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STEAM at the MT26 conference

16 October 2019

Emmanuele Ravaioli
on behalf of the STEAM team

26th Magnet Technology (MT26) conference

MT 26
International Conference on Magnet Technology
Vancouver, Canada | 2019

https://mt26.triumf.ca/

https://indico.cern.ch/event/763185/

STEAM at MT26 conference

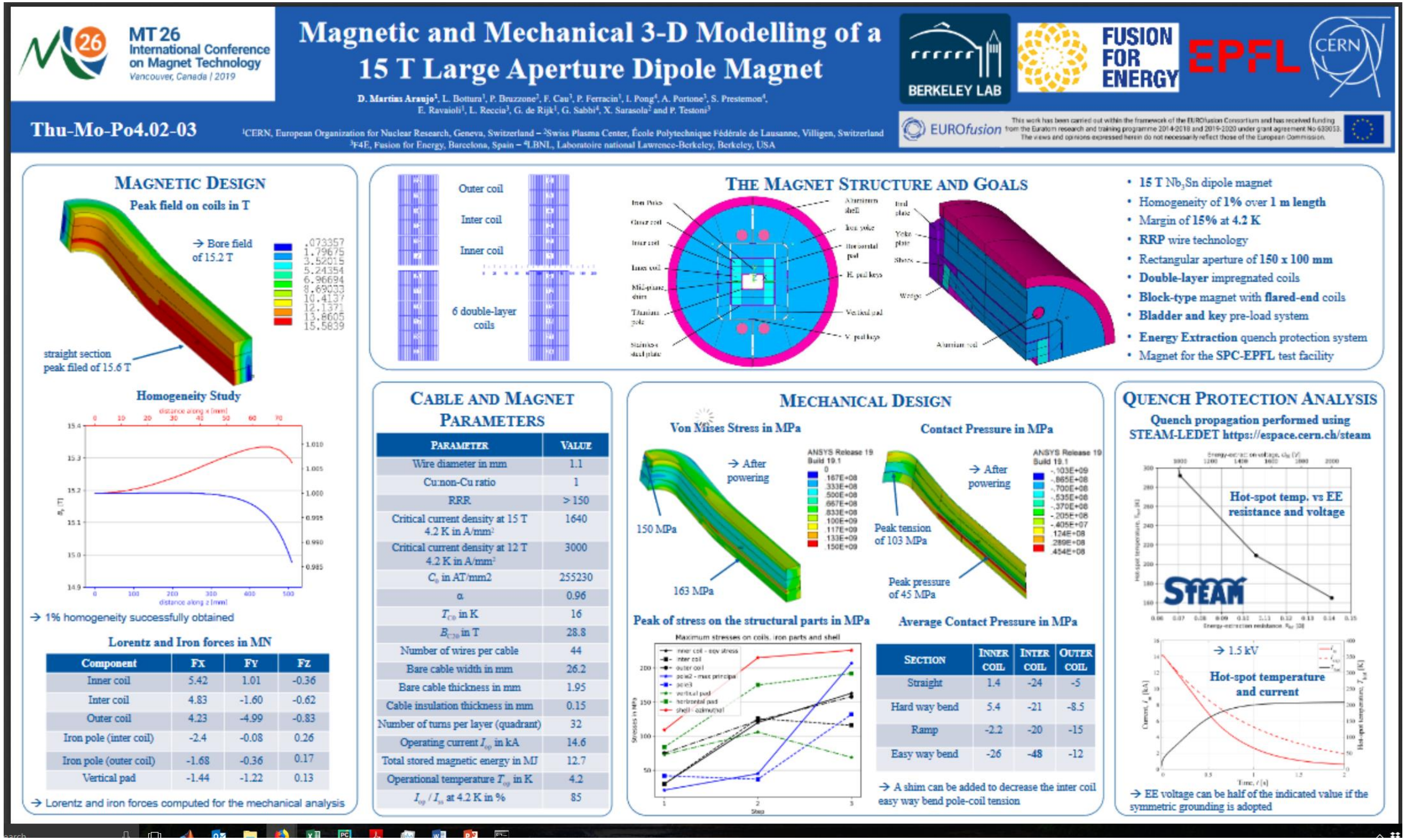
All online versions now have correct references

Name	Affiliation	Title	Type	Software	Reference
Douglas M. Araujo	CERN	Preliminary Design of HEPdipo, a Nb3Sn Large Aperture Dipole Magnet for Cable and Insert Coil testing	Poster	LEDET	**No** → Yes
Daniel Davis	LBNL	Performance, diagnostic, and quench measurements of a dipole composed of two racetrack coils wound with high temperature superconducting Bi-2212 Rutherford cable	Oral	LEDET	Yes
Helene Felice	CEA	Advances in Nb3Sn Superconducting Accelerator Magnets	Plenary	LEDET	Yes
Alexandre M. Louzguiti	CERN	Design of radiation hard spare units for the orbit corrector dipoles of LHC	Poster	LEDET	Yes
Vittorio Marinozzi	FNAL	Analysis of the heater-to-coil insulation in MQXF coils	Poster	LEDET	**No** → Yes
Samuele Mariotto	INFN	Fabrication and results of the first Round Coil Superferric Magnet at LASA	Poster	COSIM	**No** → Yes
Matthias Mentink	CERN	Protection Studies of the HL-LHC circuits with the STEAM Simulation Framework	Poster	BBQ, COSIM, LEDET, ProteCCT, SIGMA	Yes
Matthias Mentink	CERN	Quench simulations versus experimental observations on the HL-LHC MCBRD canted-cosine-theta short models and prototype magnets	Oral	BBQ, ProteCCT	Yes
Emmanuele Ravaioli	CERN	Quench protection of the 16 T Nb3Sn ERMC and RMM magnets	Oral	LEDET	Yes
Andrew Twin	Oxford Instruments	Use of Silicon Carbide Varistors For Quench Protection of Superconducting Magnets in Cryogenic Environments	Oral	ProteCCT	Yes

STEAM at MT26 conference – New contacts and future users

Name	Affiliation	Application
Rod Bateman	Tokamak Energy	Quench protection of HTS magnets
Marco Breschi	University of Bologna	Magnet transient simulations; University training
Arnaud Foussat	CERN	Quench protection studies
Piyush Joshi	BNL	Support during magnet testing
Andrew Twin	Oxford Instruments	Quench protection studies

Douglas M. Araujo (CERN)



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Magnetic and Mechanical 3-D Modelling of a 15 T Large Aperture Dipole Magnet

D. Martins Araujo[1], L. Bottura[1], P. Bruzzone[2], F. Cau[1], P. Ferracin[1], I. Pong[4], A. Portone[3], S. Prestemon[4],
E. Ravaioli[1], L. Reccia[3], G. de Rijk[1], G. Sabbi[4], X. Sarasola[2] and P. Testoni[3]

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Thu-Mo-Po4.02-03

EUROfusion This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

MAGNETIC DESIGN

Peak field on coils in T

→ Bore field of 15.2 T

straight section peak filed of 15.6 T

Homogeneity Study

→ 1% homogeneity successfully obtained

Lorentz and Iron forces in MN

Component	Fx	Fy	Fz
Inner coil	5.42	1.01	-0.36
Inter coil	4.83	-1.60	-0.62
Outer coil	4.23	-4.99	-0.83
Iron pole (inter coil)	-2.4	-0.08	0.26
Iron pole (outer coil)	-1.68	-0.36	0.17
Vertical pad	-1.44	-1.22	0.13

→ Lorentz and iron forces computed for the mechanical analysis

THE MAGNET STRUCTURE AND GOALS

- **15 T** Nb_3Sn dipole magnet
- Homogeneity of **1%** over **1 m length**
- Margin of **15% at 4.2 K**
- **RRP** wire technology
- Rectangular aperture of **150 x 100 mm**
- **Double-layer** impregnated coils
- **Block-type** magnet with **flared-end** coils
- **Bladder and key** pre-load system
- **Energy Extraction** quench protection system
- Magnet for the **SPC-EPFL** test facility

CABLE AND MAGNET PARAMETERS

PARAMETER	VALUE
Wire diameter in mm	1.1
Cu:non-Cu ratio	1
RRR	> 150
Critical current density at 15 T 4.2 K in A/mm^2	1640
Critical current density at 12 T 4.2 K in A/mm^2	3000
C_0 in AT/mm2	255230
α	0.96
T_{C0} in K	16
B_{C20} in T	28.8
Number of wires per cable	44
Bare cable width in mm	26.2
Bare cable thickness in mm	1.95
Cable insulation thickness in mm	0.15
Number of turns per layer (quadrant)	32
Operating current I_{op} in kA	14.6
Total stored magnetic energy in MJ	12.7
Operational temperature T_{op} in K	4.2
I_{op} / I_{ss} at 4.2 K in %	85

MECHANICAL DESIGN

Von Mises Stress in MPa

→ After powering

150 MPa

163 MPa

Contact Pressure in MPa

→ After powering

Peak tension of 103 MPa

Peak pressure of 45 MPa

Peak of stress on the structural parts in MPa

Average Contact Pressure in MPa

SECTION	INNER COIL	INTER COIL	OUTER COIL
Straight	1.4	-24	-5
Hard way bend	5.4	-21	-8.5
Ramp	-2.2	-20	-15
Easy way bend	-26	-48	-12

→ A shim can be added to decrease the inter coil easy way bend pole-coil tension

QUENCH PROTECTION ANALYSIS

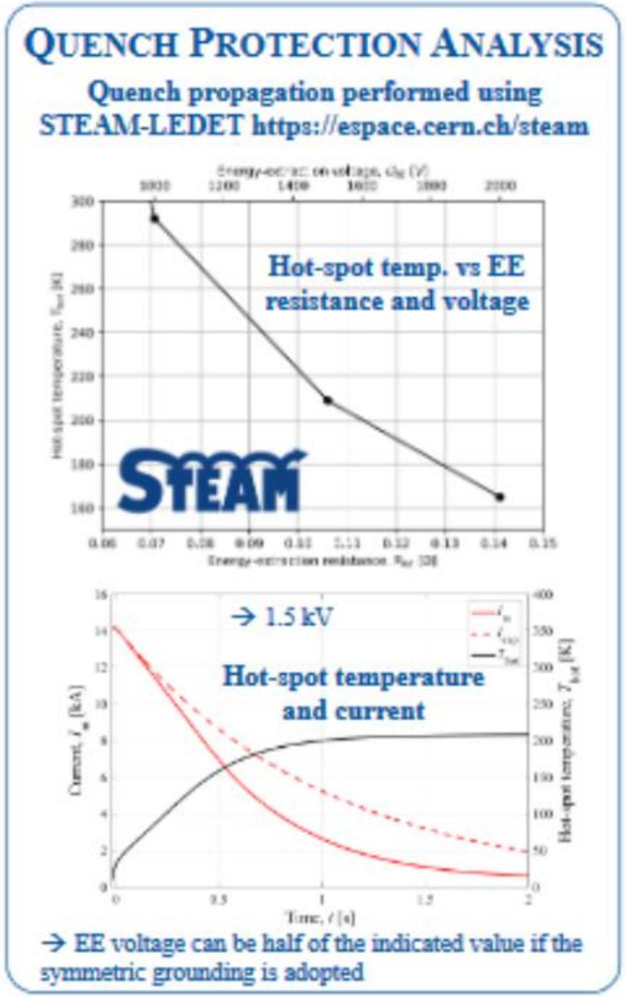
Quench propagation performed using STEAM-LEDET https://espace.cern.ch/steam

