

# **HTS Solenoid**

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## Overview



- Overall design : HTS solenoid inside the cryostat over the bellows
- Magnetic design
- Mechanical design
- Construction
- Measurements
- Future plans & Summary





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## Benefits of HTS Solenoid inside the cryostat **R&D** ERL

 Solenoid inside the cryostat and very close to cavity provides early focusing which reduces beam emittance. Originally, HTS solenoid was proposed as it can be conveniently placed inside the cryostat in a cold to warm transition region - say ~20 K.
NbTi won't work at 20 K and Cu magnet will be too big and create too much heat.

• The major advantage HTS over NbTi continues to be that it allows tests with LN<sub>2</sub> as solenoid is designed to reach the nominal field at 77 K. LN<sub>2</sub> not only makes tests an order of magnitude cheaper than testing in LHe at ~4 K (for NbTi), but also practical. Note: HTS cost is a fraction of overall solenoid cost (design, construction & testing).

• Conduction cooling and current leads become simple and attractive as temperature gradient is no longer an issue with a large thermal margin in case of HTS.

• Because the solenoid reaches the design field at ~80 K while cavity is still normal, one can go through the demagnetization cycle while cavity is still cooling down and has not yet reached the superconducting state.





## **Magnetic Design**







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#### Major Parameters of the HTS Solenoid

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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	<b>30 (2X15)</b>
Coil Length (Main Coil)	~56 mm
Coil Length (Bucking Coil)	~9 mm
<b>Conductor (First Generation HTS)</b>	BSCCO2223 Tape
Insulation	Kapton
Total Conductor Used	118 meter
Nominal Integral Focusing	1 T <sup>2</sup> . mm (axial)
Nominal Current in Main Coil	54.2 A
Nominal Current in Bucking Coil	-17 A
Max. Field on Conductor, Parallel/Perpendicular	0.25 T/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 ( + Bucking)	147 mm



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#### Bucking Coil to Reduce Field inside the cavity **R&D ERL**





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#### Bucking Coil and Inner Magnetic Shield to Reduce Field on the Superconducting Cavity



The goal is to avoid trapped field problem on cavity



 Inner magnetic shield and bucking coils makes field on the superconducting cavity very small in the operating range of the solenoid

- Field is about 10 mG in the significant part of the critical region
- These critical results are being verified experimentally





# Mechanical Design and Assembly R&D ERL



### Ship to and Return from Configurations J-Lab <u>R&D ERL</u>

- Ship partial assembly to J-Lab
- J-Lab builds hermetic string

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• Ships back along with other components



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## **Flexible HTS Leads & Heat Stationing**

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- We have developed flexible HTS leads for this application
- HTS lead with Kapton over top
- Laminated G-10 sheet, .015 thick each
- Motion during cooldown
  - radial = .011 inches cooldown
  - axial = +/-0.043 max

- Heat shield at 77K
- Copper terminals thermally connected to boss, but isolated electrically







# Cooling



- Coils are conduction cooled (avoids separate vacuum structure)
- Outside Aluminum coolars are cooled by helium
- Heat transfer to interference-fit yoke and then to HTS coil
- Attempt is made to have good conduction.
  - ➢ However, we have extremely large temperature margin (well over 50 K) because of HTS coils





Helium cooldown time to 4.2K: ~16 hours



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## **Construction of HTS Coils**





HTS tape was delivered with kapton insulation pre-wrapped on it



Main coil was layer wound (15 layers each with 12 turns) and the bucking coil was wound in double-pancake style



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## **Construction of HTS Solenoid**

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## Construction of Low Cost Test Set-up R&D ERL





• A low cost test set-up is possible because HTS solenoid reaches the desired field at 77K (LN<sub>2</sub>).

- The cost was further reduced by imaginative use of surplus equipment from farms, etc.
- Such low cost test would not have been possible for conventional LTS solenoid operating at 4 K with the cost of new test dewar.



