U.S. MAGNET DEVELOPMENT PROGRAM

TELENE Applications and Plans

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U.S. MDP Collaboration Meeting CM8
05/02/2024

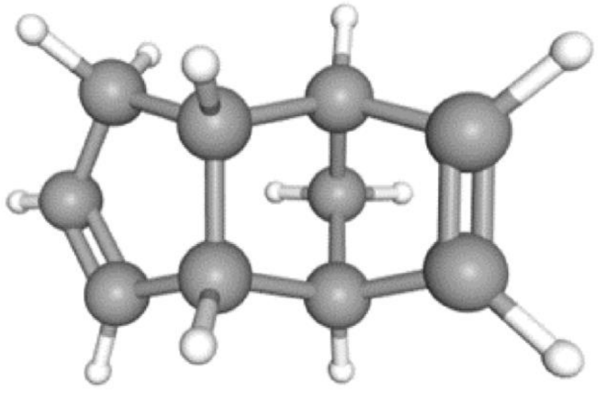
OUTLINE

- Results obtained within an U.S.-Japan Science and Technology Cooperation Program in HEP* for the first Nb_3Sn undulator impregnated with pure TELENE, and impact for accelerators.
- Original Goals and Current Results on the Material Science of TELENE
- Results for second Nb_3Sn undulator impregnated with TELENE-43wt%Gd_2O_2S and tested with advanced instrumentation.
- Next Steps

* DOE PROGRAM MANAGER IS BRIAN BECKFORD

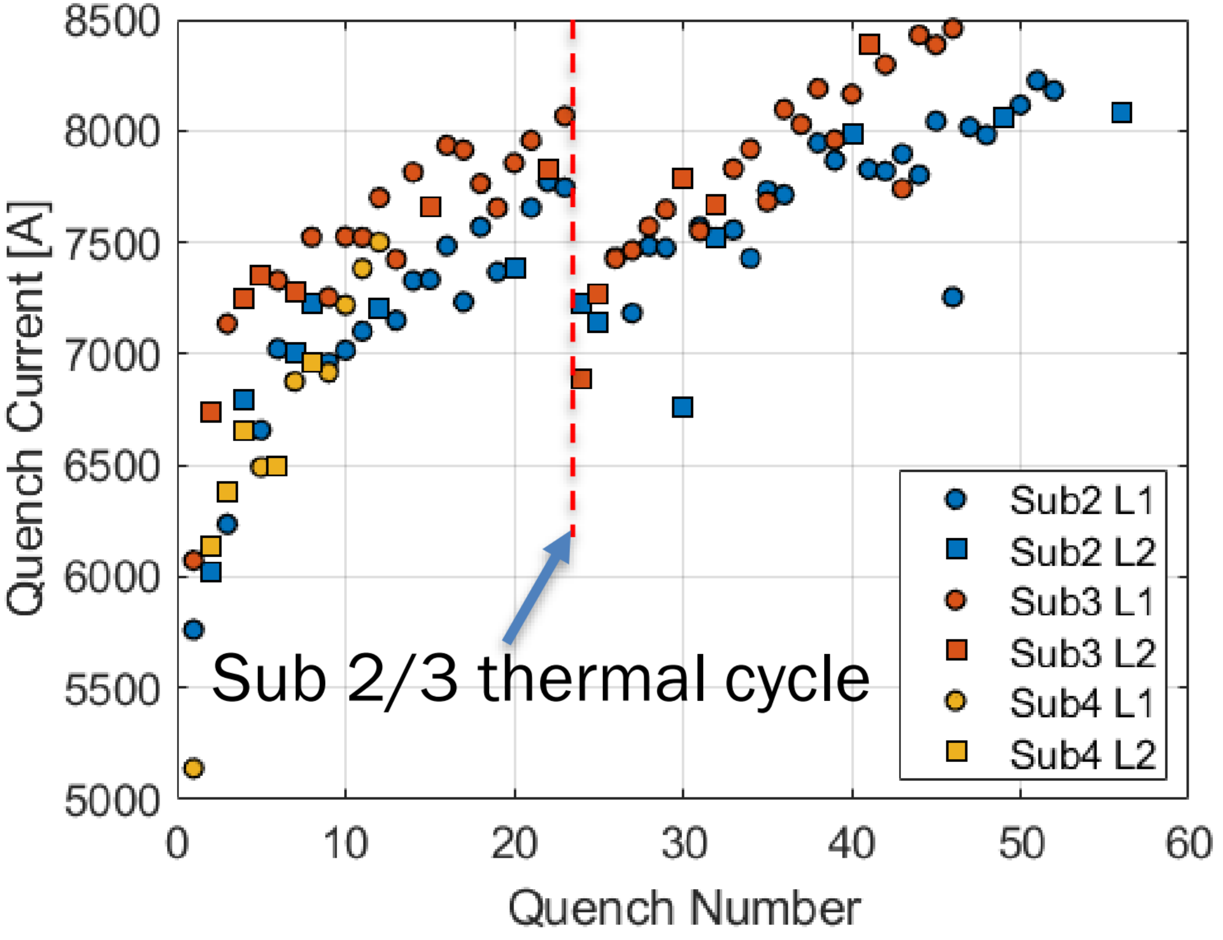
Goal 1

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 <u>organic</u> olefin-based thermosetting dicyclopentadiene (DCP) resin, commercially available as TELENE® at RIMTEC.



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

EXAMPLE OF MAGNET TRAINING

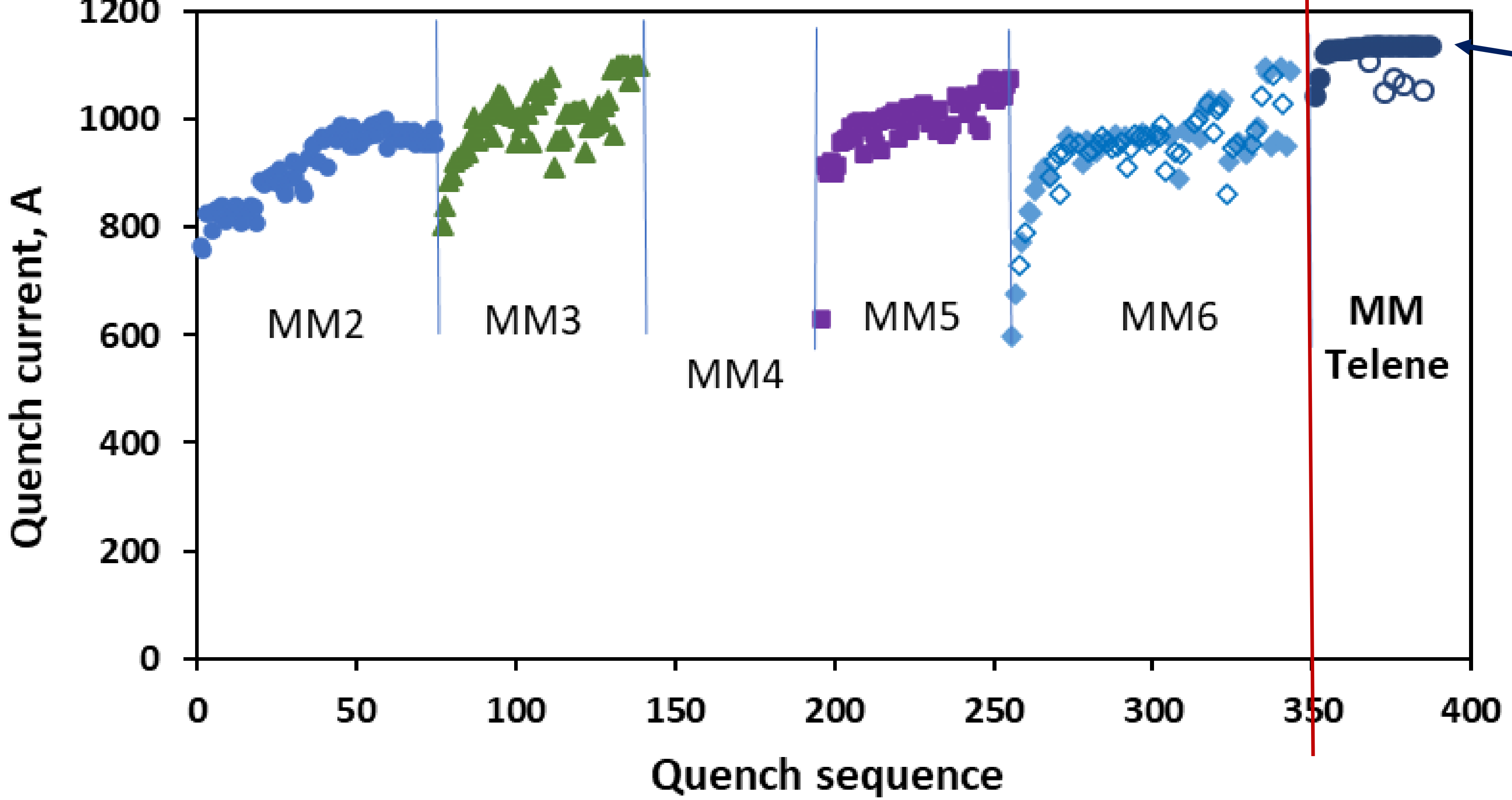


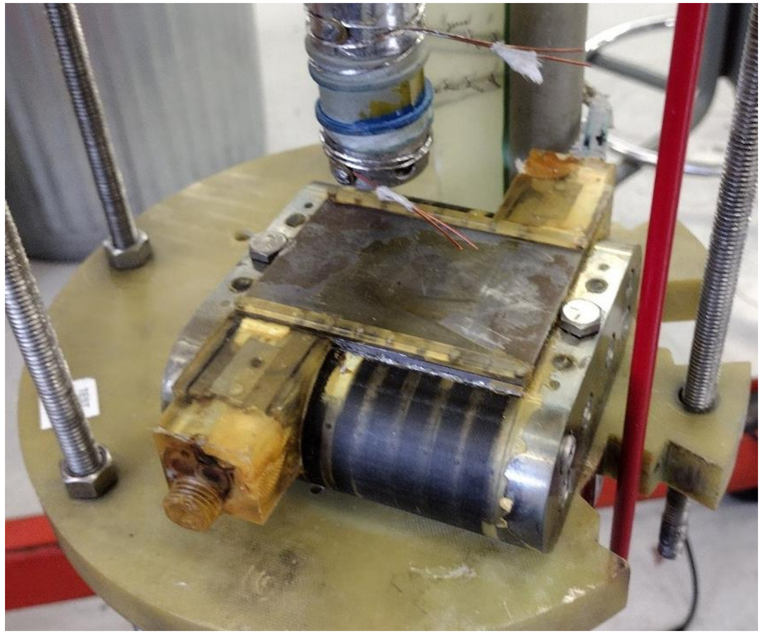
Canted Cosine Theta subscale magnet (D. Arbelaez)

