Ultimate Forces of the Grenoble Hybrid Magnet

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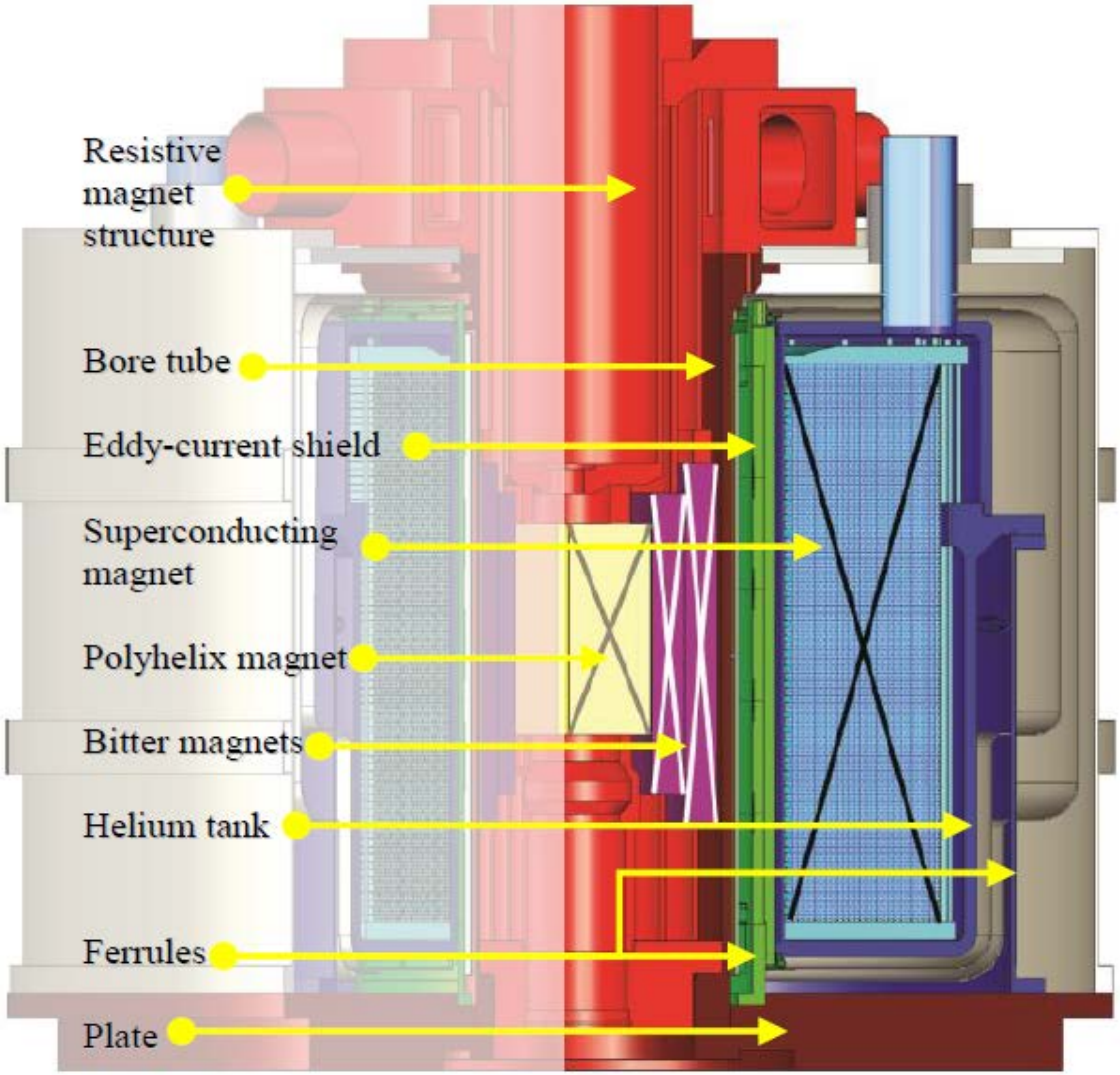
Outline

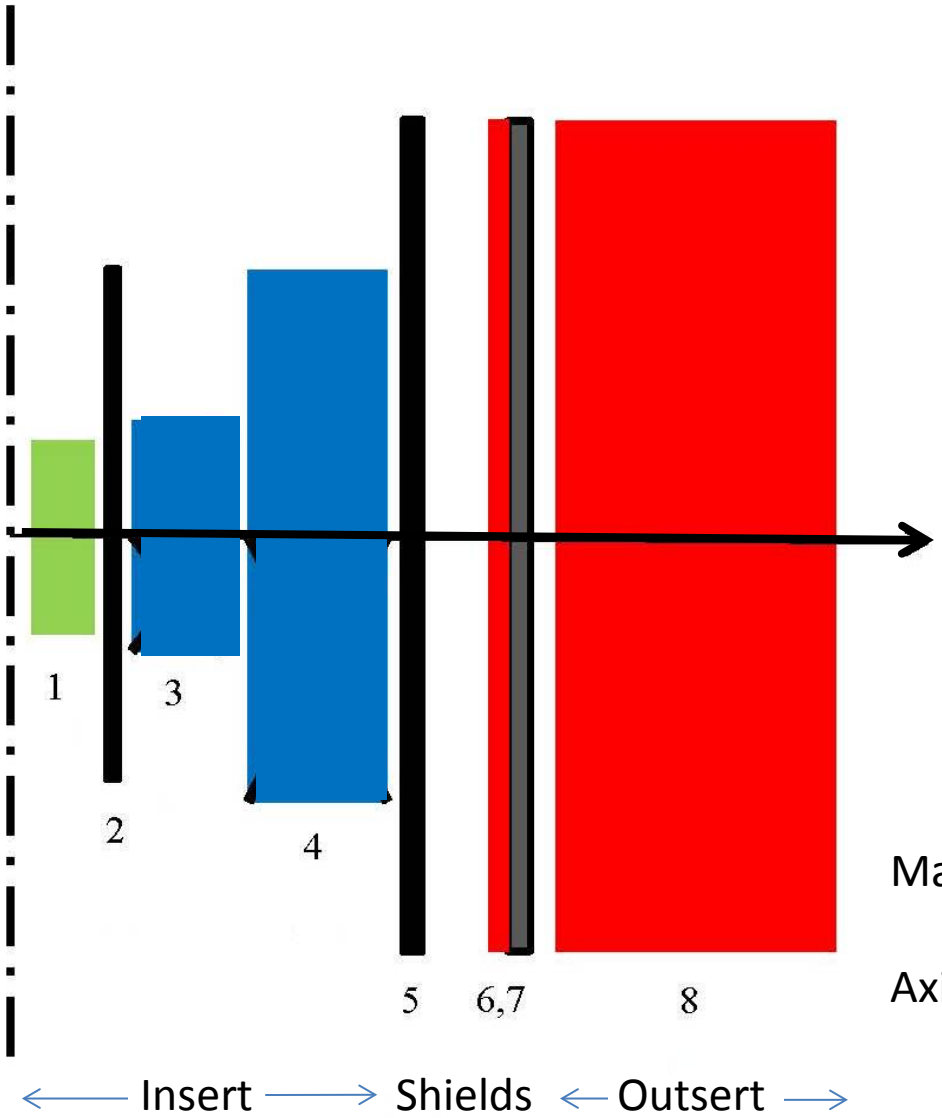
- Introduction
- Worst-case scenario
- Two approaches investigated
  - Energy transfer from shorted coil halves
    - Instantaneous
    - Imposed by mutual inductive coupling
  - Development of shorts in Bitter magnets
  - Explore parameter space
    - Shield heating
    - Switching-off delay of power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

