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COMPARISON OF SUPERCONDUCTING SEPTA TOPOLOGIES AND PARAMETER SPACE EXPLORATION

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Abstract

The unprecedented energy scale of the FCC poses challenging requirements for its magnetic elements including the septum magnets for injection and extraction. With an ambitious target field of 4 T and apparent septum thickness of only 25 mm, different superconducting septum topologies have been investigated to explore their limitations. This article will cover the currently feasible topologies, amongst which the truncated cosine-theta, the double truncated cosine-theta, the superconducting shield (SuShi) and the so called stealth dipole. A performance figure of merit will be proposed, taking into account the maximum achievable magnetic field, the septum thickness and the leak field magnitude.

TRUNCATED DOUBLE COSINE-THETA SEPTUM

The Truncated Double Cosine-theta (TDCT) concept, developed for the g-2 experiment at BNL, is explained in great detail in [1]. The concept is very similar to the TCT septum described in the following section. Since it is a so called self-contained flux magnet, the double cosine concept allows to design a very compact magnet. The concept of this magnet and the disposition of the field lines are shown in Fig. 1. A 2 mm thick MuMetal shield has been placed around the orbiting beam gap to mitigate the leak field although it is not shown for clarity.

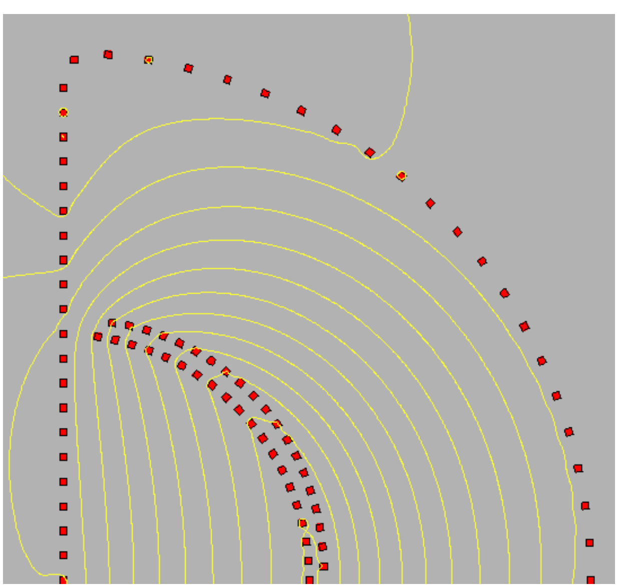

Figure 1: Upper half of the model of the cross-section of the Truncated Double Cosine-Theta septum.

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A summary of the relevant characteristics of the TDCT septum proposed for FCC-hh is presented in Table 1. The spacing of the cables should be optimized further.

Table 1: Truncated Double Cosine-Theta Septum Characteristics

Parameter	Value
B_0 (T)	4
B_{leak} (mT)	1
Apparent septum thickness (mm)	30
Gap height (mm)	56
Total current ($kA \cdot turns$)	304

TRUNCATED COSINE-THETA SEPTUM

The concept of the Truncated Cosine-Theta (TCT) septum is based on a well known Cosine-Theta magnet. By using the image current method [2], the magnetic field and the flux lines can be calculated assuming that the permeability of the iron yoke is much greated than the permeability of air. Then the Cosine-Theta coil can be truncated along one of the magnetic field lines (constant potential lines). One of the advantages of this septum topology is that it is possible to calculate a very accurate and fast analytical estimate of the current and of the yoke and coil radii. This septum topology is being considered for the FAIR project [3] and for FCC-hh with different magnetic field magnitudes, superconducting cable type and geometrical constraints. The cross section of the 4 T TCT septum proposed for FCC-hh is shown in Fig. 2. The cross section was optimized using ROXIE and Opera 2D and a MuMetal shield was placed around the zero-field region. The shield is not shown for clarity.

The main characteristics of the TCT septum proposed for the FCC-hh dump line are summarized in Table 2.

