A REBCO Persistent Current Switch, Immersed in Solid Nitrogen, Operating at Temperatures near 10 K

Philip C. Michael
Francis Bitter Magnet Laboratory
Plasma Science and Fusion Center
Massachusetts Institute of Technology, Cambridge, MA

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Representing
Jiho Lee, John Voccio (Wentworth Institute of Technology), Juan Bascunan,
Seungyong Hahn (Seoul National University), and Yukikazu Iwasa

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Outline

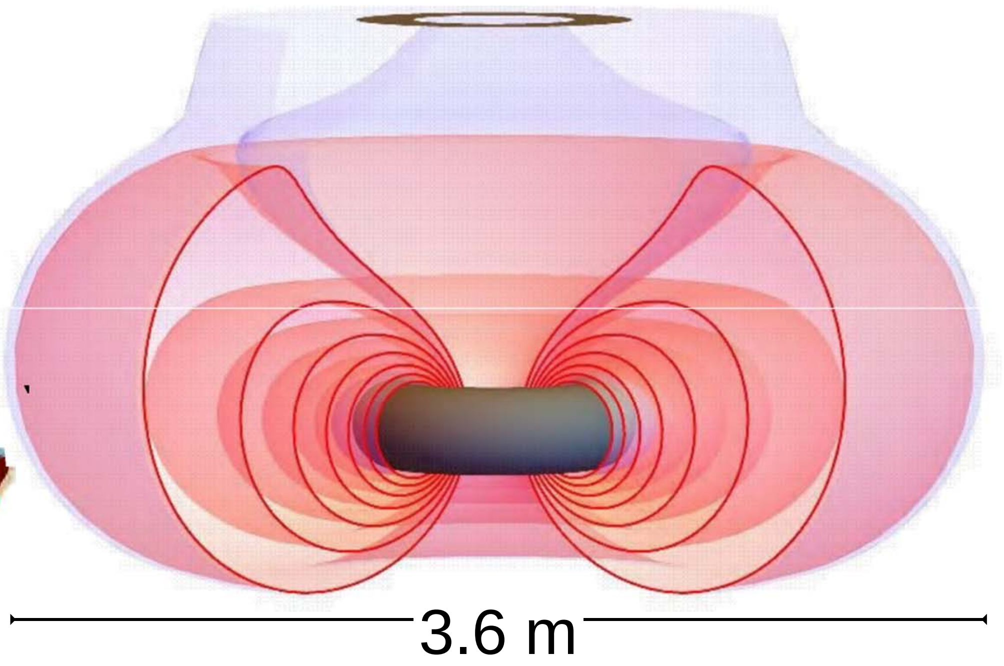
- Motivation
  - Typically two uses for persistent mode coils
    - Limited duration operation without power supply connection
    - High temporal stability for spectroscopy and imaging
- Target specifications
- PCS coil configuration
- Test arrangement
- Experimental results
- Summary

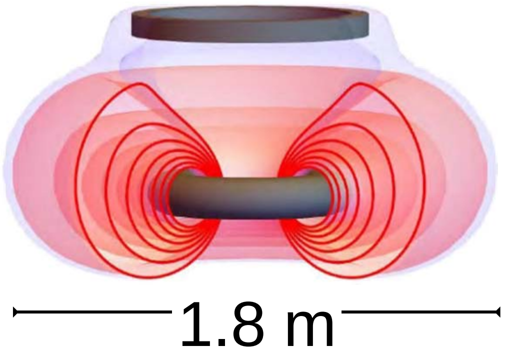
You may be asking …

Who could possibly need a REBCO PCS operating in SN2 near 10 K?

The answer is not quite so far fetched as it seems!

