Data-Driven Modeling of Quenches in Superconducting Accelerator Magnets

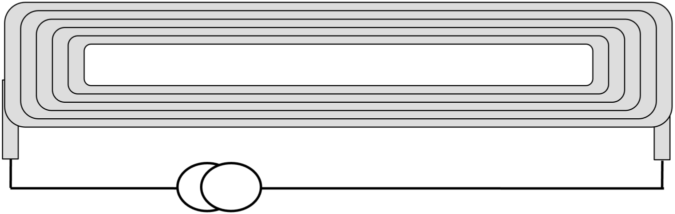
D. Paudel, F.J. Mangiarotti, M. Bonora, S. Russenschuck

October 4, 2024

Quench

Quench: Transition from SC to normal conducting state caused by beam losses, conductor movement, eddy currents etc

Propagation: Normal conducting zone generates Ohmic heat, Quench und temperature distribution determined by loss-mechanisms and cooling capacity



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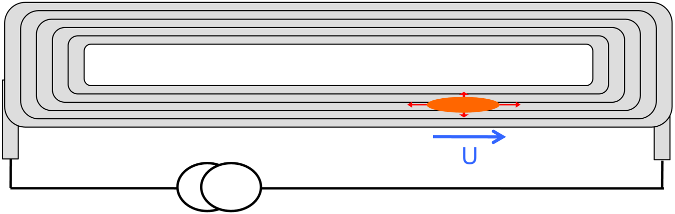

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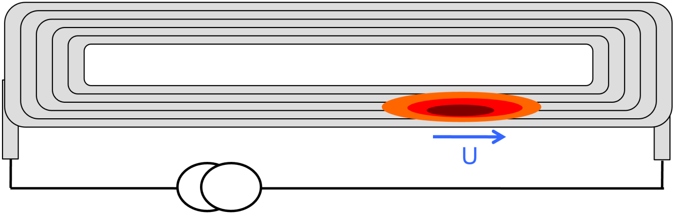

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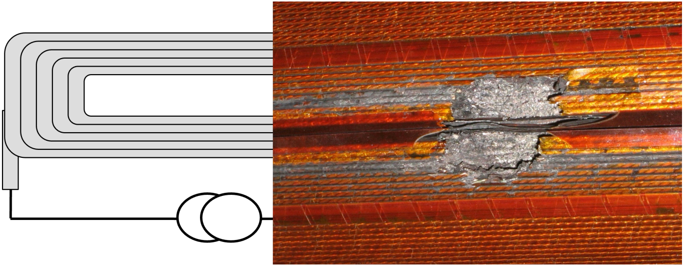
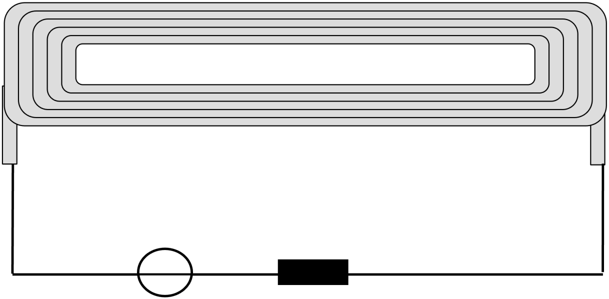


Quench Protection

Extraction resistors (R): Energy dissipation to resistor, quick transition

Quench Heaters (QH): Energy dissipation in coil, heater induced resistance, delay by few ms,

Coup. Loss-Ind. Resis. (CLIQ): Coupling loss induced energy dissipation in coil using oscillating currents



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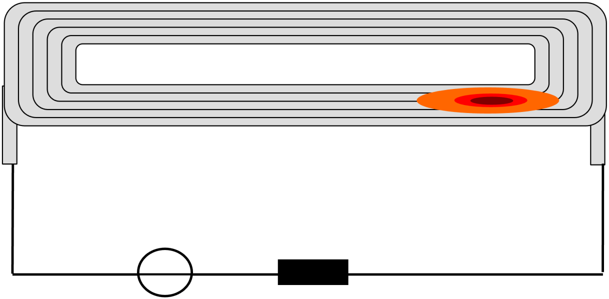

