11 T & trim in RB circuit: Consequences for operation

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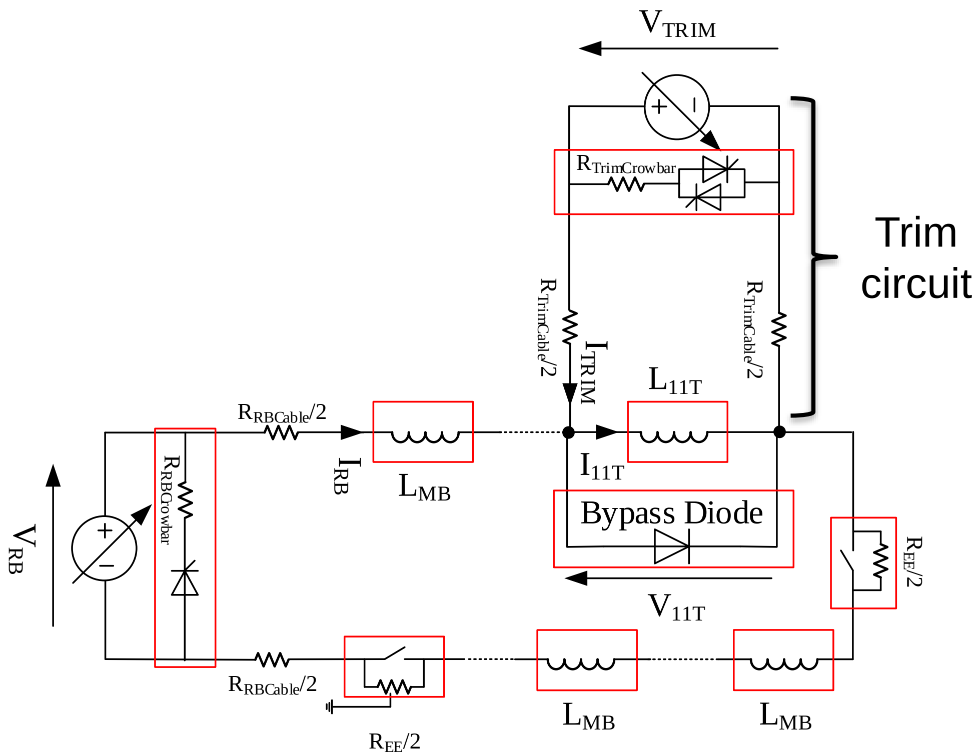
Overview

- Trim circuit in the modified RB circuit
- Quench protection of the current lead and the superconducting busbars of the trim circuit
  - Quench detection and protection during regular operation
  - Quench protection during a fast power abort of the main circuit
  - Impact of insufficient resistance in trim circuit during FPA
- STEAM co-simulations of Modified RB circuit
- Summary

Trim circuit in modified RB circuit



Source [1]

- Trim circuit adds / subtracts current (-250 A to +100 A) to 11 T magnets with respect to MB magnets to correct for transfer function
- In trim circuit: Peak current (-250 A) when main circuit is at about 6 kA
- In addition, trim circuit acts as a parallel resistor to 11 T magnets → Relevant when the main circuit is discharging during a fast power abort

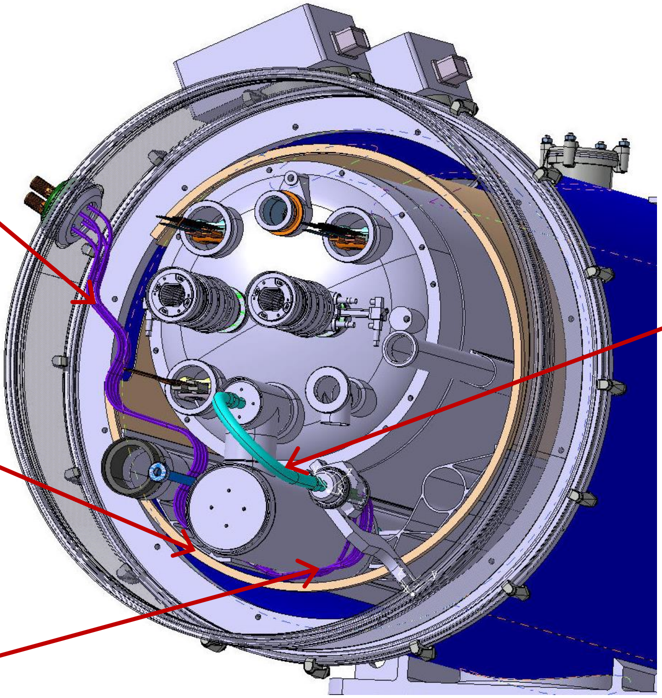
[1] 11 T Dipole circuit – Powering and Protection – EDMS 1764166

