Protection Experience and HTS Magnets at BNL

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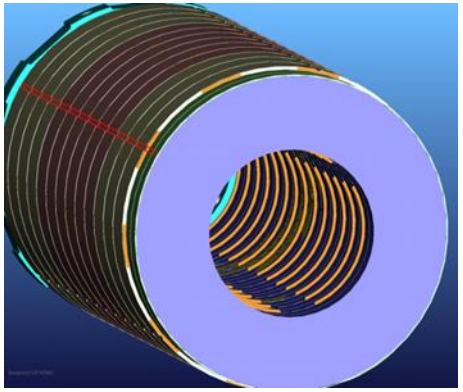
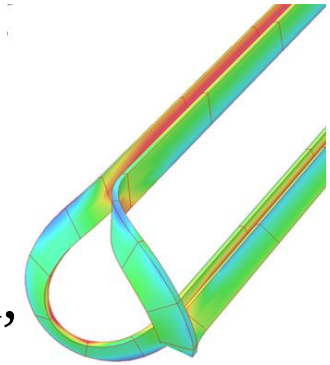


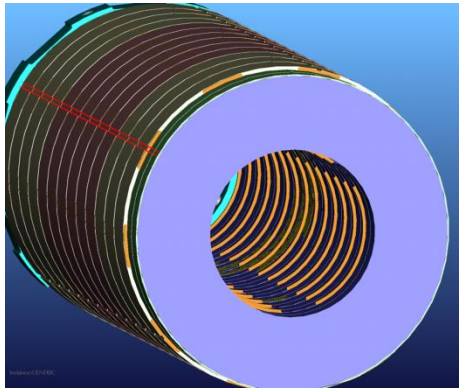
- **HTS high field magnet program (a brief discussion)**
  - Based on the ReBCO tape(s)
  - Complementary geometry to European program, thanks to common coil design

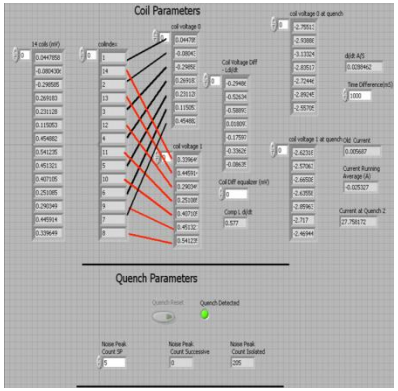


Quench Protection Strategy at BNL

BNL has relied on a multi-prong approach for quench protection in a large number of HTS coils/magnets built and tested to date

1. Stainless steel (metallic) turn-to-turn insulation to spread energy after the quench
2. Inductively coupled copper disks to transfer energy instantaneously out of HTS coils, heat up coils and reduce current to provide extra margin at a critical time
3. Sensitive electronics to detect resistive voltage quickly at the pre-quench phase
4. Fast energy extraction with electronics that can tolerate high voltage stand-off
5. Quench heaters (used in LTS magnets, not yet implemented in HTS magnets)





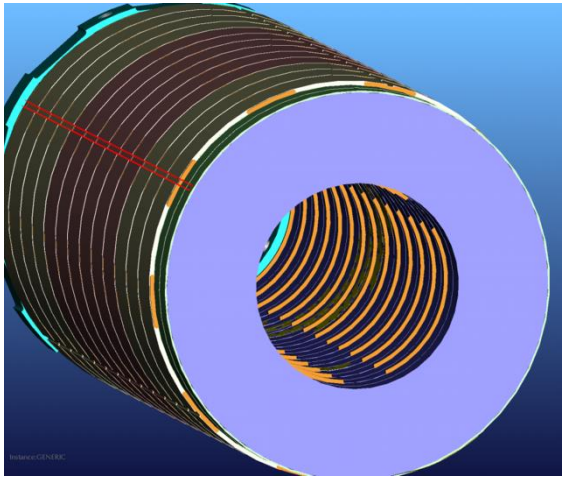
1. Co-winding with Stainless Steel Tape

- SS tape is in between no-insulation and traditional insulation and may be a desired compromise/optimization in some cases
- Quench propagation is significantly different between coils wound with traditional insulations (such as kapton) and wound with ss tape
- In case of quench, it spread faster in transverse direction
- By spreading energy, it may also partially act as quench heaters

BNL has used SS insulation in many HTS magnet projects with a positive experience

2a. Inductively-coupled Copper Discs between the Double Pancakes

- Copper discs are used for providing uniform cooling across coils to reduce thermal strain during cooldown
- They are coupled inductively to the coils which helps in fast energy extraction



High Field Solenoid for SMES (details at MT-24)

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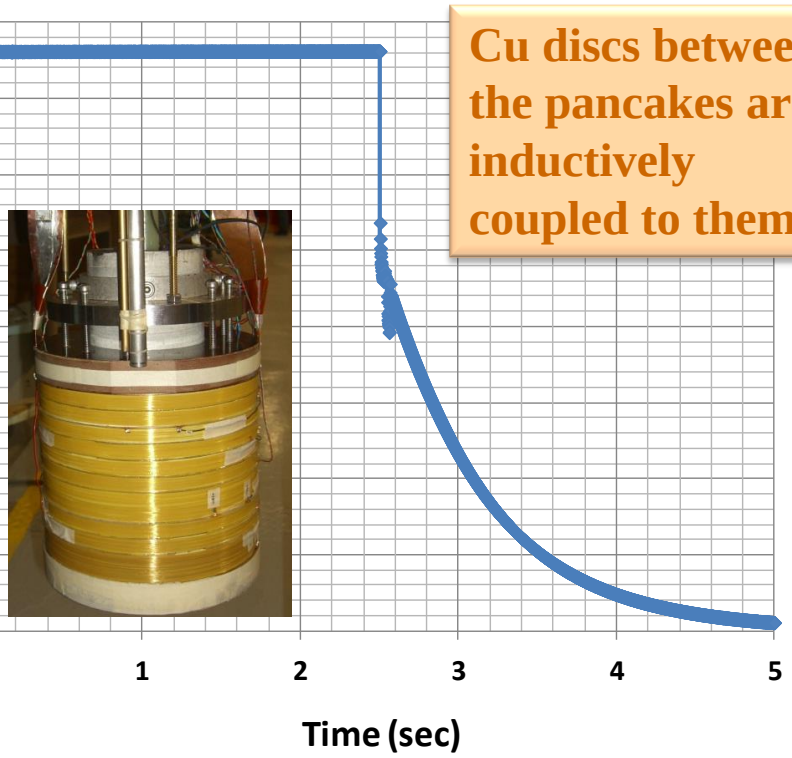
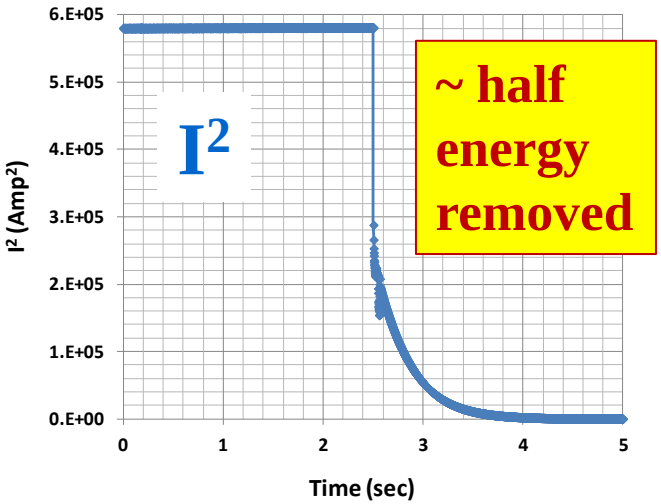
2b. Copper Disc for Initial Energy Extraction

