Analysis of the Modified RB Circuit with 11 T Cryo-assembly
status update

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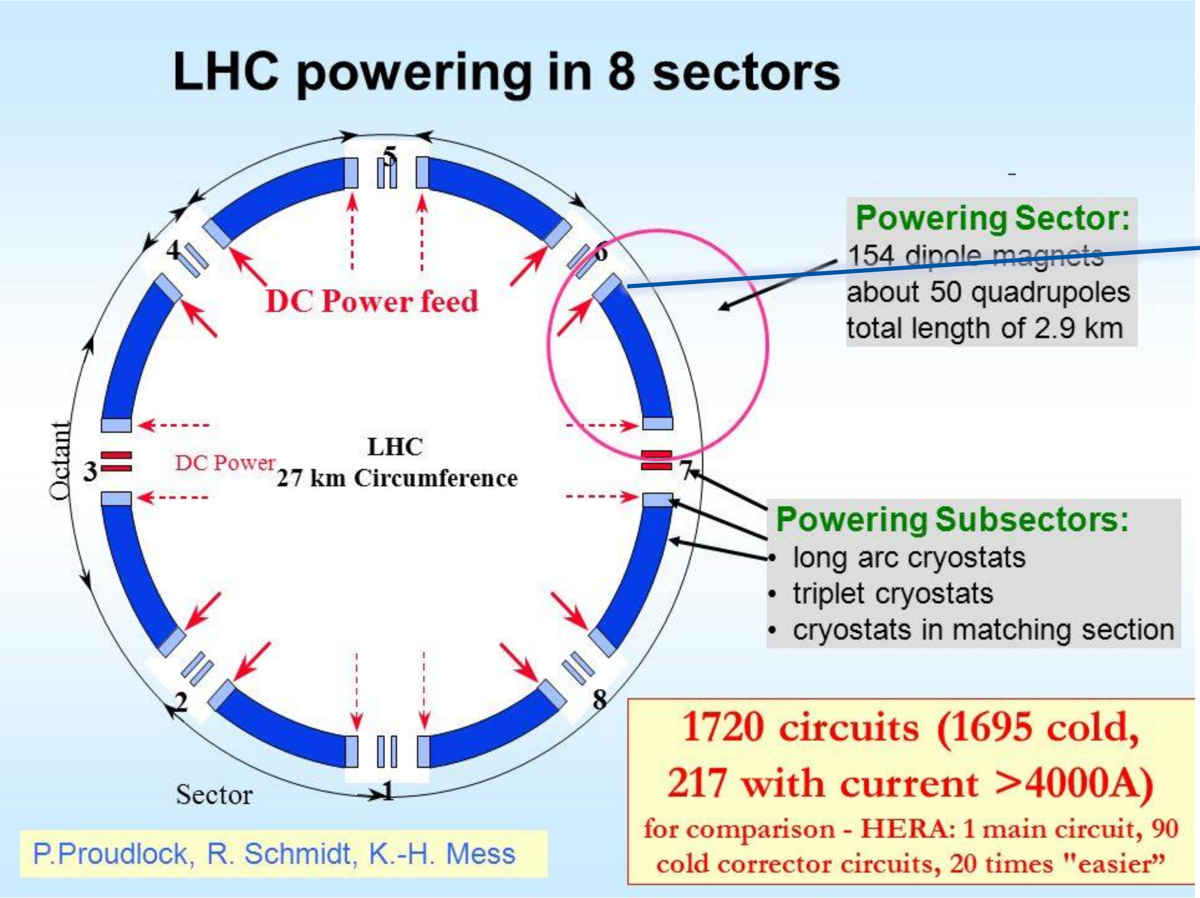
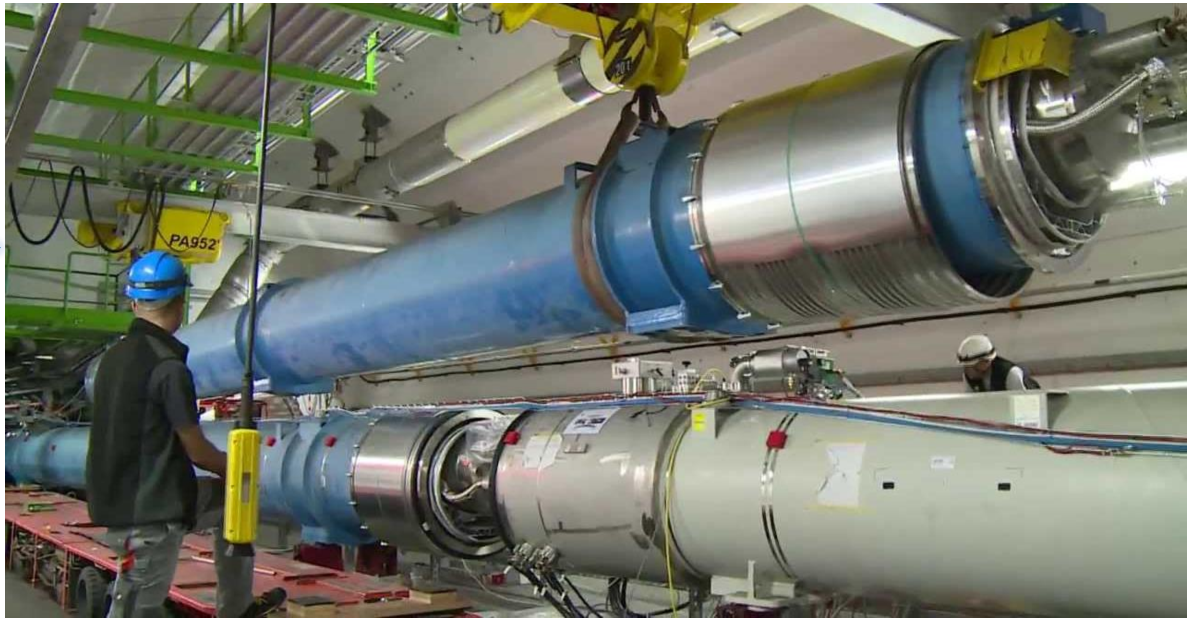
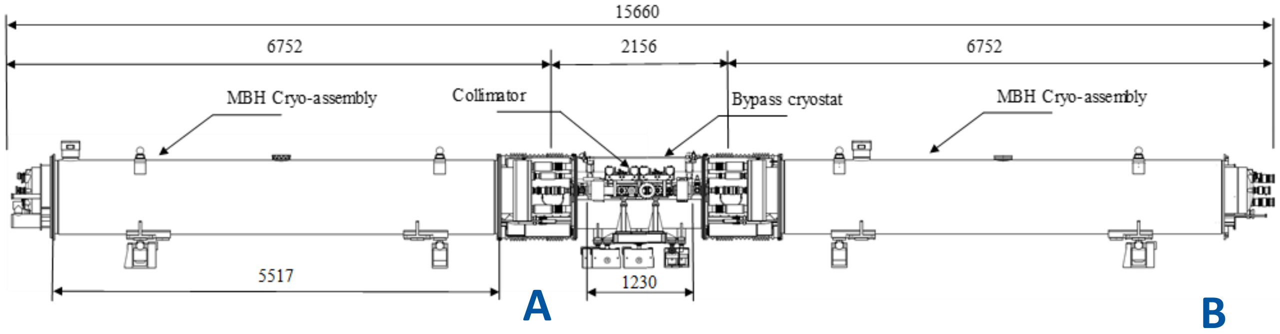
Finding extra space when there is already no space

The upcoming High-Luminosity LHC upgrade requires installation of additional collimators in sectors 67, 78. However, there is no space available for them in these sectors.

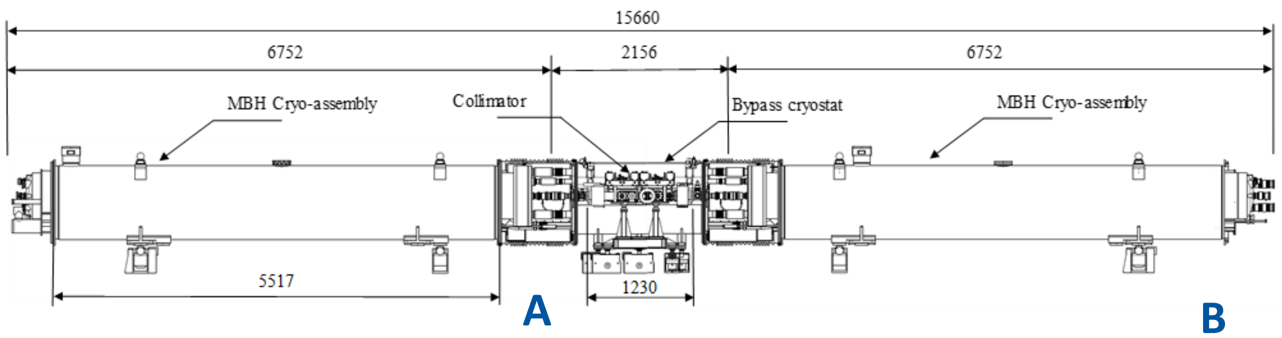




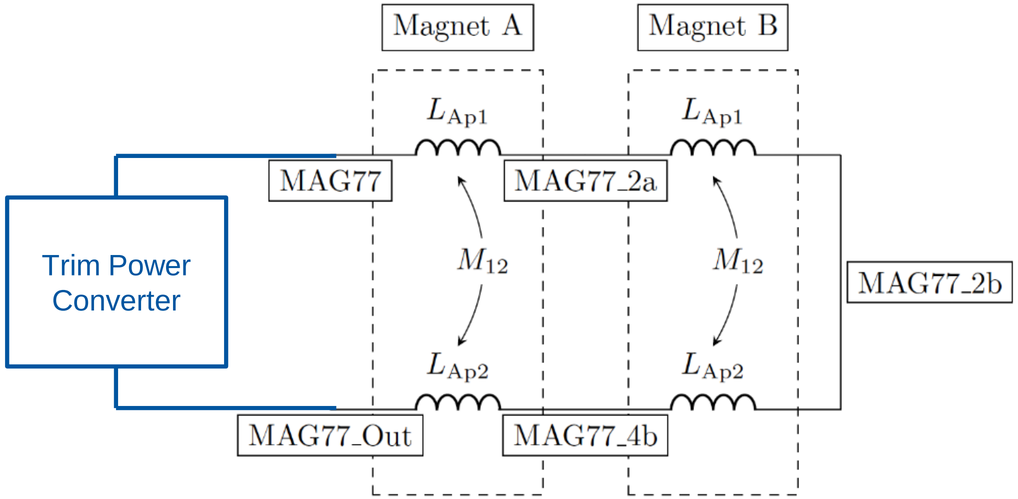


Study: *Overview*

In the upcoming HL-LHC upgrade in two main dipole (RB) circuits, a dipole magnet will be replaced with an 11 T cryo-assembly. The 11 T cryo-assembly consists of two 5.5-meter 11 T magnets connected in series.



Side view of the 11 T dipole full assembly showing the collimator installed between cold-to-warm transitions.



