Overview and lessons-learned from VIPER HTS cable testing in SULTAN

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Many thanks: The EPFL SPC team at SULTAN facility

First Workshop on User Interfaces : FNAL Cable Test Facility
22 Nov 22

Overview

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Objectives:

1. Provide insight into what is required for fusion REBCO cable testing
2. Provide input to HFVMTF to ensure maximum utility for fusion community

Actions:

1. Give overview of and lessons-learned from 4 VIPER cables tests at SULTAN
2. List many recommendations based on our experience developing a new REBCO cable and at SULTAN

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VIPER R&D focused on retiring risk for high-field DC magnets

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RISK

Fabrication	**Scalable to >100 m cable manufacturing for SPARC magnet in a few years**
Joints	**Simple, robust, low-resistance electrical joints between cables and terminations**
IxB	**Handle IxB loading + cycling equivalent to those found in SPARC >20 T magnets**
Strain	**Handle axial strains on the HTS above ~0.3% equivalent to SPARC >20 T magnets**
Quench	**Incorporate viable quench detection and possess high cryostability**

While some risks can be retired "in-house" (e.g. fabrication), SULTAN was essential for retiring all of these risks under high-fidelity magnet operating conditions.

Overview of VIPER cables designed for SULTAN testing

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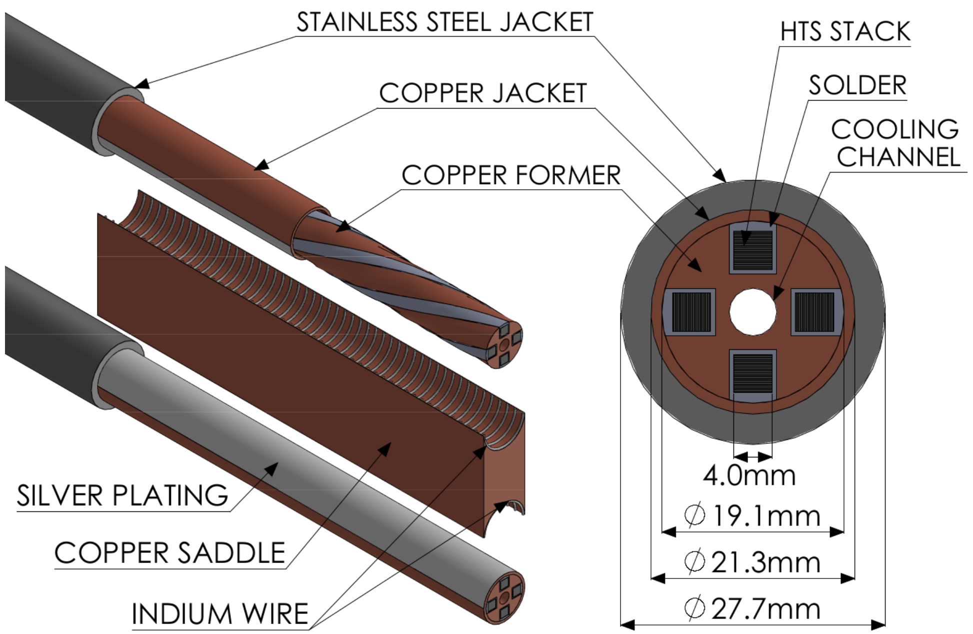
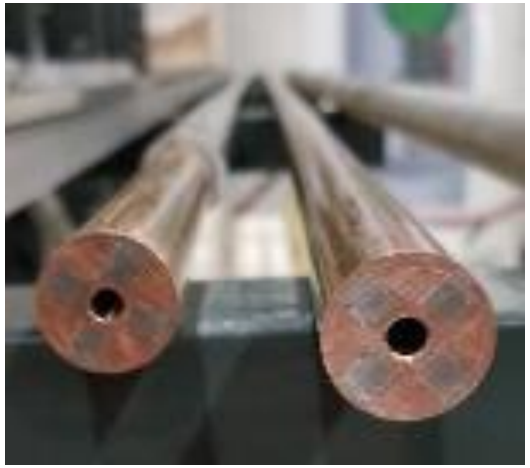
- VIPER cables were designed and fabricated specifically for SULTAN testing [1]
  - Extruded central copper former
  - Inner central cooling channel
  - Outer slots for HTS stacks (up to 4)
  - Copper jacket (VPI solder, joints)
  - Steel jacket (IxB Lorentz loading)

