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Conceptual electromagnetic design of the detector magnet for the ALICE 3 upgrade

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Abstract

Canted cosine theta (CCT) windings are often chosen for the fabrication of accelerator magnets. This innovative winding technique can also be adapted for use in detector magnets, introducing a dipole component to the magnetic field alongside the conventional solenoid field. By incorporating this dipole component, the momentum resolution at low emission angles is significantly enhanced, offering improved performance and accuracy in particle detection.

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1 The canted helicoidal winding

In the design of the detector magnet for the ALICE 3 upgrade at CERN, the need has arisen to combine a dipole magnetic field with the traditional solenoid field in order to provide better momentum resolution for particles produced at high values of pseudo-rapidity η. The pseudo-rapidity is defined as:

$$\eta = -ln[tan(\frac{\theta}{2})]. \tag{1}$$

To achieve this, the configuration proposed in the Letter of Intent for the upgrade includes a central solenoid together with two dipoles positioned at its extremities [1]. As this appears to be a costly and mechanically complex solution requiring a long R&D effort, in this technical note we propose an alternative design for a magnet that meets the upgrade requirements, using a canted-helix geometry to obtain the two fields from a single winding.

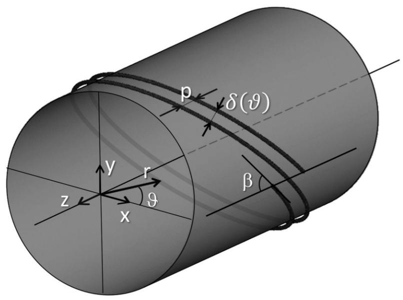

Figure 1: Sketch of a single spiral coil with indication of the main parameters.

The idea of using canted magnets was first proposed in 1970 [2] and later rediscovered at the beginning of the millennium [3]. These canted cosine theta (CCT) magnets use two superimposed helical windings to produce a pure dipole field. Each canted helical winding produces a magnetic field directed along the normal to the plane of the turns, resulting in a solenoidal component parallel to the axis of the magnet and a dipole component perpendicular to it.

By winding the two concentric helixes of the CCT magnet with opposite tilt β and circulating their current in opposite directions, the two solenoidal contributions cancel each other out, leaving a pure dipole magnetic field. If a single helix were wound, both components would be retained.

2 The field inside the magnet

Techniques similar to those used to simulate the CCT dipoles can also be used to simulate a single helix winding. We have created two different ANSYS 3D models of the ALICE3 detector magnet, using the magnetic scalar potential to evaluate the magnetic field away from the conductors, while avoiding the difficulties associated with including the helix in the mesh. As a consequence of this choice, the calculated field near the conductor is inaccurate and will require the development of a model using the vector potential in the future.

In the first design, the cable is inclined over the entire length of the magnet, while in the second, the magnet has a central body and inclined sectors at its ends. A solenoid of the same size and with a central field of about $1T$ was simulated as a reference to the baseline configuration of the ALICE 3 magnet. The current in the inclined sectors has been set to the value required to produce a 1 T field along the z-axis at the centre of the pure magnet.

Taking into account the needs of future mechanical analysis, the magnet has been divided into 5 sectors of equal length, separated by a gap; the depth of the gap and other geometric parameters can be found in tab.1. For the Partially Canted option, two values of inclination and module length are provided, the first referring to the solenoidal modules and the second to the canted modules. All calculations have been made with an iron yoke included in the model, maintaining the same yoke parameters for the three configurations.

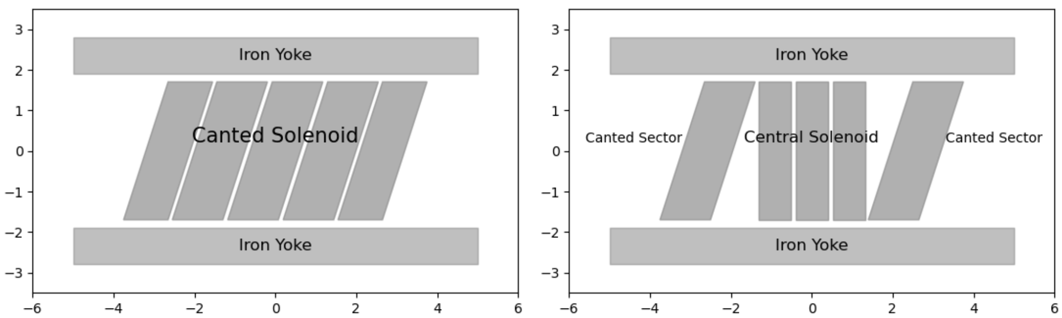

Figure 2: The two designs implementing canted modules.
Left: Completely Canted. *Right*: Partially Canted.

