Quench Behaviour of the HL-LHC Twin Aperture Orbit Correctors,

Simulations vs. Experimental Observations

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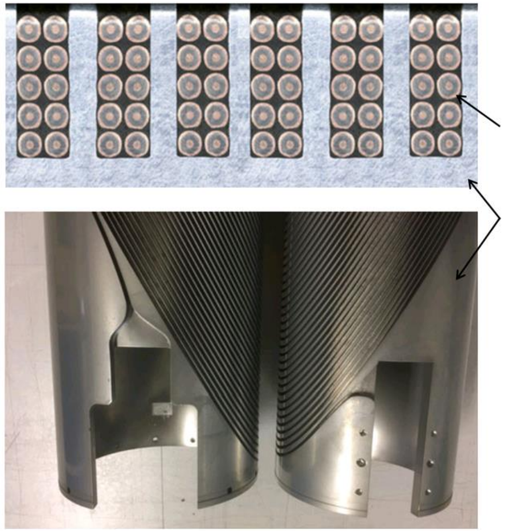
26th of September, 2019

Introduction



Individually insulated Nb-Ti/Cu strand

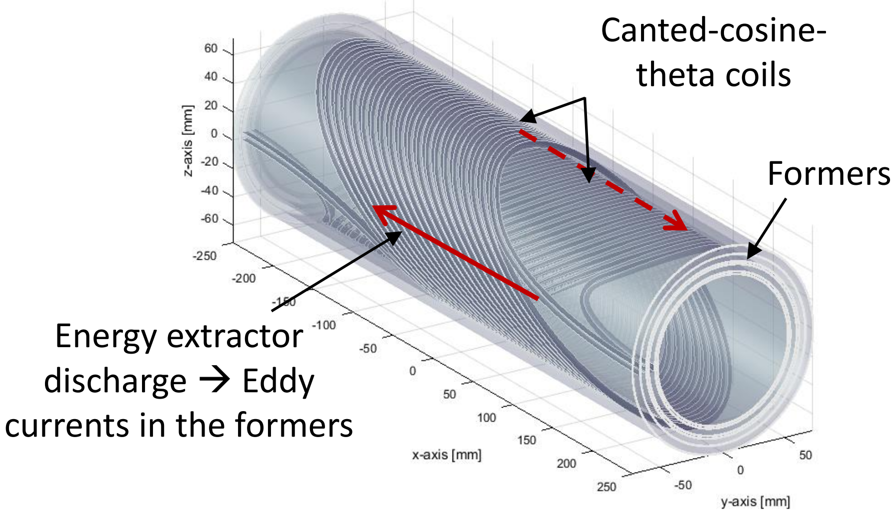
Thermally and electrically conductive aluminum-alloy former

- Twin Aperture Orbit Corrector Magnets, designated ‘**MCBRD**’
- Canted Cosine Theta geometry, where two concentric coils together produce dipole field
- Individually insulated Nb-Ti/Cu strands held in place by conductive aluminum-alloy formers
- Developed and produced for HL-LHC upgrade in collaboration between CERN (MCBRDp1 prototype + short models), IHEP, IMP, CAS and WST
- **How to protect in case of quench?**

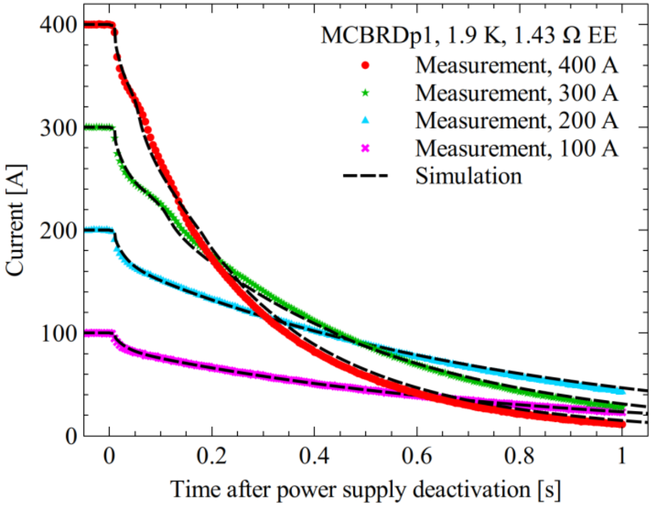
Related talks / posters:

- J. Robertson et al., Mon-Mo-Or3-3
- F. Mangiarotti et al., Thu-Af-Or22-2
- E. Ravaioli et al., Thu-Af-Or24-2
- W. Shaoqing et al., Wed-Af-Po3.20-04

Protection of the MCBRD magnets



Quench-back in MCBRD magnets



Typical discharge curves, sim vs meas, 1.43 Ω EE

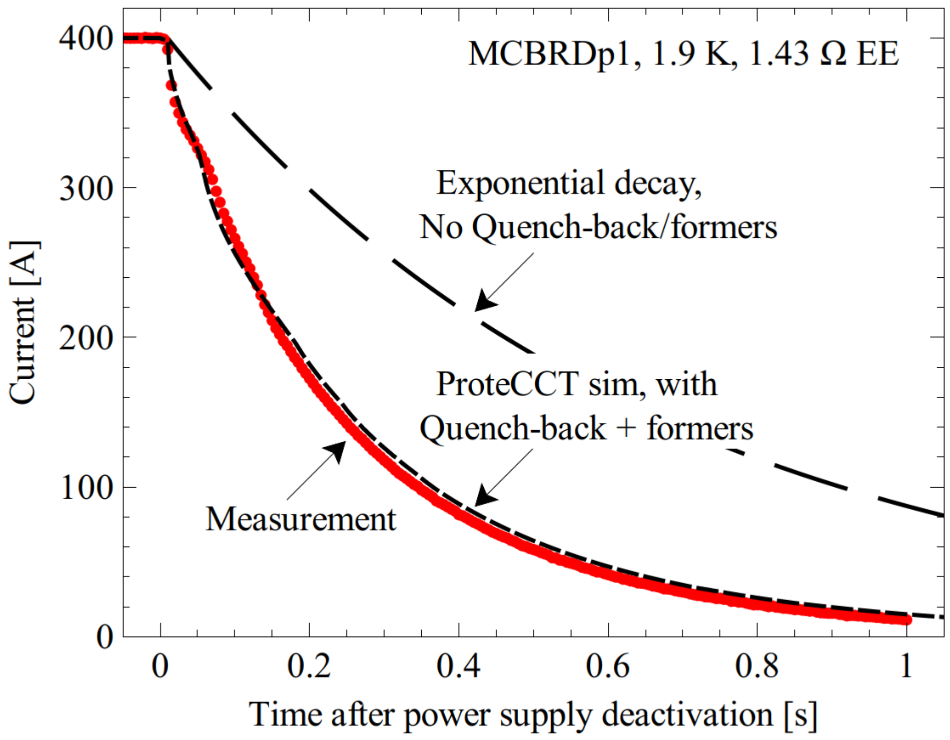
Property	Value
Ultimate current [A]	435 A
Inductance [H]	0.97
Magnetic length [m]	1.92