The Grenoble Hybrid Magnet



[courtesy of B. Hervieu]

Coils and shields of the Grenoble Hybrid Magnet



1	Polyhelix magnet	0.019/0.186 m
2	SS wall	0.19/0.195 m
3	Inner Bitter coil	0.2/0.3 m
4	Outer Bitter coil	0.305/0.401 m
5	Magnet housing	0.406/0.431 m
6	Cu shield	0.471/0.496 m
7	SS reinforcement	0.496/0.525 m
8	SC magnet	0.505/0.913 m

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

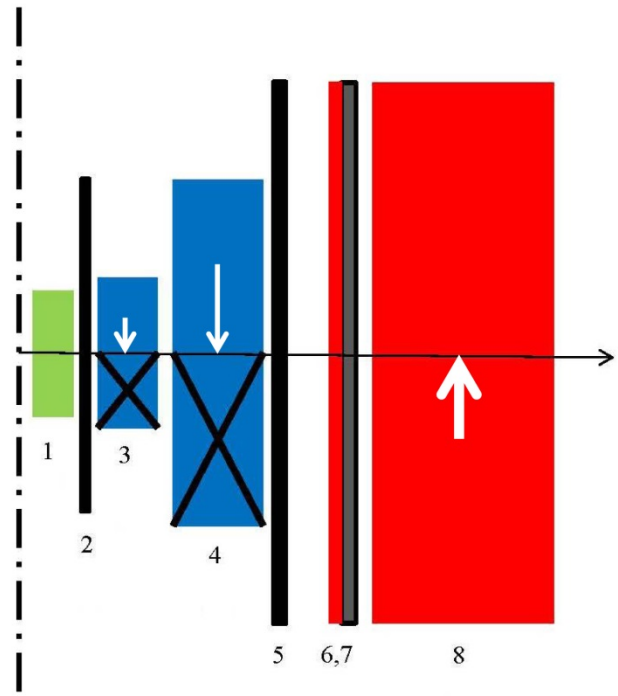
- 30 K
- ρ = 0.85 nΩm
- RRR = 44
- 25 mm Cu
- 29 mm SS
- 1.4 m high
- Shrink-fit
- Reduces AC losses

Worst case scenario

Axial force between concentric magnetic centers of two coil system:

