Canted-Cosine-Theta (CCT) magnets

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The 2nd Workshop on Accelerator Magnet in HTS (WAMHTS-2)

For the superconducting magnet group:

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The Future-Circular-Collider (FCC) is a **mandate for a change**

Some critical performance questions:

1. How much **margin** can we afford ? short-sample?
2. How much **training** can we afford ? first quench is the last quench?
3. **Technology** – "magnet business" not as usual.

Technology wish list:

1) Perfect **field** - a Cosine-n-Theta like - effective **use of the bore**
2) Low conductor **stress** at any field – magnet is **strain** independent
3) No need for **pre-stress** – easy assembly and cool-down
4) Reduce **cost** – reduce number of parts, tooling, R&D
5) Reduce complexity – less **analysis**, less optimization

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

- The **CCT** comes close to answer the technology wish list
- The **CCT** is **yet to prove** it can meet the performance wish list

- **Perfect field:**
  - As “true” a **cosine-theta current density** distribution
  - Field quality over the **straight section and “ends”**
- **Low conductor stress:**
  - **Structure intercepts Lorentz-Forces, reduced coil stress** by an order of magnitude
  - No need for pre-stress
  - Small or large bores
  - Grading - same strand in all cables
- **Cost-effective:**
  - All poles inclusive – just **like solenoids,** Inherently a **3D structure**
  - Fewer parts, simplified tooling and assembly
  - Compatibility between **NbTi, Nb_3Sn and HTS**

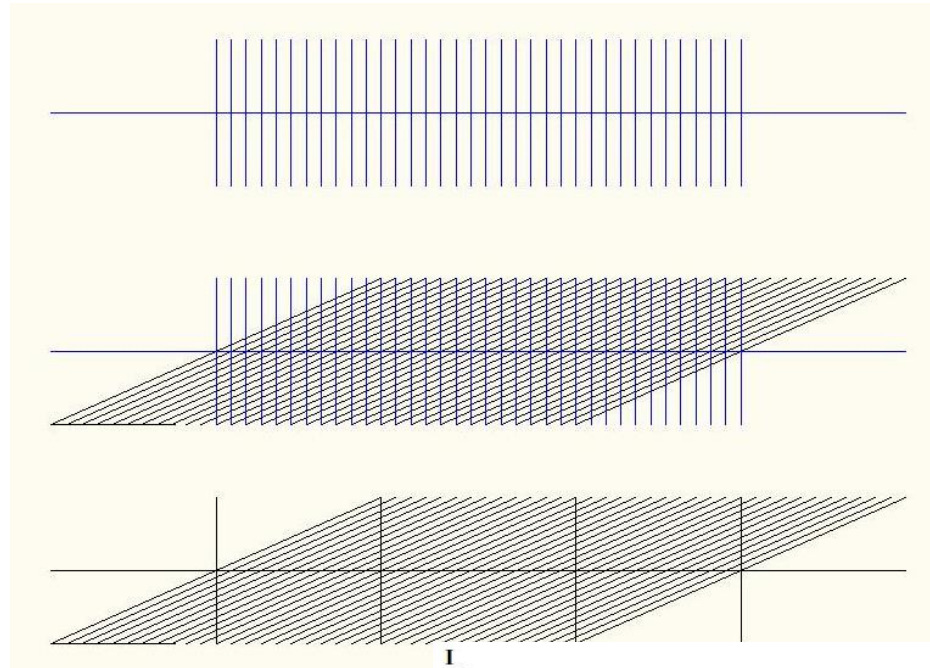
Original paper by **D.I. Meyer and R. Flasck** “**A new configuration for a dipole magnet for use in high energy physics application**”, Nucl. Instr. and Methods 80, pp. 339-341, 1970.)

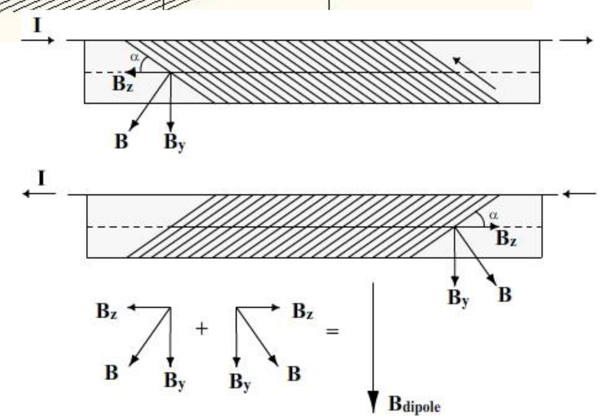
What is the Canted-Cosine-Theta (CCT) Magnet

Solenoid $J_{\vartheta} \sim const$

Canted solenoid
Canted ~15 degrees

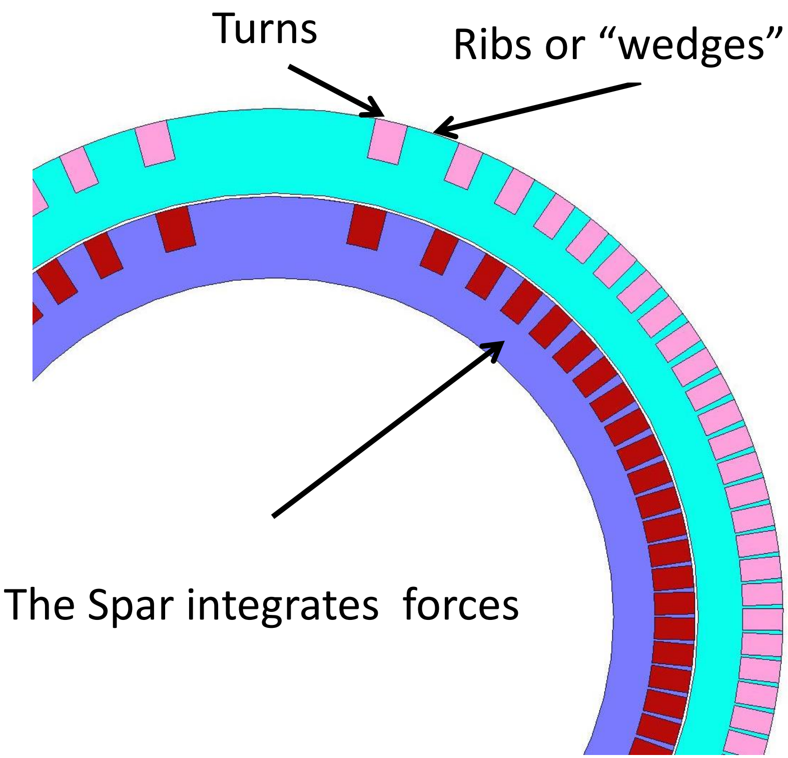
Canted-Cosine-Theta
$$J_{\vartheta} \sim const$$
$$J_z \sim \cos\vartheta$$

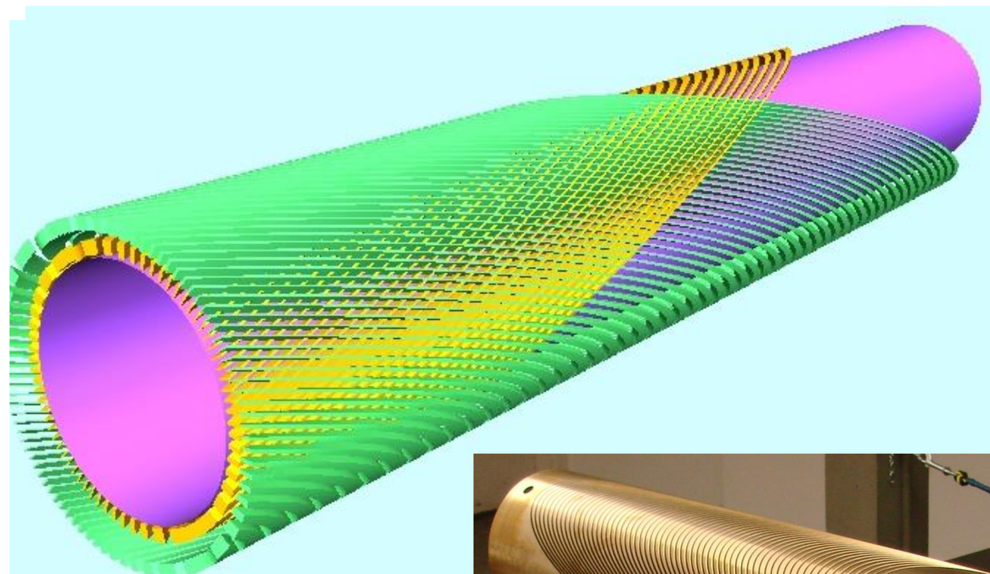




Two superimposed coils, oppositely skewed, achieve a pure cosine-theta field and eliminate axial field.