Goal 1 Close to Achievement for Nb_3Sn Undulators

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

1,138 A vs. 1,143 A SSL

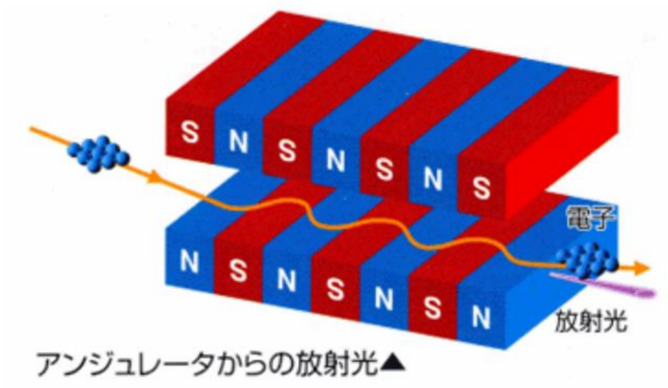


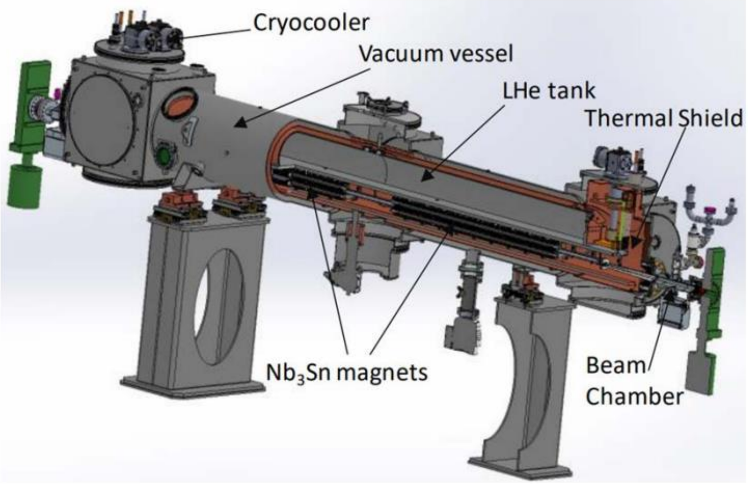


Ibrahim Kesgin – ANL Co-PI

Argonne NATIONAL LABORATORY

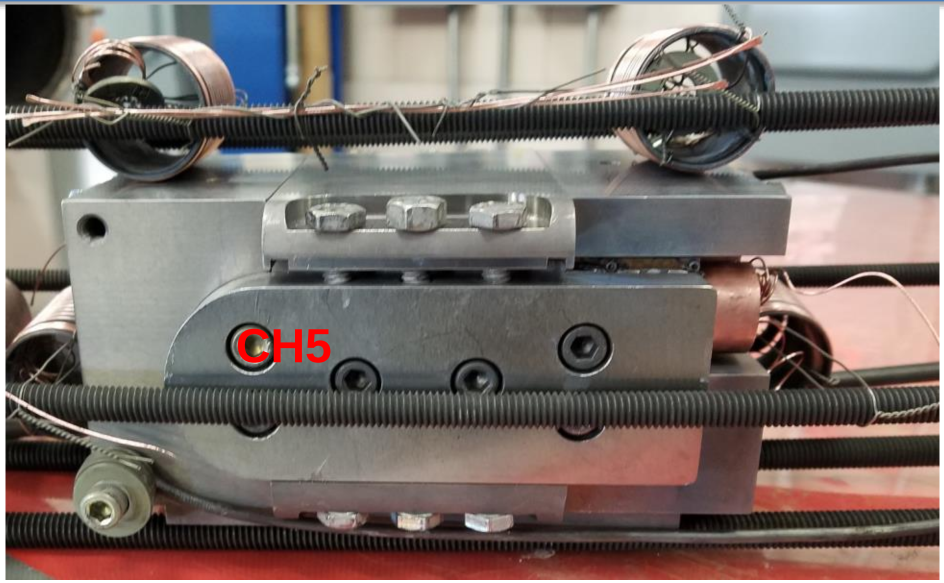
Nb_3Sn Undulator Magnets for Advanced Photon Source (APS)

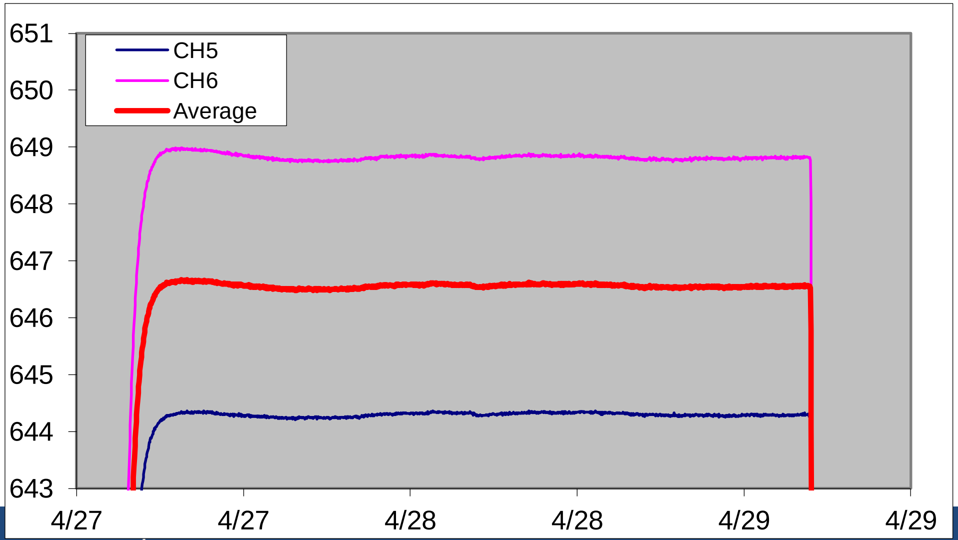




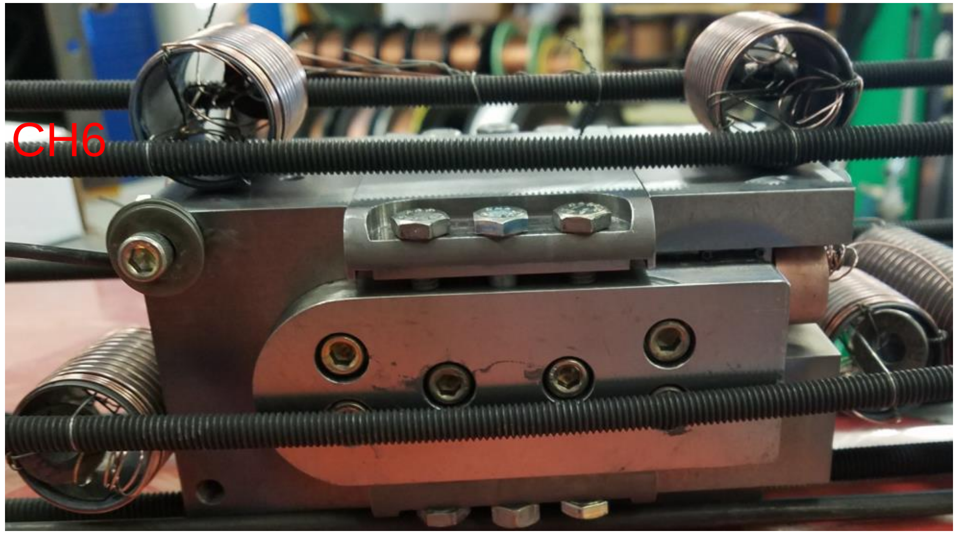
- **Each <u>Nb_3Sn undulator short model fabricated at ANL</u> has nine racetrack coils in ten poles with an S2-glass braided Nb_3Sn wire. There are 46 turns in each groove. The period length is 18 mm.**
- **After winding, the magnets were <u>heat treated at FNAL</u> in argon atmosphere using well-established treatment cycles.**
- **The first magnet was impregnated at ANL, the second at FNAL.**
- **Both were <u>tested at FNAL</u> in the Superconducting R&D lab, using a new DAQ hardware&software system for quench protection.**

Heat Treatment of 1st Small Undulator

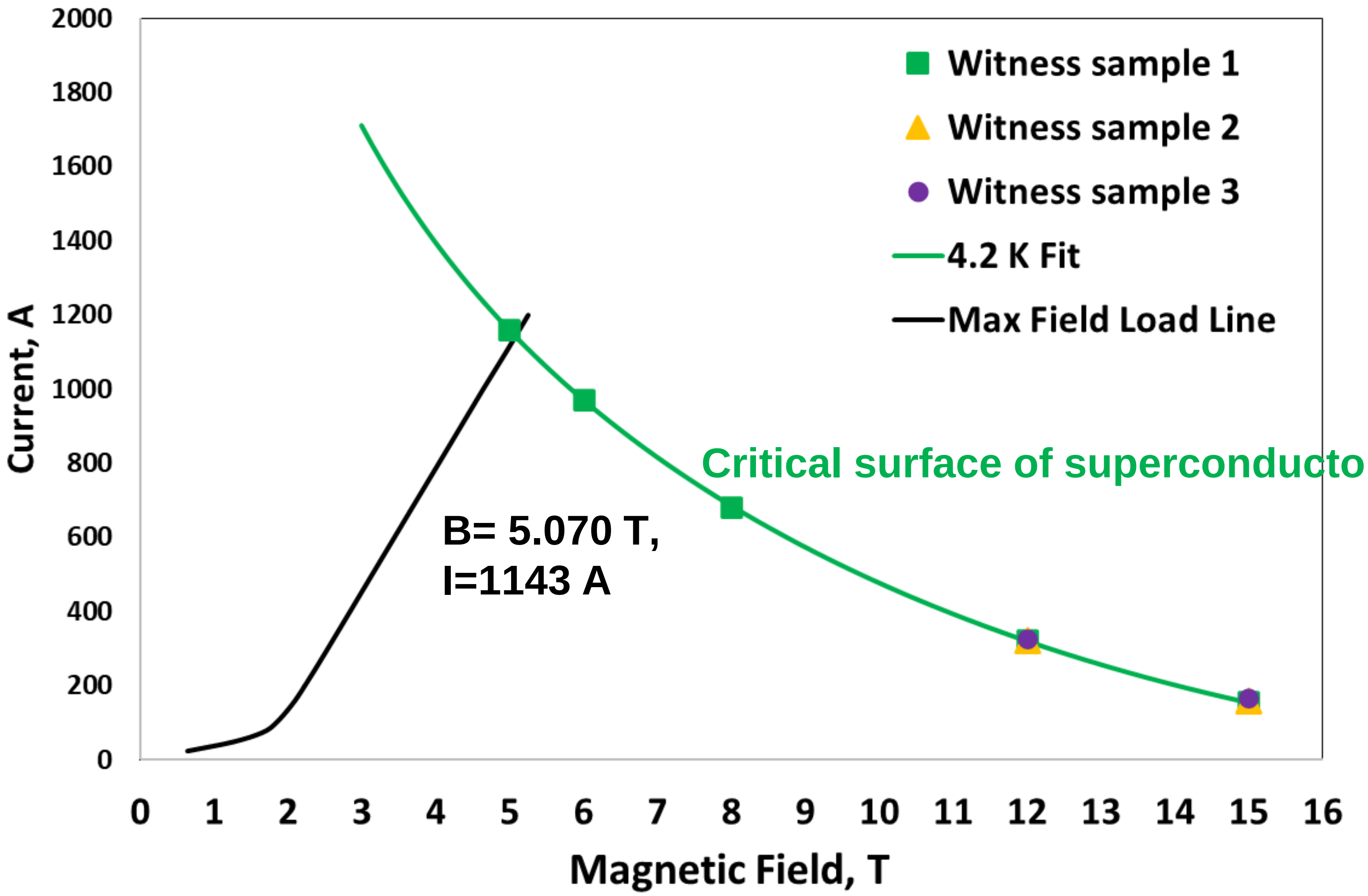




Nominal Desired on coil		Coil MM7	
Time, Hr	T, °C	Time, Hr	T Avg, °C
48	210	48	207
104	370	104	365
50	650	50	647



Short Sample Limits for 1st Small Undulator



Critical surface of superconductor used in magnet

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.

