Prospects of a 16T CCT Magnet for FCC

Shlomo Caspi

Superconducting Magnet Group
Lawrence Berkeley National Laboratory

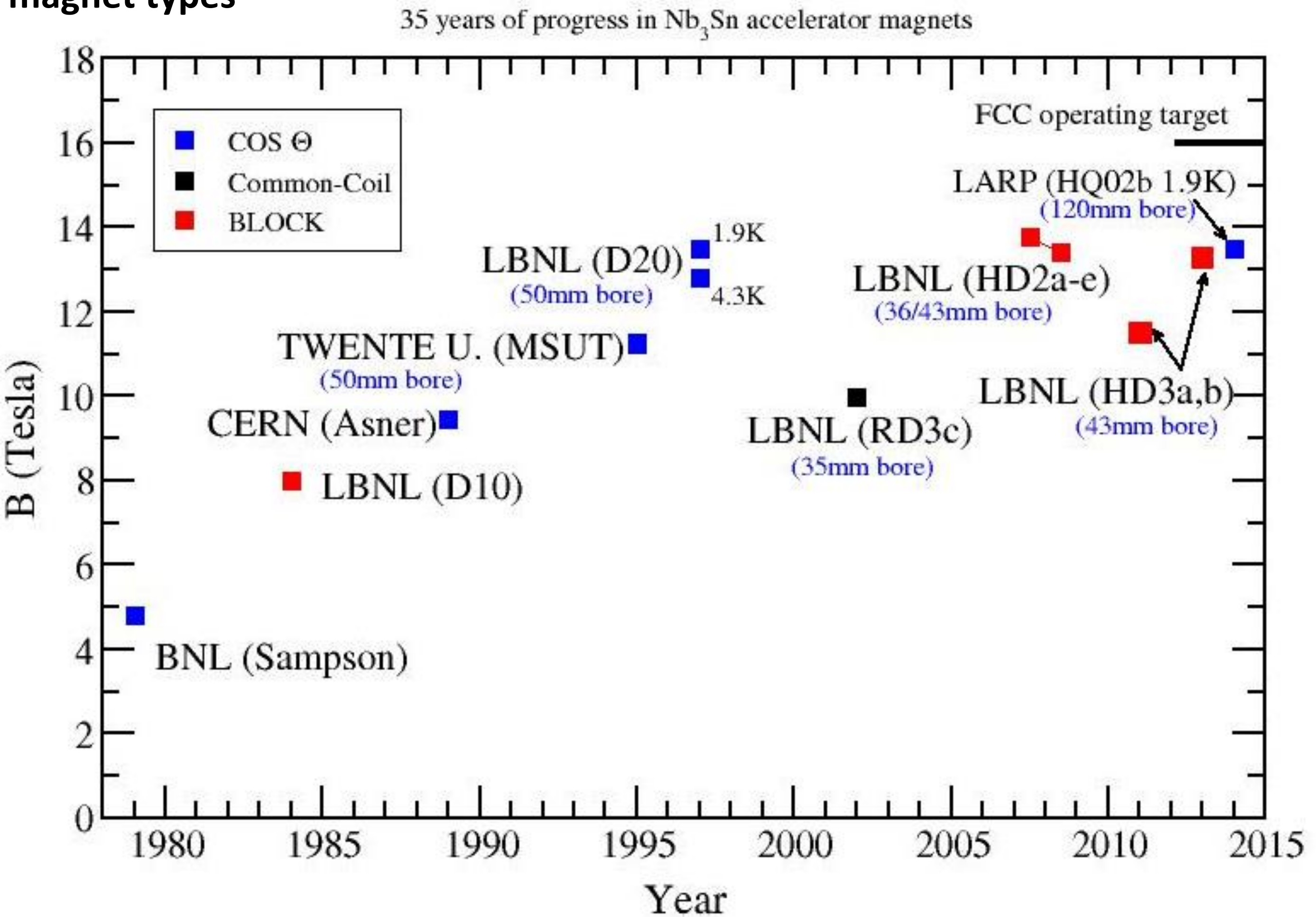
Washington, March 23-27 2015

OUTLINE

- **The CCT magnet**
- **A 16T 90mm single bore**
- **A 16T 90mm double bore**
- **Scaling to 50mm bore**

Progress in Selected Nb_3Sn magnets (with bores)

- Limited selection
- Not selected are flat racetracks and coils with no bores
- **LBNL has experience with 4 magnet types**
  - Cosine-theta
  - Common-Coil
  - Block
  - Canted-Cosine-Theta



The FCC - a **mandate for change**

The **Canted-Cosine-Theta** (CCT) magnet is a **paradigm shift** that **attempts** to addresses three critical performance issues: **Margin, Training, Technology.**

