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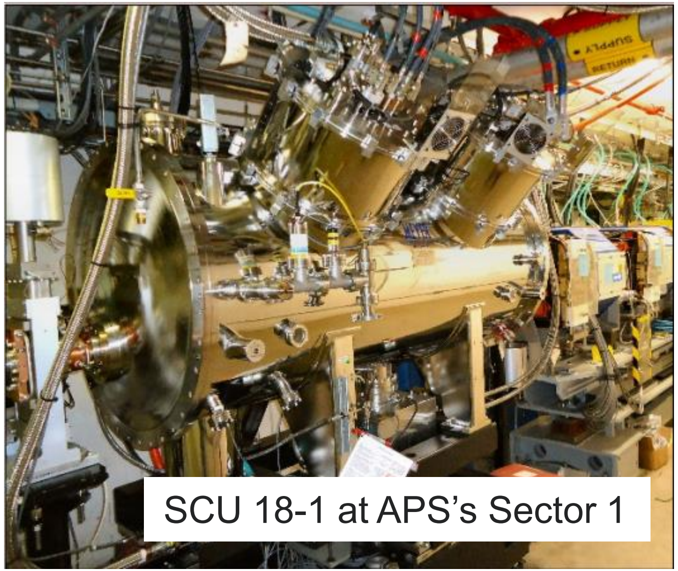
OPERATIONAL EXPERIENCE WITH THE NBTI-BASED SUPERCONDUCTING UNDULATORS (SCUs) AT THE APS

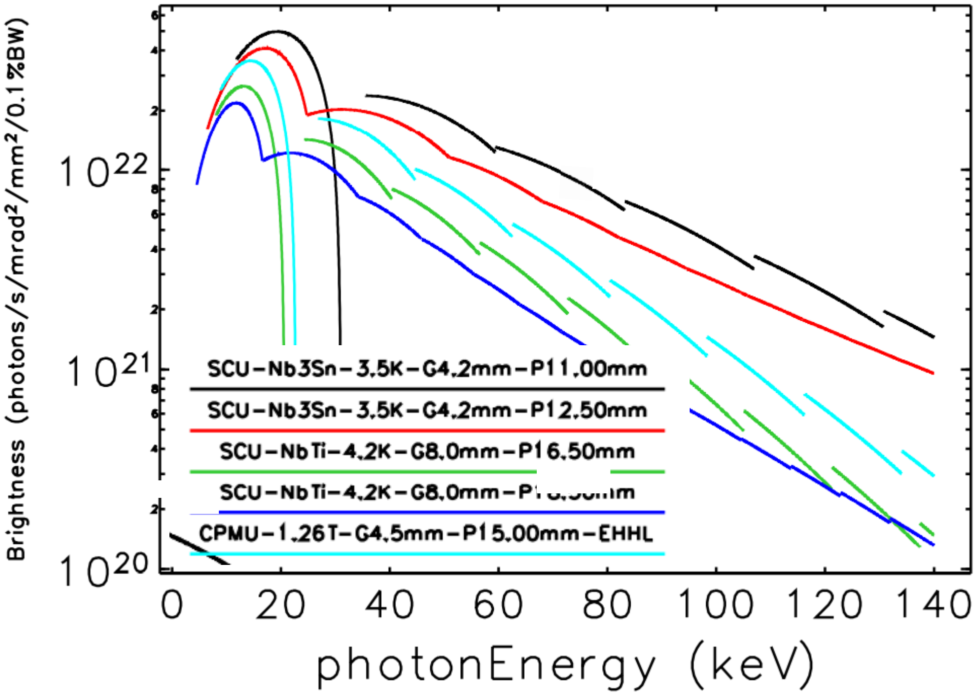
ID	Period [mm]	Magnetic length [m]	In-operation	Availability since installation [%]
SCU18-1 [1]	18	1.1	Since 2015	99.44
SCU18-2	18	1.1	Since 2016	99.99
Helical SCU [2]	31.5	1.2	Since 2018	96.76


SCU 18-1 at APS's Sector 1

- APS SCUs accumulated an excellent record of reliable performance
- Availability of SCUs for users' operation matches the best PM IDs while their radiation performance is superior.
- Building on this successful experience, 4 more SCUs will be fabricated – 2 is 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



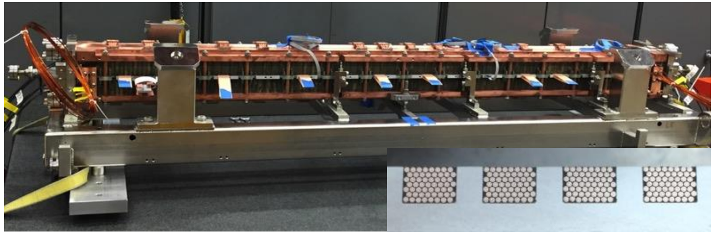
M. Borland, private communication, April 4, 2022.

