High Order Corrector update

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on behalf of the LASA team
INFN Milano - LASA

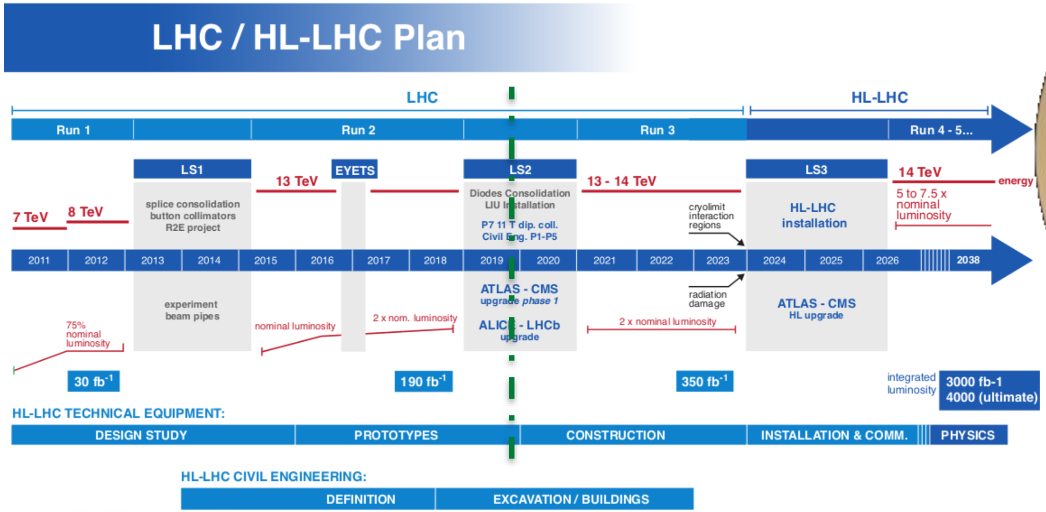
9th HL-LHC Collaboration Meeting
Fermilab – Oct 15th 2019

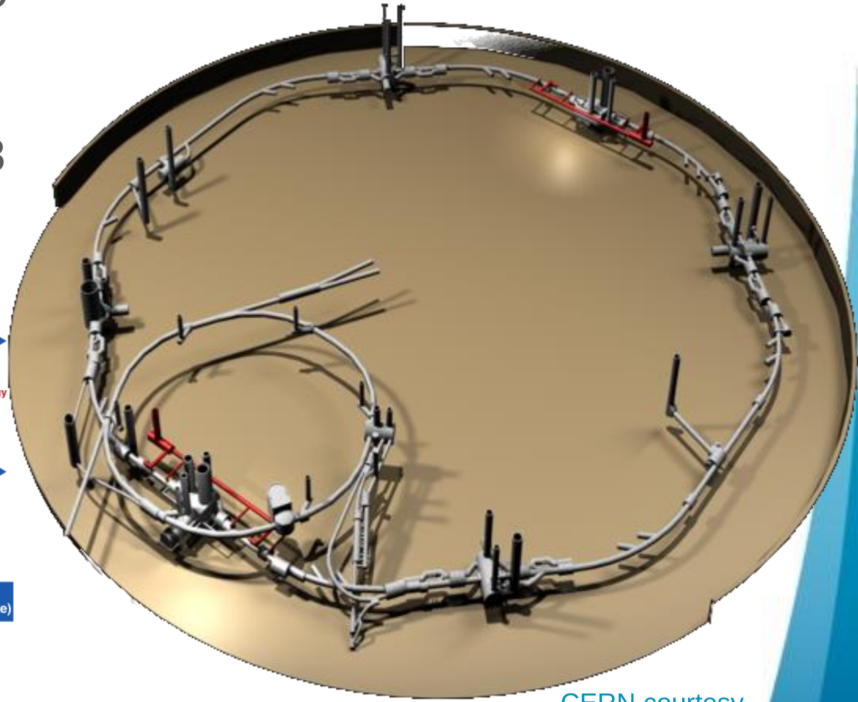
OUTLINE

- Scope: the High Order Correctors magnets
- Overview on HO Correctors
- The prototypes
- The series production
- Next steps
- Conclusions

High Luminosity LHC

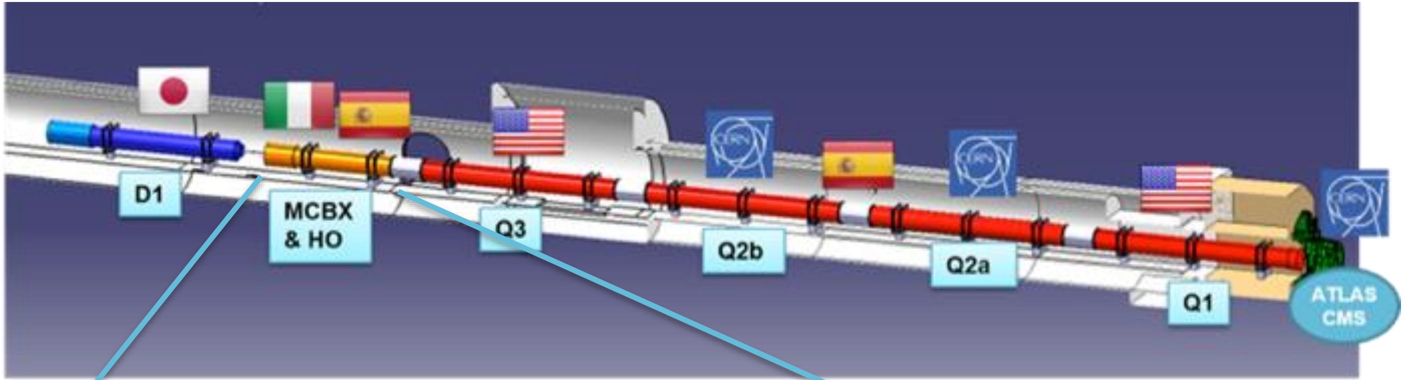
- **LHC** integrated luminosity 300 fb^{-1} by 2023
- **HL LHC**
  - upgrade interacting regions 2024/26
  - 3000 fb^{-1} integrated luminosity by 2038

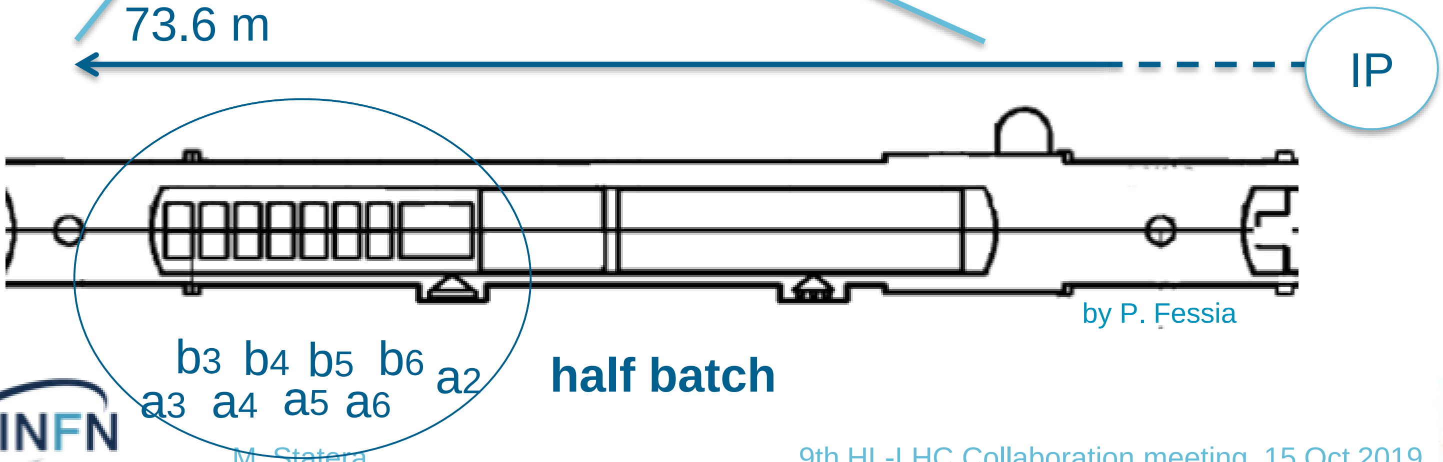




CERN courtesy

THE LOW BETA SECTION
and the High Order Correctors





SCOPE - High Order Correctors

- The INFN-LASA follows the design, construction and test of the 5 prototypes of the High Order (HO) corrector magnets for the HL interaction regions of HL-LHC. KE2291
- The INFN-LASA will follow the series production of the HO corrector magnets for the HL interaction regions of HL-LHC. KE3085

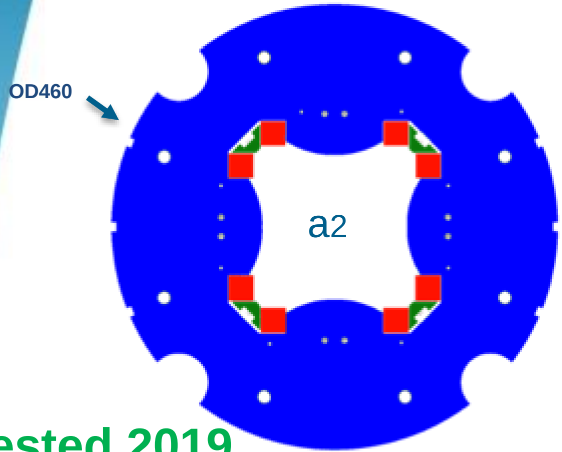
ADDENDUM No. 2 KE3085/TE/HL-LHC
to
FRAMEWORK COLLABORATION AGREEMENT KN3083
between
THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)
and
Istituto Nazionale di Fisica Nucleare (the "Institute")
concerning

Collaboration in design, procurement and testing of the high-order orbit corrector superconducting magnets in the framework of the High Luminosity upgrade for the LHC at CERN

30th Nov 2017

54 S.C. High Order Corrector magnets

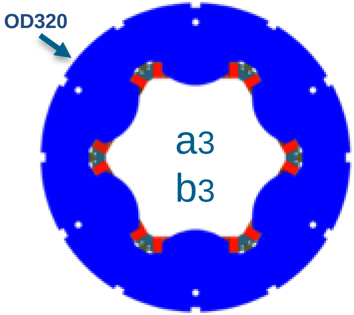
HO CORRECTOR MAGNETS ZOO



Tested 2019

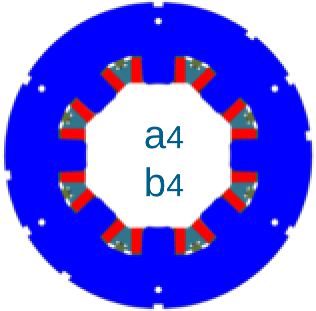
MCQSXFP1b

MCSXFP1



Tested 2016

MCOXFP1



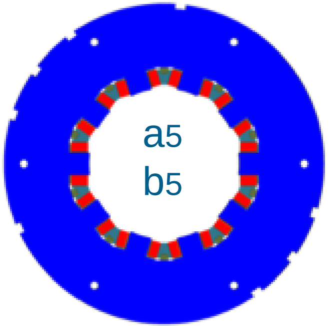
Tested 2017

Design
Construction & Test

- 5 protoptypes
- 54 series magnets

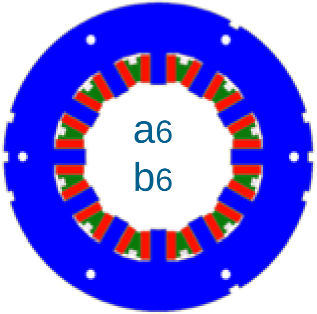
NbTi SuperFerric design
Geometrical lengths:
200 mm - 265 mm
12P, S4P: 540 mm – 580 mm