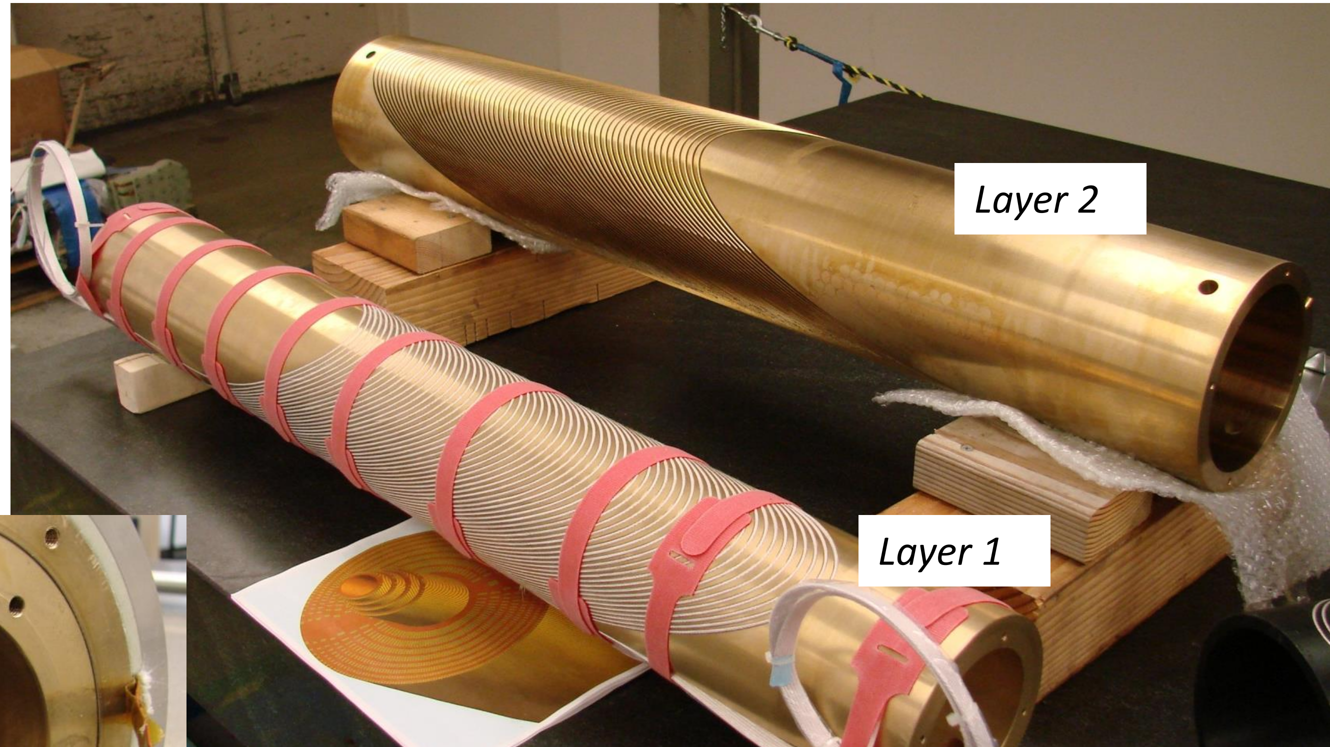
- **High quality field:**
  - Field quality of **each layer** over the **straight section and "ends"**
- **Low conductor stress:**
  - **Structure intercepts Lorentz-Forces**
  - **Limited pre-stress**
  - **Coils and structure integrated**
  - Applied to **any bore size**
  - Grading - use of a **single strand size**
- **Cost-effective:**
  - **Fewer parts**, simplified tooling and assembly
  - Compatibility between **NbTi, Nb_3Sn and HTS**

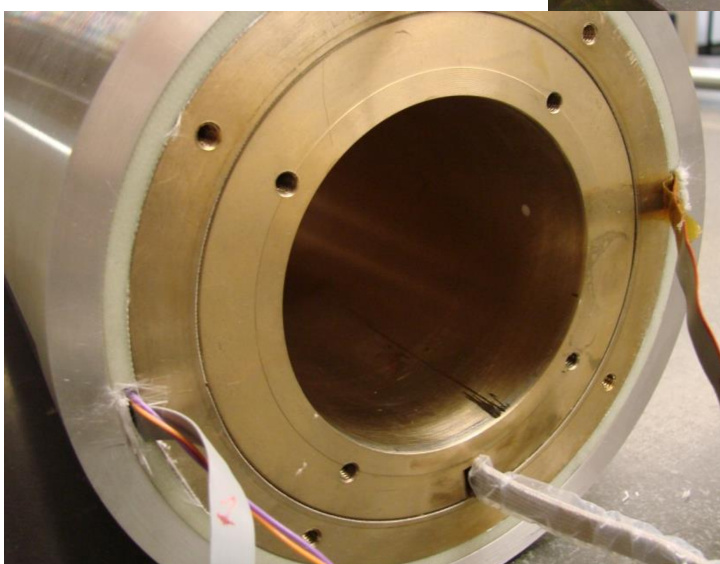
Based on paper by **D.I. Meyer and R. Flasck** "**A new configuration for a dipole magnet for use in high energy physics application**", Nucl. Instr. and Methods 80, pp. 339-341, 1970.)

