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# ***HTS Cable Test for a Fast-Cycling Accelerator Dipole Magnet***

## **E4R Test Goals and Arrangement Review**

**September 10, 2009**

Henryk Piekarz

# *Outline of Presentation*

- **Motivation**
- **Goals of the E4R test**
- **Fast cycling dipole and HTS cable designs**
- **Projected power losses for the test HTS cable**
- **HTS cable test arrangement**
- **Temperature rise, pressure drop and helium flow rate measurements in the test conductor section**
- **Component design and fabrication for HTS cable test**
- **Progress on fast-cycling dipole core fabrication**

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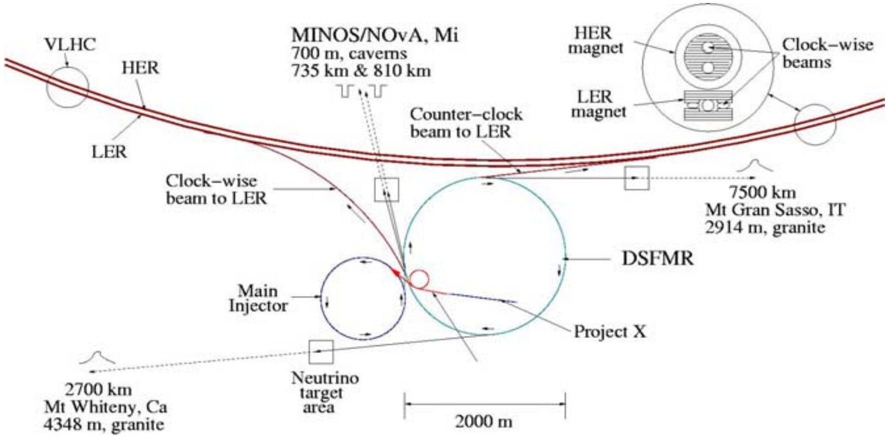
# General Purpose & Goals of the E4R Test



**Develop fast-cycling superconducting accelerator magnet energized by a transmission line HTS cable.**

**Possible applications include: PS2 and SF-SPS at CERN, and DSFMR at Fermilab.**

**DSFMR [1,2] would serve as both:**

1. **A dual 4 MW neutrino source**
2. **A dual fast injector to VLHC**

**[1] H. Piekarz, S. Hays, Y. Huang & V. Shiltsev, EPAC-08**

**[2] H. Piekarz, JINST 4 P08007, 2009**

- **E4R test stage 1**

  **Measure cryogenic power losses of a superconducting cable consisting of a stack of HTS tapes. The power losses will be induced by a sweeping external magnetic field as well as independently by the alternating transport current.**
- **E4R test stage 2**

  **Measure power losses of a 1.2 m long 2 Tesla dipole magnet energized by a superconducting HTS cable at sweeping dB/dt of up to 4 T/s.**

Safety considerations presented at this review are concerned with the Stage 1 only.

# ***Principles of HTS Cable Design***

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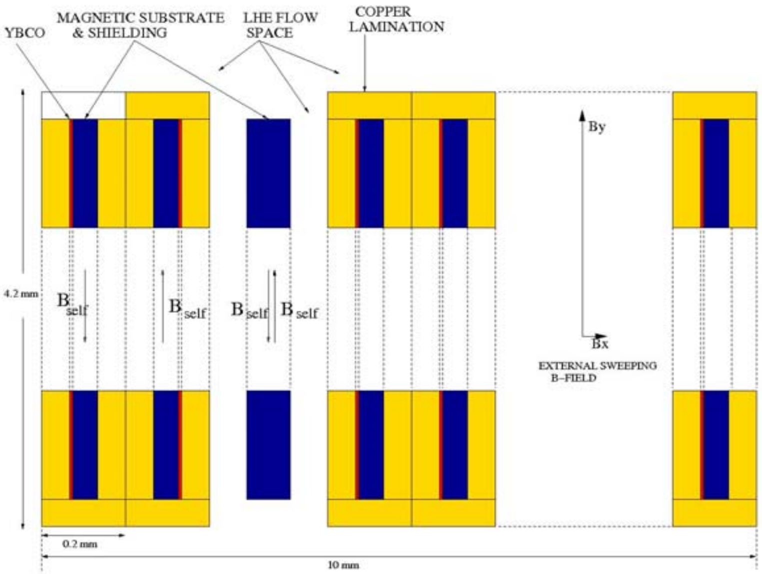
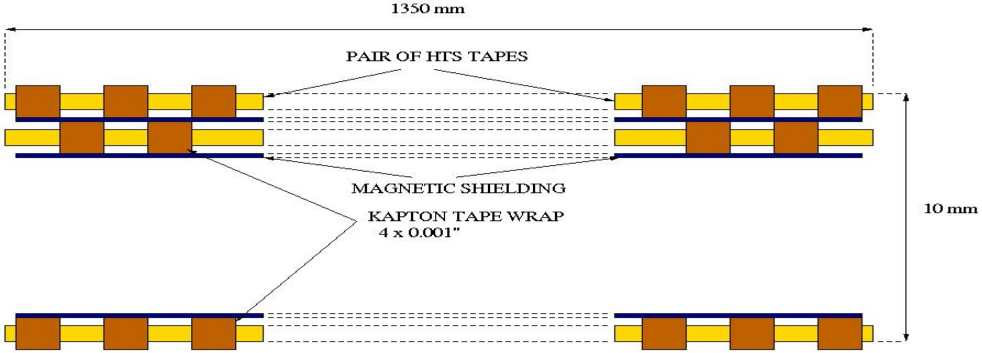
Cross-section view



Top view

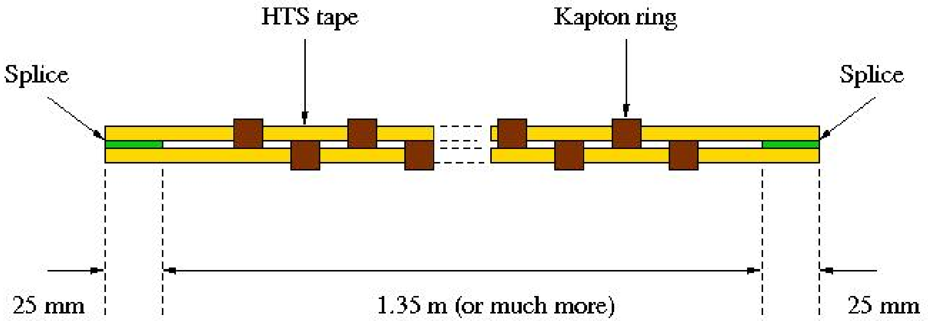


- **Narrow edge (2 um) of HTS tape faces high By magnetic field**
- **HTS tapes are paired with their magnetic substrates back to back**
- **Additional magnetic substrate tape is placed between the pairs**
- **Pairs of HTS tapes are electrically insulated from each other with staggered kapton tape rings**
- **Main LHe flow is above and below the HTS stack but helium has access to > 50% of HTS surface**

**Result:**

- **Minimization of external B-field induced power losses. Practically the “x” component of B-field that matters (2 µm vs 4000 µm)**
- **Minimization of self-field coupling (substrate saturates at < 200 G)**
- **Minimization of transport current coupling. Resistive contact can only be at the splice areas if tapes within a pair are also insulated**
- **> 50% of HTS copper lamination is exposed to helium coolant**

