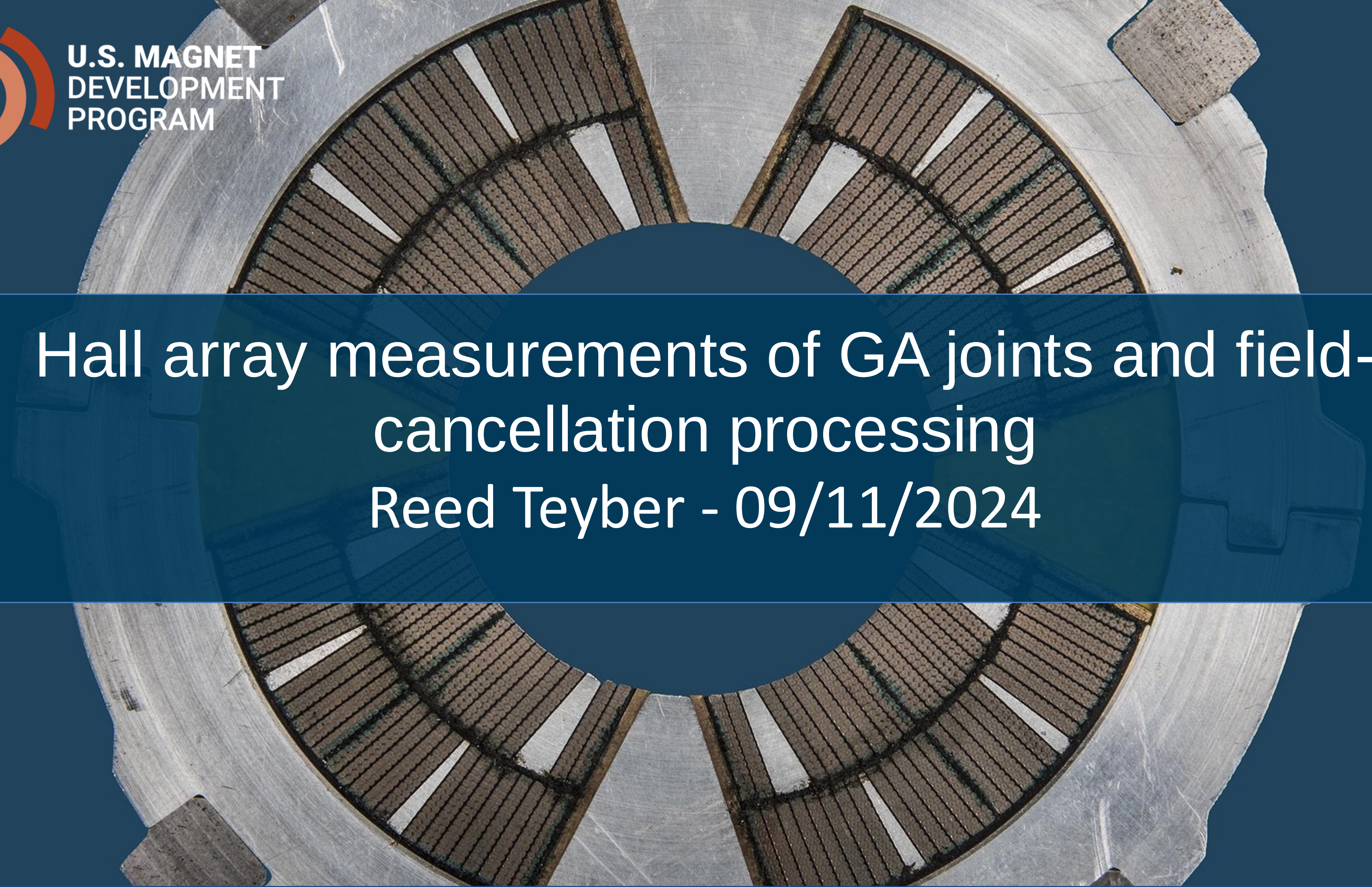


U.S. MAGNET DEVELOPMENT PROGRAM

Hall array measurements of GA joints and field-cancellation processing

Reed Teyber - 09/11/2024

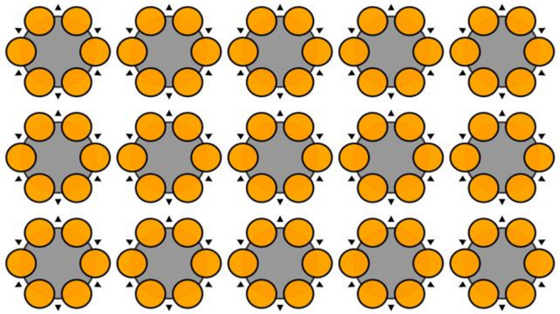
Summary

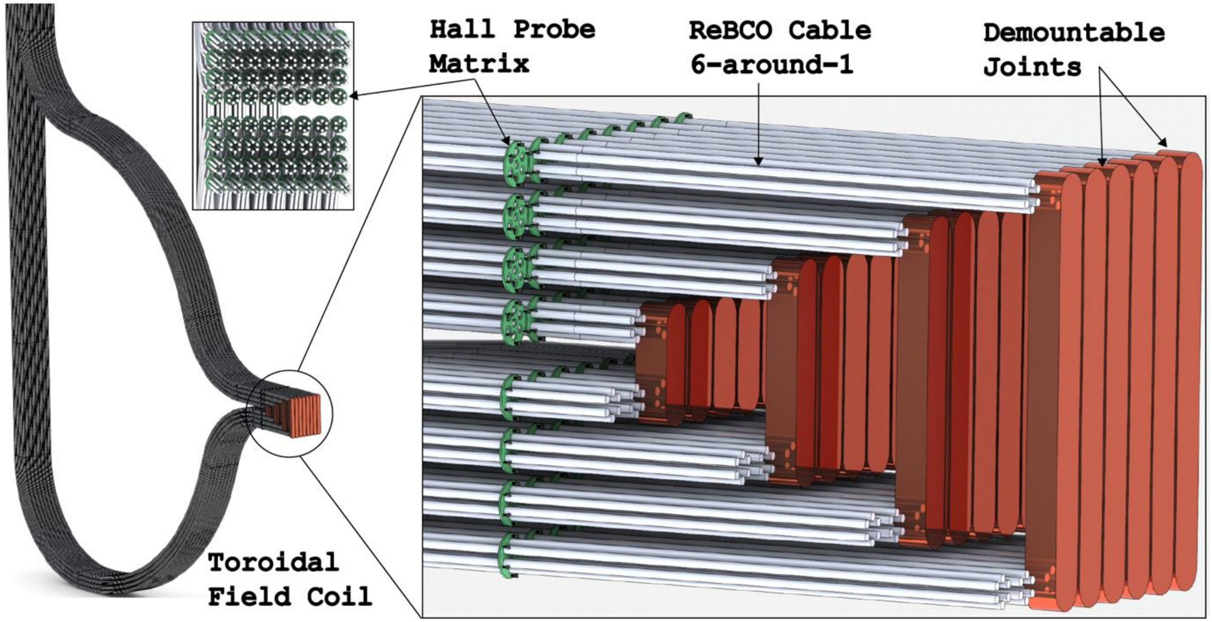
- First LBNL "hybrid" test completed in June 2024
  - Insert was a CORC fusion sample, but from facility / circuit coupling point of view, is like a "1 turn magnet" inside bore of CCT5
  - Very pleased with test and results – warrants longer talk in future
- Today's presentation focuses on diagnostic developments for cryogenic current sensing in high and variable background magnetic fields
  - Developments for SBIR phase 2B on Hall-based quench detection

