M3PoB-01

# Insulation system for high temperature superconductor cables

Philip C. Michael[1], Andrea E. Haight[2], Leslie Bromberg[1], and Kimiko Kano[2]

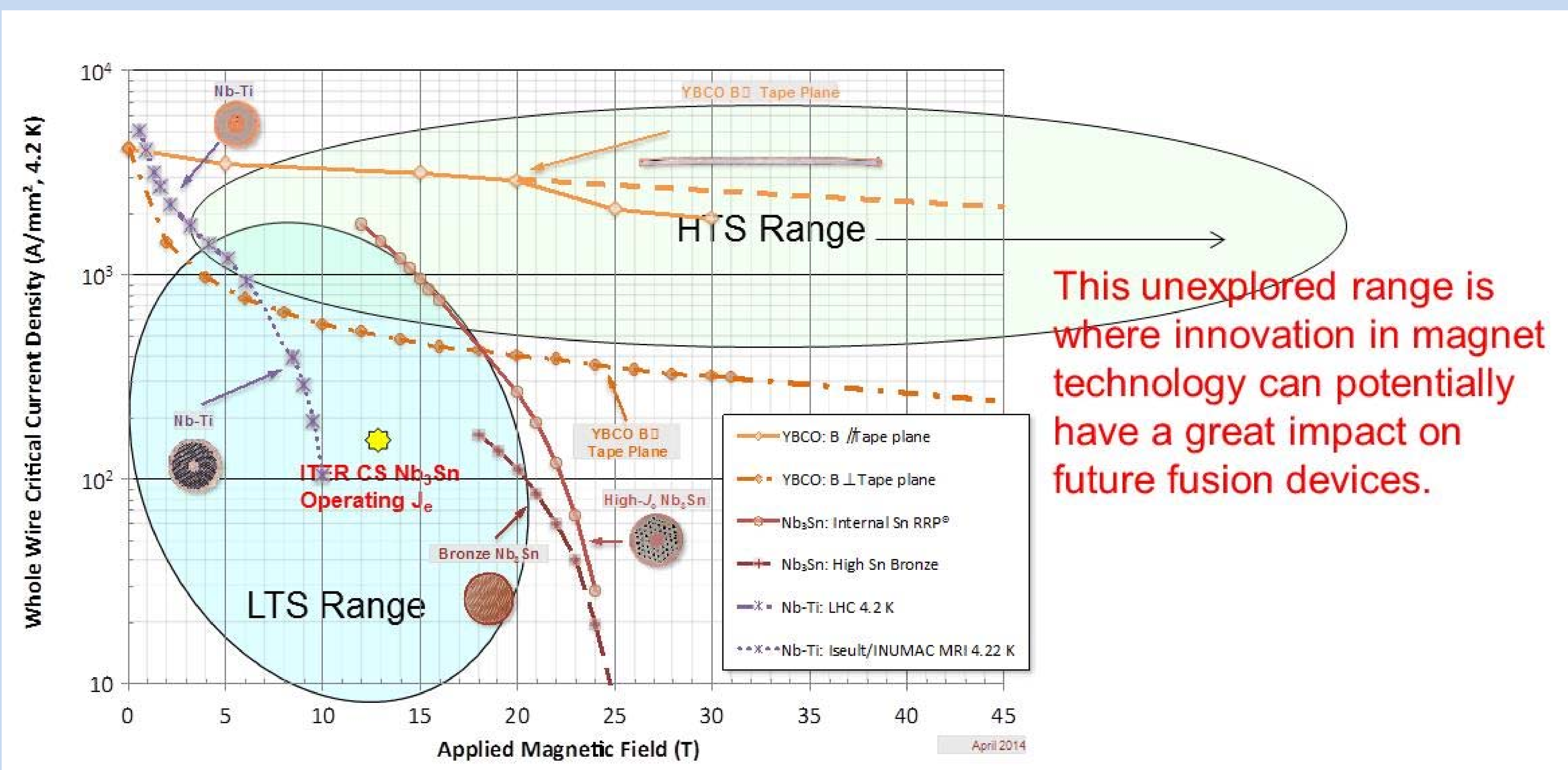
[1]MIT Plasma Science and Fusion Center, Cambridge, MA, USA

[2] Composite Technology Development, Inc., Lafayette, CO, USA

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

# Motivation

- High-current capacity cables formed from ReBCO coated conductors are being developed for
  - Compact, high-field, next-generation fusion devices, with envisioned peak field 20 T ~ 22 T
  - Potential LHC high energy upgrade, with envisioned peak field 16 T ~ 20 T
  - Both applications subject conductor and coil to high dose radiation
- Present generation, coated conductor tapes sometimes delaminate following epoxy impregnation
  - Likely due to epoxy cure shrinkage or thermal contraction mismatch
  - May be an inherent feature of coated conductors
  - Need to prevent delamination to enable large-scale coil fabrication




Conductor and insulator needs for extended high Q fusion reactor

| | Insulation | Superconductor |
|---|---|---|
| Near-term | $10^7$ Gy x 50 Mpa (shear strength) | 1,000 A/mm$^2$ (12 T, 4.2 K), 3 x $10^{21}$ n$^o$/m$^2$ |
| Long-term | $10^9$ Gy x 500 Mpa (shear strength) | 1,000 A/mm$^2$ (12 T, 77 K), 1.5 x $10^{23}$ n$^o$/m$^2$ |

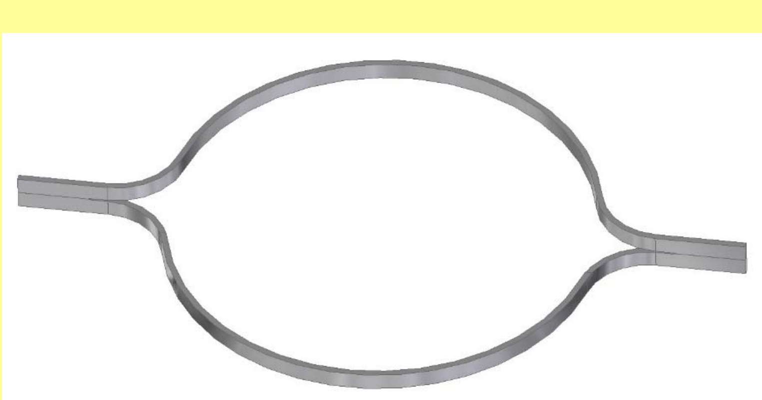
Minervini/Lee - Fusion Nuclear Science Pathways Assessment: Materials Working Group Meeting, Aurora CO, May 4, 2011

# Objectives

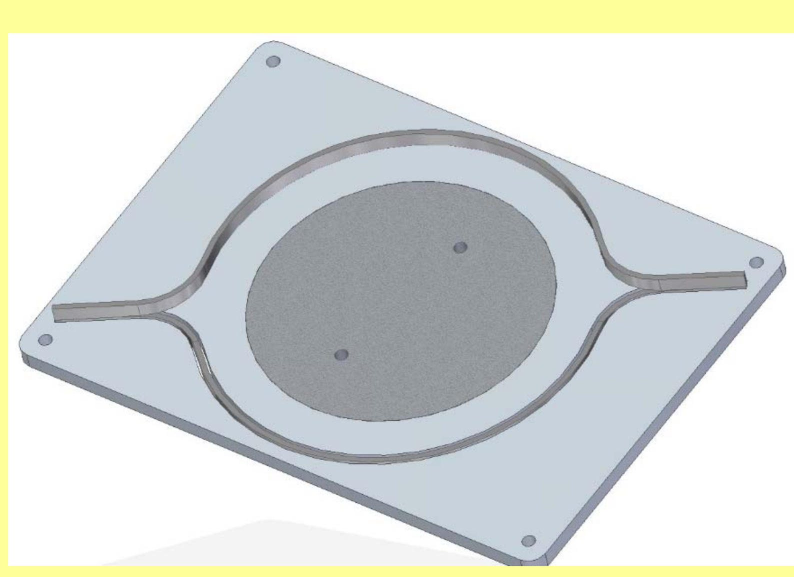
- Develop simple, repeatable, low cost screening procedure to test ReBCO cable insulations
  - Testing performed before and after application of cable insulation
  - Tested in liquid nitrogen
  - Slit-tape, trapped flux configuration
    - No current leads or lead breakouts to contend with
    - Minimal current transfer or redistribution, to increase repeatability
- Development of two-part insulation scheme
  - Barrier insulation followed by epoxy impregnation
  - Materials selected based on known or likely radiation resistance
- Emphasis on cable rather than strand insulation scheme

