# CALCULATION AND DESIGN OF THE MAGNET PACKAGE IN THE IFMIF SUPERCONDUCTING RF LINAC*

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*Abstract*

The IFMIF-EVEDA accelerator will handle a 9 MeV, 125 mA continuous wave (CW) deuteron beam which aims to validate the technology that will be used in the future IFMIF accelerator. The Linac design is based on superconducting Half Wave Resonators (HWR) operating at 4.4 K. Due to space charge associated to the high intensity beam, a strong superconducting focusing magnet package is necessary between cavities, with nested steerers and a Beam Position Monitor (BPM). First of all, this paper describes the preliminary study to choose between two quadrupoles or one solenoid as focusing device, both using NbTi wire. The solenoid shows more advantages, mainly associated to available space and reliability. Then, electromagnetic and mechanical design of the solenoid and the steerers are reported. Special care is taken in order to fulfil the fringe field limit at the cavity flange. An active shield configuration using an anti-solenoid has been adopted, avoiding remnant magnetization associated to passive shielding materials.

## INTRODUCTION

The main goal of the IFMIF-EVEDA accelerator is to demonstrate the viability of the future IFMIF project [1]. It aims to validate the feasibility of accelerating a CW high intensity (125 mA) deuteron beam. The last accelerating stage will be a superconducting RF Linac [2] composed of eight niobium cavities (HWR type) with attached magnet packages, enclosed in the same cryomodule, which will accelerate the D+ beam until 9 MeV.

Each magnet package includes a BPM, a focusing element and a pair of steerers (horizontal and vertical). For the magnetic lens, one can choose between two quadrupoles (focusing and defocusing) or one solenoid. The main specifications are collected in Table 1. The most challenging request is the short available space to provide a relatively high integrated field, due to the strong space charge effect associated to the high intensity beam.

Table 1: Magnet Package Specifications

| | | |
|---|---|---|
| Integrated on-axis field (solenoid) (*) | ≥1 | T·m |
| Integrated gradient (per quadrupole) | 5 | T |
| Steerers field | 3.5 | mT·m |
| Aperture diameter | 50 | mm |
| Flange-to-flange length | 400 | mm |
| Fringe field at the cavity flange (cold) | 20 | mT |
| Working temperature | 4.4 | K |

(*) Nominal value, a 20% margin is convenient for tuning flexibility.

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## CHOICE OF MAGNET CONFIGURATION

The first task is to find the most convenient type of magnetic lens. In the case of the quadrupole option, a superferric magnet [3] is shorter than a cos-$\theta$ one. Its overall length would be 140 mm for an integrated gradient of 5 T. The fringe field is low. Due to the short available space, the BPM must be nested inside the quadrupole, as shown in Fig. 1, and immersed in the helium bath. The reliability of the brazed joints of the feedthroughs is the main risk of this solution, as they have to be liquid helium tight after repetitive thermal cycles.

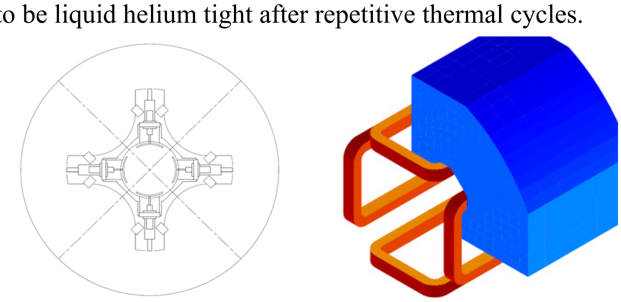

Figure 1: Cross section of the superferric quadrupole (left) and 3-D model (right).

The solenoid needs less space for the same integrated field, but the fringe field of this type of magnet is higher. There are two possibilities to decrease it: passive shielding by means of ferromagnetic materials or active shielding using an anti-solenoid.

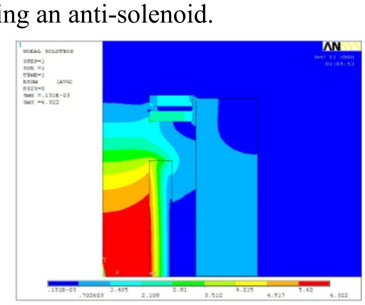

Figure 2: Field map of a solenoid with passive shielding.