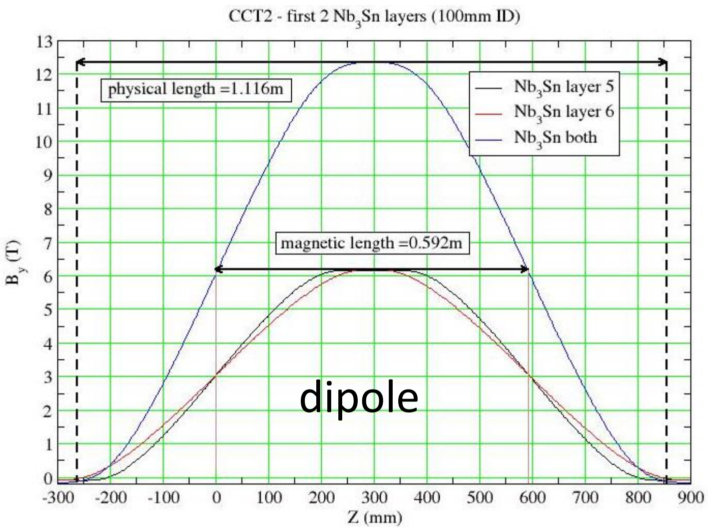
Ribs (wedges) create a "perfect" magnetic field and intercept the Lorentz forces

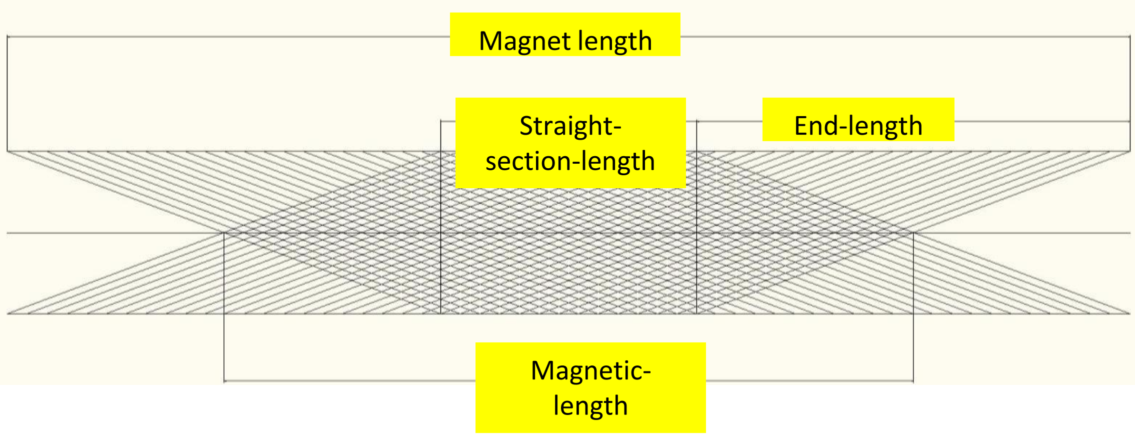




Spiral channels are cut into a cylinder.

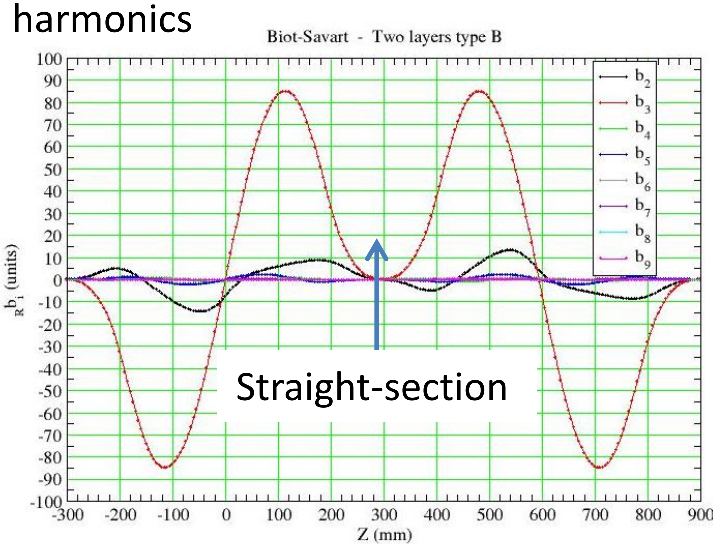
CCT Magnetic Length and “ends” (Nb_3Sn)

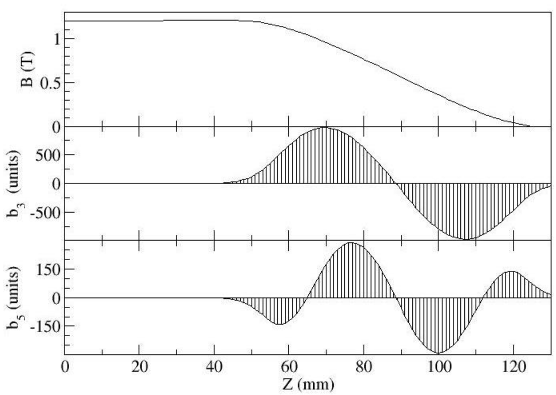


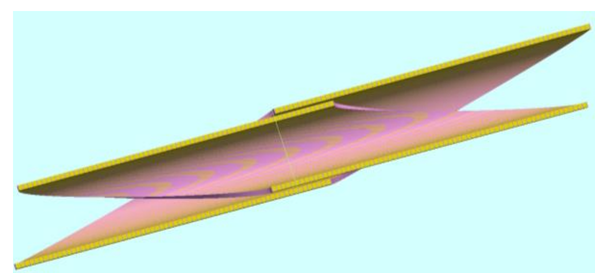


Magnetic-length = pitch*Nturns

harmonics







Harmonics over each “end” integrate to zero

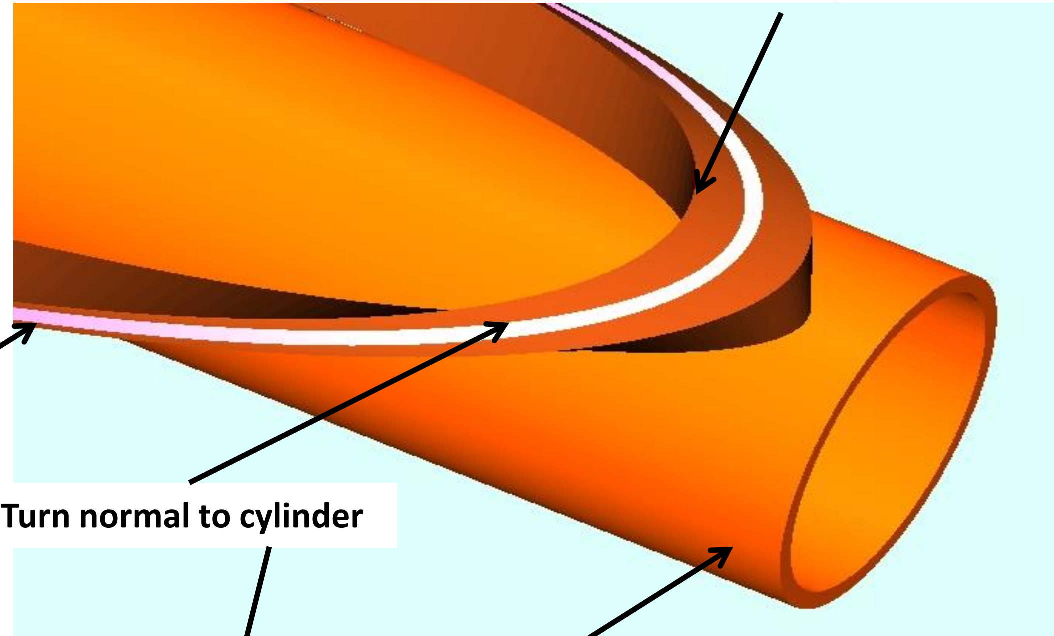
CCT – Stress Interception

The conductor (cable) is placed into a channel that is cut normal to a cylinder.

Tangential (bi-normal) forces are intercepted by the channel walls that are held by the inner spar thereby intercepting the turn to turn force.

