ALTERNATIVE PROPOSAL FOR FCC-HH EXTRACTION SEPTA

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Abstract

Challenging requirements are set for the FCC extraction septa magnets, notably for the magnetic field level, the septum thickness and the leak field. An alternative to the baseline FCC extraction layout is proposed, consisting of a Superconducting Shield (SuShi) stage and a Truncated Cosine θ (TCT) septa stage with the aim of reducing the required number of septa and installed length. The principal parameters of the septa are described and the feasibility discussed. Areas for further improvement are identified.

BRIEF DESCRIPTION OF THE SUSHI SEPTUM

In a Superconducting Shield septum (SuShi), a superconductor is placed around the orbiting beam gap to exclude the magnetic field from that region. The field is excluded by persistent eddy currents generated on the surface of the superconductor when the external magnetic field is changed. The working principle of the shield is shown in Fig. 1. The magnetic field is generated by a Canted Cosine θ (CCT) magnet with an aperture big enough to fit the SuShi and both vacuum chambers. Two materials are being currently considered, Bulk MgB_2 and a multilayer Cu/Nb/NbTi composite [1, 2]. The characteristics of both SuShi prototypes are summarized in Table 1.

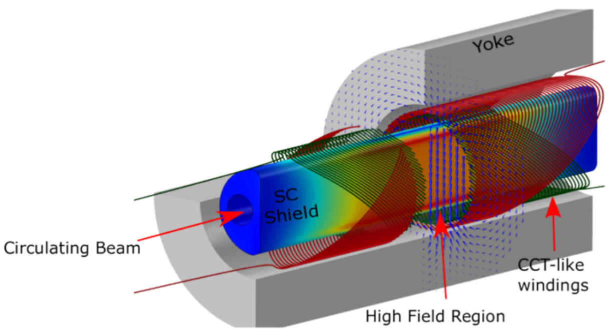

Figure 1: SuShi septum concept.

Table 1: Main Characteristics of the SuShi Prototypes Tested at CERN

Parameter	**Cu/Nb/NbTi**	**MgB_2**
B_0 (T)	3.1	2.75
B_{leak} (mT)	<0.1	<0.1
SuShi thickness (mm)	3.8	8.4
Outer diameter (mm)	47.4	49

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THE TRUNCATED COSINE θ SEPTUM

The design of a Truncated Cosine θ (TCT) septum is based on the well known Cosine θ dipole with line currents and an iron yoke. The magnetic field is created by a current distribution at a fixed radius that is scaled according to:

$$J = J_0 \cdot cos(N \cdot \theta) \tag{1}$$

With N=1, a dipole field will be generated. The image current method, analogous to the mirror charge method in electrostatics, is used to calculate the placement of the current distribution. The image currents can be replaced by an iron yoke that is not saturated and conducts the return flux of the magnet in the same way as the image currents, and its dimensions can be calculated analytically.

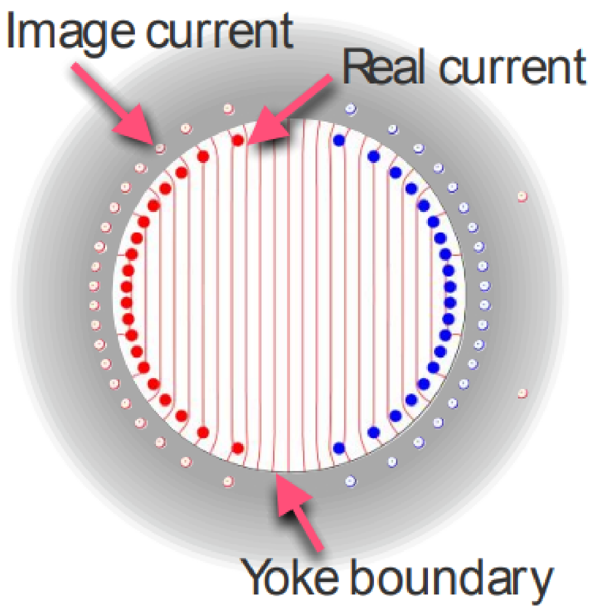

Figure 2: Cosine θ magnet concept.

