A HYBRID SUPERCONDUCTING SOLENOID AS A FOCUSING ELEMENT IN A SUPERCONDUCTING HEAVY-ION ACCELERATOR[a]

A. H. Jaffey, R. Benaroya, and T. K. Khoe

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois
U.S.A.

Introduction

Using superconducting solenoids as focusing elements in the Argonne Superconducting Heavy-Ion Linac Booster is considerably simpler than using the traditional quadrupoles. Although leakage of magnetic field is a potential source of interference with rf superconducting resonators, a soft iron shield surrounded by a mu-metal shield adequately reduces such leakage. A prototype solenoid, in all essential respects like that needed in the linac, has been constructed and tested. Its magnetic performance was as predicted theoretically. The ease of manufacture and relatively modest cost are important advantages of this type of focusing element.

The natural radial expansion of a linac beam with beam drift and the defocusing effect of the resonator require that focusing elements be placed periodically along the beam path to reconverge the beam. As a minimum requirement, at least enough focusing power is needed to keep any part of the beam from colliding with parts of the accelerator, especially the superconducting resonators, which may be severely damaged by heavy ion bombardment. The achievement of good energy resolution sets even stronger requirements on minimizing the radial extent of the beam.

When the superconducting heavy-ion linac was first considered, it was assumed that the focusing elements would be quadrupoles, which are universally used in room temperature accelerators and their beam-lines. The focusing ability of solenoids has long been known, and indeed they have been widely used for electrons, as in electron microscopes. However, for room temperature use with heavy particles, the quadrupole has far larger focusing power than the solenoid. Since focusing in a solenoid is a second-order effect, focusing power is proportional to B^2. Hence, the large increase in field available with a superconducting solenoid makes the solenoid focusing power comparable to that of a room-temperature quadrupole doublet.

Treating the focusing elements as simple lenses, the focal lengths are given by:

$$\left|\frac{1}{f_{sol}}\right| = \left(\frac{1}{2}\frac{q}{A}\frac{e}{m_o v}\right)^2 \overline{B_z^2}\; L_{sol} \qquad (1)$$

with

$$\overline{B_z^2}\; L_{sol} = \int_{-\infty}^{\infty} B_z^2 \, dz = P_s \qquad (2)$$

and

$$\left|\frac{1}{f_{quad}}\right| = \left(\frac{q}{A}\frac{e}{m_o v}\right) G L_{quad} \qquad (3)$$

where

q/A = charge/mass number ratio
e = electronic charge (coulomb)
m_o = unit rest mass (kg)
v = particle velocity (m/sec)
$\overline{B_z^2}$ = solenoid B^2, averaged over solenoid length (tesla^2)
P_s = solenoid focusing power (tesla^2 meter)
G = quadrupole field gradient (tesla/meter)
L_{sol} = solenoid length (meter)
L_{quad} = quadrupole element length (meter) $= \frac{1}{2} L_{sol}$

Then for focusing devices of about the same length, for $q/A = 0.5$ and for $v/c = 0.1$,

$$\theta = \frac{f_{sol}}{f_{quad}} = \frac{G}{\overline{B^2}}\; 1.25 \qquad (4)$$

For room temperature devices, reasonable attainable values are $G = 25$ T/m and $(\overline{B^2})^{1/2} = 0.5$ T, for which $\theta = 125$. Clearly, the solenoid focal length is much too long. However, for a superconducting solenoid, a value of $(\overline{B^2})^{1/2} = 6$ T is reasonable, for which (with the same G-value), $\theta = 0.9$. The solenoid focuses as effectively as the doublet.

Aside from the need for attaining high fields, the use of superconducting focusing elements is highly desirable in a linac enclosed within a liquid-helium environment. The use of water-cooled room-temperature elements has some undesirable features in that it would require liquid helium-to-room temperature transition regions. These would be expensive to fabricate and would lengthen the linac by increasing the drift lengths.

