SuperPower Inc.

superior performance.
powerful technology.

Second Generation HTS Wire for Electric Power Applications

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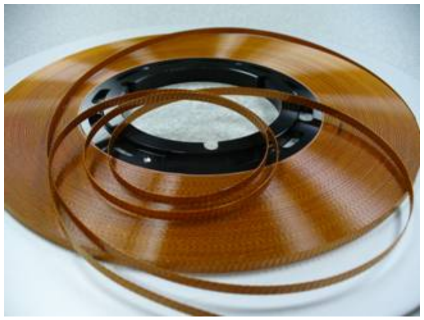
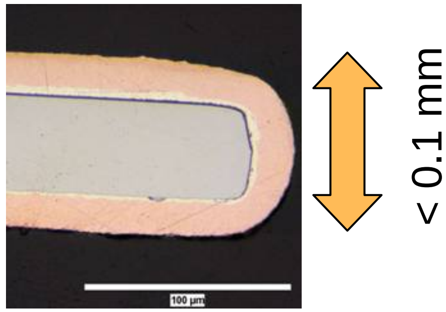
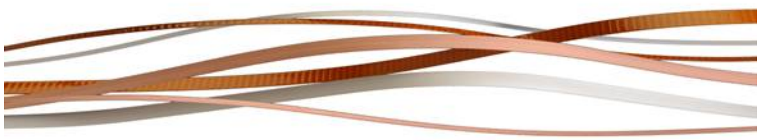
2009 KEPRI-EPRI Joint Superconductivity Conference, Nov 16-19, Daejeon, South Korea

SuperPower develops advanced 2G HTS technology and manufactures commercial wires





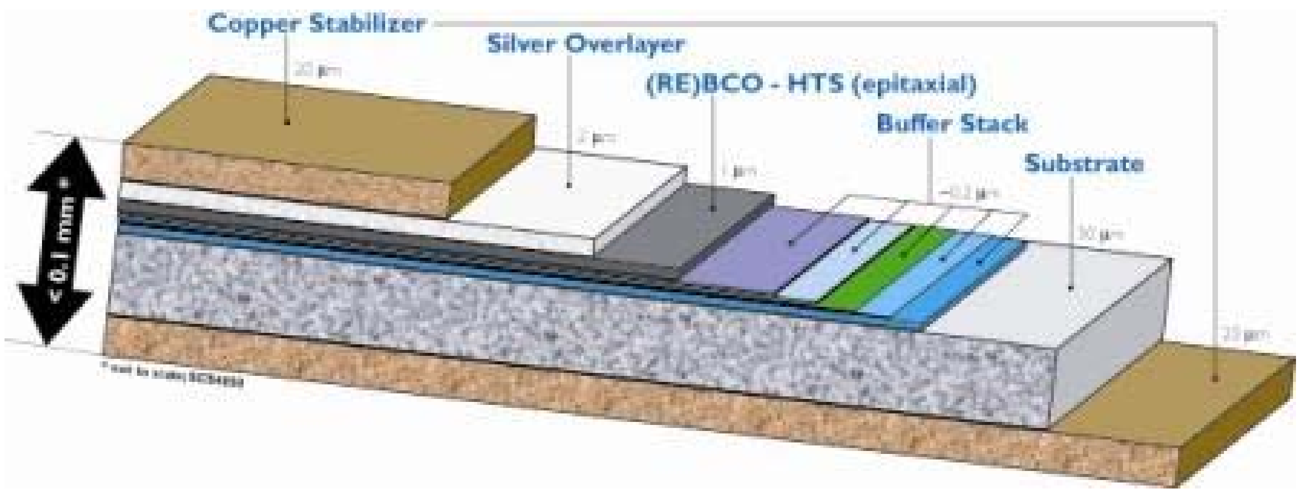


Surround Copper Stabilizer: by electroplating; electric stability, hermetic seal. Solder temperature up to 250 °C. Minimal non-HTS edges

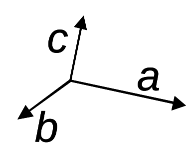
HTS layer (biaxially aligned): by *MOCVD*, high dep. rate + large dep. zone area ➔ high throughput

Buffer stack: IBAD-MgO based, biaxial texture formation with ~ 10 nm film ➔ high throughput; wide range of substrate selection

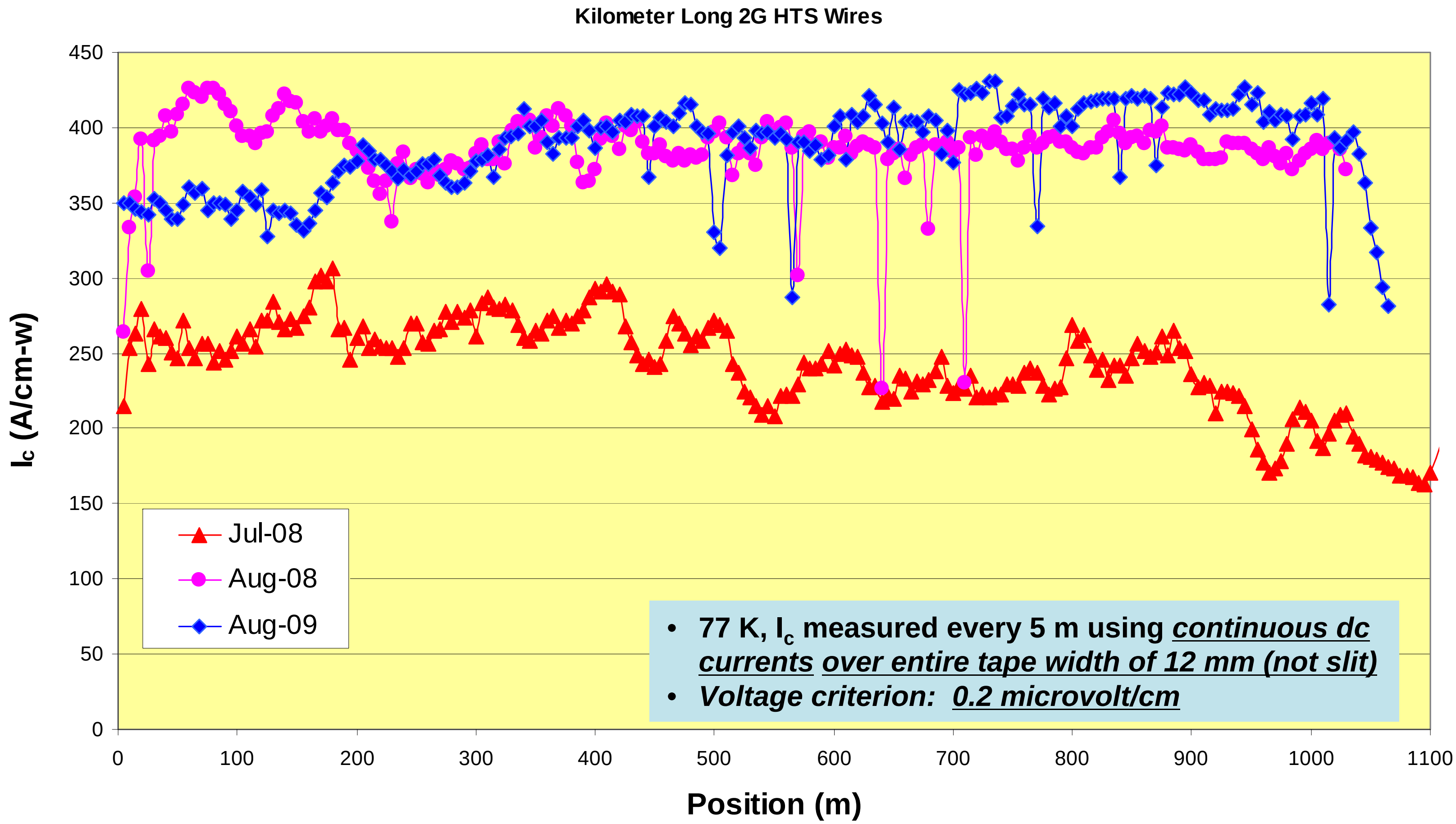
Substrate: High-strength, thin, flexible, highly resistive and non magnetic ➔ high J_e, low ac loss