Slide from ASC ELEVATE early career

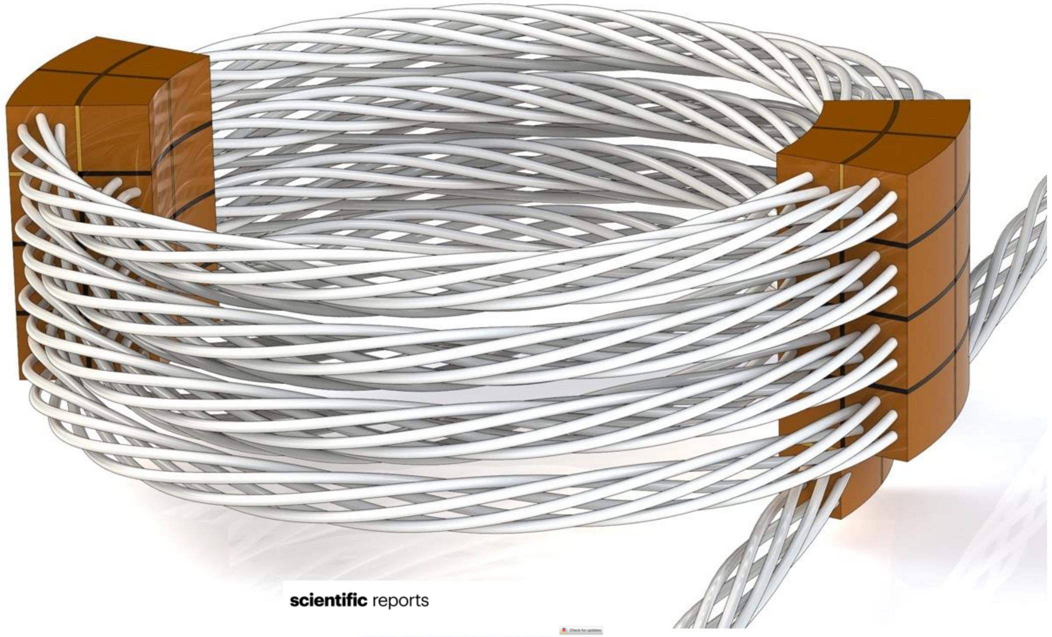
- Why the need for cryogenic current sensing in high and variable background magnetic fields?
  - Ambitious desire to track entire winding pack current distributions

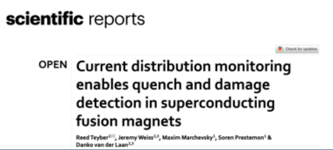
Large inverse Biot-Savart problem





Inspired from General Atomics / ACT




scientific reports

OPEN Current distribution monitoring enables quench and damage detection in superconducting fusion magnets

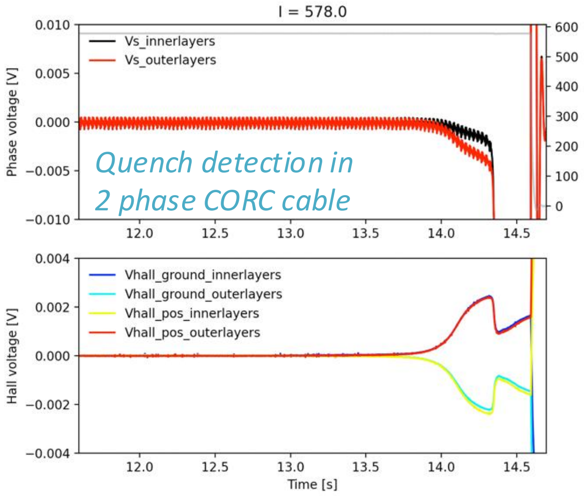
Outline

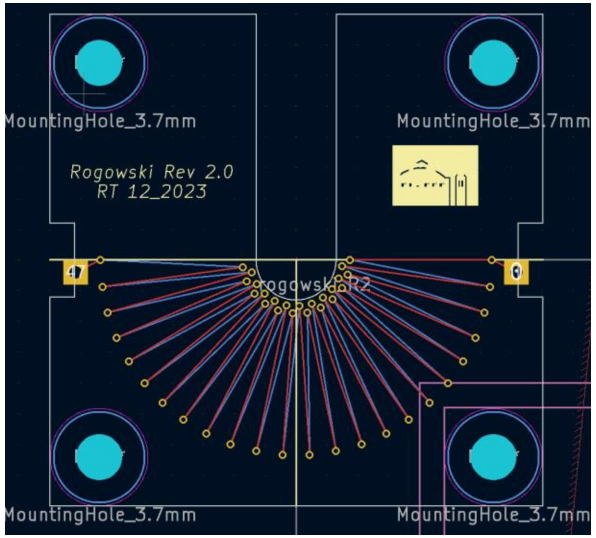
- PCB Rogowski coil design and tests
  - *Funded by DOE FES SBIR*
- Phase current sensors and processing
  - *Funded by DOE FES SBIR*
- Hall array results in GA ”hybrid” test
  - *Funded by DOE FES INFUSE*

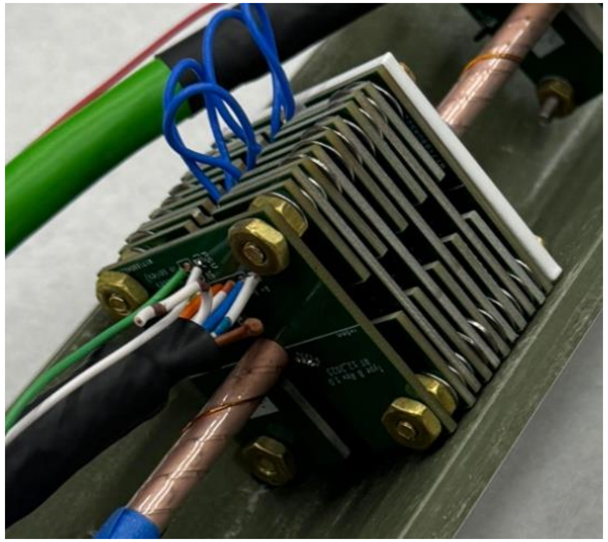
PCB Rogowski Coils

- Rogowski coils like quench antenna that capture flux from line current
  - Immune to *constant* background fields
  - Inducted voltage integrated to get current
- Python tool for scripted PCB Rogowski coil generation
  - Wired into PCB “toroidal transformer” for larger signal

```
#INPUT PARAMETERS

    ri = 3.75
    ro = 15.875
    r_offset = 0.6 #
    nlines = 23
    dtheta = np.pi/(nlines)
    theta_offset = 0

    delta_x_lead = 2
    delta_y_lead = 1
    lead_pad_width = 2
    lead_drill_diameter = 1

    line_width = 0.15
    drill_diameter = 0.4
    pad_diameter = 0.6
```

