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SIS100 EXTRACTION AND EMERGENCY KICKER MAGNET SYSTEM

K. Dunkel, M. Eisengruber, J. Hottenbacher†, M. Osemann, A. Padvi, C. Piel
RI Research Instruments GmbH, Bergisch-Gladbach, Germany
S. Heberer, I. Petzenhauser
GSI Helmholtzzentrum fuer Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

The extraction and emergency kicker system for SIS100 is a bipolar kicker system that allows for an in-situ choice between two directions: extraction to the experiments or to the beam dump. Both magnet ends are connected to pulse forming networks (PFNs), which are being charged simultaneously up to >70 kV continuously. Due to the static HV operation, which is a major difference to other pulsed kicker systems, the magnet's E-field distribution is dominated by the ferrite's conductivity, rather than its permittivity, so that the E-field is concentrated in the surrounding ceramic magnet clamp mechanism. As the field is further concentrated in gaps between ceramic and metallic parts, the high voltage layout of the magnet is a critical design task. As a magnetic field homogeneity of +/-1% is required, special shaping of the coil is required done by iterative 3D field simulations. The kicker chamber is designed to operate at a pressure level of 3e-11 mBar. As one 3 meter-chamber contains 3.5 m² ferrite surface, careful vacuum heat treatment of the ferrite is required to reach this pressure level.

INTRODUCTION

Within the FAIR project (refer to Fig. 1) that is presently being installed at GSI in Darmstadt, Germany, the kicker [1] is one part of the extraction system in the main SIS100 ring. Due to the bidirectional character (extraction to experiments or emergency kick to the beam dump), the kicker coil is permanently on a potential >70 kV. As it can be seen in Fig. 2, a magnet current pulse is generated by pulling down one of the two PFN ends by a Thyratron, depending on the kick direction. This unique system design compared with most other kicker systems under operation worldwide and in combination with the special properties of the ferrite material as further described below, leads to a big challenge in the high voltage design of the in-vacuum magnet.

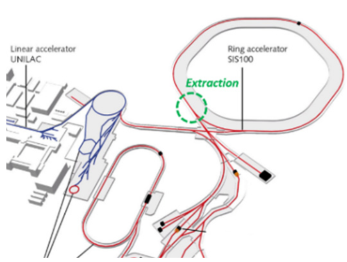

Figure 1: FAIR project [2].

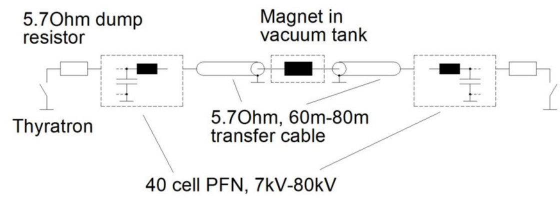

Figure 2: EE-Kicker schematic diagram.

EE-Kicker-Design

The extraction kicker system in the SIS100 ring consists of eight 750 mm-magnets (ferrite material NMG CMD5005, source: [3]) distributed in 3 vacuum chambers. To feed 6.3 kA through the magnet, required for the magnetic field of 114 mT, a voltage of approx. 74 kV is required. To achieve the short rise time of 800 ns required, the magnet as well as the connecting leads are optimized for a low inductance (< 3.2 µH).

Figure 3 shows one vacuum chamber containing 3 magnets with 2 stacked plugs (also called feedbox) per magnet on the left side of the chamber. The feedbox is oil-filled and can be detached during the 300 °C-bakout process. This is required to achieve the operation pressure level of 3e-11 mBar. As the ferrite material represents a significant gas load, several NEG-modules and ion pumps are installed on this chamber.