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

Courtesy: Y. Iwasa

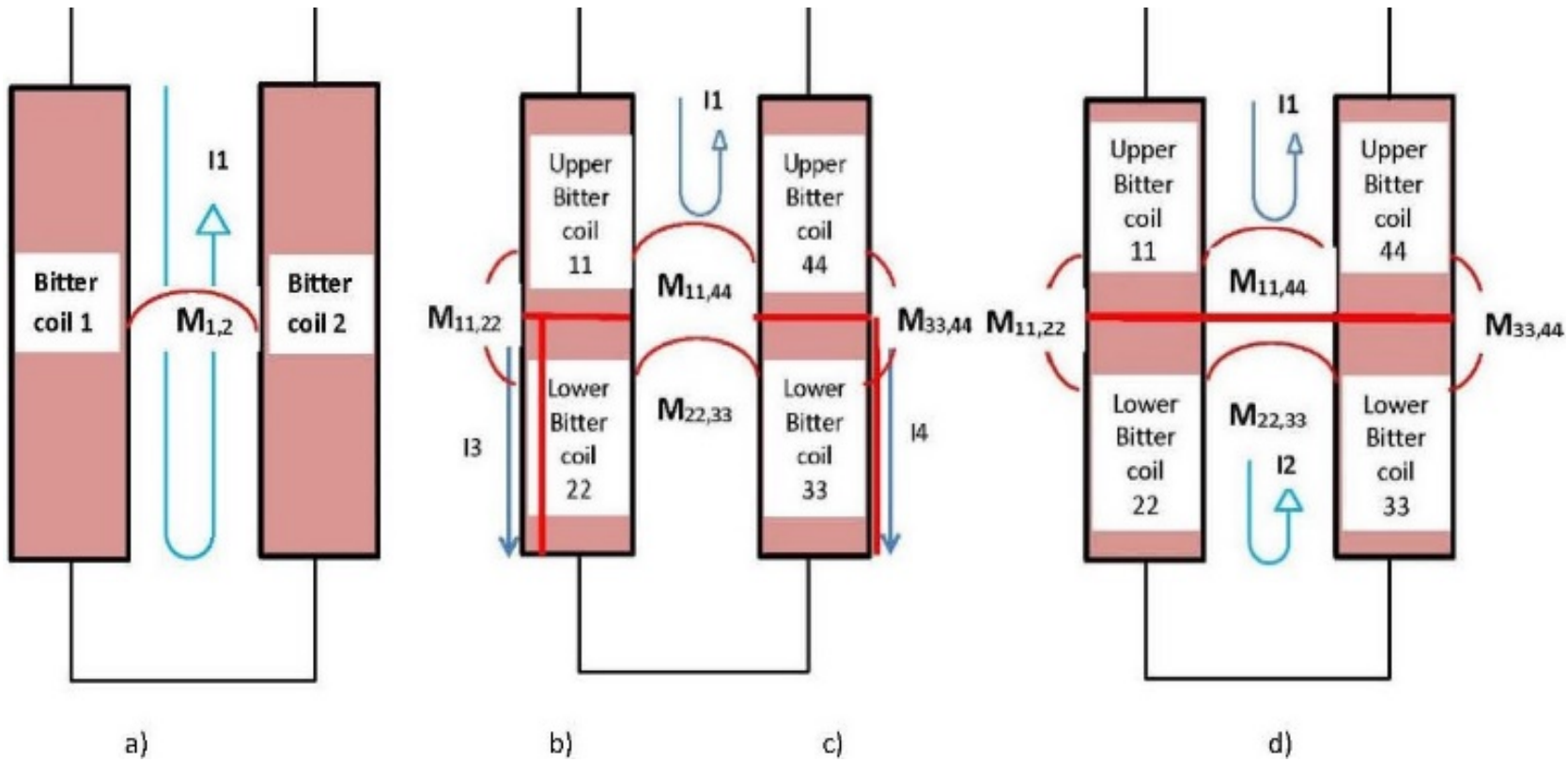


F_{x1} is maximum when half coil is shorted

<u>Worst case scenario</u>:
both Bitter coil halves suppressed

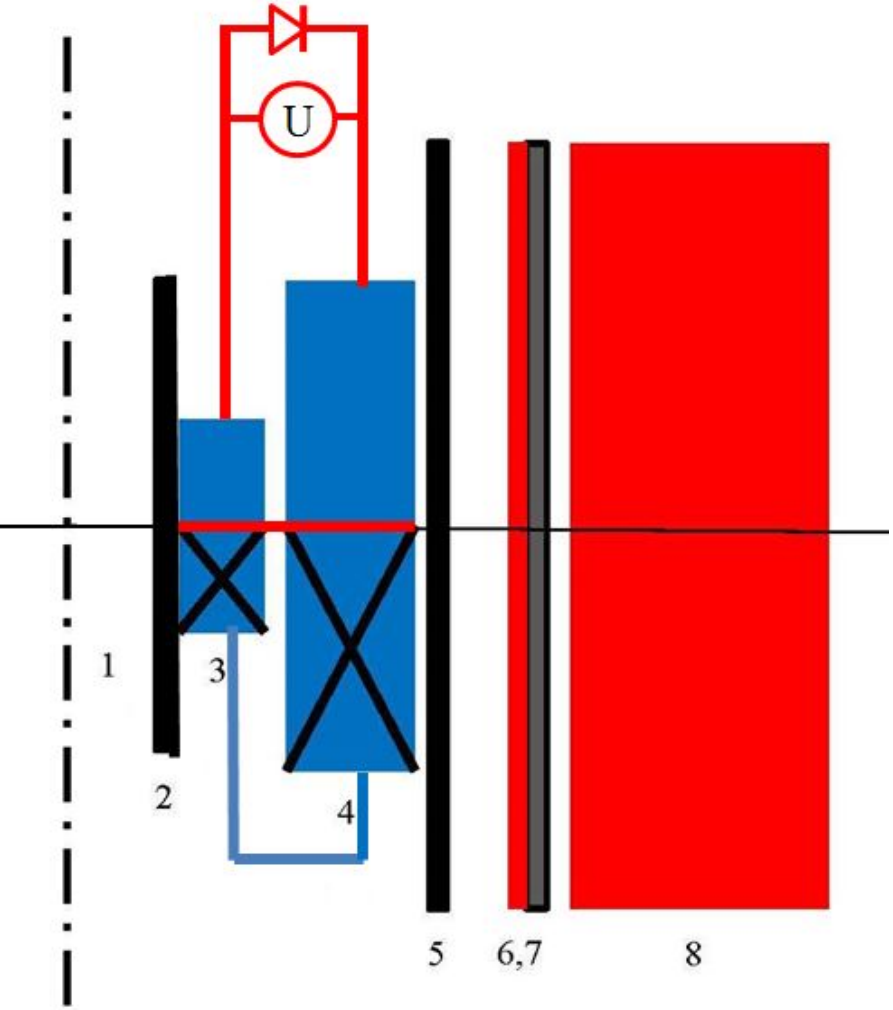
New magnetic centers realign
Design requirement
Shield(s) make interaction time dependent

The two Bitter magnets and different short scenarios



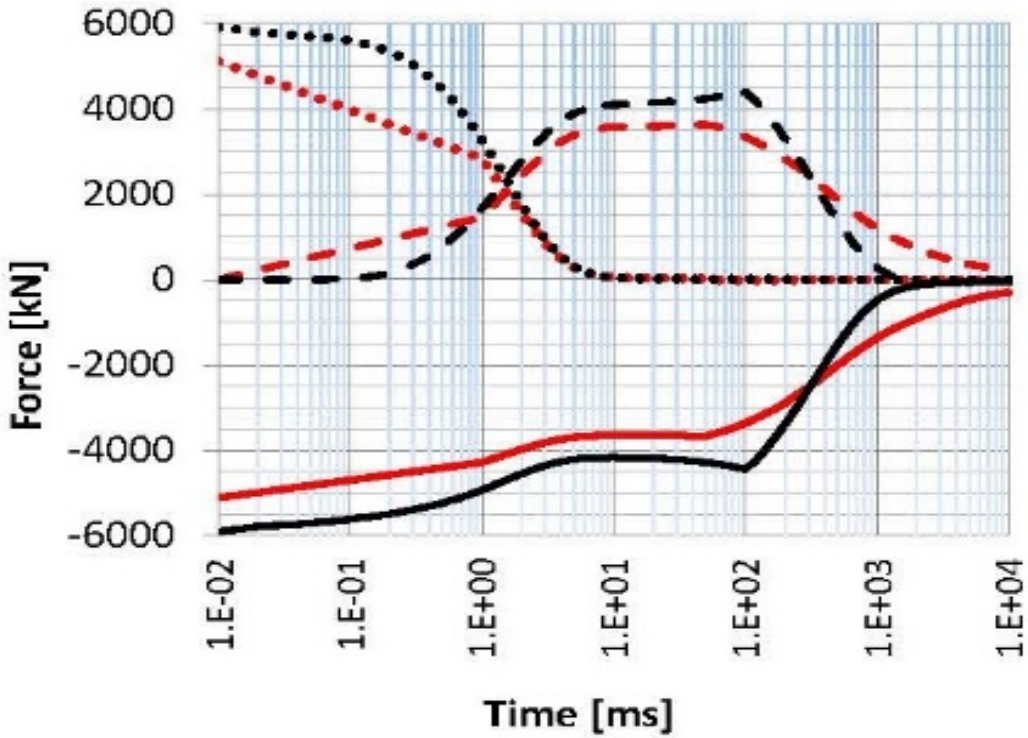
Bitter coils before (a) and after possible accidents
Electrically equal to the case of a short in the midplain

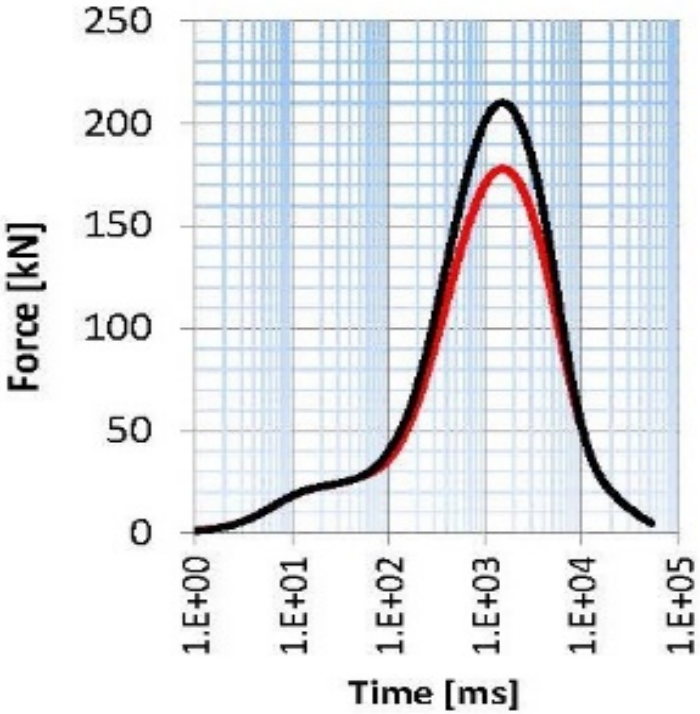
Worst-case scenario approach 1



- Perfect short at t = 0 in Δ t = 0 (immediate energy transfer)
- Conservation of flux: current jump
- Current flows via freewheeling diode
- Magnet housing (τ ≈ ms)
- Cu shield (τ ≈ s)
- Helix magnet not considered