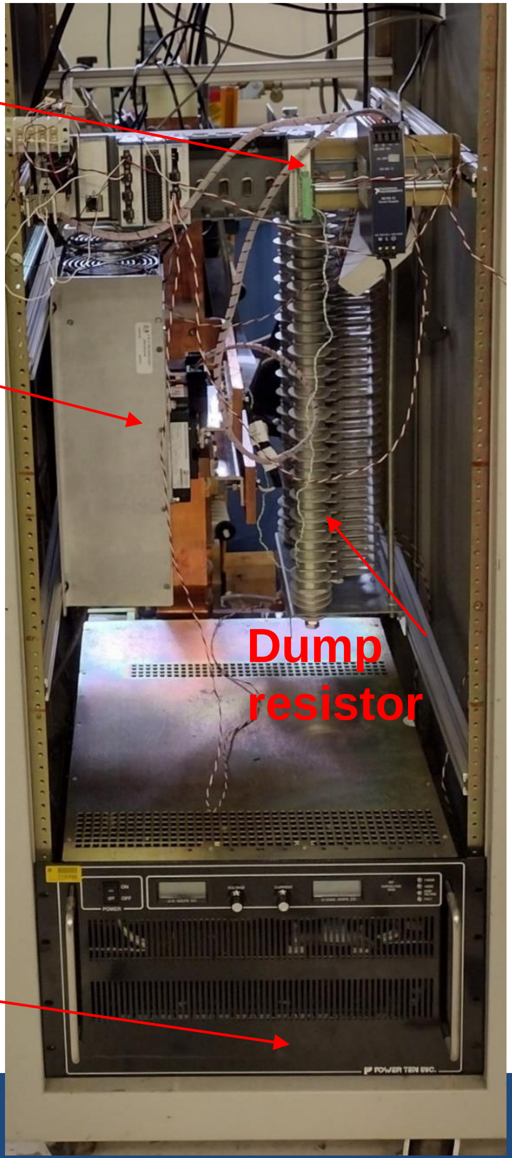
<u>Data acquisition and quench detection</u> are triggered when the bucked voltage signal is above threshold.

Dan Turrioni

NI cRIO-9073 DAQ

IGBT switch

2400 A, 0-8 V Power Supply

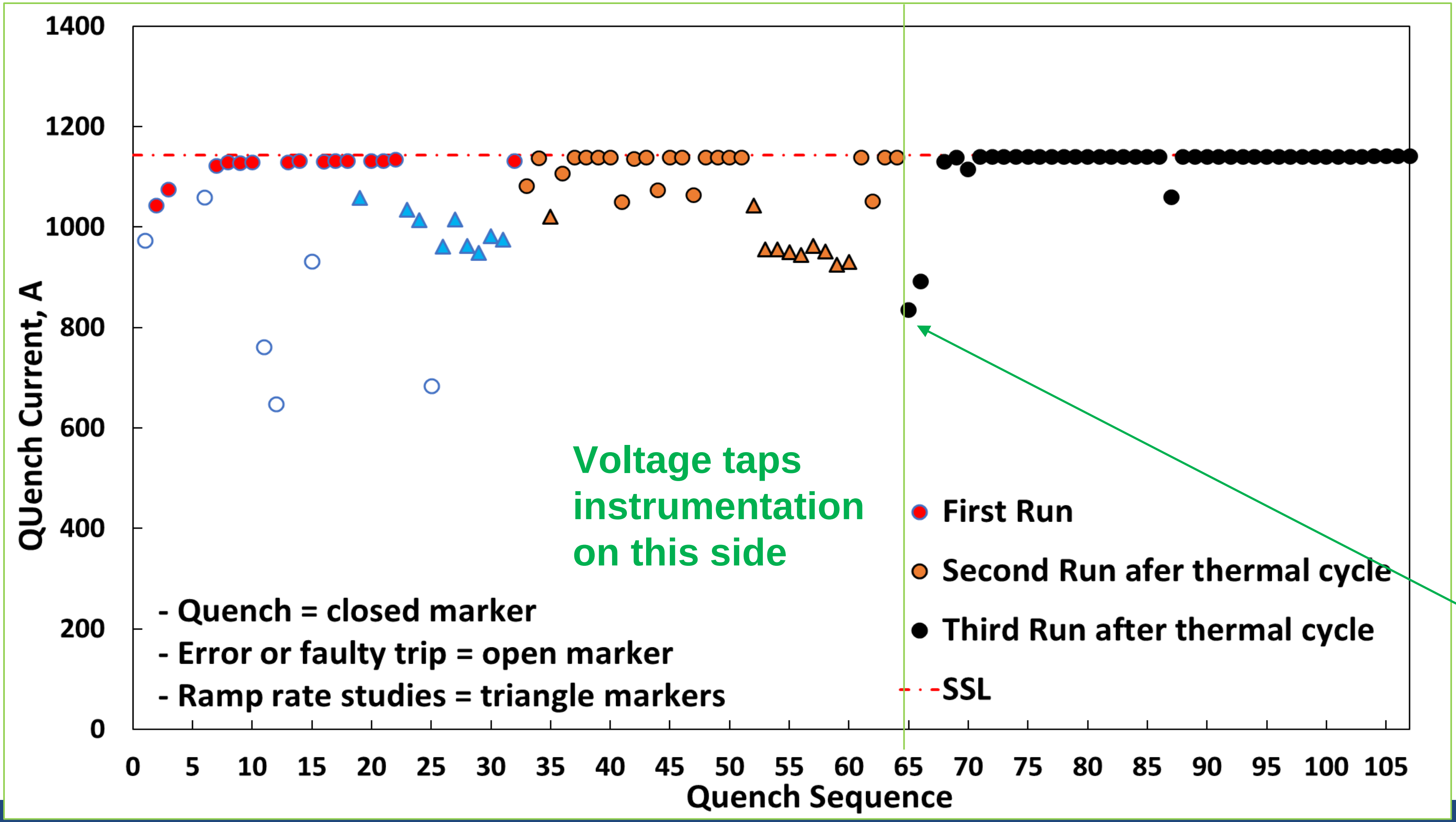


REAR

PROBE

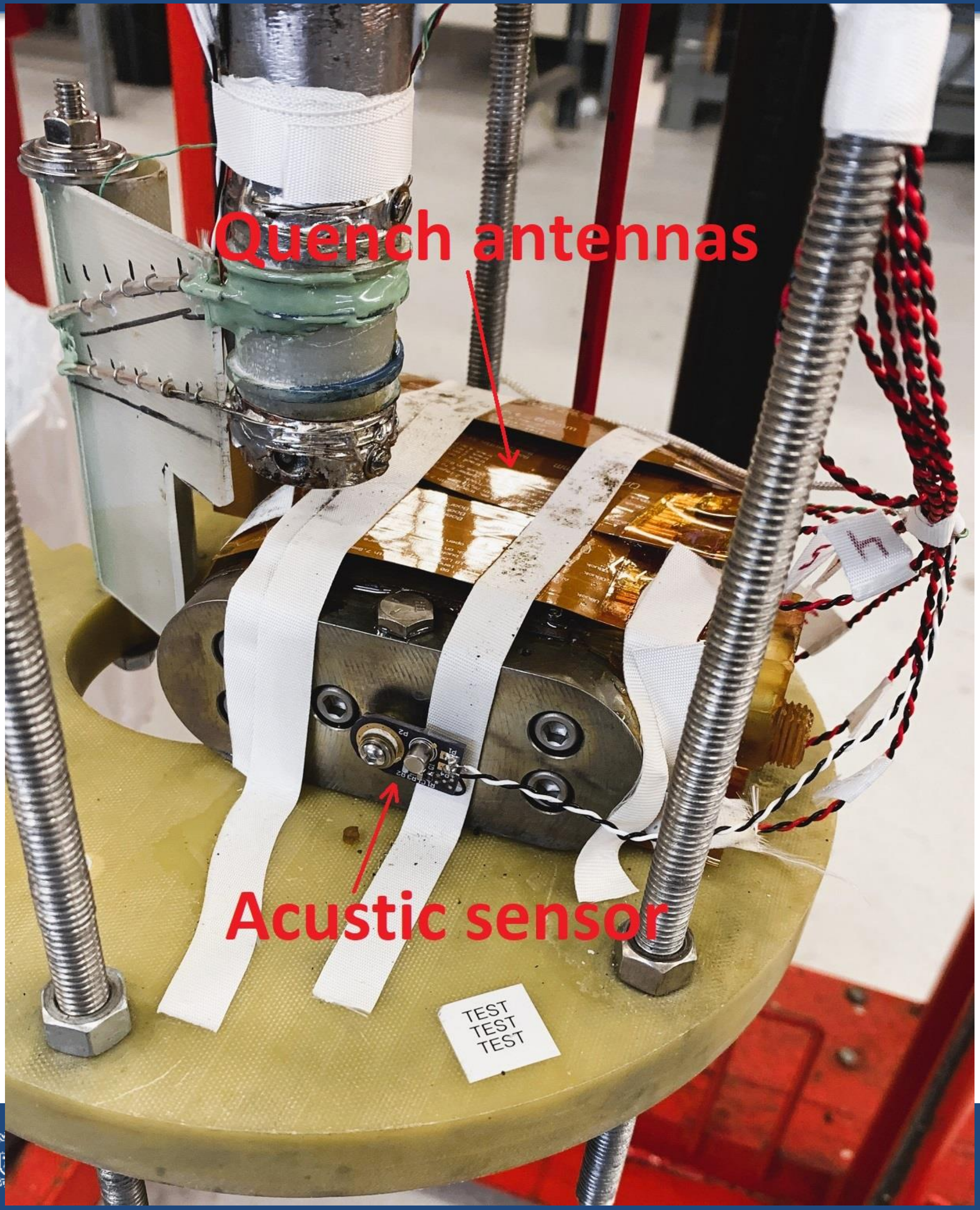
1st Nb_3Sn Undulator Test Results

Impregnated with pure TELENE



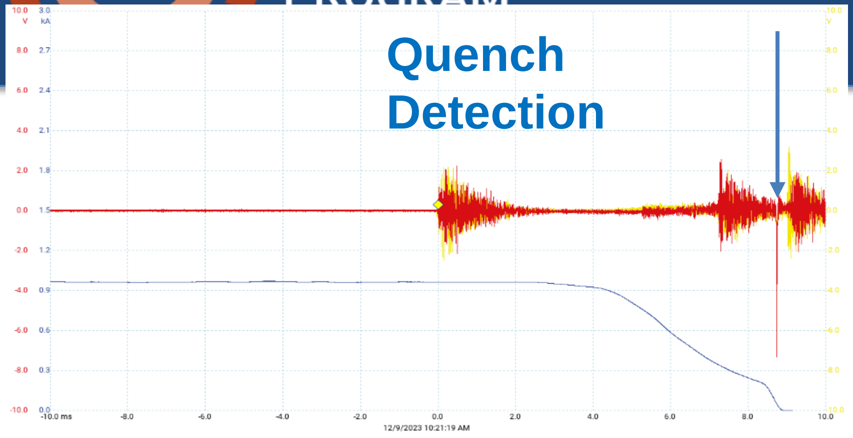
Advanced instrumentation was added for Third Run

Instrumentation Added

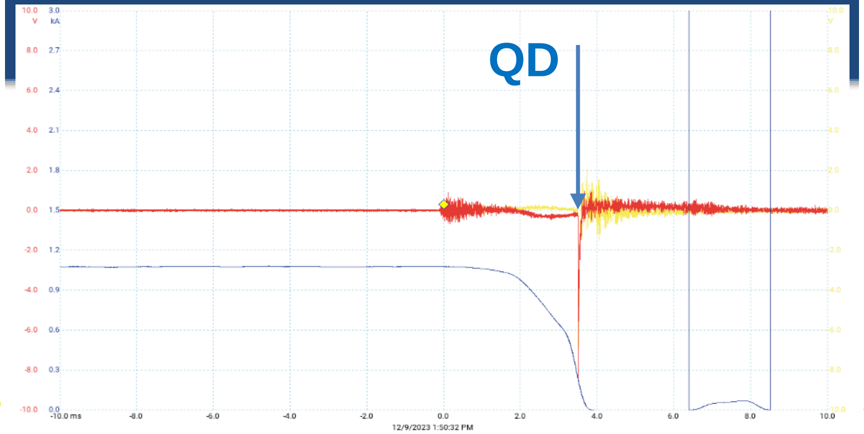


- 2 acoustic sensors (provided by S. Krave) were added, i.e. bolted on the magnet end plates, one on each side.
- 5 quench antennae (QA) wrapped the coil.
- The NI Compact Rio (25 Khz sampling rate, circular buffer of 1000 samples) was used to acquire voltage taps, QAs, and current. <u>Data acquisition and quench detection</u> are triggered when the bucked voltage signal is above threshold.
- A 20 MHz, 8-channel picoscope was used for the acoustic signals. Their data acquisition is triggered when the voltage of one of the signals is above 0.3 V.
- For synchronization of the two DAQ systems, the current channel was a shared channel.

