Ultimate Forces of the Grenoble Hybrid Magnet

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Outline

• Introduction
• Worst-case scenario
• Two approaches investigated
  – Energy transfer from shorted coil halves
    • Instantaneous
    • Imposed by mutual inductive coupling
  – Development of shorts in Bitter magnets
  – Explore parameter space
    • Shield heating
    • Switching-off delay of power supply
• Results
The Grenoble Hybrid Magnet

- Resistive magnet structure
- Bore tube
- Eddy-current shield
- Superconducting magnet
- Polyhelix magnet
- Bitter magnets
- Helium tank
- Ferrules
- Plate
Coils and shields of the Grenoble Hybrid Magnet

Dimensions not to scale
Inner/outer radii are listed
Magnetic centers have to be aligned
Axial magnetic spring constant: 25 kN/mm
The Cu shield

- 30 K
- $\rho = 0.85 \text{ n}\Omega\text{m}$
- RRR = 44
- 25 mm Cu
- 29 mm SS
- 1.4 m high
- Shrink-fit
- Reduces AC losses
Worst case scenario

Axial force between concentric magnetic centers of two coil system:

\[ F_{x1} = -2\pi \int_{b-\Delta z}^{b+\Delta z} \int_{a_1}^{a_2} J_{\theta 1}(r) B_{r2}(r, z) r^2 \, dr \, dz \]

\( F_{x1} \) is maximum when half coil is shorted

Worst case scenario:
both Bitter coil halves suppressed

New magnetic centers realign
Design requirement
Shield(s) make interaction time dependent

Courtesy: Y. Iwasa
The two Bitter magnets and different short scenarios

Bitter coils before (a) and after possible accidents
Electrically equal to the case of a short in the midplain
Worst-case scenario approach 1

- Perfect short at $t = 0$ in $\Delta t = 0$ (immediate energy transfer)
- Conservation of flux: current jump
- Current flows via freewheeling diode
- Magnet housing ($\tau \approx \text{ms}$)
- Cu shield ($\tau \approx \text{s}$)
- Helix magnet not considered
Results for immediate energy transfer

Ultimate forces (left) on
• Bitter magnet (continuous line),
• magnet housing (dotted) and
• shield (dashed)

Ultimate force on outsert by Aubert (red) and Trophime (black)
Worst-case scenario, approach 2

• Questions:
  – $\Delta t = 0$
    • Development of a short
    • Transfer of energy
  – Electrical circuit
    • Power supply/filter
    • Current jump
  – Other
    • Shield temperature
    • Energy balance
Development of a short

Short between 2 Bitter disks

- no high voltage spike
- \( \frac{dV}{dt} \)
- Short resistance: \( 35 \, \mu\Omega \rightarrow 0 \) in 10 ms
- \( \frac{dI}{dt} \): 90 A/30 ms

➤ Short develops fast
➤ Energy transfer from shorted turn to coil and reaction of power supply is slow

Courtesy of Ph. Sala
Simulation of electrical circuit with PSIM

L11 = 1.13mH
L22 = 1.13mH
L33 = 0.79mH
L44 = 0.79mH
M11,22 = 0.42mH (K=0.37)
M11,44 = 0.62mH (K=0.65)
M22,33 = 0.62mH (K=0.65)
M33,44 = 0.28mH (K=0.35)
Currents I1 and I2 after switching-on and short

Time constants for realistic energy transfer
Black: actual coupling (k = 0.36 and 0.65) → $\tau_{I1} = 422 \text{ ms}$ and $\tau_{I2} = 403 \text{ ms}$
Red: no coupling (k = 0), green: strong coupling (k = 0.94)
Bitter magnet alone: $\tau = 750 \text{ ms}$
Final comparison of results of ultimate forces

Ultimate forces on
- Bitter magnet (continuous line)
- magnet housing (dotted)
- shield (dashed)
Final comparison of results of ultimate forces