Results for immediate energy transfer





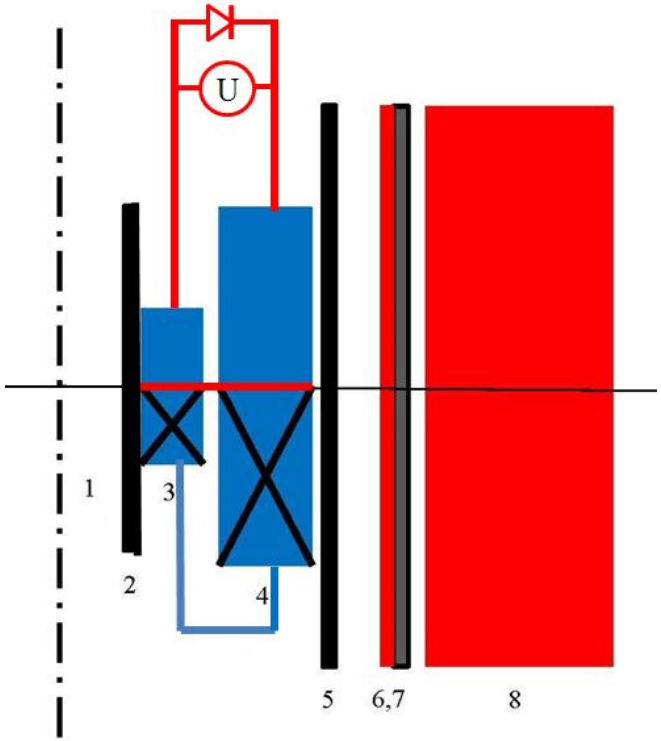
Ultimate forces (left) on
- Bitter magnet (continuous line),
- magnet housing (dotted) and
- shield (dashed)

Ultimate force on outsert

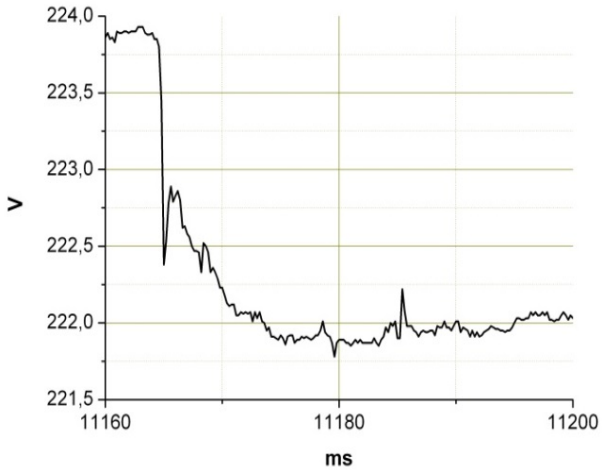
by Aubert (red) and Trophime (black)

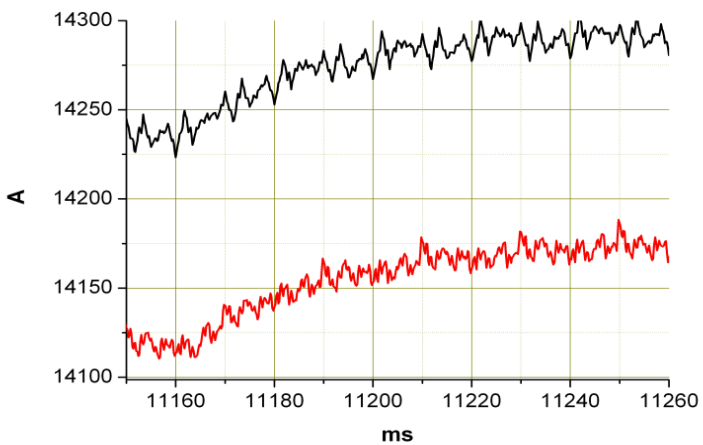
Worst-case scenario, approach 2

- Questions:
  - Δ 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





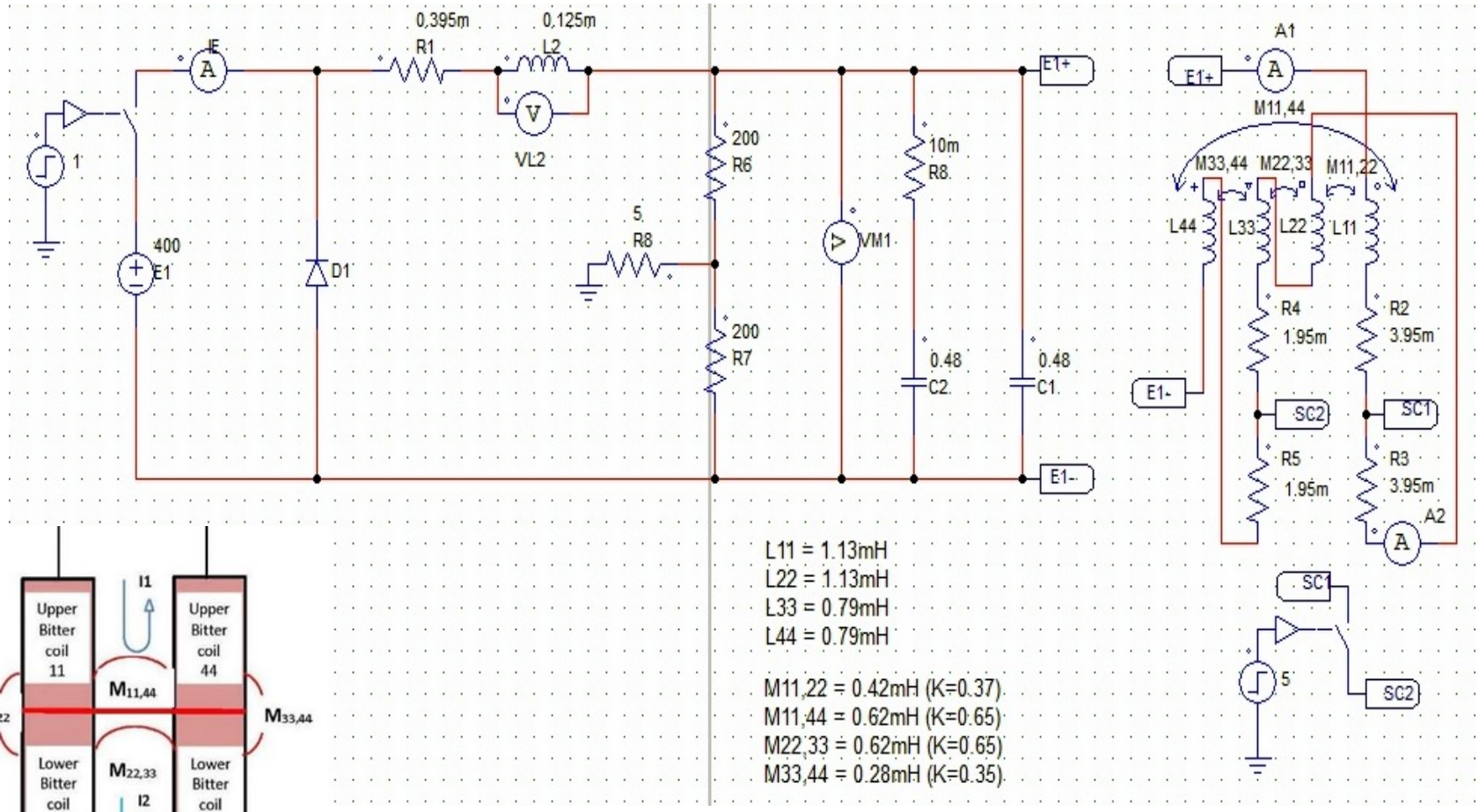
Courtesy of Ph. Sala

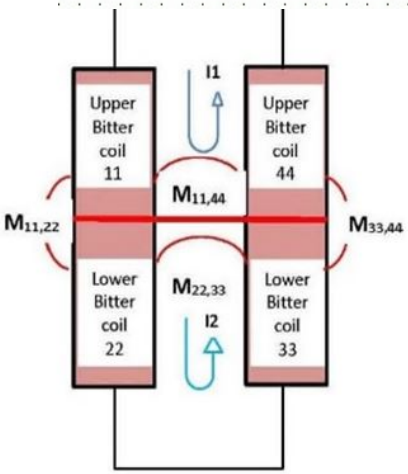
Short between 2 Bitter disks

- no high voltage spike
- dV/dt
- Short resistance: 35 μΩ → 0 in 10 ms
- dI/dt: 90 A/30 ms