Trim circuit → Main circuit:
Current leads + superconducting busbars

Room temperature to 20 K current lead section

20 K cooling stage

20 K to 1.9 K current lead section

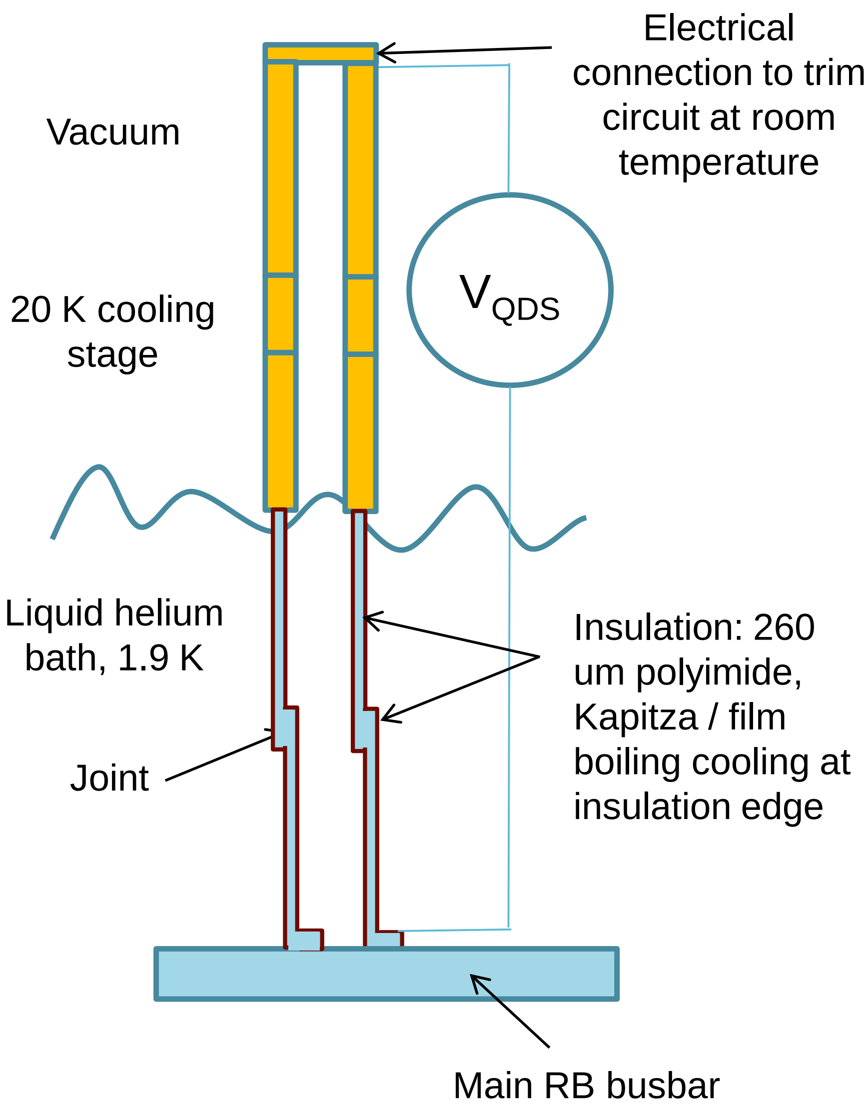


Superconducting busbar (2.0 mm^2, 90% copper, 230 ± 30 µm insulation thickness, Proj. doc. LHC-DCA-CI-0002) submersed in liquid helium

