Closing report of the OTKA K124945 grant

1 Introduction

This document presents the overview of the activities and the achieved results during the course of the OTKA grant no. K124945. These have become broader and more diversified than originally proposed, with many of the extra activities being carried out in the framework of, or related to new projects and collaborations. These activities are described in detail if they are not part of the official program of another project, or are not officially assigned to the research group. Otherwise they are only briefly mentioned to highlight the indirect benefits of the OTKA grant serving as a seed.

2 SuShi septum

The primary goal of the project was to work out the novel concept of a septum magnet utilizing a superconducting shield to create a field-free region inside the bore of a superconducting magnet; to carry out proof-of-concept experiments and simulations; and optionally, to design and build a prototype magnet. Prior to, and during the initial phase of the project, three potential shield materials have been tested: a bulk MgB_2 shield (shielding 2.9 Tesla field with a wall thickness of 8 mm)[1], an HTS screen (underperforming the expectations), and a NbTi/Nb/Cu multilayer shield (shielding 3 Tesla field with 3.2 mm wall thickness)[2]. Detailed finite-element simulations, taking into account the $J_c(B)$ characteristics of the given material and the penetration profile of the field, could precisely and quantitatively reproduce the measured phenomena. The simulation framework, validated this way, has then predicted that the field quality requirement ($\pm 1.5\%$ field homogeneity) is easily fulfilled in a real magnet design[3]. The tests with the NbTi shield have also shown that this material is stable against flux jumps at a ramp rate that is higher than required for the FCC, and that the trapped field in the shield can be removed by a degaussing cycle[2]. Based on these results, the NbTi/Nb/Cu multilayer sheet was identified as the best candidate material.

Tests with the NbTi/Nb/Cu shield have shown[2] that a simple inductive pick-up coil encircling the shield's wall, read out by a fast digital integrator can trigger the beam abort system early enough, before the magnetic field starts to rise at the location of the circulating beam, in the case of an eventual flux jump in the shield.

These results have proven the feasibility of the concept. Having an incredible support by CERN and the superconducting magnet development team of building 927 (sharing of know-how and existing CCT magnet designs, providing training for magnet winding, etc), the design of a prototype magnet was completed, which was based on the canted cosine theta (CCT) concept [4].

The magnet components have been manufactured, and (in the last year of the project) the magnet winding was completed. Compared to the simple CCT dipole magnets for the high-luminosity upgrade of the LHC (serving as a reference design for the SuShi magnet), the SuShi winding has a more complex shape, which made the winding process much more difficult - in particular, a tooling was necessary to keep the wires from popping out of the grooves. Experience gained during the winding training at CERN, and early winding tests of the SuShi septum revealed design issues which have been improved for the final SuShi design, and were channeled back to the CERN team. These include the layer jump configuration (where the superconducting strands transition from the inner layer to the outer layer, for which a very easy-to-assemble design has been achieved),

