A mole for measuring pulsed superconducting magnets

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IMMW 15@FNAL 21 - 24 August 2007
Thanks to

**GSI**
Helge. R. Kiesewetter
Thomas Mack
Thomas Knapp
Franz Klos
Stefan Rauch
Reinhold Werkmann

**CERN**
Olaf Dunkel
Guy Deferene
Louis Walckiers

**TU - Darmstadt**
Maximilian Manderla
Martin Schnecker

**Data for comparison**
Animesh Jain and his team
Outline

1. Measuring pulsed fields
   - Methods applied today
   - Superconducting magnets: is there a difference?

2. Mole
   - Overview
   - Angular positioning

3. First measurements
   - Test setup
   - Power supply Cycles
FAIR @ GSI

- many rings, 2 superconducting synchotrons
- SIS 100: 2 T, 4 T/s, 3.5 m long dipoles, 5 m long quadrupole plus correctors
- SIS 300: 2 T, 4 T/s,
  - describe / compare the quality of the magnet(s)
  - manageable data for users: e.g. beam dynamics
- this talk focuses on AC field measurement using the mole
Methods commonly applied for pulsed magnets

- synchotrons → since 50\textsuperscript{th} 
  - theoretical understanding (strong focusing, Courant - Snyder) 
  - also measured since then? 
- typically normal conducting 
  - search coils (dipole), rotating coil (quadrupole) 
    - bent to the radius for small magnets 
    - pole → mechanical reference 
    - sliding on the pole plane (@ GSI) 
    - a stack of coils (@ CERN) 
- but nowadays superconducting synchotrons 
  - Nuclotron @ Dubna 
  - SIS 100, SIS 300 @ GSI 
  - injector change @ CERN
Measuring pulsed fields
Mole
First measurements

Methods applied today
Superconducting magnets: is there a difference?

Difference measuring sc ↔ nc synchotron magnets

normal conducting

- dipole
  - field integral $\int B_y dl$
  - field homogeneity $\frac{B_y}{dx} \rightarrow \text{“normal multipoles”}$
  - angle → pole shape
- quadrupole
  - field integral $\int G_y dl$
  - axis (w.r.t. pole shoes)
  - field homogeneity (multipoles)

super conducting

- dipole
  - $\int B dl$
  - angle (no mech. ref.)
  - field homogeneity (multipoles)
  - “axis” (shape of the magnet at cold)
- quadrupole
  - $\int G dl$
  - axis
  - angle
  - field homogeneity (multipoles)
Difference measuring sc ↔ nc synchotron magnets

- chosen system must
  - provide angle
  - axis
  - suppress vibration (round anti cryostat in rectangular aperture)
- coil probe:
  - DC → rotating
  - AC →
    - regularly (in $\phi$) placed sensors
    - measure the magnet at different angles from ramp to ramp can that be done?
Circular Multipoles

Magnetic field representation in circular multipoles

$$B(z) = \sum_{n=1}^{N} C_n \left(\frac{z}{R_{Ref}}\right)^{(n-1)}$$

Flux through a coil probe

$$\Phi(t) = Re \left[ \sum_{n=0}^{N} K_n C_n e^{in\theta(t)} \right]$$
Sensitivity for a radial coil probe array

\[ K_n = \frac{NL}{n} \left[ \left( \frac{R_2}{R_{Ref}} \right)^n - \left( \frac{R_1}{R_{Ref}} \right)^n \right] \]

Induced voltage

\[ V(t) = -n \dot{\theta}(t) \text{Re} \left\{ \sum_{n=0}^{N} K_n \left\{ C_n + \frac{dC_n}{dt} \right\} e^{in\theta(t)} \right\} \frac{d\Phi(t)}{dt} \]
Spurious harmonics due to mechanical artifacts

Torsional vibrations in a dipole of $T = t \cos(p\Theta)$

$$C_{p+1}^{sd} \approx \frac{K_1}{K_{p+1}} \frac{t}{2} iC_1 \quad C_{p-1}^{sd} \approx \frac{K_1}{K_{p-1}} \frac{t}{2} iC_1$$

Torsional vibrations in a quadrupole of $T = t \cos(p\Theta)$

$$C_{p+1}^{sq} \approx \frac{K_2}{K_{p+1}} t iC_2 \quad C_{p+1}^{sq} \approx \frac{K_2}{K_{p+1}} t iC_2 ,$$

