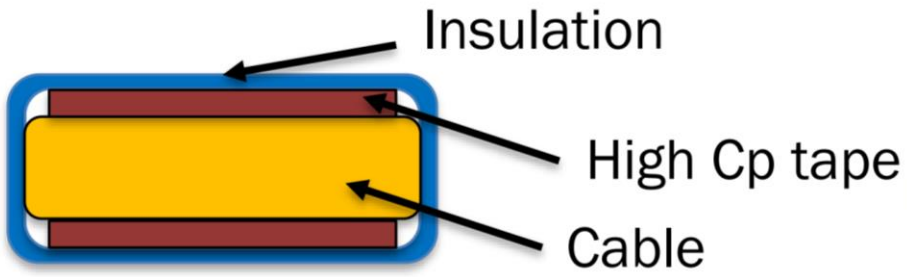
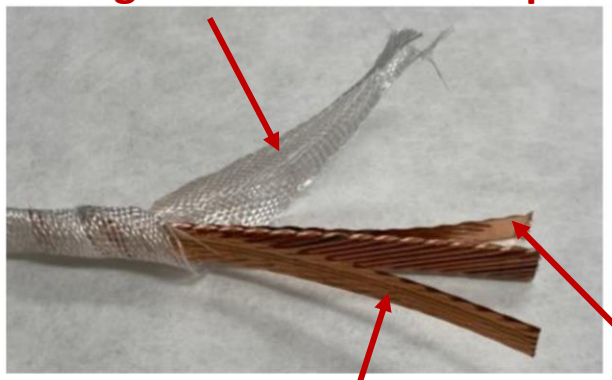
M3 - First High-C_p Cable Fabrication (1)

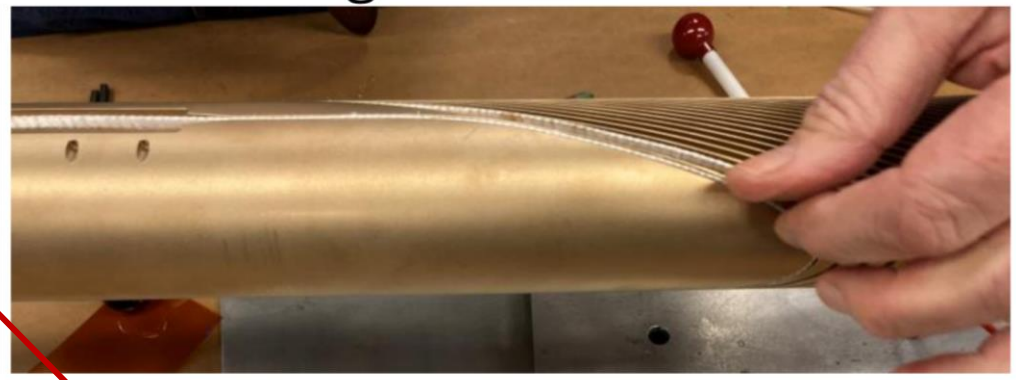
Subscale CCT Cable Test With High C_p Tape



50 micron E-glass and 50% overlap



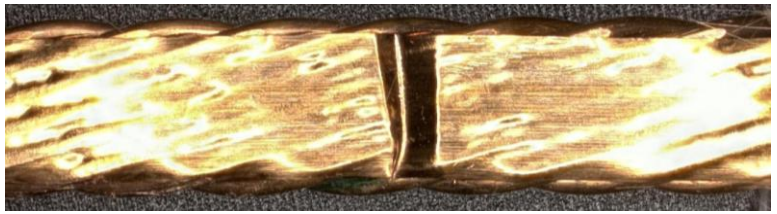
Winding of initial test cable

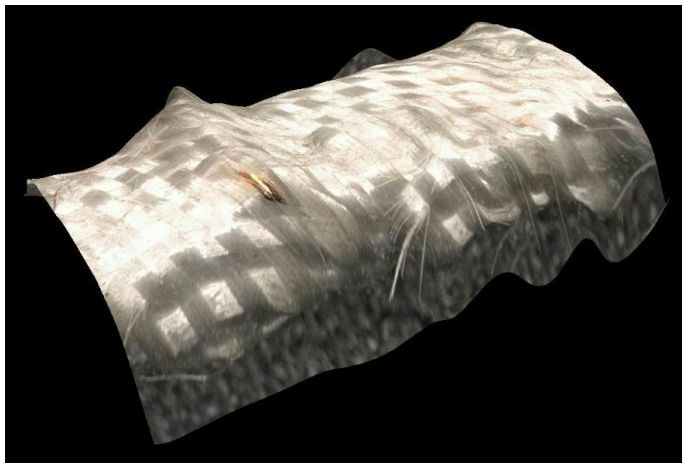


Annealed C101 99.99% pure Cu ribbon 50 μm thick x 3.175 mm running parallel to the cable at the top and the bottom

LBL Cable

Parameter	Unit	Value
Conductor Type	-	RRP 132/169
Strand Diameter	mm	0.6
Cu:non-Cu ratio	-	1.17
Number of Strands	-	11
Cable Width	mm	4
Cable Thickness	mm	1.1





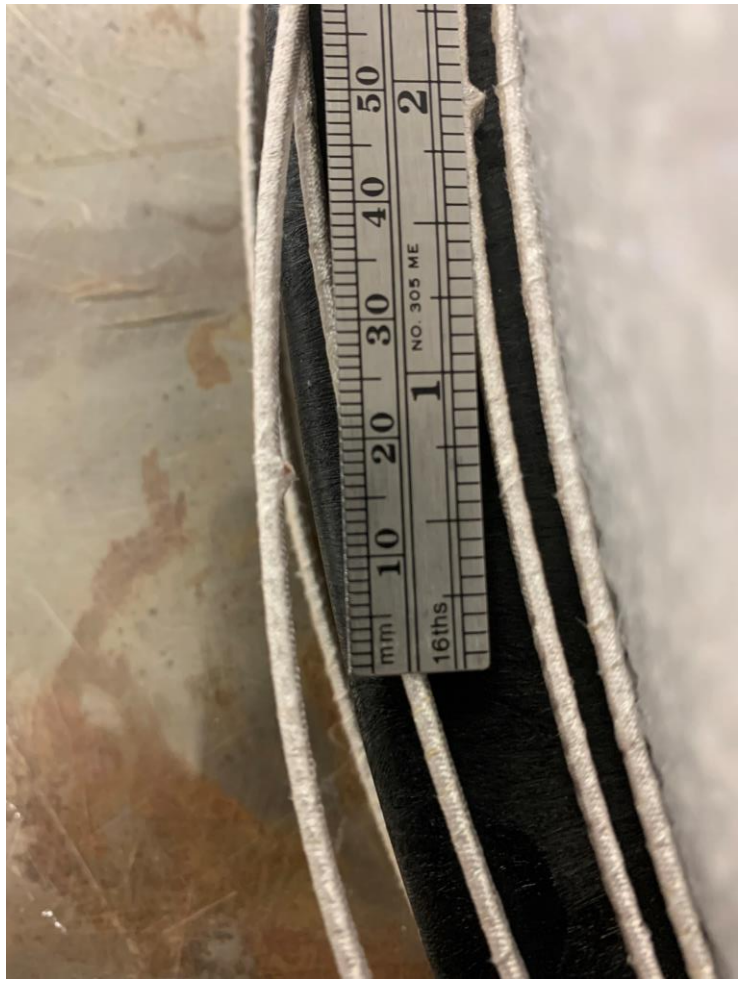
<u>OUTCOME</u> – The Cu tape developed periodic small folds which create a sharp corner that pokes through the E-glass

D. Arbelaez

M3 - First High-C_p Cable Fabrication (2)

- **Repeat experiment with 100 μm Cu tape and same 50 micron E-glass and 50% overlap ➔ The tape pops on the inner radius of a 10 ¾ inch spool when bent.**

- **The bend experiment is repeated each week to account for possible relaxation of the materials.**



US-MDP General Meeting – August 30, 2023

High heat capacity and radiation-resistant organic resins for impregnation of high field superconducting magnets

Emanuela Barzi, U.S. PI

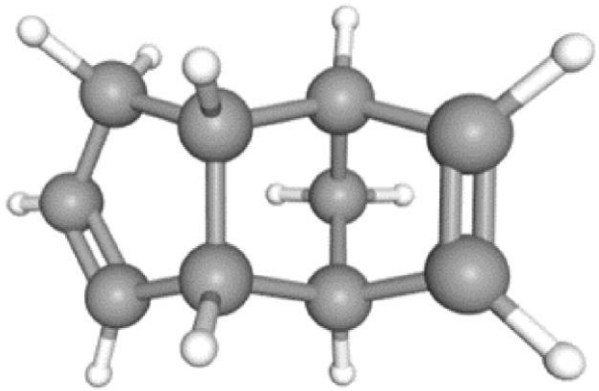
Fermilab & Ohio State University

Akihiro Kikuchi, Japan PI

Goal 1

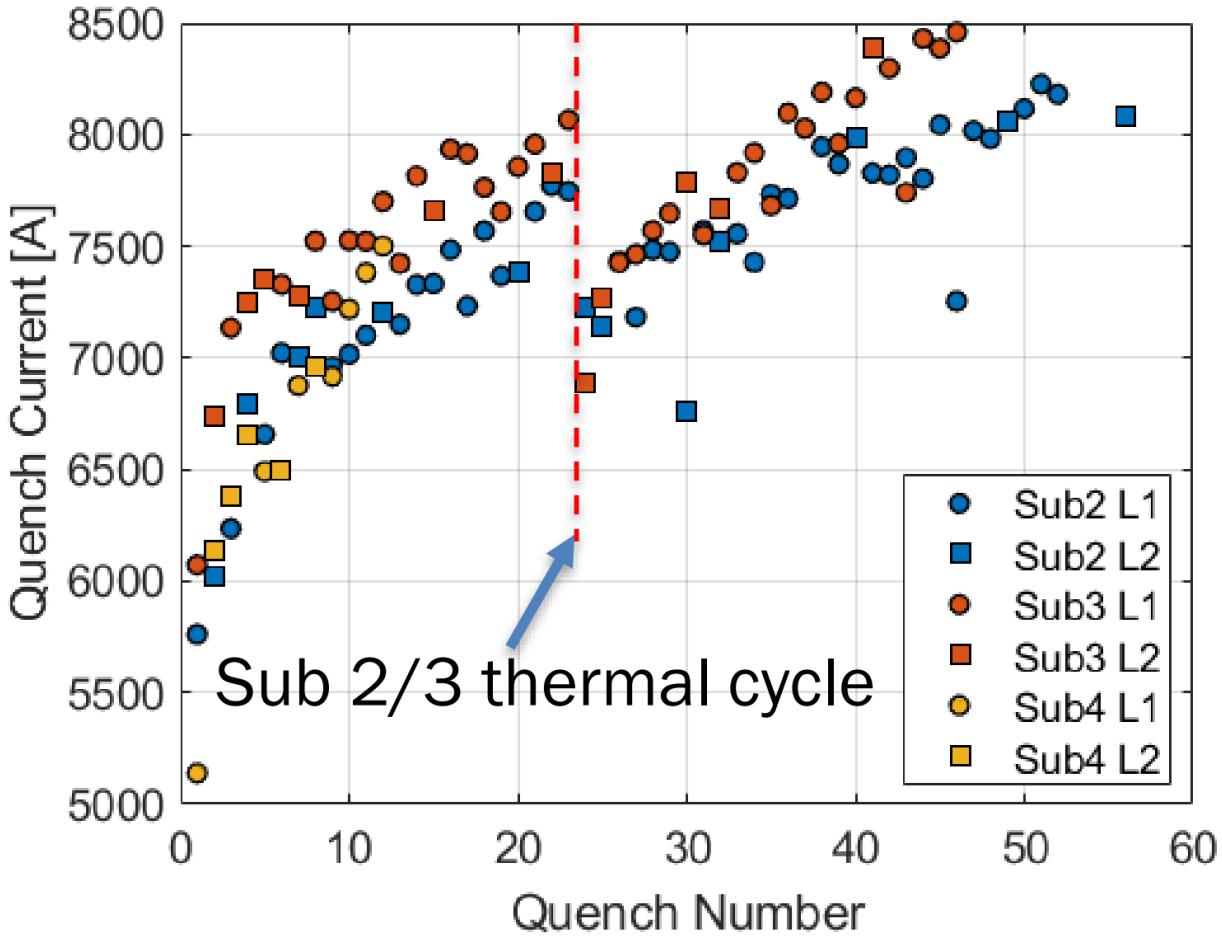
One of the main challenges of high field accelerator magnets for HEP made of superconducting Nb_3Sn is their training due to temperature variations in the coils

➔ Significantly reduce or eliminate training, by using a different impregnation resin than the epoxy currently used. This is a novel organic olefin-based thermosetting dicyclopentadiene (DCP) resin, commercially available as TELENE® at RIMTEC.