# *Transport Current & Self-field Coupling Power Loss Considerations*



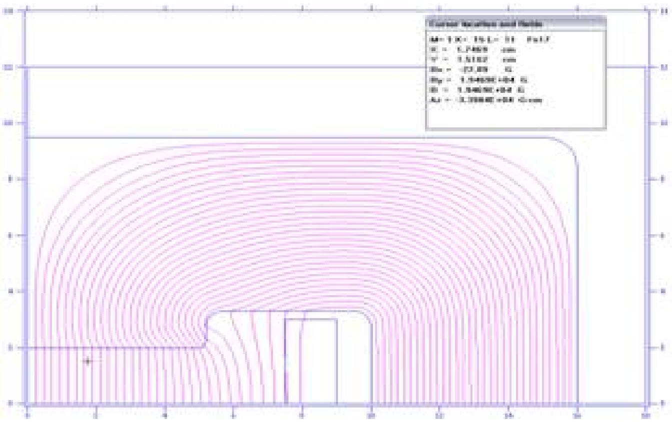
**We need to understand what is the "effective" resistance of a cable with multiple insulated HTS tapes along their entire length, except of the splice. If that resistance is determined only by the splice then insulating each individual tape will much suppress current coupling.**

**Based on [3] dI/dt losses for our test conductor will be small: ~ (1.5 – 3) W @ 200 Hz.**

**In these tests we are limited by the allowed lead current of 7 kA ac. With 70 kA current for 2 Tesla magnet the dI/dt at 0.5 Hz is 35 kA/s. So, we have to operate test conductor at least at 2.5 Hz but to really measure these losses we may need to go >> 100 Hz. For these tests we will disassemble the CDA magnet, or the test conductor loop.**

[3] Sumption et al., Supercond. Sci. Technology **18** (2005) 122-134

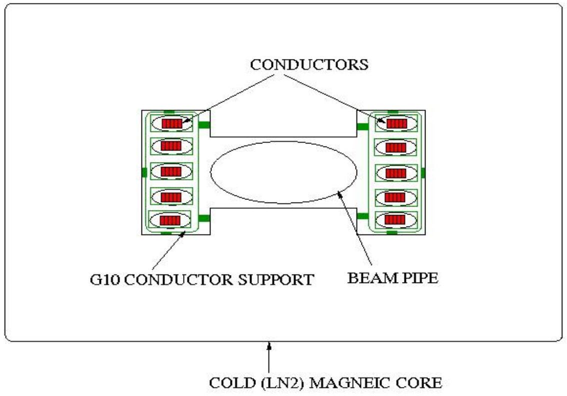
# *Fast-Cycling Dipole Design for Transmission Line HTS Cable*



**Jamie Blowers: Magnetic core design using Poisson Superfish program**

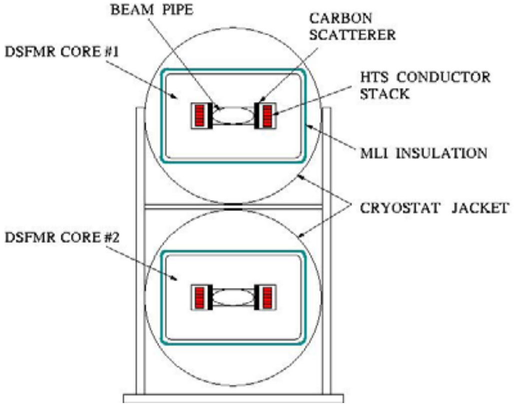
**Lamination: Fe5%Si, 100 μm, B/H curves (and steel) from Mapes & Sprowl**

**Magnet gap: 40 mm, I = 62 kA @ 2 Tesla**
**<Bx> over conductor stack space ~ 350 G**



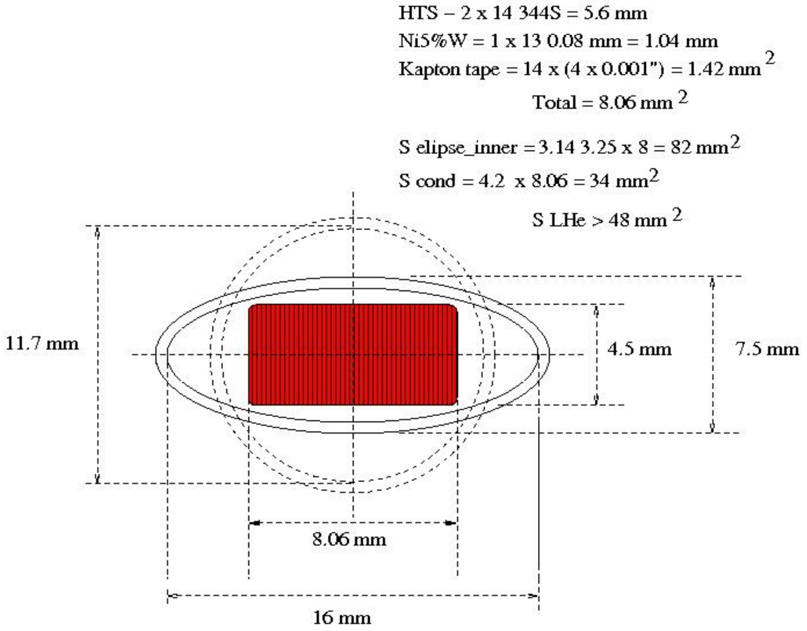
Magnetic core with conductors

For the low <Bx> value the top of conductor stack must be very close to the lamination wall leaving no room for the cryostat. Consequently magnetic core has to be cold (LN2) with the MLI wrapped around it and then placed inside the cryostat pipe.



Arrangement for DSFMR

# ***HTS Cable Design***



HTS – 2 x 14 344S = 5.6 mm
Ni5%W = 1 x 13 0.08 mm = 1.04 mm
Kapton tape = 14 x (4 x 0.001") = 1.42 mm $^2$
Total = 8.06 mm $^2$

S elipse_inner =3.14 3.25 x 8 = 82 mm $^2$
S cond = 4.2 x 8.06 = 34 mm $^2$
S LHe > 48 mm $^2$

**28 344-2G tapes in a stack**

**Ic ~ 28 kA @ 5 K**
**Ic ~ 14 kA @ 25 K**

**It ~ 14 kA @ 5 K**

**Quench margin ~ 20 K**

**Helium contact area:** **1. Edge (0.4 mm x 2 x 14 x 1350 mm x ½) = 265 cm^2**
**2. Wide surface (4.2 mm x 2 x 14 x 1350 mm x ½) = 794 cm^2**
**For heat transfer estimation only “edge” contact area was used.**

**Elliptical shape of the cold pipe helps to secure conductor in place and prevents its rotation. To insert conductor stack long axis of cold pipe will be squeezed and released.**