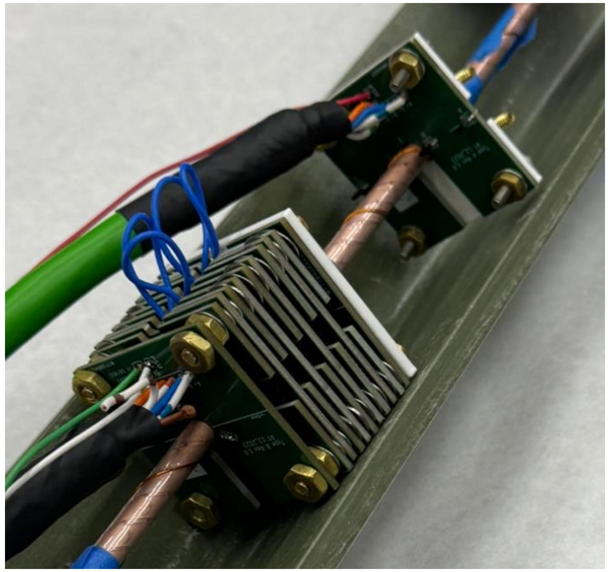


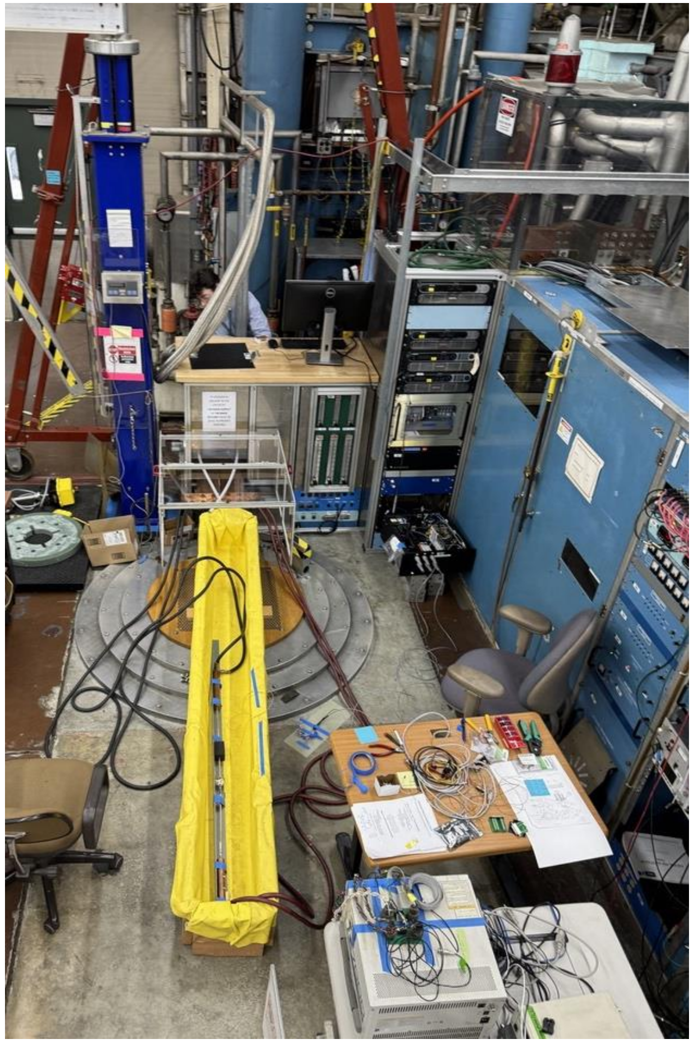


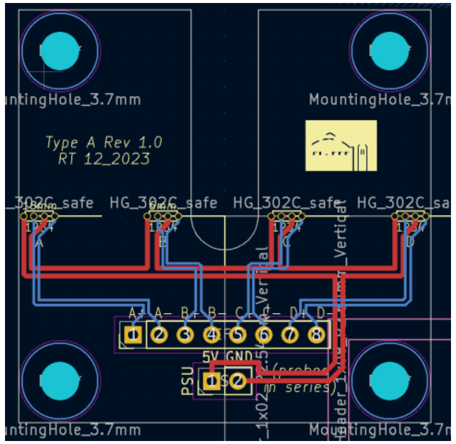


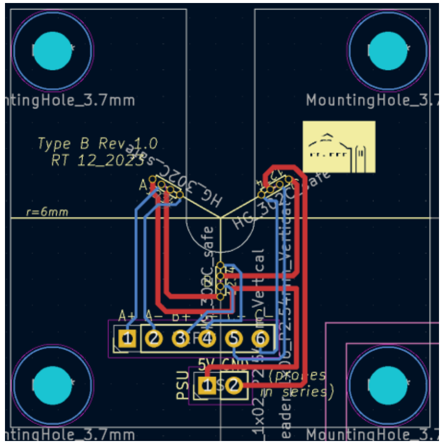
Cryogenic Current Measurements

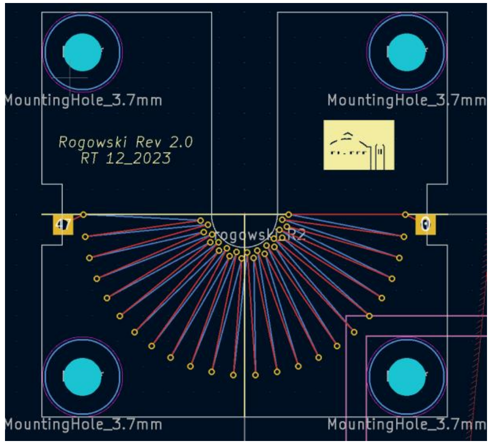
- CORC cable tested on new Sorensen insert circuit with PCB Rogowski coil and two different Hall arrays