- Desired test characteristics
  - Temperatures: 4 – 30 K (design target: 20 K)
  - Current: 20 – 80 kA (design target: 50-70 kA)
  - Fields: 0 – 10.9 T (design target: 20 T)
  - Lorentz cycles (>1000) and temperature cycles (>10)
  - AC loss and quench/current-sharing testing
  - Relevant notes:
    - Cable assemblies designed, fabricated in-house
    - Everything assembled at MIT then shipped to SULTAN
    - Instrumentation done at MIT and SULTAN

Substantial effort (and often customization) is required for SULTAN testing well-beyond in-house 77 K tests





[1] Z. Hartwig *et al.*, SuST, **33** (2021) 11LT01

We completed 77 K tests for development, bending, fabrication before going to SULTAN for high B, low T testing

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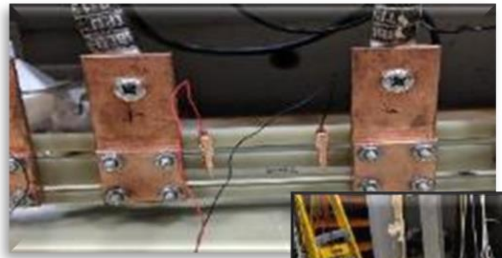
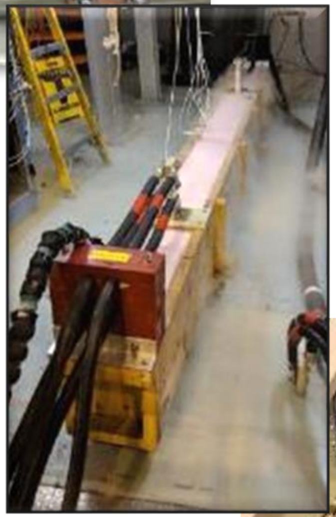
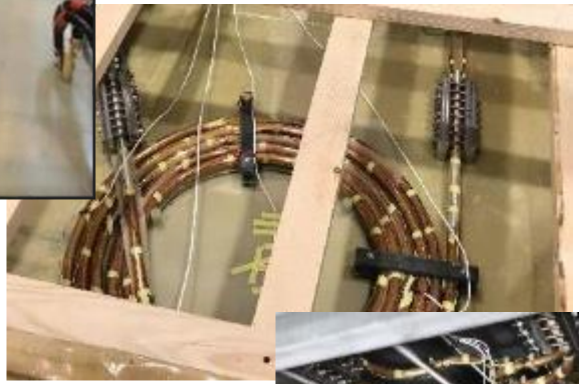


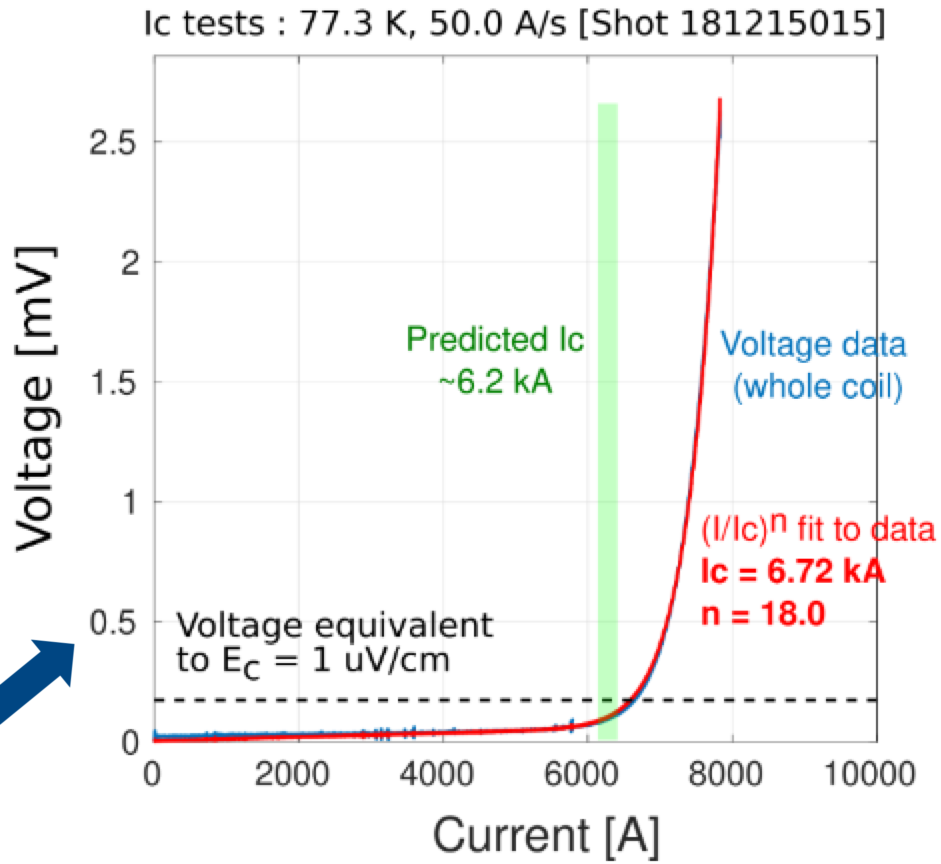
REBCO tape level (~cm)