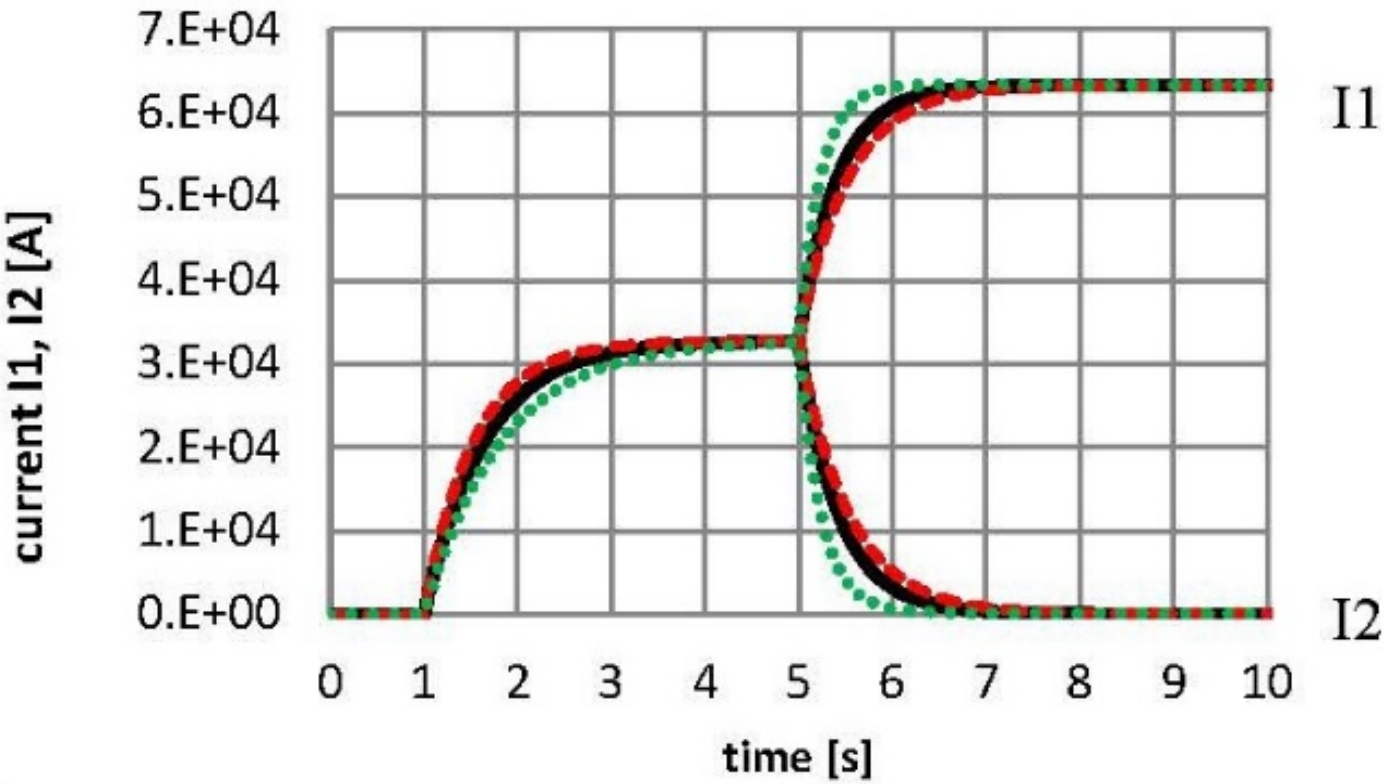
➢ Short develops fast
➢ Energy transfer from shorted turn to coil and reaction of power supply is slow

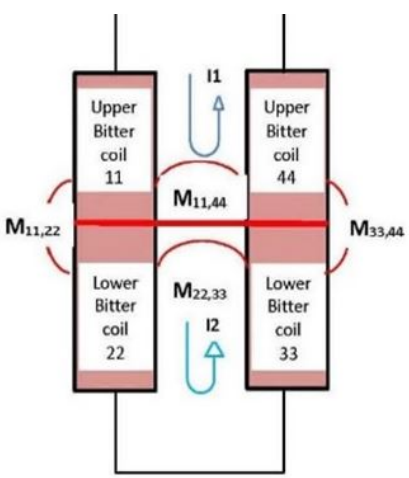
Simulation of electrical circuit with PSIM





Currents I1 and I2 after switching-on and short





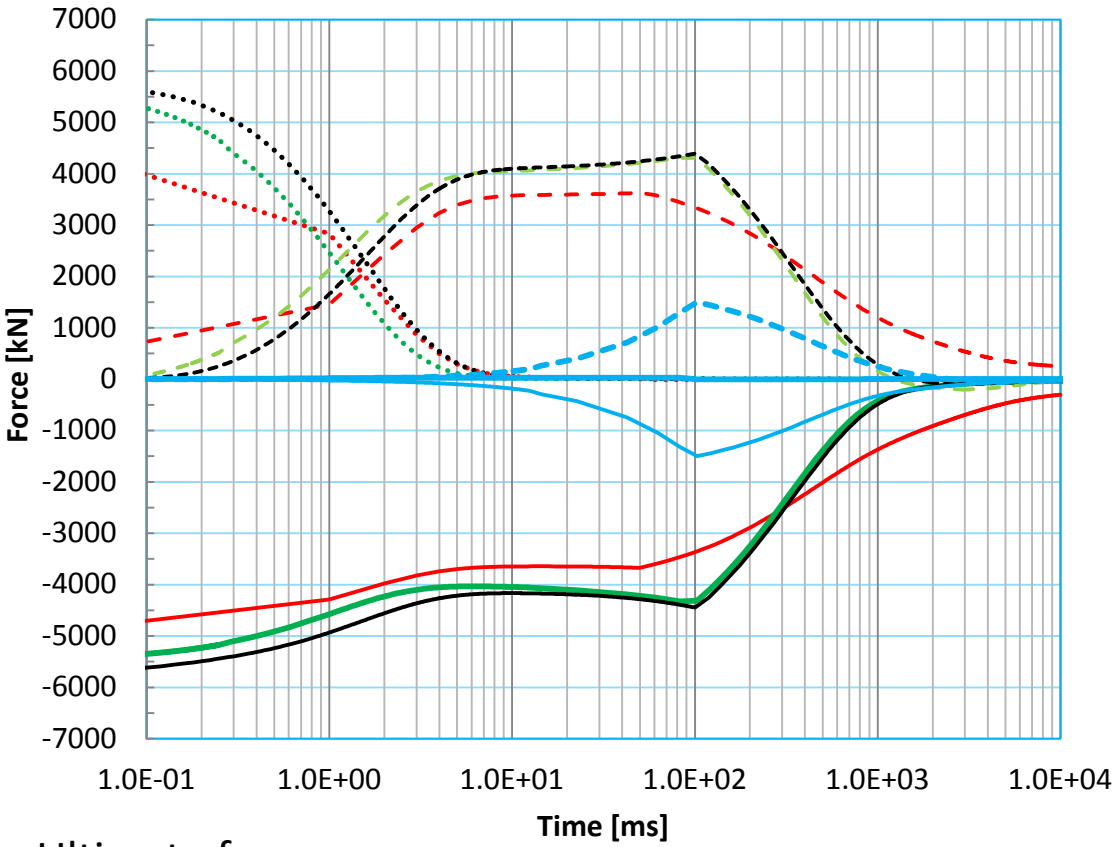
Time constants for <u>realistic</u> energy transfer

