# DEVELOPMENT OF A $NB_3SN$ SUPERCONDUCTING UNDULATOR FOR THE ADVANCED PHOTON SOURCE


**IBRAHIM KESGIN**

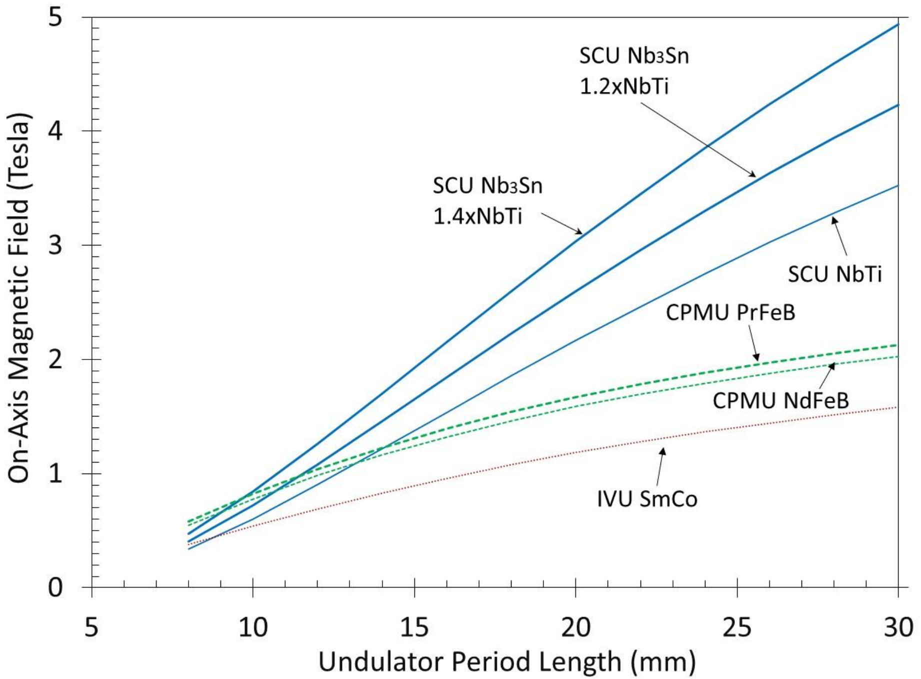
**Advanced Photon Source**
**Argonne National Laboratory**

**On behalf of APS SCU team, FNAL and LBNL collaborators**


**Virtual Superconducting Undulators for Advanced Light Sources Workshop**
**April 19- 21, 2021**


**Work supported by the U.S. Department of Energy, Office of Science under Contract No. DE-AC02-06CH11357**

# MOTIVATION



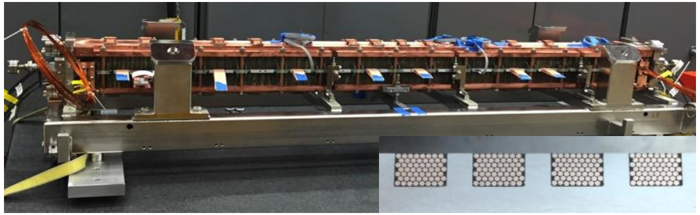

The main motivation is smaller period, compared with NbTi, for the same field and gap.

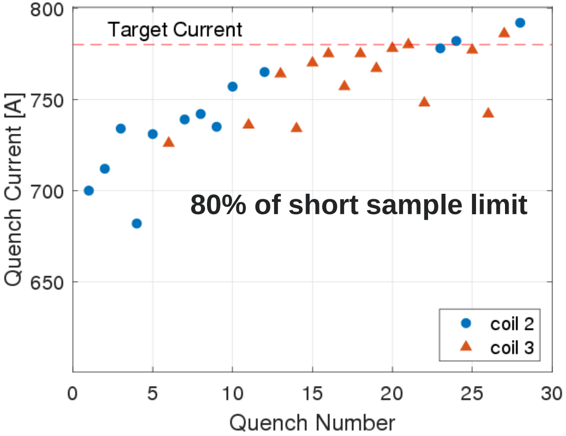
SCU magnetic gap: 5.8 mm
CPMU/IVU magnetic Gap:4.2 mm
Vacuum gap:4 mm

Adapted from E. Moog, R. Dejus, and S. Sasaki, “Comparison of Achievable Magnetic Fields with Superconducting and Cryogenic Permanent Magnet Undulators–A Comprehensive Study of Computed and Measured Values”, ANL/APS/LS-348, 2017

# NB$_3$SN SCU R&Ds IN US

## LBNL





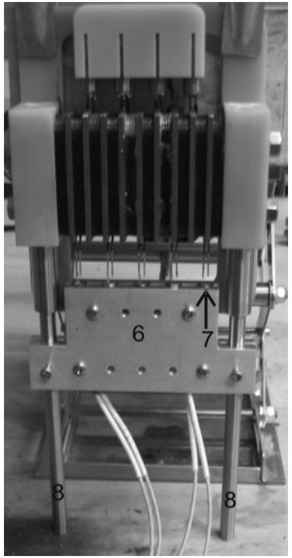

K=3.2
Length = 1.5m
λu= 19 mm
Gap = 8 mm
I max = 780 A

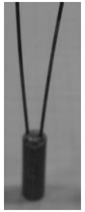
D. Arbelaez et al., ICFA Beam Dynamics Newsletter, NO. 78, 2020

