Compact curved superconducting magnets for an proton/ion therapy gantry using the Canted-Cosine-Theta (CCT) geometry

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2nd EUCARD2-workshop

Bad Zurzach Switzerland

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Outline

The Canted-Cosine-Theta Magnet (CCT)

- CCT basic concept - windings on a straight cylinder
- CCT extended concept - windings on a torus
  - introduce a new concept (AG-CCT)
- Status of developing a light-weight superconducting magnet gantry (collaboration between LBNL-PSI-Varian)

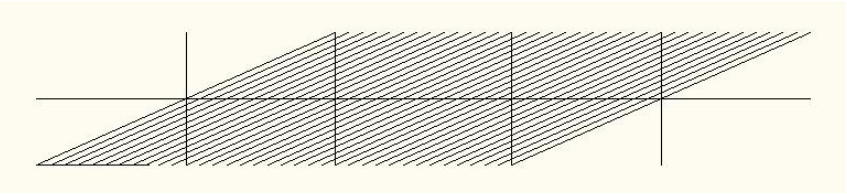
The Canted-Cosine-Theta (CCT) Magnet

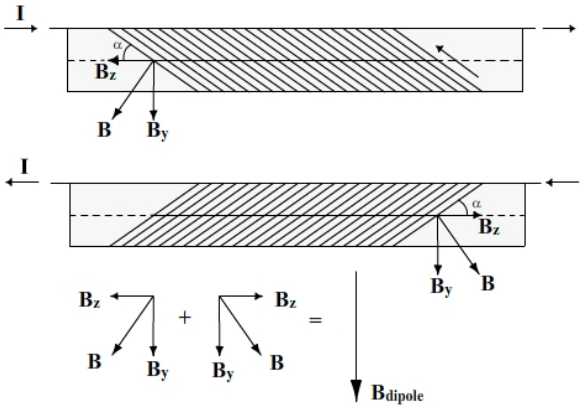
Canted-Cosine-Theta

$$J_\vartheta \sim const$$

$$J_z \sim \cos\vartheta$$

Canted solenoid ~15 degrees



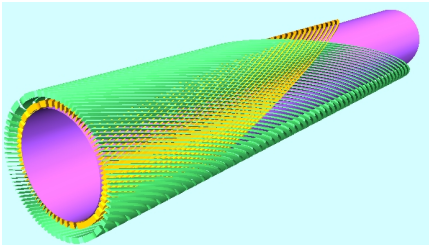


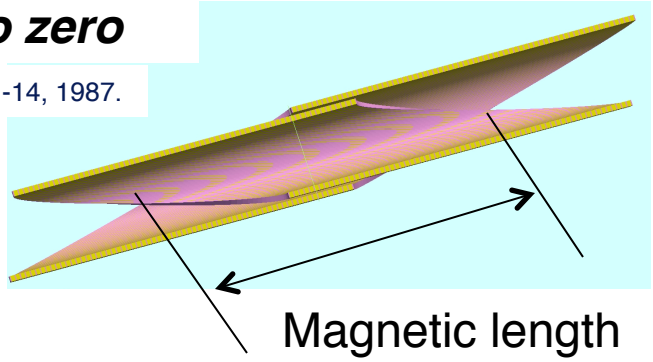
Two superimposed coils, canted oppositely, achieve a pure cosine-theta field and eliminate the axial field.

Meyer D.I. and R. Flasck "A new configuration for a dipole magnet for use in high energy physics application", Nucl. Instr. and Methods 80, pp. 339-341, 1970.

Lambertson-Coupland "Ends" –harmonics integrate to zero

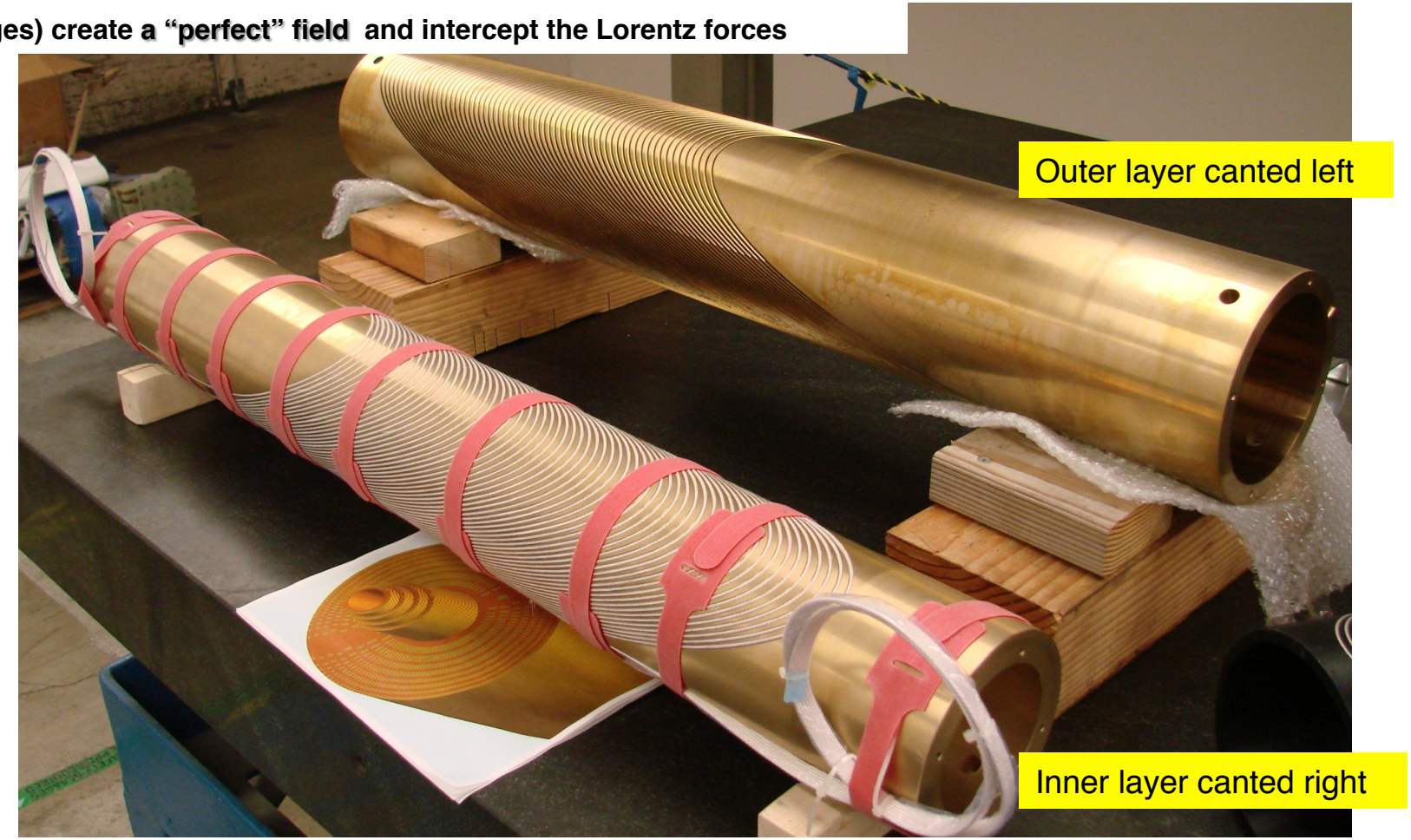
Laslett, L. J., S. Caspi and M. Helm "Configuration of coil ends for multipole magnets." Part. Accel. **22**: 1-14, 1987.