Black: actual coupling (k = 0.36 and 0.65) → **τ_{I1} = 422 ms and τ_{I2} = 403 ms**

Red: no coupling (k = 0), green: strong coupling (k = 0.94)

Bitter magnet alone: τ = 750 ms

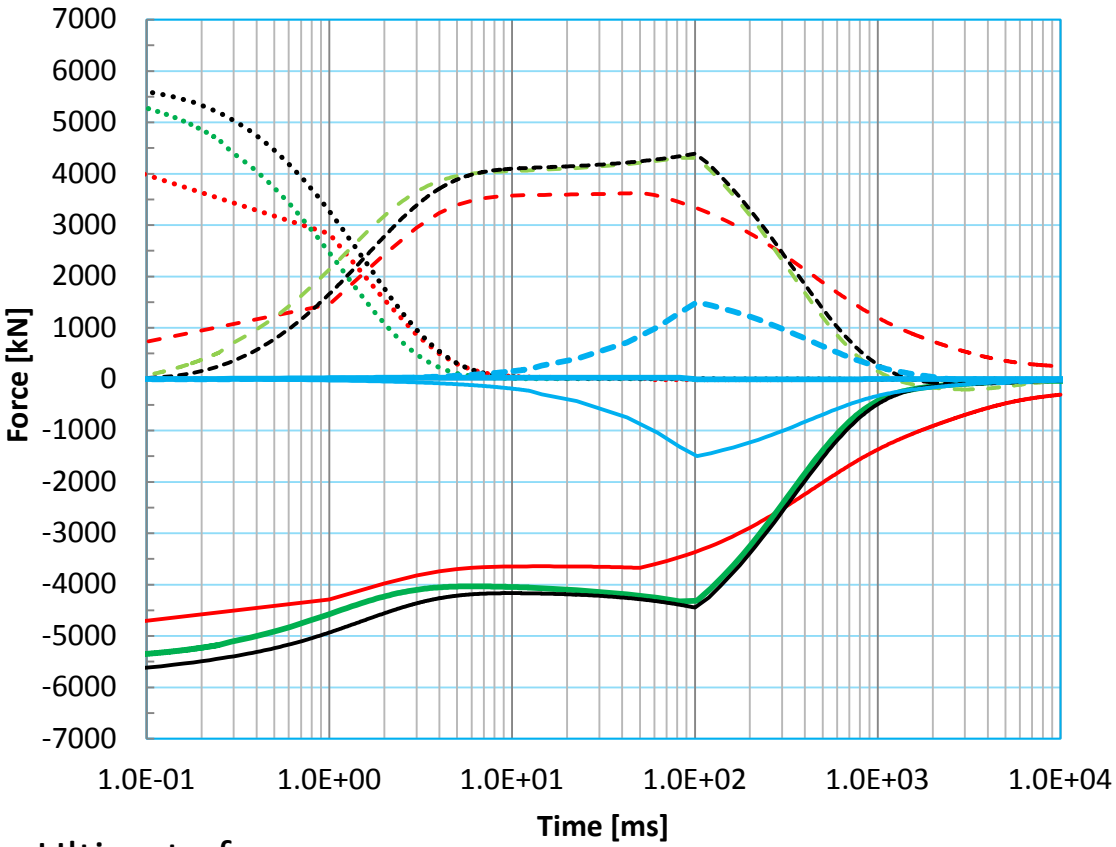
Final comparison of results of ultimate forces



Ultimate forces on

- Bitter magnet (continuous line)
- magnet housing (dotted)
- shield (dashed)

