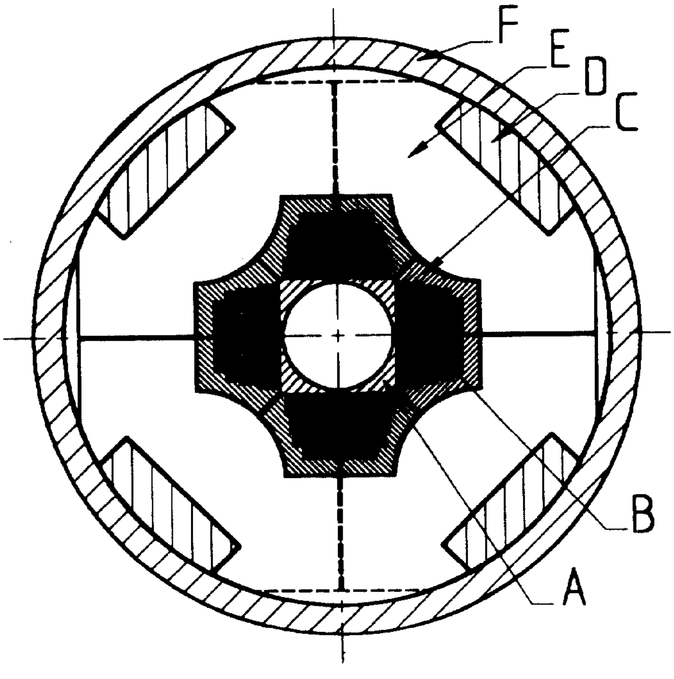

Fig. 3 Cross-section of the LHC insertion quadrupole model

The electromagnetic force pattern in one eighth of the winding is shown in Fig. 4. The net radial force is 57 $Tm^{-1}$. The inner tube supports part of the prestress, which is applied such as to maintain compression in the coil in all conditions of excitation. The current is "graded": the two outer blocks are made from cable having just over half the cross-section of the two inner blocks. In order to obtain 250 $Tm^{-1}$ in the present design, in the inner windings the peak field is 9.2 T and the average current density is 435 $Amm^{-2}$. The maximum excitation current is 5000 A.

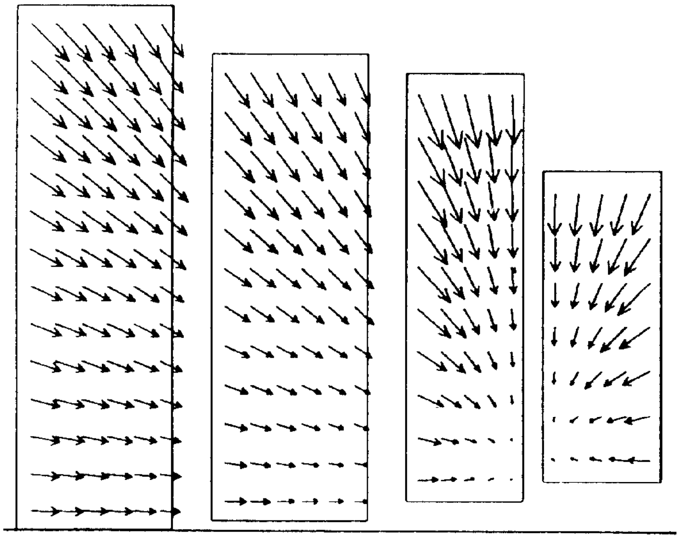

Fig. 4 Force pattern in the model

The choice of conductor has been the subject of much discussion. Good experience with the $Nb_3Sn$ dipole [3] and the cryogenic interest in cooling these magnets to 4.2 K rather than 1.8 K has focused attention on the selection of the most suitable cable for this purpose. The result of an initial comparative study is summarized in Fig. 5. This shows the possible choice of inner and outer coil diameters for achieving a gradient of 250 $Tm^{-1}$ in a cos 2 θ winding, suitably graded and including the effect of an iron shield, in the parameter space of peak field in the winding vs average current density where the peak field occurs. The performance of state-of-the-art superconducting materials, assuming a factor 3 in cross-section to allow for the stabilization and insulation, are indicated in the same diagram. We assume that filament diameters of up to 20 μm are acceptable for these few magnets, so that modified jelly-roll or internal tin technology may be applied. It can be seen that whereas the $Nb_3Sn$ may be suitable for small diameter magnets, NbTi at 2 K could be safer for a 250 $Tm^{-1}$ magnet of 60 mm or more inside diameter. This, in addition to uncertainties as to the radiation resistance of $Nb_3Sn$, would appear to indicate that NbTi at 1.8 - 2 K is presently the better choice. The advantages of $Nb_3Sn$ regarding temperature margin and the stress-free nature of the in-situ reacted winding are nevertheless strong, and more detailed study (paying special attention to the achievable filling factor for the coil) will be required before it can be decided which conductor to use for the LHC insertion quadrupoles.

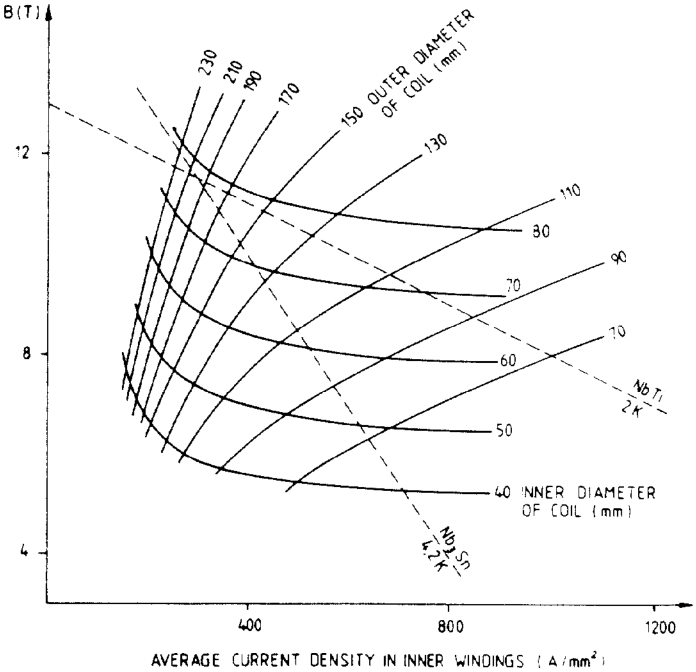

Fig. 5 Coil dimensions for 250 $Tm^{-1}$

## III. ACKNOWLEDGEMENTS

We are grateful to N. Galante for his help in making field and force calculations using the finite element program ANSYS™.

## IV. REFERENCES

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