CERN

Circuit Protection: Progress and Challenges at HL-LHC

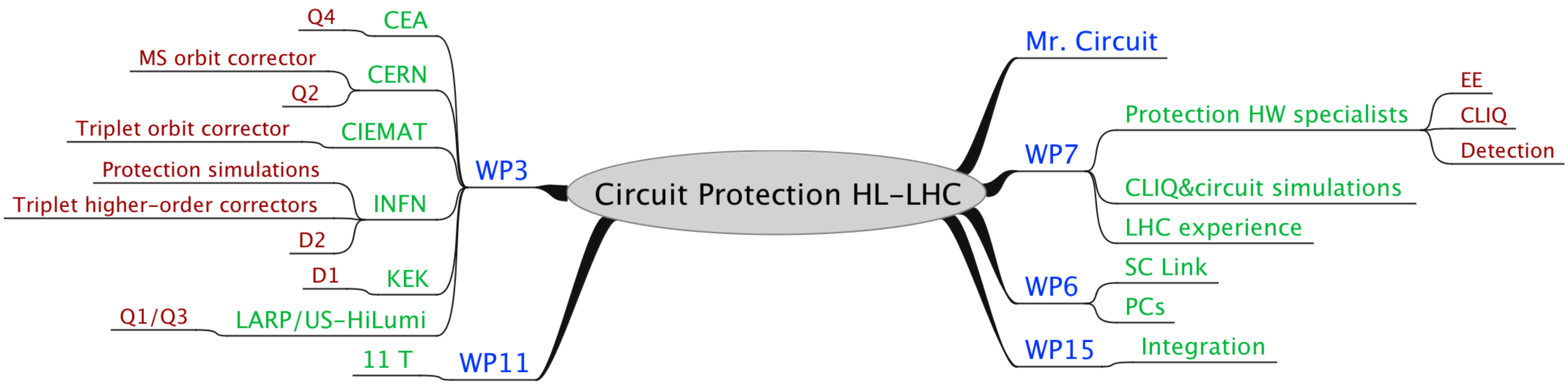
B. Auchmann (WP 7) on behalf of many people in WPs 3, 6, 7, 11 and Mr. Circuit

Outline

- Overview actors
- Circuit protection
  - progress and challenges per circuit type
- Deliverables
- Conclusion

Actors in Circuit Protection

Joint effort by numerous actors



Vast amount of work done by individual actors.

Collaboration between actors is growing closer.

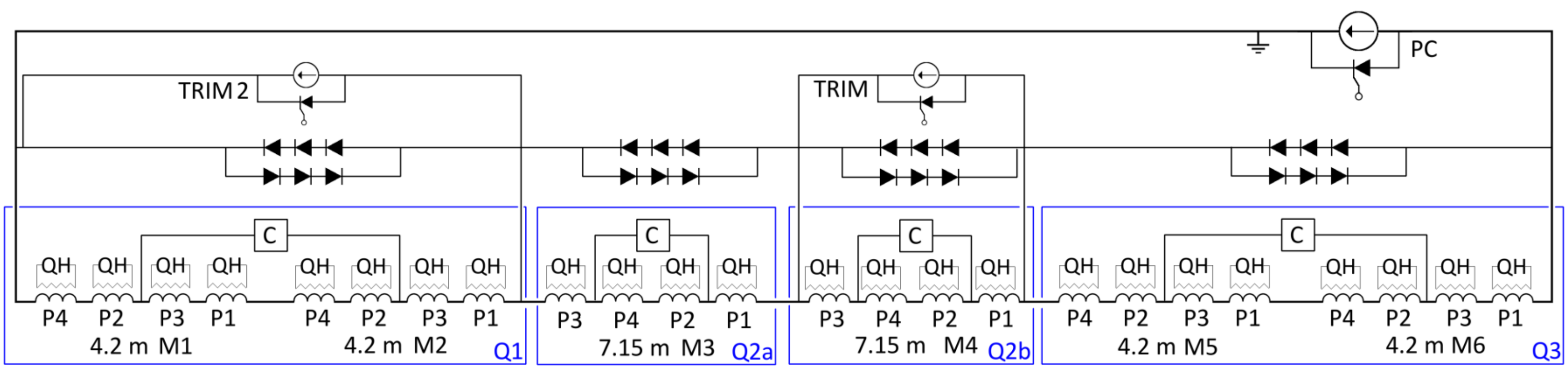
See also the joint plenary session on Wednesday morning!

Inner Triplet Circuit

Baseline: Outer- and inner-layer heaters, CLIQ, (energy extraction).

Progress:

- Protection of a single-circuit option has been studied:
  - Protection is feasible without energy extraction.
  - Reduced cost and space requirements for 4 instead of 6 CLIQs.
  - Inner-layer heaters as fall-back solution for redundancy in this study.
  - Warm by-pass elements bring voltage distribution over the circuit under control.



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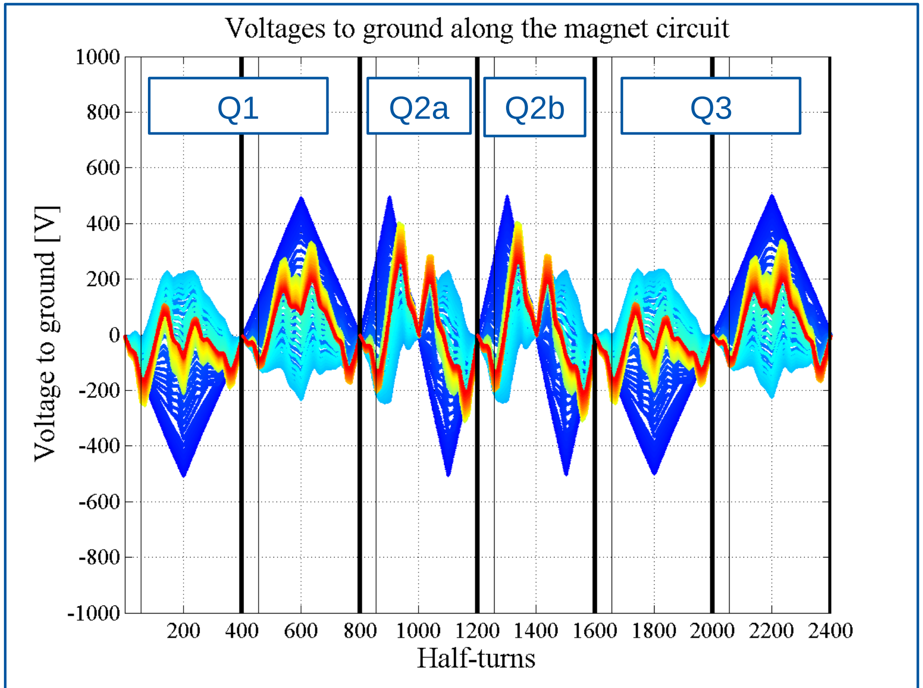

