

# DESIGN CONSTRUCTION AND TEST RESULTS OF A HTS SOLENOID FOR ENERGY RECOVERY LINAC\*

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## Abstract

An innovative feature of the proposed Energy Recovery Linac (ERL) is the use of a solenoid made with High Temperature Superconductor (HTS) with the Superconducting RF cavity. The use of HTS allows solenoid to be placed in close proximity to the cavity and thus provides early focusing of the electron beam. In addition, cryogenic testing at ~77 K is simpler and cheaper than 4 K testing. This paper will present the design, construction and test results of this HTS solenoid.

## INTRODUCTION

The HTS solenoid in the proposed ERL [1] will be situated in the transition region between the superconducting cavity at ~4 K and the cryostat at the room temperature. Solenoid inside the cryogenic structure [2, 3] provides an early focusing and hence low emittance beam. The temperature in the transition region will be too high for a conventional low temperature superconductor and resistive heat load from copper coils will be too high on cryogenic system. HTS coils also allow much higher current density and significant reduction in size as compared to copper coils. Hence HTS solenoid provide a unique and technically superior solution.

## MAGNETIC DESIGN

The overall magnetic design of the solenoid and other relevant components is shown in Fig 1. Major design parameters have been listed in Table 1. The strength of the field and variation along the axis are primarily determined by the iron. Focusing is provided by the axial component of the field and the requirement of the design is that the solenoid provides the following integral focusing:

$$\int B_z^2 dz \approx 1 T^2 . mm$$

The computed axial profile of the focusing ( $B_z^2$ ) by the solenoid coil is given in Fig. 2.

An important design consideration is to keep the field on the cavity below 10 mG (1 micro Tesla) during the operation. This is to minimize the trapped field on the superconducting cavity which could limit its operation. Therefore a bucking coil is introduced and an inner magnetic shield is placed between the solenoid and the cavity (as shown in Fig. 1) to reduce the leakage field on the cavity from the solenoid. The magnetic shielding (Meissner effect) by the superconducting cavity and other superconducting structures reduces the field inside the cavity and is included in the magnetic modelling.

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Table 1: Major Design Parameters of the HTS Solenoid

Parameters	Value
Coil Inner Diameter	175 mm
Coil Outer Diameter	187 mm
No. of Turns in Main Coil	180
No. of Turns in Bucking Coil	30 (2X15)
Coil Length (Main Coil)	~56 mm
Coil Length (Bucking Coil)	~9 mm
Conductor (First Generation HTS)	BSCCO2223
Insulation	Kapton
Total Conductor Used	118 meter
Nominal Integral Focusing	1 T <sup>2</sup> . mm
Nominal Current in Main Coil	54.2 A
Nominal Current in Bucking Coil	-17 A
Maximum Parallel Field on Conductor	0.25 T
Max. Perpendicular Field on Conductor	0.065 T
Stored Energy	~25 Joules
Inductance (main coil)	0.13 Henry
Yoke Inner Radius	55 mm
Yoke Outer radius	114 mm
Yoke Length (Main + Bucking)	147 mm

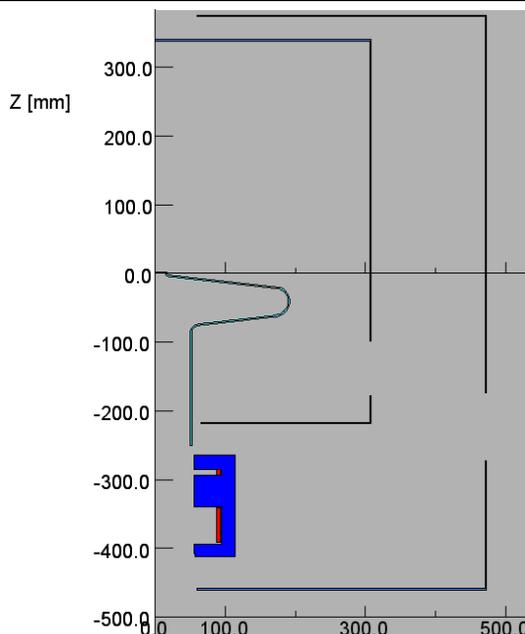


Figure 1: Overall magnetic design of the solenoid showing the main coil, the bucking coil, the yoke iron, the superconducting cavity and the inner magnetic shield.