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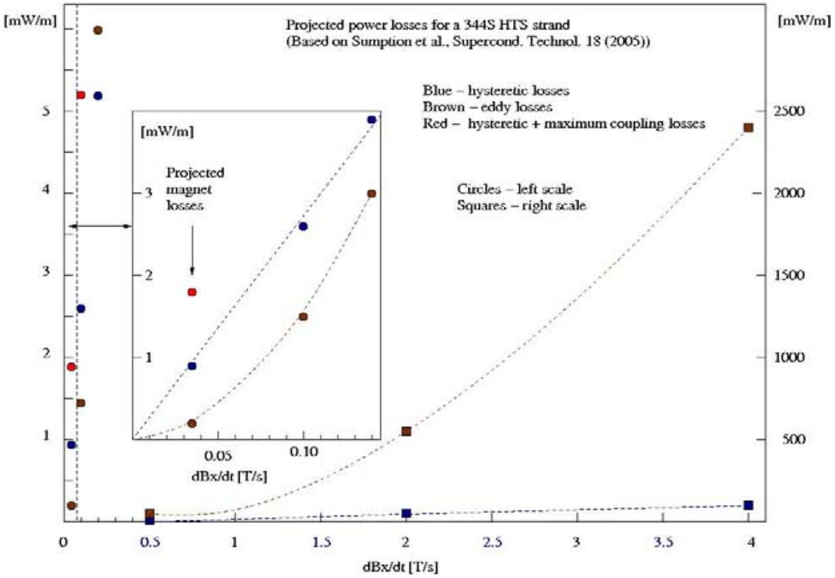
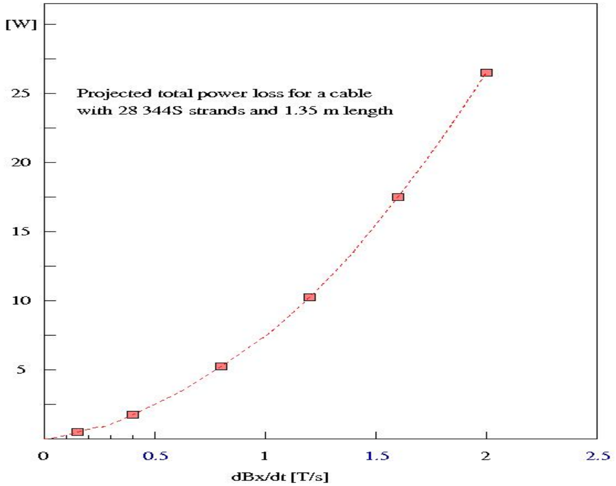
# Projected Power Losses for 344S Strand and Test Cable





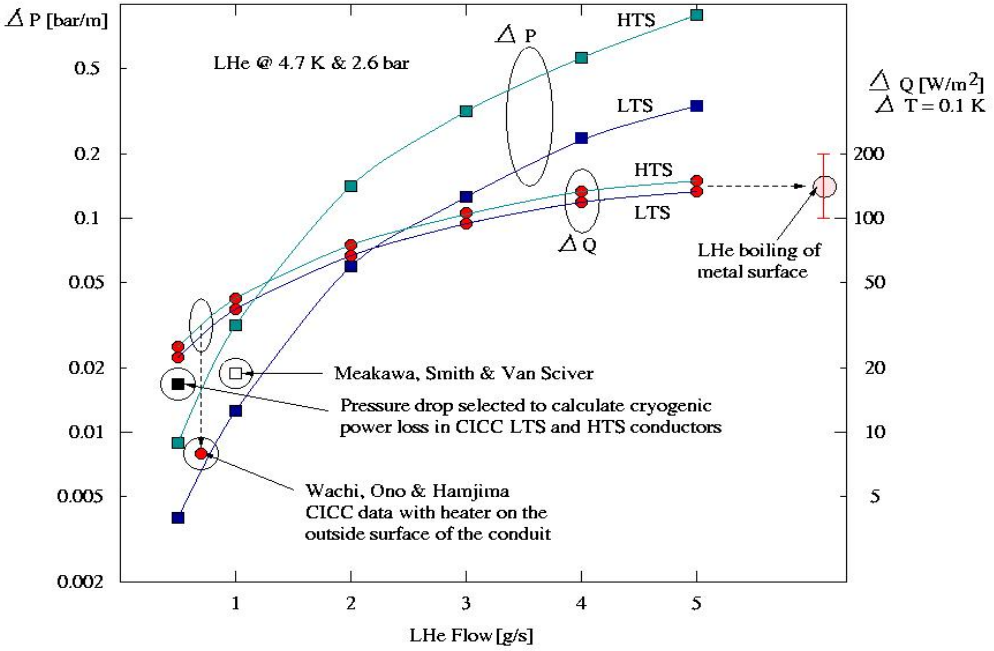
- ❖ **At low dBx/dt (as projected for the magnet) hysteretic and coupling losses are dominant**
- ❖ **At high dBx/dt eddy current losses are strongly dominant**

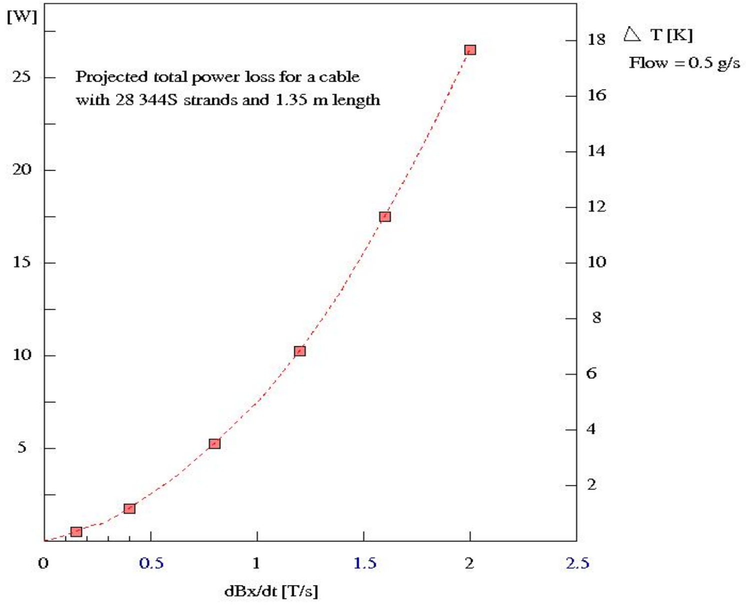
**Conclusions:**

1. **Measure precisely cable losses at high dB/dt to extrapolate eddy losses to the low values of dB/dt,**
2. **High precision measurements are required at low dB/dt range to evaluate hysteretic and coupling losses for the magnet operation regime**