The Canted-Cosine-Theta (CCT2)

Inner coil structure

Bronze tubing



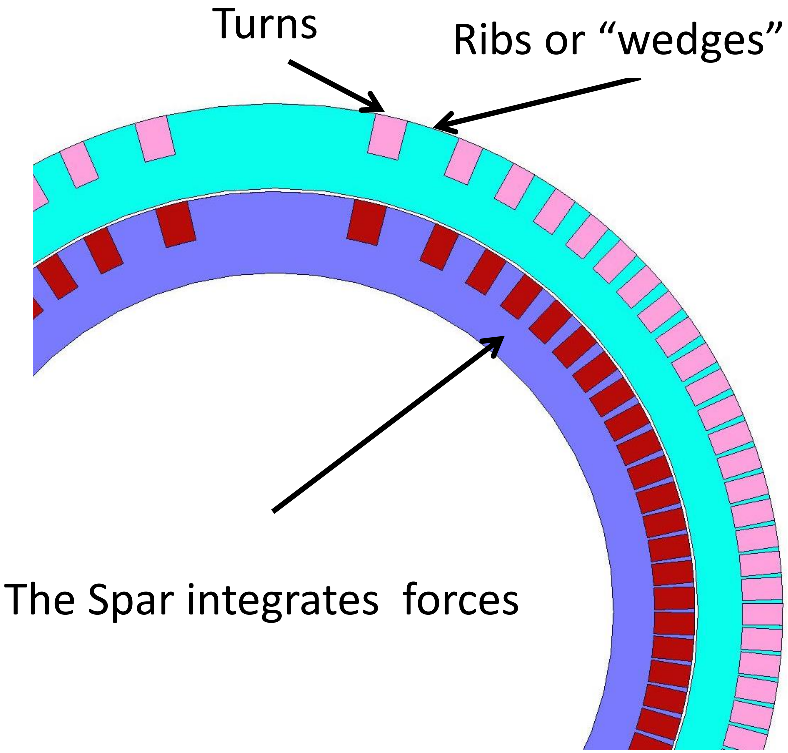


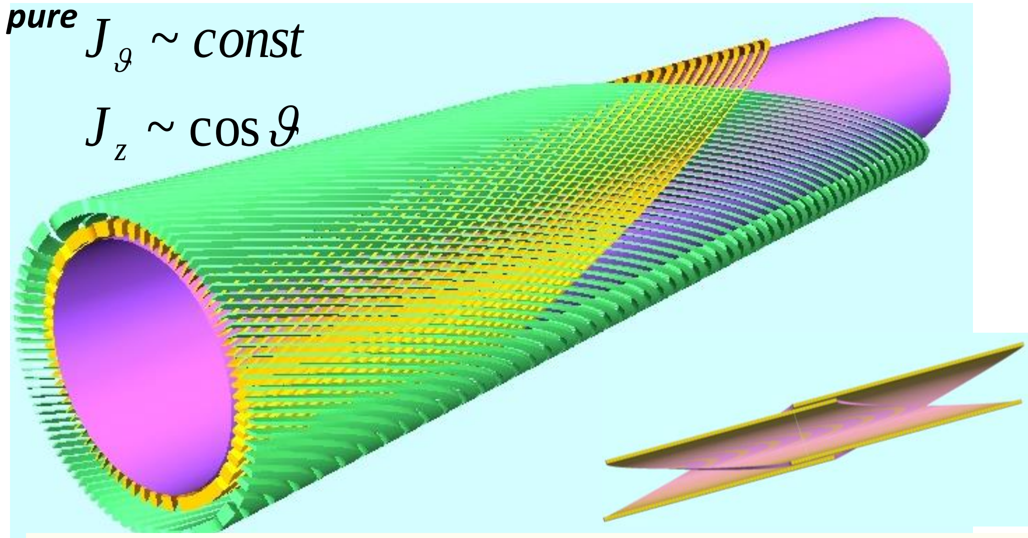
Mandrels integrate windings and structure, assemble poles and are part of the reaction and impregnation tooling.

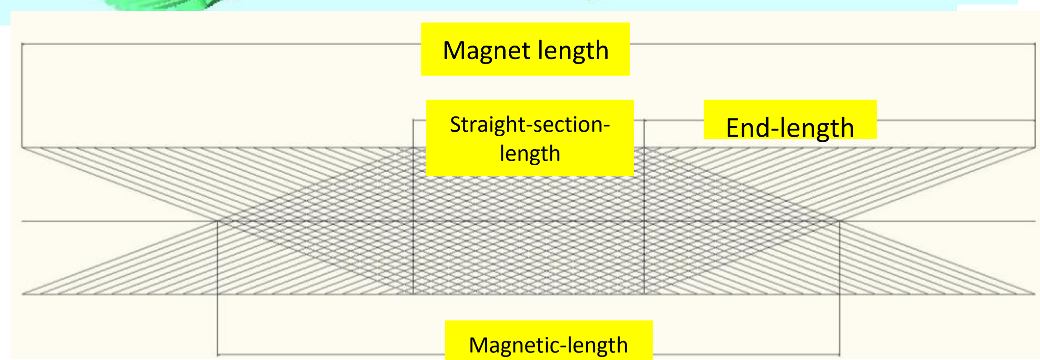
CCT2 – a 5T NbTi 90mm clear bore

Ribs (wedges) simulate a Cosine-Theta current density and intercept the Lorentz forces

