Impact of Failing Insert Coils on the Mechanical Design of the HFML 45 T Hybrid Magnet System

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Introduction

The Nijmegen 45 T hybrid magnet consists of 5 nested, water cooled Florida-Bitter type of resistive insert coils and a large superconducting outsert magnet.

The high power density resistive coils can fail due to local overheating, which may lead to melting, arcing, and electrical shorts in and between the different sub-coils. When part of a single sub-coil has become electrically short-circuited, the magnetic center of this coil no longer aligns with that of the other sub-coils of the resistive magnet and the superconducting outsert coil. This leads to large axial, so-called **fault forces** between the different coils, which develop on a time-scale of 1-300 ms.

The issues:

1. Which fault scenarios should be taken into account for the mechanical design of the coil support structures?
2. Is the commonly used static approach to calculate the so-called ultimate fault forces realistic?

Magnet properties

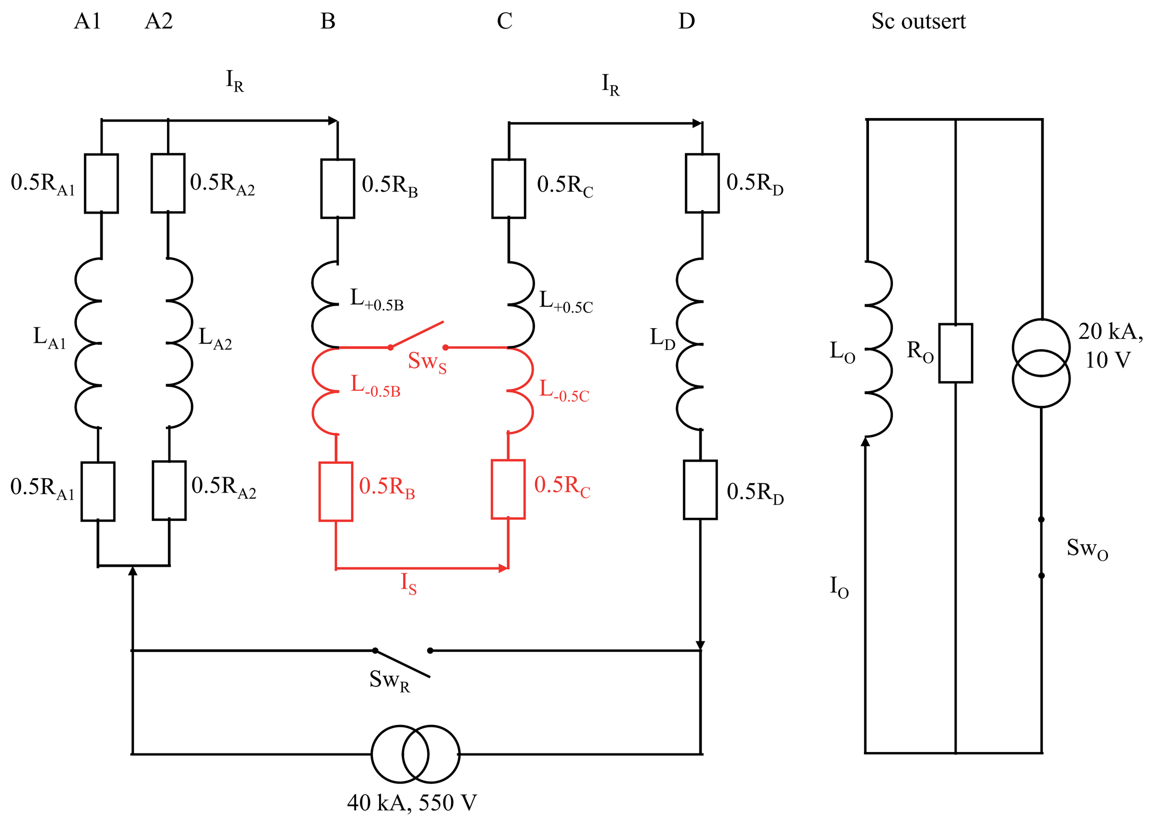
General properties of the hyrbdi magnet

Property	Insert	Outsert
Operating current [A]	40,000	20,000
Contribution to field [T]	33.0	12.3
Free RT bore diameter [mm]	32	620
Cooling medium	forced flow water ~150 l/s	supercritical helium 11 g/s @ 5 bar
Operating temperature [K]	< 360	4.6
Self-inductance [mH]	5	266
Mutual inductance [mH]	11	11
(dump) Resistance [mΩ]	13.1	130/2.5
Decay time constant [s]	0.3	2.0/106
Required power [MW]	21.5	0.2
Stored energy [MJ]	5	55