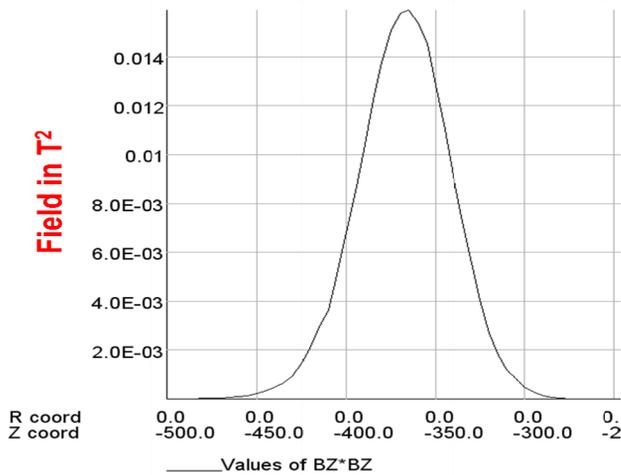


Figure 2: Computed profile of the focusing ( $B_z^2$ ) along the axis of the solenoid coil. The beam is injected in the cavity at  $z=0$  and travels along the negative  $z$ -axis.

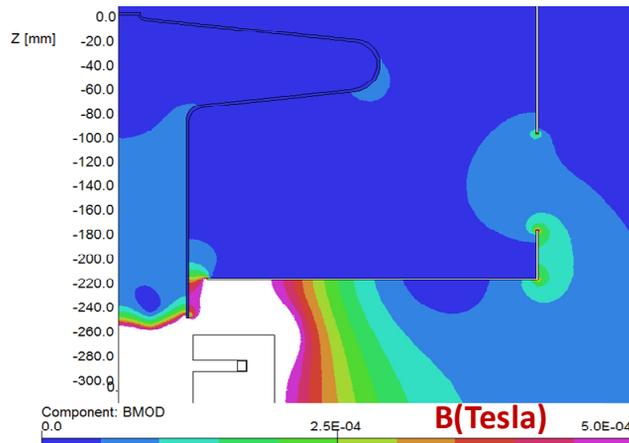


Figure 3: Magnitude of field on and around the cavity. The maximum value is clamped at 0.5 mT (5 G) to better view the lower field region near the cavity.

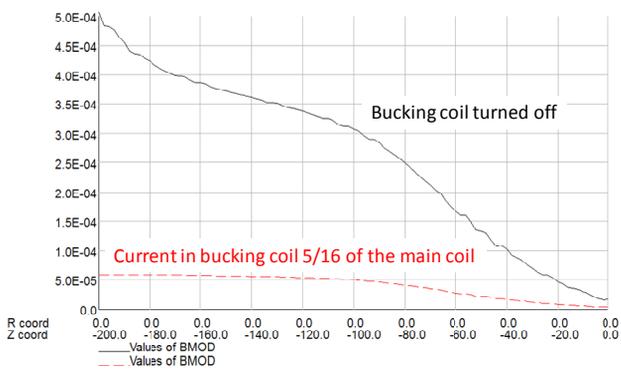


Figure 4: Field (T) along the axis (mm) of cavity with (dashed line) and without (solid line) bucking coil.

Fig. 3 shows the field map in the neighbourhood of cavity. One can see that the computed field on the cavity is well below 10 mG (1 micro Tesla). Fig. 4 shows the magnitude of the field along the axis of cavity with and without bucking coil. Beam is injected in the cavity at  $z=0$  and travels downward in the negative  $z$ -direction.