Laboratory Magnetospheres





Levitated Dipole Experiment (LDX)

(1.2 MA-turn · 550 kJ · 565 kg)

Nb_3Sn · 3 Hours Float Time

Inductively charged, 30 ppm h^{-1} decay

Ring Trap 1 (RT-1)

(0.25 MA-turn · 22 kJ · 112 kg)

Bi-2223 · 6 Hours Float Time

Charged using PCS, 0.1% h^{-1} decay

From: D. Garnier, “The Laboratory Magnetosphere,” presented at *Bringing Space down to Earth*, UCLA , 12 Apr. 2017

Principal motivation

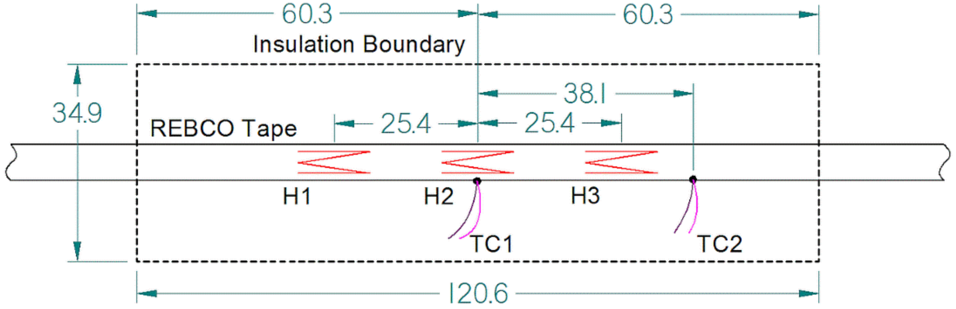
- Technology development
  - NMR above ~1 GHz requires HTS inner coils
  - Temporal stability favors persistent mode operation
  - Our 1.3 GHz NMR emphasizes no-insulation REBCO double-pancakes
- Focused on switch technology
- Superconducting REBCO joints by others
  - Our recent work emphasized MgB_2 and Bi-2212 joints
  - Several $10^{-12} \sim 10^{-13}$ Ohm joints reported recently
    - Very low resistance at lower fields and currents
    - Increasing to nOhm range with increasing field and current