HTS grain orientation



IBAD-MgO-based MOCVD 2G HTS wire is produced in kilometer lengths



- 77 K, I_c measured every 5 m using ***continuous dc currents*** ***over entire tape width of 12 mm (not slit)***
- ***Voltage criterion:*** ***0.2 microvolt/cm***

- **Minimum current (I_c) = 282 A/cm-w over 1065 m**
- **2009 new world record: $I_c \times$ Length = 300,330 A-m**

Albany HTS Cable Project

- 350m long - 34.5kV - 800A_{rms} - 48MVA
- Cold dielectric, 3 phases-in-1 cryostat, stranded copper core design
- Cooled with subcooled, pressurized LN2 operating at ~ 69K
- Two Phases – Phase I - 320m + 30m BSCCO
  – Phase II - 30m BSCCO replaced by 30m YBCO cable

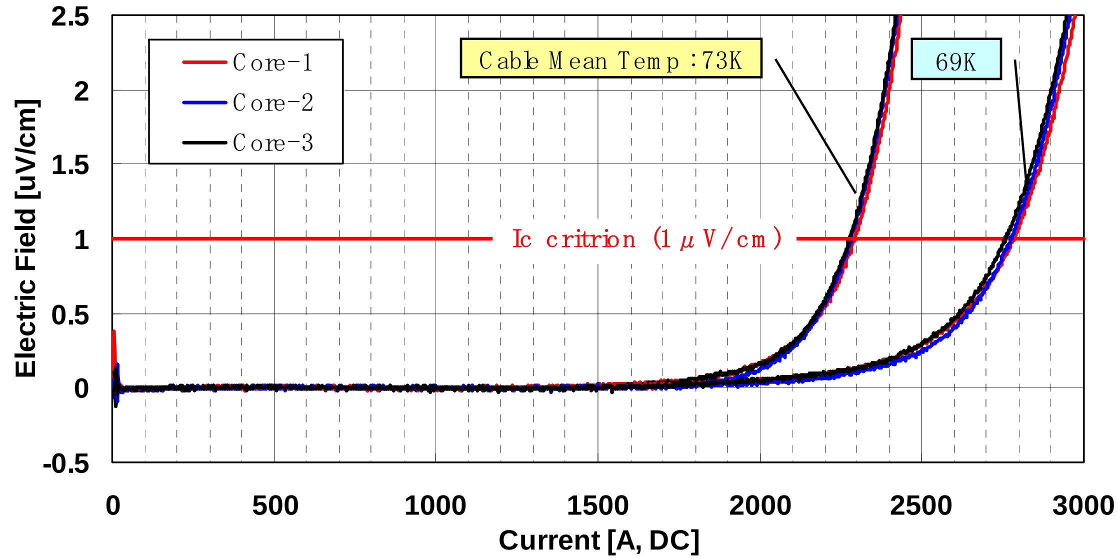
SuperPower Inc.	Project Manager; Site infrastructure, Manufacture of 2G HTS wire
nationalgrid	Host utility, conventional cable & system protection, system impact studies
SUMITOMO ELECTRIC	Design, build, install, and test the HTS cable, terminations, & joint
Linde	Design, construct and operate the Cryogenic Refrigeration System, and provide overall cable remote monitoring and utility interface
NYSERDA; Department of Energy, United States of America	Supported by Federal (DOE) and NY State (NYSERDA) Funds


Section of 30m 2G Cable in Phase II using ~ 10 km SuperPower® 2G HTS Wire

30 meter Phase II YBCO Cable

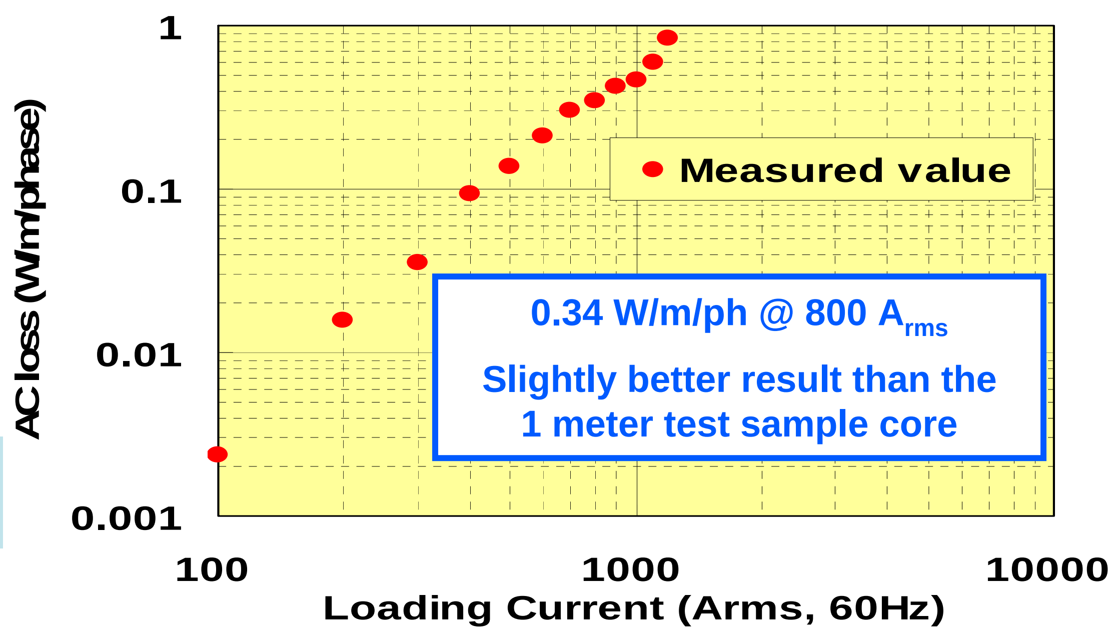
DC I_c test results

Cable I_c (DC) measurement at commissioning of Phase II – Results match Phase I performance