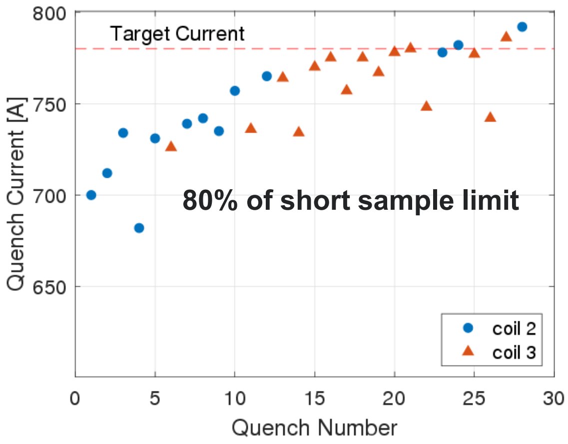
The device length is 3.8 m for SCUs and 4.4 m for CPMU

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

NB_3SN 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

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)

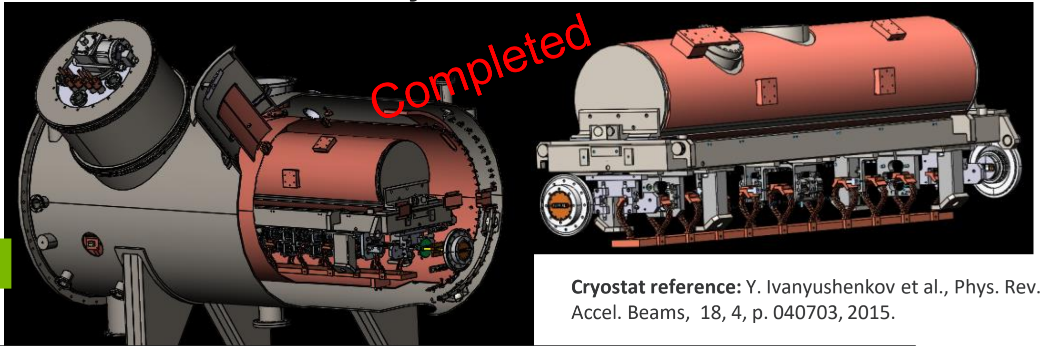
- Design optimization
- Performance confirmation

Scaling short prototypes to 26.5 periods (~0.5 m)

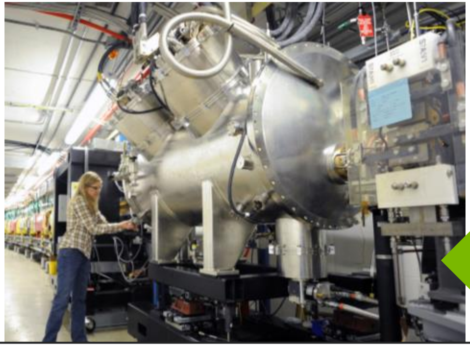
- Quench detection & protection
- Coil to ground Insulation

59.5 periods (~1.1 m) Nb_3Sn SCU magnets

Cryostat modifications



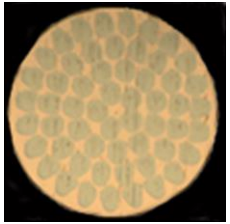
Cryostat reference: Y. Ivanyushenkov et al., Phys. Rev. ST Accel. Beams, 18, 4, p. 040703, 2015.



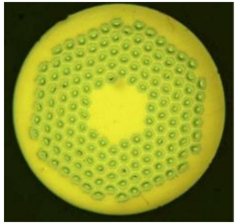
The goal is to develop a Nb_3Sn undulator and install it on the APS's storage ring for testing and operation as the first Nb_3Sn-based SCU

CHALLENGES WITH BUILDING NB_3SN SCUs AND DESIGN SPECIFICATIONS

- Stable wire
- Mechanical design
- Core/Former insulation wire insulation
- Quench detection and protection



0.6 mm NbTi wire, 65 µm filament

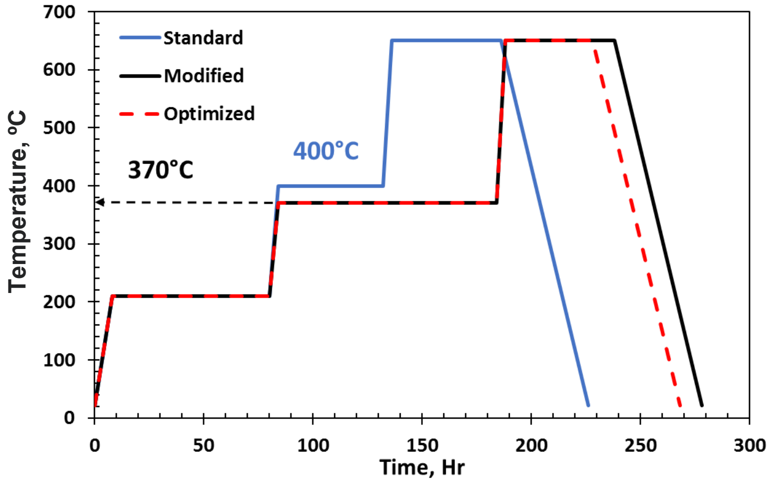


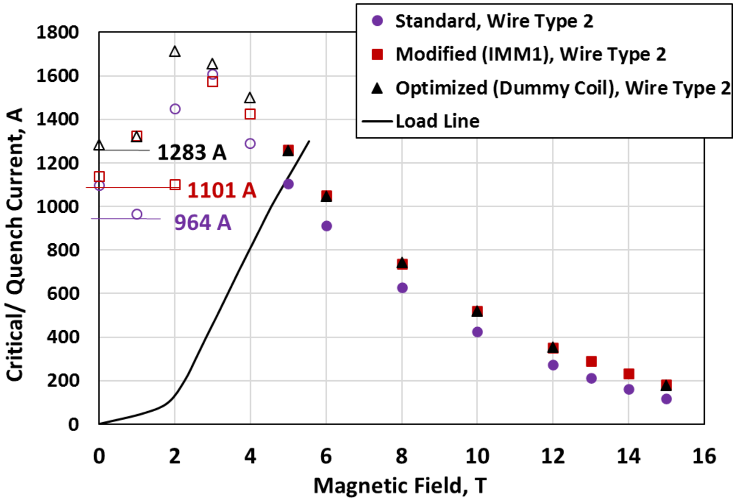
0.6 mm Nb_3Sn wire, 35 µm filament, RRP 144/169