The analytical calculation is based on two assumptions. The first one is that the permeability of the yoke is much higher than that of vacuum and not yet saturated. The second assumption is that a current wall that extends to the yoke forces the field lines to avoid the field-free region. In a conventional septum magnet, this current density needs to be constant to avoid the magnetic field leaking into the field free region. This is illustrated in [3]. The iron saturation for this calculation is set at 1.6 T. Some soft magnetic steels saturate at a higher level, but taking 1.6 T as a value therefore provides some margin. It is important to note that this magnetic field value is the peak field that can be allowed at a certain point in the yoke. If the yoke is saturated, even locally, the permeability of that region decreases and eventually becomes comparable to that of vacuum. If the permeability of the yoke is not sufficiently high, the magnetic field will leak into the field free region. It has to be noted that the boundary conditions change when the image currents are substituted by an iron yoke. In the case of the image current, the normal component of the magnetic field is zero while in the case of the iron yoke the magnetic field is normal to the iron interface.

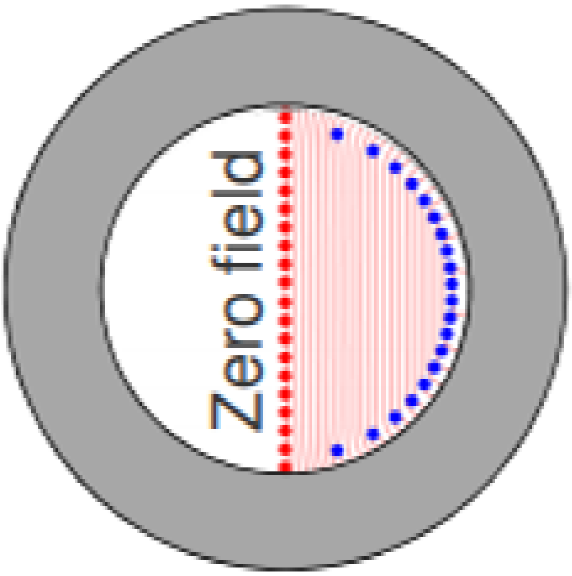

Figure 3: Truncated cosine θ concept.

Starting from a Cosine θ dipole, a truncation is applied to obtain a septum, as shown in of Fig. 3, which has been reproduced from [4]. In 2D, the magnetic field lines are lines of constant potential. Therefore, the magnet gap can be truncated along a constant potential line and the magnetic field inside the aperture will not leak outside the current wall. In this case, truncation means to place a current wall along the chosen equipotential line. Full derivation of a $\cos(N\cdot\theta)$ multipole can be found in [5] and a derivation of the truncation procedure was done by Krienen et al. [6].

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

Table 2: Main Characteristics of the Truncated Cosine θ Septum Proposed for FCC-hh

Parameter	**Value**
B_0 (T)	4
B_{leak} (mT)	0.1
Apparent septum thickness (mm)	35
Maximum gap height (mm)	70
Total current ($kA \cdot turns$)	195
Number of turns per pole (-)	31
Magnetic length (m)	4

TRUNCATED COSINE θ COIL DESIGN

The 2D cross section of the TCT septum is optimized in two parts. First, a conventional Cosine θ coil is optimized, then one of the sides of the coil is truncated. Finally, the cables in the straight part of the coil are tilted an angle that matches the corresponding cable of the Cosine θ part of the coil. Full details of the 2D design and optimization of the cross section can be found in [7].

For the 3D simulation, the coil model is made of the coil ends, the connection section and the straight section. The straight section is an extrusion of the 2D cross section, to model the central part of the TCT septum. The straight part needs to be included in the magnetic model to ensure the magnetic field in the central part of the model is vertical, as in the 2D model. This allows to simulate only the ends of the magnet, saving computation time and memory. The connection section is the intermediate part of the coil, which connects the straight section and the coil ends avoiding collisions and creating a model which is possible to mesh. It allows enough space in between the cables, which even if they do not overlap might cause problems when meshing the model due to the small interstices between cables. The connection part of the coil has been modelled as a 3 sets of 20 mm long cables that simulate a small cable bending, to avoid the cables crossing each other. The relevant part of the model are the coil ends, the straight part only simulates a long stretch of the real magnet. Simulating the full magnet is not possible due to the computational resources available. A detail of the coil end is shown in Fig. 4.