MCDXFP1



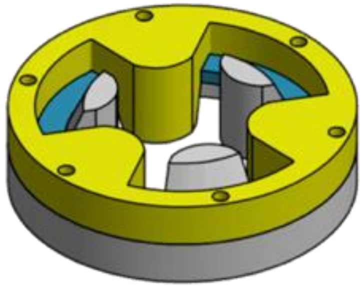
Tested 2018

MCTXFP1



Tested 2018

Round Coil Superconducting Magnet
MgB_2demonstrator



Tested 2019

SUPERFERRIC DESIGN

NbTi superconding coils

- Racetrack
- Insulation by S2 glass reinforced material

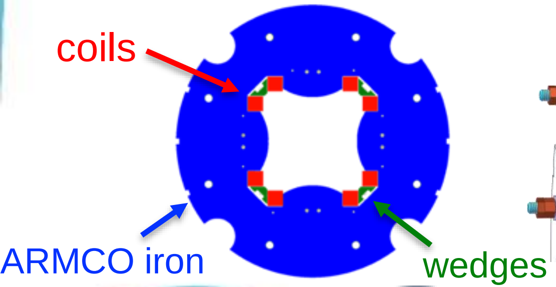
constraints

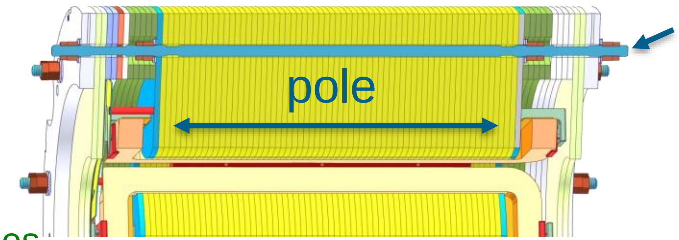
- Longitudinal dimension
- Quench protection
- Small dimension: 84kN series production (6 magnets)

Superferric design

- Compact and modular
- Strong contribution of the iron poles
- Field quality influenced by the shape of the poles

magnet	Ic @ 4.2 K	Margin @4.2 K	Margin @1.9K
4P S	315.5 A	42.3 %	57.1 %
6P	225.5 A	53.4 %	>60 %
8P	230.2 A	54.4 %	>60 %
10P	255.7 A	58.9 %	>60 %
12P N	232.6 A	54.9 %	>60 %
12P S	230.2 A	54.4 %	>60 %





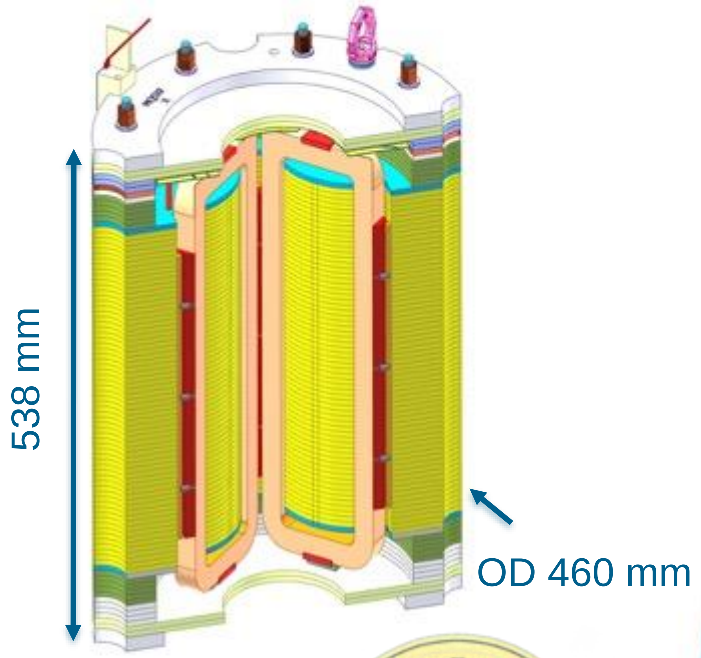
Quench protection

- No energy extraction (but 4P)
- 60% margin @ 1.9 K

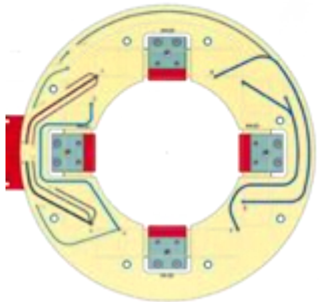
MCQSXFP1

length	538 mm
integrated field @ In @ r50 mm	0.700 Tm
magnetic length	401.1 mm
energy @Inom	30.8 kJ
harmonics	B6= -30 U at low current B6= 30 U at I_{op} B10= -8 U ÷ -12 U

- I_{nom}= 174 A I_u=197 A
- COILS
  - 754 windings
  - 815 m of Φ 0.7 mm NbTi

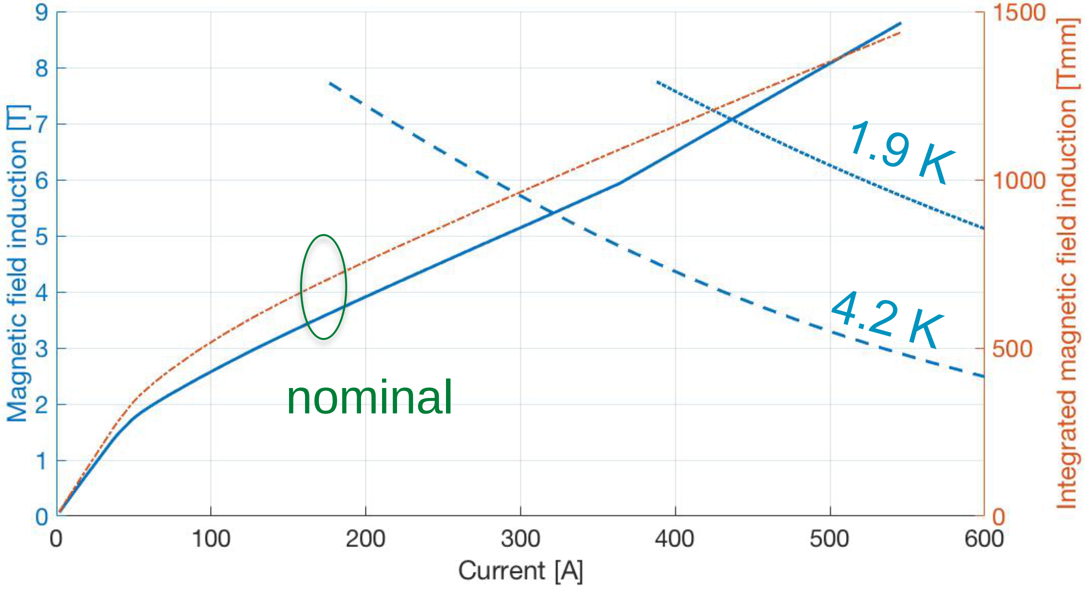


Connections on a PCB board (Arlon N85)
Double V taps

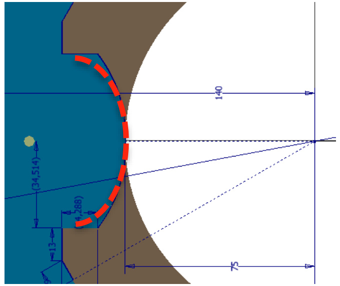


EM DESIGN

- nominal current 174 A
- field integral 0.7 Tm
- ultimate current 197 A



modifed ideal pole shape
(wire EDM laminations)

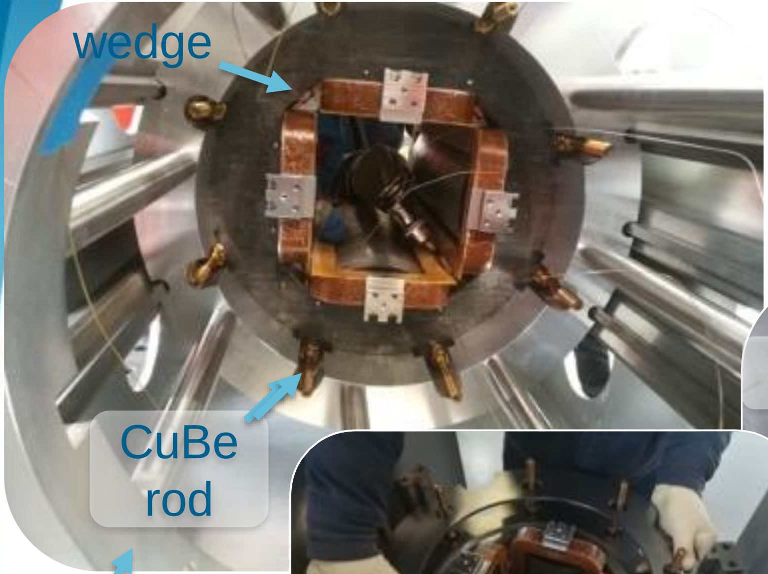


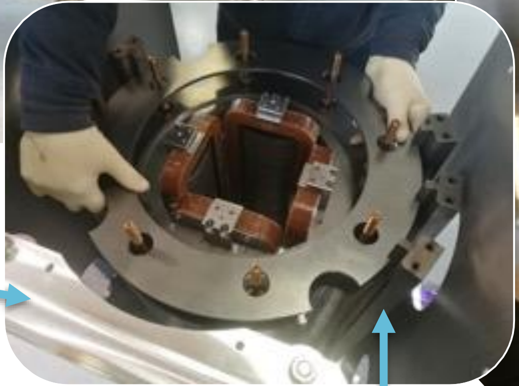
QUENCH protection
OPERA + QLASA
1.5 Ω dump resistor
ground in the middle
Max temperature 145 K
Max voltage 235 V