Undulator specifications	Nb_3Sn	NbTi version (in operation)
~ Undulator on axis design field, T (20% higher)	1.17	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

HEAT TREATMENT OPTIMIZATIONS FOR THE BEST STABILE OPERATION

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





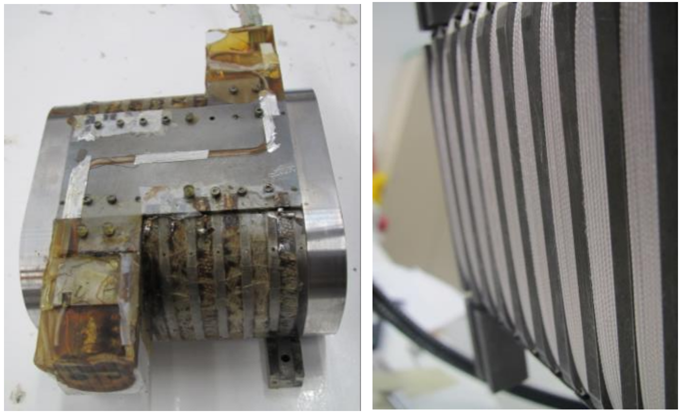
Open symbols indicate premature quenches. The optimized heat treatment increased the unstable current from the standards cycle's 964 A to 1283 A, which is greater than the Short Sample Limit (SSL) of 1205 A.

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

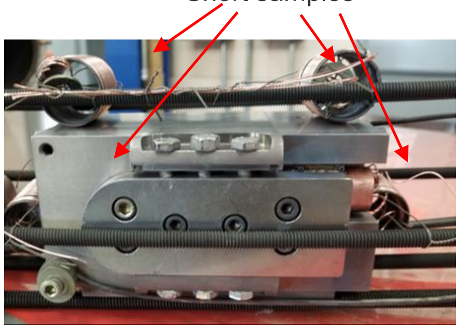
Fermilab Argonne NATIONAL LABORATORY

DESIGN OPTIMIZATIONS THROUGH 8-CM-LONG (10-POLE) PROTOTYPES

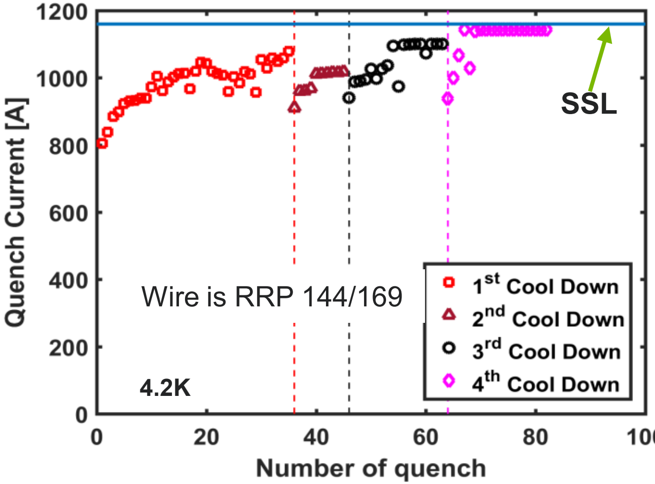
10-pole short prototypes



Short samples

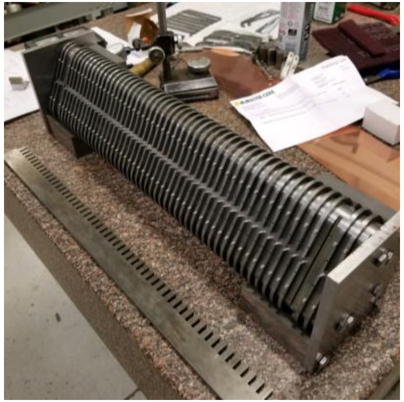


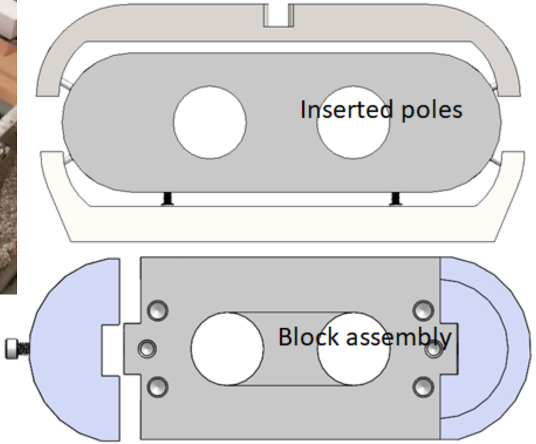
Short samples and magnet just before the heat treatment at Fermilab

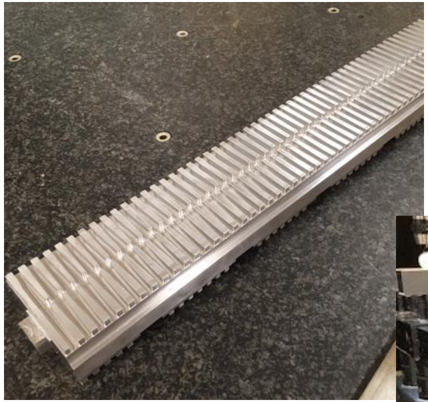


- Performed magnetic and mechanical simulations to optimize the winding groove
- Developed a new coil-to-ground mica insulation
- Optimized winding scheme

