Design and Test of a Curved Superconducting Dipole Magnet for Proton Therapy

September 26th, 2019

26th International Conference on Magnet Technology: Vancouver, Canada

Lucas Brouwer

Lawrence Berkeley National Laboratory

MT 26 International Conference on Magnet Technology Vancouver, Canada | 2019

BCMT BERKELEY CENTER FOR MAGNET TECHNOLOGY

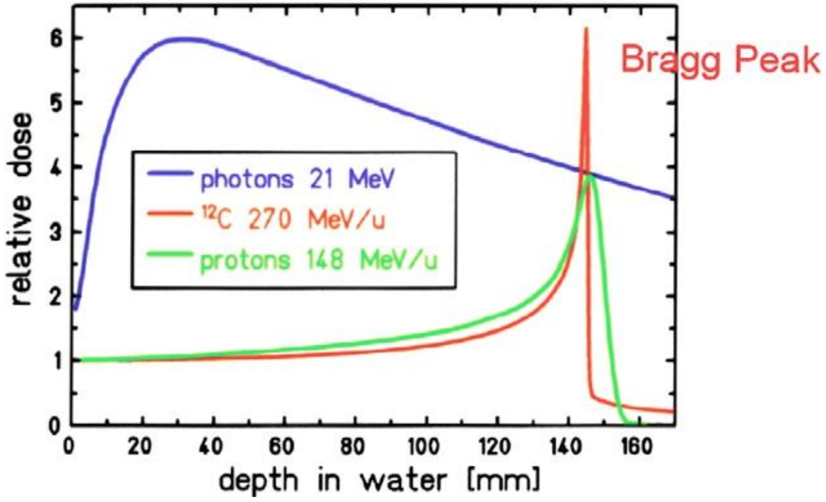
U.S. DEPARTMENT OF ENERGY | Office of Science

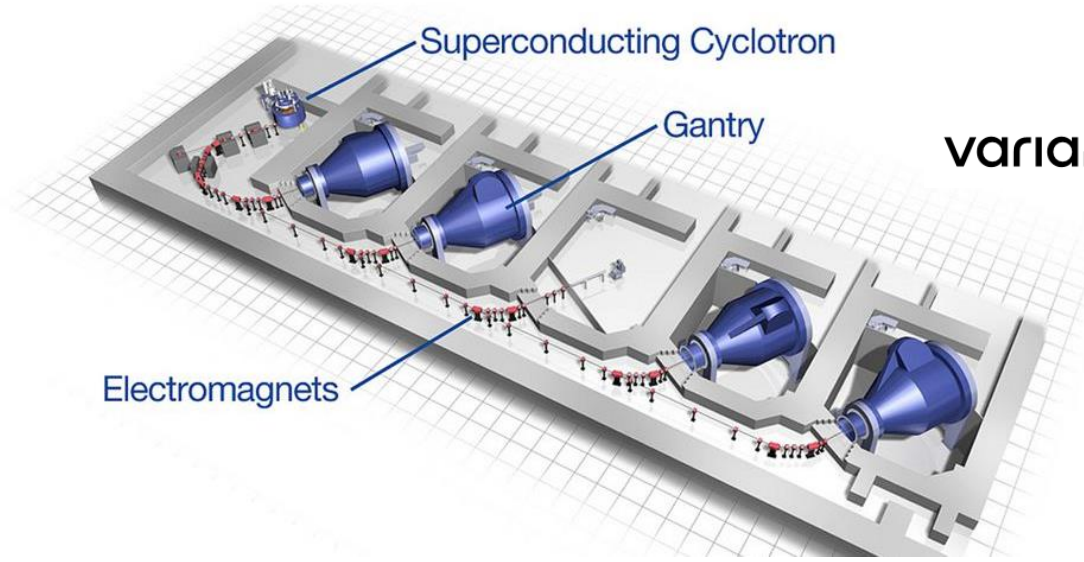
Thu-Af-Or23-06

Ion Beam Cancer Therapy

The Bragg peak is used to target the cancer tumor and minimize damage to healthy tissue

- **~95 operational facilities worldwide**
- **~215 k patients treated historically**
- **majority proton (commercial)**
- **rapid growth (43 new proton centers in ~2020*)**



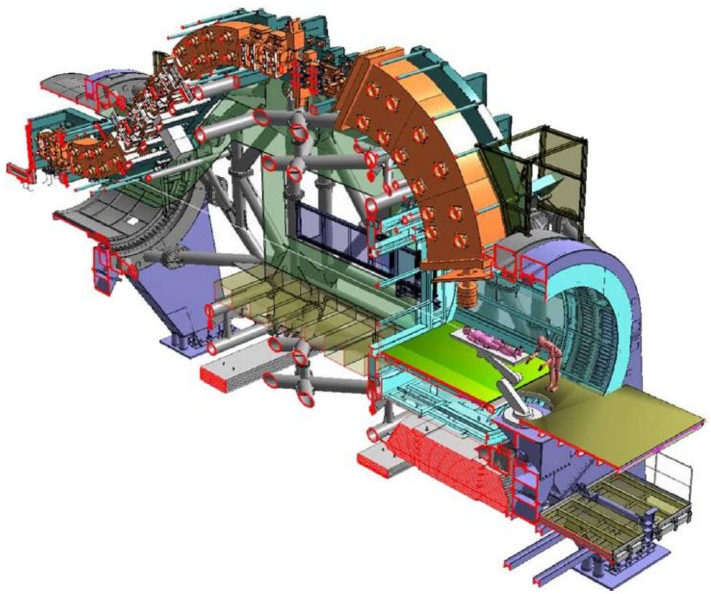


varian

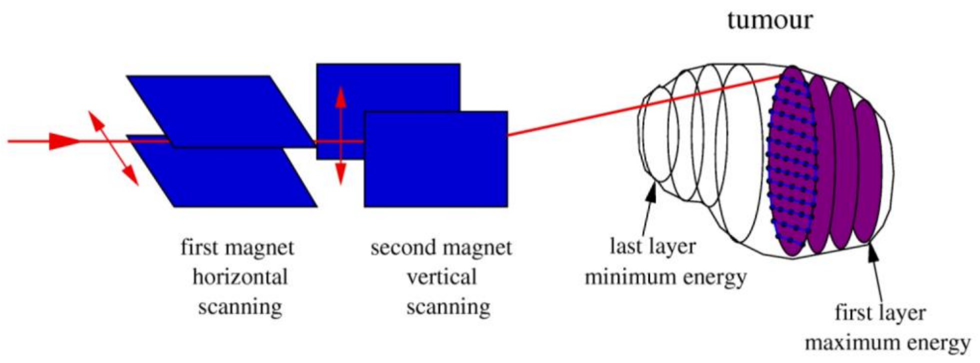
http://www.ptcog.ch/index.php/facilities-in-operation, April 2017

State of the Art Treatment Uses a Gantry with Pencil Beam Scanning*

Gantry for multiple treatment angles



3D scanning "paints" the tumor volume



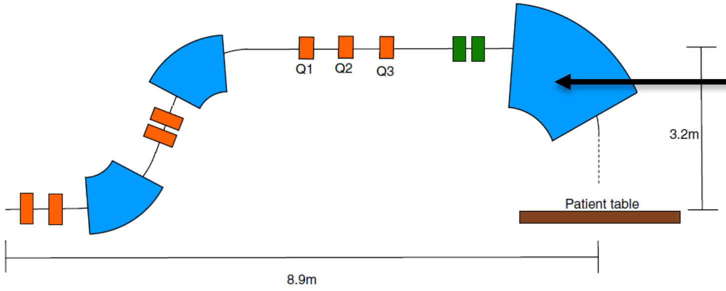
***as identified by a 2013 Joint DOE, NIH, and NCI accelerator stewardship workshop**

http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Workshop_on_Ion_Beam_Therapy_Report_Final_R1.pdf.

