The Canted-Cosine-Theta Dipole (CCT) 
For LBNL High Field Magnet Program 

Shlomo Caspi and Lucas Brouwer*
Lawrence Berkeley National Laboratory, Berkeley, CA
USA
December 11th 2012 

* PhD student UC Berkeley
Superconducting Magnet Program (SMP)

- LBNL Superconducting base program R&D on high field magnets is exploring a new dipole magnet (CCT) that specifically promises to reduce high stress on coils while maintaining field quality and efficiency.

Diego Arbelaez, Lucas Brouwer, Daniel Dietderich, Helene Felice, Ray Hafalia, Etienne Rochepault, Soren Prestemon
Arno Godeke, Dan Cheng, Xiaorong Wang, Abdi Salehi, Charles Swenson, Tiina Salmi
Outline

• Introduction
  – Short historical perspective of high field accelerator magnets

• The Canted-Cosine-Theta (CCT) – A new approach

• The CCT and the present LHC dipole

• A conceptual 18T CCT dipole magnet

• Other CCT applications

• Conclusions
33 years of progress in Nb3Sn technology

An historical perspective:
1979-2012
Introduction - Types of superconducting dipoles

D20

2D view

RD series

HD series
Introduction - Types of superconducting dipoles

Block with stress management

Managed coil blocks, plates and laminar spring

New Canted-Cosine-Theta (CCT) With stress interception

Direction of current

3D view
The CCT - History of the concept

• Published paper by D.I. Meyer and R. Flasck in 1970

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

Fig. 2. Two superimposed coils with opposite skew.

• Renewed interest during the past decade
CCT Motivation

- **Substantial reduction in coil stress**
  - No accumulation of Lorentz forces in the windings
  - Small and large apertures

- **A high field quality** over 85% of the bore.
  - Intrinsic to the geometry

- **A Modular concept** with nesting different conductor types
  - One style fits all
  - Natural for grading

- **Combined function**
The CCT dipole cross-section

Areas of current are proportional to $\cos \theta$
approaching a perfect dipole current density distribution

$$J_z \sim \cos \theta \quad \sum J_\theta \sim 0$$
The CCT coil termination

\[ J_z \sim \cos \vartheta \]

Lambertson-Coupland Termination

Harmonic components over such “ends” integrate to zero

Particle Accelerators, 1987, Vol. 22, pp. 1-14
Photocopying permitted by license only
Printed in the United States of America

CONFIGURATION OF COIL ENDS FOR MULTIPLE MAGNETS†

L. JACKSON LASLETT, S. CASPI, and M. HELM
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720
(Received October 15, 1986)
“Ends” - Termination Harmonics

- Dipole field integrates to zero
- Sextupole integrates to zero
- Decapole integrates to zero
CCT – Stress Interception

Stress interceptors (Ribs), thin on the mid-plane thick at the poles

Single conductor turn

Ribs are part of the stress collector (Spar)
Structural Interception – airplane wing

The lift force to the skin is transferred to ribs that are tied to a spar connected to the fuselage.

- **RIBS**
  - Transfers the skin loads to the SPAR

- **MAIN SPAR**
  - Ties all the RIBS together
Splitting the force and intercepting Stress

**The Lorentz force is split into two orthogonal components:**

1. The Lorentz forces **along the coil’s surface** (azimuthal and axial, not only in theta) are intercepted by ribs (no accumulation)
2. Intercepted forces are carried by the spar to which the ribs are connected
3. The **radial** Lorentz force are partially restrained by the spars and an outer structure

Ribs and Spars = “Cable-in-Conduit”
Example: a CCT type LHC dipole

Same bore size and cable as LHC dipole

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore [mm]</td>
<td>15.35</td>
</tr>
<tr>
<td>Layer 1 width [mm]</td>
<td>2.15</td>
</tr>
<tr>
<td>Layer 1 thick [mm]</td>
<td>1.25</td>
</tr>
<tr>
<td>Layer 1 keystone angle [deg]</td>
<td>15</td>
</tr>
<tr>
<td>Layer 1 tilted angle [deg]</td>
<td>0.45</td>
</tr>
<tr>
<td>Layer 1 mid-plane rib thickness [mm]</td>
<td>0.2857</td>
</tr>
<tr>
<td>Layer 1 Asc/Acable</td>
<td></td>
</tr>
<tr>
<td>Layer 2 width [mm]</td>
<td>1.73</td>
</tr>
<tr>
<td>Layer 2 thick [mm]</td>
<td>0.9</td>
</tr>
<tr>
<td>Layer 2 keystone angle [deg]</td>
<td>12.54</td>
</tr>
<tr>
<td>Layer 2 tilted angle [deg]</td>
<td>0.45</td>
</tr>
<tr>
<td>Layer 2 mid-plane rib thickness [mm]</td>
<td>0.2462</td>
</tr>
<tr>
<td>Layer 2 Asc/Acable</td>
<td></td>
</tr>
</tbody>
</table>