Connection order of apertures in a cryo-assembly

Method

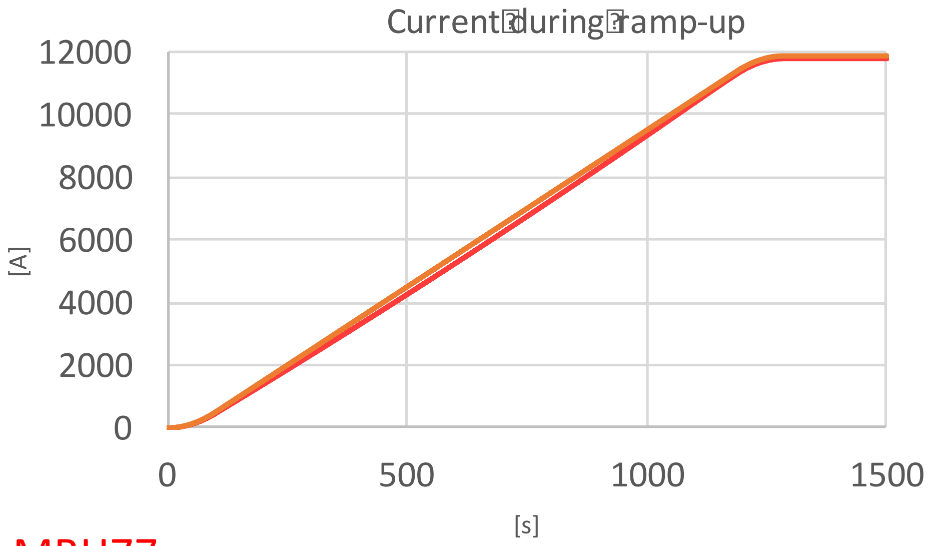
1. Monolithic circuit (STEAM-SING)
   - PSpice model of RB
   - Lumped model of MBH
2. Field/circuit coupling (STEAM-COSIM)
   - PSpice model of RB
   - STEAM-LEDET model of MBH

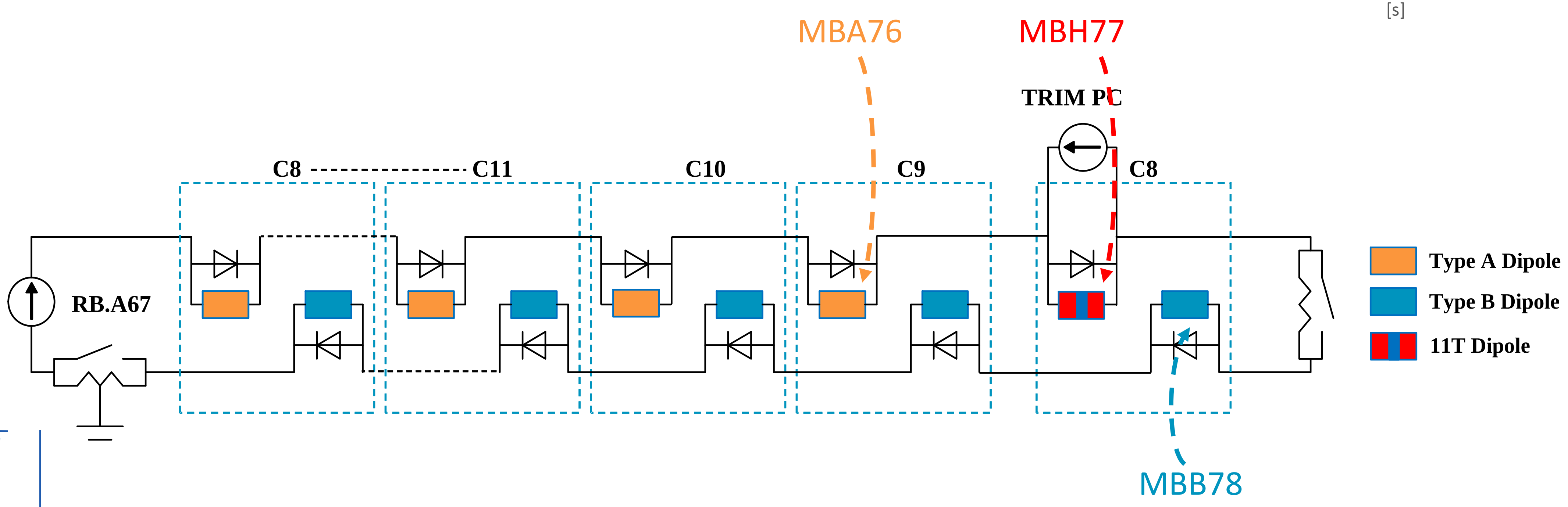
Objectives

1. Nominal operation
2. Quench protection
3. Failure scenarios

1. Circuital Analysis - Simulation Scenarios for Sector 67

1. Selection of the parallel resistor
2. Voltage across magnets during an FPA
3. Voltage feelers during a ramp-up and an FPA
4. Shorts across elements of the trim circuit
5. Shorts to ground in the trim circuit

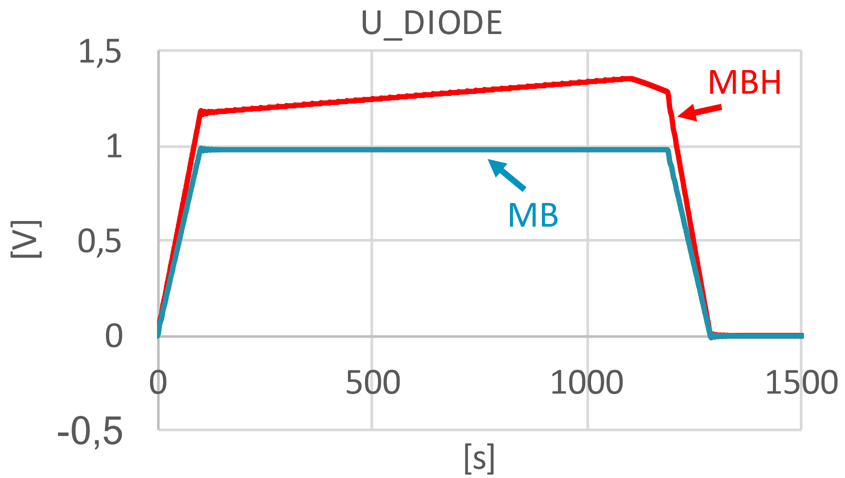


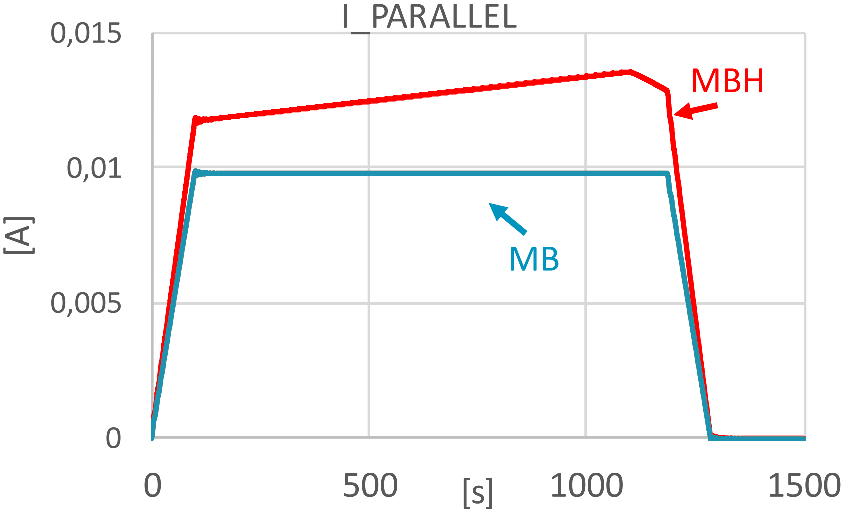


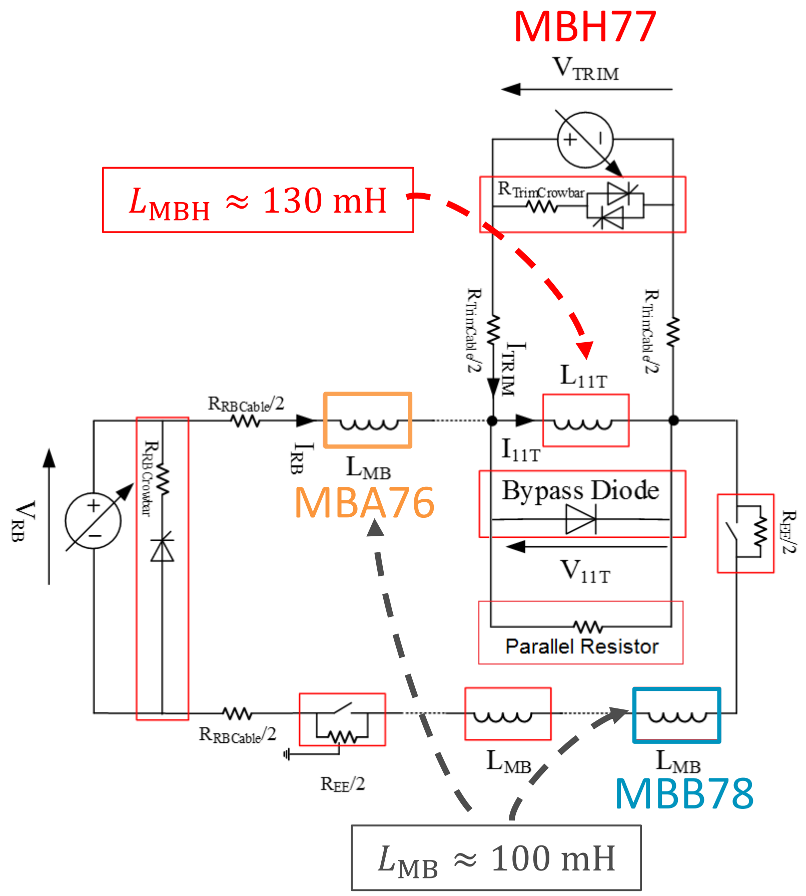
1.1. Choice of the parallel resistor – leakage current

What should be the value of the parallel resistor for the 11 T cryo-assembly?