Where the force is large the rib is thick

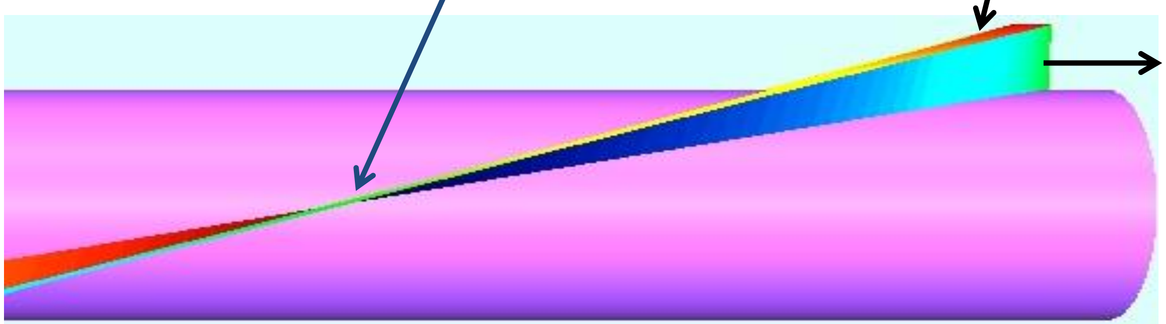
Where the force is small the rib is thin



Turn normal to cylinder

Stress integrator (Spar)