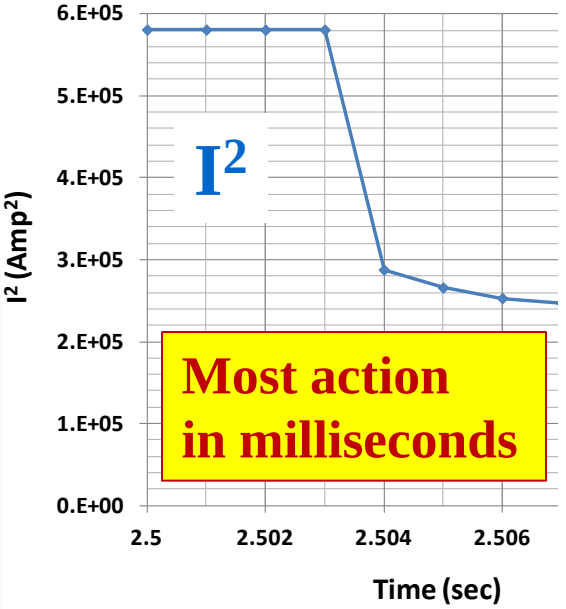


Cu discs between the pancakes are inductively coupled to them

12 pancake test at 4 K (~12 T, ~120 kJ, 100 mm)



~ half energy removed

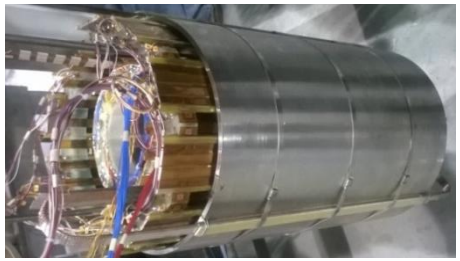


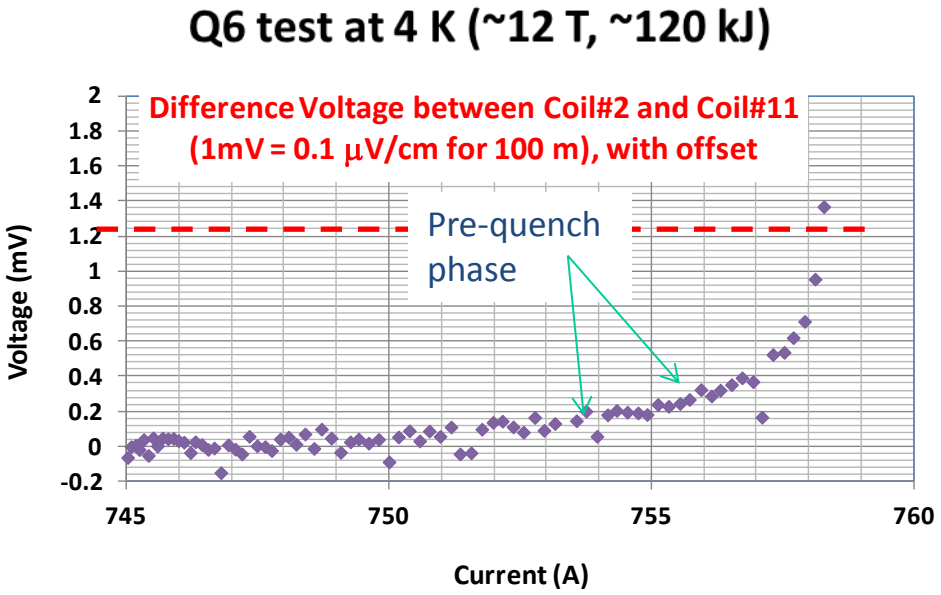
Most action in milliseconds

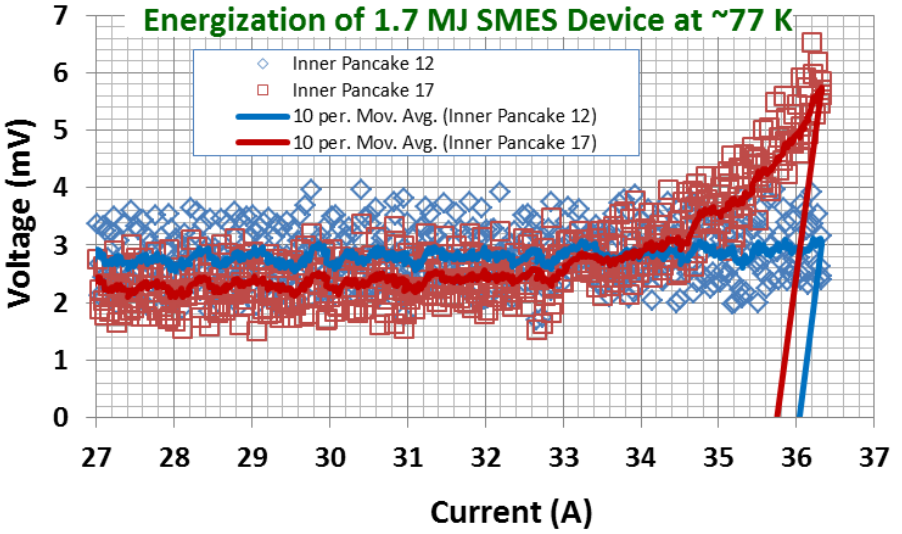
When the current is brought down, it is first transferred to copper discs (fast drop) before the L/R decay. This (a) removes significant energy quickly, (b) warms up copper discs and HTS coils (like quench heater) and (c) gives extra current margin to coil at a critical time

3. Detection of the Pre-quench Phase

- **In HTS, there is a long pre-quench phase during which the coil can be safely operated with a small resistive voltage.**
- **We detect this pre-quench phase and initiate our quench protection action during that time.**
- ***This requires detecting small resistive voltage in presence of large noise and inductive voltage.***
- ***This is accomplished with the modern hardware and software where we made significant progress.***