DOE-HEP Accelerator Stewardship Funded Project for Compact Proton Gantries with Varian Medical and the Paul Scherrer Institute

Scanning proton gantries are large and heavy which contribute to high facility cost

PSI proton gantry II: ~100 tons



46 ton final bending magnet

PAUL SCHERRER INSTITUT PSI

BERKELEY LAB

varian

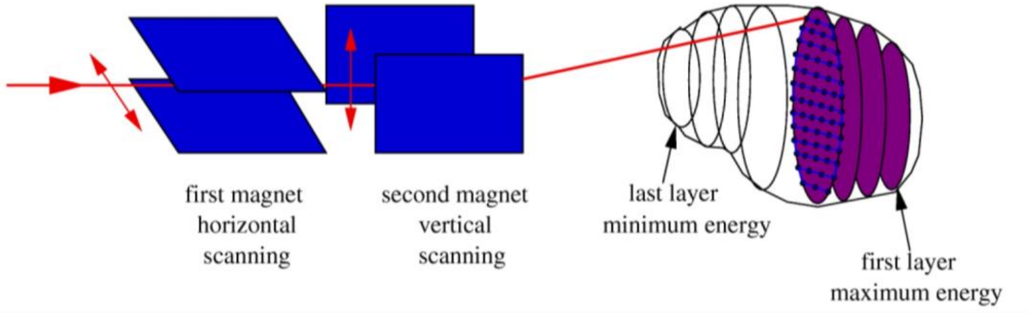
CCT NbTi final bending magnet < 1 ton

Large momentum acceptance superconducting magnets show promise for

1. Weight and size reduction (cost)
2. Novel gantry beam optics (performance)

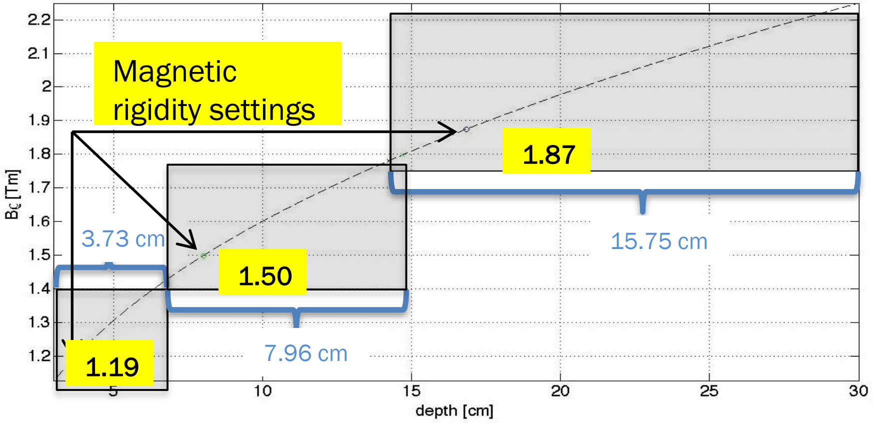
Momentum Acceptance Addresses a Key Technical Risk (Fast Field Ramping)

With little or no momentum acceptance, each energy change during scanning requires a new magnet setting



- ✘ **fast scanning: up to 0.5 T/s**
- ✘ **<u>heat from eddy currents in superconductor magnet windings/ structure is challenging for conduction cooling</u>**

With a large momentum acceptance, each magnet setting cover a range of treatment energy (e.g. 20% dp/p)

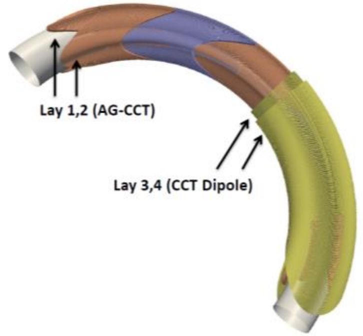


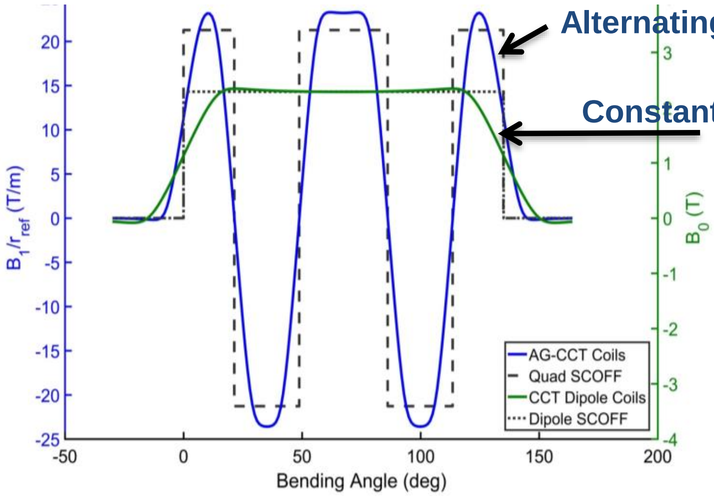
- ✓ **with 20% momentum acceptance the entire proton treatment energy range can be covered with three magnet settings**
- ✓ **<u>order of magnitude reduction in magnet field ramping</u>**
- ✘ **typically requires combined function or more complex fields and beam dynamics**

Highlights of the Accelerator Stewardship Project are: (1) the design of a SC proton gantry with 20 % momentum acceptance and (2) the test of a prototype magnet

Four layer CCT design with large acceptance (20%)

Bending Radius	900 mm
Bore Radius	105 mm
Magnetic Bend	135 deg
Momentum Acceptance ($\Delta p/p$)	20%
Constant Dipole	2.3 T
Alternating Quadrupole	±22.7 T/m
Stored Energy	0.86 MJ