MCBRDp1 properties

Magnet protected by energy extraction and quench-back

- Quench detected → Magnet discharged over external dump resistor R_{EE} → Eddy current generation in the formers → Temperature increase from eddy current heating→ Normal zone throughout Nb-Ti/Cu coils (Quench-back) → Discharge accelerates
- Stored magnetic energy dissipation at I_0 = 435 A, R_{EE} = 1.43 Ω, T_{Bath} = 1.9 K: 40% in Nb-Ti/Cu strands, 30% in energy extractor, 30% in formers and outer cylinder through eddy current heating

Motivation for dedicated simulation tool development, “ProteCCT”



Simulation versus measurement

- Standard approach to energy extraction, no inductive coupling, no quench-back:
  - Exponential decay, with $\tau = L/R_{\mathrm{EE}}$
  - For I_0 = 400 A, $QI_{\mathrm{Discharge}}$ = 20 kA^{2}s → R_{EE} = 4.2 Ω, $V_{\mathrm{Gnd,Max}} = R_{\mathrm{EE}} \times I_0$ = **1800 V**

- ProteCCT simulation with inductive coupling to conductive formers and quench-back
  - For I_0 = 400 A, $QI_{\mathrm{Discharge}}$ = 20 kA^{2}s → R_{EE} = 1.43 Ω, $V_{\mathrm{Gnd,Max}} = R_{\mathrm{EE}} \times I_0$ = **570 V**

- Discharge behavior of MCBRD magnets: Complex to simulate but factor three lower voltage-to-ground than with exponential decay, beneficial for circuit components

→ MCBRD protected with energy extraction + quench-back, so a correct and cross-checked simulation tool is a needed

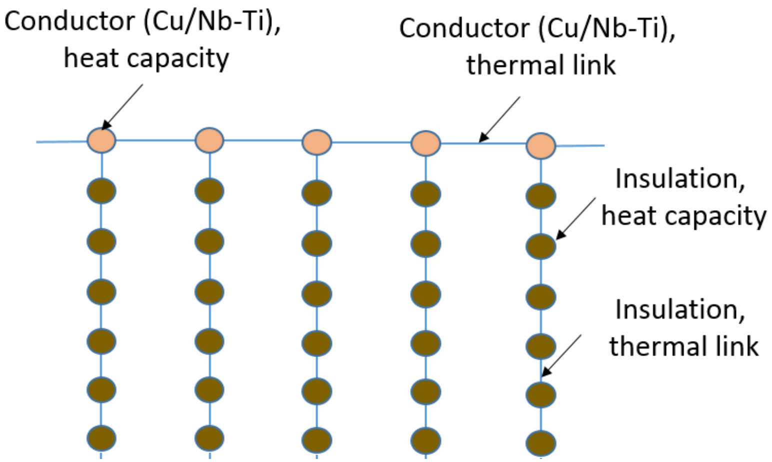
Overview

- Simulation versus experimental observations on the CERN MCBRD short models and prototype
  - BBQ simulation: Initial voltage development after a quench
  - ProteCCT simulation: Discharge of the magnet
  - BBQ: Hotspot temperature and peak voltage-to-ground for baseline protection configuration

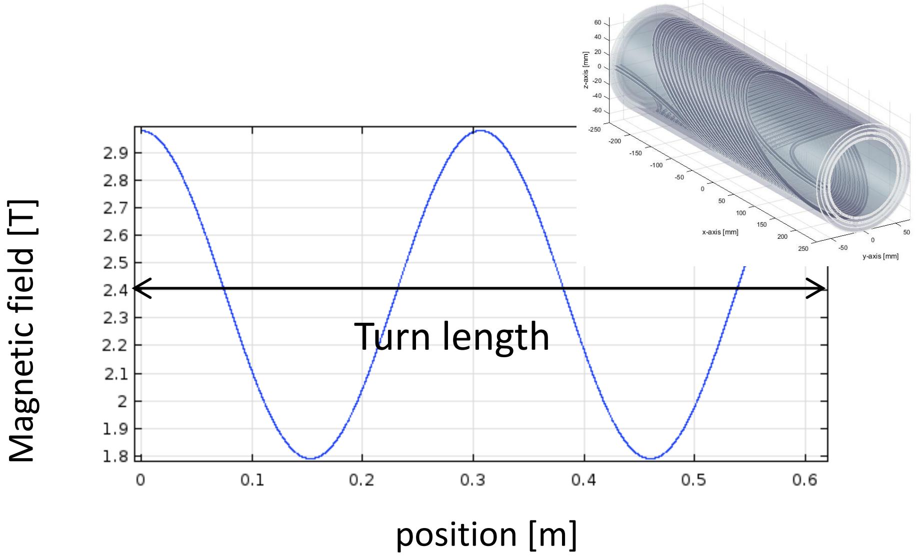
- Implications for other MCBRD variants
  - Upcoming prototype test at IMPCAS
  - Parameter variations and resulting hotspot temperature in the LHC

- Summary

BBQ simulation of initial voltage development after a quench



BBQ: 1+1D thermal implementation



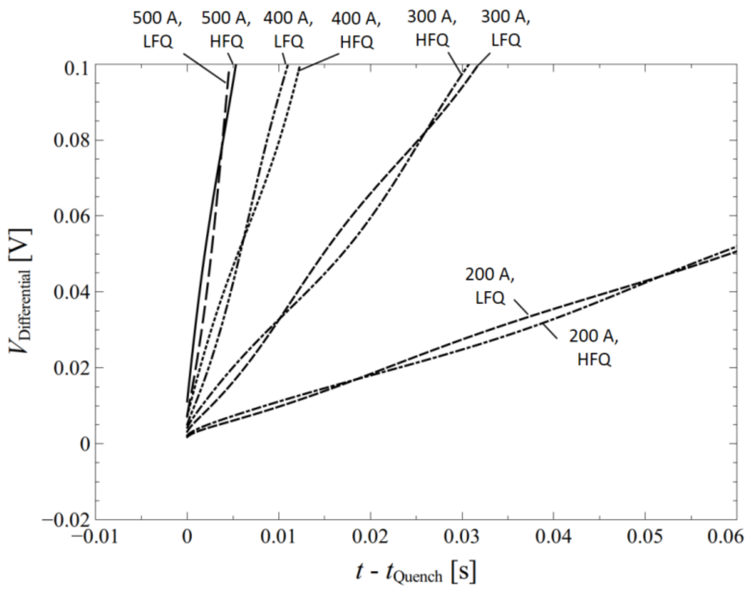
Axially varying magnetic field in CCT-type magnet

BBQ = FEM-based (Comsol) simulation tool for calculating quench-related properties of a single Nb-Ti/Cu conductor with surrounding insulation

