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**Compact Inter-cryomodule Combined Corrector Magnets
for the HIE-ISOLDE Project at CERN**

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Index Terms—Accelerator normal conducting magnets, design optimization, combined corrector magnet, HIE-ISOLDE.

I. INTRODUCTION

THE On-Line Isotope Mass Separator (ISOLDE) is a world-leading facility dedicated to the production and study of a large variety of radioactive nuclei. Located at the Proton-Synchrotron Booster of the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, it has been in operation since 1967.

In the facility, the Radioactive Beam Experiment (REX-ISOLDE) produces highly charged radioactive ion beams and post accelerates them in a short LINAC consisting of a radiofrequency quadrupole, an inter-digital H-type structure and three seven-gap and one nine-gap resonators, which allow the variation of the final energy up to 3 MeV/u.

With the objective of increasing the energy and the intensity of the delivered radioactive ion beams to greatly expand the physics program, the High Intensity and Energy ISOLDE (HIE-ISOLDE) project [1] consists in a major upgrade of the existing REX-ISOLDE facility. The most significant improvement will come from replacing most of the REX accelerating structure by a superconducting linear accelerator based on Quarter Wave Resonators housed in cryomodules, with a maximum energy of 10 MeV/u for beams of mass to charge ratio $A/q = 4.5$. An overview of the cryomodules line is given in Fig. 1.

Studies of beam dynamics seek to define a very compact accelerating lattice and consequently the shortest possible machine. This has resulted in very compact inter-cryomodule spaces where various vacuum and instrumentation equipment

Fig. 1. Layout of the accelerating structure of the HIE-ISOLDE LINAC. The corrector magnets, as well as beam vacuum and instrumentation equipment, will be housed in small inter-tank spaces of 375 mm length.

will have to live side by side with strong dual-plane beam trajectory corrector magnets.

This paper reports on the technical choices made to design these corrector magnets so that they meet the required field strength and quality in the available space.

II. TECHNICAL REQUIREMENTS

The imperfections and misalignment of the various elements of a beam line induce errors in the beam trajectory that are typically compensated by the corrector magnets. Therefore, the determination of the deflection angle needed from these magnets to adjust the beam trajectory is intimately linked to the freedom given in the design and manufacturing tolerances of the beam line elements. Regarding the HIE-LINAC, simulations [2], [3] have demonstrated that the sensitivity of the beam to several critical components like cavities, solenoids, and beam position monitors is quite important. Therefore, to avoid squeezing too much these tolerances, which would result in increased difficulties (and costs) in the design and manufacture of the already challenging cryomodules and associated equipment, the specification on the corrector field strength and homogeneity had to be set to high and stringent values.

Furthermore, the limited space available for the beam line equipment and the specific design of the cryomodules housing the RF cavities have imposed a very limited longitudinal dimension of the magnets, as well as tight conditions on the magnetic stray field close to the cavities.

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TABLE I

COMPARISON OF HIE-ISOLDE CORRECTOR SPECIFICATION PARAMETERS TO OTHER SIMILAR SIZE MAGNETS

Specification parameters	Units	HIE-ISOLDE Air-cooled Corrector	LINAC 4 Air-cooled Corrector	ISAC-II Water-cooled Corrector
Integrated flux density $\int B_0 dl$	(mT·m)	6	1.3	5
Magnet overall length $l_{o,z}$	(mm)	70	59	92
Ratio int. field / overall length $\int B_0 dl / l_{o,z}$	(T)	8.57E-2	2.17E-2	5.56E-2
Int. field homogeneity in GFR 75 % ^a $\Delta \int B_y dl / \int B_0 dl$	(%)	1.3	5	5.2

^a GFR 75 %: Good Field Region extending to 75% of the mechanical aperture.

As a result, the corrector magnet specification ends up with basic parameters out of the usual range. A comparison with similar size dual plane corrector magnets from CERN's LINAC 4 [4] and TRIUMF's ISAC-II [5] is given in Table I. The ratio between *magnet overall length* and integrated field ($\int B_0 dl / l_{o,z}$), set to 8.57E-2 T for the HIE-ISOLDE corrector, is larger than the ones of LINAC 4 and ISAC-II by a factor of about 4 and 1.5, respectively (although the latter is water-cooled). Furthermore, the requested field quality is about four times tighter than for both of these.

III. MAGNETIC DESIGN

The particular technical requirements could be met by a parametric optimization of the characteristic dimensions (marked out in *italics* in the rest of the paper) of the magnet yoke and coils, represented in the drawing in Fig. 2.

A. Longitudinal Dimension Constraint

With the longitudinal dimension of the magnet limited to 70 mm by the space and integration constraints, the *straight section* of the coil windings had to be oriented orthogonally w.r.t. the magnet longitudinal axis, as shown in Fig. 2. This allows maximizing the occupation of the longitudinal space exclusively with the yoke iron and the coil conductors: with this configuration, the areas inside the coil ends occupy space in the transversal plane of the magnet, rather than being included in the longitudinal overall dimension.