Figure 2 shows a solenoid with passive shielding by means of soft iron cylinders and plates. Soft iron is the most adequate material, due to its well-known behaviour at low temperatures and high saturation field. As the available space is very short, it is better that the helium vessel encloses only the solenoid, to place the endplates between the solenoid and the shield. Therefore, the shielding plates are relatively far away from the solenoid and shielding is more efficient for the given space.

The main disadvantage of this solution is that assembly becomes cumbersome to allow access to the screws of the end flanges: the iron must consist of different parts, with holes for helium inlet and outlet, and current leads. Besides, it would be difficult to fix them properly in order to withstand the magnetic forces and cope with the different thermal contraction coefficients of the materials. Finally, the magnetic calculation should take into account the exact iron geometry, which would imply a real 3-D calculation, instead of an axisymmetric one.

Nevertheless, the main reason to discard the passive shielding is the remnant field. Even a small fringe field as 20 µT could affect the cavities performance. It is very difficult to know the remnant field within the required accuracy, especially after cycling, both thermal and current conditions. This constraint is not in contradiction with the specification given in the Table 1 for the maximum fringe field, which assumes that the cavity is already superconducting. The smaller limit is stated for the cooling process, which implies transition from normal conducting state to superconducting one.

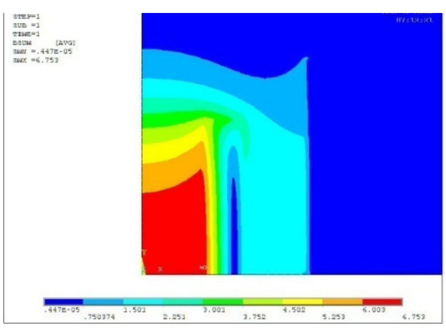

Figure 3: Field map of a solenoid with active shielding.

Figure 3 shows the second option studied: active shielding. It consists of a concentric external solenoid connected in series with the inner one but the current is established in opposite sense. It decreases the fringe field, but at the same time weakens the actual field created by the internal solenoid. This latter effect implies a number of negative consequences: higher peak field to achieve a given integrated field, higher working point on the load line, worse performance in case of quench and, finally, more cost and complexity of fabrication. Another concern is that the external solenoid has to be properly aligned; if not, shield efficiency decreases.

However, remnant field would be very low. The only cause of magnetization would be the persistent currents in the superconducting coils but, like in the case of the transport current, stray fields would be very low.

As a final remark, bucking coil could be split in two and placed at a given distance of both ends of the main solenoid [4, 5]. It would be more efficient cancelling the fringe field, but it is not feasible in the available space.

## DETAILED MAGNETIC DESIGN

### *Main Solenoid*

An optimization has been performed to obtain the required integrated field while minimizing the fringe field at the cavity flange and the working point of the superconducting wire on the load line. On-axis field profile is asymmetric, because solenoids are not centred, as the cavities are at different distance on both sides. Table 2 summarizes the main results of the electromagnetic calculations. Commercial solution is chosen for current leads, which will be cooled by helium gas. Therefore, the nominal current must be moderate. Round NbTi wire will be used, assuming the theoretical filling factor (90.7%). The real one will be checked in the prototype. If it is lower, nominal current will be increased accordingly. A maximum of 10% over the nominal integrated field is considered reasonable while keeping a safe margin to quench. Prototype test results will show if a higher field is achievable.

Table 2: Main Solenoid Parameters

| | | |
|---|---|---|
| Inner radii of inner/outer coil | 30/83 | mm |
| Outer radii of inner/outer coil | 44.4/86.35 | mm |
| Length of inner/outer coil | 187/190 | mm |
| Number of turns of inner coil | 249x22 | |
| Number of turns of outer coil | 253x5 | |
| Coil peak field | 5.85 | T |
| Nominal current | 210 | A |
| Integral field | 1.10 | T·m |
| Stored energy | 11.957 | kJ |
| Self-inductance | 0.54 | H |
| Stray field at upper/lower cavity | 22/21 | mT |
| Bare/insulated wire diameter | 0.7/0.75 | mm |
| Copper to superconductor ratio for inner/outer solenoid wire | 1.3 / 3.2 | |
| Critical current at 6/7 T, 4.2 K | 349/260 | A |
| RRR | 70 | |
| Filament diameter | <12 | µm |
| Working point on the load line | 86.2 | % |

### *Steerers*

The final configuration selected for the steerers is a pair of racetrack coils connected in series (see Fig. 4). Field quality is modest but acceptable for a corrector. Other possible arrangements, as a cos-θ coil (both glued on the beam pipe [3] or nested in between the solenoids) or a helix-type winding would need more length to achieve the required integrated field and the fabrication would be more difficult. Main parameters are collected in Table 3. The wire will be the same used for the outer solenoid.

