A NEW GENERATION OF SUPERCONDUCTING SOLENOIDS FOR HEAVY-ION LINAC APPLICATION *

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Abstract

The beam dynamics of superconducting (SC) heavy-ion linacs operating in the velocity range below 0.4c require a compact accelerating-focusing lattice. The use of SC solenoids together with SC RF resonators within a common cryostat can solve the real-estate problem. The solenoids must have low fringe fields to avoid magnetic-flux capture in the SC RF resonators. Also, incorporating dipole steering coils together with the SC solenoids in one magnet assembly can increase the compactness of the linac lattice. R&D work has been carried out to determine the feasibility of combining the three elements of high solenoid field, low fringe field, and integral dipole field, into one compact package. A 9-Tesla magnet has been initially designed and will be prototyped, with the goal of eventually developing 14-Tesla solenoids of similar design. The most important design issues are: 1) to minimize stray field in the RF cavity region using SC bucking coils and 2) to achieve adequate mechanical stability of the transverse dipole windings in the presence of forces produced by the solenoid/bucking coil assembly. The assembly, including terminals, switches, and protection circuit, are designed to fit inside a 25-cm diameter helium reservoir. The results of the preliminary design of the solenoid, including numerical simulations of the beam dynamics, are reported.

1 DESIGN OF A COMPACT MAGNET ASSEMBLY

High-intensity heavy-ion linacs, such as the proposed Rare Isotope Accelerator (RIA) driver linac [1], require that beam losses, together with the beam emittance, be kept at a minimum. This is particularly important if multiple-charge-state ions are simultaneously accelerated to overcome intensity limitations of available ion sources. For low- to medium-energy beams, drift spaces between accelerator components can cause effective emittance growth. An assembly of steering coils mounted on focusing solenoids is proposed that reduces drift spaces between resonators. R&D studies were conducted on a 9-Tesla magnet to determine the feasibility of achieving high field, low fringe field, and integral dipole field, into one compact package.

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1.1 General Assembly Layout

The most important issues to be addressed in the assembly design were:
1) to minimize stray fields in the adjacent RF cavity region using SC bucking coils, and 2) to determine the forces acting on the dipole in the presence of the solenoid/bucking coil assembly.
Figure 1 shows the complete magnet assembly. It includes one 9-Tesla solenoid with four coaxial sections, two coaxial bucking coils along the longitudinal axis at each end of the solenoid, and steering racetrack dipole coils, producing 0.2 Tesla on the horizontal and vertical axes. The solenoid and bucking coils are connected in series with a single SC switch. The bucking coils at the solenoid ends reduce the axial fringe field by an order of magnitude, providing the required low stray field, of magnitude $(B_z^2 + B_r^{2)}$ ½, at the resonator surface. The overall length of the assembly is 28 cm.

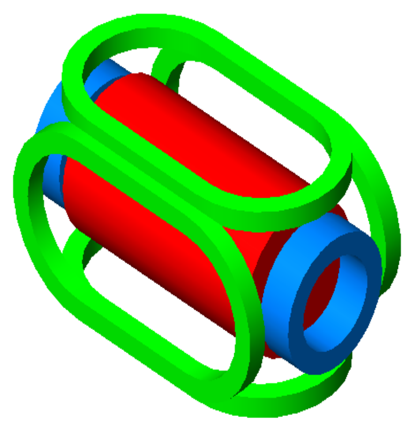

Figure 1: Magnet assembly, showing solenoid, bucking coils, and racetrack steering dipole coils.

The axial magnetic-field profile in the assembly mid-plane is shown in Figure 2. The bucking coils are sufficiently strong to minimize the stray field at distances greater then the physical length of the solenoid. As shown in the figure, the coils produce a low field region of less than 0.1 Tesla between 15 and 18 cm from the magnet centre. A finite element model was used to establish the magnitude and distribution of the interacting forces. The calculated stress on the coils were within reasonable values. Figure 3 shows the magnetic field intensity distribution, obtained from finite-element simulations.

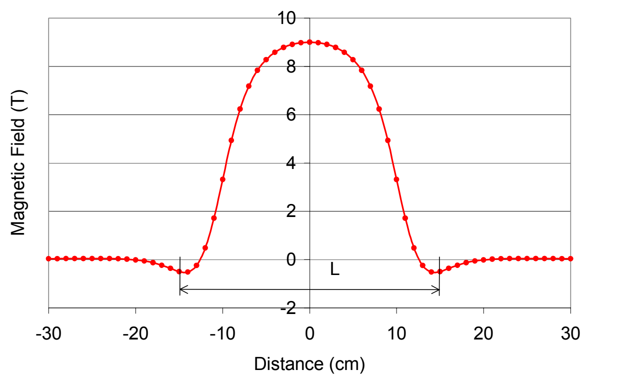

Figure 2: The axial magnetic field of the assembly. L is the physical length of the solenoid.

