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PROGRESS ON THE NB_3SN SUPERCONDUCTING UNDULATOR DEVELOPMENT AT THE ADVANCED PHOTON SOURCE

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On behalf of APS SCU team, FNAL and LBNL collaborators

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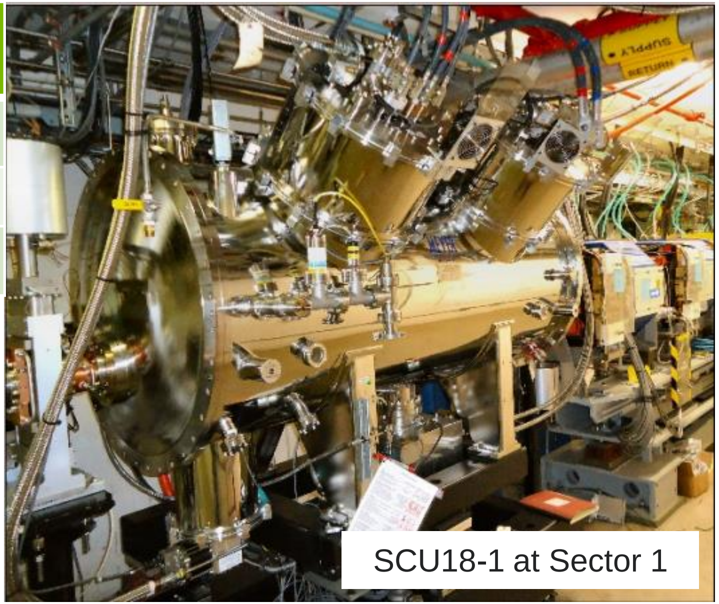
OPERATIONAL EXPERIENCE WITH THE NBTI-BASED SUPERCONDUCTING UNDULATORS (SCUs) AT THE APS

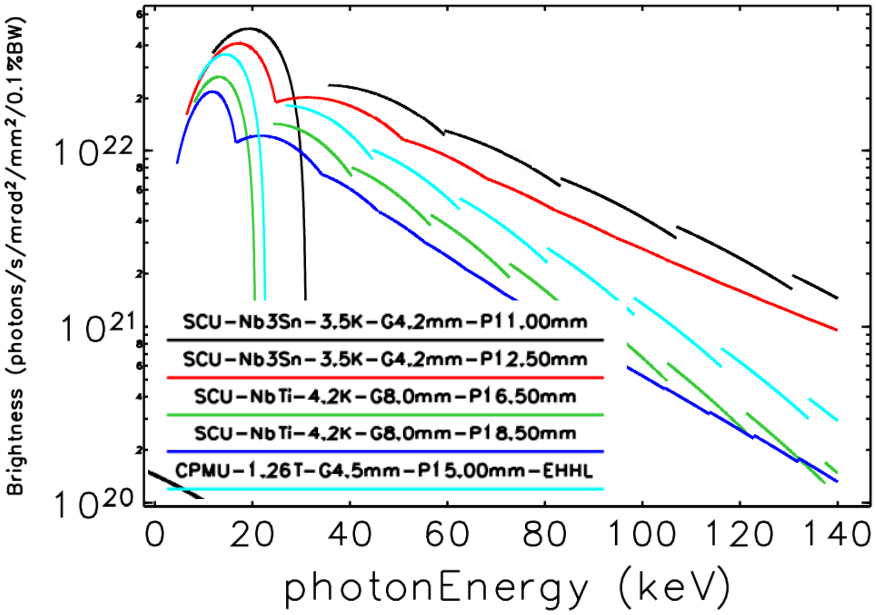
ID	Period [mm]	Magnetic length [m]	In-operation	Availability since installation [%]
SCU18-1 [1]	18	1.1	Since 2015	99.44
SCU18-2	18	1.1	Since 2016	99.99
Helical SCU [2]	31.5	1.2	Since 2018	96.76


SCU18-1 at Sector 1

- APS SCUs accumulated excellent record of reliable performance and availability of SCUs for user's operation matches the best PM IDs while their radiation performance is superior.
- Building on this successful experience, 4 more SCUs planned to be installed during the APS upgrade:
  - 4.8 m long cryostat
  - Double magnetic structure with various magnetic lengths up to 1.9m

[1] Y. Ivanyushenkov et al., Phys. Rev. Accel. Beams 20, 100701 (2017).
[2] M. Kasa et al., Phys. Rev. Accel. Beams 23, 050701 (2020).