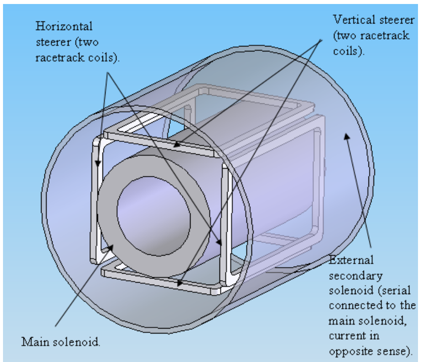


Figure 4: Coils configuration layout

Table 3: Main Parameters of Steering Coils

| | | |
|---|---|---|
| Cross section of the coil | 5.95 x 6 | mm |
| Number of turns | 9 x 8 | |
| Winding mandrel dimensions | 130 x 82 | mm |
| Distance between coils | 100 | mm |
| Nominal current | 50 | A |
| Integral field | 3.51 | mT·m |
| b3 | -1150 | units ($10^{-4}$) |
| b5 | -33.77 | units ($10^{-4}$) |
| Reference radius | 20 | mm |

## QUENCH SIMULATION

Quench calculation assuming adiabatic conditions has been performed solving the heat balance equation by means of the Finite Difference Method [3]. Thermal properties in function of temperature and magnetic field at each wire are considered. The most unfavourable case is a quench triggered in the inner solenoid. Maximum voltage is below 500 V (see Fig. 5), so the magnet is self protected, and instrumentation becomes considerably simpler.

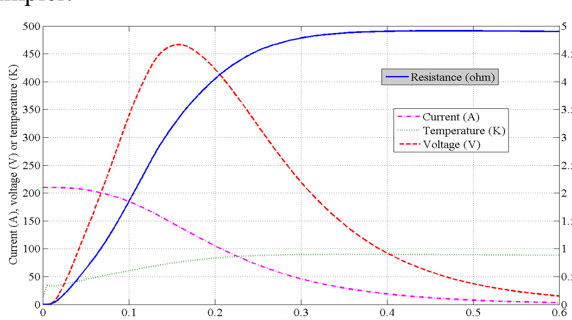


Figure 5: Quench simulation results.

## MECHANICAL DESIGN

The helium vessel will be fabricated in stainless steel. Welds will be done with TIG. It must accomplish the Japanese rules for cryogenic pressure vessels. Assuming a maximum pressure of 2.5 bars in case of quench for the mechanical analysis, tank wall should be 3 mm thick and endplates, 12 mm. The BPM body is part of the vessel endplate to save space and guarantee a good alignment with the magnetic axis. The helium vessel will have a CF 40 flange for thermo-siphon cooling. There is a bellow at each end to allow thermal differential contractions and misalignments with nearby elements.

Both solenoids will have glued glass-fibre endplates with pins for alignment. A repulsive magnetic force about 650 kg will take them apart against the endplates. In the case of the steerers, they will experiment a torque about 80 N·m per coil, which exerts a perpendicular force on each coil end of 60 kg. Therefore, a stainless steel cube-like support structure is foreseen to hold these coils, with similar contraction coefficient to the winding one.

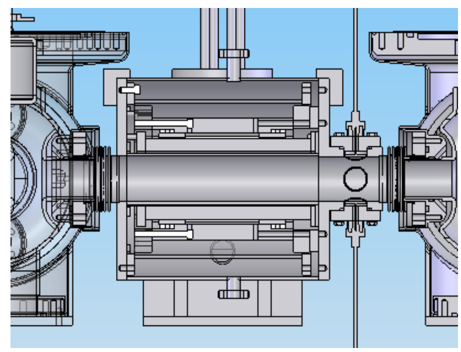

Figure 6: Magnet package and cavities assembly model.

## CONCLUSIONS

The calculation and design of the IFMIF-EVEDA Magnet Package has been described. To overcome the short available length, a solenoid has been adopted as focusing element instead of two quadrupoles, which needs a liquid helium tight BPM. Active shielding has been chosen instead of passive one to avoid stray field due to remnant magnetization. Quench simulations show that the magnet is self-protected. A prototype fabrication is ongoing to check the critical points of the calculations.

## REFERENCES

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