**NOTE: Cryostat walls, lamination and beam pipe will add to the overall magnet power loss**

# *Temperature Rise & Pressure Drop Measurements*

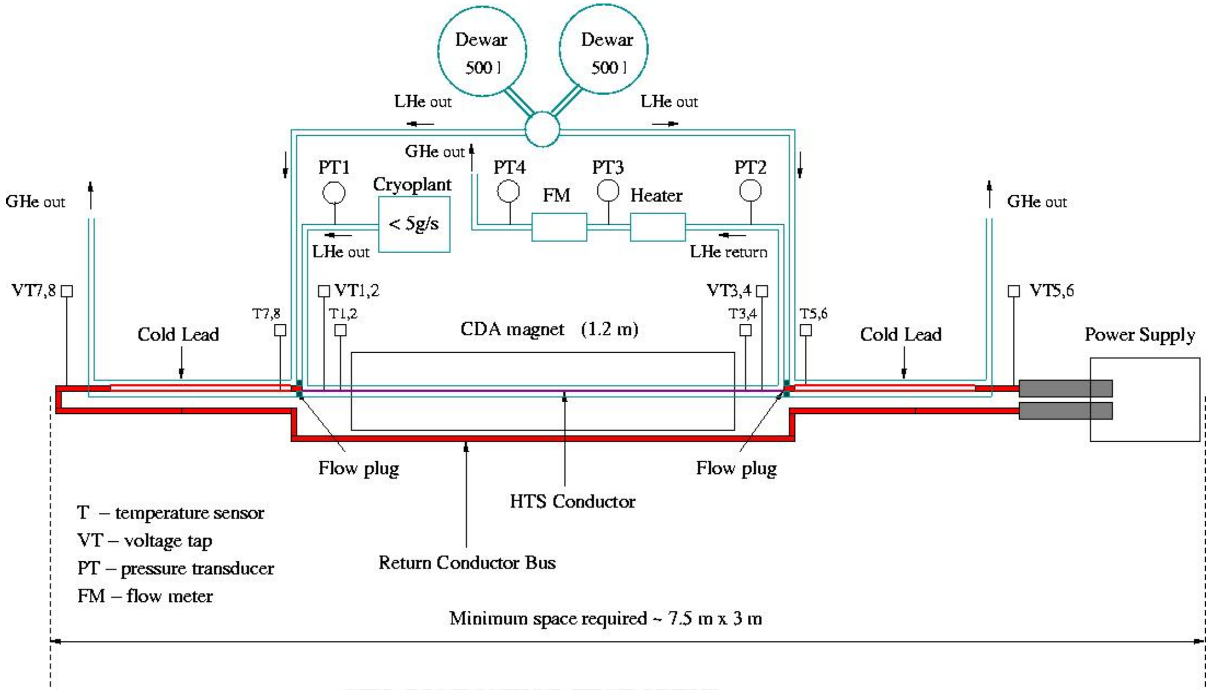




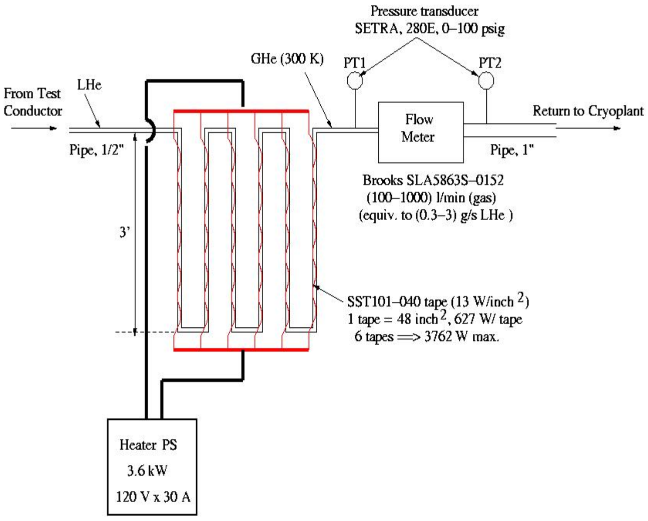
**At 0.1 T/s projected cable power loss is ~540 mW. With 0.5 g/s helium flow the temperature rise is 180 mK. Calibration from Cernox in (4-10) K range is +/- 5 mK. In MW9 experiment we measured 50 mK rise using the "house" calibrations.**

**Without correction for the temperature rise projected pressure drop at 0.5 g/s for 1.35 m cable is ~ 0.02 bar, and at 1 g/s ~ 0.04 bar – both measurable.**