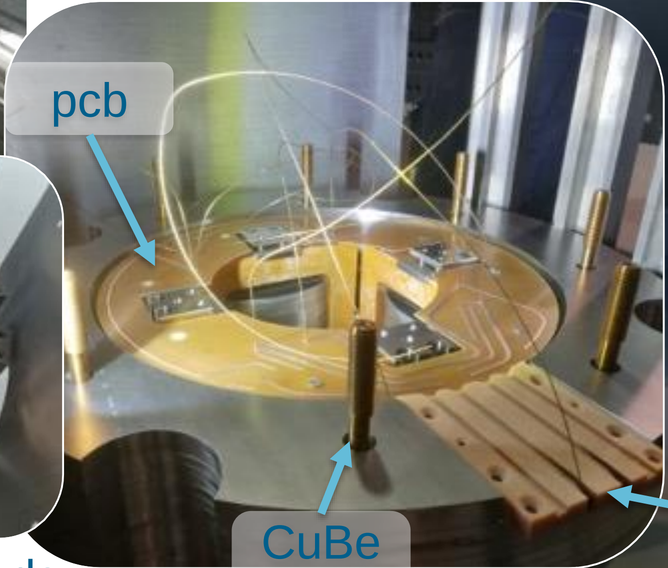
Assembly

Saes Rial Vacuum

Dec. 2018

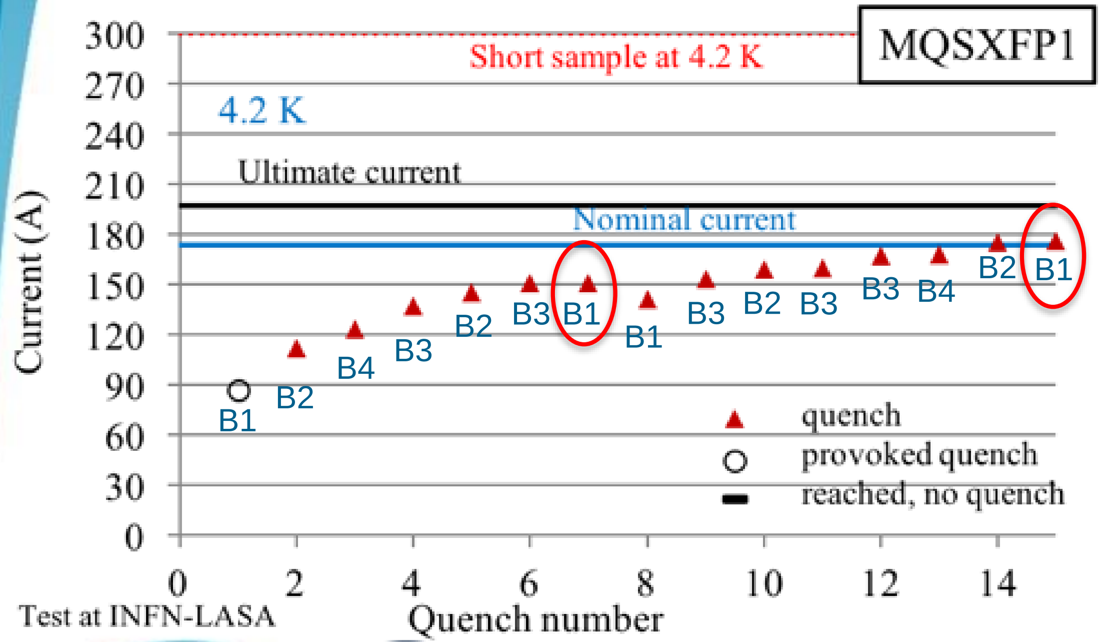




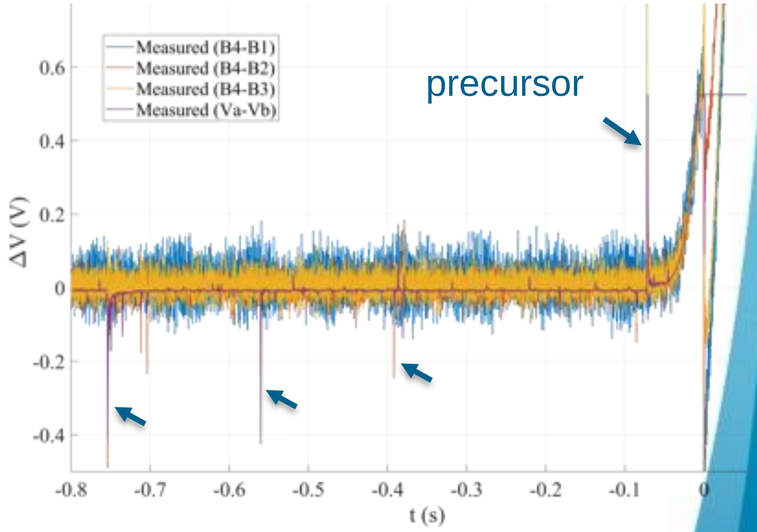


First Cooldown and Energization

- Controlled cool down: <100 K/m
- Training up to nominal



- Electrical problem

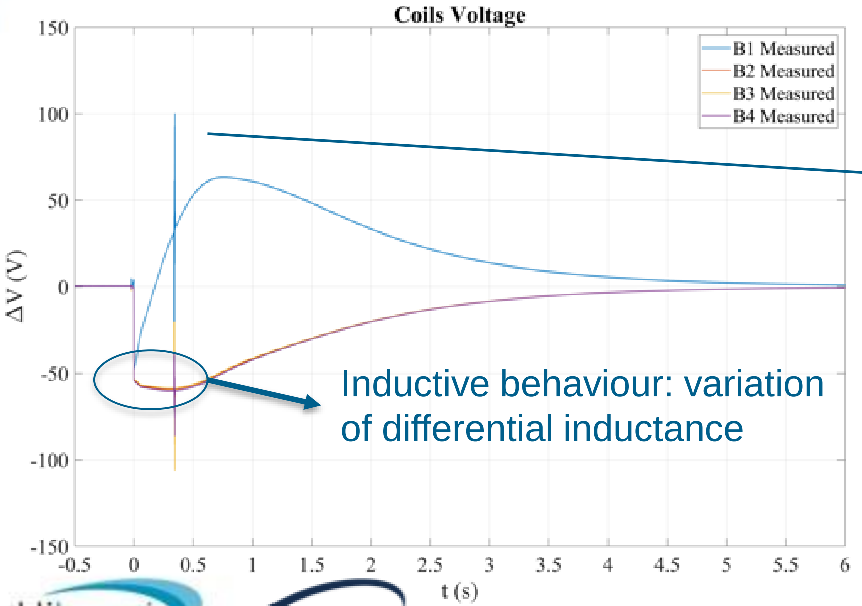


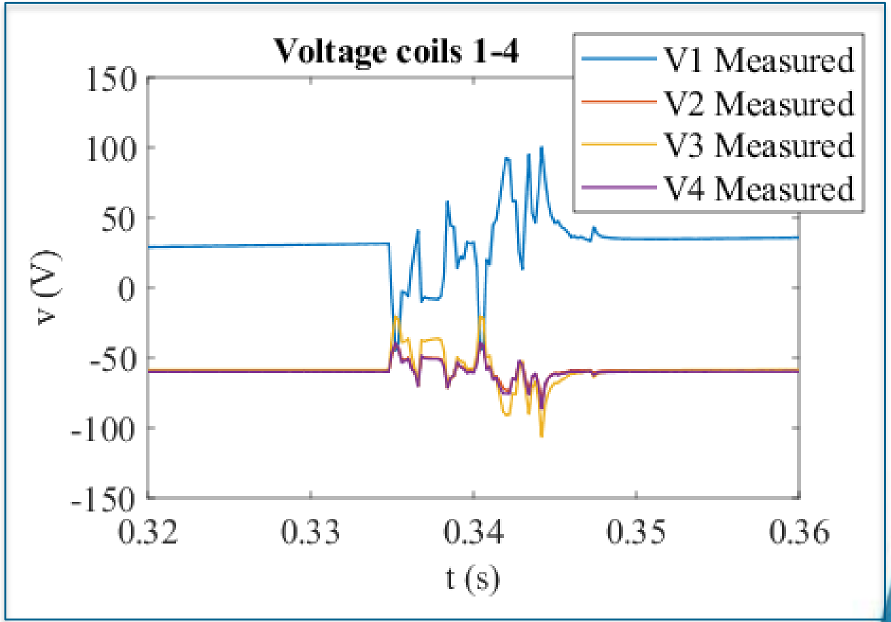
Event n.13 **B4**

- Precursor
- Recovered transitions in different coils

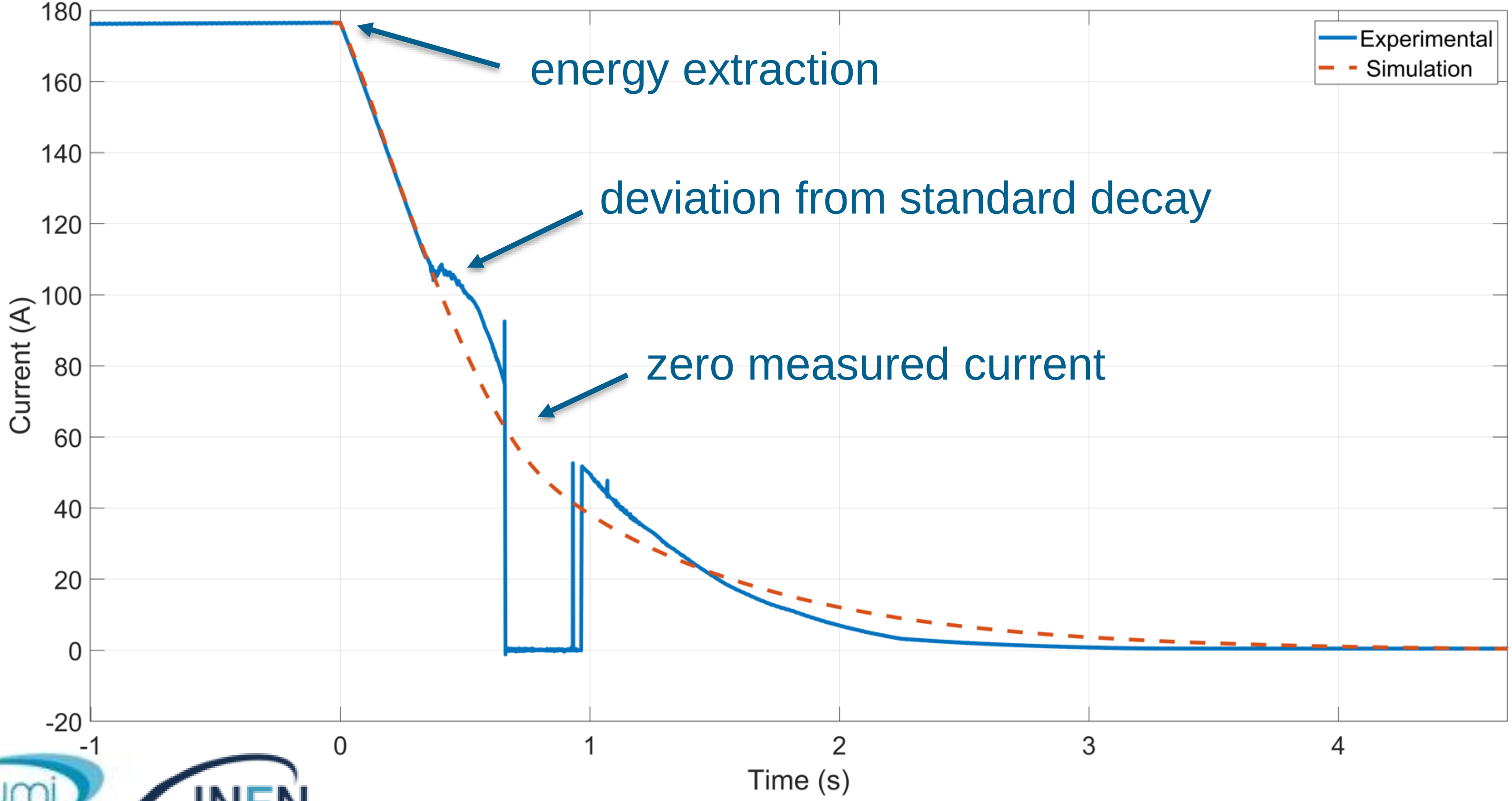
Event n.7

- Voltage instability during the discharge
- Tiny effect on current



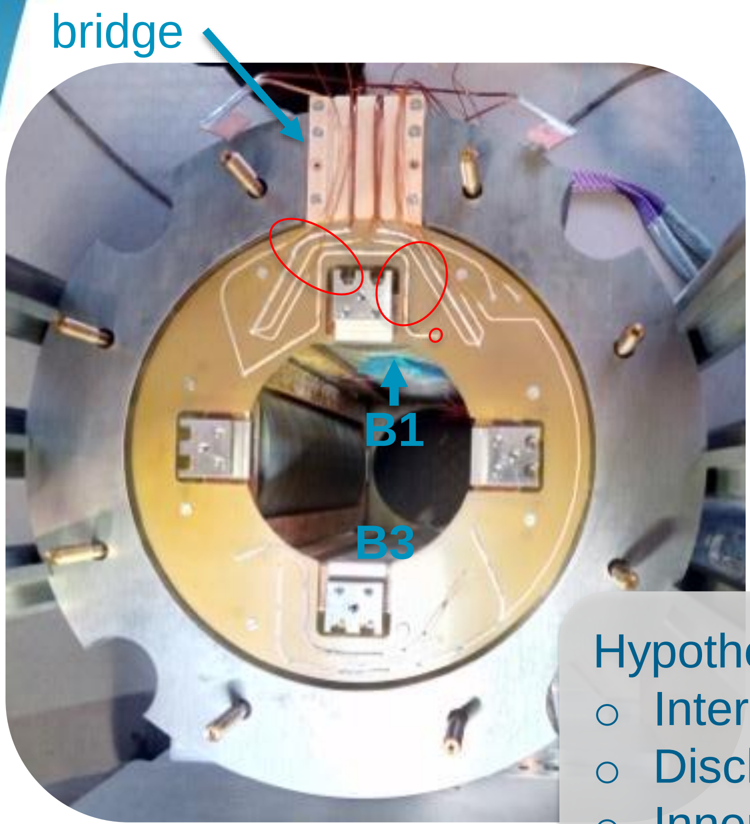


Event n.15



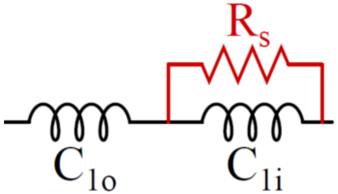
Current (A)
180
160
140
120
100
80
60
40
20
0
-20
-1
0
1
2
3
4
Time (s)
Experimental
Simulation
energy extraction
deviation from standard decay
zero measured current

Damaged Coil

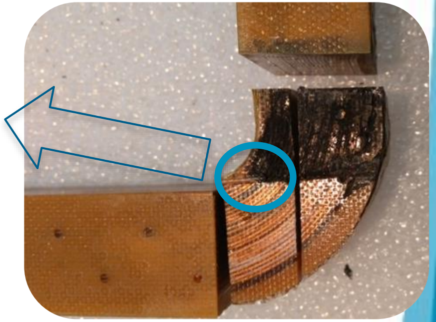


Hypothesis:
- Internal short originated in the quenched coil n.1
- Discharges between output wire and windings
- Inner layers not damaged