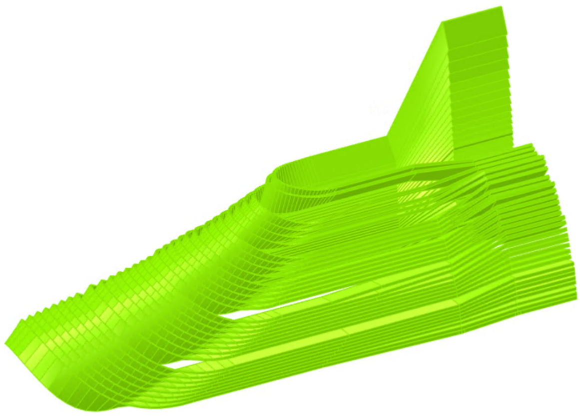

Figure 4: Detail of the TCT coil end.

A 3D simulation of the coil end, with appropriate symmetry, produced a leak field of approximately 50 mT·m for each end of the magnet. This result requires further optimization of the coil ends or the design of a compensation scheme to reduce the leak field of the TCT septum. The analysis of the stresses in the septum blade support and in the coil are discussed in detail in [7].

EXTRACTION LAYOUT

From the analysis in [7, 8] it follows that it is advisable to use two or three families in the extraction region, instead of one. For the analysis, it is assumed that the deflection of the different magnets is applied at the centre by an infinitely thin magnet with the total strength of that magnet family. The goal of this analysis is to find the best layout possible for the septa stage of the Beam Dump System (BDS). As the two septa families with the highest figure of merit are the SuShi septum and the TCT septum [7], these two families are considered for the BDS. The reason to use two different families is the knowledge obtained in [7] that the optimum number of families to use is two or three rather than one. The reason to use two different technologies is that it increases the degrees of freedom such as the magnetic field and septum thickness. In this study, the deflection provided by the extraction kickers and quadrupole will be taken into account by the apparent septum thickness (s) of the first SuShi septum. The starting point of this calculation are the apparent septum thicknesses of the SuShi septum (20 mm) and the TCT septum (35 mm). For a given kicker strength, it is necessary that the beam clears the apparent septum thickness of the SuShi septum as it arrives, which determines the drift space between the quadrupole and the first SuShi septum, although the real limit is the clearance of the cryostat at the end of the straight section. The distance between the kicker magnets and the quadrupole, as well as the strengths are taken as a fixed parameter. This is illustrated in Fig. 5.

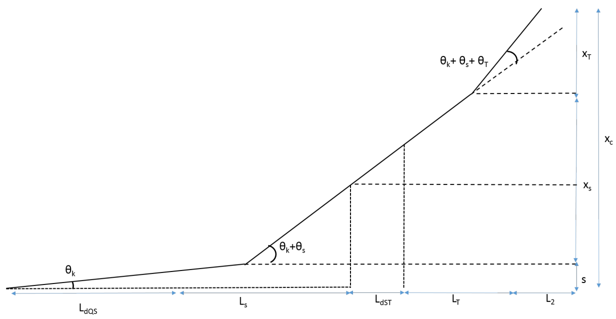

Figure 5: BDS layout schematic.

The optimization of the BDS has been performed sequentially as described in [7, 8]. The results are summarized in Tables 3 and 4. It is also possible to set up a full minimization problem for the total length, but it would involve non-linear and equality constraints, complicating the solution significantly. An intermediate approximation would be to solve the minimization problem and then approximate the solution to a close value. This approach in the end is the same as the one chosen.