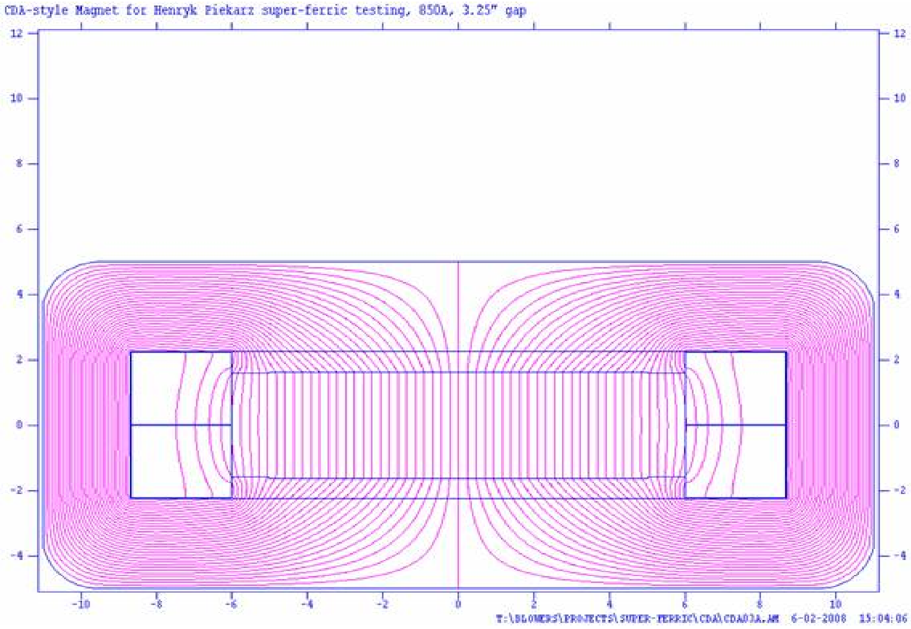
# ***HTS Cable Test Arrangement***



HTS CONDUCTOR TEST SETUP

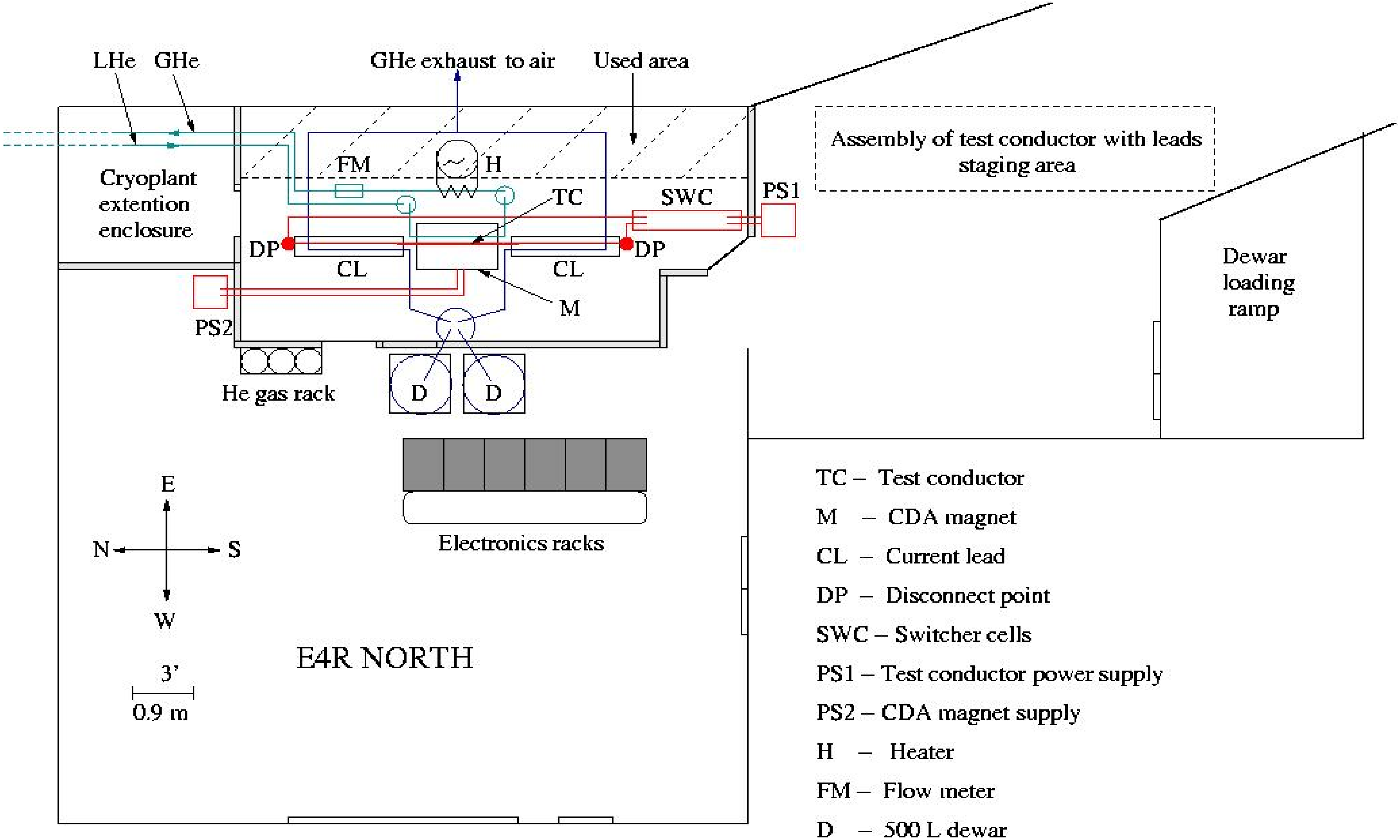


# CDA Dipole for HTS Cable Test



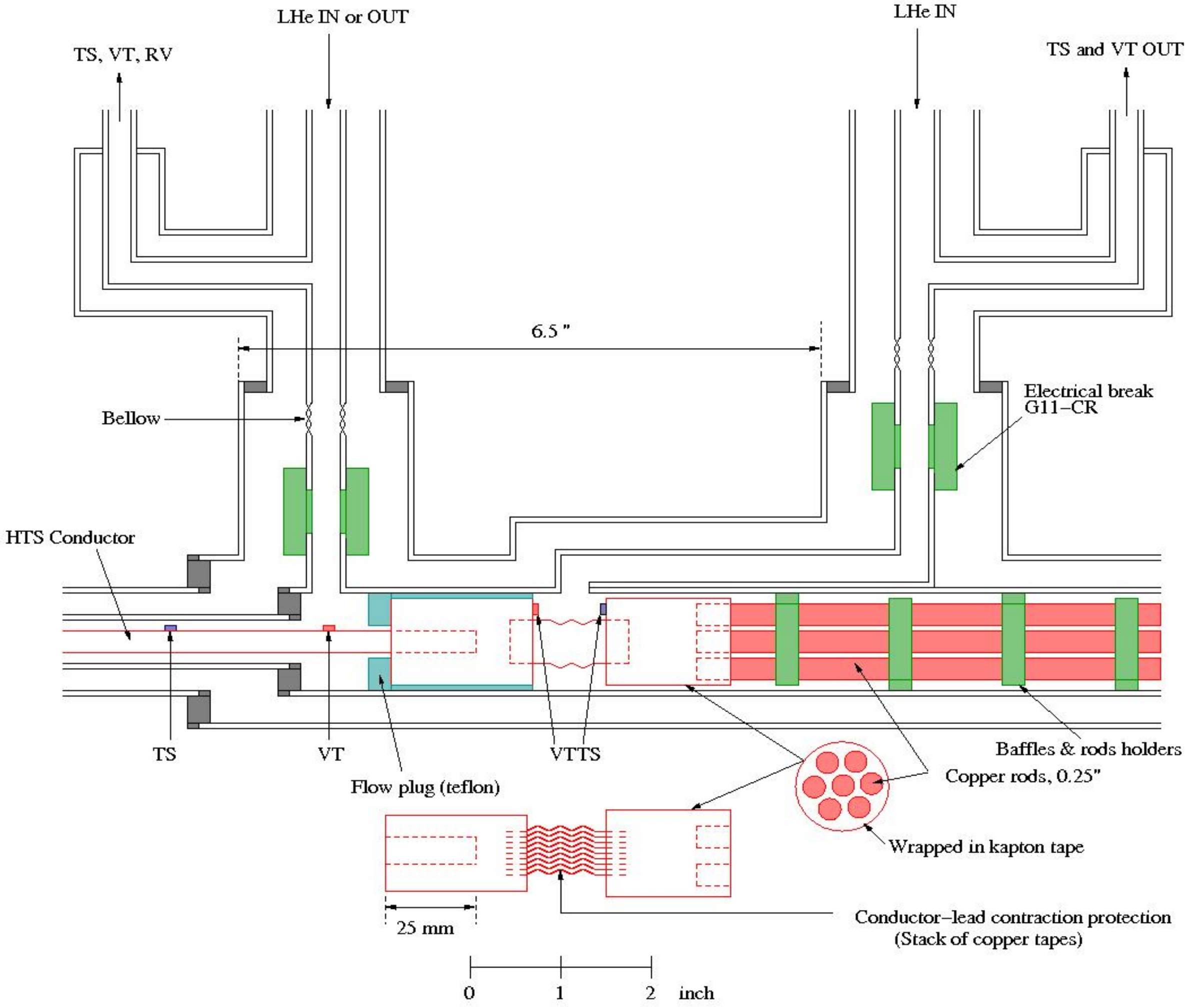
**CDA magnet can produce By- field of 0.5 T with the <Bx> value in the central space of +/- 0.5" < 50 Gauss. Rotation of the test conductor will expose its wide surface to an increasingly high B-field and at 90 deg. the dB/dt will be 2 T/s and 4 T/s at 2 Hz and 4 Hz cycling rate, respectively. Magnet can cycle up to 100 Hz.**

# E4R Test Floor Plan

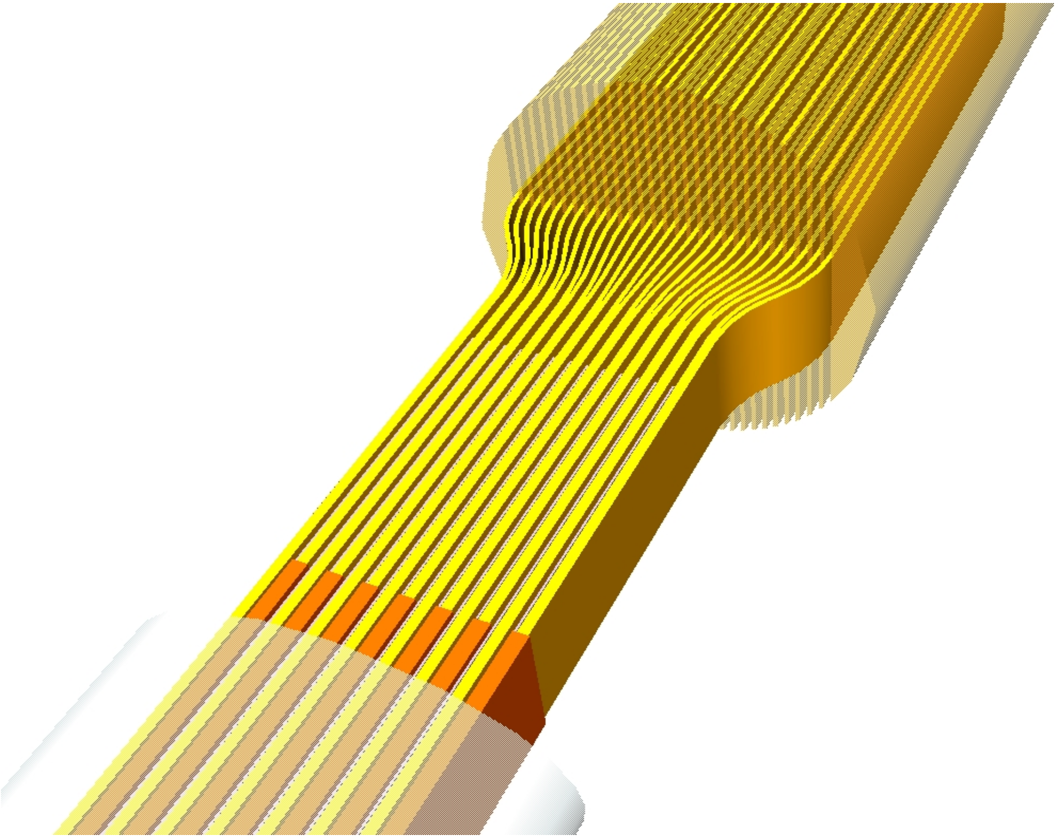


TC – Test conductor
M – CDA magnet
CL – Current lead
DP – Disconnect point
SWC – Switcher cells
PS1 – Test conductor power supply
PS2 – CDA magnet supply
H – Heater
FM – Flow meter
D – 500 L dewar