Single, laser slit ReBCO conductor

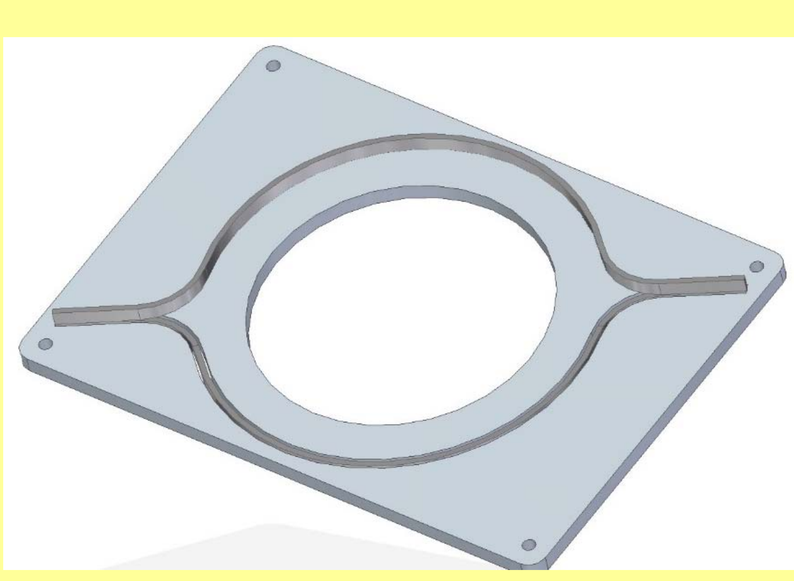
## Coil assembly sequence



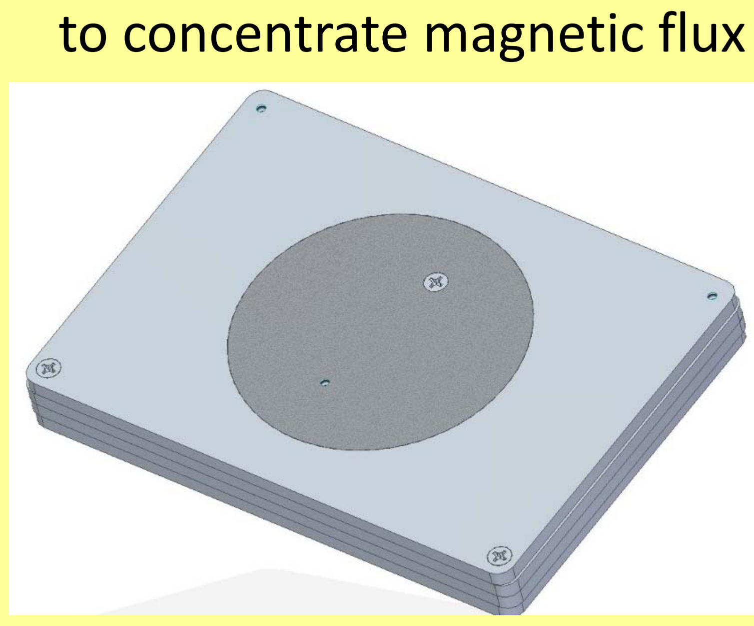
Slit-tape coil formed using 29 laser-slit, Ag-plated SuperPower tape



AISI 1018 Iron pole pieces used to concentrate magnetic flux



Conductor stack installed in water-jet-machined aluminum support plates



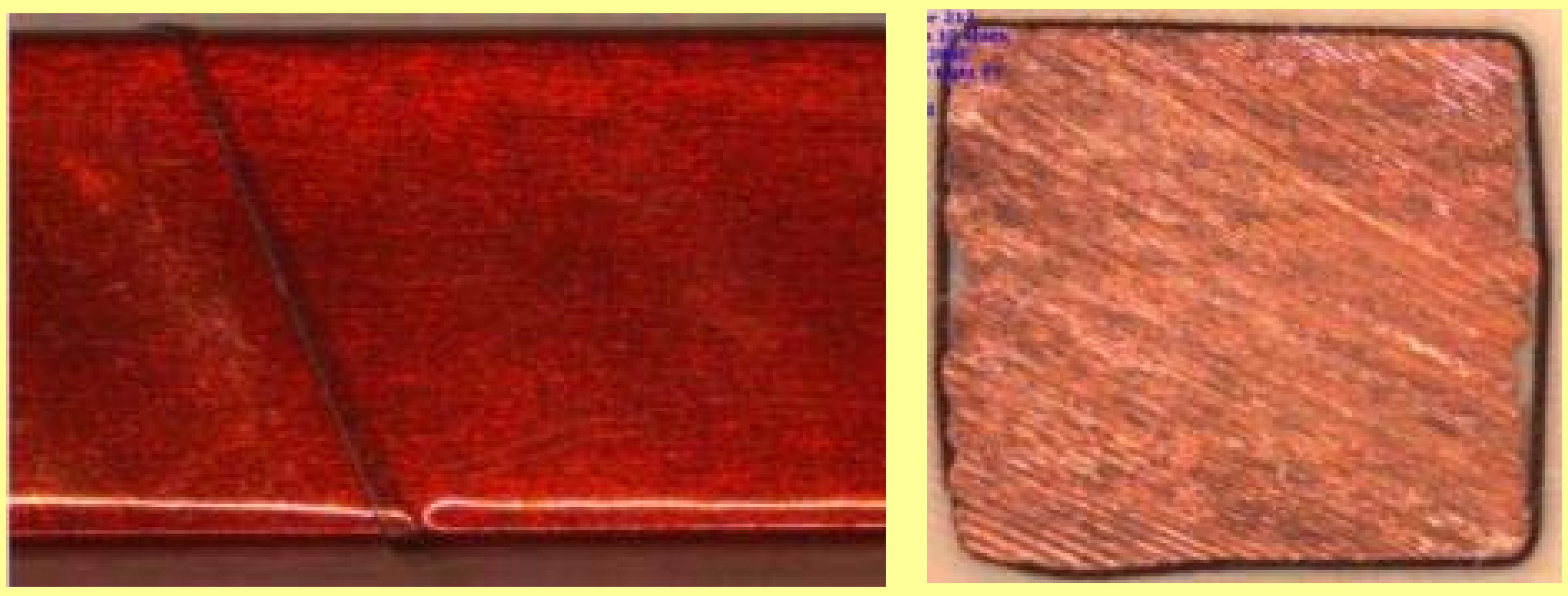
Complete coil

## Test facility

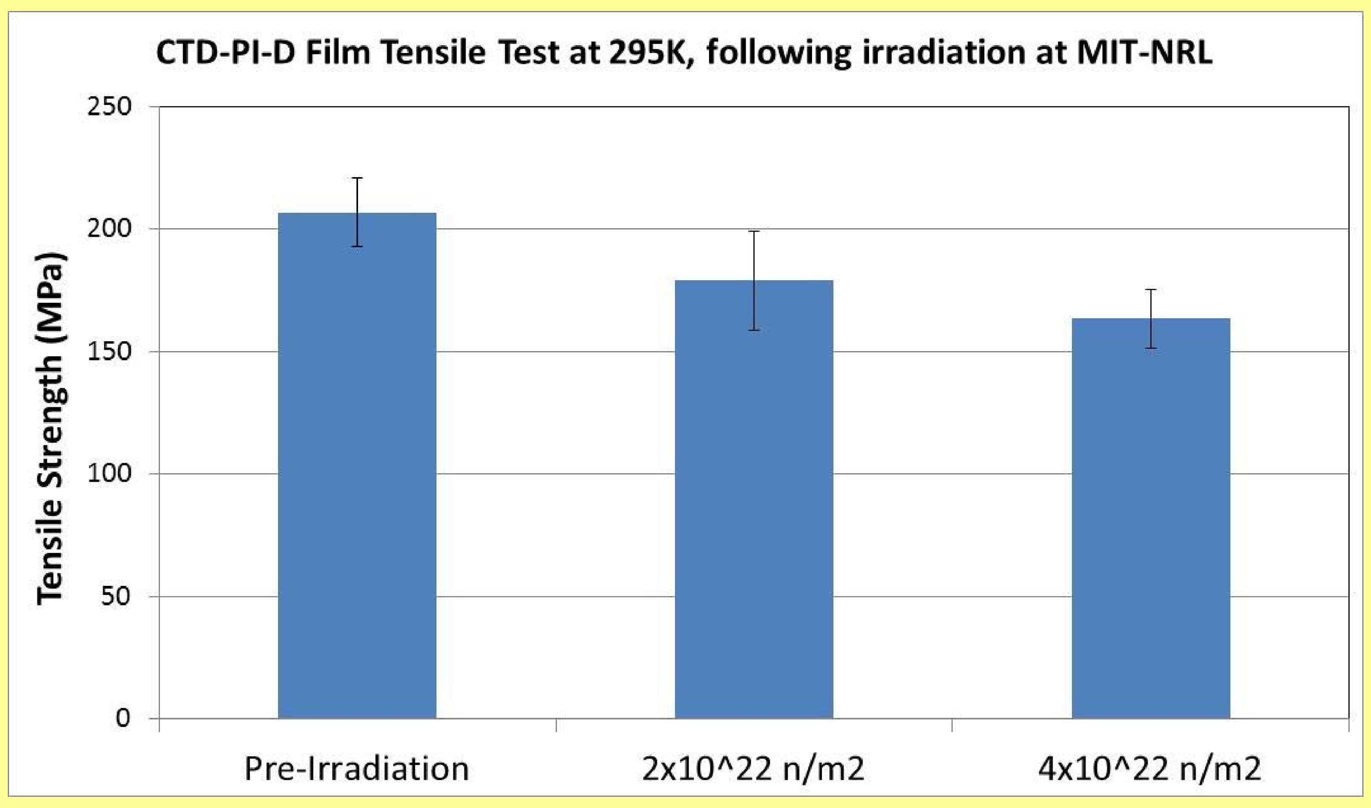
- Background field magnet with 2” x 7.25” rectangular bore
- 2 T peak field
- Background field magnet suspended below lab floor
- Coil sample placed in wooden cryostat
- Cooling by liquid nitrogen transfer into cryostat

