
# High Order Correctors end of production

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Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

13th HL-LHC Collaboration meeting
***Vancouver – Sep 26h 2023***

# OUTLINE

- Scope: the High Order Correctors magnets
- Design and production
- Selected results
- Lessons learned by series production
- Conclusions

# SCOPE - High Order Correctors

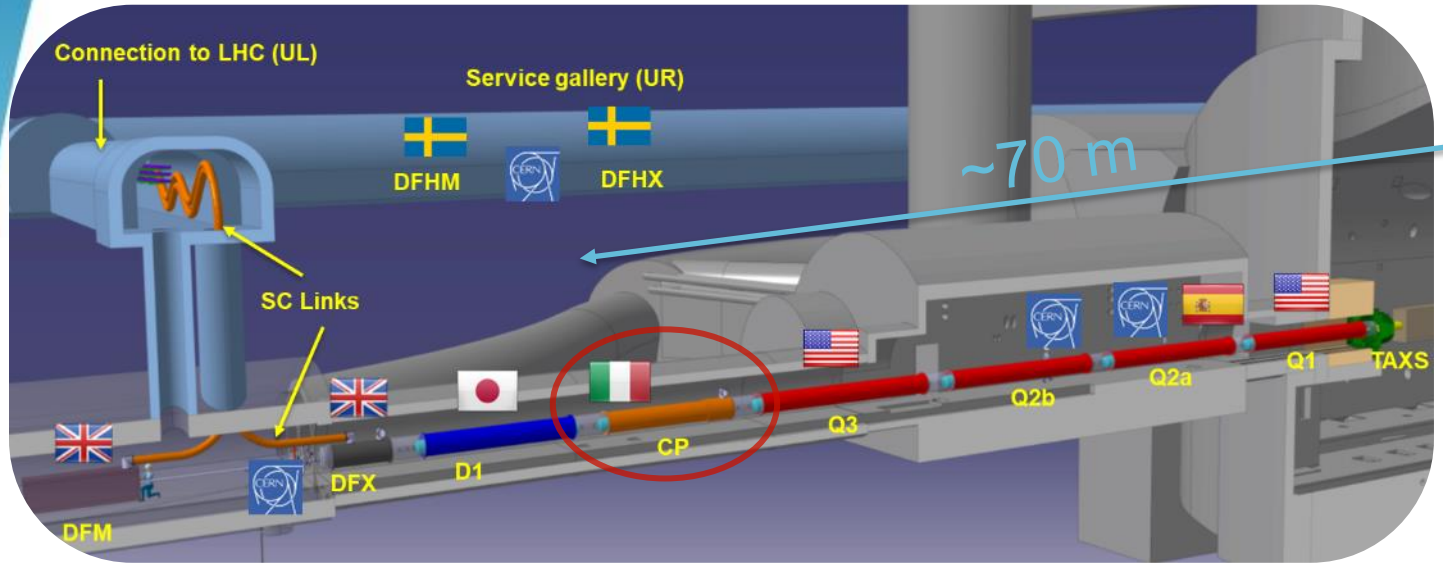
The High Order Corrector magnets mitigate the impact of the field errors of the focusing quadrupoles in the focusing sections of HL-LHC

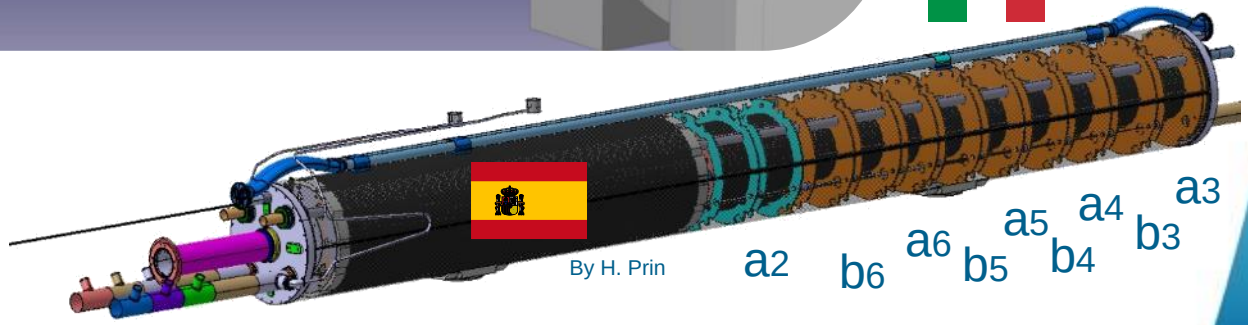
- The INFN-LASA follows the design, construction and test of the 5 prototypes of the High Order corrector magnets for the HL interaction regions of HL-LHC. **KE2291**
- The INFN-LASA will follow the series production of the 54 HO corrector magnets for the HL interaction regions of HL-LHC. **KE3085**