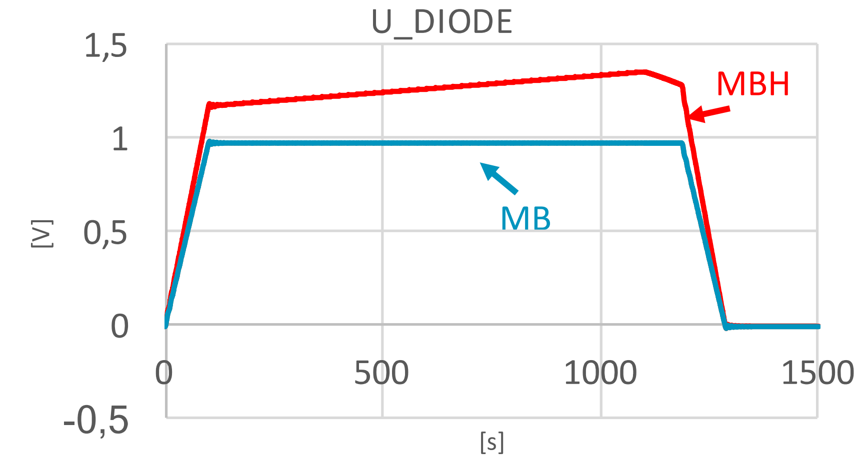
Parallel resistor of 100 Ω

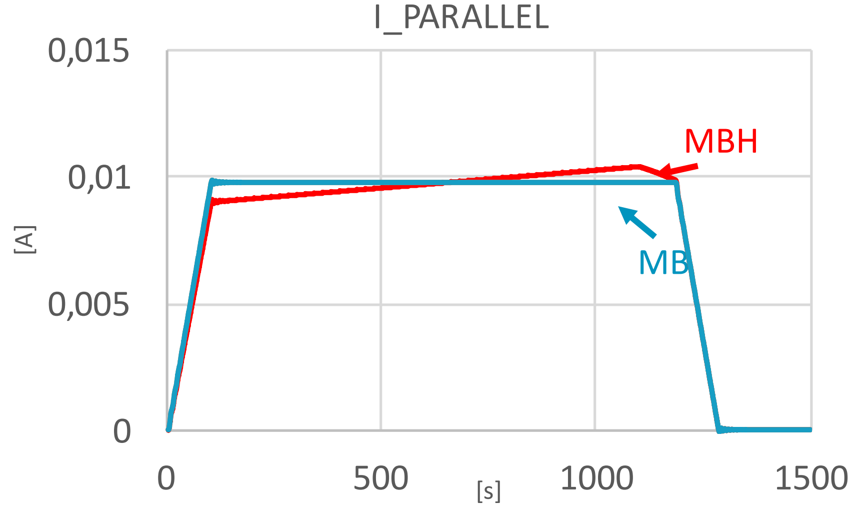






Parallel resistor of 130 Ω



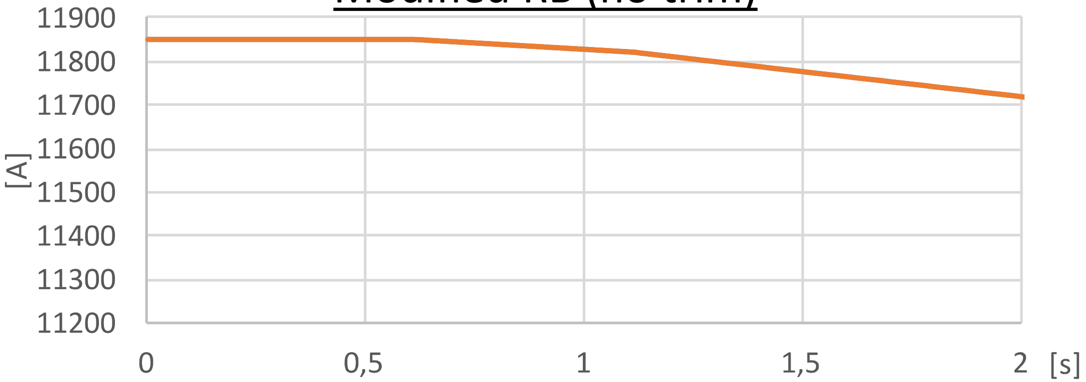


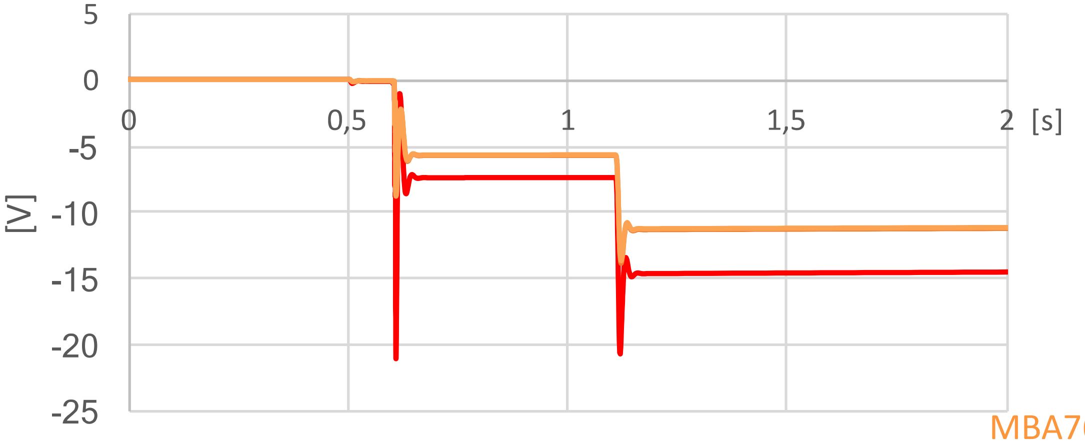
In order to achieve comparable leakage current, the parallel resistor should be equal to 130 Ω (the same time constant as MB).

1.2. Voltage Across the Magnets During an FPA

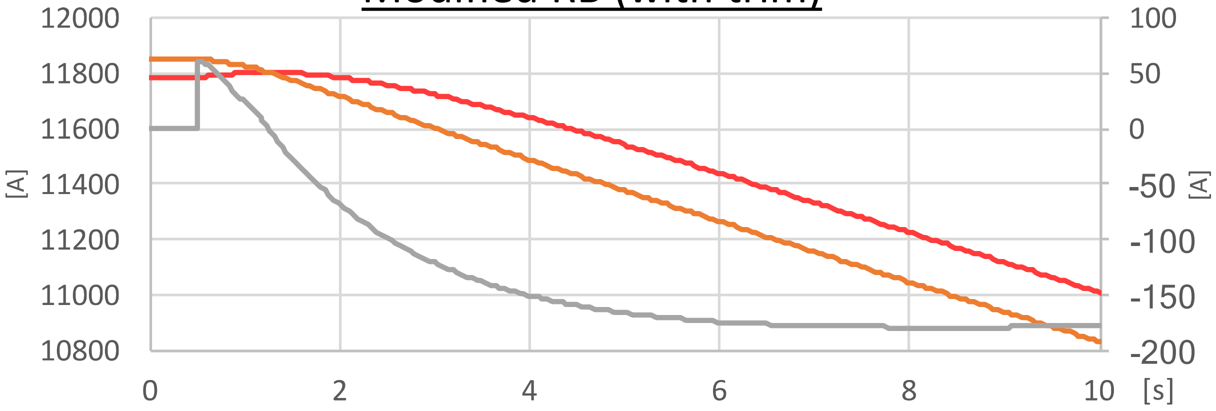
What is the influence of the trim circuit on the voltage across the considered magnets during an FPA?

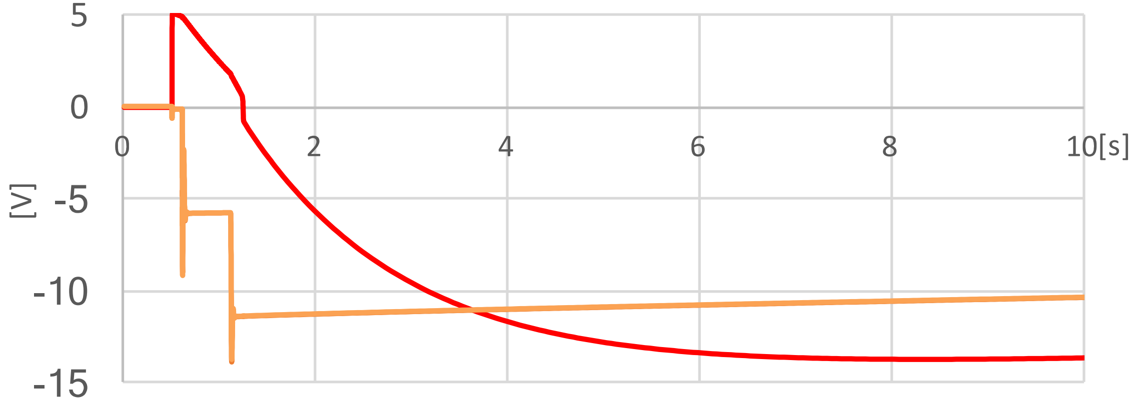
Modified RB (no trim)

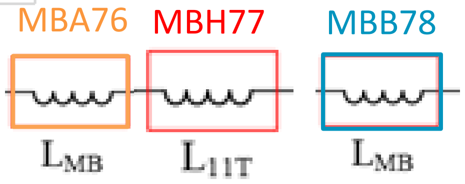




Modified RB (with trim)



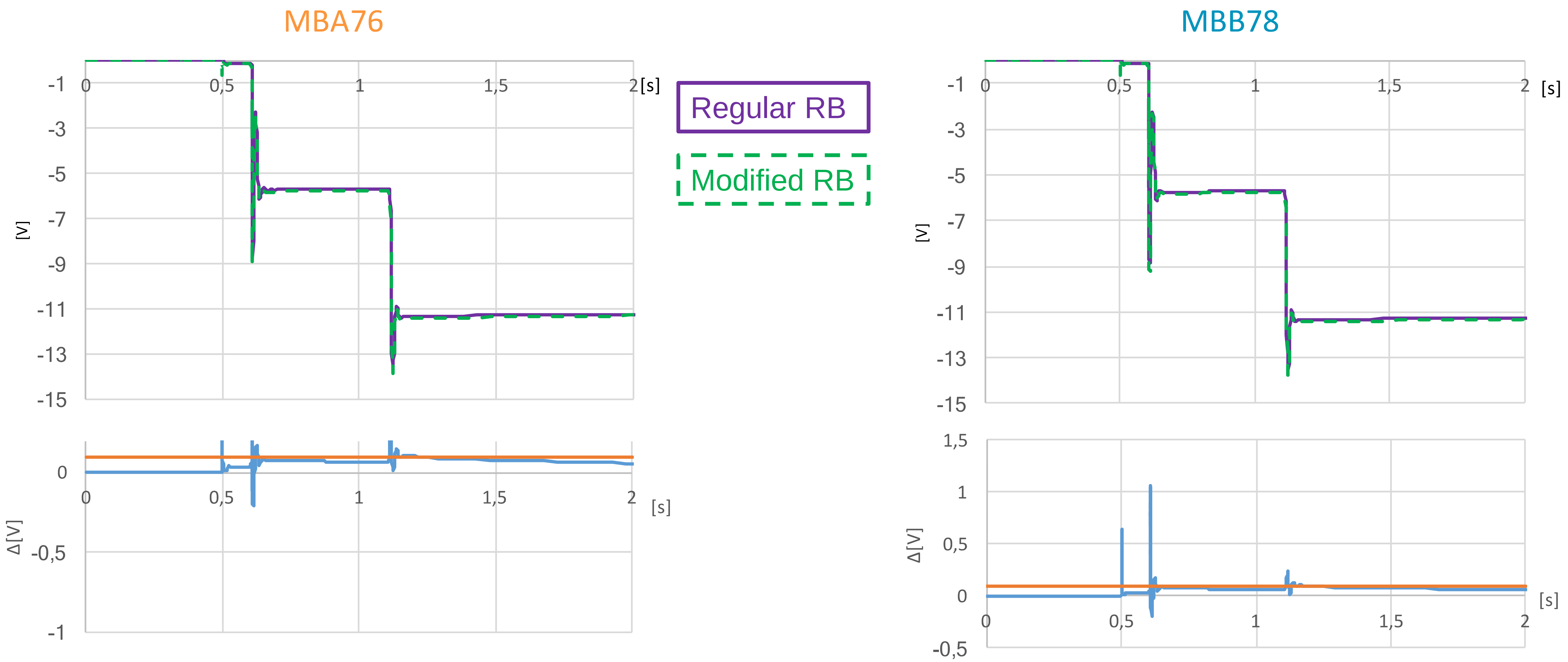




The voltage across the 11 T differs from the MBs due to the trim power converter.
The steady state difference corresponds to the inductance difference.

1.2. Voltage Across the Neighbouring Magnets During an FPA - Comparison

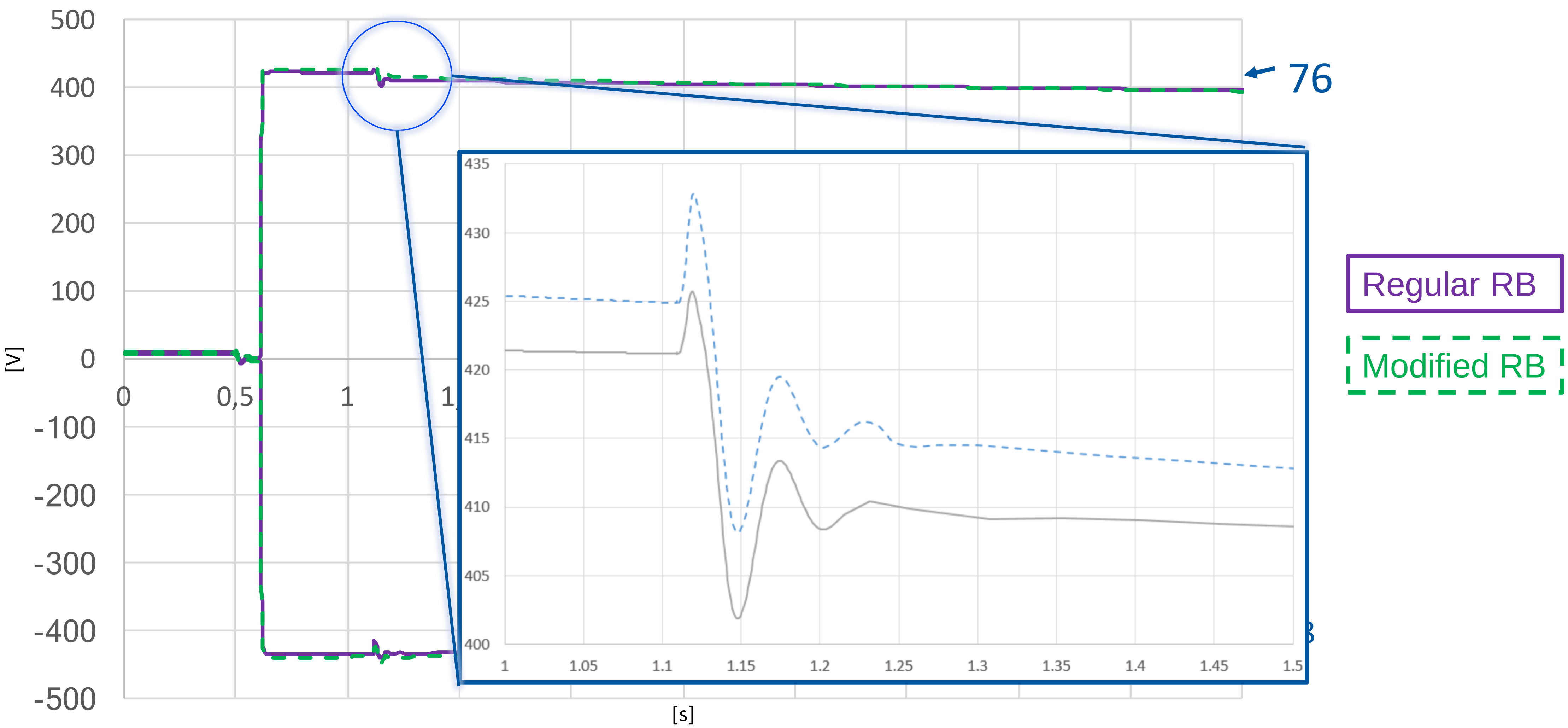
What is the influence of voltage step introduced by the trim circuit on the voltage across the neighboring magnets?