Voltage to ground from 5 ms (blue) to 100 ms (red) after activation of CLIQ. Courtesy of Emmanuele Ravaioli

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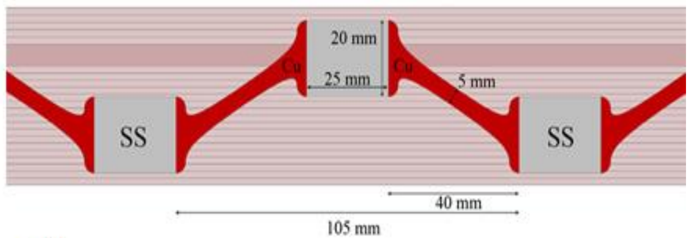
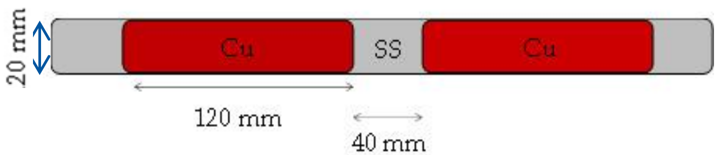
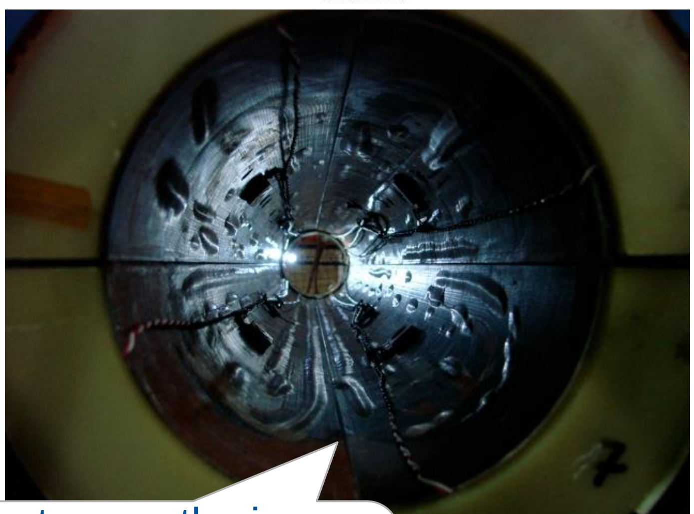
Inner Triplet Circuit

IL



OL

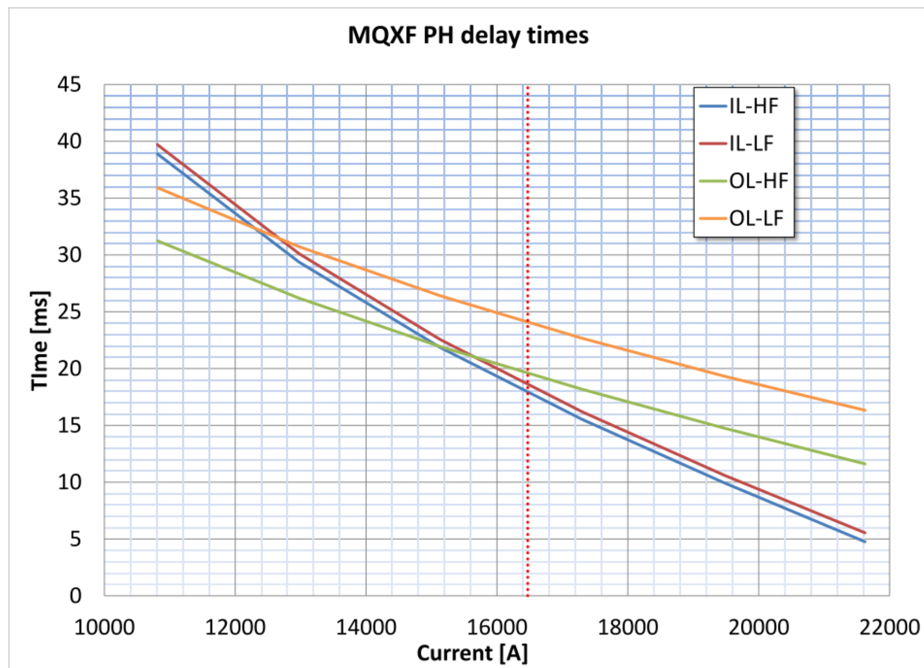




Heaters on the inner layer (HQ) may develop bubbles during operation.

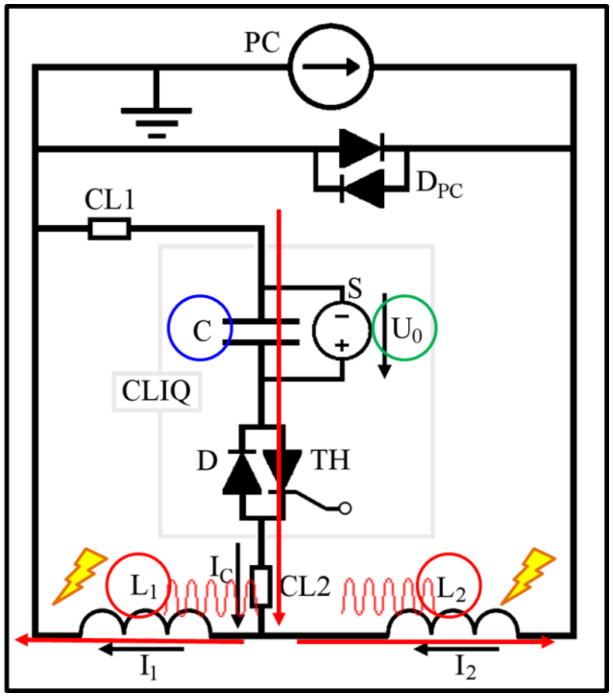
Quench heaters have been designed using copper plating for **inner** and **outer** layer:

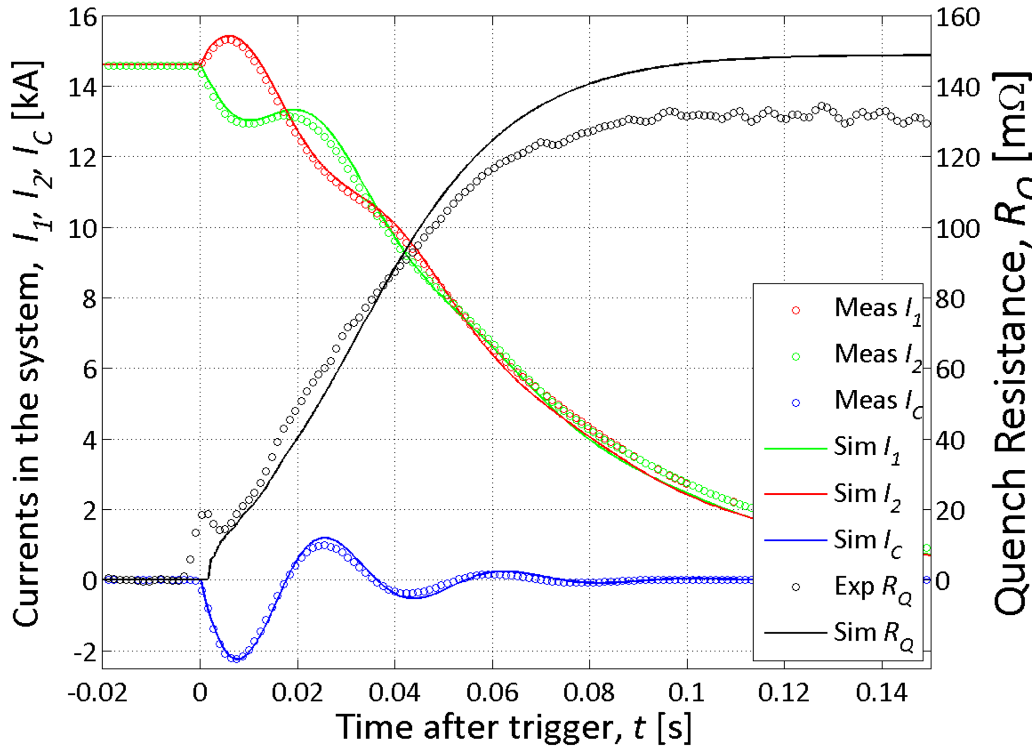
- Two strips on each side of the outer layer ("High Field" and "Low Field")
- One strip on each side on the inner layer
  - Inner layer 40% polyimide free



Courtesy of Giorgio Apollinari and Vittorio Marinozzi.

CLIQ





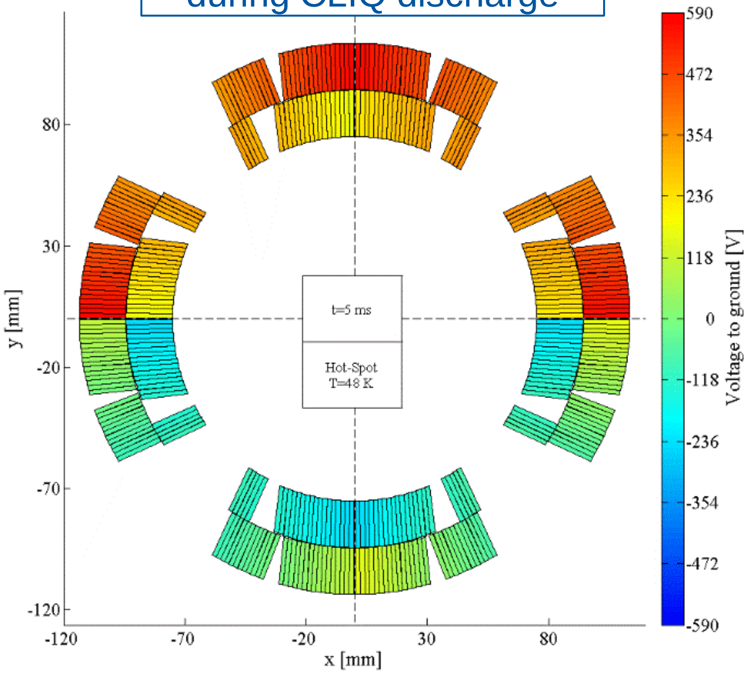
E. Ravaioli, et al., “Protecting a Full-Scale Nb3Sn Magnet with CLIQ, the New Coupling-Loss Induced Quench System”, to be published in *IEEE Trans. Appl. Supercond*. 2015.

Inner Triplet Circuit

Challenges:

- CLIQ is an active part of the circuit (reliability engineering!).
- Study circuit in many working points (diverse fault scenarios, etc.).
- Increased voltage-to-heaters vs. reduced insulation for heater efficiency.