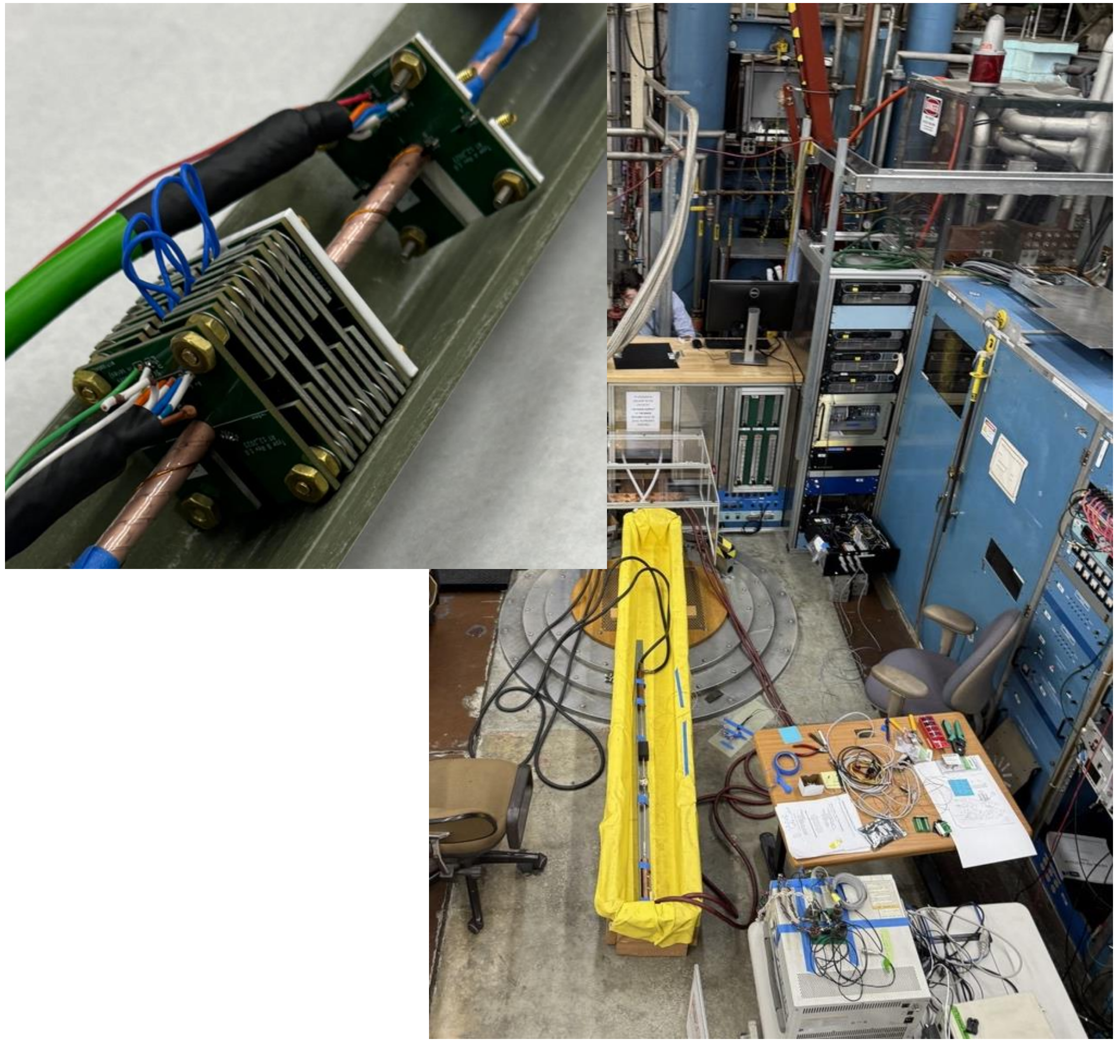




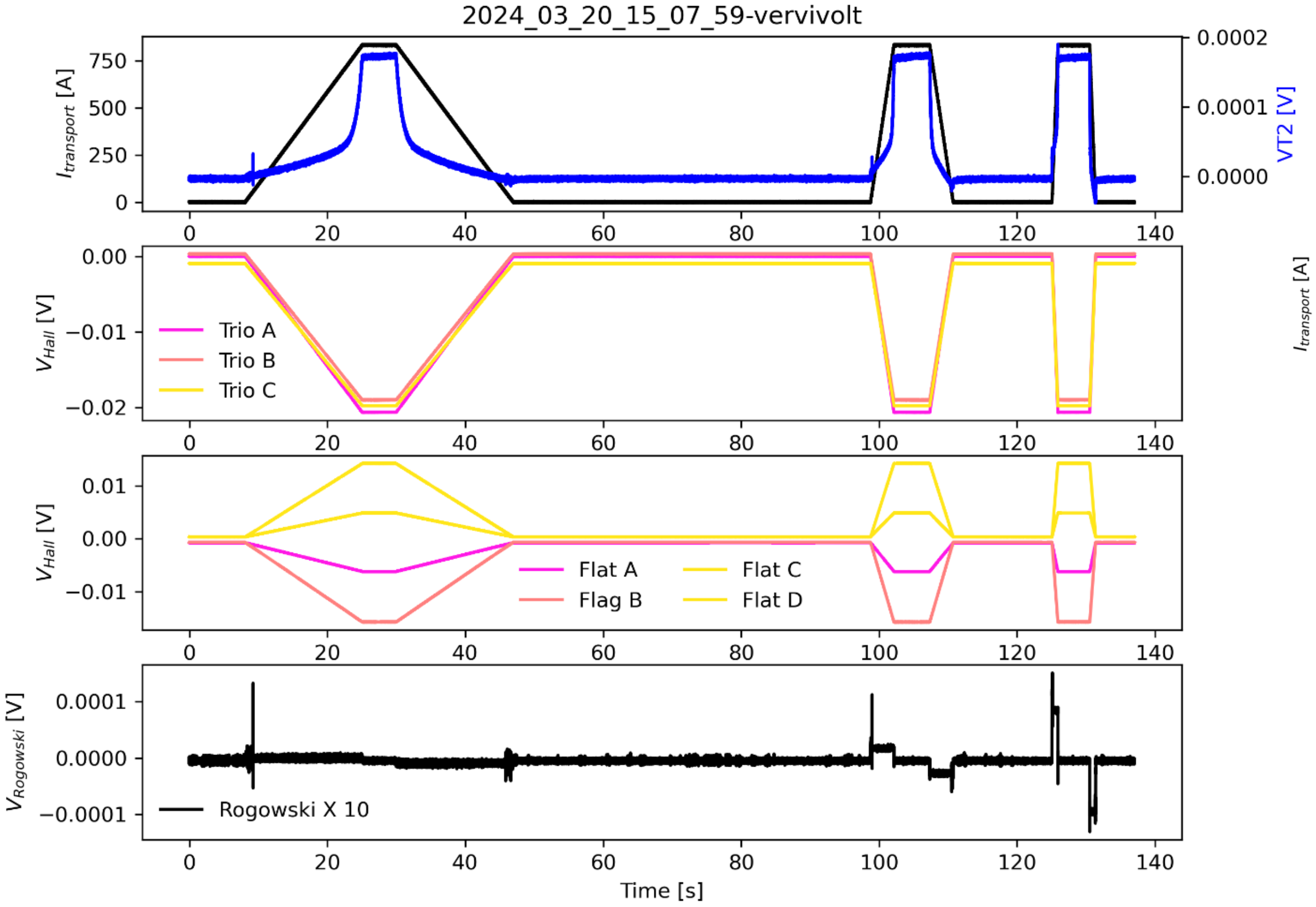


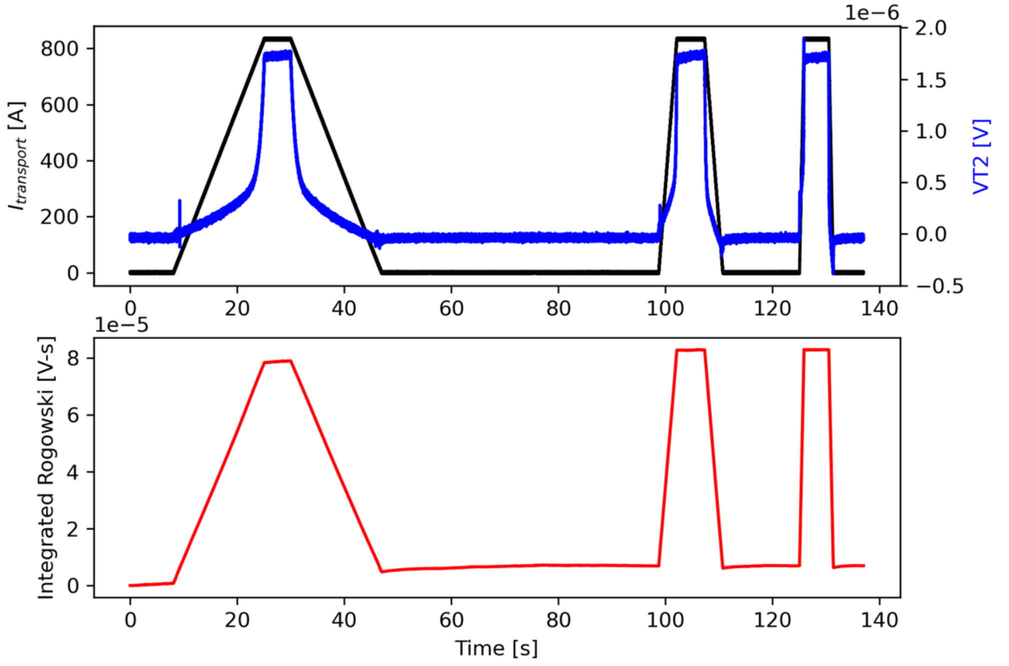
Thanks CPRD

- This is a 6 tape, 4 mm wide CORC cable which was supplied by CPRD and extremely valuable for these types of developments! Thanks Lance + Ian!



77K CORC I-V Measurements





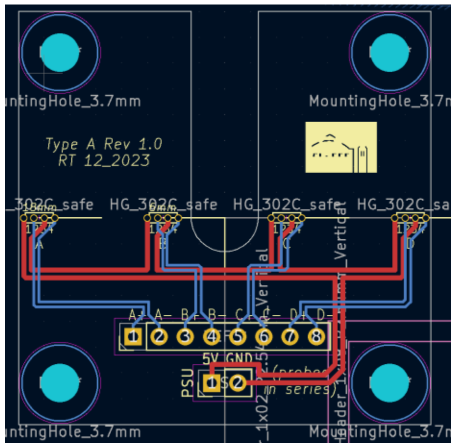
Integrated Rogowski

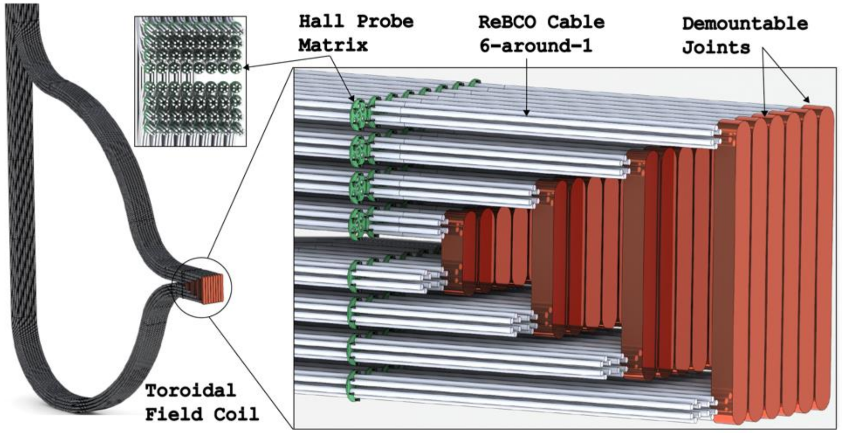
Rogowski Summary

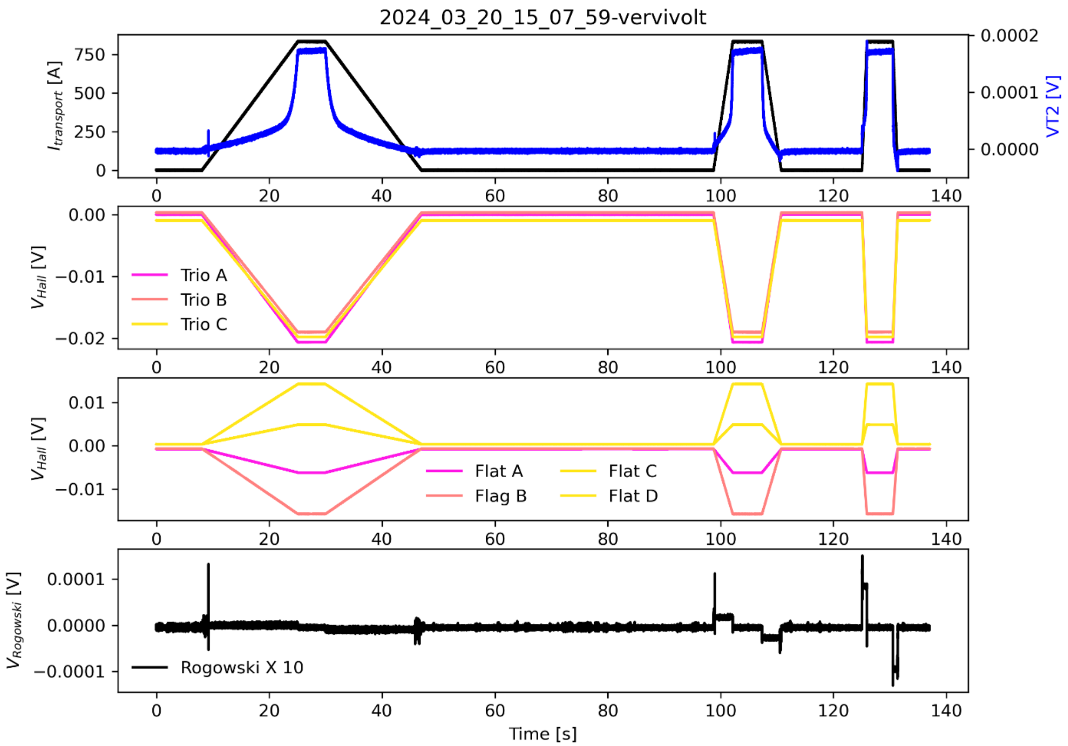
- Rogowski coil arrays completely passive, radiation resistant, immunte to background fields, “cute” and fun
- However, small signals even with toroidal stacking so put on backburner for now
  - But many advantages that should not be ignored!

