ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

BCMT BERKELEY CENTER FOR MAGNET TECHNOLOGY

Superconducting CCT Magnets: A Flexible Technology for Compact FFA’s

September 14th, 2023
2023 Workshop on Fixed Field Alternating Gradient Accelerators

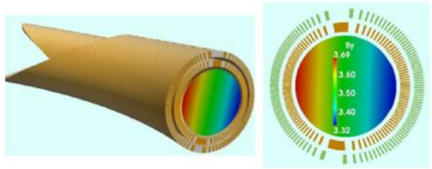
Lucas Brouwer
Lawrence Berkeley National Laboratory

Outline

Background

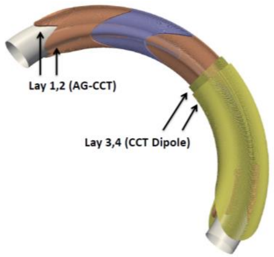
Introduction to CCT

Flexible generation of combined function fields for curved and straight magnets



Introduction to the AG-CCT

Alternating gradients for large Δp/p with fixed-field

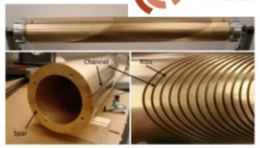


Status

HEP high-field (straight), ARDAP project for proton therapy (curved)

Nb_3Sn + HTS magnets

U.S. MAGNET DEVELOPMENT PROGRAM

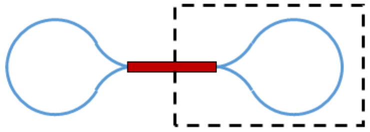


A 2.4 T curved dipole magnet

Plans

Combined function CCT's relevant to FFA's

The AG-CCT for fixed-field return arc design



- introduction to the Canted-Cosine-Theta (CCT) magnet design
- incorporating alternating gradients into a continuous coil (AG-CCT)

Abbreviated History of the Concept (HEP focused)

NUCLEAR INSTRUMENTS AND METHODS 80 (1970) 339–341; © NORTH-HOLLAND PUBLISHING CO.

A NEW CONFIGURATION FOR A DIPOLE MAGNET
FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

1970, basic concept published

Highlights: extension to combined function + curved magnets, low current demonstrators ~2-3 T

The Double-Helix Dipole—A Novel Approach to Accelerator Magnet Design

C. L. Goodzeit, M. J. Ball, and R. B. Meinke

Design, Fabrication, and Test of a Superconducting Dipole Magnet Based on Tilted Solenoids

S. Caspi, D. R. Dietderich, P. Ferracin, N. R. Finney, M. J. Fuery, S. A. Gourlay, and A. R. Hafalia

~2000-2015, revisited by industry and labs

Highlights: 8-10 T Nb_3Sn dipoles at LBNL/PSI, NbTi orbit correctors for HiLumi LHC

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. Gou… M. Krutulis, M. Marchevsky, M. Maruszewski, C. Myers, S. Prestemon… T. Shen, *Senior Member, IEEE*, J. Swanson, R. Teyber, M. Turq… and X. Wang

Michael Daly presenting on behalf of PSI Team & CERN SM18 (inputs from Franco Mangiarotti)

CD1 Test Update

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 28, NO. 3, APRIL 2018 4002205

Hi-Lumi LHC Twin Aperture Orbit Correctors 0.5-m Model Magnet Development and Cold Test

Glyn A. Kirby, Luca Gentini, Jacky Mazet, Matthias Mentink, Franco Mangiarotti, Jeroen Van Nugteren, Jaakko Samuel Murtomäki, Per Hagen, Francois Olivier Pincot, Nicolas Bourcey, Juan Carlos Perez, Gijs De Rijk, Ezio Todesco, and J. Rysti

~2015-now, push for high field Nb_3Sn magnets + CCT's going into accelerators

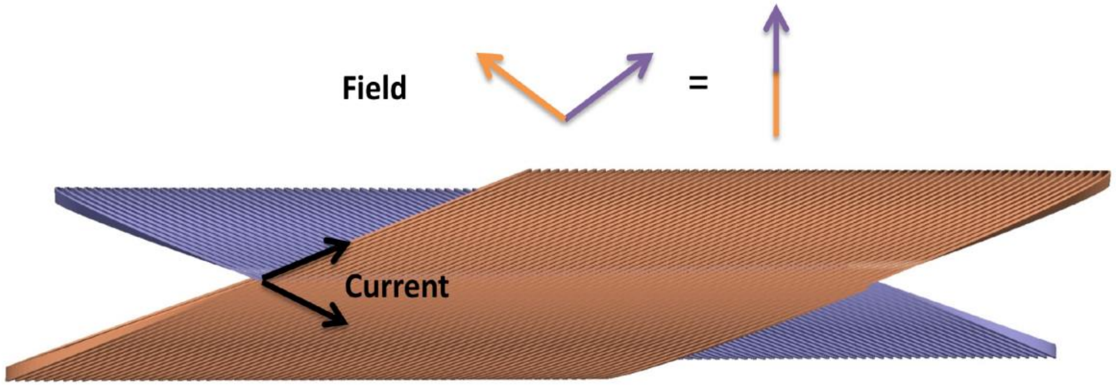
Canted-Cosine-Theta (CCT) SC Magnets

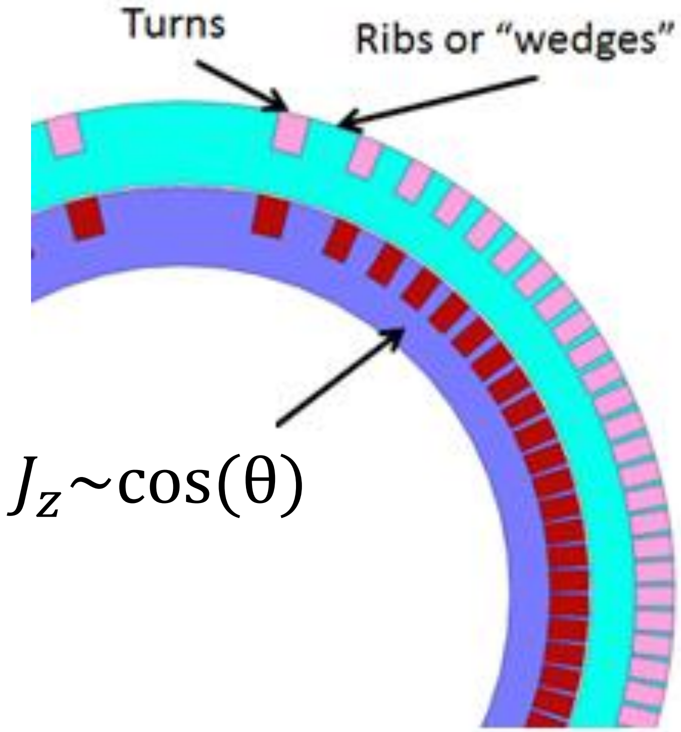
Advantages

- excellent field quality (to large % of aperture)
- stress management for high-field and/or large apertures
- combined function fields (i.e. dipole + quadrupole)

Challenges

- slightly more conductor (~15-20%)
- tradeoff of longer ends vs. efficiency for very short magnets





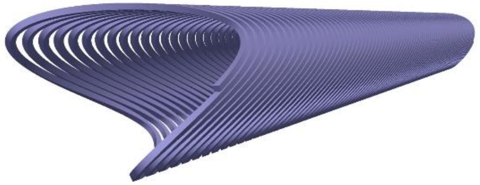
D.I. Meyer, R. Flasck, 1970, doi.org/10.1016/0029-554X(70)90784-6

The CCT is a Flexible Technology for Combined Function Fields

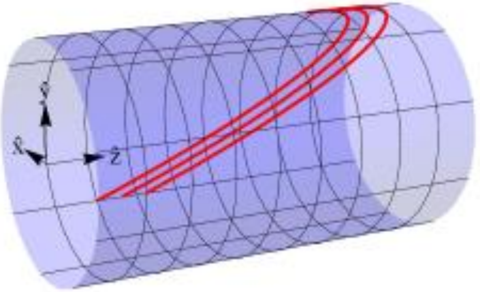
$$\vec{p}(\theta) = r_0\hat{r} + \left(\sum_{n=1} C_n \sin n\theta + \frac{w}{2\pi}\theta\right)\hat{z},$$

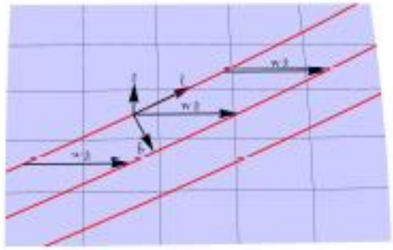
n=1, dipole

n=2, quadrupole



n=1, 2, 3, dipole+quad.+sext.



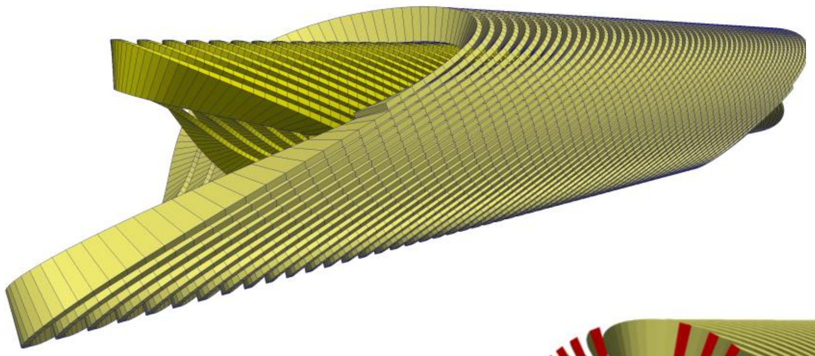


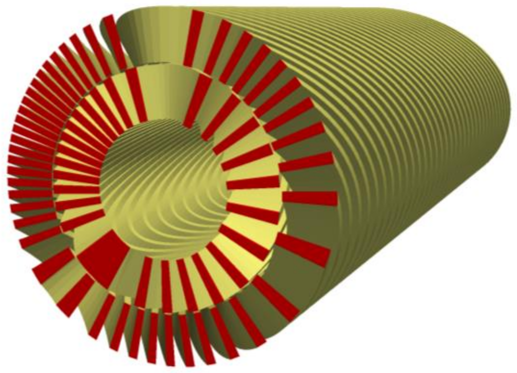
$$p_z(\theta) = \frac{wr}{I_0}\frac{j_{0nz}}{n}\sin(n\theta) + \frac{w}{2\pi}\theta, \qquad B_n = -\frac{\mu_0 I_0}{2w}\cot(\alpha)\left(\frac{R_{ref}}{r}\right)^{n-1}.$$

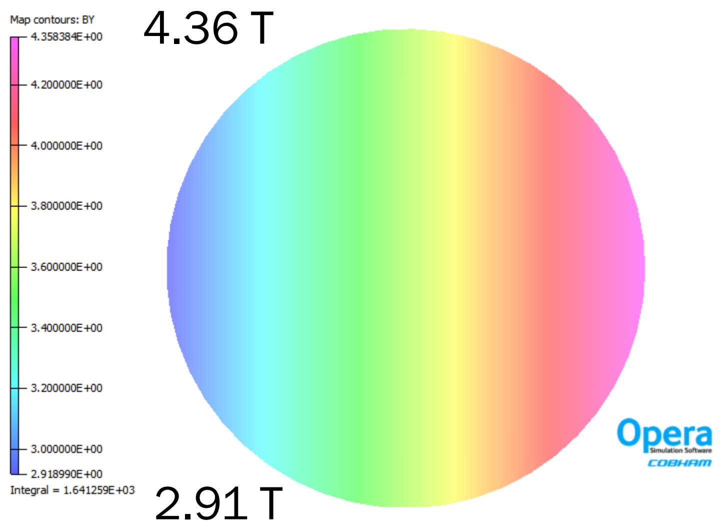
$$\vec{j}(\theta) = \frac{I_0\hat{t}}{\delta(\theta)} = I_0\frac{\vec{t}}{|\vec{t}|}\frac{|\vec{t}|}{wr} = \frac{I_0}{wr}\vec{t} = \frac{I_0}{w}\left(\hat{\theta} + \frac{p_z'(\theta)}{r}\hat{z}\right).$$