Dicyclopentadiene ($C_{10}H_{12}$)

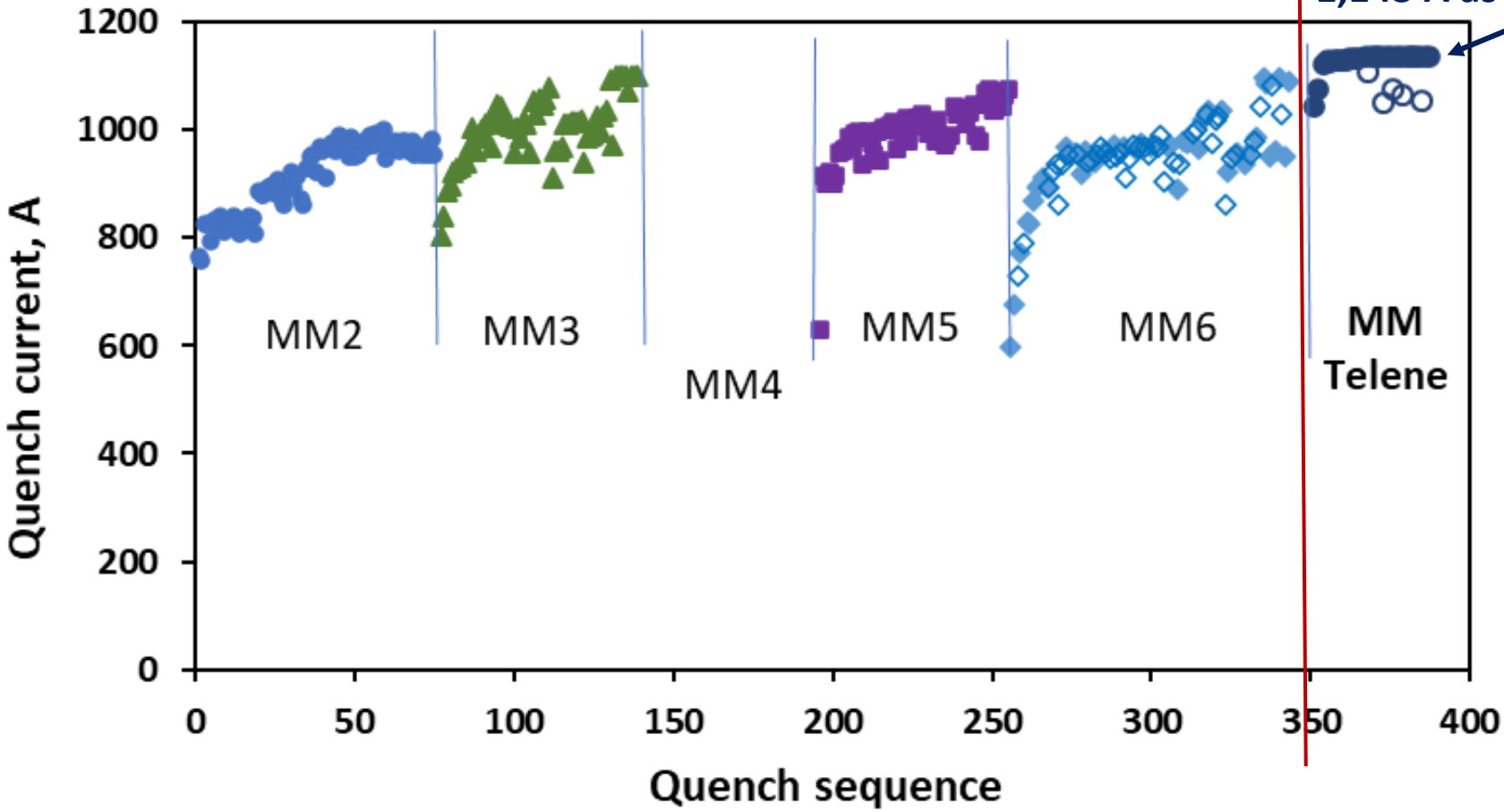
EXAMPLE OF MAGNET TRAINING

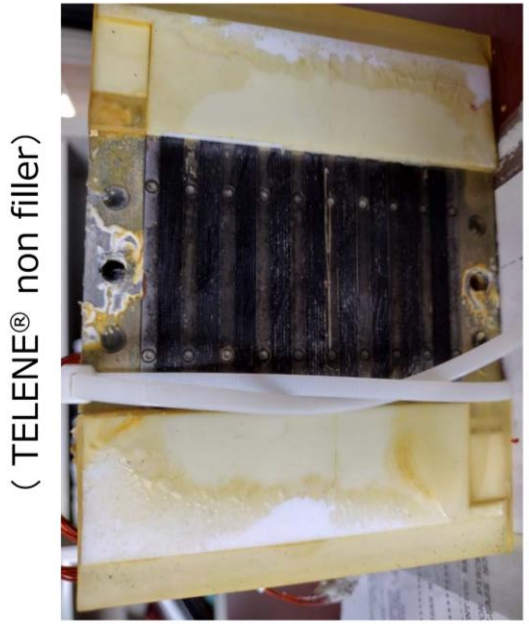


Canted Cosine Theta subscale magnet (D. Arbelaez)

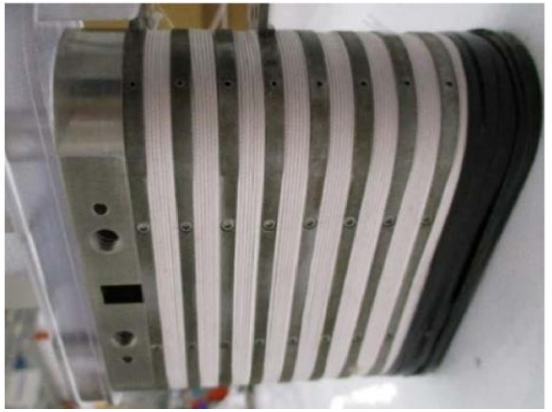
Goal 1 Close to Achievement for Small Undulator used as Fast Turn-around Tool

THE SMALL ANL UNDULATOR MAGNETS MM3 TO MM6 ON THIS SIDE WERE NEARLY IDENTICAL AND IMPREGNATED WITH CTD-101

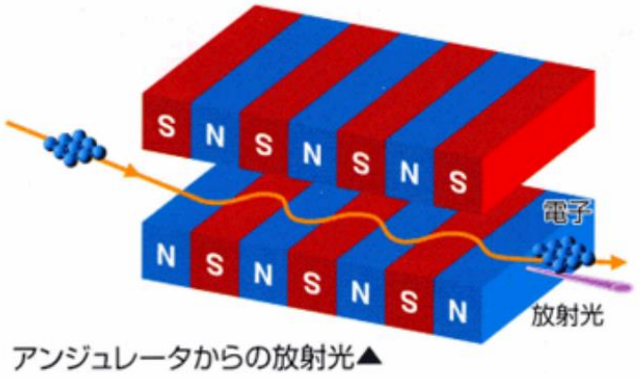




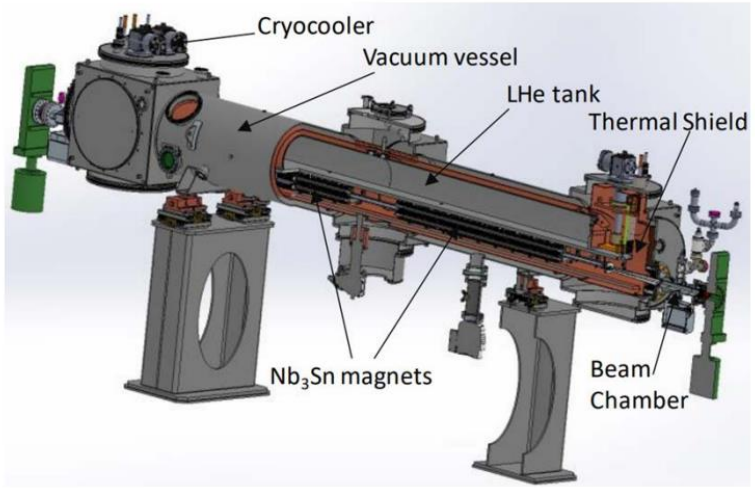
Ibrahim Kesgin – ANL Co-PI



Nb_3Sn Undulator Magnets for Advanced Photon Source (APS)

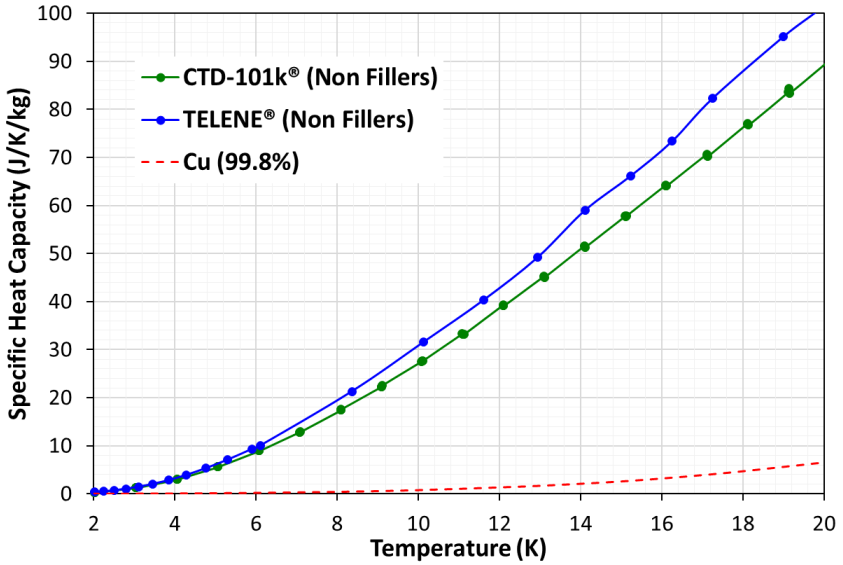


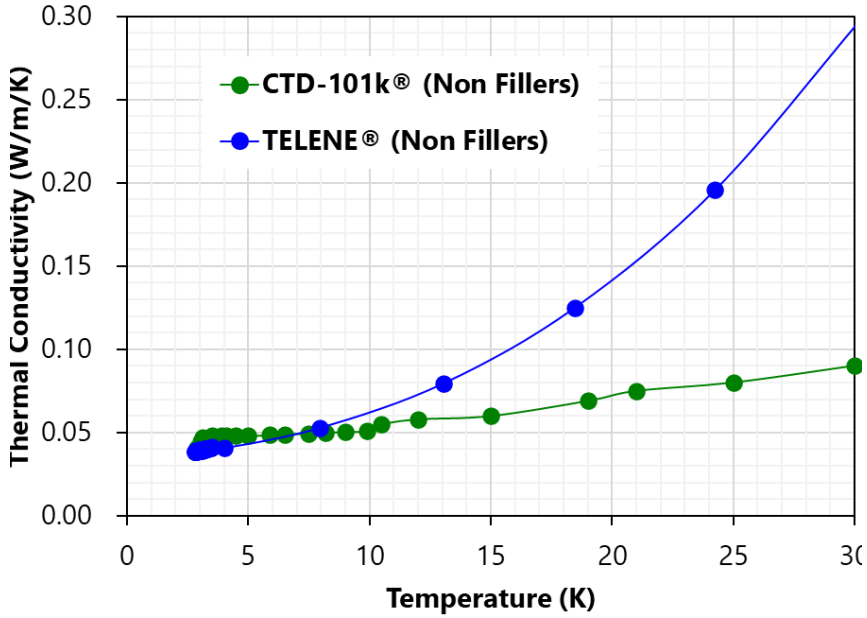
アンジュレータからの放射光▲

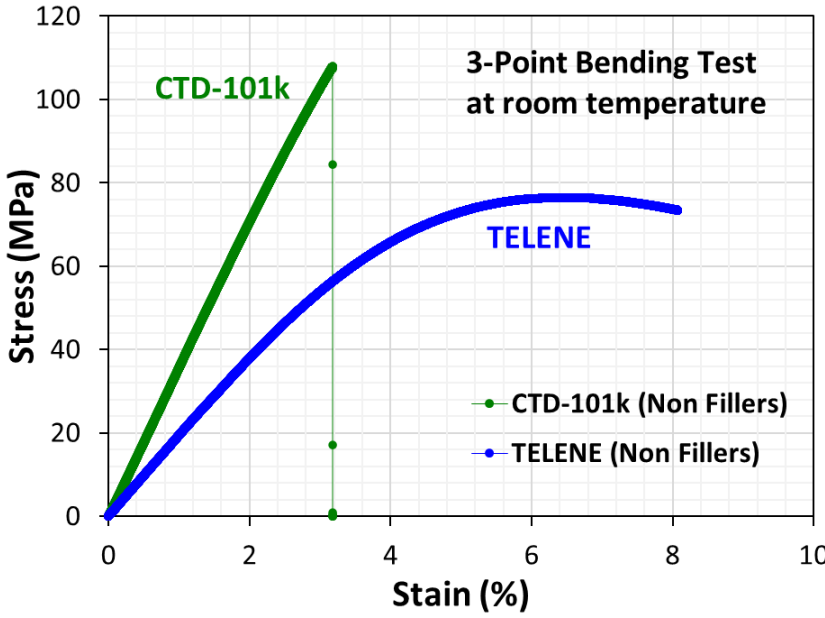


- Each <u>Nb_3Sn undulator short model fabricated at ANL</u> has nine racetrack coils wound in a groove between ten poles with an S2-glass braided Nb_3Sn wire. There are 46 turns in each groove. The period length is 18 mm.
- After winding, the magnet was <u>heat treated at FNAL</u> in argon atmosphere using well-established treatment cycles.
- Then it was placed in a leak-tight impregnation mold for <u>vacuum pressure impregnation at ANL</u>.
- Finally it was <u>tested at FNAL</u> in the Superconducting R&D lab, using a new DAQ hardware&software system for quench protection.