Presence of the trim power converter changes the voltage transients in the neighbouring magnets.
Analysis of the QPS operation (iQPS, nQPS) is in progress.

1.3. Voltage Feelers - Comparison

What is the influence of the trim circuit on the voltage feelers (76, 78) next to the 11 T cryo-assembly?

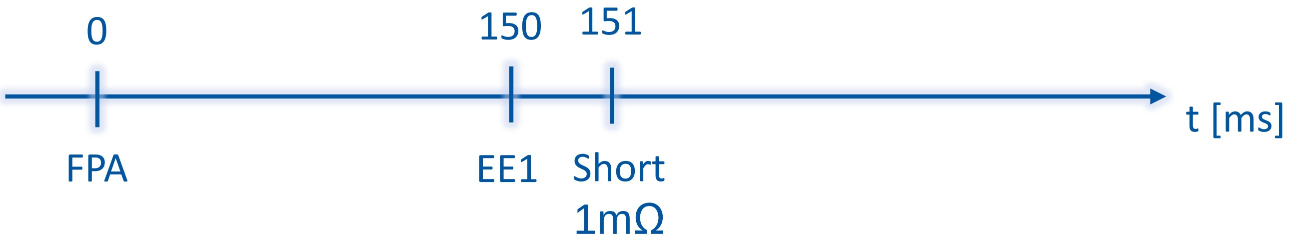


Presence of the trim power converter changes the voltage transients in the voltage feelers.

1.4. Shorts Across Elements of the Trim Circuit

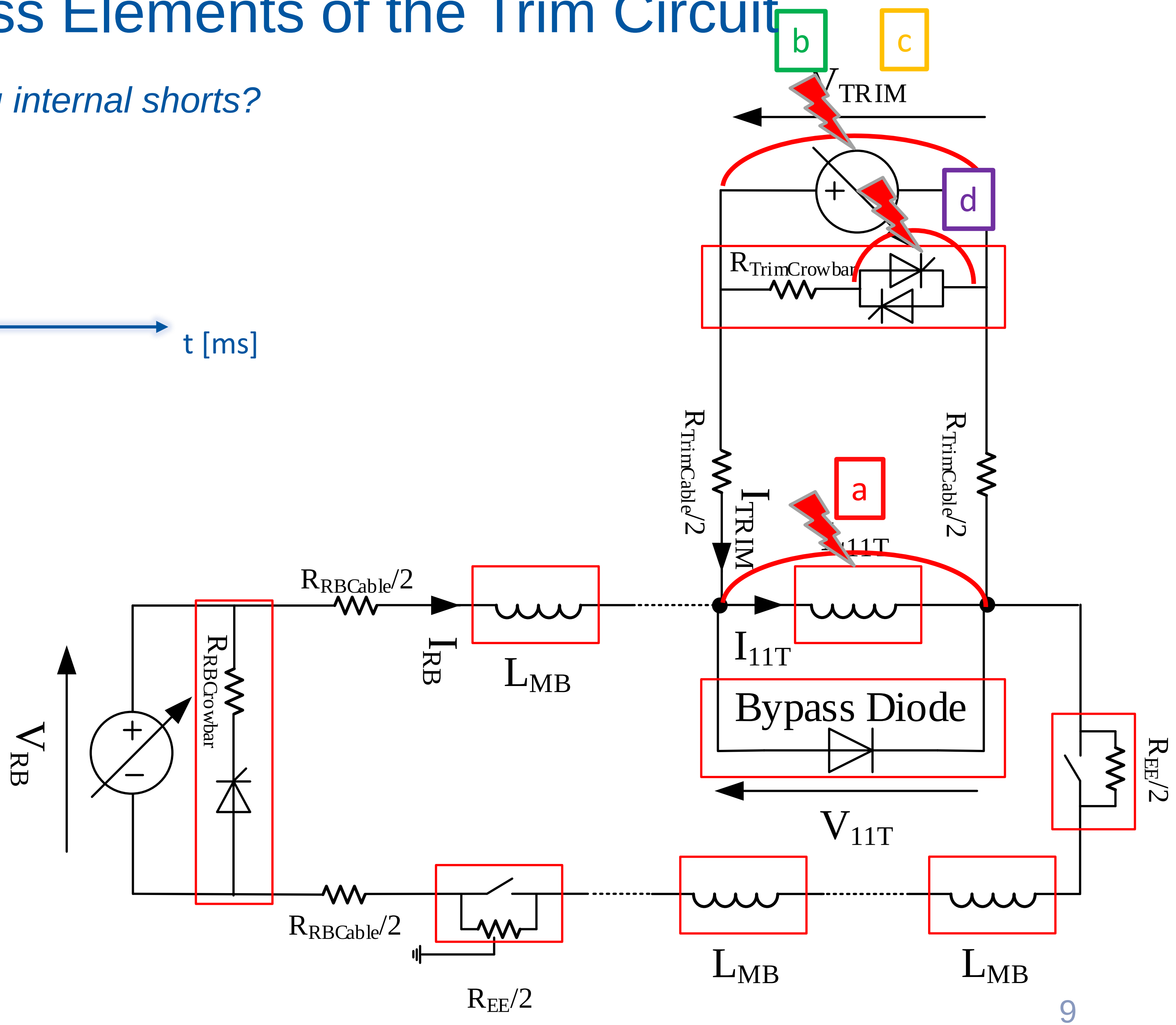
What is the current in the trim circuit during internal shorts?

Initial sequence of events



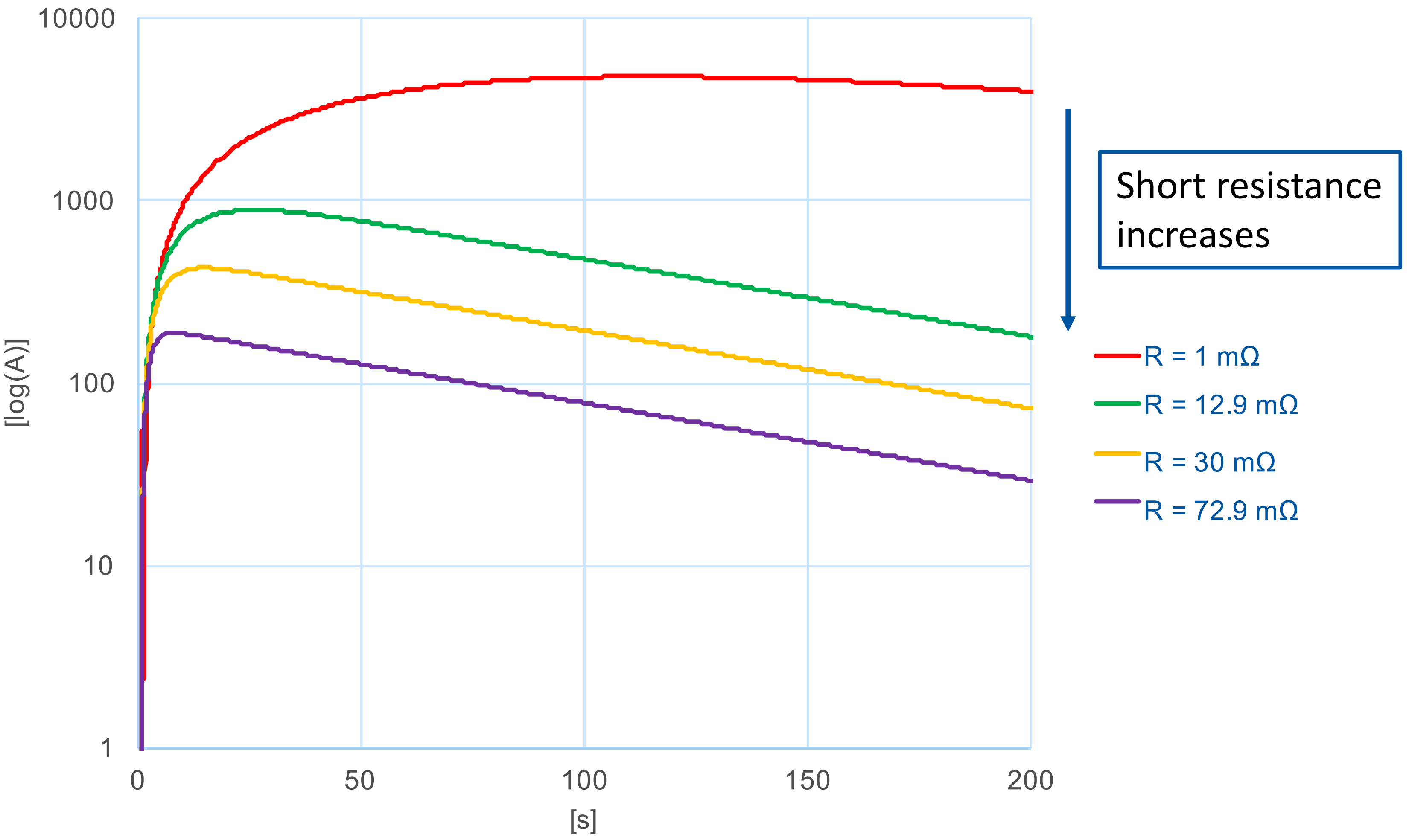
Short locations

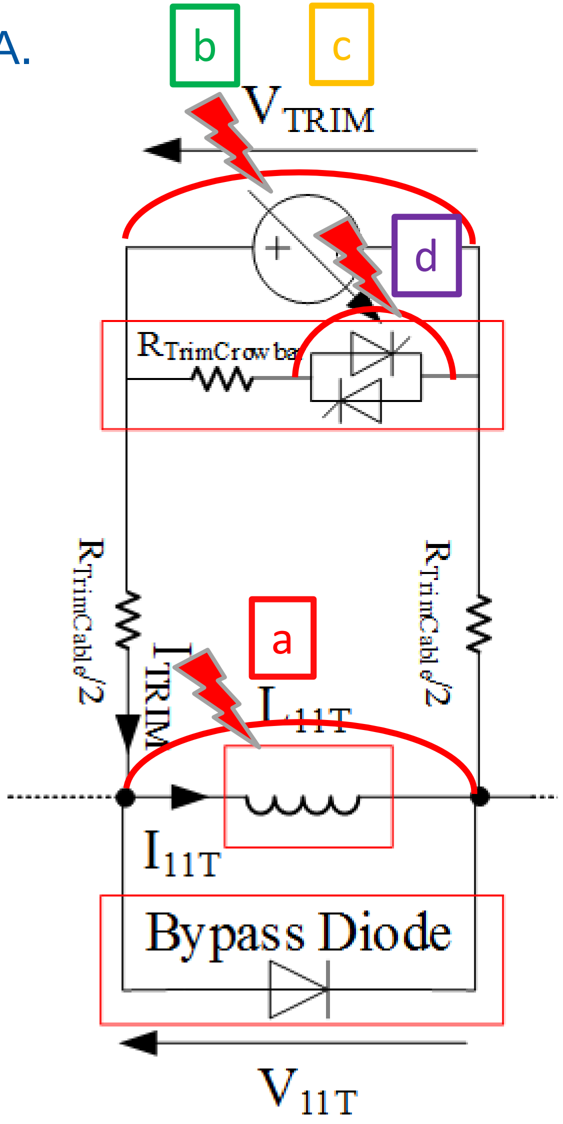
a) Across the diode
b) Across the power converter
c) Across the power converter
d) Across the thyristor



1.4. Comparison of Short Circuits in the Trim Circuit

Analysis of potential short circuits across elements of the trim power converter.
The considered scenarios differ in likelihood and severity. Initial current equal to 11.85 kA.