## ENGINEERING DESIGN AND CONSTRUCTION

Coils made with HTS (Bi2223) tape, insulated with spiral-wrap Kapton, are wound using two different techniques (see Fig. 5). The main coil is wound in a back and forth level-wind fashion and bucking coil wound as two pancakes spliced at the inner radius. The yokes for each coil are split into two unequal pieces (see Fig. 6). This is to accommodate the tangentially exiting coil leads, to help make assembly possible and to accommodate the differential thermal contraction between the coils and the yokes so that they remain in contact during cooldown. The yoke captures the coils on the outside diameter and on the two sides of each coil. A close fit between yoke and coil is designed to provide a moderate pressure on the coil both at room temperature and cold at operating temperature. A special thermally conductive epoxy and a close fit provide good thermal transfer from the yoke to HTS coils during cooldown and during operation. This also provides mechanical support (in addition to the relatively thin coil overwrap) to prevent conductor motion that could cause quenching.

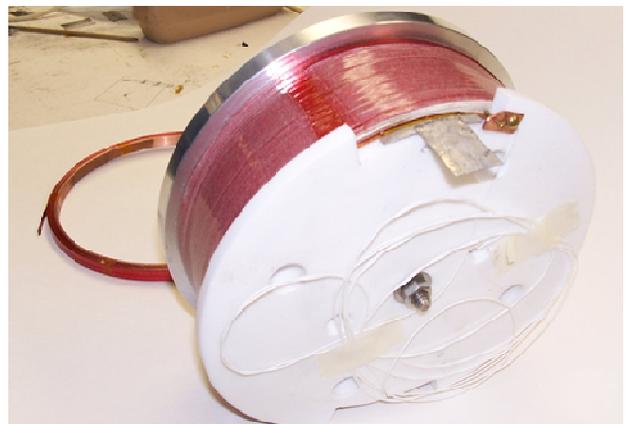


Figure 5: HTS solenoid coils – main coil (front) is layer-wound and bucking coil (back) is pancake wound.

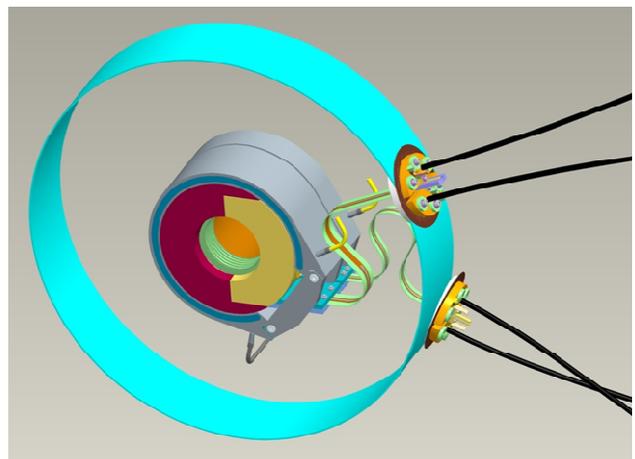


Figure 6: Solenoid assembly inside a portion of the heat shield. One can see two yoke halves, aluminium collars, cooling pipes and flexible leads to the outside terminals.

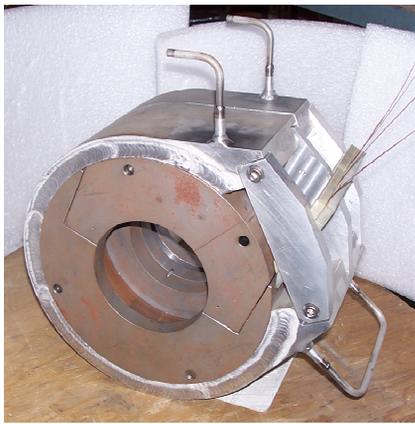


Figure 7: Completed solenoid assembly with two unequal yoke halves, aluminium collars and pipes for cooling.

Fig. 6 shows the design and Fig. 7 construction of the completed solenoid assembly of yoke halves, aluminium collars and piping for cooling. The collars press the two halves of each yoke together during cooldown and are the primary means of directly cooling the yokes, and indirectly (conduction cooled) the coils. The collars are cooled by way of single phase Helium passing through a series of small circumferential channels. A flexible lead assembly (Fig. 6) was developed to carry current from the coil to the outside terminal.