Numerical Model

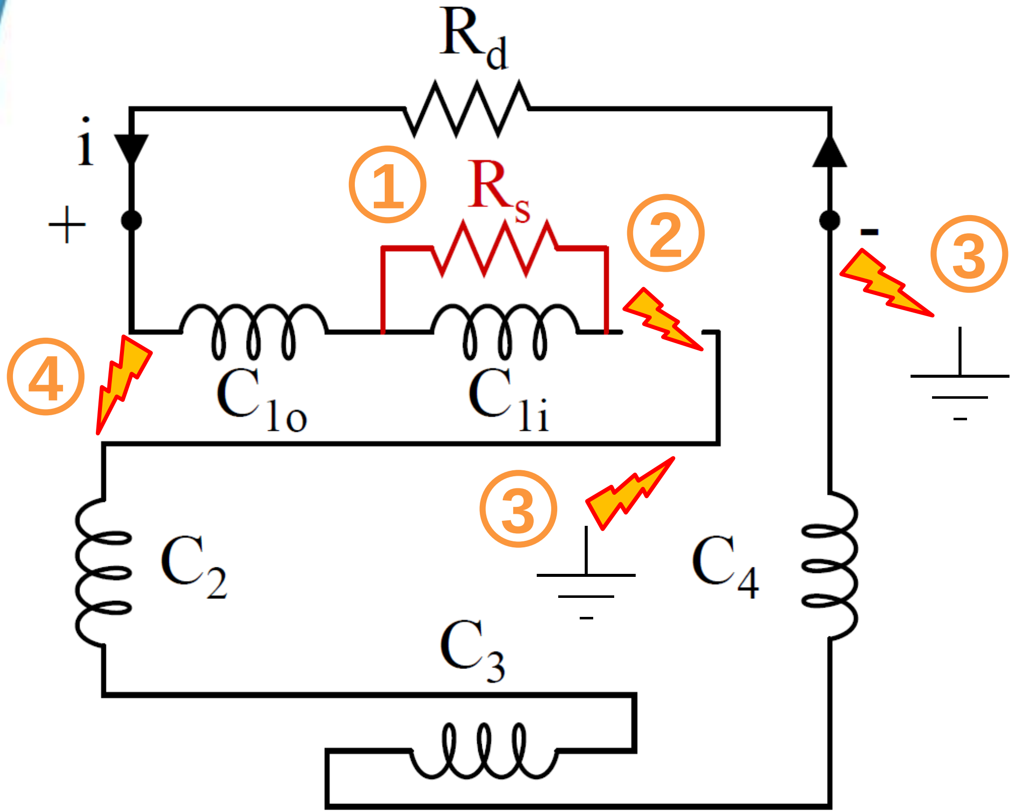


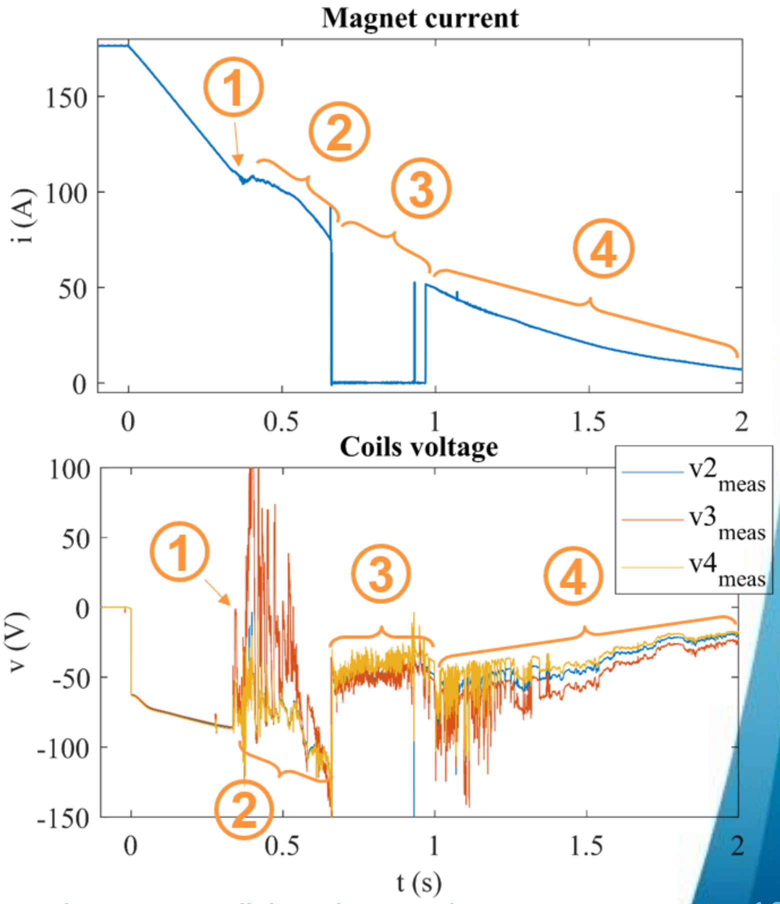
- Numerical model implemented in LTSpice, Netlist forma (M. Prioli)
- Coil 1 split into two parts:
  - Coil 1A**: 7 high-field layers** bypassed by a short-circuit
  - Coil 1B: 19 layers normally in series with the rest of the circuit



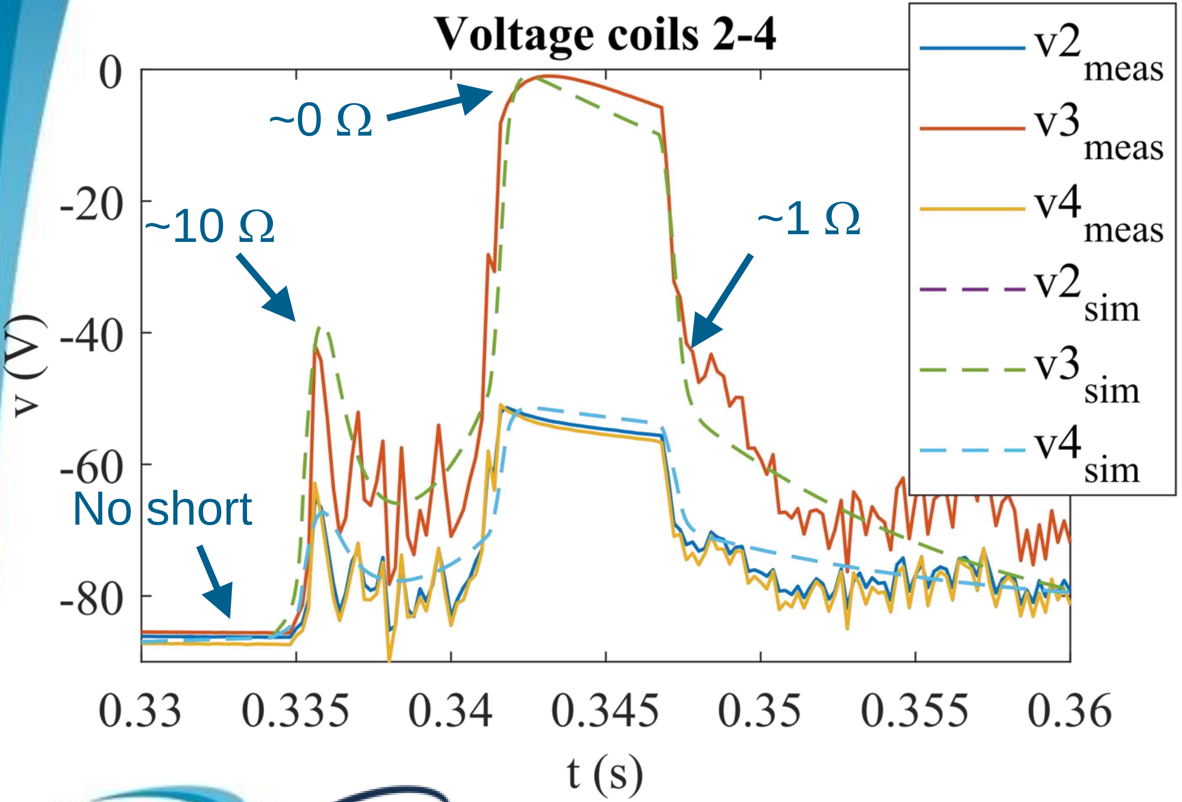
- Mutual inductance matrix (5 x 5) computed in Opera (S. Mariotto)
- Quench originated in the high-field zone (Coil 1A)
  - The resistance is not evenly distributed between coil 1A and coil 1B
  - Simulated distribution is 37% for coil 1A and 63% for coil 1B
- The **short resistance** is a variable
  - It is initially high (~10 Ω), then decreases due to a local welding (~0 Ω) then increases (~1 Ω)

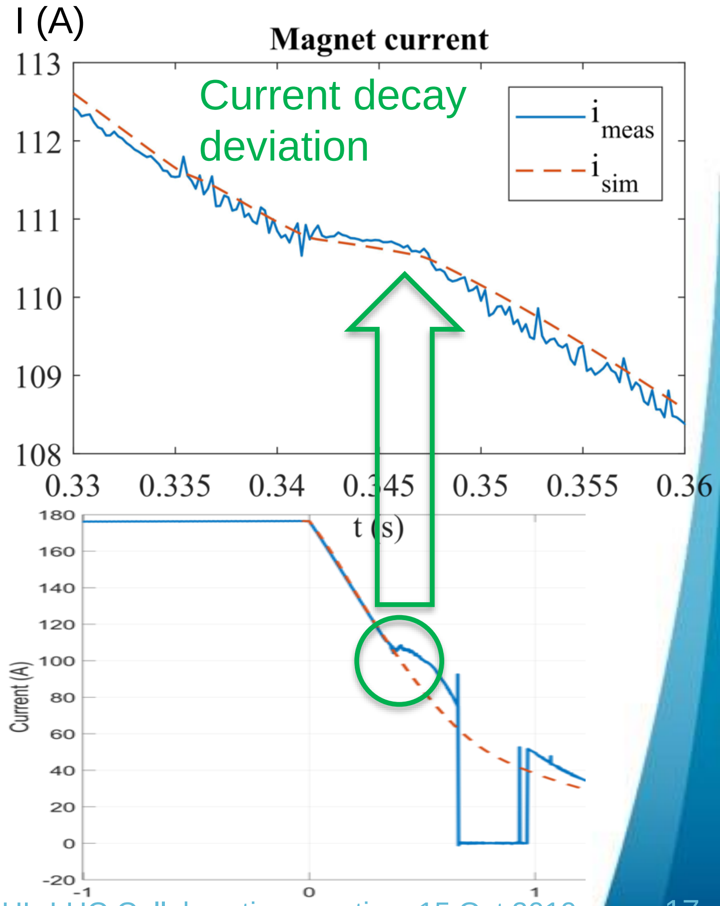
Secondary Faults



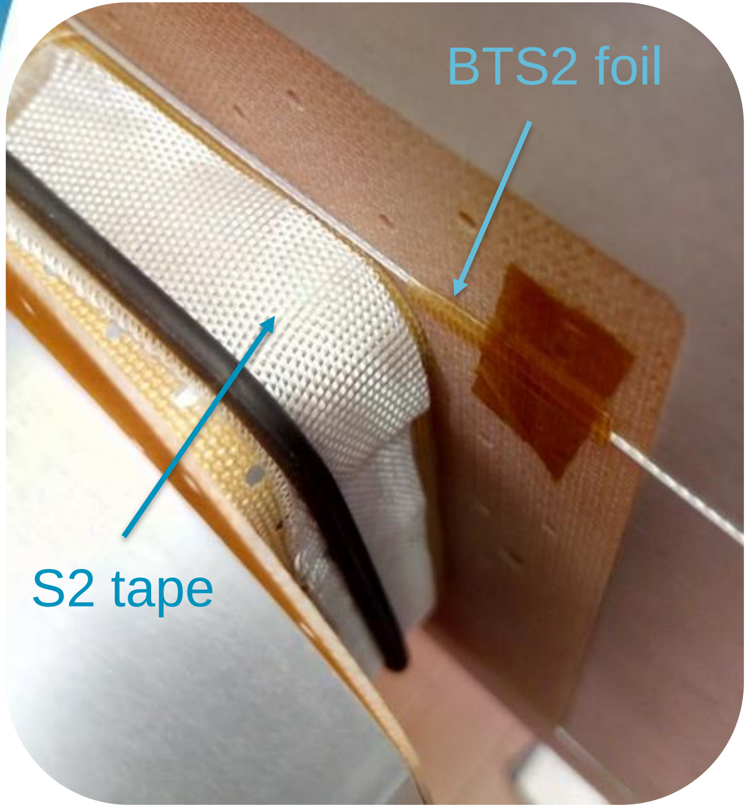


Numerical Model: Results

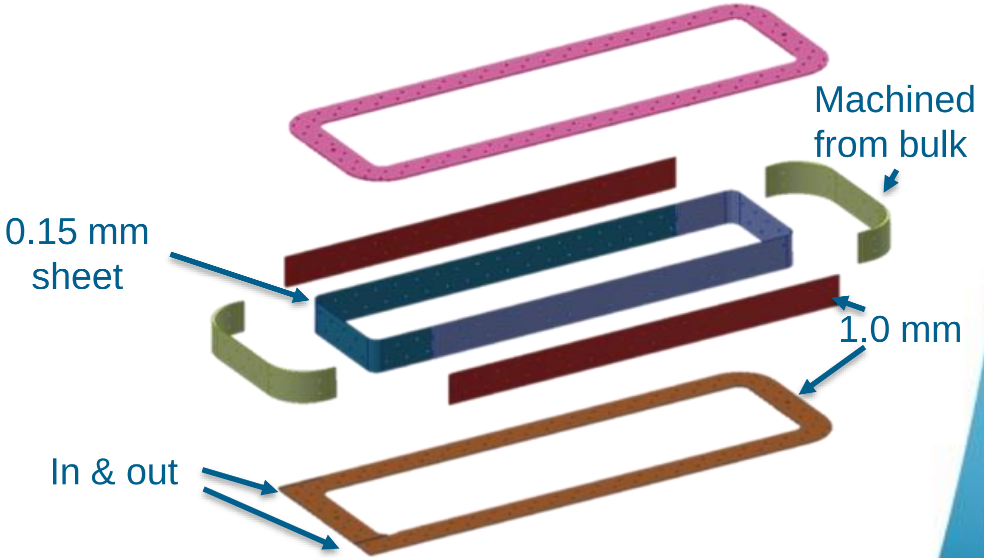




Two New Coils



- all coils compliant
- the 2 new coils installed



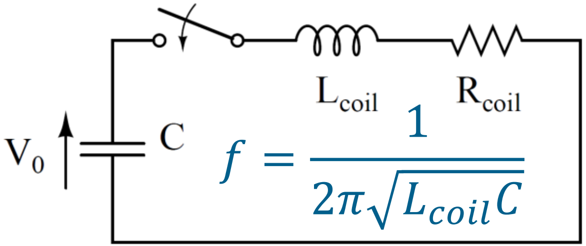
Quality Control Improvements

- The first test of MQSXFP1 proved that the QA procedures and the QC of the coils inter-turn and inter-layer insulation are fundamental in view of the series production
  - Insulation damages may be less severe than that in coil n. 1