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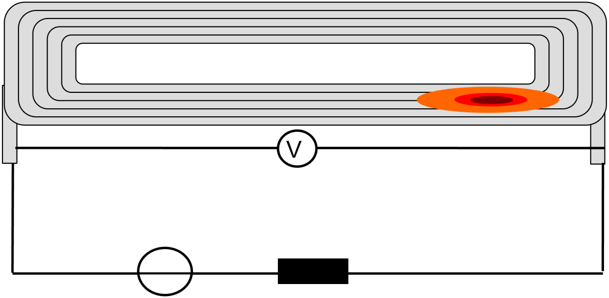

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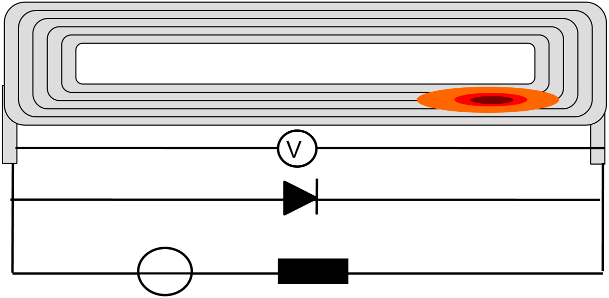

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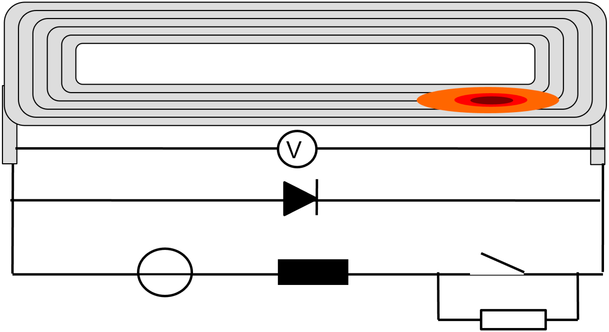

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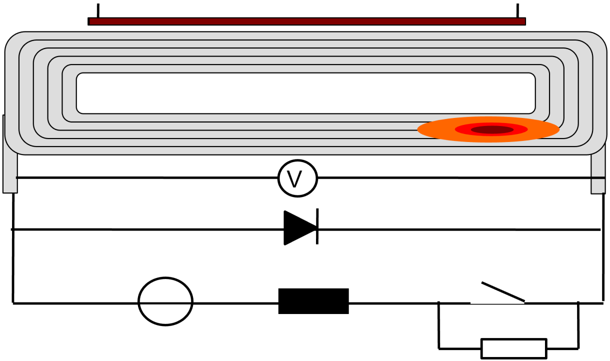

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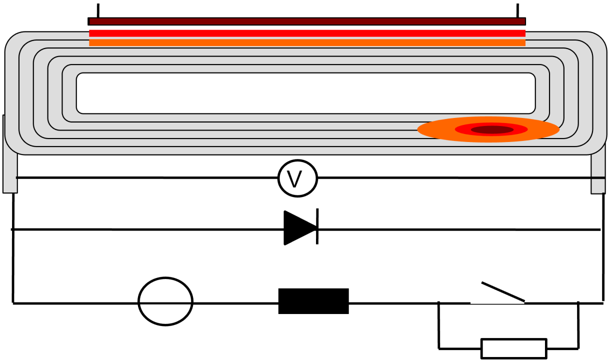