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[a] Work performed under the auspices of the U. S. Energy Research and Development Administration.

Further, if the beam tube inside the focusing element were warm, there would be sources of outgassing components from the "hot" regions which could deposit and contaminate the superconducting resonator surfaces. A beam tube cooled to very low temperatures would entail an increase in the bore of the focusing element.

Given that the superconducting solenoid provides adequate focusing power, it actually has a number of advantages over the quadrupole doublet. These advantages stem from the relative ease of accurate construction and from the fact that only one coil element is involved in a focusing lens. Among the relative disadvantages of the quadrupole system are not only the greater difficulty of accurate construction, but also the greater complexity of alignment and control for the two doublet elements.

Focusing Power Required

In the Argonne superconducting linac, it is proposed to modularize with a basic structure (or cell) having two resonators followed by a solenoid. It is planned to have the solenoid focusing power sufficient to bring the beam size to a minimum (i.e., a waist) between the two resonators of the next cell. Under such operating conditions, and for a given beam emittance, the beam size is kept as small as it can be inside the resonators.

The quality of the beam emerging from the tandem is expected to be quite good, so that requirements of energy resolution would, in fact, allow considerable relaxation of the focusing power requirements. We plan, however, to be conservative, and to use the minimum-beam focusing requirement. This conservatism provides a reserve capability so that the radial focusing properties of the linac will not limit the energy resolution even in cases of low charge and/or high-mass ions.

The beam diameter increases primarily because of the natural drifting spread, influenced in only a minor way by the radial defocusing force of the phase-stable resonator. If the defocusing is neglected, calculation indicates that the beam achieves minimum radial extent when the solenoid focal length is about half the cell length. When the defocusing effect is included, for an effective accelerating field of about 4 MV/m, minimum beam size is achieved when the solenoid focusing power is increased by 7 to 9%.

In the initial phase of construction of the Argonne superconducting booster, it is planned to include twelve resonators, dividing them into two groups of high and low β-values.

If the minimum beam size requirement is used, the solenoid focal length is fixed by the cell goemetry (the correction for the defocusing effect not varying much). Hence, from Eq. (1), the focusing power required is:

$$P_s = K \frac{\beta^2}{(q/A)^2} \frac{1}{f_m} \qquad (5)$$

where K is a constant, $f_m \equiv |f|$ and $\beta = v/c$. For $^{58}Ni^{20+}$, for which $q/A = 0.345$, this becomes $P_s = 324\ \beta^2/f_m$. For a cell length of 1.3 m and an 8% correction for defocusing, $f_m = 0.6$ m, so for $\beta = 0.1$, $P_s = 5.4\ T^2m$.

For a given type of particle, P_s increases as energy is gained in the linac if f_m does not change. For our design, f_m does change in a major way when the shift occurs from the low-β resonators to the high-β units, the latter being sizeably longer. Aside from this effect, P_s increases along the linac. Numerically, it turns out that to focus $^{58}Ni^{20+}$ ions, injected by the tandem at 1.7 MeV/nucleon and boosted to an energy corresponding to 6.5 MeV/nucleon, the values of P_s required vary from 4.4 to 6.4 tesla^2 meter. What this involves in length will be discussed below.

Design and Construction of a Focusing Solenoid

The basic elements of the design considerations were discussed in Ref. 1. In constructing a solenoid focusing unit, it was necessary to take into account the possible interference of the leakage magnetic field. Since the performance of a superconducting rf resonator is degraded by the entrance of an imposed D.C. magnetic field, it was proposed to confine the leakage field with a soft iron shield. An added bonus in using the iron return path was the improvement in magnetic efficiency. At the same current density, the P_s-value for an iron-shielded coil increased by ∿ 40% for a 6 cm coil and ∿ 13% for a 19 cm coil. As the coil gets longer, the influence of the magnetic poles formed by the shield ends has less effect upon the central field, so the increase is less marked.