3. & 4. Advanced Quench Protection Electronics with High Isolation Voltage

3.Detect onset of the pre-quench phase at < 1mV

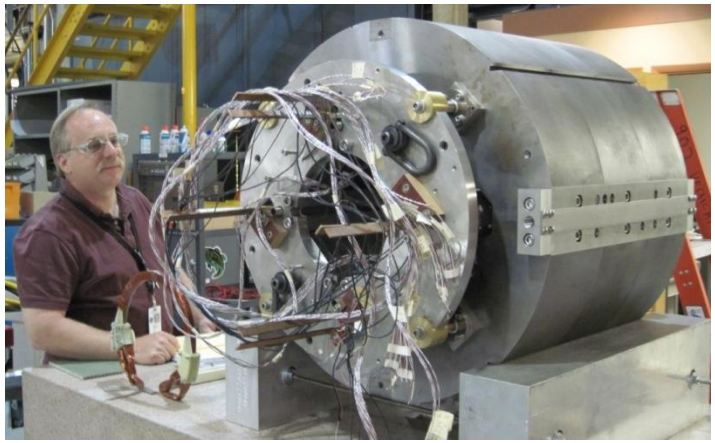
4.Fast energy extraction with high isolation voltage > 1kV

Protection Experience in HTS Quad for FRIB

(a) Accident – A Real Life experience

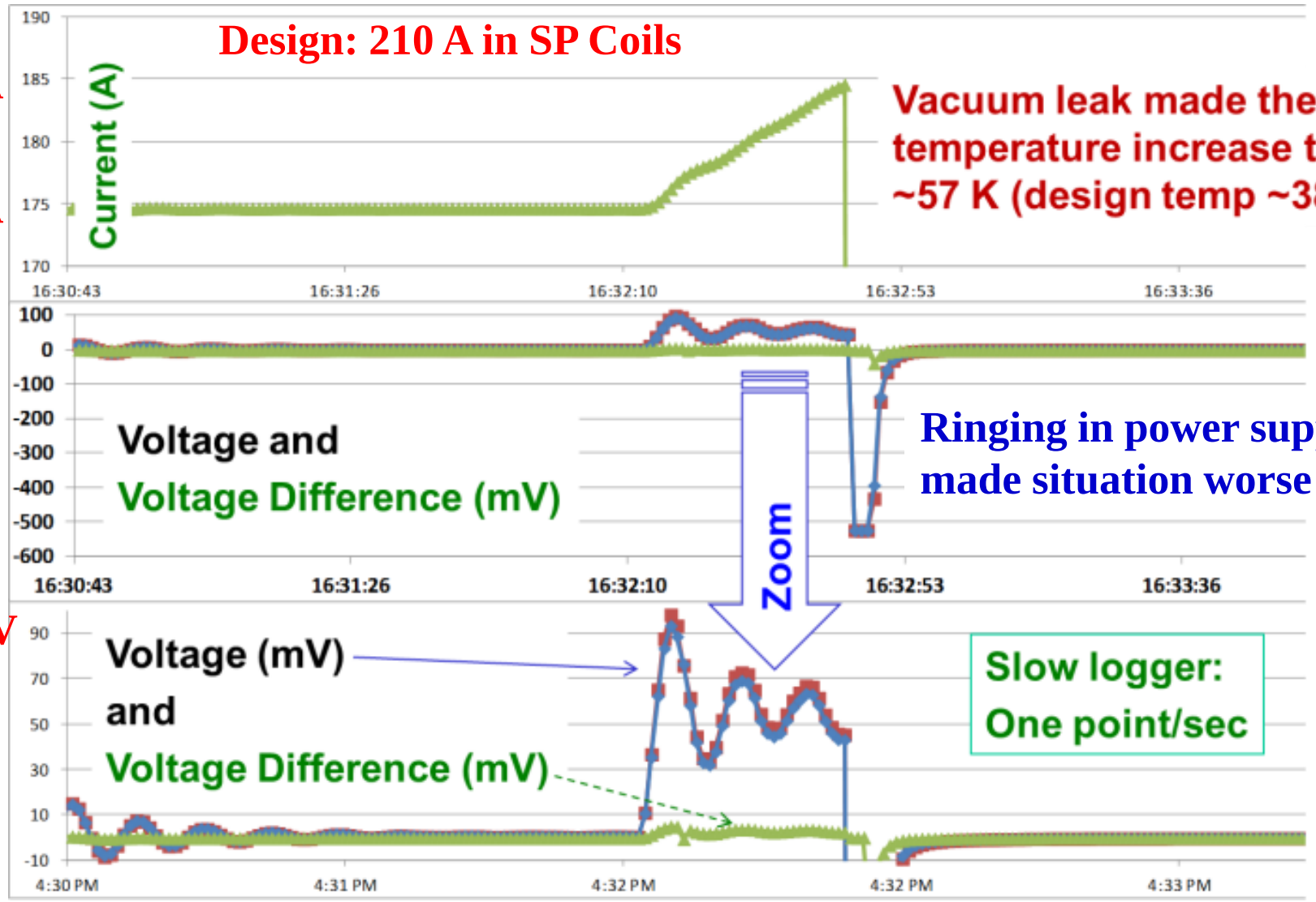
(b) Event Near Short Sample

(c) Operation at High Threshold



FRIB: Facility for Rare Isotope Beams (under construction in Michigan, USA)