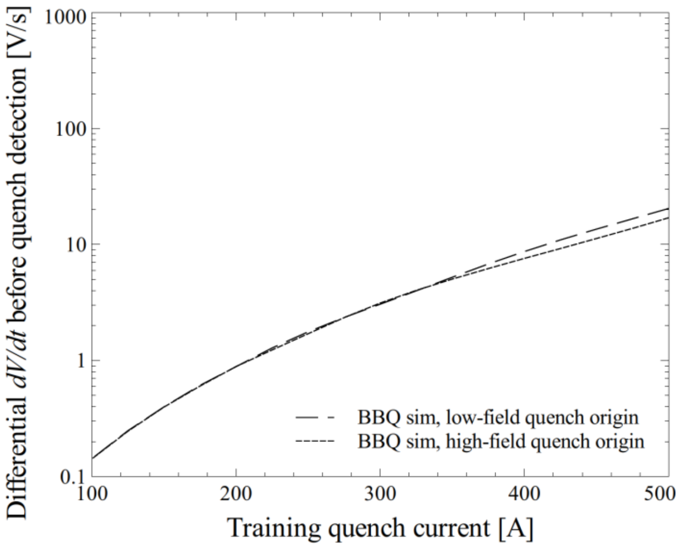
- 1+1D thermal implementation: Transverse propagation between core and insulation, and axial propagation
- With non-linear magnetic-field- and temperature-dependent properties from STEAM material library
- For MCBRD magnets: Considers axially varying magnetic field
- Free to download from Steam website (**cern.ch/steam**)

[1] M. Mentink and M. Maciejewski, “STEAM-BBQ User Manual”, EDMS Nr. 2159783 (2019).

BBQ Simulation Results



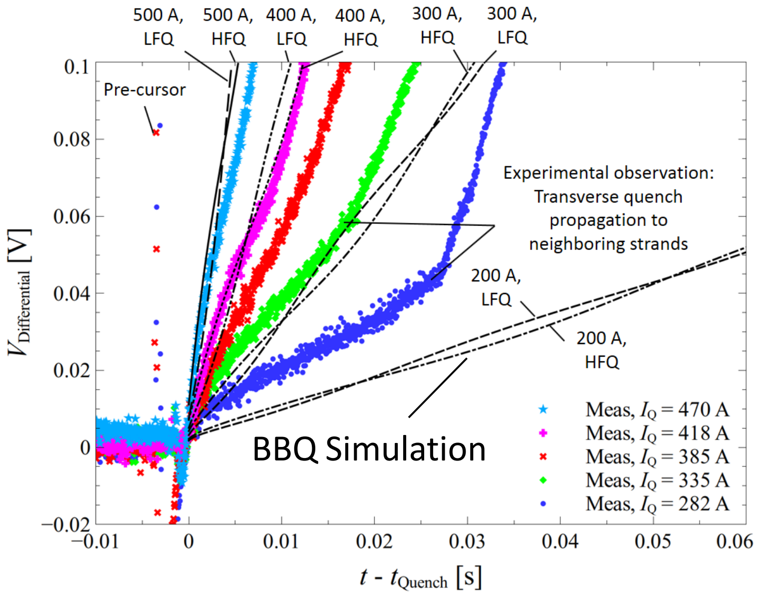
Quench origination, simulation



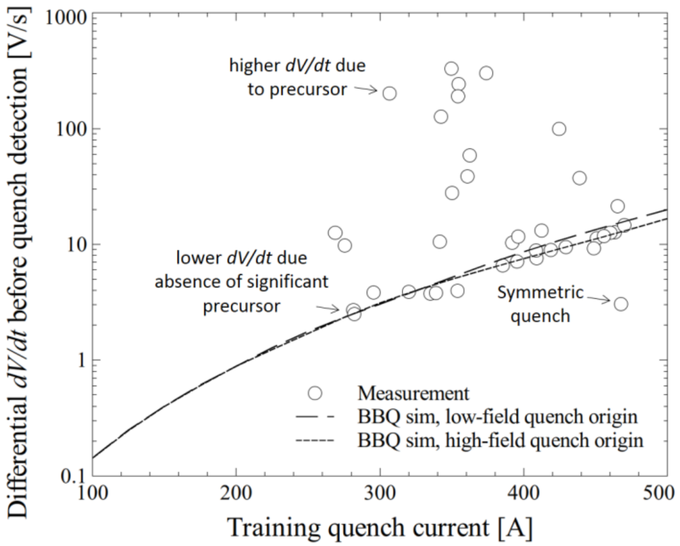
Initial dV/dt, simulation

- HFQ = Quench originating at peak field of turn, LFQ = Quench originating at minimum field in turn

Simulation results versus experimental observations



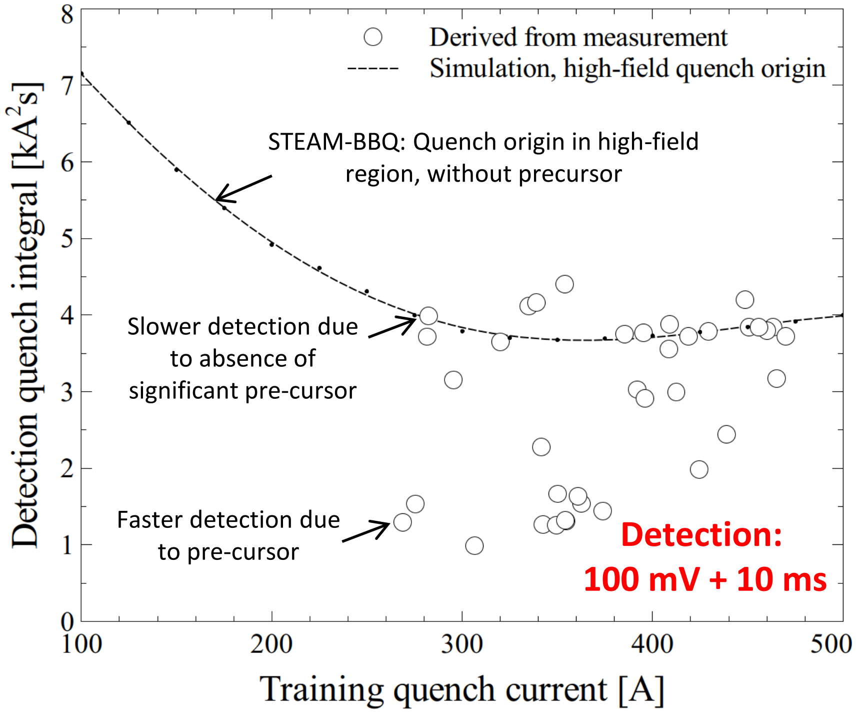
Quench origination, sim vs exp



Initial dV/dt, sim vs exp

- HFQ = Quench originating at peak field of turn, LFQ = Quench originating at minimum field in turn
- Experimental observations:
  - For some quenches: Large dV/dt due to pre-cursors, others: smaller dV/dt due to only thermal propagation
  - Voltage oscillation, consistent with simulation results
  - Strand-to-strand propagation (not simulated) is observed, but for higher currents after reaching detection threshold → Modest influence on quench detection
- **Comparison: Good consistency between simulation and measurement**

Detection + Validation of Quench



Detection QI, sim versus measurement

- Quench detection (**100 mV** threshold) + validation (**10 ms** validation time)
- For significant pre-cursors → Faster quench detection (less critical)
- Without pre-cursors → Only thermal propagation and slower detection, experimental observations consistent with simulation results
- **3.8 kA^{2}s** detection quench detection for MCBRDp1 at ultimate current (**435 A**)

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  - BBQ: Hotspot temperature and peak voltage-to-ground for baseline protection configuration