As noted in Ref. 1, the properties of the coil-shield combination were calculated with the computer program TRIM, which allows for the μ-variation with field intensity in the iron. From these calculations, it was possible to develop interpolation and extrapolation relationships which allowed evaluation of the P_s vs coil length curve shown in Fig. 1. Except at the lower end (below 9 cm), the curve is essentially straight. This results from the shielding effect of the iron, which makes the shape of the fringing field (at the ends) relatively insensitive to the coil length. An increase in the coil length essentially corresponds to the introduction of an added high field section into the middle of the coil.

It was decided to build a unit having a coil of 15 cm length. From Fig. 1, this should have a P_s-value within the range desired for the present Argonne linac design. The solenoid design is shown in Fig. 2. A mu-metal shield surrounds

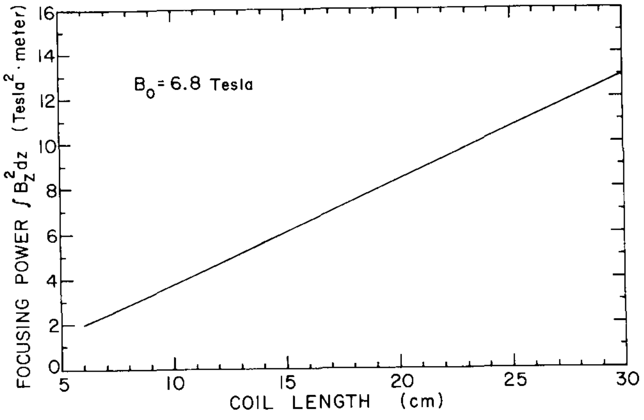

Figure 1. Focusing power P_s $\left(= \int B_z^2\, dz\right)$ vs length of Nb-Ti coil, with an iron shield as shown in Fig. 2, and with an outer coil radius of 4.25 cm. The current density in all coils is the same and has been adjusted so that the central field in the longer coils is 6.8 tesla.

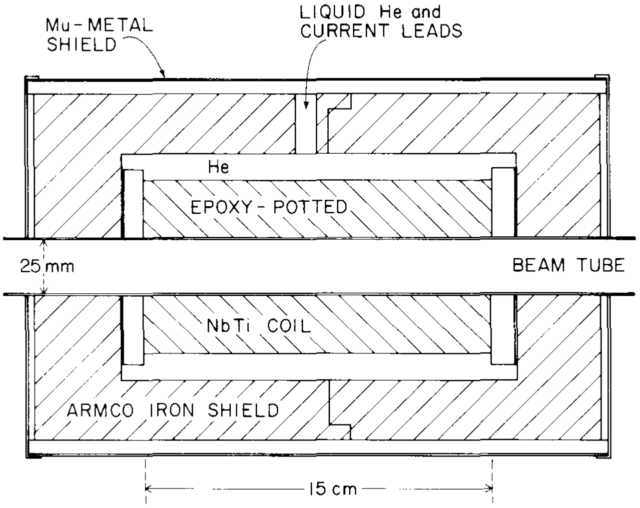

Figure 2. Basic features of the constructed focusing solenoid. The coil dimensions are: length, 15.0 cm, inner radius = 1.44 cm, outer radius = 3.6 cm. For a central field of 6.8 T, the current was 48.5 A and the current density 25400 A/cm^2. The iron shield thickness is 2.75 cm on the cylinder and 4.0 cm at the ends. The coil form and coil were directly mounted onto a section of the beam tube and the Nb-Ti (Cu) wires secured with epoxy-potting. The iron and mu-metal shields were then installed.

the iron shield. This is included because the iron, though low in carbon and annealed, has some remanent field. If this field penetrates the resonator before it is cooled below the niobium transition temperature, the magnetic flux is then "frozen-in" when the unit turns superconducting and leads to unacceptable rf losses. Such an ambient field should be reduced to the 50 mG level at the resonator position. In operation, the resonator is made superconducting before the solenoid is energized; the resonator walls then exclude the leakage flux from the solenoid.