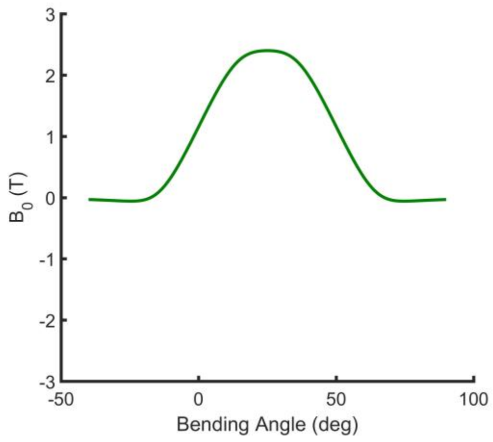
Alternating Quadrupole (± 22.7 T/m)

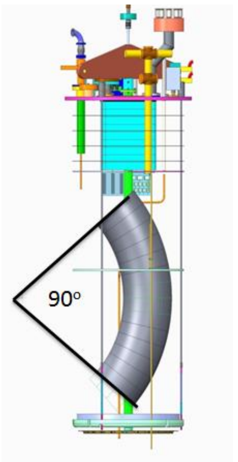
Constant Dipole (2.3 T)

Fabrication and test of two dipole layers

Bending Radius	900 mm
Clear Bore Diameter	290 mm
Magnetic Bend	50 deg
Physical Bend	90 deg
Inductance	0.541 H
Peak Operating Current (I_{nom})	922 A
Dipole Field at I_{nom}	2.4 T
Conductor Field at I_{nom}	3.2 T
Stored Energy at I_{nom}	230 kJ

2.4 T dipole in 290 mm aperture (reduced bend angle)

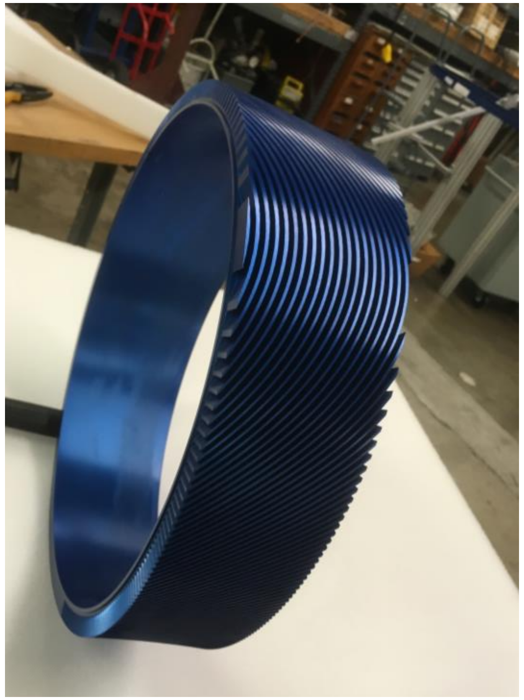




“Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry”, *Trans. on Appl. Supercond.*, vol. 27, no. 4, p. 4400106, 2017.

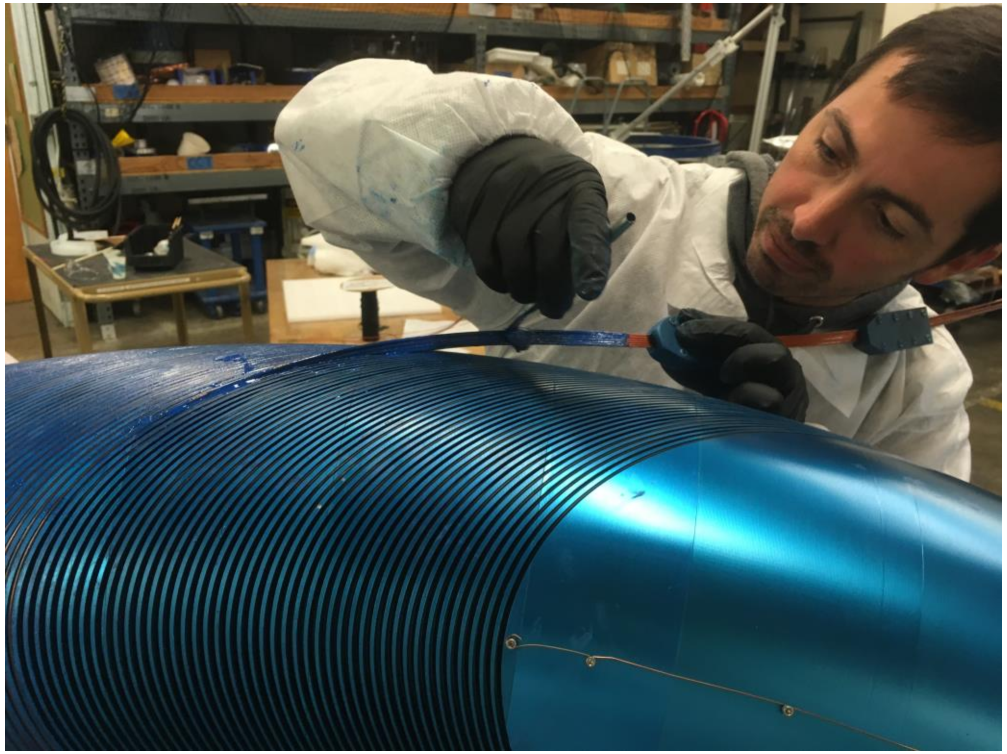
Curved Winding Mandrels Assembled from Laminations Contain Channels to Position the Conductor

- Laminations reduce eddy current losses
- Laminations accommodate milling machine size limitations
- Hard anodized aluminum provides a first layer of electrical insulation



A stack of six electrically isolated Nb-Ti wires are wet-wound into the channels of each layer