Some relevant properties of the resistive insert

Property	A1	A2	B	C	D
Coil current [kA]	13	27	40	40	40
Current density [A/mm^2]	603	345	214	111	95
Power density [W/mm^3]	9.9	3.1	1.2	0.23	0.17
Uncooled heating rate [K/s]	2868	900	338	67	50
Winding Voltage [V]	1.96	2.04	2.68	1.59	2.07

Insert failure modes



Timing coil protection system

- Short in a resistive coil: immediate voltage drop (t = 0 ms)
- Detect if voltage drop > 3 V threshold (t = 20 ms)
- Switch of both power converters (**t = 40 ms**)

Ultimate fault forces are calculated assuming steady state conditions, maximum current in normal operating coils and zero current in short-circuited sections, which is equivalent to a defective protection system.

Single coil fails
A short occurs in a single coil and propagates mainly axially within this coil.
Ultimate fault force: entire half coil vanishes.

Failing coil ->	A1	A2	B	C	D
A1	-82	98	54	29	25
A2	27	-537	392	208	180
B	33	266	-1231	722	660
C	6	44	200	-2551	1766
D	11	91	415	858	-4754
SCM	5	37	169	734	2122
Probability	High			Extremely low	
Fault develops over half a coil	Unlikely			Impossible	
Forces	Sustainable		Med.	Large	

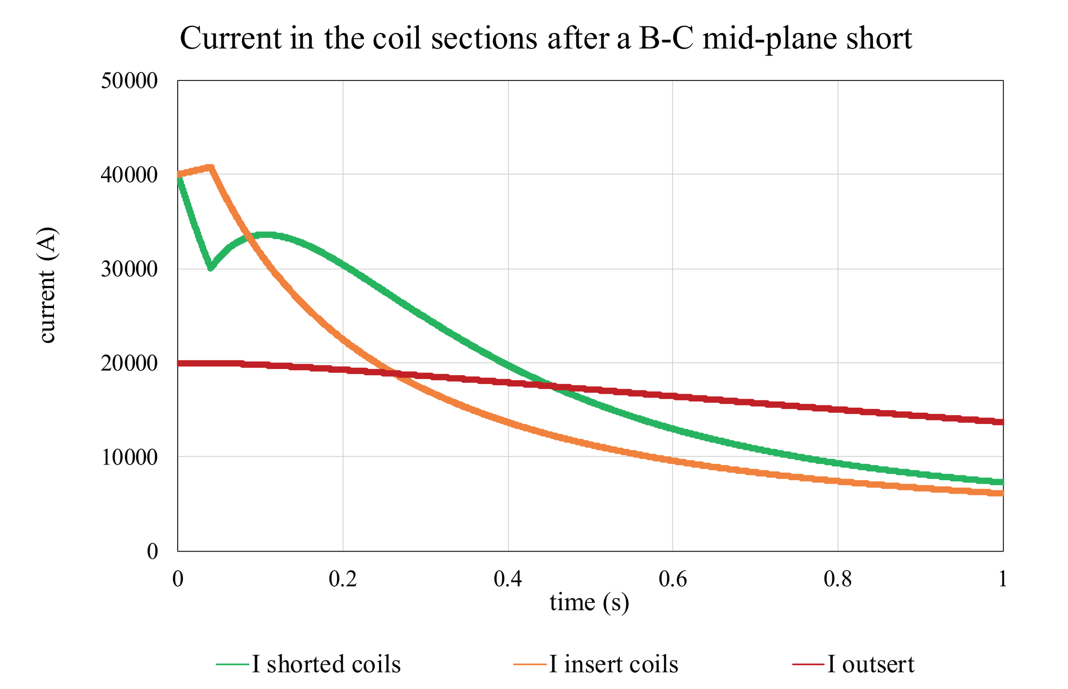
Mid-plane short-circuit between two adjacent coils.
The worst situation is a mid-plane short.
Ultimate fault force: no current in shorted half coils.