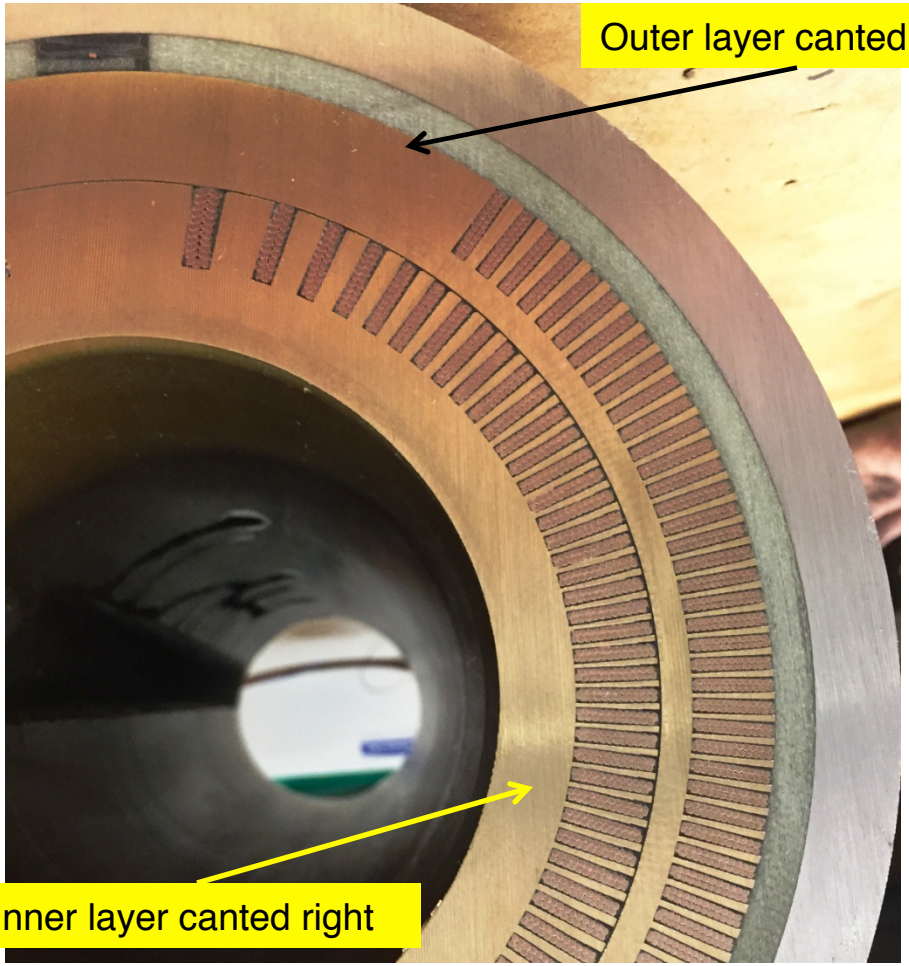
The Linear CCT2 Magnet (tested to 4.6T)

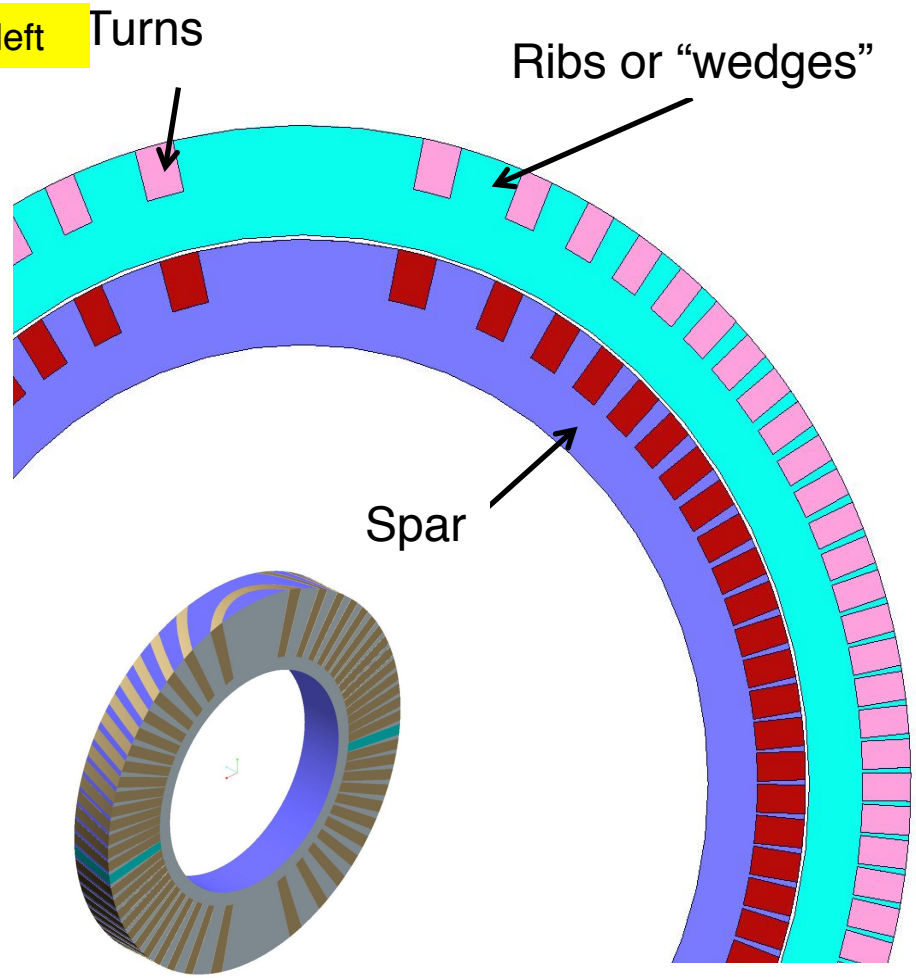
Ribs (wedges) create a "perfect" field and intercept the Lorentz forces



Same technology different SC **5T with NbTi, 10T with Nb_3Sn**

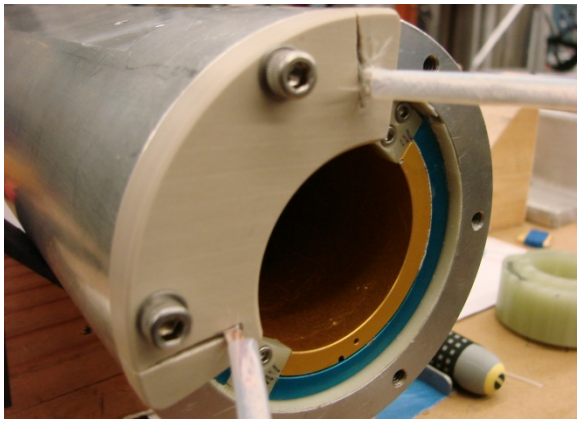
The CCT2 NbTi magnet: demonstrated field performance relevant to gantries

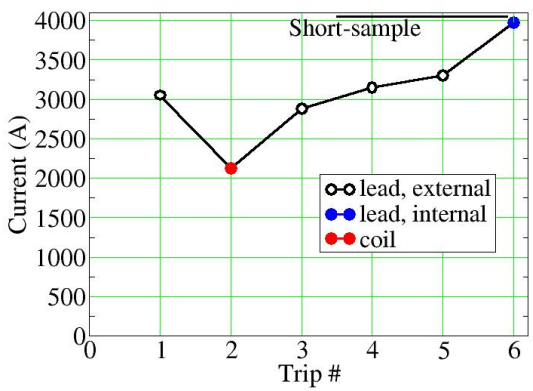




CCT1 and CCT2 – next is CCT3 Nb3Sn

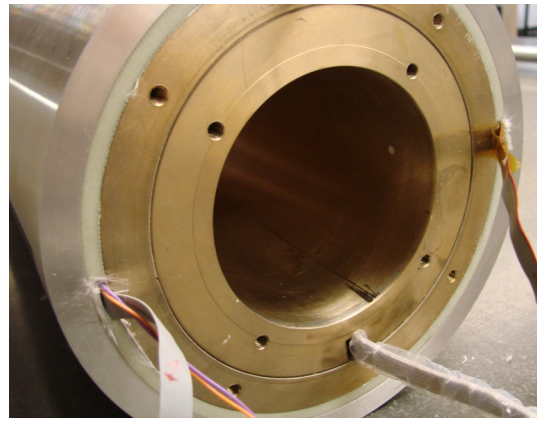
CCT1 – NbTi, clear bore 50mm, not impregnated

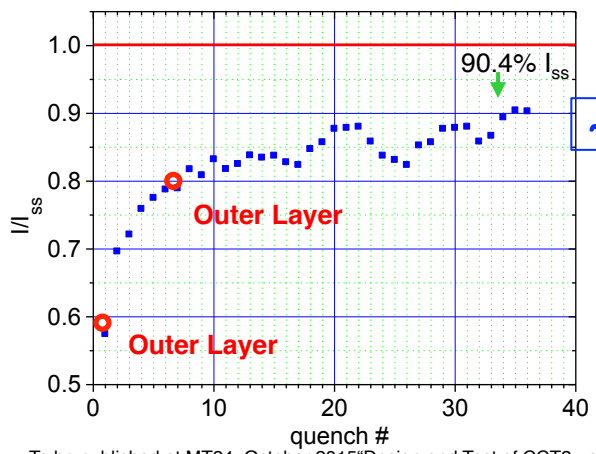




Caspi S, Brouwer L, Lipton T, Hafalia A, Prestemon S, Dietderich D, et al. Test Results of CCT1—A 2.4 T Canted-Cosine-Theta Dipole Magnet. Applied Superconductivity, IEEE Transactions on. 2015;25(3):1-4.

