Integrating Early-Separation Dipoles in CMS

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***Abstract*—Proposed methods of reducing the geometrical effects of the beam crossing angle include a dipole located close to the interaction point. In this note, I discuss the integration of the early separation dipole in the CMS detector. It appears that the forces and torques on the dipole are very great, and may prevent its use.**

I. INTRODUCTION

A potential limitation to increasing the luminosity of the LHC by decreasing β^* at the interaction point is the geometrical effect of the finite beam crossing angle. The LHC crossing angle is relatively large, almost a half milliradian, in order to decrease the effects of the long-range beam-beam interactions. The crossing angle reduces the advantages of decreasing β^*. For example, a reduction in β by a factor of two would result in a luminosity gain of a factor of two if the crossing angle were zero. With the present large crossing angle, reduction of β^* by a factor of two results in only a 30 percent gain in luminosity.[1]

Among the possible solutions to this problem is the reduction in the crossing angle afforded by the introduction of a dipole close to the interaction point – a so-called early-separation dipole.[2] The dipole is placed as close to the IP as possible consistent with its support structure and interference with the detector in order to separate the beams with the fewest possible close encounters with each other. The resulting Smaller crossing angle permits almost full advantage of reducing β^* to very small values, even less than 25 cm.

II. THE EARLY-SEPARATION DIPOLE

A. Placement of the early separation dipole

For CMS, the closest reasonable placement of an early-separation dipole is about six meters from the IP, where the magnet can be supported from the massive and solid muon-detector steel, as shown in Fig. 1. In this location, there is one close encounter of the two beams if the bunch separation is the nominal 25 ns, but none if the separation is 50 ns or 75 ns. The integrated field strength of the dipole should be at least 8 T-m to separate the beams sufficiently before the next beam-beam encounter.[3]

B. Aperture and size of the early separation dipole

The early-separation dipole is located in a region of fierce particle debris from the interaction point. These particles will shower and deposit much of their energy in the coils, increasing the temperature of the superconductor and stressing the cryogenic system. In order to decrease this effect, the early-separation dipole should have a large aperture. Since the dipole is close, and the particle flux and average energy from the interactions falls rapidly with angle, having a large aperture will significantly reduce the debris heating in the magnet. In this model, we take 0.3 m as the coil aperture. An additional advantage of having fewer particles hit the magnet is that the backscattering and albedo from the magnet is also much reduced, making the detector backgrounds much less troublesome.

The early separation dipole is also restricted in its outer

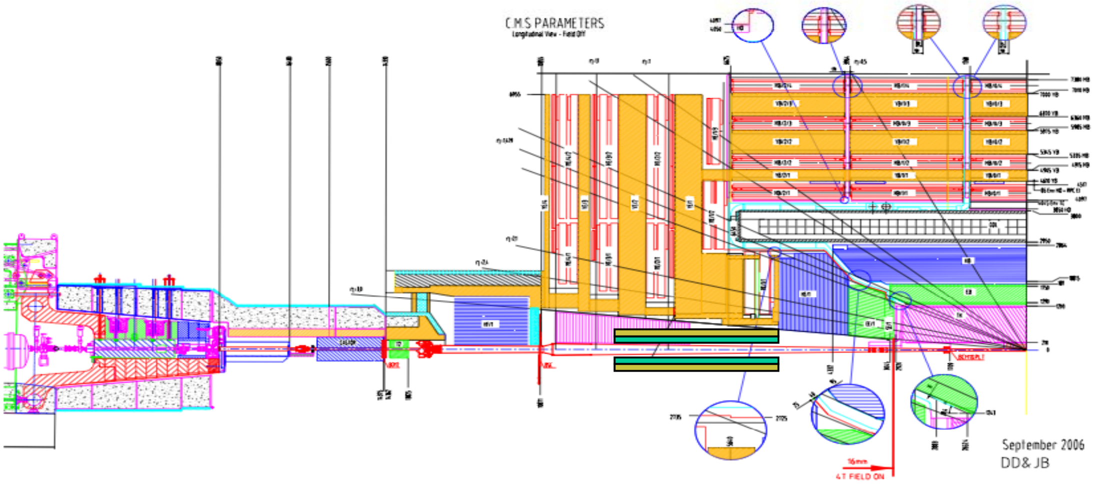

Fig. 1. An elevation view of CMS with an early-separation dipole located between 6 m and 8 m from the IP. The green shading are the magnet coils and collars. The yellow shading represents cooling channel filled with liquid helium