Voltages to ground during CLIQ discharge



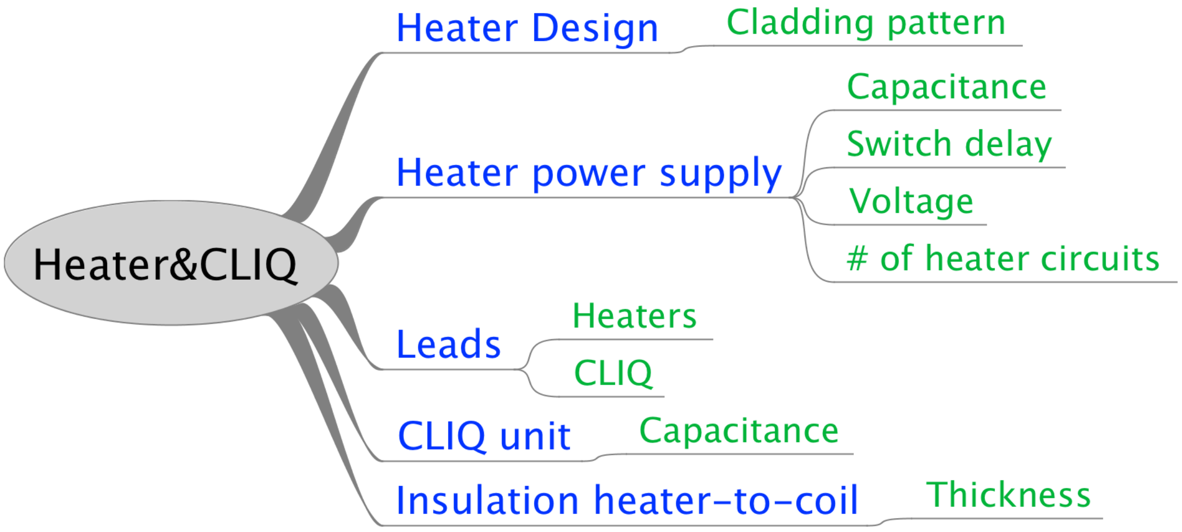
Discussed mitigation strategies	Coil-to-QH Voltage [kV]	Hot-spot T [K]
Default CLIQ + Outer QH	1.05	230
Delay QH by 10 ms	0.85	<250
Delay CLIQ by 10 ms	0.97	<250
Increase QH insulation thickness	1.05	tbp

Courtesy of Emmanuele Ravaioli

Inner Triplet Circuit

Challenges:

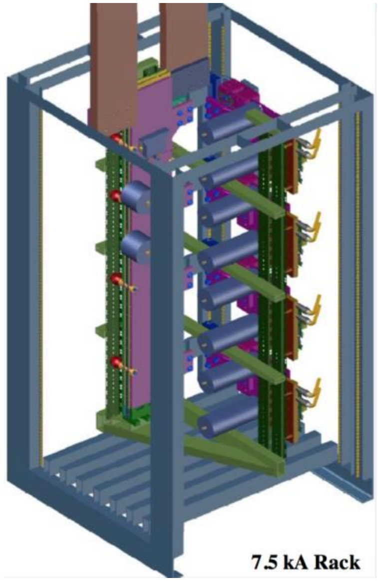
- Performance optimization of whole package necessary.
  - Reliable protection against high- and low-current quenches.
- Cost and space optimization.



Switches for Testing in SM18

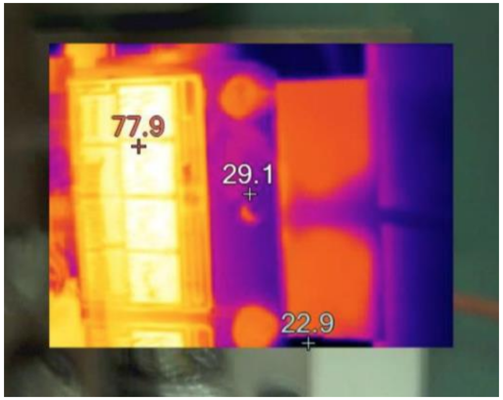
Hardware for 30-kA semi-conductor (IGBT) switches in SM18 arrives.

7.5 kA module design



IGBTs on heat sink

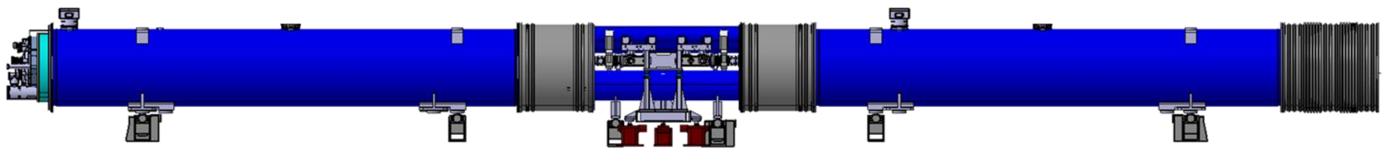
Thermal studies confirm models.



Mounted in rack

Presentation by Gert-Jan Coelingh and Alexandr Erokhin,
CERN TE-MPE Technical Meeting, October 15, '15.

