Generation of 25 T with an all-superconducting magnet system

field profile and field quality measurements of a 4 T REBCO insert coil for a 21 T LTS magnet

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Motivation

Towards all-superconducting 30-T solenoid magnets

Funded by in collaboration with

• Today: commercial systems: $B_{\text{max}} = 23.5 \text{ T} @ 2.2 \text{ K}$
• Scope: high resolution NMR, laboratory magnets

Towards 20 T accelerator magnets for HEP

Funded by coordinated by

• Today: record collision energy of 8 TeV
• Scope: future circular colliders with up to 100 TeV physics beyond the Standard Model
**Motivation**

**Call for high magnetic fields:**
- LTS (background) + HTS (highest field region)
- REBCO tapes currently most promising for high fields
  - mechanical, electrical properties
  - commercial availability

**Project: magnet field booster:**
- Layer wound REBCO insert for existing 21 T LTS magnet
- ≥ 25 T combined center field, ≥ 15 mm Ø usable bore
- Has to fit in the magnet’s VTI (48 mm max. diameter)
Conductor selection:
• SuperPower (3 mm wide), Kapton insulation

Insert coil design:
• 20 mm min. Ø, 48 mm max. Ø, 175 mm length
• 1820 turns in 50 layers, 180 m conductor
• 19.2 mH, 220 A op. current, 423 J stored

BUT: screening currents
• Tape geometry & radial field component
  → field changes induce screening currents

GOAL: understanding field profile & screening current effects
Operation of the insert coil
Coupled coils

Outsert & insert: inductively coupled

• Misalignment results in high forces
• Movable insert coil
  • load cell to detect the forces
  • stepping motor + gearbox (μm displacement)
• Outsert quench → induces high over current in insert
• Quench detection and protection
  • monitors insert & outsert
  • dissipate >> the insert’s stored 423 J
Quench detection & protection

**Quench analysis:**
- 2 Ω dump resistor, 100 ms max. reaction time
- 8 kW max. load, dissipate 1.5 kJ

**Quench detection:**
- Hardware QD: ΔU of both halves of the outsert
- Agilent 3457A with limit function: U of the insert

**Quench protection:**
- 1k A switch to bypass dump resistor in normal operation
- → 19 ± 8 ms reaction during tests
reached 25 T (all-superconducting):

- European record
- 4th highest worldwide

http://www.manep.ch/switzerland-winds-up-superconductivity/
Field profile measurements
Experimental details

Hall sensor array:
- 9 hall sensor (Arepec, 30 T), 25 mm separation
- Feed in series, read in parallel, z direction

Calibration:
- Insert coil dummy: use outsert field profile as reference

Experimental procedure:
- Ramp outsert to field, wait for relaxation (600s)
- Charge insert, wait for relaxation (1200 s)
- Discharge insert, wait for relaxation (600s)
Performed experiments

**Hall sensor array:**
- 9 hall sensor (Arepec, 30 T), 25 mm separation
- Feed in series, read in parallel

<table>
<thead>
<tr>
<th></th>
<th>Outsert</th>
<th>Insert</th>
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</thead>
<tbody>
<tr>
<td>Insert dummy</td>
<td>Ramping to 19 T</td>
<td>n.a.</td>
</tr>
<tr>
<td>Insert dummy</td>
<td>Ramping to 0 T</td>
<td>n.a.</td>
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<tr>
<td>Insert</td>
<td>0 T</td>
<td>charging to 4 T - relaxation - discharging</td>
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<tr>
<td>Insert</td>
<td>19 T</td>
<td>charging to 4 T - relaxation - discharging</td>
</tr>
</tbody>
</table>
Calibration

- Calibration till 19 T
Charging of the outsert

- Matches symmetric series expansion

\[ B(z) = B_0 + B_2 z^2 + B_4 z^4 + B_6 z^6 + B_8 z^8 + \cdots \]

- Screening currents reduce center field
- Screening currents increase side field
Charging of the outsert

outsert + insert

→ expected behavior
Charging of the insert

outsert + insert

• Outsert & insert misaligned?
  • 9 mm misalignment $\rightarrow$ >1 kN force

• Asymmetric series expansion needed

$$B(z) = B_0 + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + B_6 z^6 + B_7 z^7 + B_8 z^8 + \cdots$$
Asymmetric series expansion

outsert + insert

- Valid only in center region
Screening current decay

Evolution of series expansion after charging: $0^{\text{th}}$ order

\[ B(z) = B_0 + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots \]

Main field:

- Increases after charging
- Independent of outsert field
- 4 mT / decade $\rightarrow$ 0.1 % / decade

$\rightarrow$ expected behavior
Screening current decay

Evolution of series expansion after charging: 1\textsuperscript{st} order

\[ B(z) = B_0 + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots \]

1\textsuperscript{st} field harmonics:

- Measure of field asymmetry
- Asymmetry drifts at low outsert fields
- Constant from 10 T

\[ \rightarrow \text{ further investigation needed} \]
Screening current decay

Evolution of series expansion after charging: 2\textsuperscript{nd} order

\[ B(z) = B_0 + B_1 z + B_2 z^2 + B_3 z^3 + B_4 z^4 + B_5 z^5 + \cdots \]

2\textsuperscript{nd} field harmonics:

- Measure of field curvature
- Drifts towards more positive values (= less screening curr. effect)
- Lower drift at high outsert fields

\( \rightarrow \) expected behavior

insert current (A): 220
Insert offset

Load cell readout during outsert & insert charging:
• 115 N centering force ≠ -9 mm misalignment

Other explanations?
• Force measure error?
• Asymmetric screening current induction?
  • tilt of the insert coil?
  • tilt of the REBCO layer?
  → offset should decay after charging
  → offset should increase with field
Tilt of the REBCO layer $\rightarrow$ asymmetric screening curr.:

- Absolute value of offset increase with field
- Offsets decay after charging
Summary & outlook

Outlook

• Repeat experiment with less hall probe separation
  → more data points in field center → better for fitting
• Investigate why insert field offset ≠ measured force

• main field increases independent of outsert field
  → expected, magnetic relaxation of REBCO is field independent
• 1st harmonics (field asymmetry) drifts only at low outsert fields
  → needs further investigation
• 2nd harmonics (field curvature) drifts towards positive values (= less screening curr. effect), lower drift at high outsert fields
  → expected, high outsert fields homogenize field alignment
  → $I/I_c$ more homogeneous → homogenous screening curr.
Thank you for your attention

http://supra.unige.ch
https://www.bruker.com/
3 mm wide SuperPower REBCO tapes:

- Logarithmic magnetic relaxation
- Independent of field
- $\approx 3.4\% / \text{decade}$

$\rightarrow 33x$ the main field Drift (0.1% / decade)

perpendicular: $B \parallel c$
parallel: $B \parallel ab$
Relaxation of the central magnetic field:

- Logarithmic decay
- Independent of field
- 0.08 % / decade

→ close to calculated main field drift (0.1% / decade)