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  - Parameter variations and resulting hotspot temperature in the LHC

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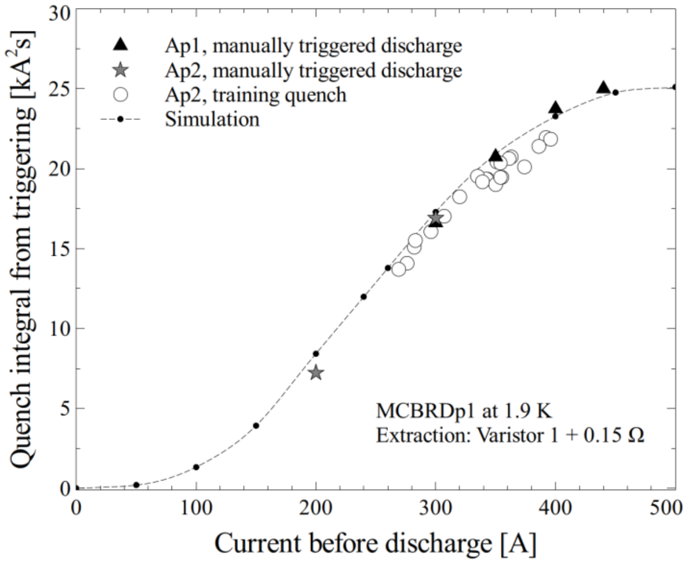
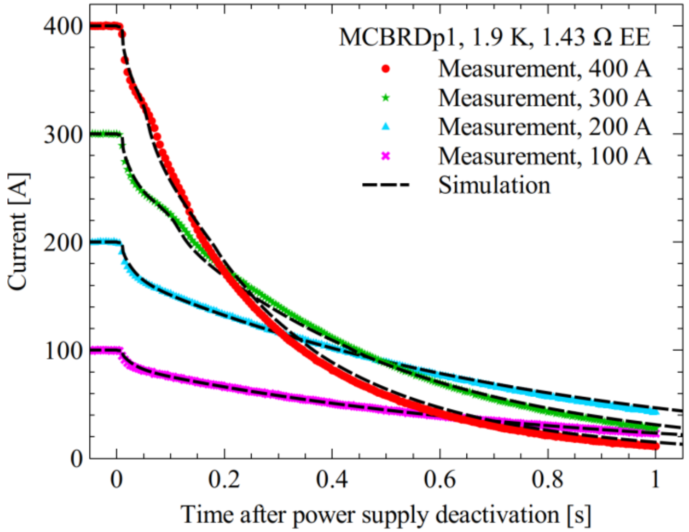
ProteCCT simulation tool



Manually triggered discharges versus training quenches on prototype MCBRDp1

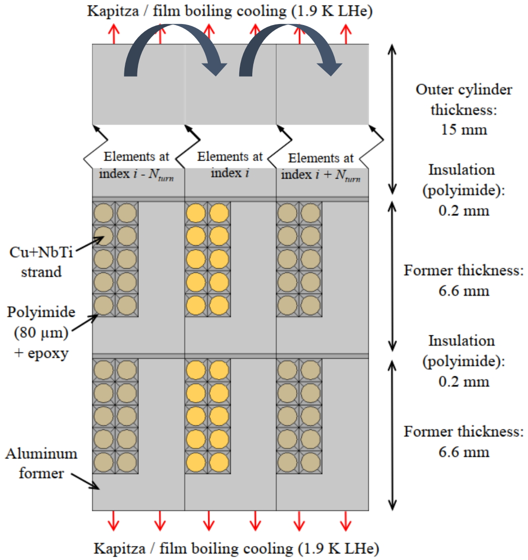


Typical discharge curves, sim vs meas, 1.43 Ω EE, prototype MCBRDp1

- Simulation tool for calculating quench behaviour of CCT-type magnets, protected with energy extractor (or CLIQ through co-simulation)
- Calculates current discharges and internal voltages from the moment of quench protection triggering
- Very fast (typically <1 min calculation time for a discharge), optimized for ease-of-use, license-free and free-to-download [2-3], compatible with STEAM co-simulation

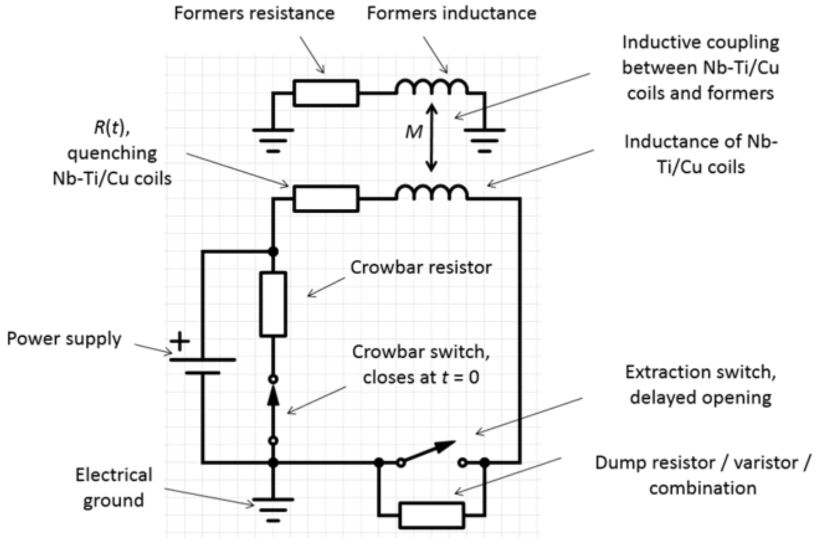
[2] M. Mentink, “STEAM-ProteCCT User Manual”, EDMS Nr. 2159478 (2019)
[3] cern.ch/steam

Internal workings of ProteCCT



Turn-to-turn periodic boundary condition

3D Thermal network

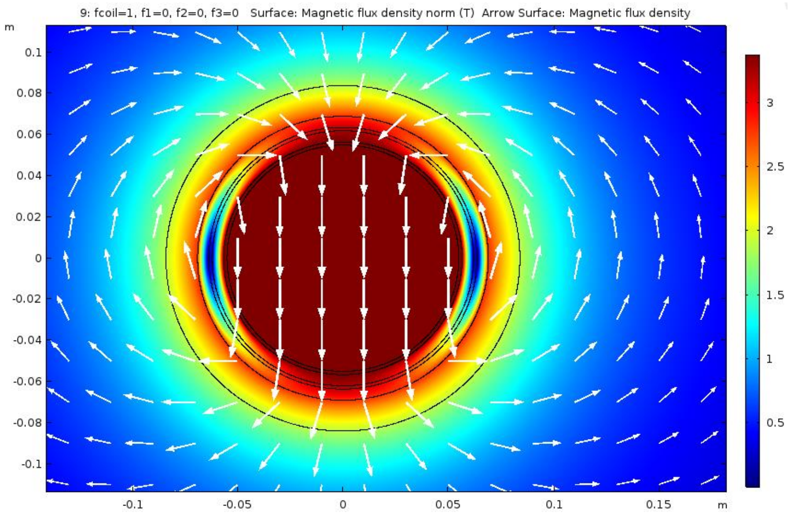


Internal circuit

ProteCCT considers:

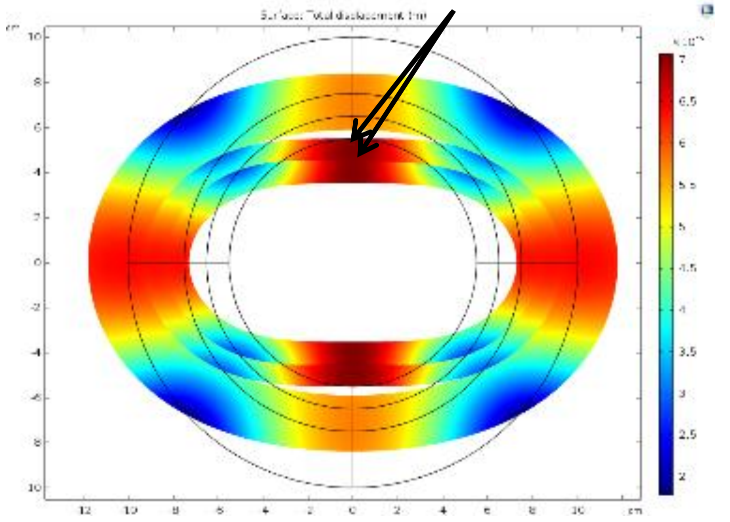
- 3D thermal network, of single periodically repeating turn, with Nb-Ti/Cu strands, insulation, formers, outer cylinder, and cooling to the bath
- Internal circuit (or complex circuit through co-simulation, such as CLIQ-protected circuit), with inductive coupling between Nb-Ti/Cu coils and formers
- Temperature and magnetic-field-dependent material properties

Two global correction factors to deal with complexities



Coupling-matrix calculated in Comsol, assuming 2D cos-ϑ current distribution

Liquid helium between formers

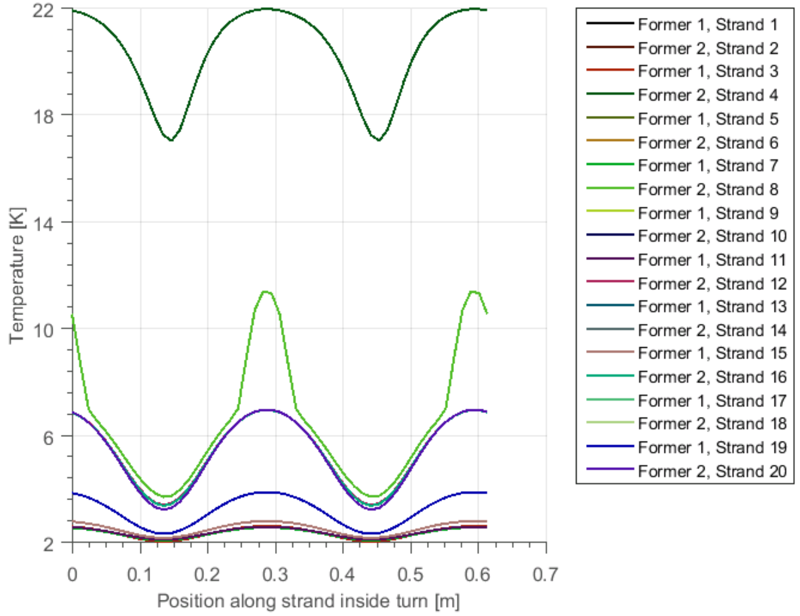


Sliding and deformation of formers during powering (Courtesy Martin Novak [4])

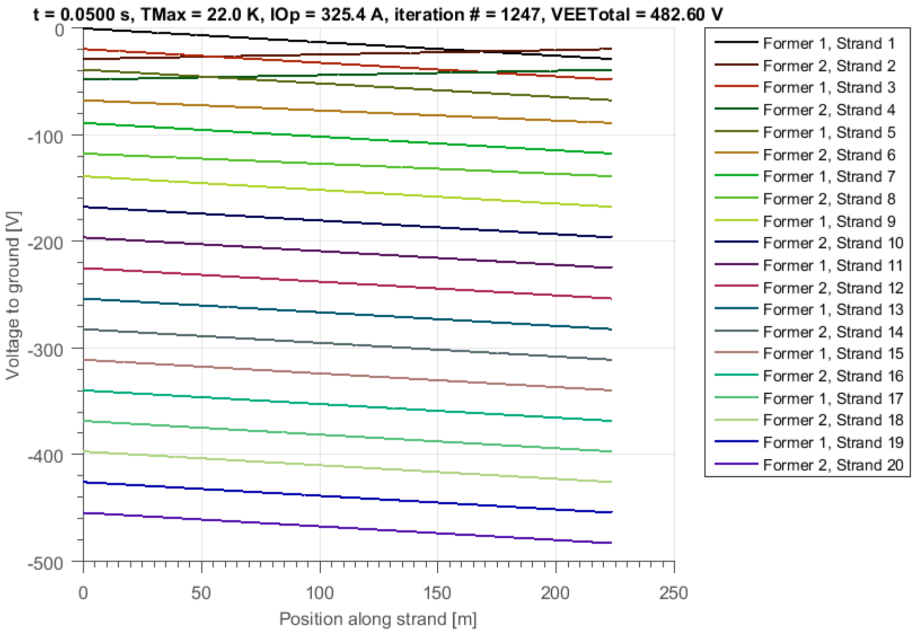
- *fLoopFactor*: To adjust former eddy current path length. Coupling matrix for coils and formers calculated with simplified 2D model using inductance of Nb-Ti/Cu coils as external input
- *addedHeCpFrac:* To account for extra heat capacity from liquid helium in gaps between formers, which slows down quench-back onset
- From fitting to experimental data: *fLoopFactor* = 2.0, *addedHeCpFrac* = 0.6%

[4] M. Novak and D. Barna, “Mechanical Simulation of a CCT Magnet”, internal document, 6th of December, (2018).

While the simulation is running…



Strand temperature development
(During simulation, t = 50 ms)

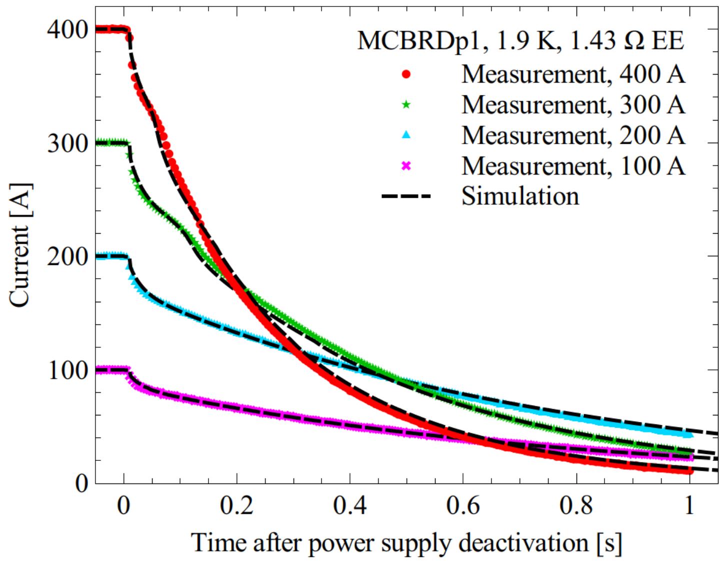


Voltage-to-ground calculation
(During simulation, t = 50 ms)