The longitudinal space has been shared between the *iron length* and the *coil thickness* with a ratio of 4/3. This gives an ideal compromise between a sufficient coil section for limiting the current density to an appropriate value (considering a given *coil width*), and a sufficient iron section to ensure a limited saturation of the iron. In this way, the *iron length* could be kept to about two times the *iron height* to still confer enough mechanical stability to the yoke frame.

Fig. 2. Magnet half-quadrant cross section at the median transversal plane. Only the upper-left eighth of the magnet is represented. The magnet centre is identified with a target sign. The characteristic dimensions in the drawing (e.g. *iron length*, *coil thickness*) refer to those cited in the text in *italics*.

B. Integrated Flux Density vs. Current Density

With a reasonable current density in the coils, the smallest transverse dimensions matching the free aperture requirement (set to 50 mm to host the vacuum pipe with room for alignment) would not have provided a sufficient total current for the required integrated flux density. Therefore, with the *coil thickness* being fixed, and considering the particular symmetry between planes of the window frame construction, the *magnetic aperture* had to be increased to free some space for enlarging the *coil width* (and consequently the coil section), which will provide an additional path for the required ampere-turns. This transversal scaling generates three effects:

- The increase of the coil section, leading to a higher total current;
- The increase of the magnetic length (enhanced by the fact that the *iron length* is much smaller than the *magnetic aperture*), leading to a higher integrated flux density;
- The increase of the *magnetic aperture*, leading to a lower flux density in this aperture.

The resulting benefit in terms of integrated flux density is thus proportional to this transversal scaling. Another benefit of the scaling is that the good field region (GFR) scales accordingly. On the other hand, this increases also the stray field to 11 mT @ 100 mm from the magnet centre, which stays however well below the maximum value of 50 mT specified to avoid magnetic coupling with the adjacent equipment. A plot of the distribution of the magnetic flux density along the longitudinal axis is given in Fig. 3.

The flux density in the iron could be kept around 1.5 T by dimensioning the *iron height* to 60 mm. Combined with the *iron length*, previously defined to 28 mm, it provides a sufficient path for the magnetic flux in the yoke to limit saturation effects. The analyses have been performed directly on the Finite Element Modeling (FEM) software OPERA 3D / TOSCA [6]. No use of 2D magnetic calculation code has been envisaged as a preliminary step since the ratio *iron length* / *magnetic aperture* is very small (~0.15).

Fig. 3. Simulated distribution of the flux density vs. the longitudinal axis for the HIE-ISOLDE corrector magnet (horizontal plane powered). The magnetic length (base of the light shaded area in the graph) is about 10 times larger than the iron length (base of the dark shaded area).

C. Field Quality

The value of the maximum allowed deviation of the field quality, given by the sum of the harmonics, has been set by the optics to $1\text{E-}3$ in a GFR extending up to 15 mm radius from the magnet centre. This corresponds to a maximum of 1.3% in 75% of the mechanical aperture, quite a tight level compared to similar size window frame magnets which have a total field error usually dominated by a strong positive sextupole component in their harmonic content.

So, although no tolerance has been set for the individual harmonics of the HIE-ISOLDE corrector magnet, the optimization process has consisted in the attenuation of this parasitic component by using the three following methods:

- The removal of ferromagnetic material from the inner corners between the yoke quadrants as to shape hints of poles, thus decreasing the magnetic gap in the centre of the magnet. This sketches the yoke frame somewhat like a ‘dual H-type’ rather than having a standard window frame yoke (with straight poles).
- The removal of conductor turns in the central part of the external conductor layers, as their contribution to the increased flux density at the extremities of the GFR is important.
- The filling of the corners between quadrants with additional turns to increase the coil current density in these regions.

These methods, illustrated in Fig. 2 and Fig. 6, are sufficient to achieve the field quality requirements. So, the use of more complex technical solutions like increasing the current density in the coil parts situated in the corners between the quadrants to extend further the GFR [7] can be avoided.

The relative integrated field error over a quadrant at the reference radius of the HIE-ISOLDE corrector magnet is given in Fig. 4. The improvement in integrated field homogeneity of the final optimized design compared to a standard window frame design is shown in Fig. 5.

Fig. 4. Simulated integrated field error vs. the angular position at reference radius $r = 15$ mm (GFR extents) for the HIE-ISOLDE corrector magnet.

Fig. 5. Comparison of simulated relative integrated field error vs. the horizontal axis for standard window frame magnet design and HIE-ISOLDE optimized window frame design, with equivalent parameters. The field quality with the optimized design is improved by a factor of ~ 5 at the GFR border.