Why TELENE?





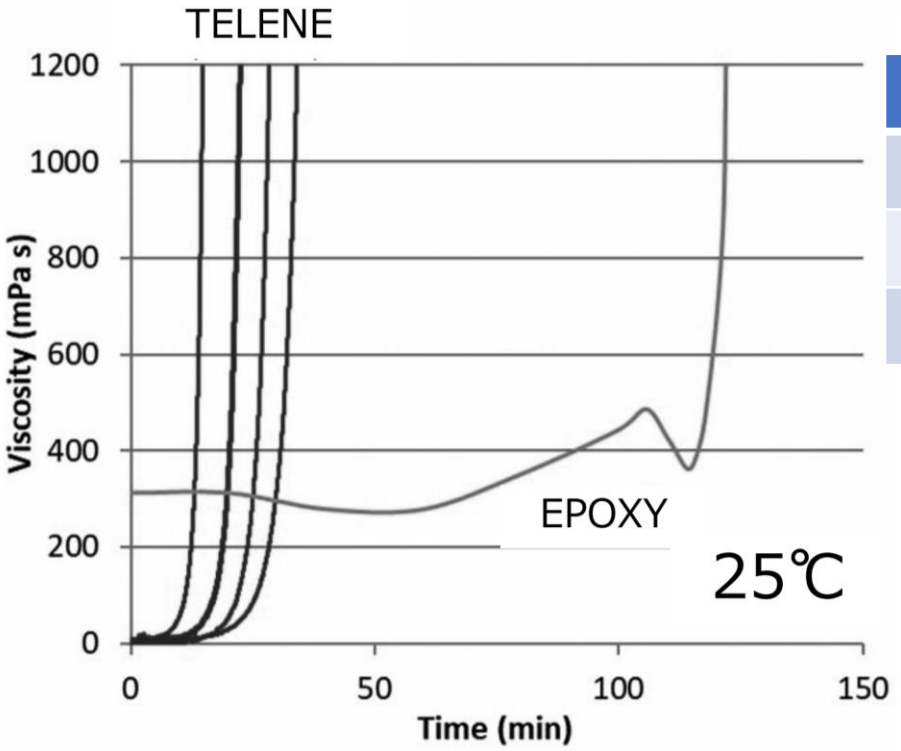


Specific heat C_p is somewhat larger than for epoxy

Thermal conductivity is larger than for epoxy

It accepts much larger strains than epoxy

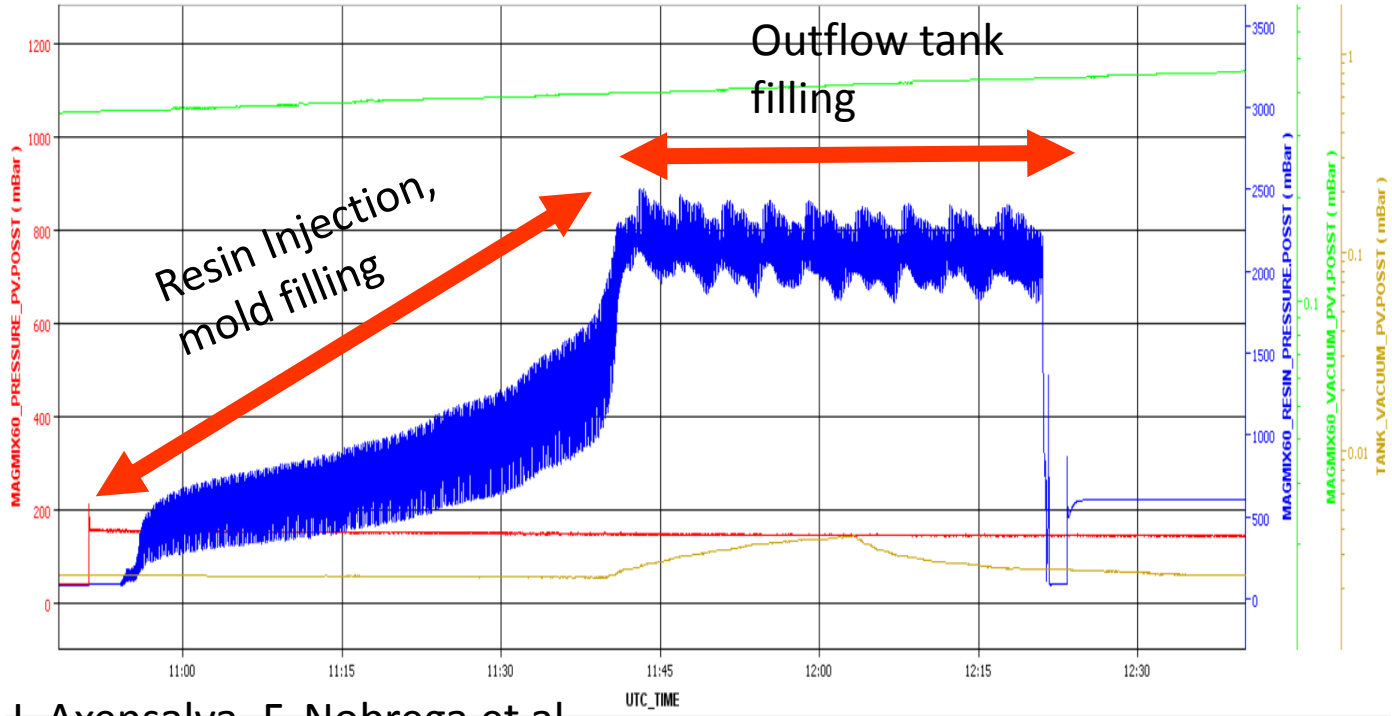
Scalability Solved



POT LIFE, min	TEMPERATURE, ºC
30	25
60	15
120	5

Max. time limit for impregnation process with TELENE

By using one epoxy inlet into the tooling with multiple vents and an inlet pressure of 2 Bar, fill times vary from 45 min to 1.5 hrs for CERN accelerator quadrupoles 7.3 m long.

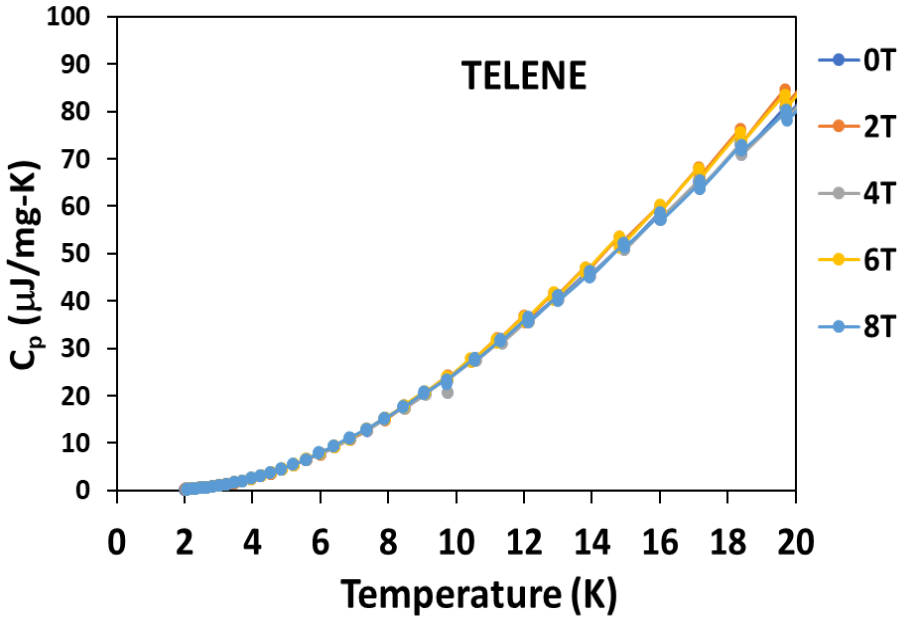


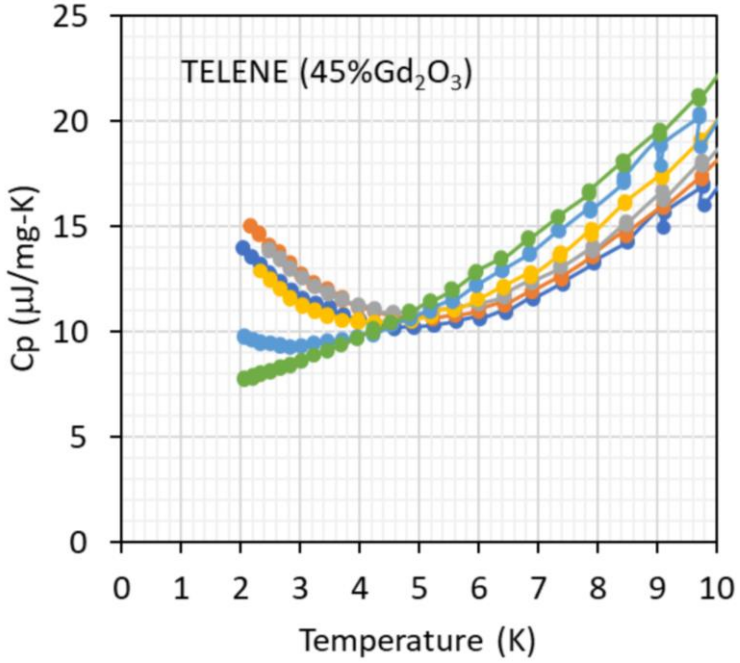
Courtesy of J. Axensalva, F. Nobrega et al.

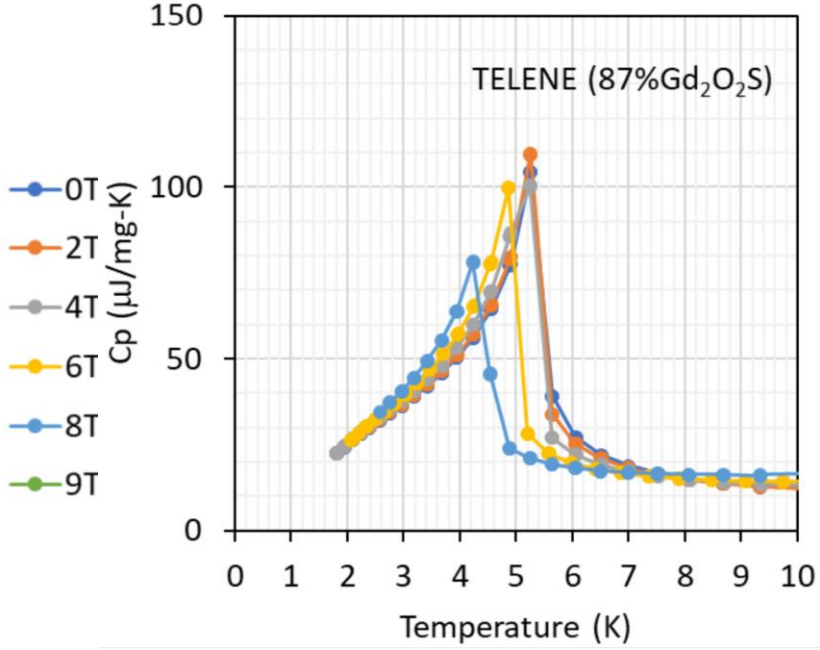
How to Further Improve Stability

- **By mixing TELENE with high-C_p ceramic powders such as Gd_2O_3 and Gd_2O_2S.**
- **This is done with a planetary mixer. The resin is then cured with a ruthenium complex. The curing time is controlled by a retardant.**