## OSU/HyperTech

M Majoros *et al., Supercond. Sci. Technol.*, **25** 115006, 2012

## NHMFL



Single magnet, only a few periods
Suffered from low field instabilities

H. W. Weijers et al., IEEE Trans. on Appl. Supercond. 17(2): 1239-1242, 2017.

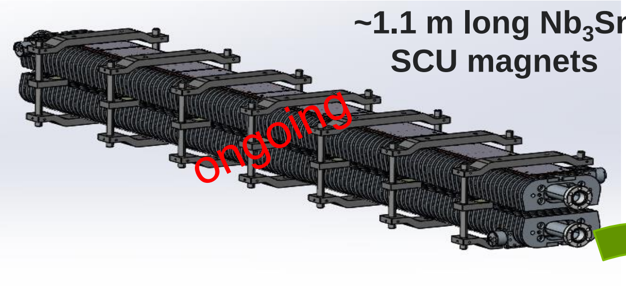
# $NB_3SN$ UNDULATOR PROJECT AT THE APS

**Short prototype studies**
**8 cm long**

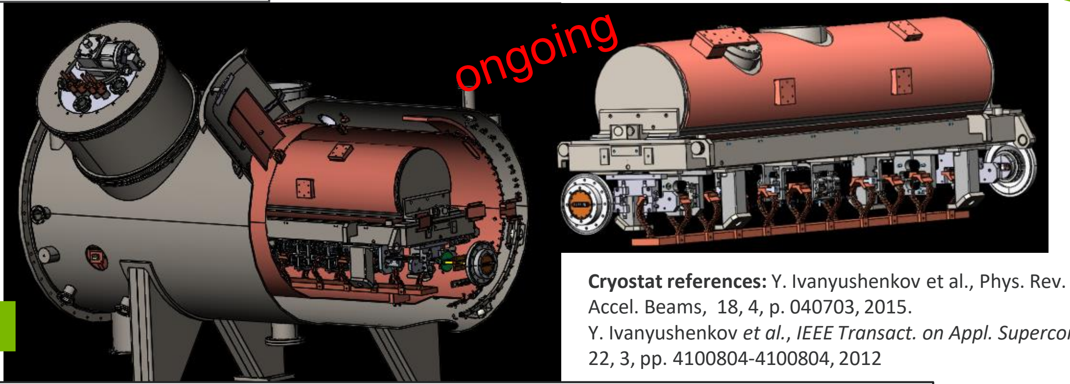

- **Design optimization**
- **Performance confirmation**

**Scaling short prototypes to**
**0.5 m intermediate lengths**


- **Three sets were fabricated**
- **Quench detection & protection**
- **Coil to ground Insulation**




**Cryostat modifications**




**Cryostat references:** Y. Ivanyushenkov et al., Phys. Rev. ST Accel. Beams, 18, 4, p. 040703, 2015.
Y. Ivanyushenkov *et al.*, *IEEE Transact. on Appl. Supercond.*, 22, 3, pp. 4100804-4100804, 2012

**The goal is to develop a $Nb_3Sn$ undulator and install it on the APS's storage ring for testing and operation as the first $Nb_3Sn$-based SCU**

Argonne NATIONAL LABORATORY

# $NB_3SN$ SCU PROJECT AT THE APS IS A COLLABORATIVE EFFORT AMONG THREE U.S. DOE NATIONAL LABORATORIES

Argonne National Laboratory (ANL) is the lead institution, and the ANL team is responsible for development of undulator magnet and cryostat designs, fabrications, and characterizations.

Matthew Kasa, Stephen MacDonald, John Andrist, Kurt Boerste, Susan Bettenhausen, Quentin Hasse, Simon Sorsher, Yuko Shiroyanagi, Hong Hu, **Yury Ivanyushenkov (APS SCU Team Leader) and Efim Gluskin (Principal Investigator of the $Nb_3Sn$ SCU project)**

Heat treatments of the $Nb_3Sn$ magnets and short sample tests were performed at Fermilab. The Fermilab team also contributed to the magnet design and various design optimizations.

Daniele Turrioni, Steve Krave, Sean M. Johnson,
Emanuela Barzi and Alexander Zlobin

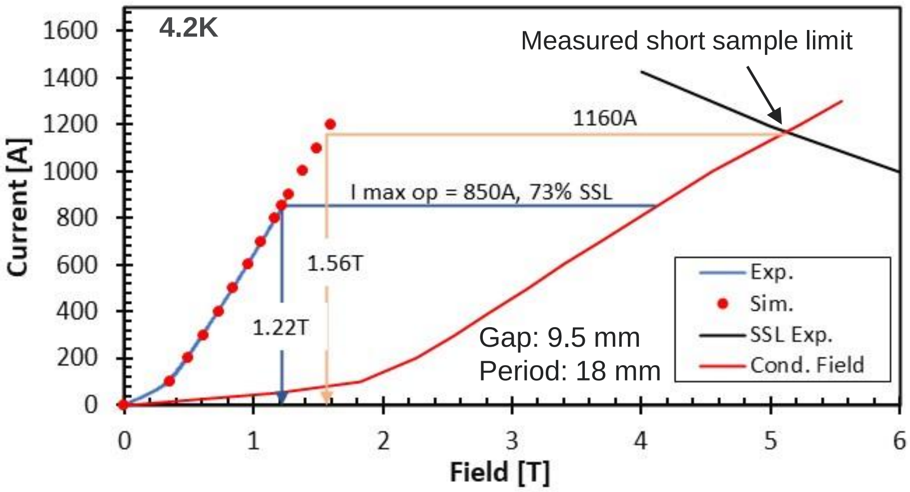
The LBNL team performed quench simulations and used those in design of the quench detection and protection system and fabricated the QDPS for us.