Hot-spot temp. vs EE resistance and voltage

→ 1.5 kV

Hot-spot temperature and current

→ EE voltage can be half of the indicated value if the symmetric grounding is adopted



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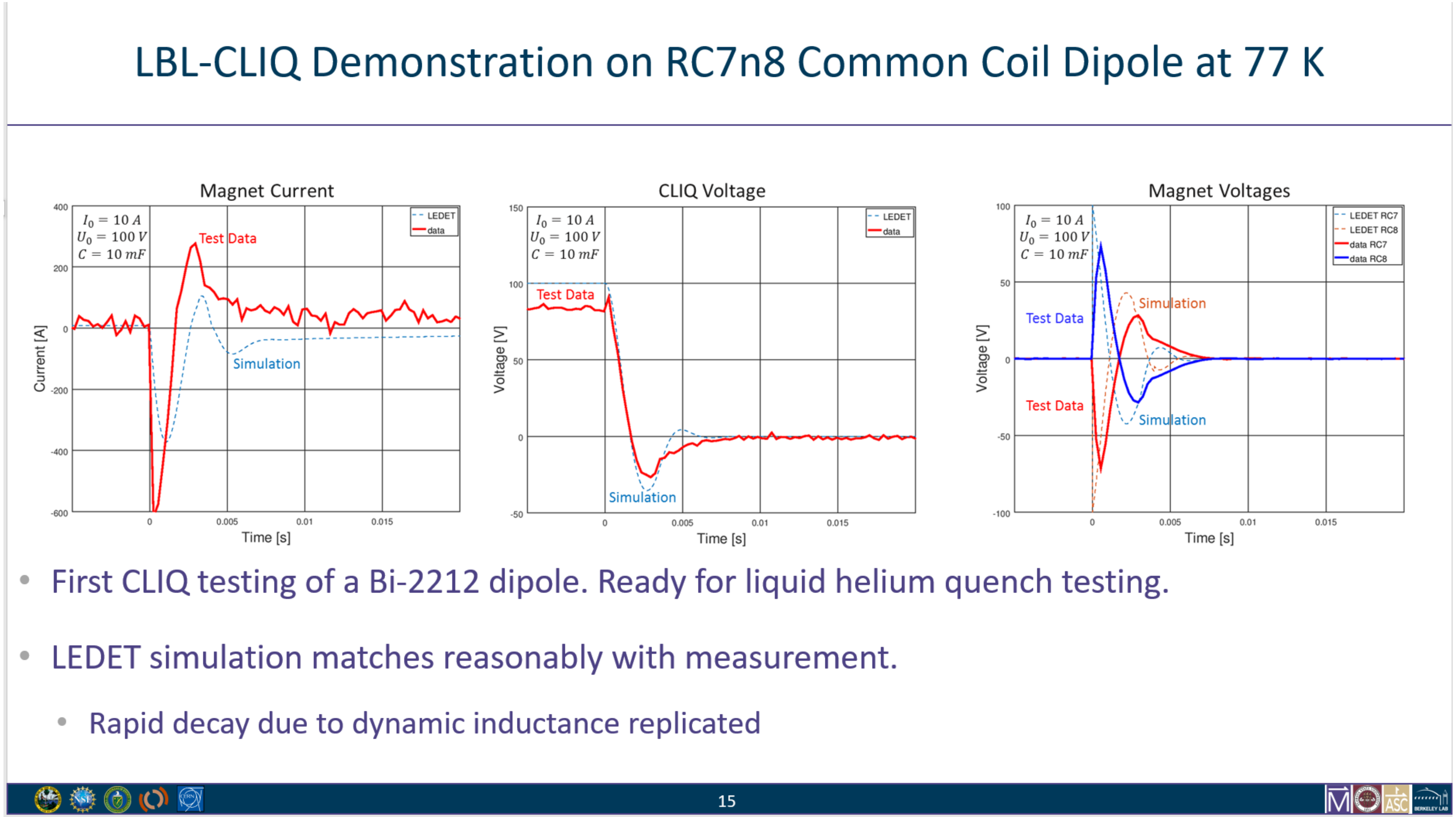
Daniel Davis (LBNL) -1a

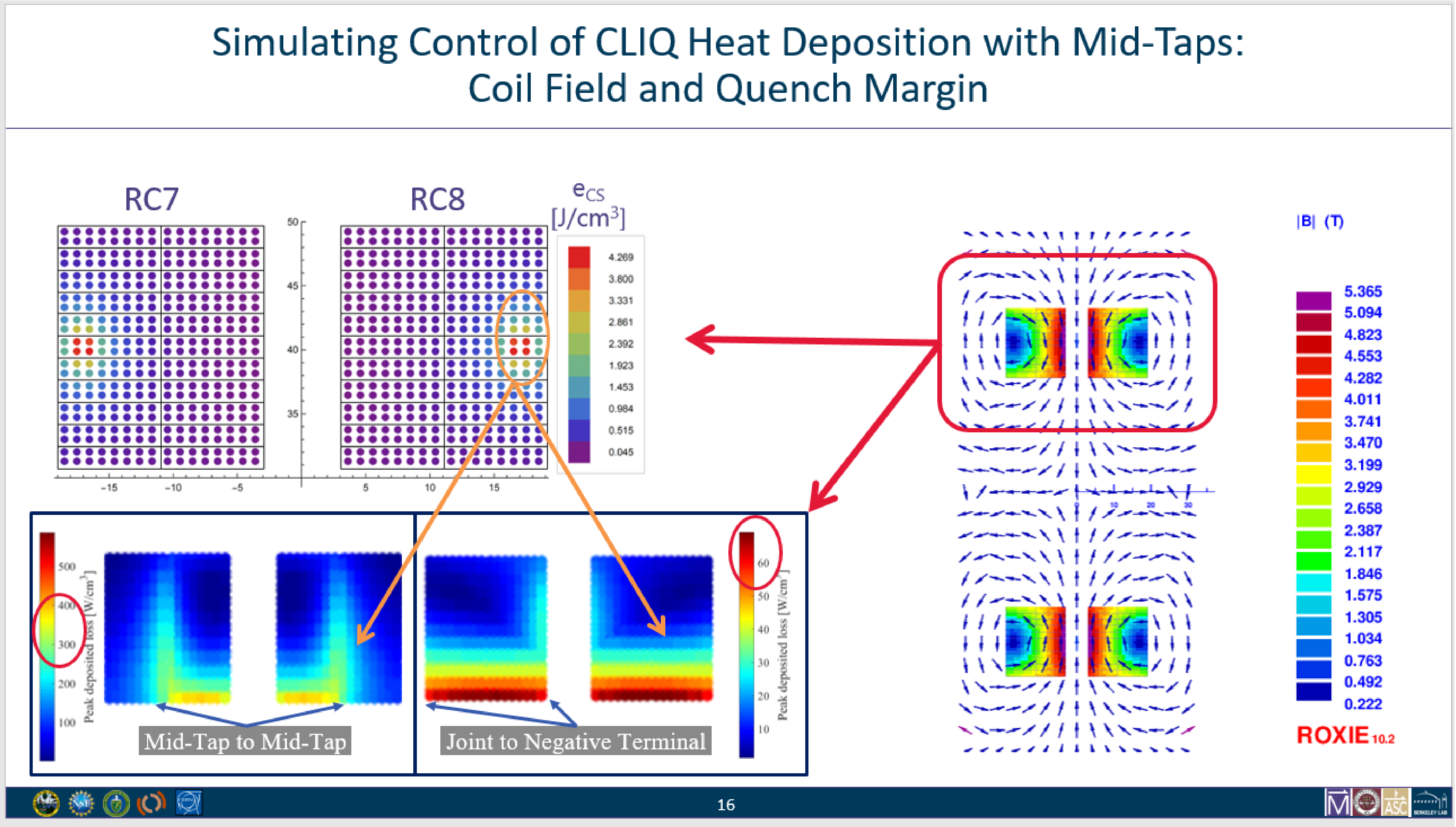


LBL-CLIQ Demonstration on RC7n8 Common Coil Dipole at 77 K

- First CLIQ testing of a Bi-2212 dipole. Ready for liquid helium quench testing.
- LEDET simulation matches reasonably with measurement.
  - Rapid decay due to dynamic inductance replicated