### TEST RESULTS

Both coils were individually tested at 77 K and both reached well above the nominal design current of 54.2 A (Fig. 8) despite the absence of yoke which would allow higher current by making the field parallel to the conductor surface. The critical current is defined as the current when the voltage gradient is 1  $\mu\text{V}/\text{cm}$ .

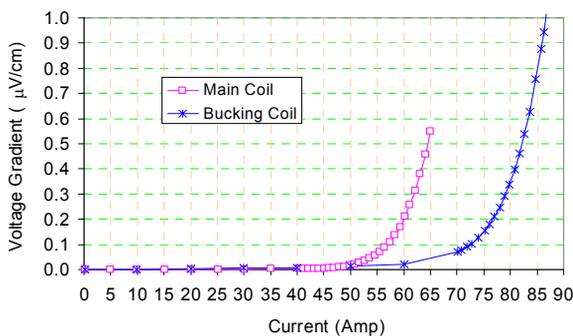


Figure 8: Measured voltage gradient at 77 K of the main HTS coil and in the bucking HTS coil made with Bi2223.

The test setup (Fig. 9) serves a dual purpose as it allows (a) the quench test of completed solenoid (with main coil, bucking coil, yoke and collar) and (b) measurement of the leakage field from the solenoid in the cavity area with the inner magnetic shield and the bucking coil powered. The use of HTS makes these measurements possible at 77 K with liquid nitrogen in a simple cryostat. Conventional superconductor would have been required a more complex and expensive cryo-structure for 4 K testing with liquid helium.

#### Accelerator Technology

#### Tech 10: Superconducting Magnets



Figure 9: Solenoid in test cryostat with shield in place for magnetic measurements at design field at 77 K.

The leakage field was extensively measured inside the shielded region with and without the bucking coil. Fig. 10 shows the field as a function of radial distance from the axis at 190 mm and 250 mm from the yoke surface when the current in the main coil is  $\sim 54$  A and in bucking coil  $\sim 17$  A. The measured field in the critical cavity region ( $\sim 250$  mm from yoke) is about 2  $\mu\text{T}$ . It is expected to be less than 1  $\mu\text{T}$  with the shielding from the superconducting cavity (not present here).

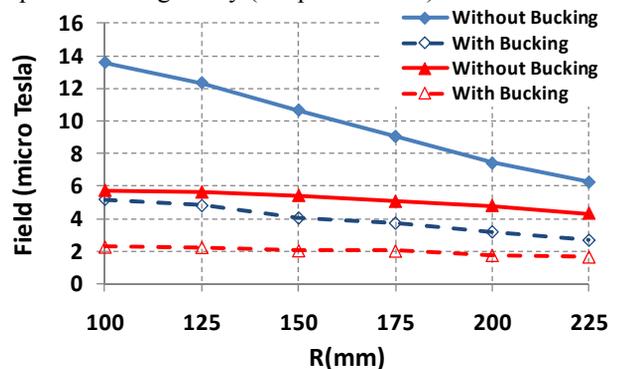


Figure 10: Measured fringe field as a function of radius with and without bucking coil at 190 mm (blue diamond) and 250 mm (red triangle) from the yoke surface.

### SUMMARY

The use of a HTS solenoid with superconducting cavity offers a unique option as it can be placed in a cold to warm transition region to provide early focussing without using additional space. Construction and test results so far are very encouraging for its use in the ERL project.

### REFERENCES

- [1] I. Ben-Zvi, et al., "Superconducting Photoinjector", Proceedings of the 2007 Free-Electron Laser Conference, Budker, Novosibirsk, Russia (2007).
- [2] R. Gupta, J. Muratore, S. Plate and W. Sampson, "HTS Solenoid for Electron Recovery Linac", Magnet Div. Note MDN-663-44, unpublished (2010).
- [3] <http://www.bnl.gov/magnets/Staff/Gupta/Talks/erl-talks.htm>.