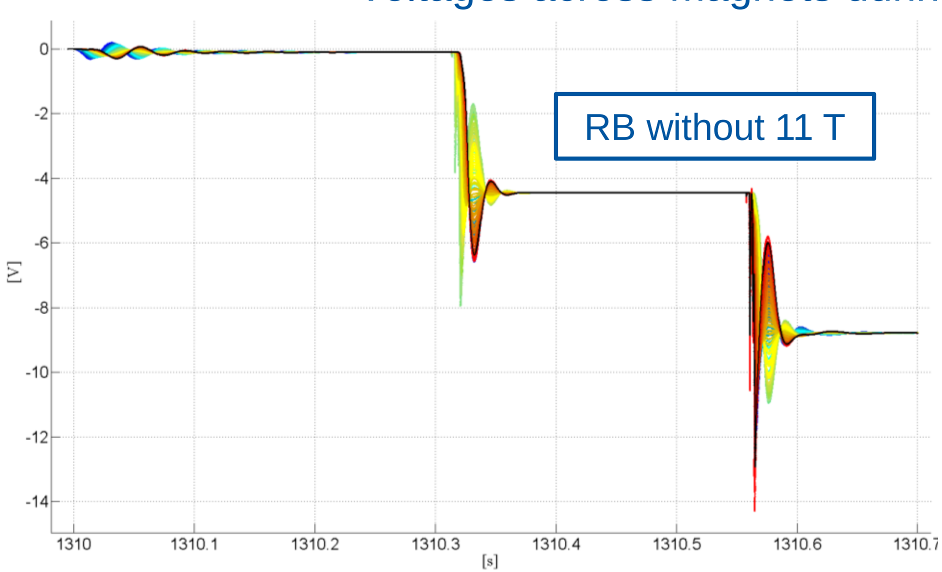
11 T

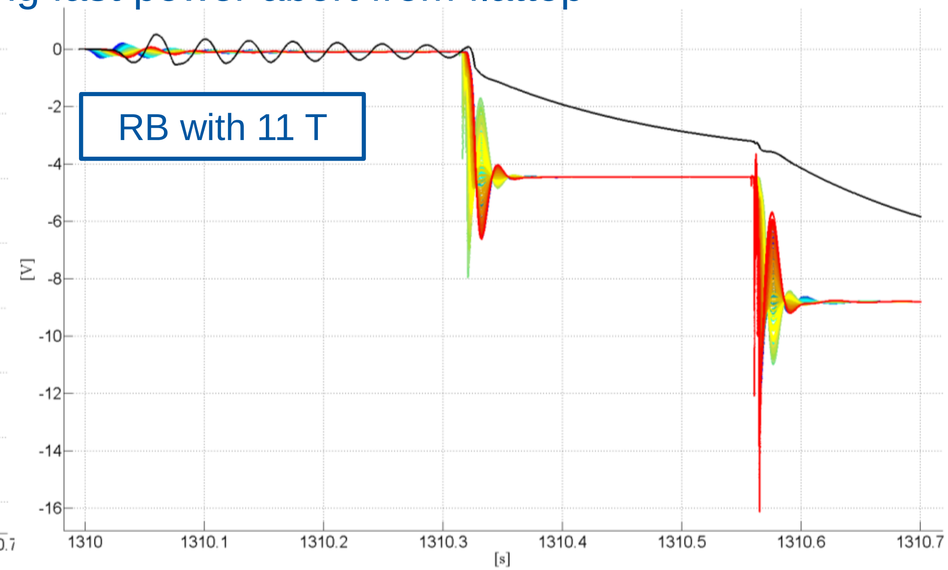


11 T in the RB circuit:

- EM wave-propagation phenomena are being studied.
- Trim power converter influences the 11-T response.
- Requires change of RB symmetric quench protection around 11 T.
- Symmetric quench protection for the 11 T need to be devised.

Voltages across magnets during fast power abort from flattop





Black line: 11-T location. Preliminary studies.
Courtesy of Lorenzo Bortot

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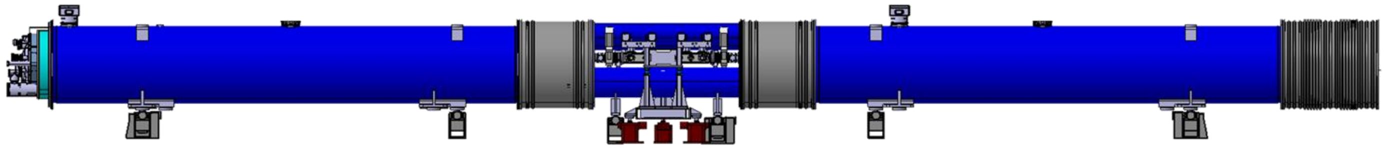
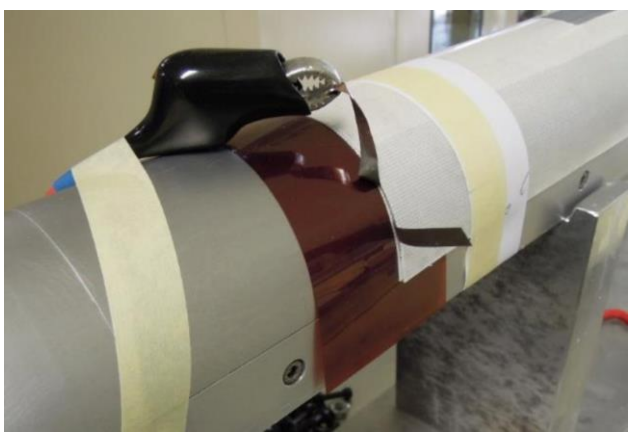
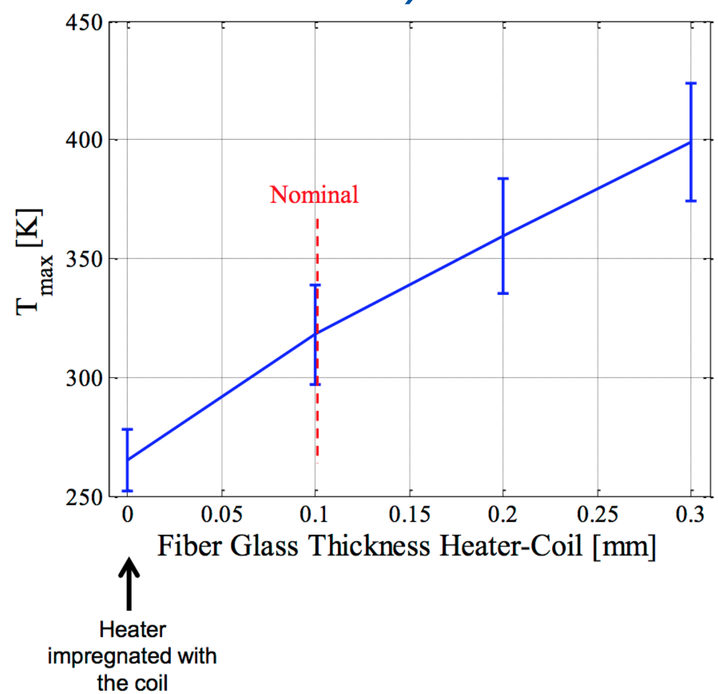
11 T



Progress on hot-spot temperature reduction

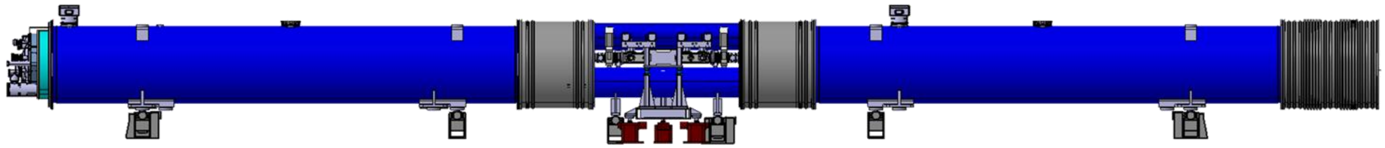
- Modelling, prototype testing, and sub-scale experimental efforts to quantify uncertainties.
- Study of reduction in heater-coil insulation
(more benign than in QXF through use of mica insulation).
- R&D on intra-layer heaters
  - 2-m-long test coil with mica-heater sandwich showed good electrical performance.
  - Remaining challenge: scale-up to 5.5 m.