INFN delivers the magnets, the vertical test of all magnets, and collaborates to the integration in the cold mass by CERN

- INFN will follow up the installation, commissioning and deployment. **KE5175**

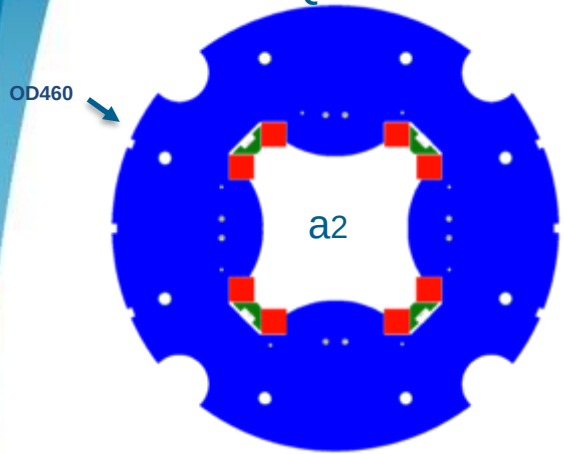
# THE LOW BETA SECTION and the High Order Correctors



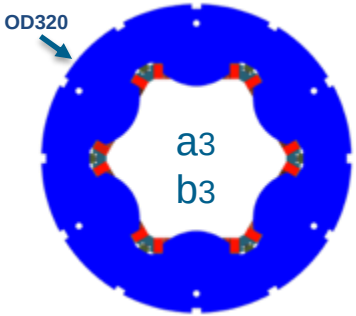



# HO Corrector Magnets Zoo

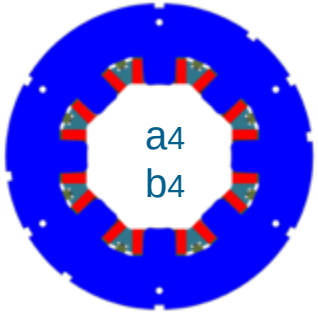
MQSXF




MCSXF




MCOXF

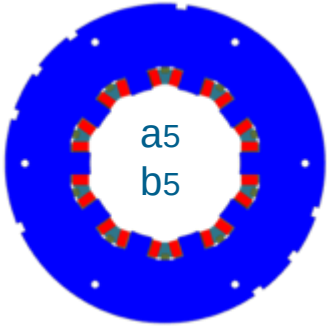



Design
Construction & Test

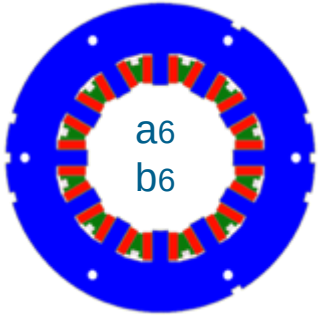
- 5 prototoypes
- 54 series magnets

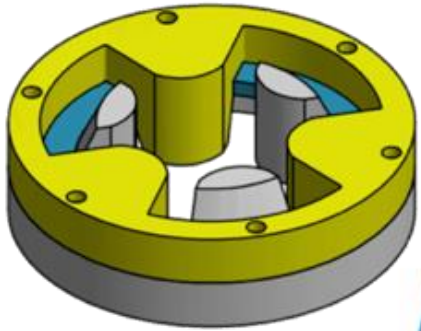
6P 8P 10P +50% Bdl

MCDXF




MCTXF



Prototypes tested 2016-2020
NbTi SuperFerric design
Geometrical lengths:
200 mm - 580 mm
Quench protection
No energy extraction (but 4P)
60% margin @ 1.9 K

Round Coil Superconducting Magnet
$MgB_2$demonstrator

# From prototypes to series production

- First prototypes assembled at LASA
- Long prototypes assembled in industry
- Series production in industry

Confirmed critical issues

- In house development
- Early involvement of industry

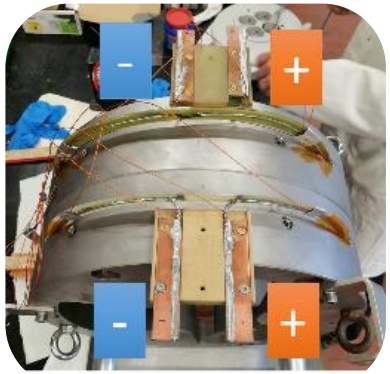
Easy on paper
Huge effort

RI vs company

- Deep understanding of the (different) goals
- Problem solving approach
- People are the key