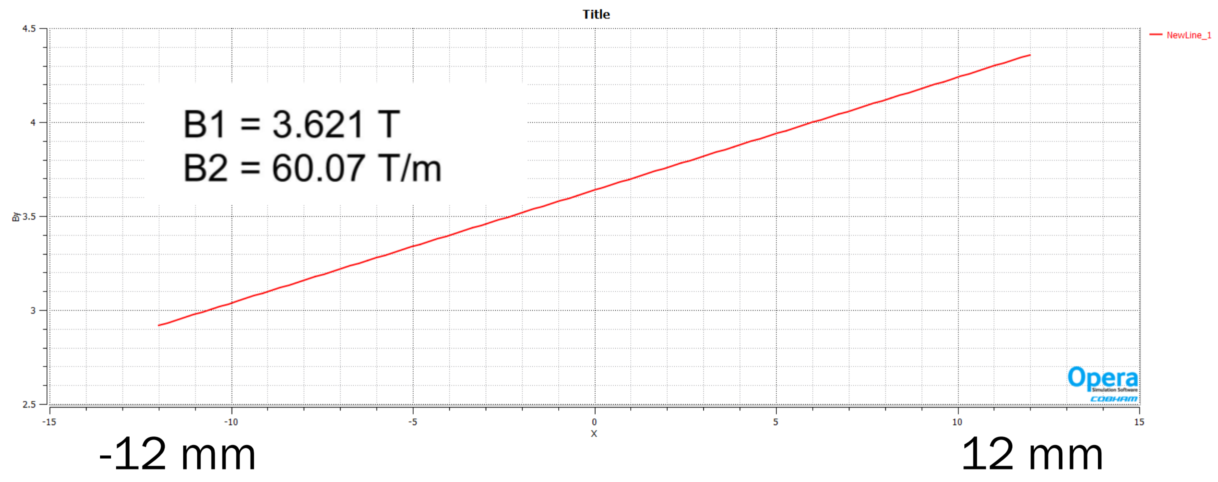
Example: Combined Function Dipole + Quadrupole (40 mm ø)

$$\vec{p}(\theta) = r\hat{r} + \left[r\cot(\alpha)\sin(\theta) + \frac{B_2^* r}{2B_1^*} r\cot(\alpha)\sin(2\theta) + \frac{w}{2\pi}\theta \right]\hat{z}$$



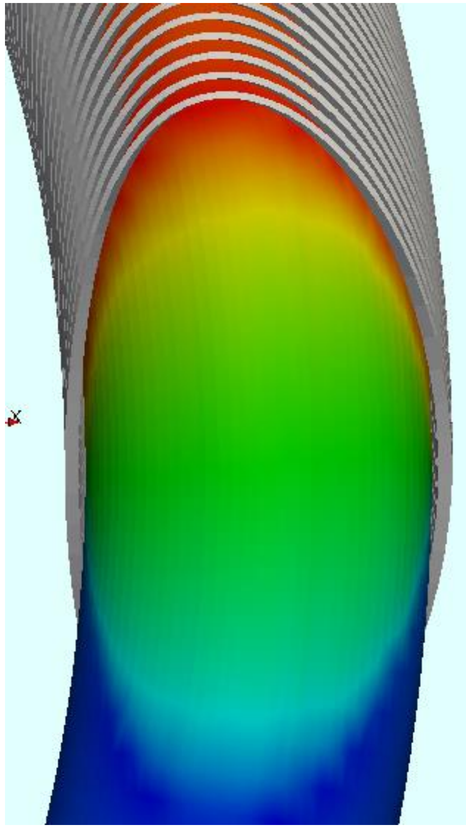




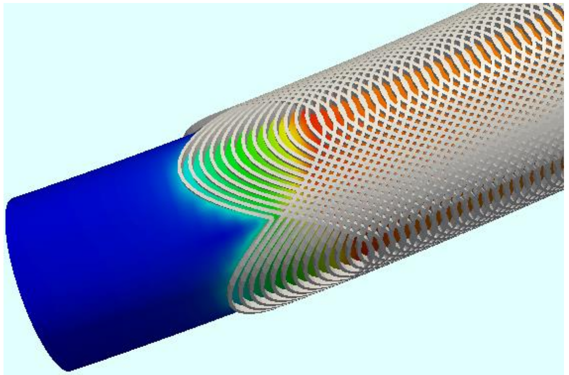


The CCT Naturally Extends to Curved Magnets

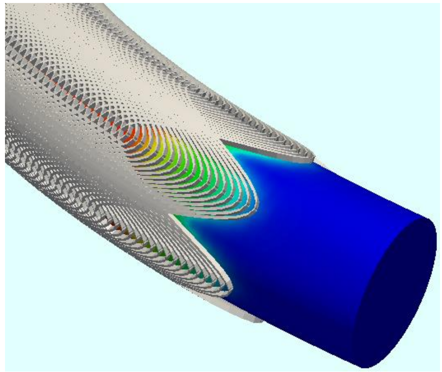
Dipole

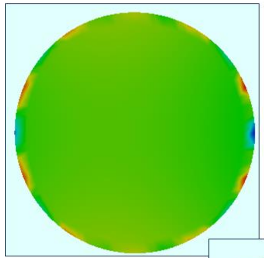
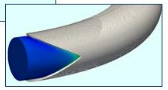


Quadrupole

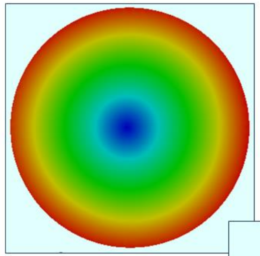
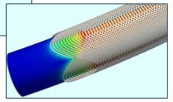


Sextupole

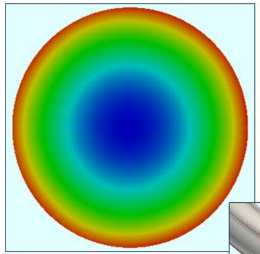
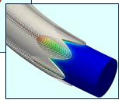


Uniform dipole field

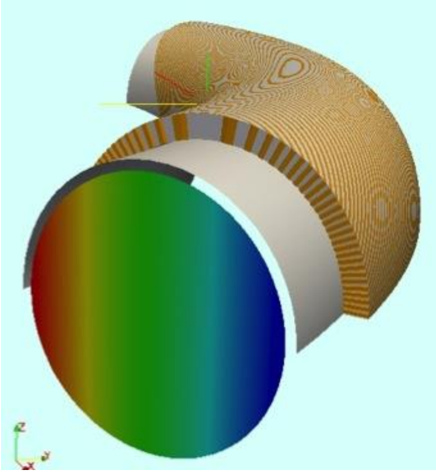



Uniform quadrupole field

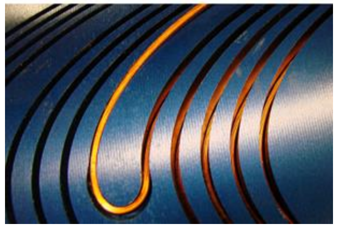



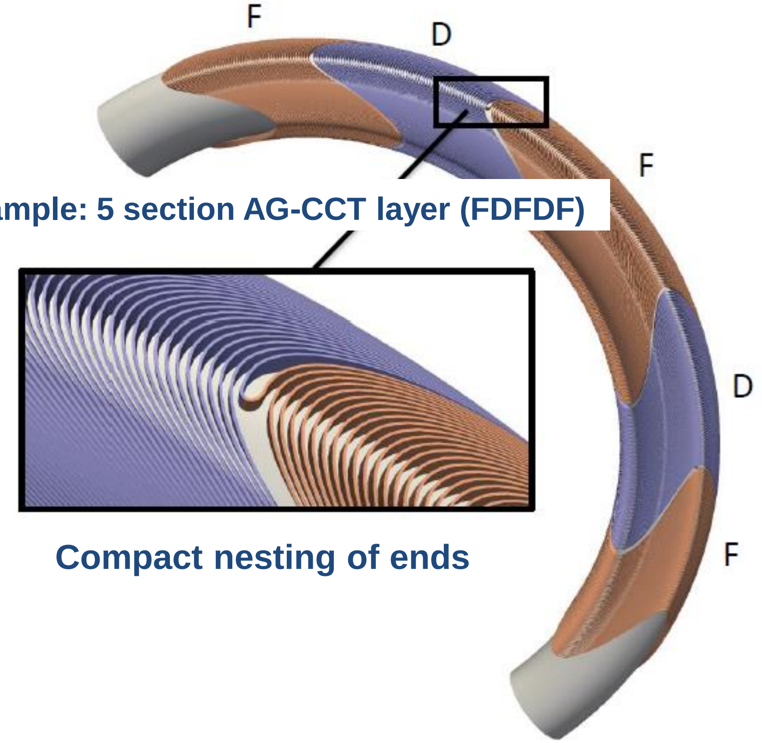
Uniform sextupole field

Single winding combined function: dipole+quad.+sext.



The alternating gradient CCT (AG-CCT) is a method for producing alternating gradient fields with continuous windings instead of separate magnets

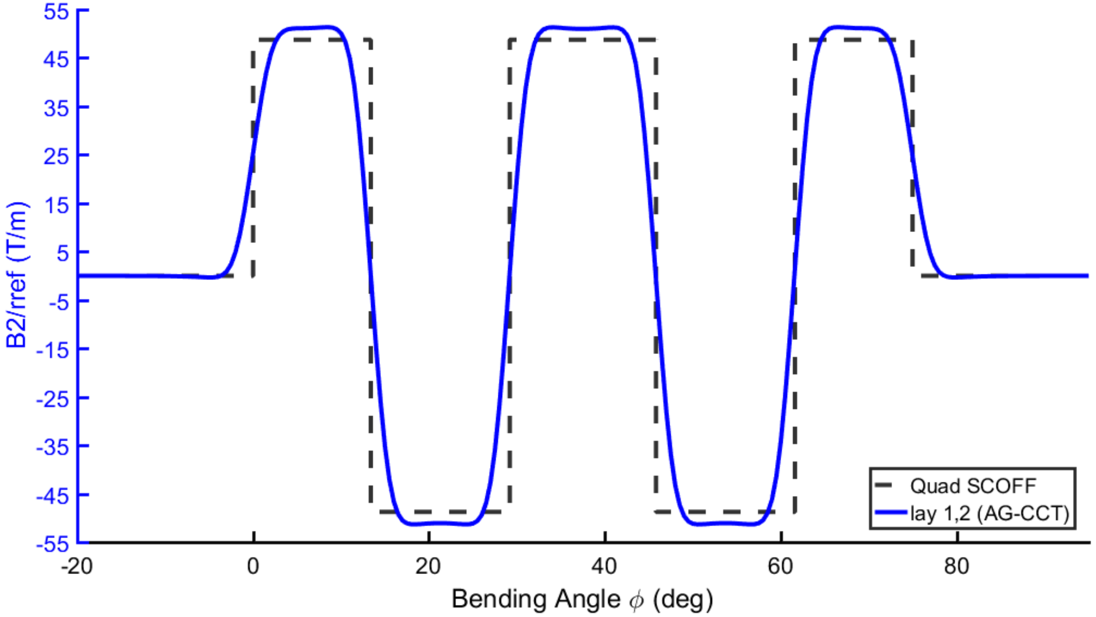




Example: 5 section AG-CCT layer (FDFDF)

Compact nesting of ends

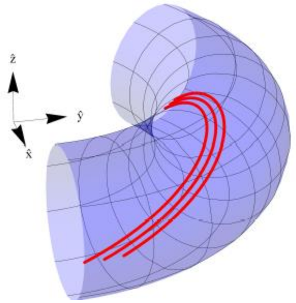
Quadrupole fields along the bend, blue is produced by AG-CCT and dash-black is desired integral

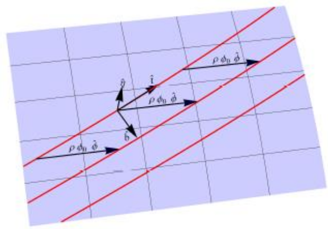


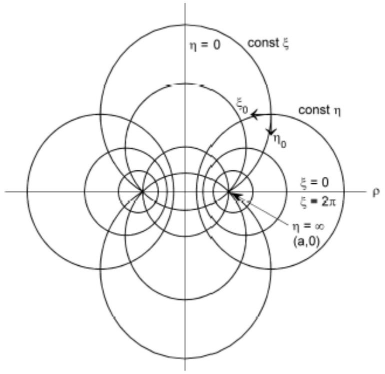
W. Wan, et al., PRAB, 2015, https://doi.org/10.1103/PhysRevSTAB.18.103501

Magnetic design of curved CCTs: in toroidal (binormal) coordinates you can derive the relation between the winding path and the toroidal harmonics (<u>but is it useful</u>?)