REBCO cable level (~m)



REBCO coil level (~10m)



Many users/cables will have substantial 77 K test experience, important for guiding the prized high B, low T testing time

- Voltage taps at 2m spanning the main cable measured Ic in good agreement with prediction
- Leads showed no Ic degradation and all joints demonstrated acceptable resistance at 77.3 K

Overview of the four VIPER cable tests at SULTAN (2019)

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Four SULTAN tests (2 identical cables per test) were carried out between Feb 2019 and June 2019

The VIPER cables, HTS performance, and assembly were designed for specific test objectives:

- *Test Alpha*: Cable + assembly qualification; critical current model validation; moderate IxB tests
- *Test Bravo*: VIPER performance under SPARC-relevant IxB per HTS stack for loading and cycling
- *Test Charlie*: Bravo objectives PLUS axial strain on HTS to replicate magnet operating conditions
- *Test Delta*: Qualification of quench detection techniques; assessment of quench dynamics

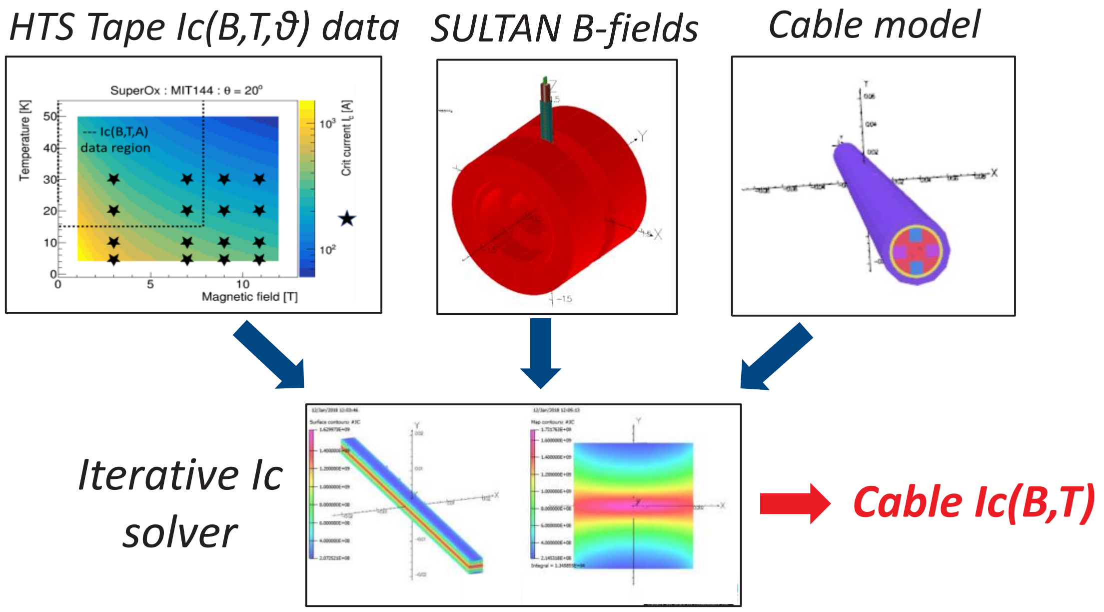
Cable	HTS channels filled with:
Alpha	1 of 4 w/ low Ic HTS
Bravo	1 of 4 w/ high Ic HTS
Charlie	1 of 4 w/ high Ic HTS; 3 w/ dummy
Delta	4 of 4 w/ with low Ic HTS