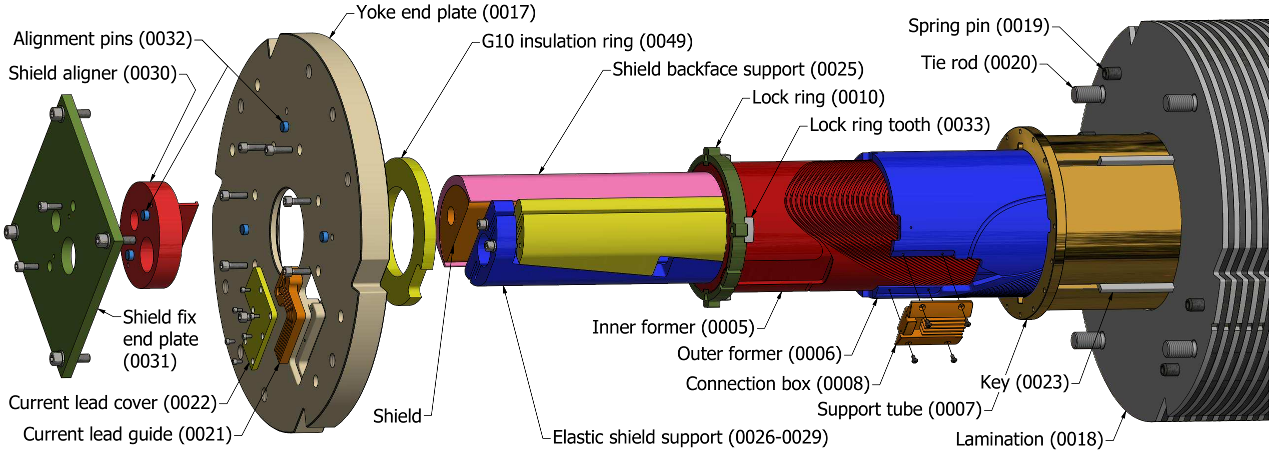

Figure 1: Exploded view of the CAD model of the SuShi septum prototype.

the azimuthal alignment mechanism between the formers, and the redesign of the impregnation mold which copes with the different thermal expansion rates of the assembly components during hot impregnation, and allows the application of a higher pressure.

Manufacturing defects of the formers (burrs and other sharp features, hard to see by the naked eye and taking a considerable time to discover) damaged the insulation of the superconducting strands several times. The strands (received from CERN's inventory) for the magnet winding have shown the signs of prior usage, and had some insulation defects. These caused the coils to fail during the high-voltage tests, making the partial unwinding and repair necessary and delaying the completion of the winding. Difficulties due to the COVID pandemic have also caused a serious delay in the progress.

Figure 1 shows the exploded view of the CAD model. Figure 2 shows the completed magnet winding.

3 Quench simulation software

A standalone quench simulation software has been developed based on the commercial finite-element software COMSOL, which is able the approximate the electro-thermal behavior of the discharging magnet in a quasi-3D manner. It takes into account both the transversal heat propagation along the cross-section of the magnet and longitudinal heat propagation along the superconducting strands.

The simulation was validated using experimental data for discharges of the CERN high-luminosity LHC corrector magnet. The model could reproduce the experimental current discharge curves with at most 12% (average 6.6% for all test cases) relative difference in the adiabatic hot spot temperature. The simulation satisfies the requirement of being pessimistic, it overestimated the experimental hot spot temperatures in all cases.

For the SuShi septum magnet, the resulting temperatures ranged between 31.4 K and 42.2 K for realistic values of the dump resistor, giving a large safety margin for the magnet protection.

These results, supported by experimental data from the CERN high-luminosity LHC corrector CCT magnets with similar parameters, provided evidence that the SuShi prototype magnet can be safely protected by the same external energy extraction circuit. Subsequently, the resources were concentrated on the experimental work and consequently the documentation of the simulation framework and the achieved results got pushed backward in the priority queue. They are planned to be published together with the experimental results obtained during the magnet tests.

