VALIDATION OF THE CERN PS EDDY CURRENT INJECTION SEPTA

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Abstract

As part of the upgrade of the CERN PS accelerator from 1.4 GeV to 2 GeV, new injection septa have been developed. The system is comprised of a pulsed eddy current septum magnet and a pulsed eddy current bumper magnet. Both magnets will be housed in a common vacuum vessel and powered by independent power converters. In-depth studies and simulations have been performed to reduce as much as possible the leak field by designing specific magnetic shielding, combined with dual function beam impedance shielding. A prototype magnet was built and measured to validate the simulations. The final complete system will be bake-able at 200 °C and uses demineralised water for cooling. Closed circuit cooling systems have been integrated to reduce risks of vacuum leaks. This report describes the electromechanical design from the concept and simulation stages to the prototyping and final manufacturing. Results of the initial magnetic measurements, including field homogeneity and leak field mitigation methods are presented.

INTRODUCTION

The PS Booster (PSB) extraction energy will be increased from 1.4 GeV to 2 GeV in the framework of the LIU project [1]. Consequently, the septa used for the PS injection will be upgraded [2]. An 'Eddy Current' device to achieve the required integrated magnetic field using a more robust topology will replace the present injection septum for the PS. To obtain the required integrated field for the 2 GeV beam, the new injection septum magnet requires the full length of SS42 to be available. The injection bump is achieved with five bumper magnets. Since one of them, BSW42 is located in injection straight section of the PS, it has to be installed next to the septum in the same vacuum vessel. For this bumper a 'direct drive like' eddy current septum topology is used to improve the field homogeneity.

DESIGN CONCEPT

In an eddy current septum the main coil is located around the back leg of a C-shaped yoke and the insulation and conductor cross section can be chosen more conservatively compared to a conventional septum magnet. When the eddy current septum is pulsed, the septum blade is therefore not directly driven by the power supply, but the magnetic field in the magnet gap induces eddy currents in the septum blade, counteracting the leak field created. To minimise the leak field next to the septum conductor, a "return" copper box is generally constructed around the yoke, and a full sine pulse of relative short duration is desired. The duration of the current pulse is ideally chosen such that the septum thickness corresponds to approximately 5 to 10 times the skin depth of the current in the septum conductor.

Additionally, a magnetic screen is placed next to the septum conductor, supplemented by a magnetic beam screen, which is copper coated on the inside to limit the beam impedance.

PRINCIPAL DESIGN PARAMETERS

The table below (Table 1) outlines the principal design parameters for the injection system.

Table 1: Design Parameters

Parameter	SMH42	BSW42
Nominal Beam Energy	2 GeV	2 GeV
Physical length	940 mm	350 mm
Magnetic length	913 mm	322 mm
Septum thickness	5.8 mm	5 mm
Nominal septum position w.r.t. orbiting beam	54 mm	
Radial Position range	50–64 mm	
Angular range	9 –16 mrad	
Gap height	70 mm	70 mm
Gap width	95 mm	145 mm
Nominal deflection	55 mrad	11.4 mrad
Bgap	0.543 T	0.375 T
Integrated Field	0.510 Tm	0.106 Tm
Peak Current (Nom)	30.7 kA	18.3 kA
Pulse length	2 ms, full sine	1 ms, ½ sine

MAGNETIC DESIGN & SIMULATIONS

Electromagnetic simulations focused on the septum leak field calculation, mitigation measures and improvement of the field homogeneity in the gap of the bumper. To ensure accurate calculation of eddy currents and to reduce the simulation time, sufficient layering was used in the copper box. The number of layers used were five due to the fact that the pulse duration is long compared to usual assumptions in eddy current septa, which makes the skin depth bigger than usual.