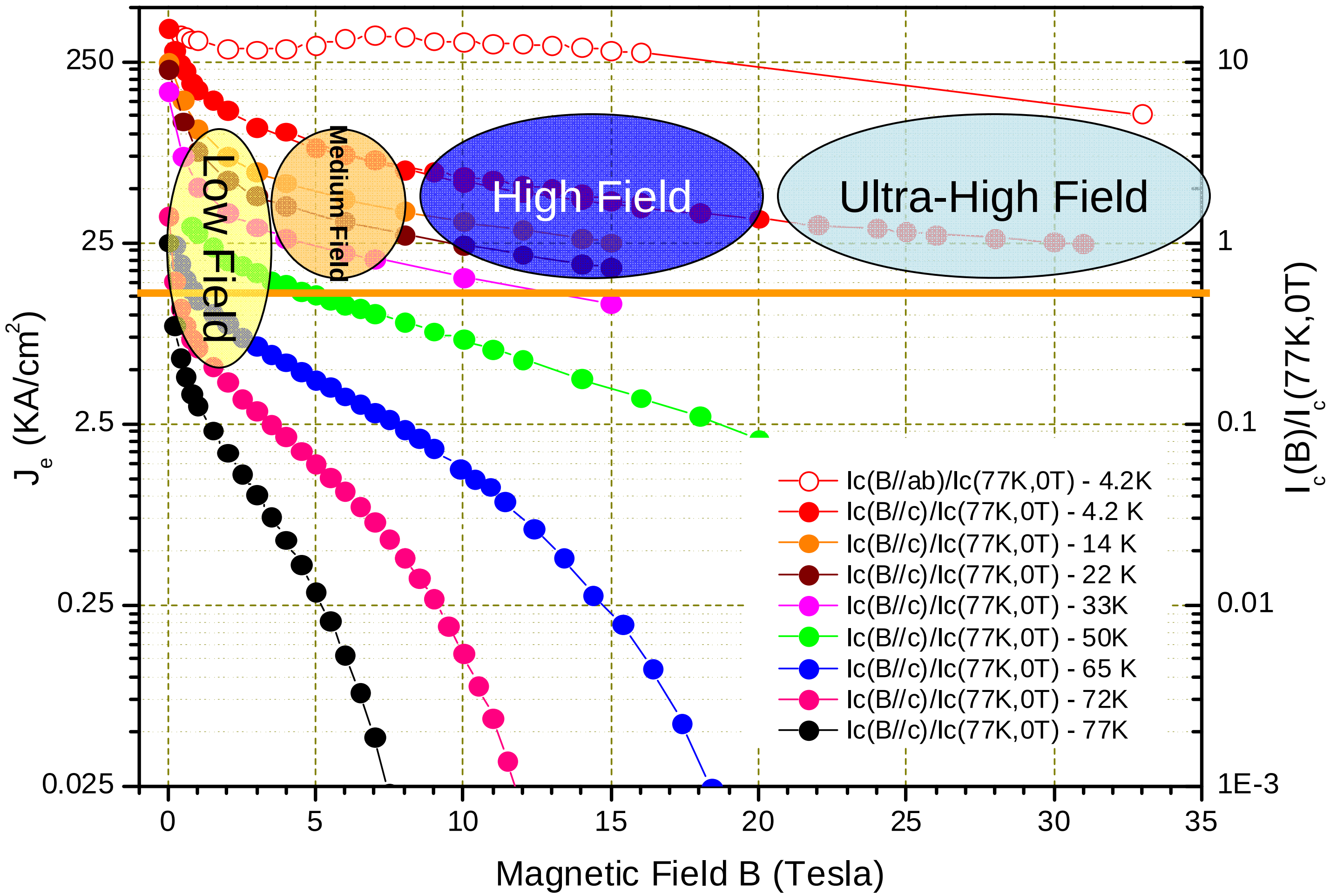
AC Loss Measurement

- Sample: 2.5 meter single core
- Current loading: go & return through conductor and shield
- Measuring: Lock-in amplifier with electrical 4 terminals



Phase II in operation for 3 months in 2008 with satisfactory performance

Excellent in-field performance makes a wide range of real-world applications possible



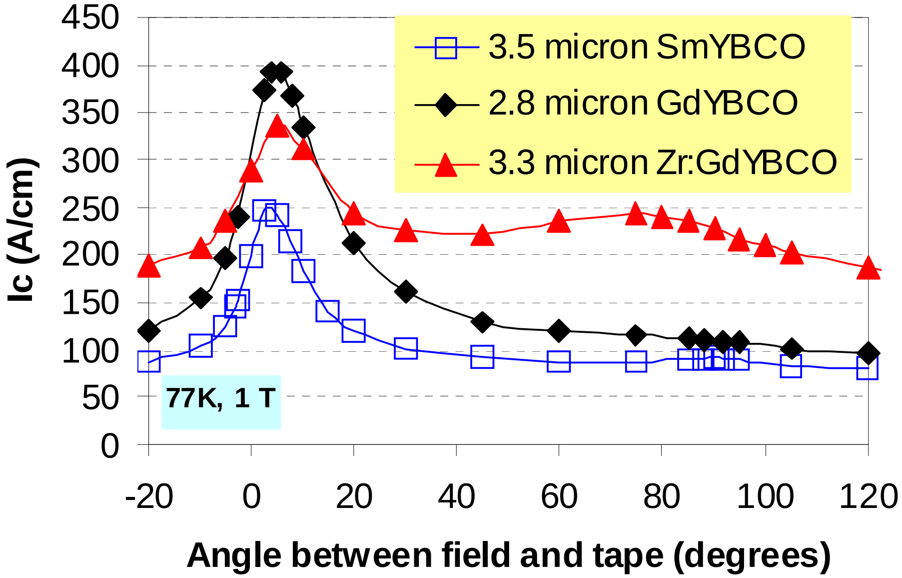
High Temp, Low Fields:
- Cable
- SFCL
- Transformer
- Motor/generator
- Plasma Confinement
- Xtal growth magnet
- Magnetic separation

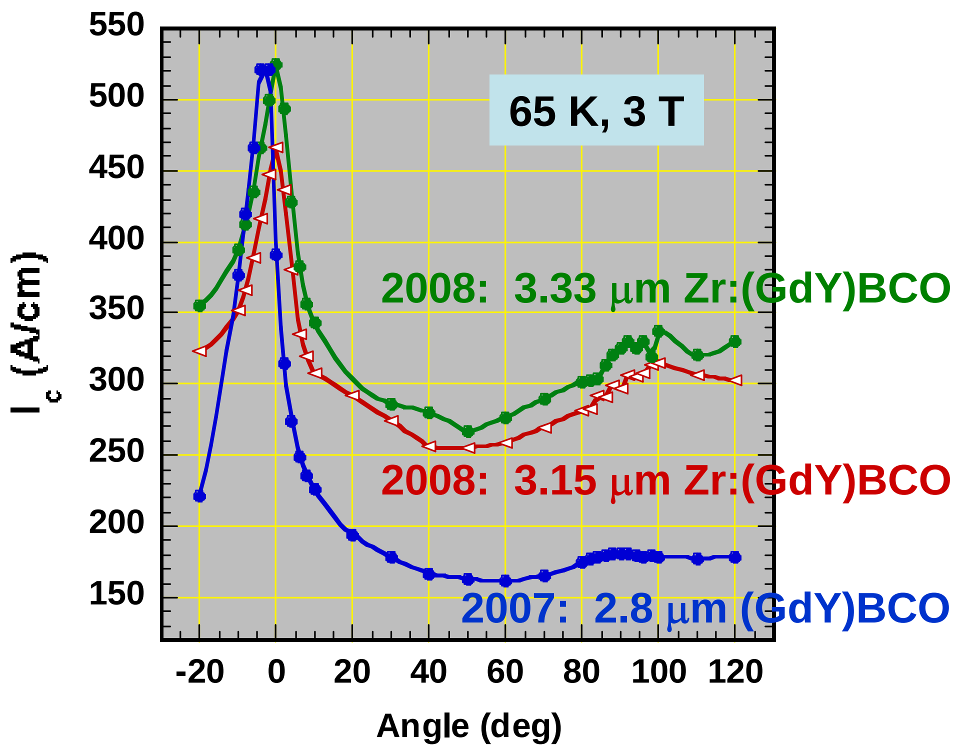
Medium Temp, Medium Fields:
- Motor/generator
- Plasma Confinement
- Crystal Growth Magnet
- Magnetic separation
- Maglev
- SMES

Low Temp, High Fields:
- SMES
- High-Field MRI
- High-Field Insert
- NMR

* J_e is calculated based on I_c (77 K, 0T) = 100 A/4 mm (surr. copper stabilized) and scaling factors measured by D. Larbalestier, *et al* at FSU and E. Barzi, *et al*. of Fermi Lab.