A Nb-Ti coil was wound and epoxy-potted commercially.[a] The total cost of the unit, including coil, vapor-cooled leads, power supply, persistent switch, shield fabrication and annealing was less than \$5000. Some decrease in cost per unit is reasonable when a number of solenoids are manufactured. For operation in the Argonne linac, there would also be a moderate increase in the unit cost due to the need for an enclosure. Because the solenoid is suspended in a vacuum, it would be necessary to enclose it in a vacuum-tight stainless steel can, with provision for current leads and for feeding in liquid helium and removing the vapor.

The magnetic field was measured with search coils and integrating circuits, with the results shown in Fig. 3. A special TRIM calculation was made, using the dimensions of the as-built coil. Agreement was very good in the coil center, with some disagreement near the iron shield. The explanation may be that the TRIM program used a μ-vs-field table different from that of the very low carbon Armco iron. The measured results indicate that the field actually dropped off more rapidly than indicated by the TRIM calculation. This is also evident in the field results outside the shield, as shown in Fig. 4.

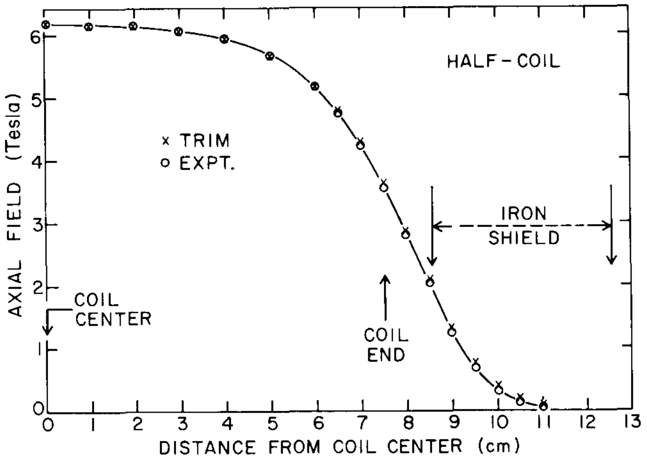

Figure 3. Measured and calculated axial field of manufactured solenoid within the iron shield.

With the solenoid activated, the axial leakage field dropped to 10 G at a distance of 1 cm beyond the iron shield. With no coil current, and with the earth's field excluded with a large magnetic shield, the remanent magnetic field was measured to be 50 mG at a distance of 2.5 cm from the mu-metal shield.

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[a] American Magnetics, Oak Ridge, Tennessee.

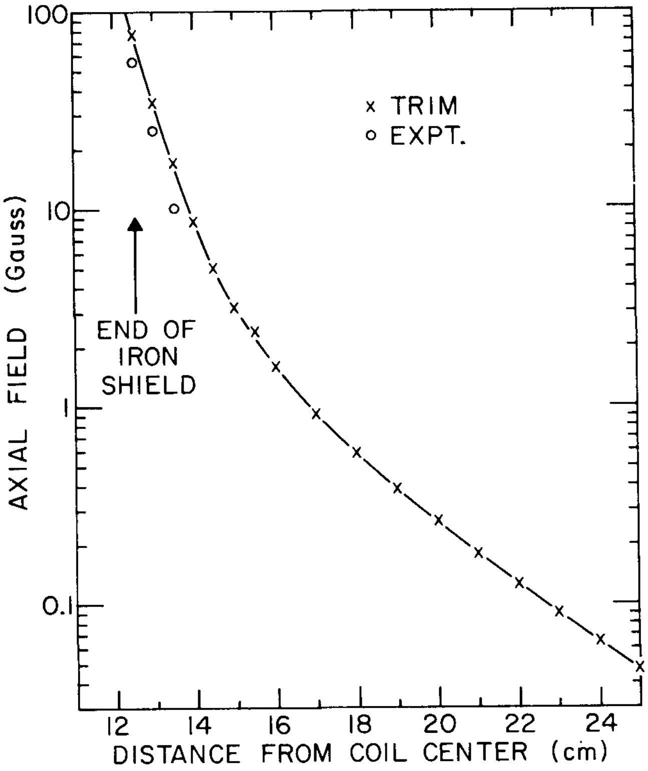

Figure 4. Measured and calculated axial field of manufactured solenoid outside the iron shield.