THE MAIN MOTIVATION IS TO REDUCE THE PERIOD LENGTH AND INCREASE THE UNDULATOR MAGNETIC FIELD



APS technical note AOP-TN-2022-014 by M. Borland (April 4, 2022), "Potential brightness improvements in APS-U with advanced superconducting undulators."

Nb_3Sn has the potential to significantly increase the brightness for wide range of photon energies.

Nb_3Sn UNDULATOR PROJECT AT THE APS*

***The project is funded by the Accelerator and Detector Research Program at BES-DOE**

Short prototype studies 4.5 periods (~8-cm)

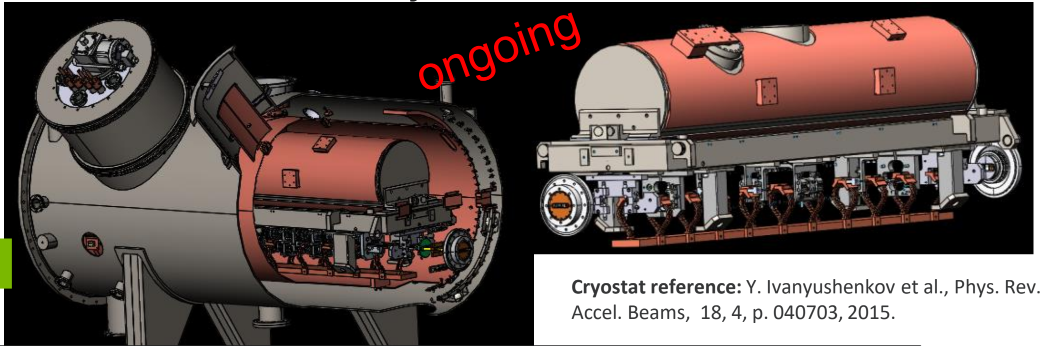
- Design optimization
- Performance confirmation

Scaling short prototypes to 26.5 periods (~0.5 m)

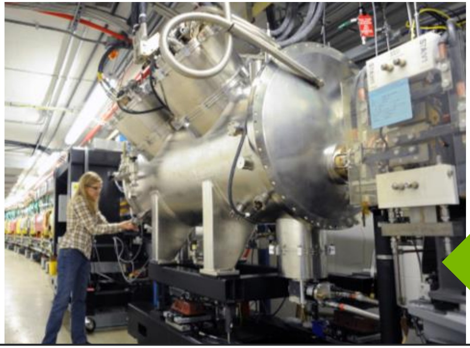
- Quench detection & protection
- Coil to ground Insulation

59.5 periods (~1.1 m) Nb_3Sn SCU magnets

Cryostat modifications



Cryostat reference: Y. Ivanyushenkov et al., Phys. Rev. ST Accel. Beams, 18, 4, p. 040703, 2015.