2008: Zr doping was demonstrated in MOCVD to achieve dramatic improvements in in-field performance





- 97% increase in minimum I_c to 186 A/cm corresponds to J_e of 28,500 A/cm^2 (no copper)
- 85% increase in I_c (B ⊥ tape) to 229 A/cm corresponds to J_e of 35,200 A/cm^2 (no copper)

- 67% increase in minimum I_c to 267 A/cm corresponds to J_e of 41,000 A/cm^2 (no copper)
- 88% increase in Ic (B ⊥ tape) to 340 A/cm corresponds to J_e of 52,300 A/cm^2 (no copper)

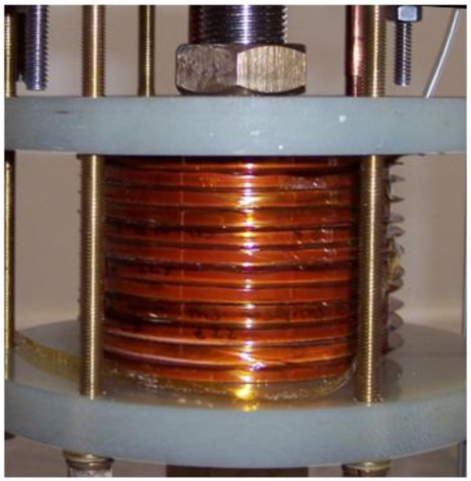
In 2009, Zr-doping chemistry successfully transferred to production line

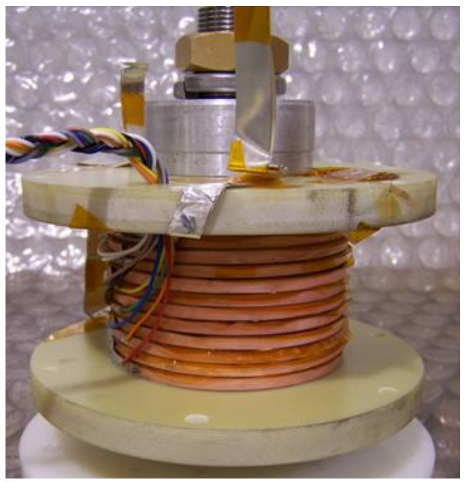
Selvamanickam, Xie and Dackow, 2009 DOE HTS Program Review

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

Two coils made with Zr-doped 2G wire

Identical size, same quantity of Zr-doped wire with similar critical current performance at 77 K, zero field.



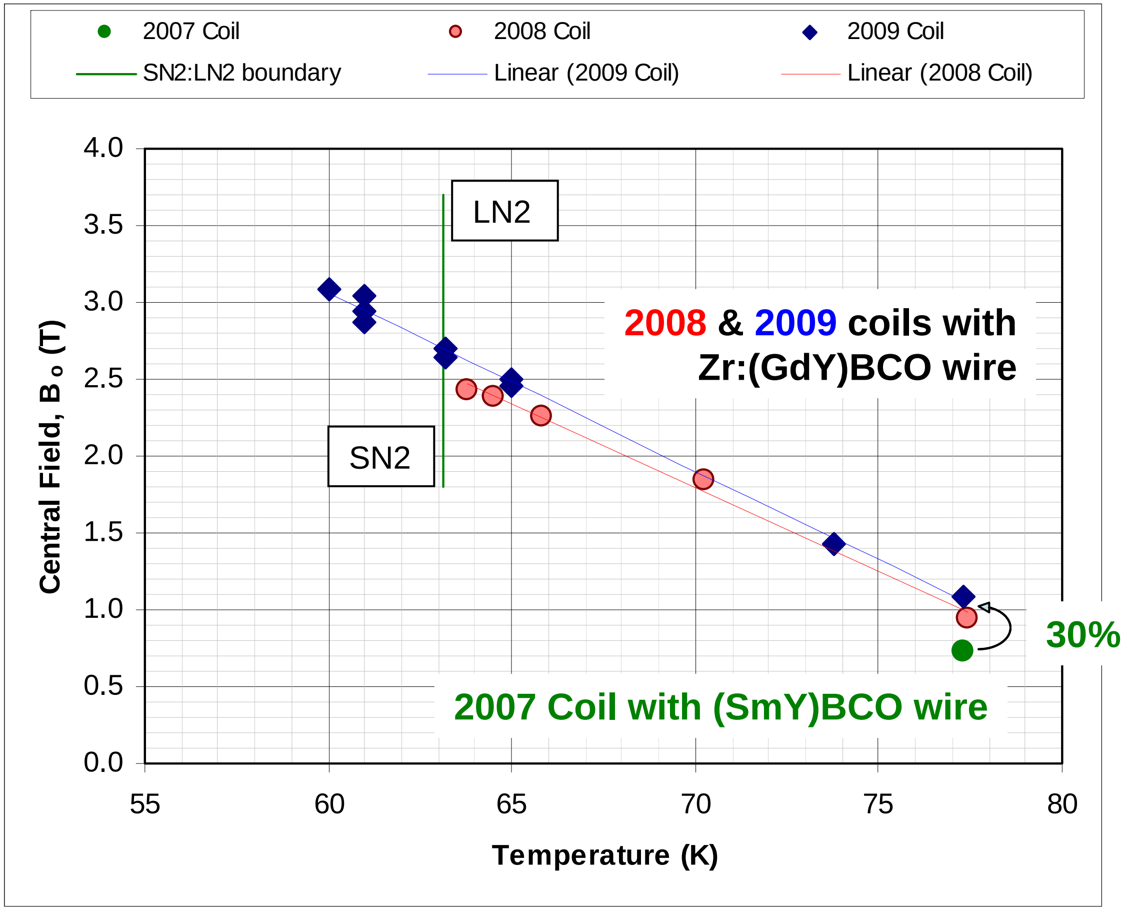


	Coil -1	Coil - 2
Field at 77 K	**0.97 T**	**1.09 T**
Field at 65 K	**2.39 T**	**2.5 T**
Field at 61 K		**3.0 T**

	Coil -1	Coil - 2
Coil ID	21 mm (clear)	21 mm (clear)
Winding ID	28.6 mm	28.6 mm
Winding OD	~ 87 mm	~ 84 mm
Coil Height	~ 56.7 mm	~ 57.8 mm
# of Pancakes	12 (6 x double)	12 (6 x double)
2G wire used	~ 480 m	~ 480 m
# of turns	~ 2664	~ 2688
Coil Je	~ 163.5 A/mm^2 @ 100A	~ 167.9 A/mm^2 @ 100A
Coil constant	41.9 mT/A	42.2 mT/A
Tape Ic (77 K, sf)	72 to 97 A	90 to 101 A