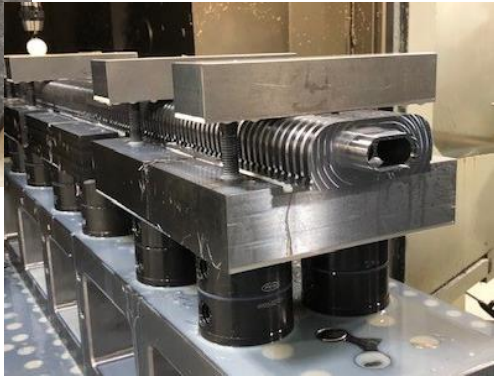
THE MAGNETIC CORE MACHINING OPTIMIZATIONS







Assembly and holding tight tolerance requirements (50 μm on the winding grooves and 30 μm flatness) have become very challenging



Single piece 1.1 m long magnet design

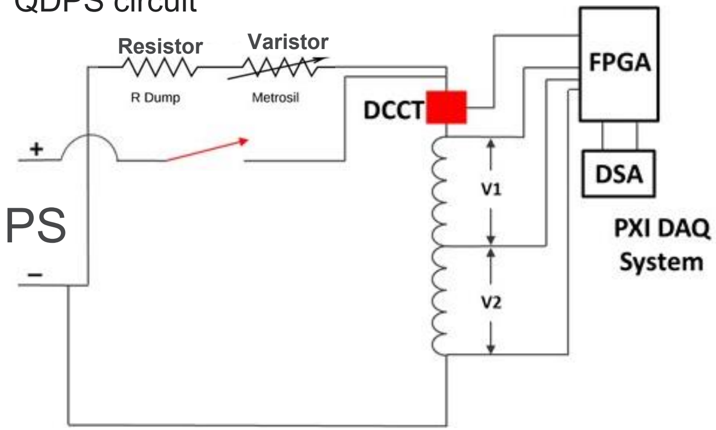
- Optimized the magnet former structure to easy machining and hold the tight tolerance requirements
- Materials (core and reaction tooling) were stress relieved at above the maximum reaction temperature to prevent deformation

I. Kesgin *et al.*, *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-5, Aug. 2021, Art no. 4100205

IMPROVEMENTS ON THE 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
  - incorporated varistor in series to resistors
  - Designed and fabricated the QDPS.