Table 2: Truncated Cosine-Theta Septum Characteristics

Parameter	Value
B_0 (T)	4
B_{leak} (mT)	0.1
Apparent septum thickness (mm)	30
Maximum gap height (mm)	70
Total current ($kA \cdot turns$)	195
Number of turns per pole (-)	31
Magnetic length (m)	4

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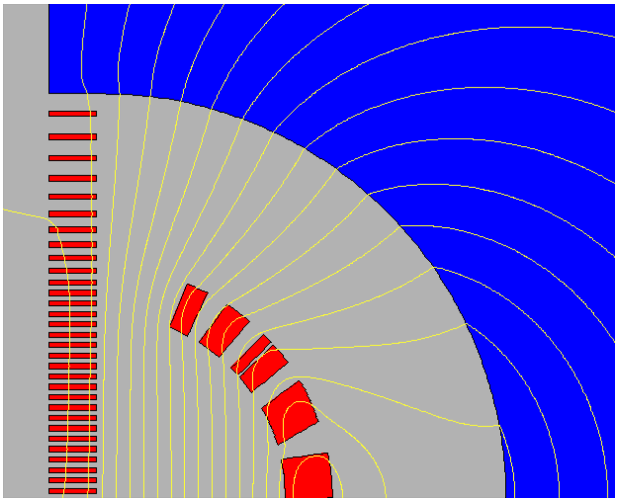

Figure 2: Upper half of the model of the 4 T Truncated Cosine-Theta septum proposed for FCC-hh.

STEALTH DIPOLE

The stealth dipole is based on a direct drive septum to which compensation coils are added to reduce its leak field in the orbiting beam gap. This approach is valid when the iron yoke is below saturation level, to ensure a high enough magnetic permeability of the yoke compared to the permeability of air. It is possible to add one compensation coil contiguous to the septum blade and returning on the outside of the yoke. Given that it is not desirable to increase the septum blade thickness, it is better to add two compensation coils, above and below the septum blade, as shown in Fig. 3. Further information about the concept of the stealth dipole can be found in [4]. As in the TCT case, a 2mm thick MuMetal shield was placed around the zero-field region.

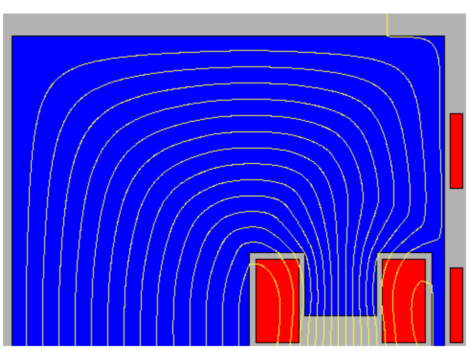

Figure 3: Upper half of the model of the stealth dipole concept reproduced in Opera 2D with FCC-hh parameters.

A summary of the main characteristics of a possible FCC-hh stealth dipole is presented in Table 3.

Table 3: Stealth Dipole Characteristics

Parameter	Value
B_0 (T)	4
B_{leak} (mT)	0.1
Apparent septum thickness (mm)	25
Gap height (mm)	19
Total current ($kA \cdot turns$)	87
Main current / Compensation coil current (-)	36

SUPERCONDUCTING SHIELD SEPTUM

A different approach to the septa described in the previous section is to use a Superconducting Shield (SuShi) septum [6]. A bulk superconductor is placed inside a high magnetic field around the orbiting beam gap to exclude the magnetic field from that region. At the same time, the magnetic field in the high field region of the septum is shaped by the shape of the superconducting material. In the current test phase, the external magnetic field is generated by an LHC MCBY magnet [5]. In a second test phase, the magnetic field will be generated by a Canted Cosine-theta (CCT) magnet with an aperture big enough to fit the SuShi and both vacuum chambers for the extracted and orbiting beams. Two different superconducting materials are currently being considered: bulk MgB_2 and a multilayer Cu/Nb/NbTi composite. Detailed information on the measurements and the experimental setup of the MgB_2 and HTS tape prototypes is presented in [6]. The multilayer material is being tested at CERN at the time of writing this article and the preliminary results are shown in Table 5. Detailed information on this prototype and the tests performed can be found in [7]. Figure 4 shows the concept of the SuShi septum.

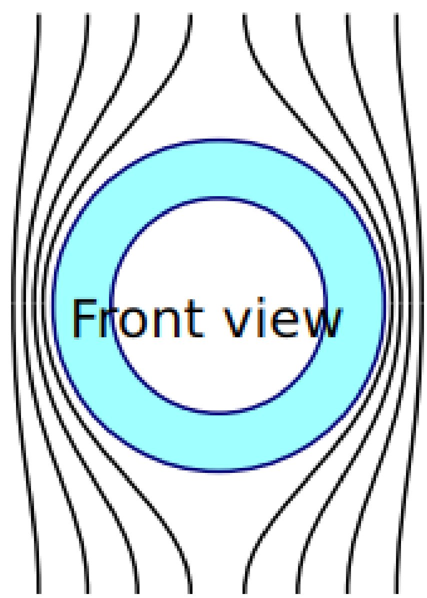

Figure 4: Sushi septum concept.