L_S is the SuShi septa magnetic length, L_{ST} is the length of the drift space between the SuShi and the TCT septa. L_T is the TCT septa magnetic length and L_2 is the drift space downstream from the TCT septa. The indicated physical lengths are an estimation of the physical length of the SuShi and TCT septa.

Considering a magnetic length of 1.25 m for the SuShi septa and 4 m for the TCT, the necessary number of magnets for each option is compared in Table 4.

Table 3: Physical Lengths of the Extraction Septa System

Parameter	Optimized layout	Baseline
L_S (m)	15	20
L_S (physical)	16.6	22.2
L_{ST} (m)	61.7	20
L_T (physical)	55.6	43.9
L_T (m)	50	39.5
L_2 (m)	265.4	425
Total length (m)	399.3	511.1

Table 4: Number of Septa in the Extraction Septa System

Parameter	Optimized layout	Baseline
Number of SuShi magnets	12	12
Number of TCT magnets	14	11
Total number of magnets	26	23

The proposed layout in this study requires three TCT septa more than the baseline but the total length required for this alternative is almost 22% less than the baseline. The cost analysis is quite a complex problem because it involves many other aspects apart from the septa. Given the small difference in the number of septa needed for both options, a choice has to be made considering all the implications.

Although not shown in Fig. 5, there needs to be a passive protection device upstream from the injection quadrupole magnet. This device is different than the protection device that protects the extraction septa as it needs to protect the quadrupole magnet and not the septum blade. Space is reserved in the lattice for this device [9] and therefore it was not considered further in this study.

CONCLUSIONS

An alternative to the baseline extraction layout has been presented. It has been obtained with a systematical optimization and although it requires 3 more septa than the baseline, the total length is 22% shorter. This may have a significant impact in the cost evaluation, which is outside the scope of this study. Full details of this optimization can be found in [7].

It has been established that the SuShi septum is a great candidate for the FCC-hh BDS. The TCT also has enormous potential although it requires careful optimization of the leak field at the ends. The two identified improvement directions are either a geometry modification or a compensation coil scheme. Passive shielding works in the central part of the magnet, but it is not sufficient in the vicinity of the coil ends. As it is explained in [7], it is advisable to simulate the full TCT septum, which is not possible at the moment due to computing resources available, and then build a prototype to validate the simulation and the manufacturing of the coil.

REFERENCES

[1] D. Barna *et al.*, *First experimental results with a superconducting shield (SuShi) septum prototype.* FCC Week 2017.

[2] D. Barna *et al.*, *SuShi septum status report: Testing the NbTi/Nb/Cu multilayer shield and update on the concept*, CERN, 2018.

[3] E. Fischer *et al.*, "Superconducting septa and fast ramped cosine-theta magnets", in *FCC Week 2015*, https://indico.cern.ch/event/340703/contributions/802239/attachments/668821/919340/FCC_SC_Septa-FRM_EF_ID48.pdf

[4] E. Fischer *et al.*, "Design studies for a fast ramped high field superconducting septa", in *FCC Week 2016*, https://indico.cern.ch/event/438866/contributions/1085009/attachments/1257884/1857713/FCC-2016_ScSepta_ID86.pdf

[5] S. Russenschuk, "*Field computation for accelerator magnets: analytical and numerical methods for electromagnetic design and optimization"*, Wiley, 2010, https://cds.cern.ch/record/1221810

[6] F. Krienen *et al.*, "The truncated double cosine theta superconducting septum magnet", in *Nucl. Instrum. Meth*, A28, 1989, https://doi.org/10.1016/0168-9002(89)91249-7

[7] A. Sanz Ull, "Optimization of the magnetic septa for the Future Circular Collider", Ph.D. thesis, TU Eindhoven, 2019.

[8] A. Sanz Ull and B. Balhan, "Upgrade limitations for LHC Lambertson septa for FCC", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper MOP057, this conference.

[9] A. Lechner, *FCC-hh protection absorbers and dumps*. FCC Week 2018, Amsterdam, https://indico.cern.ch/event/656491/contributions/2930779/attachments/1629787/2597491/2018_10_04_fccabsorbersdump.pdf