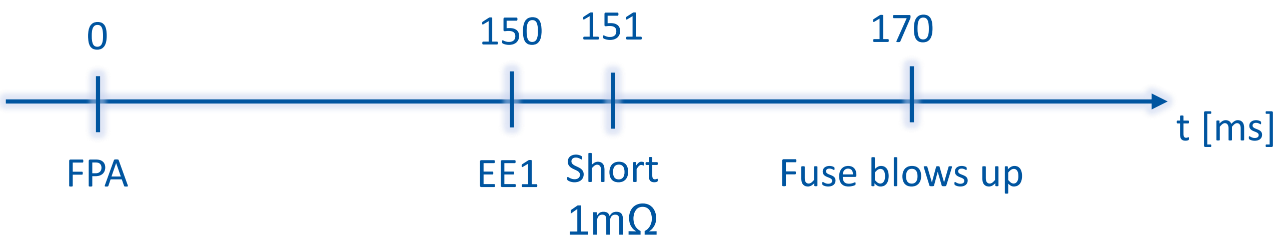


For case [a] current flows only through the short and bypasses the trim circuit.
For cases [a-d] current flows through the trim circuit. Case [d] is the nominal operation of the trim circuit.

1.5. Shorts to Ground in the Trim Circuit

What is the current in the trim circuit during internal shorts to ground?

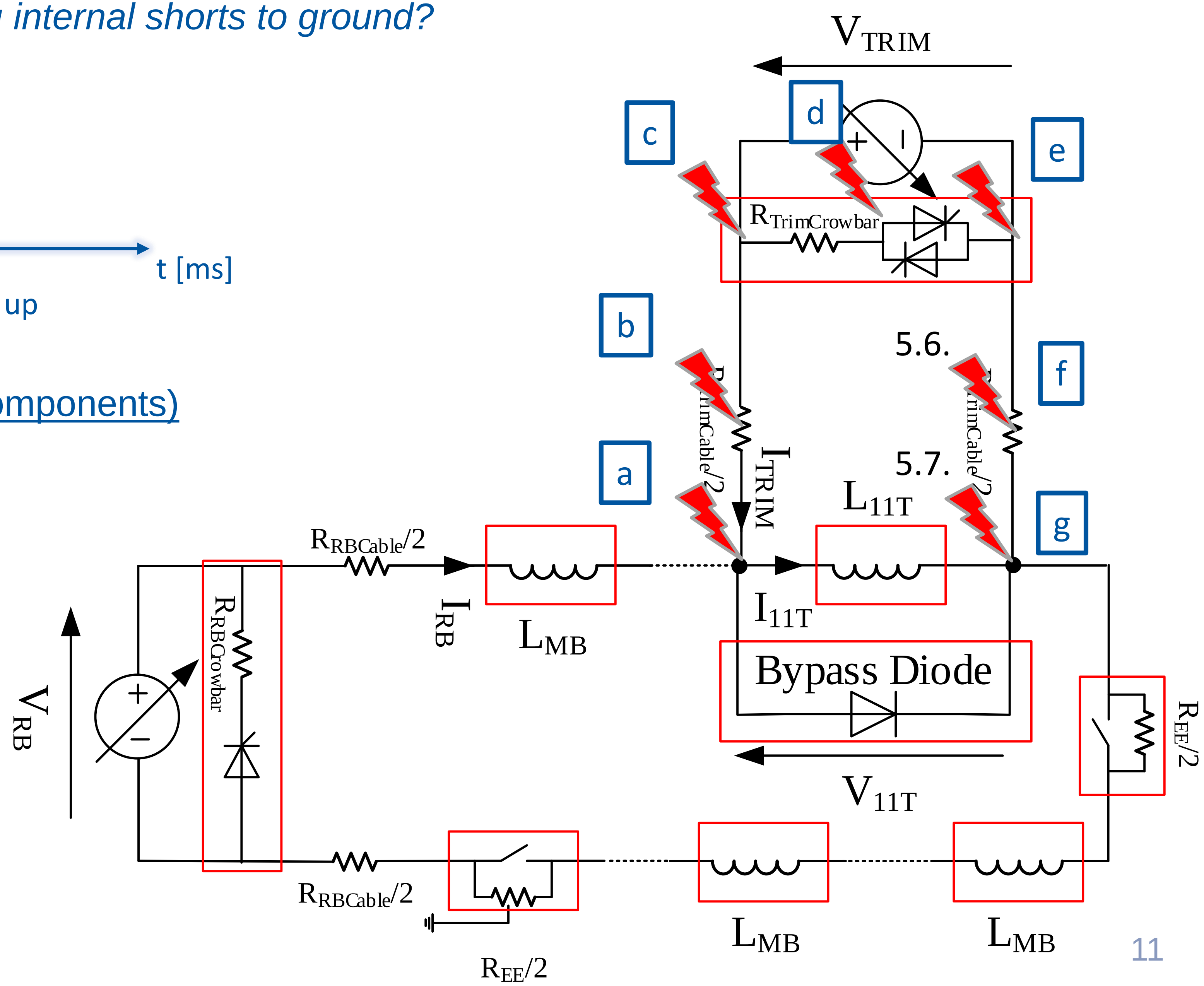
Sequence of events



Short locations (at interconnects between components)

a) At the input terminal
b) Between H→C* and current lead
c) Between CL** and power converter
d) Between resistor and thyristor
e) Between power converter and CL
f) Between current lead and H→C
g) At the output terminal

*Hot→Cold transition
**Current Lead



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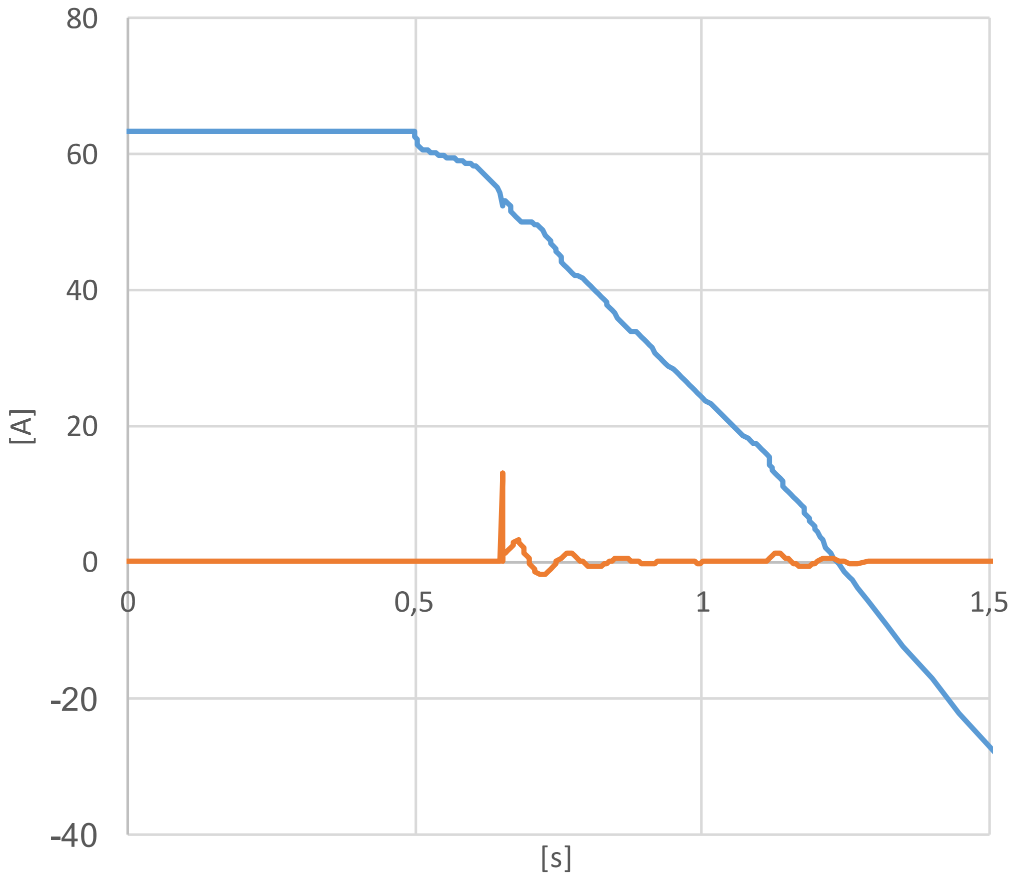
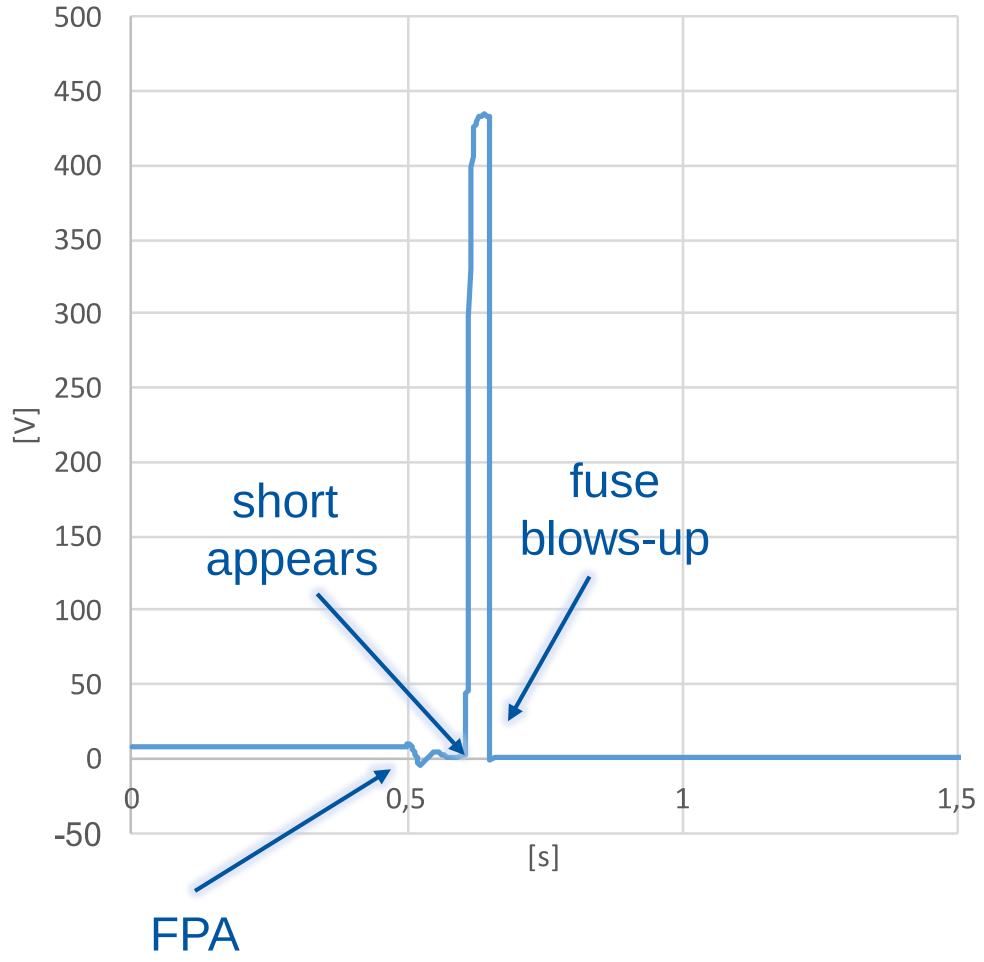
1.5. Shorts to Ground in the Trim Circuit

Initial current equal to 11.85 kA.