# Barrier Insulation Evaluation

- Applied to cable (not strands)
- Initial work with PTFE/FEP shrink tube
  - Inadequate radiation stability for fusion applications
  - Not compatible with slit-tape configuration
  - 350$^{o}$ C shrink temperature incompatible with ReBCO conductor processing
- Selection of heat-shrink polyimide tape
  - Free of acrylic adhesives (known radiation sensitivity)
  - High dielectric strength
  - Achieves 8% shrink after 30 minutes at 150$^{o}$ C, compatible with ReBCO thermal requirements
  - Conforms to and tightly compresses conductor stack when applied with high initial tension
  - Applicable to arbitrary length cables
  - Effectively precludes resin flow inside of wrap
- Tensile testing of polyimide tape performed following irradiation in MIT nuclear reactor



Early trial on stacked copper cable: insulated with polyimide shrink tape (left) and potted with CTD-101G (right). Undamaged after repeated slow immersion in liquid nitrogen.

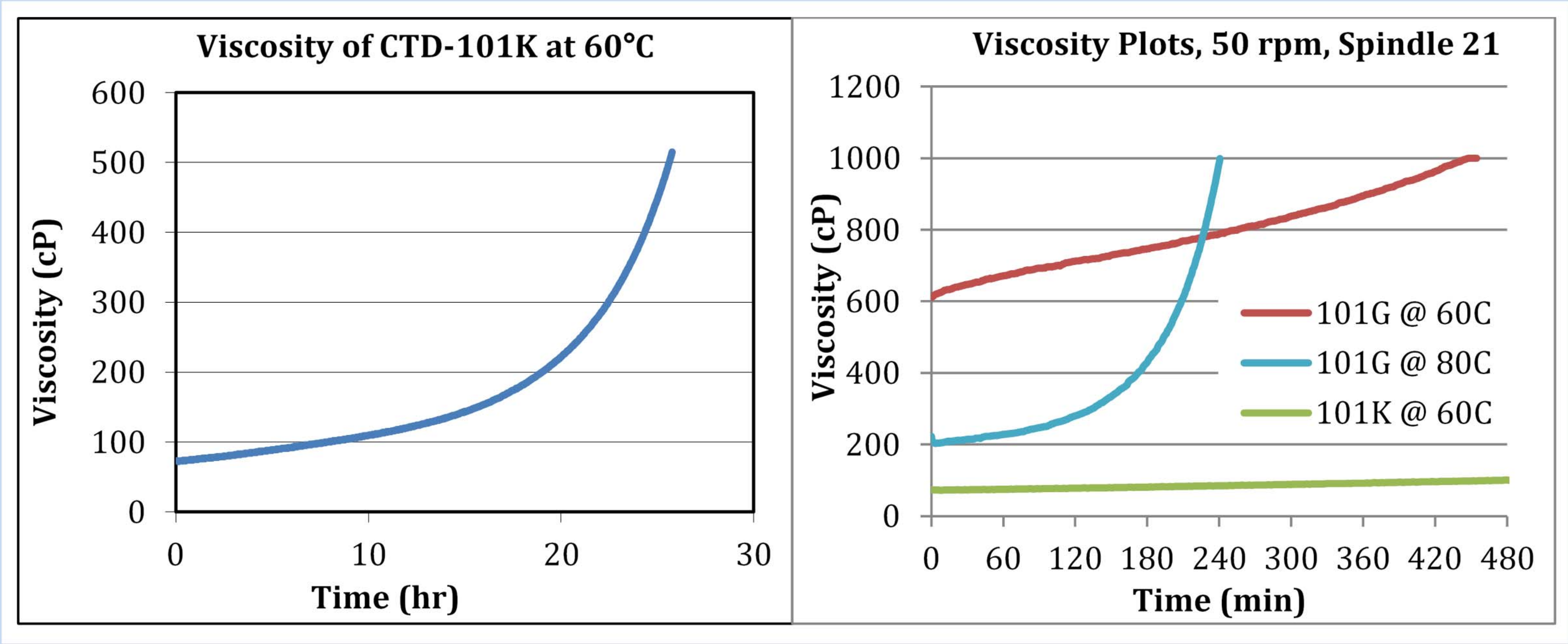



Slight reduction in polyimide tensile strength following irradiation to 4x10$^{22}$ n/m$^2$ (4x ITER limit)

# Potting Resin Evaluation

- Two resin systems considered:
  - CTD-101K – developed for and used in fusion magnets, low viscosity, long pot life
  - CTD-101G – similar formulation but with fillers to improve thermal conductivity and reduce shrinkage
- CTD-101G selected following evaluation screening
- Short beam shear strength testing performed following irradiation at MIT nuclear reactor, on resin/S2-glass laminate specimens made using each resin candidate

### Viscosity vs. time/temperature comparison

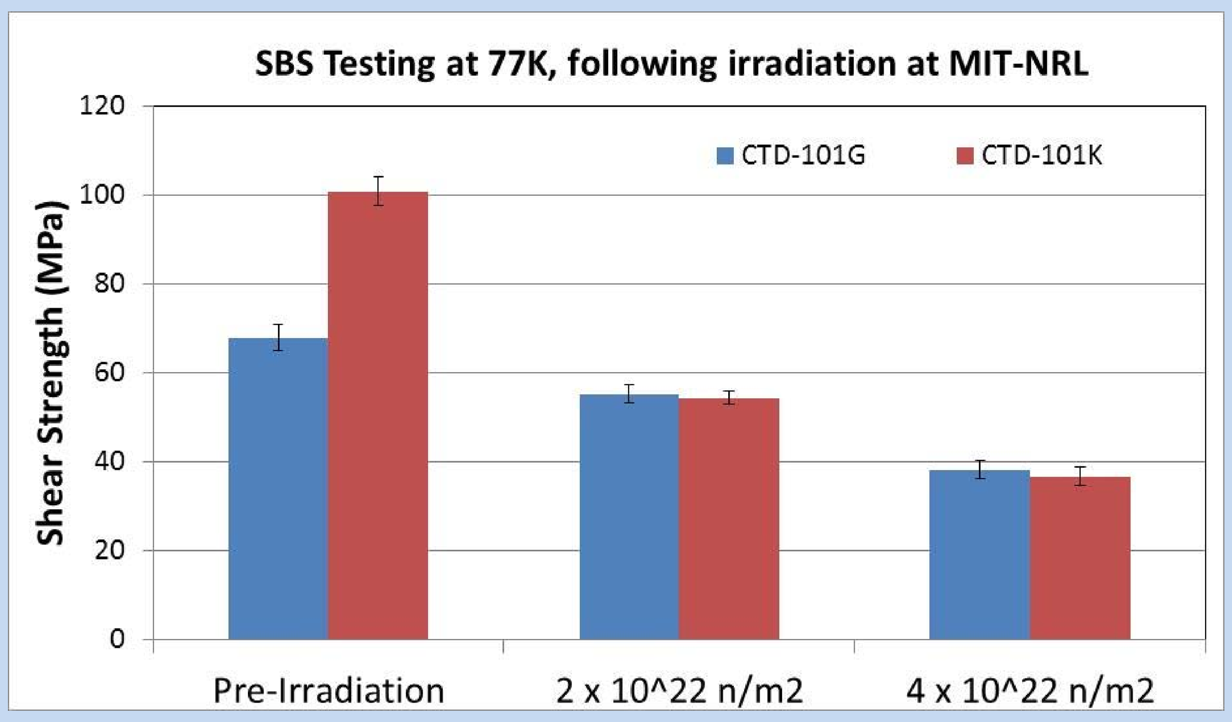



### Mold shrinkage comparison

| Material | Cure Schedule | Percent Linear Shrinkage |
|---|---|---|
| CTD-101G | 5 hr @ 110°C<br>1.5 hr @ 135°C | 0.55 $\pm$ 0.04% |
| CTD-101K | 5 hr @ 110°C<br>1.5 hr @ 135°C | 0.64 $\pm$ 0.04% |
| CTD-101K | 24 hr @ 80°C | 0.41 $\pm$ 0.01% |
| CTD-101K (post-cured) | 24 hr @ 80°C<br>1.5 hr @ 135°C | 0.71 $\pm$ 0.03% |