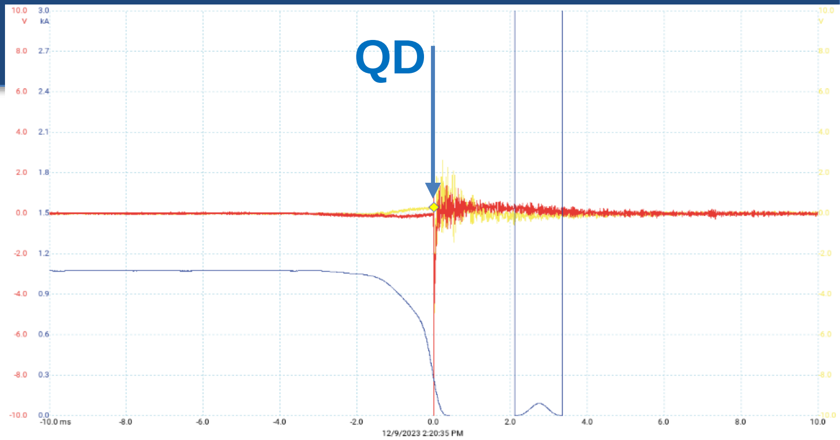
Identified Acoustic Patterns



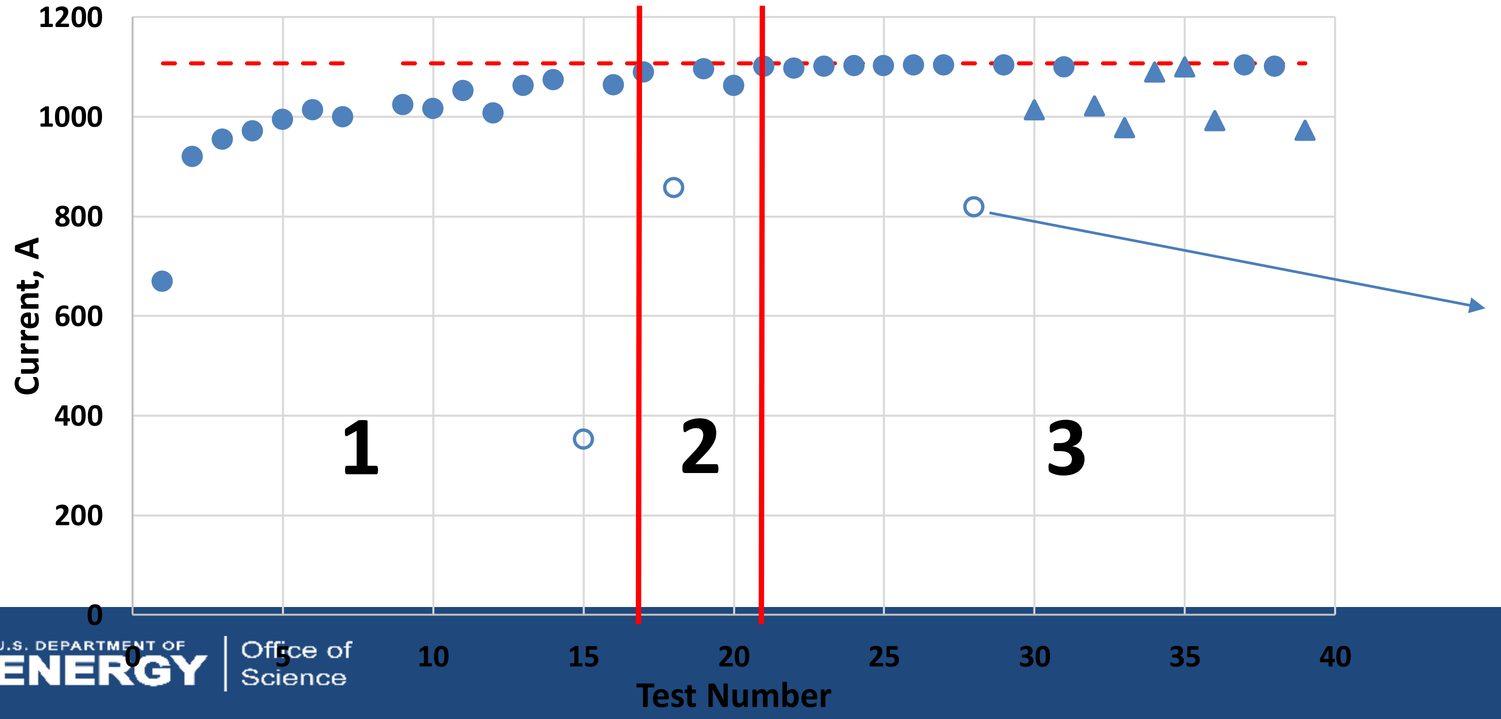
Zone 1

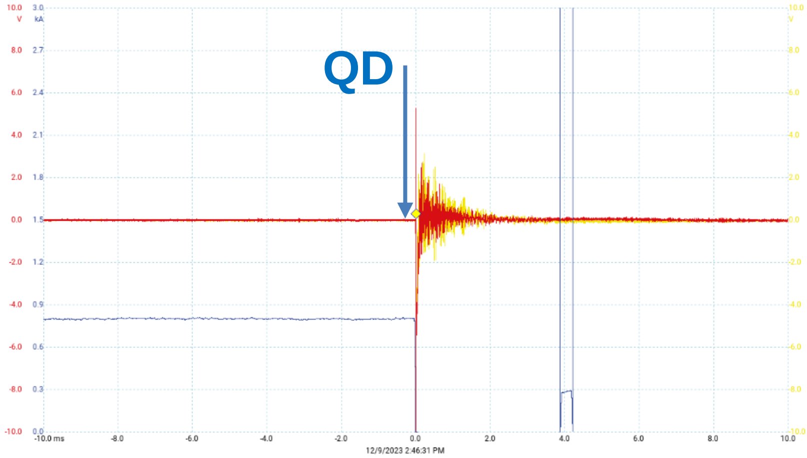


Zone 2



Zone 3





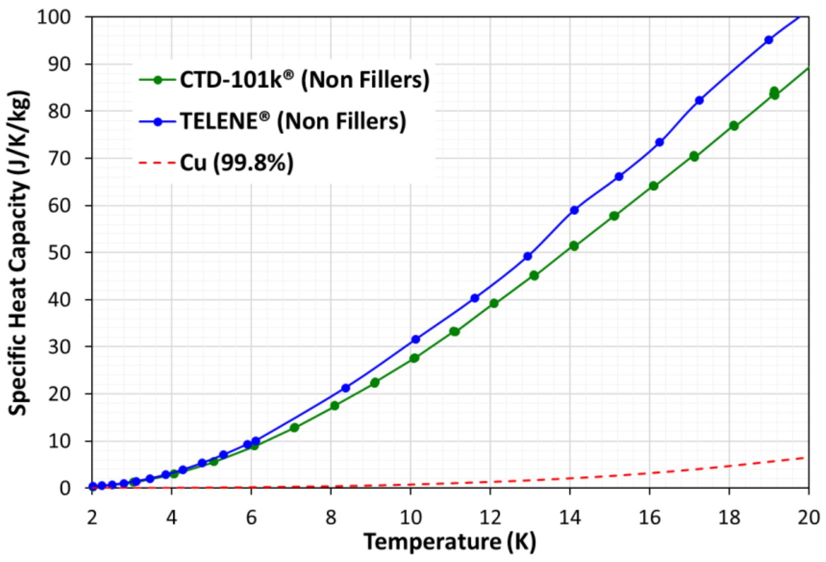
False trip

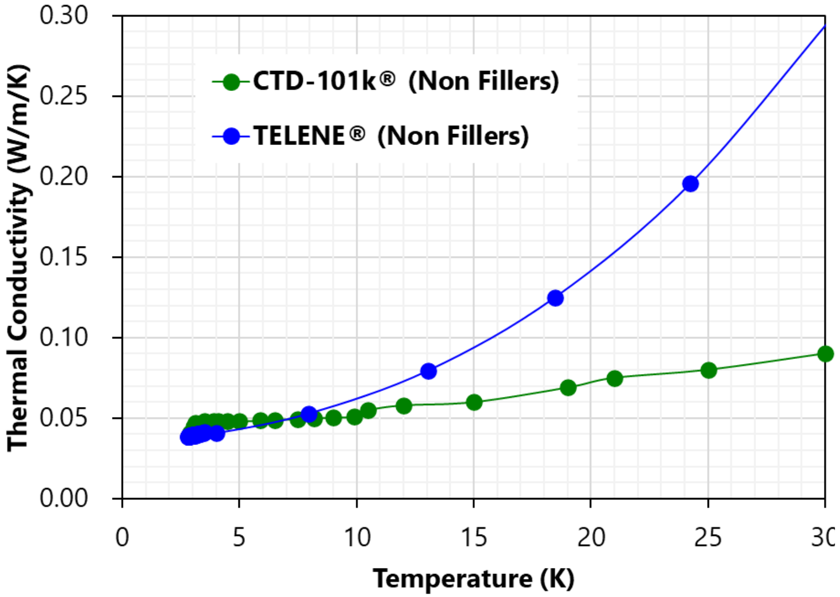
To Date Impact on Accelerators

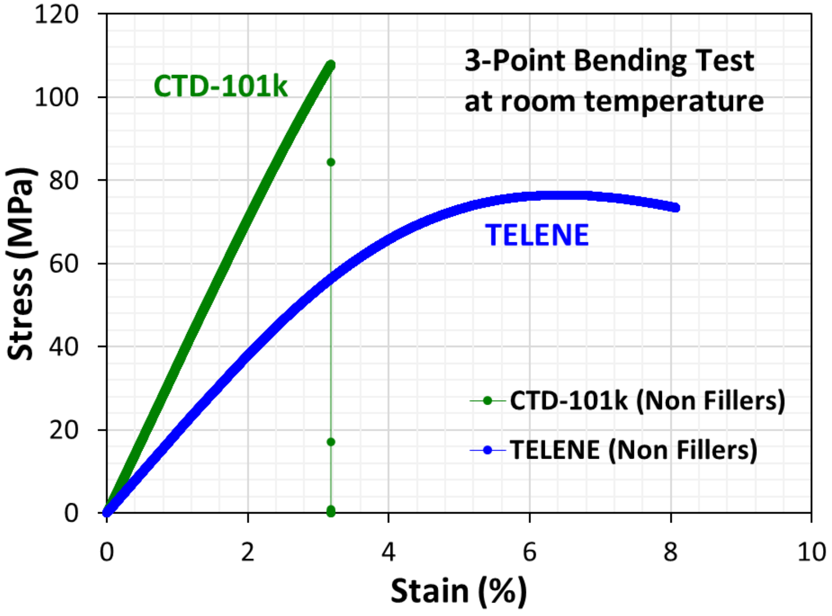
- ANL magnets showed performance reproducibility ~100% of the short sample limit, and a design field increase of 20% at 820A. However, **the long training did not allow obtaining the expected 50% increase of the on-axis magnetic field** with respect to the 1.1 T produced at 450 A current in the ANL NbTi undulator. With TELENE®, training and magnet retraining after a thermal cycle were nearly eliminated, with only a couple of quenches needed before reaching short sample limit at over 1,100 A.