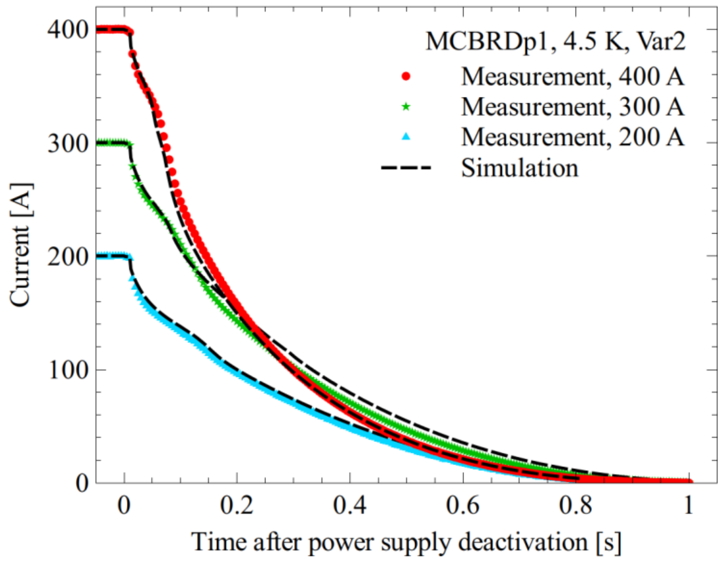
Optional simulation output during discharge calculation

- Temperature evolution in strands (ProteCCT 3D internal thermal network)
- Voltage-to-ground calculation (ProteCCT internal electrical network)

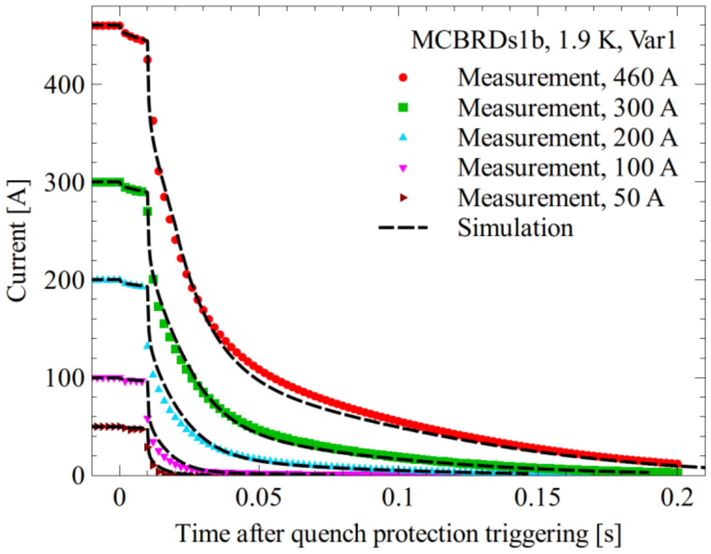
Simulation versus experimental observations (1/2)



MCBRDp1 prototype, discharge over 1.43 Ω dump resistor



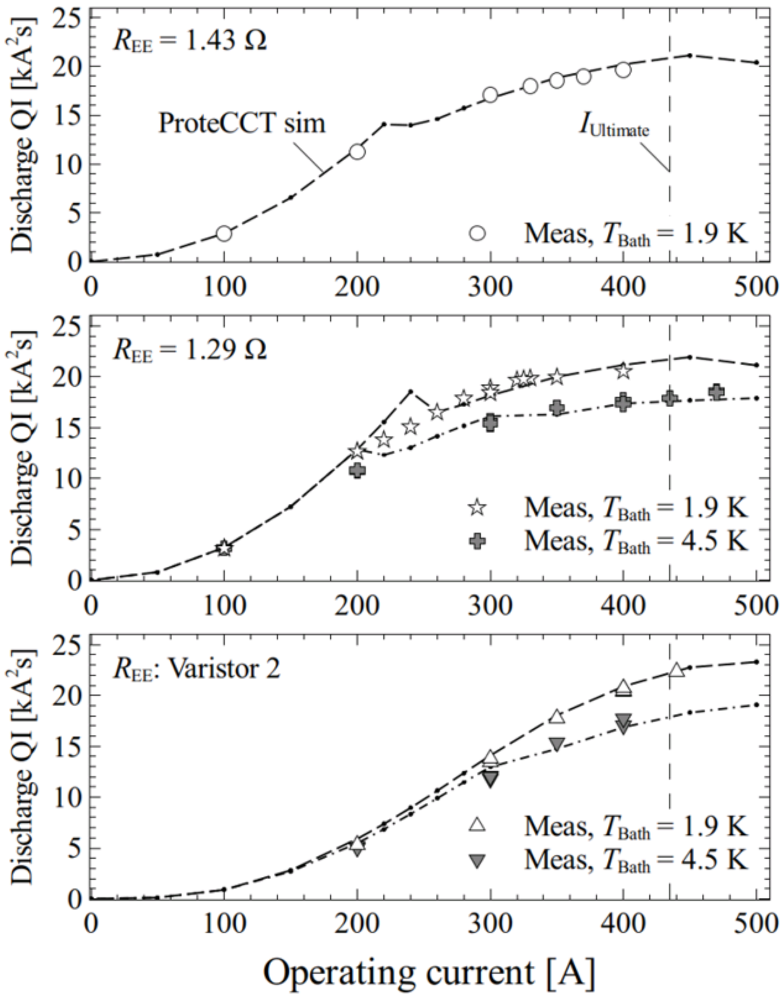
MCBRDp1 prototype, discharge over non-linear varistor



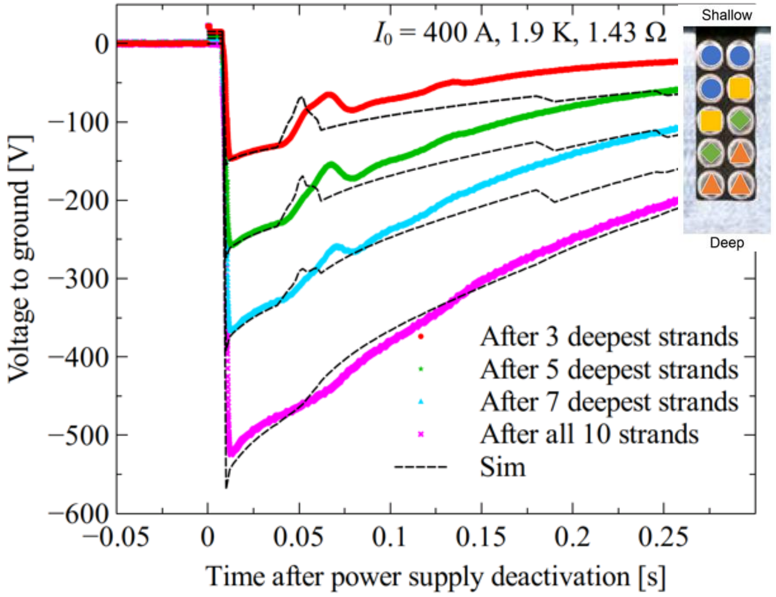
MCBRDs1b short model, discharge over non-linear varistor