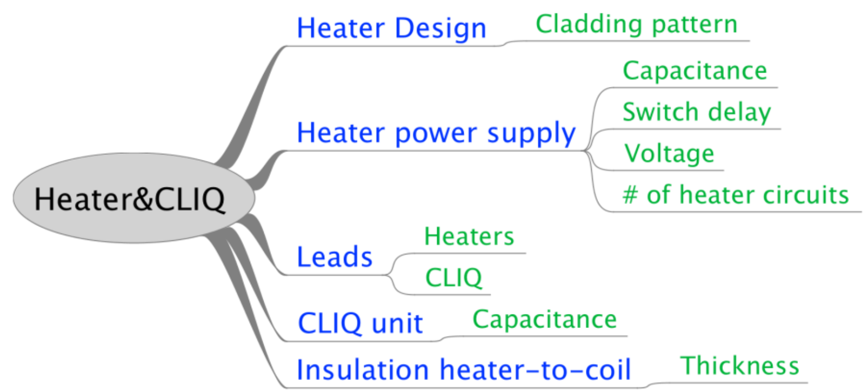
Courtesy of Susana Izquierdo Bermudez.

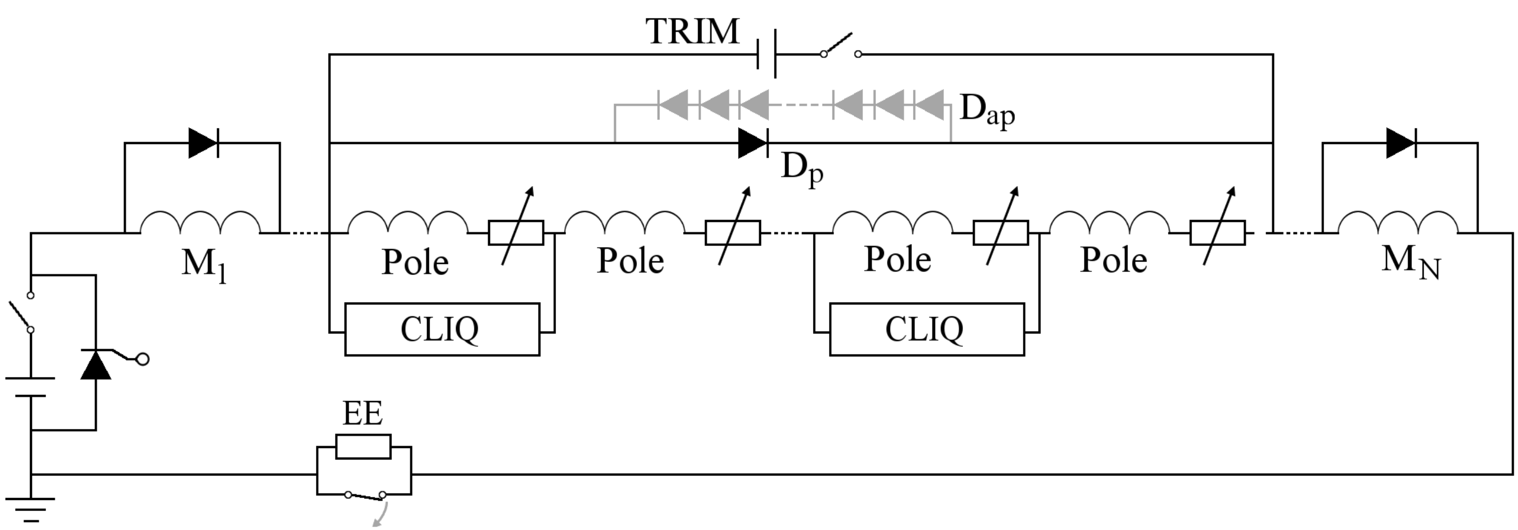
11 T



CLIQ-heater combination could much lower hot spot temperature.

- Compatibility with remaining circuit through warm reverse diodes.
- Optimize all aspects of heater and CLIQ solution in unison.
- Study circuit in many working points (failure scenarios, etc.).
- Check R2E situation in detail (diode, tunnel electronics).