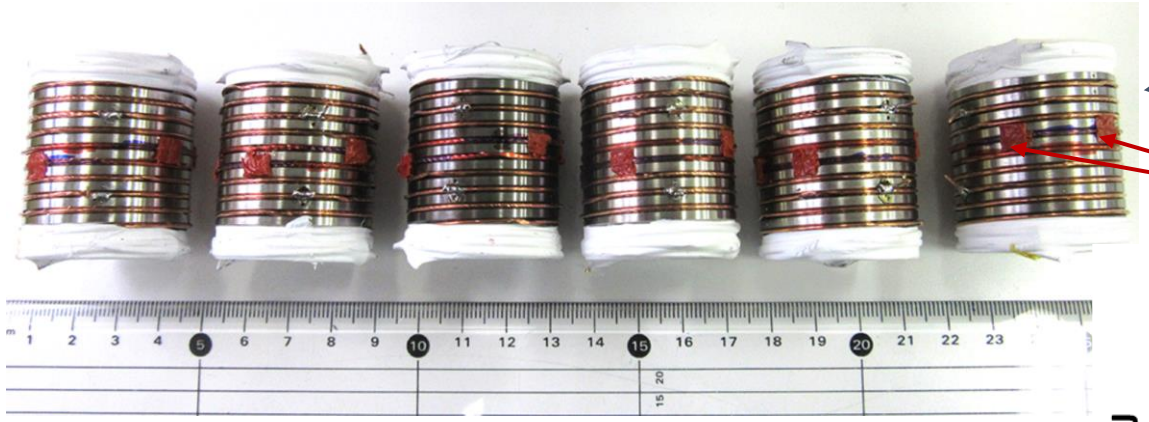
Specific Heat as Function of Magnetic Field of TELENE Resin Mixed with High-C_p Ceramic Powders







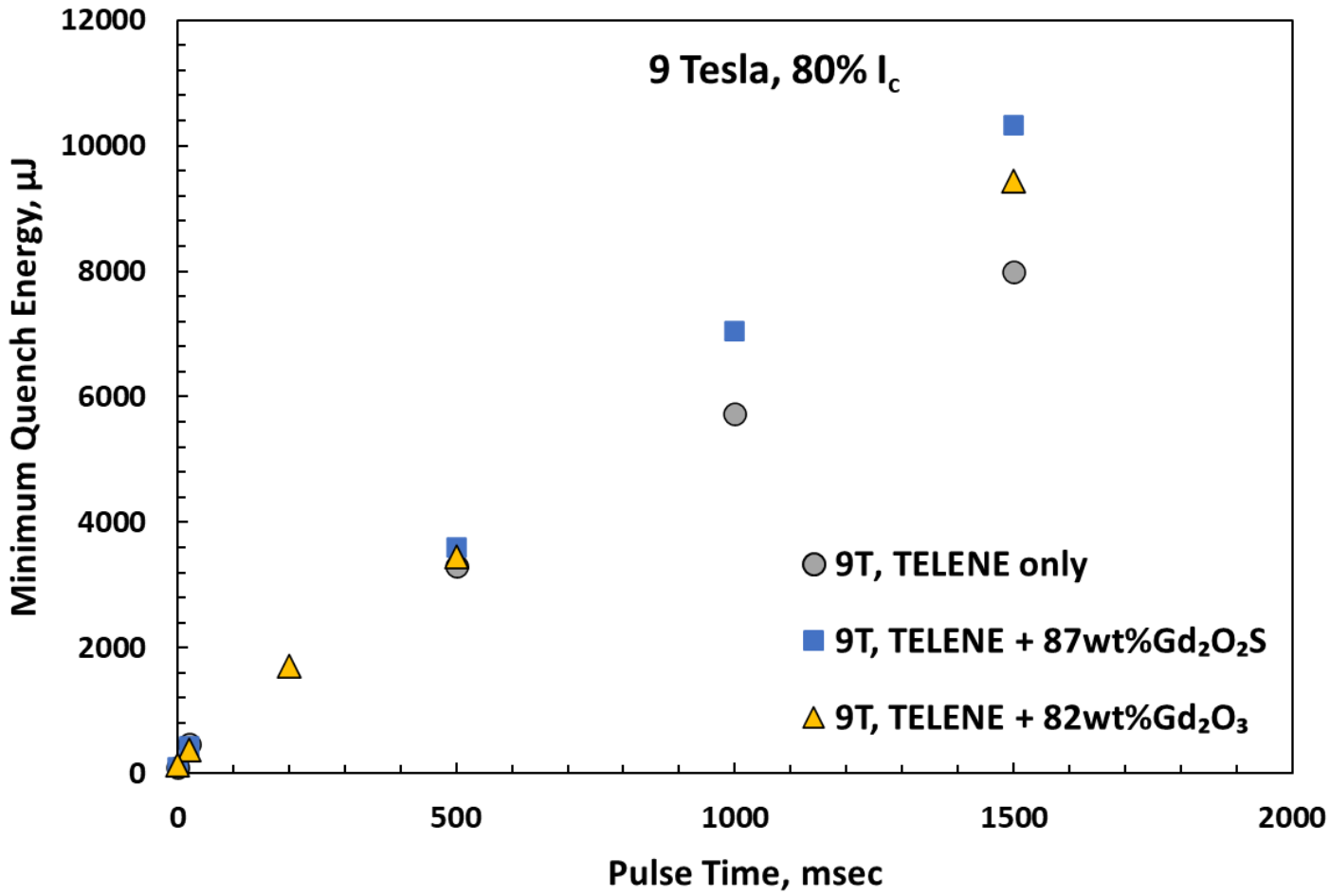
Measurements of Minimum Quench Energy of Impregnated Wire Samples



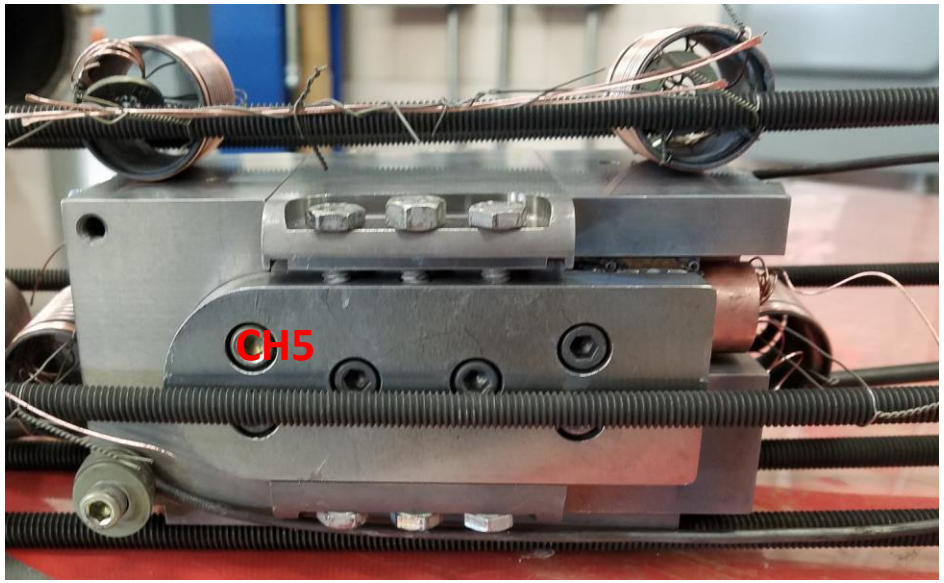
0.8 mm NbTi wire; I_c(9T) = 114 A; I_c(8T) = 235 A

Locations of heaters

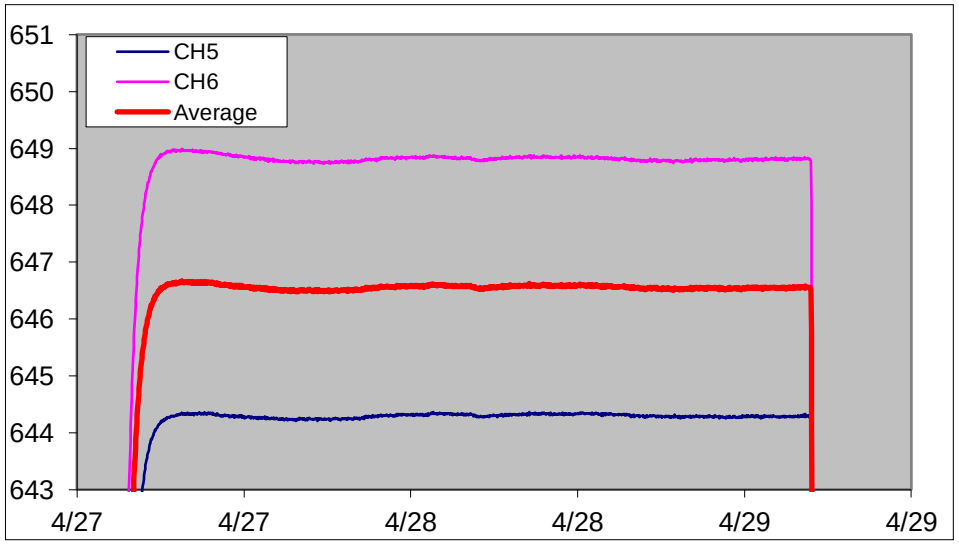
- A dozen 0.8 mm NbTi wire samples were prepared at FNAL and sent to NIMS for impregnation with MIXED resins.
- The Minimum Quench Energy was then measured at FNAL at 80% of the critical current I_c and various magnetic fields, for pulse durations from 200 ms to 2 s.