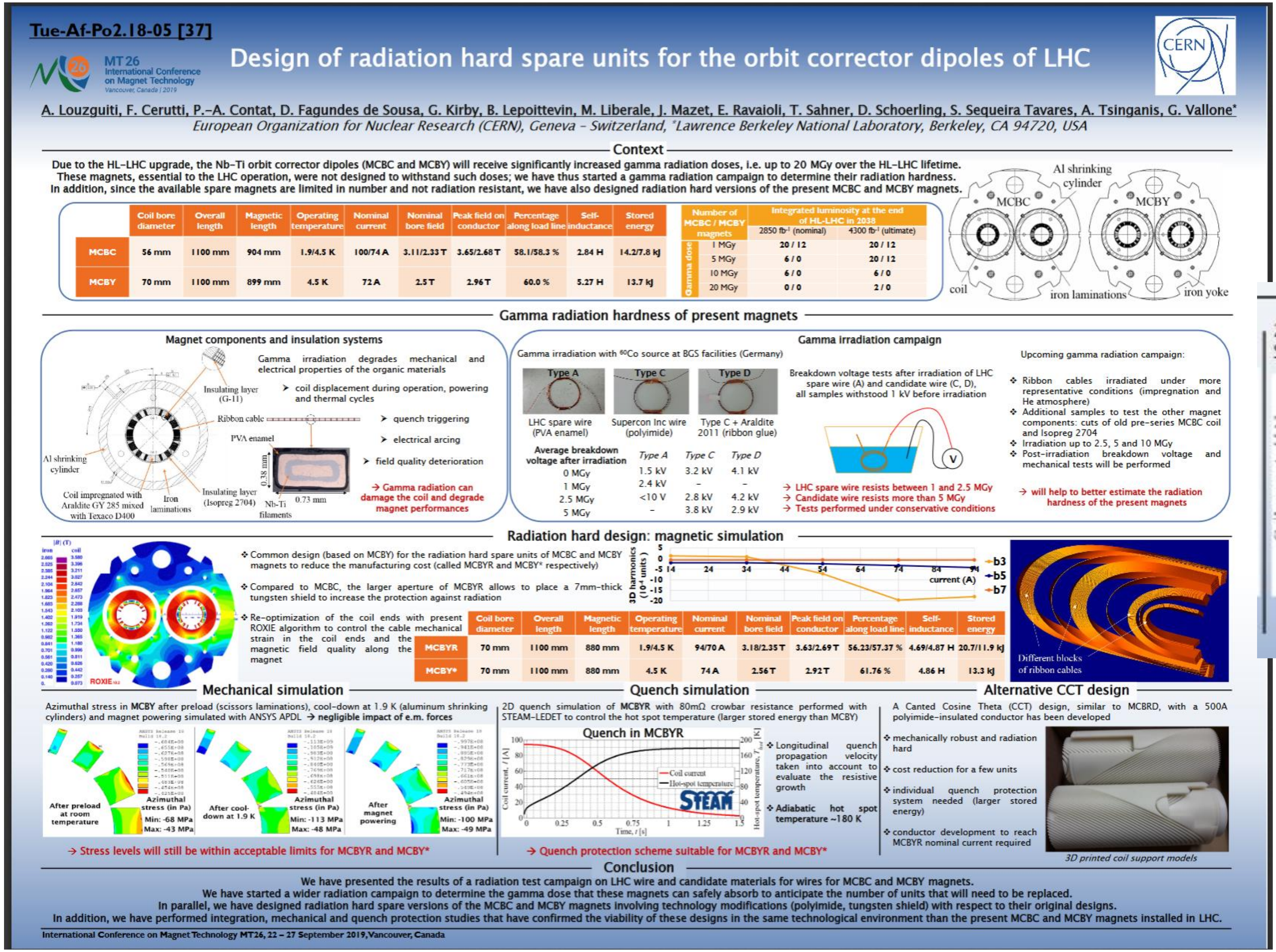
15

Daniel Davis (LBNL) -1b



Simulating Control of CLIQ Heat Deposition with Mid-Taps: Coil Field and Quench Margin

Alexandre M. Louzguiti (CERN)



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Design of radiation hard spare units for the orbit corrector dipoles of LHC

A. Louzguiti, F. Cerutti, P.–A. Contat, D. Fagundes de Sousa, G. Kirby, B. Lepoittevin, M. Liberale, J. Mazet, E. Ravaioli, T. Sahner, D. Schoerling, S. Sequeira Tavares, A. Tsinganis, G. Vallone*
*European Organization for Nuclear Research (CERN), Geneva – Switzerland, *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Context

Due to the HL–LHC upgrade, the Nb–Ti orbit corrector dipoles (MCBC and MCBY) will receive significantly increased gamma radiation doses, i.e. up to 20 MGy over the HL–LHC lifetime. These magnets, essential to the LHC operation, were not designed to withstand such doses; we have thus started a gamma radiation campaign to determine their radiation hardness. In addition, since the available spare magnets are limited in number and not radiation resistant, we have also designed radiation hard versions of the present MCBC and MCBY magnets.

	Coil bore diameter	Overall length	Magnetic length	Operating temperature	Nominal current	Nominal bore field	Peak field on conductor	Percentage along load line	Self-inductance	Stored energy
MCBC	56 mm	1100 mm	904 mm	1.9/4.5 K	100/74 A	3.11/2.33 T	3.65/2.68 T	58.1/58.3 %	2.84 H	14.2/7.8 kJ
MCBY	70 mm	1100 mm	899 mm	4.5 K	72 A	2.5 T	2.96 T	60.0 %	5.27 H	13.7 kJ

Number of MCBC / MCBY magnets		Integrated luminosity at the end of HL-LHC in 2038	
		2850 fb^{-1} (nominal)	4300 fb^{-1} (ultimate)
Gamma dose	1 MGy	20 / 12	20 / 12
	5 MGy	6 / 0	20 / 12
	10 MGy	6 / 0	6 / 0
	20 MGy	0 / 0	2 / 0

Gamma radiation hardness of present magnets

Magnet components and insulation systems

Gamma irradiation degrades mechanical and electrical properties of the organic materials

- ➤ coil displacement during operation, powering and thermal cycles
- ➤ quench triggering
- ➤ electrical arcing
- ➤ field quality deterioration

→ Gamma radiation can damage the coil and degrade magnet performances

Gamma irradiation campaign

Gamma irradiation with ^{60}Co source at BGS facilities (Germany)

LHC spare wire (PVA enamel) | Supercon Inc wire (polyimide) | Type C + Araldite 2011 (ribbon glue)

Average breakdown voltage after irradiation	*Type A*	*Type C*	*Type D*
0 MGy	1.5 kV	3.2 kV	4.1 kV
1 MGy	2.4 kV	-	-
2.5 MGy	<10 V	2.8 kV	4.2 kV
5 MGy	-	3.8 kV	2.9 kV

Breakdown voltage tests after irradiation of LHC spare wire (A) and candidate wire (C, D), all samples withstood 1 kV before irradiation

→ LHC spare wire resists between 1 and 2.5 MGy
→ Candidate wire resists more than 5 MGy
→ Tests performed under conservative conditions

Upcoming gamma radiation campaign:

- ❖ Ribbon cables irradiated under more representative conditions (impregnation and He atmosphere)
- ❖ Additional samples to test the other magnet components: cuts of old pre-series MCBC coil and Isopreg 2704
- ❖ Irradiation up to 2.5, 5 and 10 MGy
- ❖ Post-irradiation breakdown voltage and mechanical tests will be performed

→ will help to better estimate the radiation hardness of the present magnets

Radiation hard design: magnetic simulation

- ❖ Common design (based on MCBY) for the radiation hard spare units of MCBC and MCBY magnets to reduce the manufacturing cost (called MCBYR and MCBY* respectively)
- ❖ Compared to MCBC, the larger aperture of MCBYR allows to place a 7mm-thick tungsten shield to increase the protection against radiation
- ❖ Re-optimization of the coil ends with present ROXIE algorithm to control the cable mechanical strain in the coil ends and the magnetic field quality along the magnet

	Coil bore diameter	Overall length	Magnetic length	Operating temperature	Nominal current	Nominal bore field	Peak field on conductor	Percentage along load line	Self-inductance	Stored energy
MCBYR	70 mm	1100 mm	880 mm	1.9/4.5 K	94/70 A	3.18/2.35 T	3.63/2.69 T	56.23/57.37 %	4.69/4.87 H	20.7/11.9 kJ
MCBY*	70 mm	1100 mm	880 mm	4.5 K	74 A	2.56 T	2.92 T	61.76 %	4.86 H	13.3 kJ

Mechanical simulation

Azimuthal stress in **MCBY** after preload (scissors laminations), cool-down at 1.9 K (aluminum shrinking cylinders) and magnet powering simulated with ANSYS APDL → **negligible impact of e.m. forces**

→ Stress levels will still be within acceptable limits for MCBYR and MCBY*

Quench simulation

2D quench simulation of **MCBYR** with 80mΩ crowbar resistance performed with STEAM-LEDET to control the hot spot temperature (larger stored energy than MCBY)

- ❖ Longitudinal quench propagation velocity taken into account to evaluate the resistive growth
- ❖ Adiabatic hot spot temperature ~180 K

→ Quench protection scheme suitable for MCBYR and MCBY*

Alternative CCT design

A Canted Cosine Theta (CCT) design, similar to MCBRD, with a 500A polyimide-insulated conductor has been developed

- ❖ mechanically robust and radiation hard
- ❖ cost reduction for a few units
- ❖ individual quench protection system needed (larger stored energy)
- ❖ conductor development to reach MCBYR nominal current required

3D printed coil support models

Conclusion

We have presented the results of a radiation test campaign on LHC wire and candidate materials for wires for MCBC and MCBY magnets.
We have started a wider radiation campaign to determine the gamma dose that these magnets can safely absorb to anticipate the number of units that will need to be replaced.
In parallel, we have designed radiation hard spare versions of the MCBC and MCBY magnets involving technology modifications (polyimide, tungsten shield) with respect to their original designs.
In addition, we have performed integration, mechanical and quench protection studies that have confirmed the viability of these designs in the same technological environment than the present MCBC and MCBY magnets installed in LHC.

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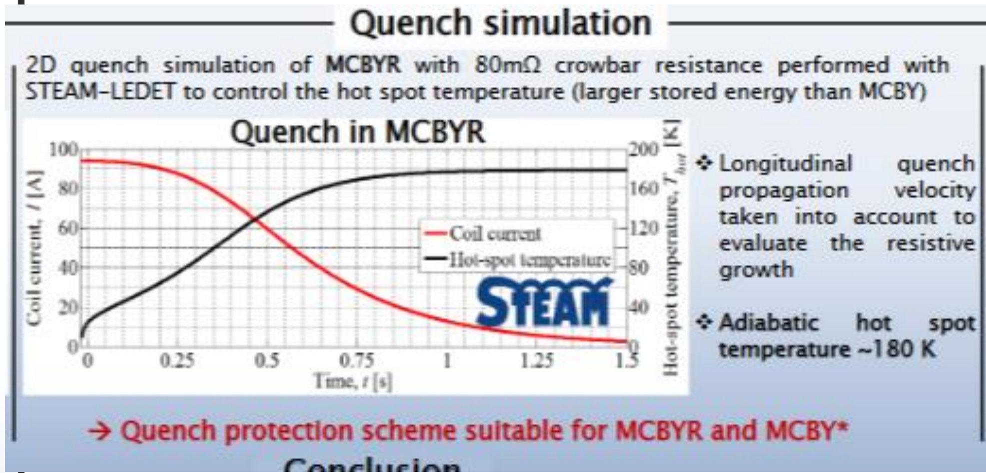