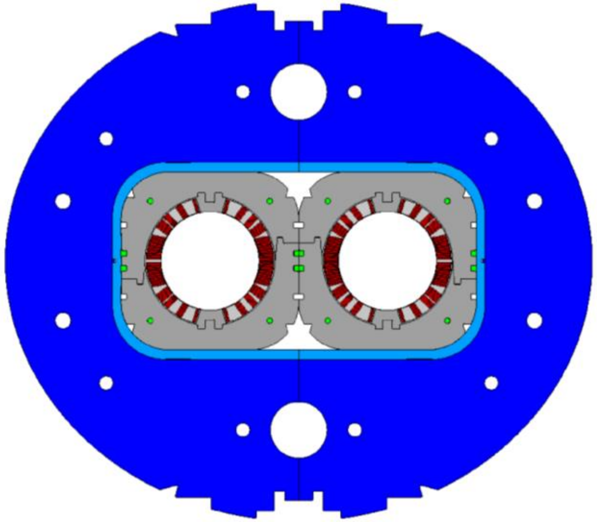




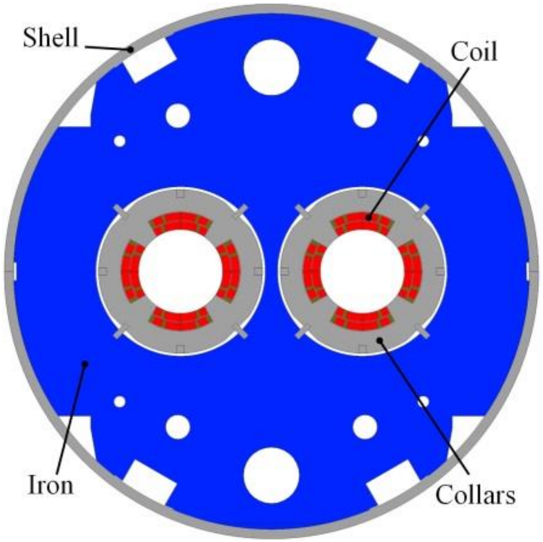
High-Current Nb-Ti Circuits

- New baseline for D1, D2, Q4 (Q5): outer-layer heaters.
- Studies ongoing:
  - CLIQ as an alternative to heaters.
  - Circuit simulations for D1-D2 powering in series (fault scenarios, etc.).
  - Size & cost estimates for CLIQ option.

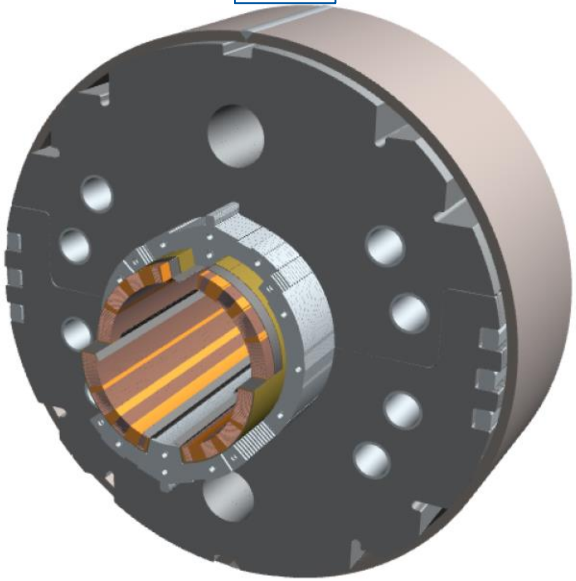
D2



Q4



D1

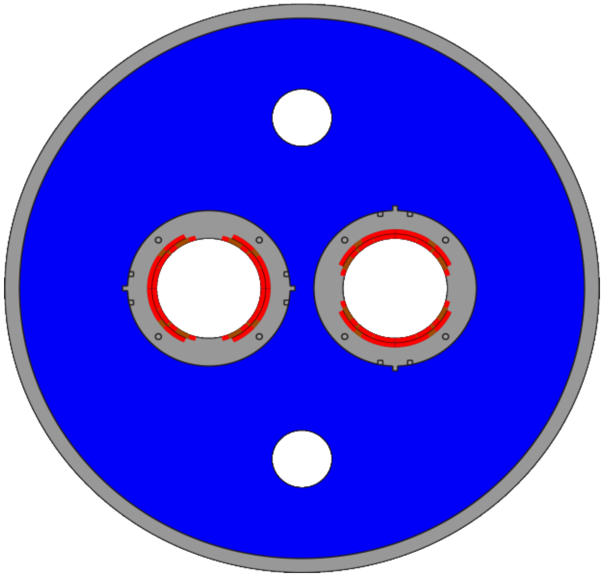


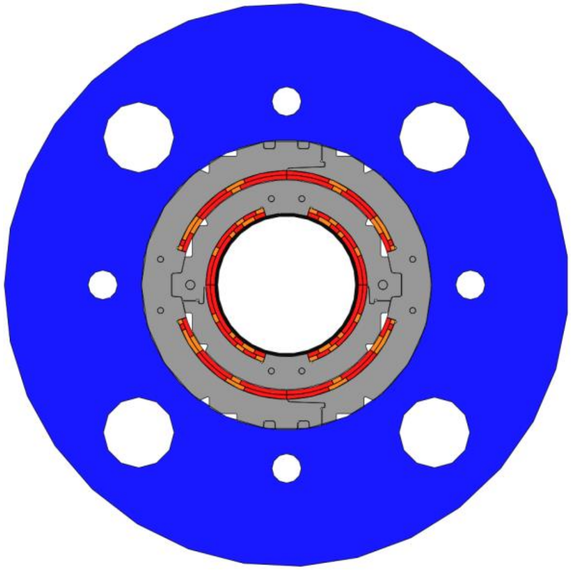
See also presentations by Michinaka Sugano, Pasquale Fabbricatore, and Jean-Michel Riflet, Friday, 9h45, Kjell Johnson Auditorium.

Intermediate-Current Circuits

2 kA orbit-corrector circuits:

- Baseline: Energy extraction.
- Studies ongoing:
  - Switch market survey.
  - Heaters as alternative.
  - Low-current version of MS orbit corrector (Reduce cost of power converters).