- How to implement the early defect detection?
  - Ground insulation test
  - Resistance measurement
  - PJ method (capacitor discharge)
  - Ferromagnetic coupling

PJ Test

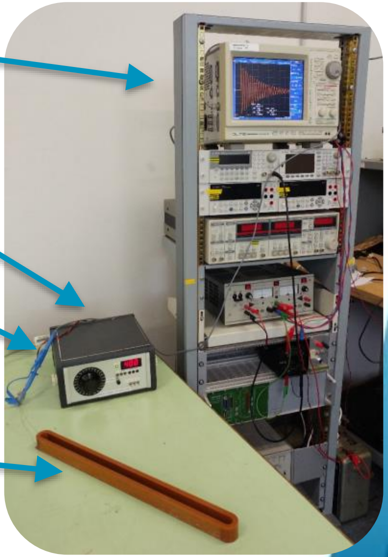
- Charged capacitor connected across the coil under test



$$f = \frac{1}{2\pi\sqrt{L_{coil}C}}$$

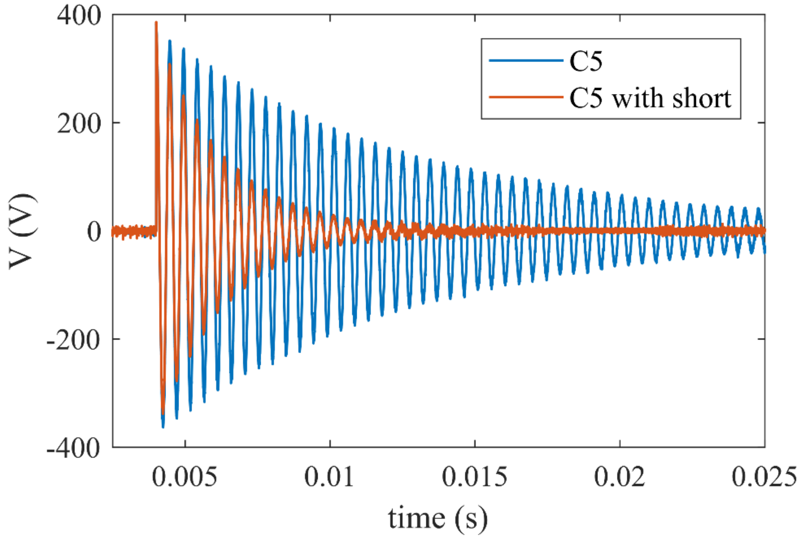
- Surge tester
- C=2 nF, V=5 kV

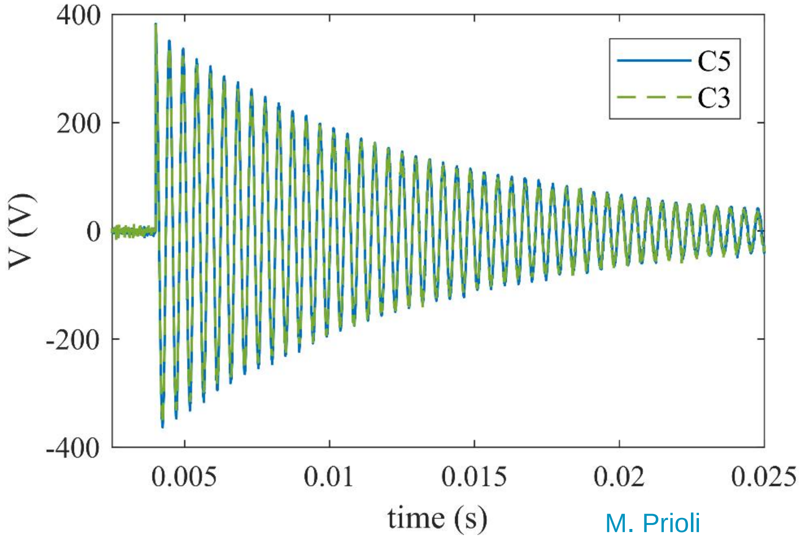
- Oscilloscope
- Capacitor bank (up to 400 V) and control unit
- High voltage probe
- Coil



PJ test results

- Following the analysis, C was set to 20 nF
- One turn in short was reproduced

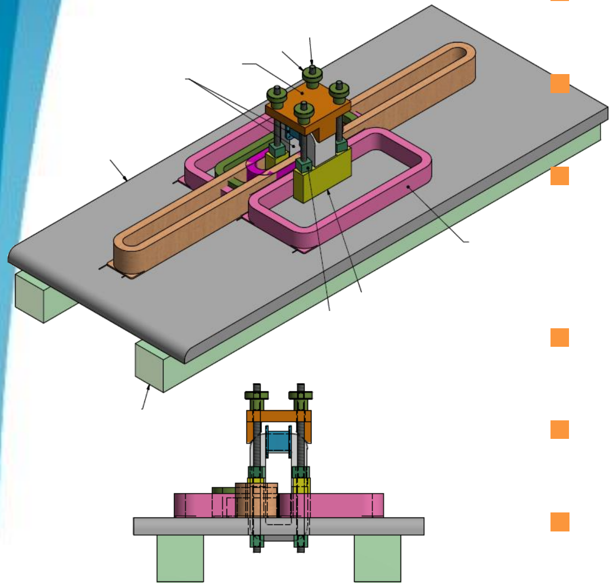




M. Prioli

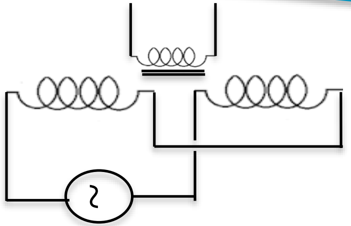
- The short can be easily discerned, measurement are repeatable

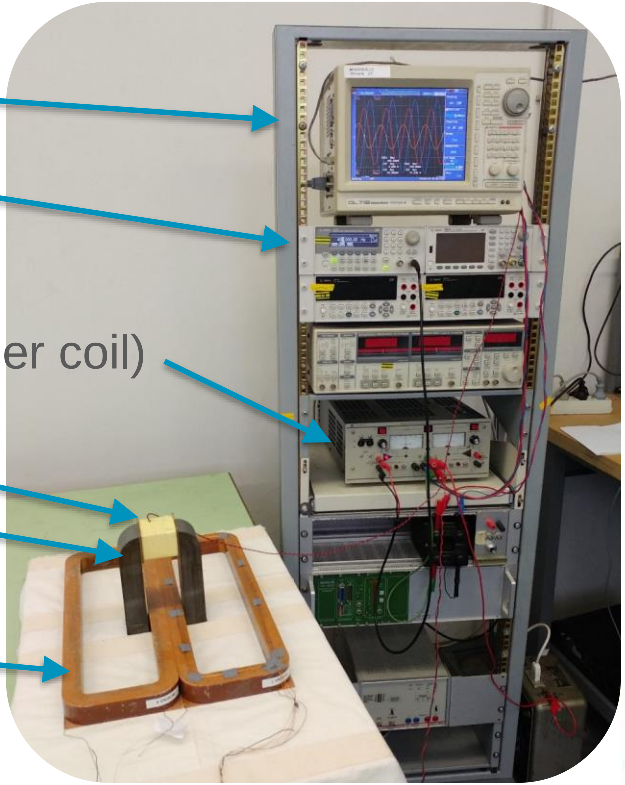
Ferromagnetic coupling - setup



M. Todero

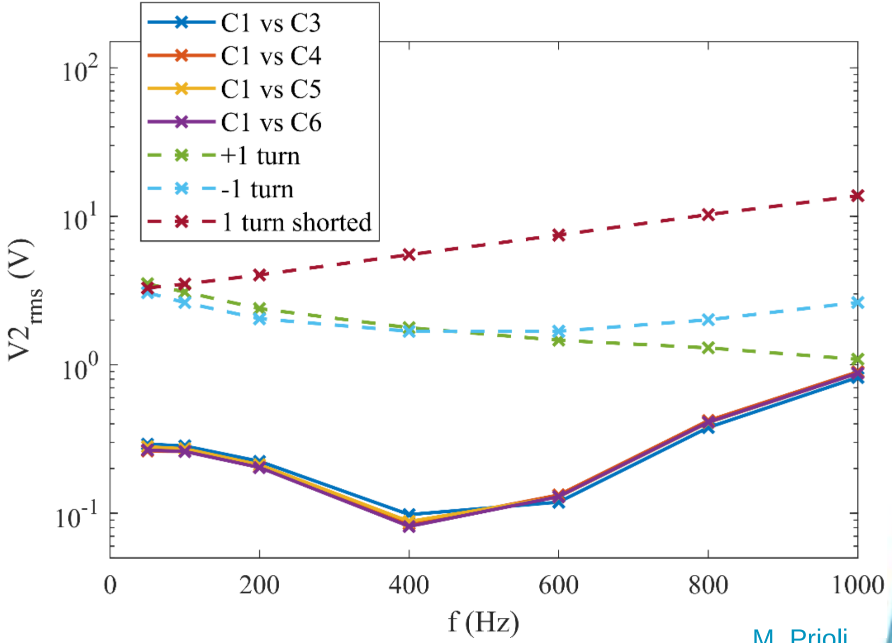
- Oscilloscope
- Signal generator
- 4 quadrants PC
  - Low AC voltage (36 V per coil)
- Pickup coil
- Ferromagnetic core
- 2 coils





Ferromagnetic Coupling - Measurements

- Optimal frequency 500 Hz
  - Allows also to distinguish the origin of unbalance (number of turns or short)



M. Prioli

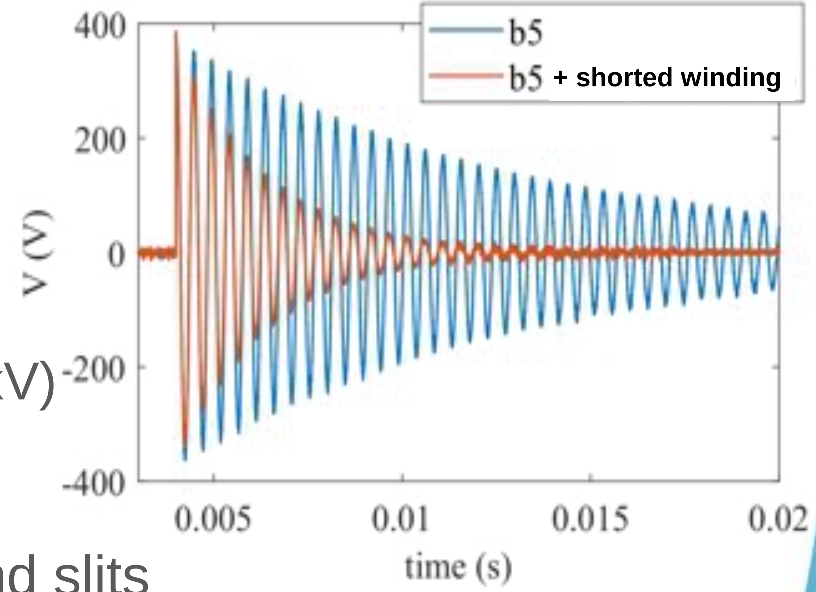
- Optimal frequency 500 Hz
  - Allows also to distinguish the origin of unbalance (number of turns or short)