HTS Ic selected to avoid exceeding practical limits of 100 kA SC transformer

Users will ideally come with very sharp test objectives that facility must be able to satisfy

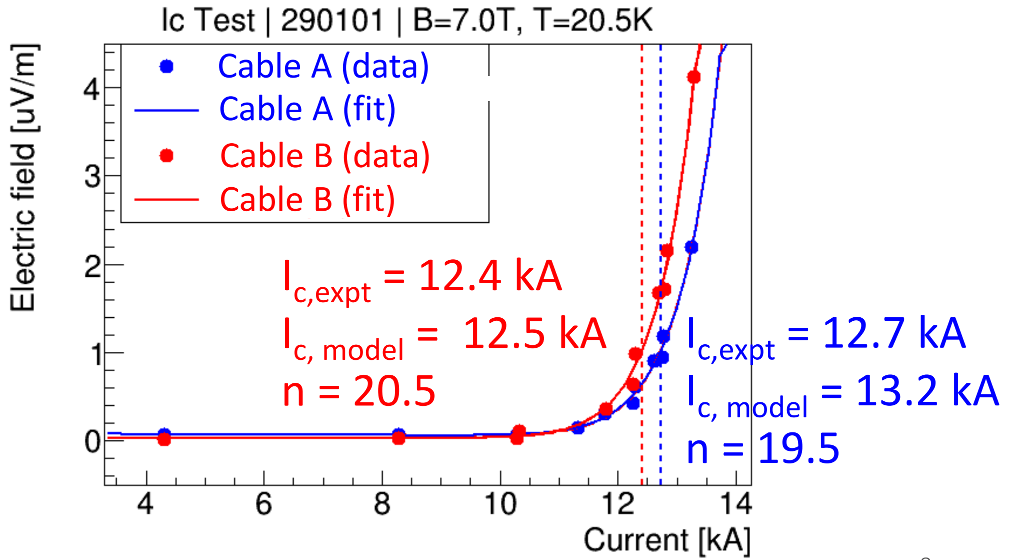
Alpha: Confirmed testing capability, moderate IxB, Ic modeling

1. Qualified VIPER testing capability at SULTAN including mechanical assembly, joints, cryogenics, instrumentation, facility interfaces
2. Validated high-fidelity cable Ic model with high resolution HTS data, with model predicting Ic within 2%-4% across a wide range of B and T
3. Confirmed VIPER performance at moderate operating currents (185 kN/m per stack)



Modeling and advanced layout of test program with SULTAN team optimized time-on-test

On-the-fly analysis and real-time guidance of test program by users at SULTAN was key



Bravo: ~4% Ic decrease at 382 kN/m/stack at 1550 cycles

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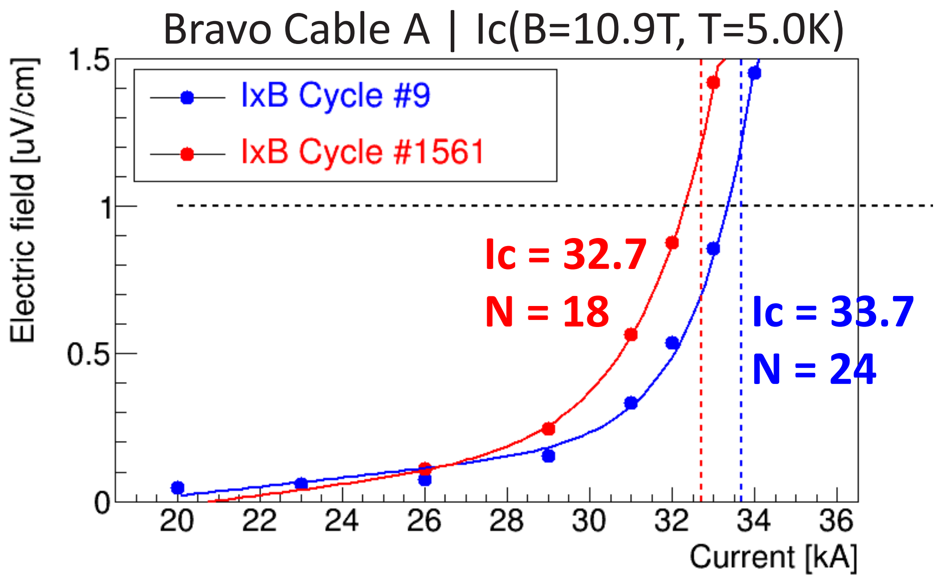
Following initial checks and DC characterization (5,10,20,30 K and 0,3,9,10.9 T), IxB cycling was carried out on the cable pair:

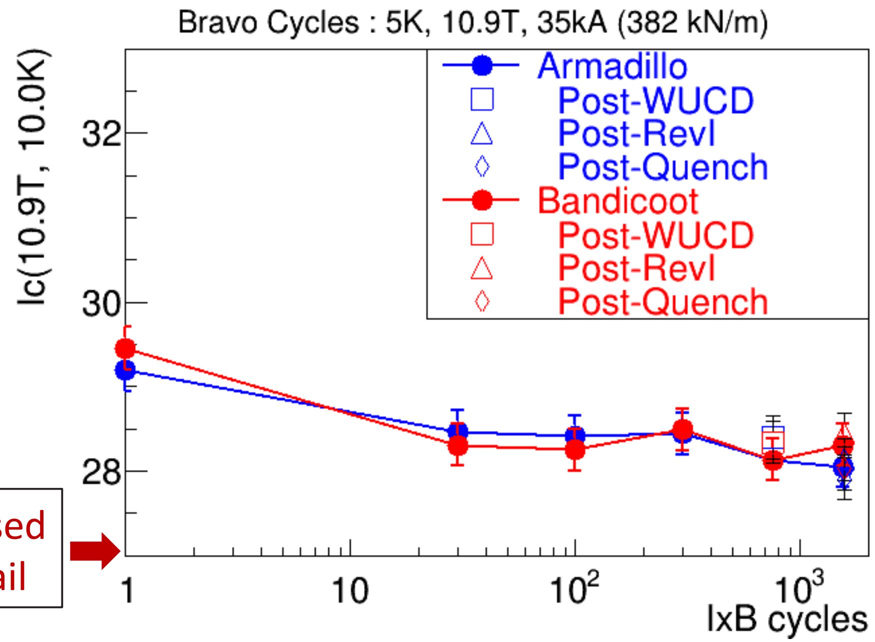
- IxB cycling: 1550 @ 382 kN/m (10.9T x 35 kA)
- Two "reverse" IxB cycles at 320 kN/m
- One warm-up/cooldown halfway through cycling

Ability to exceed IxB loads under high-fidelity conditions provides confidence in risk retirement

"Reverse" IxB cycles provides highly stringent test of cable/strand degradation due to movement

Thermal cycles very low due to multi-day requirements at SULTAN. Faster would be nice!