For the Canted options, a Cartesian coordinate system was used with the origin coinciding with the centre of the magnet and the axes oriented as shown in the figure fig.3. For the Pure Solenoid option, a cylindrical coordinate system with the same origin and z axis was considered; this was done because for this design we don't have a real

	Solenoid	Partially Canted	Canted
Magnet			
R_{cond} [m]	1.45		
R_{bore} [m]	1.25		
$Lenght$ [m]	7.5		
β	0°	0° // 20°	20°
Modules			
$Number$	5		
$Lenght$ [m]	1.43	0.90 // 2.28	2.28
Gap [mm]	87		
Iron Yoke			
R_{in} [m]	1.75		
R_{out} [m]	2.65		
$Lenght$ [m]	10		

Table 1: Geometric parameters of the three designs. R_{bore} is the radius of the free bore of the magnet, while R_{cond} refers to the radius at which superconducting cables are located.

dipole field, instead all the field perpendicular to the axis of the solenoid comes from the radially closing field lines.

For the two tilted designs we have recorded the B_z and B_y components of the field along the paths inside the magnet defined by three values of the pseudorapidity η ($\eta = 0, 1, 4$) and $\phi = -90$, where ϕ is defined as the angle with respect to the x axis in the xy plane. We have done the same for the B_z and B_r components of the magnetic field for the solenoid. For each path and component of the field, its integral along the path has been calculated and its value reported within the relevant plots.

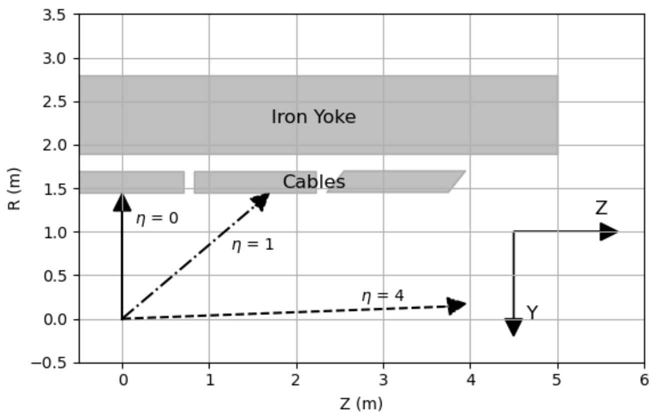

Figure 3: The paths along which the plots are taken and the integrals calculated.

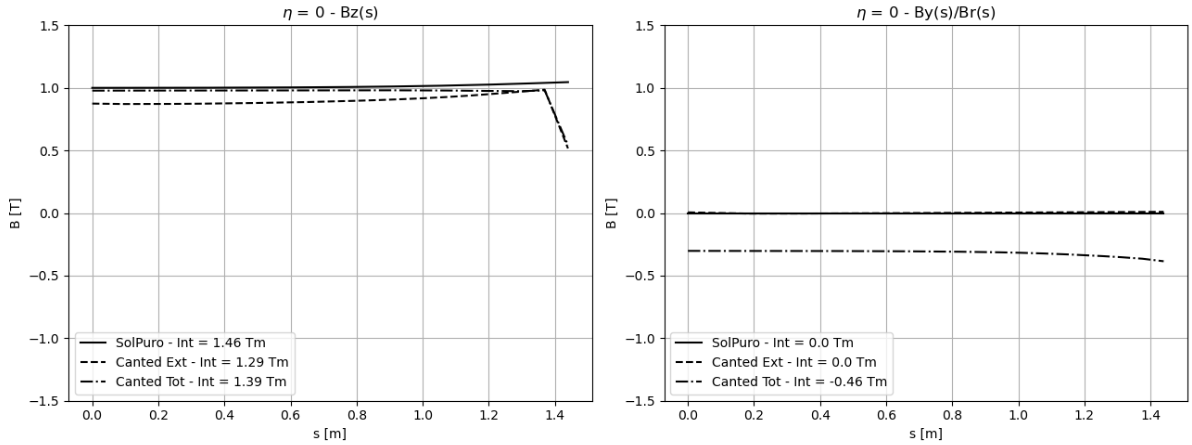

Figure 4: B_z and B_y along $\eta = 0$. The solid line is for the Pure Solenoid, the dashed line for the Partially Canted and the line point-dash line for the Completely canted solenoid. The same is true for the $\eta = 1$ and $\eta = 4$ plots.

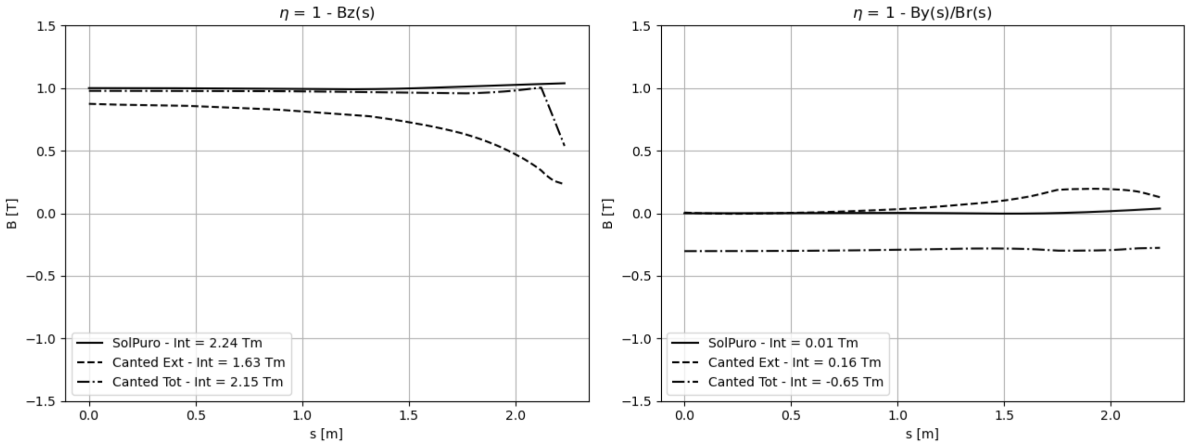

Figure 5: B_z and B_y along $\eta = 1$.