1.6 x 1.6 mm square, formvar insulated NbTi wire, 2.8:1 Cu:Sc

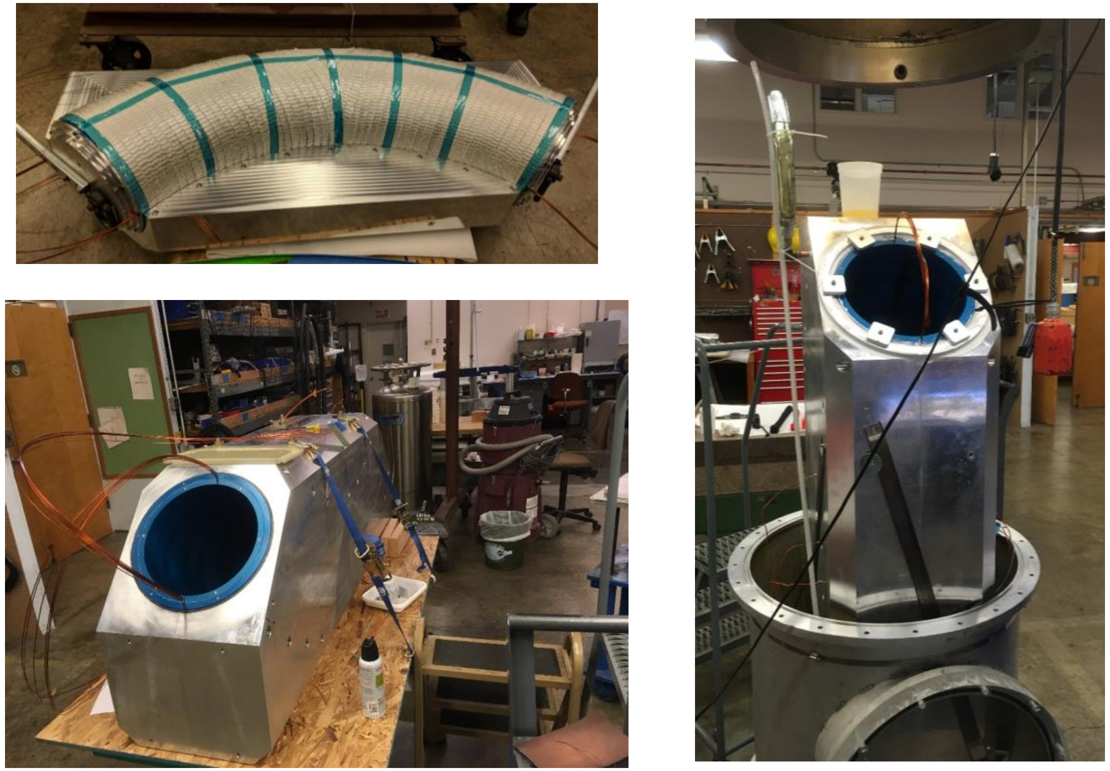


Assembly and Vacuum Impregnation

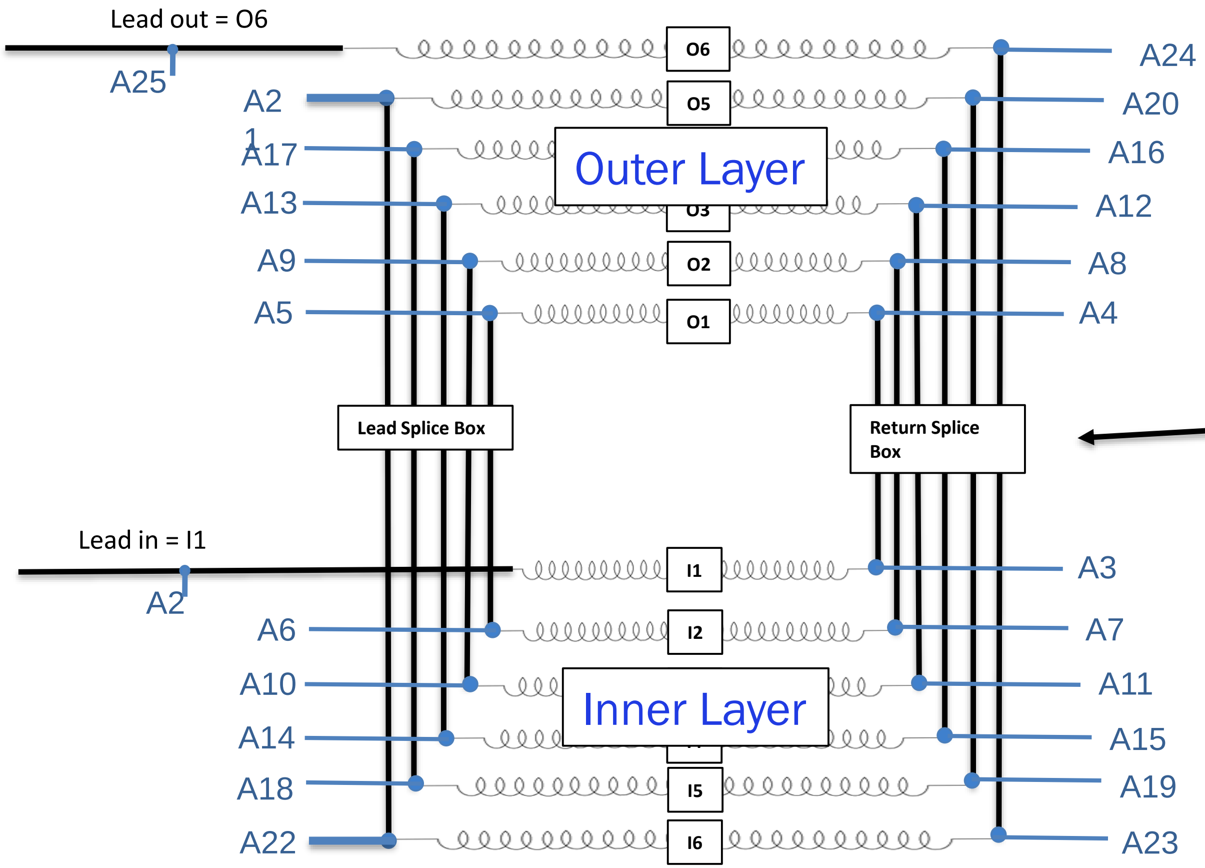
Layer to layer assembly

VPI between layers

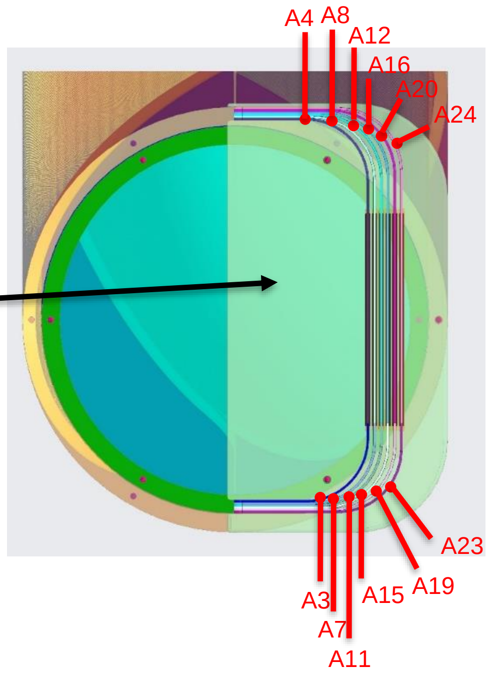
Assembly into clamshell structure with final VPI



Splicing of the wires in series and voltage tap layout

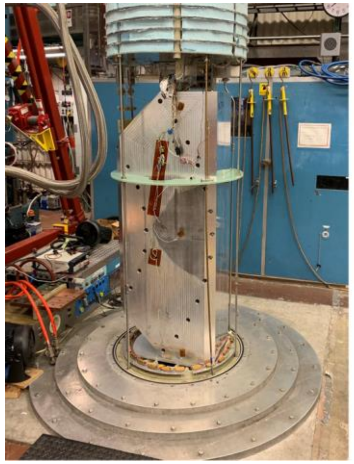


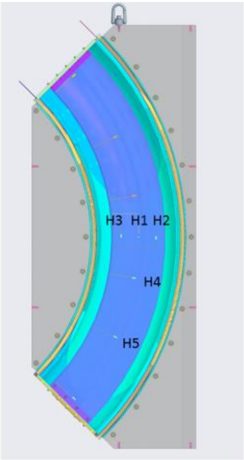
Voltage taps added outside the magnet to cover every wire in each layer
-> quench can be resolved in any of the 12 wire layers