TELENE will enable operation of Nb_3Sn undulators much closer to their short sample limit, expanding the energy range and brightness intensity of light sources.

Why TELENE?





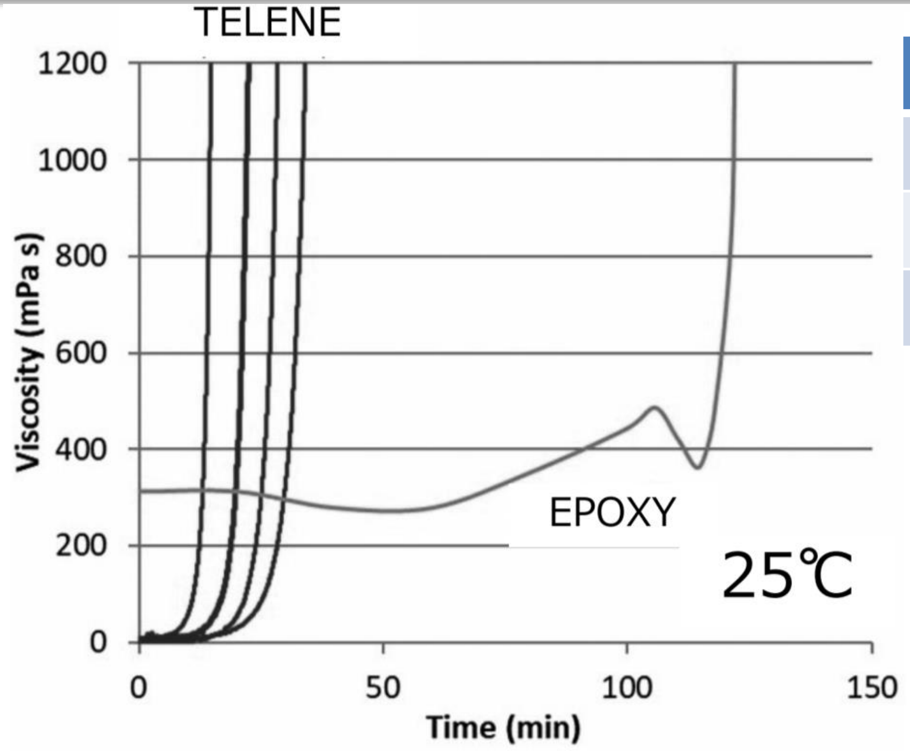


Specific heat C_p is only somewhat larger than for epoxy

Thermal conductivity is larger than for epoxy

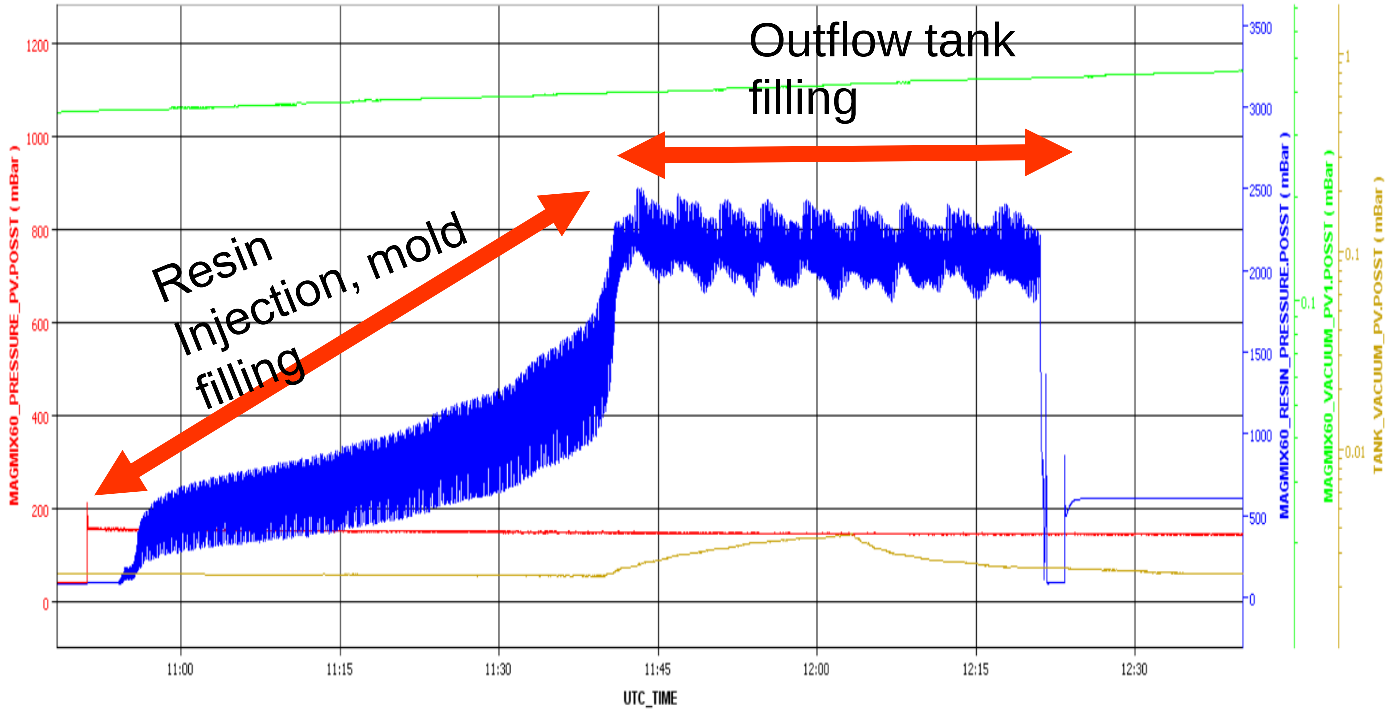
It accepts much larger strains than epoxy, <u>also at cryogenic temperature</u>

Scalability Solved



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

Time limit for impregnation process with TELENE

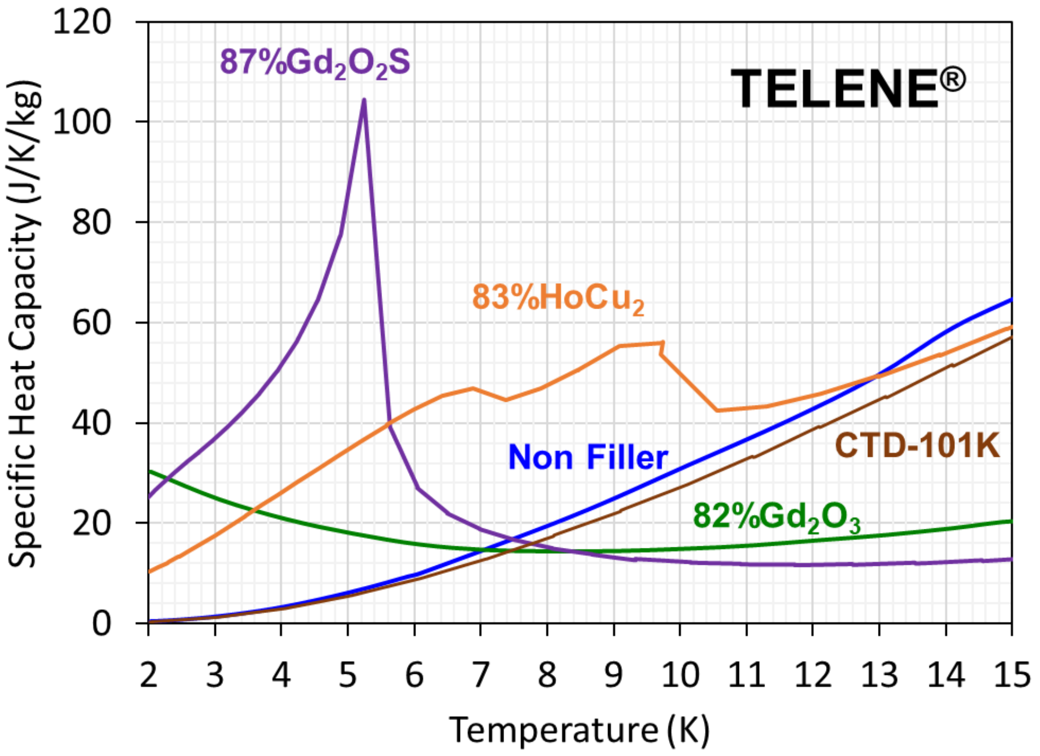


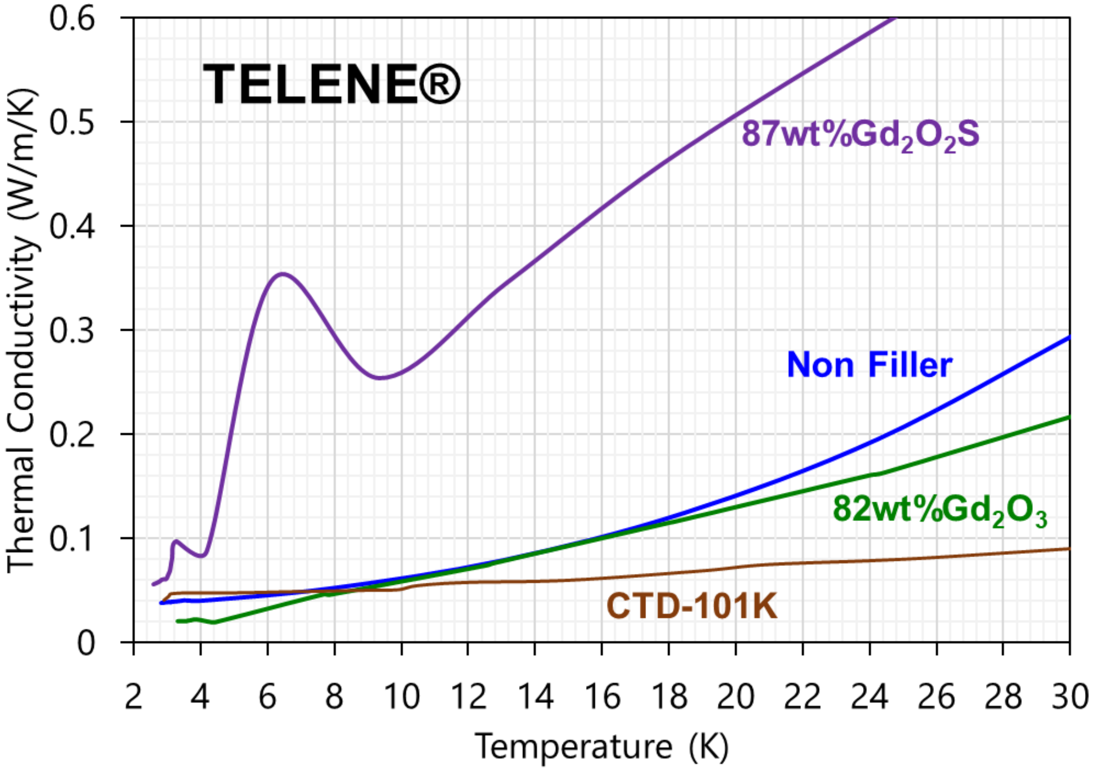
By using one epoxy inlet into the tooling with multiple vents and an inlet pressure of 2 Bar, fill times vary from 45 min to 1.5 hrs for CERN accelerator quadrupoles 7.3 m long.