Radial Stress **Max**
Bi-normal Stress 🗀

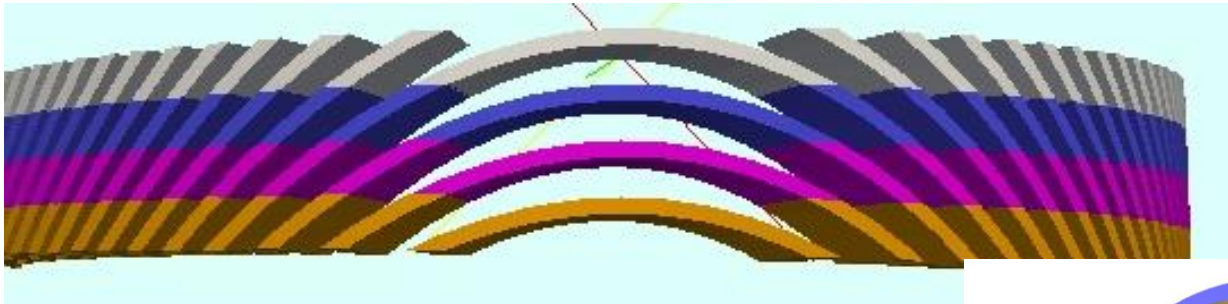


Bi-normal Stress (z direction)
💣*♋⊠
Radial Stress 🗀

Bi-normal Stress ~ Sin(theta)
Radial Stress ~ Cos(theta

Lamination

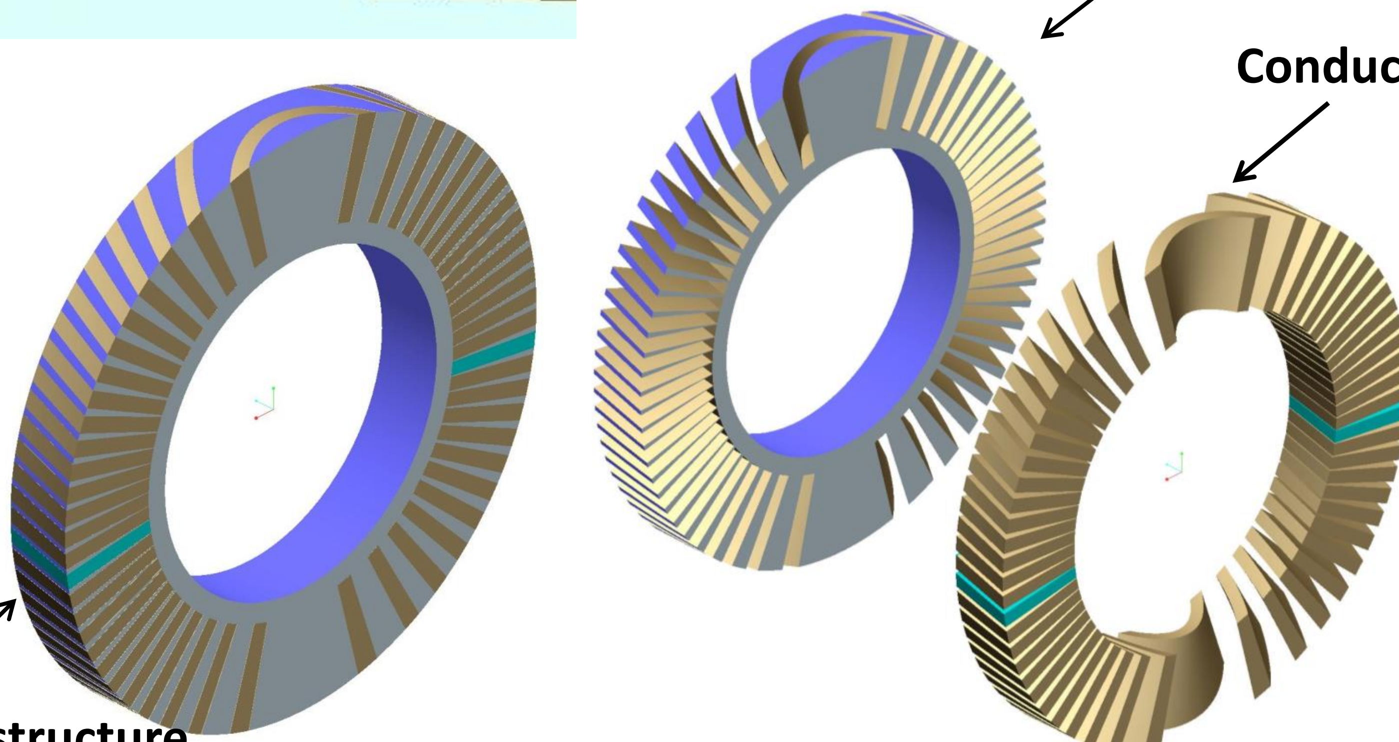
Laminations repeat every pitch length



Mandrel
= Internal structure
= ribs and spar

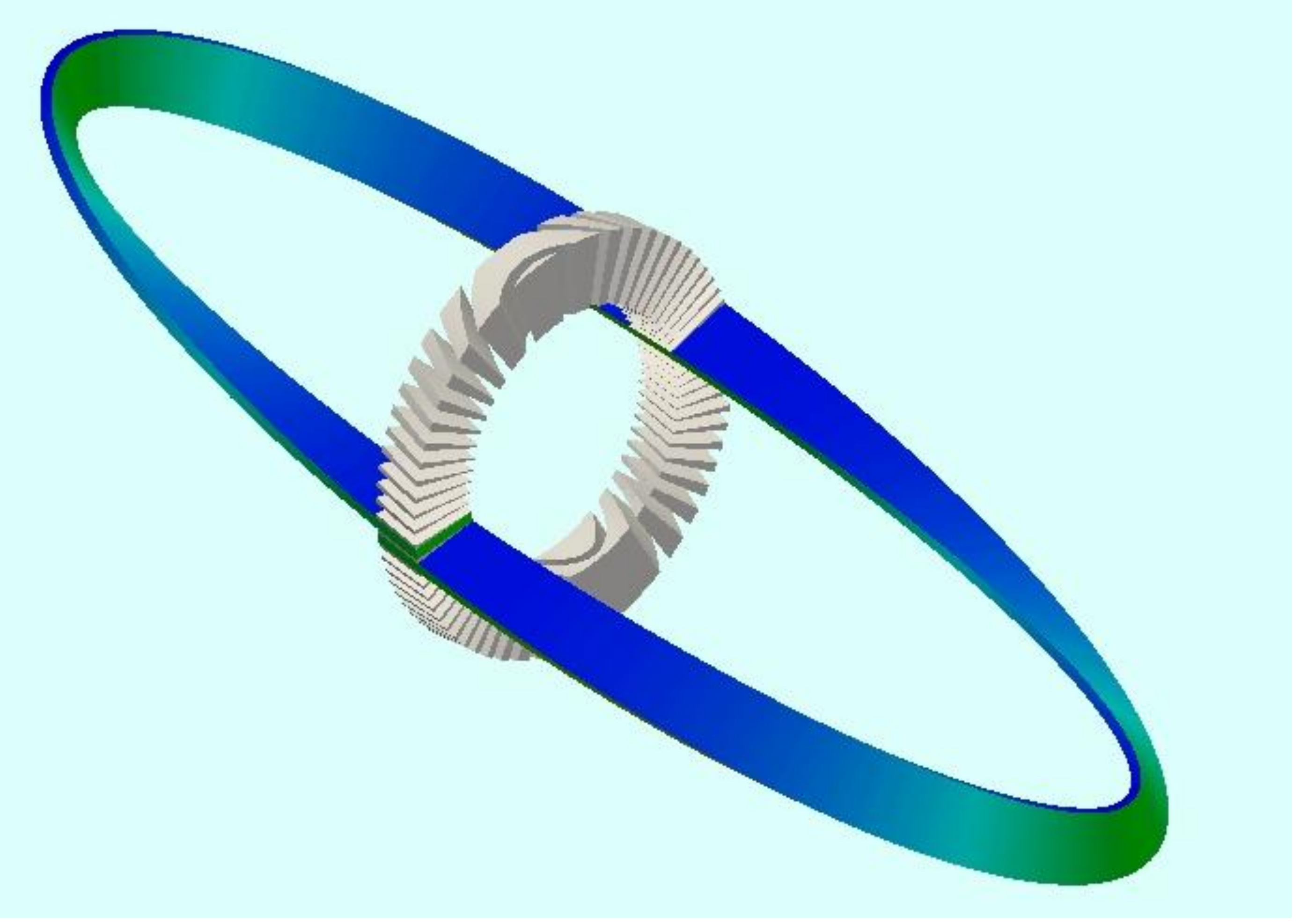
Conductor

Impact:
Construction
Computation



Conductor and structure

The CCT is a 3D object - lamination



Summary – Nb3Sn Magnets

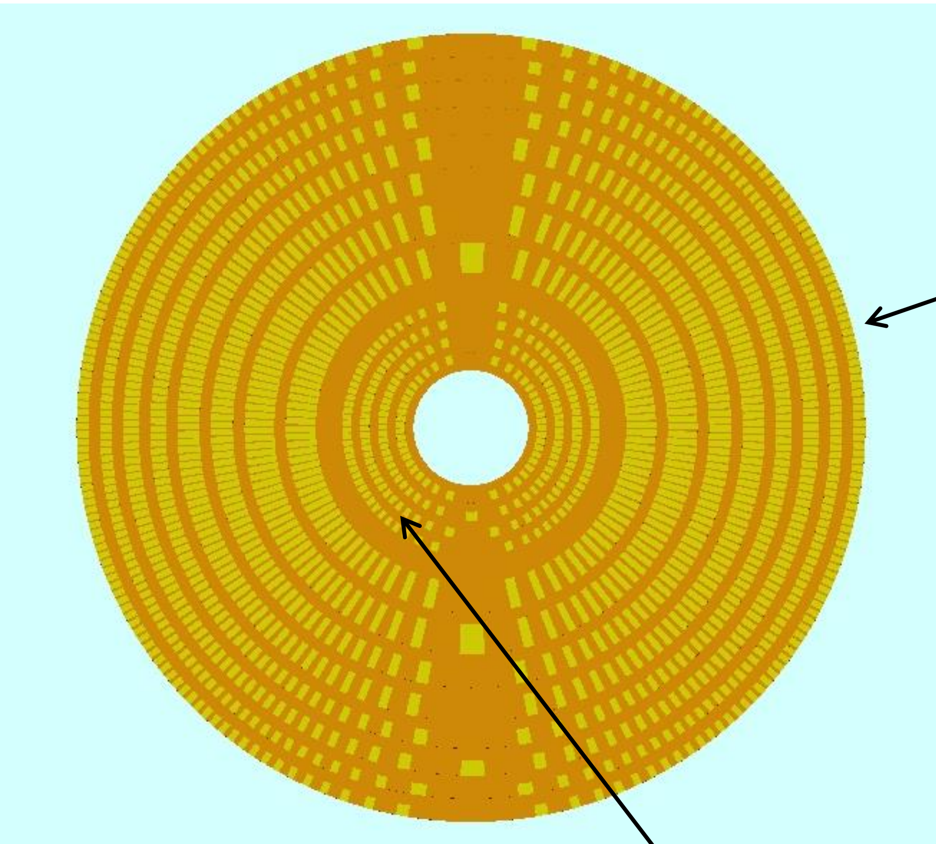
Operation	Non CCT	CCT
Winding tooling	Mandrel, clamps, tension	Mandrel
Coil parts	islands, “end” spacers, wedges	
Winding	binding	
Curing	cavity tooling, press	
Reaction	Cavity tooling	Wrap
Potting	Cavity tooling	Wrap
Pre-assembly	assemble poles with pads, align	
Final-assembly	Outer structure -Iron, Shell	Nest and align layers
Pre-stress	azimuthally	
Pre-stress	axially	