Second Assembly Assessment

Coil

- Geometry
- HV ground insulation (2,5 kV)
- Wire-wire insulation (2kV), turns

All coils are compliant
(spare coils tested up to 7 kV)

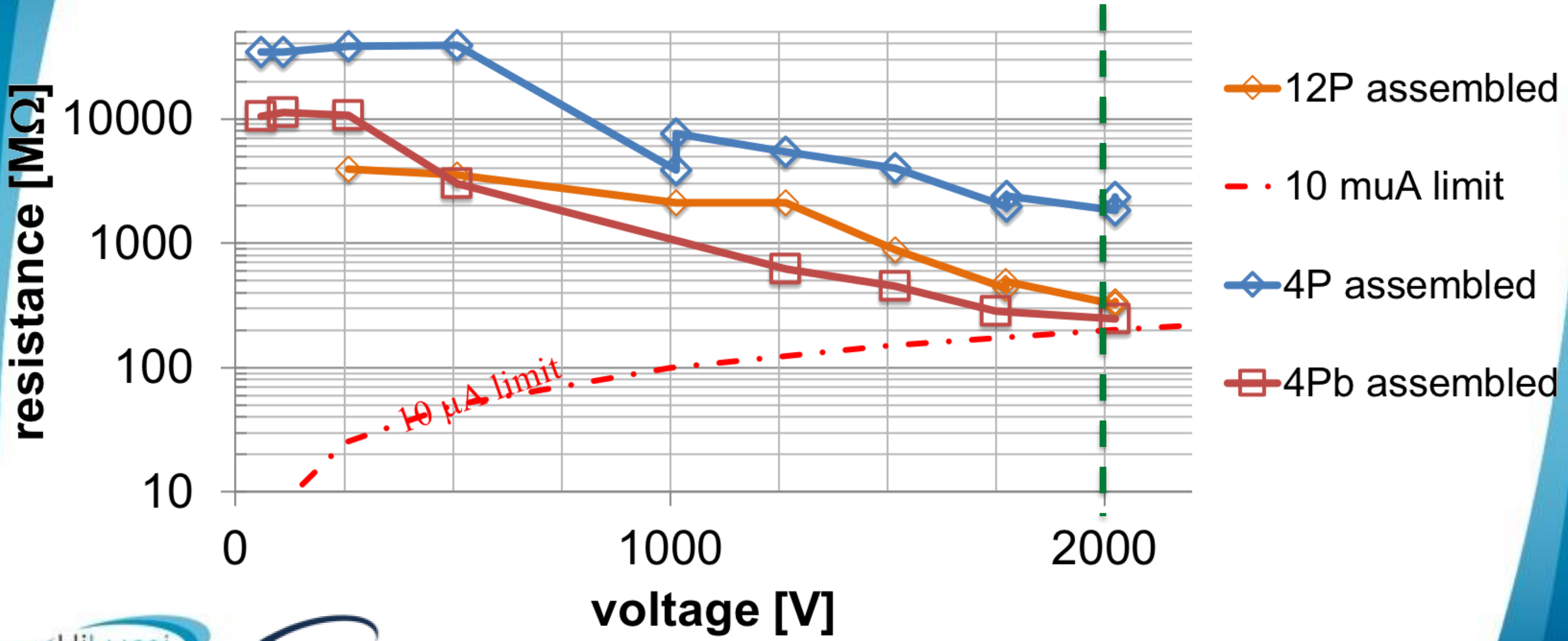


Magnet

- Laminations' profiles and slits
- Alignment of the assembly
- HV ground insulation of the magnet (up to 2 KV)

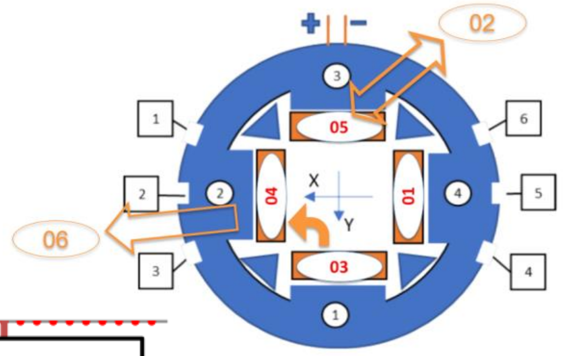
procedures validated
- second assembly
- coil replacement

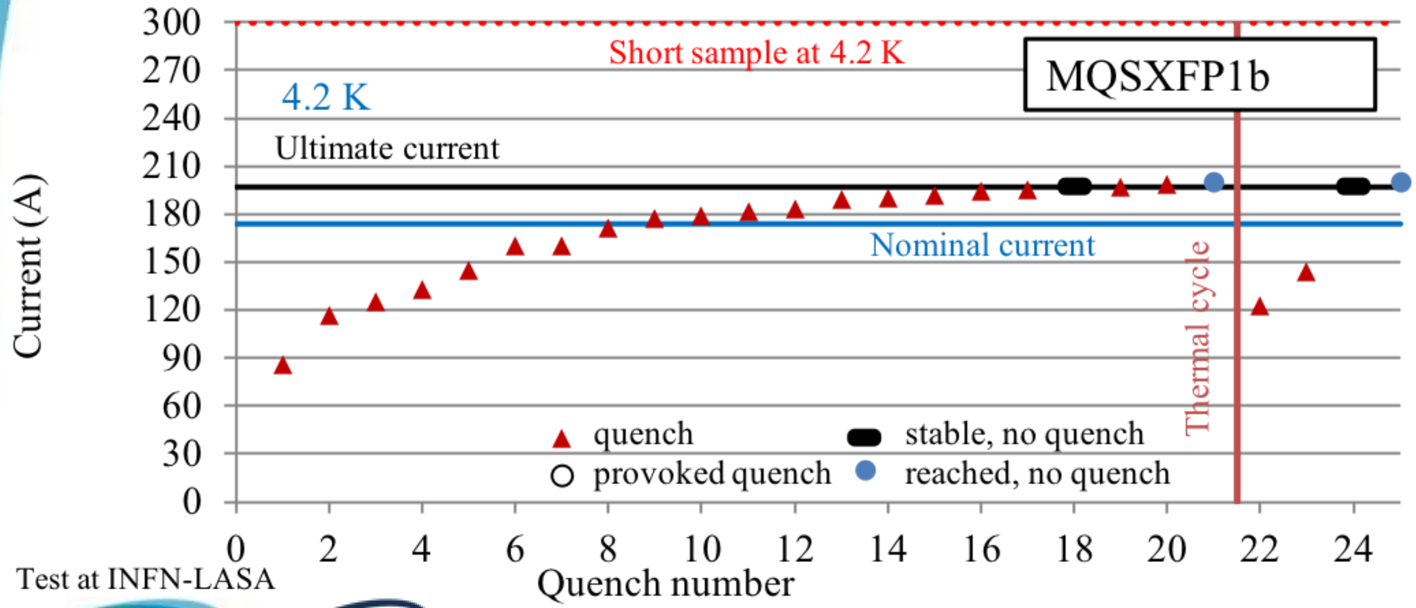
Magnet Ground Insulation



Power Test

- Most quenches in new coils
- Good stability after reaching 200 A (> I_{ult} 197 A)
- Stable 1 h @ ultimate after thermal cycle



