Multipole Magnets for the HIAF Fragment Separator Using the Canted-Cosine-Theta (CCT) Geometry

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Two weeks ago when we visit CERN, we saw a car...
Then in downtown Geneva...

FUTURE STYLE
Reincarnation(Cycle) between past and future in *Fashion field*!
It also happens in Magnet field!
OUTLINE

- CANTED–COSINE–THETA MAGNET
- INTRODUCTION OF HIAF & HFRS
- MAGNET DESIGN
- SUBSCALE MODEL COIL
- SUMMARY & FUTURE WORKS
First suggested by D.I. Meyer and R. Flasck in 1969

AML, LBNL & CERN renewed interest in it from 2003

Compared with conventional cosine-theta coil, it is an almost perfect approximation of a cosine-theta magnet, thus yields very good field distribution (especially for integral field)

The combined function coil can be easily achieved

Avoid tight bends for the ends of the coils

Less sensitive to positional (but need more conductor)

\[ x(\theta) = R \cdot \cos(\theta) \]
\[ y(\theta) = R \cdot \sin(\theta) \]
\[ z(\theta) = \frac{h\theta}{2\pi} + \sum_n A_n \cdot \sin(n\theta + \varphi_n) \]
Brief overview

2003 □ □ AML Prototype

2005~2008 □ Two prototype in LBNL

2012 □ PAMELA FFAG testing coil
Brief overview

- **CCT1**
  - $B_0=2.5T$
  - NbTi Cable
  - 50mm clear bore

- **CCT2**
  - $B_0=4.7T$
  - NbTi Cable
  - 90mm clear bore

- **CCT3**
  - $B_0=7.4T$
  - Nb$_3$Sn Cable
  - 90mm clear bore

- **CCT4**
  - $B_0=9.14T$
  - Nb$_3$Sn Cable
  - 90mm clear bore

**Brief overview**

- Canted Cosine Theta option for the 16-T FCC-hh main dipole (PSI)
CERN has finished the prototype;
China (IHEP, IMP & WST) will provide 12 units of CCT magnets for HL-LHC;
BNL direct winding technology

- For complicate coil, special winding machine and techniques are needed, such as BNL’s direct winding technology;
- Too long R&D cycle and high cost of the winding machine.

Thermally embedded wire process (3D printing coil)

Figure 2 – Thermally embedded wire (a) conceptual depiction of embedding process and (b) in actual example in a 3D printed substrate (fractal antenna)
(II) Conductor/Cable placement in grooves

- **Cable:**
  - **High current**
  - **Less** layers and **mandrels**
  - Easy to fabricate mandrels, wind and assembly

- **Conductor:**
  - **Low current**
  - **More** layers and **mandrels**
  - Difficult to fabricate mandrels, wind and assembly

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Rutherford cable in grooves (Metal)
R.B. Meinke, MAGNETICS 2010

Round mini cable in grooves (Composite)
S. Caspi, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015

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**We want low current & low cost!**
(III) Coil placement in grooves

Several turns of insulated conductor into one grooves (CERN’s method):
- Remain low operation current while reduce the number of mandrels;
- Need more splices between coils of two mandrels.

Insulated mini round cables into one grooves (Our variant):
- More flexibility of insulation design;
- Easier to wind;
- Lower coupling loss between strands.

Have the best of both worlds
Introduction of HIAF & HFRS

Canted–Cosine–Theta Magnet

Magnet Design

Subscale Model Coil

Summary & Future Works
Overview of the HIAF project

SRing: Spectrometer Ring
Circumference: 273.5 m
magnetic rigidity: 15 Tm

BRing: Booster Ring
Circumference: 530 m
magnetic rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

SECR: Superconducting ECR ion source
45GHz

iLinac: Superconducting Linac
17MeV/u(U³⁴⁺)
- Production, separation and identification of exotic nuclei
- Primary and secondary beams
- High magnetic rigidity: 25 T·m
- Big beam acceptance: ± 160 mm
Options for Multipole Magnet Design