dimension, because of the tight space in which it must fit. If placed 6 m from the IP, the outer diameter of the cryostat cannot be more than about 1 m, probably significantly less when one takes into account the required services. For an aperture as large as 0.3 m, this permits very little space for a cold-iron yoke. Hence, this magnet is either without a steel return yoke, with a relatively thin warm iron yoke, or with a combination of thin cold and warm iron yokes. In any case, the fringe field of the magnet will be strong.

C. *Field strength of the early separation dipole*

For the purposes of this paper I have taken the central field in the dipole to be 4 T, easily reached by NbTi technology. Because of the significant particle debris heating, even for a large-aperture dipole, Nb_3Sn may be required to gain greater temperature margin. Hence, the effective length of the dipole is about 2 m. A 0.3 m aperture dipole requires about 1500 kA-turns to generate a central field of 4 T.

D. *Other advantages of the early separation dipole*

There are additional advantages of a separation dipole besides decreasing the crossing angle. One is that it offers the possibility of leveling the luminosity by changing the crossing angle, thought to be a more robust and stable technique than varying the β at the IP. In addition, the smaller crossing angle makes crab cavities easier since the bunch rotation angle is smaller. Crab cavities, if they can be made to work, could reduce the effective crossing angle to zero.

III. THE FORCES ON THE EARLY SEPARATION DIPOLE

A. *Parameters of the CMS solenoid*

A significant feature of the CMS detector is the length, diameter and strength of the CMS solenoid magnet. Its coil is 12 m long and 4 m in diameter, and its central field is 4 T. A Its axial field along the beam line as a function of distance is shown in Fig. 2. Because it has a steel return yoke that is 13 m long, its field at 6 m from the IP, where the near end of the early-separation dipole is placed, is about 2.6 T. At the other end of the dipole, 8 m from the IP, the field is about 0.75 T. The early separation dipole feels a force due to the interaction of the current in its windings and the solenoid field.

B. *Model and calculation of forces on the dipole*

For the purposes of this paper, it is sufficient to idealize the solenoid field as uniform and everywhere parallel to the solenoid axis, and the dipole configuration to have ideal coils that are rectangular, with the sides parallel to the solenoid axis. I assume that the magnet bends in the horizontal plane. In this model, only the end turns of the dipole feel the forces caused by the solenoid field. The two ends feel forces in opposite directions, as shown in Fig. 3. The end closer to the IP then feels a force

$$F = B_{sol} \times I_{dip} = 3900 \text{ kN/m}$$

For a coil 0.3 m wide this means a total force of about 1200 kN, or 120 tons in the vertical direction. The force on the other end of the magnet is about 35 tons, in the opposite direction. Hence, there is a net force of 85 tons, vertically, and a couple, that is, a torque around the center of the magnet of 1235 kN-m.

Of course, the model is not exactly accurate because the solenoid field is not exactly parallel to axis but is diverging. This results in components that are perpendicular to the coil along the long sides of the dipole. These forces may increase or decrease the net force and the torques, depending on details of the geometry. For the purposes of this paper, we are ignoring these higher-order effects.

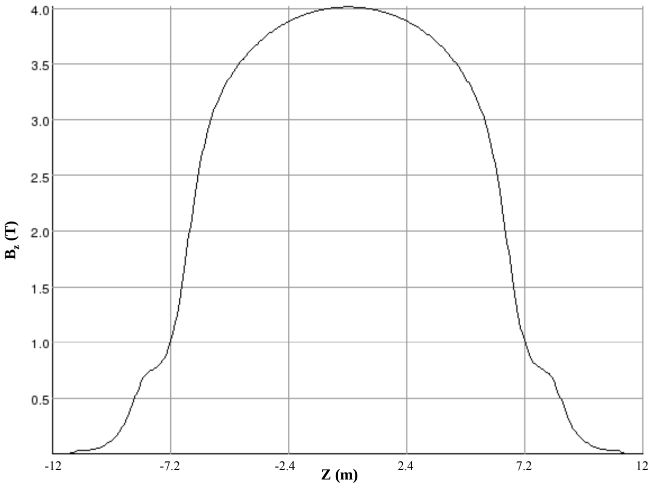

Fig. 2. The axial field of the CMS solenoid along the beam line as a function of distance along the beam line. (Courtesy of Vyacheslav Klyukhin, CMS & Moscow State University)