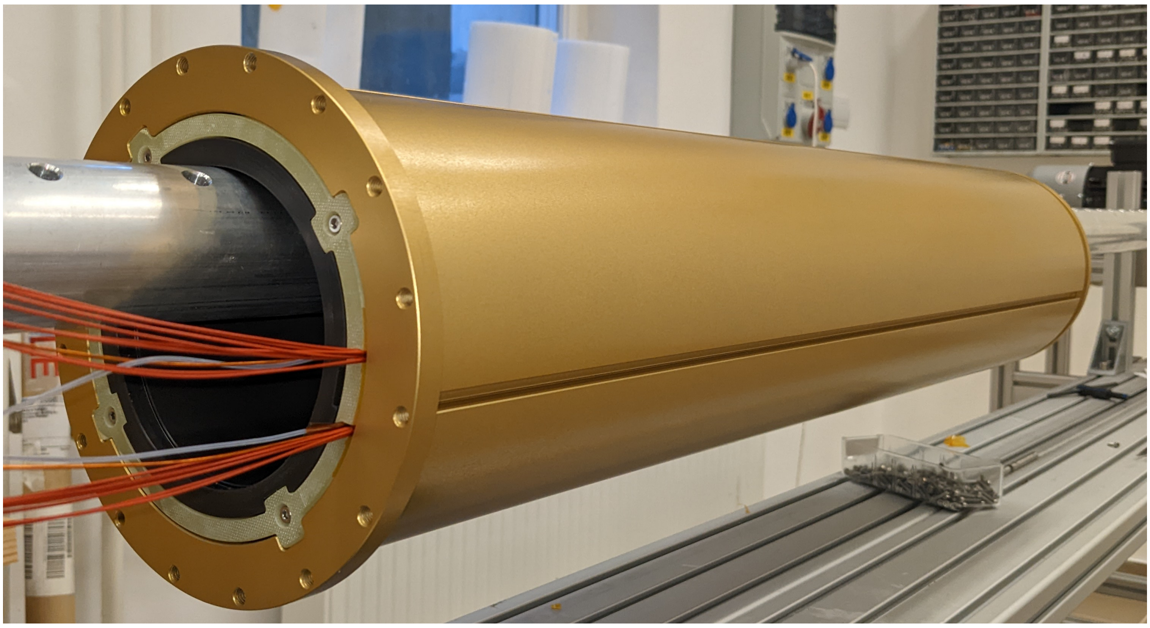

Figure 2: The assembled SuShi septum magnet (without the yoke yet).

4 Wax impregnation

Recent experiments at PSI[5] demonstrated that in a stress-managed cable configuration (where individual superconducting cables are installed in rigid support channels), wax-impregnated Nb_3Sn cables outperformed all standard epoxies, reaching the short sample limit without training. Wax has the additional benefits of being cheap, non-toxic, requiring a lower treatment temperature (melting point around 54-56 °C), and providing a reversible impregnation process: in case of a failing magnet (defective splices, or high-voltage spark) the wax can be removed, and the winding can be remade, sparing the expensive formers of the CCT magnet. Since the SuShi prototype was at the right phase, i.e. before impregnation, we have decided to study the feasibility of wax impregnation for a realistic CCT magnet, and develop a reliable method. The challenge is to make a void-free mold despite the 10-15% contraction of wax upon solidification. A very simple and cheap setup (a 0.5 m CCT former received from CERN, wound with remaining, trashed strands from the SuShi winding, installed in a removable Plexi tube) was used for the series of tests, which have demonstrated that the "progressing phase boundary" approach can lead to void-free molds. In this approach heating and cooling are applied simultaneously in a controlled way to define a clear planar phase boundary between liquid and solid wax, and this boundary is progressively moved upwards, allowing the continuous refill of liquid from a local reservoir on the top, without being blocked.

The method developed during these tests are of potential interest for the HITRIPlus (WP8), I.FAST (WP8) and the Fusillo projects (the latter is a CERN-Spanish project to create a large-aperture curved combined-function CCT magnet). HTS CCT magnets (I.FAST WP8) could especially benefit from this method since HTS conductors can delaminate if impregnated in epoxy.

These tests have delayed the impregnation and the completion of the SuShi septum magnet.

5 NbTi/Cu multilayer sheet R&D

The NbTi/Nb/Cu multilayer sheet, a key material for the SuShi septum, was developed several decades ago by Nippon Steel Ltd. Since then the product has been discontinued. Procurement of the samples used in the tests was very difficult (semi-finished products from the remaining stock of the company, post-processed by an external company) and expensive. Future availability was not guaranteed. In order to keep or recreate the know-how, and potentially develop a cheaper manufacturing technology, the University of Miskolc, Hungary (Institute for Physical Metallurgy, Metalforming and Nanotechnology) joined the project. Initial activities of the PI in this research direction were running under the umbrella of the OTKA grant, but the project has soon become independent, with funding secured by the Miskolc team from other sources. These results are therefore only briefly touched on here. A manufacturing method has been developed which can eliminate the Nb layer from the structure. This layer has the sole purpose of being a diffusion barrier during the hot forming phase, to avoid the formation of hard Cu-Ti intermetallics, which do not co-deform, and lead to the puncture or breakage of the superconducting layers. Elimination of the Nb layer leads to cost savings on the raw materials, and also makes the bonding between the layers easier.