(a) Vacuum Leak
Operational Accident Near Design Current



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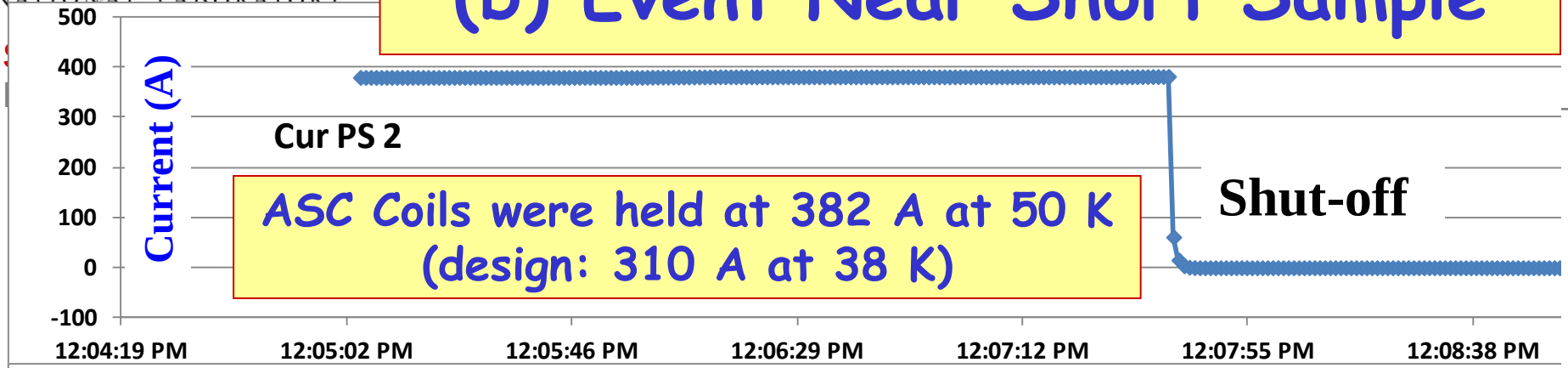
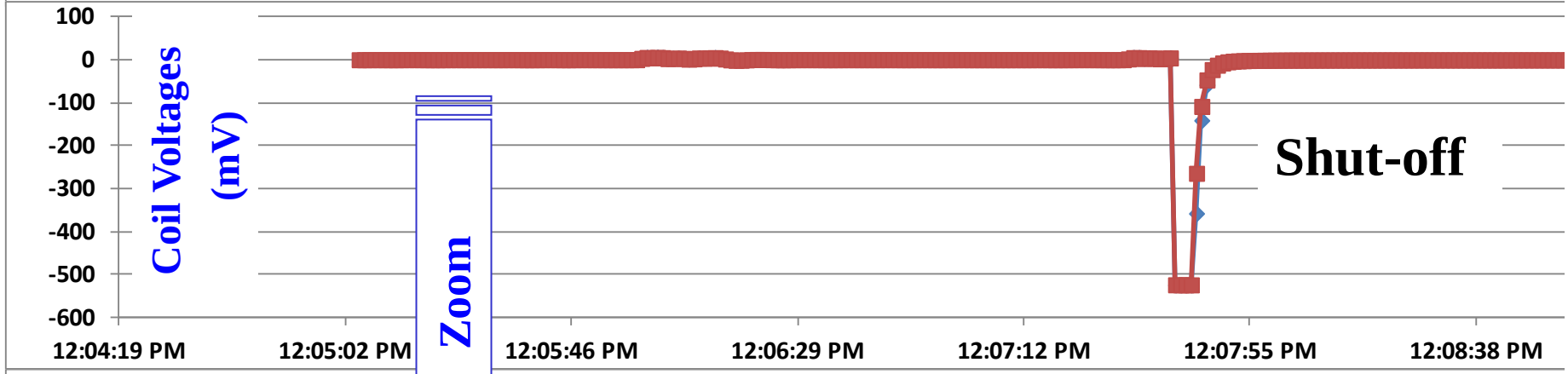
(b) Event Near Short Sample



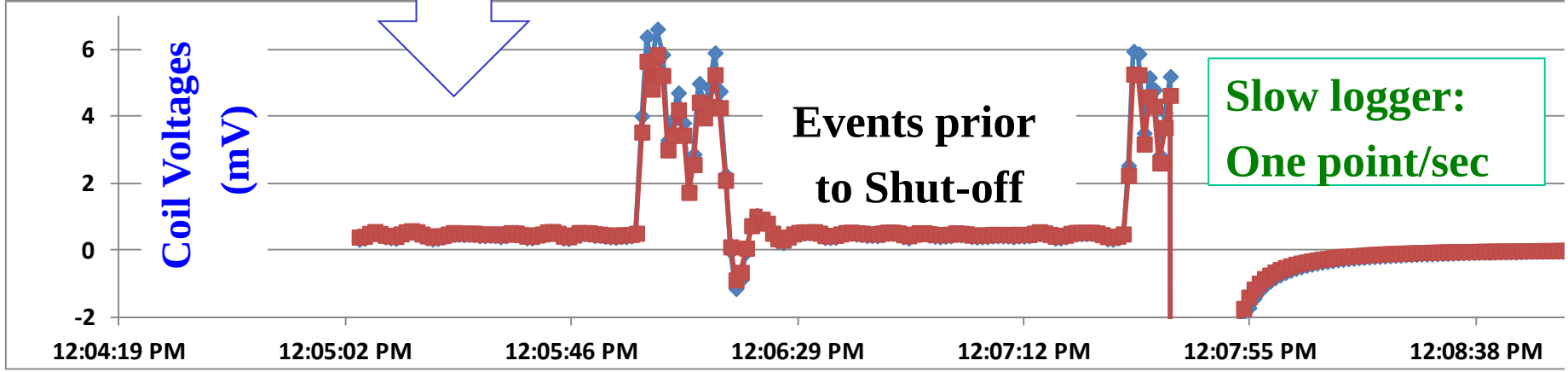
ASC Coils were held at 382 A at 50 K
(design: 310 A at 38 K)

Shut-off



Shut-off

Zoom



Events prior to Shut-off

Slow logger:
One point/sec

Summary of Protection Experience

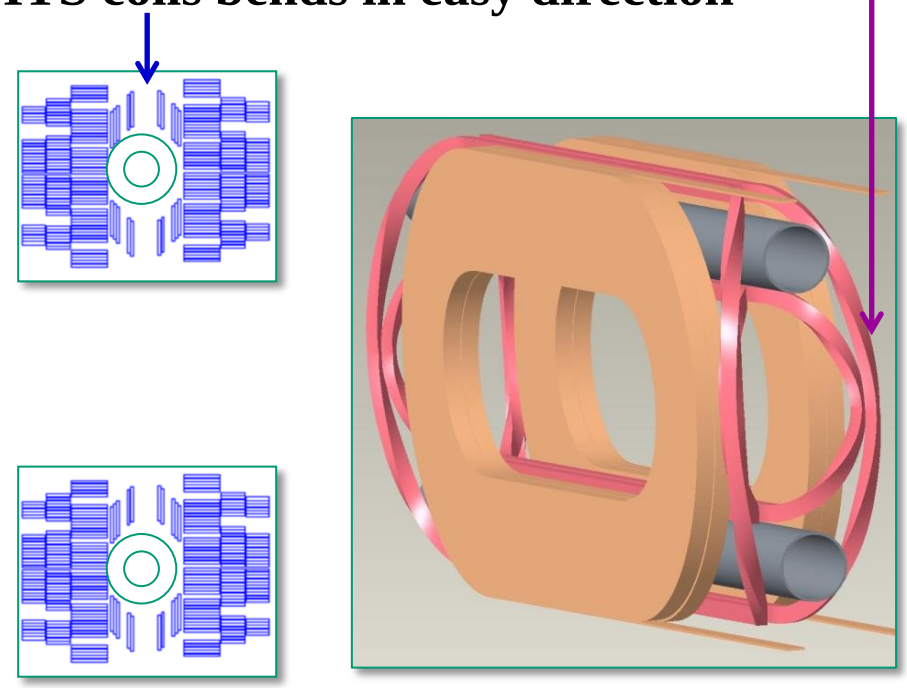
- We had a variety of incidences while operating HTS quadrupole for FRIB
- No damage or degradation in performance was observed after those events
- There was even a local defect in one coil, which didn't seem to deteriorate
- The multi-prong approach was able to protect the FRIB HTS coils in all cases
- We also have experience with several other HTS magnets (including 4K test with high current densities and stored energy in coil, such as those for muon collider and SMES). There were cases when HTS coils got damaged but none due to quench or runaway situation with an active quench protection on
- Caveat: Most of these tests, however, were done in a project manner – where the focus was to demonstrate, rather than find out the limits of the approach