CCT2 – NbTi, clear bore 90mm, impregnated



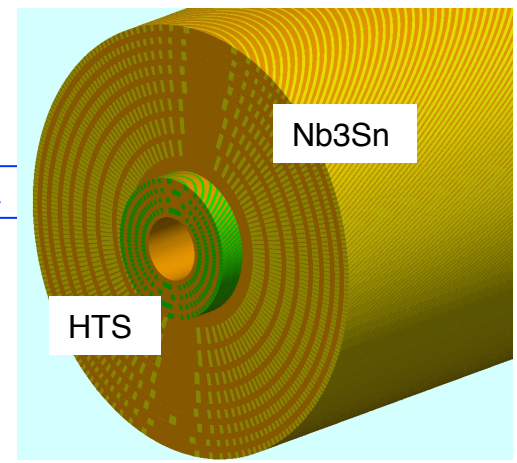


To be published at MT24, October 2015"Design and Test of CCT2 - a 5T Canted-Cosine-Theta Superconducting Dipole Magnet"

CCT3 – Nb3Sn, clear bore 90mm, same geometry as CCT2 reacted at 650C and impregnated

	Bexpected (T)	Bmeasured (T)
CCT1 -	2.5	2.4
CCT2 -	5.0	4.6
CCT3 –	10.0	---
……		
CCT# -	17.7	----

~9,000 A



Caspi S, Brouwer L, Lipton T, Hafalia A, Prestemon S, Dietderich D, et al. Design of an 18-T Canted Cosine–Theta Superconducting Dipole Magnet. Applied Superconductivity, IEEE Transactions on. 2015;25(3):1-5

The Canted-Cosine-Theta (CCT) – a paradigm shift

- **Field quality:**
  - Excellent field quality – **straight and curved magnets**

- **Low conductor stress:**
  - **Internal Structure intercepts Lorentz-Forces, reduced coil stress**
  - **no pre-stress**
  - Small or large **bores**

- **Cost-effective:**
  - Poles not separated– just **like solenoids**
  - Fewer parts, simplified tooling and assembly
  - Compatibility between **NbTi, Nb_3Sn and HTS**

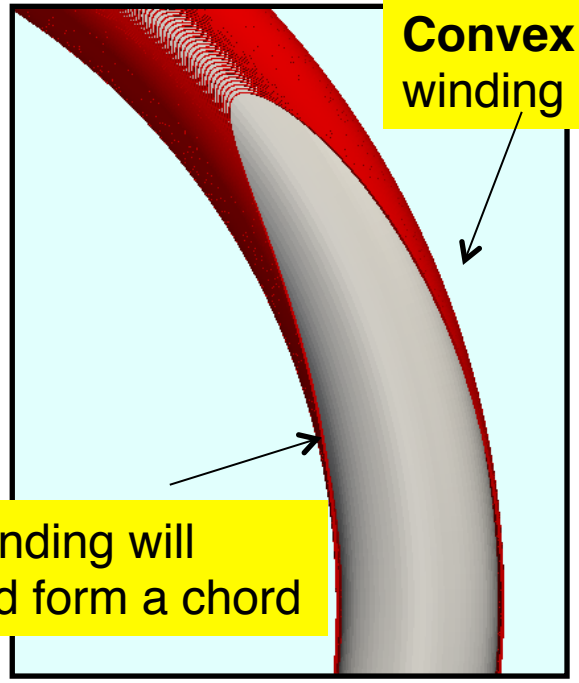
CCT winding on a Torus

Curved Windings

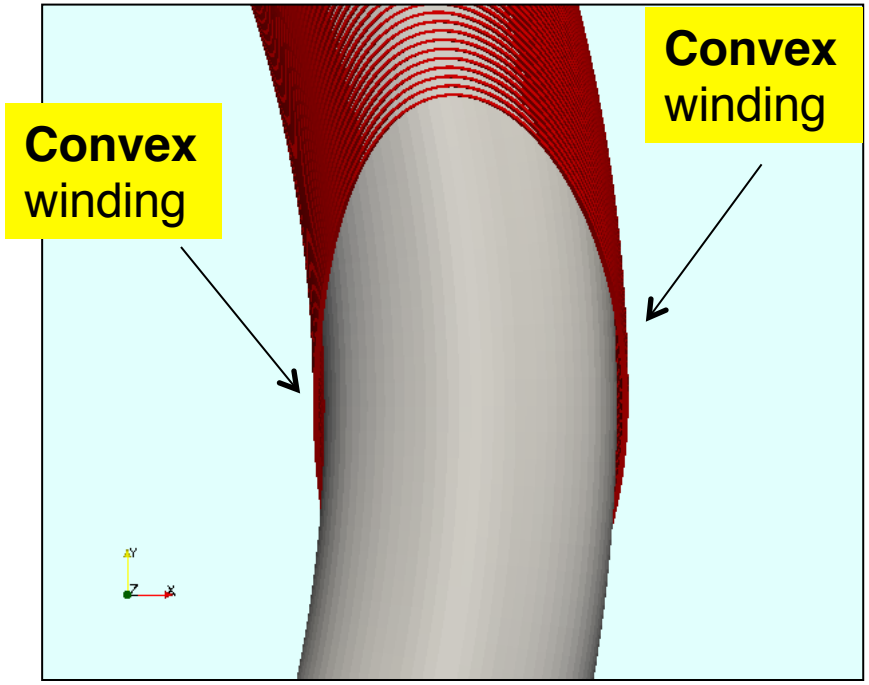
- By limiting the tilt angle,

The CCT windings maintain contact with the spar on both inner and outer curves (no need for further tooling)

Undesirable

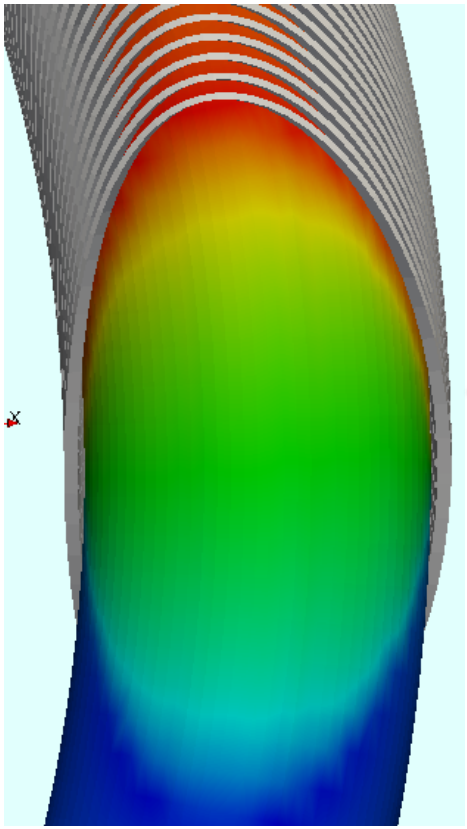


Desirable

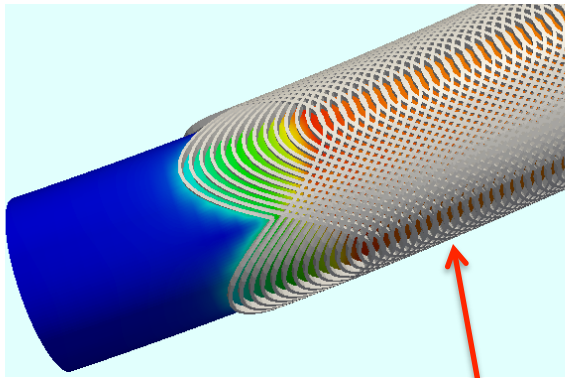


Windings and Multipoles in a Curved Geometry

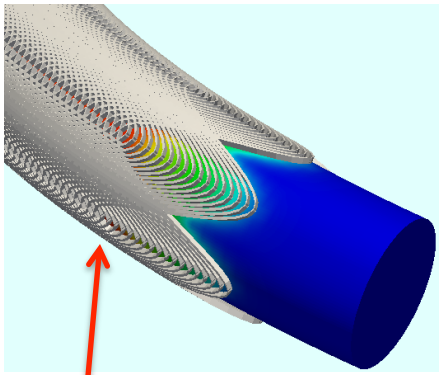
"a_0- Dipole"



"a_1- Quadrupole"



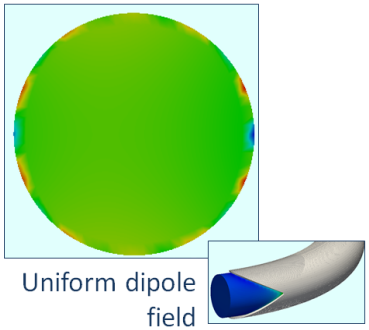
"a_2- Sextupole"



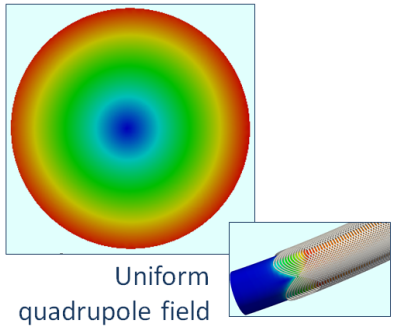
$$\phi = \theta / n + a_0 \sin\theta + a_1 \sin 2\theta + a_2 \sin 3\theta$$

- Relation between ϕ and θ $\phi = f(\theta)$, determine the winding path:

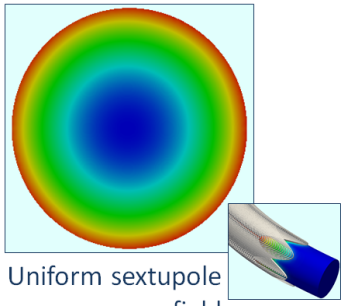
The coefficients depend on the bore and torus radii and the solenoid field (or tilted angle).