Processing Flat 4 array

- Goal is to develop current sensing that would scale to something like shown
  - Focusing now on the flat 4 array

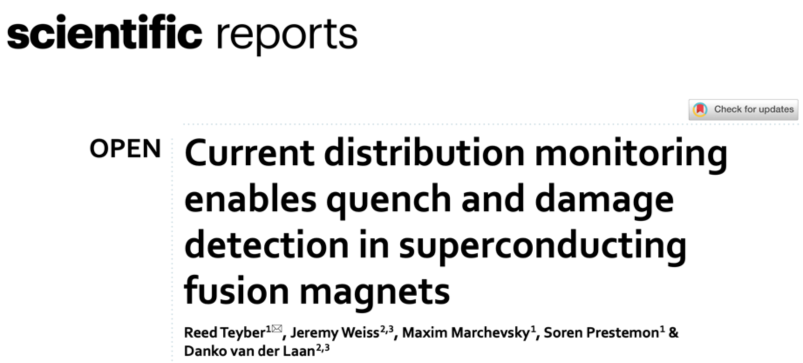






Processing Flat 4 array

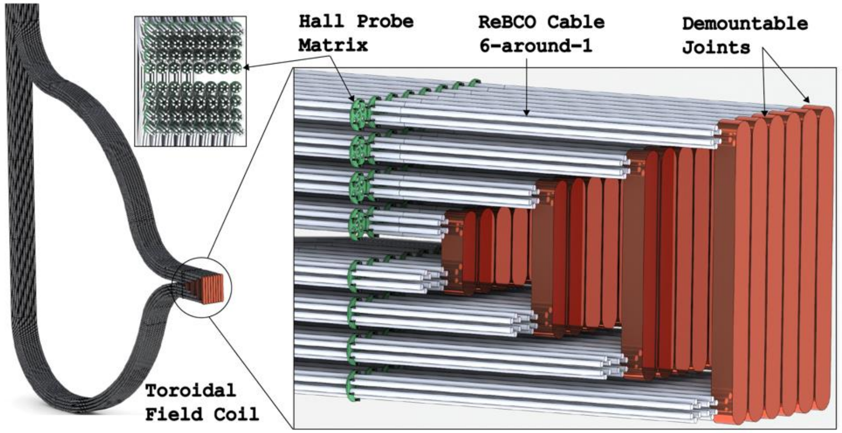
- In shown paper – inverse Biot-Savart routine to recreate 3 cable currents from 4 magnetic field sensors in real time
- New development today
  - Numerical approach to recreate the single phase current and background magnetic field from the four sensors in flat four array
    - *And do it in a way that scales to ->*


scientific reports

Check for updates

OPEN **Current distribution monitoring enables quench and damage detection in superconducting fusion magnets**

Reed Teyber[1]✉, Jeremy Weiss[2,3], Maxim Marchevsky[1], Soren Prestemon[1] & Danko van der Laan[2,3]



Processing Flat 4 array

Summary – method consistent with inverse Biot-Savart approach to date, should scale well

Analytic solution to find current and background field from four hall sensor measurements

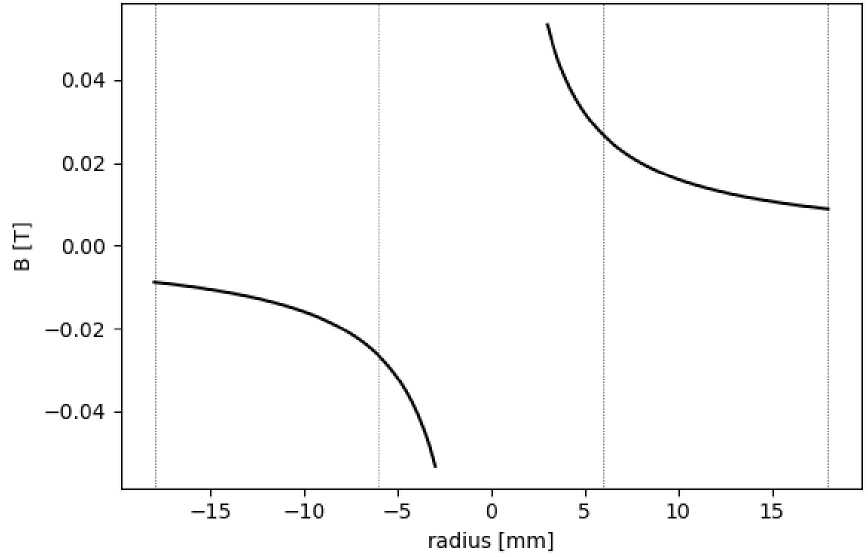
$$A^T A x = A^T b$$

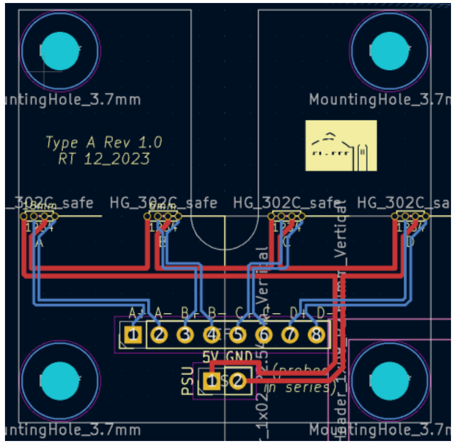
$$\begin{bmatrix} I \\ B_{ext} \end{bmatrix} = (A^T A)^{-1}(A^T b)$$

$$A^{-1} = \frac{1}{AD - BC}\begin{bmatrix} D & -B \\ -C & A \end{bmatrix}$$

$$\begin{bmatrix} I \\ B_{ext} \end{bmatrix} = \left(\frac{1}{(a_A^2 + a_B^2 + a_C^2 + a_D^2) - (a_A + a_B + a_C + a_D)^2}\right) * \ldots$$

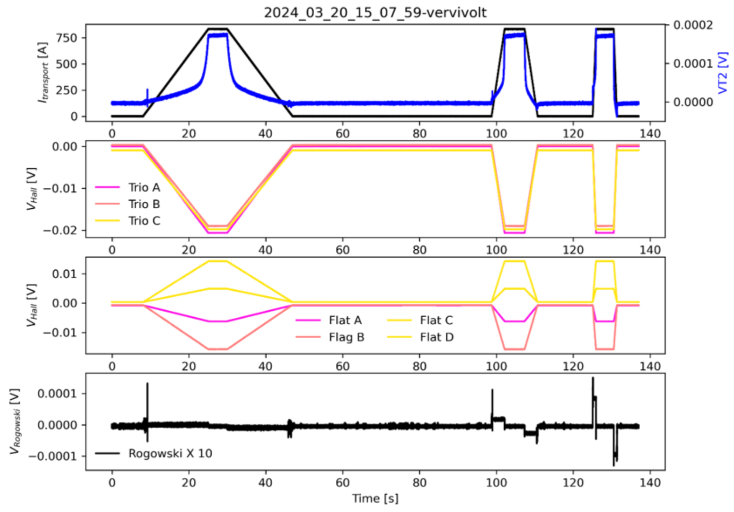
$$\ldots * \begin{bmatrix} 1 & -(a_A + a_B + a_C + a_D) \\ -(a_A + a_B + a_C + a_D) & (a_A^2 + a_B^2 + a_C^2 + a_D^2) \end{bmatrix} \begin{bmatrix} (a_A B_A + a_B B_B + a_C B_C + a_D B_D) \\ B_A + B_B + B_C + B_D \end{bmatrix}$$