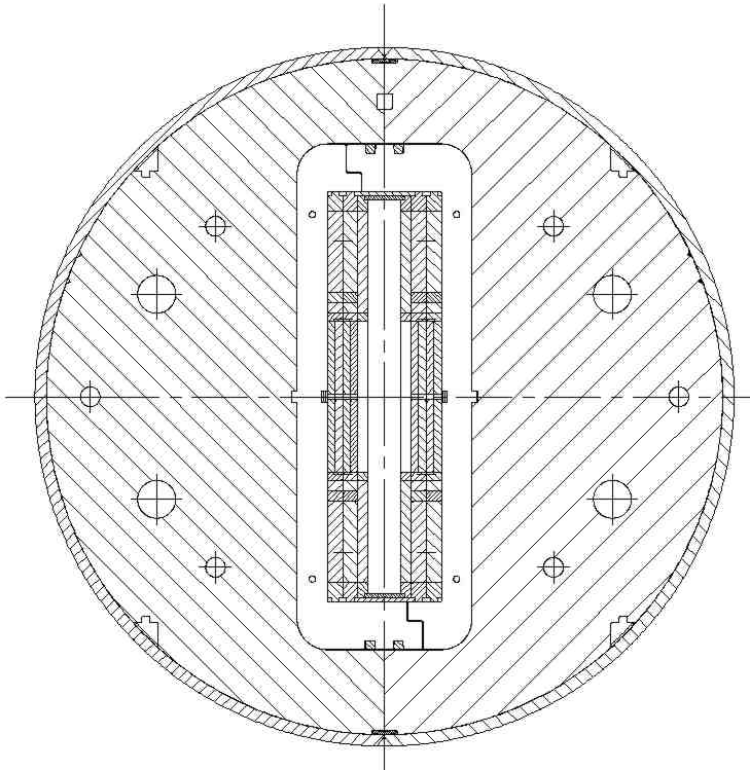
High Field Magnets for Accelerators

Windings for Lower Magnetization

Narrow side of the HTS tape aligned perpendicular to the field produces lower magnetization (proportional to the width) and higher critical current

In 2-in-1 common coil design, conductor in HTS coils bends in easy direction





Common coil design provides easy segmentation between HTS & LTS

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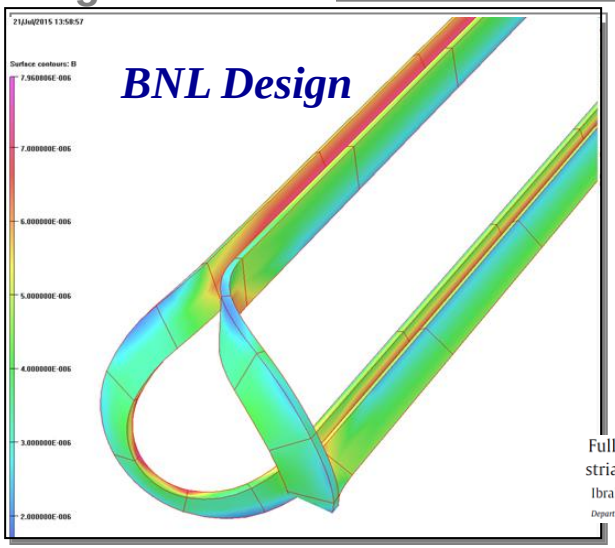
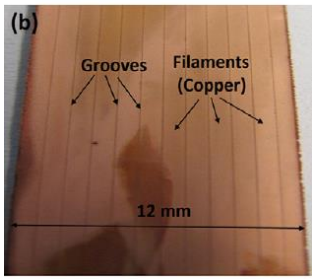
Complementary Nature of BNL and CERN HTS Magnet Programs



Cable options

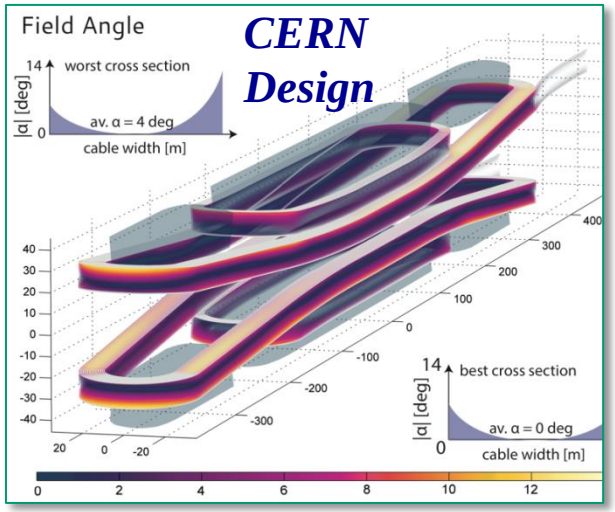


Fully filamentized HTS coated conductor via striation and selective electroplating

Ibrahim Kesgin, Goran Majkic, Venkat Selvamanickam*

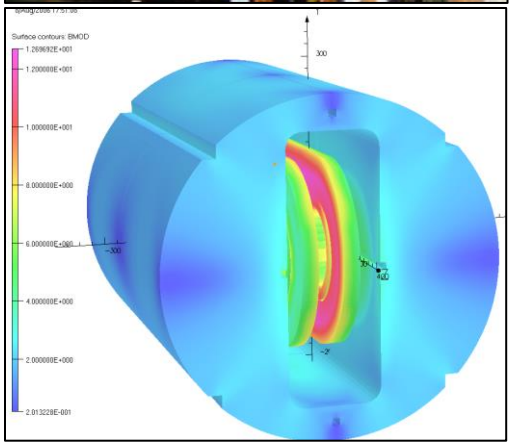
Department of Mechanical Engineering and Texas Center for Superconductivity, University of Houston, Houston, TX 77204, USA