Picture courtesy of R. Betemps

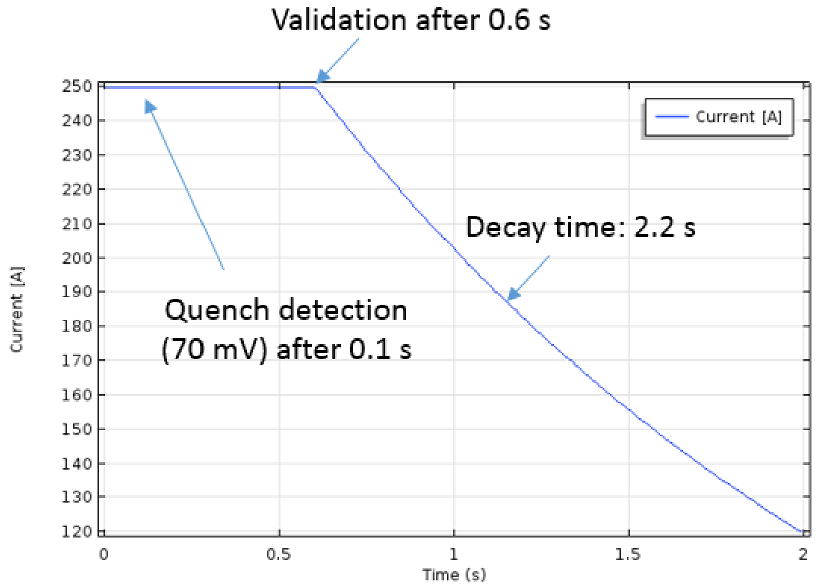
- To carry 250 A from warm leads to the main busbar:
  - Two parallel conduction-cooled current leads (developed by TE-MSC-SCD), each carrying about 125 A amps
  - Two parallel superconducting busbars, each in series with a conduction-cooled current lead, to connect the current leads to the main busbar

Quench detection setup

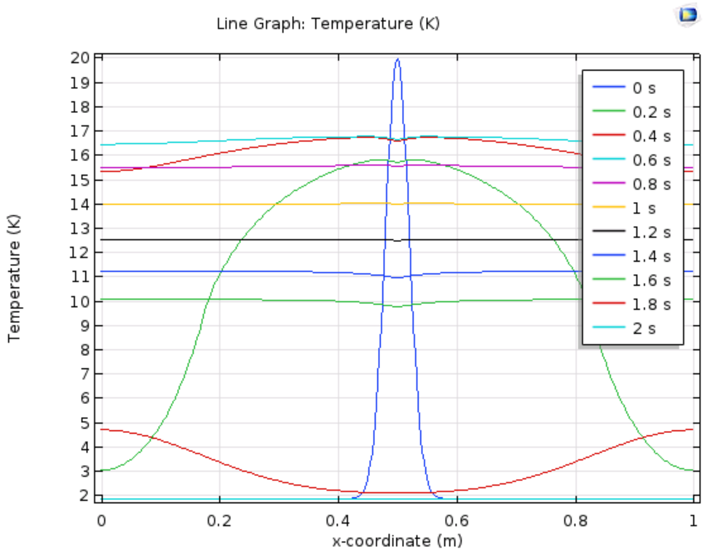


- Common QDS voltage detection for current lead and busbar (70 mV threshold, 0.5 s detection time), redundant monitoring
- Current distribution monitoring between the two parallel current leads (not shown here)
- Upon quench detection or unequal current distribution: Trim circuit discharges over crowbar