Repeatable enhanced coil performance demonstrated with Zr-doped 2G wire

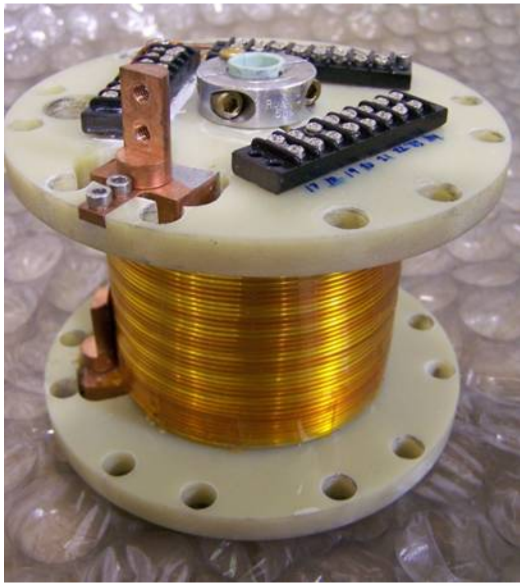
Zr doping provides enhanced performance in nitrogen cooling



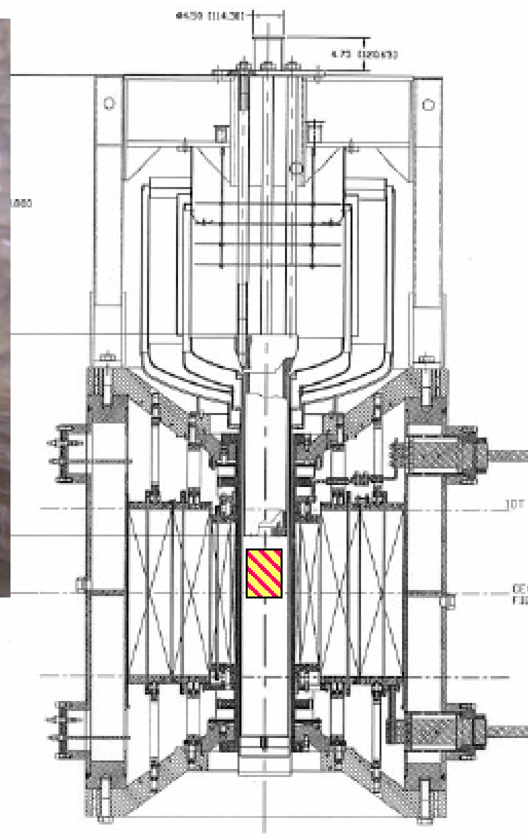
	T (K)	B_0 (T)
2009	77.3	1.09
	73.8	1.43
	65	2.47
	63.2	2.67
	61	2.95
	60	3.08
2008	77.4	0.95
	70.3	1.84
	65.8	2.26
	64.5	2.39
	63.8	2.43
2007	77	0.73

- 30% higher field in coils with made with Zr-doped chemistry
- 2008 and 2009 coils have larger winding I.D. and lower coil constant

2009 high field insert coil achieves record performance



Insert coil tested in NHMFL's unique, 20 T, 20 cm wide-bore, Bitter magnet



Coil ID	12.7 mm (clear)
Winding ID	19.1 mm
Winding OD	~ 84 mm
Coil Height	~ 73.6 mm
# of Pancakes	16 (8 x double)
2G wire used	~ 600 m
# of turns	~ 3696
Coil J_e	~155.3 A/mm^2 @ 100A
Coil constant	~ 51.8 mT/A
Wire I_c (77 K, sf)	120 A – 180 A (non Zr-doping)

Temperature (K)	77	65	4.2
Central field – self field (T)	**1.39**	**2.49**	**10.4**
Total Central Field – in background field (axial) (T)	**1.93**	**4.60**	**27.4**
With Background field (T)	1.0	3.0	19.89

Patrick Noyes,
Ulf Trociewitz, Huub Weijers,
Denis Markewicz,
David Larbalestier

HTS generator project

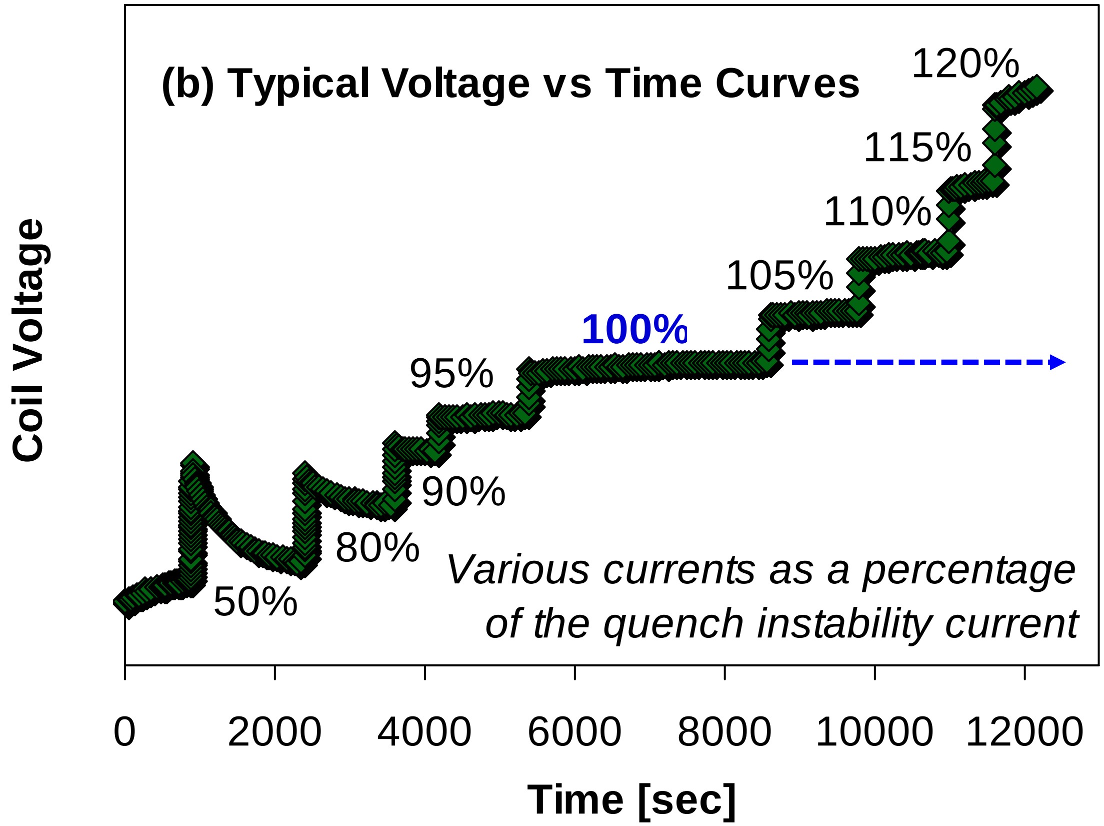
- Funded by US Office of Naval Research (ONR)
- Target operation: 36.5 MVA
- Partners: SuperPower, Baldor Electric, General Dynamics-Electric Boat, Naval Surface Warfare Center (Philadelphia), Naval Research Lab, Oak Ridge National Lab
- Current Phase: Conceptual design / risk reduction studies
  - Smaller / lighter weight tradeoff studies vs. efficiency vs. cost
  - HTS windings development
  - Rotor / stator design / development
  - Fabrication of test articles