IV. MECHANICAL DESIGN AND TECHNOLOGY

A. The Yoke

In the same way as the REX-ISOLDE magnets, those of HIE-ISOLDE will be operated in DC mode. Thanks to this and to the limited number of corrector magnets to produce (seven in total, including one spare), the yokes can be machined in solid blocks of pure iron (ARMCO Grade 4 [8]) without increasing significantly the manufacturing costs compared to a laminated version. This also allowed:

- The shaping of round pole tips inside the inner radius of the coil winding (Fig. 2 and 6) therefore allowing the reduction of the magnetic air gap, which is beneficial to the integrated field. (This would have been much more difficult with laminated yokes.)
- The improvement of the mechanical resistance of the magnet quadrants bolted assembly, which is necessary to allow the magnet dismounting without opening the beam vacuum circuit (as to limit the machine downtime in case of future maintenance interventions).

B. The Coils

To provide the necessary field strength while meeting the geometrical constraints explained here above, the coil current density had to be set to more than 2 A/mm^2 , an upper limit for air-cooled magnets with impregnated coils. However, the

Fig. 6. On the left: magnetic 3D model in OPERA software environment. The translucency of the coils allows seeing the rounded pole tips shape. On the right: mechanical 3D model in the CATIA software environment [9]. The central parts of the coils correspond to the aluminum inserts (also represented in Fig. 2) used to enhance the thermal power dissipation.

TABLE II
DESIGN PARAMETERS OF HIE-ISOLDE CORRECTOR MAGNET

Parameter	Units	H-I corrector magnets
Overall width x height	(mm) x (mm)	490 x 460
Overall length	(mm)	70
Iron length	(mm)	28
Free aperture	(mm) x (mm)	130 x 130
Peak current	(A)	40
Current density	(A/mm ²)	2.1
Dissipated power (per plane)	(W)	76
Coils resistance @ 20°C (per plane)	(mΩ)	47
Magnetic inductance (per plane)	(mH)	8.8
Peak flux density (per plane)	(mT)	20
Integrated flux density (per plane)	(mT·m)	6.1
Max. flux density in iron (both planes powered)	(T)	1.52
Max. relative integrated field error in GFR ($r = 15$ mm)		< 7.6E-4
Max. stray field in a transversal plane @ $z = 100$ mm from magnet center (both planes powered)	(mT)	11

water-cooled construction would not have been appropriate because:

- The overall space constraints make it difficult to envisage a water-cooled version due to additional components (such as hydraulic insulators, hoses, connectors or indirect cooling power dissipater plates) that would have to fit in a 70 mm wide path around the magnet, without interfering with the adjacent equipment.
- The manufacturing and operational costs would have increased significantly due to, respectively, the greater complexity and the greater dissipated power of the water-cooled version over the air-cooled one (considering that the current density is larger at equivalent coil section).
- The reliability of air-cooled magnets is obviously better since water leaks are the most extended failure mode in normal conducting magnets for particle accelerators, although air-cooled ones often run at higher temperatures.

C. Thermal Aspects

To avoid any degradation of the coil insulation with the temperature, the 102 turns winding is made of OFE copper wire enameled with polyimide (*Thermex 240 Grade 2* [10]), which performs adequately well at elevated temperatures. A square section of 4.5 mm has been selected as this shape allows filling as much as possible the volume, as well as the corners between quadrants, while matching in four layers the required *coil thickness* determined during the earlier optimization of the ratio *iron length / coil thickness*. It also leads to suitable resistance and inductance characteristics of the magnet circuits for the choice of commercially available power supplies. These characteristics, as well as the other design parameters of the magnet, are summarized in Table II.

As to ease the thermal power dissipation, the coil will be molded under vacuum with charged resin to improve its global thermal conductivity. Efforts are now concentrated on defining a suitable combination of filler and resin, and

implementing it in a prototype magnet to perform measurements during thermal runs. Since the dependence of thermal conductivity with the filler content is most often quadratic [11], [12], depending however on the filler particles shape and size distribution, the goal is to maximize this value while keeping a sufficiently low viscosity to allow the impregnation. Fillers with high thermal conductivities like aluminum oxide, boron nitride, and even diamond powder are considered.

To further reduce the thermal resistance of the coils as well as to ease the mould design, aluminum parts have been inserted to fill the volume let by the missing conductor turns in the central parts of the coils. These have been hard anodized to provide an electrical insulation layer and ease the adherence of the resin.

V. CONCLUSION

The tough specifications in terms of performance, accuracy and longitudinal compactness of the inter-cryomodule dual plane corrector magnets could be met with an original design of the coils and yoke. The manufacture of a prototype magnet is currently ongoing at CERN. The magnetic measurements of the prototype are expected in November 2011.

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