Zero suppressed to show detail

Charlie: Novel approach for IxB + strain in straight cables

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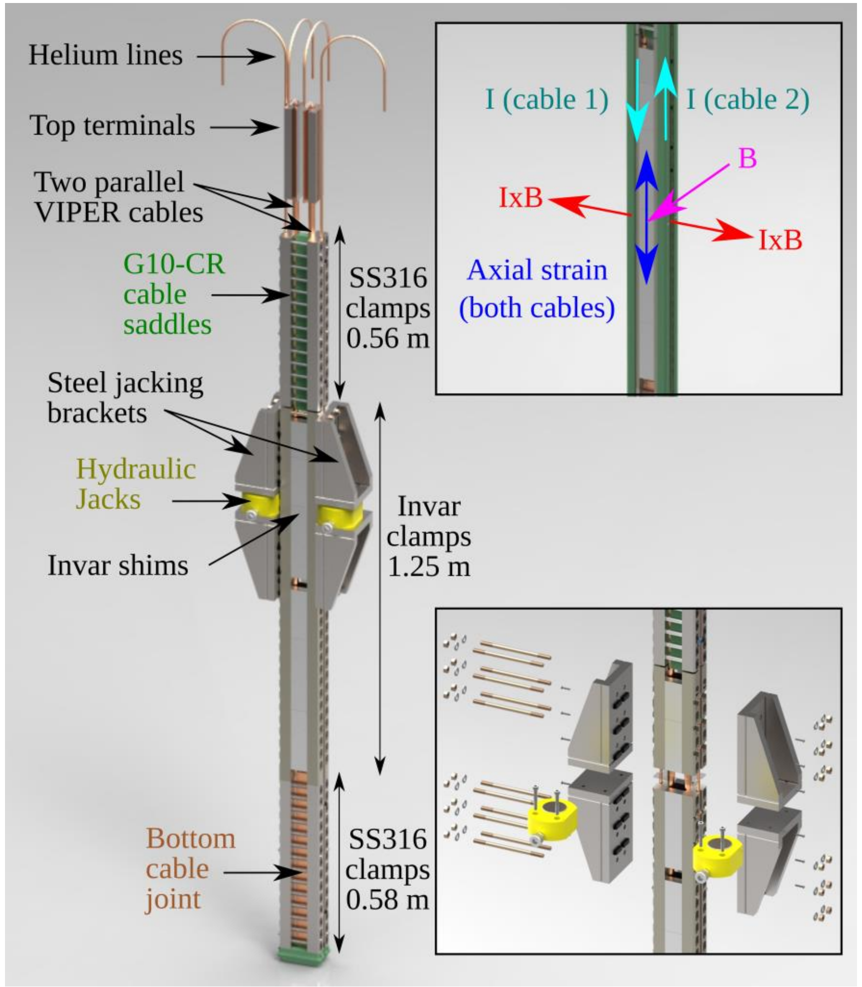


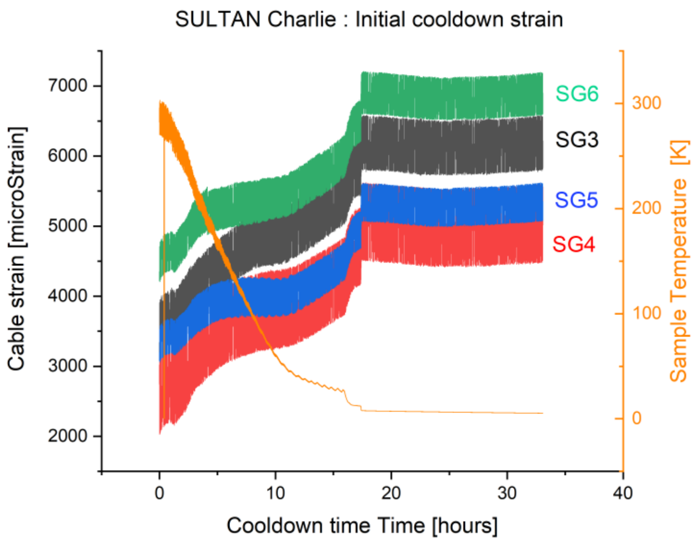
[3] V Fry *et al.* SuST, **35** (2022) 075007.

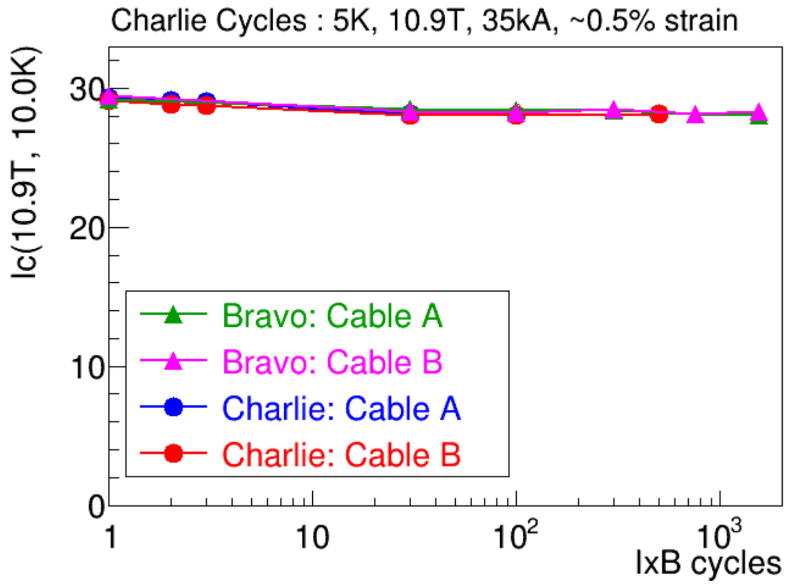
A SULTAN cable assembly system was designed to impart axial strain to HTS

