SEPTUM MAGNET USING A SUPERCONDUCTING SHIELD

D. Barna*, Wigner Research Centre for Physics, Budapest, Hungary
F. Burkart, CERN, Geneva, Switzerland

Abstract

A field-free region can be created within a dipole magnet using a superconducting shield, which maintains persistent eddy currents induced during the ramp-up of the magnet. We will study the possibility to realize a high-field superconducting septum magnet using this principle. Properties of different configurations will be presented, and compared to the requirements of the FCC dump system.

INTRODUCTION

The parameters of the hadron-hadron ring of the Future Circular Collider Study (FCC-hh, Table 1) impose serious requirements on the beam extraction system: kickers and septa. Scaling the septum technology of LHC (Lambertson septa with ~1 T) in length would lead to 6 MW power dissipation for the two beams, and a beamline of over 500 m including pumps, gauges, etc, largely exceeding the available space. Even though more space could be allocated for the septum section, a more compact solution is highly desirable. The necessary increase of the field of the magnet to above 2 T requires superconducting coils to keep the power consumption acceptable. At such high fields the saturation of the iron yoke and the resulting leakage field to the circulating beam [1] require further changes of the topology. In order to be ready for a safety beam abort at any time, the septum magnet must follow the energy of the ring, i.e. operate in slow-ramp or quasi-DC mode.

Table 1: Parameters of the LHC and FCC Injection and Extraction Systems

	LHC		FCC-hh	
	inj.	ext.	inj.	ext.
Beam energy[TeV]	0.45	0.45-7	3.3	3.3-50
Stored beam energy[GJ]		0.36		8.4
Defl. by septum[mrad]	12	2.4	12.4	3
$\int B\,\mathrm{d}l$ [Tm]	18	56	136	500
Avail. space[m]			120	245
Septum thickness[mm]	(inc. vac. pipe etc)			26

SUPERCONDUCTING SHIELD

A field-free region within a magnetic field (such as that needed for a septum magnet) can be realized using superconductors:

- The Meissner-effect is of little practical use for this purpose since the critical field of type-I superconductors is typically a few-10 mT.
- Persistent shielding currents are excited on the surface of the material in a ramped magnetic field, which oppose any change of the field within the material.

A superconducting shield installed around the circulating beam and cooled below the critical temperature T_c in zero field will therefore “freeze” the zero field at its interior, as long as the shield thickness is large enough and the lifetime of the shielding currents is sufficiently long. The principle is similar to that used by eddy current septa except that the shielding currents do not decay, and the device can be used in slow-ramp or quasi-DC mode as required. The principle is illustrated in Fig. 1. The idea to create a field-free region within a strong magnetic field using superconductors is not new [2–7], but it has not yet been applied to create an accelerator septum magnet (the shield applied in [6] only shielded the leakage field of the magnet, and not the full field).

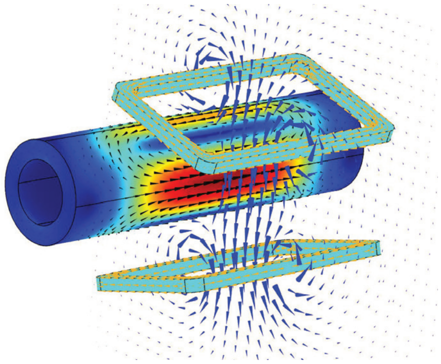

Figure 1: The principle of the superconducting shield. Blue arrows show the magnetic field in the transverse midplane; black arrows and colour show the shielding currents on the superconductor’s surface.

The principle has the following advantages. The shielding currents are automatically arranged by nature, there is no need for precise coil windings to create zero field at the circulating beam. The continuous 2D shielding current distribution perfectly shields the field inside, in contrast to the discrete wires of magnets. According to the critical state model the shielding currents flow everywhere at the local critical current density $J_c(B)$, i.e. the highest possible value, giving the thinnest possible shield. There is no need for insulating materials between windings, the shield can be a contiguous block giving good thermal and mechanical stability.

The disadvantages of this configuration are as follows. The high radiation in the extraction zones can affect the reliability of the device, and lead to heating and quenches (this holds for all superconducting solutions). The shield is a passive device, i.e. it has no current leads - this means that there

---

[*] barna.daniel@wigner.mta.hu

is no “recovery” (i.e. restoration of the ideal state) in case of a thermal perturbation when the excluded field penetrates more into the shield, even if the superconductor recovers thermally and does not fully quench finally. This means that the field configuration and the shield state are not a function of the controllable parameters T and B only, but also that of the history of the device. In case of field penetration a full “reset-cycle” is needed to recover the device: heating above T_c and cooling down in zero field.

POSSIBLE MATERIALS AND CONFIGURATIONS

The 1 mm thick multilayer NbTi/Nb/Cu sheet (the 2D analogue of standard multifilamentary NbTi superconducting cables) used by the BNL g-2 inflector [6, 7] consists of 30 layers of 10 μm thick NbTi sandwiched between Nb and Cu layers. 4 stacked sheets (i.e. 4 mm total thickness) could shield a field of 3 T [7]. The allowed physical septum thickness of about 15 mm (excluding vacuum pipes and gaps, etc) could contain even more sheets to have a safety margin. The sheets could be embedded in a copper block as shown in Fig. 2a, which would serve as a mechanical support and thermal stabilizer, and could include liquid-He cooling channels. The sheet is a discontinued commercial product of Nippon Steel Ltd.; semi-finished blocks requiring some rolling and heat treatment stages are still available from the vendor.