The magnet windings are designed for an adequate safety margin of the critical current at 4.2K and with an appropriate copper to superconductor ratio for safe quench protection. The assembly, including terminals, switches and protection circuit, fits inside a 25-cm diameter helium reservoir.

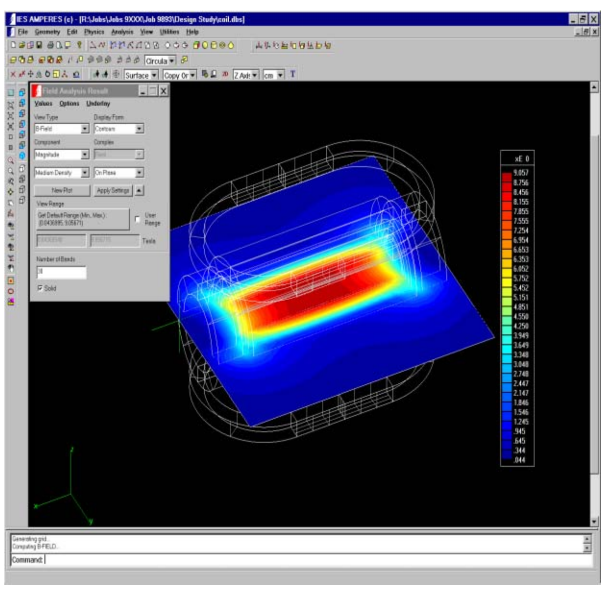

Figure 3: Output from Ampere V6.0, showing the magnetic field intensity distribution in the mid-plane of the magnet assembly.

1.2 Beam Steering Dipole Coils

In order to make the design and fabrication of the 9-Tesla solenoid more cost-effective the beam steering dipole-field coil is located outside the solenoid. The geometrical configuration of the steering coil can be saddle-shaped, racetrack or circular (ring-shaped). The saddle-coil configuration would be more compact in coil length, but its winding is more complicated than the winding in the other configurations and may require a separate inner tube for the coil. We choose a pair of racetrack coils as our reference design and the major coil parameters are listed in Table 1. When the straight section of the coil is increased from 12 cm to 22 cm, the field integral along the beam axis is increased from 47.2 T-mm to 66.4 T-mm.

Table 1: Parameters for the Racetrack Coil

Straight Section (cm)	12
Total Length (cm)	28
Coil Diameter and Vertical Separation (cm)	14.8
Central Magnetic Field (T)	0.2 @ 31.7 kA
Field Integral on the Beam Axis (T-mm)	47.2

An optional beam steering coil composed of four rings is shown in Fig. 4. The average radius of each ring is 7.7 cm and the two rings are separated by 10 cm in the longitudinal direction so that the two coils overlap approximately by 5.4 cm. Because of the coil overlapping the field integral of the circular coil is approximately 12% lower than that of the racetrack coil.

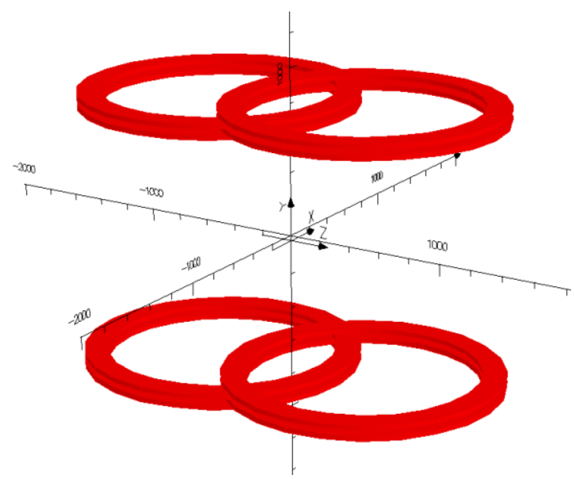

Figure 4: Four-ring coil configuration with a radius of 7.7 cm and an overlap of 5.4 cm.

For the latter configuration, at x = ± 6 mm of the symmetry plane, y=0, the field integral along the coil length is reduced to 0.4 % of the field integral at x = 0. For the circular coil the reduction is about 0.5 %.