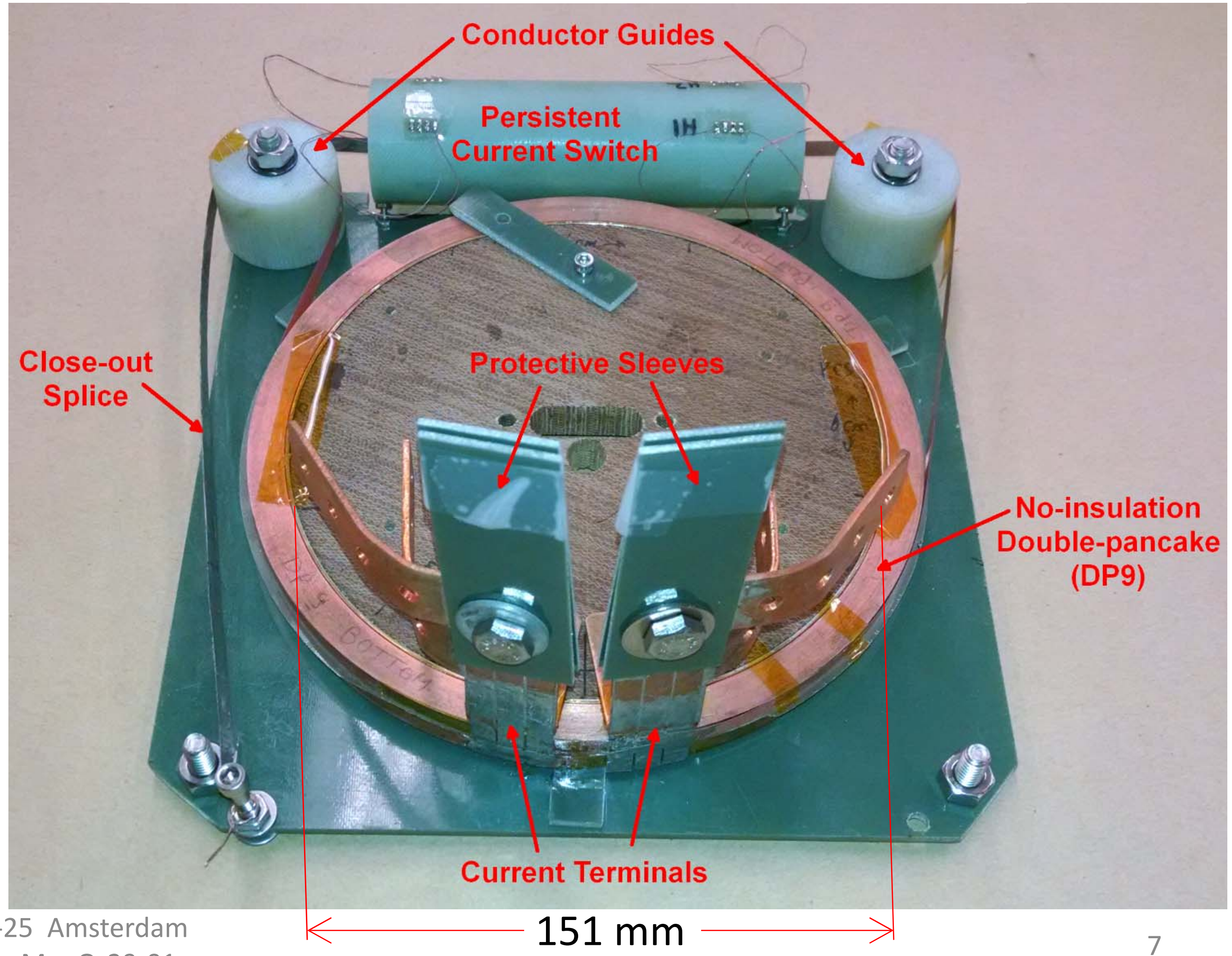
Target specifications

- Heater power to open <1W near liquid helium temperature
  - To facilitate operation in recondensing helium bath
- Open-state resistance >1 mOhm near liquid helium temperature
  - ~4x characteristic resistance of NI coil in test setup
  - >2 mOhm resistance demonstrated with 0.25W heating power at 77 K

PCS coil configuration

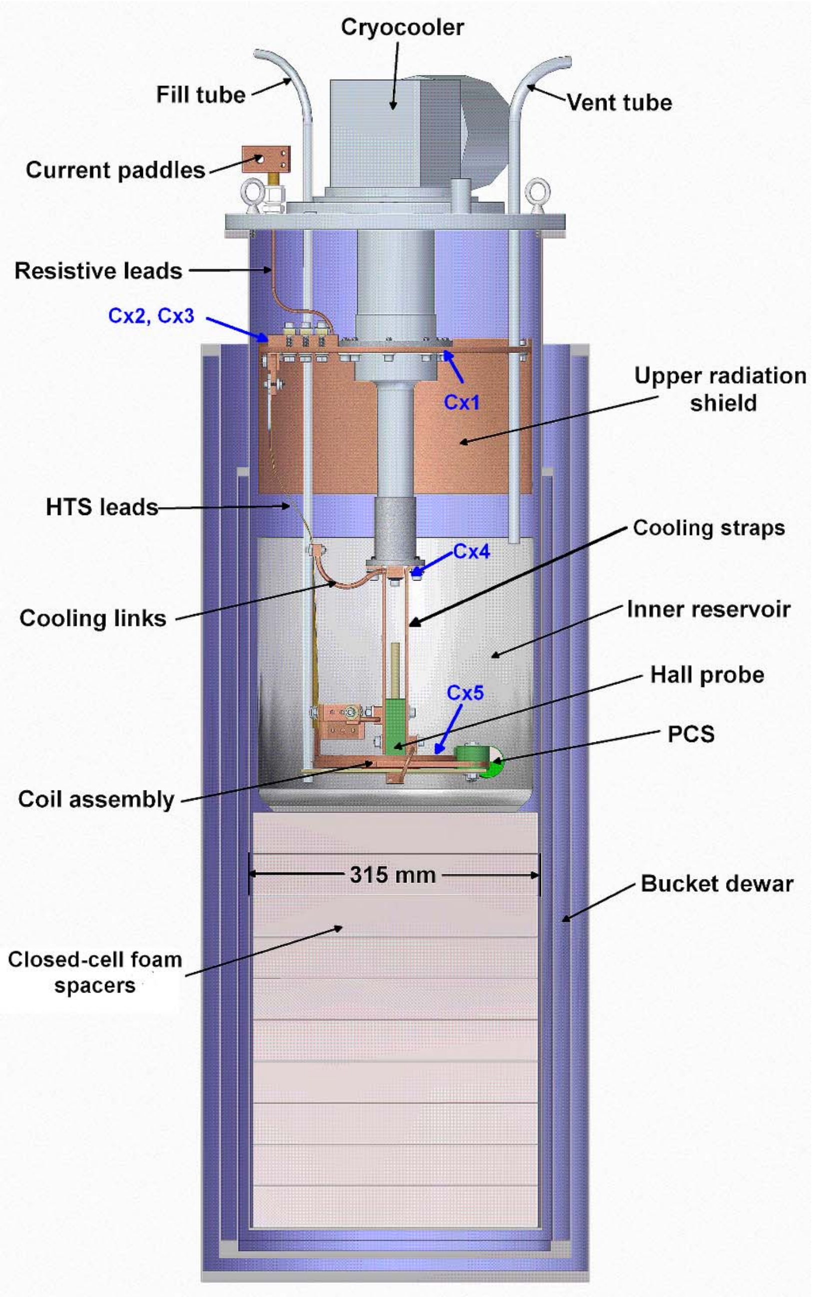
- Assembled from NI REBCO DP remaining from Coil 2 of our H800 insert for 1.3G
  - 6 mm x 76 mm REBCO tape
  - 151 mm ID, 243 turn
  - 17.7 mH self-inductance
- Analytical model of heater presented at ASC in 2016
- 150 mm long close-out joint with ~6 nOhm resistance