Quenching busbar at -250 A, main circuit at 6 kA



Trim circuit response after quench

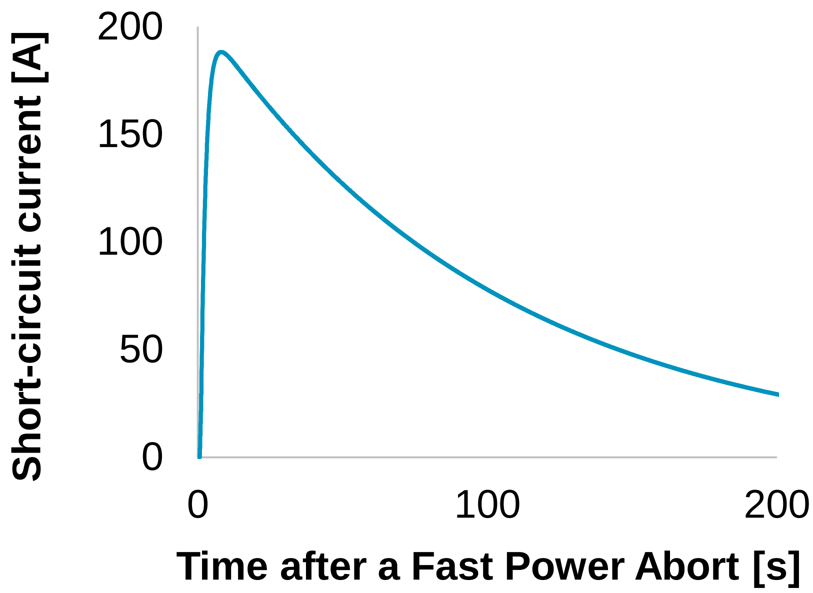


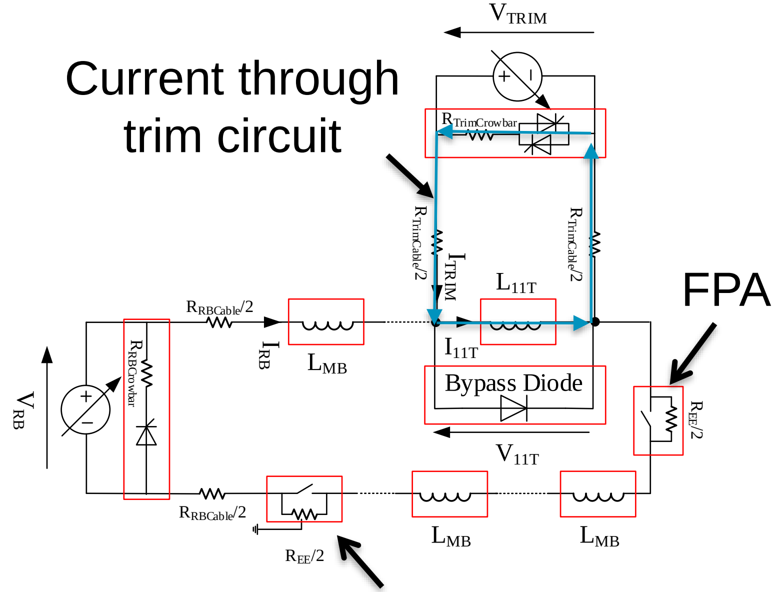
Temperature distribution over superconducting busbar as a function of time

- In-depth study of transient behavior of current lead and superconducting busbar was previously presented (Magnet circuit forum, 7/8/18)
  - Regular operation
  - Various fault scenarios
- Extreme scenario shown here: All current in single current lead + quenching busbar with conservative conductor properties (RRR = 80, 260 µm polyimide insulation)