Uniform dipole field



Uniform quadrupole field



Uniform sextupole field

A single windings path can combine several harmonic terms

Curved CCT Magnet

Collaboration between LBNL-PSI-Varian

- LBNL's interest in using superconducting magnets for gantries began in 2008
- Proposal with PSI and Varian Medical began to DOE HEP Stewardship program (2014)
- Proposal funded for 3 years (2015)

Goal:

- Develop the technology of a light-weight superconducting magnet that will reduce the size and weight of particle beam delivery systems
- Build and test a prototype gantry bending magnet

Principle Investigator
LBNL (Lead Lab)
Soren Prestemon

Collaborator (End-user)
PSI
Marco Schippers

Magnet/optics
LBNL
David Robin & Weishi Wan

Collaborator (Industry)
Varian Med. Sys. , Particle Theraphy
Matt Murphy

M$1.95 awarded by DOE, with contribution from Varian and PSI

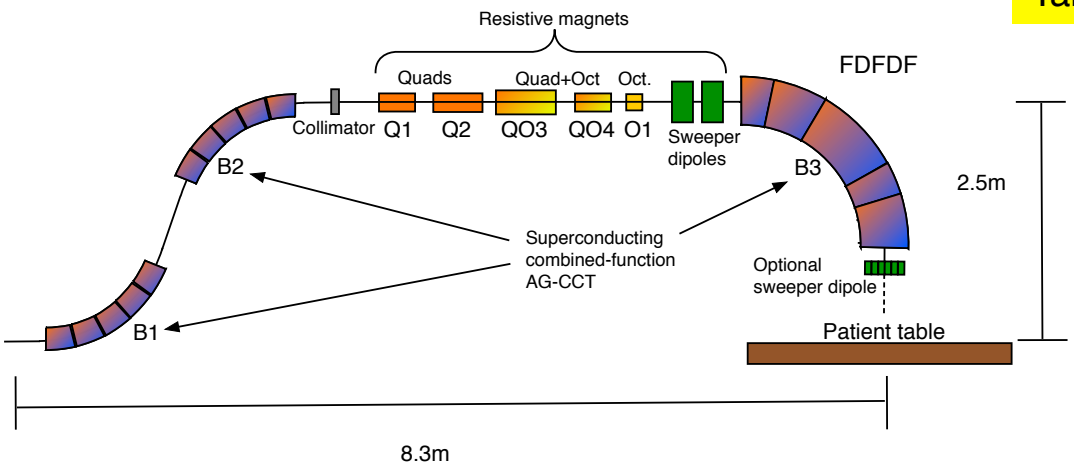
The promise of using superconducting magnets

A high momentum acceptance:

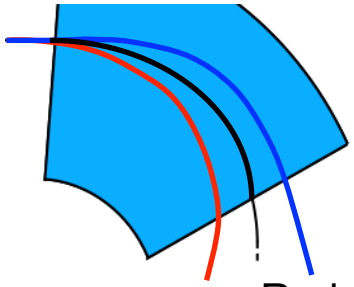
- **Over come the challenge of fast ramping and allow fast scanning depth**
- **Beams with different energy without changing the field of the magnet**
- **CCT is a very efficient way for AG (compact ends)**

CCT Final bend and Alternating Gradient CCT Quads

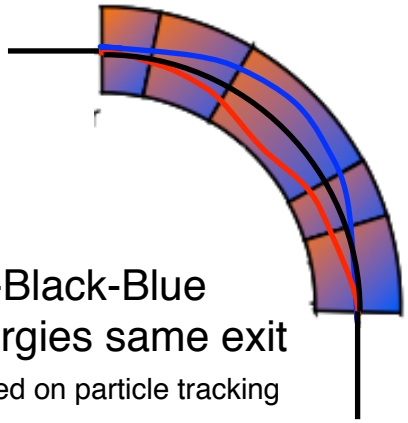
Talk by Weishi Wan



Pure dipole



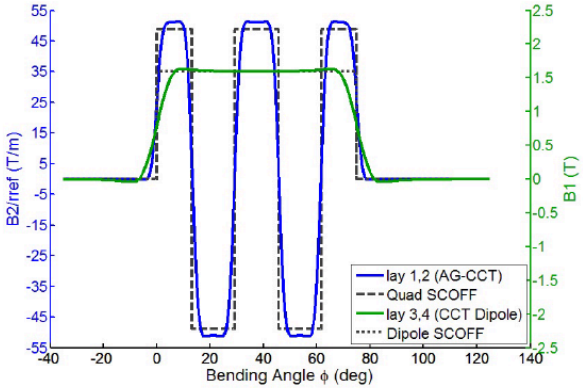
Locally achromatic



Red-Black-Blue
Different energies same exit

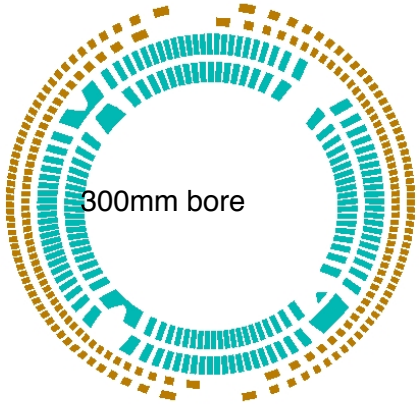
Winding position is based on particle tracking

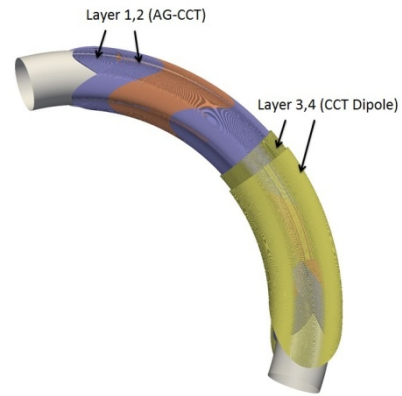
- Example of SCOFF model for B1 and B2



Paper accepted by PRSTAB

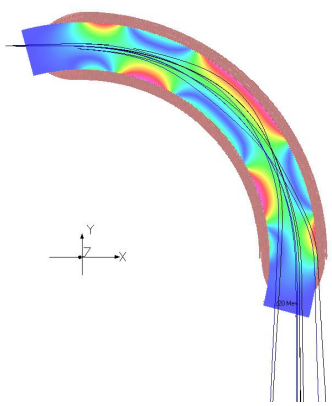
Final bend
Combined Alternating Gradient CCT Quads

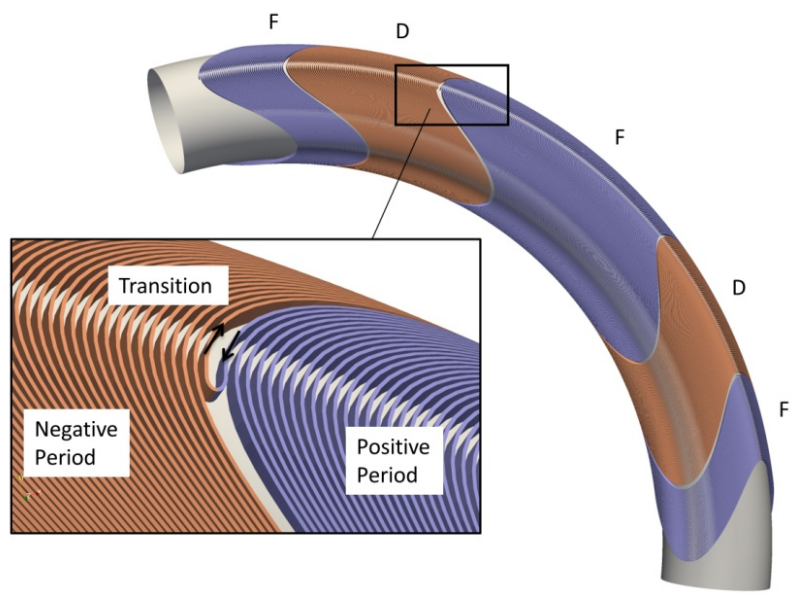




4 layers
2 dip. and 2 quad.