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





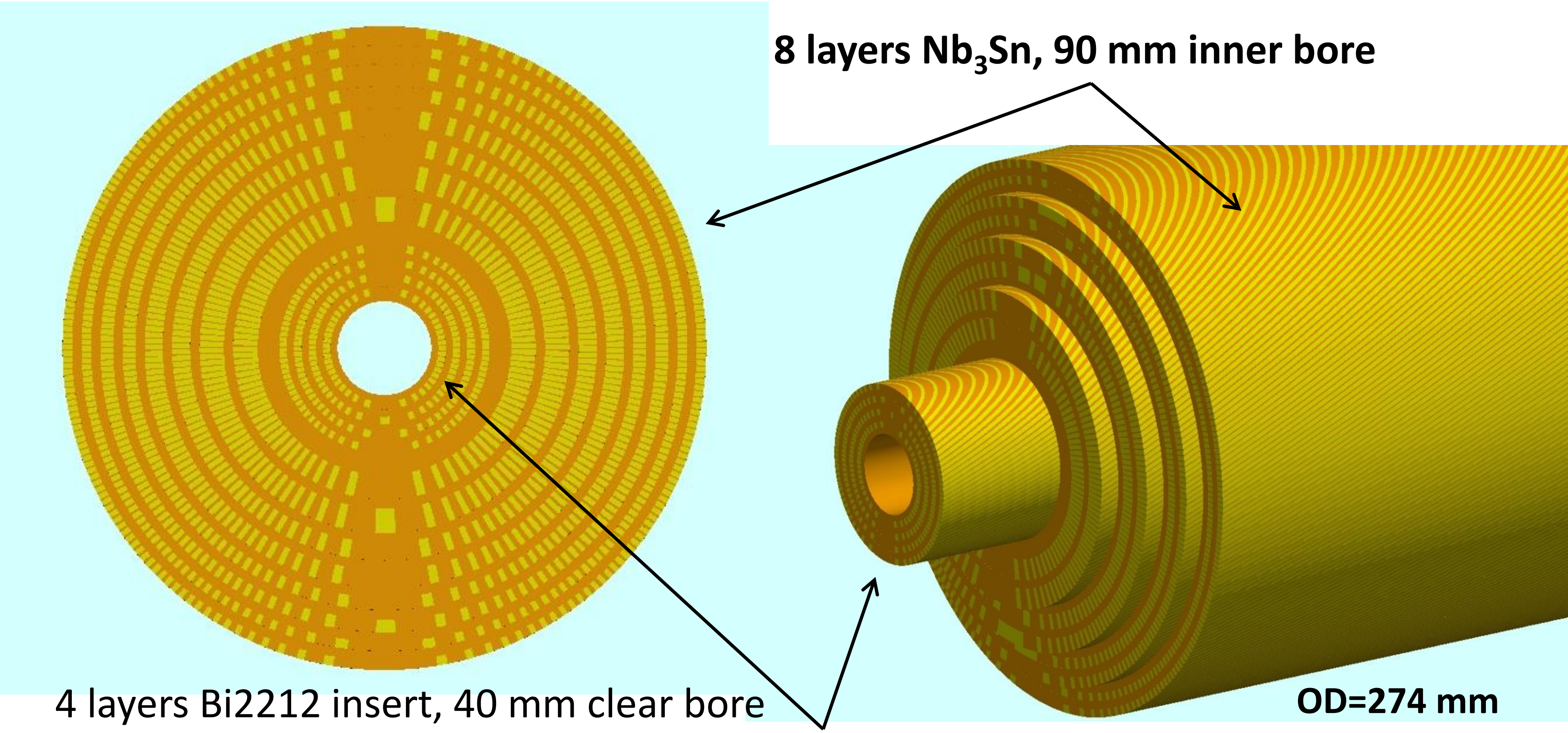


Magnetic-length = pitch*Nturns

Harmonics over each “end” integrate to zero

- L. J. Laslett, S. Caspi, and M. Helm, Configuration of coil ends for multipole magnets, Particle Accelerators, 1987, Vol. 22, pp. 1-14.

CCT7 - 18T Graded Design



Total length of **Nb_3Sn strand** (0.8mm) **20.3Km/1m-magnetic-length (graded),** 36.5(Km/m) (not graded)
Total length of **Bi2212 strand** (0.8mm) **2.2Km/1m-magnetic-length**

* S. Caspi, F. Borgnolutti, L. Brouwer, D. Cheng, D.R. Dietderich, H. Felice, A. Godeke, R. Hafalia, M. Martchevskii, S. Prestemon, E. Rochepault, C. Swenson and X. Wang "Canted-Cosine-Theta Magnet (CCT) - a Concept for High Field Accelerator Magnets", ieee transactions on applied superconductivity, vol. 24, no. 3, p. 4001804, june 2014.