Kathleen Edwards, Lucas Brouwer, Marcos Turqueti, Jordan Taylor,
Diego Arbelaez and Soren Prestemon

# $NB_3SN$ SCU: CHALLENGES, DESIGN SPECIFICATIONS, AND PERFORMANCE

- Stable wire & Insulation
- Mechanical design
- Core insulation
- Quench detection and protection
- End terminals

| Undulator specifications | $Nb_3Sn$ | NbTi version (in operation) |
|---|---|---|
| Undulator on axis design field, T | 1.2 | 0.97 |
| ~ K value | 2 | 1.6 |
| Design current, A (~70 % and ~80% of the $I_c$) at 4.2 K | 850 | 450 |
| Period length, mm | 18 | 18 |
| Magnetic gap, mm | 9.5 | 9.5 |
| Magnetic length, ~m | 1.1 | 1.1 |



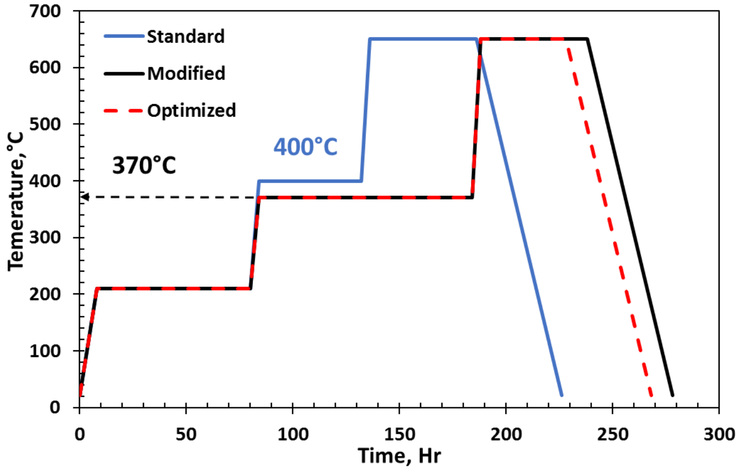

Conductors: 0.6 mm $Nb_3Sn$ Restack Rod Process (RRP) 144/169, Deff = 35 µm, from Bruker OST
0.6 mm NbTi 56-filament from Supercon, D=60 µm

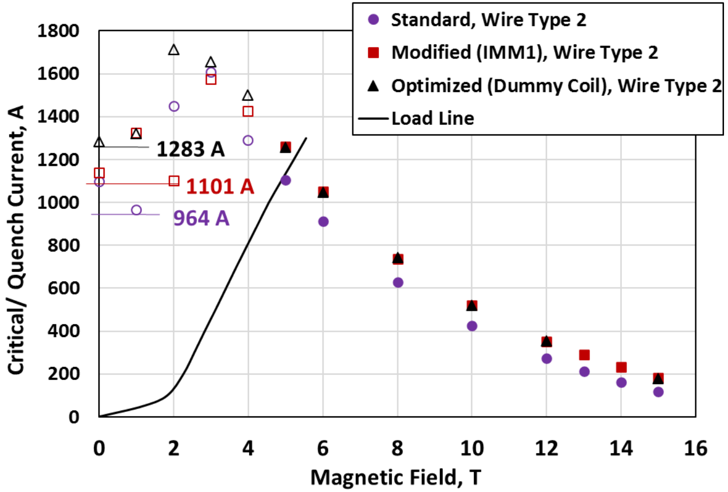
**Short sample $I_c$ (B) results confirm that 1.56T undulator field is achievable with $Nb_3Sn$ – about 40% more than a NbTi version (1.12T) at 4.2 K**

# OPTIMIZATION OF HEAT TREATMENT FOR STABILITY *

E. Barzi, D. Turrioni, and A. Zlobin

Fermilab performed extensive heat treatment optimization studies of the $Nb_3Sn$ wire (RRP 144/169) for the SCU applications



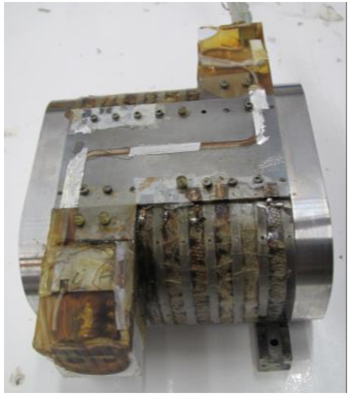

**Open symbols indicate premature quenches. The optimized heat treatment increased the unstable current from the standards cycle's 964 A to 1283 A, which is greater than the Short Sample Limit of 1205 A.**

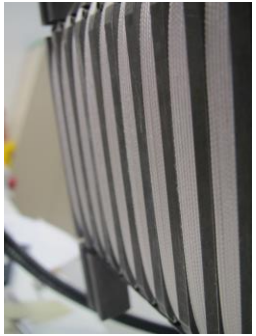
E. Barzi, et al., "Heat Treatment Studies of Nb3Sn Wires for Superconducting Planar Undulators", IEEE *Transact. on Appl. Supercond.*, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 6001005