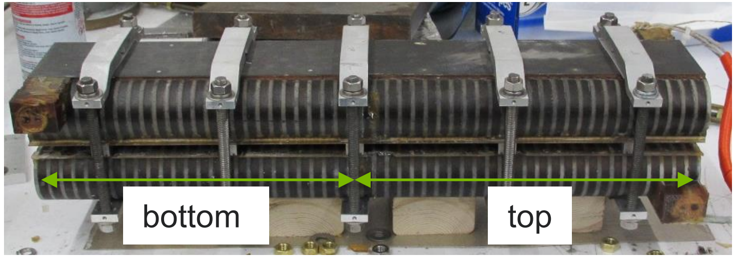
QDPS circuit



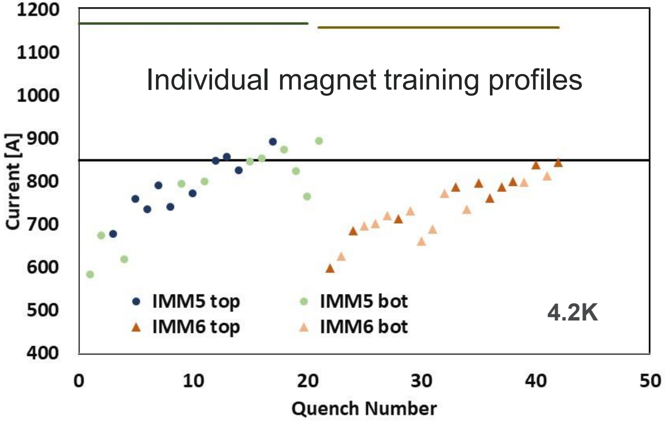
QDPS

Varistor is used to limit the maximum voltage

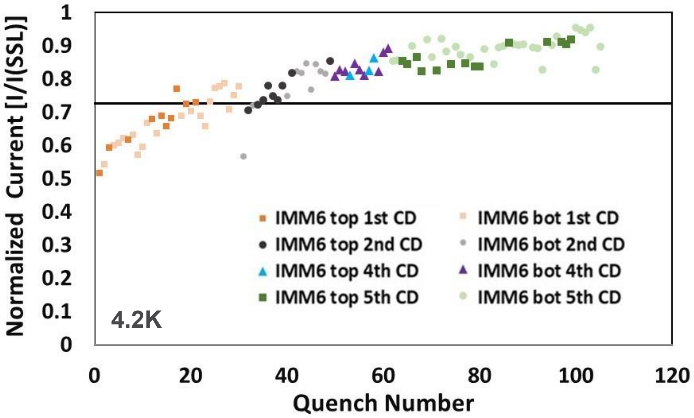
EVALUATING THE DESIGN BY 0.5 M LONG (26.5 PERIOD) NB_3SN UNDULATOR MAGNETS



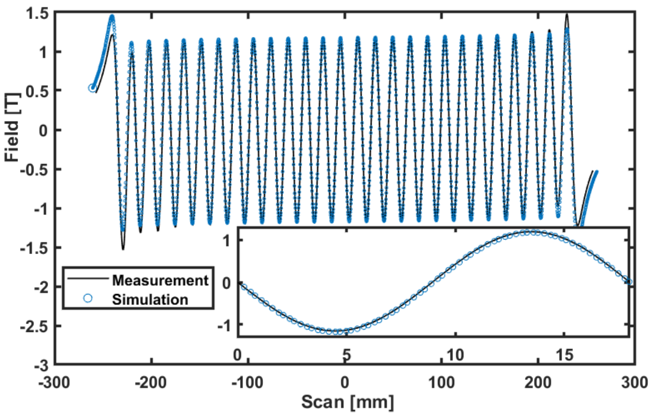
0.5-m-long Nb_3Sn undulator



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 magnetic structures successfully tested and delivered the required performance

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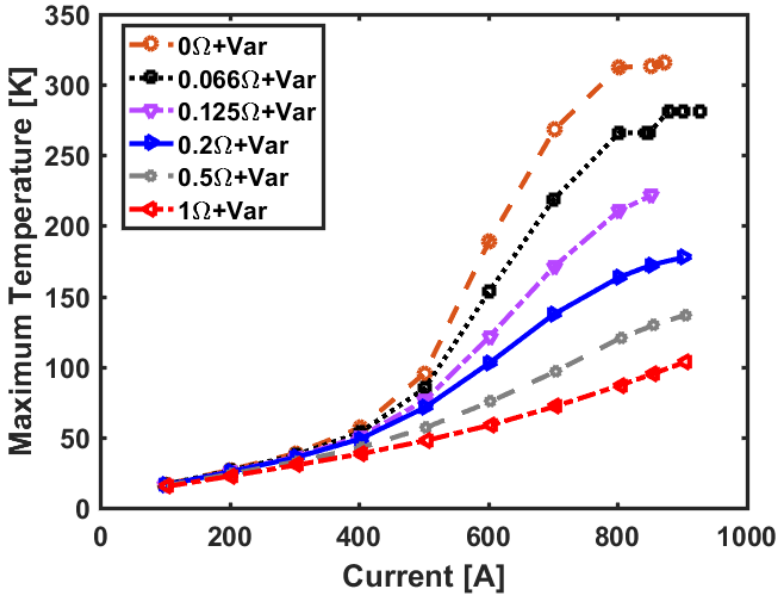
SAFE VOLTAGE AND HOT SPOT TEMPERATURE ANALYSIS DURING A QUENCH

$$\int_{t0}^{tend} \frac{I^2(t)}{A_w A_{Cu}} dt = \int_{T_0}^{T_{max}} \frac{C(T)}{\rho_{Cu}(B, T)} dT$$

T_{max} is the time dependent maximum hot spot temperature
I is the time dependent current
t_0 to t_{end} are the quench start and end times
$\rho_{Cu}(B, T)$ is the temperature and magnetic-field-dependent copper resistivity.
A_w and A_{Cu} are the cross-sections of the wire and copper stabilizer
$C(T)$ is the temperature dependent volumetric specific heat

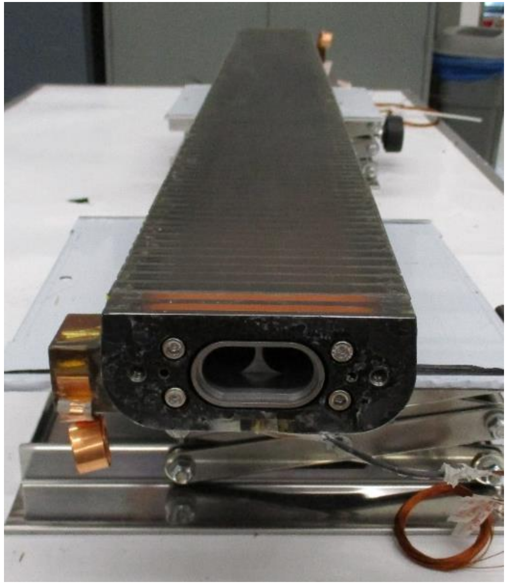
A delicate balance between the hot spot temperature and maximum quench voltage is required