Parametrization of winding path







ε = 50/100   ε = 50/250   ε = 50/5000

$$
\begin{aligned}
\eta &= \eta_0 \\
\xi &= \xi \\
\phi(\xi) &= p_\phi(\xi),
\end{aligned}
$$

$$\vec{t}(\xi) = ak^{-1}\hat{\xi} + ak^{-1}\sinh\eta_0 p'_\phi(\xi)\hat{\phi},$$

Current density sheet (pitch averaged) →

$$\vec{j}(\xi) = \frac{I_0}{|\delta|}\frac{\vec{t}}{|\vec{t}|} = \frac{I_0}{\rho(\xi)\phi_0}\frac{\vec{t}}{\vec{t}\cdot\hat{\xi}} = \frac{I_0 k}{a\phi_0\sinh\eta_0}\left(\hat{\xi} + \sinh\eta_0\, p'_\phi(\xi)\hat{\phi}\right).$$

Field harmonics (arbitrary combinations allowed)

$$B_\eta^{in} = \frac{-a_n k^{3/2}}{a}\left(n\sin n\xi + \frac{1}{2}k^{-1}\sin\xi\cos n\xi\right)Q^1_{n-1/2}(\cosh\eta)$$

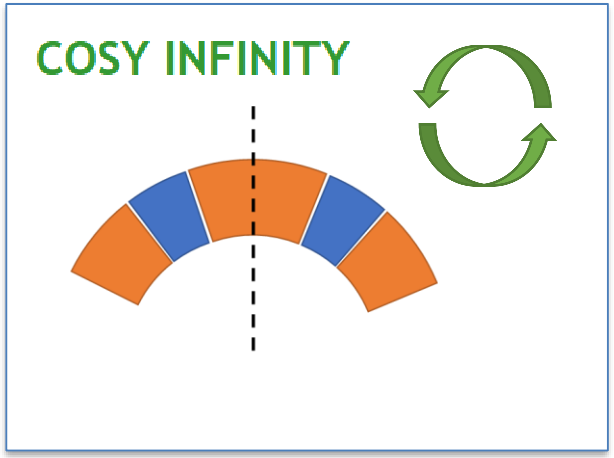
$$B_\eta^{out} = \frac{-b_n k^{3/2}}{a}\left(n\sin n\xi + \frac{1}{2}k^{-1}\sin\xi\cos n\xi\right)P^1_{n-1/2}(\cosh\eta)$$

$$B_\xi^{in} = \frac{-a_n k^{3/2}}{a}\left(\frac{n+\frac{1}{2}}{\tanh\eta}Q^1_{n-1/2} - \frac{1}{2}\sinh\eta k^{-1}Q^1_{n-1/2} - \frac{n+\frac{1}{2}}{\sinh\eta}Q^1_{n-3/2}\right)\cos n\xi$$

$$B_\xi^{out} = \frac{-b_n k^{3/2}}{a}\left(\frac{n+\frac{1}{2}}{\tanh\eta}P^1_{n-1/2} - \frac{1}{2}\sinh\eta k^{-1}P^1_{n-1/2} - \frac{n+\frac{1}{2}}{\sinh\eta}P^1_{n-3/2}\right)\cos n\xi.$$

Instead, parameterize the CCT geometry in the beam dynamics software COSY INFINITY

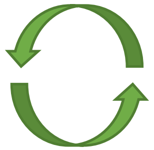
Initial Hard Edge Model

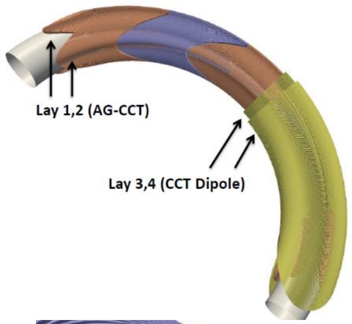


generate “seed” set of curved CCT winding coefficients approximating hard-edge solution

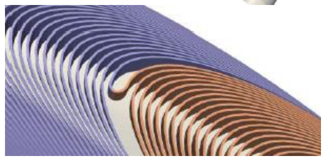
Biot-Savart Model from Coil Parameterization

COSY INFINITY





$$\vec{p}(\xi) = \eta_0\hat{\eta} + \left(\sum_{n=1} C^*{}_n \sin n\xi + \frac{\varphi_0}{2\pi}\xi\right)\hat{\varphi},$$



- Motivation: analytic coil design in curved frame is difficult, but coil parameterization is straight-forward
- Directly connects coil geometry to beam optimization (eliminates field parameterization in curved system)
- Biot-Savart model includes all end effects and coil transitions

example: W. Wan et. al., 2015, doi.org/10.1103/PhysRevSTAB.18.103501

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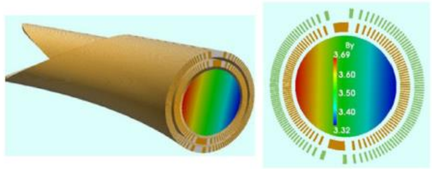

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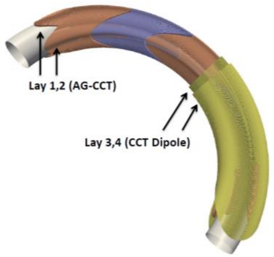

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Nb_3Sn + HTS magnets

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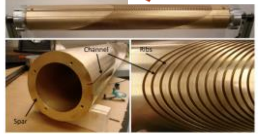


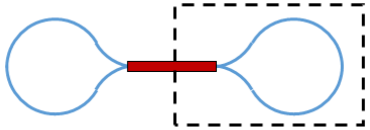
A 2.4 T curved dipole magnet

Plans

Combined function CCT's relevant to FFA's

The AG-CCT for fixed-field return arc design

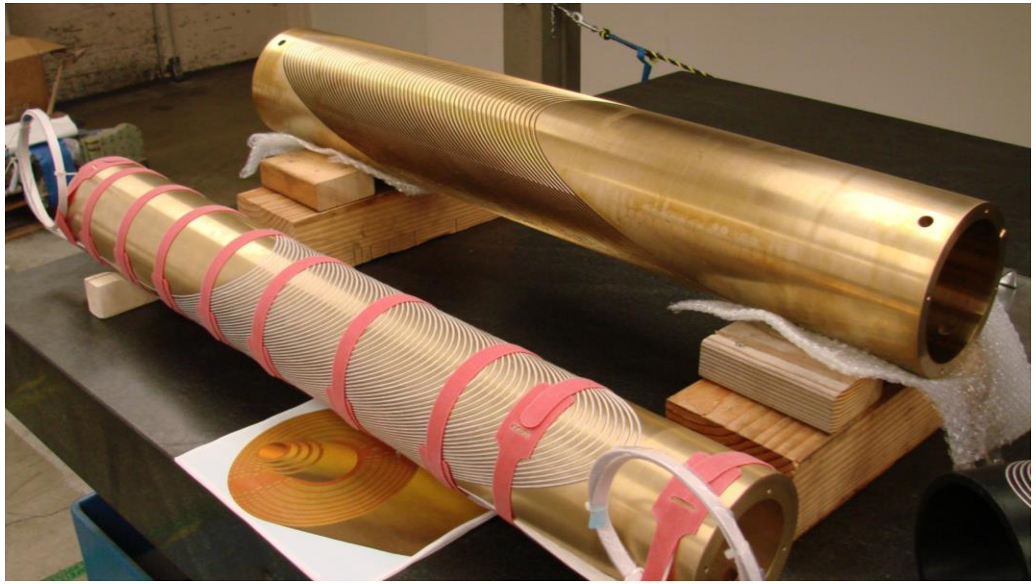
1-5 GeV Muon RLA



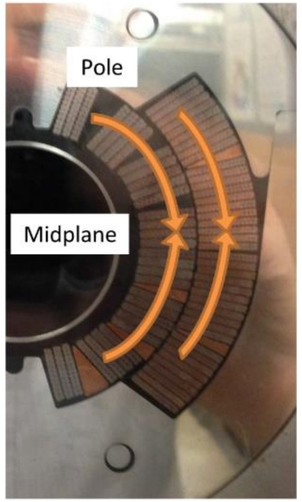
Two pass, fixed-field return arc

- US-MDP program for Nb_3Sn and HTS magnets
- AG-CCT design for proton therapy
- fabrication and test of curved dipole layers

Metallic Winding Mandrels Accurately Position the Conductor and Intercept Lorentz Forces for Stress Management



Force accumulation in traditional Cos(θ)



CCT ribs intercept force

- Important for high field magnets with strain sensitive conductor (Nb_3Sn/HTS)
- Important for large aperture magnets

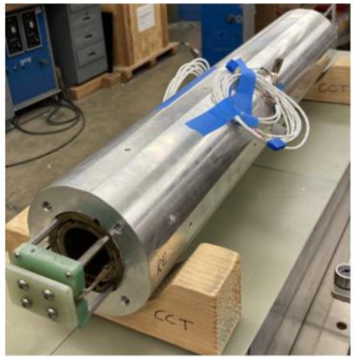
Nb_3Sn and HTS CCT Dipole Development at LBNL (within the HEP - US Magnet Development Program)

Nb_3Sn: 9 T demonstrated in a 90 mm bore, 13 T to be demonstrated in a 120 mm bore in ~3 years

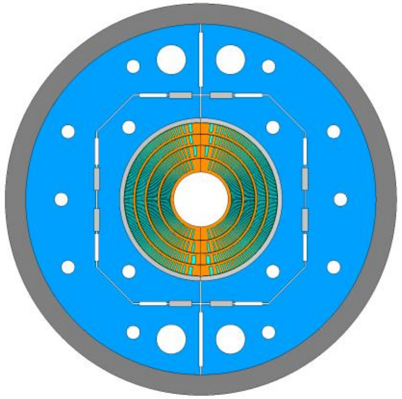
HTS: demonstrated 1.5-3 T, future focus is hybrid ~15 T (HTS+Nb_3Sn)

CCT3,4,5: 9.2 T, 90 ø (2015-2018)

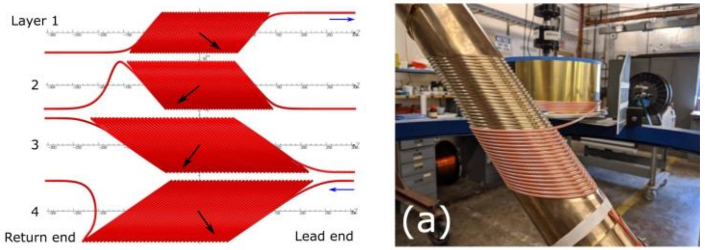
subscale: 5 T, 50 ø (now)



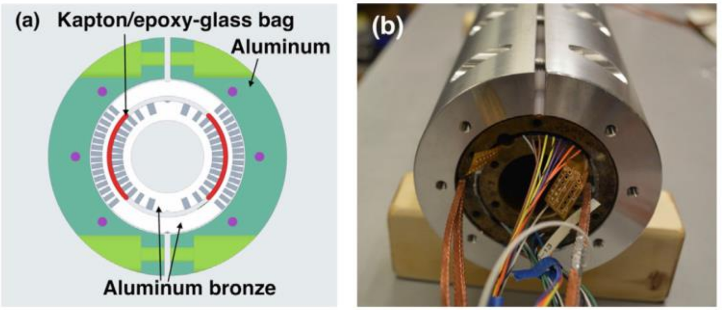
CCT6: 13 T, 120 ø (2026)