LBNL CCT High Field Program **(no iron, 4.25K)**

Adding 2 new layers to each test **1-in-1 version**

Name	layers	Clear Bore (mm)	Material	I (A)	|B-cond| (T)	B-bore (T)	Inner Layer J_{strand} (A/mm^2)	Energy (MJ/m)	Inductance (mH/m)
CCT1	2	50	NbTi	4050		**2.5**		0.016	0.194
CCT2	*2*	90	NbTi	10600	5.9	**5.3**	917	0.272	4.84
CCT3	*1-2*	90	Nb_3Sn	20700	11.6	**10.3**	1790	1.04	4.84
CCT4	1-2-3-4	90	Nb_3Sn	13550	13.8	**13.1**	1172	2.31	25
CCT5	1-2-3-4-5-6	90	Nb_3Sn	10100	15.2	**14.7**	874	3.63	71
CCT6	1-2-3-4-5-6-7-8	90	Nb_3Sn	8100	16.2	**15.8**	700	5.03	153
CCT7	8+4	40	Nb_3Sn+ Bi-2212	7580+ 2620	18.1/16.3	**17.7**	651/655		
CCT-Bi	4	40	Bi-2212	3950	4.9	4.4	982		

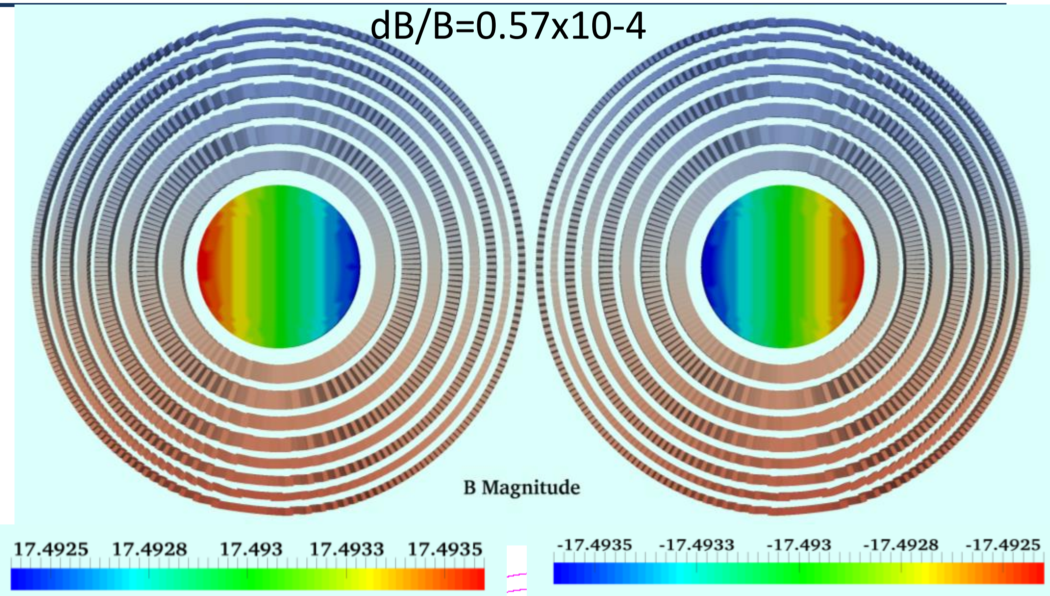
Bore diameter	(mm)	90	50
0.8mm strand/1m magnetic length (CCT6)	(Km/m)	20	16
Conductor volume	(m^3/m)	0.010	0.0081
Conductor Nb_3Sn /assume 70Km dipoles (CCT6)	(ton)	6000x1	4750x1
Structural Bronze/assume 70Km dipoles (CCT6)	(ton)	21420x 1	16730x 1

Stress at short-sample	Layer	Max/Min σ_t	Max/Min σ_r	Max/Min σ_b
CCT7	Inner Nb3Sn	41/-28	27/-29	36/-48
CCT7	Inner Bi2212	74/-35	43/-48	60/-59