# HTS Cable - Lead Connection

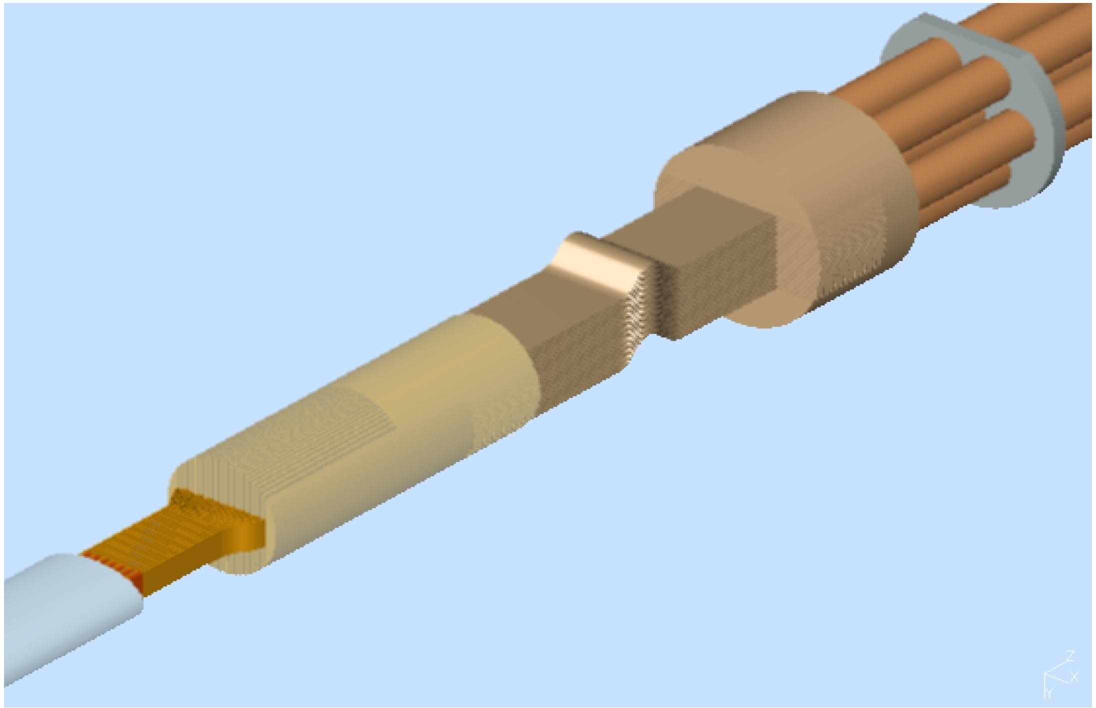


# HTS Cable Engineering Design 1



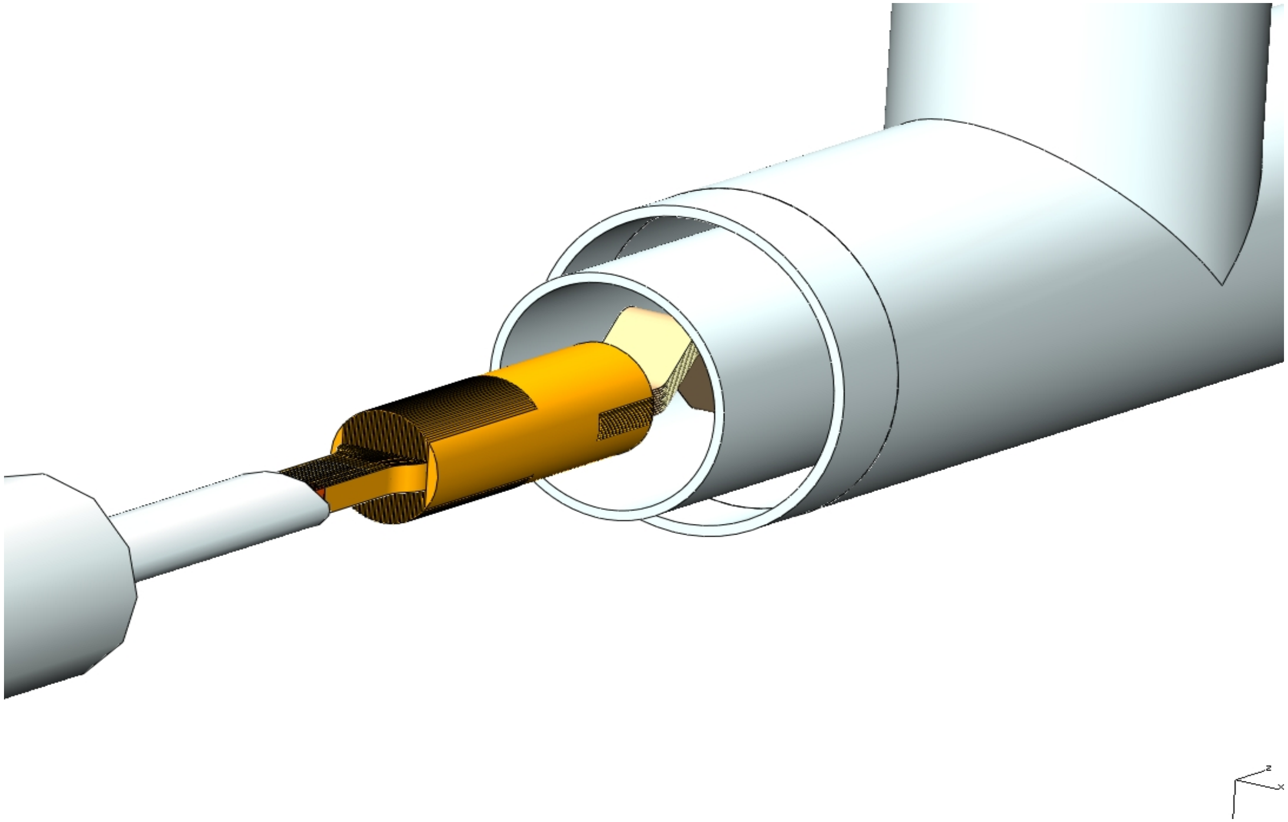
**Stack of 14 pairs of HTS tapes connecting to the Cu block for spliceing. Each tape has its own splice space. The magnetic shielding does not splice and remains isolated.**

# *HTS Cable Engineering Design 2*



**Connection of HTS splice block to power leads. A stack of copper tapes allows to compensate for thermal contraction of both HTS Conductors and copper rods of the power leads.**