  → Busbar temperature stays below 20 K at all times, and reaches 2 K after 2 s

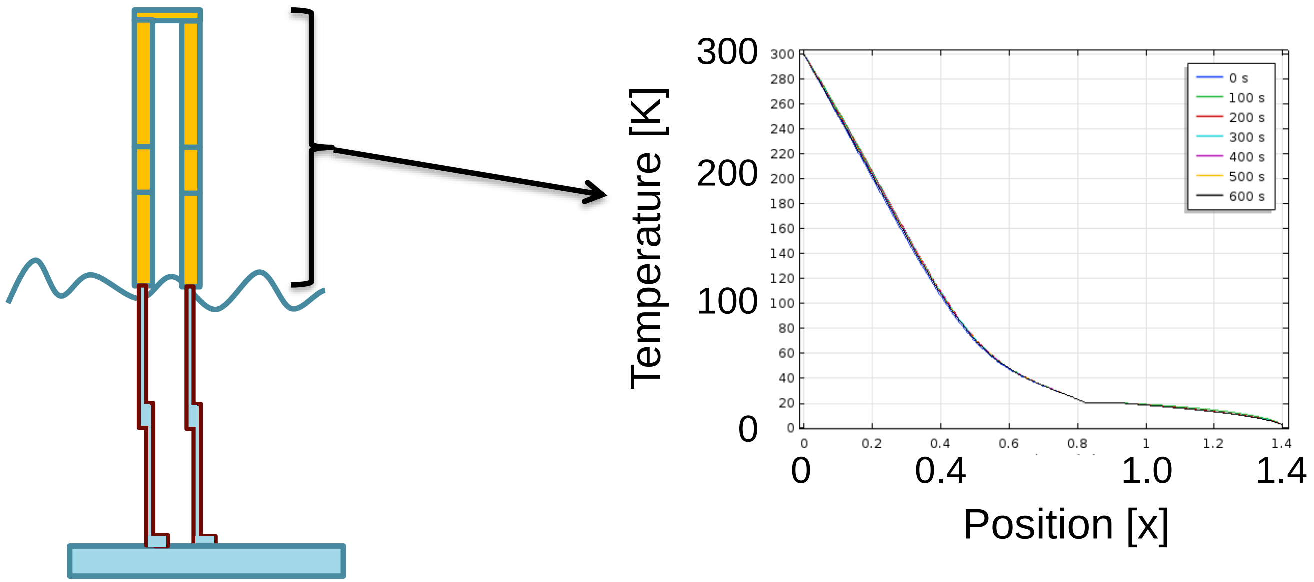
Fast power abort of main circuit at 12.8 kA





- During a fast power abort of the main circuit, the combined stored magnetic energy of the 11 T magnets is partially discharged in the trim circuit (= parallel resistor to 11 T magnets)
- During an FPA the power converter of the trim circuit is deactivated
- The trim circuit crowbar limits the current to below 200 A, **with a time constant of 100 s**, provided sufficient resistance is present

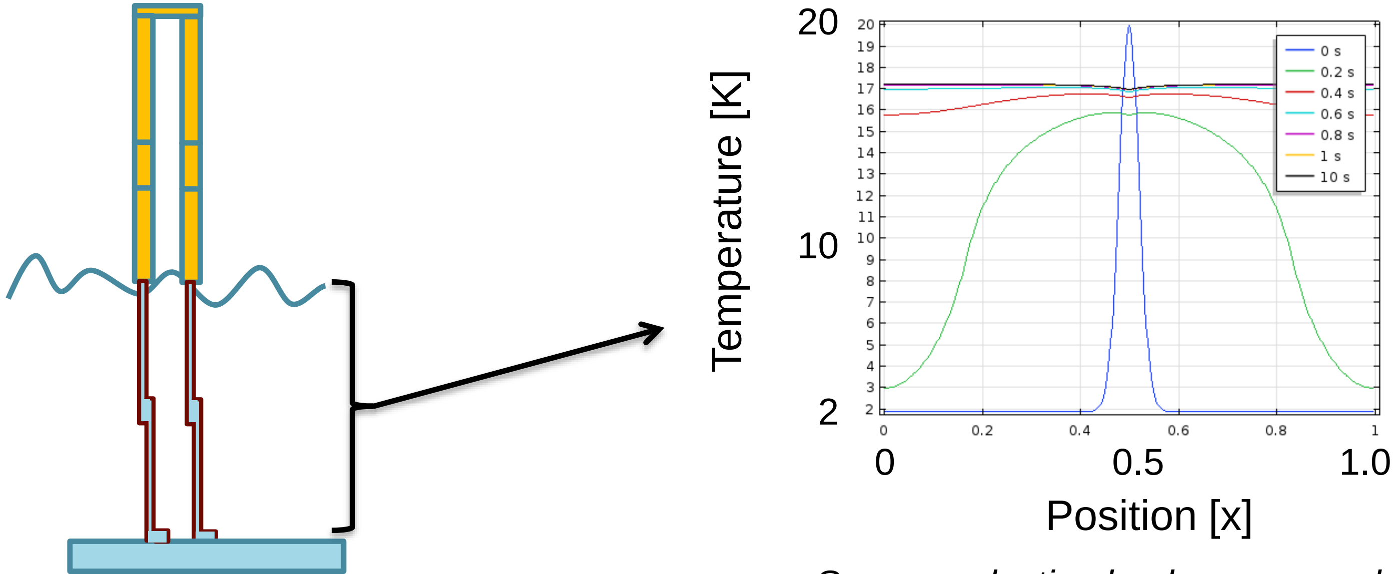
Time constant of 100 s, is this okay?