C2: 3 T, 60 ø (2021) - REBCO

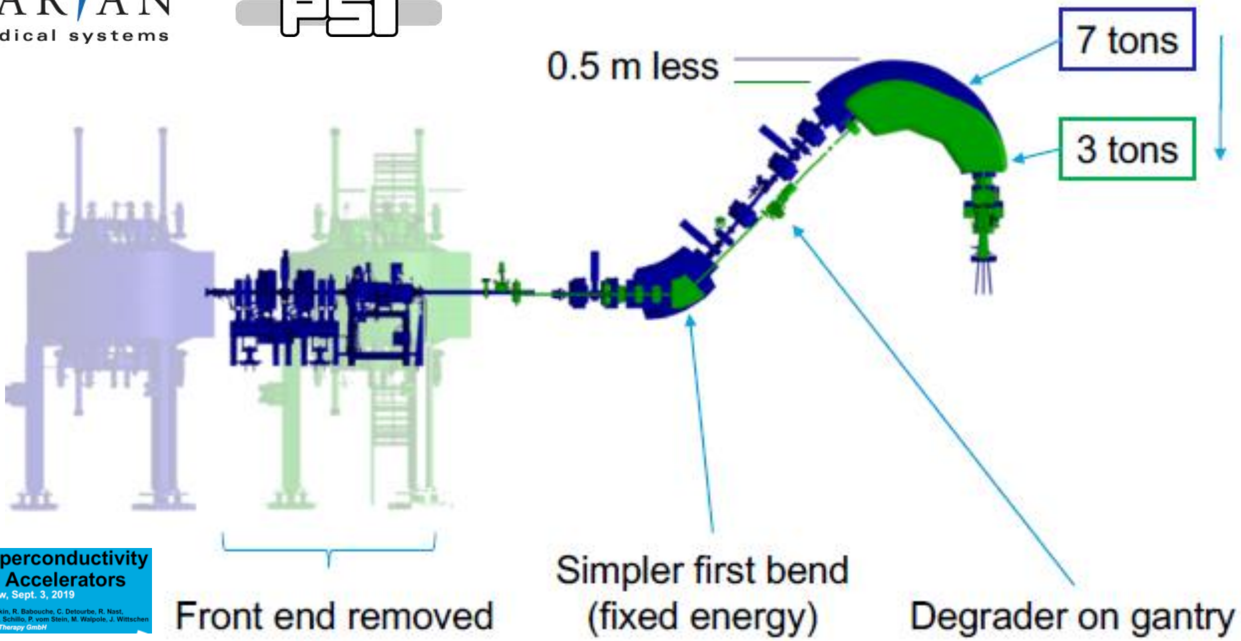


BIN5c: 1.6 T, 31 ø (2021) – Bi2212

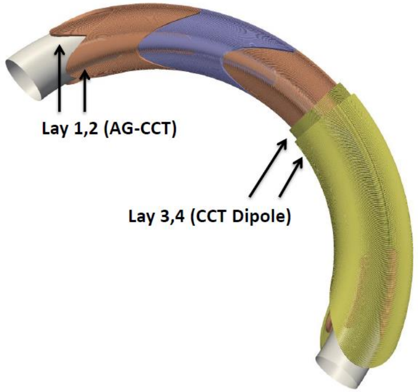


D. Arbelaez et. al, 2022, doi.org/10.1109/TASC.2022.3155505
X. Wang et al., 2021, doi.org/10.1088/1361-6668/abc2a5
T. Shen et al., 2022, DOI: 10.1103/PhysRevAccelBeams.25.122401

ARDAP Accelerator Stewardship project to develop a large momentum acceptance SC gantry for proton therapy



Applied Superconductivity for Medical Accelerators
EUCAS 2019, Glasgow, Sept. 3, 2019
A. Godeke, L. Alberty, E. Alcoeltekin, R. Babouche, C. Detourbe, R. Nast, Ch. Radermacher, H. Roecken, M. Schillo, P. vom Stein, M. Walpole, J. Wittschen
Varian Medical Systems Particle Therapy GmbH



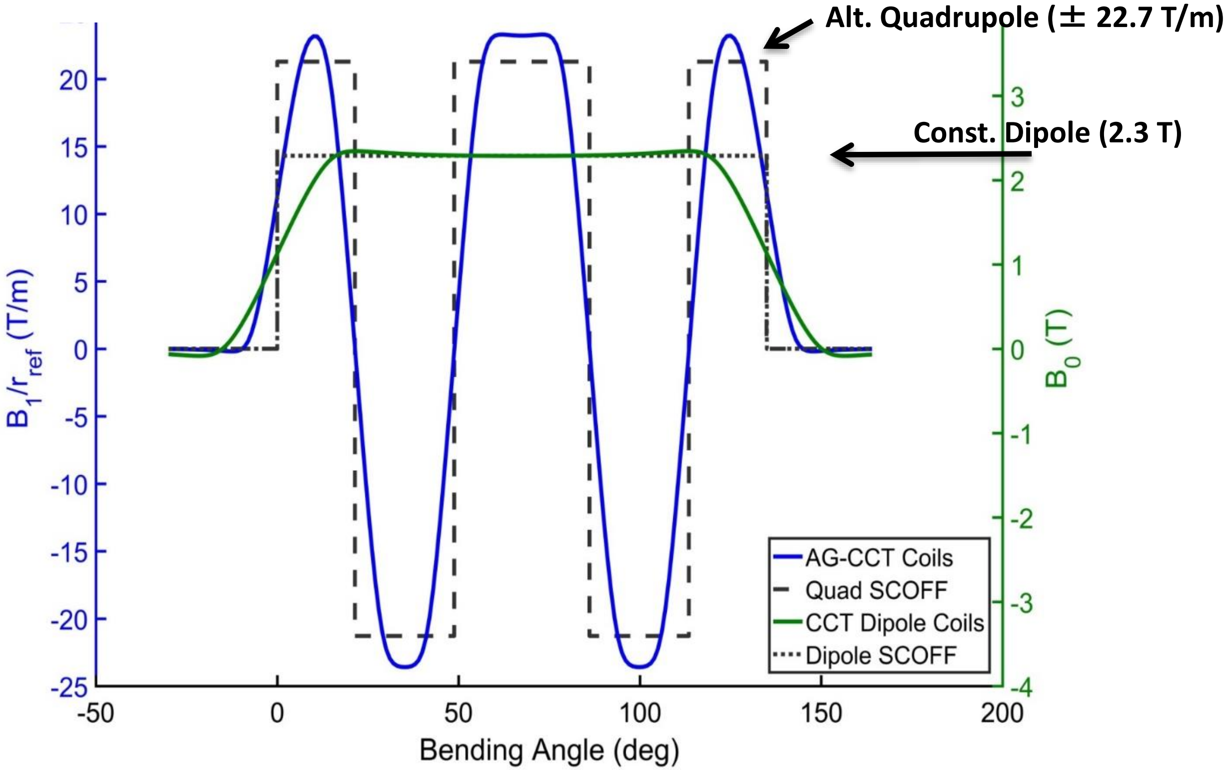
OVERVIEW OF MAGNET PARAMETERS

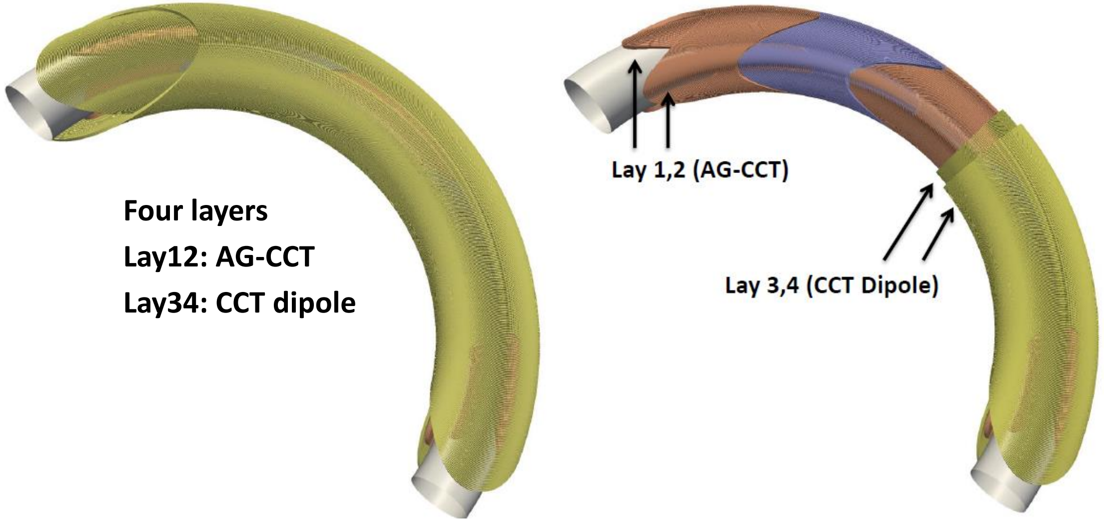
Bending Radius	900 mm
Bore Radius	105 mm
Magnetic Bend	135 deg
Momentum Acceptance (Δp/p)	20%
Constant Dipole	2.3 T
Alternating Quadrupole	$\pm$22.7 T/m
Stored Energy	0.86 MJ

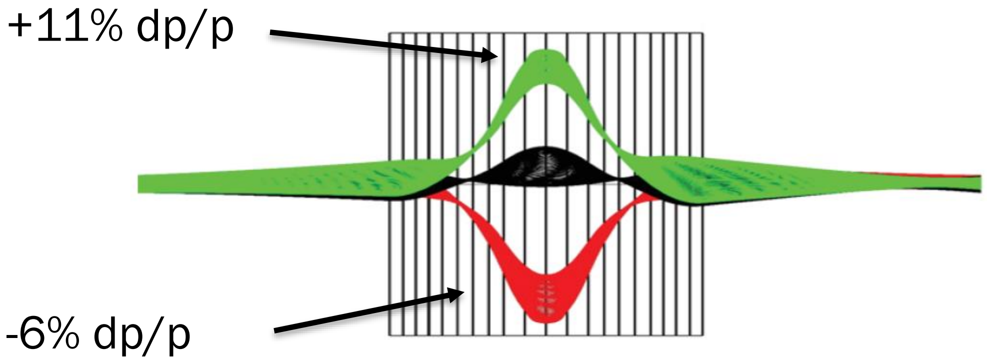
A single AG-CCT magnet provides 1:1 imaging from the degrader source to patient (with large momentum acceptance)

L. Brouwer, et al., IEEE Trans. Appl. Supercond, 2017,
https://doi.org/10.1109/TASC.2016.2628305

Large momentum acceptance beam optics with a single, 5 T magnet for proton therapy gantries (70-250 MeV)







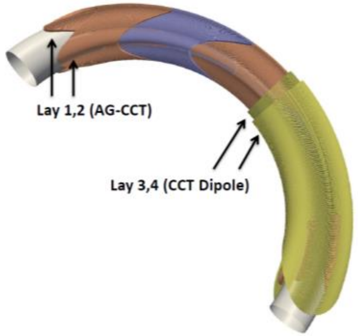
VARIAN medical systems

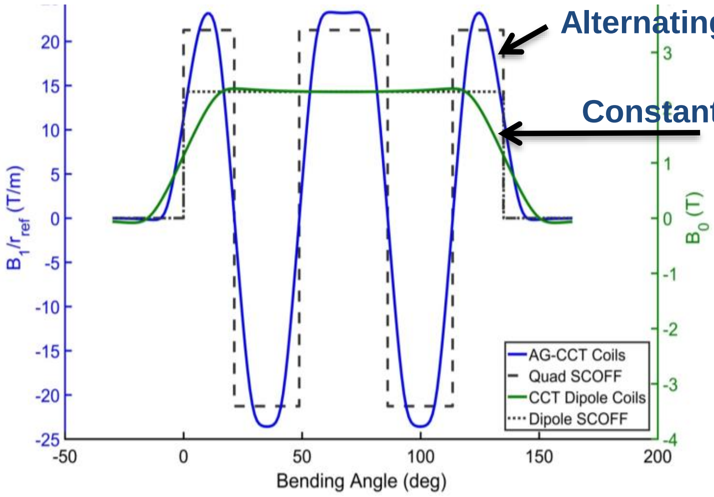
PAUL SCHERRER INSTITUT PSI

A reduced bend prototype for a first test

Four layer CCT design with large acceptance (20%)