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

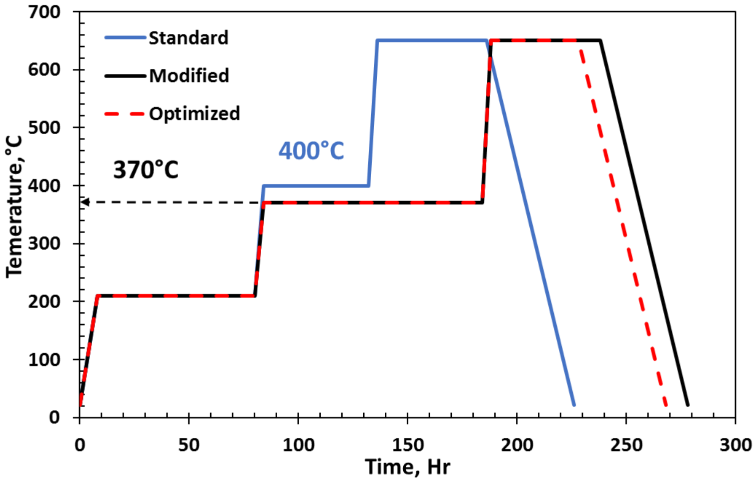
CHALLENGES WITH BUILDING NB_3SN SCUs AND DESIGN SPECIFICATIONS

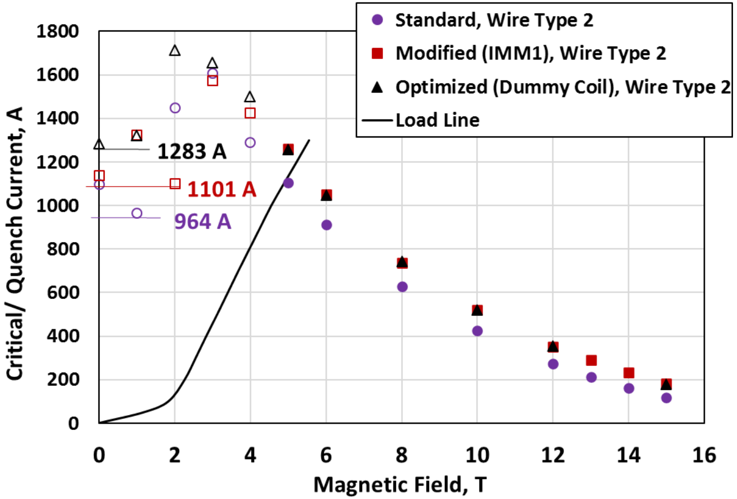
- Stable wire & Insulation
- Mechanical design
- Core insulation
- Quench detection and protection
- End terminals

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

OPTIMIZATION OF HEAT TREATMENT FOR THE BEST STABILE OPERATION

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 (SSL) 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

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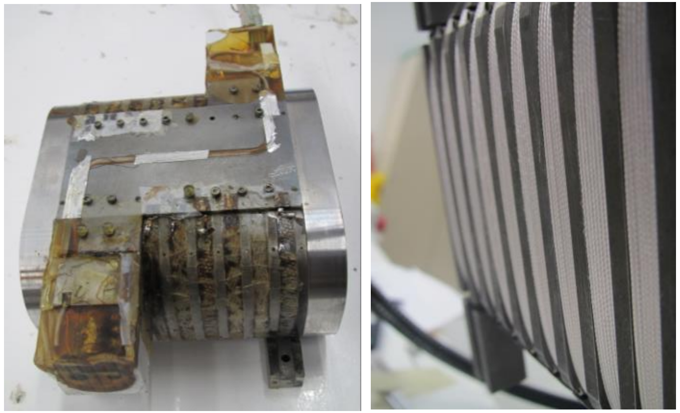
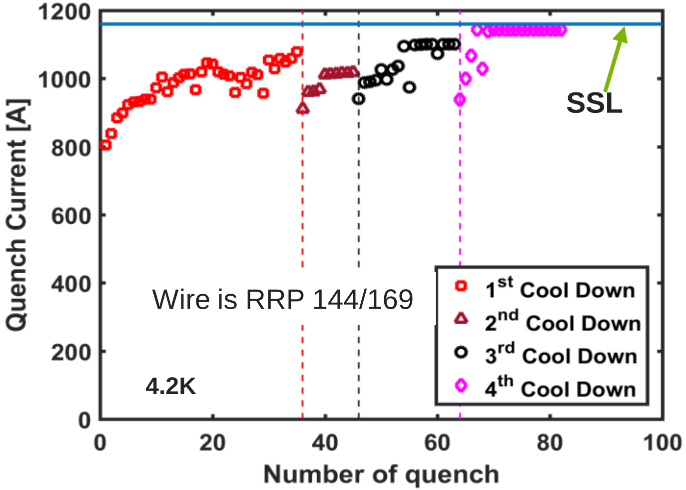
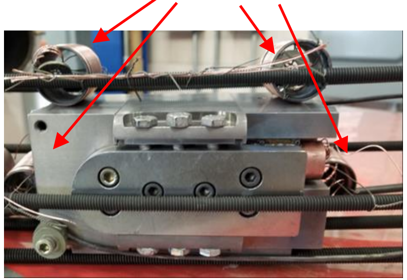
OTHER OPTIMIZATIONS THROUGH 8-CM-LONG PROTOTYPES