Commercially available superconducting tapes (HTS, Nb_3Sn, MgB_2) have a small width (10-15 mm) which is insufficient to make a jointless tube with a diameter of about 4 cm that does not intercept the path of the shielding currents. The technology developed at CERN to produce wide Nb_3Sn tapes [5] did not make its way to the market. A superconducting shield could nevertheless be produced by helically winding and soft-soldering several layers of tape onto a supporting tube (Fig. 2b), each layer shifted by half the tape width. The mechanism of shielding is illustrated in [8]. The efficiency of this configuration is yet to be tested. These tapes have typically a minimum bending radius (~5 cm) which is compatible with the parameters of a septum magnet.

A third option is bulk MgB_2, which can be produced either by the reactive liquid Mg infiltration [9] or the powder-in-tube method. While the former results in a material with slightly better performance and higher density, the latter is more adequate for the proposed geometry and mastered by industry. MgB_2 powder is filled between two concentric titanium tubes and a copper rod is inserted into the inner one to reinforce it. After compacting the powder the assembly is rolled to the shape shown in Fig. 2c, and the central copper rod is drilled or etched away. A final heat treatment at 500-600 °C fuses the grains of the powder.

SHAPING THE FIELD

A magnetic field of 3-4 T would penetrate a high-J_c superconductor only a few millimeters, which is much less than the characteristic size of these shields. As an approximation one can treat the superconductor surface as a perfect magnetic insulator, i.e. an iso-surface of the A_z magnetic scalar potential of 2D magnetostatics. Since the shield is a passive device with no current leads, the induced currents must integrate to zero. This configuration is equivalent to a floating metal electrode with zero net charge in 2D electrostatics. The 2D problem of a cylindrical shield can be solved using the conformal mapping $w \equiv u + iv \equiv \log(R) + i\phi = f(z) = \log(z) \equiv \log(x + iy)$, where x and y are the 2D coordinates, $R = |z|$ and ϕ is the argument of z. This mapping transforms the exterior of a circle into a semi-infinite band as shown in Fig. 3. The magnetic scalar potential A_z due to a single wire with current $+I$ can be calculated in the w-plane by mirroring it through the surface of the cylinder with opposite current (-I) to guarantee a constant potential along the cylinder surface, and then replicating both of these along v by $\pm 2n\pi$ ($n \in \mathbb{Z}$) to respect the cyclic boundary condition in v. To compensate the net current -I inside the cylinder, a current of +I must be attributed to the cylinder surface (i.e. a current density $+I/2\pi$), and -I must be attributed to infinity (i.e. $u = \infty$). This gives an extra linear term $-u \cdot \mu_0 I/2\pi$ to the magnetic potential created by the wire pattern.

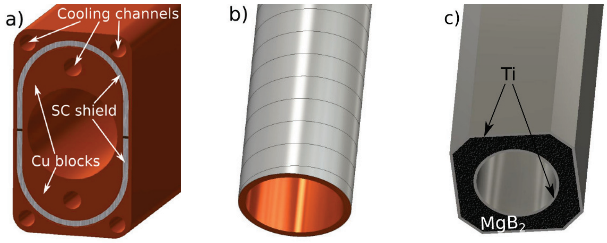

Figure 2: Possible shield configurations for different materials. See text for details.

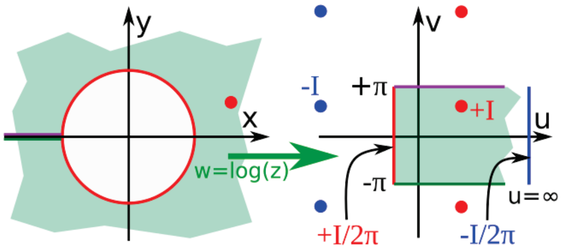

Figure 3: Transformation of the exterior of a circle by the conformal mapping $w = \log(z)$.

The simplicity and high speed of this algorithm allows a brute force optimization: evaluating all possible wire configurations on a predetermined grid. Figure 4a. shows the optimal wire configuration around a cylinder with 6 positive and 6 negative wires, for a given field strength. The resulting field pattern has a quadrupole-like structure. For a rectangular shield it seems natural to position the wires such that the zero field is aligned with the corner of the shield (Fig. 4b.). The flat wall of the shield makes it easy to produce a homogeneous field for the extracted beam.