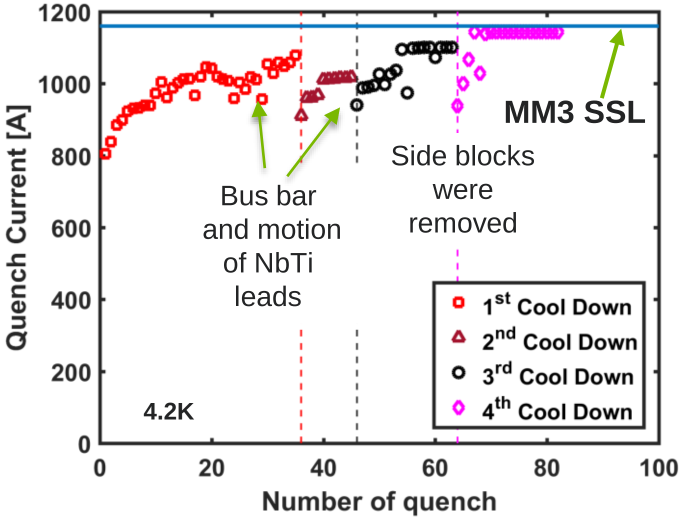
*Slide by E. Barzi

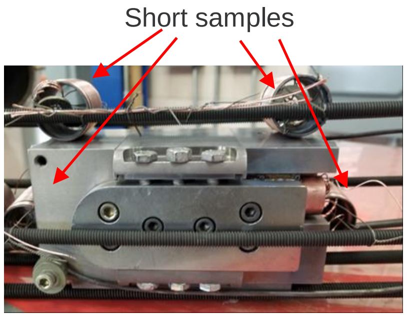
# 8-CM-LONG (18 MM PERIOD) PROTOTYPE STUDIES AND PERFORMANCE

Magnet design follows the footsteps of the APS's NbTi magnets. Three magnets were fabricated








Short samples and magnet just before the heat treatment at FNAL

**Key optimizations:**

- Performed magnetic and mechanical simulations to optimize the winding groove dimensions, winding former, and support structures
- Developed a new coil-to-ground mica insulation with FNAL

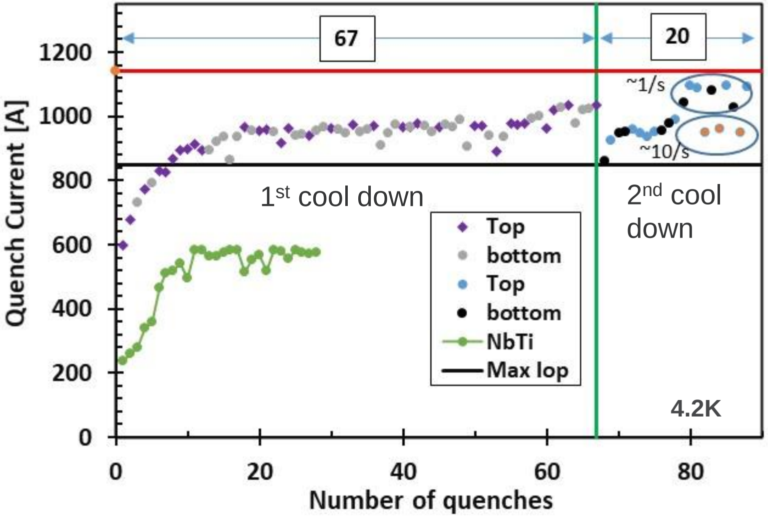
**Third short prototype reached the short sample limit (SSL):**

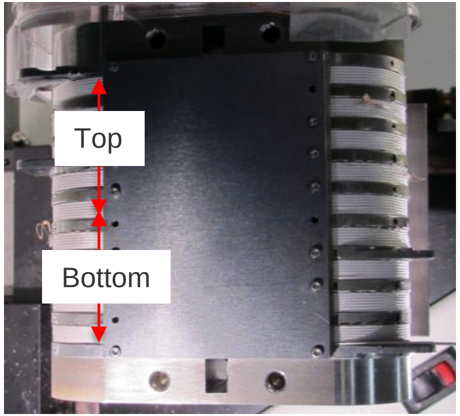
- Limit epoxy pockets to minimum, optimize the winding to achieve this
- Reinforce the windings with fiberglass cloths
- Proper vacuum pressure impregnation (VPI) for a good mechanical support and avoid voids

I. Kesgin *et al.*, *IEEE Transact. on Appl. Supercond.*, vol. 29, no. 5, pp. 1-4, 2019

# SIMPLIFYING THE DESIGN – CONTINUING 8-CM LONG PROTOTYPE STUDIES

- Three more 8-cm-long prototypes were fabricated to simplify the design
- Winding scheme optimized for a convenient winding
- No fiberglass cloths was used, but very thin epoxy pockets preserved
- Optimized the conductor: copper to superconductor ratio is increased in the conductor architecture to have more room for the protection (RRP 144/169)




Last 8-cm-long prototype reached 96% of its short sample limit and the same design is scaled to 0.5 m lengths.

I. Kesgin *et al.*, "Fabrication and Testing of 10-Pole Short-Period Nb3Sn Superconducting Undulator Magnets," *IEEE Transact. on Appl. Supercond.*, vol. 30, no. 4, pp. 1-5, 2020.

# 1ST 0.5 M LONG $NB_3SN$ SCU PROTOTYPE

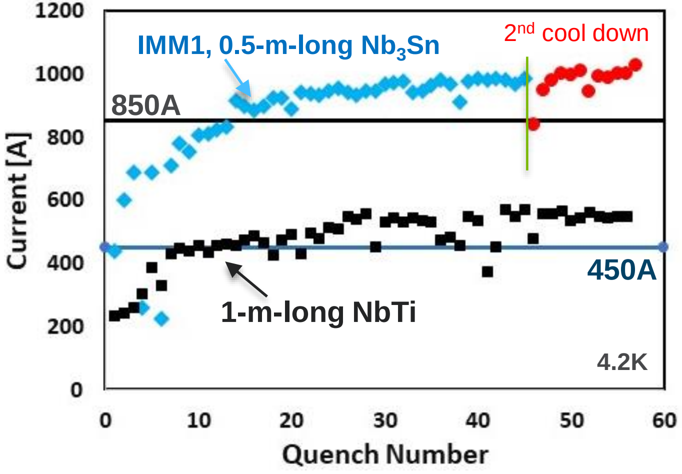
0.5 m long prototype magnets were fabricated and assembled with a magnetic gap of 9.5 mm