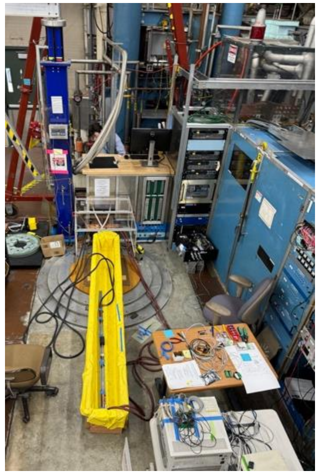




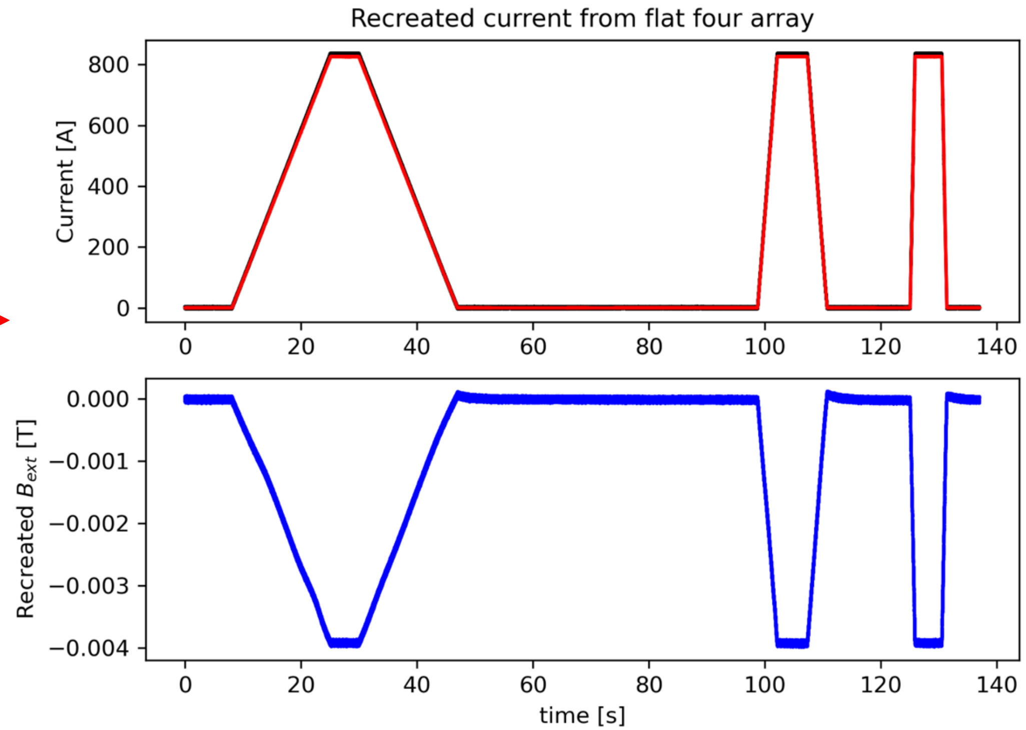
Processing Flat 4 array

- First prototype in Python using previous data (no applied field)



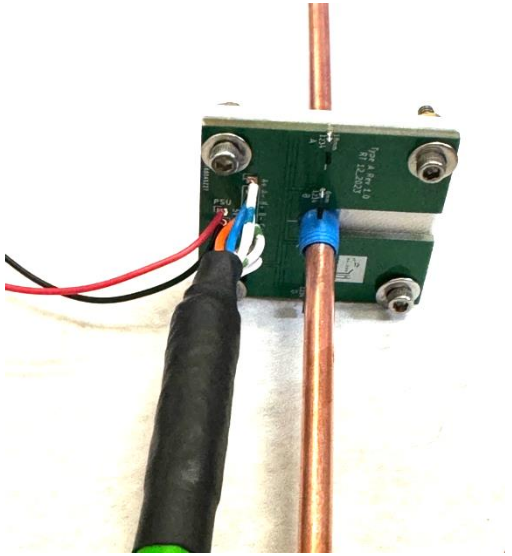


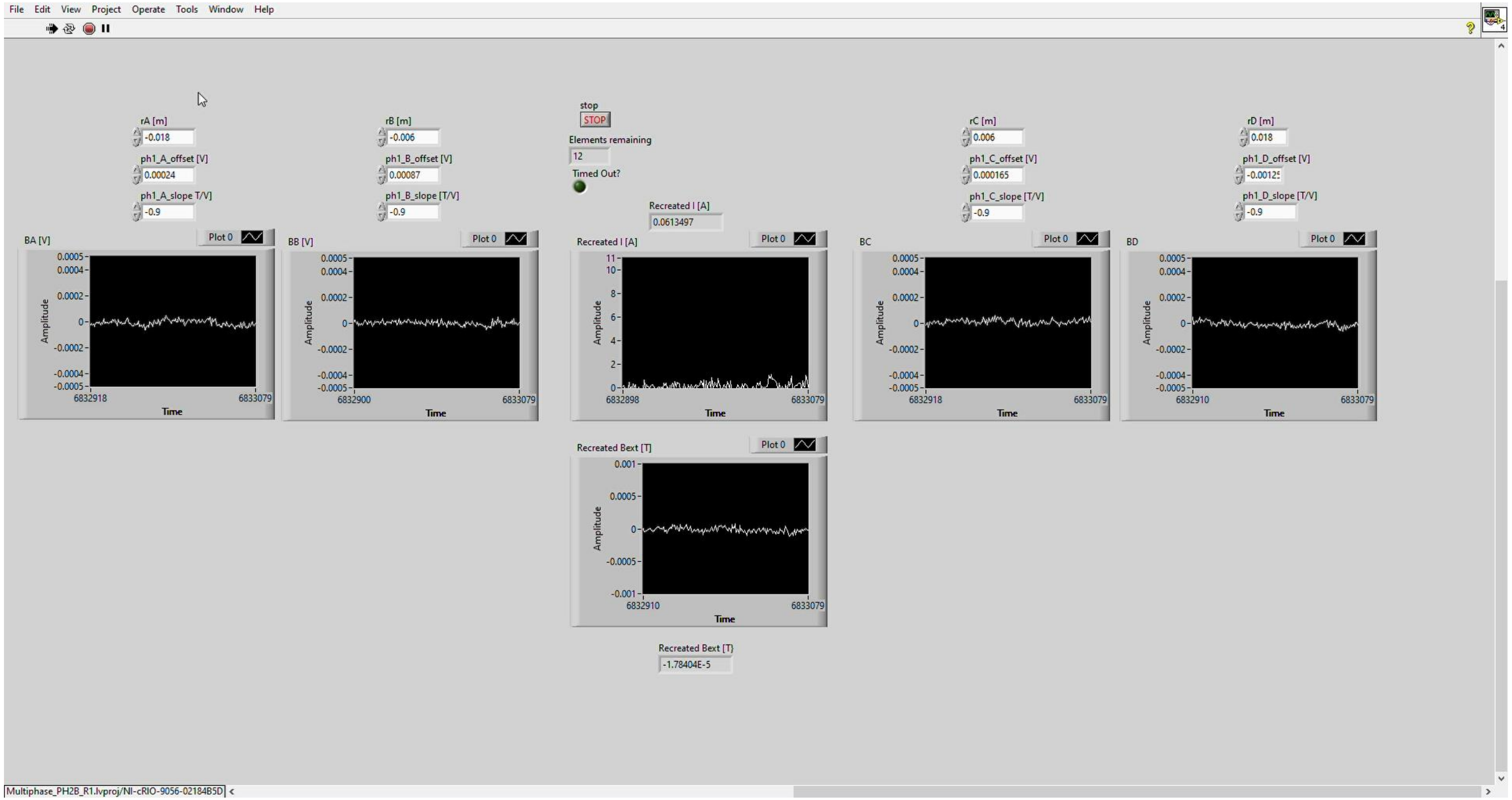
B ext should be 0, likely result of hall sensor sensitivity variations – but very small



Promising results in noisy background!