### Neat resin tensile property comparison

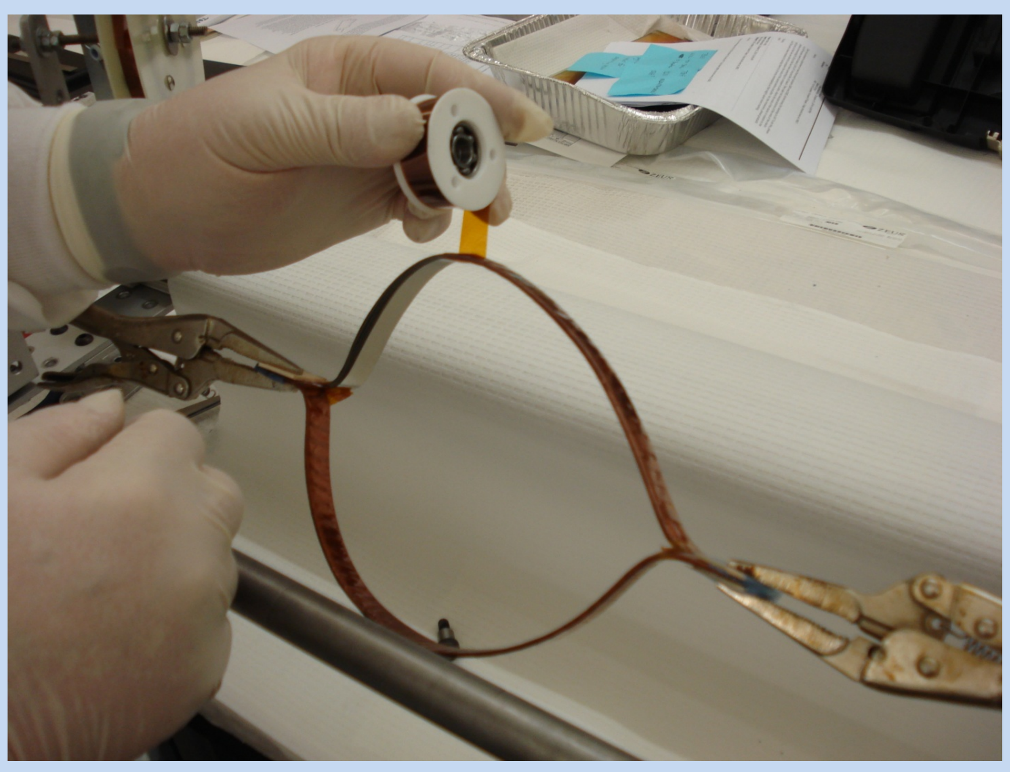
| Material | Temperature (K) | Tensile Strength (MPa) | Tensile Modulus (GPa) | Strain to Failure |
|---|---|---|---|---|
| 101G | 77 | 96.1 | 19.12 | 0.51% |
| 101G | 295 | 38.5 | 11.43 | 0.32% |
| 101K | 77 | 74.7 | 6.98 | 1.11% |
| 101K | 295 | 45.4 | 4.03 | 1.22% |

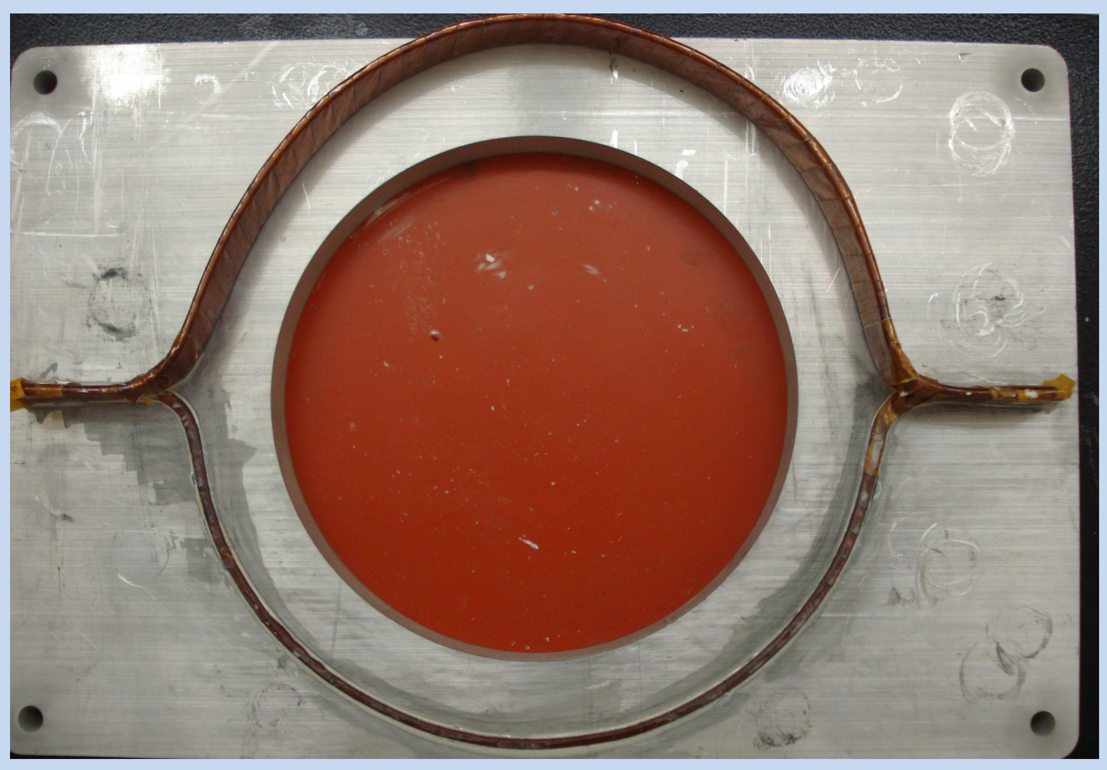


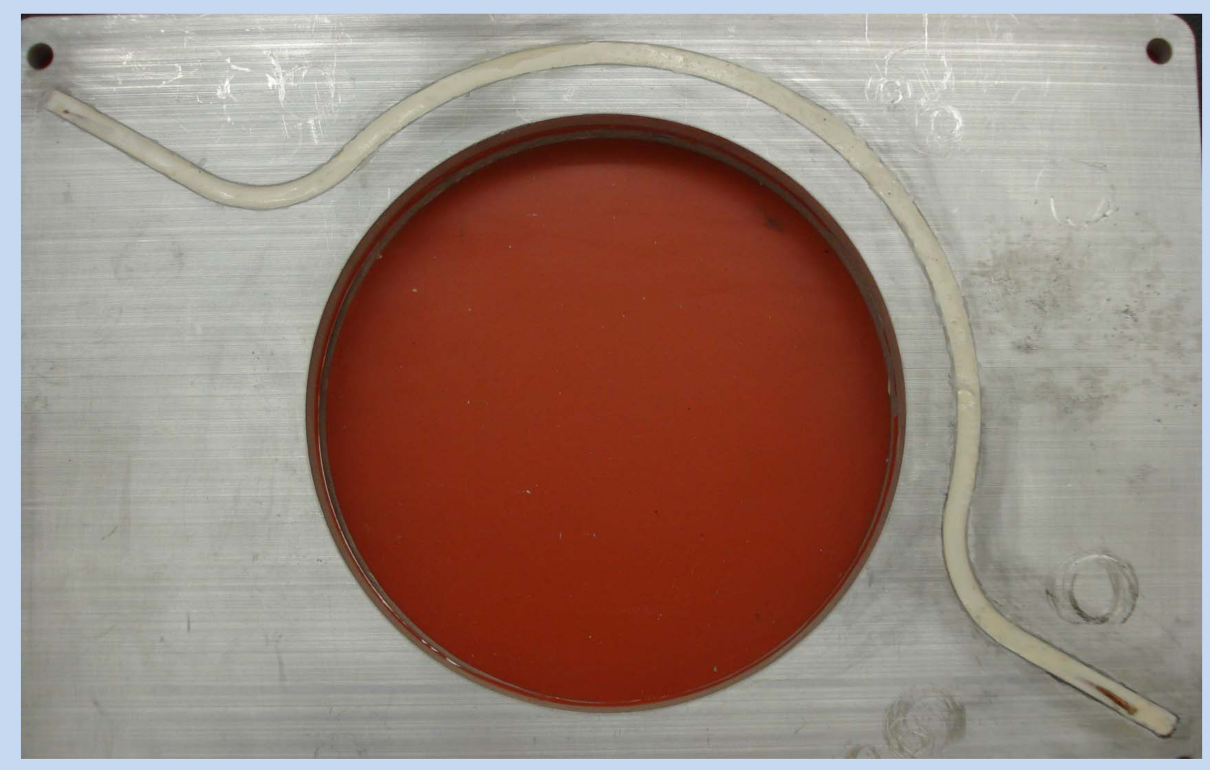

Negligible difference in laminate shear strength following irradiation to 4x10$^{22}$ n/m$^2$ (4x ITER limit)

# Insulation Application

- Process development from conductor surrogate to ReBCO stacked-tape conductor
  - 50 μm thick Inconel strip for initial conductor trials
  - 26 ReBCO tapes with 20 μm thick copper plate for first samples, to simulate likely magnet conductor
  - 29 ReBCO tapes with 2 μm thick silver plate for final samples, to minimize laser-slitting artifact
- Polyimide tape applied and shrunk at 150º C for 30 minutes, inside aluminum formers
- Silicone sheet gasket applied to aluminum former to pot first coil half. Cure schedule: 3hr ramp to 110º C; 5hr soak @ 110º C; 1.5hr ramp to 135º C; 1.5hr soak @ 135º C; 2hr cool-down to 22º C.
- Silicone sheet gasket installed between aluminum formers to pot second half of coil using same cure schedule.