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

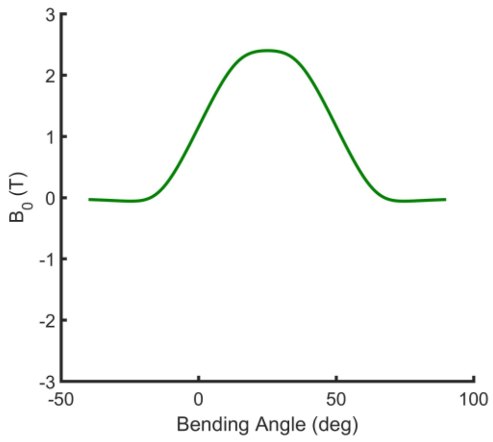


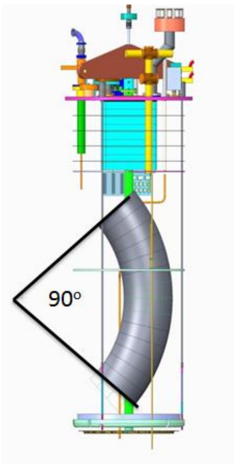


Fabrication and test of two dipole layers

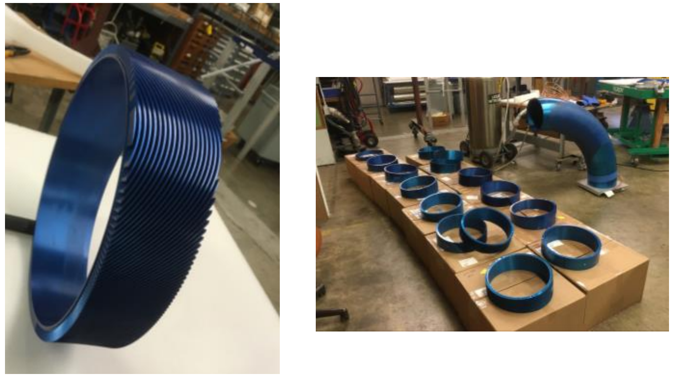
Bending Radius	900 mm
Clear Bore Diameter	290 mm
Magnetic Bend	50 deg
Physical Bend	90 deg
Inductance	0.541 H
Peak Operating Current (I_{nom})	922 A
Dipole Field at I_{nom}	2.4 T
Conductor Field at I_{nom}	3.2 T
Stored Energy at I_{nom}	230 kJ

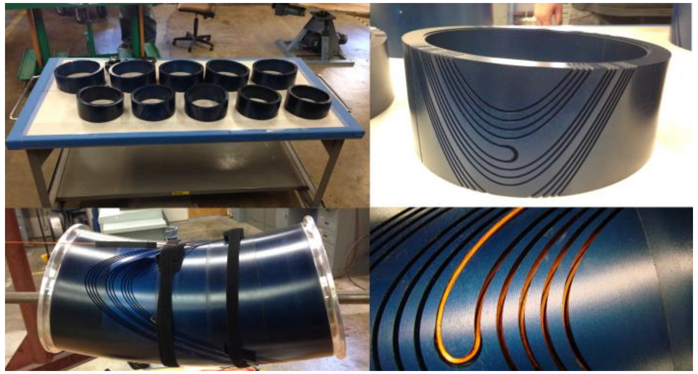
2.4 T dipole in 290 mm aperture (reduced bend angle)

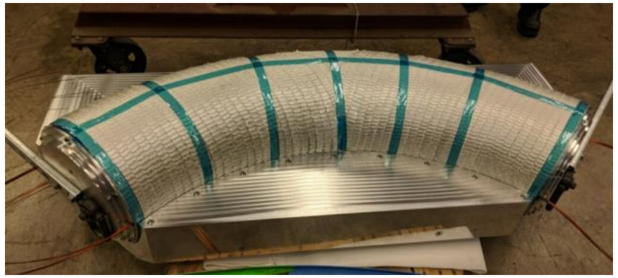


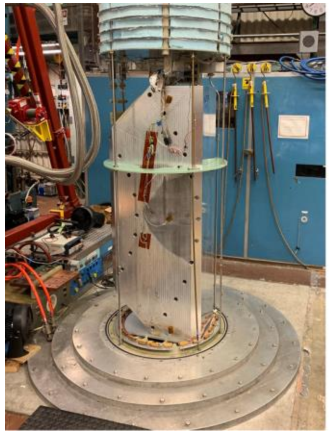


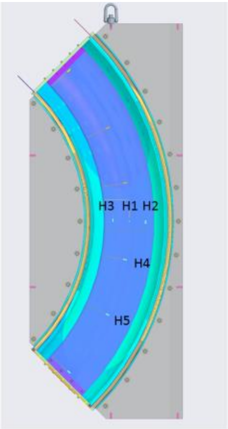
Baseline technology established for design, fabrication, and test of high-curvature CCT magnets with very large apertures





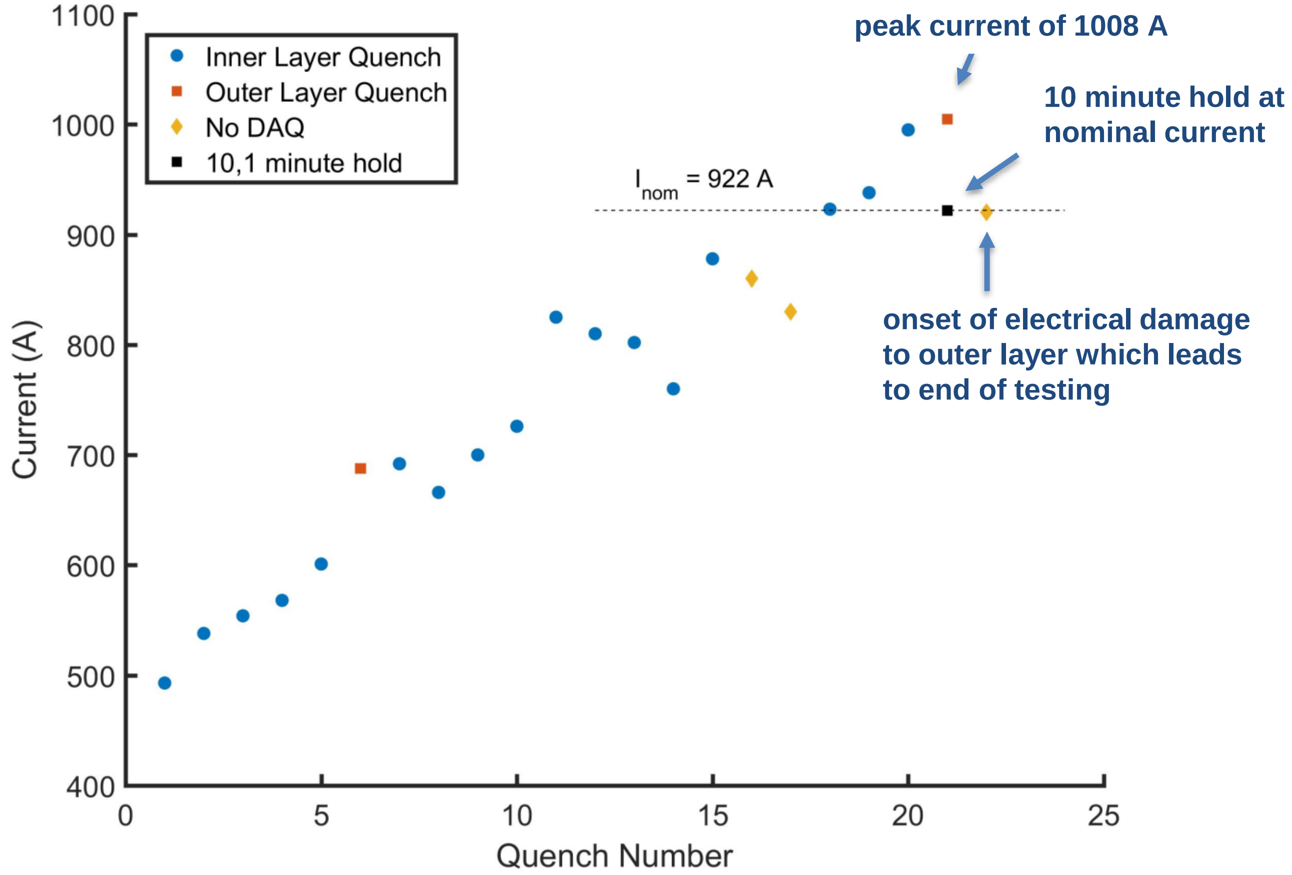






A prototype magnet consisting of the two dipole layers reached the design field in a liquid helium bath (4.5 K)

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



2.4 T dipole field in very large aperture (290 mm) with tight bend radius (ρ=0.9 m)

LBNL: L. Brouwer, 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

Varian Medical: A. Godeke, M. Schillo, A. Huggins, R. Nast

Paul Scherrer Institute: M. Schippers, A. Gerbershagen, C. Calzolaio, S. Sanfilippo

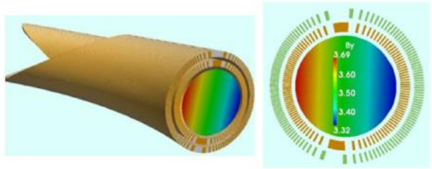
L. Brouwer et al., “Design and test of a curved superconducting dipole magnet for proton therapy,” NIM-A, vol. 957, p. 163414, Mar. 2020, https://doi.org/10.1016/j.nima.2020.163414

Outline

Background

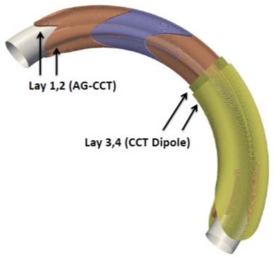
Introduction to CCT

Flexible generation of combined function fields for curved and straight magnets



Introduction to the AG-CCT

Alternating gradients for large Δp/p with fixed-field

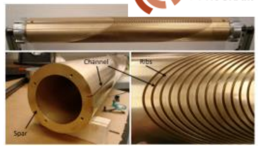


Status

HEP high-field (straight), ARDAP project for proton therapy (curved)

Nb_3Sn + HTS magnets

U.S. MAGNET DEVELOPMENT PROGRAM

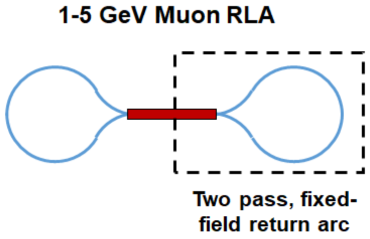


A 2.4 T curved dipole magnet

Plans

Combined function CCT's relevant to FFA's

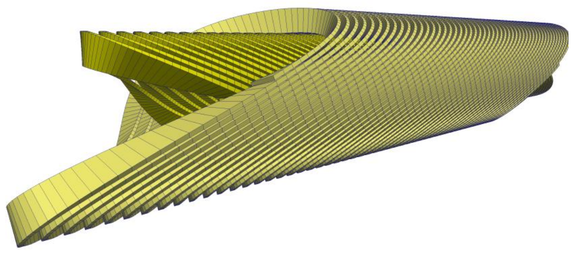
The AG-CCT for fixed-field return arc design