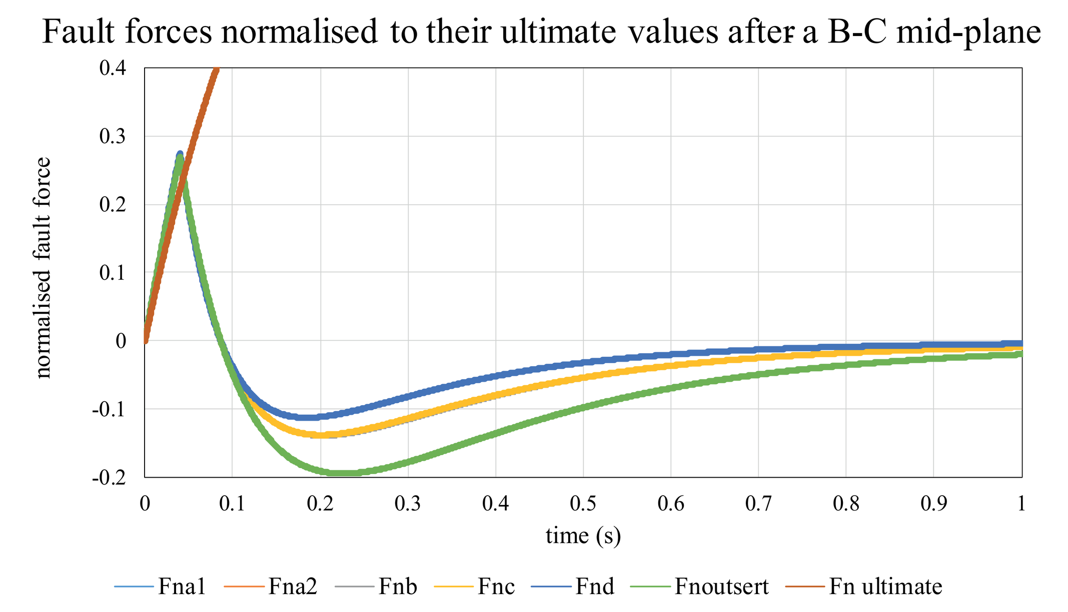
Failing coils ->	A1+A2	A2+B	B+C	C+D	A1+A2+B	A2+B+C	All
A1	-55	-153	83	-54	22	182	-125
A2	-439	271	600	-389	173	-227	-271
B	300	840	-1032	-1383	785	-640	-451
C	49	-244	-1829	1694	-249	-1620	536
D	103	-507	1274	2988	-519	1365	3377
SCM	42	-206	903	-2856	-211	940	-3067
Probability	High			Probable		Low	None
Forces	Sustainable		Very high		Sustain	High	High