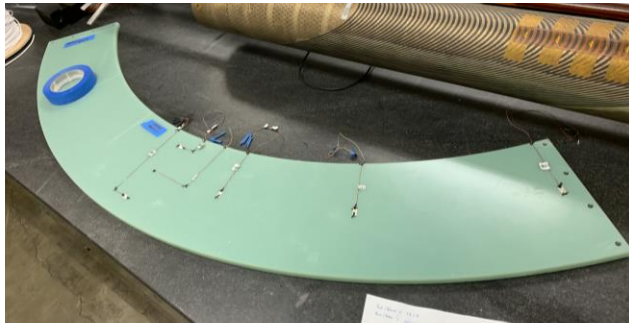


Additional Instrumentation

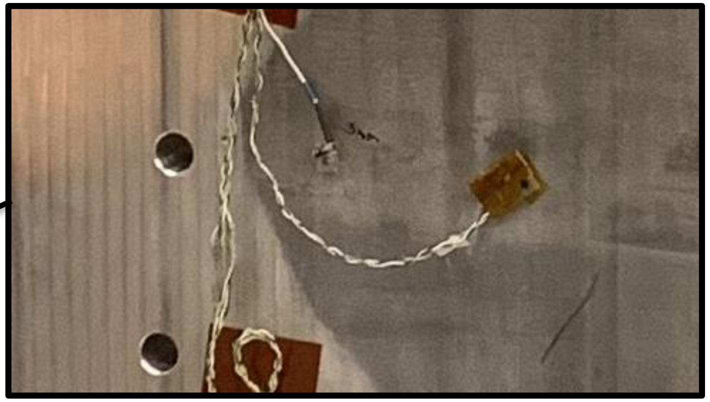
Hall probe array fixed in bending plane measures vertical field in five locations







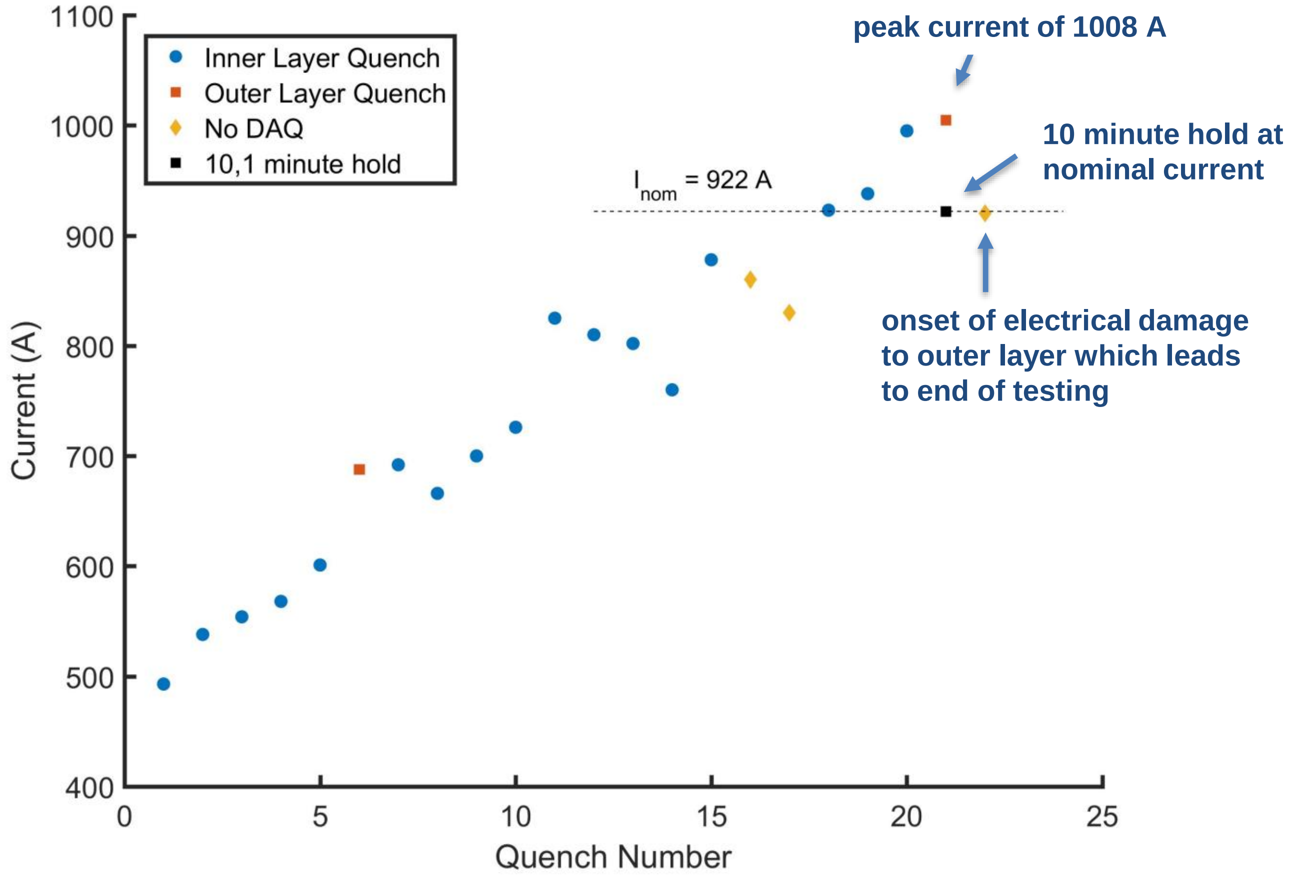
Single acoustic sensor placed on the external structure (M. Marchevsky)