Bonded wire production line



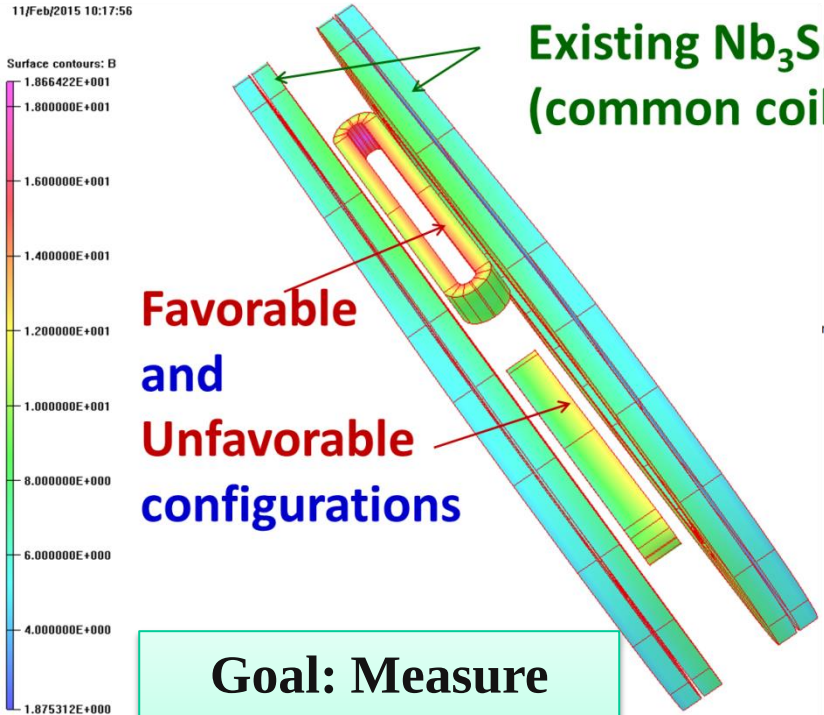
- **BNL and CERN are both pursuing ReBCO technology, but with very different designs**
- **BNL bends tape in easy direction in ends (allowed by common coil design); CERN bends in hard direction**
- **BNL is exploring/proposing simple multi-tape (multi-tape for higher current and reliability) and striation to further reduce magnetization) or CORC cable (since large radii allowed in common coil); CERN is focusing on Roebel cable (both for > 10 kA current)**

Test of Principle in A Real Magnet
(measure and compare magnetization in two configurations)

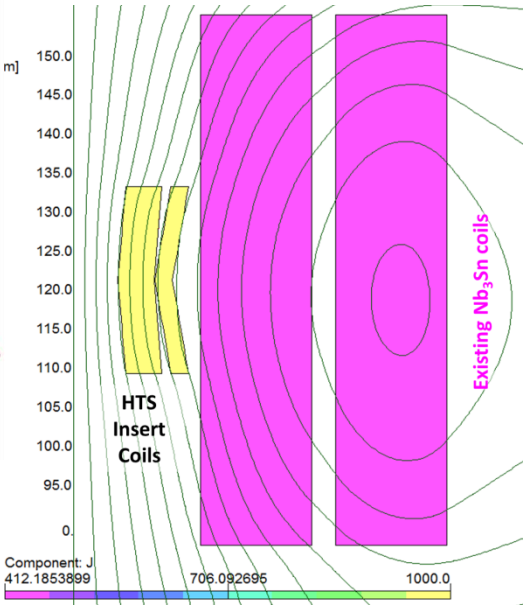


BNL Common Coil Dipole with a large open space

- HTS coils can be inserted without opening the magnet



PBL/BNL Phase II STTR



Goal: Measure magnetization due to HTS coils in two configurations

SUMMARY

- **Quench protection is a major challenge in HTS magnets.**
- **A multi-prong approach (metallic insulation, sensitive electronics for pre-quench action, inductive energy transfer out of coil and fast energy extraction with electronics that can tolerate high voltage) has worked in a number of R&D magnets tested at BNL.**
- **These approaches, however, needs to be further tested, expanded, and supplemented by other techniques to provide sufficient protection for large high stored energy magnets.**
- **With a reliable quench protection system and magnet designs that make efficient use of HTS and produce tolerable field errors (such as those discussed in this presentation), there is a potential of making very high field HTS/LTS hybrid accelerator magnets.**

Backup Slides

1. Co-winding with Stainless Steel Tape

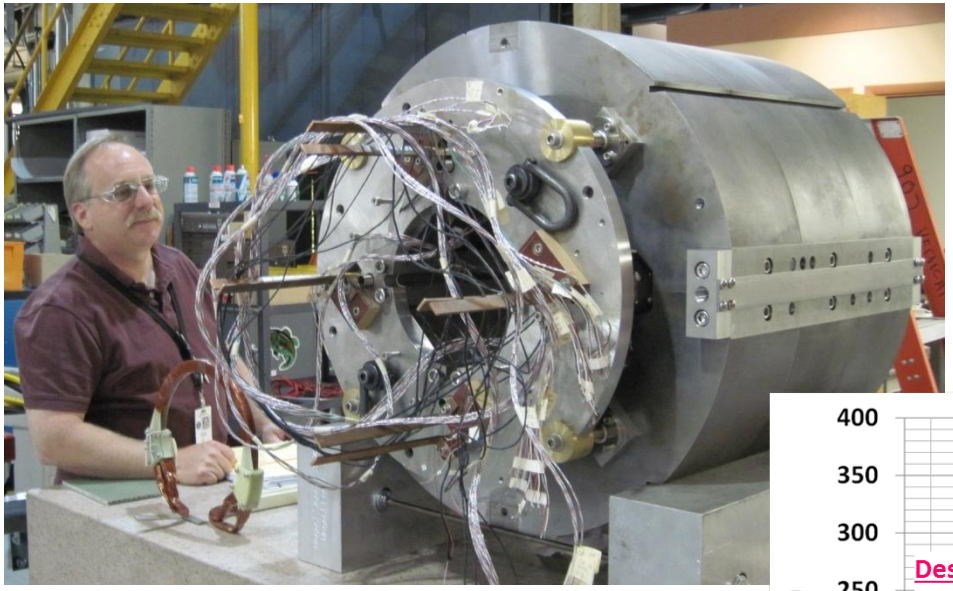
Benefits of Stainless Steel (metallic) insulation in HTS coils:

- Radiation resistant (critical for high radiation environment)
- Extra support structure (critical for high field magnets – e.g. SMES)
- **Quench protection – spread energy (critical for HTS magnets)**

- Quench propagation is significantly different between coils wound with traditional insulations (such as kapton) and wound with ss tape
- SS tape is in between no-insulation and traditional insulation and may be a desired compromise/optimization in some cases
- For R&D magnets, natural surface resistance has been adequate but for machine magnets providing controlled surface may be desired