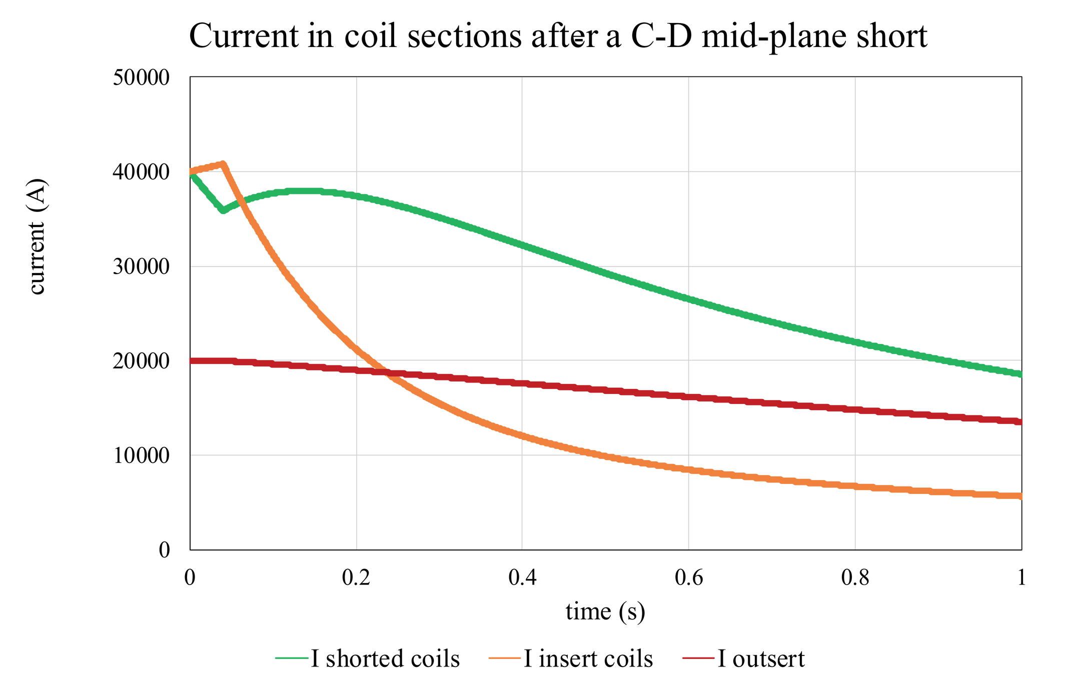
Provided coil protection works properly

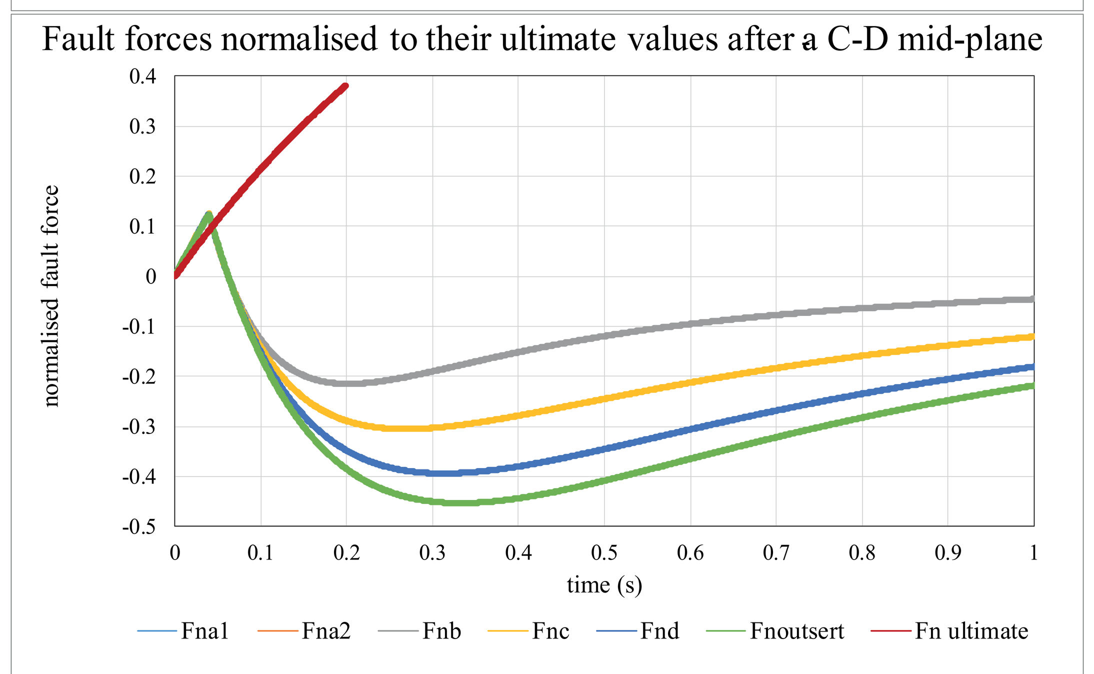
- All fault forces < 50% of ultimate forces
- Maximum depends critically on timing power convertor switching
- Direction of fault forces may even reverse