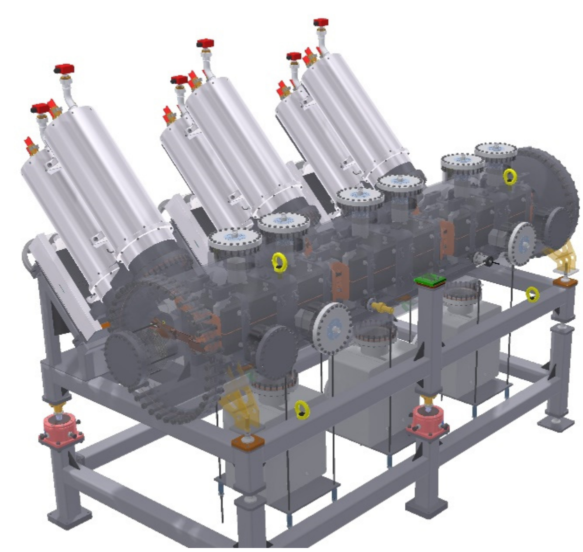

Figure 3: One kicker chamber containing 3 magnets.

Each magnet is driven by a pulse generator containing two adjacent 40 cell PFNs to create bidirectional 7 µs

† johannes.hottenbacher@research-instruments.de

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pulses with rise times of <800 ns. Since the pulse generator will be situated outside of the accelerator tunnel, the magnet will be connected via coaxial high voltage cables of 60 m to 80 m length (see Table 1).

Table 1: Main Parameters of the EE-Kicker System

Number of magnets	8 in 3 vacuum tanks
Pulse repetition rate	1 Hz
Current rise time	800 ns (1% to 99%)
Current flat top duration	7 µs
Magnet current on flat top	6’335 A
Current stability on flat-top	+/- 1%
Magnet voltage	74 kV
Magnet B-field	114 mT
B-Field homogeneity	+/- 1%
Vacuum level	3e-11 mBar
In-situ bakeout temperature	300 °C
Alignment after bakeout	0.3 mm

ELECTRIC FIELD STRENGTH IN THE MAGNET

Since the magnet will be on high voltage potential continuously, the ferrite blocks need to be insulated from its grounded support structure. Therefore, vacuum suieq insulators made from Macor, a glass ceramic, will be used. The ferrite blocks and Macor insulators have different material properties and are therefore forming an R-C voltage divider. To describe the potential distribution across these materials, a simplified model will be used in this paper as it can be seen in Fig. 4, neglecting the surrounding vacuum.

During short voltage pulses, as usually used in other kicker systems, the magnet’s ferrite material can be considered as dielectric material as the susceptance of the capacitor ($B = \omega C$) is dominating over the ohmic conductance G for higher frequencies. For most insulating materials this is valid also for lower frequencies due to the high resistivity of insulators. With $\sigma_{Ferrite} = 1e\text{-}8$ S/m the conductivity of the ferrite material is relatively large compared to other insulating materials (cf. Macor with approx. $\sigma_{Macor} = 1e\text{-}14$ S/m).

The frequency where (when being further reduced) the ohmic conductivity starts dominating the susceptance of the capacitor is derived from $X_C = R$ and amounts to:

$$f = \frac{1}{2\pi}\frac{\sigma}{\varepsilon} = \frac{1}{2\pi}\tau = 13\ \mathrm{Hz}$$

The voltage distribution of a series connection built from ferrite and Macor according to the equivalent circuit shown in Fig. 4 is given by the well-known equations for electrical circuits. If the series connection is built from blocks of the same geometry, the voltage relation is geometry-independent and can be written as follows:

$$\frac{U_{Ferrite}}{U_0} = \frac{1}{1 + \frac{\sigma_{Ferrite} + j\omega\varepsilon_{Ferrite}}{\sigma_{Macor} + j\omega\varepsilon_{Macor}}}$$

The corresponding curve is shown in Fig. 4. As expected, the voltage over the ferrite part drops around $f = 13$ Hz where $\sigma_{Ferrite} = \omega\,\varepsilon_{Ferrite}$.