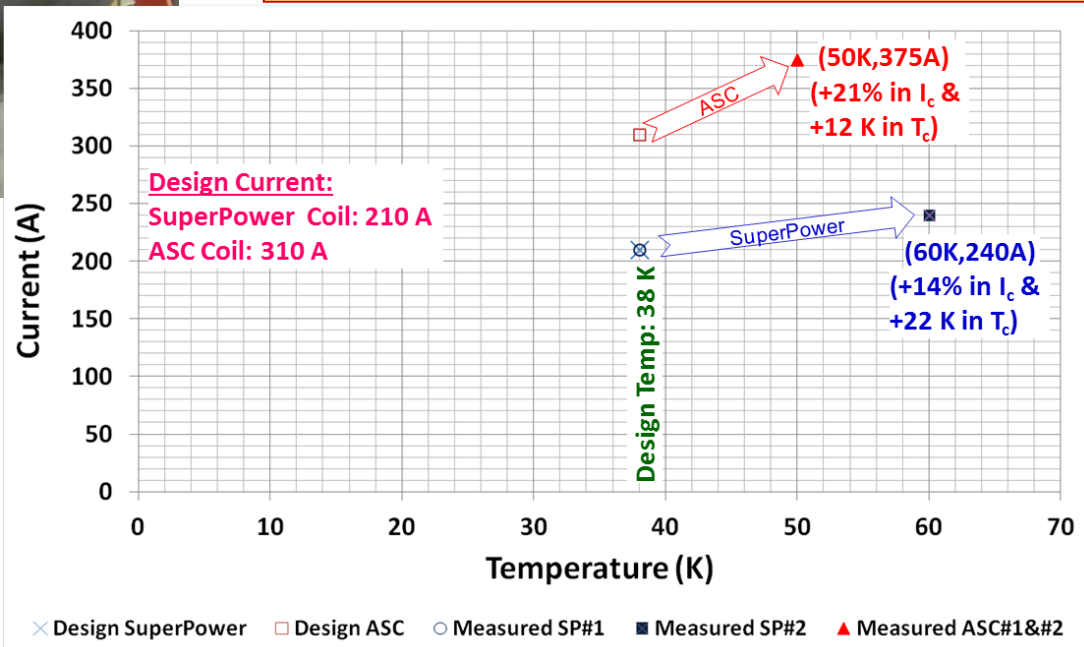
BNL has used SS insulation in many HTS magnet projects with a positive experience

HTS Quad for FRIB



YBCO from two vendors ASC and SuperPower

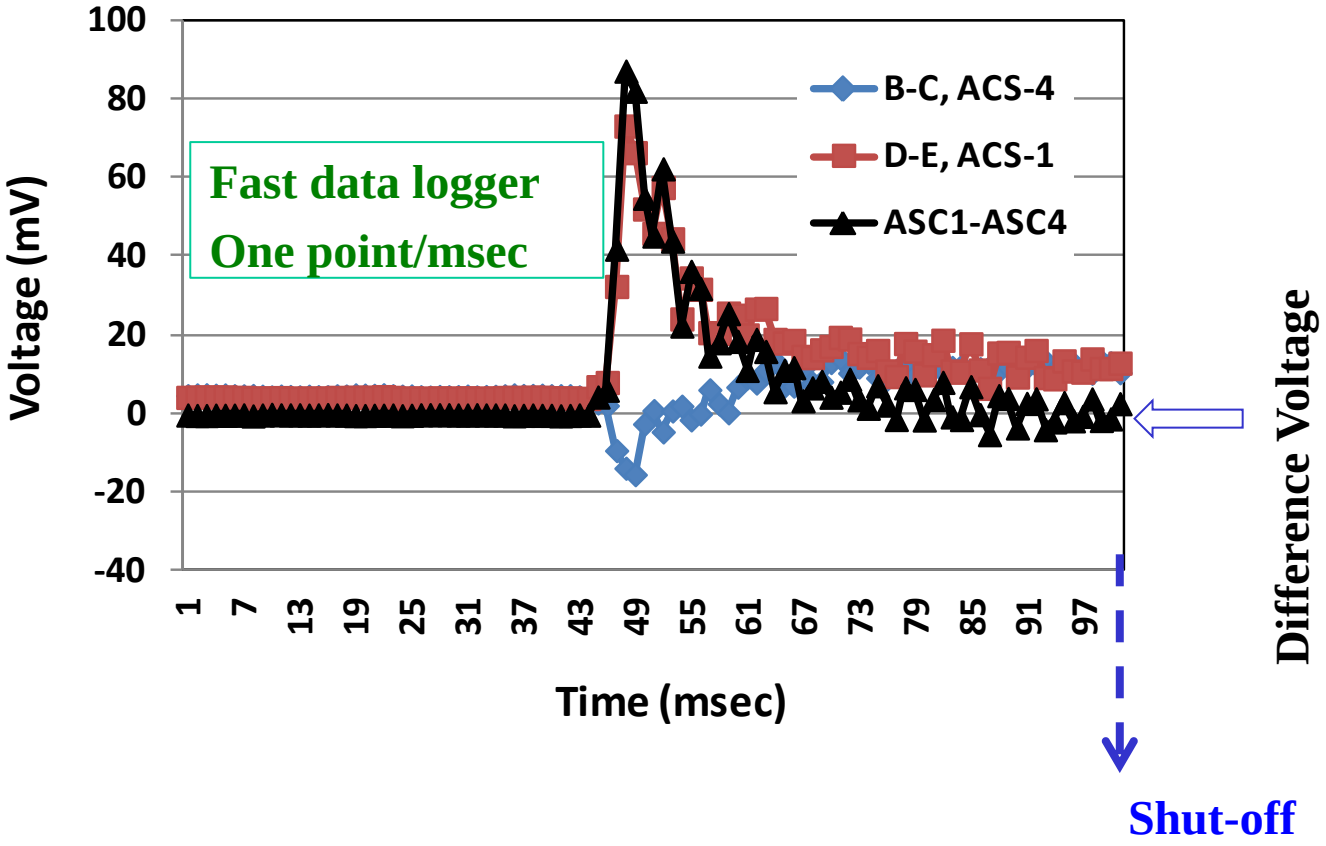
Large Temperature Margins (only possible with HTS)



HTS provides robust operation against local and global heat loads

Snap Shot of the Event in ASC Coils (individual and difference voltages)

- This event appear to be a sign of flux jump
- Exceeded quench threshold, triggered shutoff & energy extraction