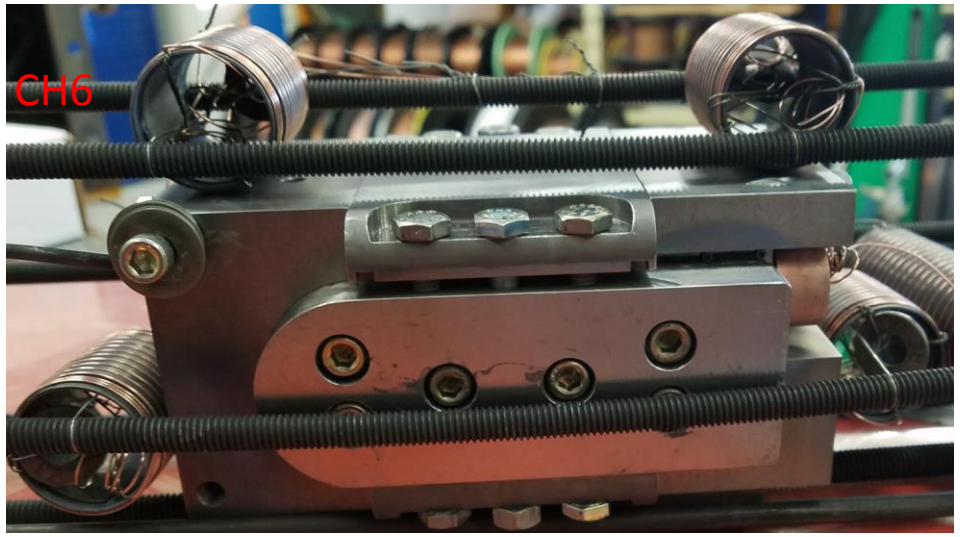


Heat Treatment of Small Undulator

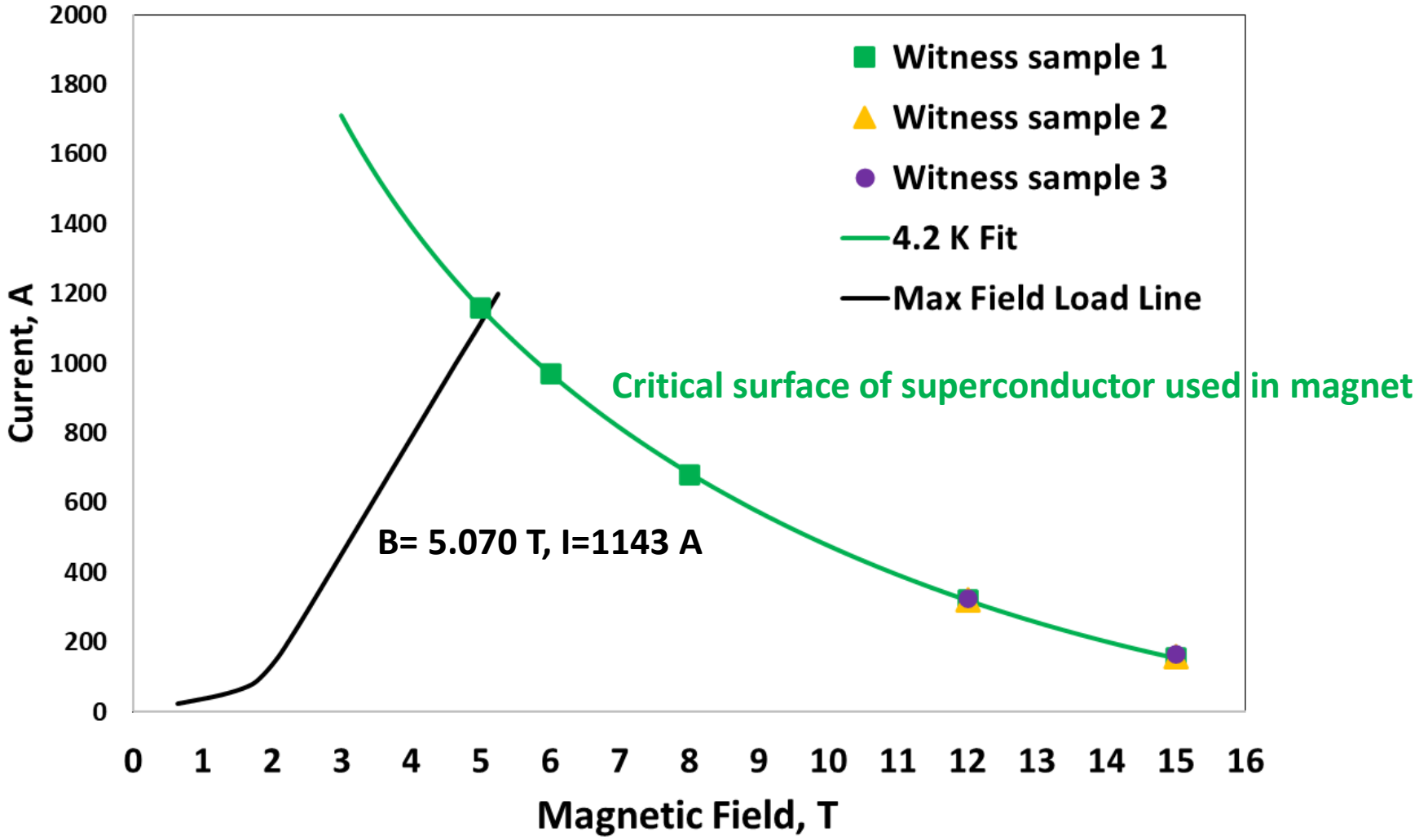


Nominal Desired on coil		Coil MM7	
Time, Hr	T, °C	Time, Hr	T Avg, °C
48	210	48	207
104	370	104	365
50	650	50	647



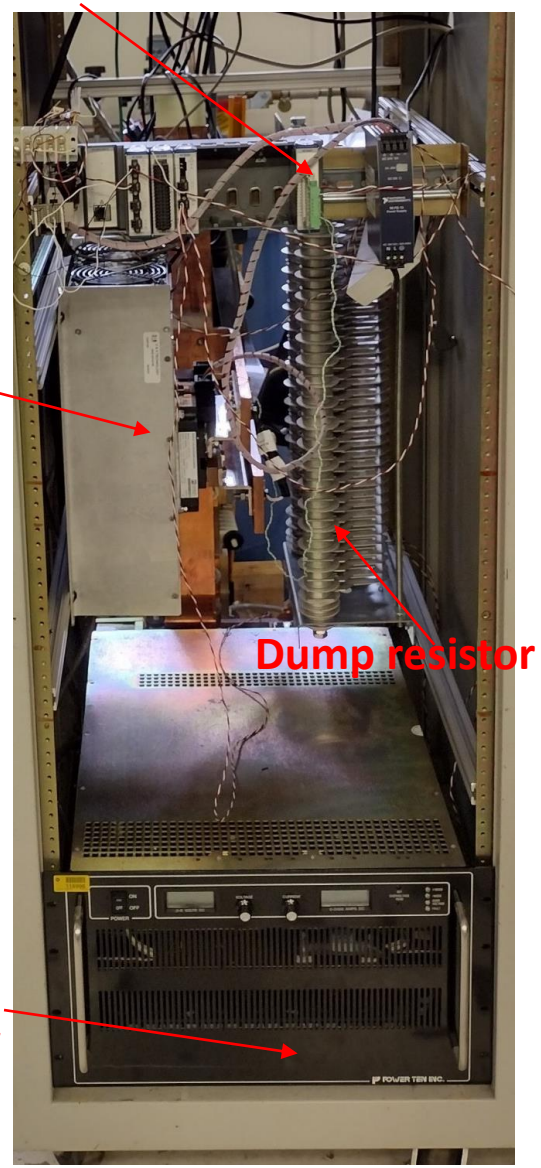


Short Sample Limits for Small Undulator

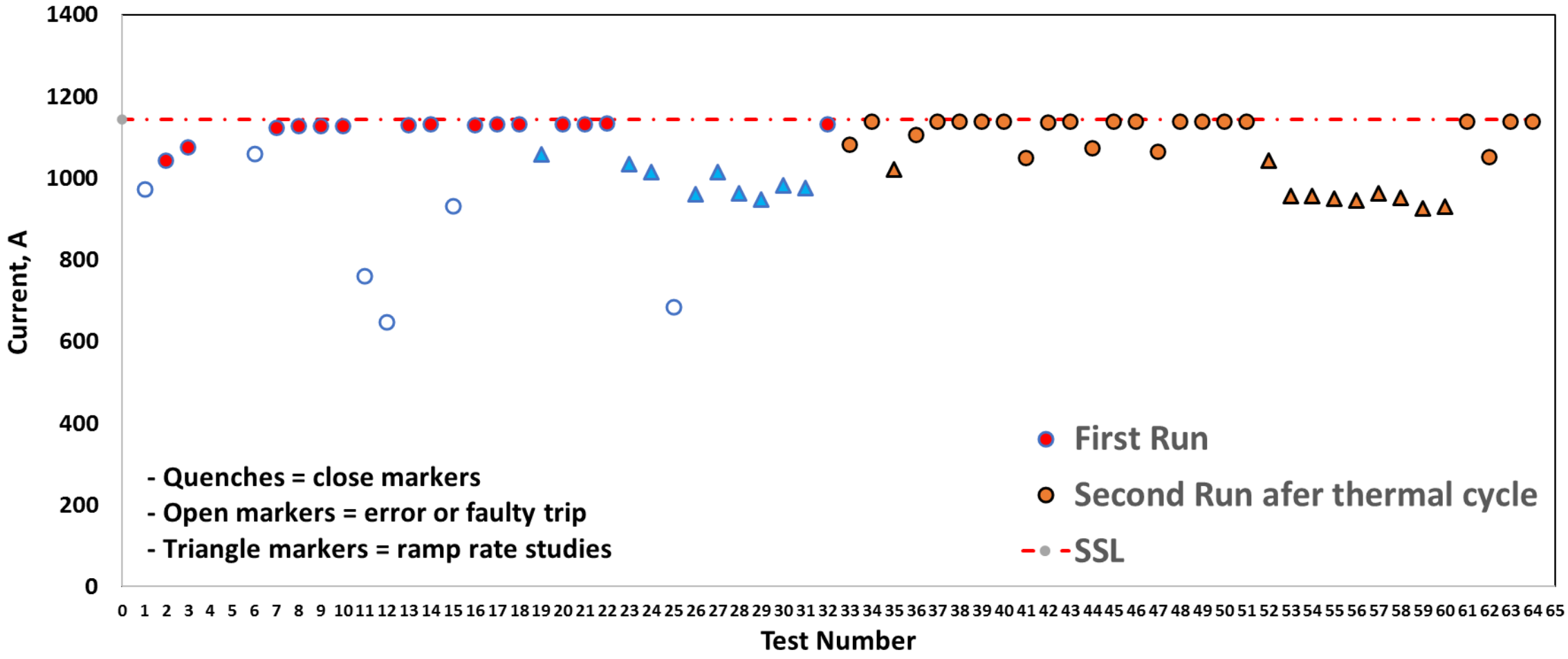


New FNAL DAQ/Quench Protection System

A quench protection system with a fast IGBT (insulated gate bipolar transistor) switch, dump resistor and a NI compact RIO DAQ system was used.



Undulator Test Results

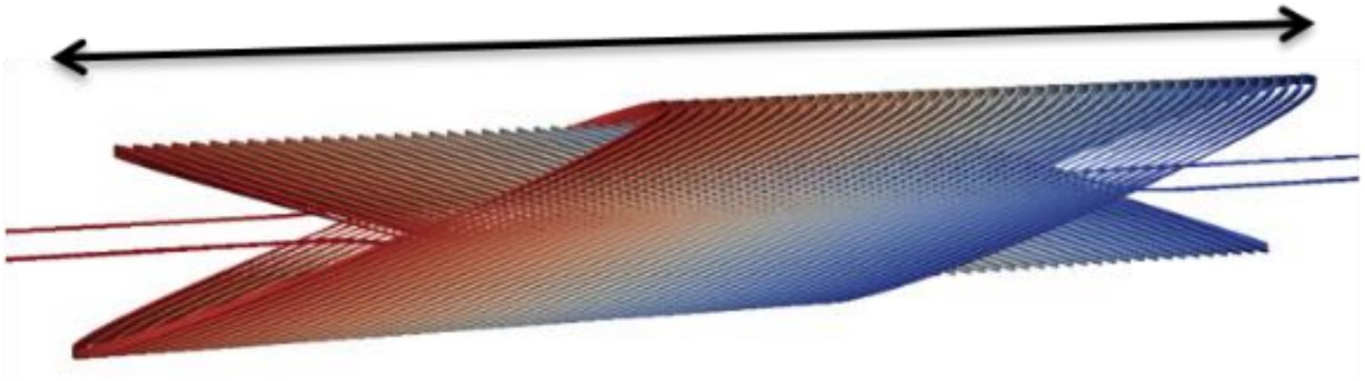


TELENE Application to LBL Canted Cosine Theta

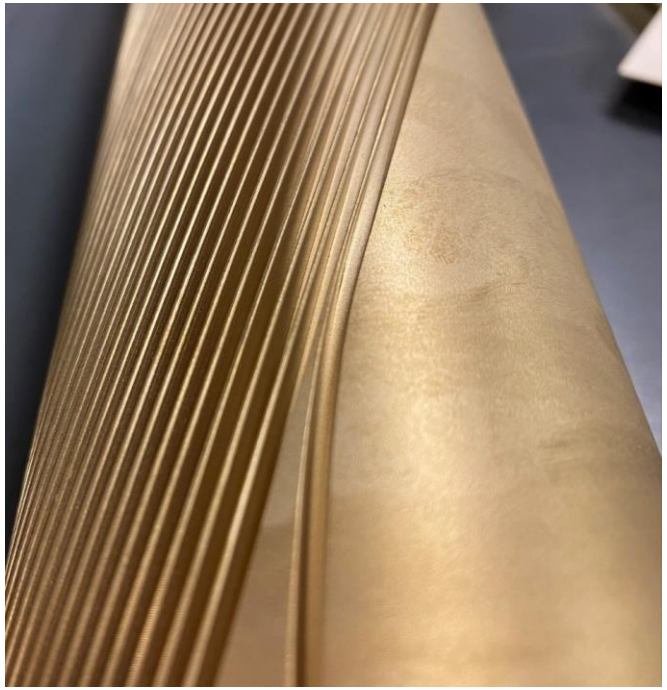
TO CHECK PERFORMANCE UNDER LARGER LORENTZ FORCES

Design developed within the U.S. Magnet Development Program - Synergy

45 turns / layer = 500 mm physical length



D. Arbelaez, J. L. Rudeiros Fernandez et al.



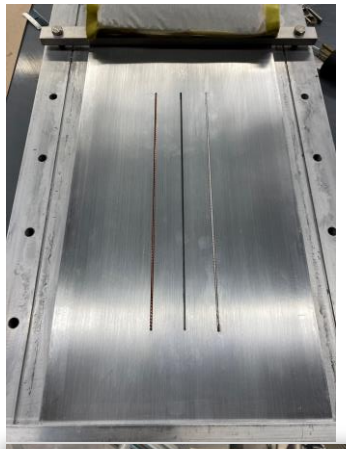
Plans for TELENE impregnated Subscale CCT at LBL