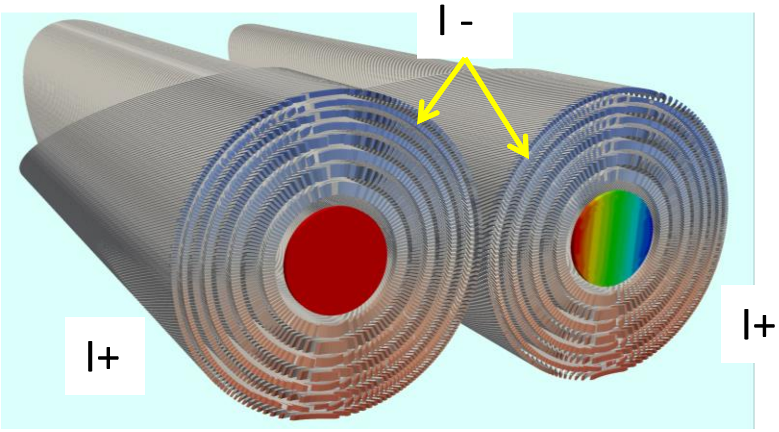
2-in-1 Dipole - Combined Function CCT

Harmonic Content at 66% of Clear Bore from Opera3D

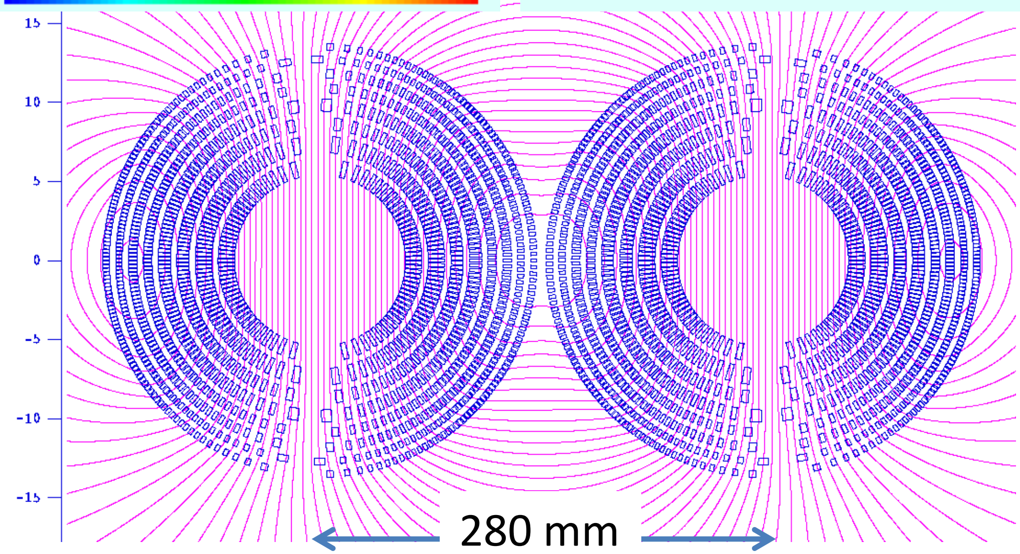
n	$b_{n,left}$ (units)	$b_{n,right}$ (units)
1	10^4	10^4
2	-0.71312	0.69591
3	-0.089069	-0.097592
4	-0.011185	0.01235
5	-0.078566	-0.082402
6	0.0003119	0.0021986
7	0.10155	0.10108
8	-9.4006e-05	0.00033846
9	-0.12062	-0.12095