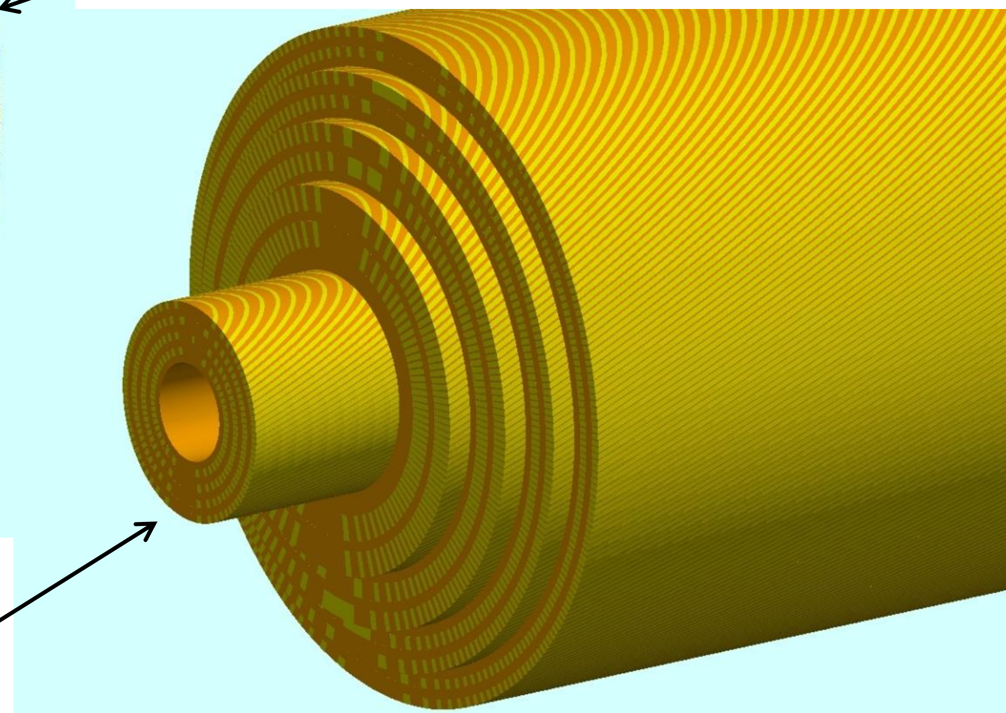
A High Field CCT Dipole Design

A 18T CCT

Clear bore ID=40mm,
OD=274.3mm

8 layers Nb_3Sn

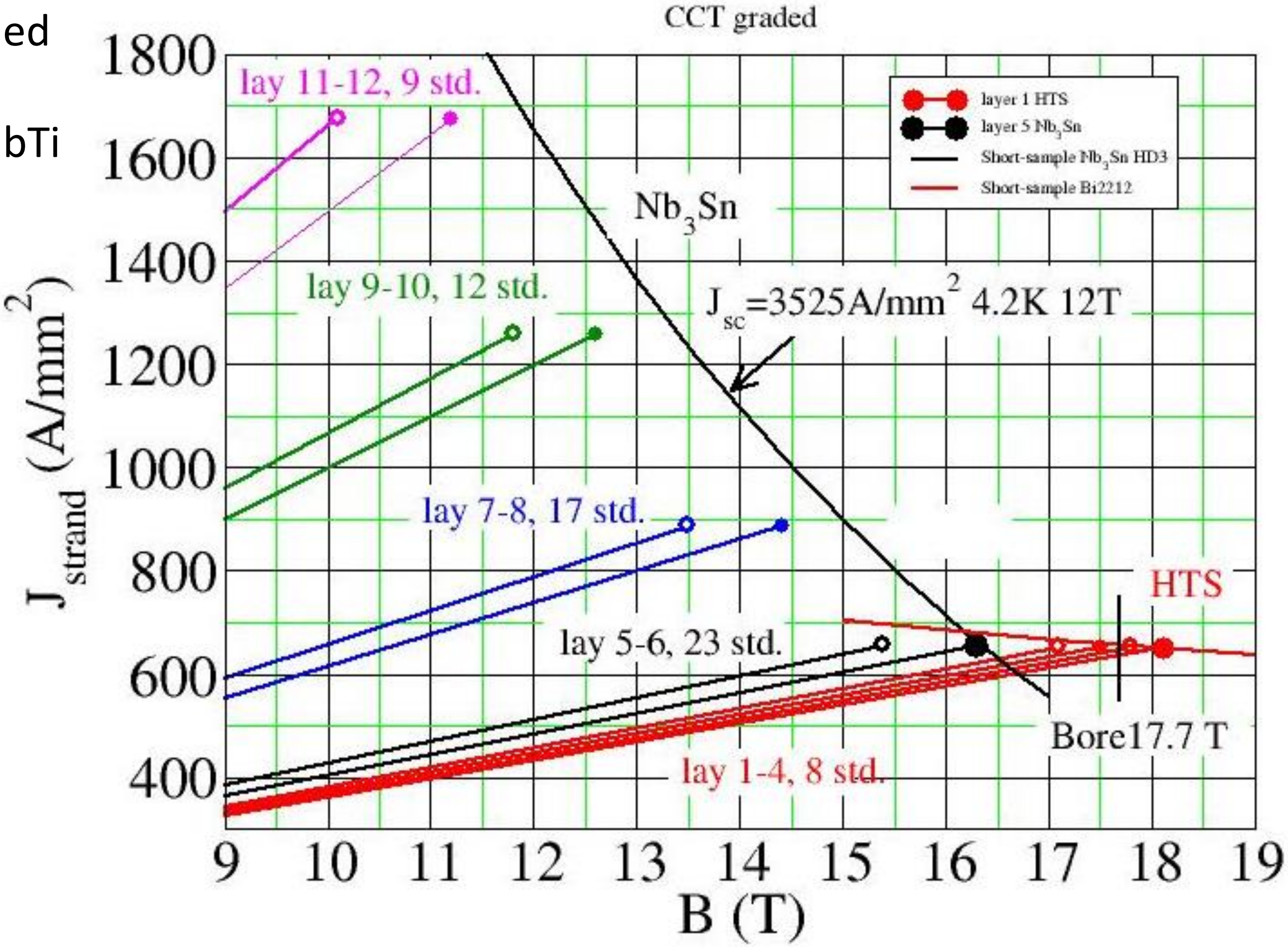




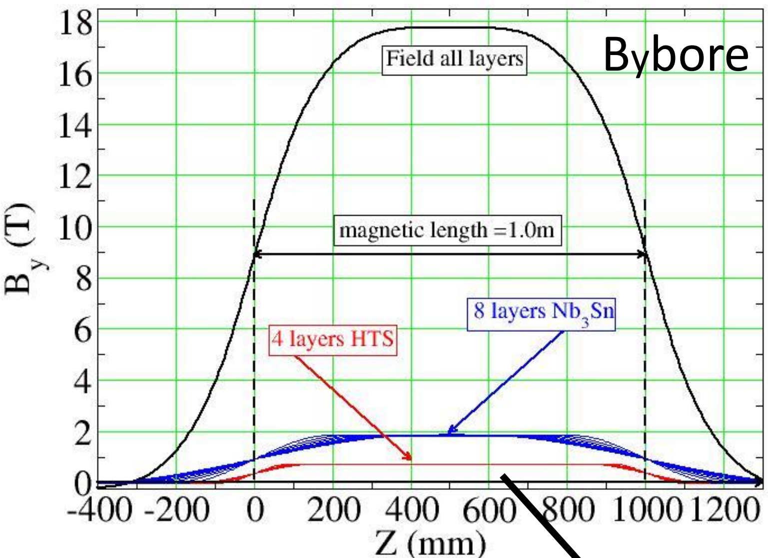
4 layers Bi2212 insert

A 12 layers Nb_3Sn-Bi2212 CCT

- Nb3Sn double layers graded
- Bi2212 not graded
- Field > 10T, cannot use NbTi

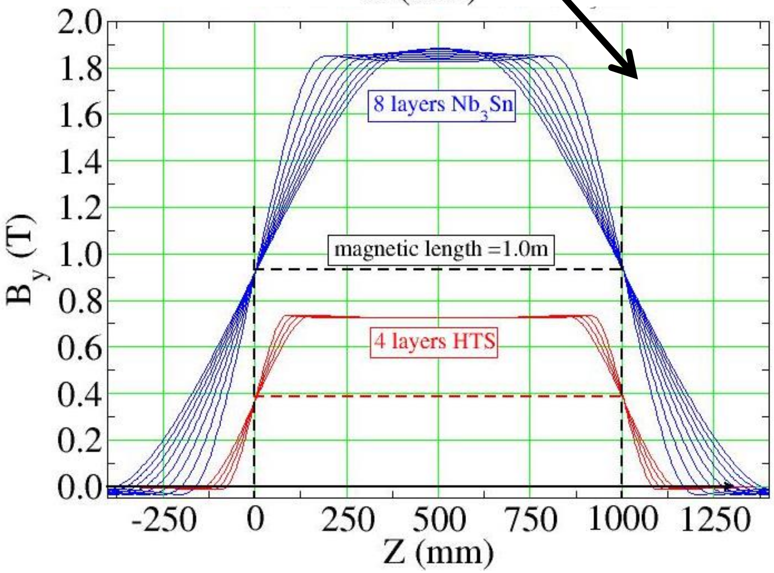


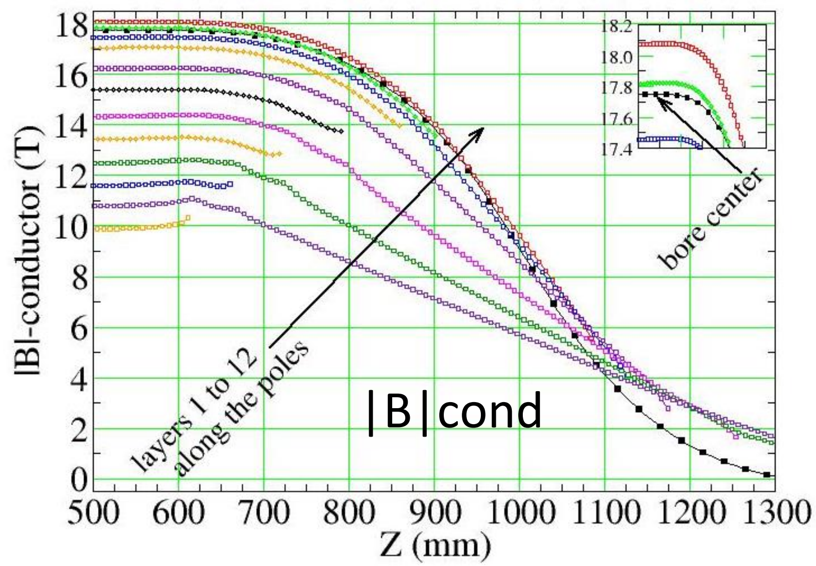
8 layers Nb_3Sn + 4 layers Bi2212



- **8 layers of Nb_3Sn** contributing **1.9T/layer** (7580A)
- **4 layers of Bi2212**, contributing **0.7T/layer** (2620A)
- Each layer has the same number of turns and angle
- **Same magnetic length** each layer 1m=pitchXturns
- The magnet has **no-iron**
- Conductor |Bmod| is at the magnet center
- Bore field is 17.7T |Bmod|max=18.1T (2.2% higher))

Pitch=7.63mm, 131 turns





~18T CCT with 8 layers Nb_3Sn + 4 layers Bi2212

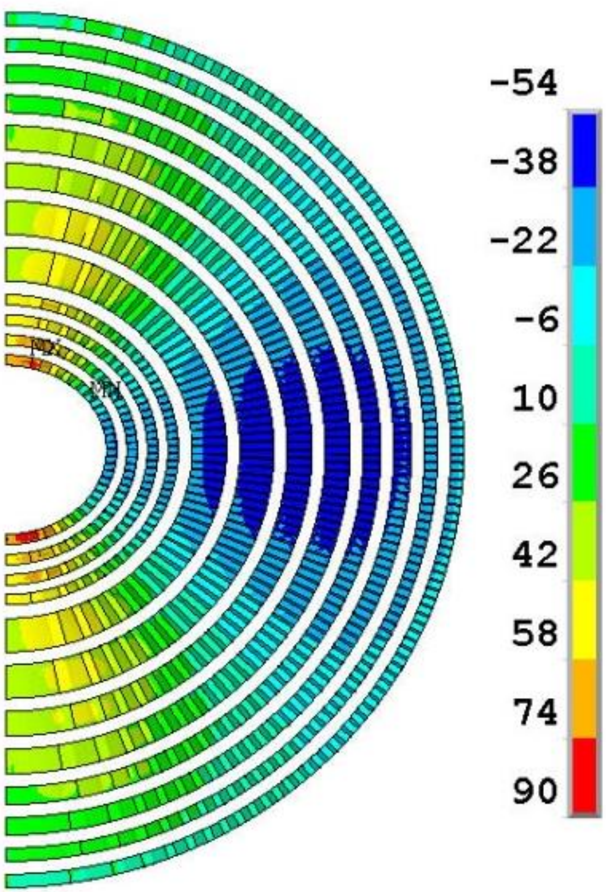
Layer	MATERIAL	I (A)	J_{SC} (A/MM^2)	J_{STRAND} (A/MM^2)	$J_{CHANNEL}$ (A/MM^2)	|B-COND-MAX| (T)	STRAND (M/M)	CABLE (M/M)	CONDUCTOR (KG/M)
1	Bi-2212	2620		651	455	**18.1**	395.8	49.48	
2	Bi-2212	2620		651	455	17.8	495.6	61.95	
3	Bi-2212	2620		651	455	17.5	595.3	74.42	
4	Bi-2212	2620		651	455	17.1	695.1	86.9	
1	Nb_3Sn	7580	1395	655	364	**16.3**	2450.1	106.5	10.85
2	Nb_3Sn	7580	1395	655	364	15.4	3046.0	132.4	13.49
3	Nb_3Sn	7580	1887	887	493	14.4	2650.4	155.9	11.73
4	Nb_3Sn	7580	1887	887	493	13.5	3007.9	176.9	13.32
5	Nb_3Sn	7580	2673	1256	698	12.6	2351.1	195.9	10.41
6	Nb_3Sn	7580	2673	1256	698	11.8	2554.7	212.8	11.31
7	Nb_3Sn	7580	3565	1675	931	11.2	2057.7	228.6	9.11
8	Nb_3Sn	7580	3565	1675	931	**10.1**	2188.4	243.1	9.69