B1: 1.52 T
B2: 19.7 T/m





Magnetics

Short-Sample for highest setting*

Magnet setting for highest energy range:

Bore values:
B1: 1.52 T
B2: 19.7 T/m
Conductor values:
B1: 5.13 T
B2: 6.07 T

. Short Sample at Highest Magnet Current

		90 degree/300 mm bore (B3)			
Lay	Type	I/strand (A)	$B_{cond.}$ (T)	strands	margin (%)
1	AG-CCT	220.7	6.03	37	21
1	AG-CCT	220.7	6.07	37	21
3	CCT dipole	325	5.13	12	26
4	CCT dipole	325	4.03	12	45

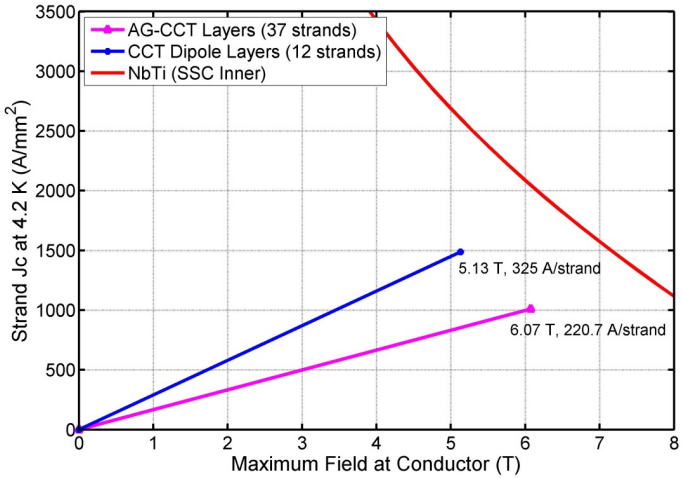
		90 degree (B3)			
Lay	Type	Ri	Ro	Wall Thick.	Channel
1	AG-CCT	150	169	19.0	2.0/16.0
1	AG-CCT	169	188	19.0	2.0/16.0
3	CCT dipole	188	196.2	8.2	2.0/5.2
4	CCT dipole	196.2	204.4	8.2	2.0/5.2

TABLE I. SSC Inner NbTi Strand

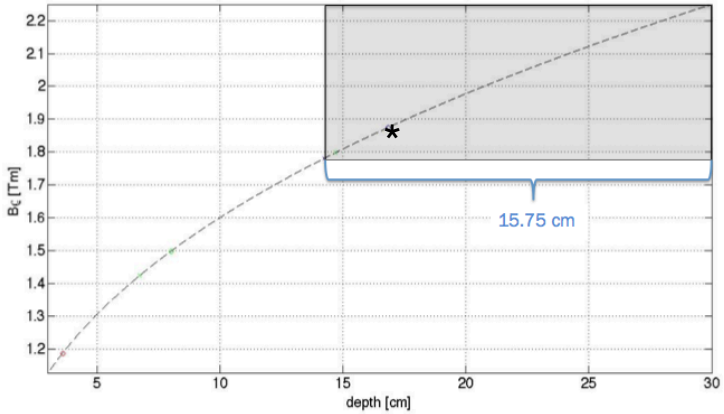
Diameter	0.8 mm
Jc at 5T,4.2K	2750 A/mm^2
Cu/SC	1.3
Filament	6.0 μm

Channel Depth is adjusted for # of strands
- linear ratio of 10mm/23strands

r =1250mm



Highest energy range



Magnet Design

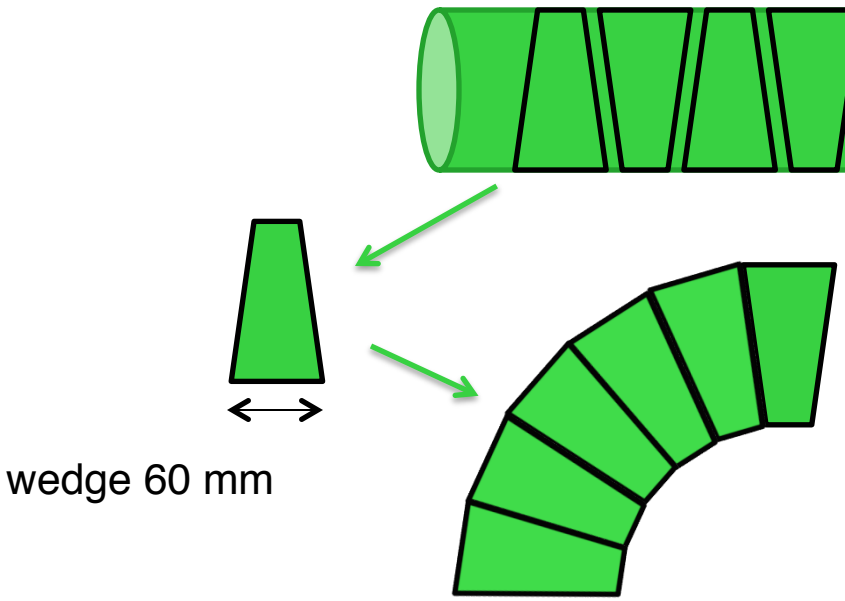
Magnetic, Structure, Thermal and CAD work

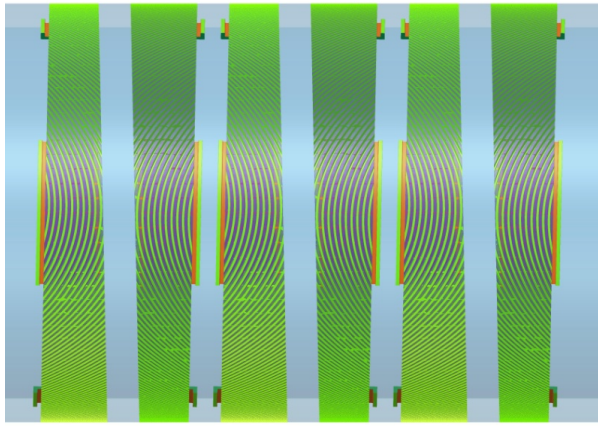
Integrated analysis - magnetic, Lorentz forces, Structure stress , displacements and thermal using TOSCA, ANSYS and ProE

Progress in Curved Mandrel Fabrication

We are currently exploring options for fabricating a torus

- Approximate Torus with machined **Identical wedges** cut from a cylinder or plates
- Each wedge is ~60mm thick (equivalent to 10 lamination)
- A faceted wedge departs by **0.28mm** from the true toroid surface. (bending radius of 1250 mm)
- The wedge faceted surface is **included in the analysis**