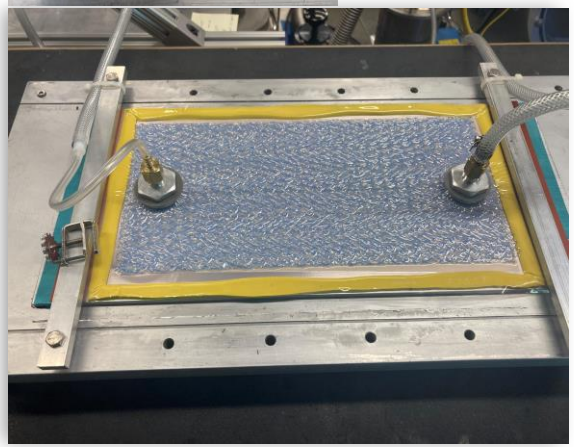
SLIDE BY DIEGO ARBELAEZ

Four liters of TELENE were directly shipped to LBL by Dr. Masaki Takeuchi at RIMTEC

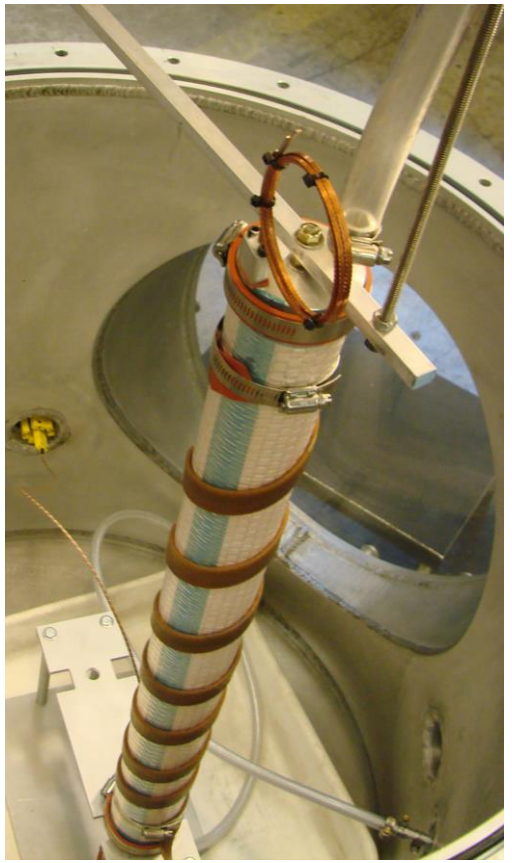
- Will initially perform testing of resin transfer and fill quality on flat plate setup
  - Same setup that is used for Stycast testing
  - Flat plate with grooves to insert cable
  - Uses consumable materials for resin transfers (vacuum bag, flow media, peel ply)
- Flat plate tests will be used to determine if same materials are compatible with TELENE impregnation (relative to resin cure temperature and pot life)
- Inner layer CCT Subscale coil will be impregnated once flat plate test is completed successfully

Resin Impregnation Test Setup



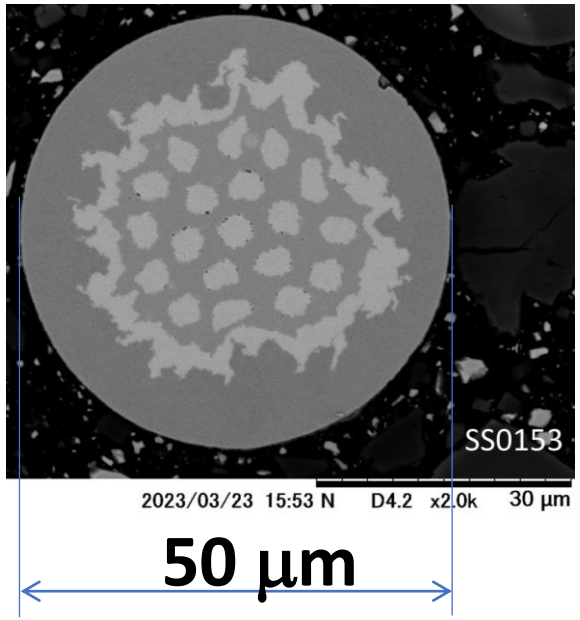


Subscale CCT Impregnation

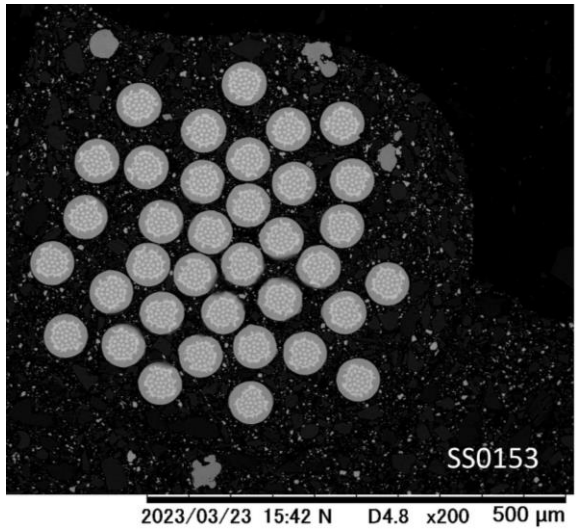


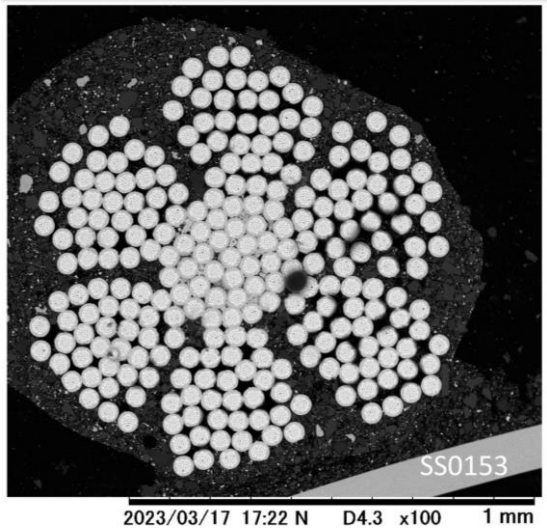
Effort at LBL led by Jose Luis Rudeiros Ferndandez, Jim Swanson, Diego Arbelaez

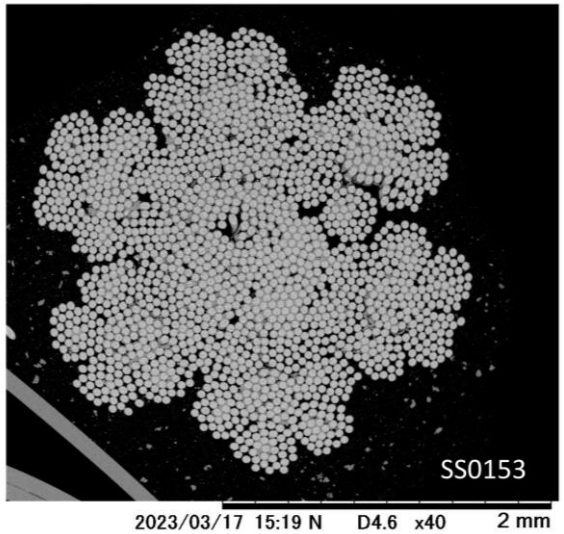
Multi-stage Conductor with Small AC Losses

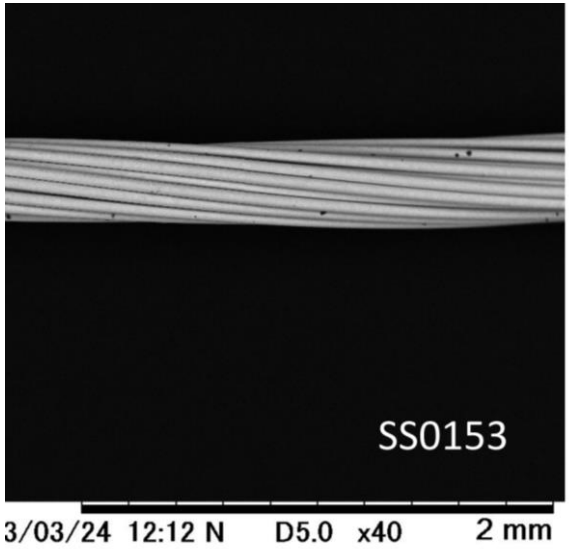


Superfine Nb_3Sn wire separately developed at NIMS - Synergy

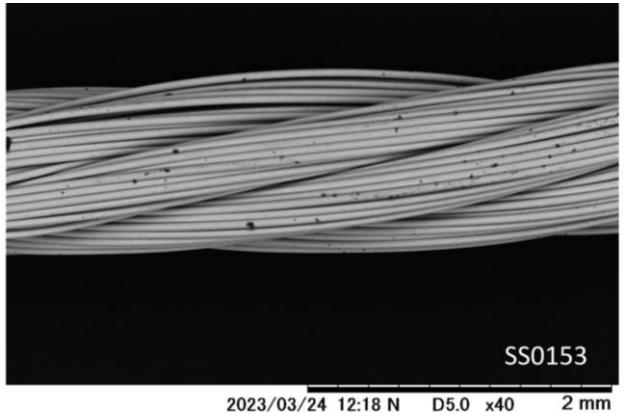




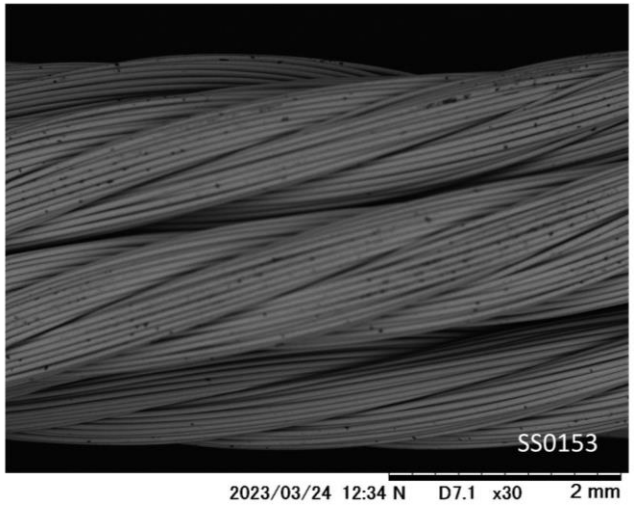




36/0.05 Strand Primary Cable (Cable Diameter: 0.33 mm)



7/36/0.05 Strand Secondary Cable (Cable Diameter: ~1 mm)



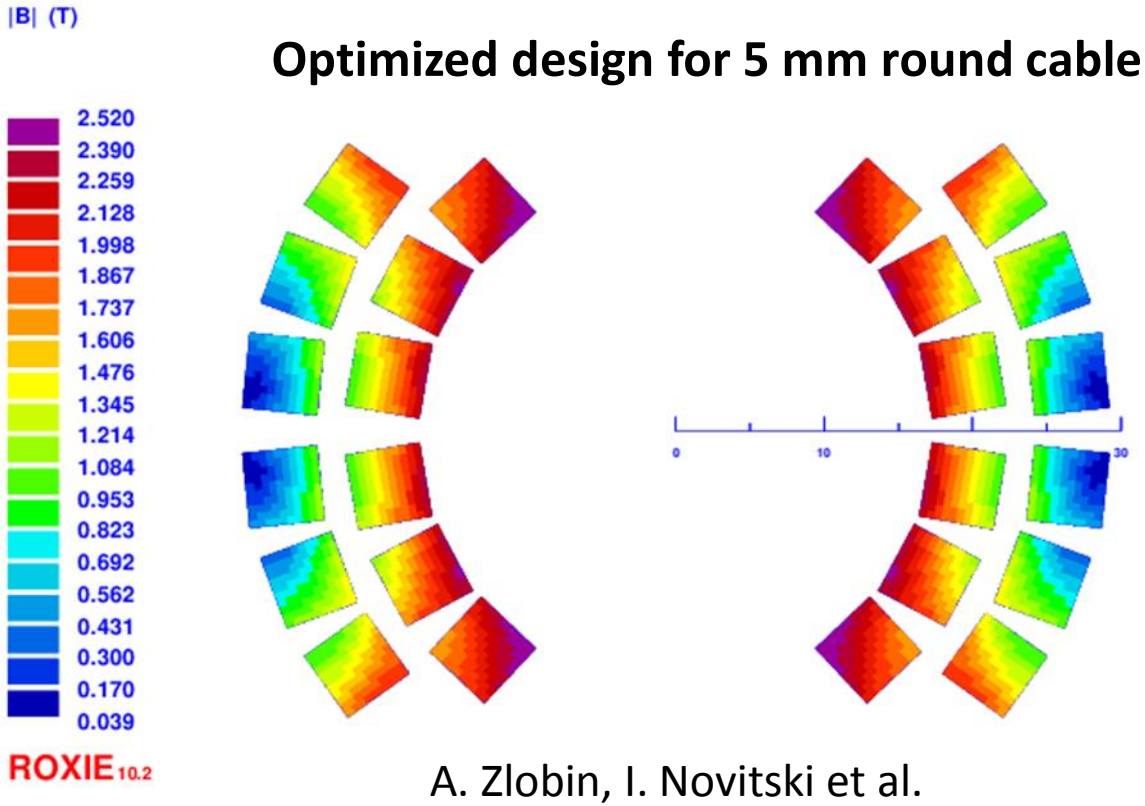
7/7/36/0.05 Strand Tertiary Cable (Cable Diameter: ~3.0 mm)