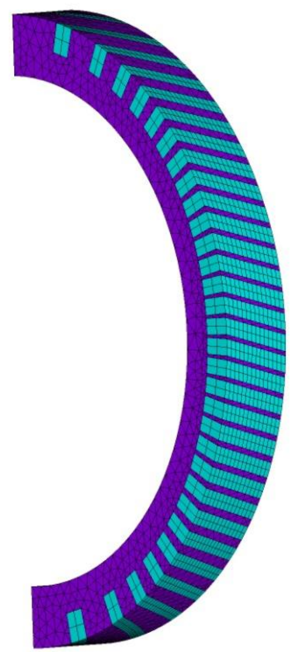
*|B-cond-max| is the maximum conductor field at the pole.
***STRAND, CABLE AND CONDUCTOR WEIGHT ARE PER 1M MAGNETIC LENGTH

Total length of Nb3Sn strand (0.8mm) **20.3Km/1m-magnetic-length** (~180k$)
Total length of Bi2212 strand (0.8mm) **2.2Km/1m-magnetic-length** (factor of 10 ?)

3D ANSYS Stress Analysis

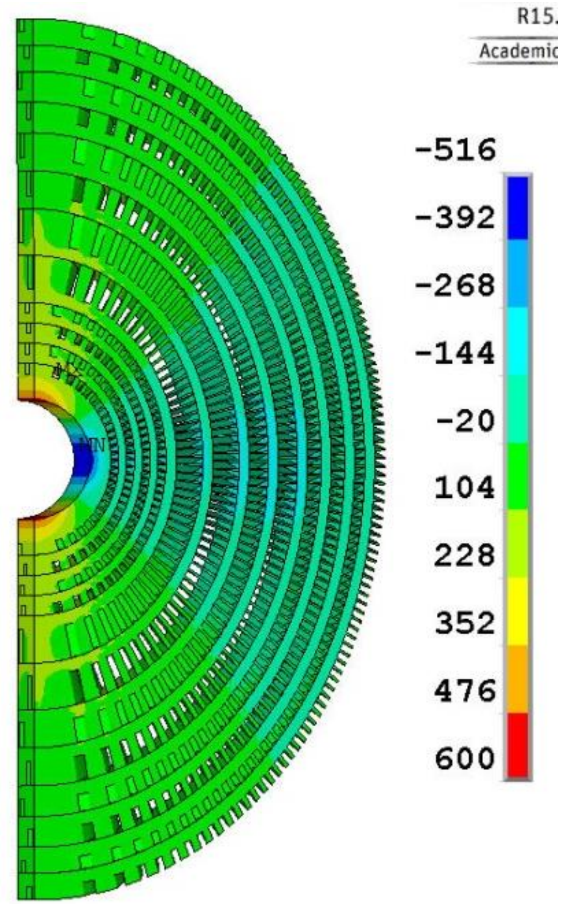
Conductor **Azimuthal** Stress





Meshed layer

Structure **Azimuthal** Stress

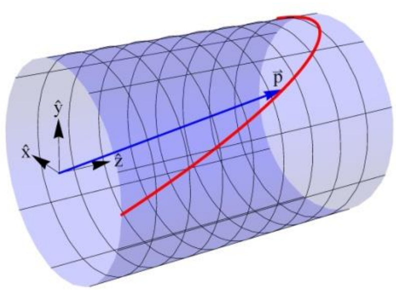


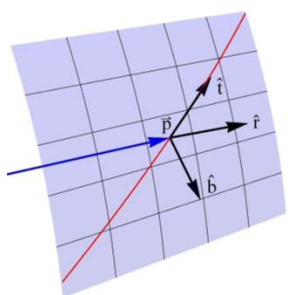
See L. Brouwer, S. Caspi, and S. Prestemon "Structural Analysis of a 18 T Hybrid Canted-Cosine-Theta Superconducting Dipole"
IEEE Transactions on Applied Superconductivity paper 4LPO2F-08 to be published ASC 2014
See L. Brouwer, D. Arbelaez, S. Caspi, H. Felice, S. Prestemon, and E. Rochepault "Structural Design and Analysis of Canted–Cosine–Theta Dipoles"
IEEE Transactions on Applied Superconductivity, vol. 24, no. 3, june 2014

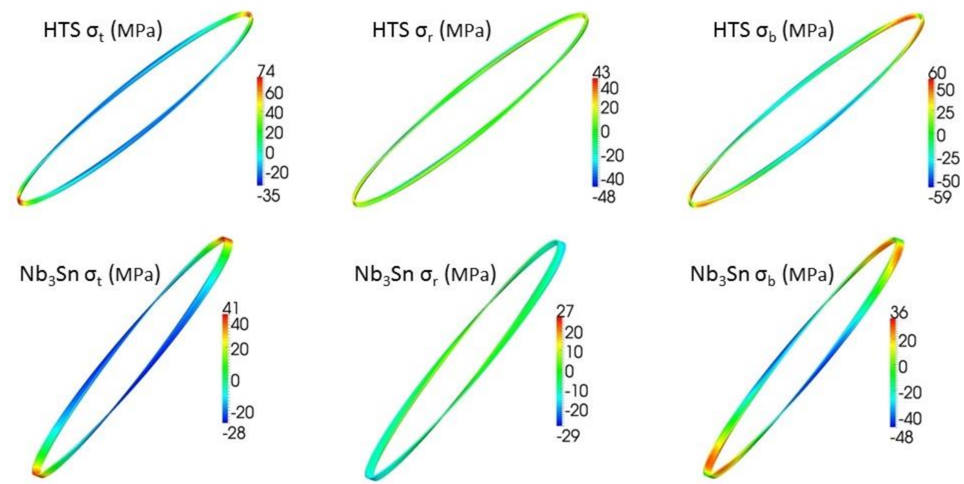
ANSYS ~18T with 8 layers Nb_3Sn + 4 layers Bi2212

Layer	rib (mm)	Spar (mm)	Ri (mm)	Ro (mm)	Channel (mm)	Type	Sigma-t(MPa)	Sigma-r(MPa)	Sigma-b(MPa)
1	0.381	8.0	20.0	31.2	1.8/3.2	Bi2212	74/-35	43/-48	60/-59
2	0.381	3.0	31.2	37.4	1.8/3.2	Bi2212	76/-36	41/-38	43/-47
3	0.381	3.0	37.4	43.6	1.8/3.2	Bi2212	51/-29	36/-32	46/-46
4	0.381	3.0	43.6	49.8	1.8/3.2	Bi2212	59/-32	35/-32	35/-42
5	0.381	4.2	49.8	64.4	2.0/10.4	Nb3Sn	41/-28	27/-29	36/-48
6	0.381	4.0	64.4	78.8	2.0/10.4	Nb3Sn	48/-31	14/-30	25/-50
7	0.381	4.0	78.8	90.4	2.0/7.69	Nb3Sn	37/-33	5/-34	25/-48
8	0.381	4.0	90.4	102.1	2.0/7.69	Nb3Sn	37/-32	8/-36	17/-49
9	0.381	4.0	102.1	111.6	2.0/5.43	Nb3Sn	52/-34	9/-37	16/-44
10	0.381	4.0	111.6	121.0	2.0/5.43	Nb3Sn	52/-30	7/-37	10/-42
11	0.381	4.0	121.0	129.0	2.0/4.07	Nb3Sn	54/-30	16/-32	12/-33
12	0.381	4.0	129.0	137.1	2.0/4.07	Nb3Sn	47/-23	7/-22	10/-28

σt, σR, σB are stress along the path, radial and normal to the rib (bi-normal) **ANSYS**

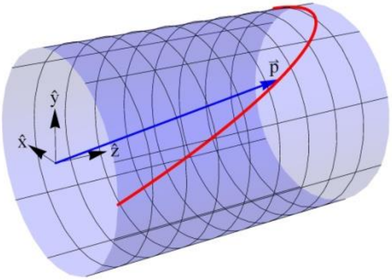


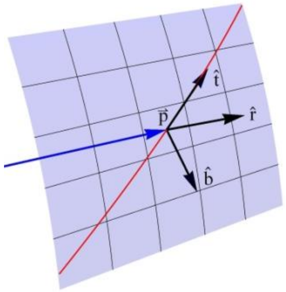




Stress plotted around a single turn for the innermost Bi2212 and Nb3Sn layer.