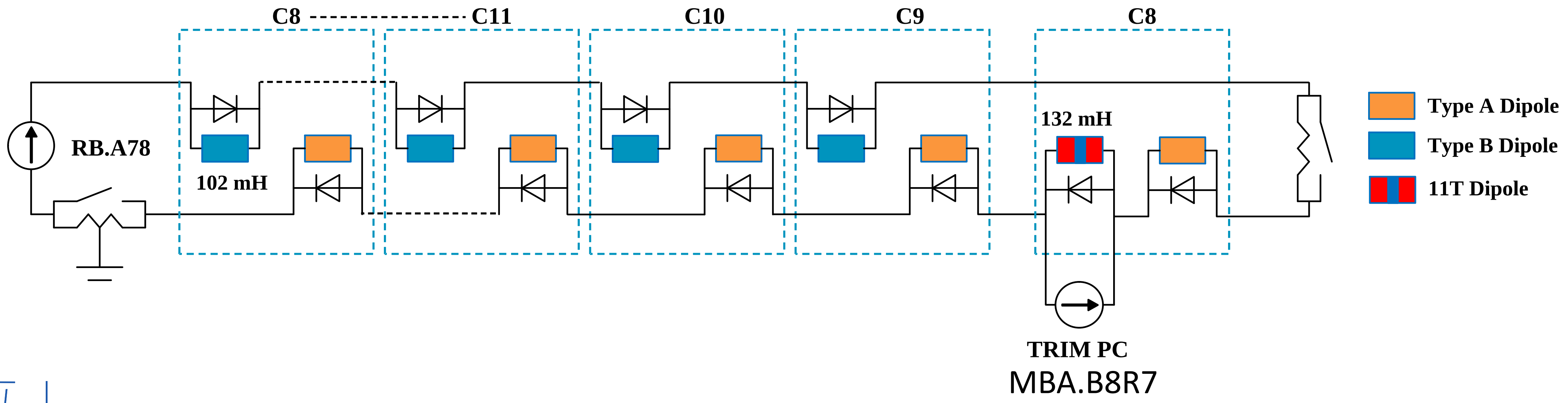




All cases [a]-[g] have similar behavior: no significant influence on the trim circuit current and voltage spike.
After fuse blow up the voltage feelers experience voltage redistribution.

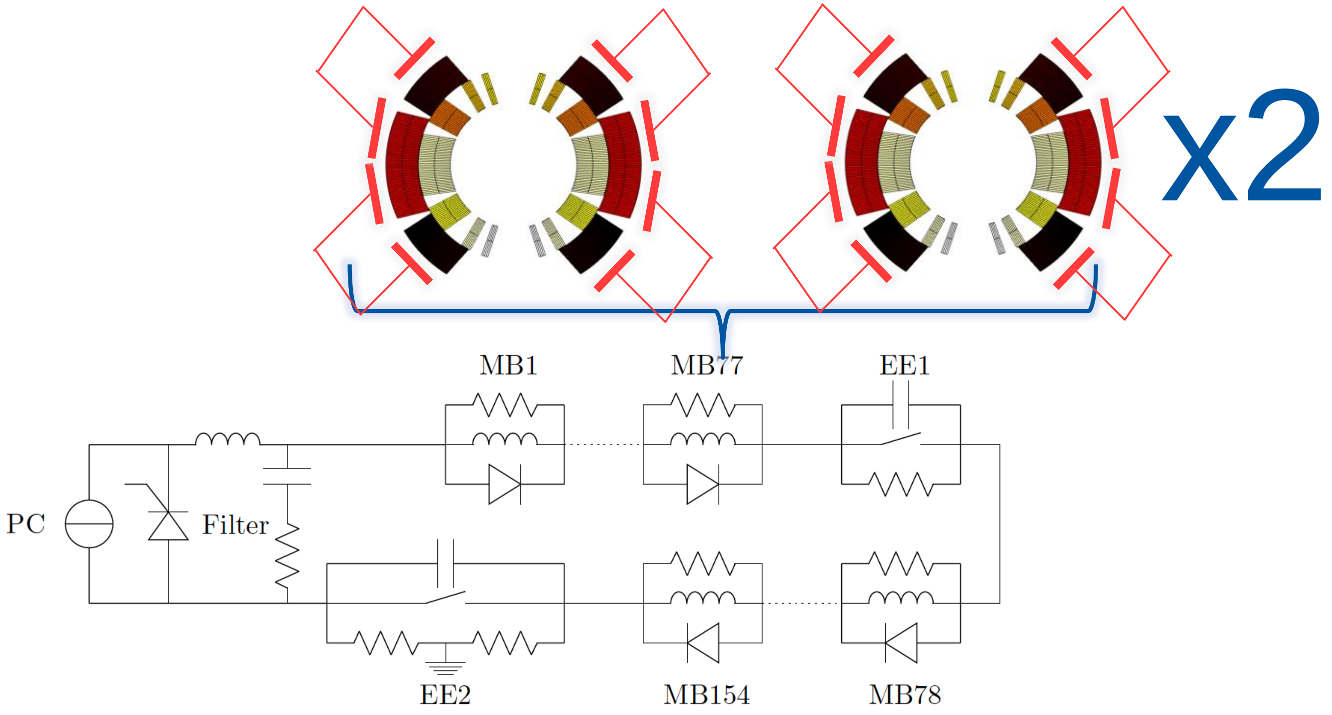
1. Circuital Analysis - Simulation Scenarios for Sector 78

1. Selection of the parallel resistor → 130 Ω
2. Voltage across magnets during an FPA → the same profiles
3. Voltage feelers during an FPA → reverted voltage polarity
4. Shorts in the trim → the same profiles
5. Shorts to ground in the trim → the same profiles

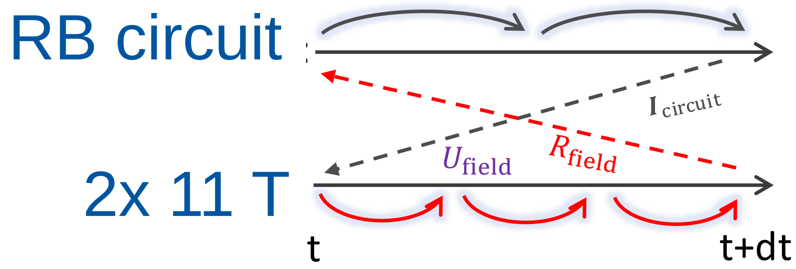


2. Field/Circuit Coupling Study: *Overview*

1. Execute again analysis carried out already for the 11-T magnet
   1. Until now the analysis was only carried out for a standalone magnet
   2. New analysis considers 11-T cryo-assembly in the main dipole circuit
2. Study new failure scenarios that could potentially occur after the change
   1. Impact of two magnets connected in series with a single diode
   2. Impact of the trim power converter

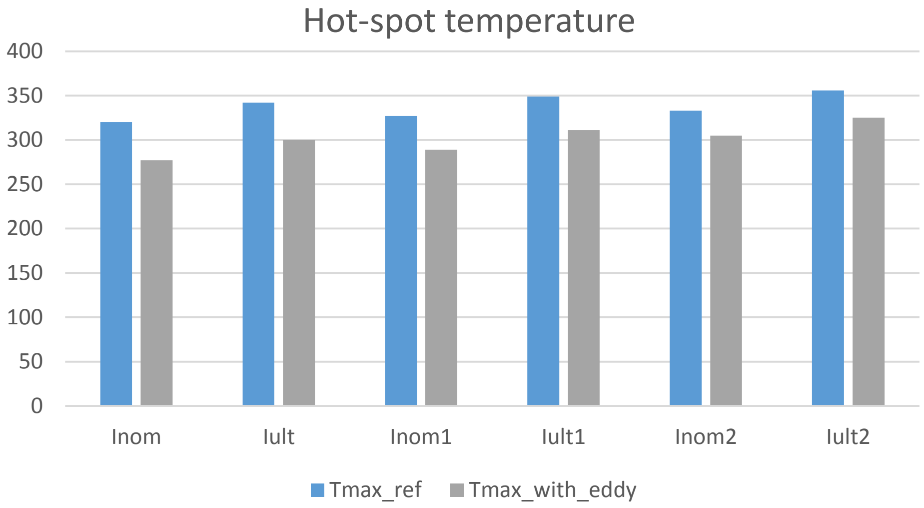


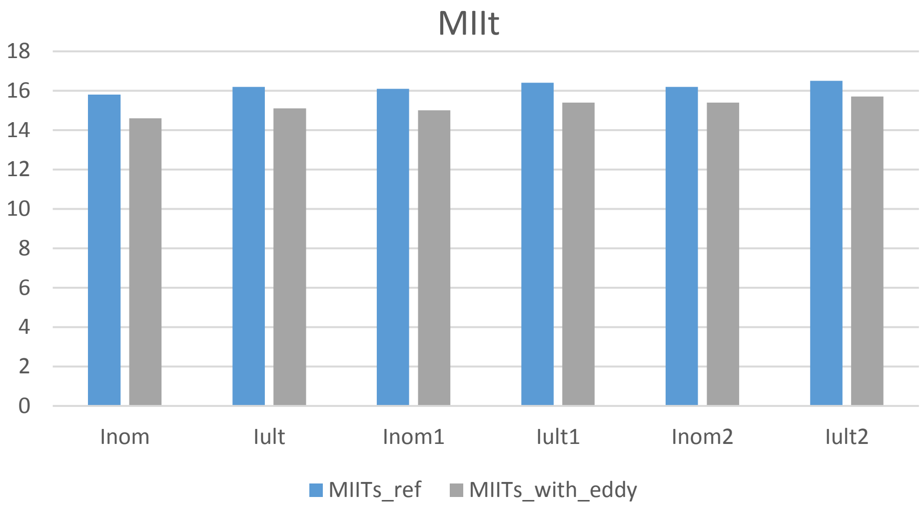
Field/circuit coupling

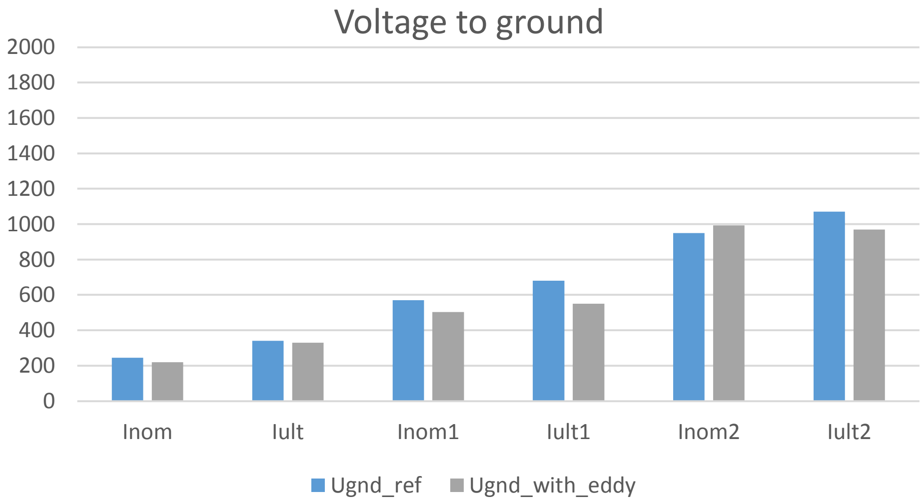


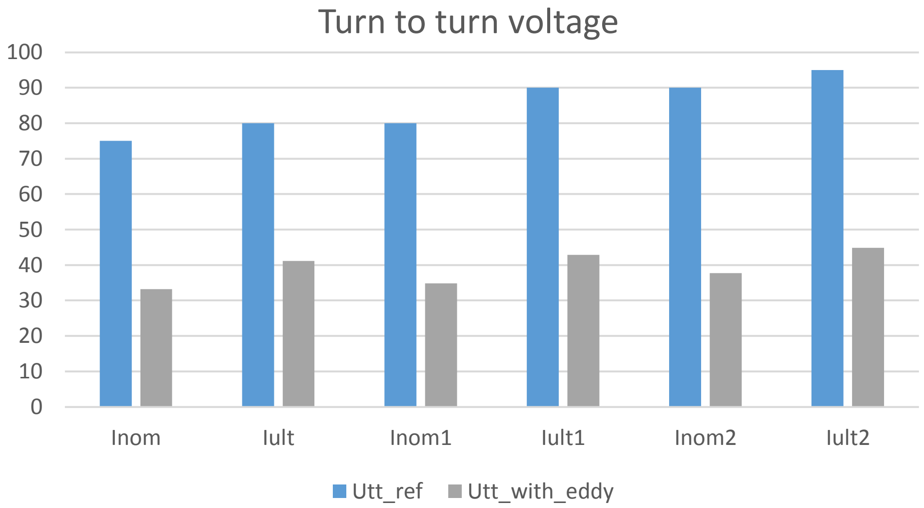
2.1. Comparison of simulation results for the standalone setup

Reference results: S. Izquierdo Bermudez et al.: Quench Protection of the 11 T Nb_3Sn Dipole for the High Luminosity LHC, IEEE Transactions on Applied Superconductivity, 28(3), 2018