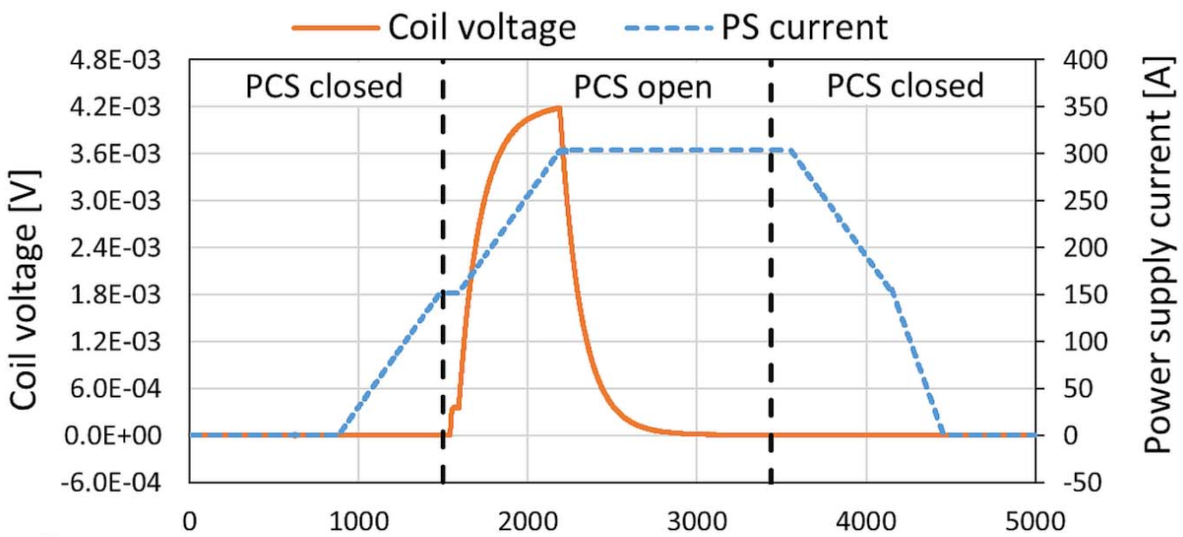
Test apparatus

- Conduction-cooled with RDK-408 cryocooler
- Housed in straight bucket cryostat
- SN2 contained in 16 liter inner reservoir
  - For heat transfer and thermal stability
  - Cooling to 65 K by evacuation
  - Cooling to 10 K by cryocooler
- Binary current leads
  - Resistive stage cooled at 1st stage
  - Cooling partway along HTS leads via thermal links to 2nd stage
- Five strategically placed Cernox to monitor thermal performance