Current lead, undergoing current transient resulting from FPA

- Calculation of thermal behavior of current lead and quenching busbar:
  - **During FPA, quench detection and current monitoring over the current lead and superconducting busbar has no effect, since the trim circuit is already discharging over the crowbar**
  - For current lead: Due to its thermal mass, temperature increase is negligible even when all current is passing through a single lead

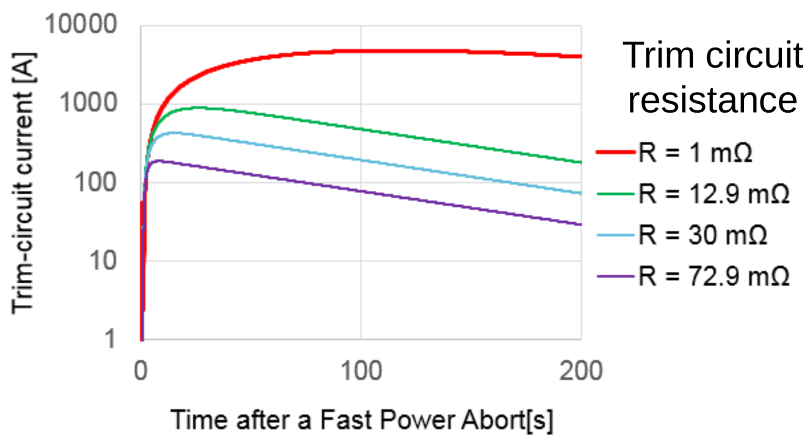
Time constant of 100 s, is this okay?



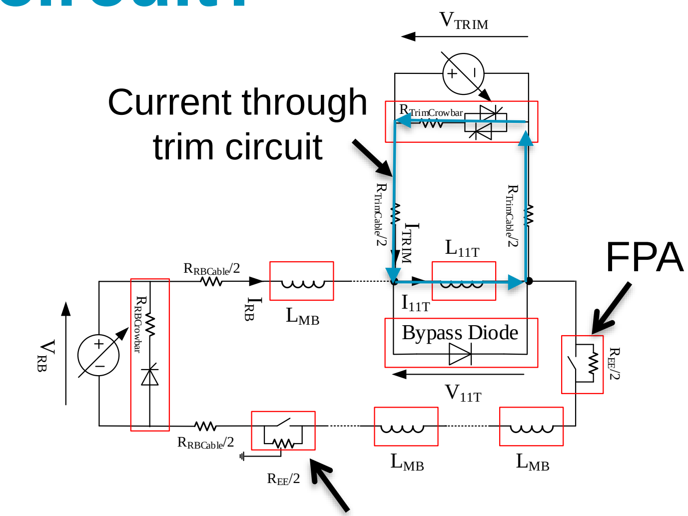
Superconducting busbar, powered at 250 A

- Calculation of thermal behavior of current lead and quenching busbar:
  - For quenching busbar (RRR=80, 260 µm polyimide insulation)
    - Quench at 125 A (regular current distribution) → Quench recovery
    - Quench at 250 A (extremely uneven current distribution) → Busbar will remain below 20 K as long as it is submersed in liquid helium → Protected by cryo-stability
- **Conclusion: Even under very pessimistic assumptions no thermal runaway occurs, provided that sufficient liquid helium is present and the trim circuit has sufficient resistance**

What if there is insufficient resistance in the trim circuit?