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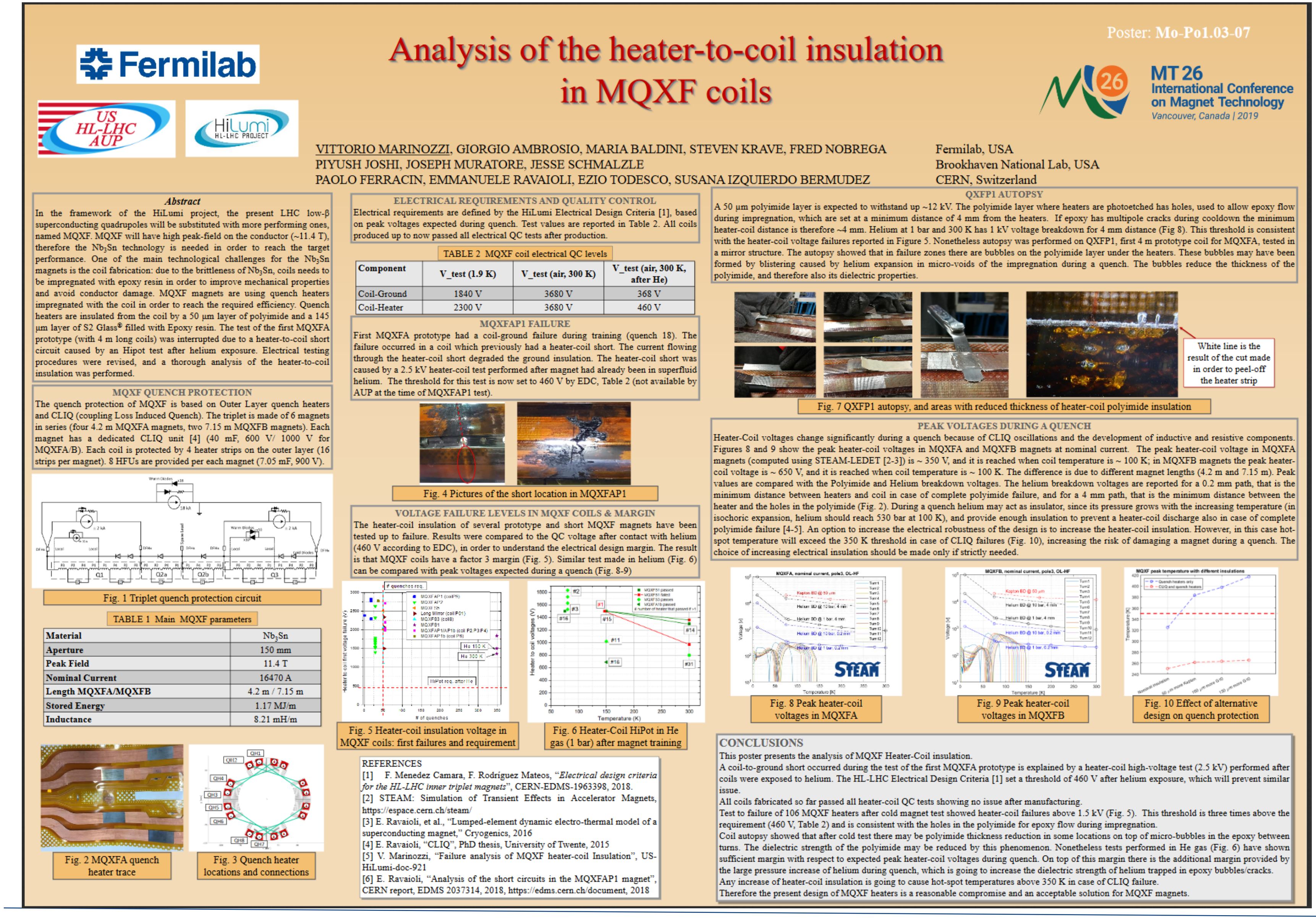
Vittorio Marinozzi (FNAL)



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Analysis of the heater-to-coil insulation in MQXF coils

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VITTORIO MARINOZZI, GIORGIO AMBROSIO, MARIA BALDINI, STEVEN KRAVE, FRED NOBREGA — Fermilab, USA
PIYUSH JOSHI, JOSEPH MURATORE, JESSE SCHMALZLE — Brookhaven National Lab, USA
PAOLO FERRACIN, EMMANUELE RAVAIOLI, EZIO TODESCO, SUSANA IZQUIERDO BERMUDEZ — CERN, Switzerland

Abstract

In the framework of the HiLumi project, the present LHC low-β superconducting quadrupoles will be substituted with more performing ones, named MQXF. MQXF will have high peak-field on the conductor (~11.4 T), therefore the Nb_3Sn technology is needed in order to reach the target performance. One of the main technological challenges for the Nb_3Sn magnets is the coil fabrication: due to the brittleness of Nb_3Sn, coils needs to be impregnated with epoxy resin in order to improve mechanical properties and avoid conductor damage. MQXF magnets are using quench heaters impregnated with the coil in order to reach the required efficiency. Quench heaters are insulated from the coil by a 50 µm layer of polyimide and a 145 µm layer of S2 Glass® filled with Epoxy resin. The test of the first MQXFA prototype (with 4 m long coils) was interrupted due to a heater-to-coil short circuit caused by an Hipot test after helium exposure. Electrical testing procedures were revised, and a thorough analysis of the heater-to-coil insulation was performed.

MQXF QUENCH PROTECTION

The quench protection of MQXF is based on Outer Layer quench heaters and CLIQ (coupling Loss Induced Quench). The triplet is made of 6 magnets in series (four 4.2 m MQXFA magnets, two 7.15 m MQXFB magnets). Each magnet has a dedicated CLIQ unit [4] (40 mF, 600 V/ 1000 V for MQXFA/B). Each coil is protected by 4 heater strips on the outer layer (16 strips per magnet). 8 HFUs are provided per each magnet (7.05 mF, 900 V).

Fig. 1 Triplet quench protection circuit

TABLE 1 Main MQXF parameters

Material	Nb_3Sn
Aperture	150 mm
Peak Field	11.4 T
Nominal Current	16470 A
Length MQXFA/MQXFB	4.2 m / 7.15 m
Stored Energy	1.17 MJ/m
Inductance	8.21 mH/m

Fig. 2 MQXFA quench heater trace

Fig. 3 Quench heater locations and connections

ELECTRICAL REQUIREMENTS AND QUALITY CONTROL

Electrical requirements are defined by the HiLumi Electrical Design Criteria [1], based on peak voltages expected during quench. Test values are reported in Table 2. All coils produced up to now passed all electrical QC tests after production.

TABLE 2 MQXF coil electrical QC levels

Component	**V_test (1.9 K)**	**V_test (air, 300 K)**	**V_test (air, 300 K, after He)**
Coil-Ground	1840 V	3680 V	368 V
Coil-Heater	2300 V	3680 V	460 V

MQXFAP1 FAILURE

First MQXFA prototype had a coil-ground failure during training (quench 18). The failure occurred in a coil which previously had a heater-coil short. The current flowing through the heater-coil short degraded the ground insulation. The heater-coil short was caused by a 2.5 kV heater-coil test performed after magnet had already been in superfluid helium. The threshold for this test is now set to 460 V by EDC, Table 2 (not available by AUP at the time of MQXFAP1 test).

Fig. 4 Pictures of the short location in MQXFAP1

VOLTAGE FAILURE LEVELS IN MQXF COILS & MARGIN

The heater-coil insulation of several prototype and short MQXF magnets have been tested up to failure. Results were compared to the QC voltage after contact with helium (460 V according to EDC), in order to understand the electrical design margin. The result is that MQXF coils have a factor 3 margin (Fig. 5). Similar test made in helium (Fig. 6) can be compared with peak voltages expected during a quench (Fig. 8-9)

Fig. 5 Heater-coil insulation voltage in MQXF coils: first failures and requirement

Fig. 6 Heater-Coil HiPot in He gas (1 bar) after magnet training

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[4] E. Ravaioli, "CLIQ", PhD thesis, University of Twente, 2015
[5] V. Marinozzi, "Failure analysis of MQXF heater-coil Insulation", US-HiLumi-doc-921
[6] E. Ravaioli, "Analysis of the short circuits in the MQXFAP1 magnet", CERN report, EDMS 2037314, 2018, https://edms.cern.ch/document, 2018

QXFP1 AUTOPSY

A 50 µm polyimide layer is expected to withstand up ~12 kV. The polyimide layer where heaters are photoetched has holes, used to allow epoxy flow during impregnation, which are set at a minimum distance of 4 mm from the heaters. If epoxy has multipole cracks during cooldown the minimum heater-coil distance is therefore ~4 mm. Helium at 1 bar and 300 K has 1 kV voltage breakdown for 4 mm distance (Fig 8). This threshold is consistent with the heater-coil voltage failures reported in Figure 5. Nonetheless autopsy was performed on QXFP1, first 4 m prototype coil for MQXFA, tested in a mirror structure. The autopsy showed that in failure zones there are bubbles on the polyimide layer under the heaters. These bubbles may have been formed by blistering caused by helium expansion in micro-voids of the impregnation during a quench. The bubbles reduce the thickness of the polyimide, and therefore also its dielectric properties.

White line is the result of the cut made in order to peel-off the heater strip

Fig. 7 QXFP1 autopsy, and areas with reduced thickness of heater-coil polyimide insulation

PEAK VOLTAGES DURING A QUENCH

Heater-Coil voltages change significantly during a quench because of CLIQ oscillations and the development of inductive and resistive components. Figures 8 and 9 show the peak heater-coil voltages in MQXFA and MQXFB magnets at nominal current. The peak heater-coil voltage in MQXFA magnets (computed using STEAM-LEDET [2-3]) is ~ 350 V, and it is reached when coil temperature is ~ 100 K; in MQXFB magnets the peak heater-coil voltage is ~ 650 V, and it is reached when coil temperature is ~ 100 K. The difference is due to different magnet lengths (4.2 m and 7.15 m). Peak values are compared with the Polyimide and Helium breakdown voltages. The helium breakdown voltages are reported for a 0.2 mm path, that is the minimum distance between heaters and coil in case of complete polyimide failure, and for a 4 mm path, that is the minimum distance between the heater and the holes in the polyimide (Fig. 2). During a quench helium may act as insulator, since its pressure grows with the increasing temperature (in isochoric expansion, helium should reach 530 bar at 100 K), and provide enough insulation to prevent a heater-coil discharge also in case of complete polyimide failure [4-5]. An option to increase the electrical robustness of the design is to increase the heater-coil insulation. However, in this case hot-spot temperature will exceed the 350 K threshold in case of CLIQ failures (Fig. 10), increasing the risk of damaging a magnet during a quench. The choice of increasing electrical insulation should be made only if strictly needed.

Fig. 8 Peak heater-coil voltages in MQXFA

Fig. 9 Peak heater-coil voltages in MQXFB

Fig. 10 Effect of alternative design on quench protection

CONCLUSIONS

This poster presents the analysis of MQXF Heater-Coil insulation.
A coil-to-ground short occurred during the test of the first MQXFA prototype is explained by a heater-coil high-voltage test (2.5 kV) performed after coils were exposed to helium. The HL-LHC Electrical Design Criteria [1] set a threshold of 460 V after helium exposure, which will prevent similar issue.
All coils fabricated so far passed all heater-coil QC tests showing no issue after manufacturing.
Test to failure of 106 MQXF heaters after cold magnet test showed heater-coil failures above 1.5 kV (Fig. 5). This threshold is three times above the requirement (460 V, Table 2) and is consistent with the holes in the polyimide for epoxy flow during impregnation.
Coil autopsy showed that after cold test there may be polyimide thickness reduction in some locations on top of micro-bubbles in the epoxy between turns. The dielectric strength of the polyimide may be reduced by this phenomenon. Nonetheless tests performed in He gas (Fig. 6) have shown sufficient margin with respect to expected peak heater-coil voltages during quench. On top of this margin there is the additional margin provided by the large pressure increase of helium during quench, which is going to increase the dielectric strength of helium trapped in epoxy bubbles/cracks.
Any increase of heater-coil insulation is going to cause hot-spot temperatures above 350 K in case of CLIQ failure.
Therefore the present design of MQXF heaters is a reasonable compromise and an acceptable solution for MQXF magnets.