Charging behavior

- Upramp to 150 A with PCS closed shows no coil voltage
- Jump in voltage during PCS opening from small current mismatch
- Subsequent voltage shows 1st order NI coil behavior, with $\tau \sim 130$ s
- Hall probe also shows similar charging delay
- Field decay measured starting from return of PS to zero current



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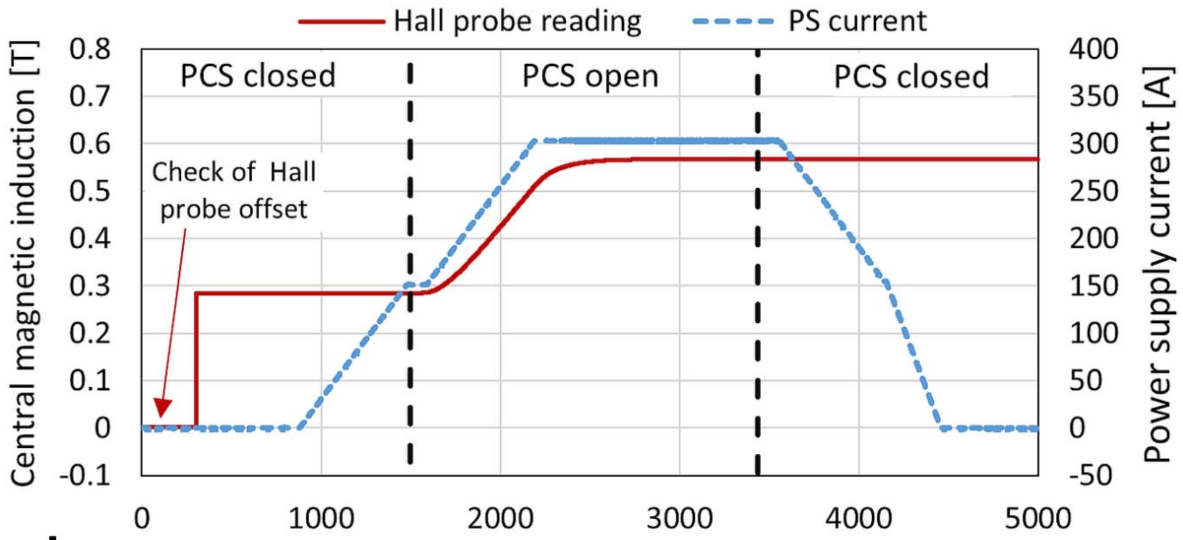