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.**





Measurements of Minimum Quench Energy of Impregnated Wire Samples

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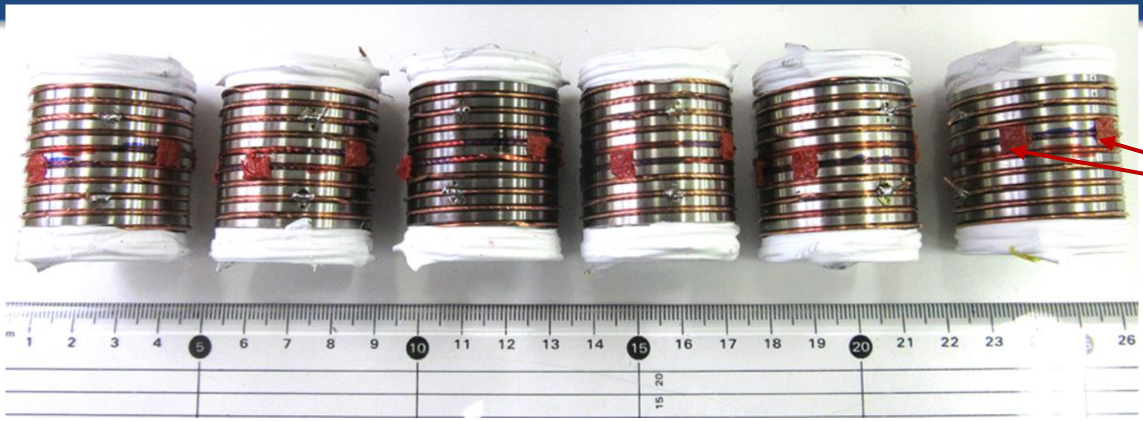
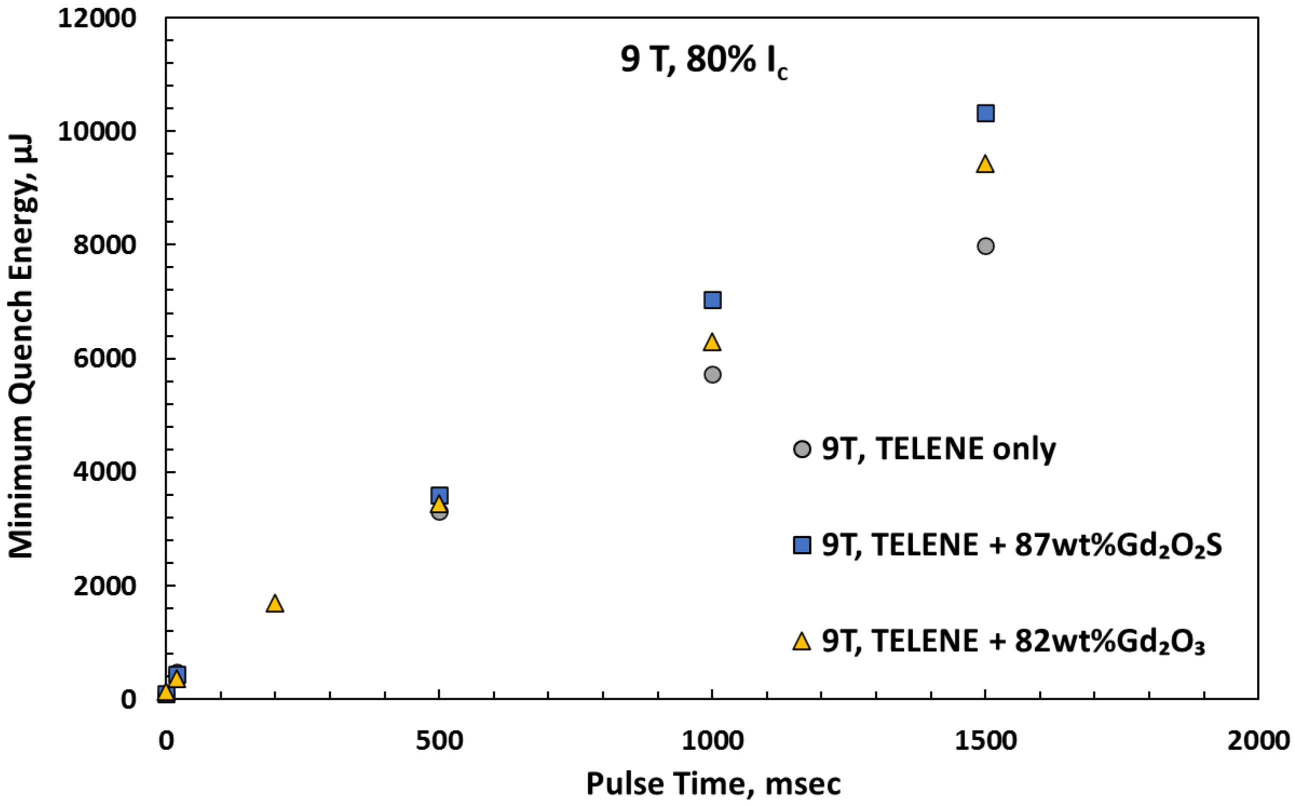


- **A dozen 0.8 mm NbTi wire samples were prepared at FNAL and sent to NIMS for impregnation with MIXED resins.**

- **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.**



Goal 2

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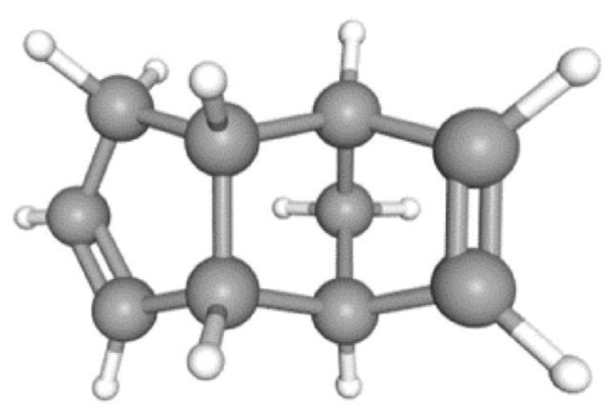
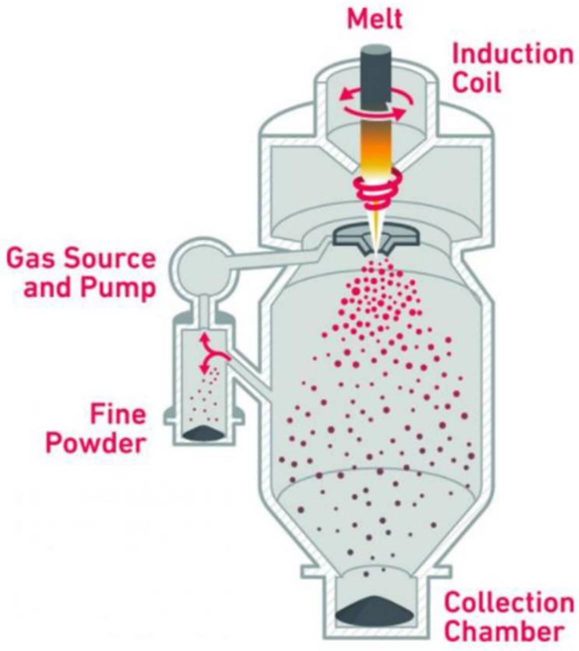
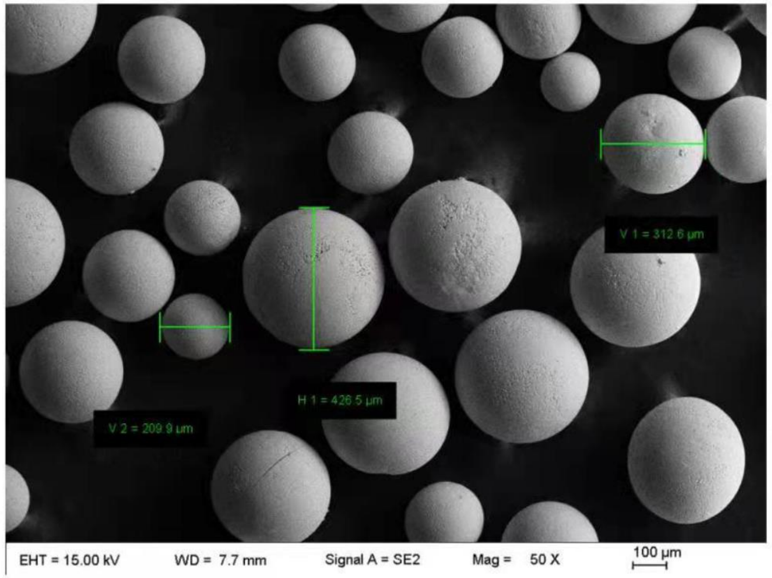
Radiation strength of insulating materials used in superconducting accelerator magnets is another critical parameter. The common limit of HL-LHC type magnets is 25 MGy of proton radiation for the current epoxy. There are indications in literature that DCP could do better ➔ Measure and study resins mechanical 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 allegedly radiation resistant $HoCu_2$ by a melt and casting process.