10-pole short models





Short samples



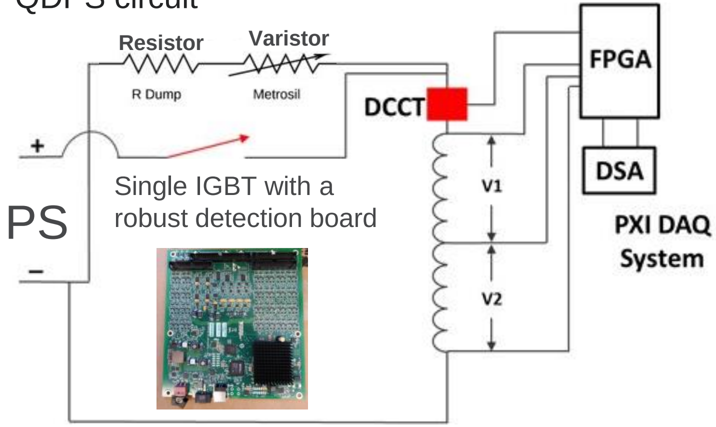
Short samples and magnet just before the heat treatment at FNAL

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

IMPROVEMENTS ON COIL-TO-GROUND INSULATION AND THE QUENCH DETECTION AND PROTECTION SYSTEM

- Coil-to-ground insulation:
  - Only mica insulation around the winding grooves was found to be insufficient
  - Additional plasma sprayed Al_2O_3 layer was incorporated
  - Tested only Al_2O_3 layer to simplify the winding
- Quench detection and protection system (QDPS): LBNL
  - performed quench simulations to optimize the dump resistor value
  - fabricated the QDPS.

QDPS circuit

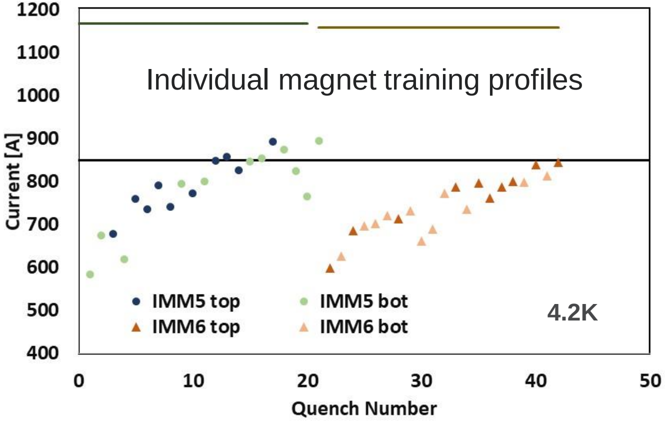


QDPS

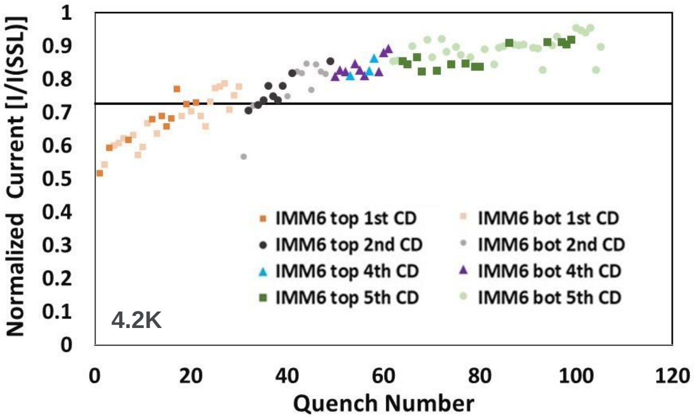
Varistor is used to limit the maximum voltage