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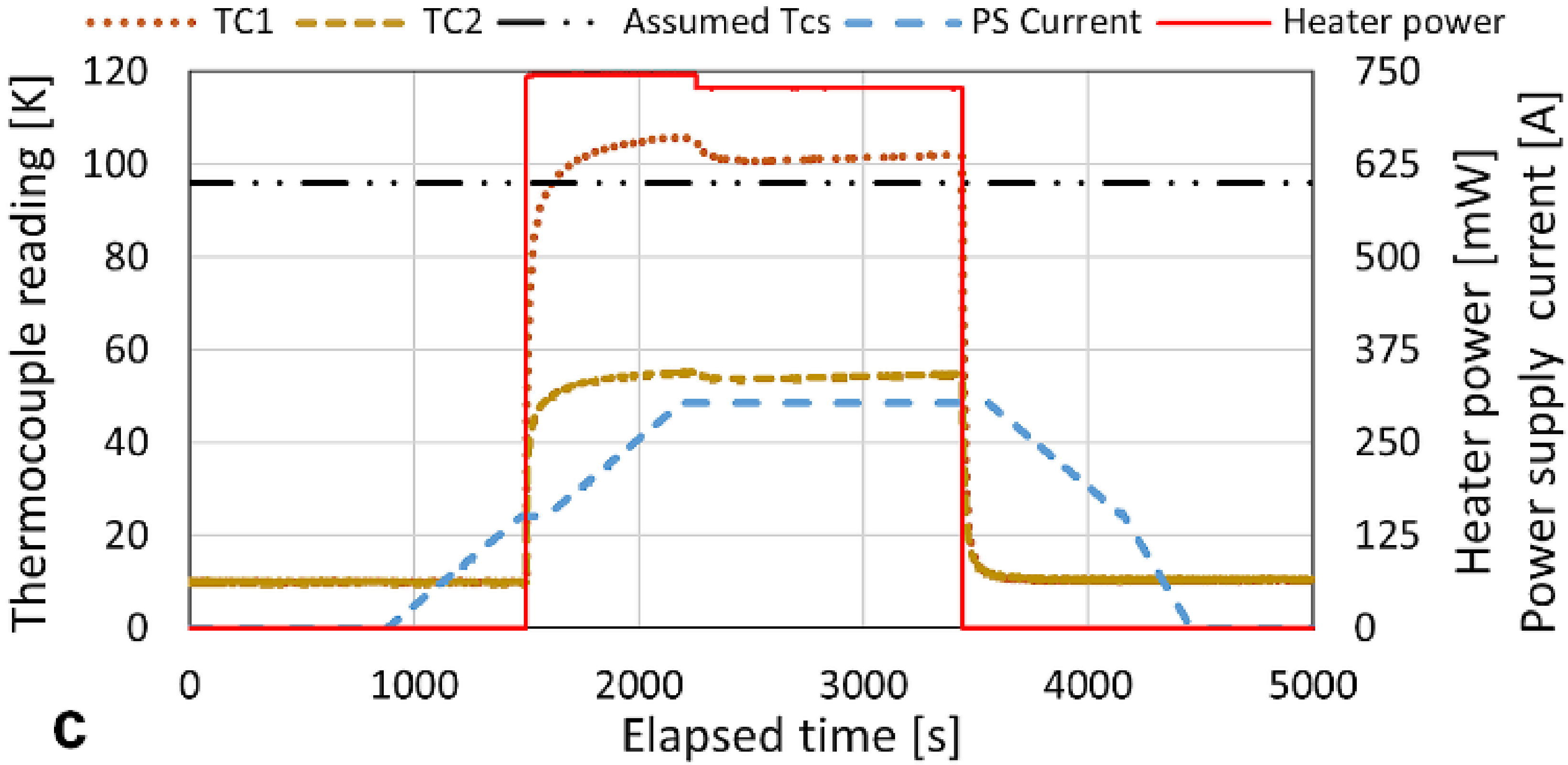
P.C. Michael
<michael@psfc.mit.edu>