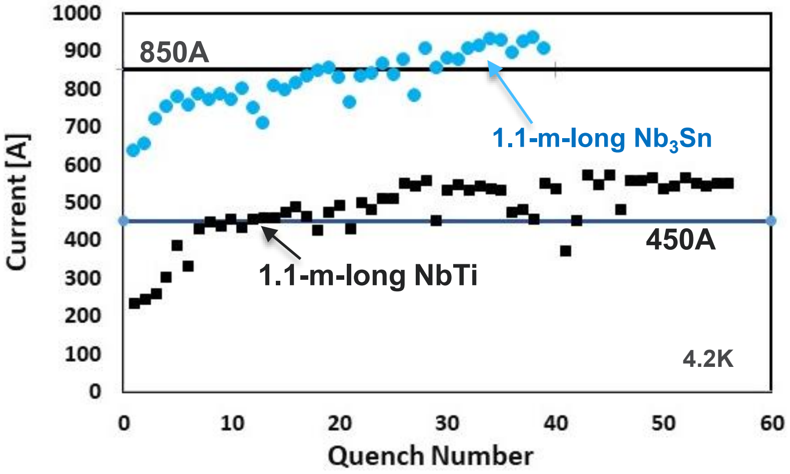
0.5-m-long undulator magnetic structure

I. Kesgin *et al.*, *IEEE Trans. on Appl. Supercond.*, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4100605,

TRAINING OF THE FIRST 1.1-M-LONG NB_3SN MAGNET (59.5 PERIODS) AND COMPARISON WITH THE SAME LENGTH NBTI VERSION



A photo of 1.1-m-long Nb_3Sn undulator magnet

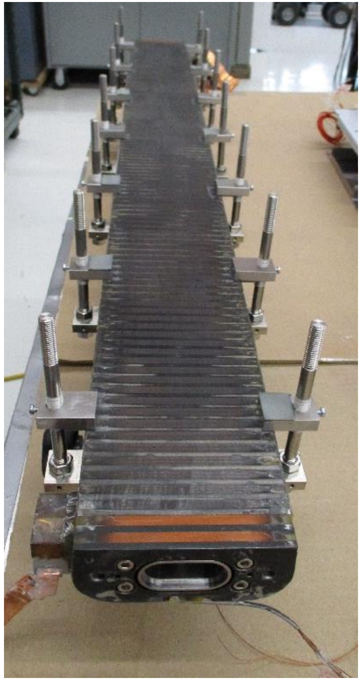


- The first 1.1m-long SCU magnet was successfully trained at above the maximum operational current of 850A.
- The training behavior is similar to NbTi SCU magnets.

The magnet design scaled to 1.1-m-long final length and the first magnet was successfully trained up to 960A in the second cool-down, which is 13% higher than the maximum operating current

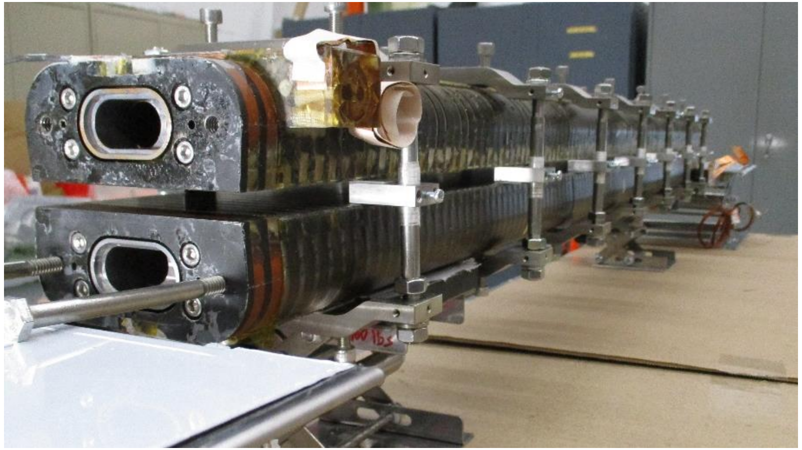
TESTING UNDULATOR MAGNET ASSEMBLY

Magnet during assembly



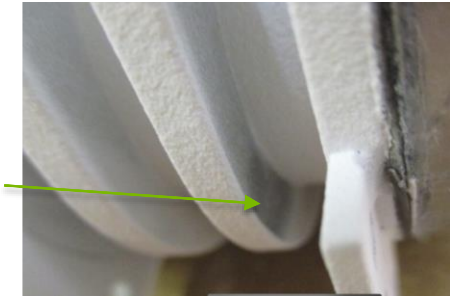
Gap spacers were used to secure the magnets

Assembled undulator magnetic structure



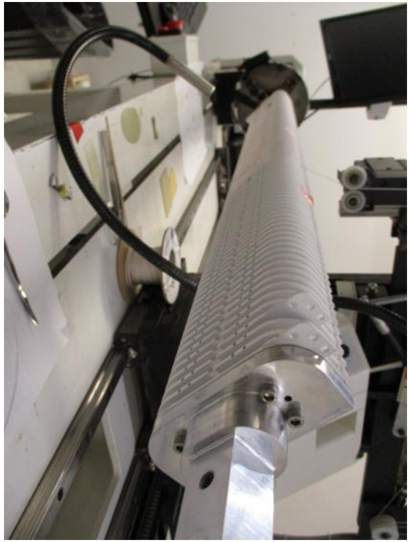
- The first magnet demonstrated excellent training memory
- Consistent behavior observed in the 0.5-m-long prototypes

Non-uniform coating resulted in a very thin coating layer in some areas and caused damage in the second magnet

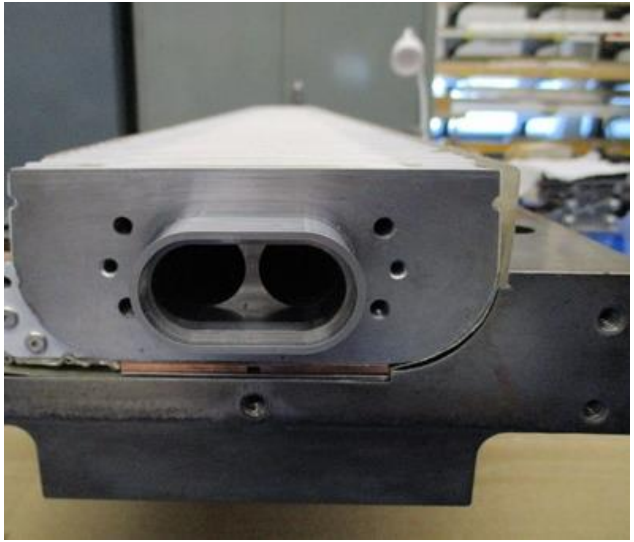


FABRICATION OF THE 3RD 1.1-M-LONG MAGNET

Coating imperfections were discussed with the company to improve the quality control