Transversal vibrations in a quadrupole of $D = d \cos(p\Theta)$

$$C_{p+1}^{sq} = \frac{K_1}{K_{p+1}} \frac{d}{2R_{Ref}} - iC_2 \quad C_{p-1}^{sq} = \frac{K_1}{K_{p-1}} \frac{d}{2R_{Ref}} iC_2.$$
Mechanical Requirements

- based on a radial compensation coil
  - first coil probe CERN LHC head #41 → allows to “buck” the dipole and quadrupole by a factor of 1000 and 100 respectively
  - insert in relevant formulae
Coil probe parameters

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<tbody>
<tr>
<td>$R_2 [mm]$</td>
<td>20.378</td>
<td>12.242</td>
<td>4.000</td>
<td>12.157</td>
<td>20.482</td>
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<tr>
<td>$N$</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
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<tr>
<td>$L [mm]$</td>
<td>699.5</td>
<td>699.5</td>
<td>699.5</td>
<td>699.5</td>
<td>699.5</td>
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## Required Mechanical Precision

<table>
<thead>
<tr>
<th></th>
<th>abs</th>
<th>cmp</th>
<th>unit</th>
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<tbody>
<tr>
<td>Dipole</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$p$</td>
<td>2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>0.5</td>
<td>80</td>
<td>7.5 mrad</td>
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<tr>
<td>Quadrupole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td>3</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>0.5</td>
<td>45</td>
<td>5 mrad</td>
</tr>
<tr>
<td>$d$</td>
<td>0.2</td>
<td>5</td>
<td>mm</td>
</tr>
</tbody>
</table>

- compensation measurement uses bucking ($A - C$ for dipole)
- compensation measurement uses bucking ($A - B - C + D$ for quadrupole)
Choise of Method

- “bucking” relaxed mechanical parameters
- small team @ GSI, different apertures
- → step by step method
- previously applied by:
  - Nikolay Smirnov, Piotr Shcherbakov; UNK @ IHEP
  - Alexander Kovalenko; Nuclotron @ Dubna
  - A. Dael; superconducting models for CERN SPS @ Saclay
  - Hallbach and Bill Hasenzahl?
Sketch of the Mole

levelling piezo motor 1, 2
coil rotation piezo motor 3, 4
inclinometers 5
slip rings 6
angular encoder with 512 ticks, 7
coil probes 8
angular encoder with 7500 counts 9
its inclinometer and 10 levelling motor
Angular positioning I/II

- piezo motor → allows precise positioning
- chosen type (SHINSEI USR 30) → default driver only allows 8 mrad.
- piezo motors → far better → study at TU Darmstadt → 0.1 mrad reachable (see IMMW 14)
Signal Generation / Control Loop

- function generator realised in FPGA
- must produce variable 50.5 – 51 kHz within 10 Hz steps
- must shift phase between channel A and B

Courtesy of S. Rauch, T. Mack
Power Amplifier

- piezo motor → capacitive load
- amplifies signal to 15 V / 3 A
- separation transformer → 110 V
- still requires a parallel inductance

Courtesy of T. Mack, T. Knapp, R. Werkmann
Angular positioning II/II

- Angles below 0.5 mrad reachable (only limited by the encoder)
First test

- GSI 001 (modified RHIC magnet) on the test bench
- mole not available ... but LHC quadrupole coil probe
- test of power supply reproducibility
Bricolage set up

Power Supply

DCCT

VME Crate Integrators

DVM

PC

Shaft

Pitch Circle

Magnet

Coil Probe

Measuring pulsed fields
Mole
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Power supply Cycles

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Bricolage set up

- coil was hold by teflon rings
- coil fixed with teflon and capton to carbon tube
- carbon tube fixed to pitch circle
- step by step turned by hand
- data compared to BNL Measurements (at 2 T / s)
- power supply reproducibility found to 2.5 units
To 3 and 4 Tesla with $\approx 1 \text{T/s}$
Measuring pulsed fields
Mole
First measurements

Flux measured by compensation array

\[ \Phi_{\text{cmp}} \ \text{[mT]} \]

Data Points:
- 3.9
- 3.1
- 2.1
- 1.1
- 0.0

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Mole for pulsed SC Magnets
Main dipole strength

Start offset due to missing rotating coil measurement. Integrator trigger to 3 T 40 Hz, to 4 T 500 Hz, different coil length different positions dashed lines → Measurement by A. Jain @ 2 T/s.
Harmonics $C_3$

![Graph showing the relationship between $c_3$ and $C_1$]
Harmonics $C_5$
Conclusion

- Mechanical requirements (bucking) → allow step by step power supply reproducibility → good
- Piezo motor can do angular steps
- Bricolage test shows good results for harmonic quality
- Main field measurement requires improvement