# ***HTS Cable Engineering Design 3***



**HTS cable and the splice block connecting to lead**

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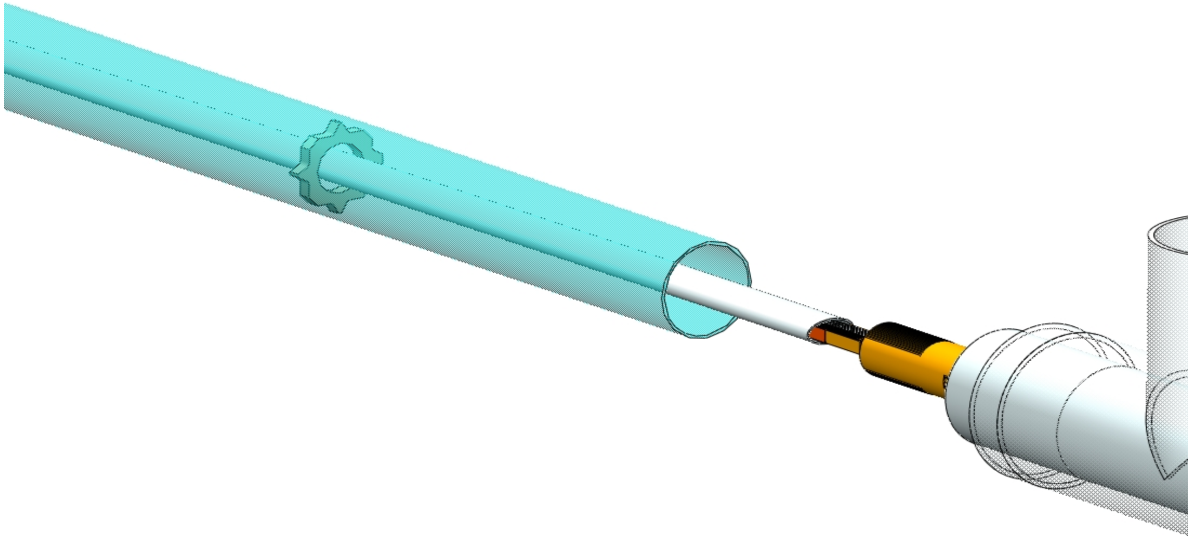
# HTS Cable Engineering Design 4



**Cold pipe support for the HTS cable.**
**There will be one support per 30 cm of cable length.**

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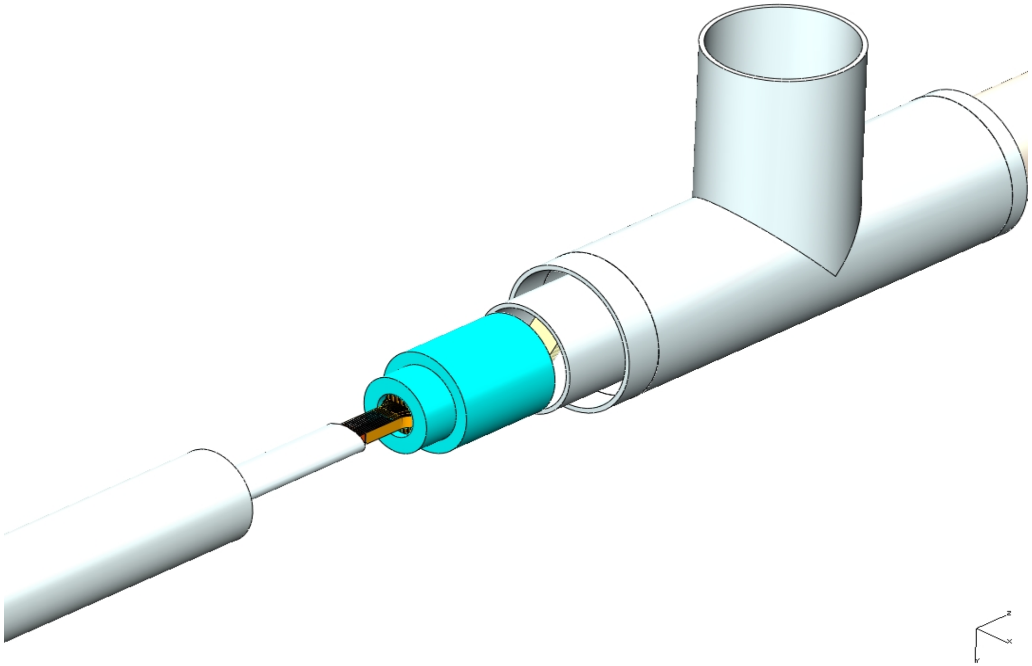
# HTS Cable Engineering Design 5



**Flow plug arrangement. It separates HTS cable supercritical helium flow from the power lead two-phase helium flow.**

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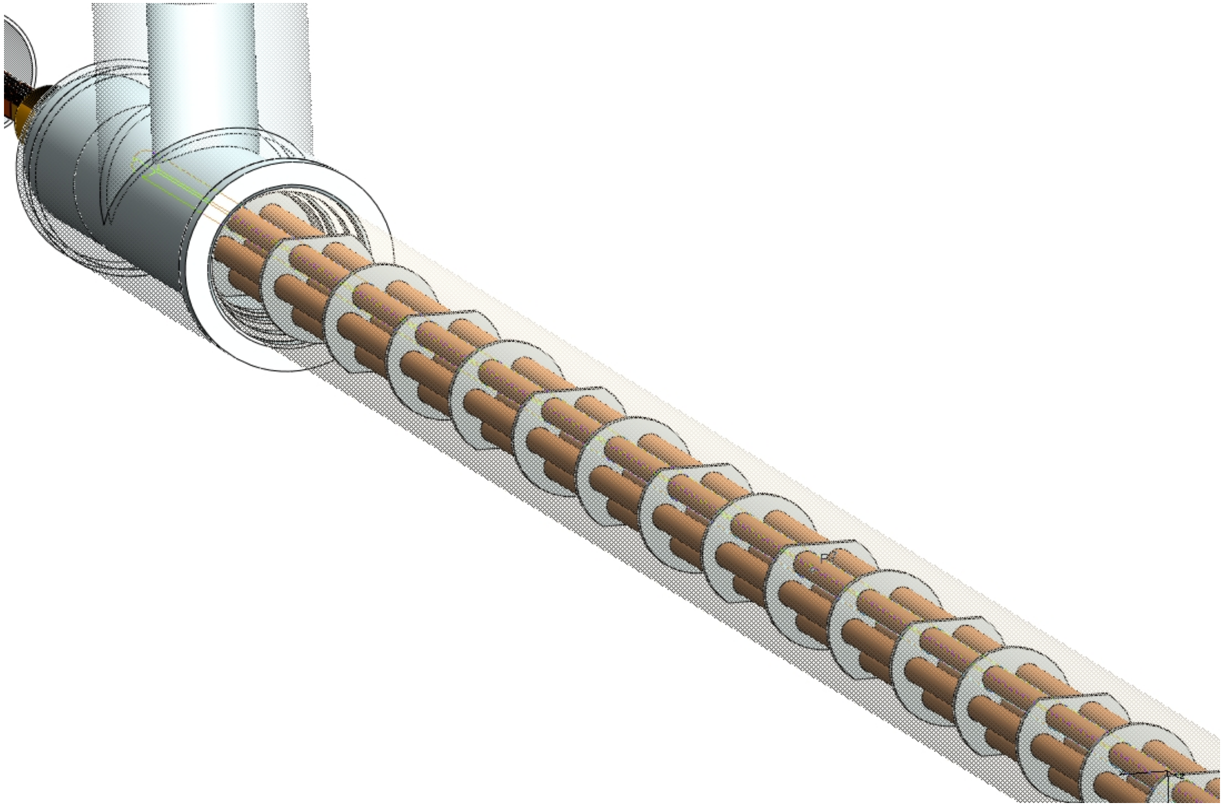
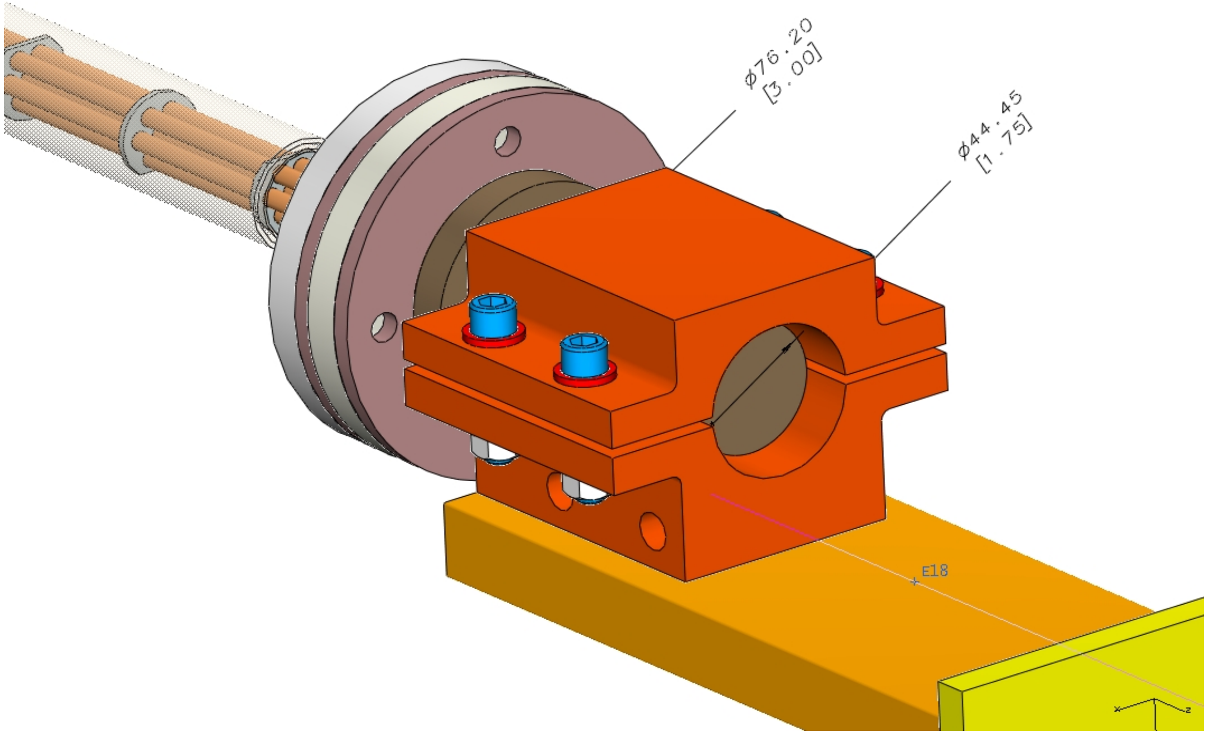
# HTS Cable Engineering Design 6