Final comparison of results of ultimate forces



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

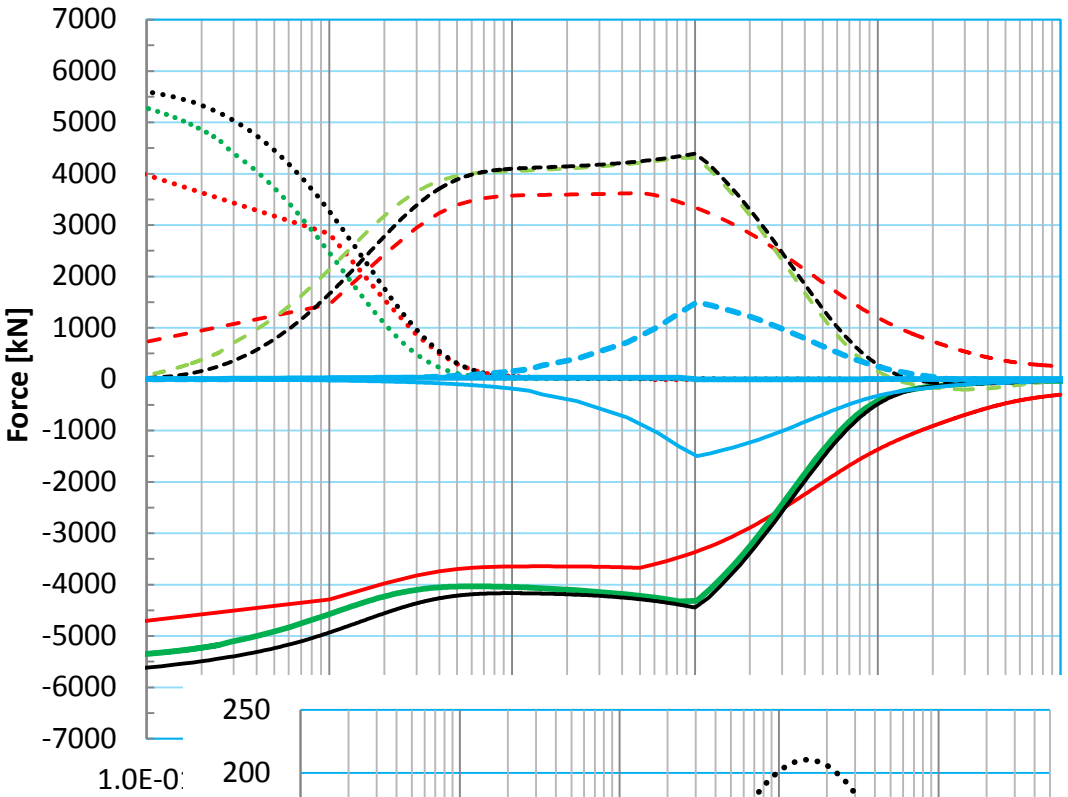
e) constant
f) increasing

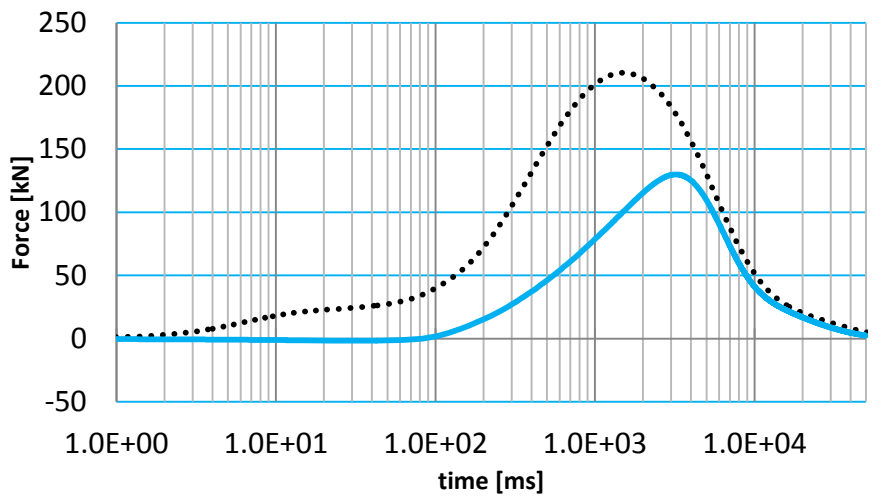
Switch-off time of power supply

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





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- Bitte
- mag
- shiel

Parameter space

Energy transfer

a) immediate

b) realistic

Immediate energy transfer:

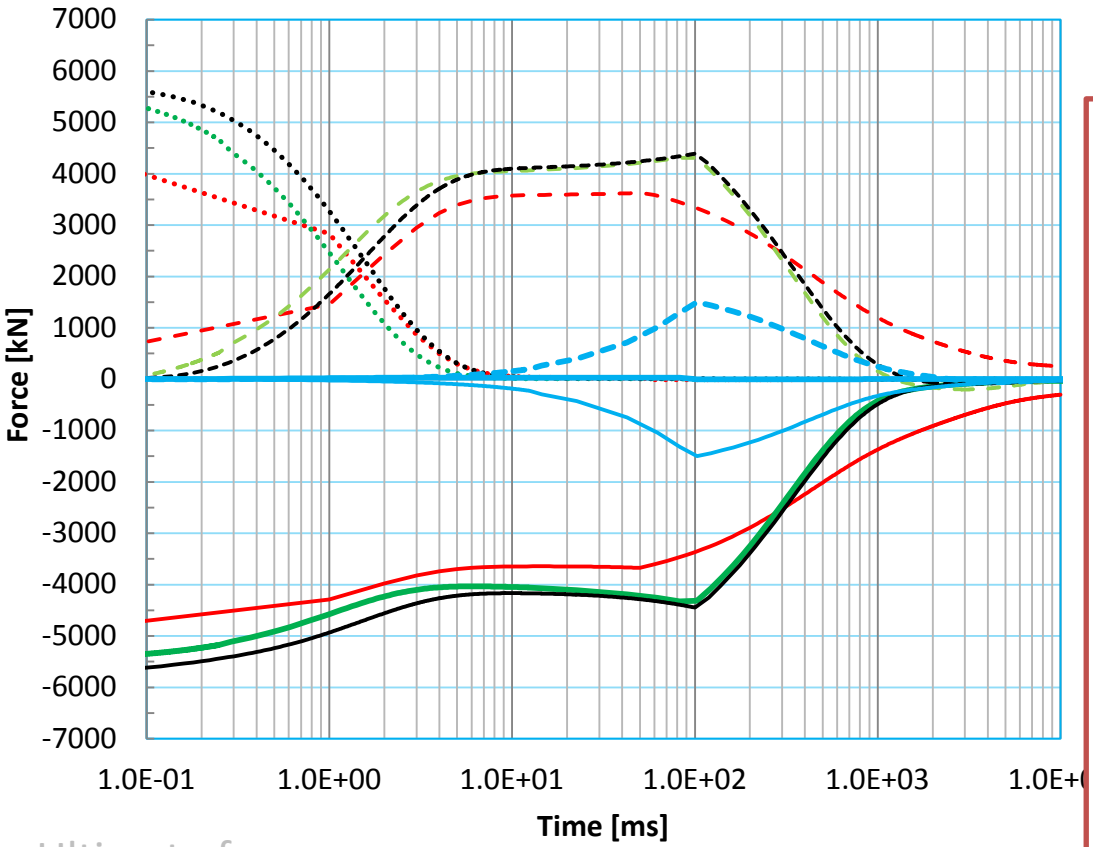
- results correspond quite well

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

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



Ultimate forces on

- Bitter magnet (continuous line)
- magnet housing (dotted)
- shield (dashed)

