Design Construction and Test Results of a HTS Solenoid For Energy Recovery Linac

R. Gupta, M. Anerella, I. Ben-Zvi, G. Ganetis, D. Kayran, G. McIntyre, J. Muratore, S. Plate, W. Sampson
Brookhaven National Laboratory, Upton, NY 11973 U.S.A.
M. Cole, D. Holmes

Presented at the Particle Accelerator Conference (PAC11)
New York City, NY
March 28 – April 1, 2011

May 2011

Superconducting Magnet Division
Brookhaven National Laboratory

U.S. Department of Energy
University of Michigan

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author’s permission.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party’s use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DESIGN CONSTRUCTION AND TEST RESULTS OF A HTS SOLENOID 
FOR ENERGY RECOVERY LINAC*

R. Gupta#, M. Anerella, I. Ben-Zvi, G. Ganetis, D. Kayran, G. McIntyre, J. Muratore, 
S. Plate and W. Sampson, Brookhaven National Laboratory, Upton, NY, 11973 USA 
and M. Cole and D. Holmes, Advanced Energy Systems, Inc., Medord, NY, 11763 USA

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:

\[ \int B_z^2 dz \approx 1 \, \text{T}^2 \cdot \text{mm} \]

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.

Table 1: Major Design Parameters of the HTS Solenoid

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

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.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Dept. of Energy
#Corresponding author: Ramesh Gupta, gupta@bnl.gov.
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.

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.
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 \( \mu \)V/cm.

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.

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 ~54 A and in bucking coil ~17 A. The measured field in the critical cavity region (~250 mm from yoke) is about 2 \( \mu \)T. It is expected to be less than 1 \( \mu \)T with the shielding from the superconducting cavity (not present here).

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

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

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