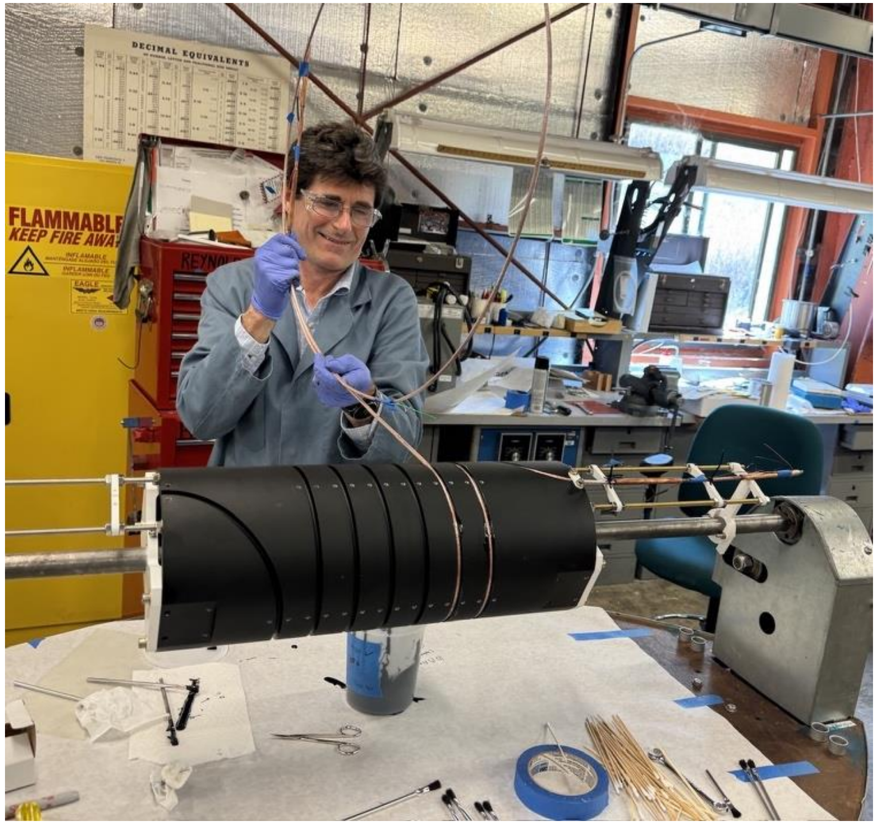
- Low current tests with large permanent magnet in my office





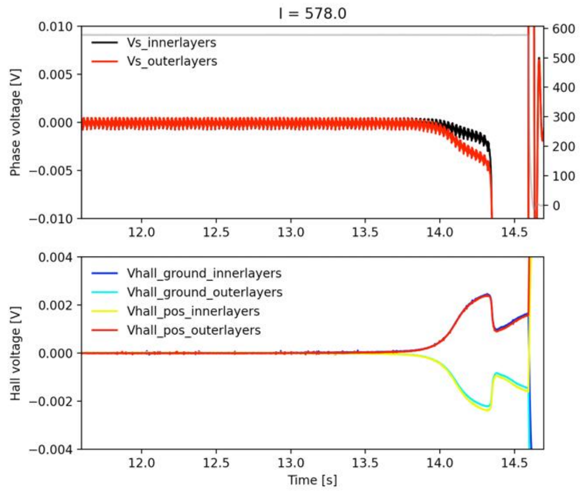
Winding a 2 phase CORC cable

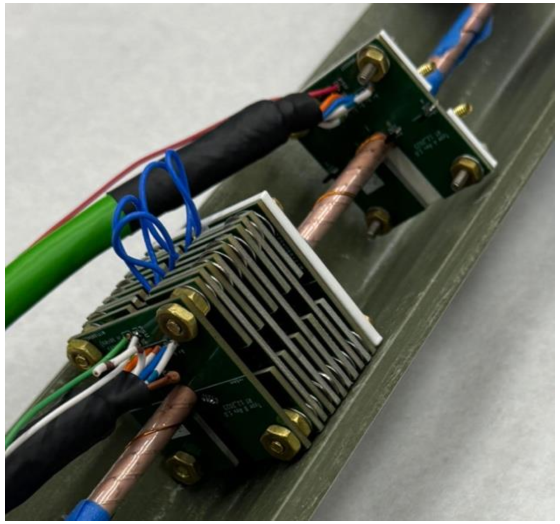
- ~ 4 meter, two-phase CORC cable wound into loose solenoid and ready for testing
  - Developments above to track phase currents for quench detection system



Summary

- New cryogenic current sensor developed that actively / digitally removes background magnetic fields, implemented on compactRIO
- Recreated currents (and identified redistribution) to be used in quench detection system for two-phase CORC cables
- Next steps are to expand linear algebra for non-uniform background magnetic fields and for more complex CICC inverse Biot-Savart





GA Hybrid test

- Really don't have time to go over the June LBNL Hybrid test today, let's get more into details another time (deserves focused presentation)
  - Next few slides are from ASC talk
- However, the test had a Hall probe array in the joint, and was able to measure fine trends in joint current distributions in fields up to 6 Tesla which is very encouraging

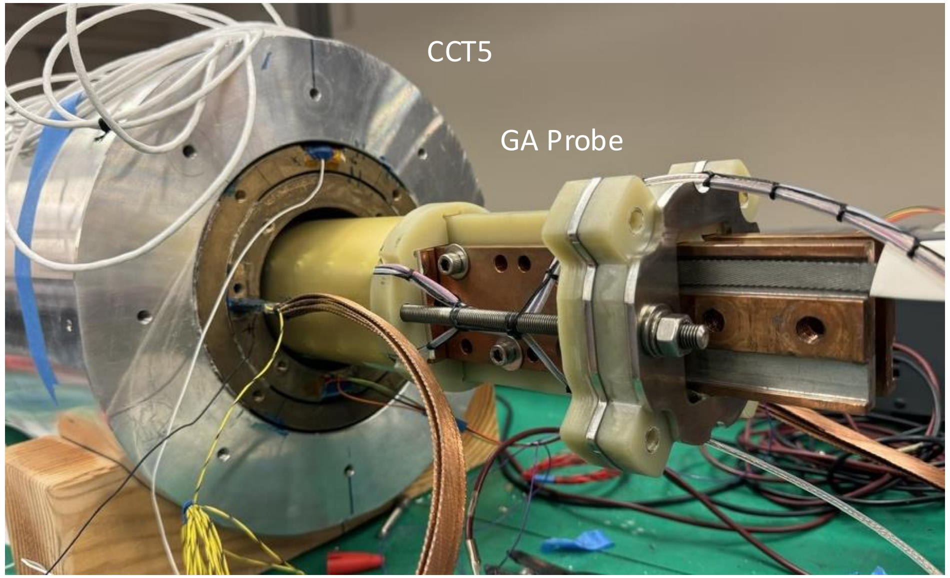
Demountable Joint and Probe

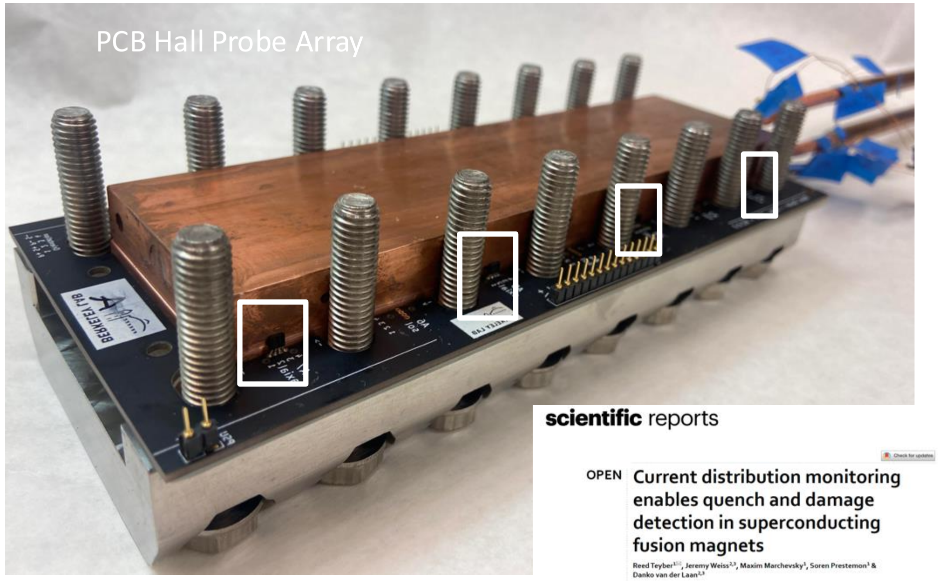
- Probe created to test demountable joint in bore of CCT 5
  - Joint prepared by General Atomics
  - Probe and test by LBNL
    - Hall probe array to probe current distribution
- CCT5 is 90 mm bore, ~9.7 T SS Nb3Sn CCT dipole magnet