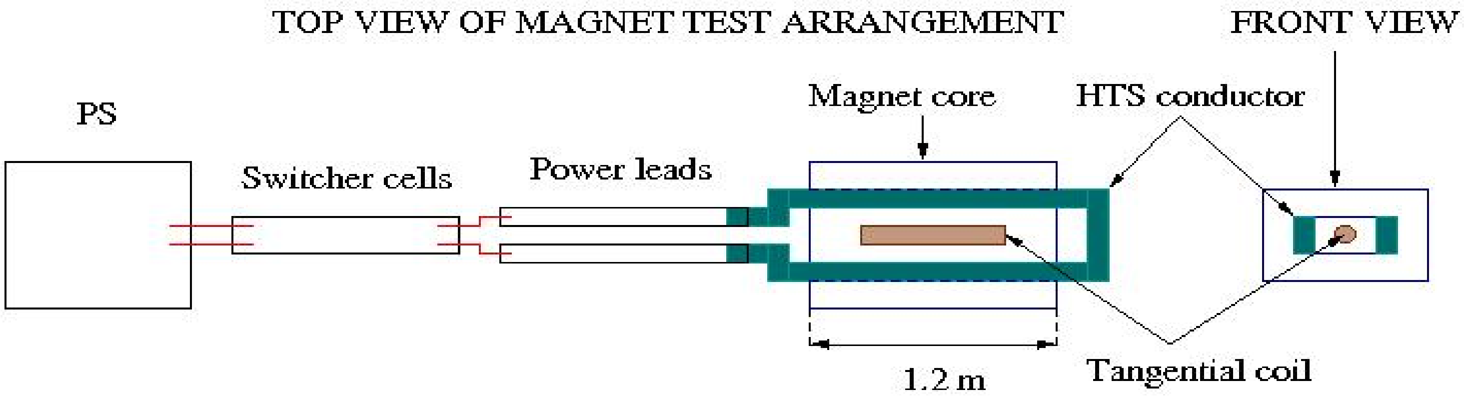
**Power leads are scaled down from VLHC magnet test at MS6. The length is 1.6 m with 7 rods. The structure was designed to pass fully assembled through the CDA magnet gap.**

# ***HTS Cable Engineering Design 7***

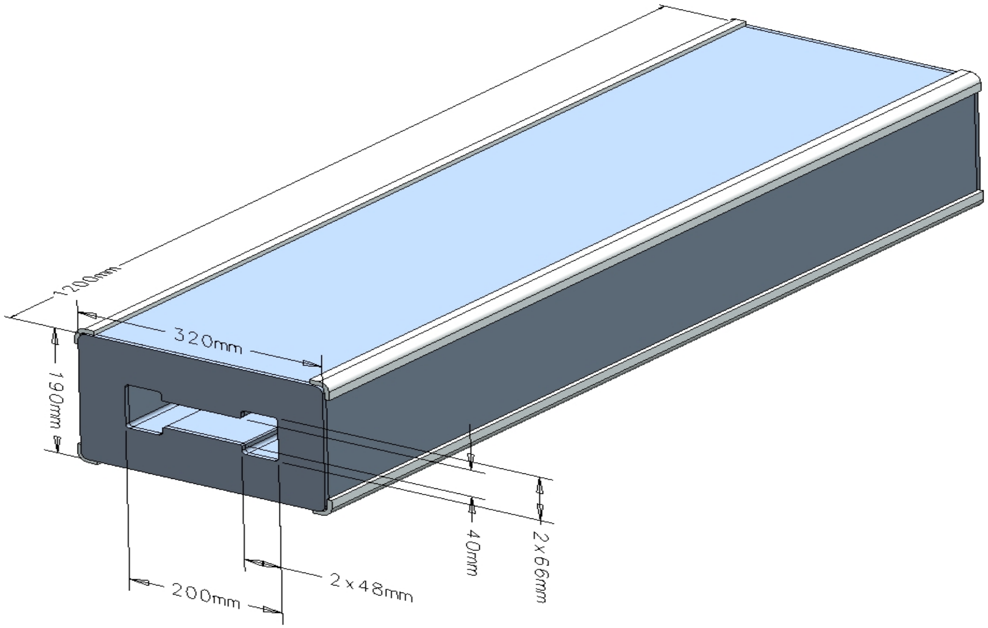


**Warm end of power lead. The clamp will allow to rotate (0-90) deg. the entire HTS test cable assembly.**

# Fast Cycling Magnet Test in FY10


TOP VIEW OF MAGNET TEST ARRANGEMENT

FRONT VIEW



**Magnetic core design is complete. We had several meetings with Mapes & Sprowl discussing details of lamination quality (B/H data), fabrication and the core assembly work.**

**Planning for a site visit soon.**

# Summary

- Conceptual design of HTS cable for fast-cycling magnet has been advanced to the level that cryogenic tests are well warranted
- Engineering design of a test cable including its cryogenic support and the connections to power leads is nearly complete
- Lamination for the test dipole magnet was designed and the core procurement is in progress
- HTS strands to power the 1.2 m test magnet up to 70 kA as well as all 316LN tubing were received