- The iron dominated magnets with superconducting coils have been widely used:
  - Easier to fabricate and wind;
  - Low request for coils installation precision;
  - Easier to do quench protection.
- Coil dominated magnet was sometimes requested:
  - Small cold mass (speed up cool down or minimize radiation heat load);
  - No saturation effect;
Iron-dominated option

MSU/NSCL A1900 Triplet  RIKEN Big-RIPS Triplet  GSI/FAIR Super-FRS Multiplet
Iron-dominated design

Field Harmonics components

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n2</td>
<td>1</td>
</tr>
<tr>
<td>n6</td>
<td>$8.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>n10</td>
<td>$0.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>n14</td>
<td>$1.8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Cross section of coils | 50mm $\times$ 48mm

$J_e$ | 106 A/mm

Dia of Iron | 1,240 mm

Weight of Iron | 7.8 ton

- Hard to achieve good field quality at both low and high field;
- End chamfer needs to be carefully optimized.

Field gradient homogeneity $\approx 0.03\%$
Iron-dominated design

- Easy to reach the field quality;
- Weight of the cold iron is 2.14 ton.
- **Large cold mass.** Heaviest cold mass of one module is about 40 tons. It will need long time to cool down and warm up;

- Triplets, sextupole and steering dipole **integrated** into modular cryostats. The longest magnet column is about **7 m**. Difficult for cold mass **support and alignment**.

- **Large helium containment** will cause big pressure rise after a quench;
Coil-dominated option

Air-core type triplet for BigRIPS (Simple racetrack coil)

- Advantages of **light weight** and **good field linearity**;
- Magnetic field are more **sensitive** to positioning error;
- **Difficult** to fabricate and wind, especially Walstrom type coil.

S. Manikonda, 17 Feb, 2016
Outline

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- SUBSCALE MODEL COIL
- SUMMARY & FUTURE WORKS
### Specifications of Quadrupoles

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>11.43 T/m</td>
</tr>
<tr>
<td>Effective length</td>
<td>0.8(Q1), 1.1(Q2), 1.5(Q3) m</td>
</tr>
<tr>
<td>Horizontal aperture</td>
<td>±160 mm</td>
</tr>
<tr>
<td>Vertical gap</td>
<td>±85 mm</td>
</tr>
<tr>
<td>Field Quality</td>
<td>±8 \times 10^{-4}</td>
</tr>
</tbody>
</table>

### Specifications of Sextupoles

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>30 T/m²</td>
</tr>
<tr>
<td>Effective length</td>
<td>0.8(S1), 1.1(S2), 1.5(S3) m</td>
</tr>
<tr>
<td>Horizontal aperture</td>
<td>±160 mm</td>
</tr>
<tr>
<td>Vertical gap</td>
<td>±85 mm</td>
</tr>
<tr>
<td>Field Quality</td>
<td>±5 \times 10^{-3}</td>
</tr>
</tbody>
</table>

A typical triplets

- Large bore□
- Pole-tip fields: ~2.4T□
- Low current □< 500 A□
- Liquid Helium bath cooling □
- **Quadrupole** and **sextupole** based on Canted Cosine-Theta (CCT) coil;
- Sextupole, octupole and steering dipole **nested** to reduce the length;
- Weight of cold mass greatly decreased (40 ton → 4 ton)

A typical configuration of HFRS triplets
Coil design

CCT quadrupole coil

CCT sextupole coil

Octupole coil

Steering dipole coil
## Coil design (quadrupole)