Mid-plane faults



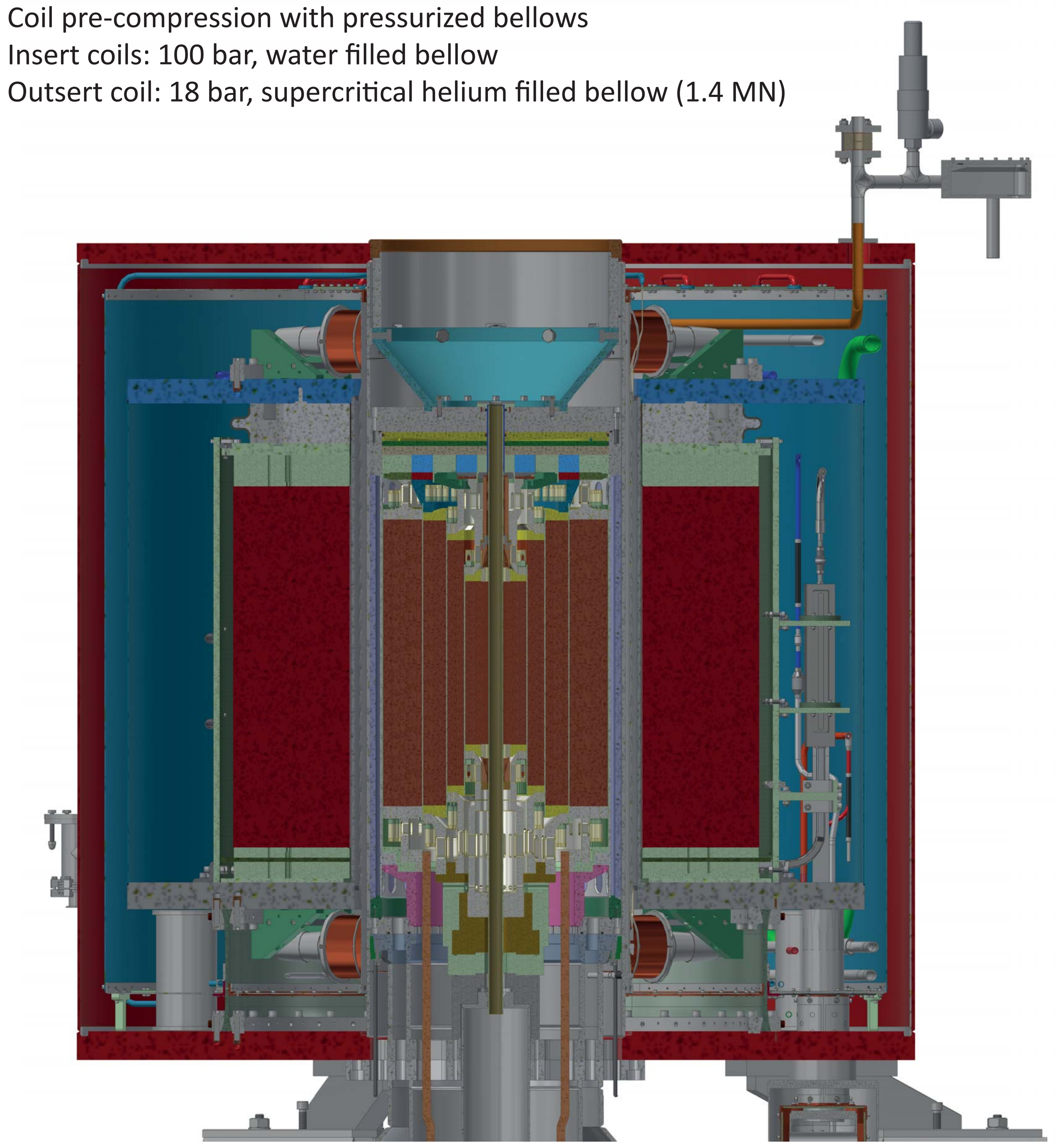






Coil Support Structures

Coil pre-compression with pressurized bellows
Insert coils: 100 bar, water filled bellow
Outsert coil: 18 bar, supercritical helium filled bellow (1.4 MN)



Conclusions

The steady state, ultimate fault force approach

- ignores the reliability of coil protection systems
- includes unrealistic fault scenarios
- overestimates conceivable fault forces by 100%

which results in over-conservative specifications for the coil support structures in hybrid magnets.

A more realistic approach to deal with fault forces

- assumes an operative coil protection system
- selects critical cases based on local power density in the coils
- includes an analysis of the temporal evolution of currents in the system, based on the specific behavior of the electrical components and a realistic switching sequence of the protective hardware.

NWO Netherlands Organisation for Scientific Research
EMFL European Magnetic Field Laboratory
Radboud University