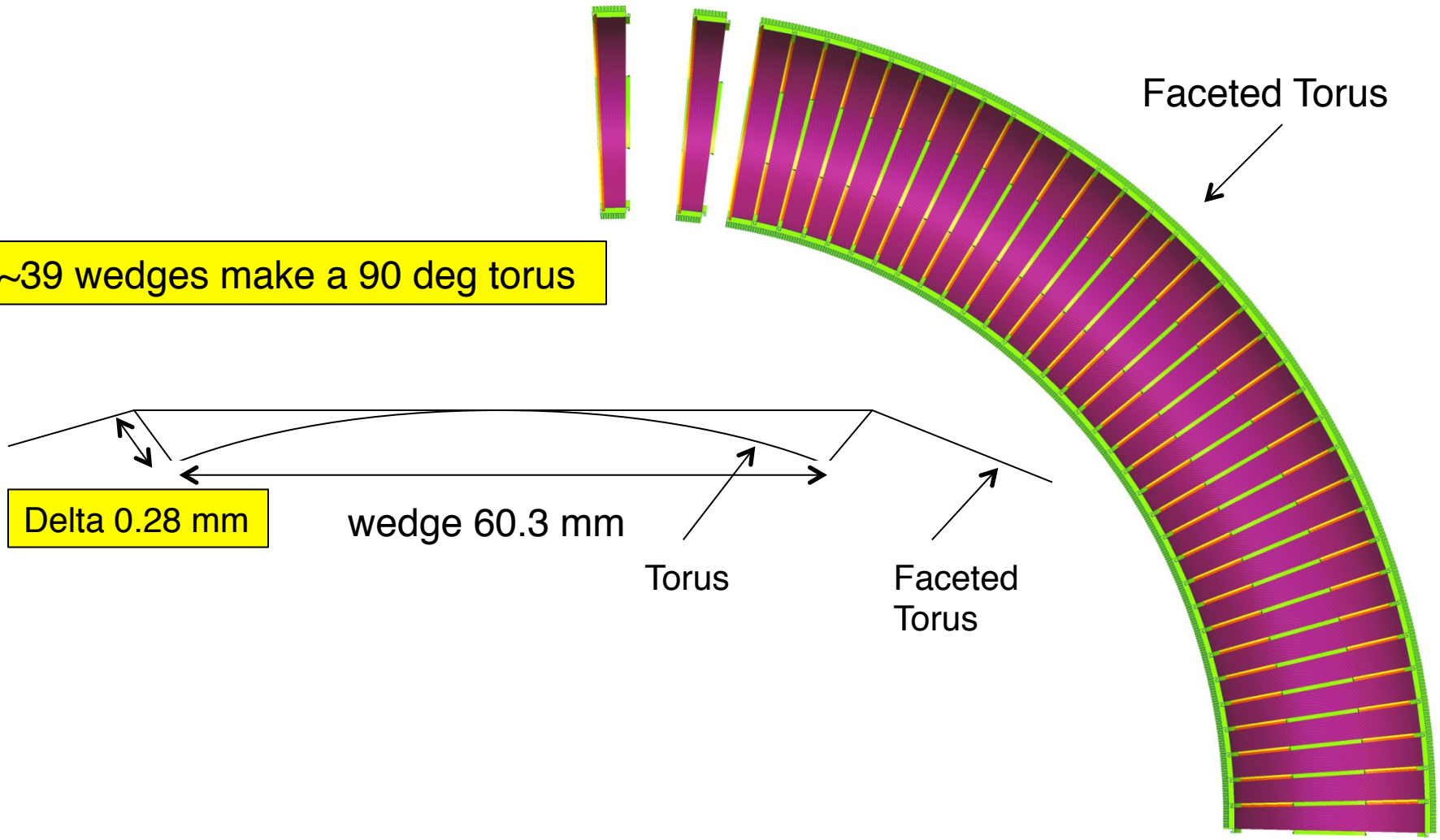




Machine grooves into wedge

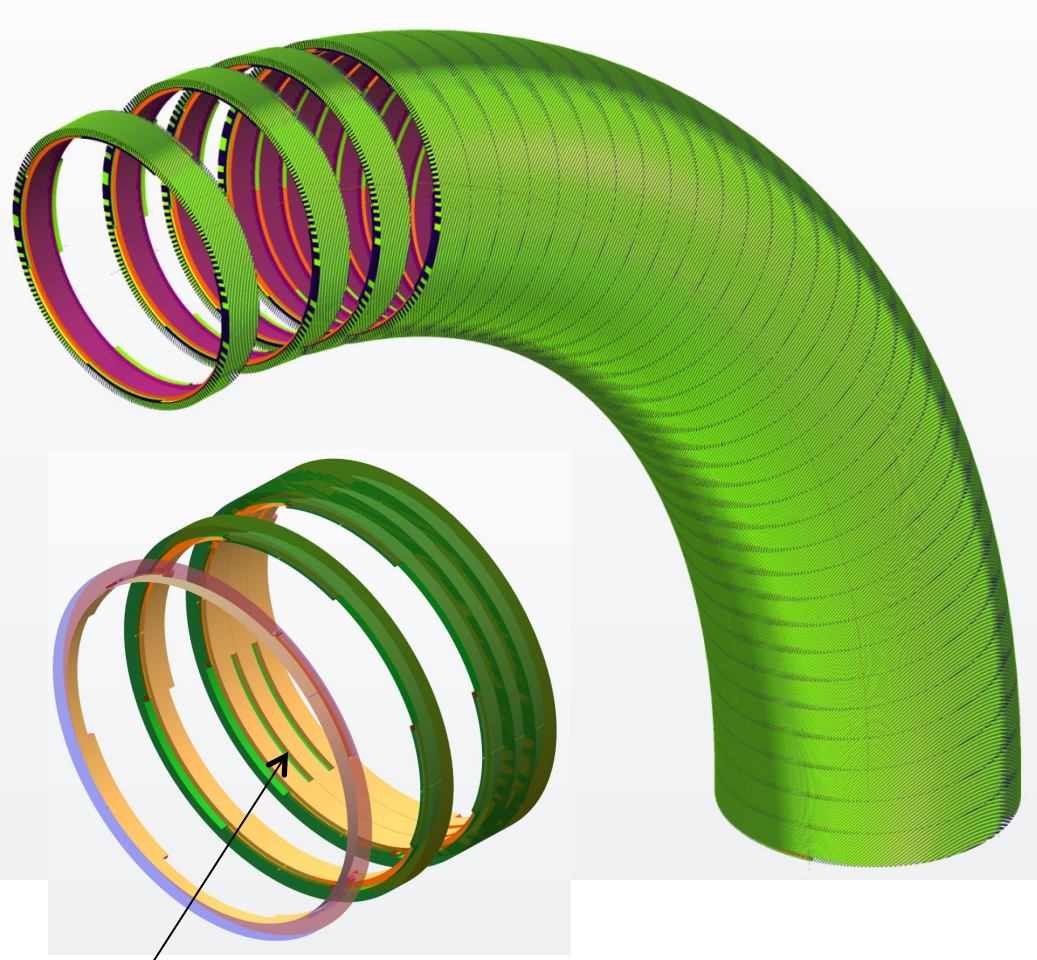
Caspi S, Arbelaez D, Brouwer L, Dietderich D, Felice H, Hafalia R, et al. **A superconducting magnet mandrel with minimum symmetry laminations for proton therapy**. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2013;719:44-9.