The septum will be powered by a 2 ms full sine wave and the signal used for the bumper will be a 1 ms half sine. For the measurements, due to availability and reproducibility issues with the power supply, it was decided to measure the leak field and the field homogeneity with a 1.5 ms half sine wave. It is a good compromise between feasibility and obtaining representative measurement. Further measurements with a full sine wave shall be carried out in the near future.

Two different pulse lengths (half-sine waves of 1 and 1.5 ms) were simulated and measured. The field homogeneity is defined as $\int Bdl / \int B_{ref}dl$ in which the reference has been taken in the middle of the gap. The difference between the 2 simulated pulse lengths on the field homogeneity is minimal. Although a significant difference was observed

close to the septum between the simulated and the measured fields (due to the coarse meshing of the simulation model to limit computation time), the difference between the measured 1 and 1.5 ms pulse length was below the measurement accuracy (see Fig. 1).
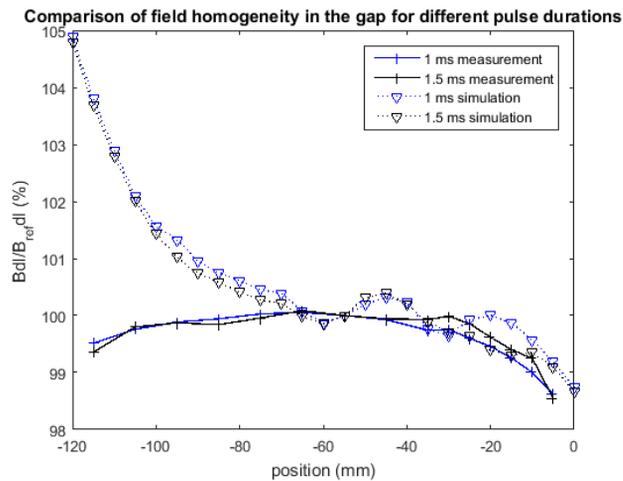
Figure 1: Integrated field Homogeneity across the magnet gap where the return conductor is located at -140 mm and the septum at 0 mm.

The leak field of the septum has been measured and simulated. Initially, measurements and simulations with no magnetic shielding were performed and compared with different screen geometries. To reduce further the leak field, a soft iron U shaped shield, 3mm thick and extending 20 mm beyond the end of the septum, has been adopted. The width of the U shape is 72 mm. Figure 2 shows the comparison between the measurements and simulations of both the shielded and unshielded magnet.
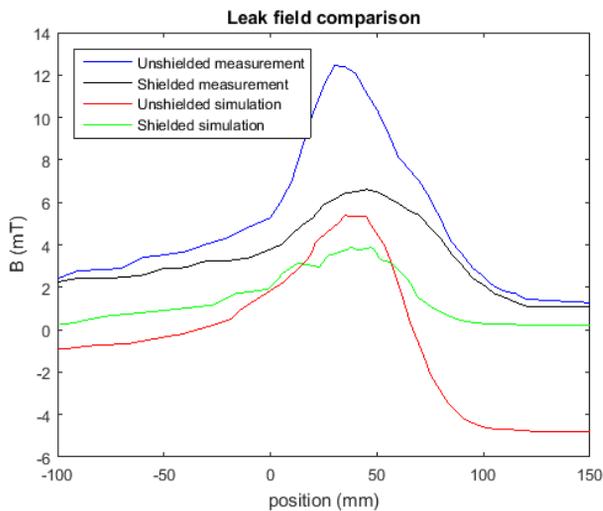
Figure 2: SMH42 leak field with and without shielding in addition to the leak field predicted by simulations. (100mm inside screen, 150mm beyond magnet end).

MECHANICAL DESIGN

The PS injection system (Fig. 3) consists of a vacuum tank housing two magnets, one eddy current septum and one eddy current bumper. The magnets are pulsed through transformers and electrical stripline type connections with current measurement by means of DCCT's situated on the secondary of the transformer.