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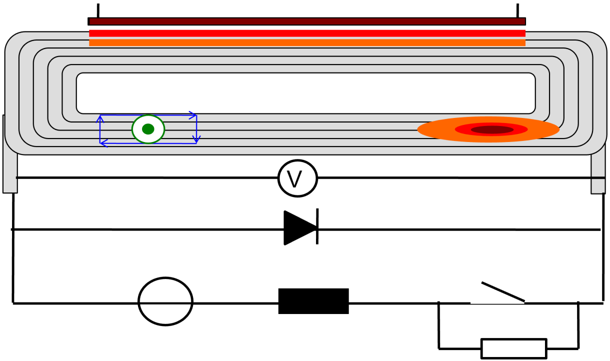
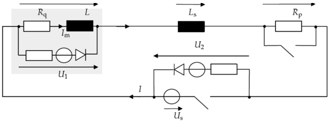
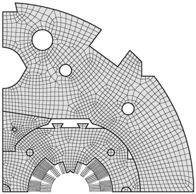
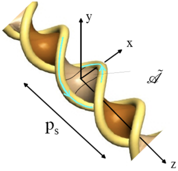
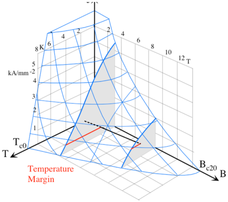


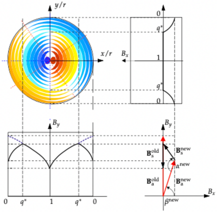
Quench modelling

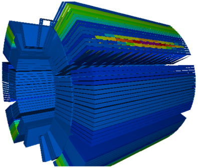


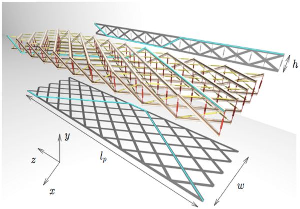






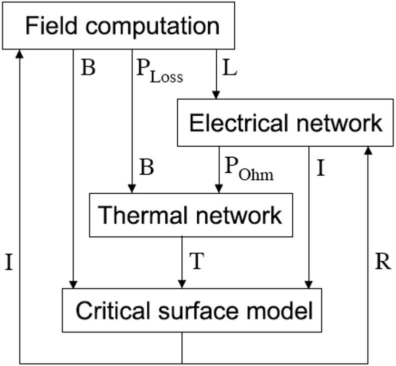




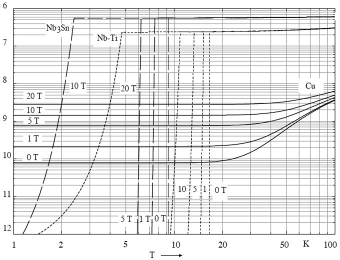


Challenges

Multi domains: Thermo, Mechanics, Electric, Magnetic
Multi physics: Coupling of the domains, Software tools
Multi scale: Filaments (6 μm), Strands (1 mm), Cable (1 cm), Magnet (10 m), String (3.2 km)