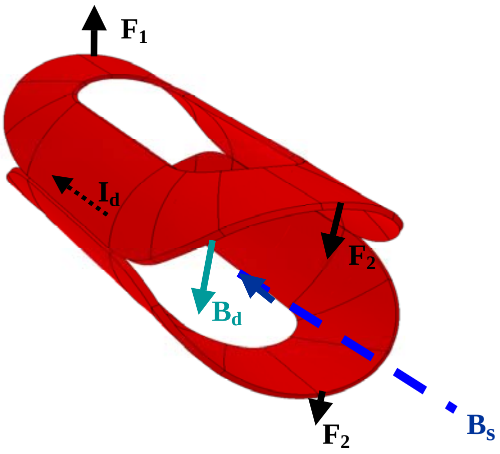

Fig. 3. A cartoon of an early-separation dipole showing the directions of the solenoid field B_s, the dipole current I_d, the dipole field B_d, and the forces on the ends of the magnet F_1 and F_2.

C. *Effects of the forces on the dipole*

The large forces and couple on the dipole make a massive support structure necessary. To get an idea of the scale of these forces, imagine a large airplane, a Boeing 757, for example, perched on one end of the dipole. This is one reason why the dipole cannot be cantilevered from the muon system to be closer to the IP. In fact, the support structure will be so massive that it will necessarily interfere with access to the detector and be the source of high backgrounds.

The forces on the upper and lower ends of the dipole coils are in the same direction, but because those forces must be reacted, the net effect is to crush the ends of the coil. The body of a cosine theta coil is robust under crushing forces because it is a Roman arch in compression, but the ends are not. Hence, the ends of the magnet must have some sort of strong inner support in direct contact with the insulated coils to prevent them from collapsing. This will decrease the effectiveness of the cooling just at the location of maximum debris heating, and increase the possibility of friction due to coil motion against this support. To my knowledge, no superconducting accelerator magnet has been made to work reliably with an internal coil support.

The forces on the coil ends are similar in magnitude to the self-generated forces of a high-field dipole, and will contribute stresses on the conductor of the order of 150 MP. This additional stress may make the use of Nb_3Sn impossible. This would be unfortunate if the temperature margin of Nb_3Sn is required for reliable operation.

IV. POSSIBLE OTHER SOLUTIONS

There are at least two other possibilities that may solve some of the force problems. Neither of these solutions has been investigated to any great extent.

The CMS solenoid field could be locally cancelled near the dipole, at least approximately, by surrounding the dipole with a solenoid. This will cancel, or at least reduce the transverse forces on the dipole, substituting hoop stress and longitudinal forces on the small solenoid. These forces are large and will require support, but whether they are easier to deal with is not yet known. The increased size of the cryostat may require that the dipole have smaller aperture in order that the whole assembly can fit into the tight space allotted.

Another possibility is to have a complete iron yoke. Again, this may require a smaller aperture and consequently greater debris heating. It is not yet known whether this will decrease the forces on the dipole.

Neither of these solutions seems attractive due to the complexity and possible aperture decrease, but they will be investigated in the near future.

V. CONCLUSIONS

The forces on the coils of an early-separation dipole inside the field of a strong solenoid are very great, the order of 100 tons. They will require a massive support structure and internal support of the dipole coils at the coil ends. The additional stress on the conductor may make the use of Nb_3Sn impossible. From this analysis alone, it appears that the use of an early-separation dipole will be very challenging. The results should inspire us to investigate other schemes to decrease the effects of finite crossing angle.

ACKNOWLEDGMENTS

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