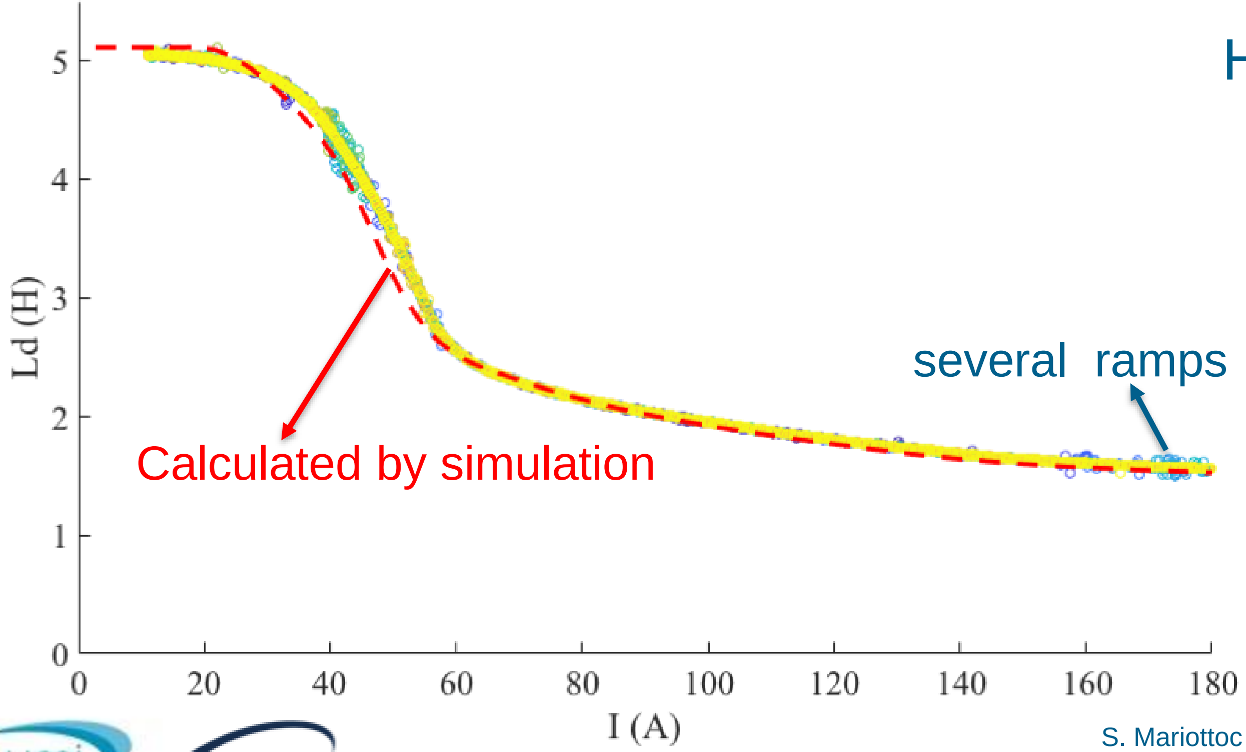


Test at INFN-LASA

B1	B1
B3	B3
B5	B3
B3	B1
B1	B4
B3	B3
B1	B3
B3	B3
B4	B4
B1	**B3**
	B3

Dinamic Inductance

Measured during current ramps



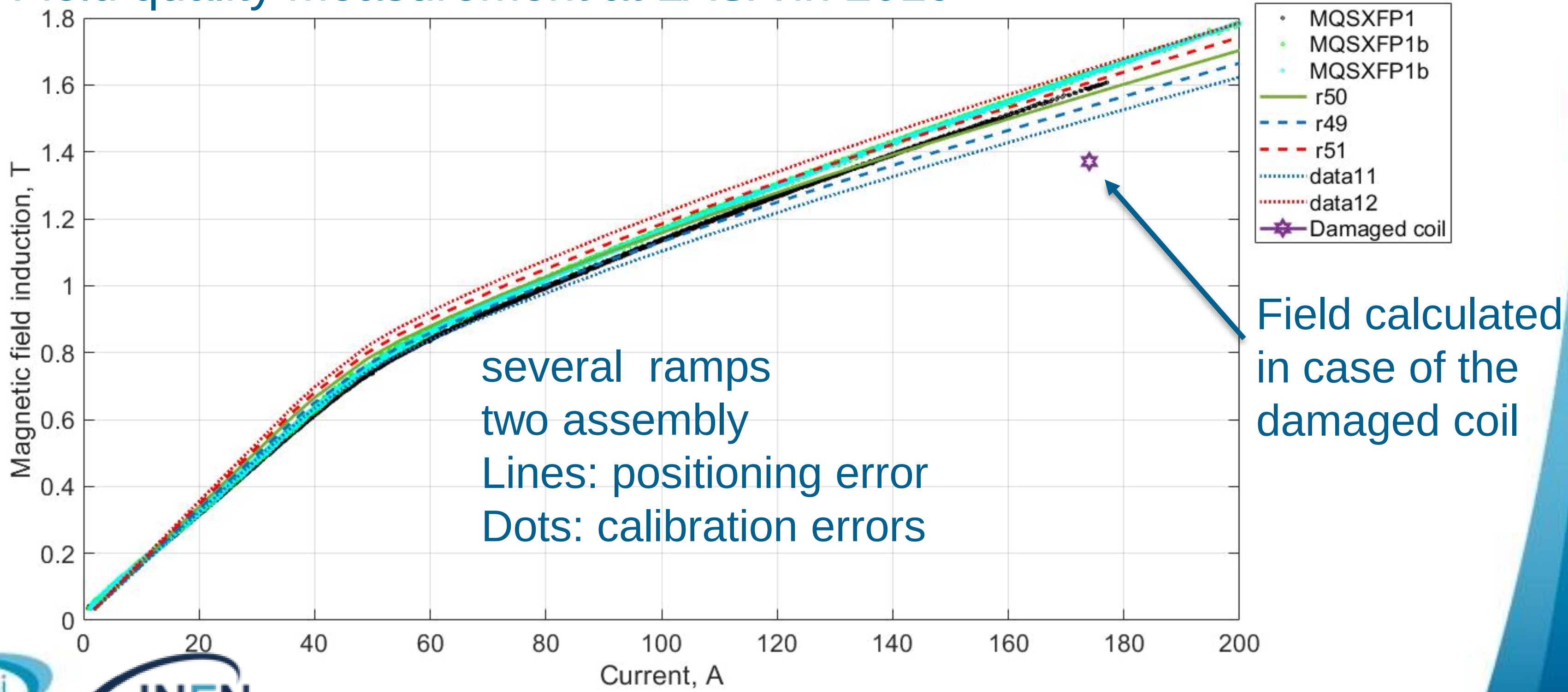
S. Mariottoc

High reproducibility

Good agreement with simulations

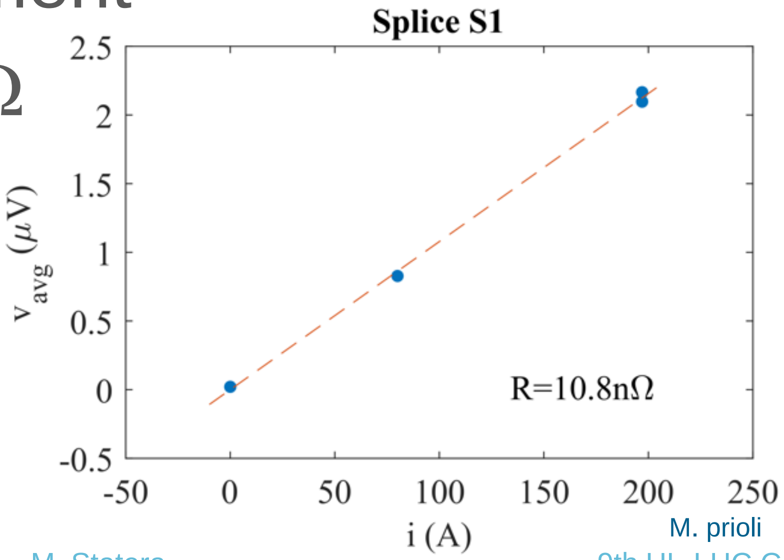
Single Point Field Measurement

- Low accuracy positioning
- Field quality measurement at LASA in 2019

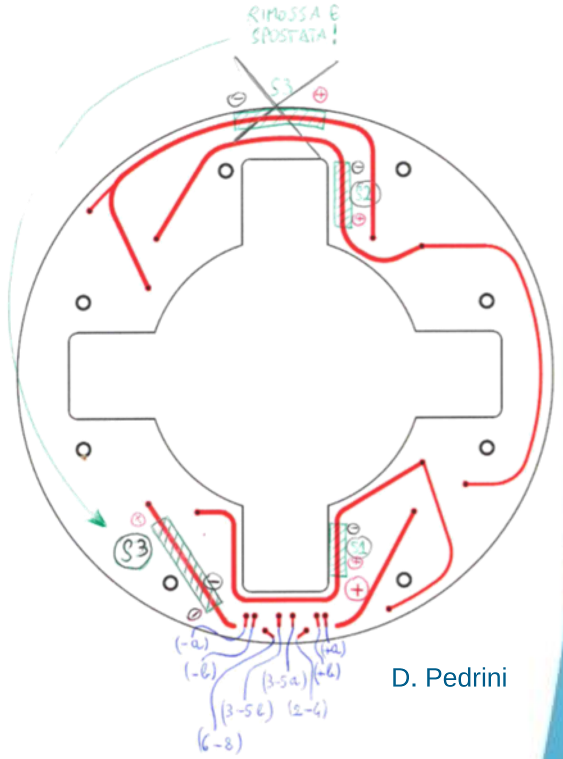


Splice Resistance

- Splice resistance measurement
- dedicated channels in DAQ
- 3 measurement
- about 10 nΩ



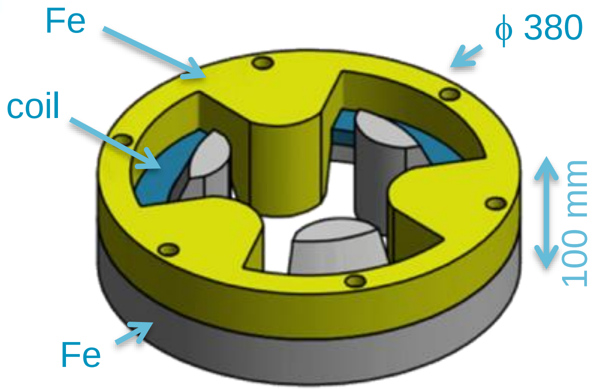
M. prioli



D. Pedrini

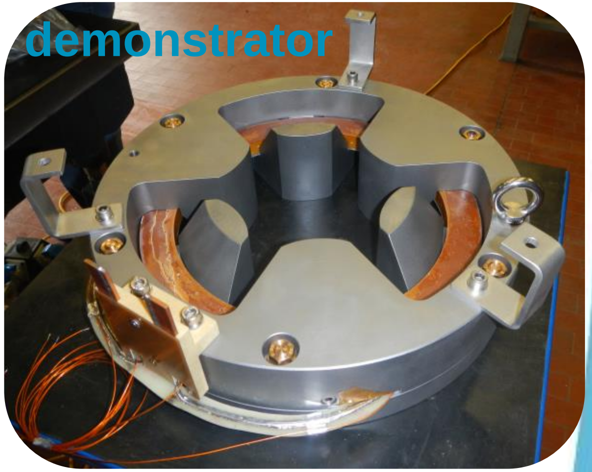
Round Coil Superconducting Magnet

demonstrator

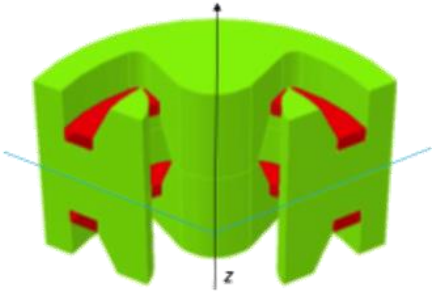


G. Volpini et al. Eletromagnetic Study of a Round Coil Superferric Magnet,IEEE Tr. App. Sup, 26, 4 (2016)

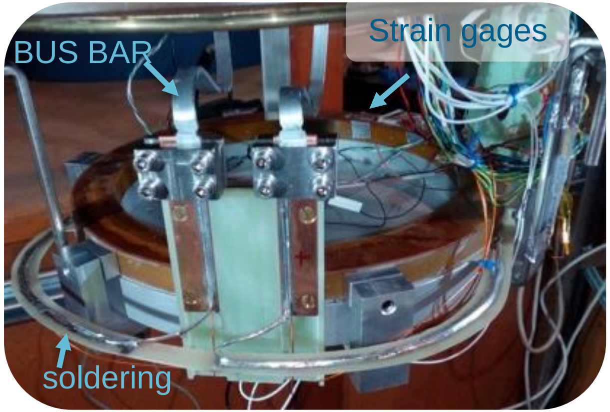
- Multipolar MgB_2 magnet
- Inner bore ϕ 150 mm
- Single MgB_2 coil
  - Diameter > 200 mm
  - Wire diameter 1 mm
  - T_c 39 K



single module



single coil



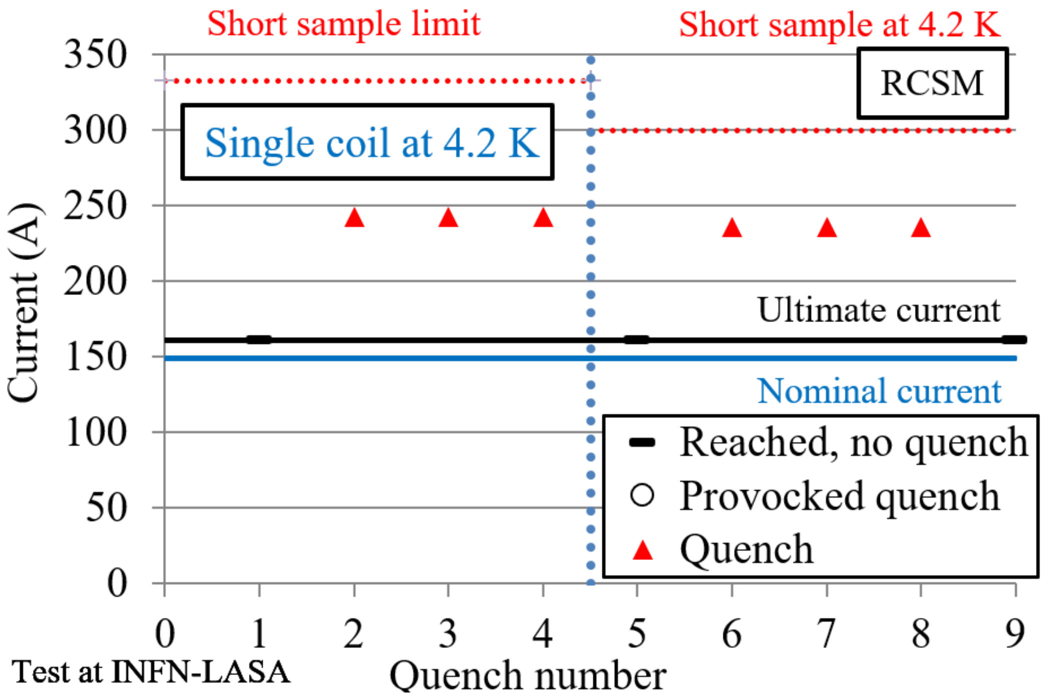
No quench training

The Coil is stable at the Ultimate Current (108% I_{op})

Maximum value of the current reached: >75% of the Short Sample Limit

Single coil and RCSM test results

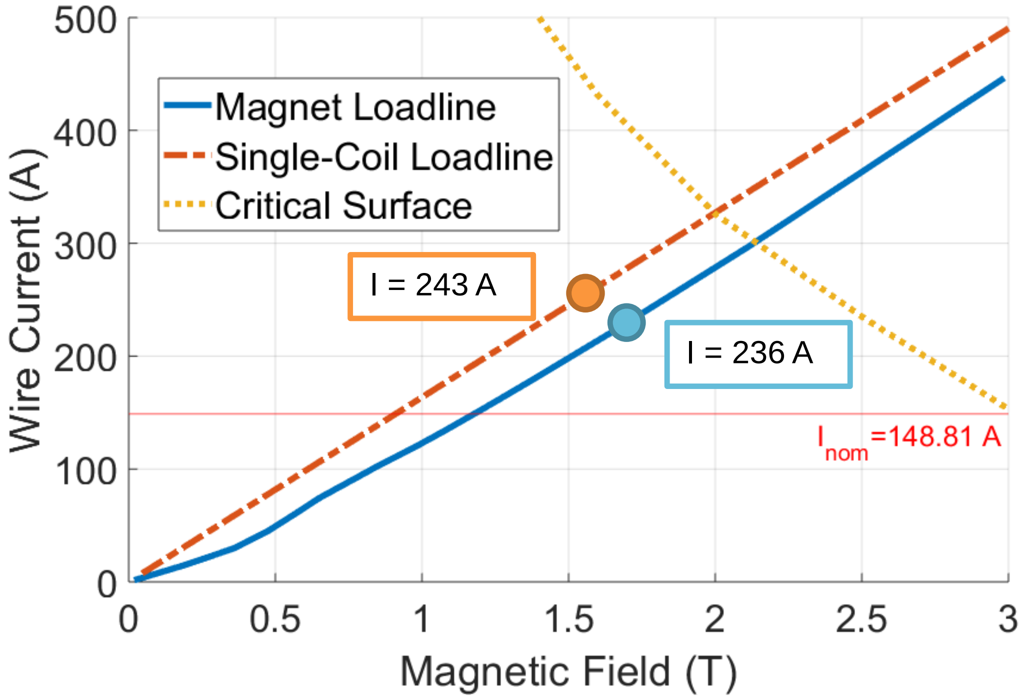
- **Ultimate current reached** without any training
- **1 h stability** test succesfully passed
- 3 different spontaneous quenches occurred at:
  - **243 A**, single coil
  - **236 A**, RCSM