The magnet yokes consist of laminations (0.35 mm thick) which are stacked, aligned, compressed and tensioned using a tie-rod arrangement which also fixes the ceramic coated endplates to the yoke. The complete assembly is therefore always kept under compression.

The alignment precision is 0.1 mm radial and 0.1 mrad in the angular direction. The total range of movement is 14 mm radial and 9 mrad angular.

The septum and bumper are clamped together in the vacuum tank and are equipped with a beam screen on the downstream side. The beam screen also forms part of the leakage field reduction mechanism.
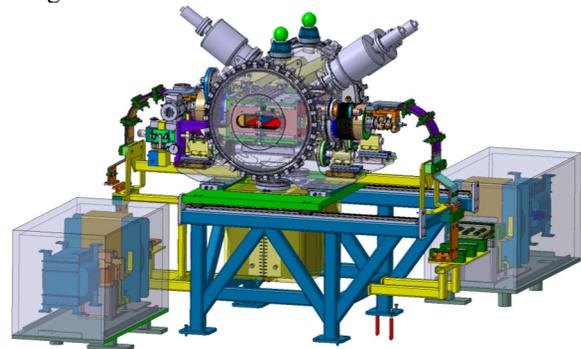
Figure 3: 3D model of complete system.

The main coil also uses tie-rods to pre-tension the assembly and secure it to the yoke via apertures in the laminations.

Due to the inherent design principles of eddy current magnets there are challenges arising such as vacuum outgassing, pumping and cooling methods.
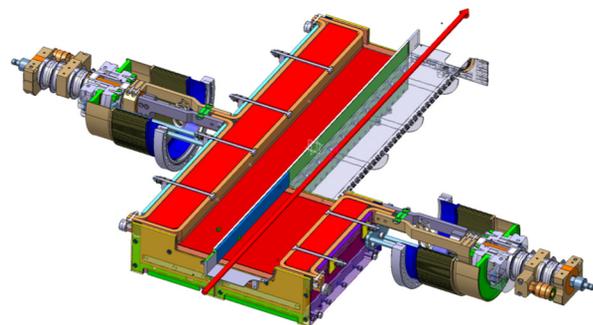
Figure 4: Cross section of septum and bumper module.

Since the laminated magnet is completely enclosed in a copper box a method of pumping the compressed interlaminate volumes, without significantly disrupting eddy current flow which reduces the stray field, has to be incorporated. The solution has been to integrate pumping ports on the copper structure, which allow for gas flow to the ion pumps and sublimators.

Electromechanically induced forces on the septum plate are damped by a dual function beam impedance

screen/magnetic shield. The screen (Fig. 4) is reinforced and bolted securely to the yoke using embedded nuts which slide in dovetail slots in the yoke laminations. To allow for relative displacement of the magnet assembly, floating RF contact arrays, fitted to the end of the screen, assure the impedance continuity between each end of the vacuum vessel.

To reduce intervention time, the septum, bumper and impedance screen can be installed as one common module using specially designed lifting apparatus.

THERMAL ISSUES

The thermal issue with the magnets has been extensively studied and a cooling system has been developed using two independent circuits. The energy dissipation due to joule heating effect originates both from the main drive coil and from the eddy currents circulating in the copper box. To cool the coil, a conventional solution of a brazed cooling tube (on the conductor) has been adopted which consists of three individual segments. The cooling tubes are connected in series using stainless steel 'collectors' which are welded after completion of the assembly of the magnet structure. The copper box is cooled using a clamp-on cooling circuit, which is fixed to the upper surface of the copper box assembly.

The power dissipation in the septum and bumper has been estimated at 150W and 20W respectively. FEA simulations have been performed and show a steady state temperature of 26.8 °C after 200 hrs of operation at nominal current, table (1). The steady state temperature of the magnet yoke has been estimated at 31 °C. All cooling circuits use demineralised water from the main PS supply at 12 bar and inlet temperature 21 °C.