Conductor stress for different layers – ANSYS*





σ_t : Tangential Stress (along cable)
σ_r : Radial Stress
σ_b : Binormal Stress (perp. to rib)

Stress at short-sample	Max/Min σ_t	Max/Min σ_r	Max/Min σ_b	Layer
2 Layer: 10 T (Nb_3Sn)	60/-38	18/-42	27/-67	inner
8 Layer: 16 T (Nb_3Sn)	102/-45	28/-51	72/-76	inner
12 Layer: 18 T (Nb_3Sn)	41/-28	27/-29	36/-48	5'th
12 Layer: 18 T (Bi2212)	74/-35	43/-48	60/-59	inner

Depending on how the Lorentz force density and rigidity scale,
going to higher field by increasing the number of layers could have very little effect,
or even improve the situation

* Courtesy of L. Brouwer

Present and Future Plans

Present and Future Plans

What has been done and what is being done:

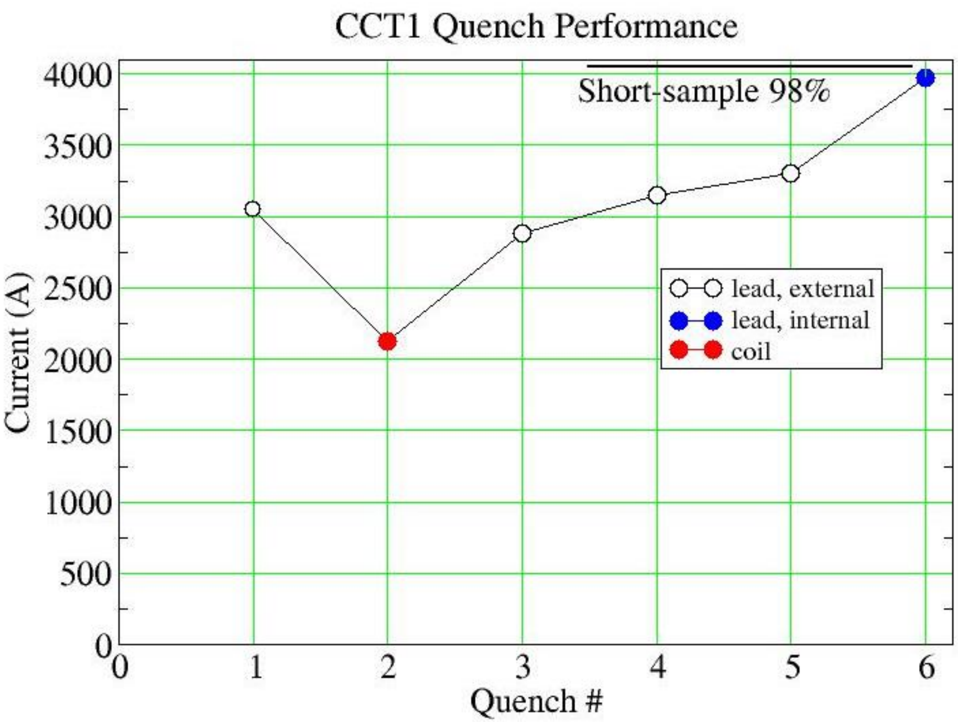
1) Tested a 2.4-T NbTi CCT dipole.
2) Designed a short 2 layer dipole 5T NbTi (CCT2) and a 10T Nb3Sn (CCT3)
3) Fabricate identical mandrels for both magnets (Q1 2015)
4) Designed an 18-T dipole - field quality, loads and mechanical stresses for the various stages.
5) Develop fabrication processes and cost-effective tooling.

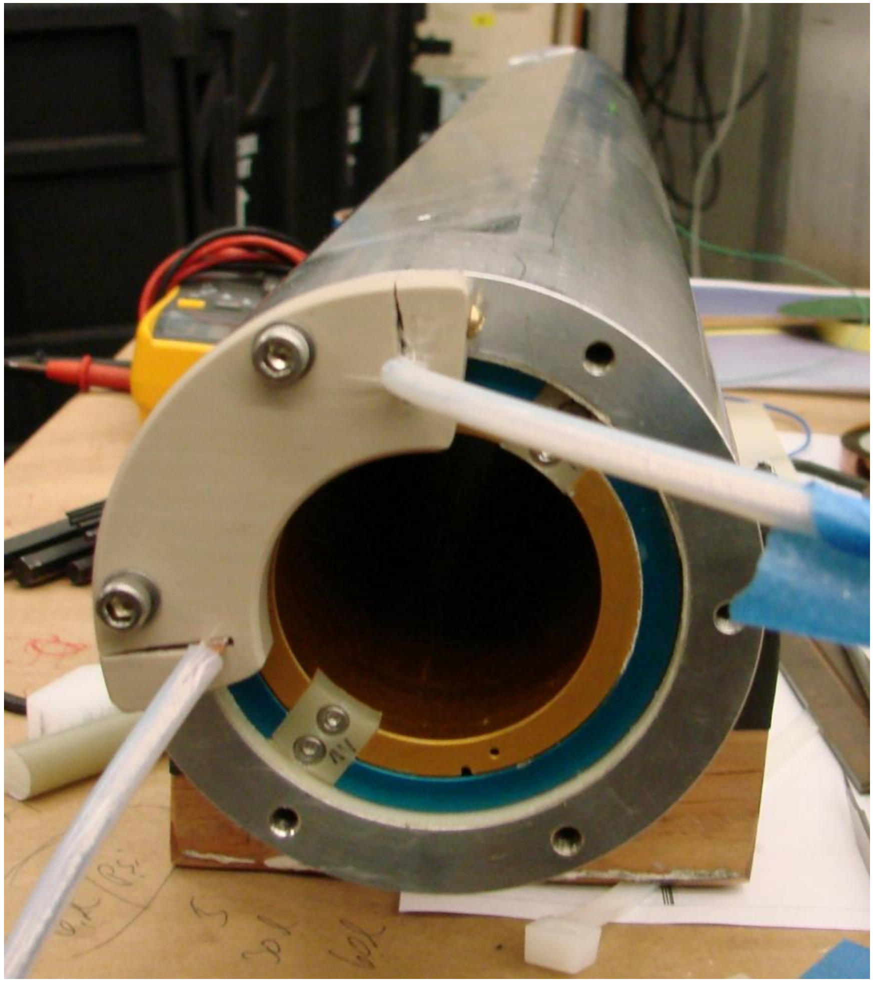
18T in sequential steps:

1) 8 layers of Nb_3Sn coils with progressive fields from 10T to 16T (several independent tests)) (2015-16)
2) Develop a HTS insert raising the field to 18T (2016)

CCT1

- NbTi Cable 1.3x3 mm (SSC outer strand)
- 2 aluminum mandrels
- **No impregnation** (cable free within the channel)
- 56mm clear bore
- Magnet reached 2.5T

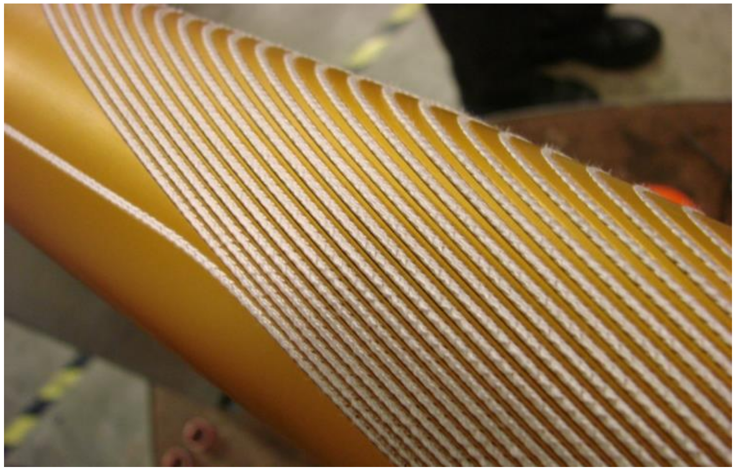




b3~7, b5~0, b7~0.5 units at 3900A (Ref=66%)