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022 4003207

Status of the Nb_3Sn Canted-Cosine-Theta Dipole Magnet Program at Lawrence Berkeley National Laboratory

D. Arbelaez, T. Bogdanof, L. Brouwer, *Member, IEEE*, S. Caspi, *Member, IEEE*, D. Dietderich, J. L. Rudeiros Fernández, P. Ferracin, *Senior Member, IEEE*, S. Gourlay, *Senior Member, IEEE*, R. Hafalia, M. Krutulis, M. Marchevsky, M. Maruszewski, C. Myers, S. Prestemon, *Senior Member, IEEE*, M. Reynolds, T. Shen, *Senior Member, IEEE*, J. Swanson, R. Teyber, M. Turqueti, *Member, IEEE*, G. Vallone, and X. Wang

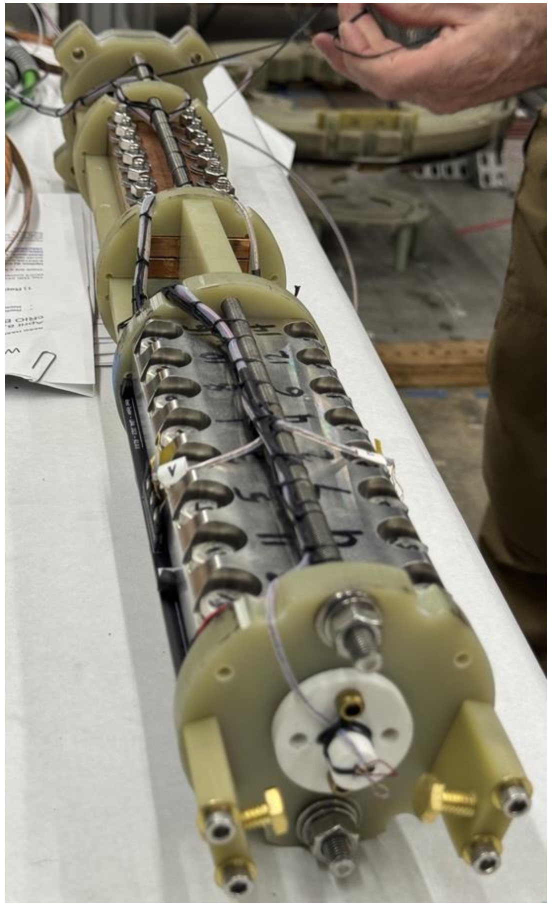




scientific reports

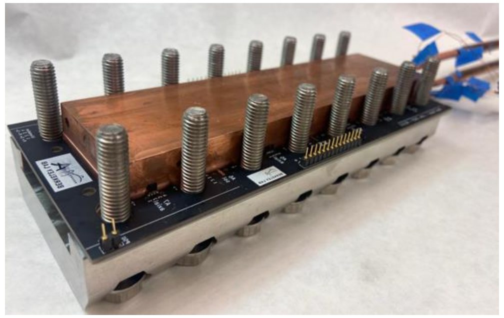
OPEN **Current distribution monitoring enables quench and damage detection in superconducting fusion magnets**

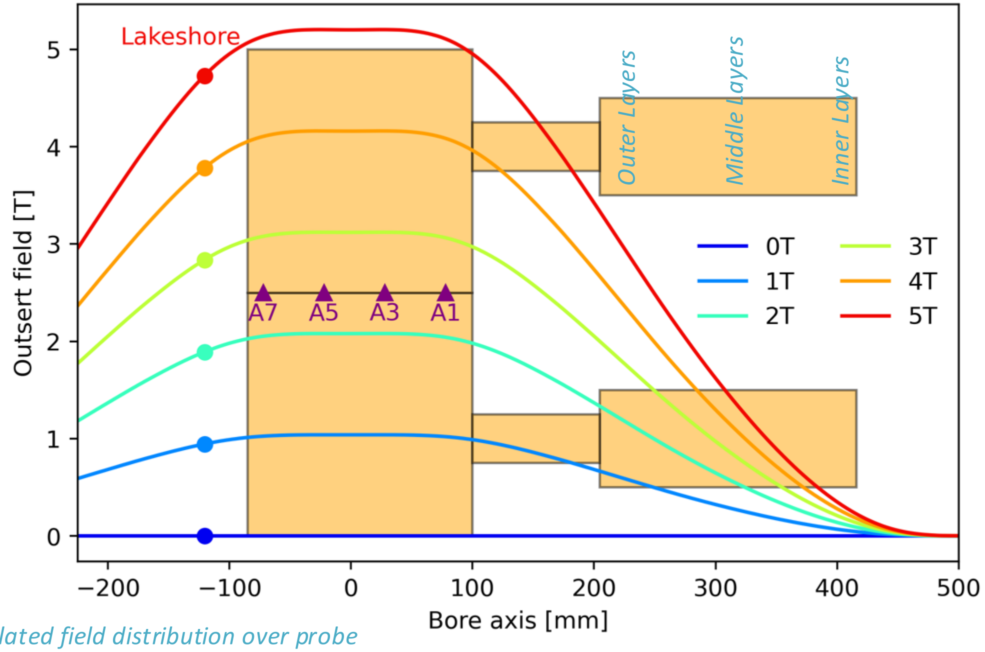
Reed Teyber[1], Jeremy Weiss[2,3], Maxim Marchevsky[1], Soren Prestemon[1] & Danko van der Laan[2,3]



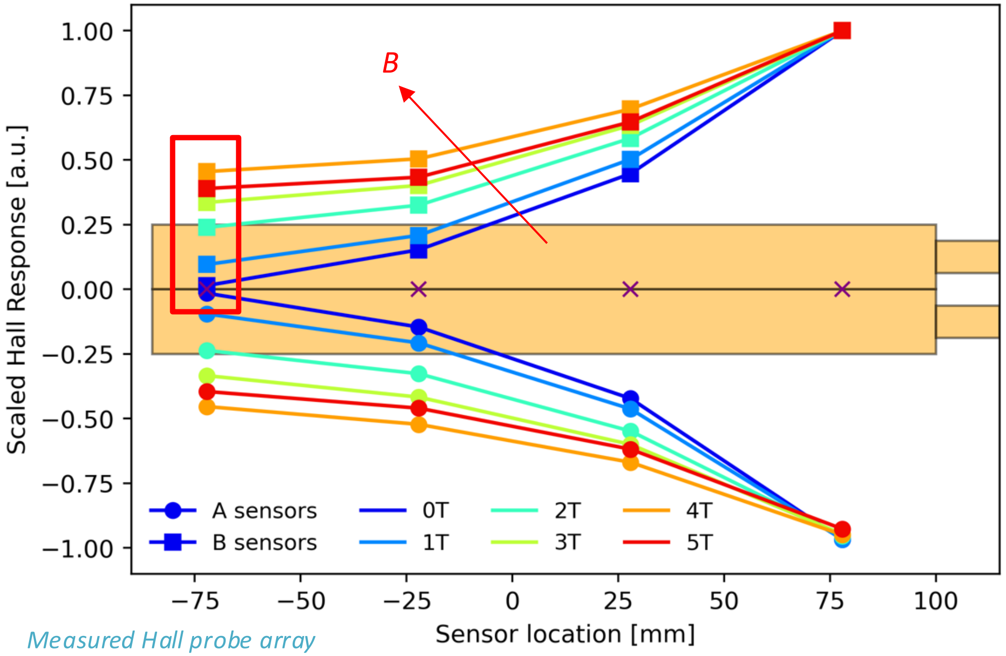
Joint Current Distribution

- Higher fields push current to rear of joint (inner layers)
  - Largest change in 1-3T range, where R(B) above most nonlinear
    - Larger field on outer layers may play role
  - May be caused by increased copper resistance
    - But magnetoresistance ~ linear





Simulated field distribution over probe



Measured Hall probe array

Conclusion

- Other progress / developments
  - Benjamin born June 1, 2024!
    - *"Bengiamino"*