Parameter space

Energy transfer

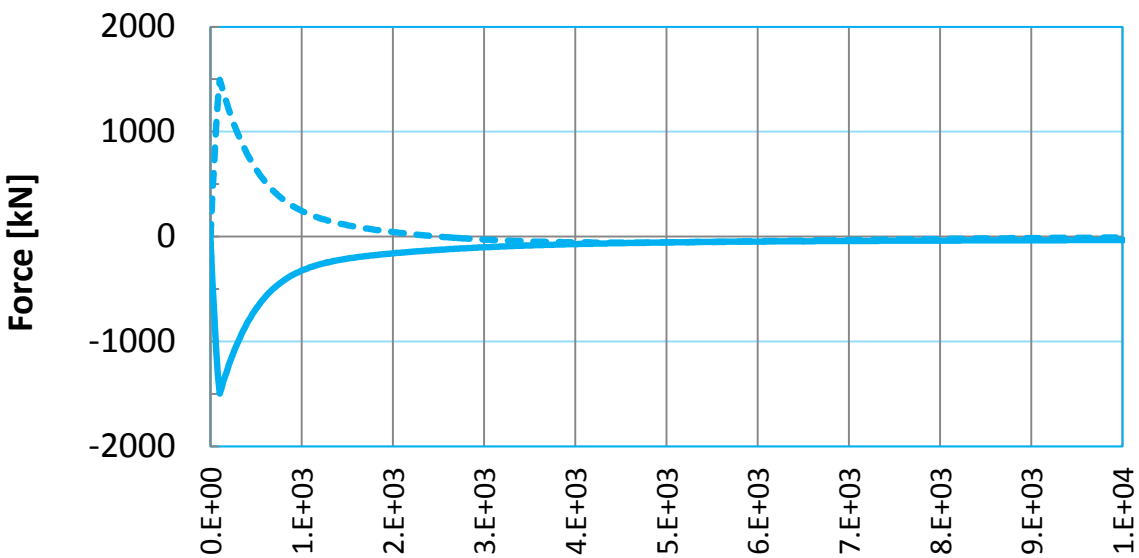
➢ **A) without shield:**

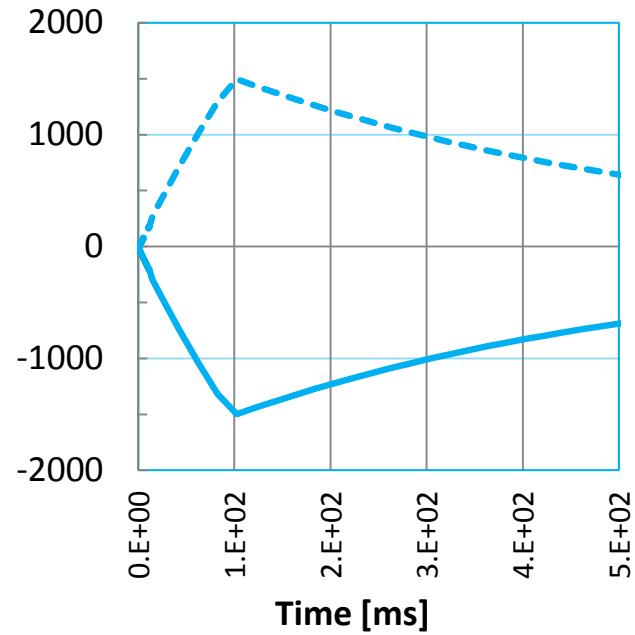
- force on outsert = force on insert
- Assumption of constant current source not correct
- Switch-off delay determines forces
- Example: 3 MN (∞)
  - → 1.5 MN (100 ms)
  - → 0.7 MN (50 ms)

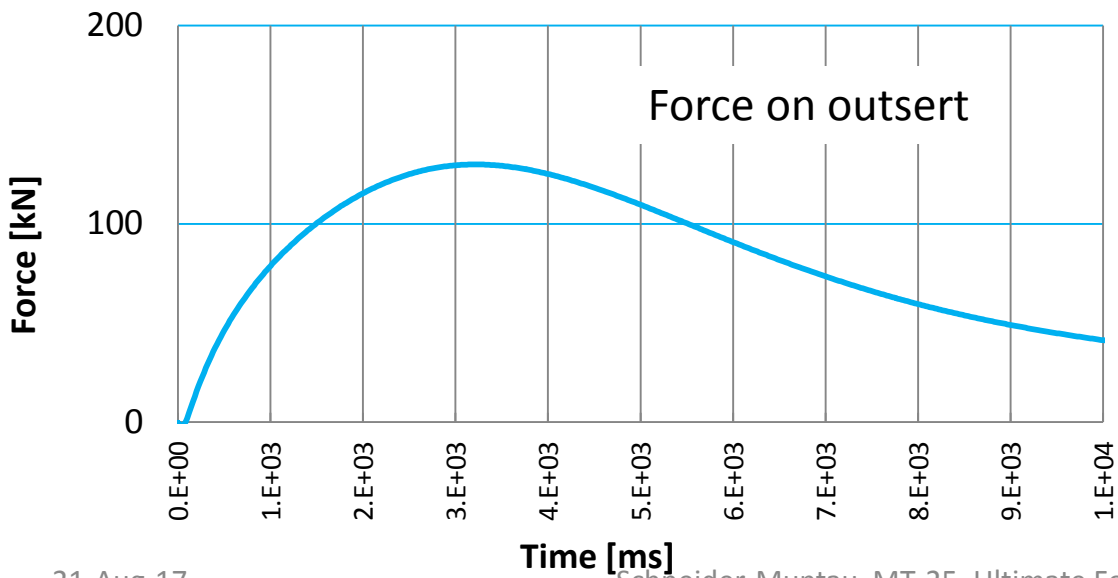
➢ **B) with shield:**

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

Ultimate forces for realistic energy transfer







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

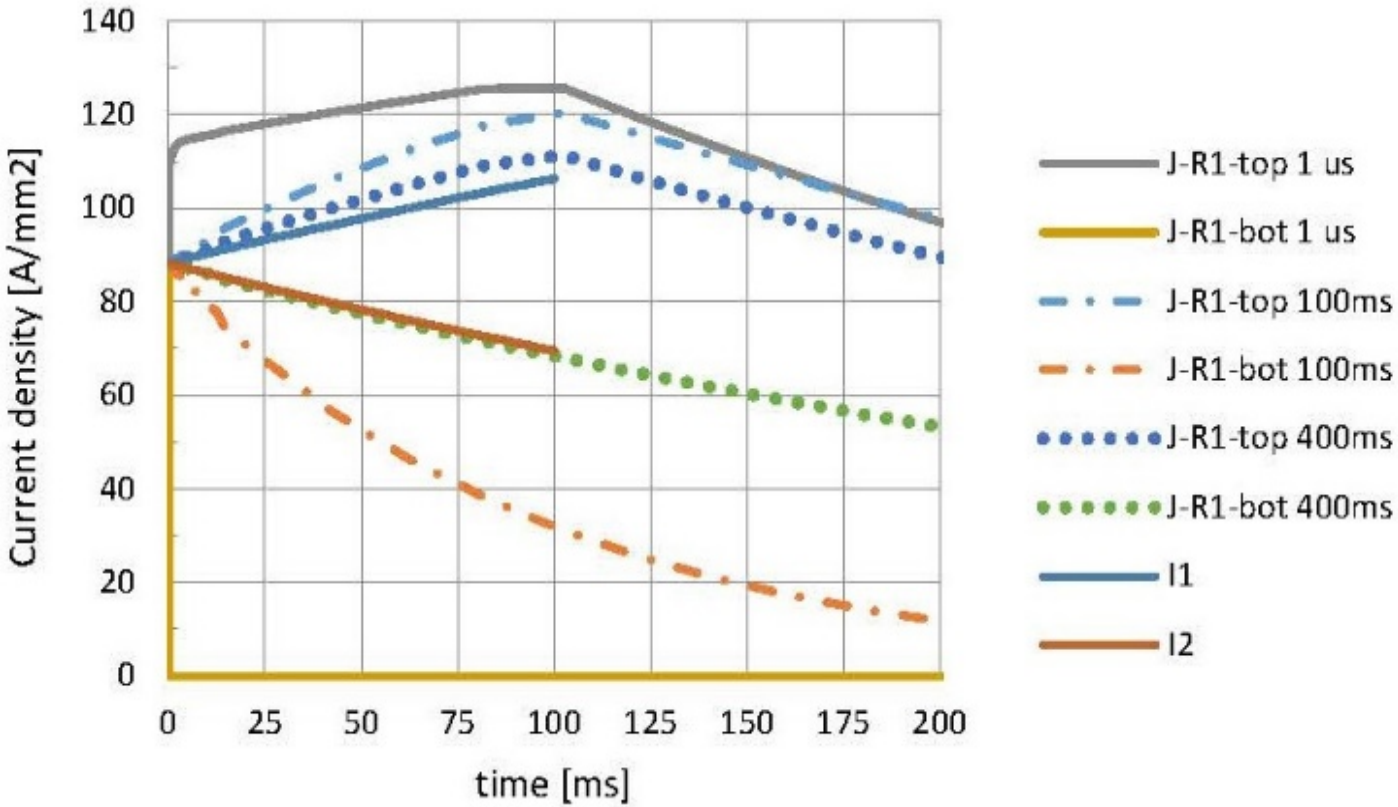
Summary

- 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_{inner} = 88.15 A/mm^2 of the inner magnet R1 → I1 = I2 = 33 kA.
τ_{dump} = 1µs, 100 ms, 400 ms. From PSIM: τ_{I1} = 422 ms and τ_{I2} = 403 ms