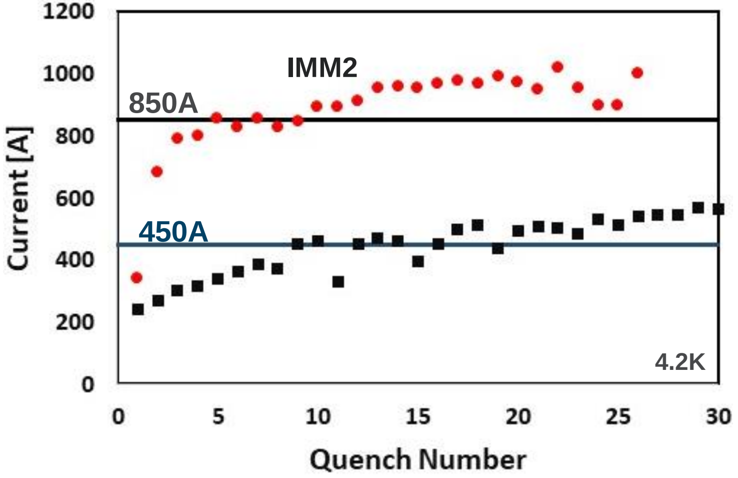
I. Kesgin *et al.*, *IEEE Transact. on Appl. Supercond.*, vol. 30, no. 4, pp. 1-5, 2020.

**IMM1, single magnet test**

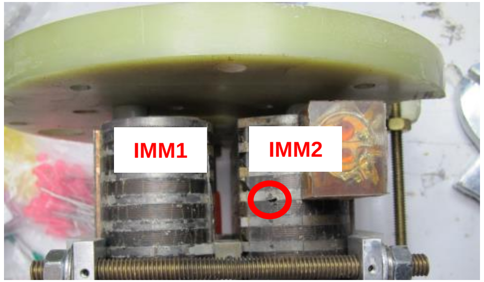
**IMM1 and IMM2 undulator test**

# TRAINING OF 1ST $NB_3SN$ 0.5M-LONG INDIVIDUAL MAGNETS AND COMPARISONS TO NBTI




- Individual magnets were successfully tested and trained very fast up to the maximum design current. The training behavior is similar to NbTi magnets.
- When the magnets paired, they failed. The reason for this is the weak insulation behavior. The winding groove dimensions were not ideal, and the mica insulation was damaged in some regions that caused insulation breakdown.




I. Kesgin *et al.*, *IEEE Trans. on Appl. Supercond.*, pp. 1-1, 2021.

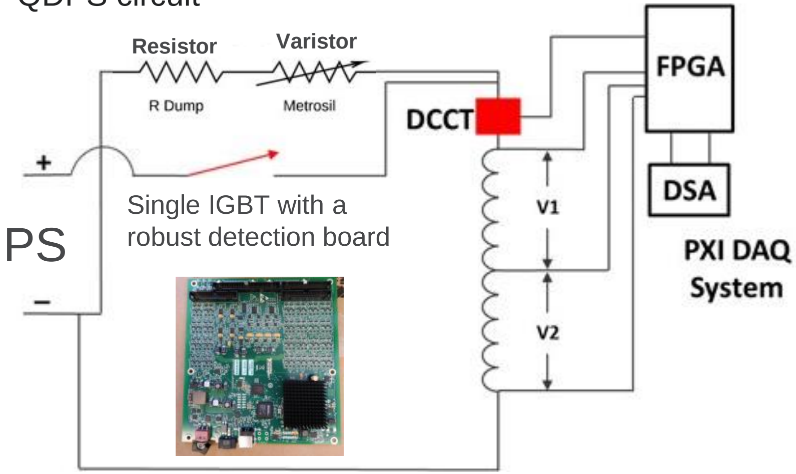
**To establish a reliable and robust fabrication procedure, it was decided to fabricate and test two more 0.5-m-long prototypes.**

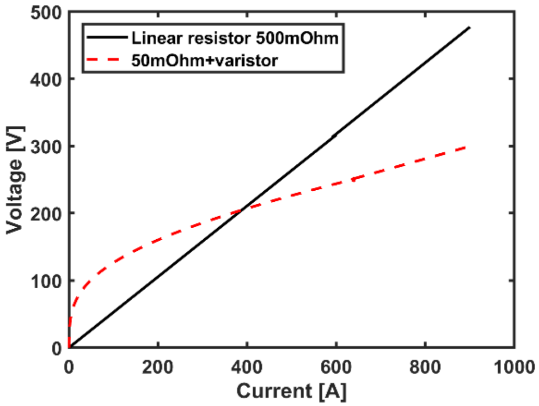
# INSULATION IMPROVEMENT AND QUENCH DETECTION AND PROTECTION SYSTEM (QDPS)

**Key improvements:**

- Improved coil-to-ground insulation: Used mica insulation around the winding grooves and magnets were also plasma sprayed with an $Al_2O_3$ layer.
- Improved quench detection and protection system (QDPS): LBNL performed quench simulations to optimize the dump resistor value and fabricated a QDPS and suggested incorporation of a varistor to clamp the maximum voltage at ~250 V at around 900A.