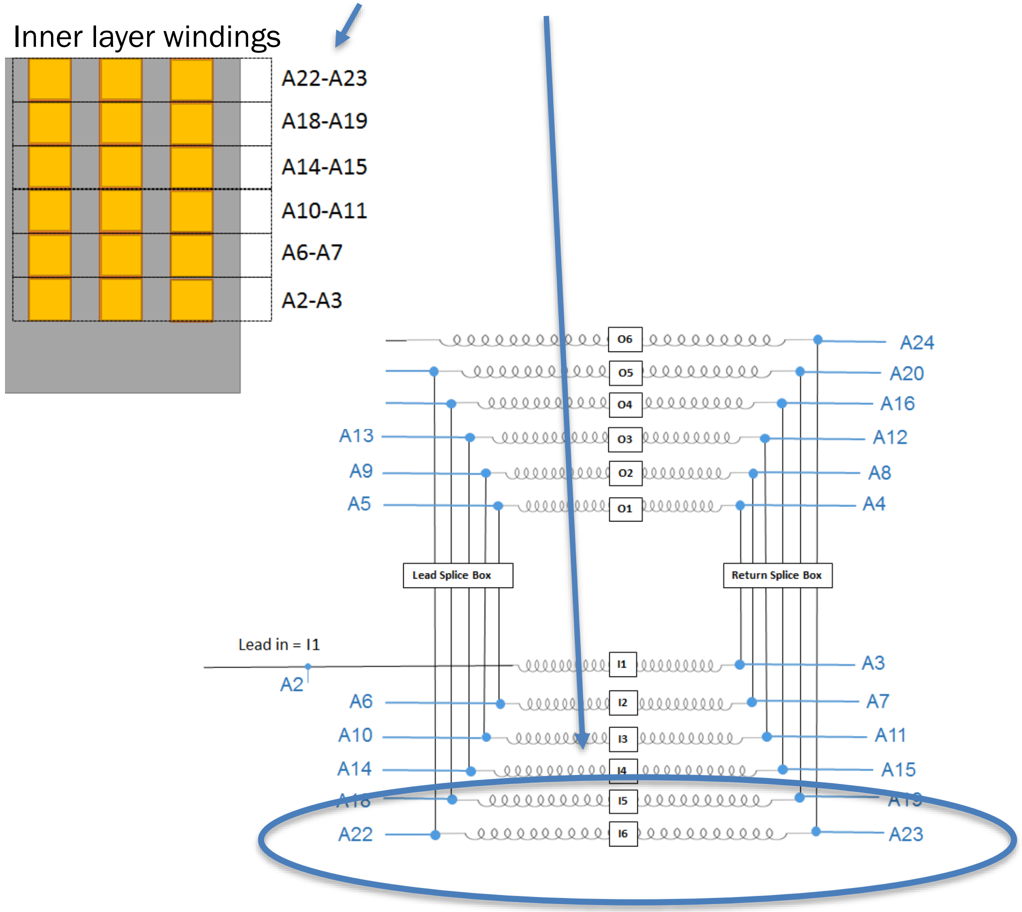
Fri-Mo-Or25-07: Analysis of the transient mechanics behind superconducting accelerator magnet training

Test Results: Quench Training

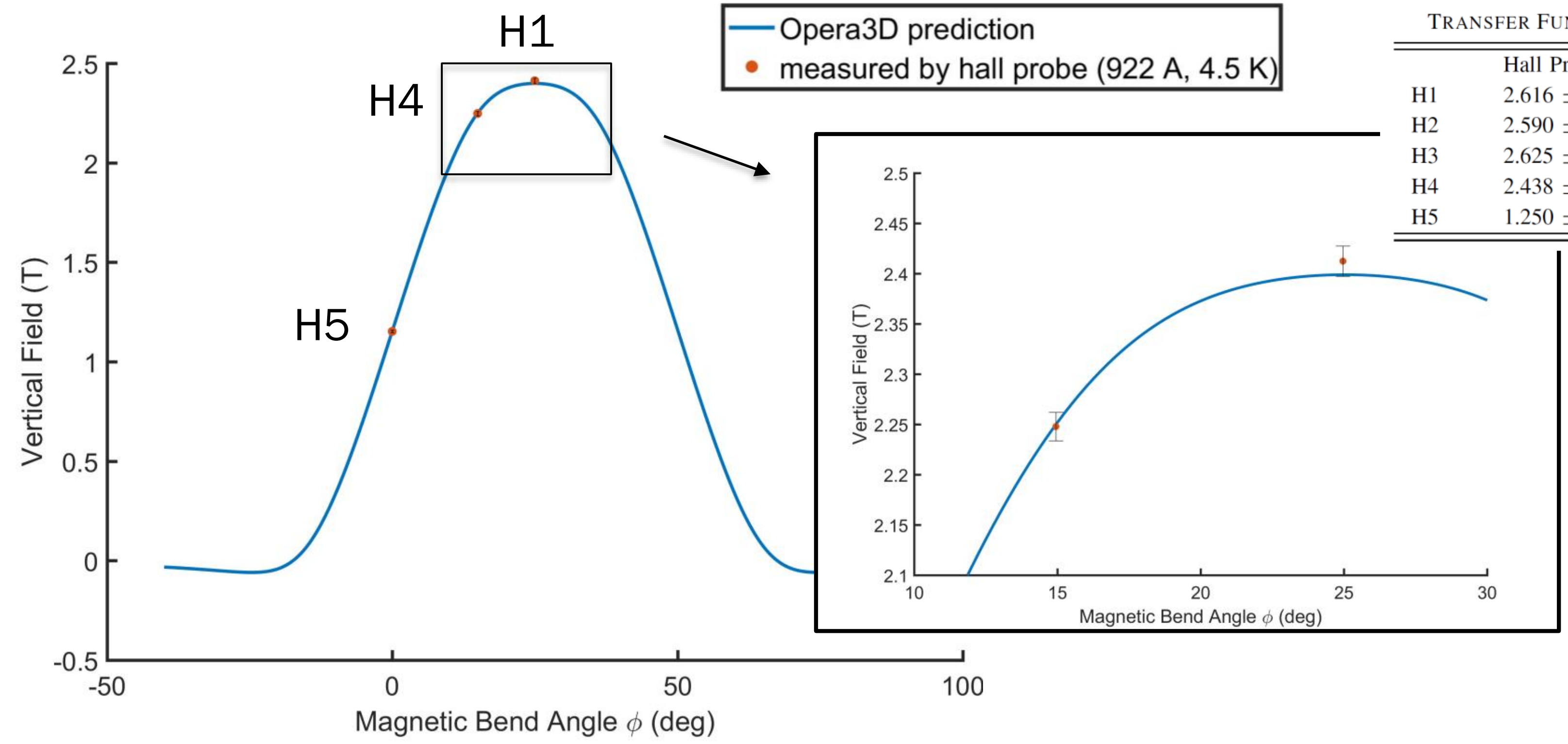
The magnet reached nominal current after 17 quenches (60% of wire short-sample)



16 of the 21 quenches were in the same wire (outermost of the inner layer stack)

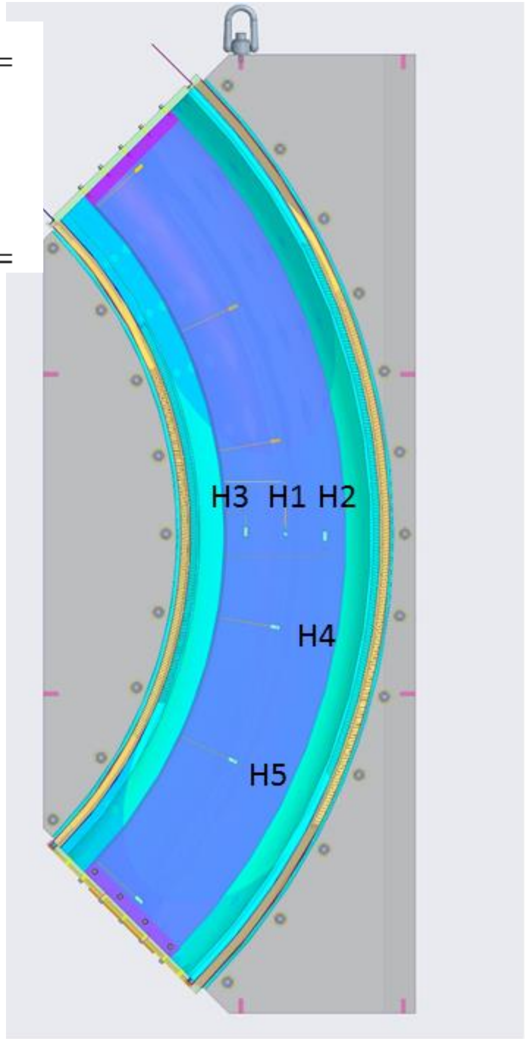


Hall Probe Measurements Verify Design Field at Nominal Current (4.5 K, 922 A)