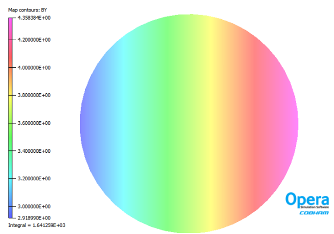


- new program to build and test combined function CCT magnets relevant to FFA's

We have new R&D funding to develop combined function CCT magnets (relevant to FFA applications)

Combined function CCT's map onto existing layouts

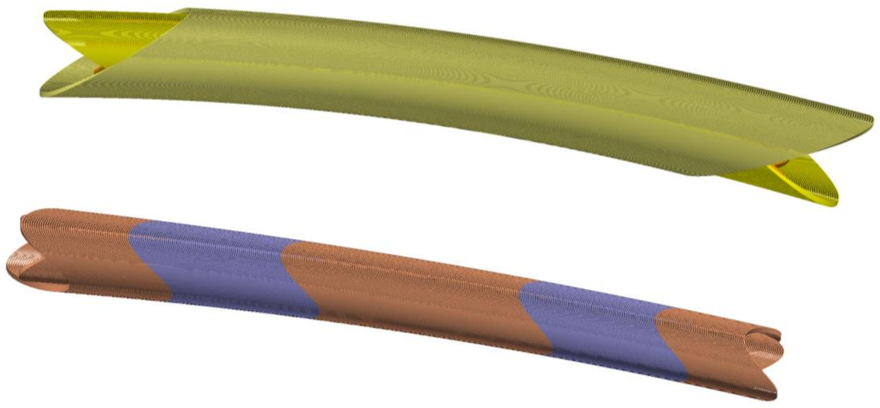




Goals for five year program:

1. develop the technology for combined function, superconducting CCT magnets
2. build and test a prototype magnet to demonstrate performance in the 5-7 T range

New accelerator layouts leveraging the AG-CCT?



Near term: solidify design parameters for the prototype magnet within 1 year.

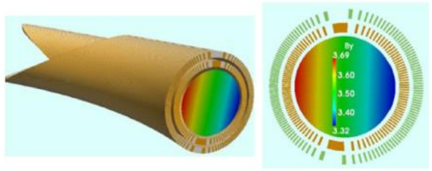
Question for this workshop - what do you see as the key aspects of SC magnet technology which needs to be demonstrated for future FFA's?

Summary

Background

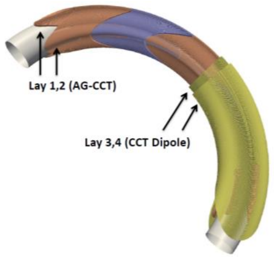
Introduction to CCT

Flexible generation of combined function fields for curved and straight magnets



Introduction to the AG-CCT

Alternating gradients for large Δp/p with fixed-field



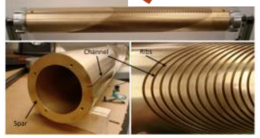
- CCT is flexible design for combined function fields in straight and curved geometries
- The AG-CCT integrates alternating gradients into a single magnet

Status

HEP high-field (straight), ARDAP project for proton therapy (curved)

Nb_3Sn + HTS magnets

U.S. MAGNET DEVELOPMENT PROGRAM



A 2.4 T curved dipole magnet

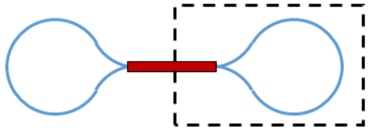
- 8-10 T Nb_3Sn dipoles for HEP (US-MDP)
- 2.4 T curved NbTi dipole for proton therapy

Plans

Combined function CCT's relevant to FFA's

The AG-CCT for fixed-field return arc design

1-5 GeV Muon RLA

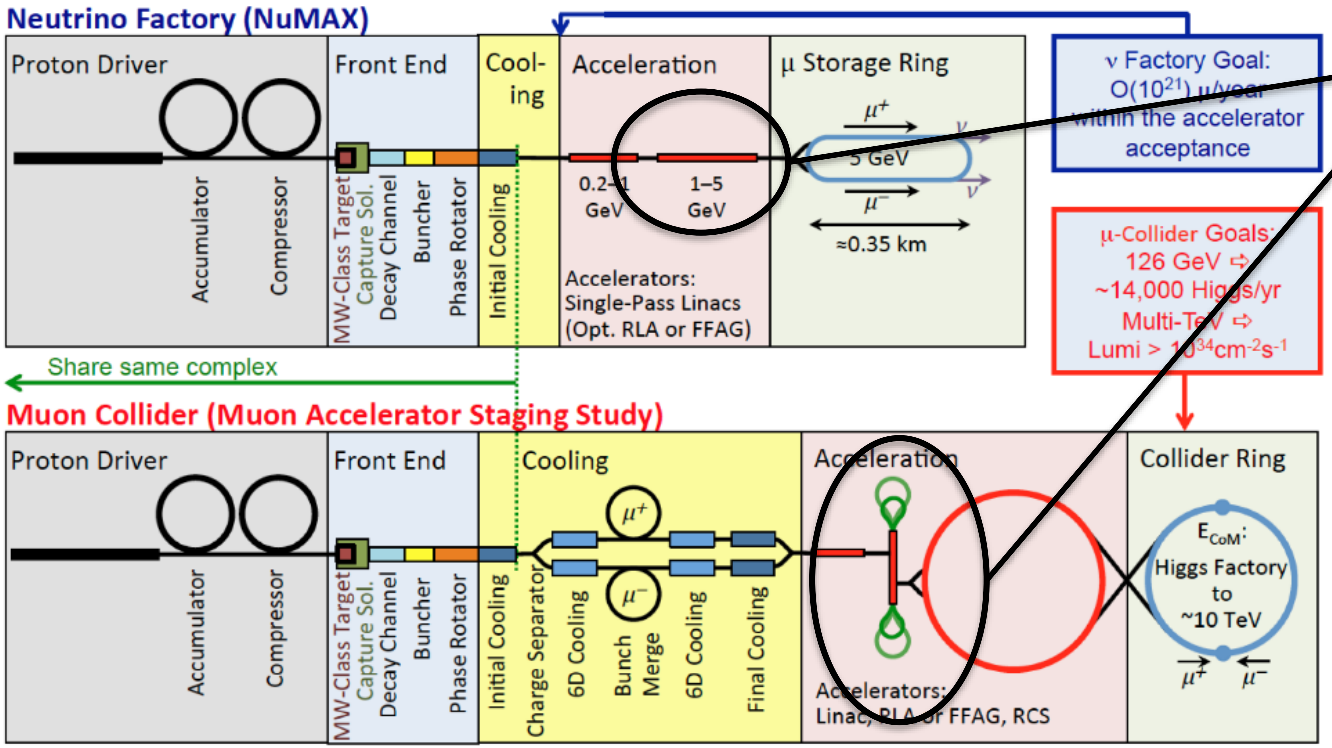


Two pass, fixed-field return arc

- 13 T, 120ø Nb_3Sn dipole
- plan to build and test ~5 T combined function CCT magnets relevant to FFA's (now is an excellent time for community feedback)

Backup Slides

Focus on scoping the AG-CCT design to 1.2, 2.4 GeV/c passes in collaboration with LBNL's Accelerator Modeling Program (AMP)



Muon Acceleration Concepts for NuMAX: "Dual-use" Linac and "Dogbone" RLA[1]

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 060101 (2012)

Linear fixed-field multipass arcs for recirculating linear accelerators

V. S. Morozov,[1] S. A. Bogacz,[1] Y. R. Roblin,[1] and K. B. Beard[2]
[1]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[2]*Muons, Inc., Batavia, Illinois 60510, USA*

(Received 6 April 2012; published 14 June 2012)

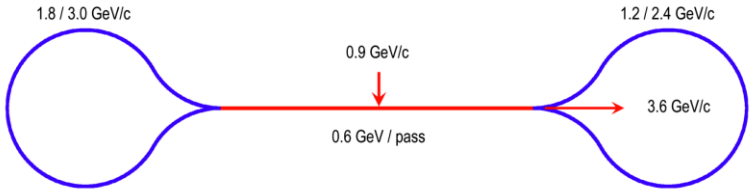
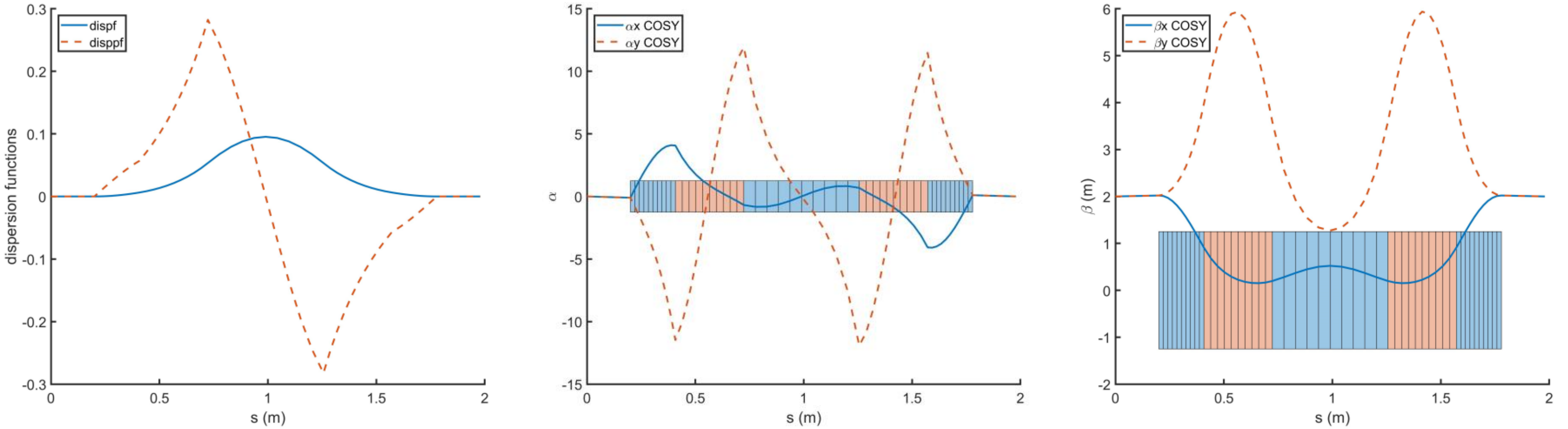


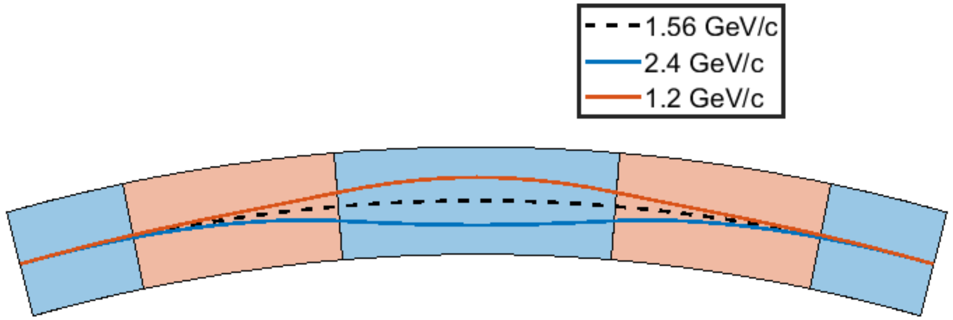
FIG. 1. Schematic layout of a 4.5-pass 3.6 GeV/c muon RLA.