- Hydraulic jacks attached to outer clamps enabled dynamic adjust of strain pre-test
- Combination of SS316 (moderate CTE) and Invar (no CTE) provided fixed additional axial strain due to cooldown
- Strain gauges through assembly monitored during preparation and testing
- HTS strain confirmed through additional

Clever use of cables ***AND*** *assembly enabled IxB + strain in SULTAN instead of a time, cost, and facility intensive 3D coil test*

Users on the ground played critical role in cable installation as well as in real-time to test program





Delta: Quench detection and dynamics measurements

Test program primarily focused on quench and AC loss once DC operating characteristics established [1]

- *Note:* Important limitation at SULTAN due to SC transformer preventing full quench evolution (improved at SULTAN with 15 kA DC system)

Cables were instrumented with the following:

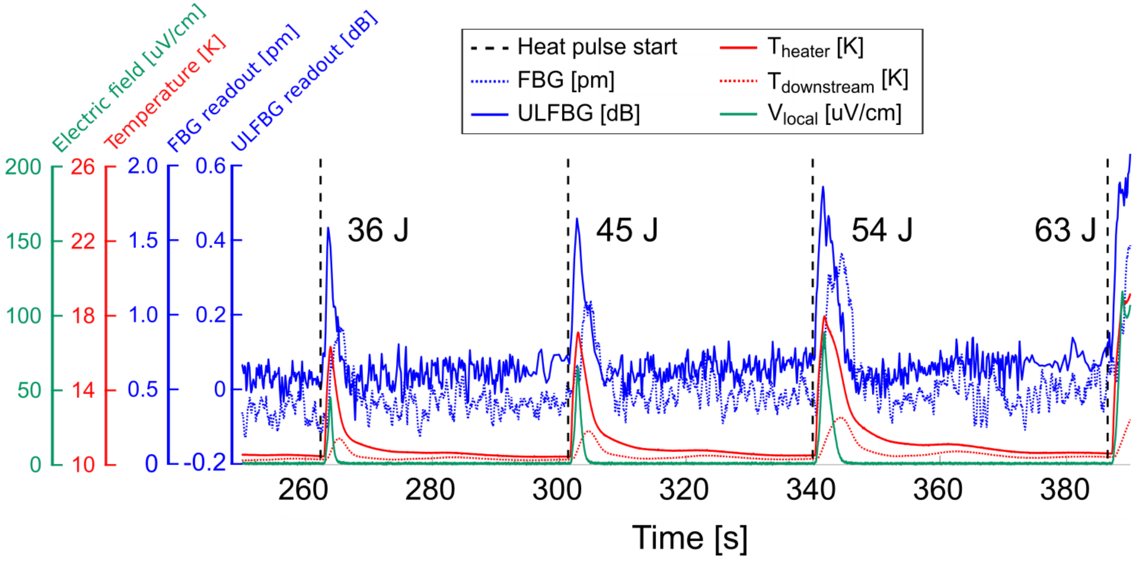
- Standard voltage taps, Cernoxes
- 2 resistive surface heaters (50 W each) per cable
- 4 fiber optic quench detection systems
- 2 acoustic quench detection systems

Erica Salazar working on Delta assembly at SPC facilities at PSI

Heavy and unique instrumentation suite required additional and special feedthroughs as well as complex routing of all signal cables to 300K flanges.

MIT, CFS, CERN, RRI worked very closely with SULTAN staff for weeks onsite to assemble and install the sample.