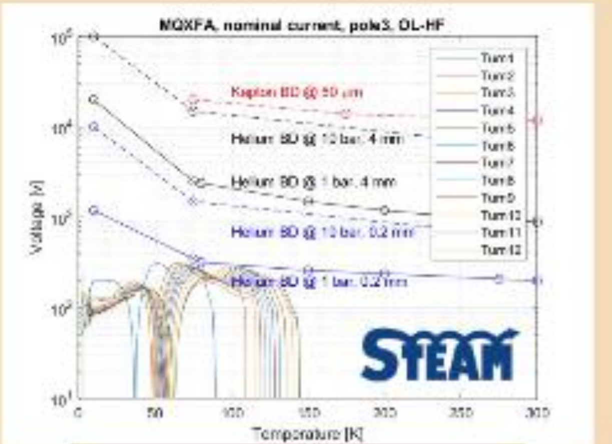


Fig. 8 Peak heater-coil voltages in MQXFA

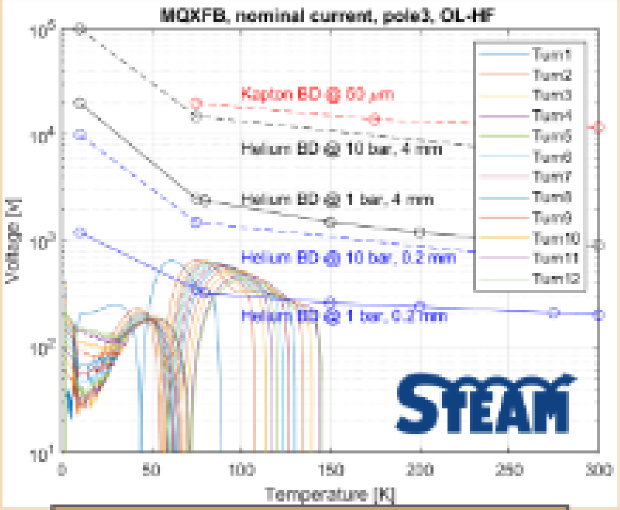
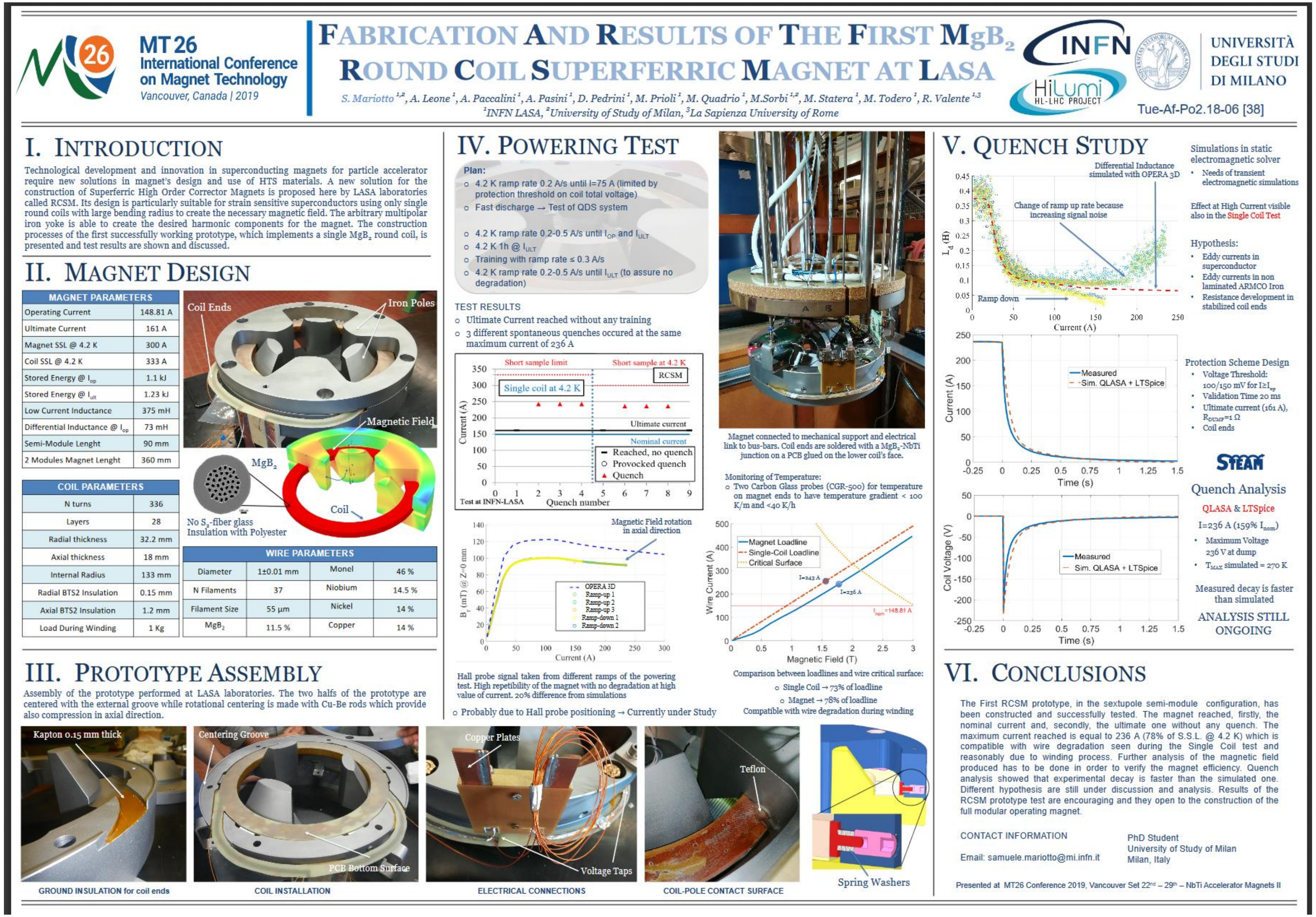


Fig. 9 Peak heater-coil voltages in MQXFB

Samuele Mariotto (INFN)



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FABRICATION AND RESULTS OF THE FIRST MgB_2 ROUND COIL SUPERFERRIC MAGNET AT LASA

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HiLumi HL-LHC PROJECT
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Tue-Af-Po2.18-06 [38]

I. INTRODUCTION

Technological development and innovation in superconducting magnets for particle accelerator require new solutions in magnet's design and use of HTS materials. A new solution for the construction of Superferric High Order Corrector Magnets is proposed here by LASA laboratories called RCSM. Its design is particularly suitable for strain sensitive superconductors using only single round coils with large bending radius to create the necessary magnetic field. The arbitrary multipolar iron yoke is able to create the desired harmonic components for the magnet. The construction processes of the first successfully working prototype, which implements a single MgB_2 round coil, is presented and test results are shown and discussed.

II. MAGNET DESIGN

MAGNET PARAMETERS	
Operating Current	148.81 A
Ultimate Current	161 A
Magnet SSL @ 4.2 K	300 A
Coil SSL @ 4.2 K	333 A
Stored Energy @ I_{op}	1.1 kJ
Stored Energy @ I_{ult}	1.23 kJ
Low Current Inductance	375 mH
Differential Inductance @ I_{op}	73 mH
Semi-Module Lenght	90 mm
2 Modules Magnet Lenght	360 mm

COIL PARAMETERS	
N turns	336
Layers	28
Radial thickness	32.2 mm
Axial thickness	18 mm
Internal Radius	133 mm
Radial BTS2 Insulation	0.15 mm
Axial BTS2 Insulation	1.2 mm
Load During Winding	1 Kg

No S_2-fiber glass Insulation with Polyester

WIRE PARAMETERS			
Diameter	1±0.01 mm	Monel	46 %
N Filaments	37	Niobium	14.5 %
Filament Size	55 µm	Nickel	14 %
MgB_2	11.5 %	Copper	14 %

III. PROTOTYPE ASSEMBLY

Assembly of the prototype performed at LASA laboratories. The two halfs of the prototype are centered with the external groove while rotational centering is made with Cu-Be rods which provide also compression in axial direction.

GROUND INSULATION for coil ends

COIL INSTALLATION

ELECTRICAL CONNECTIONS

COIL-POLE CONTACT SURFACE

IV. POWERING TEST

Plan:

- 4.2 K ramp rate 0.2 A/s until I=75 A (limited by protection threshold on coil total voltage)
- Fast discharge → Test of QDS system
- 4.2 K ramp rate 0.2-0.5 A/s until I_{OP} and I_{ULT}
- 4.2 K 1h @ I_{ULT}
- Training with ramp rate ≤ 0.3 A/s
- 4.2 K ramp rate 0.2-0.5 A/s until I_{ULT} (to assure no degradation)

TEST RESULTS

- Ultimate Current reached without any training
- 3 different spontaneous quenches occured at the same maximum current of 236 A

Magnet connected to mechanical support and electrical link to bus-bars. Coil ends are soldered with a MgB_2-NbTi junction on a PCB glued on the lower coil's face.

Monitoring of Temperature:

- Two Carbon Glass probes (CGR-500) for temperature on magnet ends to have temperature gradient < 100 K/m and <40 K/h

Hall probe signal taken from different ramps of the powering test. High repetibility of the magnet with no degradation at high value of current. 20% difference from simulations

- Probably due to Hall probe positioning → Currently under Study

Comparison between loadlines and wire critical surface:

- Single Coil → 73% of loadline
- Magnet → 78% of loadline

Compatible with wire degradation during winding

V. QUENCH STUDY

Simulations in static electromagnetic solver

- Needs of transient electromagnetic simulations

Effect at High Current visible also in the Single Coil Test

Hypothesis:

- Eddy currents in superconductor
- Eddy currents in non laminated ARMCO Iron
- Resistance development in stabilized coil ends

Protection Scheme Design

- Voltage Threshold: 100/150 mV for I≥I_{op}
- Validation Time 20 ms
- Ultimate current (161 A), R_{DUMP}=1 Ω
- Coil ends

STEAM

Quench Analysis

QLASA & LTSpice

I=236 A (159% I_{nom})

- Maximum Voltage 236 V at dump
- T_{MAX} simulated = 270 K

Measured decay is faster than simulated

ANALYSIS STILL ONGOING

VI. CONCLUSIONS

The First RCSM prototype, in the sextupole semi-module configuration, has been constructed and successfully tested. The magnet reached, firstly, the nominal current and, secondly, the ultimate one without any quench. The maximum current reached is equal to 236 A (78% of S.S.L. @ 4.2 K) which is compatible with wire degradation seen during the Single Coil test and reasonably due to winding process. Further analysis of the magnetic field produced has to be done in order to verify the magnet efficiency. Quench analysis showed that experimental decay is faster than the simulated one. Different hypothesis are still under discussion and analysis. Results of the RCSM prototype test are encouraging and they open to the construction of the full modular operating magnet.