Because it was desired to investigate the possibility of using persistent currents in the solenoid, commercial fabrication included installation of a persistent switch. This allows operation of the solenoid without constant connection to the current source. It was briefly tested over a period of 8 hours and showed no field change within the measuring accuracy (0.1%). In actual operation, it would not be necessary to have both a persistent switch and vapor-cooled leads, although both were used in the test operation.

The solenoid was operated at a number of activating currents. Data for Figs. 3 and 4 were taken with a central field B_o = 6.2 T. The solenoid was tested up to B_o = 7.05 T without quenching; the available power supply did not allow operation at higher fields. Fig. 1 was calculated for B_o = 6.8 T, a reasonably safe value.

Discussion

We have established that it is straightforward to construct solenoid focusing elements adequate for use in the Argonne booster, and that the fabrication cost per unit is modest. The lengths required are quite moderate, when it is considered that only 13 cm additional length is needed for the coil form, the iron and mu-metal shields, and the enclosing vacuum can. Thus, for coils of this design, the physical length of a solenoid needed for a particular P_s-value would be the length given in Fig. 1 plus 13 cm. For situations in which high P_s-values were needed, the coil length could be reduced (relative to Fig. 1) by increasing the number of turns and wire size, hence the outer coil diameter. This would allow an increase of B_o to ∿ 8 T, which corresponds to an increase in the slope of Fig. 1 by ∿ 40%.

References

1. A. H. Jaffey and T. Khoe, Nucl. Inst. and Methods 121, 419-419 (1974).

DISCUSSION

E. Regenstreif, Univ. of Rennes: Did you make a comparison between the phase acceptance of a solenoid and the phase acceptance of a quadrupole system under comparable conditions?

Jaffey: I cannot give you a quantitative comparison. I have not calculated the acceptance of a corresponding quadrupole doublet. Qualitatively, however, for a given bore the doublet must have a smaller acceptance because the first element of the doublet defocuses in one dimension. The quadrupole bore must accept the defocused beam, so can tolerate a beam of lesser divergence than the solenoid which focuses all radial directions at the same time. Quantitative comparisons have been discussed in the literature, see Ref. 1 of this paper, and these agree with the qualitative comment just made.

The radial acceptance of this solenoid is approximately 120 mm.mrad. If we insert collimators, this number would be decreased. We expect that we may have to install some collimators in order to ensure that stray particles do not cause radiation damage to the superconducting surfaces of the resonators. Our beam is so small that such collimators can be installed with no interference with the beam.

H. Klein, Frankfurt: Is this figure for the acceptance normalized?

Jaffey: The acceptance calculated is A^2/β where A is bore radius and β is the coefficient of r^2 in the expression for the transverse phase ellipse at the solenoid center. For the case considered here, where a waist is formed, β is approximately the cell length.

Klein: Is it not possible to make use of superconducting material for magnetic shielding instead of iron?

Jaffey: In theory, yes, and I have considered using such a shield. It is an attractive idea, having the virtue that the shield has a small mass compared to the iron shield. The iron shield itself weighs about 20 kg for a coil 15 cm long (P_s ∿ 6 T^2m for B_o = 6.8 T). This is a sizeable mass for cooldown to liquid He temperature.

However, the fabrication of superconducting shields is not simple. Shields would be expensive and not commercially available. I rejected the superconducting shield because I wanted to keep the total cost below the $5000 figure I mentioned.