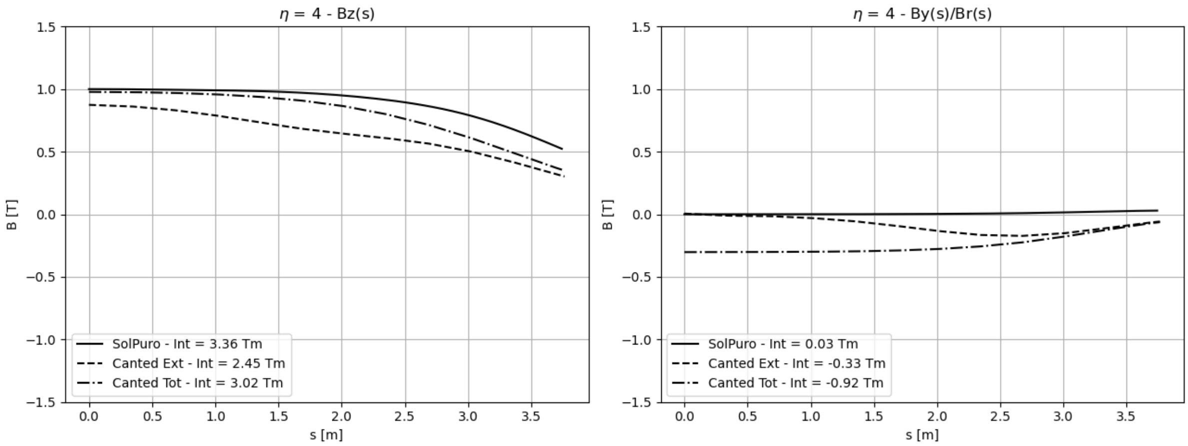

Figure 6: B_z and B_y along $\eta = 4$.

As can be seen from the graphs in Fig.6, both canted configurations are able to provide a much larger integrated transverse component at large values of η, while maintaining values of B_z close to those of the pure solenoid at small η. In particular, the fully canted option achieves a value of $|\int B_y ds| = 1.06\,Tm$, in line with the ALICE 3 requirements [1]. Tab.2 shows the values of the integrated field components together with the percentage changes compared to the pure solenoid.

		Solenoid	**Partially Canted**		**Canted**	
		$\lvert\int B\rvert$ [Tm]	$\lvert\int B\rvert$ [Tm]	Var. to Sol.	$\lvert\int B\rvert$ [Tm]	Var. to Sol.
$\eta = 0$	z	1.46	1.29	-11.6%	1.39	-4.8%
	y	0.0	0.0	-	0.46	-
$\eta = 1$	z	2.24	1.63	-27.2%	2.15	-4.0%
	y	0.01	0.16	$\sim$ 15 times	0.65	>60 times
$\eta = 4$	z	3.36	2.45	-27.1%	3.02	-10.1%
	y	0.03	0.33	$\sim$ 10 times	0.92	$\sim$ 29 times

Table 2: **B** components integrated along the paths.

In the case of the Completely Canted design, it should be noted that having both the B_z and B_y components along the entire length of the magnet introduces a non-trivial dependence of the trajectory on the particle's emission angle ϕ.

The Partially Canted avoids this problem at low η, but as can be seen in Fig.5 for intermediate values ($0.75 \leq \eta \leq 1.5$) it is affected by the radial field due to the closure of the field lines of the central solenoid sector. It also shows a significant reduction of the integral $|\int B_y ds|$, having only one inclined sector. Future optimisations will attempt to extend the inclined region and add an interface region between the solenoid and inclined modules, where the coils are gradually inclined to avoid the solenoid return effect.

3 Conclusions

We have shown the magnetic characteristics of three preliminary designs for the solenoid detector planned for the ALICE experiment upgrade, highlighting their non-standard geometries and magnetic field characteristics for three relevant values of pseudorapidity η.

In particular, the tilted designs would allow a dipole field to be obtained from the same winding as the solenoid field, in line with the upgrade requirements. Although this is only a preliminary analysis at this stage and more detailed studies are required, this could allow a reduction in cost and a simplification of the mechanics compared to the original design with a system of three different magnets.

Future developments in the field of magnetic simulation will be concerned with improving the field homogeneity in the partially canted version. In addition, the stability of the superconducting transition in these magnets and the necessary mechanical supports will be studied.

4 References

References

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