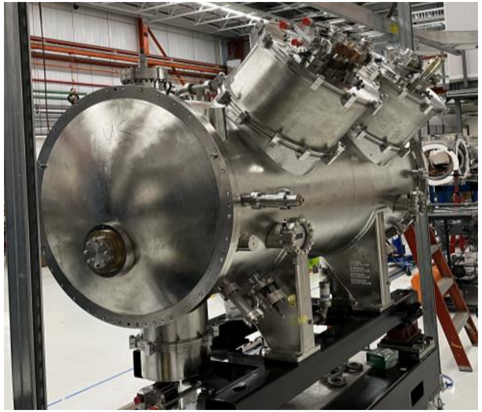
During winding



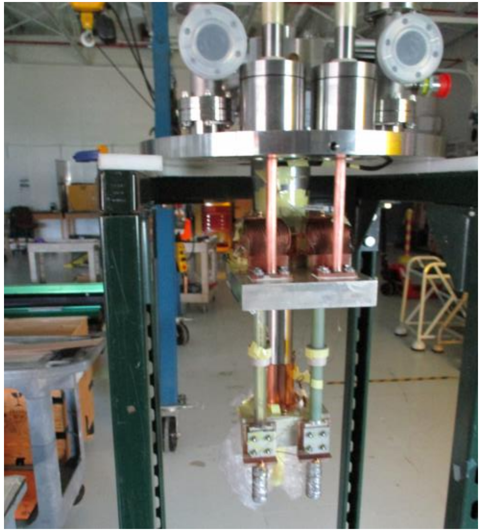
Magnet and reaction tooling assembly

Currently, the assembled structure is being heat treated at the Fermilab facility

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
  - Closed-system, operating zero boil-off mode

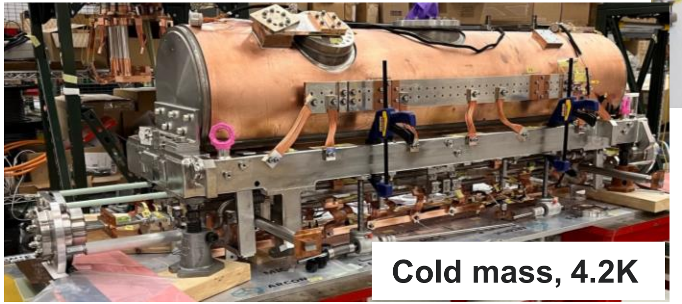


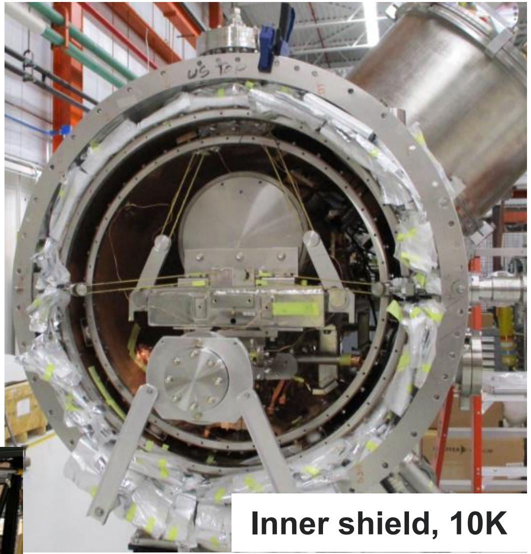
Cryostat modifications

- Optimized the current lead design for the 850A, which almost doubles the NbTi version, 450A
- Added windows to monitor the cold mass movement.
- All the flexible thermal connections were redesigned and newly fabricated.