QDPS circuit



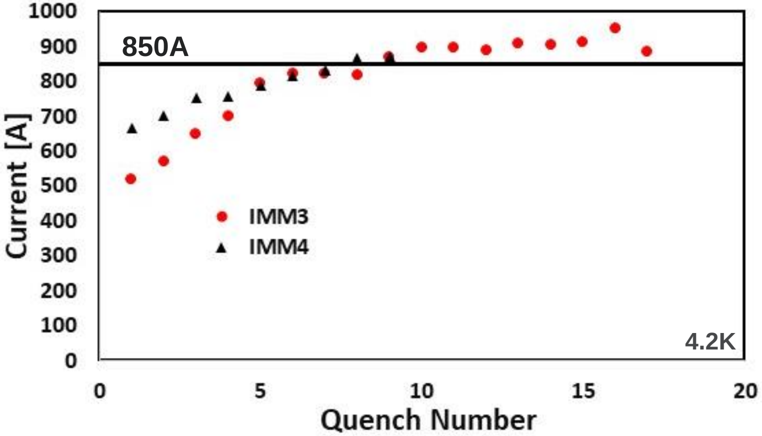
# 2ND 0.5-M-LONG $NB_3SN$ MAGNETS AND INDIVIDUAL TESTS – 1ST COOL DOWN

IMM3

IMM4

0.5 m long magnets after epoxy impregnation

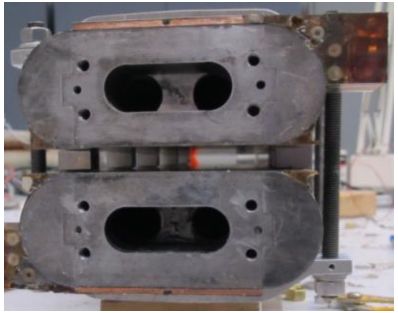
Training profiles for individual magnets



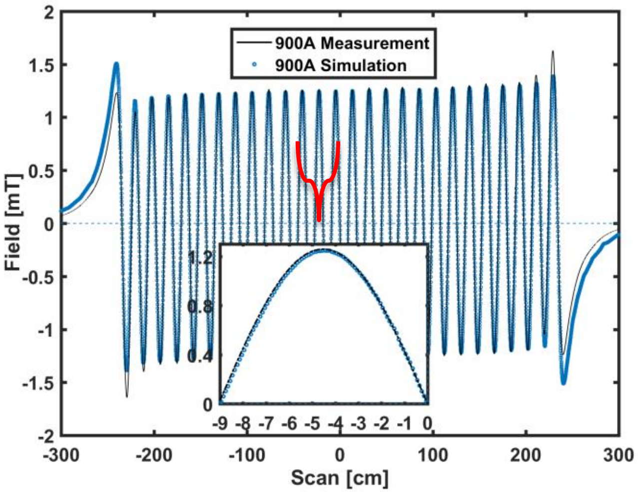

**A few quenches to reach the design current.**

Magnet trainings were stopped after the magnets reached the design current, and the magnets were assembled into the undulator configuration for magnetic field measurements.

# $2^{ND}$ 0.5 M LONG UNDULATOR ASSEMBLY AND TESTING – $2^{ND}$ COOL DOWN



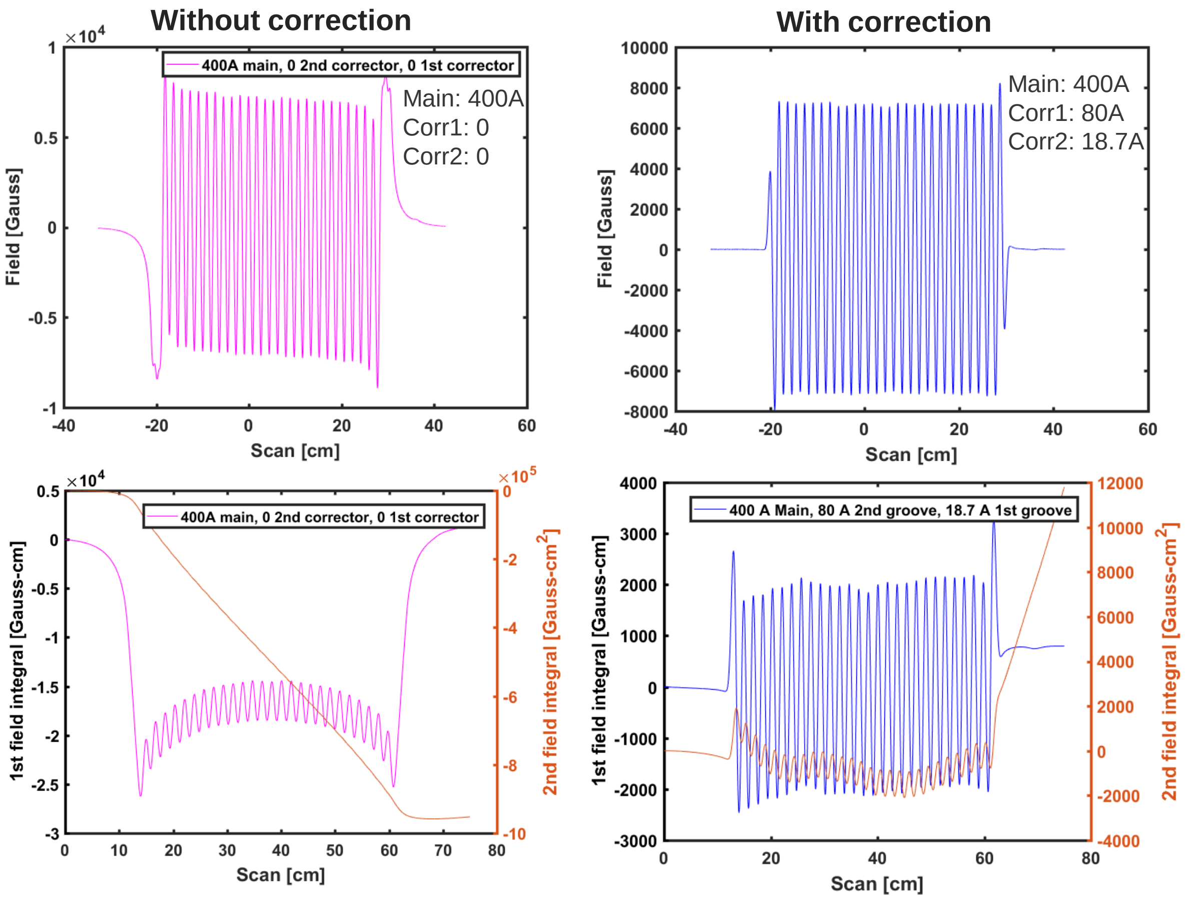
- **Excellent quench training memory** – no quench was observed up to the design current of 850A in $2^{nd}$ cool down
- Design field of 1.2T was achieved at 850A
- Very good agreement between the simulation and measured field values – except the ends