FIGURE OF MERIT

To compare different septa topologies, it is of interest to create a common metric with fixed criteria. Parameters of interest related the performance of a septum magnet are the main field, the leak field, the septum thickness, the aperture

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Table 4: Figure of Merit for Different Septa Topologies

Septum	B_0/B_{ext} **(T)**	B_{sat}/B_c **(T)**	B_{pole}/B_{peak} **(T)**	B_{leak} **(mT)**	**h (mm)**	**s (mm)**	**K (-)**
Shielded TCT	4	6.5	5	0.1	35	30	36
Shielded TDCT	4	6.5	6.5	1	56	30	7.56
SuShi MgB2	2.6	8.4	8.4	0.1	50	8.4	154
SuShi NbTi	3	4	4	0.1	50	4	375
Shielded Stealth	4	6.5	3.76	0.1	19	25	17.5

Table 5: Main Characteristics of the SuShi Prototypes

Parameter	**Cu/Nb/NbTi**	MgB_2
B_0 (T)	3	2.6
B_{leak} (mT)	<0.1	<0.1
SuShi thickness (mm)	4	8.4
Inner diameter (mm)	50	50

height and the saturation of the magnetic yoke. The proposed figure of merit is a non dimensional variable that increases with a better septum performance and decreases when the parameters differ from the optimal values. The formula to calculate the figure of merit is presented in Eq. (1). The first factor corresponds to the ratio between main field and leak field, a septum will be better when the main field is strong and the leak field is low. The second factor introduces the saturation of the iron yoke. B_{sat} is the saturation value of the iron and B_{pole} is the magnetic field at the pole. For a normal conducting septum this factor should be close to 1 since it is quantifying the efficiency of the iron use in the yoke. In the case of superconducting septa, B_{sat} is taken as the critical field of the superconductor and B_{pole} as the peak field in the coil, regardless of its location. Above the critical field the superconductor will quench and the septum will not work, so it is a factor quantifying the efficiency in the use of superconducting material. A lower factor will indicate an over-dimensioned design, hence increasing the costs and possibly using more space than necessary. In the case of the SuShi septa, there is no coil or iron yoke apart from the external magnet that produces the magnetic field independently of the SuShi, so this factor will be replaced by the ratio between the thickness of the SuShi device and the penetration depth at the corresponding working point. It is obvious that this factor can never be 1 because there needs to be a margin to the load line. The last factor is a comparison between the gap height (h) and the septum thickness (s). A thinner septum blade is preferable to a thicker one, while a bigger gap height is preferable for impedance and loss reduction.

$$K = \frac{B_0}{B_{leak}} \frac{B_{pole}}{B_{sat}} \frac{h}{s} \tag{1}$$

For SuShi septa, the figure of merit is adapted according to Eq. (2), where d_p is the penetration depth of the external magnetic field. Equation (2) can be simplified but it is presented as the multiplication of three ratios for similarity with Eq. (1).

$$K = \frac{B_0}{B_{leak}} \frac{s}{d_p} \frac{h}{s} \tag{2}$$

The figure of merit also expresses that septum design is a trade off between conflicting goals and can be a useful tool in septum design, especially in the early stages of the design, in which one has to decide which topology suits the requirements better. The figure of merit calculated for every septum presented in this article can be found in Table 4. The values obtained by the SuShi prototypes are significantly higher than the other topologies because the SuShi operates always at critical current which makes an almost perfect shielding thanks to the persistent eddy currents present in the surface. The unshielded TCT, DTCT and the Stealth dipole present a very low figure of merit (not shown in this paper due to the fact that the septum will include the shielding). This is due to the fact that both designs produce a leak field that is two orders of magnitude higher than the SuShi prototypes since they rely on compensation coils or iron rather than in a natural phenomenon like eddy currents. However, the leak field can be mitigated by placing a shield around the zero-field region.

CONCLUSIONS AND OUTLOOK

A systematic way of characterizing different septa designs for a given set of parameters has been presented. This figure of merit ranks the different topologies and serves as a way of choosing a septum topology. Although the examples presented in this article are all superconducting, it can also be applied to normal conducting septa. Future development of the figure of merit includes taking into consideration the dynamic behaviour of the septa magnets, introducing a factor to consider the maximum ramp rate of the magnetic field (*dB/dt*).

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