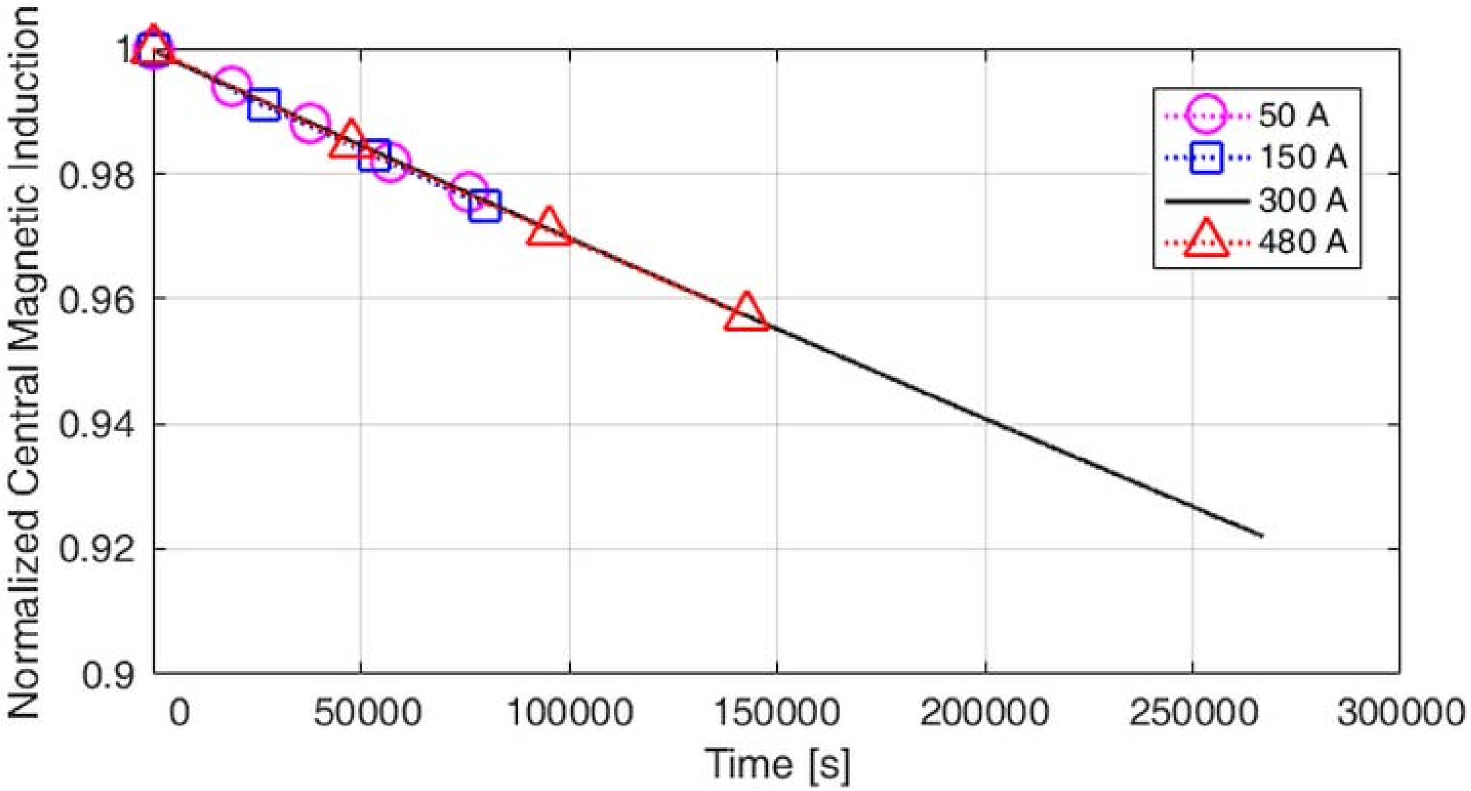
Switch performance

- Switch opening at ~0.75W heating power
- Steep temperature gradient - strong thermal conductor along copper
- On-state resistance ~0.2 mΩ at this low heating power



Persistent decay

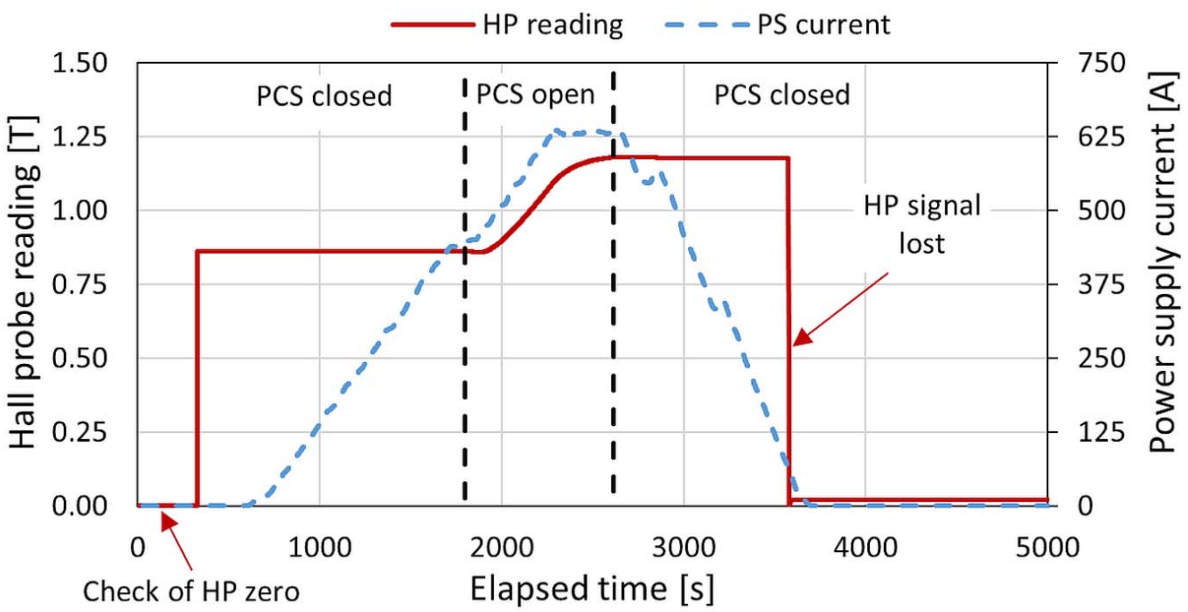
- Field decay at 50A, 150A, 300A and 480A all show same trend
- Exponential fit shows $3.3x10^6$ s time constant, 0.1% h^{-1} field decay rate
- L/R time constant matches 5.5 nΩ measured splice resistance