Faceted Torus made of wedge lamination



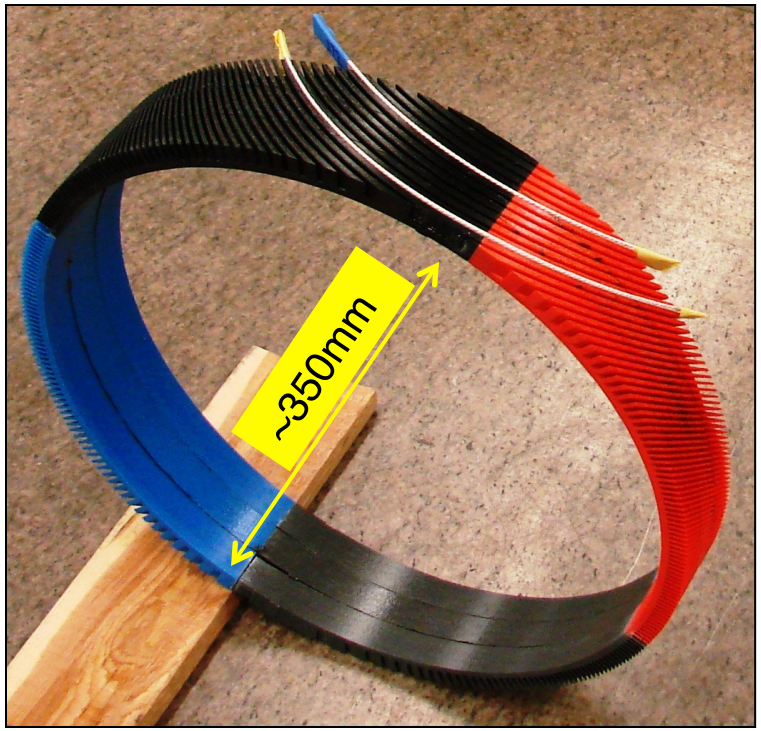
Exploring option for connecting wedges

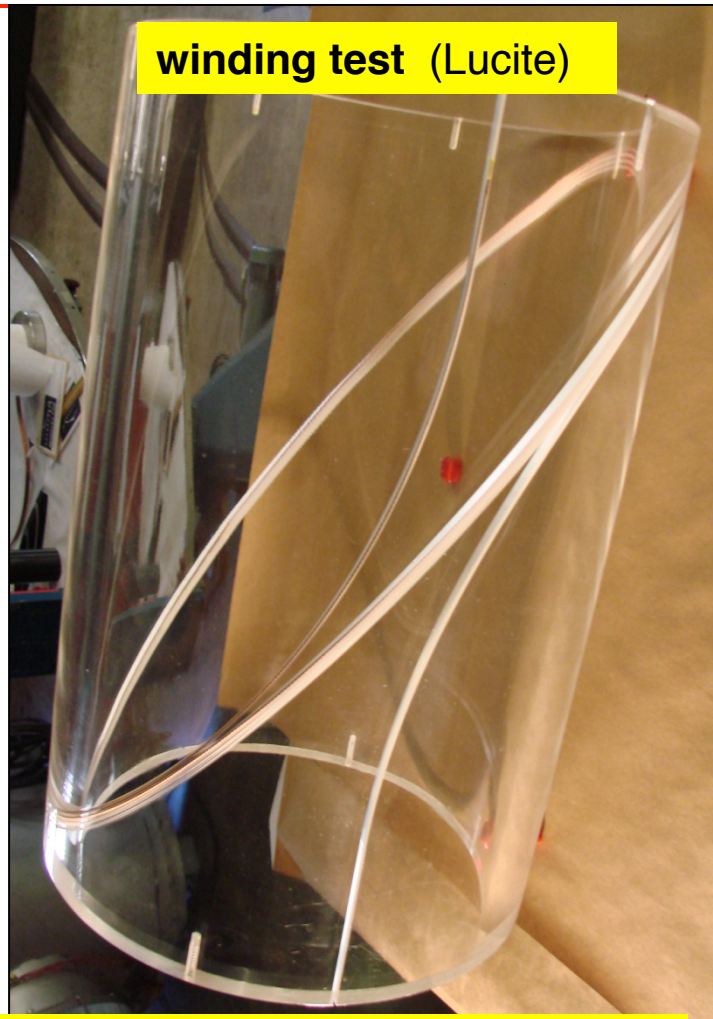
Locking features
A bayonet mount



Cryo-tubing channels

Curved Mandrels and Winding Test

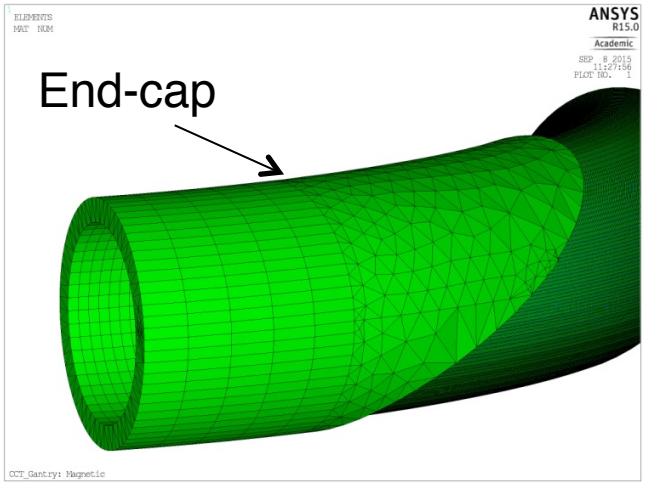


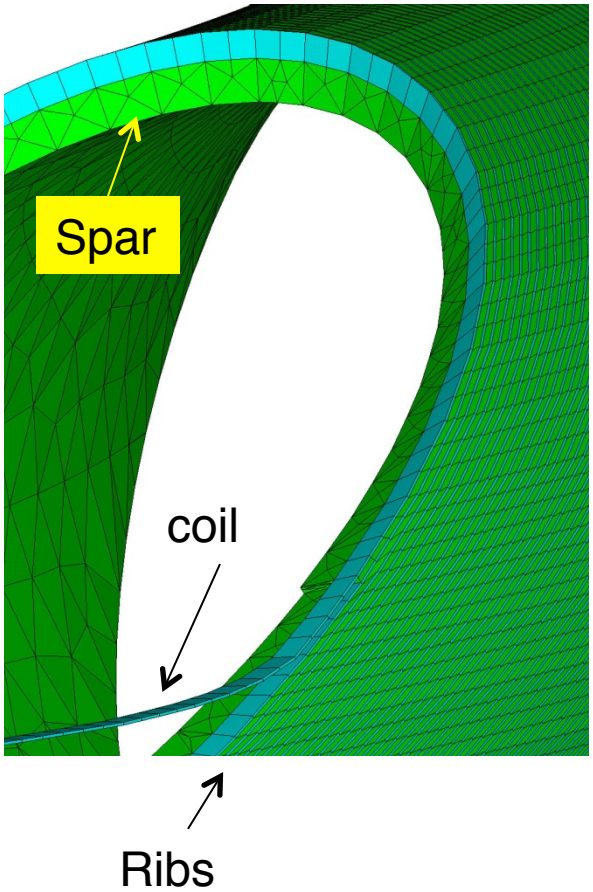


3 identical wedges (Rapid-Prototyping)

4 complete channels (machined)

One mesh – integrates – Magnetic, Structure, Thermal analysis





<u>Work in Progress</u>

•Ribs require a dense mesh
•By replacing **<u>element types</u>** a single model is used for field, stress and temperature

Magnetic: solid236
Structural: solid186
Thermal: solid90

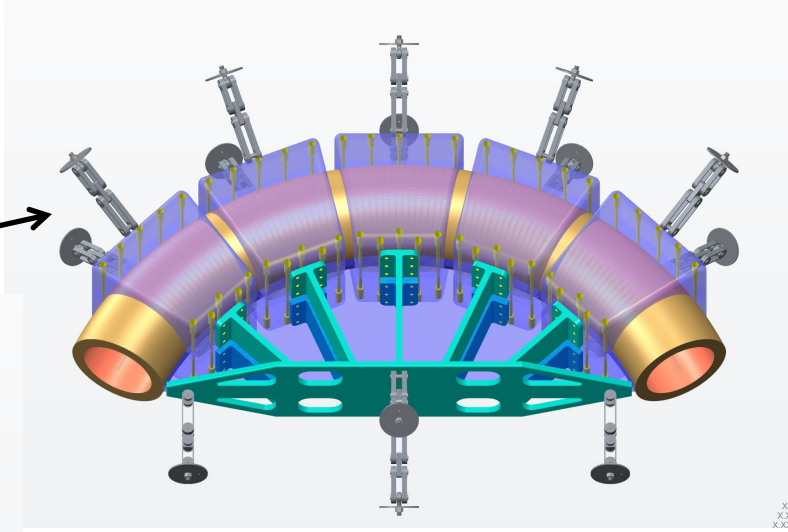
<u>Assumptions:</u>
Turns are glued to ribs,
Layer to layer are glued or will be allowed to slip

* Courtesy Lucas Brouwer (LBNL)

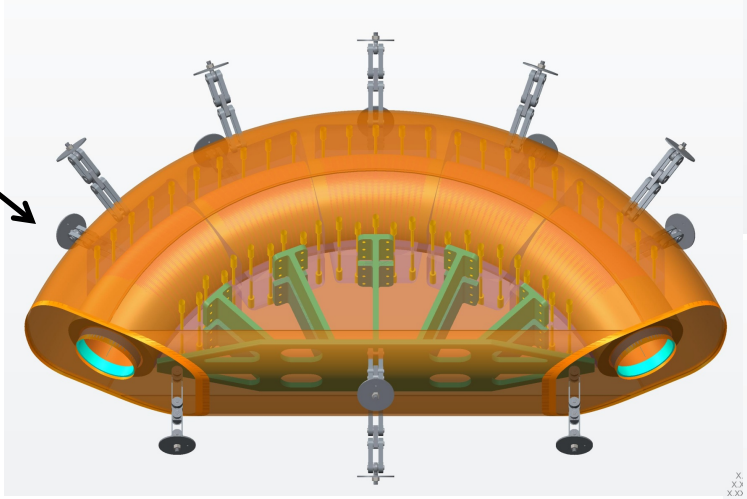
Coil+Structure+Thermal+Vacuum-Shields

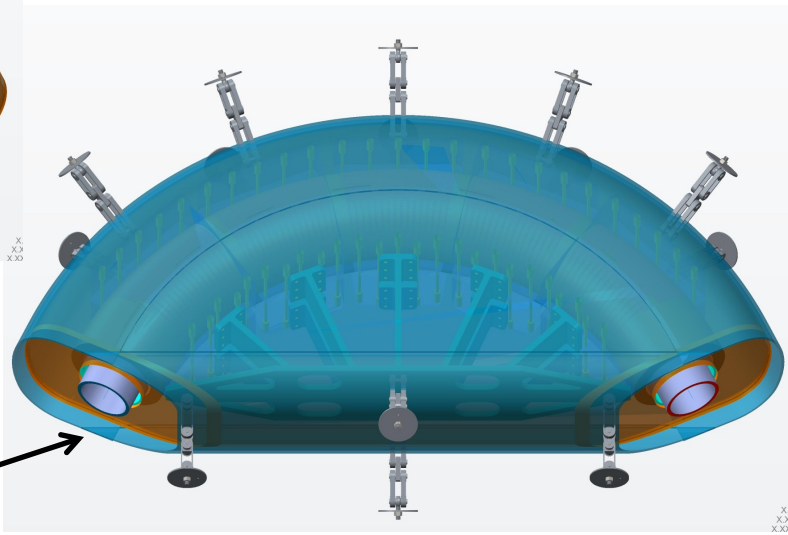
Total weight 5076 (Kg) – first estimate

Al mandrels (442) and SS structure (2856)



Al shield (661)