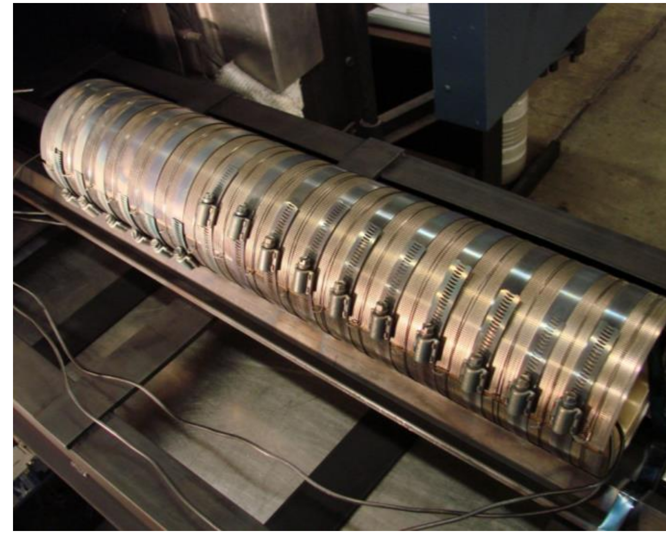
CCT Magnet Technology – in progress

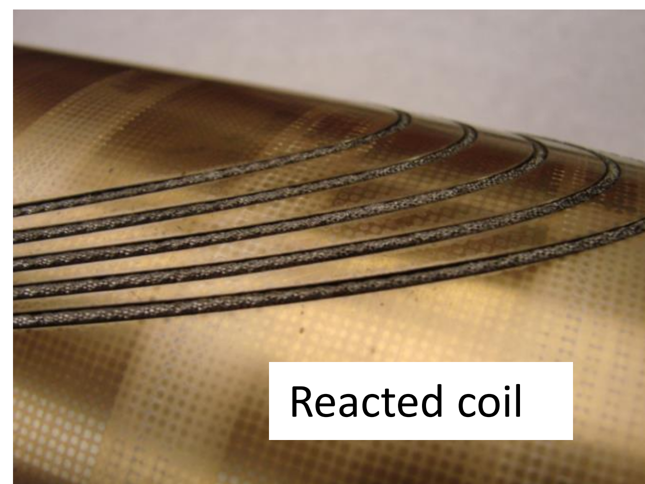
Winding, no tension no curing



Potting tooling

Reaction tooling





Reacted coil

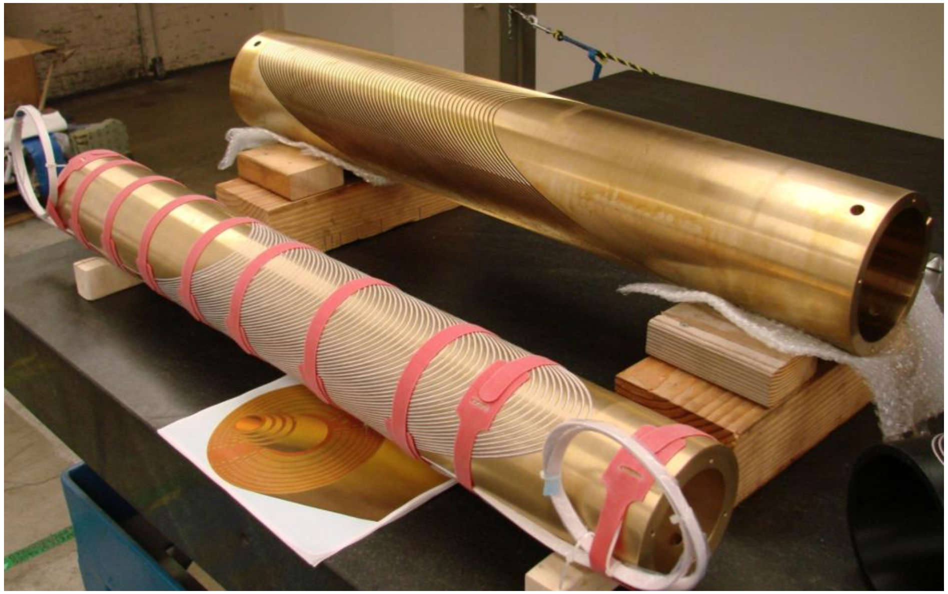
Wind using a **deeper channel** --2x10mm

Test **reaction tooling** and winding position

Test **potting tooling** and winding position

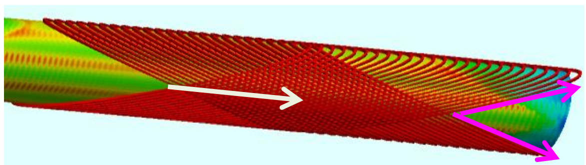
The CCT – Plans

# of layer	Material	I (A)	|B-cond-max| (T)	B-bore (T)	JssXBss (N/mm^3)
1-2	NbTi	10600	5.9	5.3	
1-2	Nb_3Sn	20700	11.6	10.3	10
1-2-3-4	Nb_3Sn	13550	13.8	13.1	
1-2-3-4-5-6	Nb_3Sn	10100	15.2	14.7	
1-2-3-4-5-6-7-8	Nb_3Sn	8100	16.2	15.8	5
1-2-3-4	Bi-2212	3950	4.9	4.4	



Curved Accelerator Magnets

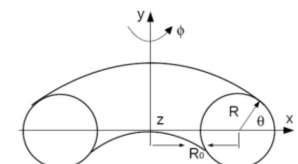
Linear configuration



Direction of current

Curved configuration

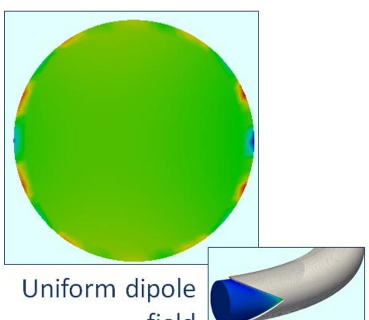
- A winding concept on a toroid that produces a combined function field and higher multipole fields (e.g. gantry magnets for proton-carbon beam therapy)



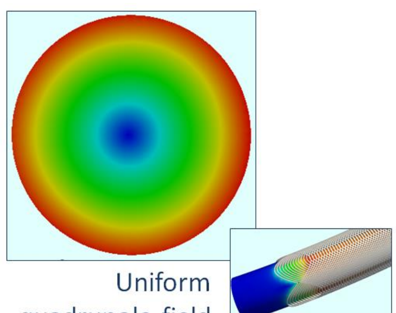
Toroidal coordinate system.

Multipole Winding Path

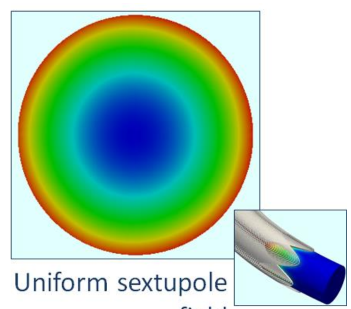
$$\varphi = \frac{R}{R_0}\left(\frac{2\cdot B_d}{B_{0-sol}}\sin\theta + \frac{2\cdot G\cdot R}{2\cdot B_{0-sol}}\sin 2\theta + \frac{2\cdot S\cdot R^2}{3\cdot B_{0-sol}}\sin 3\theta + \cdots\right)$$



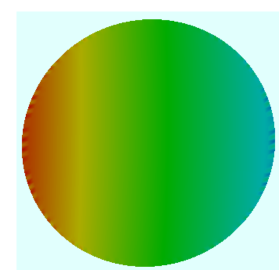
Uniform dipole field



Uniform quadrupole field



Uniform sextupole field



Combined function

CCT - Summary

1. **A New Magnet Type –** Canted-Cosine-Theta
2. **Magnetic and structural elements** (Islands, wedges, “end” spacers) **replaced by spar and ribs**
3. **Stress interception** with applied **Lorentz Force** (large bore ok)
4. Assembly and cool-down - **no pre-stress** required
5. **Grading not limited,** the **same** strand in all cables
6. **2D and 3D high field quality** over an extended range (no optimization)
7. **Conductor insulation to ground only (**ceramic coating=no cable insulation)
8. **Generic design for all conductor types** – NbTi, Nb3Sn, HTS
9. **Simplified tooling**
10. **A linear structure** (e.g. dominated by structure not conductor properties)
11. **Combined function field**, (handle geometric errors)
12. Extended technology to **curved coils** and other magnet types

Conclusions

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

2. **The CCT has the potential of reducing cost** especially at high fields

3. We proposed a R&D program that **demonstrate CCT technology with NbTi , Nb3Sn and HTS** (we have addressed the choice of material, mandrel manufacturing, coil winding, reaction, impregnation and analysis)

4. Part of a **cost analysis of a high field option for the FCC**