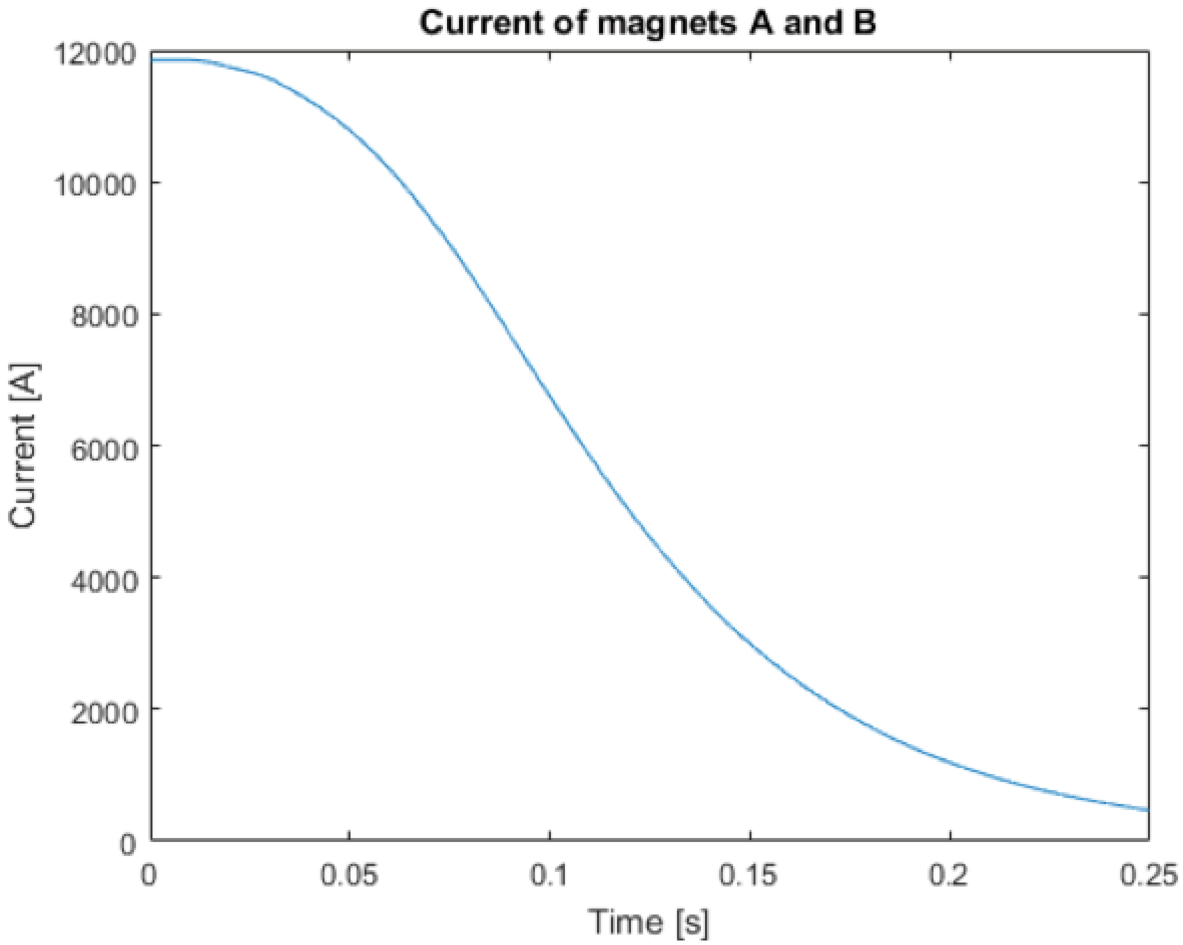


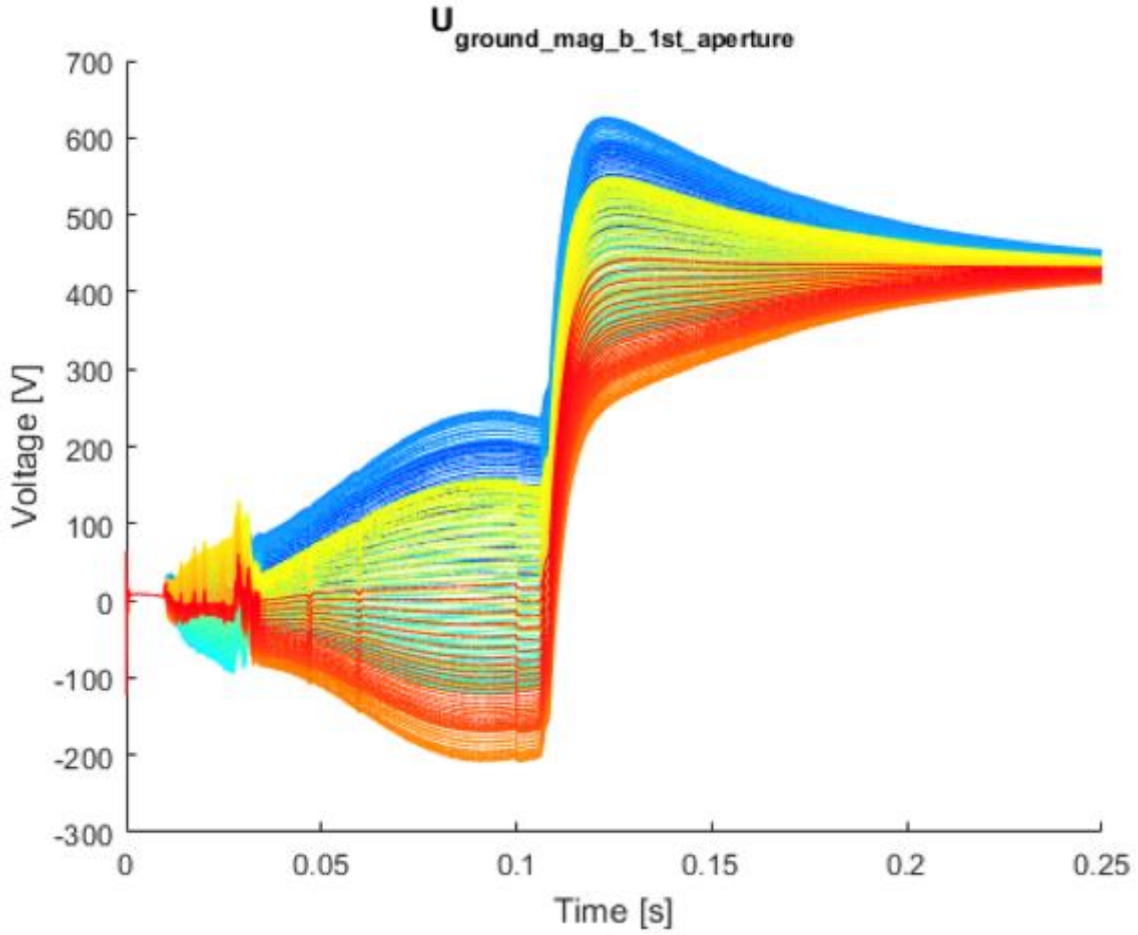


Despite different modelling assumptions (presence of eddy currents, heat transfer between turns), the obtained results are in a reasonable agreement.

2.1. Simulation results for the main dipole circuit setup

Initial current equal to 11.85 kA, all heater circuits correct.

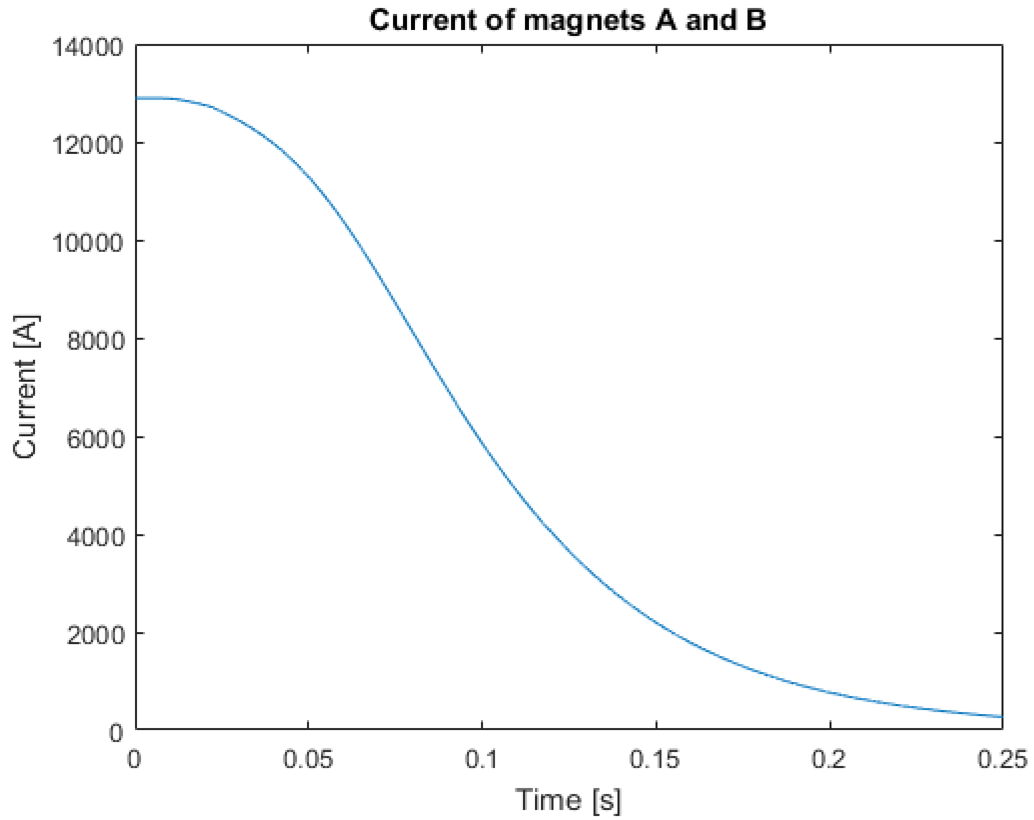


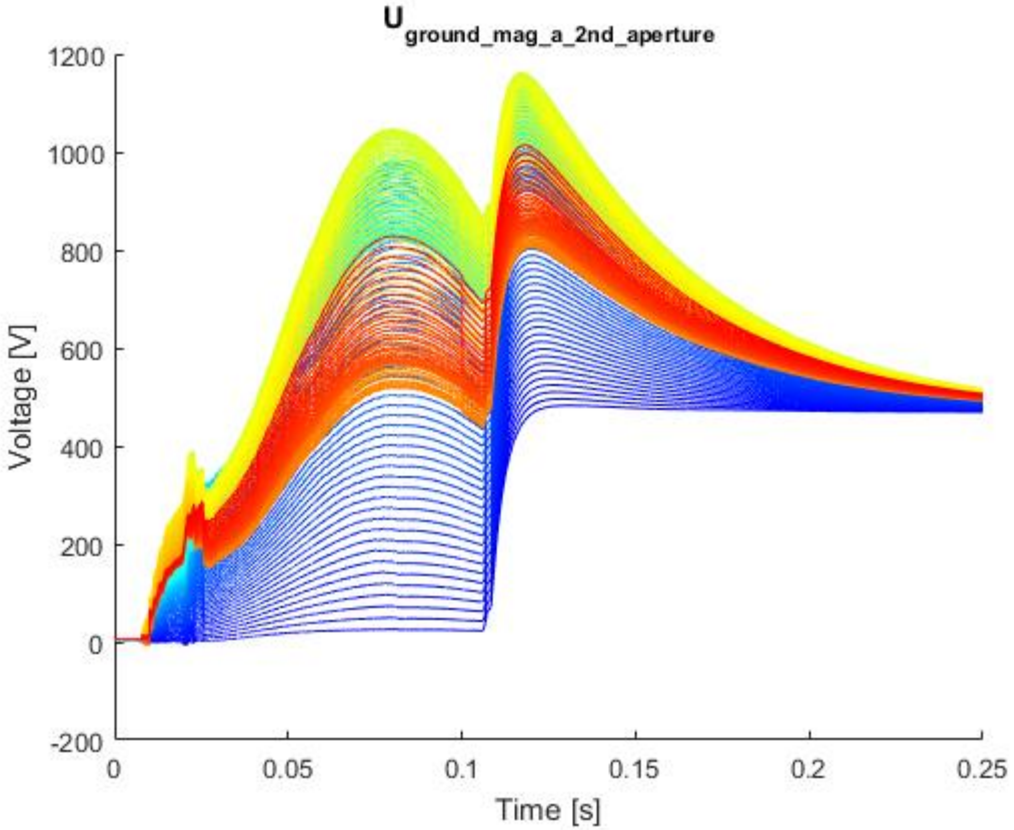


Voltage to ground in MBH depends on the nodal voltage in the circuit.
The peak voltage to ground coincides with the opening of the first energy-extraction switch.