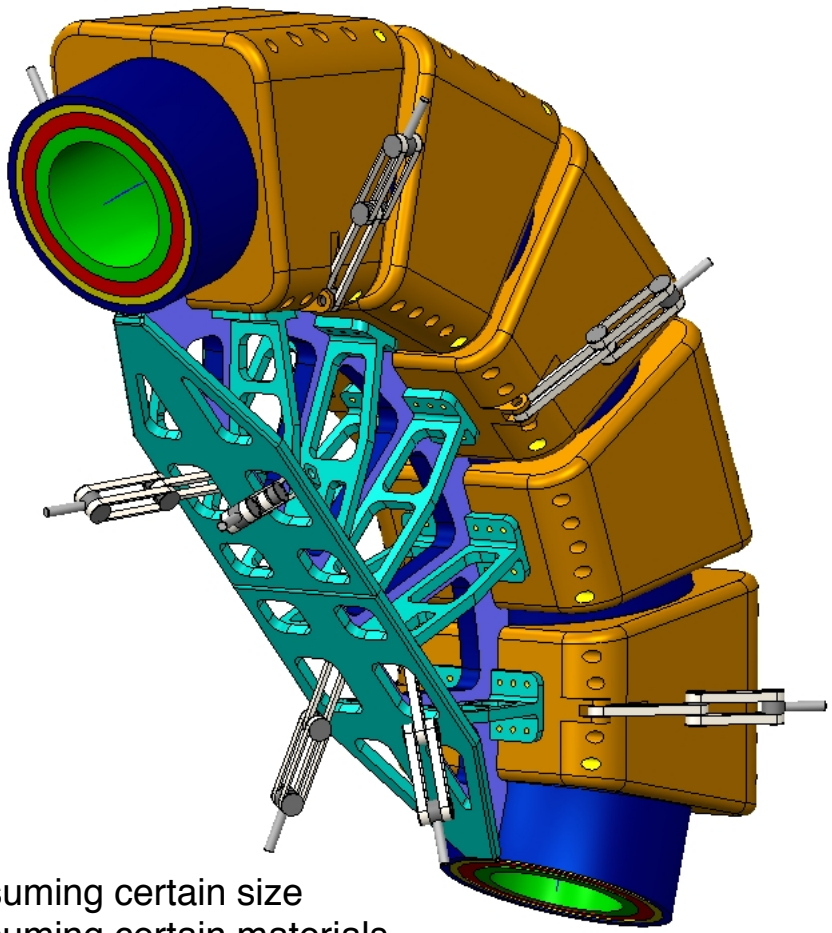


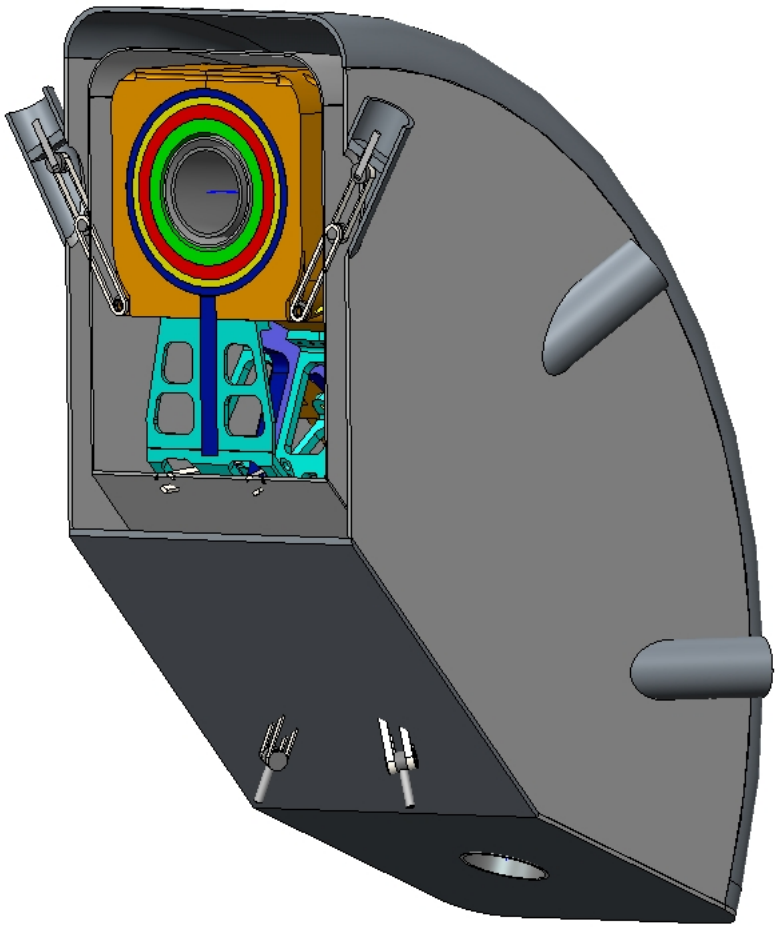
- Assuming certain size
- Assuming certain materials
- To be analyzed and optimized

Vacuum shield (1118)

* Courtesy Ray Hafalia (LBNL)

Coil+Structure+Thermal+Shields



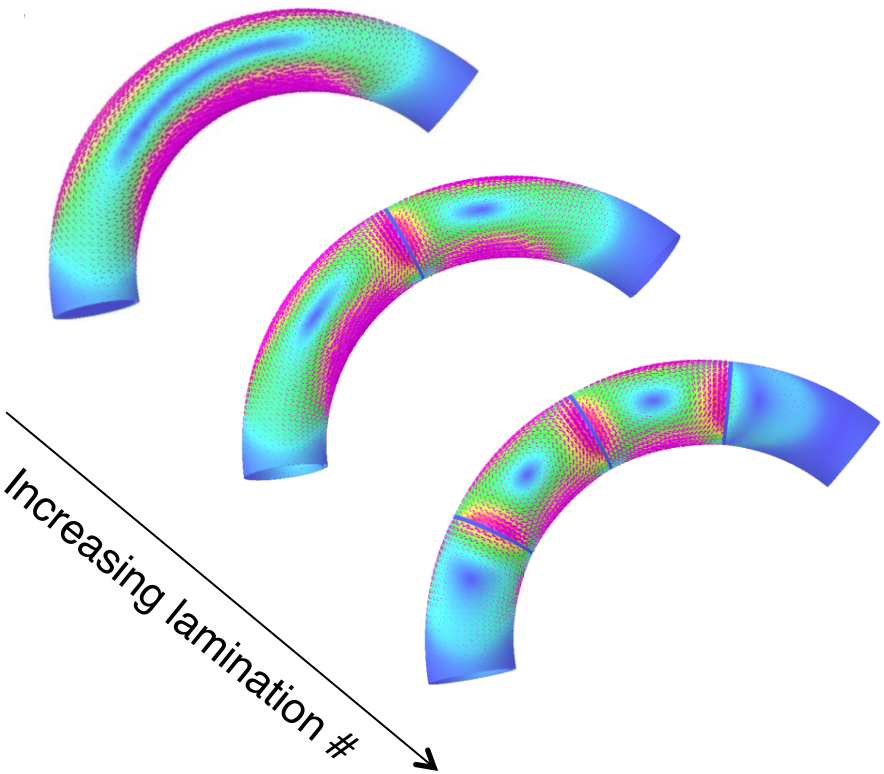


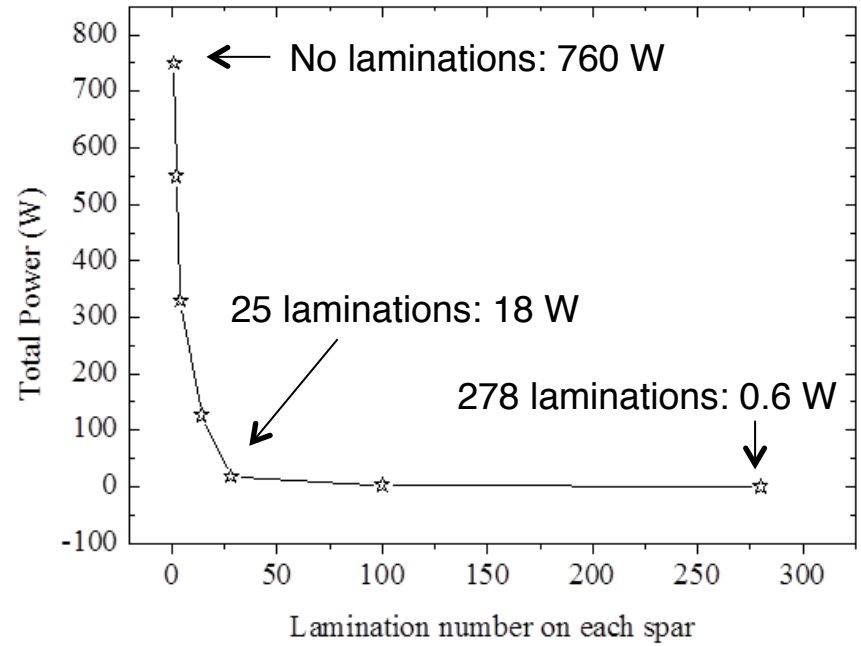
- Assuming certain size
- Assuming certain materials
- To be analyzed and optimized

* Courtesy A. Hodgkinson (LBNL)

Example: 3T Proton Gantry (Ramp Losses*)

- Similar case that is indicative
- 3T dipole field ramped down at 0.5 T/s
- 125 mm clear bore, two 3 mm thick mandrel Aluminum 6061 spars





* Courtesy of Heng Pan (LBNL)

Conclusions

1. **The CCT is a paradigm shift in the design of SC magnets and the potential of high gain in SC magnet technology** (reduce stress, improve training and "short-sample" expectation, field quality etc)

2. LBNL HEP R&D magnet program is underway to **demonstrate CCT technology with NbTi , Nb3Sn and HTS conductors.**

3. **The CCT is particularly beneficial for winding curved magnets**

4. **AG-CCT new concept** for compact gantries with a goal/potential for reduced stress, improve training and reduce operating margin, excellent field quality and reduce magnet cost and can be applied to **any multipole** (not just quads)
5. **Demonstrated integration between optics and magnet design**

6. **Large Energy/Momentum Acceptance**
   - May not need to change field while scanning depth

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THANK YOU