90 mm bore

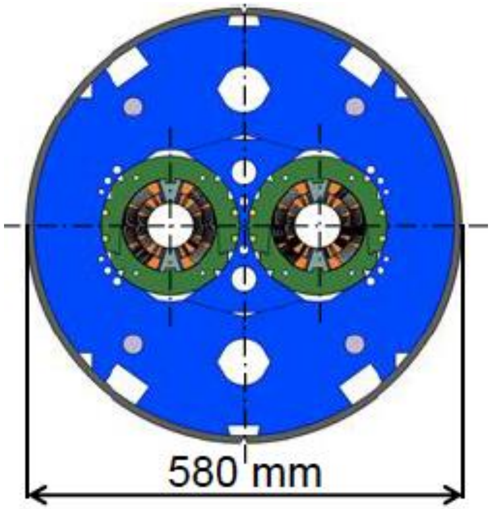


Reduces harmonics cross-talk and distance between bores

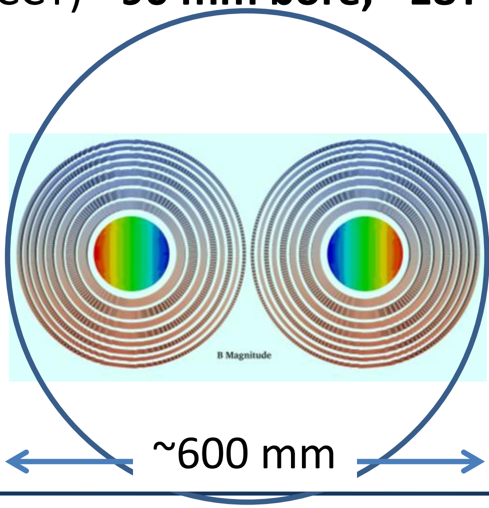


2-in-1 magnets

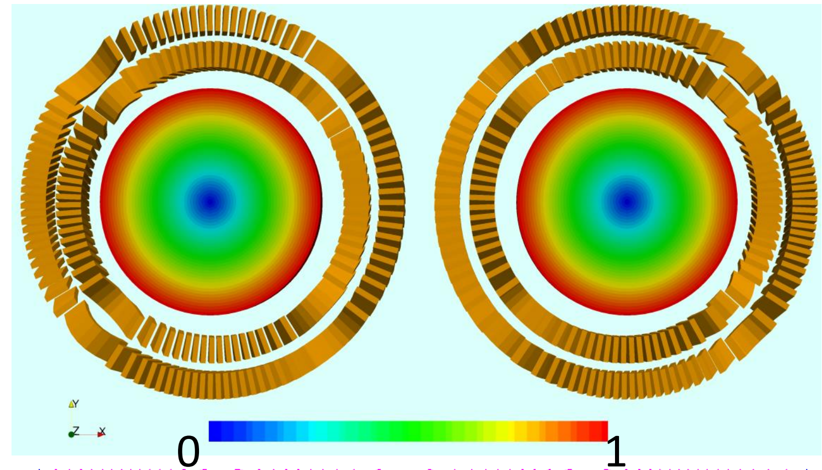
LHC - **56mm bore, ~10T 1.9K**

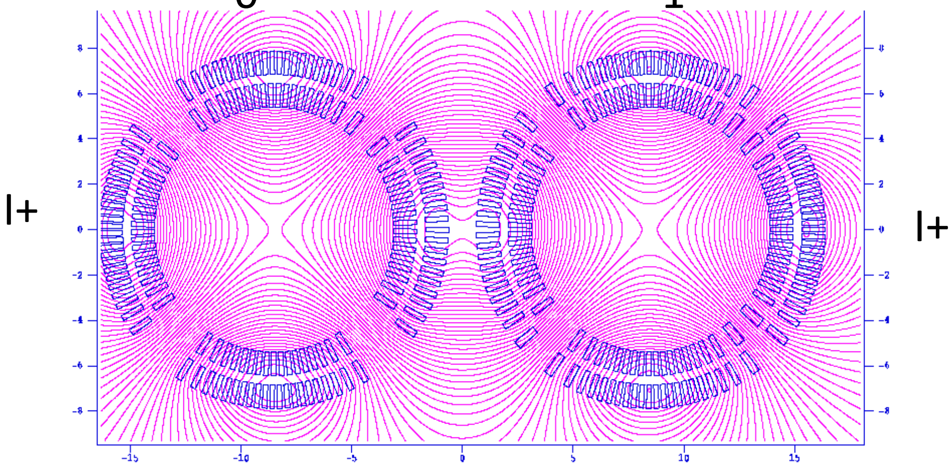


FCC (CCT) - **90 mm bore, ~18T 1.9K**



Example – 2-in-1 quads





- **Iron placed outside the cryostat, not part of the structure**

Short-Sample for 1-in-1 and 2-in-1 Dipole

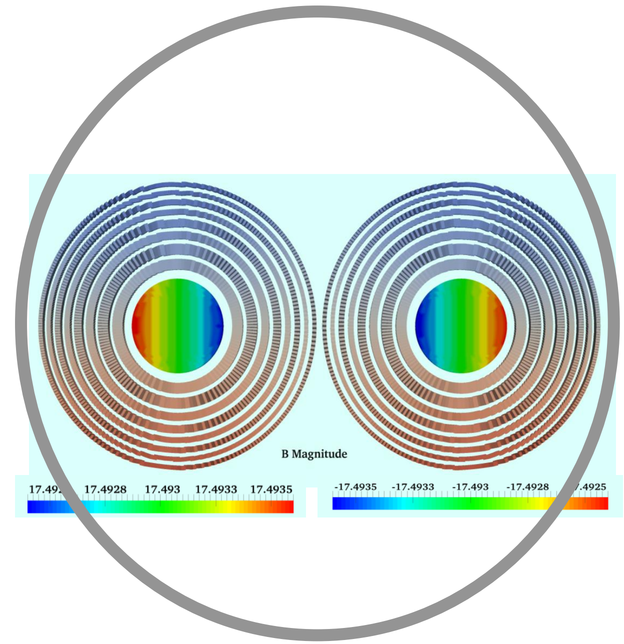
Type	Non-Cu (%)	T (K)	B_{bore} (T)	$B_{conductor}$ (T)	J_{strand} (A/mm^2)	I_{cable} (A)
1-in-1	47	4.25	15.6	16.1	700	8100
1-in-1	60	**4.25**	16.3	16.9	732	8500
2-in-1	60	**4.25**	**16.7**	17.2	680	7820
1-in-1	60	**1.9**	17.9	18.5	803	9230
2-in-1	60	**1.9**	**18.2**	18.8	740	8510

Strand 0.8mm dia.
8 layers Nb_3Sn (no insert)
23 strands inner layer
90 mm clear bore
No-iron
J_{strand} HD3-Coil-2 with J_{sc}=3525 A/mm^2 at 12 T, 4.2K

*Nb_3Sn only (no HTS)