I. Kesgin *et al*., Presented at the Virtual Applied Superconductivity Conference 2020

# FIELD PROFILES AND FIELD INTEGRALS WITH AND WITHOUT CORRECTIONS

- Correction scheme are based on our NbTi magnets
- Preliminary results showed that the corrector magnets significantly reduces the field integrals below the SR physics requirements
- Corrector current leads were limited to 100 A and we only tested correctors at 400 A main current
- These results are in good agreement with the numerical modeling of the undulator fields
- Field imperfections are due to the poor machining quality



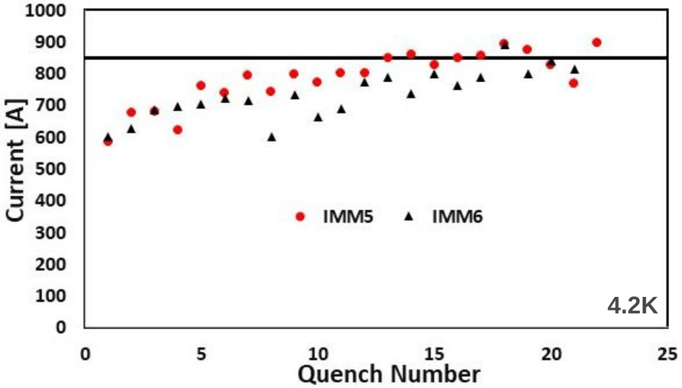



Argonne NATIONAL LABORATORY

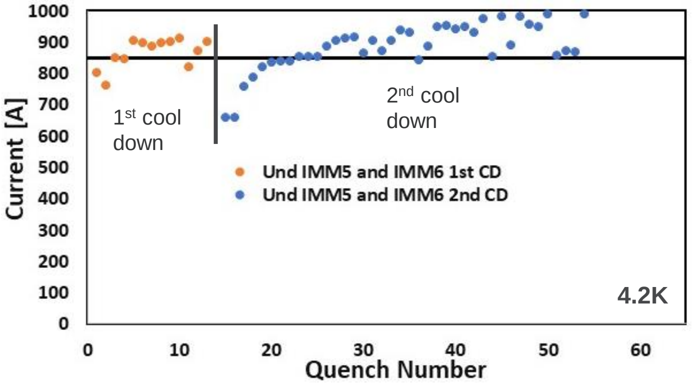
# $3^{RD}$ 0.5 M LONG $NB_3SN$ UNDULATOR ASSEMBLY AND TESTS

Another set of 0.5 m long magnets was fabricated to validate the robustness of fabrication steps

To further simplify the winding, mica insulation is removed from the design and only $Al_2O_3$ coating applied (similar approach previously used by LBNL)




Individual magnet training – 1st cool down

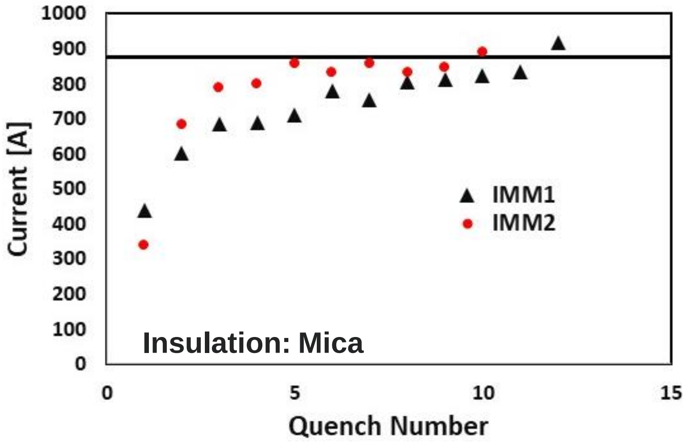


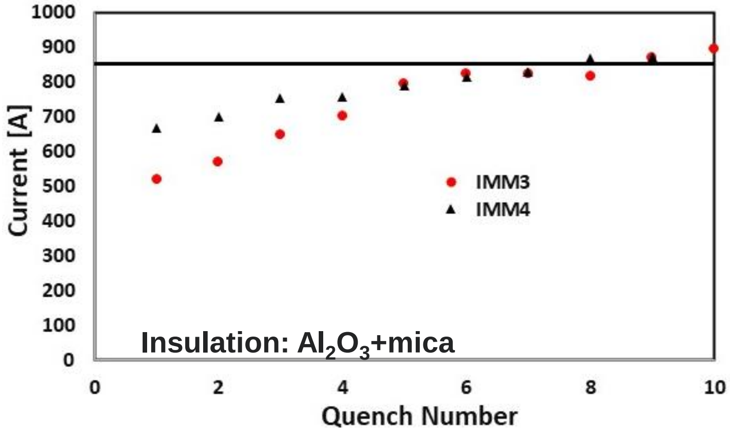

Training of a pair in an undulator configuration – 1st and 2nd cool downs

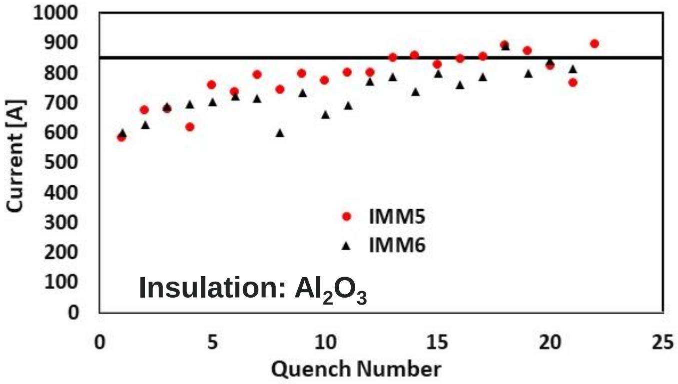
Maximum quench current is 1000A

**A second 0.5-m-long undulator successfully tested and delivered the required performance – ensures robust fabrication steps**