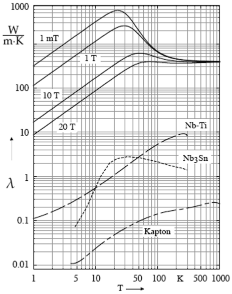


Materials

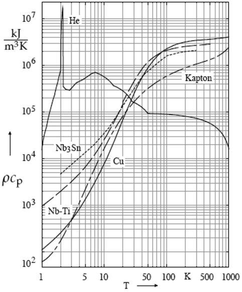


Electrical resistivity

Thermal conductivity

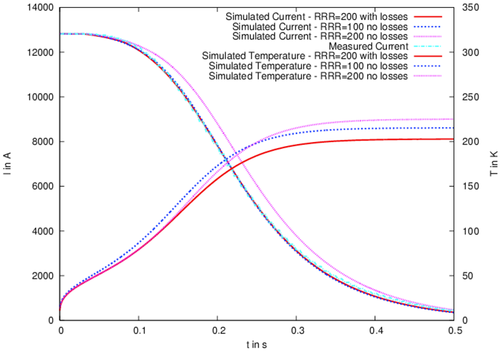


Volumetric heat capacity



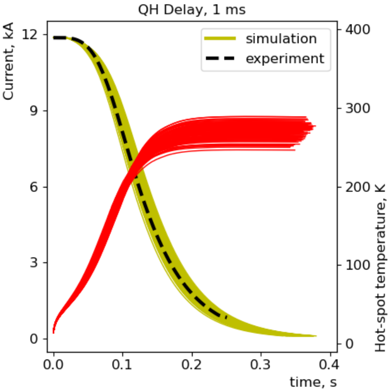
Parameters and observables

Peak current, I_{peak}
Residual Resistivity Ratio, RRR
Copper-Superconductor Ratio, f_{Cu2Sc}
Max critical Temp., (at $B = 0$), T_{c0}
Max critical field, (at $T = 0$), B_{c20}
Normalization constant, C_0
Operating temperature, T_{op}
Strand diameter, d_{strand}
Differential inductance, dL
Aperture diameter, $d_{aperture}$
Magnet length, L
CLIQ current profile , I_{CLIQ}
Dump voltage profile, V_{dump}
Quench-heater, $I_{quench\ heater}$



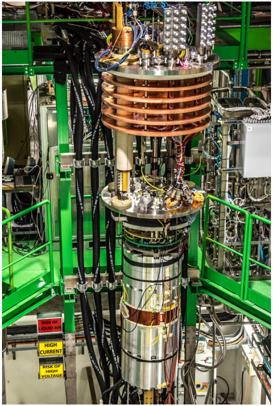
Challenges: Input uncertainties, modelling uncertainties and uncertainty propagation

Quench heater delay



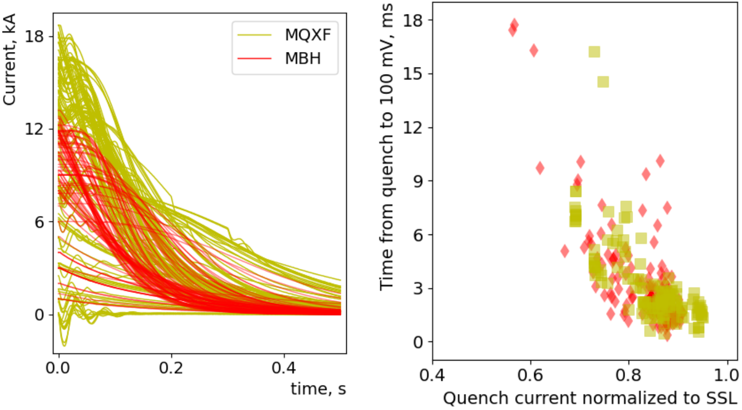
11T cosine θ Nb_3Sn dipole magnet performance considering input uncertainties

Prototype tests



SM18 test facility, HL-LHC Prototype test, Vertical stations, Horizontal stations

Prototype tests

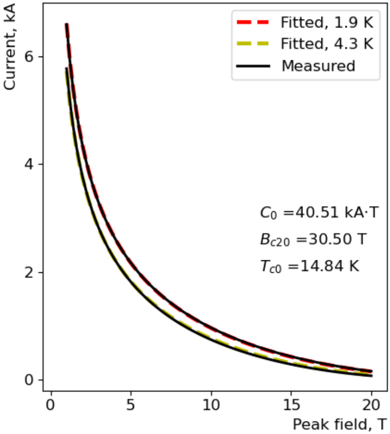


A library of magnet performance data, after triggering of the protection measures

Cable properties

$$J_c(B,T) = \frac{C(t)}{B_p} b^p (1-b)^q,$$
$$B_{c2}(t) = B_{c20}(1-t^\nu)$$
$$C(t) = C_0(1-t^\nu)^\alpha (1-t^2)^\alpha,$$