2.1. Simulation results for the main dipole circuit setup

Initial current equal to 12.8 kA, failure of two heater circuits in one coil.





Voltage to ground in MBH depends on the nodal voltage in the circuit.
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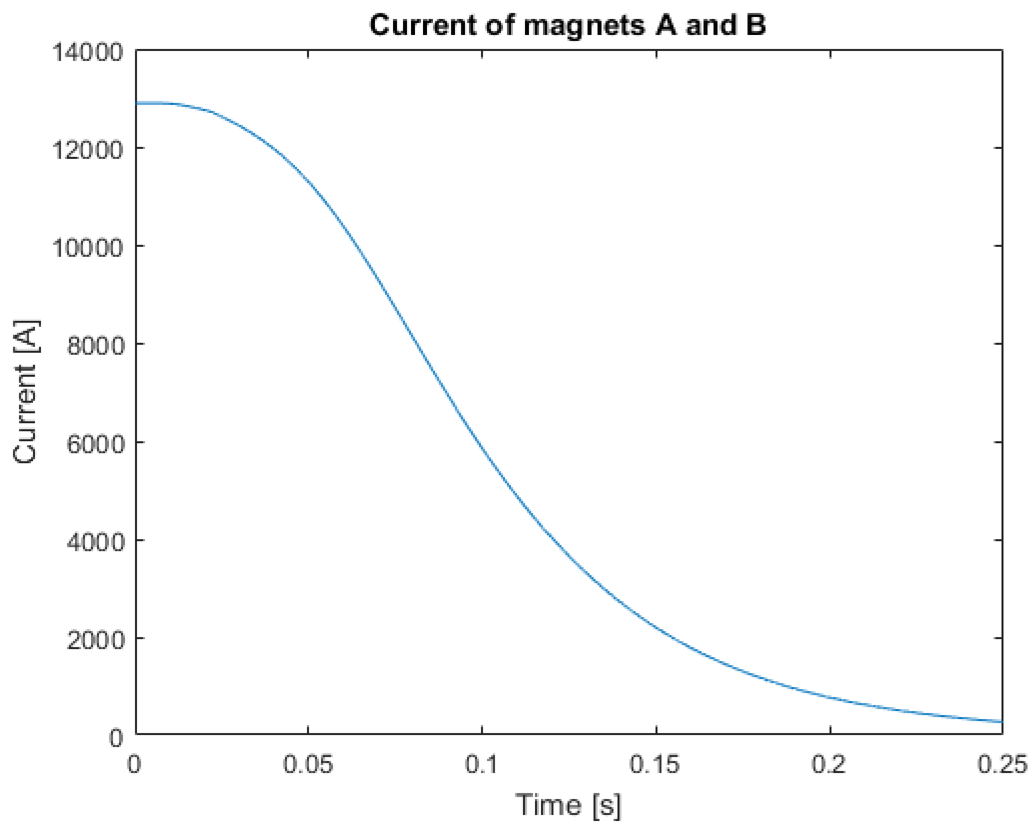
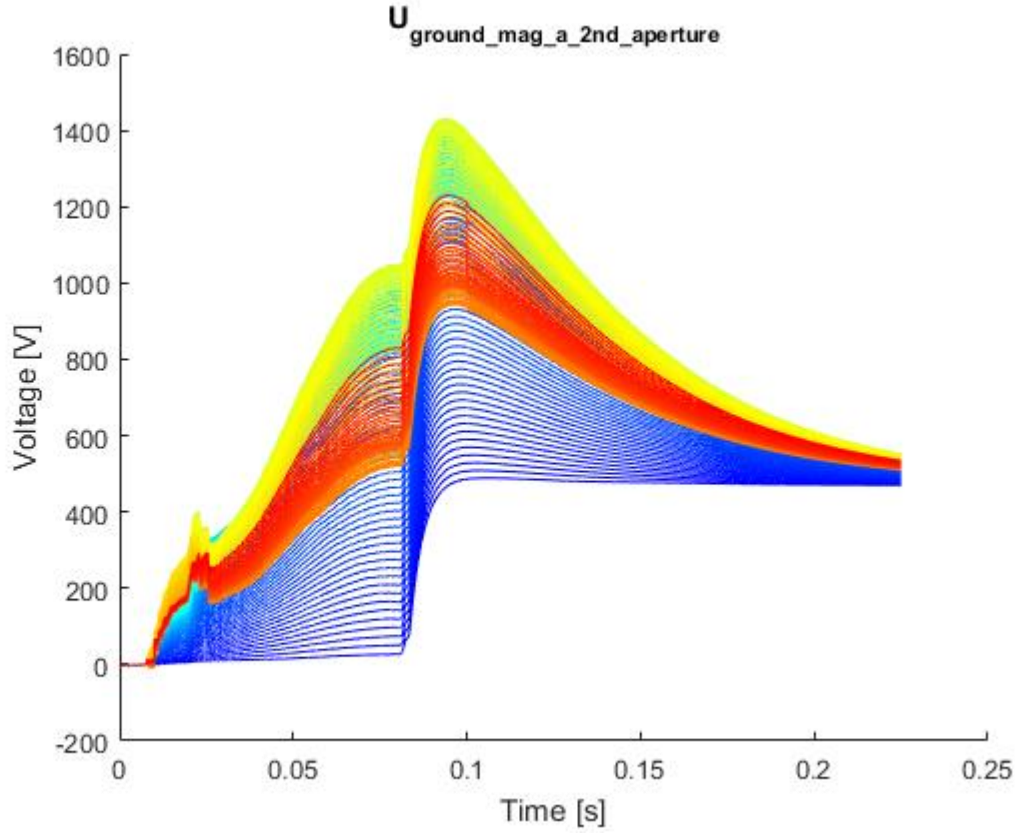
2.1. Simulation results for the main dipole circuit setup

Initial current equal to 12.8 kA, failure of two heater circuits in one coil.



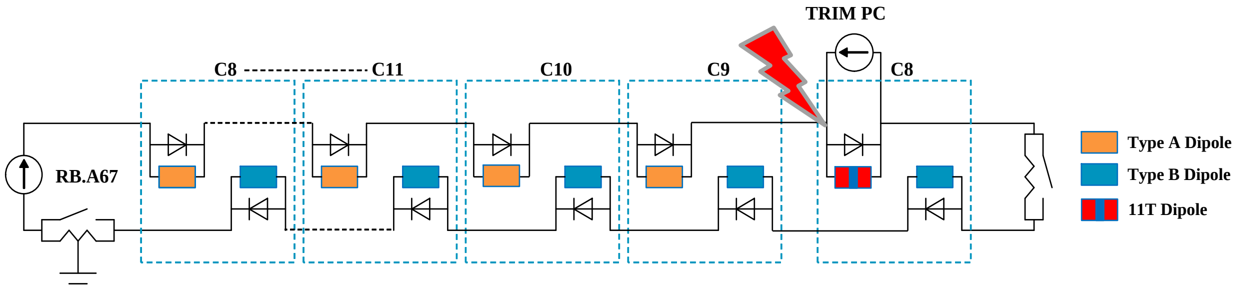


Voltage to ground in MBH depends on the nodal voltage in the circuit.
The peak voltage to ground coincides with the opening of the first energy-extraction switch.

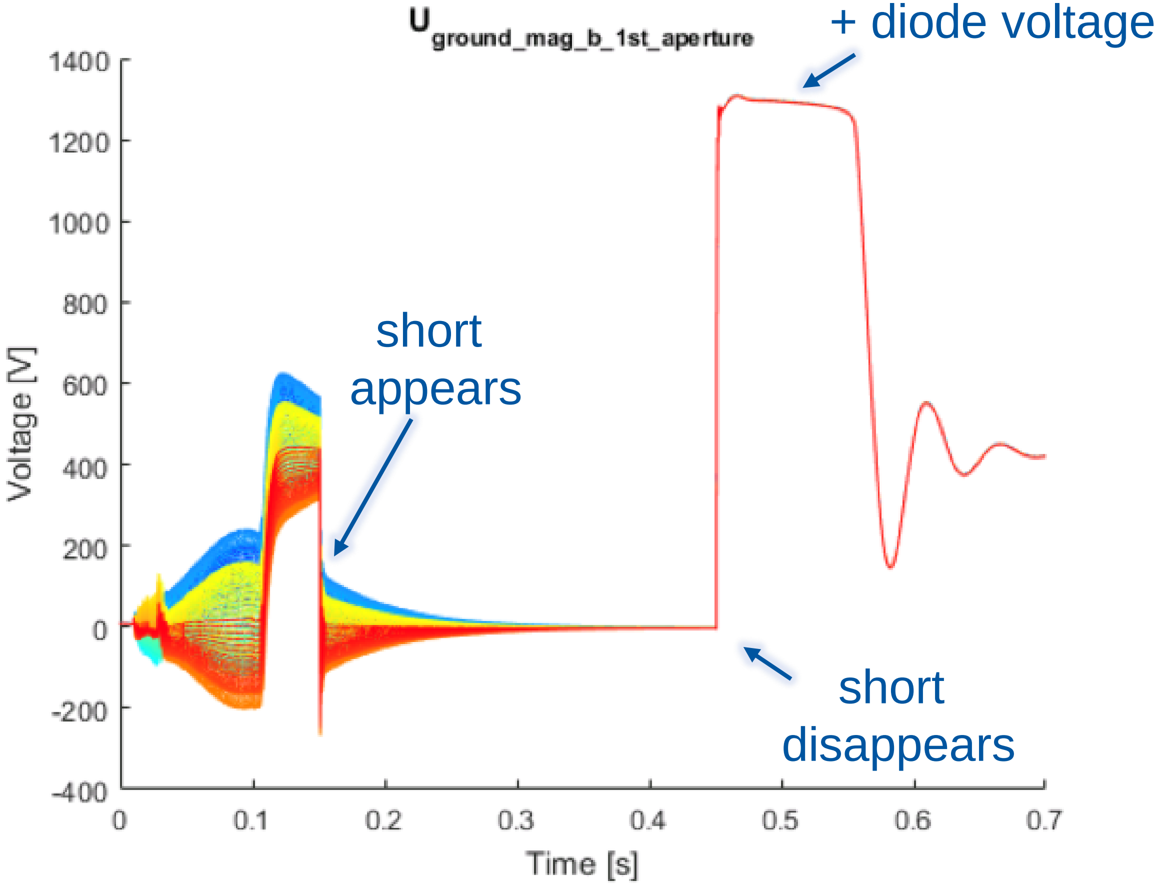
2.2. Simulation results for the main dipole circuit setup

Short to ground at one node of the 11-T cryo-assembly

1. Three current levels (6 kA, 11.85 kA, 12.8 kA)
2. Three quench heater powering scenarios
   (all correct, single failure, two failures)
3. Several short scenarios



Intermittent short at current equal to 11.85 kA, failure of two heater circuits



In case a short disappears, the short current flows through the diodes effectively closing them. This translates into large voltage to ground.

Conclusion and Outlook

1. Monolithic circuit

1. Value of the parallel resistor is recommended to be equal to 130 Ω
2. The trim circuit introduces a step voltage during an FPA which propagates to neighboring magnets

   → quench protection study (iQPS, nQPS) in progress
3. Short in the trim circuit (12.9 mΩ) can lead to up to a 1 kA current in the trim circuit
4. Shorts to ground in the trim circuit lead to the redistribution of voltage

2. Field/circuit coupling

1. The existing results and simulations carried out are in a reasonable agreement
2. In case of protection of 11 T in the circuit, the voltage to ground is shifted up by ~400 V
3. Short to ground can shift the voltage by up to 1.3 kV (diode voltage and energy extraction resistor voltage)
4. Assumed homogeneous cable parameters result in compensation of resistive and inductive voltage
   1. Analysis carried out by Susana indicate dependence of RRR and fraction of copper
5. Developed tools allow studying coupled field and circuit models