6 Optimization of the FCC beam dump dilution pattern

Beyond the program of the original proposal, the research team proposed and worked out the concept of optimizing the beam dump dilution pattern of the FCC using the very same hardware as in the baseline design, using slightly detuned, beating frequencies by different groups of the beam dilution kicker magnets. This resulted in a homogeneous energy deposition density distribution on the dump target, and as a consequence, in an 18% reduction of the maximum excursion of the pattern (i.e. the dump target size), and 13% reduction of the total kicker strengths [6, 7]. Subsequently, the optimization of the full FCC dump beamline optics has been carried out[8]. Benedek Facskó won the first prize at the National Scientific Students' Associations Conference (OTDK) in 2021 for his work.

7 Field distortions due to HTS beam screen coating

Induced persistent currents in the planned HTS beam screen coating of the Future Circular Collider could lead to field quality degradation. The proposed method to master these disturbances [9] was not further studied, K. Brunner moved to CERN for a PhD position, working on the development of a radio-frequency impedance measurement system, aimed at analyzing different beam screen candidates at cryogenic temperatures in a magnetic field.

8 HITRIPlus

As a consequence of our experience with CCT-like magnets and the recognition of the achievements, the research group has been invited to participate in the HITRIPlus H2020 project, which aims to develop the reference design of a compact (8×8 m) superconducting synchrotron for hadron therapy, and construct the prototypes of the key elements, including the ring and gantry magnets.

8.1 Curved CCT magnets

The group participates in the simulation/design of the curved CCT ring magnets, and is the leader of Task 8.3 (Preliminary Engineering Design for Accelerator and Gantry Magnets). A working group (chaired by D. Barna and E. Benedetto) has been set up to work out the characterization framework for the field quality of curved accelerator magnets. An optimization algorithm for the winding geometry of curved CCT magnets was developed by the team[10] and subsequently used to define the winding geometry of the HITRIPlus prototype magnet.

8.2 Opposite-field septum magnet

One of the key elements of the extraction systems of particle accelerator rings is the septum magnet, which creates two regions with different values of the magnetic field in close proximity, with a physical, current-carrying wall, called the septum blade separating the two regions. Upon extraction, the beam normally passing through one of the apertures is kicked into the other aperture by a fast upstream kicker magnet. A large jump of the magnetic field across the blade is required for a large separating power, in order to decrease the length of the septum magnet or its distance to the next downstream ring magnet. A small blade thickness is required to reduce the requirements on the kicker strength, and/or keep the kicker-septum distance small. These contradictory requirements can be satisfied using superconducting wires (allowing high current densities in the wall, and thereby a large field jump despite the small blade thickness), and magnetic fields of the same magnitude but opposite sign in the two apertures, eliminating the magnetic pressure on the blade.

The research group proposed a novel concept of an opposite-field superconducting septum magnet. The 2-dimensional wire arrangement has been determined using a smart application of the truncated cosine theta concept [11]. This design promises a ± 0.7 T magnetic field (i.e. a separation field difference of ΔB=1.4 T), with a wall thickness of around 5 mm. As a comparison, the "thin" and "thick" normal-conducting extraction septum magnets of the MedAustron medical accelerator have blade thicknesses of 10.5 and 21 mm for nominal maximum fields of 0.49 and 0.98 T, respectively.

Subsequently, an automated python code has been developed, which generates the full 3D winding geometry, ensuring clear access to the two apertures, respecting a minimum bending radius of the wires, avoiding self-intersection of the wire paths, and creating a layered coil end structure which guarantees practical windability [12], see Fig. 3. Detailed three-dimensional simulation of the field pattern using the software RAT demonstrated that an accelerator-grade field quality is achieved even for the 3-dimensional coil geometry. The same python code automatically generates the CAD model (for Autodesk Inventor) of the complex coil end formers, for which a manual design would be very cumbersome. The code also generates the G-code for CNC machines for these elements to spare CAM programming, which – based on detailed discussions with potential manufacturers – would be a significant fraction of the manufacturing costs. The detailed CAD model of the magnet has been developed, see Fig. 4. A journal article manuscript describing the 3D design and simulation is in preparation.