TRANSFER FUNCTION AT 4.5 K, 922 A (T/KA)

	Hall Probe Meas.	Opera3D
H1	2.616 ± 0.013	2.6018
H2	2.590 ± 0.013	2.6183
H3	2.625 ± 0.013	2.5942
H4	2.438 ± 0.012	2.4424
H5	1.250 ± 0.006	1.253

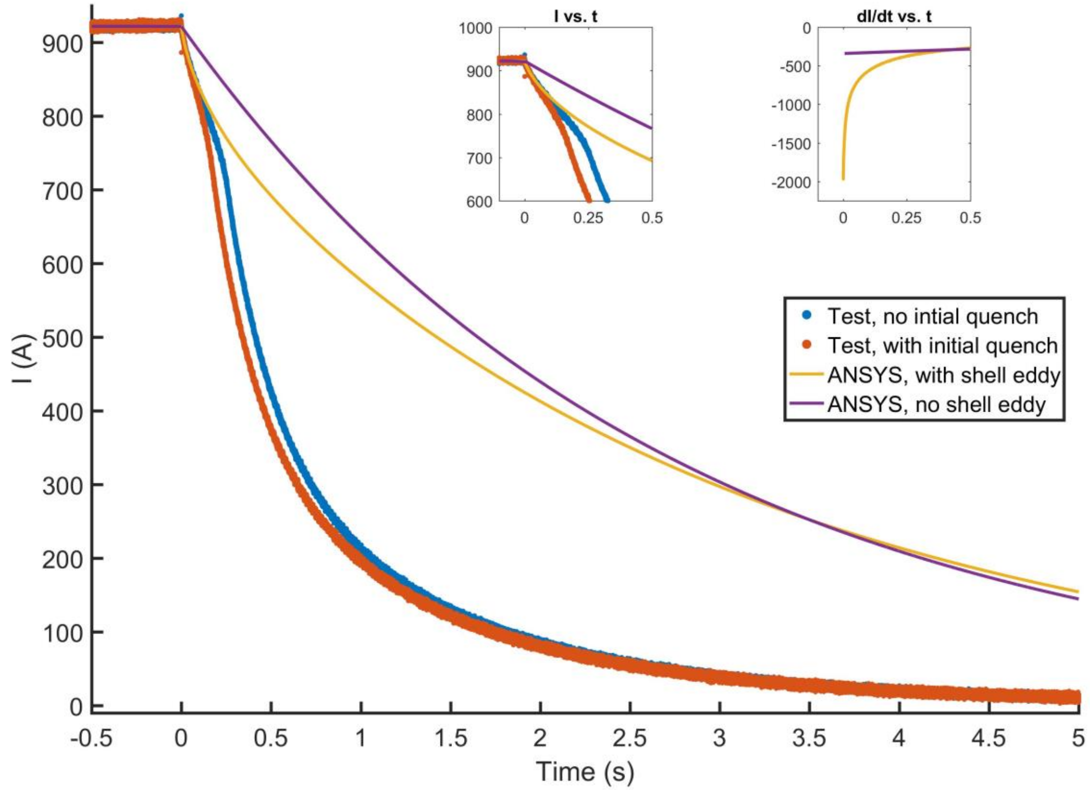


At 4.5 K and nominal current of 922 A

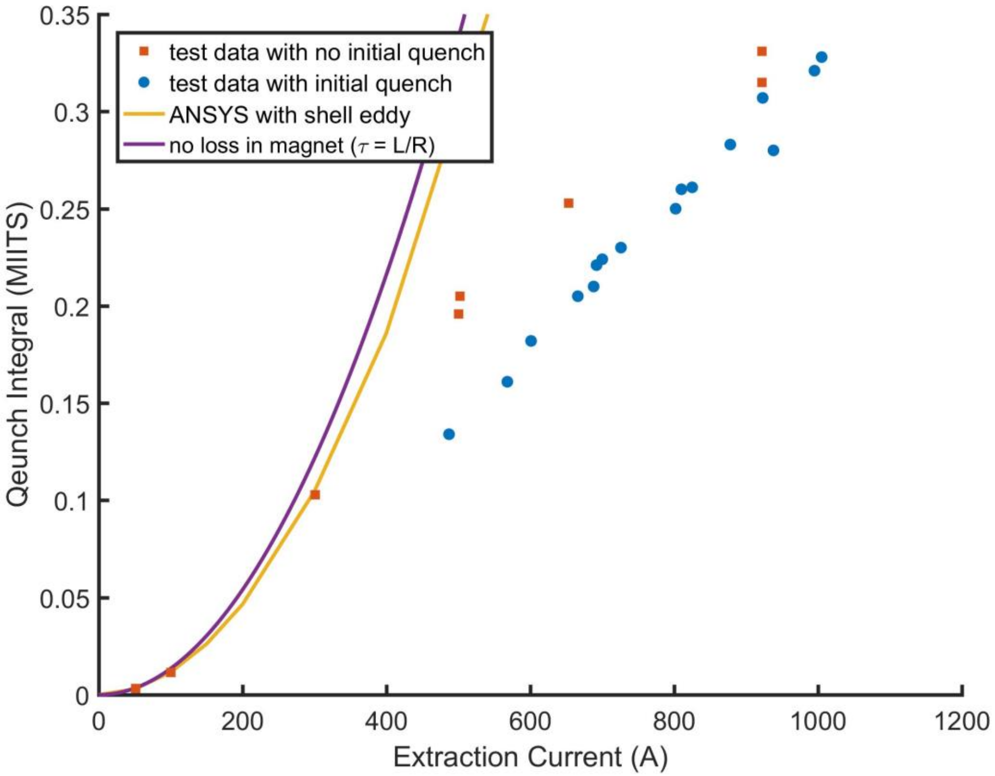
- probes/predicted agree within error on center axis: H1, H4, H5
- probes/predicted fall slightly outside error off center axis: H2,H3
- at room temperature we see similar results with a 5 % offset (still investigating)

Test Results: Quench Back and Inductive Coupling

Inductive coupling with structure induces higher dI/dt -> faster quenchback



Strong quenchback observed starting around 400 A



Summary

- **Lighter and more compact proton therapy gantries can be designed with superconducting technology**