2-in-1 CCT Dipole with 90mm and 50mm clear bore

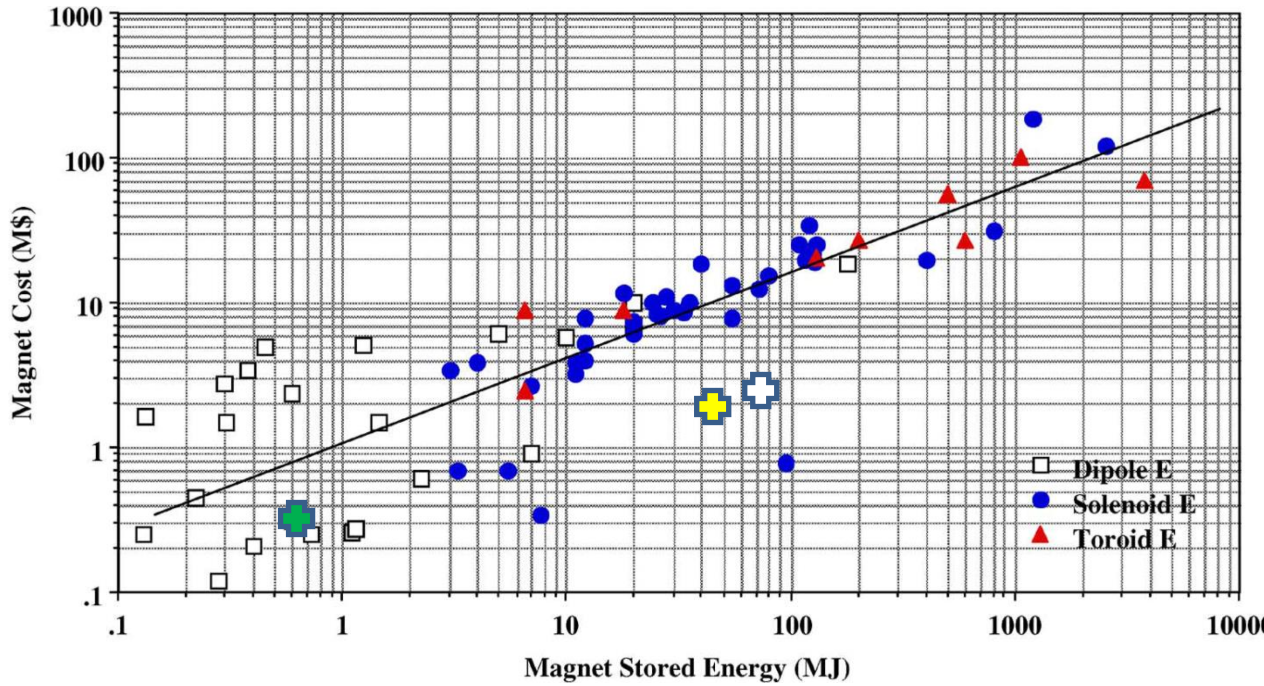
Number of apertures	(-)	**2**	**2**
Aperture (clear)	**(mm)**	**90**	**50**
Inter-aperture spacing	(mm)	280	240
Operating current	(A)	7480	7480
Operating temperature	**(K)**	**1.9**	**1.9**
Operating field	**(T)**	**16**	**16**
Peak field	(T)	16.53	16.53
Margin along the loadline	(%)	**12**	**12**
Stored magnetic energy	(MJ/m)	5x2	3.2x2
Inductance (single bore)	**(mH/m)**	**153**	**94**
2-in-1- OD (no iron)	(mm)	300x2	260x2
Weight (coil+bronze)	(kg/m)	(85+306)x2	(67+239)x2
Strand current density	(A/mm^2)	650	650
Peak/mid-plane/pole stress	(MPa)	28/72	28/72
Short-Sample conductor field	(T)	18.8	18.8
Short-Sample bore field	**(T)**	**18.2**	**18.2**
0.8mm strand/1m magnetic length	(Km/m)	20x2	16x2
Total amount of Nb3Sn /70Km ring	**(ton)**	**6000x2**	**4750x2**
Total amount of structural Bronze/70Km ring	(ton)	21420x2	16730x2



CCT - Summary

1. **The CCT is a paradigm shift** in SC magnet design
2. **3D field quality** in each layer (no optimization; not a result of cancellation between layers)
3. **Coils and structures are integrated –** Lorentz forces are intercepted
4. **No/reduced pre-stress -** Simplified assembly and tooling
5. **Structure dominated and no iron** - Linear analysis , reduced components
6. **Generic design** – NbTi, Nb3Sn, HTS
7. **Combined function fields** (2-in-1 and curved geometry)
8. **Future R&D:**
    a) **Improve ground insulation and remove conductor insulation**
    b) **Address quench protection and quench-back**

CCT Cost Versus Stored Energy



* Fig. 2. Superconducting magnet costs (M$) versus stored energy (MJ) for solenoid magnets (closed circles), dipole and Quadruple magnets (open squares) and toroid magnets (closed triangles).

*Reference: Michael A. Green and Bruce P. Strauss ***"The Cost of Superconducting Magnets as a Function of Stored Energy and Design Magnetic Induction Times the Field Volume",*** IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008.

CCT6 cost of single bore 8 layers 16T magnet (14.3 m long)

90mm clear bore		**50mm clear bore**		CCT3 - 90mm 2 layers , 10T Nb3Sn
Conductor	2.25 (M$)	Conductor	1.75 (M$)	
Structure	0.25 (M$)	Structure	0.2 (M$)	
Total	**2.5 (M$)**	**Total**	**1.95 (M$)**	
Stored Energy 72 (MJ)		**Stored Energy 46 (MJ)**		