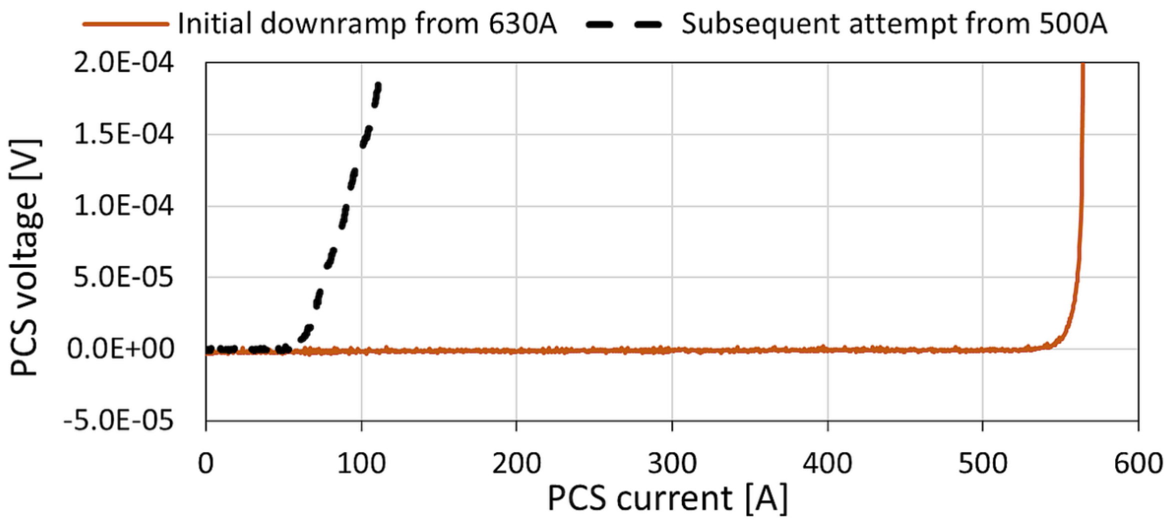


Need for PCS protection

- Hall signal lost during downramp from 630 A
- Premature quench of PCS conductor
- NI DP are largely self-protecting during quench
- Much smaller PCS conductor wasn’t, and was significantly damaged
- Future use of parallel shunt resistor for PCS protection?

(See for example T. Tosaka, *et al. IEEE Trans. Appl. Supercond., vol. 16, no. 2, pp. 910-913, Jun. 2006)*





Summary

- Small NI-DP PCS coil, designed, built and tested at 10K in SN2
- Design objectives largely fulfilled
  - Heater power to open <1W
  - Quasi-persistent operation at up to 480 A with 0.1% h^{-1} field decay rate
- Further development needed
  - Incorporation of protection resistor into coil circuit
  - Generation of larger open-state resistance without increasing heater power
  - Use of existing analytical models to guide future designs – e.g. reduce copper?
- Pending applications for similar PCS heaters
  - LDX upgrade
  - Flux-pumped Z1/Z2 shim coils

Spare

Thermal performance

- Initial cooling by LN2 transfer
- Sub-cooling by evacuation
- Activation of cryocooler at ~65 K
- Base temperatures within a day
  - ~39K 1st stage, 41~42K leads
  - ~9K 2nd stage, 10K coil
- Rapid rise in lead and 1st stage temperatures above ~450A, the leads' "optimized" operating point
- 2nd stage and coil temperature constant to within 1K