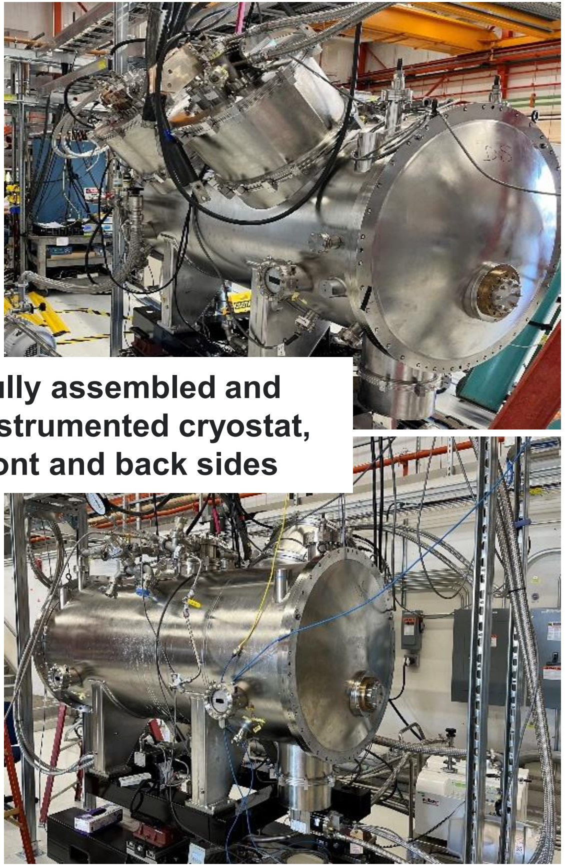
CRYOSTAT ASSEMBLY FOR ENGINEERING COOLDOWN


Outer shield, 50K


Cold mass, 4.2K

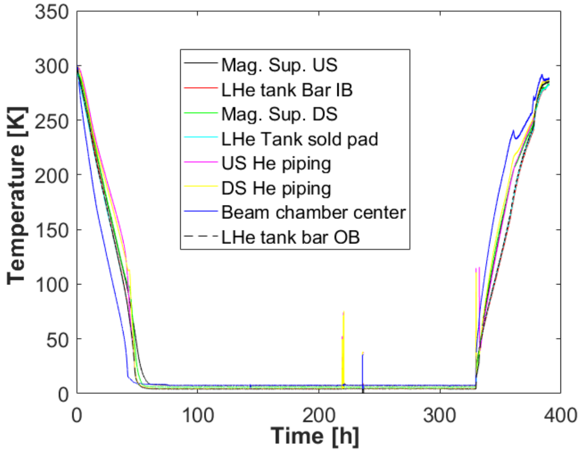

Inner shield, 10K

Beam chamber was thermally tied to the inner shield and runs about 10K

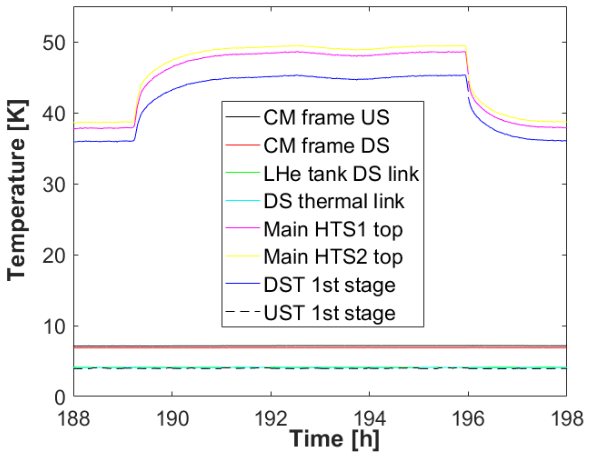

Fully assembled and instrumented cryostat, front and back sides

ENGINEERING COOLDOWN TESTS AND PERFORMANCE

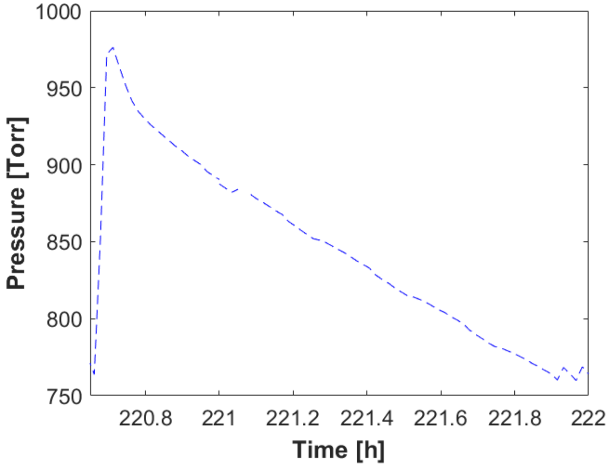
The cryostat was instrumented with 40 temperature sensors,13 heaters, and voltage taps to test the mechanical, cryogenic, electrical, and electronic components with dummy magnets



- Temperature timeline profiles of 8 out of 40 sensors
- The cryostat was maintained normal operation condition for about 11 days.
- 2.5 days for the warmup and 2.5 days for the cooldown.



Temperatures at the top HTS leads increased by about 12 K at full operating currents, but the absolute temperature was less than the maximum allowed limit of 65 K



The quench recovery time is about 70 minutes. It is about 50 minutes when energy dissipation through the dump resistor is considered, which is comparable to the currently operating devices.

The newly modified cryostat has successfully tested and demonstrated excellent performance. It is currently ready to accept the Nb_3Sn undulator magnets.

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SUMMARY

- ✓ APS continues to develop state-of-the-art superconducting undulator technologies.
- ✓ The Nb_3Sn undulator magnet design has been iteratively optimized using simulations.
- ✓ 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).
- ✓ 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 960A in the second cooldown, which is 13% higher than the maximum operating current of 850A.
- ✓ The second magnet displayed weak insulation behaviors and fabrication of the third magnet is ongoing.
- ✓ Cryostat modifications completed and cool down test showed excellent cryogenic performance. It is ready for the assembly of the 1.1-m-long Nb_3Sn magnets.
- ✓ Once the device is fully characterized, we plan to install it on the APS’s storage ring to deliver 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 magnets, fabrications, and characterizations. Also design of the cryostat modifications, their fabrications and assemblies.

Stephen MacDonald, Matthew Kasa, John Andrist, Joel Fuerst, 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)

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The Fermilab team optimized and performed heat treatments of the Nb_3Sn magnets and tested the short samples. The Fermilab team also contributed to the magnet design.

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

Fermilab

The LBNL team performed quench simulations, used those in the design of the quench detection and protection system (QDPS), and fabricated the QDPS.

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

BERKELEY LAB

Thank you so much !

References:

1. 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, 2022, Art no. 4100605.
2. 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, Art no. 4100205, 2021.
3. 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, Art no. 4100605, 2020.
4. I. Kesgin et al., "Development of Short-Period Nb3Sn Superconducting Planar Undulators," IEEE Trans. on Appl. Supercond., vol. 29, no. 5, pp. 1-4, Art no. 4100504, 2019.
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.
6. A. V. Zlobin *et al.,* "Advantage and Challenges of Nb_3Sn Superconducting Undulators," 9th International PAC, Vancouver, Canada, 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.