The magnets shall be baked at maximum 200 °C using infrared heating elements. The duration of the flat top expected to be 24 hrs with a corresponding cool-down time (Fig. 5) estimated to be 50 hrs from 200 °C to 50 °C. The simulation is based on a lumped capacitance model (low Biot number), which assumes a negligible temperature variation in the magnet core.
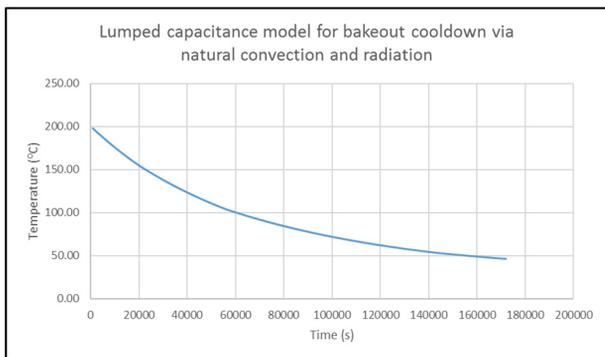
Figure 5: Simulations of cool down after bake out.

MAGNET SUPPORT AND REMOTE DIS- PLACEMENT SYSTEM

Both the Septum and Bumper are mounted on a common mobile support (Fig. 6) and can be adjusted in the radial and angular direction. The displacement system utilizes two 48 V AC 3-phase motors driving through reduction gears and bevel gear boxes to a precision leadscrew. Position measurement is by means of radial potentiometers, using a system of reduction gears, which are calibrated using standard micrometer dial gauges. All support bearings and linear slides are located outside of the vacuum vessel and reduce the possibility of trapped volumes inside the tank.
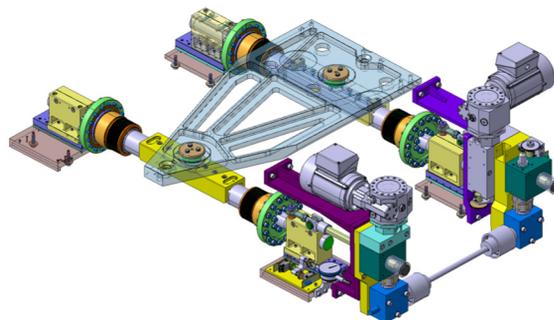
Figure 6: Remote displacement and support system.

INTEGRATION IN PS ACCELERATOR

The current septum magnet occupies 75 % of the straight section but the new system will use 100 % of the straight section. Space is very limited so several new features are included in the new layout. The septum and bumper have dedicated transformers situated very close to the magnets, reducing secondary impedance as much as possible. The vacuum tank has been fitted on precision slides which allow the tank to be withdrawn from the vacuum chamber before removal. This reduces the intervention time and subsequent radiation dose to personnel during replacement. It also reduces the risk of inadvertent damage to the adjacent flanges, which can otherwise occur when lowering the tank into position directly over the vacuum chamber.

Verification of the alignment of the tank, hence magnets, is also a simple and easy process. The flexible electrical connection can be easily dismantled to allow tank exchange, and replacement if necessary.

CONCLUSIONS

Magnetic performance has been validated and is within specifications. The leak field has been reduced using a combination of magnetic shielding both on the septum and as part of the beam impedance screen. Prototypes of both the septum and bumper have been constructed and tested successfully. To further reduce the leak field from the injection septum, it is planned to attenuate the second half of the full sine current pulse. The amount of attenuation will be determined by testing and may be limited by the possibilities to integrate the damping resistor in the power converter.

The assembly of a complete system has started and completion of the magnets in their vacuum tanks is foreseen for summer 2018, in time for the installation in the PS accelerator during Long Stop 2.

REFERENCES

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[2] Z. Szoke *et al.*, "Direct Drive and Eddy Current Septa Magnet Designs for CERN's PSB Extraction at 2 GeV", in *Proc. MT24*, Seoul, Korea, 2015, paper 1PoBM06.