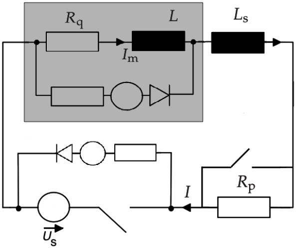
$T\ [K]$	$B_{c2}\ [T]$	$C_{min}\ [A \cdot T]$	$C_{max}\ [A \cdot T]$
1.9	28.9	38142	41470
4.3	26.7	31951	35060

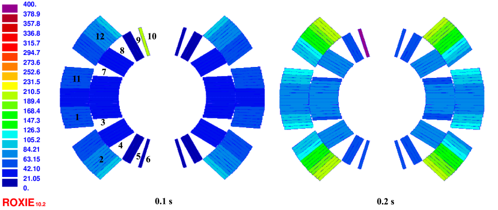


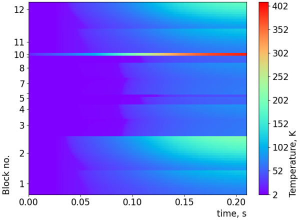
Critical values closely satisfying current-field curve at 1.9 and 4.3 K selected from 1E6 Latin Hypercube Samples

ROXIE quench model

I_{peak}	17 kA	RRR	106 - 195
T_{op}	1.9 K	f_{Cu2Sc}	1.08 - 1.18
d_{strand}	0.85 mm	C_0	40.49 - 43.82 kA·T
dL	15.6 H	T_{c0}	14.88 - 15.46 K
$d_{aperture}$	56 mm	B_{c20}	30.28 - 30.43 T
L	5.5 m	delay	10 - 18 ms







Quench initiated at nominal current on block no 10, 12T VE dipole protected with outer layer quench heaters

The data model

Input	Source
Peak current, I_{peak}	test file
Residual Resistivity Ratio, RRR	witness sample
Copper-Superconductor Ratio, f_{Cu2Sc}	witness sample
Max critical Temp., (at $B = 0$), T_{c0}	witness sample
Max critical field, (at $T = 0$), B_{c20}	witness sample
Normalization constant, C_0	witness sample
Operating temperature, T_{op}	quench reports
Strand diameter, d_{strand}	witness sample
Differential inductance, dL	design team
Aperture diameter, d_{aperture}	design report
Magnet length, L	design report
CLIQ current profile , I_{CLIQ}	test file
Dump voltage profile, V_{dump}	test file
Quench-heater current profile, $I_{\text{quench heater}}$	test file

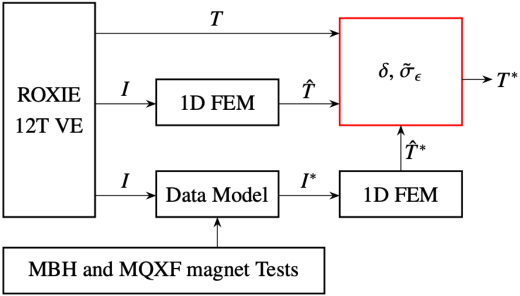
Output: Current decay, $I(t)$

MLP Regressor, activation: hyperbolic tangent, 724 hidden layers, 232058 random variables, 0.00858 matrix tolerance

1D heat diffusion

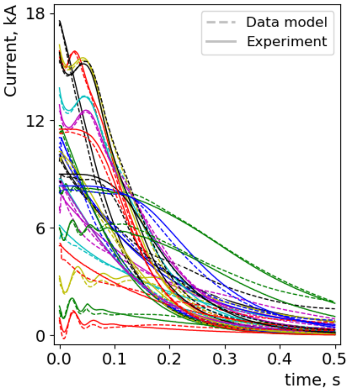
- 1D Cable using 1 mm Finite Elements, Cable length long enough for zero heat flux on either ends
- Quench load (current decay curve)
- Explicit Euler time discretization, adaptive to a maximum temperature rise of 1 K per step