2 NUMERICAL SIMULATIONS

The steering coils can introduce non-linear effects on the beam dynamics. Numerical simulations were performed with the tracking code TRACK [2] to determine the beam response to the realistic (3-D) magnetic field distributions including the steering coils. The 3-D magnetic field distribution of the steering coil is obtained by analytical continuation of the dipole axial field on its mid-plane [3]. The steering algorithm corrects the horizontal and vertical beam slopes, x'_0 and y'_0, but not the beam displacements. For slope correction, both the horizontal and vertical slopes, as well as the beam-centre displacements, must be measured at the entrance of the solenoid/dipole assembly, due to the beam axial rotation in the solenoid. The steering-field strength is set to the strength necessary to correct the beam slope calculated at the end of the solenoid with the dipole current turned off. We present results from simulations on the first part of the medium-β section of the RIA SC driver linac, downstream of the first stripper [2]. Some of the beam and lattice parameters of this section are summarised in Table 2.

Table 2: Parameters of the First Medium-β Section

Beam Energy (MeV/u)	9.2 – 47.3
Geometrical Beta of SC Resonator	0.19
Focusing -period Length (cm)	173.4
Transv. Phase Advance / Period (deg)	67.5
Solenoid Effective Length (cm)	30.
Solenoid Focusing Field (T)	6.0 – 9.0

The simulations were performed in two steps. The most effective steering dipole-coil distribution over the lattice was determined by tracking one-charge-state uranium beams in the presence of steering or cavity and solenoid alignment errors. We then simulated five-charge-state uranium beams to determine the effective emittance growth under errors and its value after correction. Placing both vertical and horizontal pairs of coils on a focusing solenoid is more effective in reducing trajectory oscillations and beam emittance growth than placing a vertical or a horizontal pair of dipole coils on a focusing solenoid, alternatively along the lattice.

The simulation results for a five-charge-state uranium beam, with initial horizontal displacement of 5 mm and slope of 3 mrad are depicted in Figures 5 and 6. We used 20,000 macro particles in the simulation, with 4,000 macro particles per charge state. As seen in Table 3, there is no emittance growth for the one-charge-state beam. The emittance growth for the corrected five-charge-state beam comes from the multiplicity of charge states [4]. The steering coils do not produce non-linear effects on the beam. The beam distortions are negligible and well within the large lattice aperture of 3.0 cm.

Table 3: Summary of the Normalized Transverse Emittance in the Horizontal Plane at the Entrance and Exit of the Lattice.

Beam	One-charge-state		Five-charge-state	
Emittance (cm-mrad)	4-rms	Total	4-rms	Total
No Error (a) (b)	0.0593 0.0599	0.1145 0.1161	0.0593 0.0601	0.1145 0.1332
Uncorrected Error	0.0593 0.0597	0.1145 0.1175	0.0593 0.3633	0.1145 0.6906
Corrected Error	0.0593 0.0597	0.1145 0.1161	0.0593 0.0761	0.1145 0.2077

(a) Initial Value (b) Final Value

Additional studies are planned to design a correction algorithm that takes into account the realistic beam rotation through the solenoid, which couples the horizontal and vertical beam motion.

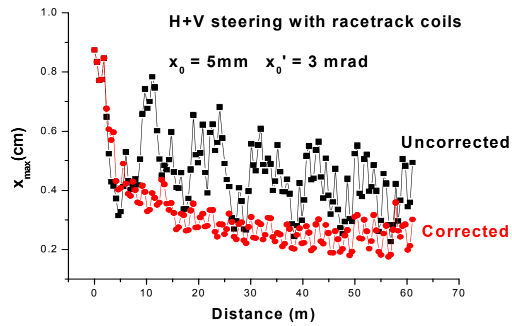

Figure 5: Horizontal envelope for the five-charge-state uranium beam, before and after steering correction.

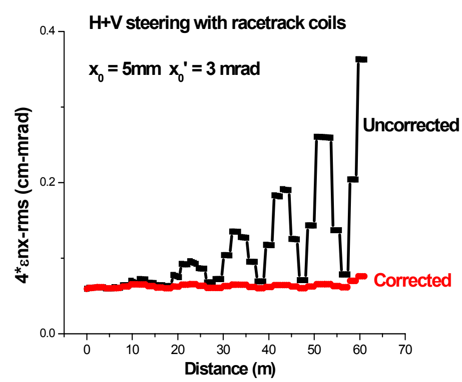

Figure 6: 4-εxn-rms emittance for the five-charge-state uranium beam, depicted in Fig. 4. After correction, the emittance is reduced by a factor of three.

3 SUMMARIES

Preliminary R&D on an assembly of a focusing solenoid, bucking coils, and steering dipole coils, indicates a feasible design that provides the required minimization of stray fields in a compact set. The structure is designed to withstand hoop stresses as well as axial and radial forces that will arise both during normal operation and during quench conditions. Simulations showed no non-linear effects on the beam emittance. Further beam-dynamics studies are required that will include the solenoid-induced coupling in the steering algorithm.

4 REFERENCES

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