- **Extensive** measurement campaign by SM18 personnel
- Comparison of simulation to experimental observations for: Different magnetic lengths, energy extractor types, helium bath temperatures, operating currents
- No free parameters except global constants *fLoopFactor* = 2.0, *addedHeCpFrac* = 0.6%

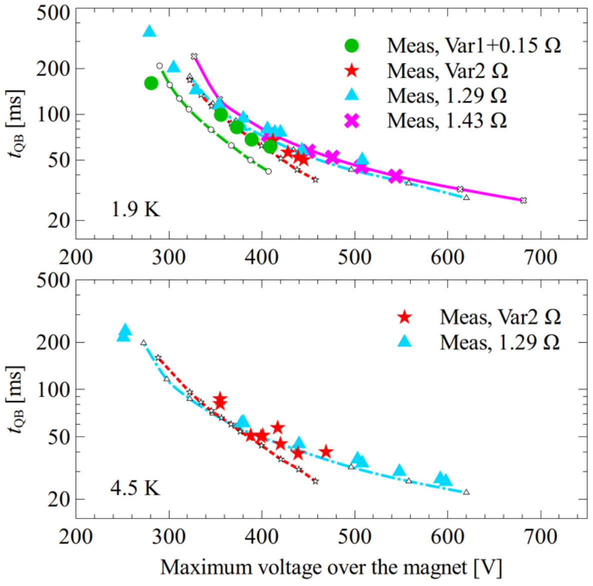
Simulation versus experimental observations (2/2)



Discharge quench integrals of MCBRDp1, simulation versus experimental observation



Internal voltages during discharge of MCBRDp1



Quench-back onset as function of maximum voltage over magnet

- Some minor inconsistencies (Example: ProteCCT is somewhat pessimistic for quench-back at intermediate current)
- Nevertheless, overall good consistency with experimental observations
- **Implies that ProteCCT incorporates the relevant physics!**

Overview

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  - **BBQ: Hotspot temperature and peak voltage-to-ground for baseline protection configuration**

- Implications for other MCBRD variants
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  - Parameter variations and resulting hotspot temperature in the LHC

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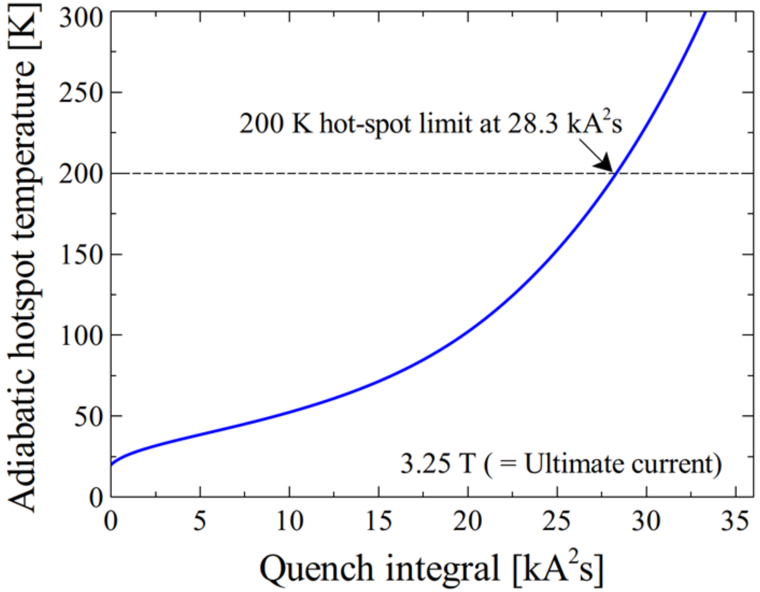
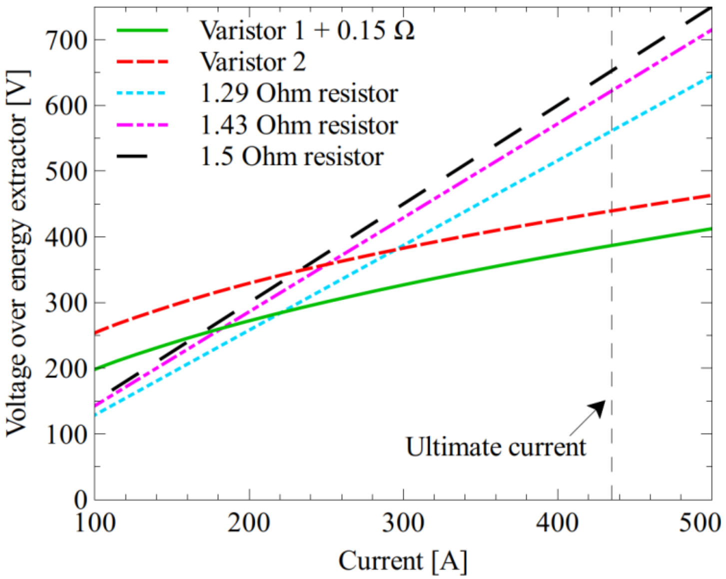
Resulting hotspot temperatures and peak voltages-to-ground



Adiabatic hotspot temperatures as a function of quench integral (BBQ)



Energy extractor characteristics: Linear resistors and non-linear varistors

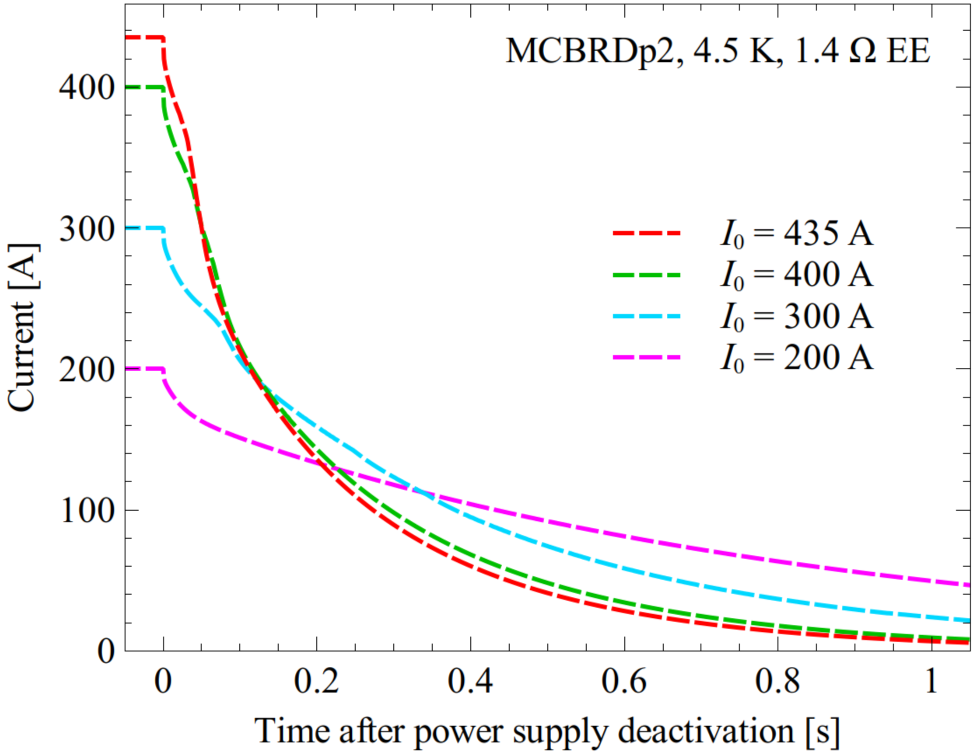
EE type	QI [kA²s]	T_{Hotspot} [K]	$V_{\text{Gnd,max}}$ [V]
1.5 Ω (baseline)	3.8 + 20.5	143	590
Varistor 2 (option)	3.8 + 22.4	167	440

Hotspot temperatures and voltages-to-ground at ultimate current (435 A)

How to calculate hotspot temperature and voltage-to-ground?