When charging the magnet, after less than 1 second the ferrite material is nearly E-field free and must be considered as a conductor instead of an isolator. Figure 4 compares the field distribution for short pulses (high frequency region, upper right picture) with the field distribution for quasi-static operation (upper left picture) where the fields are pushed out of the ferrite material. The voltage drop is concentrated in the surrounding ceramic support structure built from Macor and the electric fields are increased significantly.

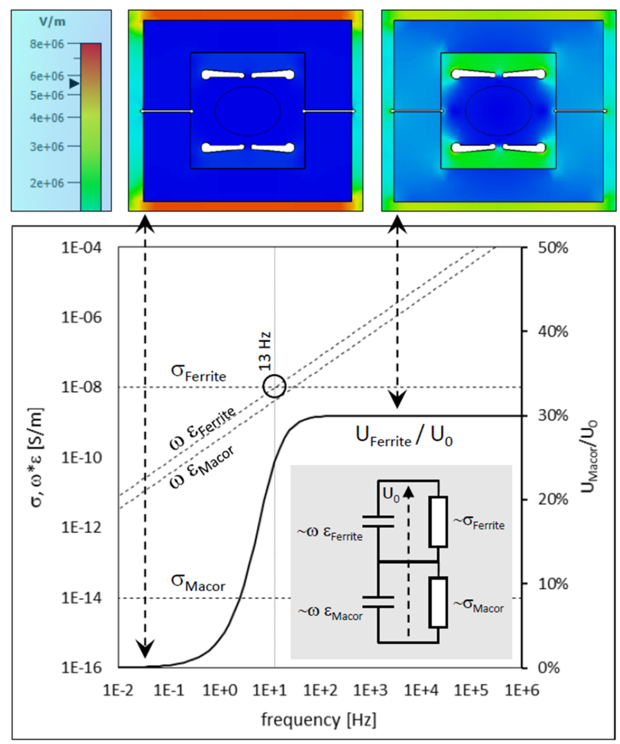

Figure 4: Field displacement.

Handling of Gaps

Insulating Macor parts are clamped by the surrounding grounded metal structure to the magnet. In the corresponding tiny gaps, the field is further concentrated, making the high voltage layout of the magnet a critical design task.

Slight local electron field emission due to surface imperfections and according to the tunneling mechanism described by Fowler-Nordheim [4] can be possible, even if the global field strength is below the threshold of significant field emission. This can cause electron accumulation on insulating surfaces and eventually arcing. Therefore, it is mandatory to keep the design electric field strength below the Kilpatrick limit [5] also inside gaps.

For small gaps (dielectric material and vacuum) it is assumed that the global electric flux density D is not

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influenced by the gap. Without charges in gap or insulator, the flux density is equal in insulator and gap as given by the Maxwell equation *div*D = ρ.

$$D_{gap} = \text{constant} = \varepsilon_0\, E_{vacuum} = \varepsilon_0\, \varepsilon_{r,isolator}\, E_{isolator}$$

The electric field E_{vacuum} in the gap cannot be covered by the 3D electric field simulation (here CST Studio Suite [6] as it is far below the mesh size. Instead, based on the equation above, the electric field in the insulator directly next to the gap can be evaluated to get the field in the gap:

$$E_{vacuum\ gap} = \varepsilon_{r,insulator}\, E_{insulator\ next\ to\ gap}$$

Magnet Support

Due to the challenges described, a simple metallic magnet support is not possible and is substituted by a complicated ceramic support structure. The required position reproducibility of 0.3 mm after 300 °C heat cycling, in combination with significantly different thermal expansion coefficients of the materials involved, gives stringent requirements to this support structure as shown in the following Fig. 5:

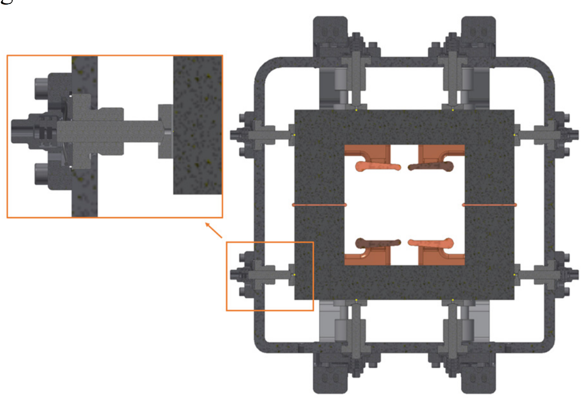

Figure 5: Magnet support structure.