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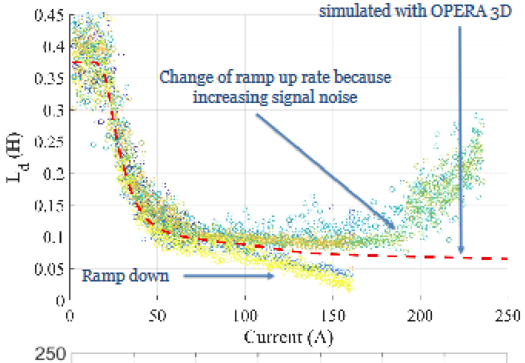
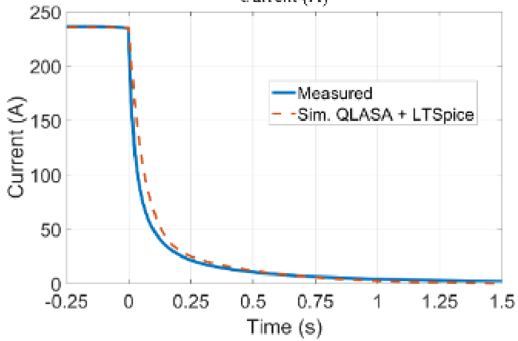
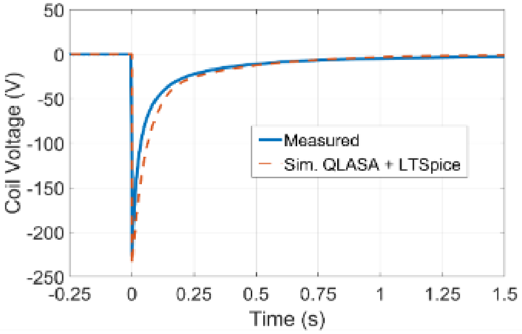
Presented at MT26 Conference 2019, Vancouver Set 22nd – 29th – NbTi Accelerator Magnets II







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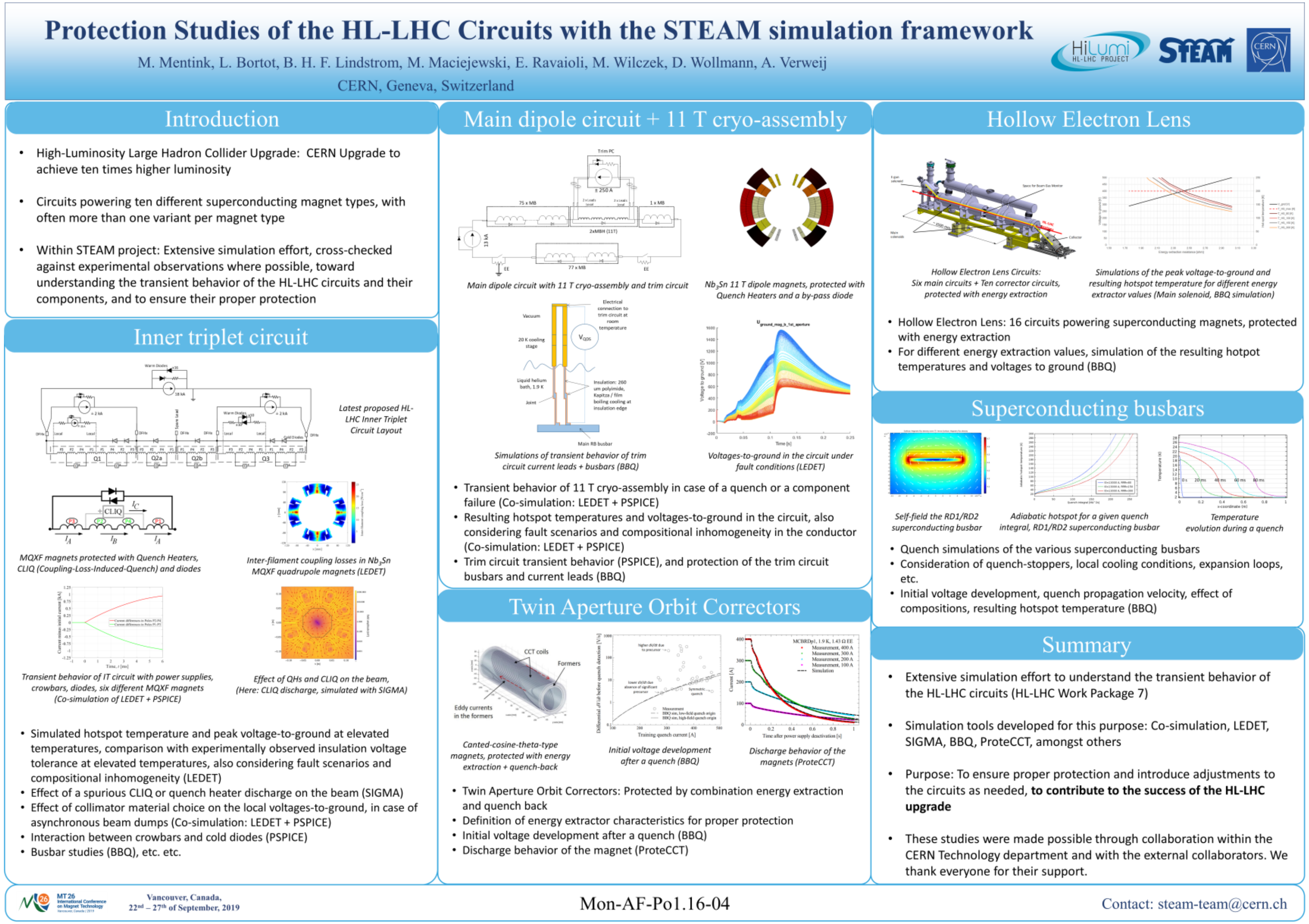
ANALYSIS STILL ONGOING

Matthias Mentink (CERN) -1



Protection Studies of the HL-LHC Circuits with the STEAM simulation framework

M. Mentink, L. Bortot, B. H. F. Lindstrom, M. Maciejewski, E. Ravaioli, M. Wilczek, D. Wollmann, A. Verweij
CERN, Geneva, Switzerland

Introduction

- High-Luminosity Large Hadron Collider Upgrade: CERN Upgrade to achieve ten times higher luminosity
- Circuits powering ten different superconducting magnet types, with often more than one variant per magnet type
- Within STEAM project: Extensive simulation effort, cross-checked against experimental observations where possible, toward understanding the transient behavior of the HL-LHC circuits and their components, and to ensure their proper protection

Inner triplet circuit

Latest proposed HL-LHC Inner Triplet Circuit Layout

MQXF magnets protected with Quench Heaters, CLIQ (Coupling-Loss-Induced-Quench) and diodes

Inter-filament coupling losses in Nb_3Sn MQXF quadrupole magnets (LEDET)

Transient behavior of IT circuit with power supplies, crowbars, diodes, six different MQXF magnets (Co-simulation of LEDET + PSPICE)

Effect of QHs and CLIQ on the beam, (Here: CLIQ discharge, simulated with SIGMA)

- Simulated hotspot temperature and peak voltage-to-ground at elevated temperatures, comparison with experimentally observed insulation voltage tolerance at elevated temperatures, also considering fault scenarios and compositional inhomogeneity (LEDET)
- Effect of a spurious CLIQ or quench heater discharge on the beam (SIGMA)
- Effect of collimator material choice on the local voltages-to-ground, in case of asynchronous beam dumps (Co-simulation: LEDET + PSPICE)
- Interaction between crowbars and cold diodes (PSPICE)
- Busbar studies (BBQ), etc. etc.

Main dipole circuit + 11 T cryo-assembly

Main dipole circuit with 11 T cryo-assembly and trim circuit

Nb_3Sn 11 T dipole magnets, protected with Quench Heaters and a by-pass diode

Simulations of transient behavior of trim circuit current leads + busbars (BBQ)

Voltages-to-ground in the circuit under fault conditions (LEDET)

- Transient behavior of 11 T cryo-assembly in case of a quench or a component failure (Co-simulation: LEDET + PSPICE)
- Resulting hotspot temperatures and voltages-to-ground in the circuit, also considering fault scenarios and compositional inhomogeneity in the conductor (Co-simulation: LEDET + PSPICE)
- Trim circuit transient behavior (PSPICE), and protection of the trim circuit busbars and current leads (BBQ)

Twin Aperture Orbit Correctors

Canted-cosine-theta-type magnets, protected with energy extraction + quench-back

Initial voltage development after a quench (BBQ)

Discharge behavior of the magnets (ProteCCT)

- Twin Aperture Orbit Correctors: Protected by combination energy extraction and quench back
- Definition of energy extractor characteristics for proper protection
- Initial voltage development after a quench (BBQ)
- Discharge behavior of the magnet (ProteCCT)

Hollow Electron Lens

Hollow Electron Lens Circuits: Six main circuits + Ten corrector circuits, protected with energy extraction

Simulations of the peak voltage-to-ground and resulting hotspot temperature for different energy extractor values (Main solenoid, BBQ simulation)

- Hollow Electron Lens: 16 circuits powering superconducting magnets, protected with energy extraction
- For different energy extraction values, simulation of the resulting hotpot temperatures and voltages to ground (BBQ)

Superconducting busbars

Self-field the RD1/RD2 superconducting busbar

Adiabatic hotspot for a given quench integral, RD1/RD2 superconducting busbar

Temperature evolution during a quench

- Quench simulations of the various superconducting busbars
- Consideration of quench-stoppers, local cooling conditions, expansion loops, etc.
- Initial voltage development, quench propagation velocity, effect of compositions, resulting hotspot temperature (BBQ)

Summary

- Extensive simulation effort to understand the transient behavior of the HL-LHC circuits (HL-LHC Work Package 7)
- Simulation tools developed for this purpose: Co-simulation, LEDET, SIGMA, BBQ, ProteCCT, amongst others
- Purpose: To ensure proper protection and introduce adjustments to the circuits as needed, **to contribute to the success of the HL-LHC upgrade**
- These studies were made possible through collaboration within the CERN Technology department and with the external collaborators. We thank everyone for their support.