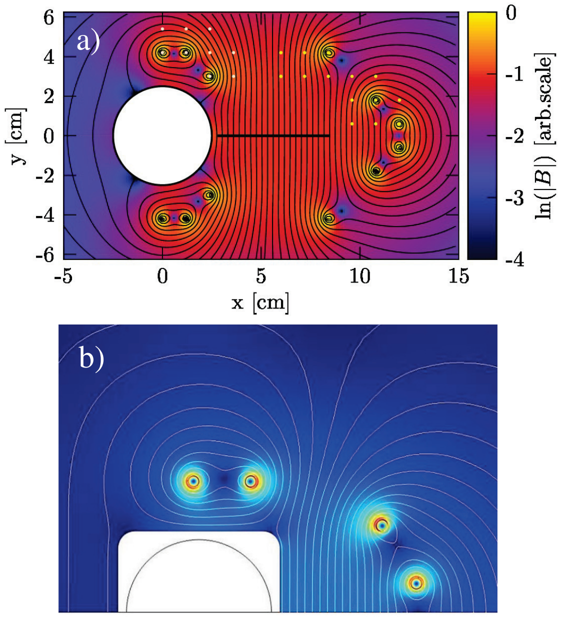

Figure 4: a) Optimized wire configuration around a cylindrical shield. The black line shows the region where the field was required to be homogeneous. b) Magnetic field around a rectangular shield (not optimized).

MASSLESS SEPTUM

In case of an asynchronous dump (when the kicker magnets fire out of synchrony with the particle-free abort gap) the beam is swept across the septum blade. Since at the FCC the impact of even a single bunch can damage conventional materials, sophisticated protection elements are needed upstream of the septum magnets. However, the particle showers created in these elements can still reach the septum magnets and lead to heating and quenches. A massless septum (which has no material in the way of the swept beam) is insensitive to this problem; protection elements could be installed more conveniently downstream of the septa to protect the rest of the beamline. Due to the symmetry of the system the shielding currents do not cross the midplane of the shield (Fig. 1), and an opening on the shield does not intercept the path of the shielding currents (Fig. 5a.) A detailed simulation of the shielding current pattern around the massless gap and the penetration of the field through the gap, as well as an evaluation of the mechanical stability of this geometry is necessary to evaluate the suitability of this configuration.

CONCLUSIONS AND OUTLOOK

The parameters of the FCC-hh ring require a septum magnet with a magnetic field above 2 T for the extraction. A device using a superconducting shield is proposed which creates a field-free region within a strong magnetic field via the persistent shielding currents excited in the shield by a ramped external field. Projects of the past have demonstrated that shielding 3-4 T is possible with a shield thickness that is compatible with the requirements of the FCC. Different materials and technologies are available today to construct the shield, and several vendors have offered to deliver prototypes within a short time. A series of tests with these prototypes is planned to prove the principle and evaluate their properties: the highest field they can shield; lifetime of the shielding currents; stability against thermal perturbations, flux jumps; effect of radiation on the shield; highest safe warm-up and cool-down rates and the length of a "reset-cycle"; detection of degraded shielding (i.e. shielding currents below J_c). These tests are planned to be carried out at CERN.

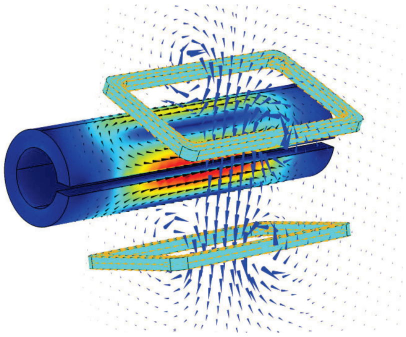

Figure 5: A massless septum configuration with the superconducting shield (illustration).

REFERENCES

[1] M. Atanasov, "FCC beam dump septum requirements and suitability of different septa technologies and topologies", presented at the FCC Week 2016, Rome, Italy, Apr. 2016, unpublished.

[2] F. Martin, S.J.St. Lorant, W.T. Toner, "A four-meter long superconducting magnetic flux exclusion tube for particle physics experiments", *Nucl. Instr. Meth.* vol. 103, p. 503, 1972.

[3] M. Firth, E.U. Haebel, L. Krempasky, F. Schmeissner, "Performance of the superconducting field shielding tube for the CERN 2 meter hydrogen bubble chamber", in *5th Int. Conf. on Instrumentation for High-energy Physics*, Frascati, Italy, May 1973, p. 79.

[4] M. Firth, L. Krempasky, F. Schmeissner, "Preliminary work on field-free particle beam paths from hollow superconducting shielding tubes", CERN internal note.

[5] "CERN 6 Tesla superconducting persistent dipole", CERN Courier, May 1979, `https://cds.cern.ch/record/1730426`

[6] A. Yamamoto *et al.*, "The superconducting inflector for the BNL g-2 experiment", *Nucl. Instr. Meth.* vol. A491, p. 23-40, 2002.

[7] I. Itoh, K. Fujisawa, H. Otsuka, "NbTi/Nb/Cu multilayer composite materials for superconducting magnetic shielding", *Nippon Steel Technical Report*, no. 85, p. 118, Jan. 2002.

[8] S. Samolienkov *et al.*, "Customized 2G HTS wire for applications", *Supercond. Sci. Technol.* vol. 29, p. 024001, 2016.

[9] G. Giunchi, "High density MgB_2 obtained by reactive liquid Mg infiltration", *Int. J. Mod. Phys.*, vol. B17, p. 453, 2003.