Current over trim circuit as a function of time



Trim circuit is designed to have 12.9 mΩ in the warm leads, and an additional 60 mΩ in the crowbar. Power supply is placed in series with DC contactor switch to enhance reliability.

- Everything works as it is supposed to: 72.9 mΩ in total → Less than 200 A through trim circuit during FPA → No thermal runaway in superconducting busbar due to helium cooling
- Crowbar is shorted: 12.9 mΩ in total → Up to about 1000 A in trim circuit during FPA, ~500 A per busbar → Superconducting busbars (with joints etc.) are no longer cryo-stable and thus not protected
- Occurrence of low resistance short (~1 mΩ) → Up to kilo-amps through trim circuit

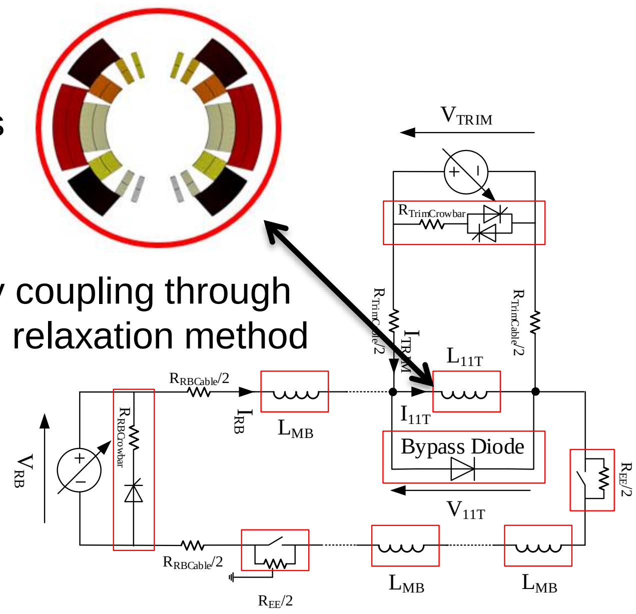
→ Protection of the superconducting busbars relies on correct operation of trim circuit and absence of shorts

New activity: STEAM co-simulation of modified RB circuit

Magnet quench simulation models (STEAM-LEDET)

Two-way coupling through waveform relaxation method

Detailed electrical circuit model (PSPICE)



STEAM co-simulation of modified RB circuit: Circuit solver (PSPICE) coupled to magnet quench simulations in STEAM-LEDET

- New activity being undertaken by Michal Maciejewski
- Co-simulation [2] of detailed electrical model of modified RB circuit, coupled to quench simulation models of 11 T magnets [3,4]
- Objectives:
  - Analysis of fault scenarios (Extension on previous work [5])
  - Investigation of “travelling wave” phenomenon and impact on QDS
  - Repository of circuit parameters in a single model, for future use during LHC operation
- Results to be presented in upcoming Magnet Circuit Forum meeting

[2] cern.ch/Steam
[3] Ravaioli et al. Cryog. 80, p 346 (2016)
[4] Mentink, Ravaioli, EDMS 2008495 (2018)
[5] Bermudez et al. IEEE trans 28, p. 4006405 (2018)

Summary

- Trim circuit:
  - Provides up to 250 A during regular operation
  - Acts as a parallel resistor to the 11 T magnets during a fast power abort

- Quench protection
  - Quench in trim circuit superconducting busbar or incorrect current distribution between current leads without FPA → Adequate protection of current lead and superconducting busbar
  - Fast power abort in main circuit:
    - Trim circuit is already discharging over crowbar, therefore quench detection in busbar has no resulting action
    - Crowbar limits current to below 200 A, and protection of the superconducting busbars requires helium cooling
    - In case of insufficient resistance over trim circuit → Over-current through trim circuit and superconducting busbars are not protected → Correct operation and absence of shorts is critical.

- STEAM co-simulation of modified RB circuit
  - Extensive effort to check for fault scenarios, implications of travelling wave phenomenon on quench detection, etcetera
  - First results to be presented in the Magnet Circuit Forum