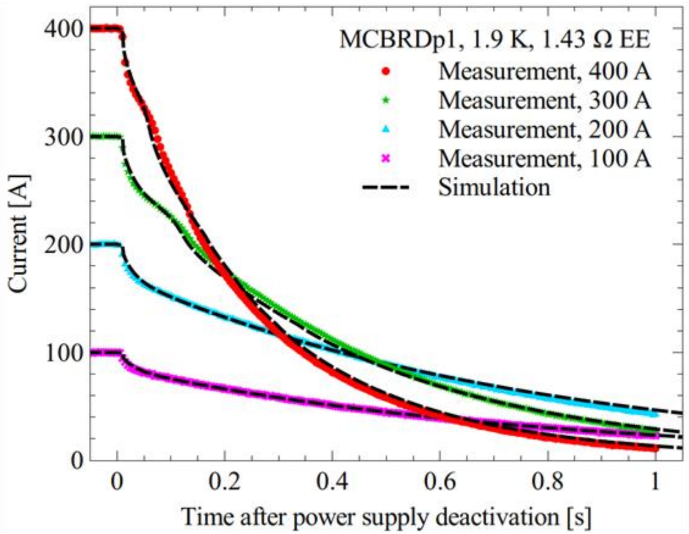
MT26 International Conference on Magnet Technology
Vancouver, Canada, 22nd – 27th of September, 2019

Mon-AF-Po1.16-04

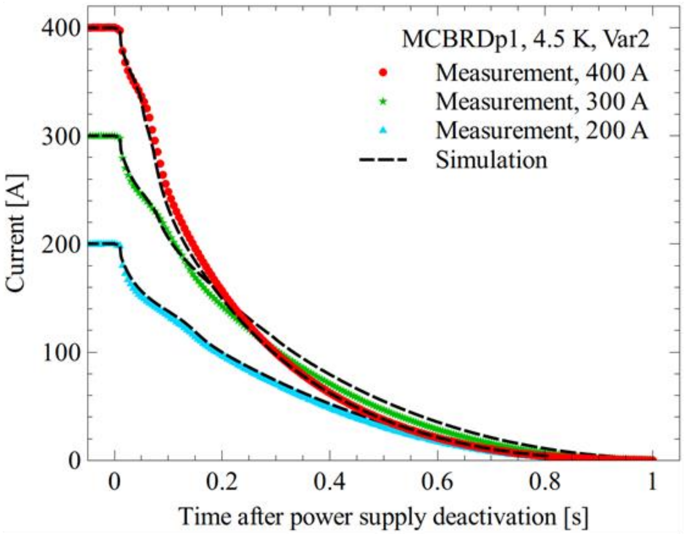
Contact: steam-team@cern.ch

Matthias Mentink (CERN) -2

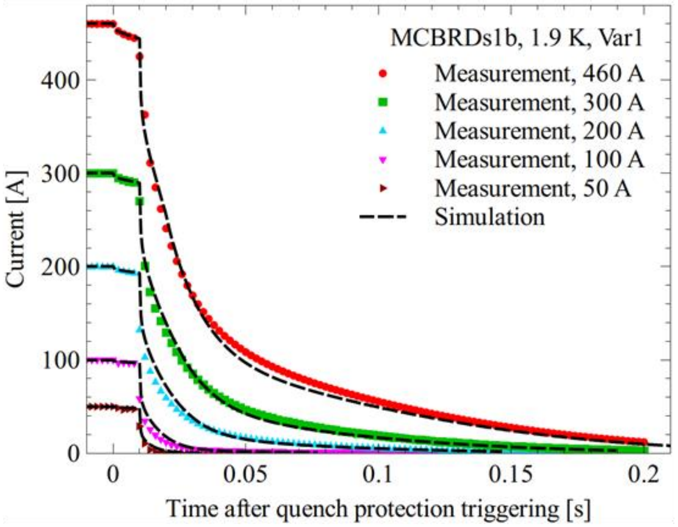
Simulation versus experimental observations (1/2)



MCBRDp1 prototype, discharge over 1.43 Ω dump resistor



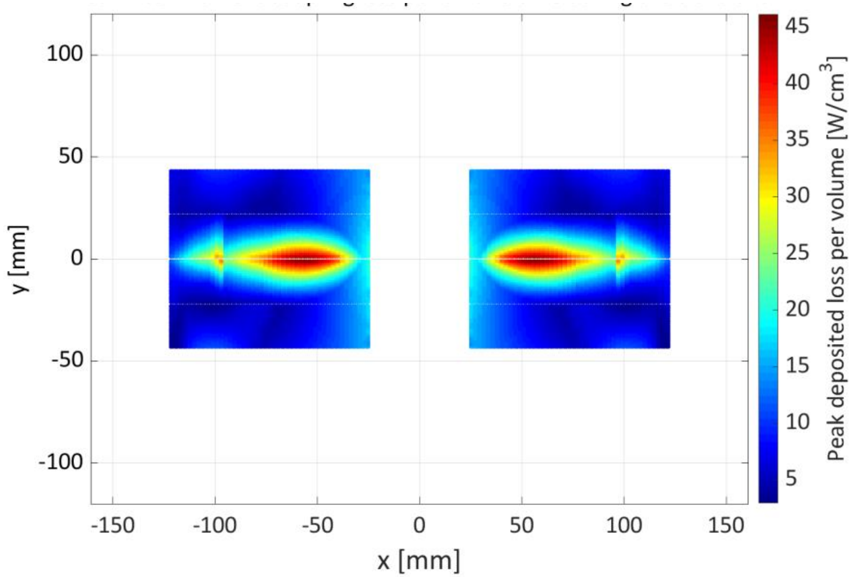
MCBRDp1 prototype, discharge over non-linear varistor

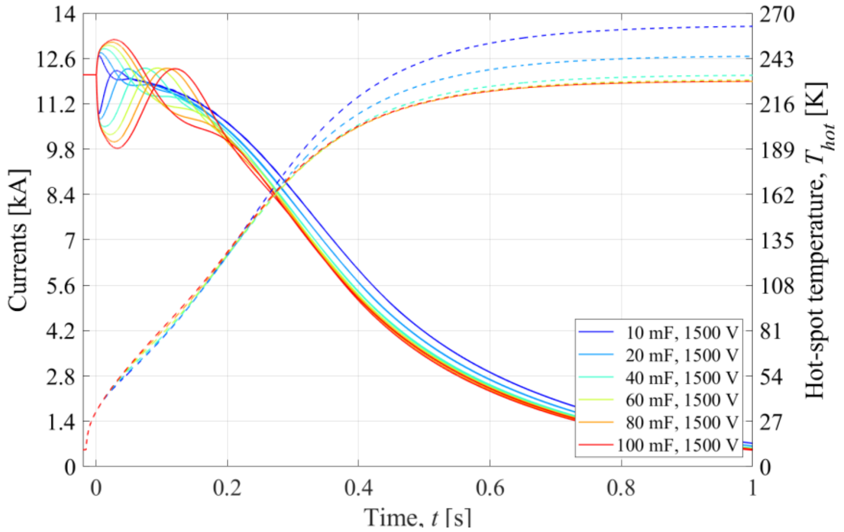


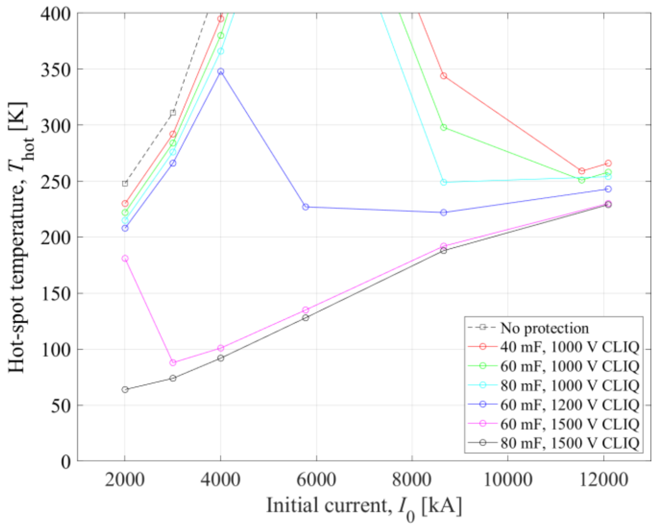
MCBRDs1b short model, discharge over non-linear varistor

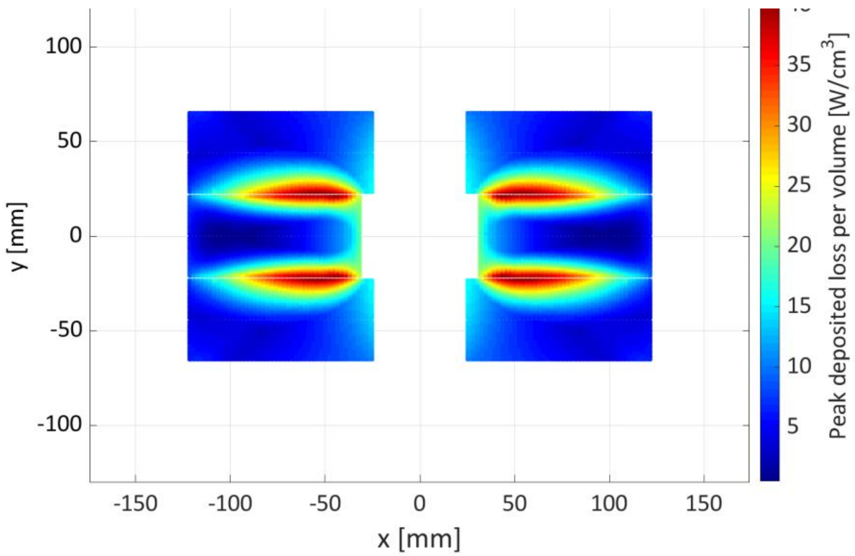
- **Extensive** measurement campaign by SM18 personnel
- Comparison of simulation to experimental observations for: Different magnetic lengths, energy extractor types, helium bath temperatures, operating currents
- No free parameters except global constants *fLoopFactor* = 2.0, *addedHeCpFrac* = 0.6%