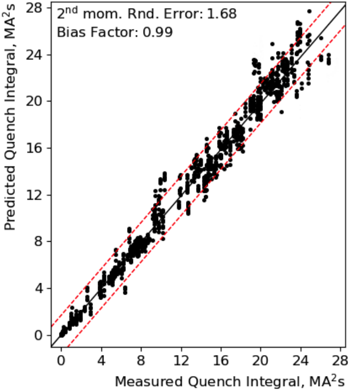
Uncertainty management



Compensating modelling uncertainty using δ and σ_ϵ

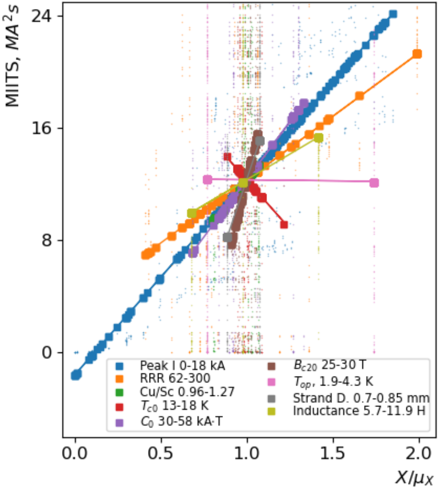
Data model validation





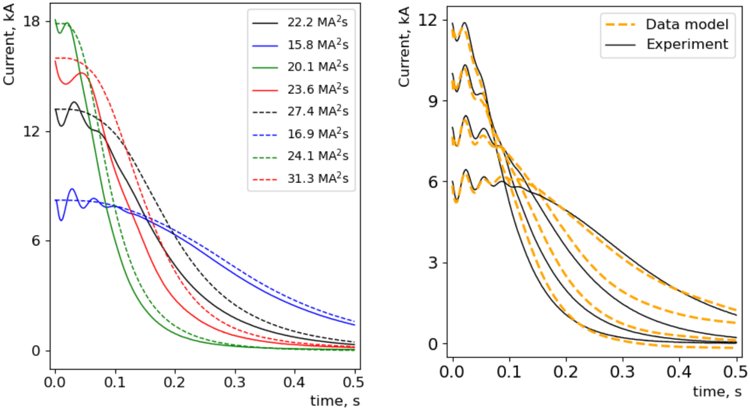
24 random cases from 218 test cases and repetition for 50 instances

Data model validation



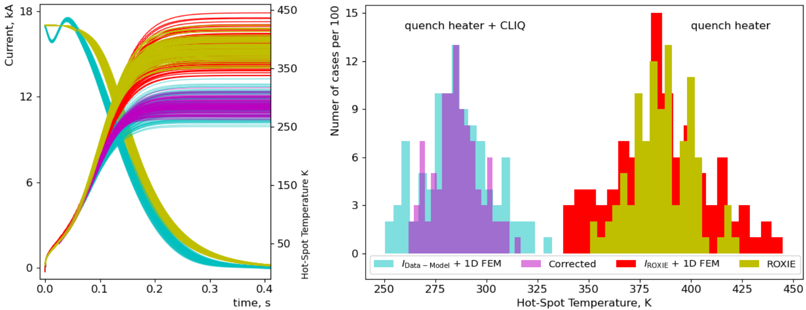
Quench load sensitivity to input parameters, Measurement vs predictions

11T Dipole



Prediction using MQXF and MBH test data < 1 MA^{2}s
CLIQ reduces quench load by $\sim$ 5 MA^{2}s

12T VE Dipole



Predicted using MQXF and MBH test data and ROXIE simulations

Conclusion

- Large set magnet test data to propose a data-driven model update of numerical quench protection studies
- Protection scheme and the magnet operating condition determine the quench protection status
- The input uncertainty results in a peak temperature difference up to 80 K
- CLIQ protection reduces quench integral by $\sim$ 5 MA^2s
- 12T VE dipole simulations suggest peak temperature 350 - 430 K for the quench heater only protection and below 320 K for combined quench heater and CLIQ protection