TELENE Application to Fast-Ramping ±2 T Accelerator Magnets

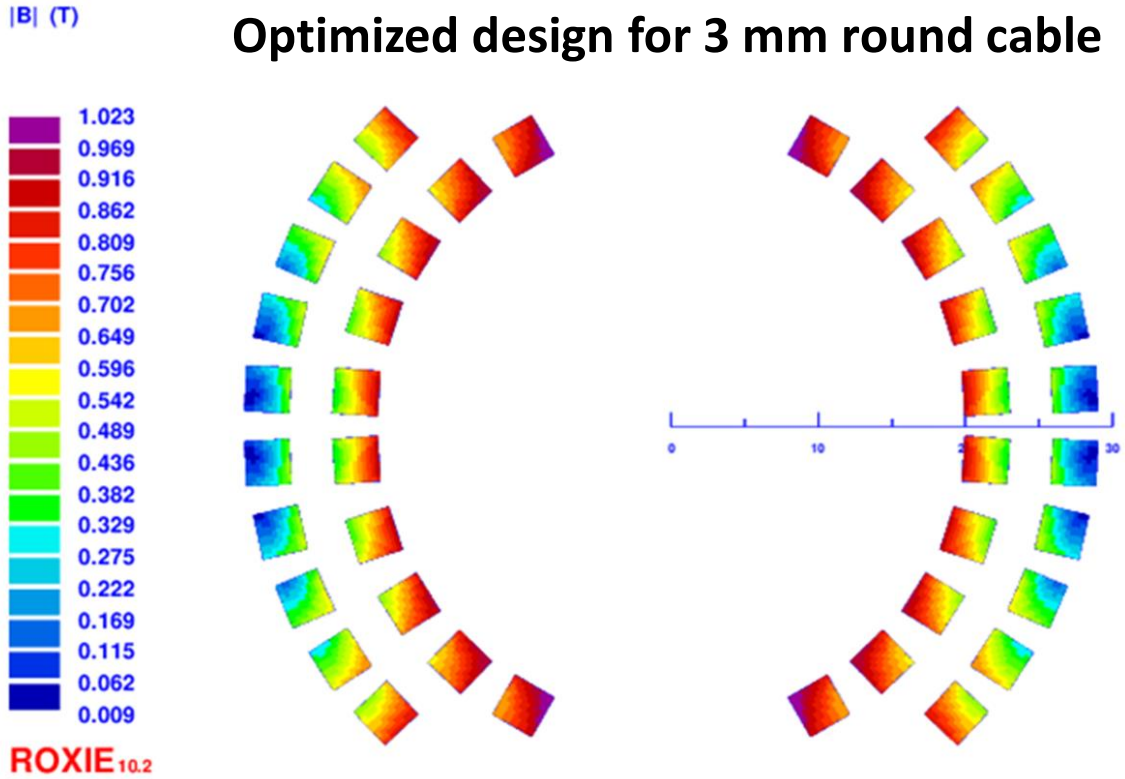
TO CHECK PERFORMANCE UNDER ALTERNATE LOADS

Design developed within the U.S. Magnet Development Program - Synergy

Optimized design for 5 mm round cable



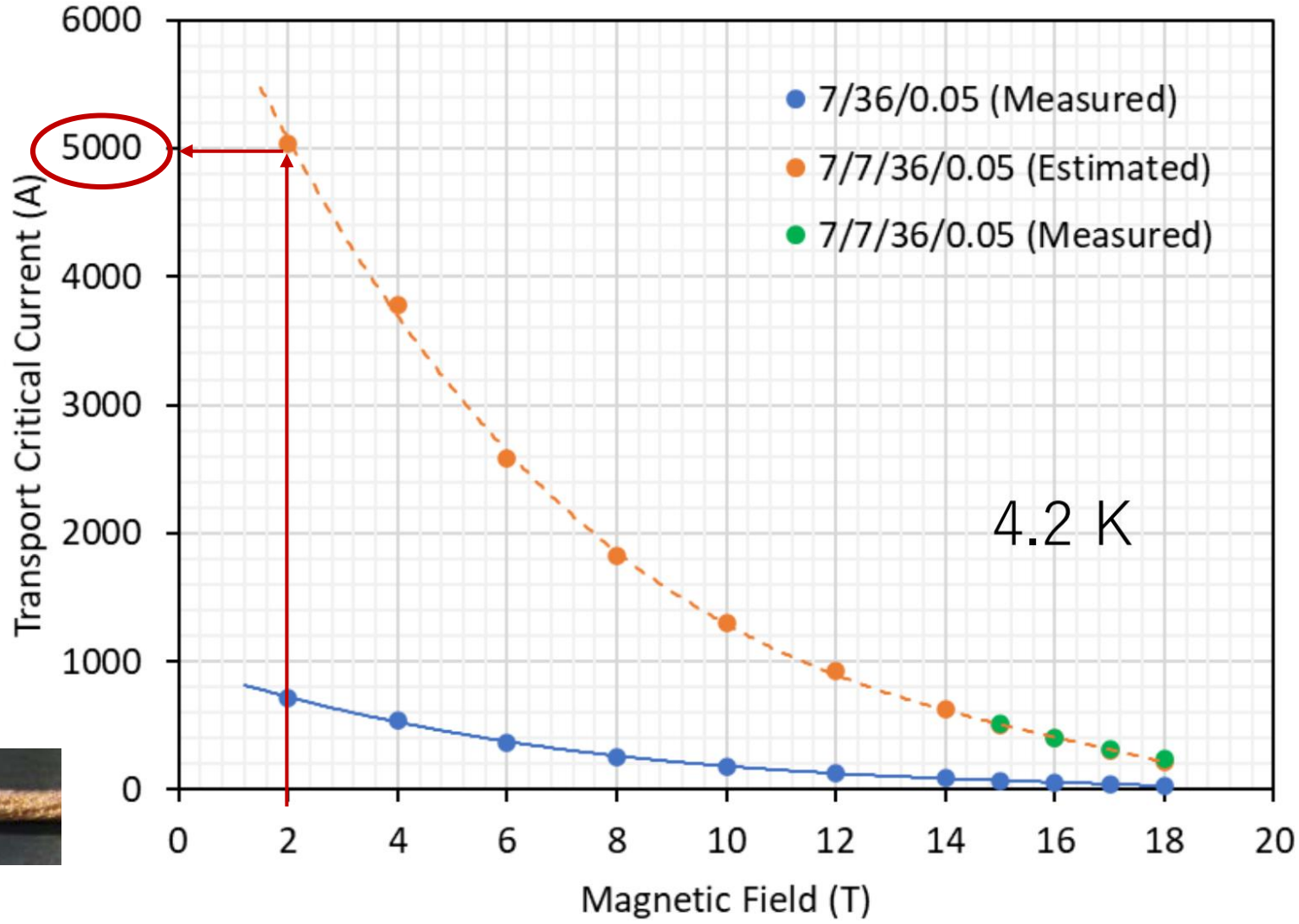
Optimized design for 3 mm round cable



A. Zlobin, I. Novitski et al.

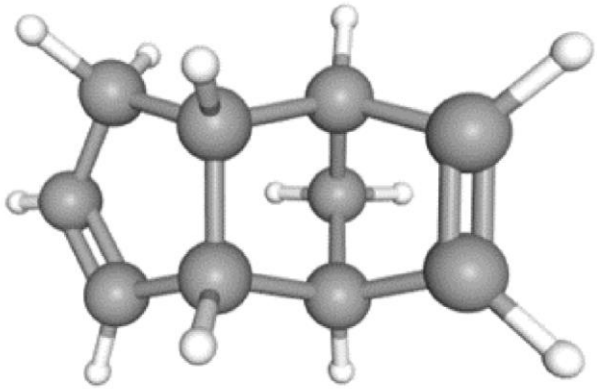
Test of Multi-Stage Conductor

- **Target specifications with a cable outer diameter of 3 mm are 3-4 kA for a magnetic field of 2T.**
- **Cable was tested in Japan and provides 5 kA at 2 T.**



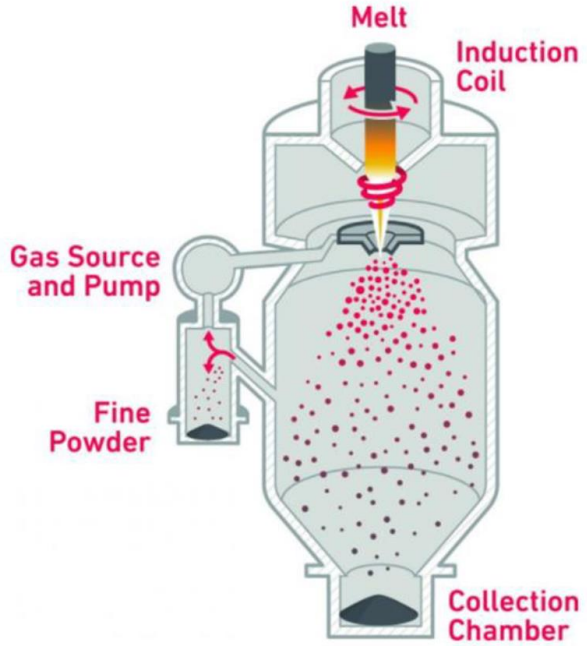
Goal 2

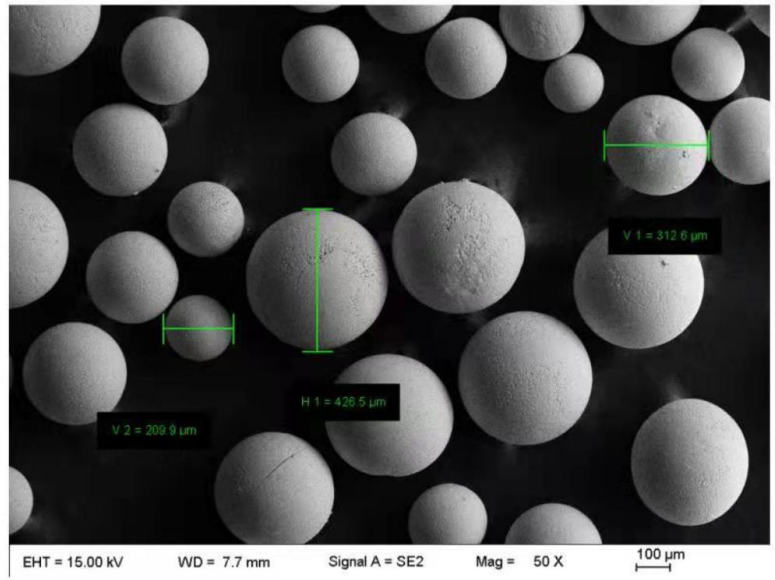
Radiation strength of insulating materials used in superconducting accelerator magnets is another critical parameter. The common limit of HL-LHC type magnets is 25 MGy of proton radiation for the current epoxy. There are indications in literature that DCP could do better ➔ Measure and study resins mechanical and chemical properties before and after irradiation.