Load line comparison

- Single coil: **73%** of load line
- RCSM: **78%** of load line

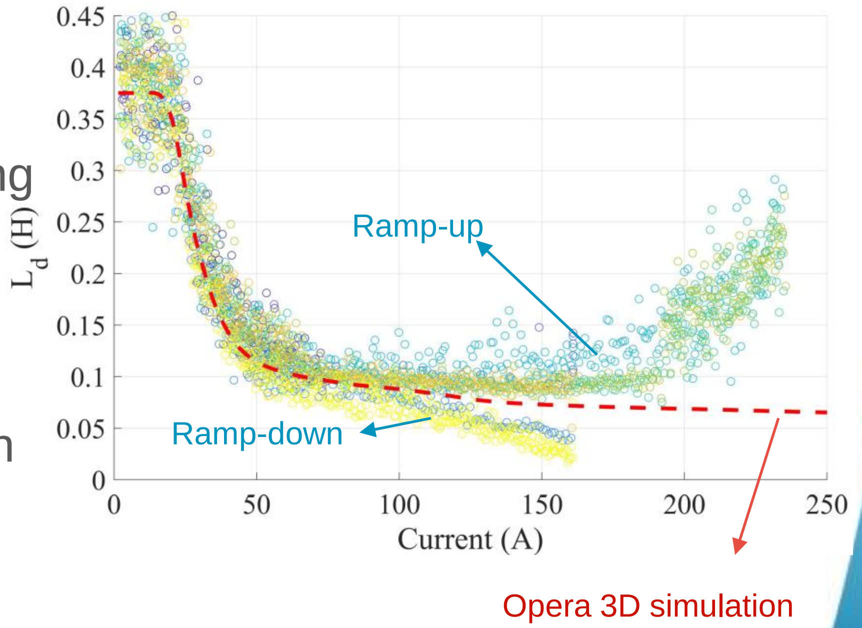
Compatible with wire degradation of 21.4% in the coil ends, during winding procedure



Differential inductance in RCSM

- **Eddy currents in superconductor**: excluded because the inductance increasing occurs at high current
- **Eddy currents on non-laminated ARMCO iron**: excluded because the same phenomenon can be seen during the single coil test and is exluded by OPERA simulation
- **Resistive region growing** (current sharing regime): escluded in the coil ends by measurement, not excluded in the winding
- Heat dissipation in **current leads** (?)

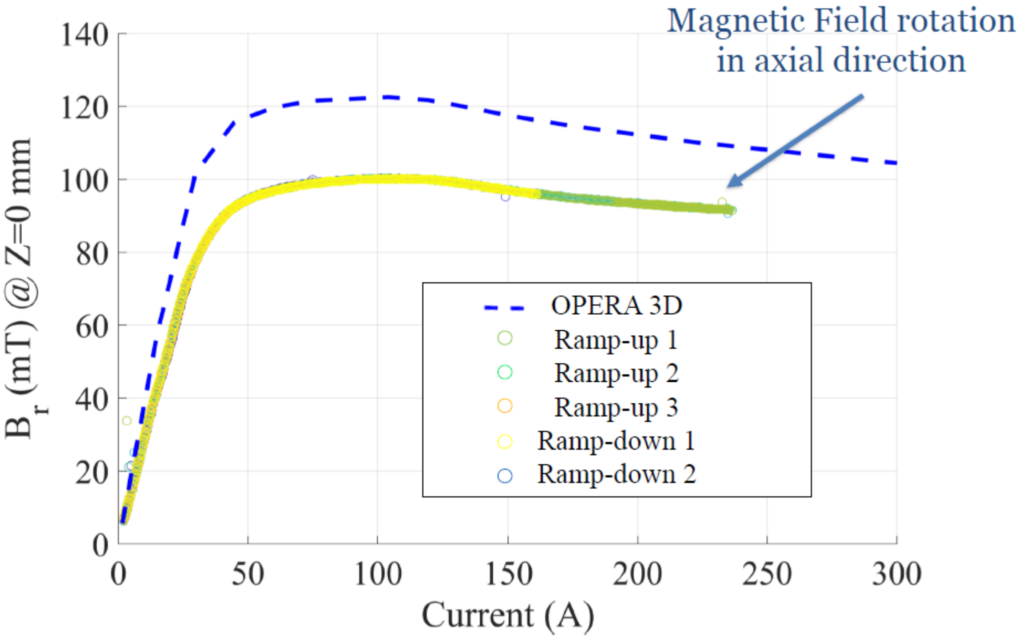
Differential inductance



Magnetic field

Hall probe signal taken from different current ramp-up and ramp-down

- **high repetibility** of the magnet with no degradation at high current level
- **Difference of about 20%** between the magnetic field measured and simulated:
  1. Presence of the air gap & holes: excluded by OPERA 3D simulation
  2. Hall probe calibration: ongoing test
  3. Hall probe positioning: excluded by OPERA 3D simulation
  4. B-H curve: exluded



SERIES PRODUCTION

- 17/9/2018 call for tender
- 15/1/2019 evaluation of quotations
- 28/2/2019 contract awarded by Giunta Esecutiva to Saes Rial Vacuum (SRV)
- 17/6/2019 contract signed
- 24/6/2019 kick off meeting
- 1/10/2019 production started (machining)

SHEDULE

In May 2018 an "Engineering Change Request" has been requested by CERN, to increase magnetic (and geometric) length of 3 magnets and decrease the 4-pole skew

In Feb 2019 an electrical problem with the skew quadrupole

Milestones:

M1.1	Engineering Design of the series completed	July 2018	
M1.2	First coil wound	May 2019	**Nov 2020**
M1.3	First batch delivered to INFN-LASA for test (2 magnets per type)	November 2019	**Jul 2020** (1a Mar 2020)
M1.4	Second batch delivered to INFN-LASA for test (2 magnets per type)	July 2020	**Dec 2020**
M1.5	Third batch delivered to INFN-LASA for test (2 magnets per type)	March 2021	**Jun 2021**

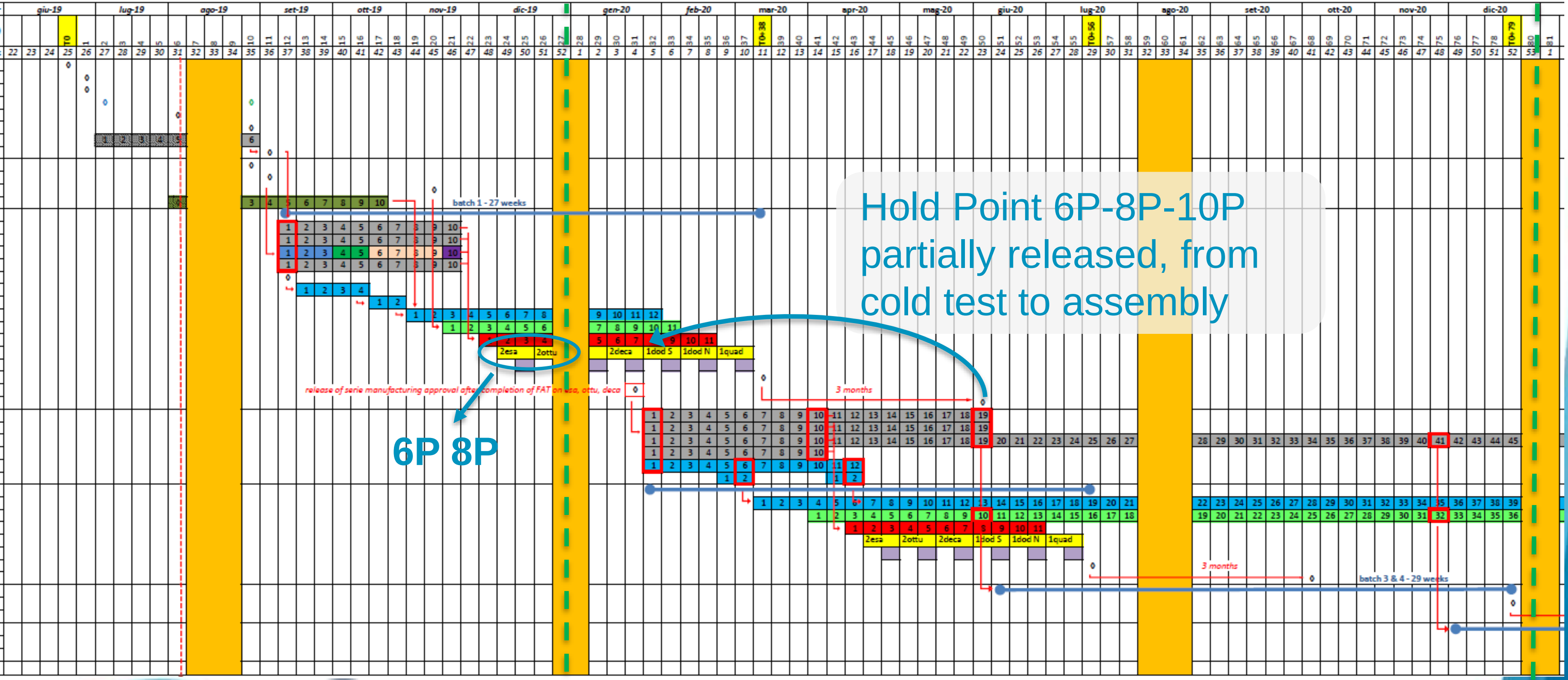
Deliverables:

D1.1	Award for the contract of the series construction	January 2019	Feb 2019 signed Jun 2019
D1.2	First tested batch delivered to CERN (2 magnets per type)	March 2020	**Oct 2020** (1a Jun 2020)
D1.3	Second tested batch delivered to CERN (2 magnets per type)	November 2020	**Mar 2021**
D1.4	Third tested batch delivered to CERN (2 magnets per type)	June 2021	**Sep 2021**

Schedule 2

- Engineering done
- Procurement: S2 insulated NbTi wire not delivered (Aug 2019)
- Machining started
- Winding and assembly not affected

Schedule 3



Hold Point 6P-8P-10P partially released, from cold test to assembly

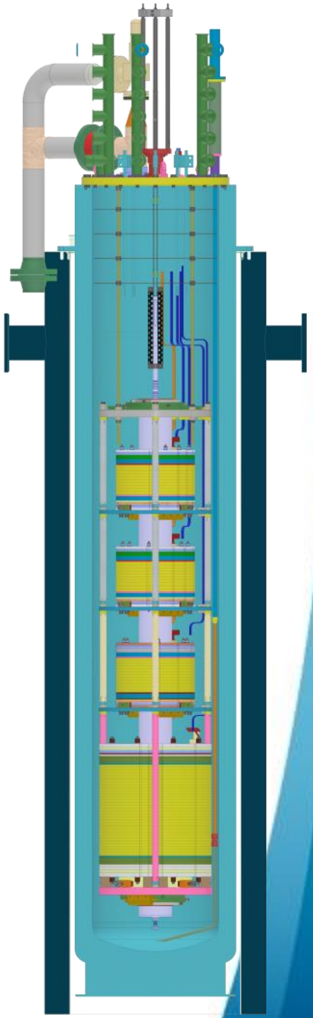
6P 8P

2019 2020 2020

FIELD MEASUREMENTS AT LASA

- measure field quality of MQSXFP1b at LASA Nov-Dec 2019
  - New frame supporting the magnets **done**
  - Install field probe (not the final one) **done**
  - Cabling for series tests **ongoing**
  - Install skew quadrupole
- Finalize the field probe for the series **ongoing** (L. Fiscarelli, S. Mariotto)
- Assembly of a new power converter 600 A
  - Dump resistance
  - IGBT polarity switch

ongoing



CONCLUSIONS

- High Order Correctors prototypes tested
  - 5 superferic and 1 Round Coil Superconducting Magnet
  - Tested second assembly procedure
  - Updated QC for early defect detection
- High Order Correctors series production started
  - Engineering done, procurement ongoing, machining started
- Delay of about 6 months with respect original plans -> scheduled 3 month at last delivery
  - First series magnet in 2019
- Field measurements at LASA in preparation
  - First measurement in 2019
  - Cabling for series magnets

INFN
LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

THANK YOU

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CERN

HiLumi HL-LHC PROJECT INFN

SPARES