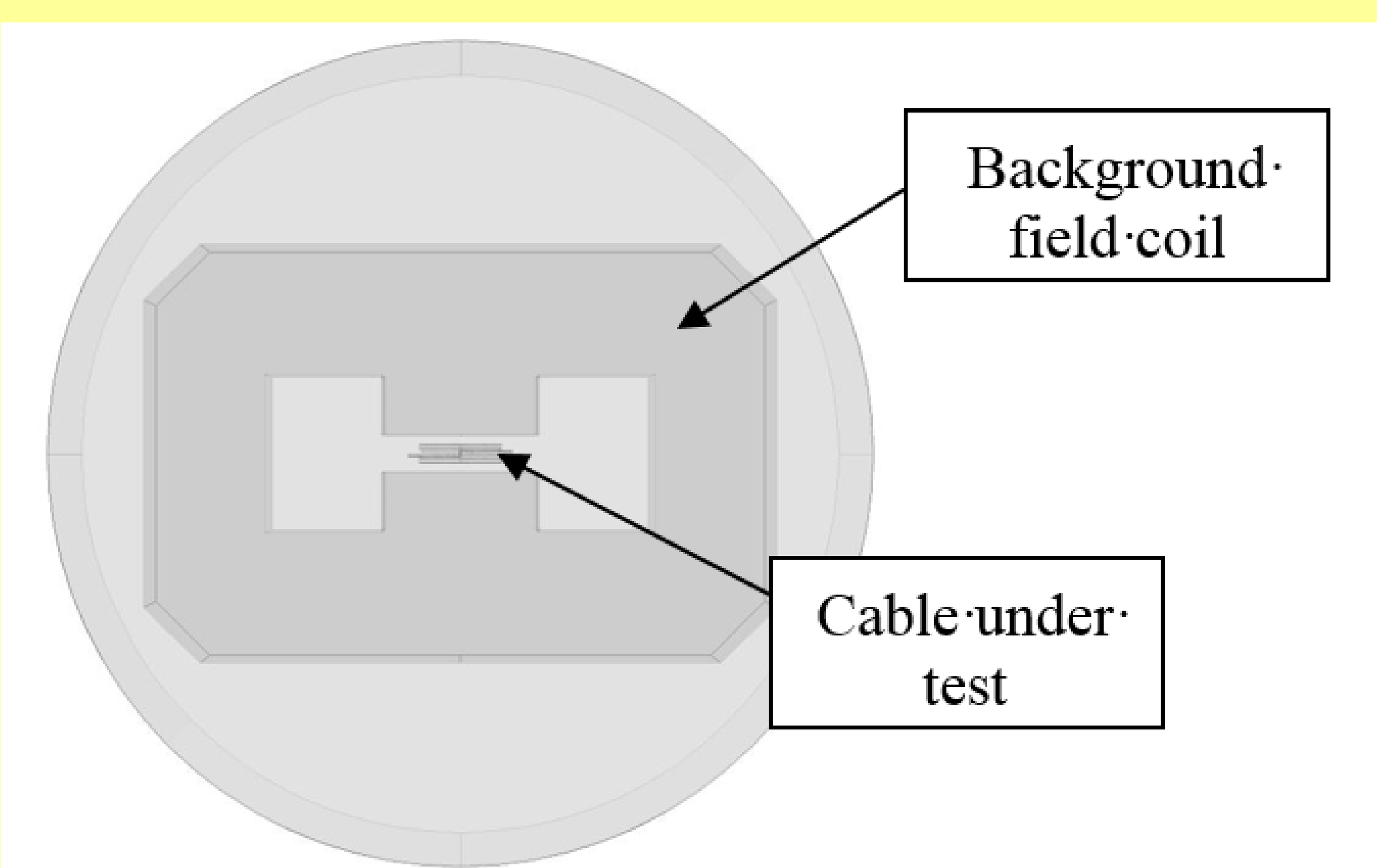




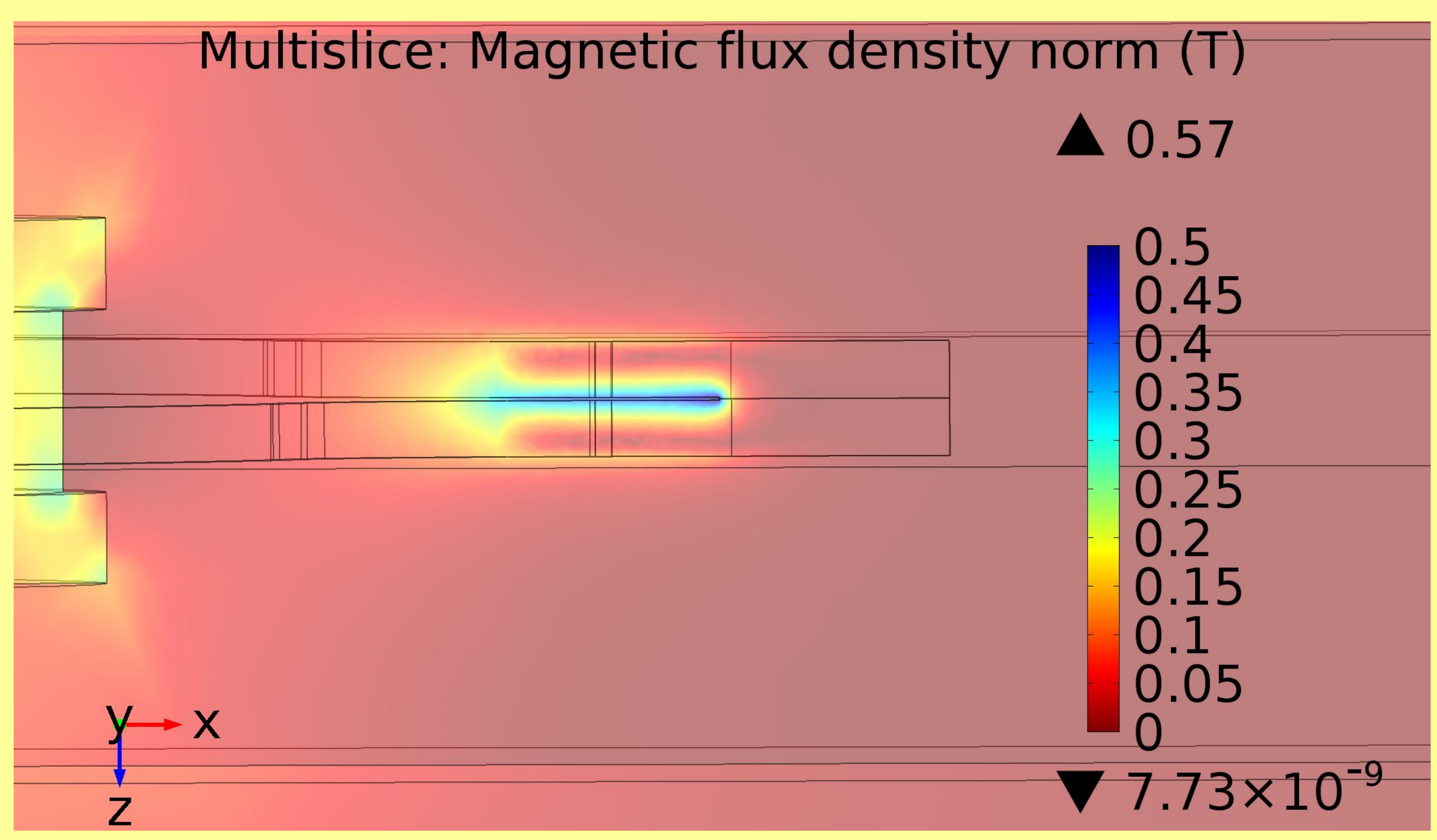


# Electromagnetic Modeling

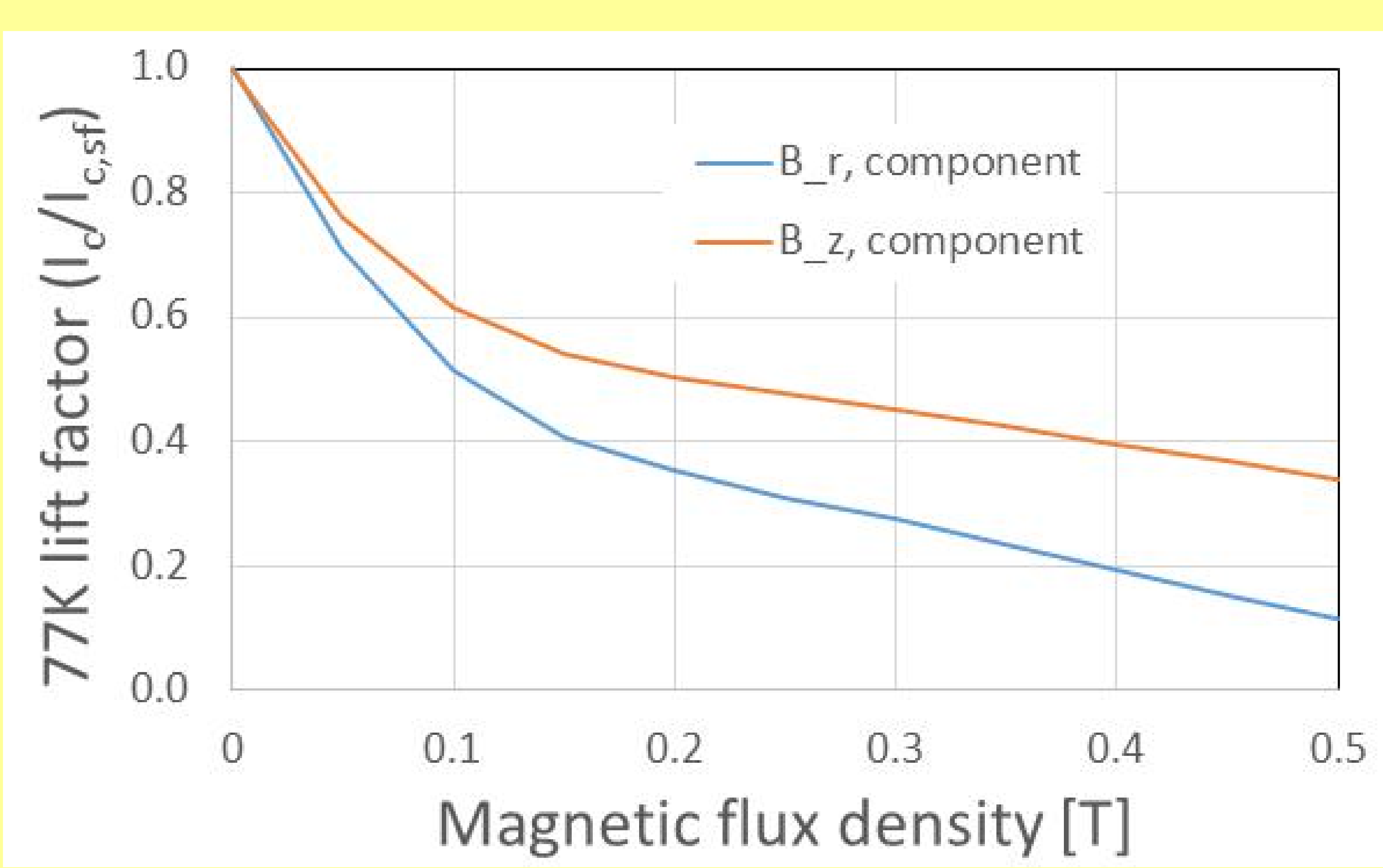
- High-fidelity, 3D COMSOL model of test arrangement
  - Cable current related to magnetic flux density measured by Hall probes on sample surface
  - Cable critical current related to magnetic field distribution over cable cross-section
  - Match between expected and measured cable critical current