Gamma Ray Irradiation at the QST

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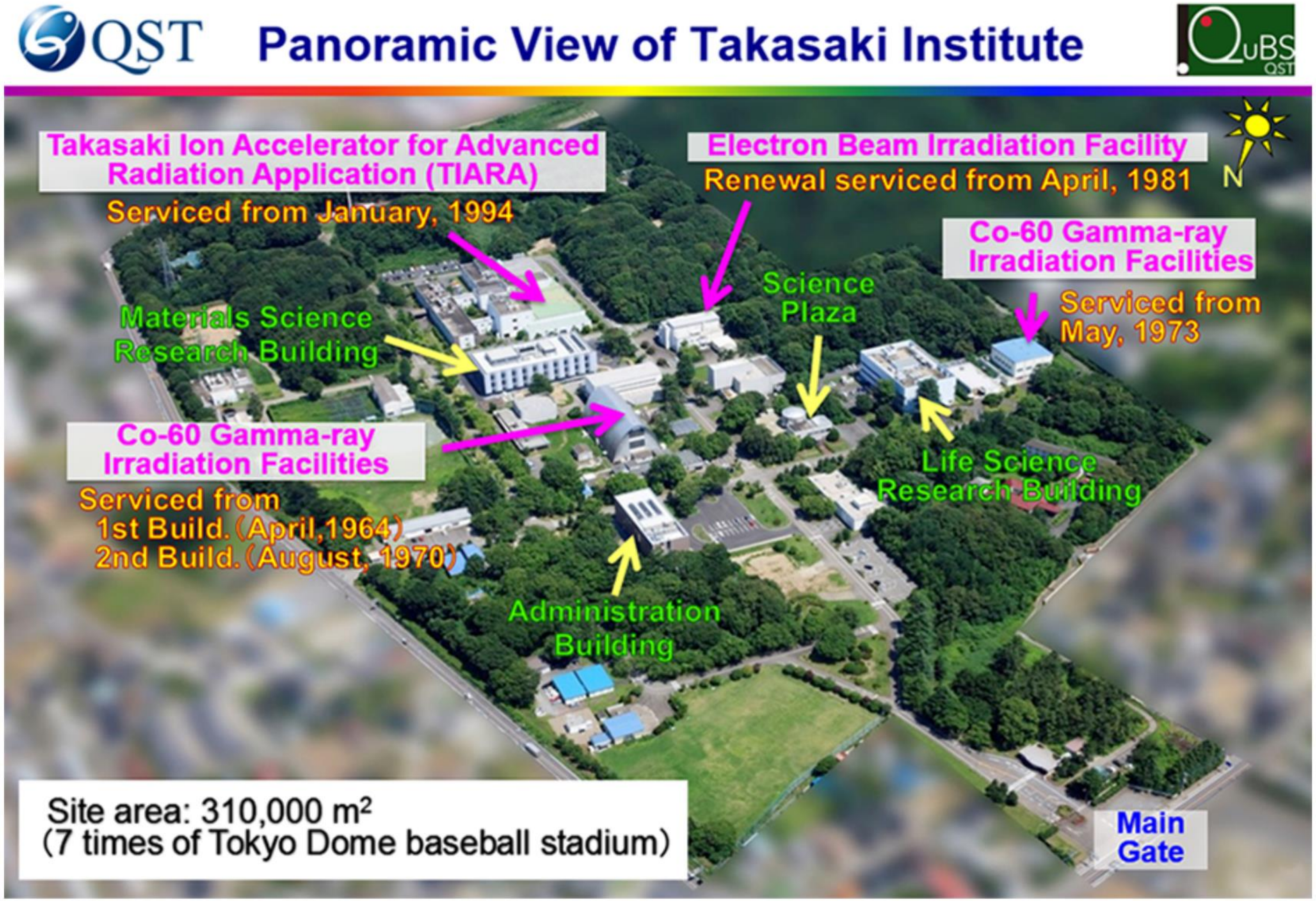
Gamma Ray irradiation can be performed at the Takasaki Advanced Radiation Research Institute, which is part of the National Institutes for Quantum Science and Technology (QST) in Takasaki.



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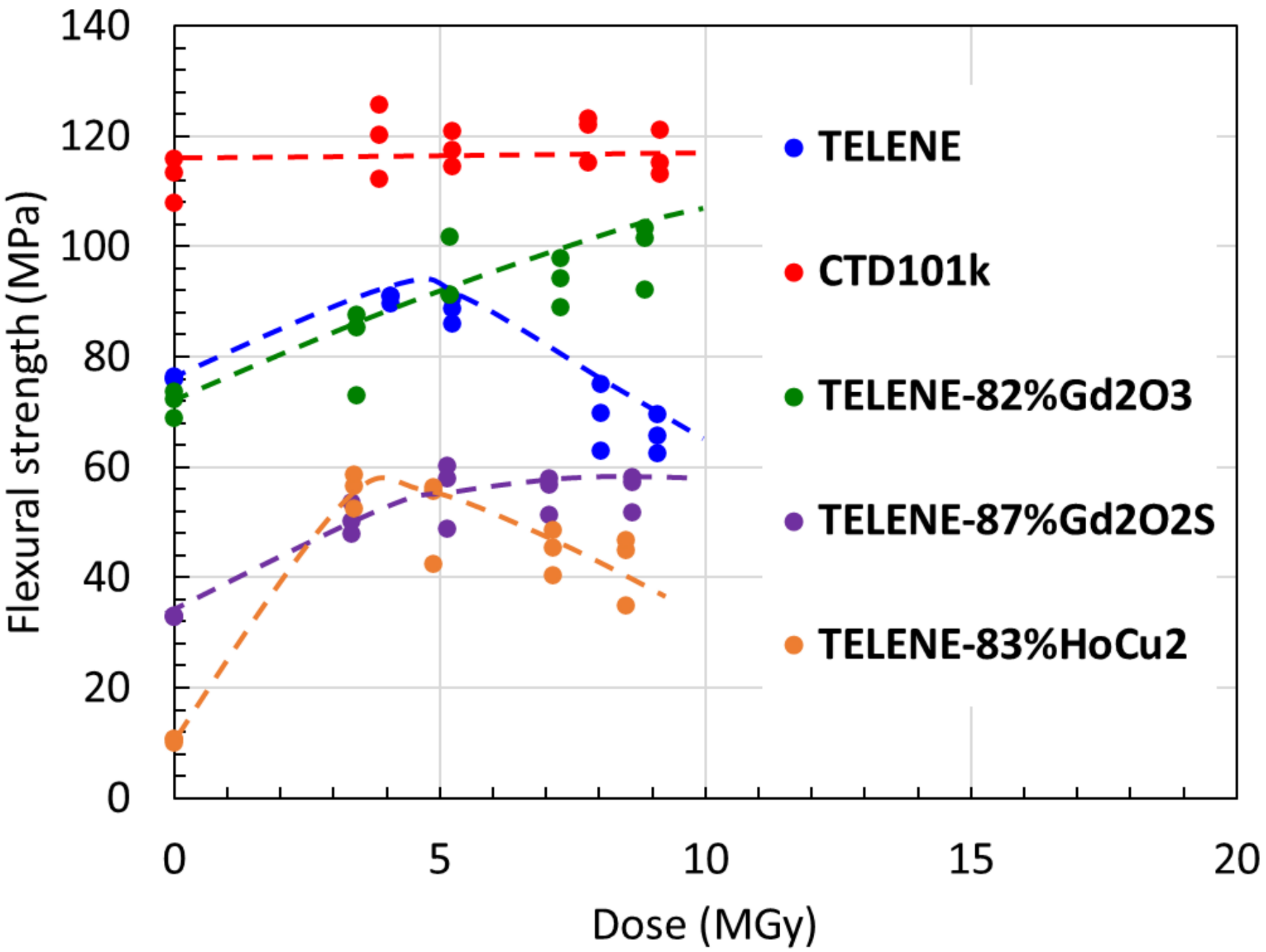
Cobalt-60 Gamma Ray Irradiation

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, 40 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