EVALUATING THE DESIGN BY 0.5 M LONG (26.5 PERIOD) NB_3SN UNDULATOR MAGNETS

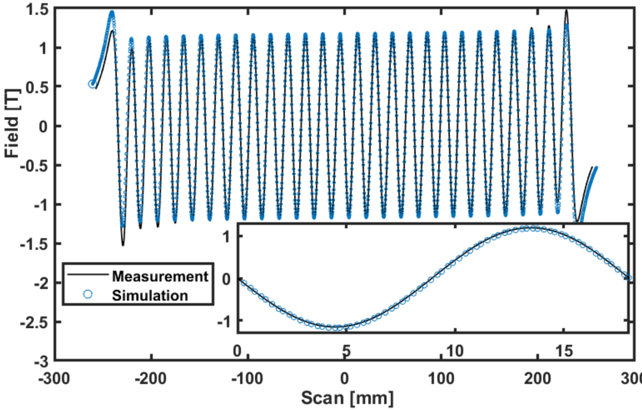
0.5-m-long Nb_3Sn undulator



I. Kesgin et al., *IEEE Trans. on Appl. Supercond., vol. 32, no. 6, pp. 2022, Art no. 4100605*



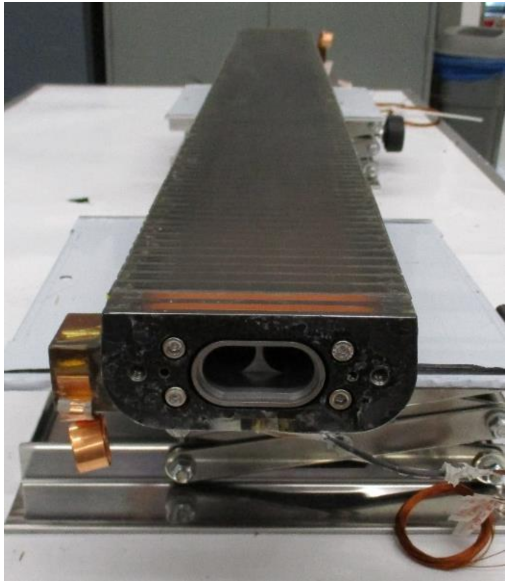
IMM6 maximum quench current reached is 1110 A (>95% of SSL) after multiple cool downs.



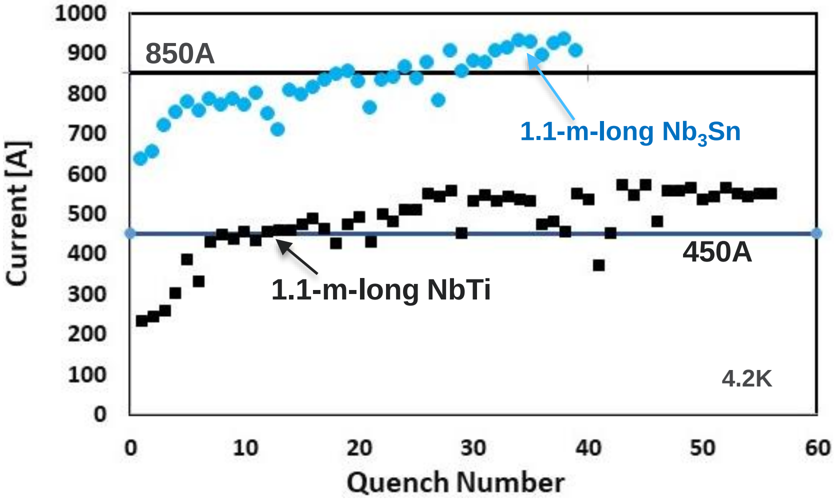
Very good agreement between the simulation and measured field values – except the ends

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

TRAINING OF THE FIRST 1.1-M-LONG NB_3SN MAGNET AND COMPARISON WITH A 1.1-M-LONG NBTI VERSION



A photo of 1.1-m-long Nb_3Sn undulator magnet

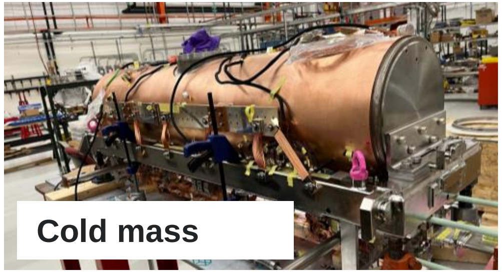


- The first 1.1m-long SCU magnet was successfully trained at above the maximum operational current of 850A.
- The training behavior is similar to NbTi SCU magnets.

The magnet design scaled to 1.1-m-long final length and the first magnet was successfully trained up to 950A, which is 10% higher than the maximum operating current