<table>
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<tr>
<th>Force [kN]</th>
<th>Time [ms]</th>
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<td>1.0E-01</td>
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</tr>
</tbody>
</table>

Ultimate forces on:
- Bitter magnet (continuous line)
- magnet housing (dotted)
- shield (dashed)

Parameter space:

Energy transfer:
- a) immediate
- b) realistic

Conservation of:
- c) flux
- d) flux and energy

Shield temperature:
- e) constant
- f) increasing

Switch-off time of power supply:
- g) 50 ms
- h) 100 ms

Red: Aubert  a, c, e, g
Black: Trophime a, c, e, h
Green: Eyssa  a, d, f, h
Blue: Eyssa  b, d, f, h
Final comparison of results of ultimate forces

Parameter space
Energy transfer
a) immediate
b) realistic

Immediate energy transfer:
• results correspond quite well

Realistic energy transfer:
• Force on shield
  3.7/4.4 MN → 1.5 MN
• Within insert
  5/6 MN → 0
• Force on outsert
  210 kN → 130 kN

Ultimate
• Bitte
• mag
• shiel

Red: Aubert a, c, e, g
Black: Trophime a, c, e, h
Green: Eyssa a, d, f, h
Blue: Eyssa b, d, f, h
Final comparison of results of ultimate forces

Parameter space
Energy transfer

- A) without shield:
  - force on outsert = force on insert
  - Assumption of constant current source not correct
  - Switch-off delay determines forces
  - Example: 3 MN (∞)
    - → 1.5 MN (100 ms)
    - → 0.7 MN (50 ms)

- B) with shield:
  - force on outsert = difference current decay between shield/insert
  - Controlled switch-off could reduce forces → 0

Ultimate forces on
- Bitter magnet (continuous line)
- magnet housing (dotted)
- shield (dashed)
Ultimate forces for realistic energy transfer

- Shield reduces and delays force peak
- Switching-off delay determines savings in support structure
- Fail save redundant switching-off required
Summary

• Two approaches to worst-case scenario investigated
• Parameter space explored
  1. Immediate/realistic energy transfer
  2. Conservation of flux/energy
  3. Constant or changing shield temperature
  4. Switch-off time of power supply
• Dramatic differences only for 1) and 4)
  – Shield/insert: 3.7/4.4 MN → 1.5 MN
  – SC magnet: 210 kN → 130 kN
  – Magnet housing/Bitter magnet: 5/6 MN → 0
  – Shield/insert: 1.5 MN → 0.7 MN for switch-off time
    100 ms → 50 ms
• Structure adequate for higher power levels (36 MW)
• Time development of forces also true for hybrids without shield
  PS switching-off time determines ultimate forces
References

• G. Aubert, « Etude d’un incident sur un aimant hybride », LNCMI, 2011, guy.aubert@ext.univ-poitiers.fr

• Y. Eyssa, “Force calculations of the Worst Case Scenario for the Grenoble Hybrid magnet”, LNCMI Grenoble, May 2013, y_eyssa@hotmail.com

• Ch. Trophime, « Projet Hybride II, Calcul des forces, version révisée », LNCMI, Grenoble, February 2012, christophe.trophime@lncmi.cnrs.fr

• Powersim, www.powersimtech.com

• Ph. Sala et al., Transient recoding system, MT-25, philippe.sala@lncmi.cnrs.fr
Change of current density in the upper and lower magnet half of the inner Bitter magnet after the incident

At $t = 0$: $J_{\text{inner}} = 88.15 \, \text{A/mm}^2$ of the inner magnet $R1 \rightarrow I_1 = I_2 = 33 \, \text{kA}$. $\tau_{\text{dump}} = 1\,\mu\text{s}, 100 \, \text{ms}, 400 \, \text{ms}$. From PSIM: $\tau_{I_1} = 422 \, \text{ms}$ and $\tau_{I_2} = 403 \, \text{ms}$