Dicyclopentadiene ($C_{10}H_{12}$)

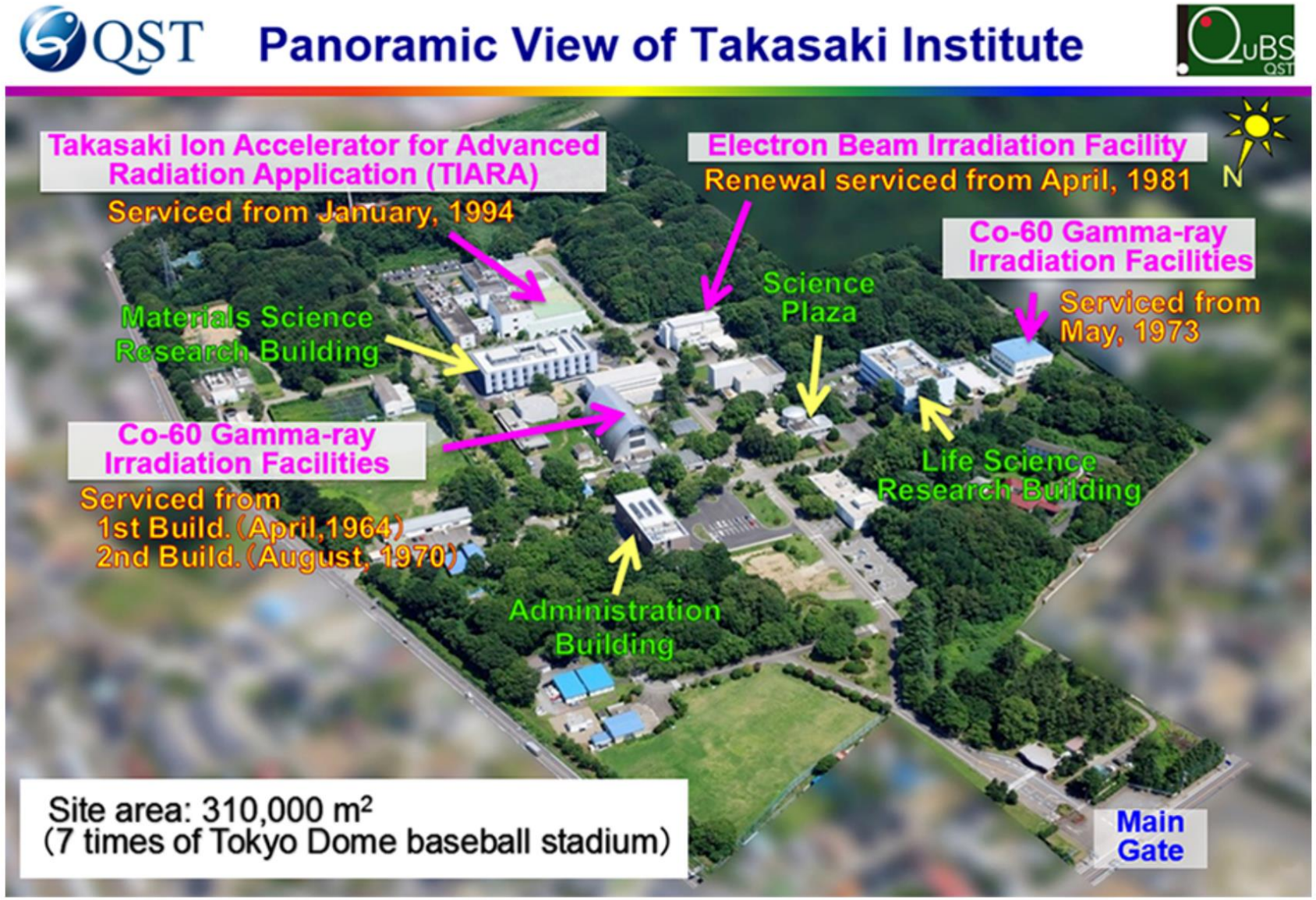
In addition to Gd_2O_3 and Gd_2O_2S, NIMS has been producing ceramic powders of radiation resistant $HoCu_2$ with a gas atomization process.





Gamma Ray Irradiation at the QST

Gamma Ray irradiation can be performed at the Takasaki Advanced Radiation Research Institute, which is part of the National Institutes for Quantum Science and Technology (QST) in Takasaki.

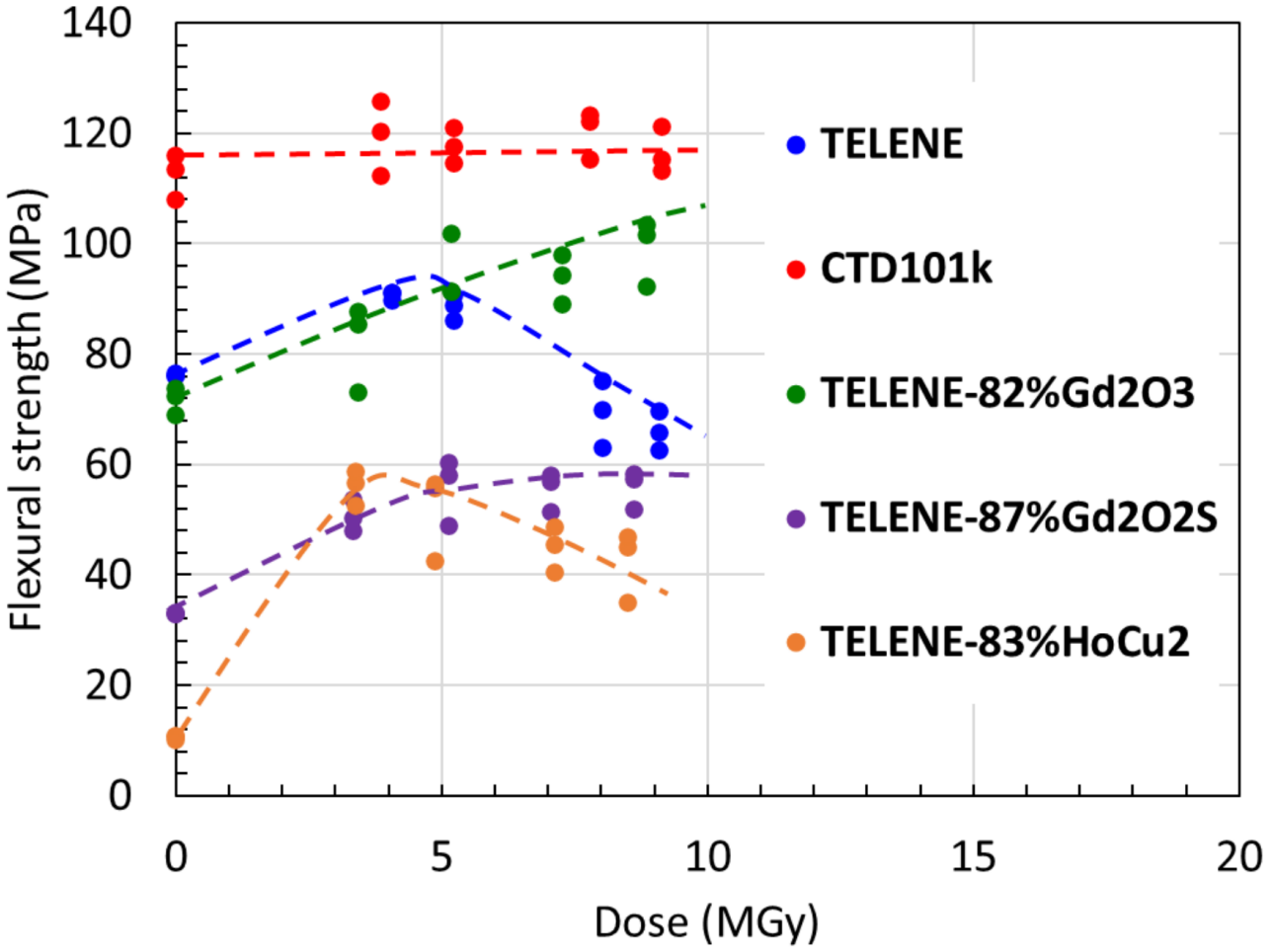


Cobalt-60 Gamma Ray Irradiation Experiment

1. TELENE
2. CTD-101
3. TELENE+82wt%Gd_2O_3
4. TELENE+87wt%Gd_2O_2S
5. TELENE+83wt%$HoCu_2$

- **For each resin shown, 6 samples are being irradiated at Takasaki at a dose rate of 8 kGy/hr. The goal is to achieve 10MGy +.**
- **For nonorganic materials, there is a dependence of material response on the type of beam irradiation. However, such a dependence is modest for organic materials, and the absorbed dose can be used to qualify their radiation resistance.**
- **At a later stage, this could be confirmed with proton beam irradiation experiments at the BLIP facility at BNL.**

Flexural Strength at Room Temperature



Increased to 5MGy and decreased

No changed

Monotonically increased

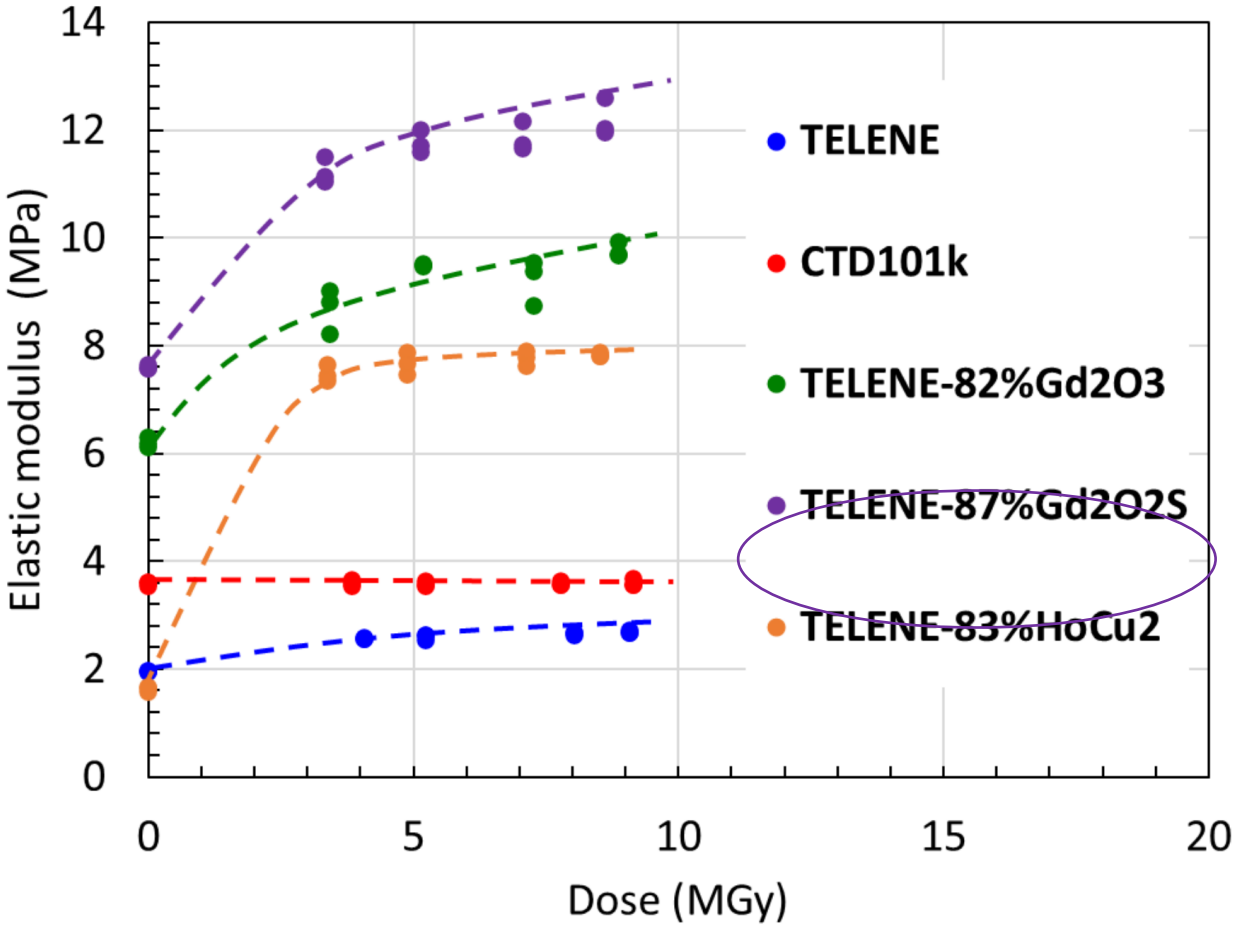
Increased to 5MGy and saturated

Large increased to 5MGy and decreased

Dr. Xudong and Dr. Nakamoto of KEK

Results presented at CEC/ICMC 2023, July 9-13, by Prof. A. Kikuchi

Elastic Modulus at Room Temperature



Gradually increased

No changed

Large increased

Large increased

Large increased to 5MGy and saturated

Dr. Xudong and Dr. Nakamoto of KEK

Results presented at CEC/ICMC 2023, July 9-13, by Prof. A. Kikuchi

Next Plans

- **Use at least 2 more ANL small undulator coils with mixed resins to measure the effect of the ceramic powders.**
- **By leveraging the U.S. Magnet Development Program, use either pure resin or mixed resin to impregnate LBL Canted Cosine Theta sub-scale magnets to check performance under larger Lorentz forces.**
- **By leveraging the U.S. Magnet Development Program and NIMS own research programs, use either pure resin or mixed resin to impregnate FNAL Cosine Theta coil made of superfine Nb_3Sn to check performance under alternate loads in a fast ramping magnet.**
- **Continue studying irradiation effects.**

BACK-UP

High heat capacity and radiation-resistant organic resins for impregnation of high field superconducting magnets

- A major focus of Nb_3Sn high field accelerator magnets for HEP is on significantly reducing or eliminating their training.
- ΔT is proportional to Q/C_p ➔ Use high-C_p impregnation.
- Mix organic olefin-based thermosetting dicyclopentadiene (DCP) resin, commercially available as TELENE® by RIMTEC Corporation in Japan, with high heat capacity ceramic powders such as such as Gd_2O_3, Gd_2O_2S.