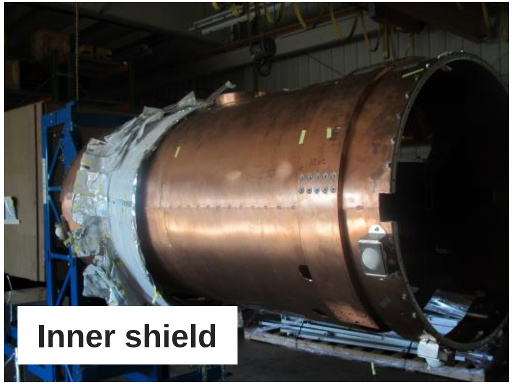
CRYOSTAT OVERVIEW AND MODIFICATIONS TO ACCOMMODATE THE NB_3SN UNDULATOR MAGNETS

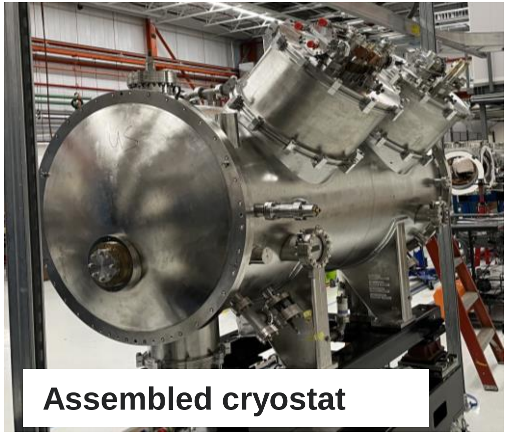
- An existing cryostat was refurbished for the Nb_3Sn project
  - 2-m-long vessel
  - 4 Sumitomo cryocoolers (two 418D and two 408S)
  - Two shields, running at 10K and 40K
  - Closed-system, operating zero boil-off mode



Cryostat modifications

- Optimized the current lead design for the 850A, which almost doubles the NbTi version, 450A
- Added more current leads to operate the corrector magnets
- Added ports to monitor the cold mass movement





The modified cryostat demonstrated an excellent performance and waiting for the assembly of the Nb_3Sn undulator magnets

SUMMARY

- ✓ APS continues to develop state-of-the-art superconducting undulator technologies.
- ✓ The Nb_3Sn undulator magnet design has been iteratively optimized using simulations and then the magnetic and mechanical designs were evaluated by using short and intermediate prototypes.
- ✓ Several 85-cm- and 0.5-m-long prototype undulator magnets have been successfully fabricated and tested. Their performance exceeded the design current and field of 850A and 1.2T **(at least 20% more than NbTi).** These confirmed the robust fabrication steps.
- ✓ After confirming the performance with 0.5-m-long Nb_3Sn SCU magnets,1.1-m-long long magnets were fabricated and the first magnet was successfully trained up to 950A, which is 10% higher than the maximum operating current of 850A. Fabrication of the second magnet is ongoing.
- ✓ Cryostat modifications completed and cool down test showed excellence cryogenic performance. It is ready for the assembly of the 1.1-m-long Nb_3Sn magnets.
- ✓ A more robust quench detection and protection system was fabricated and proven to be successful protecting the Nb_3Sn SCU magnets.
- ✓ APS is planning to install the first Nb_3Sn-based SCU into its storage ring in early 2023 to deliver a wide range of hard x-rays to its users.

THE Nb_3Sn SCU PROJECT 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.

Stephen MacDonald, Matthew Kasa, John Andrist, Danlu Zhang, Jason Ackley, Ethan Gubbels, Kurt Boerste, Susan Bettenhausen, Quentin Hasse, Simon Sorsher, Yuko Shiroyanagi, **Yury Ivanyushenkov (APS SCU Team Leader), and Efim Gluskin (PI 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, used those in the design of the quench detection and protection system (QDPS), and fabricated the QDPS for us.

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

Thank you so much !

References:

1. I. Kesgin *et al.*, "Fabrication and Testing of 18-mm-Period, 0.5 m Long Nb_3Sn Superconducting Undulator," *IEEE Trans. on Appl. Supercond.,* pp. 1-1, 2021.
2. I. Kesgin *et al.*, "Fabrication and Testing of 10-Pole Short-Period Nb_3Sn Superconducting Undulator Magnets," *IEEE Trans. on Appl. Supercond.,* vol. 30, no. 4, pp. 1-5, 2020.
3. I. Kesgin *et al.*, "Development of Short-Period Nb_3Sn Superconducting Planar Undulators," *IEEE Trans. on Appl. Supercond.,* vol. 29, no. 5, pp. 1-4, 2019.
4. I. Kesgin *et al.*, "Design, Construction, and Testing of 0.5-m, 18-mm Period Nb_3Sn Superconducting Undulator Magnets," *IEEE Trans. on Appl. Supercond.,* vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4100605, doi: 10.1109/TASC.2022.3152712.
5. 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.
6. 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.
7. E. Barzi, *et al.,* "Heat Treatment Studies of Nb_3Sn Wires for Superconducting Planar Undulators," *IEEE Trans. on Appl. Supercond.,* vol. 30, no. 4, pp. 1-5, June 2020, Art no. 6001005.