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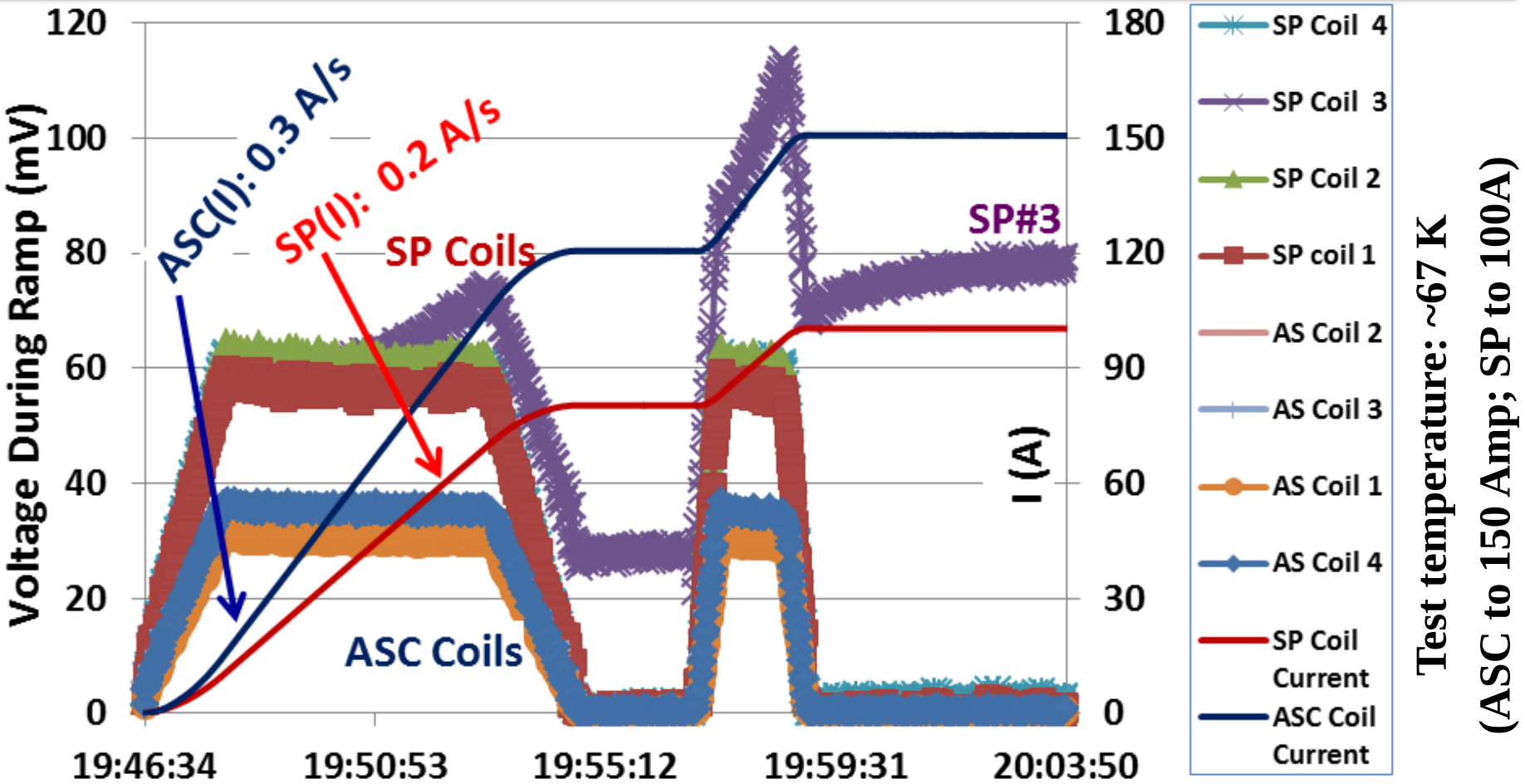
Operation at the High Detection Threshold Voltage

Operated at about two order of magnitude beyond the quench detection threshold (>100 mV instead of < 1mV initially planned)



Test temperature: ~67 K (ASC to 150 Amp; SP to 100A)

Design Technique to Reduce Magnetization

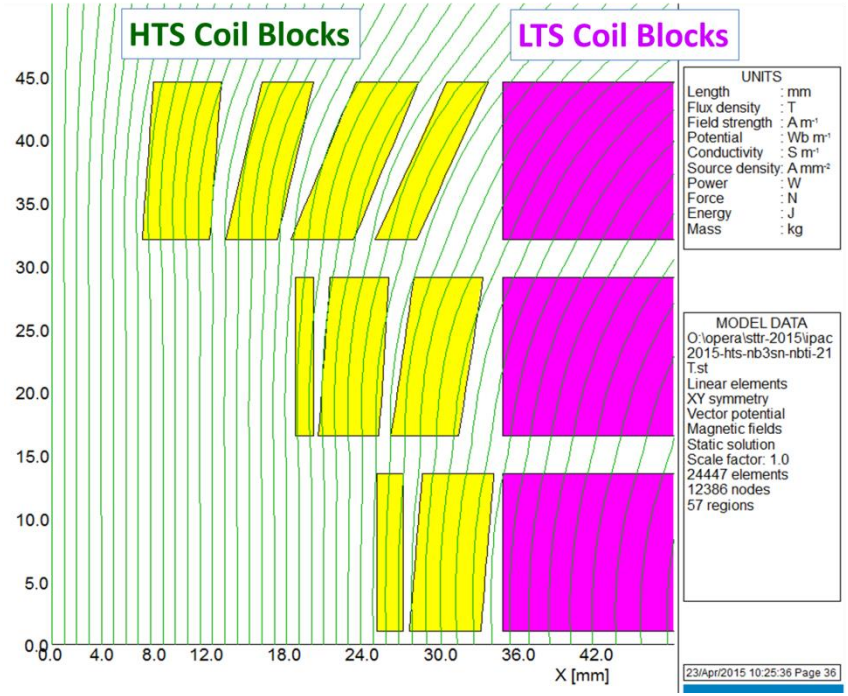
Design Technique to Reduce Magnetization Effects:

- Align the tape conductor (thickness few μm) such that primarily the

  "narrow side sees the perpendicular field"

- It is possible to align HTS tape to a good extent in **hybrid designs**

  "by carefully designing the coil (both HTS and LTS conductor blocks)"



Effective filament size of 12 mm reduces

⇨ **to a few mm in an ideal design**

Magnetization in an actual magnet will depend on the level of optimization and on how things work in real world (beyond computations)

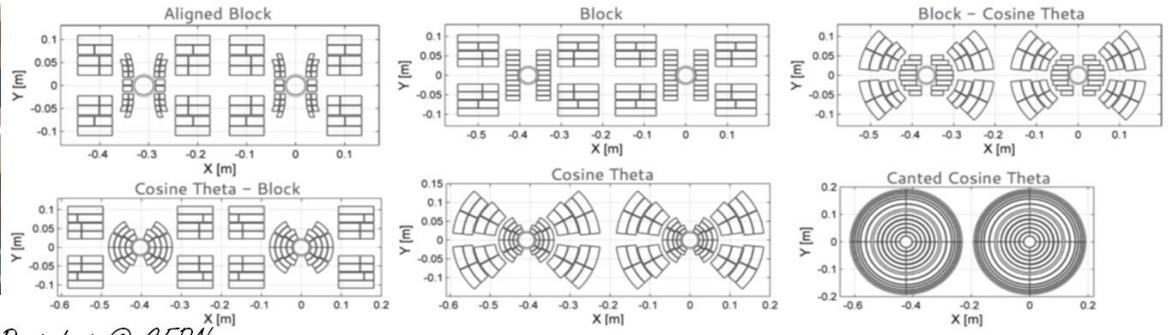
Another Major Benefit of the Aligned Tape Design (conductor efficiency)

Survey of 20 T Magnet design possibilities

Courtesy:

J. Van Nugteren

CERN



Jeroen Van Nugteren PhD student @ CERN