2G HTS coil for thermal cycle testing at NRL

Terminal Blocks

- Model Coil 1: ~ 250 mm x 150 mm
- 250 m of 4 mm wide 2G HTS wire

NRL test results: Quench stability

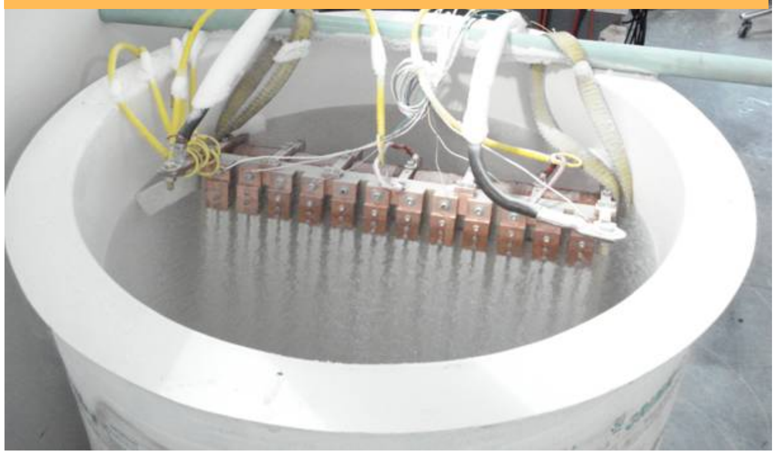


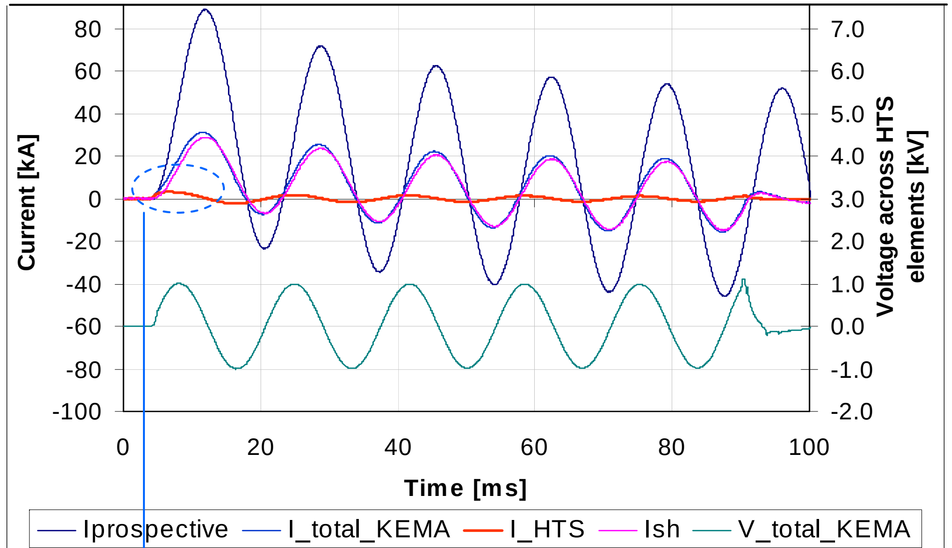
(b) Typical voltage-time curves for the same HTS coil. For each value of current, the voltage is monitored for some period of time to determine if it is stable. The highest current at which the voltage exhibits long term stability is designated the quench instability limit current.

Data from R. Holtz, NRL

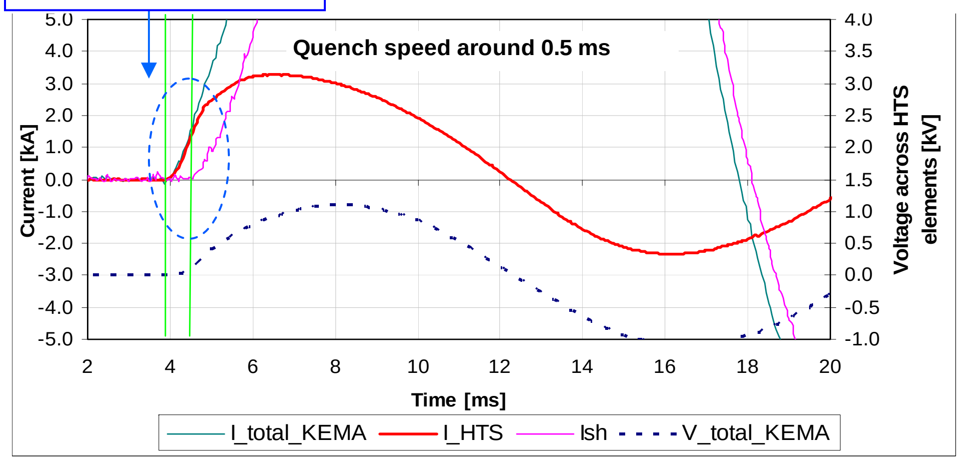
Proof of concept - 2G conductor for SFCL shows consistent, excellent performance

- **12 elements, 40 cm long with four 2G wires in parallel per element**





Fast response time



High-power SFCL test	2G
Prospective current	90 kA*
Limited current	32 kA
Peak current through element	3 kA
Response time	< 1 ms
Element quality range	Narrow

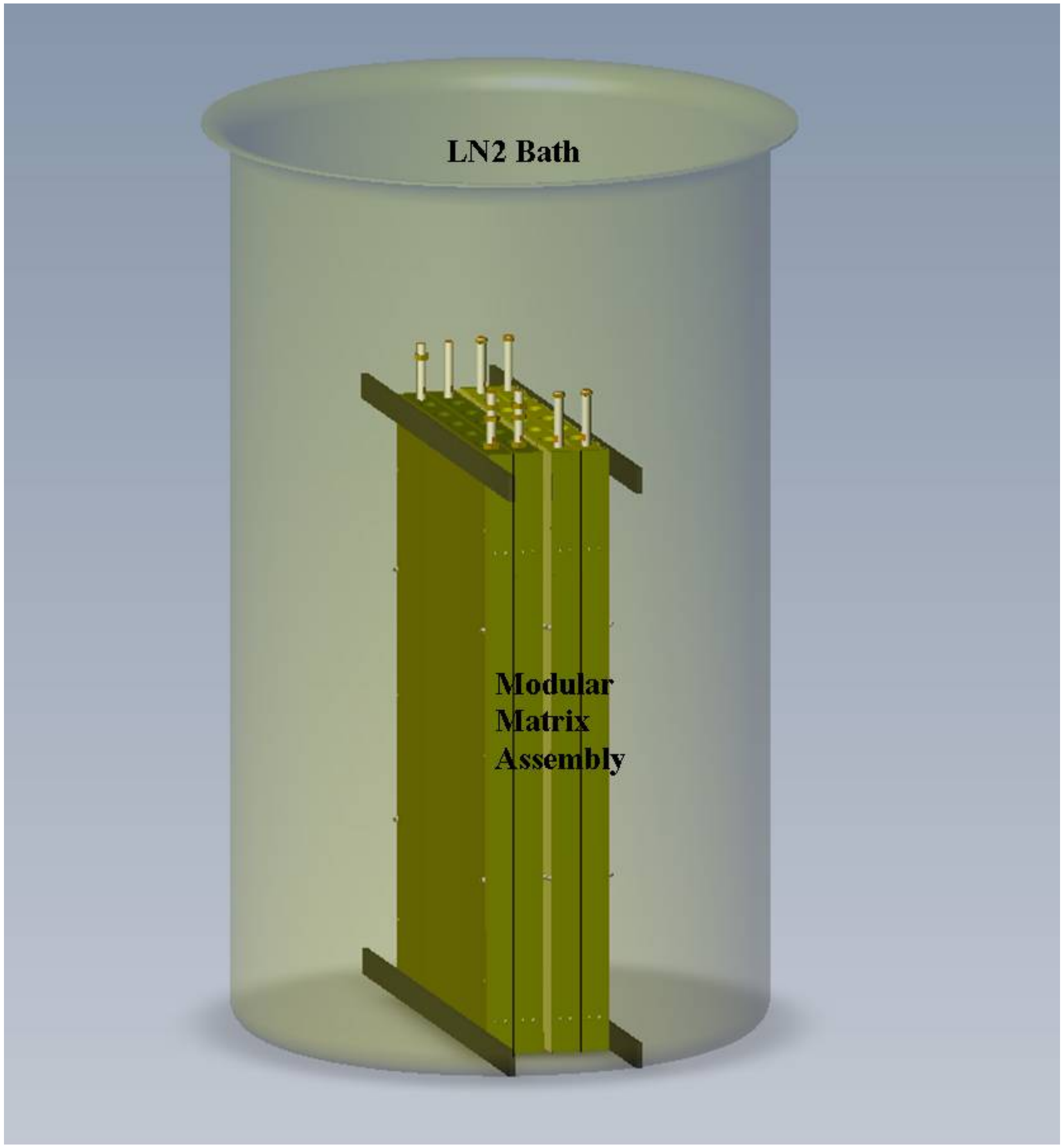
SFCL modular system design – components integration