Planned for the HITRIPlus medical ring, the magnet would need to support high ramp rates, therefore the formers need to be manufactured from materials with low conductivity. We have adopted PEEK (polyether ether ketone) with 30% glass fiber content as the baseline candidate material, similarly to the HITRIPlus curved magnet R&D efforts. PEEK is radiation tolerant, has a thermal expansion coefficient matching those of metals, has excellent mechanical properties, is easily machinable, and can even be 3D printed. Given the high price of the material, the development of cost-efficient manufacturing methods with minimal material loss is very important. A proposal has been worked out and submitted to the "I.FAST Innovation Fund" to study and develop the best manufacturing methods (including and combining compression molding, 3D printing, CNC machining) and construct a prototype magnet, in a consortium formed by Wigner Research Centre for Physics, the Institute for Physical Metallurgy, Metalforming and Nanotechnology of the University of Miskolc, and Camilleon Ltd.

8.3 Optics

Since the opposite-field septum magnet has a non-zero magnetic field in both of its apertures, it would be part of the ring optics. Therefore the group started participating in the design of the ring and the extraction optics as well during the summer of 2022. The baseline ring layout of the project is a triangular shape with the 120° 2-in-1 magnets at the corners being segmented into 4 parts. With the fully constrained geometry, and requiring that the quadrupole gradients of the two external (k_1) and two internal (k_2) combined-function magnets are equal, the optimization problem is two-dimensional. Optically stable islands in (k_1,k_2) space have been identified, beamsize in the two planes has been studied. While a final conclusion is yet to be reached, the following statements have been made:

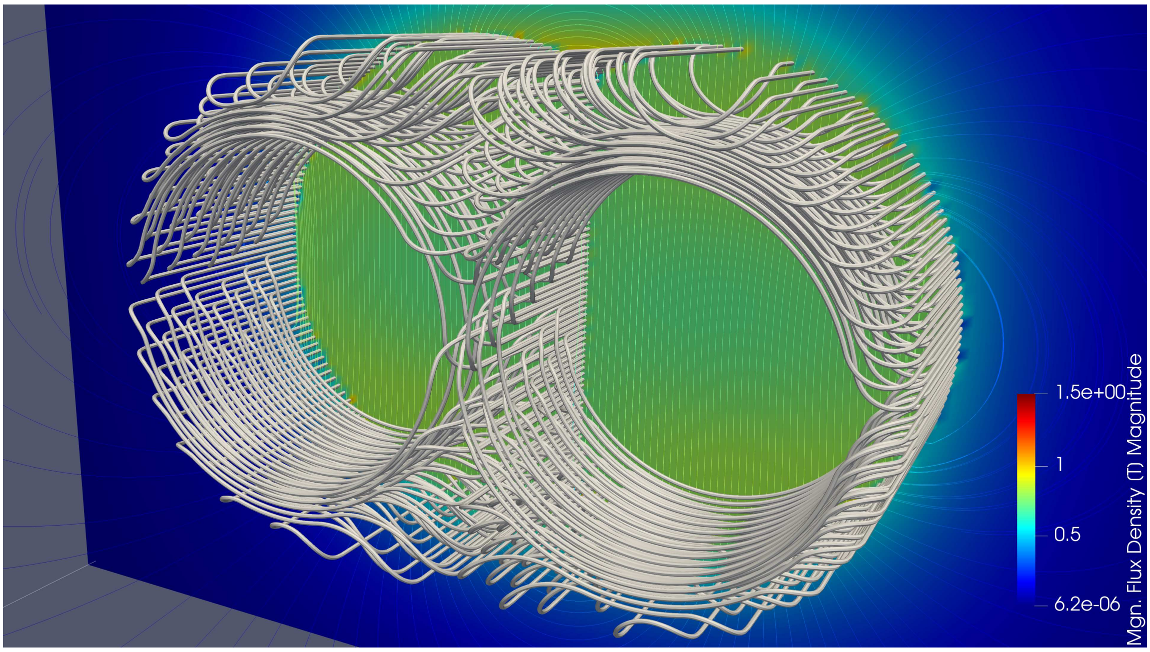

Figure 3: 3D winding geometry of the opposite-field septum magnet generated by the automated python code, and the 3D field map calculated using the software RAT