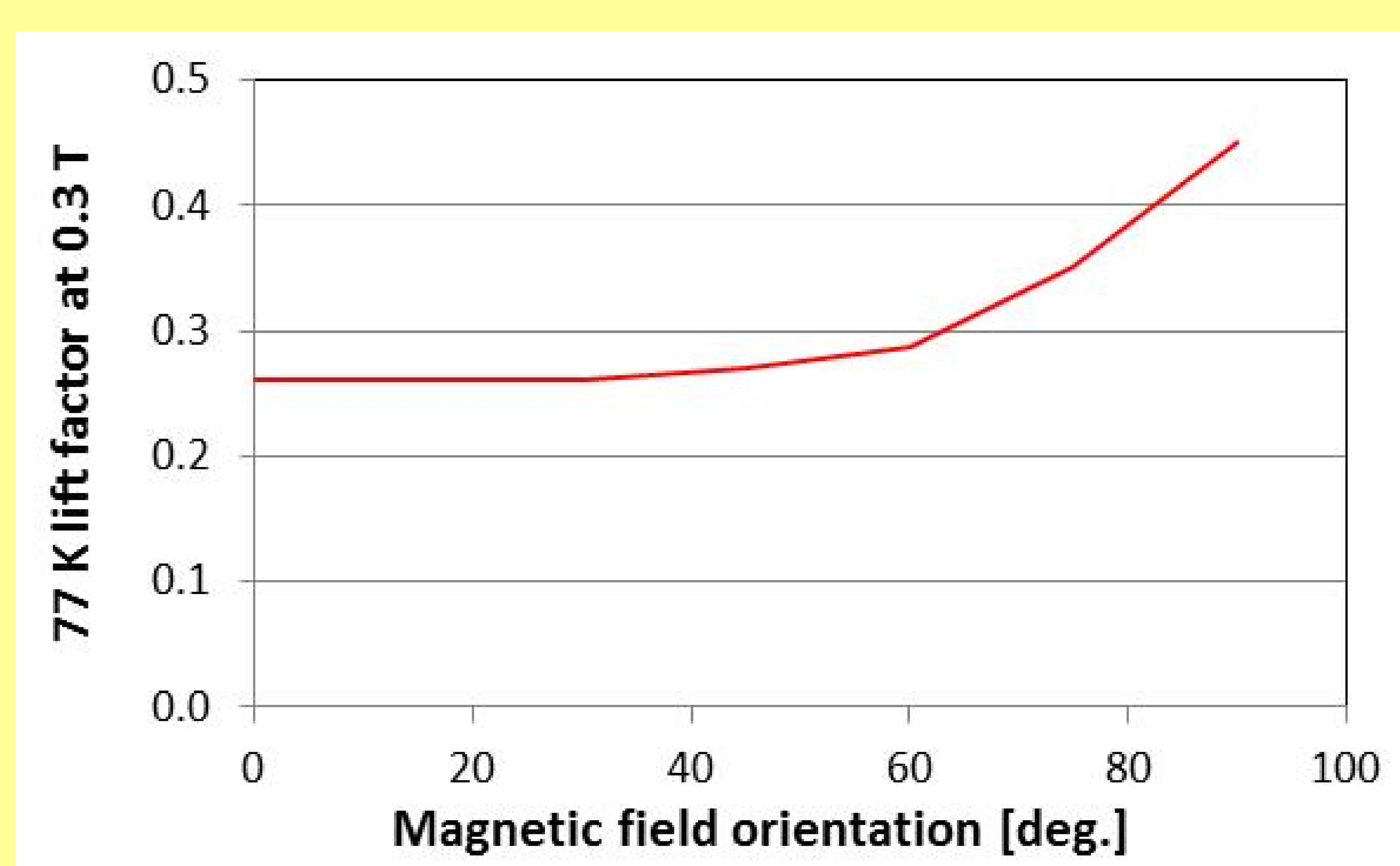



COMSOL model image showing test sample placement within background field magnet




Cable critical current is limited by field enhancement near ends of slits

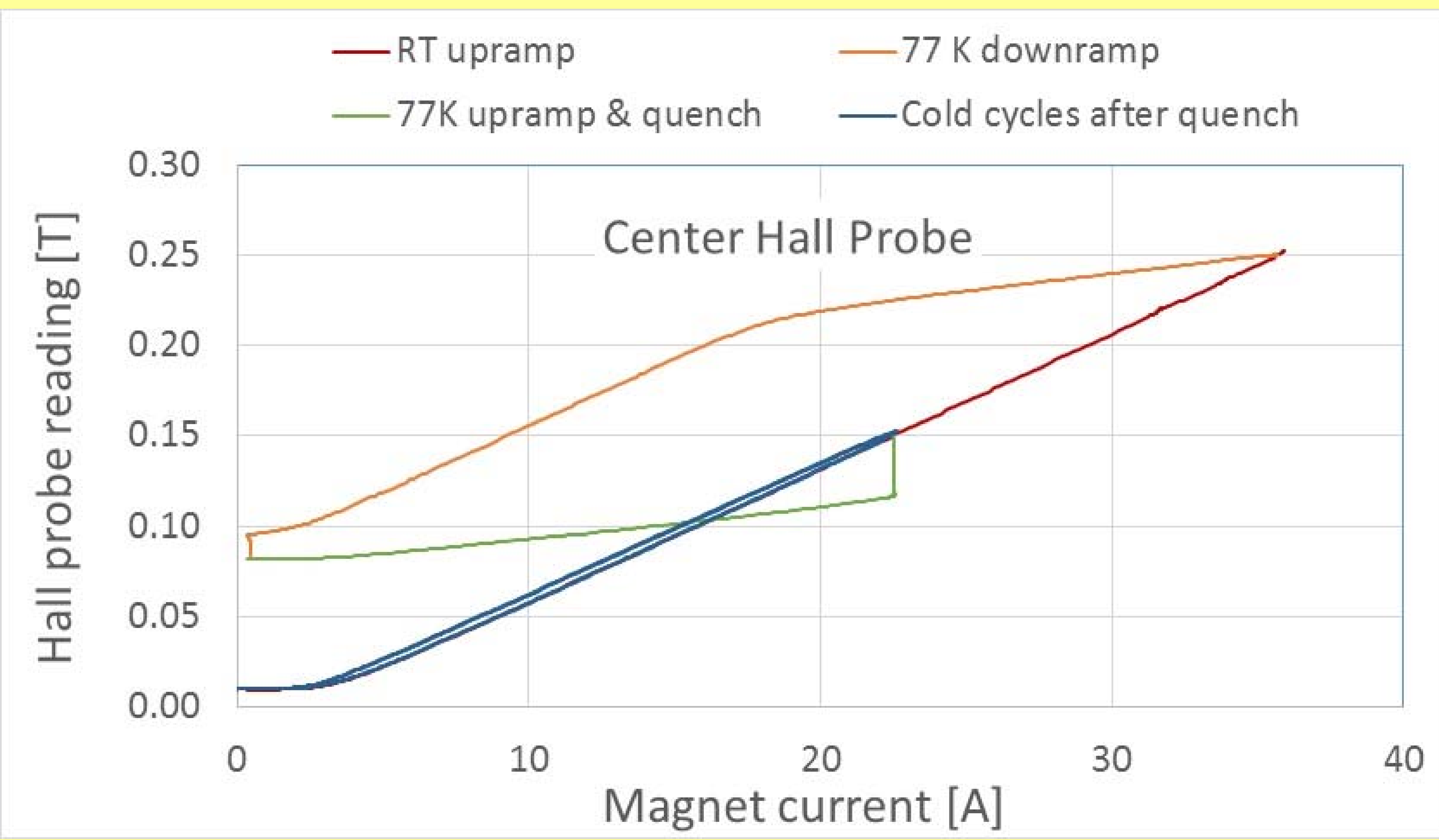


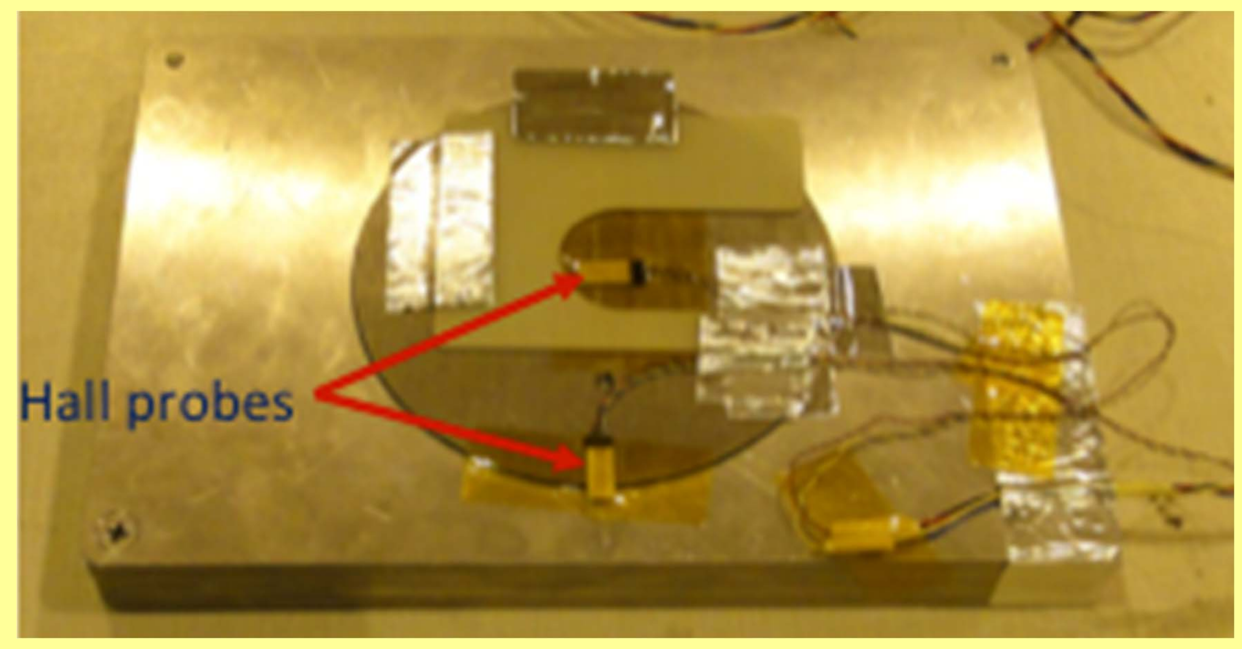

Assumed variation in 77 K lift factors for SuperPower advanced pinning HTS tapes as a function of magnetic flux density (left), and magnetic field orientation relative to the broad face of the HTS layer (0.3 T data shown at right), based on measurements reported by Takayasu (ASC-2014)