Module Design Specification and Criteria

- **2G tape** – J_c, J/cm/tape, RUL Arms/tape, mechanical, thermal and electrical properties
- **Shunt Coils** – Zsh = Rsh + jXsh, X/R ratio, EM force withstand, thermal and electrical properties, connectors, size, weight, over-banding, ease of assembly and manufacturablity
- **HTS assembly** – Tape per element, RUL per element, element energy capability, connectors, size, cooling orientation, failure mechanisms and mitigation, losses and their effects on cryogenics design
- **HV design** – LN2 and GN2 design stress criteria, spacing between tapes, elements and modules, stress shield dimensions, using solid barriers or not, bushings and assembly integration, assembly supporting structure (post insulators), overall assembly to cryostat spacing and integration
- **Cryogenics** - LN2 flow control, LN2 and GN2 interface, pressurizing, safety issues, thermal handling of fault and steady state losses

Complete Transmission / Distribution System Design Boundaries

- Instrumentation, control and condition monitoring of SFCL system
- **Systems issues** - SFCL device testing, systems study and utility interfaces



2G modular RUL capabilities tested at FSU-CAPS

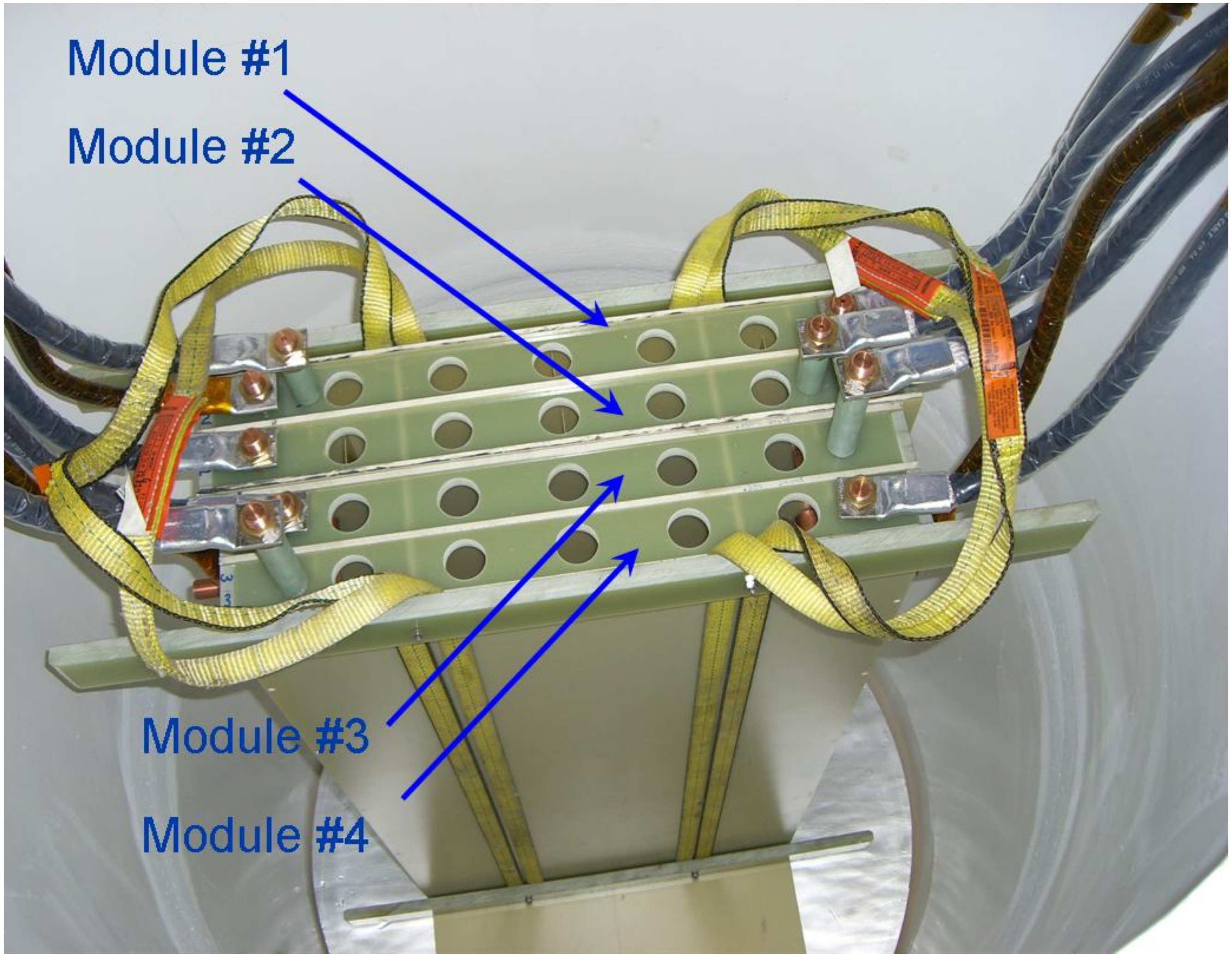
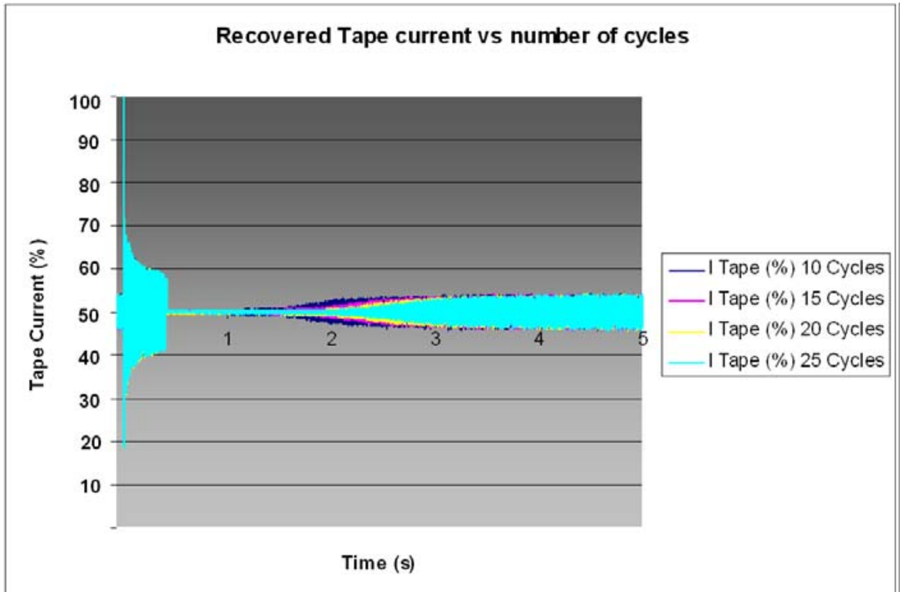