SC transformer drops out early in quench evolution (~35 K maximum temperatures) prevent key learning



[1] E. Salazar *et al.* SuST **34** (2021) 035027

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Recommendations: General facility capabilities

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- *Cable current*: 0 – 100 kA (SC) and 0 – 50 kA (DC)
  - SC transformer w/ sufficient volt-seconds to last 8 hours if secondary voltages achieved
  - DC power supply (up to 50 kA or more) for full quench evolution (dynamics, detection)
  - Fast SC/DC power supply to maximize IxB cycles per test session (1000's cycles minimum)
  - Ability to reverse sample current for opposite IxB force direction
- *Cable temperature*: 4 – 50 K
  - Supercritical helium (not bath-cooled) with programmable mass flow rates
  - Flexibility in cryogenic routing (series vs. parallel in cables, top vs. bottom inlets, etc.)
  - Mechanism to cycle sample 4-300-4 K rapidly (1-2 times a day?) for thermal testing
- *External field:* 0 – 15 T
  - Ability to raise samples and place joints in-field for IxB and magnetoresistance testing
  - Ability to change fields rapidly during testing session to maximize test time
  - Not possible in HFVMTF: Fast ramp (1-2 T/s) for pulsed external field testing of joint and conductor stability (e.g. for CS magnets) is essential but not achievable in this facility

Recommendations: General facility capabilities

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- Quench testing capabilities (High priority)
  - DC power supply capable of ~50 kA -> full evolution of quench
  - Different quench methods (sample warm-up, AC loss induction, surface heaters)
  - Quench instrumentation (next slide); helium instrumentation
- AC loss testing capability (Medium priority)
  - Frequencies for fusion are ~1 HZ but other fields may benefit from up to 200 Hz
  - Implement fast-ramp power supply for cable current? Possible to implement oscillating external B-field?
  - Different test methods: calorimetry? electrical via lock-in amplifier?
- Users will want flexibility to perform Ic (*e.g.* I vs. V) and Tc (*e.g.* T vs. V) characterizations
  - Excellent control of helium needed (including heaters on inlets): T stability for Ic, T increase for Tc
- Flexibility for user-designed cable assemblies
  - Clever design of assembly can multiply facility utility (e.g. VIPER Charlie enabled IxB + strain at SULTAN)
  - External magnet and test well must be sufficiently large and flexible to accommodate
- Option to facility-provided sample assemblies
  - Not all users may have resources/expertise to design and build assemblies
  - FNAL could consider providing "standard assemblies" to users to decrease barrier-to-test

Recommendations: Instrumentation and data acquisition

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- Provide a standard "base" instrumentation layout for all tests
  - *User samples*: Voltage taps (high-field, joints), Cernoxes, etc.
  - *Facility:* Voltages (e.g. sample-facility joints), Cryogenics (p,m-dot, etc), B-field, etc.
- Flexibility to accommodate user-requested/supplied instrumentation
  - Additional voltage taps and Cernoxes specific to user sample
  - Surface heaters (with larger gauge wires and in-house power supplies)
  - Strain gauges (w/ 3 or 5 wire cable runs), acoustic sensors, fiber optics, hall probes, etc.
  - Sample cryogenic measurements (pressure, mass flow, etc.)
  - *Ensure clear instrumentation wire/cable routing from sample to 300 K feedthroughs*
  - *Ensure standard feedthroughs (e.g. D-sub) for all facility and user instrumentation*
  - *Ensure sufficient spare feedthroughs/flanges beyond "base" instrumentation*
  - *Ensure sufficient spare low- (~0.1Hz) and high-rate channels (~100 Hz) in DAQ*
  - *Ensure users can bring their own I&C systems for specialized testing needs*
  - *Ensure user I&C can tie into facility I&C (esp. timing/synchronization signals)*

Recommendations: User support and resources

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- Maintain a comprehensive, up-to-date facility manual with all necessary specifications (geometry, interfaces, operational parameters, instrumentation, etc.) for facility users
- Generate a post-test summary report (including sample and facility data) and basic set of analyses on sample performance from FNAL to users
- Ensure it is straightforward to obtain FNAL-User agreements. Protection of user data and IP-sensitive science and engineering aspects likely critical for privately-funded users.
- The following should be provided to maximize user experience and test benefit:
  - A clear costing structure for testing + additional labor from FNAL at user's request (and ensure it is competitive with SPC EDIPO-II/SULTAN!)
  - A clear scheduling system based on samples delivered at some threshold of readiness
  - Detailed shipping/receiving instructions (esp. for international users)
  - Access to expert FNAL technicians for sample preparation and installation
  - A secure workshop area where users can prepare their own sample (w/ FNAL technicians if needed)
  - Dedicated area for users in facility control room (observe/guide test program, analyze data in real time)