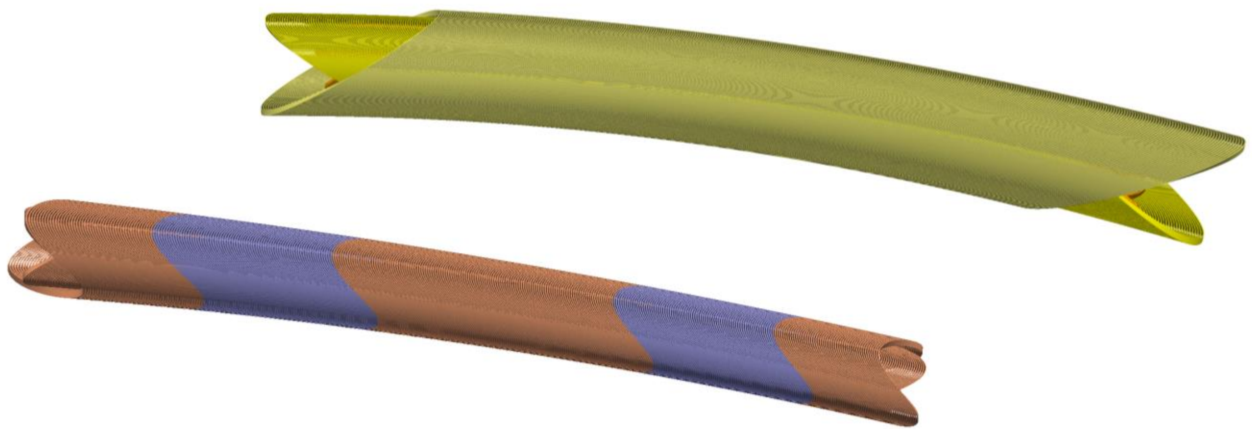
Focus on scoping the AG-CCT design to 1.2, 2.4 GeV/c passes in collaboration with LBNL's Accelerator Modeling Program (AMP)

B0 = 1.725 T
G = 87.67 T/m
ϕtot = 30 deg
ϕsplit = 3.95, 6.0, 10.11, 6.0, 3.95
aperture = 100 mm
ρ = 3.02 m

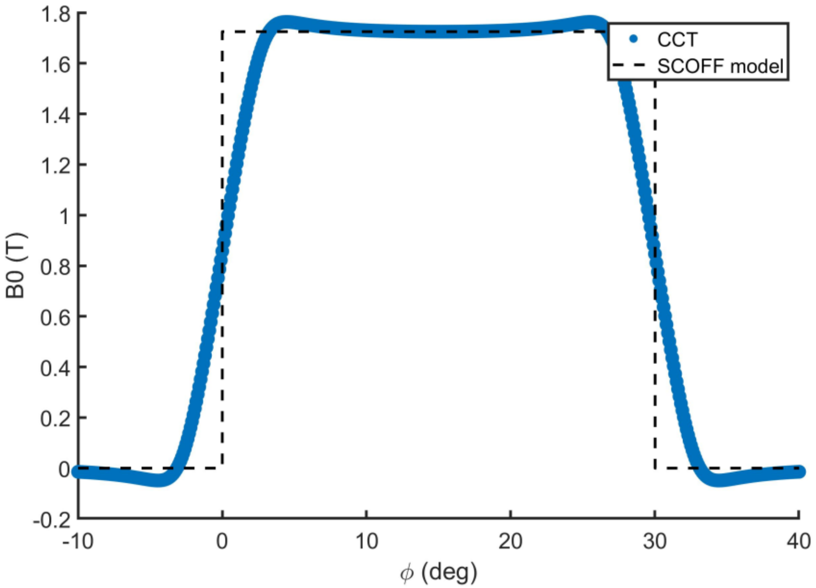
For reference energy

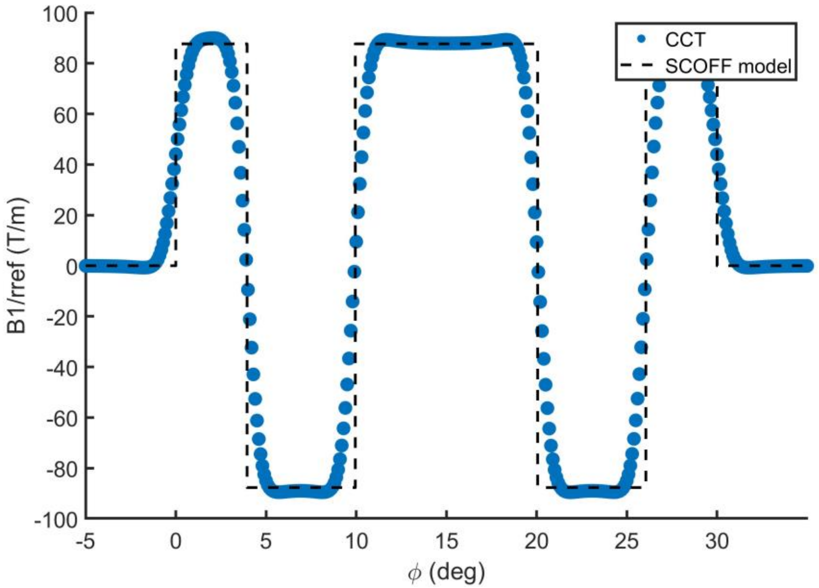


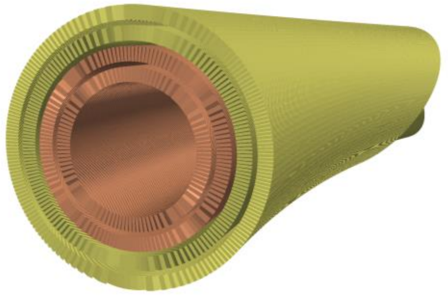




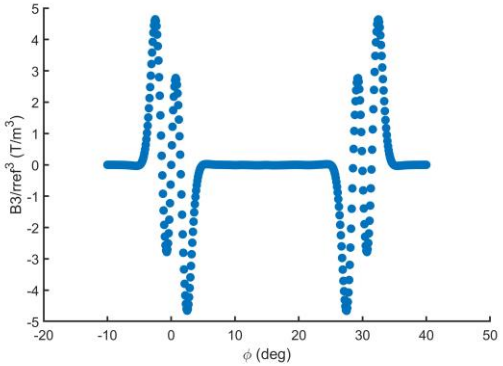
Harmonics along the length for coil design based on SCOFF model (at 30 mm reference radius – 60% of aperture)



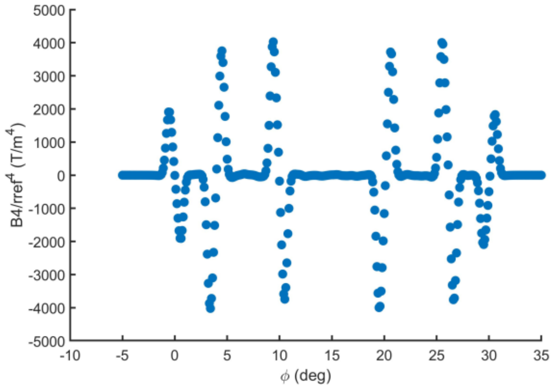




B3 integrates to zero through ends



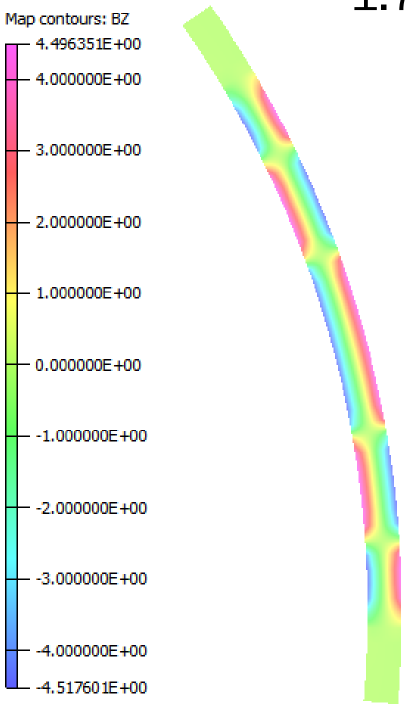
B4 integrates to zero through ends



In plane fields for perfect sectioning + peak field on conductor

Quad Layers

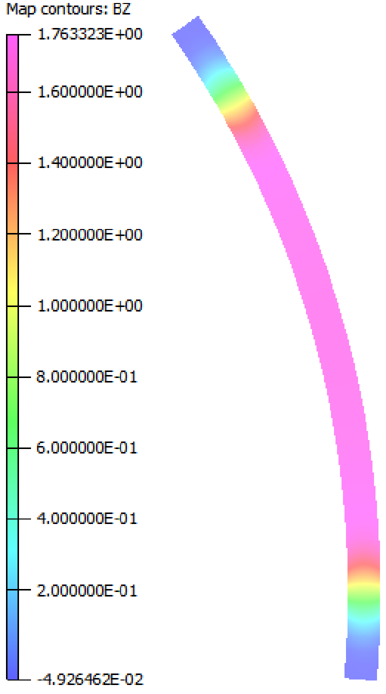
4.5 T



-4.5 T

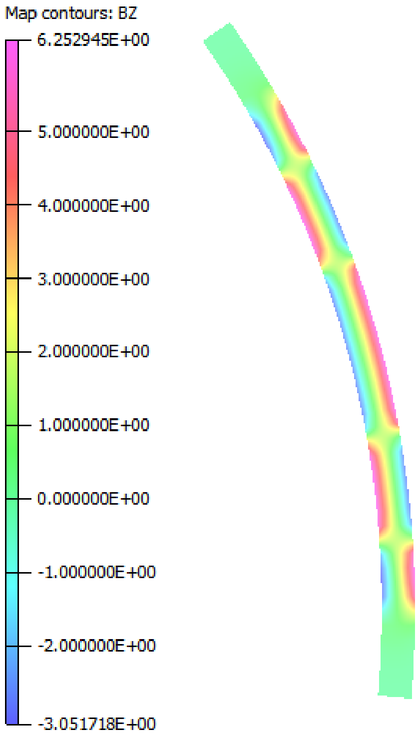
Dipole only

1.76 T

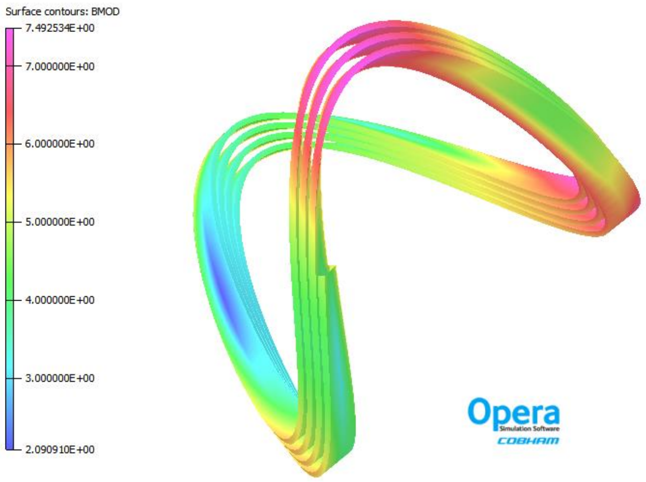


Combined

6.25 T

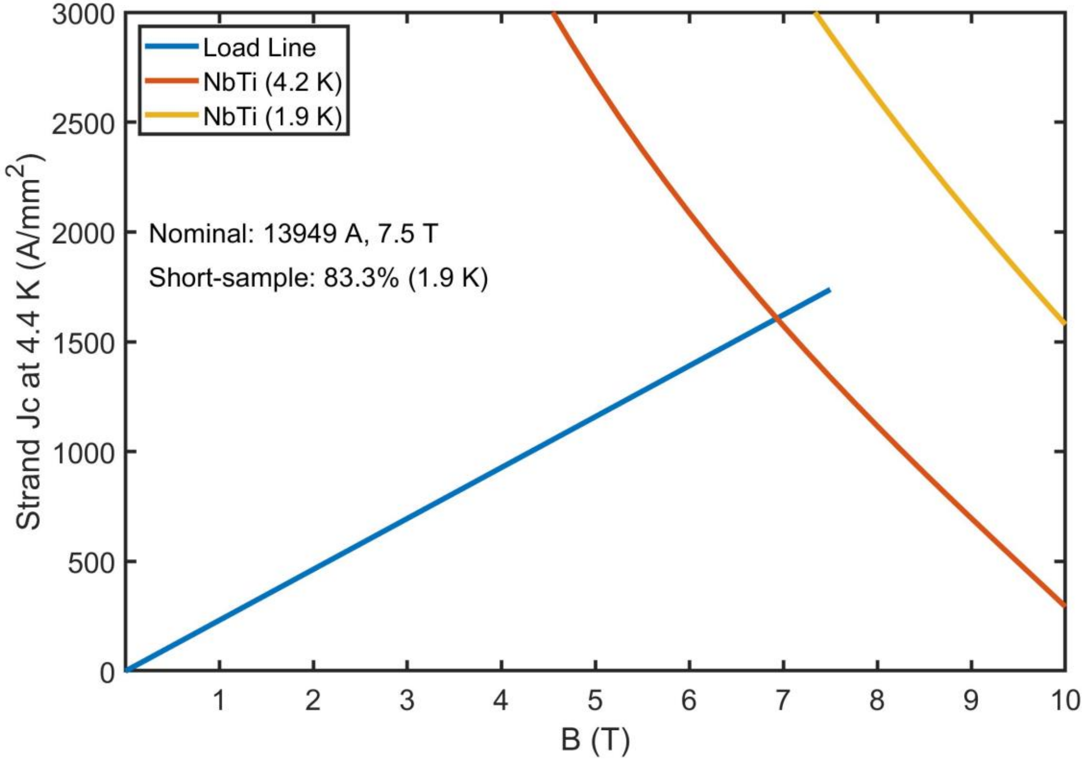


Peak field on the conductor is 7.5 T, a 23% rise (from 6.11 T of dipole+gradient)