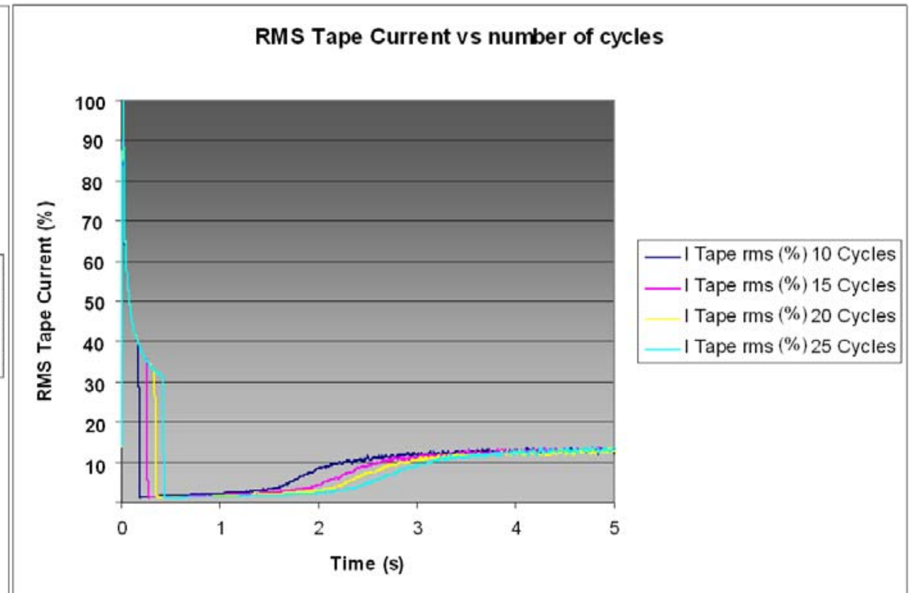
Photo of 4 modules in test dewar ready for test

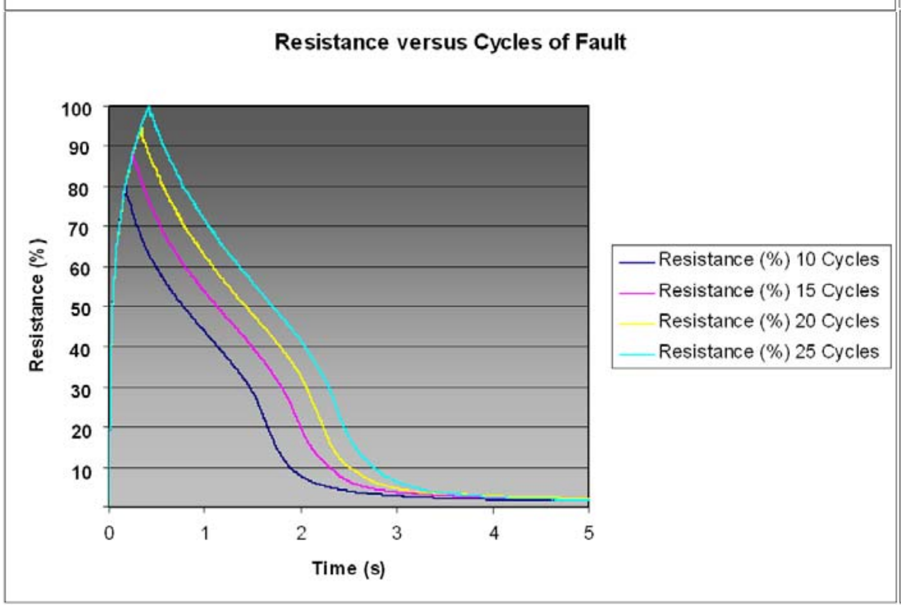
Test conditions evaluated:

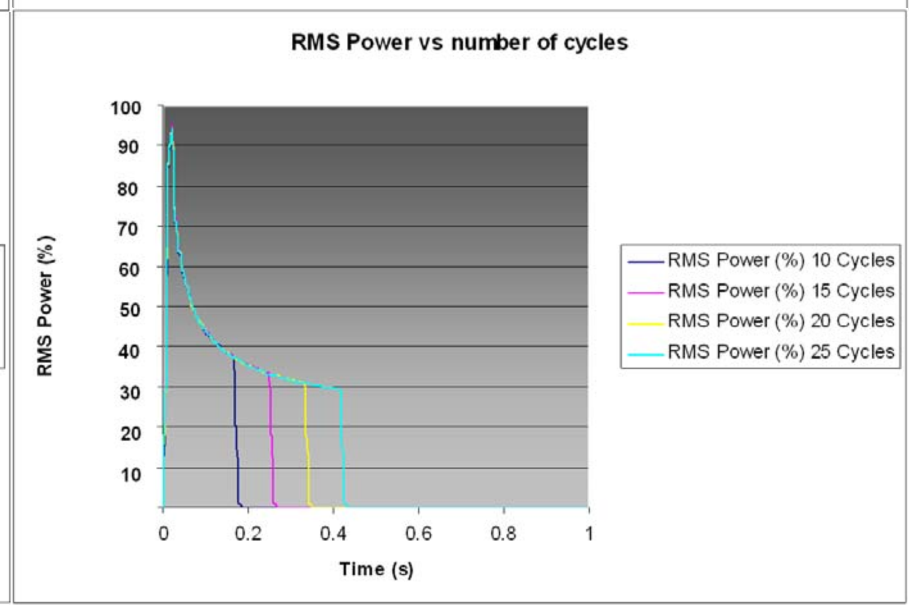
- 2 SFCL tapes configurations ("standard" and new configuration) are evaluated with 2 types of modules
- Follows AEP sequence
- Module current scalable in multiples of 500 A peak
- Module voltage scalable from 400 V - 1 kV peak
- Prospective fault currents scalable from 5 - 10 kA peak

RUL *vs.* Fault Duration / Occurrence.









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Summary

- SuperPower routinely produces 2G HTS wire in a manufacturing line. New 2009 world record performance of $I_c \times L$ = 300,330 A-m achieved in km long wires.
- Albany Cable Project – World's first in-grid 2G HTS device demonstrated the suitability of SuperPower® 2G wire for power cable and low ac loss.
- In-field performance enhancement at all field angles achieved *via* Zr-doping; technology has been transferred into production line
- High-field coils with consistently improved performance demonstrated with SuperPower® 2G wire. Self field was increased from 0.73 Tesla to above 1 T at 77 K and more than 2 T at 65 K. At 4.2 K, maximum fields of 10.4 T and 27.4 T were achieved in self-field and with 19.9 T background, respectively
- Model coils for HTS generator fabricated and demonstrated reliable performance
- Proof-of-concept for resistive 2G SFCL demonstrated. Developed generalized SFCL module specification:
  - Module current scalable in multiples of 500 A peak
  - Module voltage scalable from 400 V - 1 kV peak
  - Prospective fault currents scalable from 5 - 10 kA peak

Questions?

Thank you for your interest!

For further information about SuperPower,
please visit: www.superpower-inc.com

or e-mail: info@superpower-inc.com