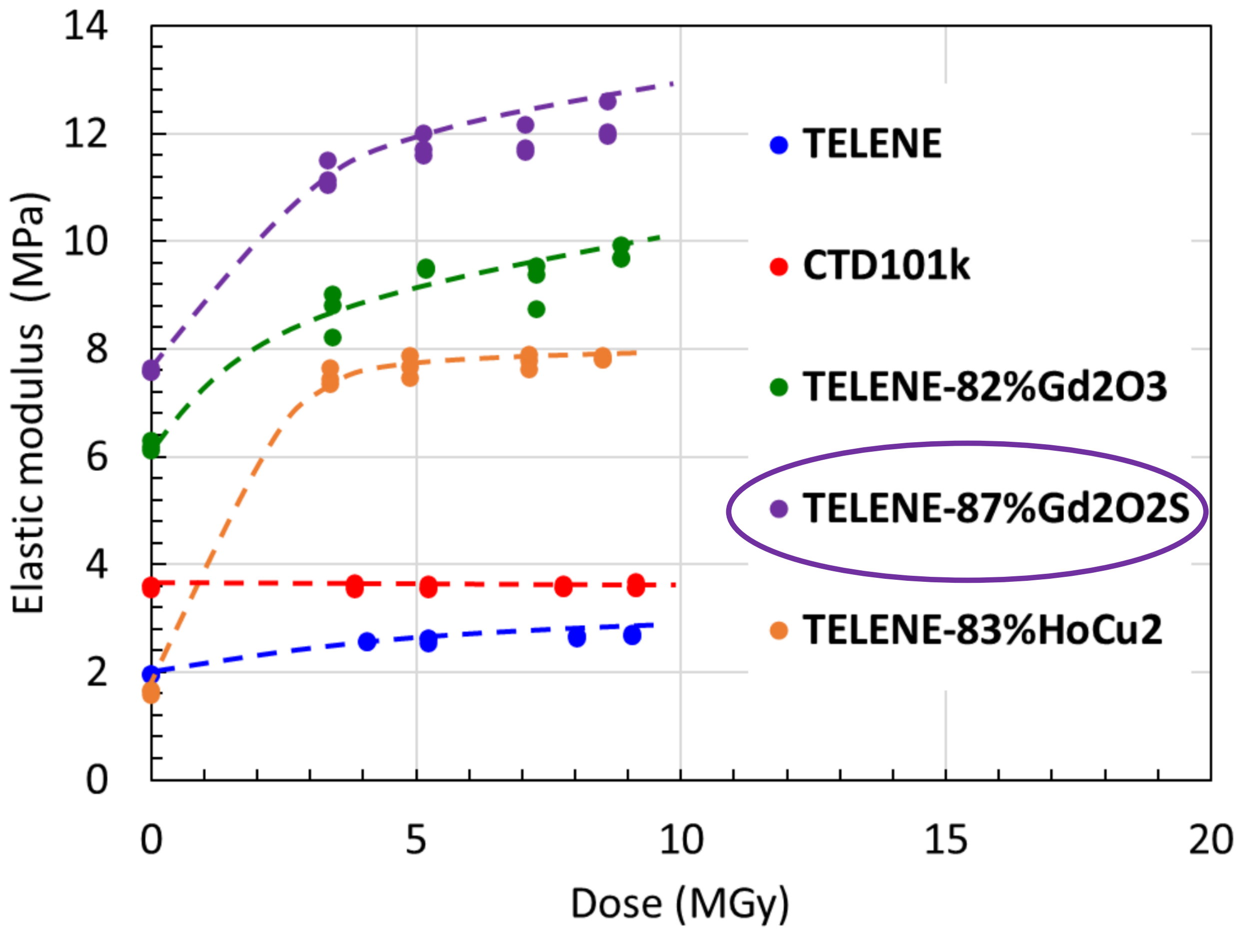
Increased to 5MGy and saturated

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

Flexural Modulus at Room Temperature



Gradually increased

No changed

Large increased

Large increased

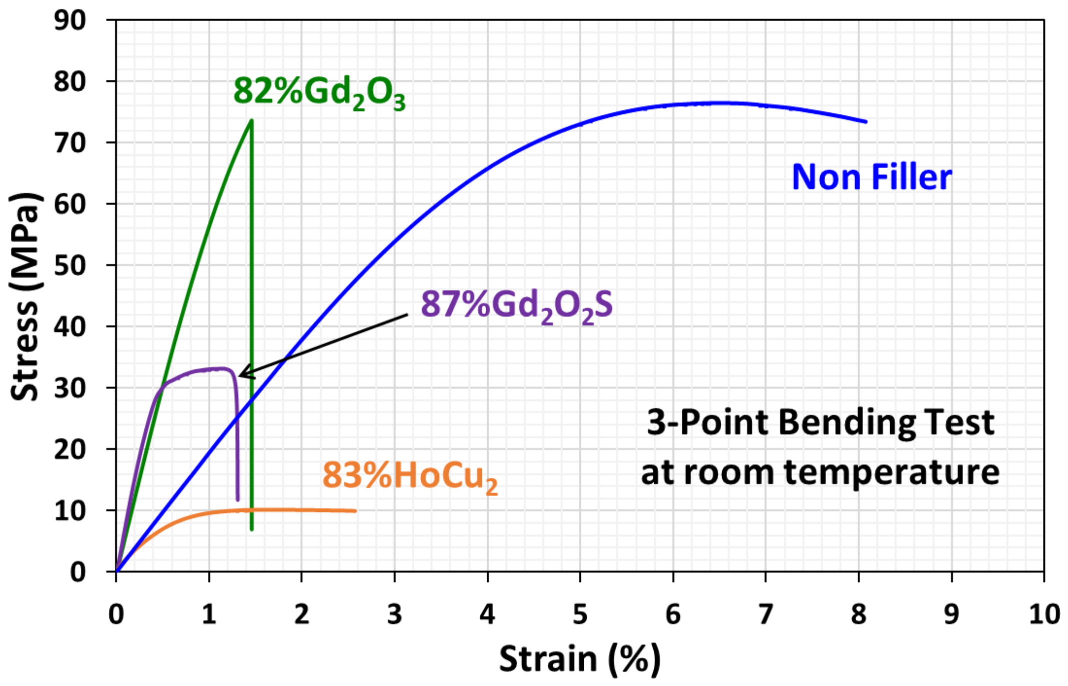
Large increased to 5MGy and saturated

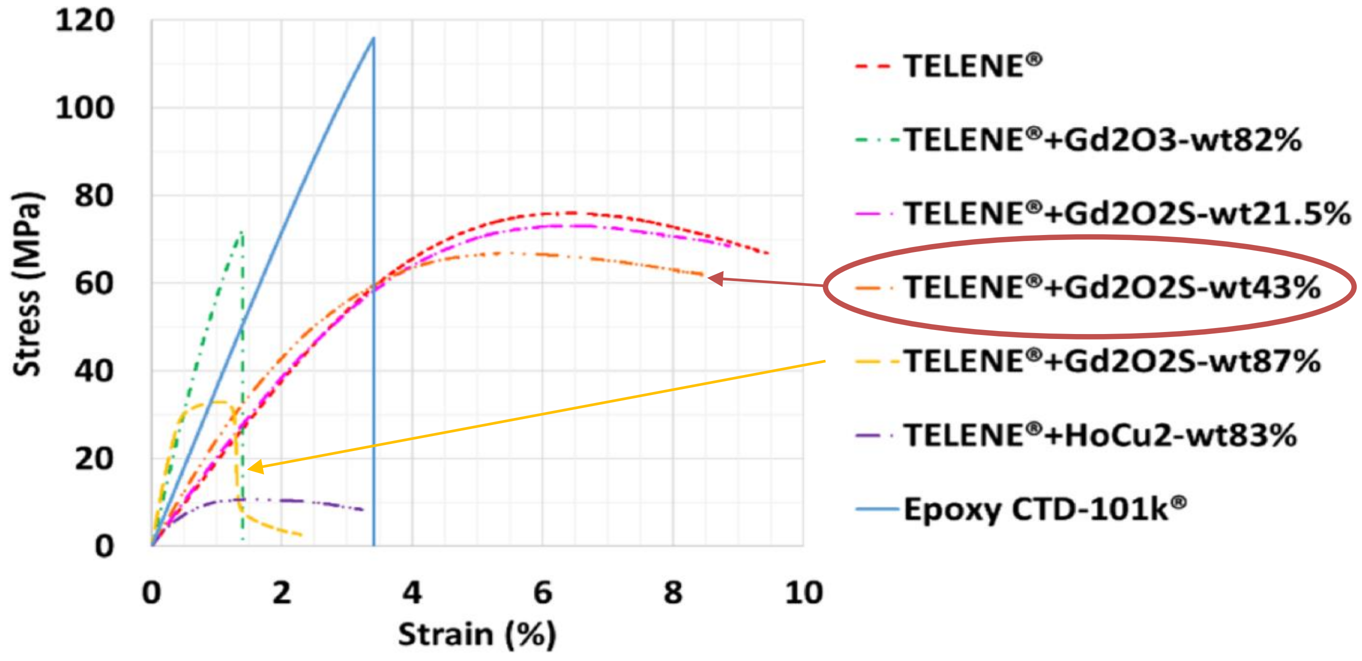
Dr. Xudong and Dr. Nakamoto of KEK

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

Mechanical Properties

Flexural Stress vs. Strain

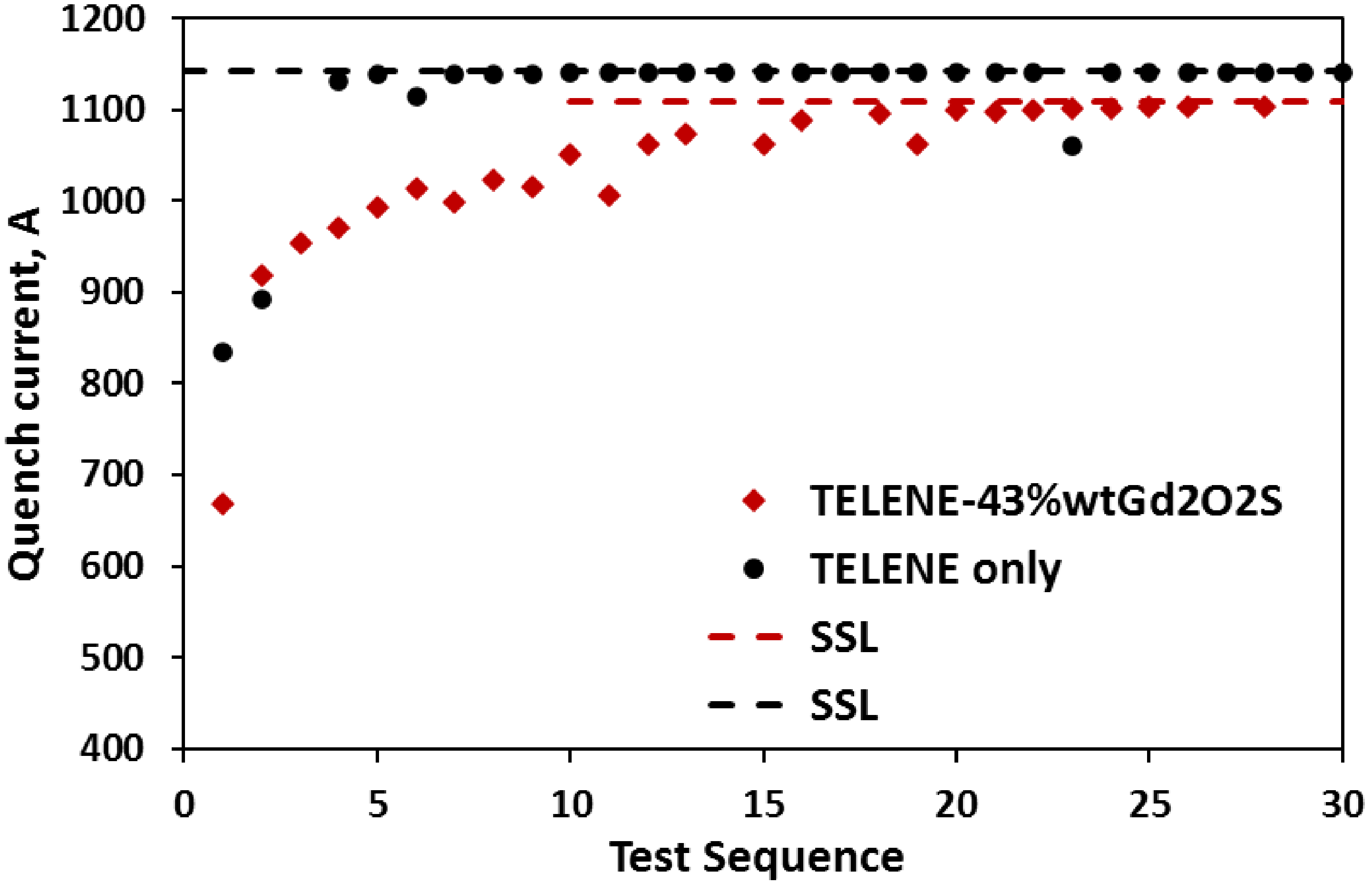




2^{nd} Nb_3Sn Undulator Test Results

Impregnated with TELENE-43wt%Gd_2O_2S

- A reason for the TELENE-43wt%Gd_2O_2S to be less effective than pure TELENE in eliminating training is its much lower thermal diffusivity $D = k/(\rho C_p)$ than for pure TELENE, due to its larger C_p.
- Thermal conductivity of these resins needs to be increased through materials engineering.



Next Steps

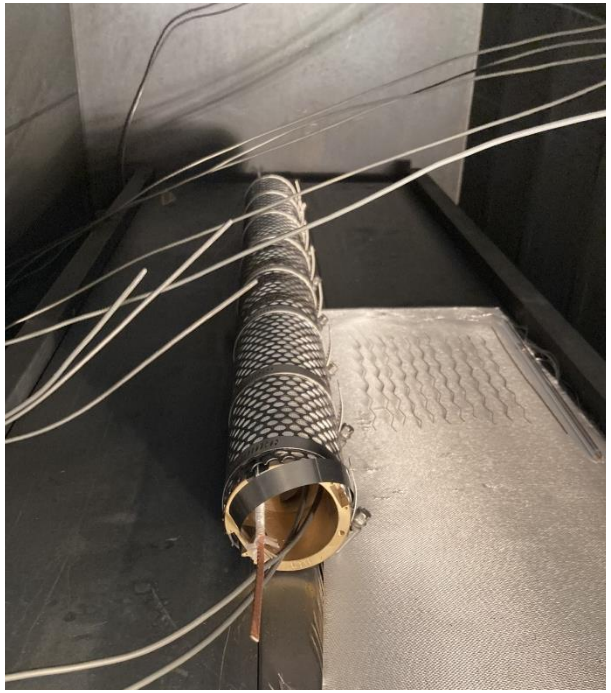
- **TELENE was successful to prevent training in the Nb_3Sn ANL undulator, which produces a maximum magnetic field of about 5 T and maximum equivalent stress on the conductor of less than 100 MPa. The next necessary step is to check whether the developed resins can lead also to a reduction in training in stress managed magnets, which is the current core design in the US Magnet Development Program (US-MDP).**
- **High-C_p ceramic powders mixed in TELENE have proven to be exceptionally radiation resistant to Co-60 gamma irradiation. When combined with the ductility and toughness properties of TELENE, these resins have already shown superior training performance with respect to CTD-101K. To fully exploit their characteristics, the last necessary step is that of increasing their thermal diffusivity D by adding high-thermal conductivity components in these resins.**
- **A 2-year extension was proposed for this grant, with FNAL, ANL, LBNL and BNL on the US side.**

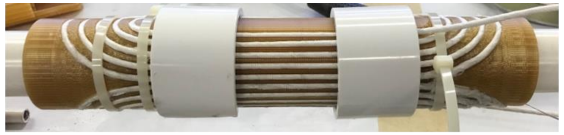
PUBLICATION

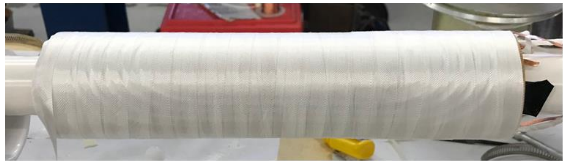
Emanuela Barzi, Daniele Turrioni, Ibrahim Kesgin, Masaki Takeuchi, Wang Xudong, Tatsushi Nakamoto, and Akihiro Kikuchi, Emanuela Barzi et al, "A New Ductile, Tougher Resin for Impregnation of Superconducting Magnets", 2024 Supercond. Sci. Technol. 37 045008 (2024)

PLANS FOR TELENE IMPREGNATION

- Sub-scale CCT coil is being heat treated at LBL for impregnation with pure TELENE at FNAL
- A FNAL practice insert was successfully impregnated with pure TELENE in preparation to impregnating FNAL Bi2212 insert
- A PSI box is being prepared at PSI for impregnation with pure TELENE







Newest Results on High-k TELENE Resins