Same straight section of 0.7m using 41m of cable
Example: a CCT LHC dipole

Comparison of a canonical LHC dipole with an equivalent CCT

- Field
- Field quality
- Stored Energy
- Stress
- Conductor length

Coil

Ribs and Spar
### Short-sample comparison at 1.9 K

<table>
<thead>
<tr>
<th>Short-Sample</th>
<th>LHC With-Iron</th>
<th>CCT With-Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>56 mm bore, 2 layers, same cables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>9.7</td>
<td>9.2</td>
</tr>
<tr>
<td>$B_{\text{max}}$ (T)</td>
<td>10.0</td>
<td>9.6</td>
</tr>
<tr>
<td>$I_{\text{max}}$ (kA)</td>
<td>13.8</td>
<td>15.67</td>
</tr>
<tr>
<td>$J_e$ (A/mm^2)</td>
<td>419</td>
<td>475</td>
</tr>
<tr>
<td>$E$ (kJ/m)</td>
<td>334</td>
<td>294</td>
</tr>
<tr>
<td>Inductance (mH/m)</td>
<td>3.48</td>
<td>2.39*</td>
</tr>
<tr>
<td>$S_{\theta}$ (MPa)</td>
<td>88</td>
<td>~ 8</td>
</tr>
</tbody>
</table>

For this comparison we chose to keep the same bore, number of layers, strand sizes and cable sizes.

Choosing other parameters would have raise the field.

- Lower field, proportional to slanted angle $\cos(15)=0.966$
- Low stress
- Similar stored energy and inductance
- Similar conductor length

* Courtesy of Jeoren Van Nugteren
Field (Bmod) around inner bore

Field (Bmod) between layers
CCT – Harmonics (no-iron)

CCT - less than 2 units at 85% of the bore

LHC
b3 ~ 3 units
b5 ~ -1 unit
Field profiles along the z axis

LHC Field along Z, 2 layers, lay1-15deg., lay2-12.5deg.

No iron
Stress on Ribs and Spar

Radial forces are intercepted by spars and structure

Radial Stress $\sim \cos(\theta)$

Normal Stress $\sim \sin(\theta)$
Modeling and Minimum symmetry

Coil Minimum Symmetry

Coil

Spar with Ribs
Lamination can simplify analysis
Reduce cost
Reduce losses
The lamination hold exactly one turn of coil, rib and spar
Lamination
Laminated Model in TOSCA
Bmod (14.85 kA)
We have just started stress analysis on the coil ribs and spar.

1. Need to demonstrate that stress interception works, the force carried by the spar and the ribs should withstand the force

2. Three mechanical models in progress

- ANSYS Workbench
  one lamination at 10T and 20T

- ANSYS Classical
  one lamination

- CASTEM
  one turn at 10T and 20T
Workbench - Ribs and Spar

20T – Azimuthal stress spar and ribs

10T - Axial deformation spar and ribs
CASTEM Model – 20T

Coil Von-Mises Stress

<table>
<thead>
<tr>
<th>VAL - ISC</th>
<th>5.44E+01</th>
<th>5.62E+00</th>
<th>&gt; 5.62E+00</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.</td>
<td>52.</td>
<td>49.</td>
<td>47.</td>
</tr>
<tr>
<td>44.</td>
<td>41.</td>
<td>39.</td>
<td>36.</td>
</tr>
<tr>
<td>33.</td>
<td>31.</td>
<td>28.</td>
<td>26.</td>
</tr>
<tr>
<td>23.</td>
<td>20.</td>
<td>18.</td>
<td>15.</td>
</tr>
<tr>
<td>12.</td>
<td>9.7</td>
<td>7.0</td>
<td>4.4</td>
</tr>
<tr>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rib + ring + coil Axial displacement