<table>
<thead>
<tr>
<th></th>
<th>Q1 (L=0.8m)</th>
<th>Q2 (L=1.1m)</th>
<th>Q3 (1.5m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient Field (T/m)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Current (A)</td>
<td>440</td>
<td>440</td>
<td>440</td>
</tr>
<tr>
<td>Layers</td>
<td>2×(6+1)</td>
<td>2×(6+1)</td>
<td>2×(6+1)</td>
</tr>
<tr>
<td>CCT angle</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Turns per layer</td>
<td>66</td>
<td>90</td>
<td>124</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>12.2</td>
<td>12.2</td>
<td>12.2</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>320×170</td>
<td>320×170</td>
<td>320×170</td>
</tr>
<tr>
<td>Wire Diameter (mm)</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Cable Diameter (mm)</td>
<td>2.8±0.01</td>
<td>2.8±0.01</td>
<td>2.8±0.01</td>
</tr>
<tr>
<td>Bpeak (T)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Loadline</td>
<td>67.7%</td>
<td>67.7%</td>
<td>67.7%</td>
</tr>
<tr>
<td>Conductor length (km)</td>
<td>6.4</td>
<td>8.7</td>
<td>11.9</td>
</tr>
<tr>
<td>ID of mandrel (m)</td>
<td>420 mm</td>
<td>420 mm</td>
<td>420 mm</td>
</tr>
<tr>
<td>Coil groove size</td>
<td>2.8 mm × 5.8 mm</td>
<td>2.8 mm × 5.8 mm</td>
<td>2.8 mm x 5.8 mm</td>
</tr>
</tbody>
</table>

**Quadrupole with warm iron yoke (6% enhancement of B)**

**Quadrupole & Sextupole coils**
Mechanical design for the system with a capacity of 40 tons and a reduced capacity of 4 tons.
**Main Design Parameters of Quadrupole Magnet**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>40</td>
<td>T/m</td>
</tr>
<tr>
<td>Effective length</td>
<td>160</td>
<td>mm</td>
</tr>
<tr>
<td>Operation current</td>
<td>400</td>
<td>A</td>
</tr>
<tr>
<td>Winding pitch</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>45</td>
<td>deg</td>
</tr>
<tr>
<td>Inductance</td>
<td>10</td>
<td>mH</td>
</tr>
<tr>
<td>Aperture</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>Good field</td>
<td>± 20</td>
<td>mm</td>
</tr>
<tr>
<td>Uniformity</td>
<td>± 4E-4</td>
<td></td>
</tr>
</tbody>
</table>

**Parameters of the NbTi/Cu strand**

<table>
<thead>
<tr>
<th>Description</th>
<th>Monolith</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire type</td>
<td>Monolith</td>
</tr>
<tr>
<td>Insulation</td>
<td>Formvar</td>
</tr>
<tr>
<td>Bare size</td>
<td>0.72 mm</td>
</tr>
<tr>
<td>Insulated size</td>
<td>0.77 mm</td>
</tr>
<tr>
<td>Outer Insulated with Nylon braid</td>
<td>0.9 ± 0.005 mm</td>
</tr>
<tr>
<td>Cu/SC</td>
<td>1.3:1</td>
</tr>
<tr>
<td>RRR (293 K/10 K)</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Ic (6 T, 4.2 K)</td>
<td>442.7 A</td>
</tr>
</tbody>
</table>
Subscale model coil - fabrication

Milling

Measurement

Winding

Anodized

Former Fabrication

Finished winding

After Vacuum impregnation

Coil Winding and Impregnation
Subscale model coil - fabrication

- Cold test insert
- Voltage decay curve
- Current decay curve
- Quench protection circuit
- Excitation curve
- Quench back effect
Thanks for the modern manufacture technology, CCT magnet (old technology) has a new life (High field, Gantry, FFAG, LHC-HL);

CCT magnet: Simple manufacturing, low coil stress, field quality but reduced efficiency;

CCT magnet will be used in HIAF-HFRS spectrometer: lower field, low current & large aperture;

Coil in groove with insulated mini-round-cable is proposed and will be used;

Subscale testing coil has been successfully fabricate and tested.
Future works

- Detailed error analysis of magnetic field;
- Structural analysis of the magnet;
- Quench simulation and protection design;
- Fabrication of the half-size and full size nested multiplet prototype in next 2 years;
- Serial production of 13 multiplets modules in next 5 years.
Thanks a lot for your attention!

Thanks for Prof. Glyn Kirby, Prof. Lucio Rossi (CERN) and Prof. Shlomo Caspi’s (LBNL) suggestions and help!