# COMPARISONS OF INSULATION SCHEMES AND TRAINING PERFORMANCES




Mica insulation can be eliminated at the expense of more training; this significantly simplifies the winding

| | IMM1 | IMM2 | IMM3 | IMM4 | IMM5 | IMM6 |
|---|---|---|---|---|---|---|
| ~SSL [A] @max on cond. field | 1200 | 1185 | 1200 | 1180 | 1170 | 1160 |
| Ins | mica | mica | $Al_2O_3$ +mica | $Al_2O_3$+ mica | $Al_2O_3$ | $Al_2O_3$ |

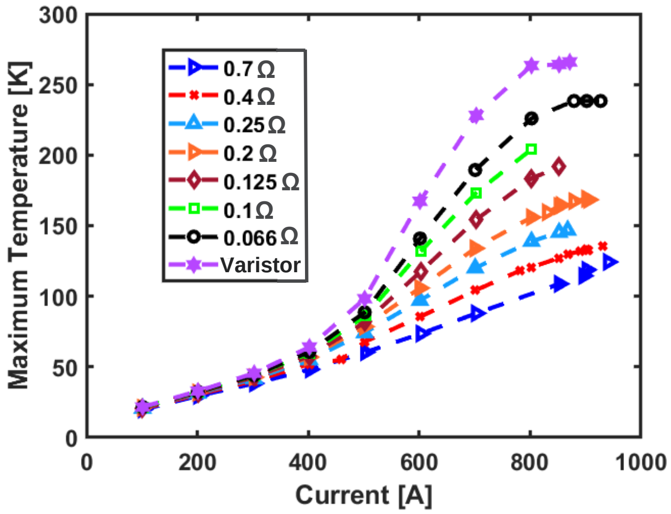
# TO BE ADDRESSED IN THE REMAINING PART OF THE PROJECT

**During offline testing of the device in cryostat**

- Testing magnets in conduction (indirectly) cooled environment and quench behavior
- Quench recovery
- Measurements of field quality, integrals, phase errors, and trajectory
- Extended testing of the powered device

**During operation in the storage ring**

- Sensitivity to the beam dumps
- Long time stability




Hot spot calculations are a good representation of the magnet behavior in the conduction cooled environment.

This device, as a first demonstrator, will address many questions related to the quality and reliability of a $Nb_3Sn$ SCU in operation and it will be a significant steppingstone for future SCUs

# SUMMARY

- ✓ APS continues to develop state-of-the-art superconducting undulator technologies. The $Nb_3Sn$ conductor has potential to **increase the on-axis field by 40%** compared to the NbTi version. There is room for further optimizations – such as the insulation thickness, heat treatment cycle, conductor architecture, etc., -- that could increase this number.
- ✓ The $Nb_3Sn$ undulator magnet design has been iteratively optimized using short prototypes and simulations.
- ✓ The design has been further optimized using the lessons learned from testing the first 0.5-m-long undulator. A more robust quench detection and protection system was fabricated and proven to be successful protecting the $Nb_3Sn$ SCU magnets.
- ✓ Second and third 0.5-m-long undulator magnets have been successfully fabricated and tested. Their performance exceeded the design current and field of 850A and 1.2T, respectively **(20% more than NbTi).** These confirmed the robust fabrication steps.
- ✓ Design of the final magnets is finalized, and fabrication is ongoing. Cryostat modifications are underway to accommodate the $Nb_3Sn$ undulator magnets.
- ✓ APS is planning to install the first $Nb_3Sn$-based SCU into its storage ring in 2022 to deliver a wide range of hard x-rays to APS users.


**References:**

1. I. Kesgin *et al.*, "Fabrication and Testing of 18-mm-Period, 0.5 m Long $Nb_3Sn$ Superconducting Undulator," *IEEE Transactions on Applied Superconductivity,* pp. 1-1, 2021.
2. I. Kesgin *et al.*, "Fabrication and Testing of 10-Pole Short-Period Nb3Sn Superconducting Undulator Magnets," *IEEE Transactions on Applied Superconductivity,* vol. 30, no. 4, pp. 1-5, 2020.
3. I. Kesgin *et al.*, "Development of Short-Period $Nb_3Sn$ Superconducting Planar Undulators," *IEEE Transactions on Applied Superconductivity,* vol. 29, no. 5, pp. 1-4, 2019.
4. Y. Ivanyushenkov *et al.*, "Status of the Development of Superconducting Undulators at the Advanced Photon Source," *Synchrotron Radiation News,* vol. 31, no. 3, pp. 29-34, 2018/05/04 2018.
5. A. V. Zlobin *et al.,* "Advantage and Challenges of $Nb_3Sn$ Superconducting Undulators," presented at the 9th International PAC, Vancouver, BC, Canada, 04/29-05/04/2018, 2018.
6. E. Barzi, *et al.,* "Heat Treatment Studies of Nb3Sn Wires for Superconducting Planar Undulators," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 6001005.