<table>
<thead>
<tr>
<th>VAL - ISC</th>
<th>5.63E-02</th>
<th>5.46E-02</th>
<th>&gt; 5.46E-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.64E-02</td>
<td>5.00E-02</td>
<td>4.47E-02</td>
<td>3.93E-02</td>
</tr>
<tr>
<td>3.39E-02</td>
<td>2.86E-02</td>
<td>2.32E-02</td>
<td>1.79E-02</td>
</tr>
<tr>
<td>1.25E-02</td>
<td>7.15E-03</td>
<td>1.79E-03</td>
<td>3.57E-03</td>
</tr>
<tr>
<td>-8.93E-03</td>
<td>-1.43E-02</td>
<td>-1.97E-02</td>
<td>-2.50E-02</td>
</tr>
<tr>
<td>-3.04E-02</td>
<td>-3.57E-02</td>
<td>-4.11E-02</td>
<td>-4.65E-02</td>
</tr>
<tr>
<td>-5.18E-02</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Stress Values

<table>
<thead>
<tr>
<th></th>
<th>Coil (MPa)</th>
<th>Rib (MPa)</th>
<th>Spar (3mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Von-Mises</td>
<td>0-55</td>
<td>0-200</td>
<td>200-400</td>
</tr>
</tbody>
</table>

Date: 12/11/2012

Superconducting Magnet Group - S. Caspi
Example – 6 layers 18T dipole, 56mm bore

- 3D analysis, no iron
- 6 layers graded.
- Coil is 60mm thick (no spars*)
- Current 10.5 kA
- Bore field 18 T at 1.9K
- Intercepted stress < 30MPa
Example – 6 layers 18T dipole, 56mm bore

Layer 1, 30 strands
Layer 2, 26 strands
Layer 3, 22 strands
Layer 4, 18 strands
Layer 5, 14 strands
Layer 6, 12 strands

- Proof of principle
- Spars omitted*
- Spars and stress analysis will be next

* Adding spars of any size will not change the field in the bore
Example – Load lines (no iron)

Stored Energy:
- 18T
- 10.5kA
- 2.22 MJ/m
- 44 mH/m
Field along the magnet center
Mid-plane Stress - without interception

The mid-plane stress in each of the layers if the Lorentz force is not intercepted.
The Lorentz stress in each of the layers if the Lorentz force is intercepted.
Other Applications – A curved CCT dipole for a gantry

*D. S. Robin, C. Sun, A. Sessler, W. Wan, M. Yoon
A “pure” dipole field

\[ B_d = 5T \]
A “pure” quadrupole field

\[ G = -25 \text{T/m}, \]

Single layer

Double layers
A “pure” sextupole field

S=400 T/m²

Single layer

Double layers
Combined Function - Dipole+Quad+Sextupole

$B_d=5T, G=-2.26T/m, S=1.3\ T/m^2$
Other Applications – ECR
1. **A New Magnet Type** – Canted-Cosine-Theta
2. **Generic design** – for all NbTi, Nb3Sn, HTS, simplified tooling
3. **Stress interception** not accumulation (independent of the # of turns)
4. **A linear structure** (not dominated by conductor Young’s modulus)
5. **High field quality** over an extended range (no optimization, better quality)
6. Magnet “end harmonics” naturally integrate to zero (no end spacers)
7. **Combined function field**, (offsets in geometric errors included)
8. Islands and wedges replaced by ribs
9. **Grading** using a **single strand** with different cables, **hybrids** Nb3sn+HTS
10. Possible **no conductor insulation** (to ground only, ceramic coating)
11. Extended technology to **curved coils** and other type magnets
Need to Explore

1) Fabrication:
   - Nb3Sn dimensional changes during heat treatment
   - Electrical integrity (conductor to spar)

2) Mechanics:
   - Structure, pre-stress, cool-down
   - Shear stress at interface

3) Protection:
   - Protection scheme
   - Protection heaters and other instrumentation

4) Short-sample and training
Possible Next Steps

1. Subscale demonstrators – a 3T-4T, 56mm bore NbTi dipole

2. Subscale demonstrators – a small bore HTS dipole (YBCO)

3. Subscale demonstrators – a 12T, 56mm bore Nb3Sn dipole

4. A full scale ~20T design
Selected References