- Total quench integral = Detection/Validation quench integral (BBQ) + Discharge quench integral (ProteCCT)
- Total quench integral → Adiabatic hotspot calculation (BBQ)
- Peak voltage-to-ground = $I_0 \times R(I_0)$
- **For R_{EE} = 1.5 Ω (baseline) and the varistor option, T_{Hotspot} = 143 and 167 K, and $V_{\text{Gnd,Max}}$ = 590 and 440 V, respectively**

Upcoming prototype test at IMPCAS



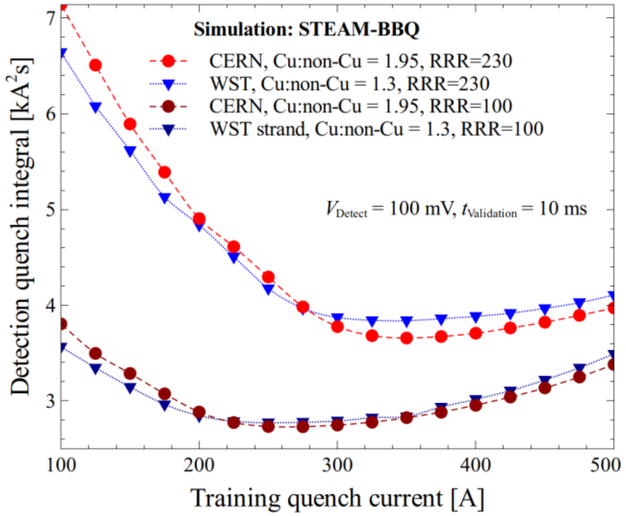
ProteCCT simulation results for upcoming MCBRD prototype test at IMPCAS

Chinese collaboration variant of MCBRD, different magnet properties from CERN variant:

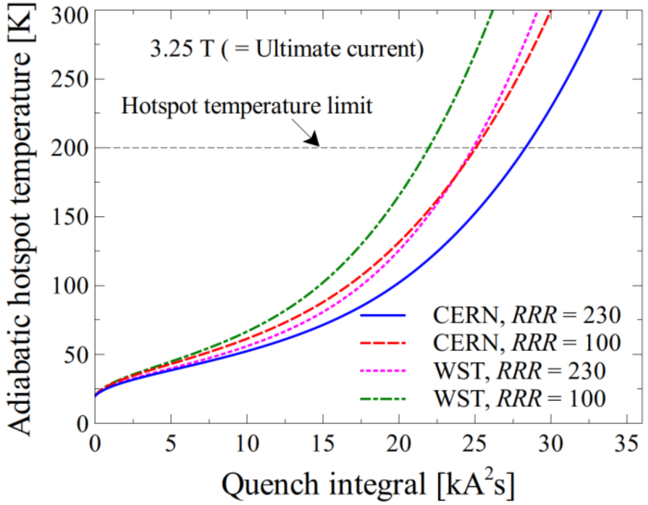
- Nb-Ti/Cu strand: slightly bigger strand diameter, lower copper fraction (Cu:non-Cu = 1.3), higher critical current
- Tests at IMPCAS to be done at 4.5 K (→ gives lower $QI_{\mathrm{Discharge}}$ than at 1.9 K), with R_{EE} = 1.4 Ω
- Strand (in magnet) and former RRR presently not yet measured. Here assumed to be identical to MCBRDp1 (Measured strand RRR = 230, former RRR = 8 [5])

[5] F. Pincot, MCBRD Former RRR measurement, email correspondence, 14th of December, (2019).

Parameter variations and resulting hotspot temperature



Conductor-dependent quench detection



Hot-spot temperature

MCBRD material property variation, Implications at ultimate current (435 A)	Detection/Validation + discharge quench integral [kA^2s]	Adiabatic hotspot temperature at fixed field [K]
CERN variant, strand *RRR* = 230, Former *RRR* = 8, t_{EEDelay} = 10 ms	3.8 + 22.4	167
CERN variant, strand *RRR* = 230, Former *RRR* = 8, t_{EEDelay} = 2 ms	3.8 + 20.8	146
IHEP-IMP-WST variant, strand *RRR* = 230, Former *RRR* = 8, t_{EEDelay} = 2 ms	3.9 + 20.6	193
IHEP-IMP-WST variant, strand *RRR* = 100, Former *RRR* = 8, t_{EEDelay} = 2 ms	3.0 + 16.4	170
IHEP-IMP-WST variant, strand *RRR* = 230, Former *RRR* = 6, t_{EEDelay} = 2 ms	3.9 + 23.5	255

Effect of magnet parameter variations on quench integral and hotspot temperature

- Boundary conditions: Ultimate current (435 A), Varistor 2 ($V_{\text{Gnd,Max}}$ = 440 V), T_{Bath} = 1.9 K
- Hotspot temperature lower for R_{EE} = 1.5 Ω (baseline), with $V_{\text{Gnd,Max}}$ = 590 V
- Lower hotspot temperature given by: Faster EE switch opening, lower critical current, more copper in the conductor, lower strand RRR, and **higher RRR for formers and outer cylinder**
- **Hotspot temperature < 200 K for 1.5 Ω baseline and varistor option, provided former and outer cylinder RRR are sufficiently high**

Summary

Quench protection of Twin Aperture Orbit Corrector Magnets (MCBRD)

- Canted-Cosine-Theta-type magnets, protected with energy extraction and quench-back from conductive formers
- **Factor three faster discharge** with respect to exponential decay (no quench-back, no conductive formers)
- Initial voltage development, subsequent magnet discharge, and resulting hotspot temperature calculated with **BBQ** and **ProteCCT** (multi-purpose tools, freely available on **cern.ch/steam**)
- Cross-checked against extensive experimental data-set
- Provided the former and outer cylinder RRR is sufficiently high, for the 1.5 Ω baseline energy extraction resistor and the non-linear varistor option, $\boldsymbol{T_{\mathrm{Hotspot}} < 200\ \mathrm{K}}$, $V_{\mathrm{Gnd,Max}} = 590$ and 440 V, respectively
- These studies were made possible by the HL-LHC collaboration. The authors want to thank everyone for their support!