# Test Results

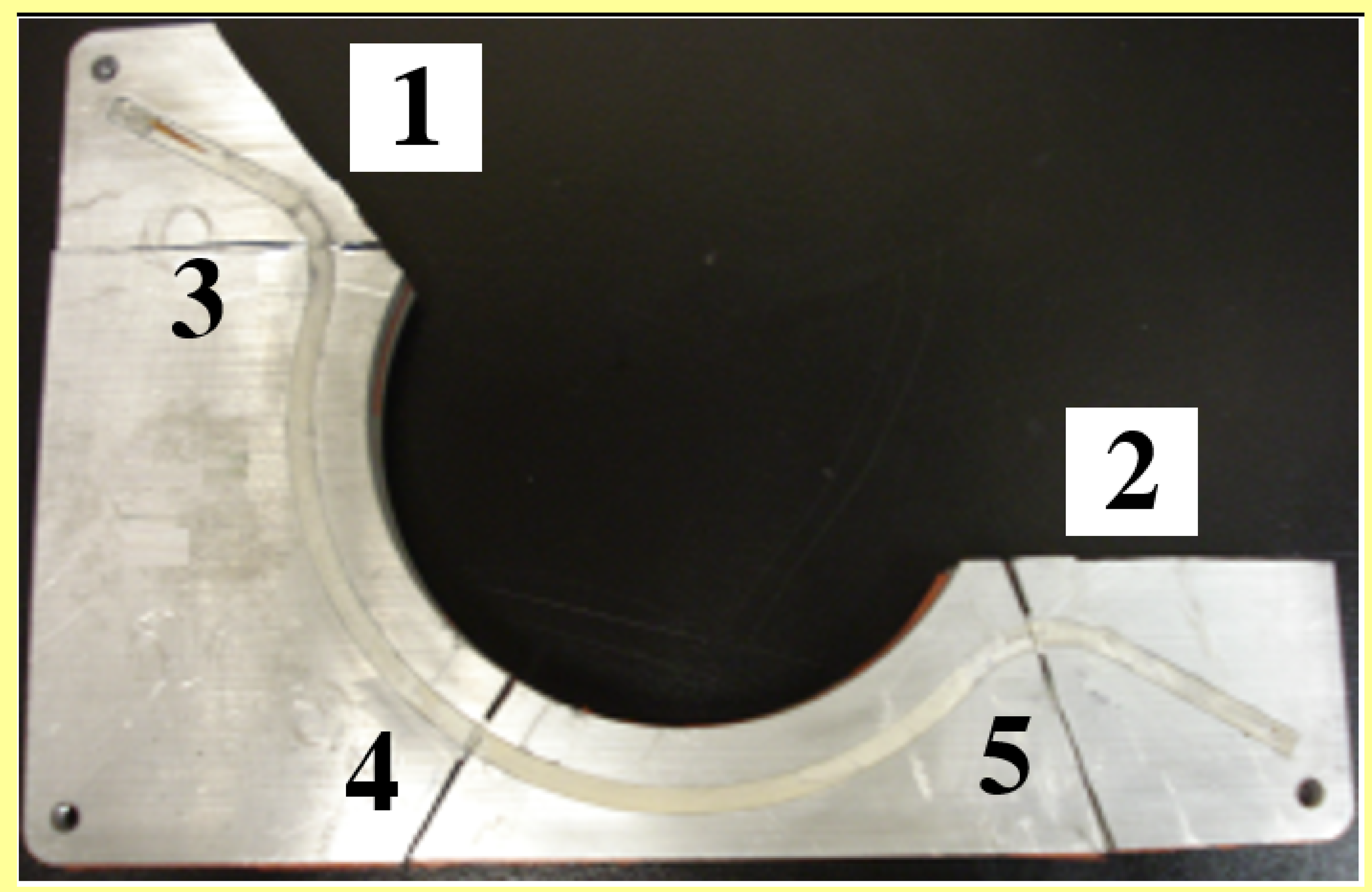
- Two-component electrical insulation developed and successfully applied to ReBCO cables
  - Polyimide shrink tape to consolidate cable and act as barrier to resin penetration
  - High thermal conductivity, low shrinkage CTD-101G resin as potting compound
  - ~20% degradation observed for cable sample with copper-plated ReBCO conductors due to slight resin infiltration within polyimide layer
  - No detectable degradation in cable sample with silver-plated ReBCO conductors at $I_c$ =1800 A