- **LBNL, PSI, and Varian are working on large momentum acceptance SC gantries**
  - **allowing for treatment over a range of proton energy with fixed magnetic field**
  - **lowering cooling requirements and risk (order of magnitude reduction in magnet ramp rate)**

- **A first curved, superconducting NbTi CCT magnet has been built and tested**
  - **reached 2.6 T dipole field in a large aperture (290 mm)**
  - **reached nominal current after 17 quenches in liquid helium at 4.5 K**
  - **preliminary magnetic measurements verify design field**

The Gantry Magnet Team

<u>LBNL</u>: S. Caspi, J. Herrera, J. Swanson, M Maruszewski, M. Marchevsky, K. Edwards, J. Taylor, W. Wan, S. Prestemon, X. Wang, C. Myers, S. Myers, R. Hafalia, M. Turqueti, C. Sun, D. Robin, M. Reynolds, A. Hodgkinson, T. Lipton

<u>Varian Medical</u>: A. Godeke, M. Schillo, A. Huggins, R. Nast

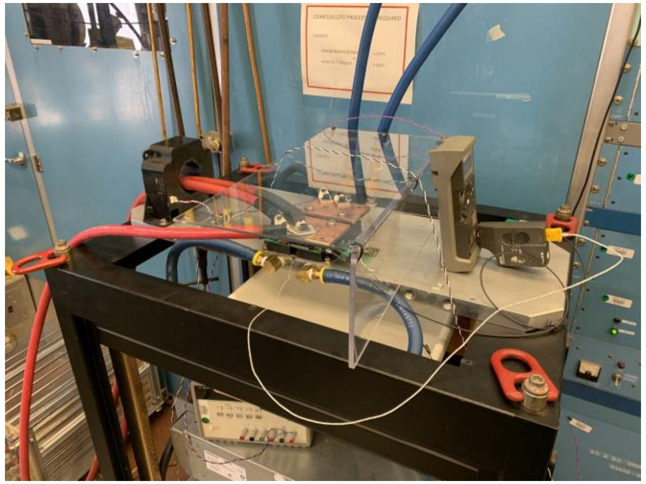
<u>Paul Scherrer Institute</u>: M. Schippers, A. Gerbershagen, C. Calzolaio, S. Sanfilippo

Challenging "first-time" curved CCT fabrication relied heavily on the input and skill of LBNL technician staff

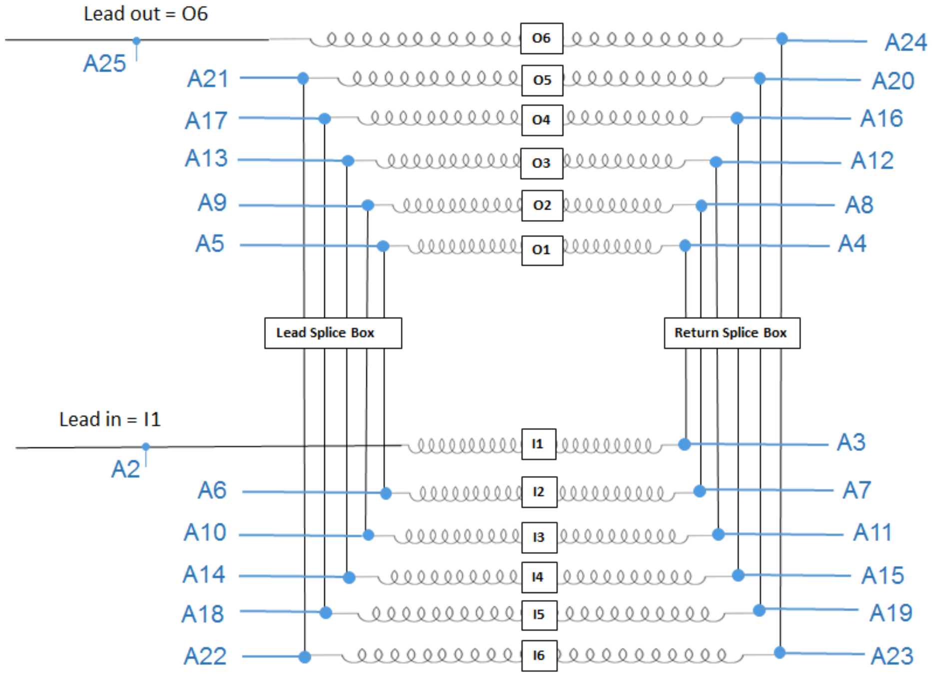
Extra Slides

Quench Protection (M. Turqueti, J. Taylor)

Fast IGBT switch places dump resistor in series with the magnet

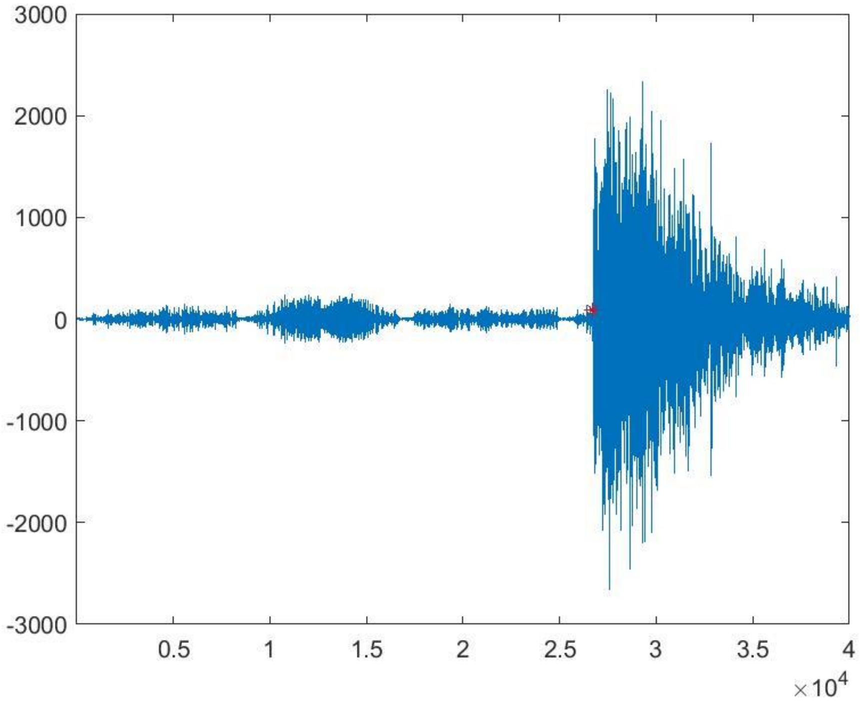


FPGA quench detection system monitors unequal split of coil along length (with inductive scalings) -> switch trigger



Test Results: Preliminary Acoustic Measurements

This points to a very short timescale of the original events (short pulse has a broadband spectrum), and is consistent with the epoxy cracking



Fri-Mo-Or25-07: Analysis of the transient mechanics behind superconducting accelerator magnet training

Quench Propagation at 922 A