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# **Measurements**

- 1. Assure that the HTS solenoid reaches design current with margin
- 2. Assure that the fringe fields on cavity are within acceptable limit
- 3. Assure that solenoid provides desired focusing (field on the axis)







- Both coils exceed design current (~54 A & ~17 A) at 77 K itself
- These tests were performed with no iron yoke over the coils



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### HTS Solenoid Has More Margin with Iron Yoke **R&D** ERL

Wire specifications for 77 K, self field Scaling ratio determines performance [mm] -320.0 at any temperature & field combination -330.0 > In HTS it depends on the direction -340.0 -350.0 -360.0 2.4 -370.0 Field 2.2 64K -380.0 Perpendicular b(T,B)Ad(77K,0) 2 -390.0 .8 -400.0 .6 -410.0 Ratio, 1 1.2 8.0 Sali 0.4 2 Inved -3201 0.2 -340.0 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 Perpendicular Magnetic Field (Tesla) -360.0 -380.0 400.0 Field 64 -O- 70k 2.2 -420.0 + 77K Parallel le(T,B)/le(77K,0) 2 -440.0 .8 .6 2.4845TE-05 Ratio, 8.0 Scaling 0.4 0.2 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 Parallel Magnetic Field (Tesla)

#### Components of the fields in the absence of yoke iron



Components of the fields in the presence of yoke iron ✓ A significantly reduction in the perpendicular component ✓ Thus actual solenoid (with iron) will have extra margin

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## Preparation of the Fringe Field Measurements **R&D ERL**

The goal is to measure (a) field on the axis of solenoid and (b) fringe field at the location of cavity in the operating range with bucking coil and inner magnetic shield in place. We have made initial measurements and are getting ready for more detailed measurements. There is a generally good agreement between calculations and Measurements.



LN<sub>2</sub> Test cryostat with shield in place



Vertical transporter and computer control cart



Warm Finger



Transverse and axial fluxgates



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# Summary



- HTS solenoid offers a unique solution
  - It allows solenoid very close to cavity
  - It allows a conduction-cooled design with large margin
  - It allows critical tests to be performed at liquid nitrogen itself which not only significantly reduces the cost of the overall system but make some of them possible as well.
- Measurements show that HTS solenoid reaches the design field at 77 K itself (would have a large margin at operating temperature <20 K)</li>
- Fringe field measurements are being carried out







# **Additional Slides**



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#### Challenges with HTS Solenoid inside the Cryostat and how we deal with them (1) R&D ERL

#### HTS is considered to be a new technology

- > We do a number of performance tests at several stages
- > We have a very large margin design current is over an order of magnitude below the critical current
- BNL has successfully built and tested many HTS coils & magnets









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# HTS Magnets Technology at BNL R&D ERL





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#### Solenoid close to SC cavity may create significant fringe field

- > We have a tunable bucking coil and inner magnetic shield to
- make field within ~10 mG to avoid trapped field problem on cavity
- > We have an experimental program to verify that the fields are low





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#### **Field Measurements**

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Fluxgate magnetometers measurement setup

Transverse (left) and axial (right) fluxgate probes in holders



Warm finger for hall probe measurements for field on the axis



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## Status of the Fringe Field Measurements **R&D ERL**

- Solenoid reaches the design performance at 77 K itself (that means a large temperature margin), now with yoke over the coil (earlier it was measured without iron)
- Initial measurements have been performed for field on the axis and one position off axis with hall probe in and outside solenoid
- Initial high precision, low field fringe field measurements have been performed with fluxgate probes in the region where cavity will be placed
- There is a general agreements between calculations and measurements.



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# Axial Field

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Variation of  $B_z^2$  along the z- axis





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#### Fringe field with the shielding from Superconducting Cavity R&D ERL (Nominal current in Main and Bucking Coils)





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#### Fringe field with <u>NO</u> shielding from Superconducting Cavity (Nominal current in Main and Bucking Coils)

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#### Fringe field components with <u>NO</u> shielding from Superconducting Cavity (Nominal current in Main and Bucking Coils) R&D ERL





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#### Fringe field with NO shielding from Superconducting Cavity NOTE: Extended Shielding (Nominal current in Main and Bucking Coils)

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