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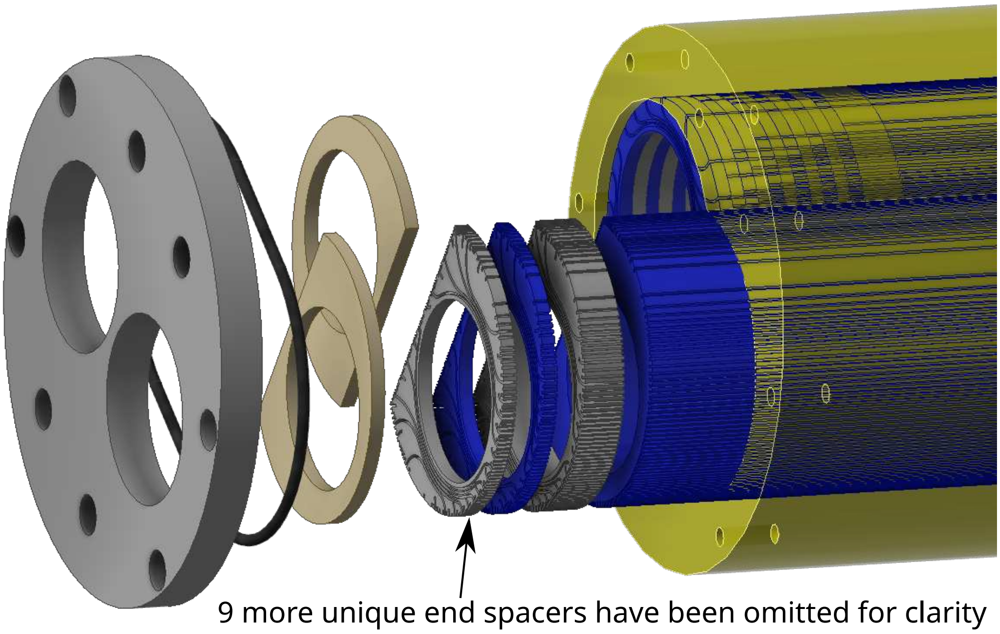

Figure 4: Exploded view of the opposite-field septum magnet CAD model.

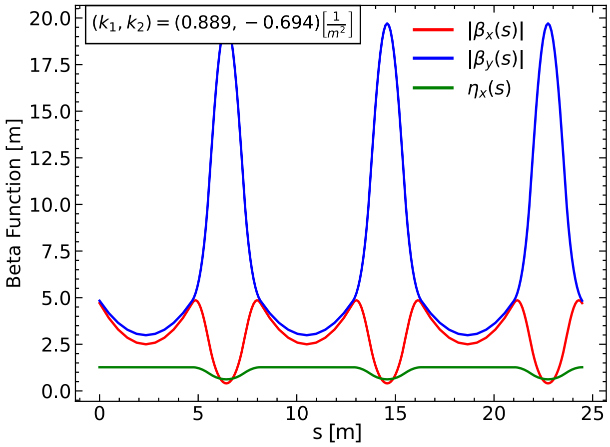

Figure 5: Optics of the HITRIPlus ring.

- The compact ring layout, and the short straight sections do not make it possible to install both the kicker and septum magnets into the same straight section.
- In the optimal arrangement the kicker is right upstream of, and the septum magnet is right downstream of a bending section.
- Therefore the extracted/displaced beam needs to traverse the bending magnets. The very thin blade of the opposite-field septum magnet may be a key to fit both the circulating and extracted beams within the aperture of the bending magnets.

Figure 5 shows the optics functions for a particular, feasible ring configuration. The work on this subject is ongoing, the results are unpublished yet.

9 I.FAST

The research group participates in the design and construction of a straight combined-function HTS and NbTi canted cosine theta magnet prototype. These activities are very strongly linked to the activities of, and the experience gained during the present OTKA project, but are not covered here.

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