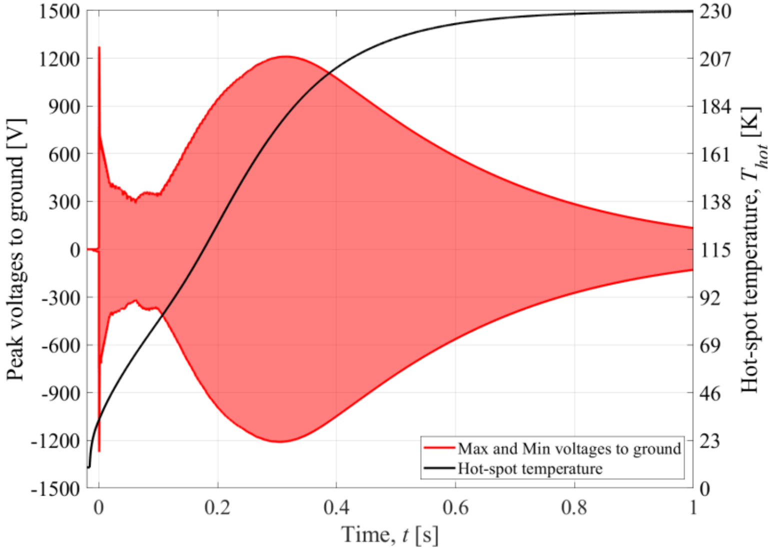
Emmanuele Ravaioli (CERN)

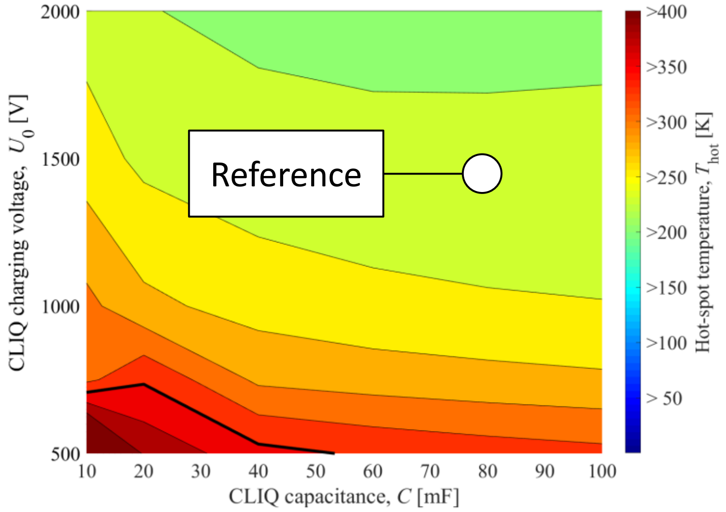










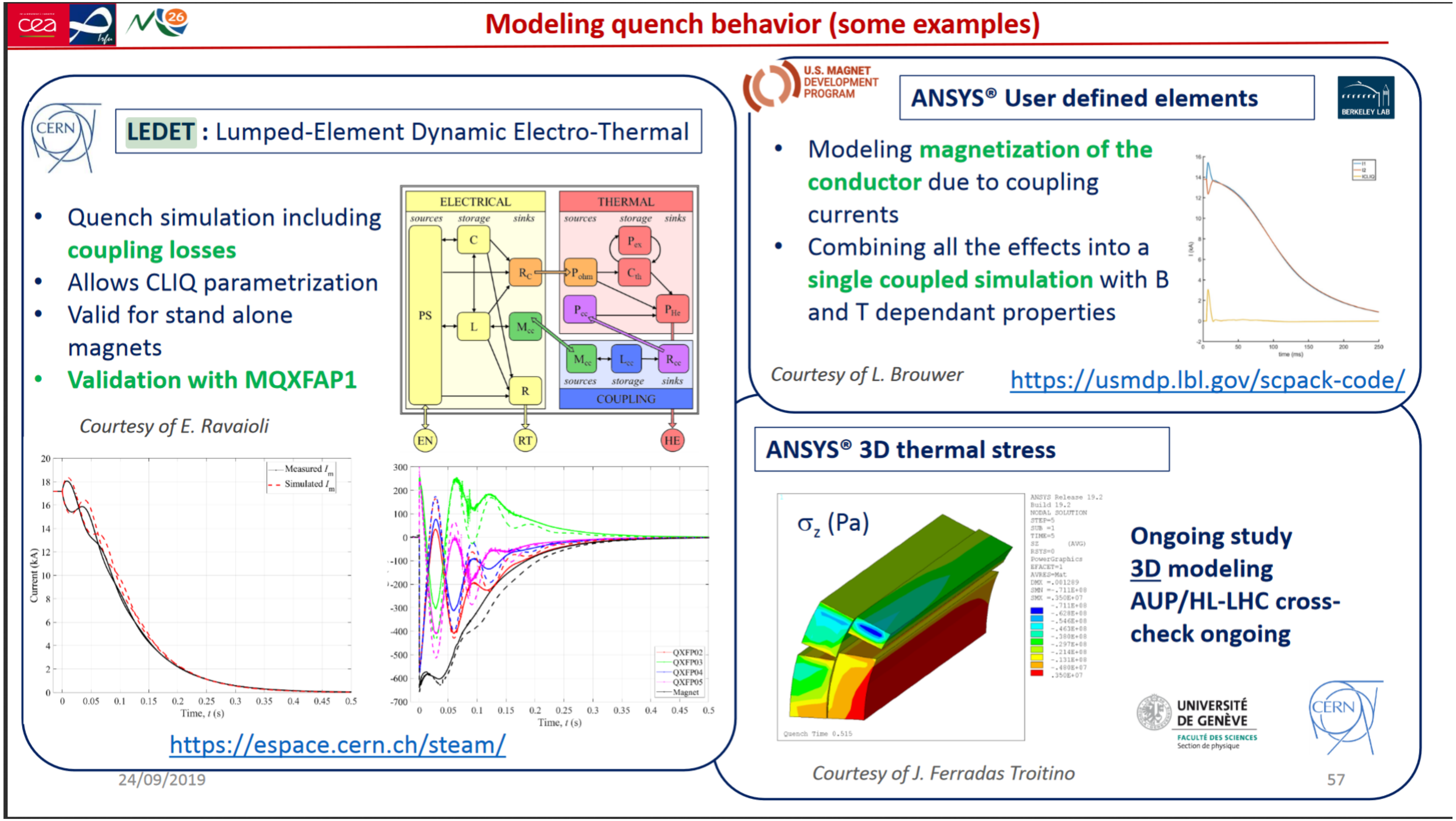


Andrew Twin (Oxford Instruments)

No presentation available

Andrew Twin presented Matthias' simulations of transients in CCT magnets performed with ProteCCT

Helene Felice (at her plenary talk)



Modeling quench behavior (some examples)

LEDET : Lumped-Element Dynamic Electro-Thermal

- Quench simulation including **coupling losses**
- Allows CLIQ parametrization
- Valid for stand alone magnets
- **Validation with MQXFAP1**

Courtesy of E. Ravaioli

https://espace.cern.ch/steam/

24/09/2019

U.S. MAGNET DEVELOPMENT PROGRAM

ANSYS® User defined elements

- Modeling **magnetization of the conductor** due to coupling currents
- Combining all the effects into a **single coupled simulation** with B and T dependant properties

Courtesy of L. Brouwer https://usmdp.lbl.gov/scpack-code/

ANSYS® 3D thermal stress

Ongoing study
3D modeling
AUP/HL-LHC cross-check ongoing

Courtesy of J. Ferradas Troitino

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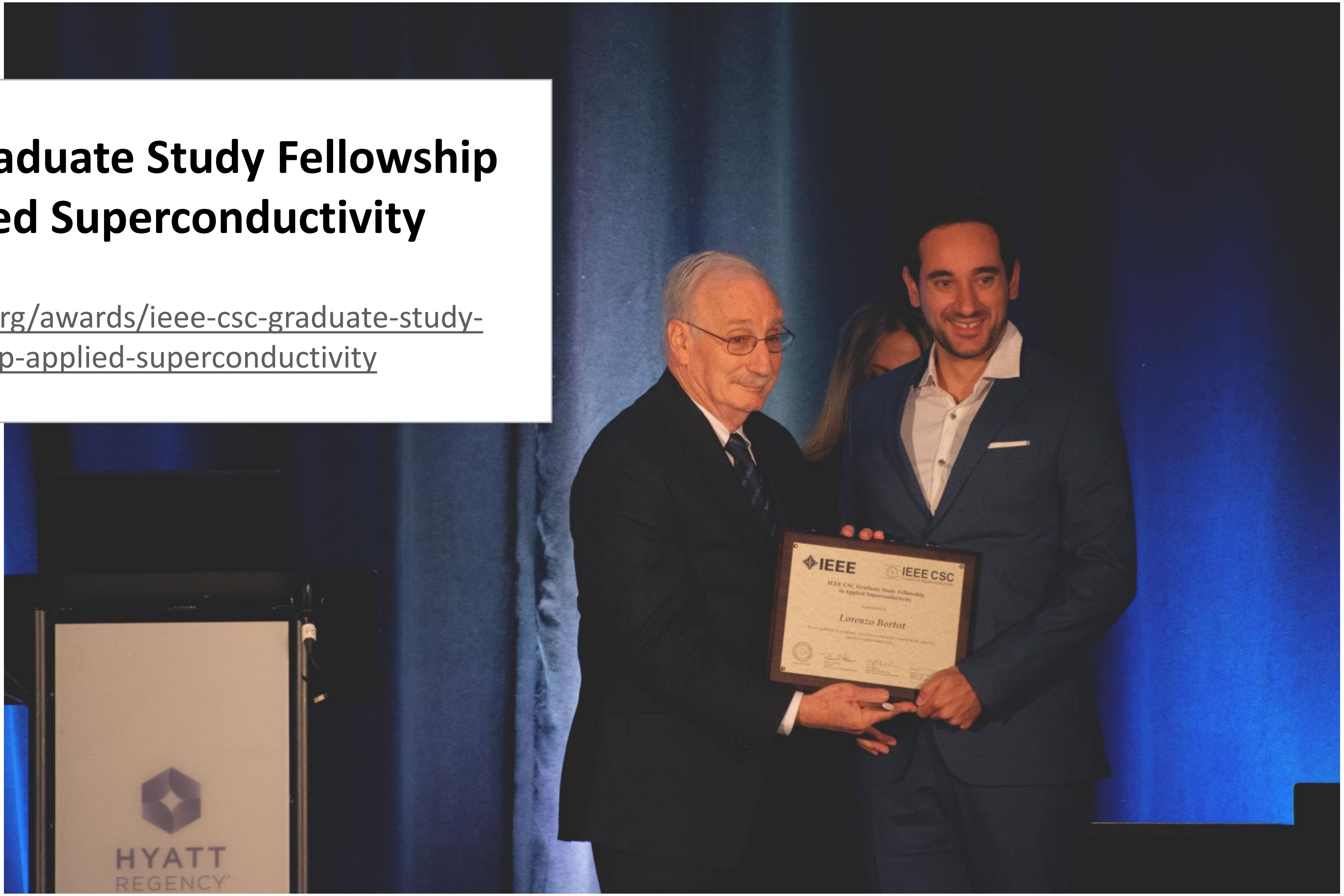
Congratulations to Lorenzo!



IEEE CSC Graduate Study Fellowship in Applied Superconductivity

https://ieeecsc.org/awards/ieee-csc-graduate-study-fellowship-applied-superconductivity