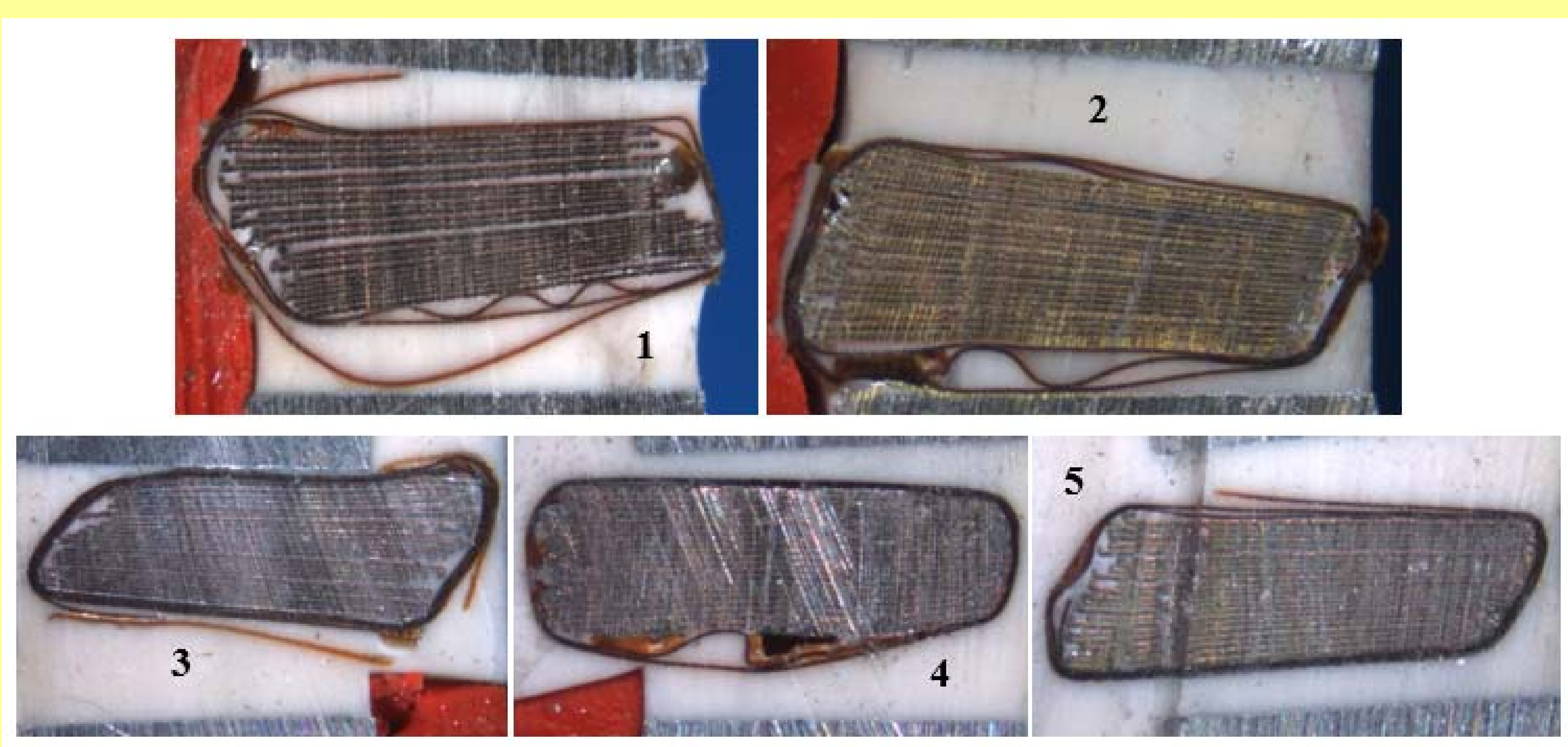

Minimum test sequence to determine trapped-flux, cable critical current



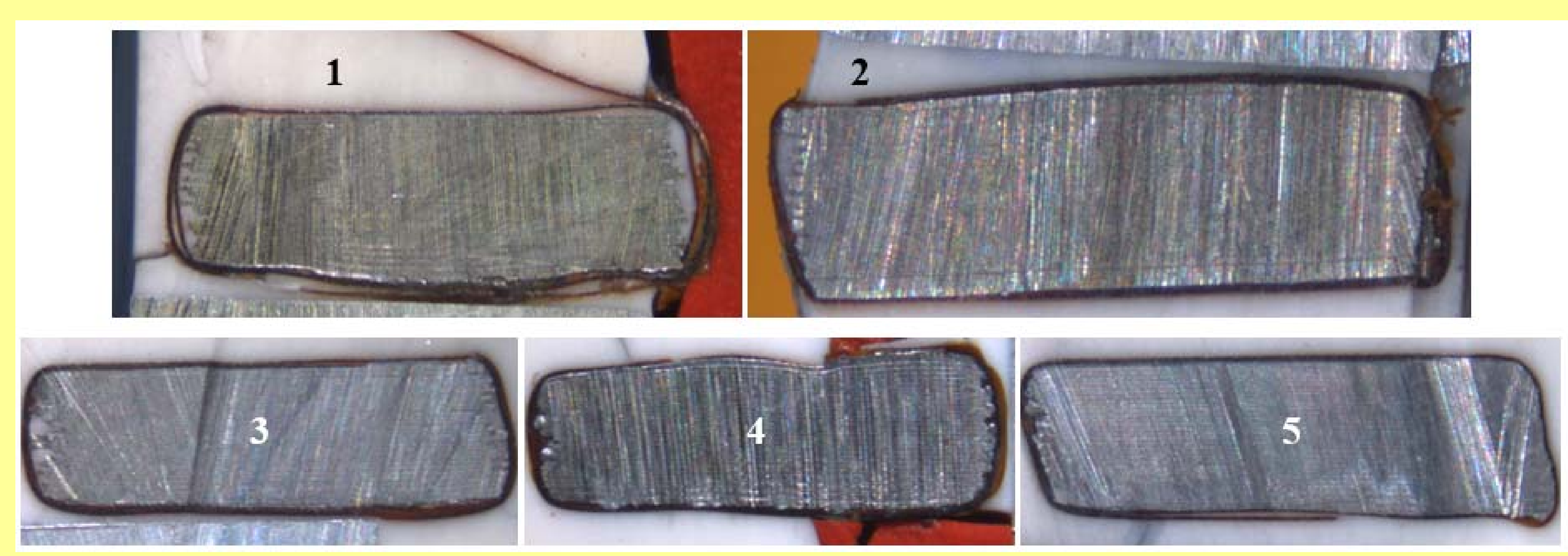

Instrumented test sample




Section lines for post-test analysis




Section views for cable sample with copper-plated ReBCO conductor, showing slightly trapezoidal cross-section and resin infiltration between conductors




Section views for cable sample with silver-plated ReBCO conductor, showing well compacted, regular cross-section with no resin infiltration between conductors

# Conclusions

- Simple, low-cost cable insulation screening test developed
  - Test performed before and after application of cable insulation
  - Test evaluation based on high-fidelity 3D COMSOL model of setup
  - Good agreement between predicted and measured results
- Development of two-part cable insulation scheme
  - Polyimide barrier insulation followed by epoxy impregnation using CTD-101G
  - Materials selected based on known or likely radiation resistance
  - Compatible with large-scale continuous processing
  - Effective prevention of critical current degradation when properly applied
- Preliminary assessment of radiation resistance performed
  - Polyimide barrier insulation retains high tensile strength following irradiation
  - Negligible difference between CTD-101K and CTD-101G composite shear strengths following irradiation

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