All gaps where ceramic pieces get in contact with the surrounding metallic ground potential are shielded to remove the fields from these gaps (see Fig. 5 left detail).

During the short current pulse, the potential distribution in the magnet is changing compared with the static situation as the voltage is dropping over the coil. The coil consists of two windings. The distance of neighboring coils must be large to withstand the voltage difference during the pulse (max. 40 kV assumed) but even though small to maintain the magnetic field homogeneity. A compromise of 8 mm was chosen based on parameter studies.

As within an 80 x 60 mm ellipse (black line in Fig. 6) inside the 135 x 80 mm beam aperture a magnetic field homogeneity of +/- 1% is required to maintain the beam quality, special shaping of the magnet coil is required as found during iterative 3D field simulations.

MAGNET VACUUM DESIGN

The kicker chamber is designed to operate at a pressure level of 3e-11 mBar. As one 3 meter-chamber contains 3.5 m² ferrite surface, careful vacuum heat treatment of the ferrite material is required to reach this pressure level. The ceramic magnet support structure is optimized to have small surfaces and to avoid gaps and trapped volumes. The magnet chamber can be in-situ-baked up to 300 °C.

The measures described above, especially the carefully tested ferrite vacuum heat treatment, provide best vacuum properties of the magnet structure. Nevertheless, due to the large ferrite surface, 8 NEG-modules and 3 ion pumps must be installed on one chamber (see Fig. 7).

COIL SHAPE

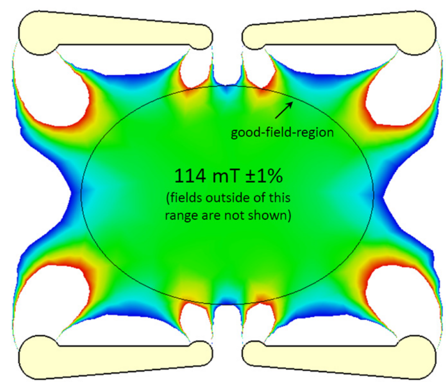

Figure 6: Magnetic field scaled to 114 mT +/-1%.

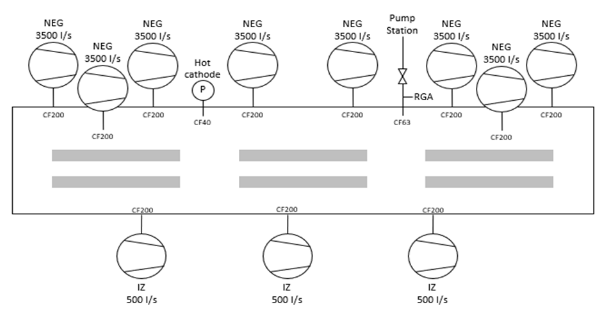

Figure 7: Vacuum setup.

CONCLUSION AND OUTLOOK

The low resistivity and high permittivity of the NiZn-ferrite material in combination with challenging requirements regarding field homogeneity, mechanical reproducibility and vacuum properties, caused unexpected complexity during the design of the magnet ceramic support structure that is capable operating under quasi-static high voltage. After an intensive physical design phase, the final design work has begun, and manufacturing of the first magnet is planned to start this summer. The vacuum kicker magnet chamber assembly as well as the PFN-pulse generator will be manufactured in house at RI Research Instruments GmbH.

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