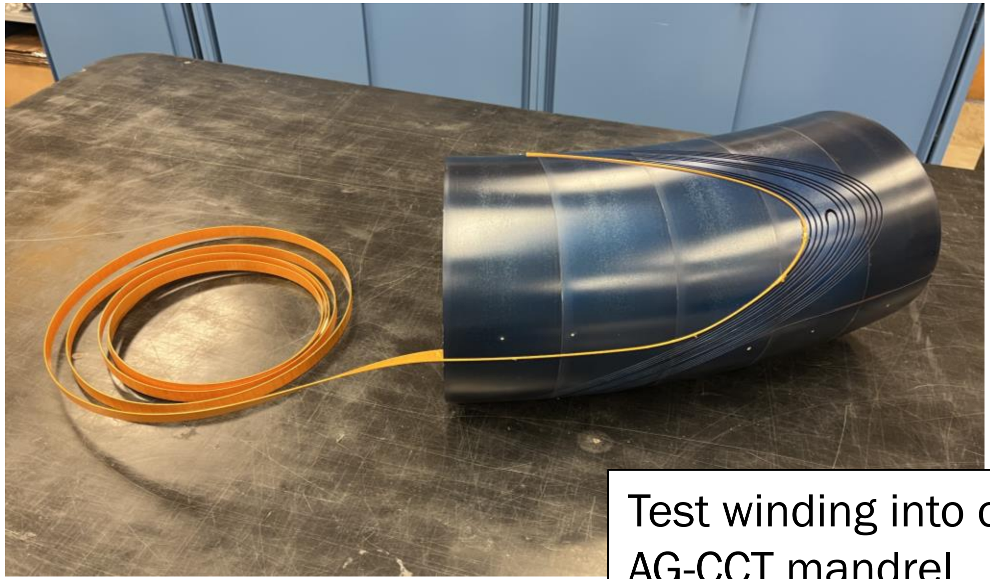


These fields are a bit high for Nb-Ti, but feasible with respect to conductor performance (the LHC NbTi cable is a good reference)

Short-sample assuming LHC NbTi cable



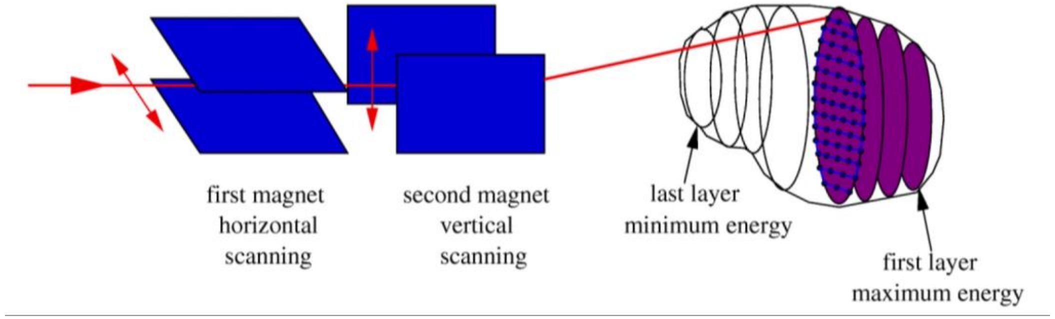
36 strands of 0.825 mm wire (15.1 mm thick)



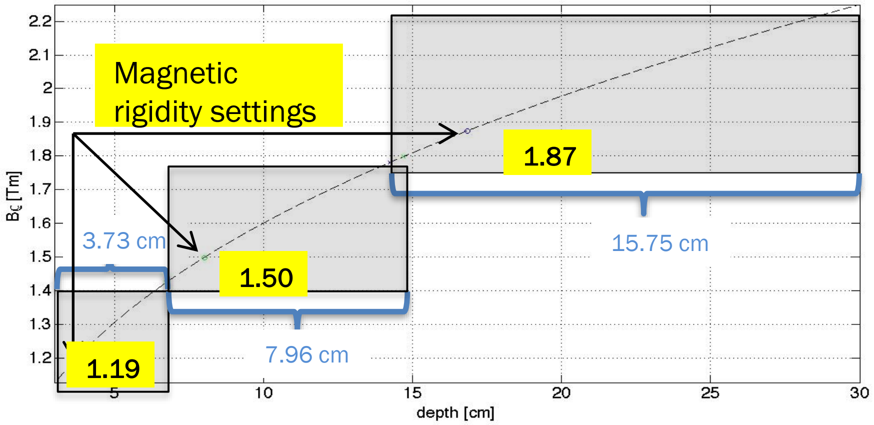
Test winding into old AG-CCT mandrel

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

Fast depth scanning with beam energy is desired during treatment

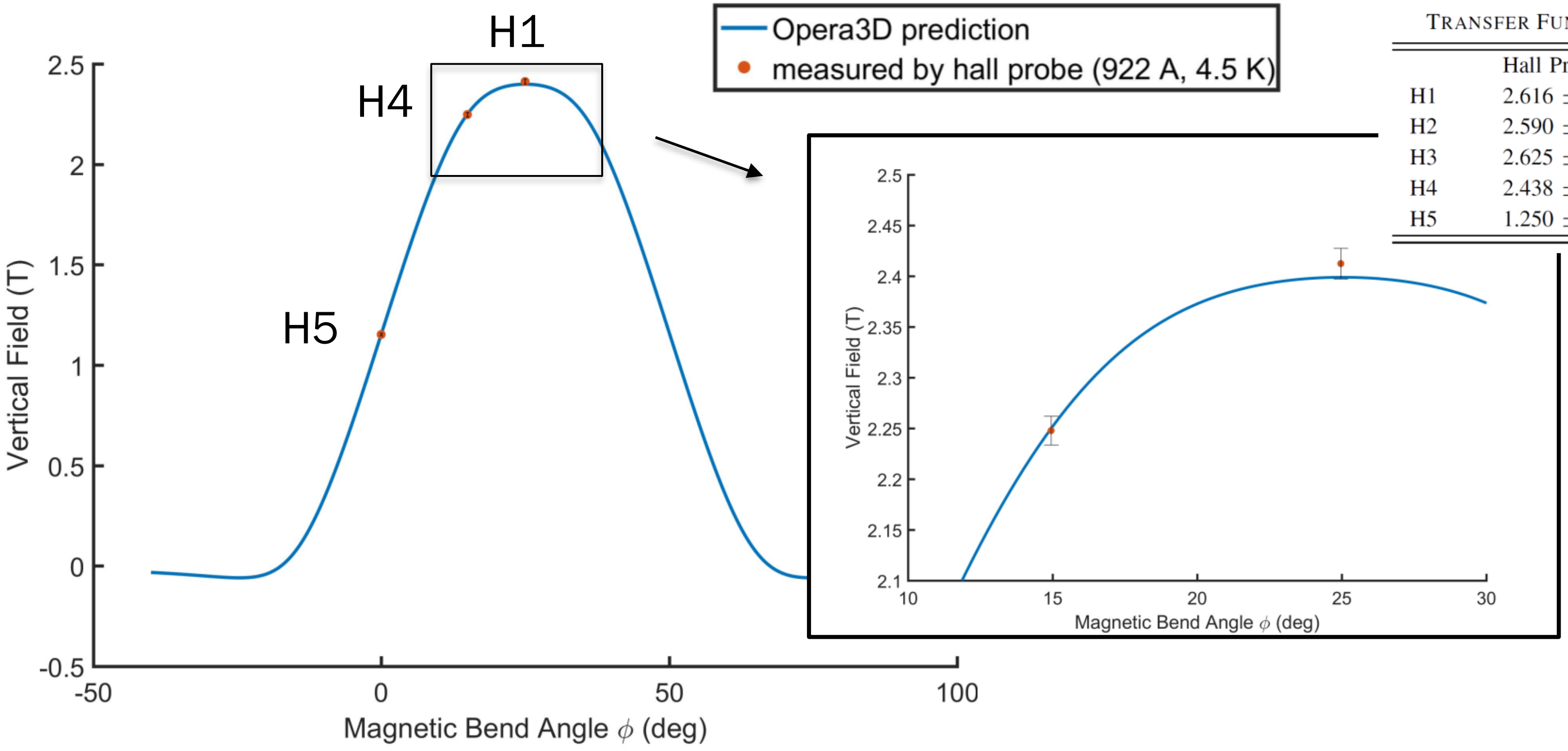


With a large momentum acceptance, each magnet setting covers a range of treatment energy (e.g. 20% dp/p)



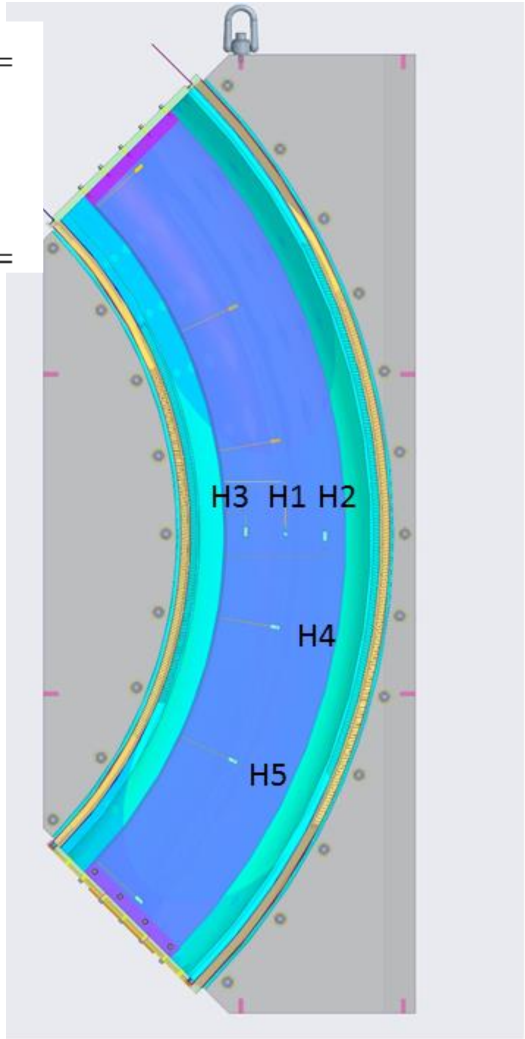
- ✓ **some tumors can be treated at fixed-field**
- ✓ **order of magnitude reduction in magnet field ramping for worst-case scenario**

Hall probes verified the design field at nominal current, a more complicated measurement system is required for future field quality characterization determining the harmonic content



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