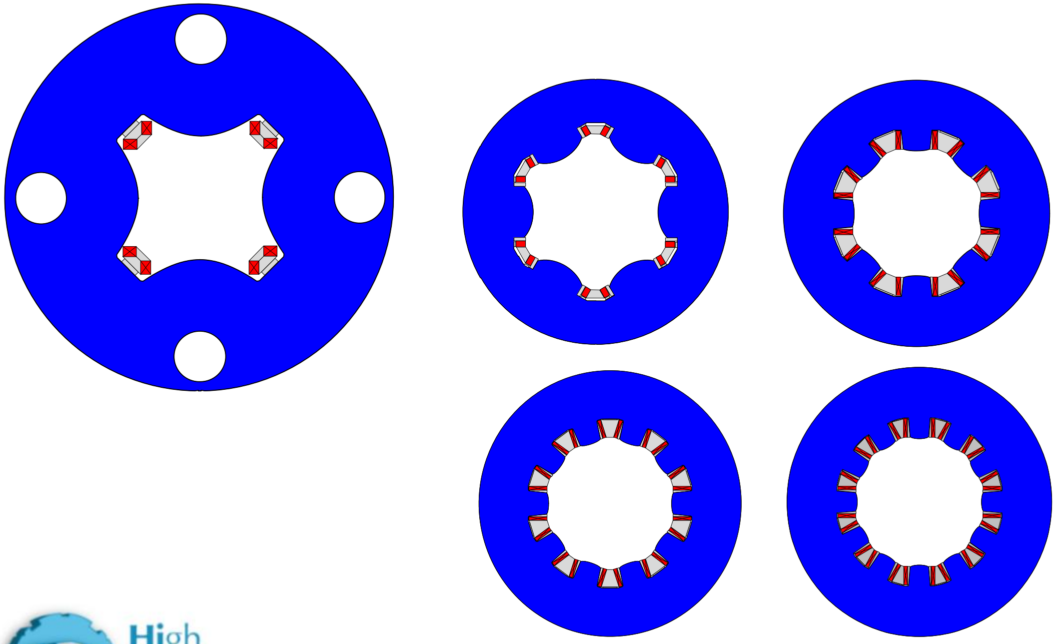


See also presentation by Fernando Toral, Friday, 9h45, Kjell Johnson Auditorium.

Low-Current Circuits

100-200 A higher-order triplet corrector circuits

- Baseline: Energy extraction and/or crowbar.
- Studies ongoing:
  - Energy extraction could use 600-A switches under procurement.
  - Determine need for EE vs. protection with crowbar.



See also presentation by Giovanni Volpini, Friday, 10h10, Kjell Johnson Auditorium.

Deliverables and Actors

For each circuit type:

- Detection specification (Mr. Circuit, WPs 3, 6, 7, 11)
    - Magnet (symmetric/asymmetric), busbar and joints, leads, SC link.
        - V-tap definition
        - Thresholds voltage and evaluation time,
            - documentation of flux-jump voltage spikes,
            - peak temperature vs. threshold parameters.
        - Documentation of measured propagation velocities (long. & transv. in high and low field region).

Deliverables and Actors

For each circuit type:

- Detection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Heater design documentation (WPs 3, 7, 11)
    - Documentation of heater-efficiency experiments and simulations.

Deliverables and Actors

For each circuit type:

- Detection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Heater design documentation (WPs 3, 7, 11)
- Active-protection specification (Mr. Circuit, WPs 3, 6, 7, 11)
  - Crowbar
  - EE (max. current, max. load, switch delay)
  - CLIQ (capacitance, leads dimensions)
  - Heater power-supplies (capacitance, switch delay, leads dimensions)

Deliverables and Actors

For each circuit type:

- Detection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Heater design documentation (WPs 3, 7, 11)
- Active-protection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Specification of ELQA tests voltages (Mr. Circuit and WPs 3, 6, 7, 11)
  - During manufacture, at reception, and in tunnel.

Deliverables and Actors

For each circuit type:

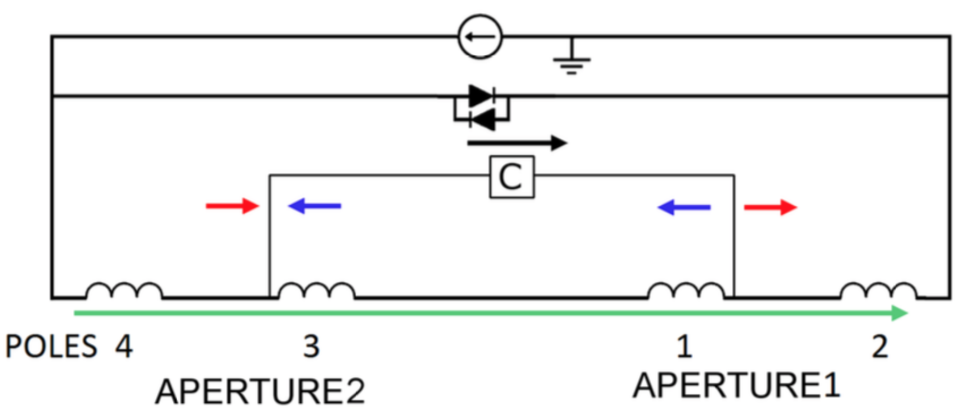
- Detection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Heater design documentation (WPs 3, 7, 11)
- Active-protection specification (Mr. Circuit, WPs 3, 6, 7, 11)
- Specification of ELQA tests voltages (Mr. Circuit and WPs 3, 6, 7, 11)
- PIC interface documentation (Mr. Circuit, WP 7)
- Busbar specification (Mr. Circuit, WPs 3, 6, 7, 11)
- CLIQ, EE: reliability studies (Mr. Circuit, WP 7)
- Electric circuit diagram incl. instrumentation (Mr. Circuit, WPs 3, 11, 15)
- Definition of instrumentation routing (Mr. Circuit and WPs 3, 6, 11, 15)

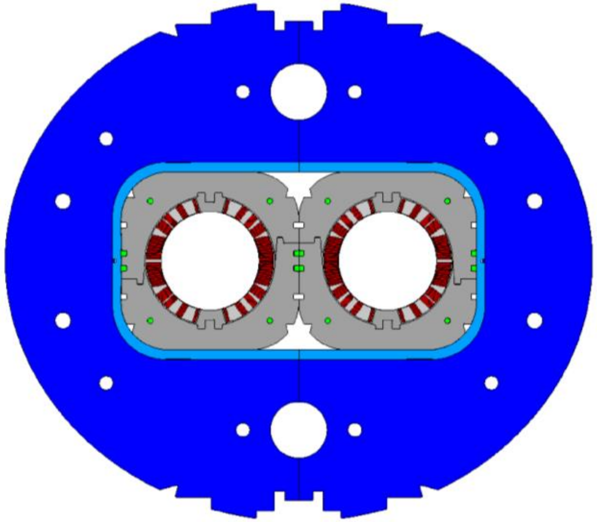
Conclusion

- Close collaboration of numerous actors.
- Large amount of work already done in individual WPs.
- Still a fair amount of work ahead.
- Interesting solutions exist for all circuits.
- Optimization of cost, and performance ongoing.
- Measurements on prototypes will complement the modeling work.
- More information and discussions in the joint parallel session Wednesday morning, Kjell Johnson Auditorium, (Bldg. 30).

CLIQ in Nb-Ti Circuits

D2





Courtesy of Alejandro Fernandez Navarro