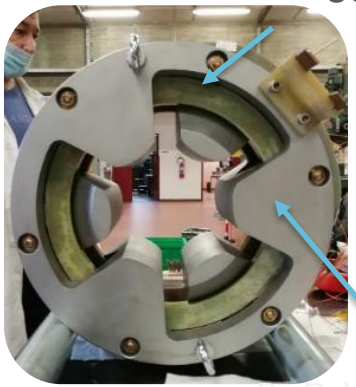
# Exploring different designs

- The development of the round coil magnet idea is a way to introduce HTS superconductors in accelerators
- Not the best choice for HL but suitable for lower energy accelators and/or to operate at higher temperature
- One way toward higher sustainability of accelerators (10 K – 20 K operaton)



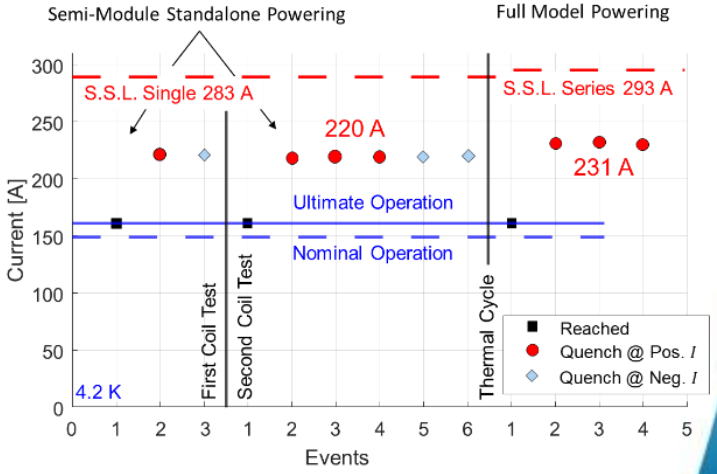

Full module

conductor



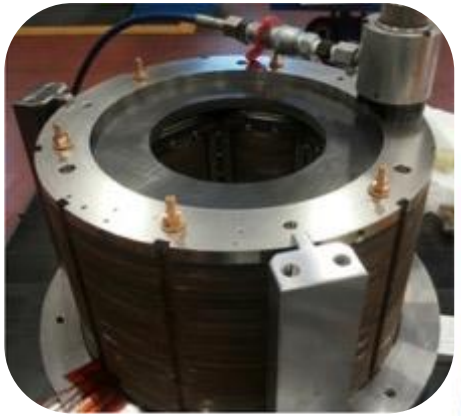
iron

By R. Valente

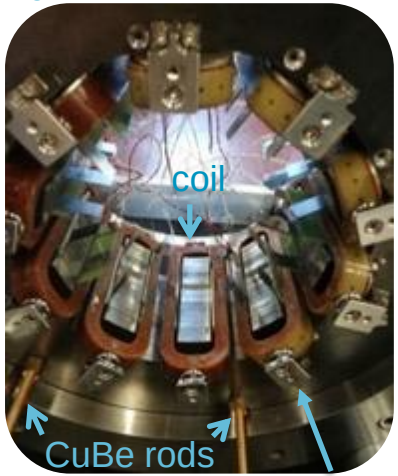


# HOC ASSEMBLY

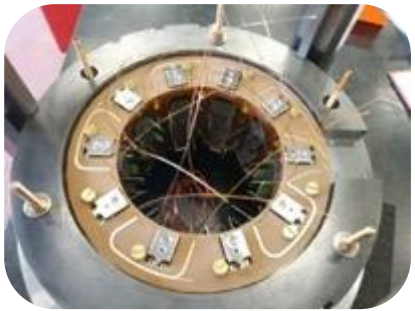

- Procedure developed at LASA on prototypes
- 6P, 8P, 10P assembled at LASA
- 12P and 4P assembled in industry

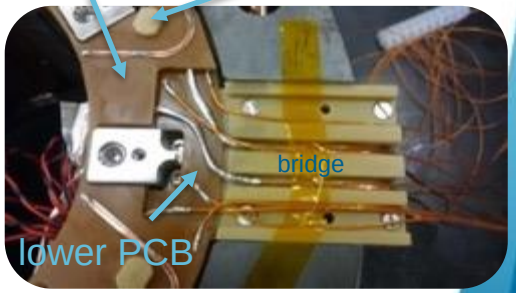


Coil technology and magnet assembly procedure have been developed at LASA
Developing and transfering and QA are key point to pursuit reproducible results









# Quality Control of coils

**Produced coils 508**

29 NC (6%)

QC developed by LASA

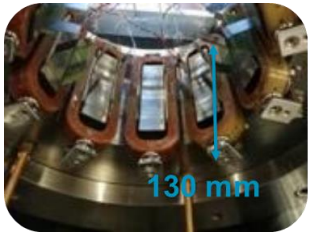
Measurements in industry

The number of turns is checked through a custom measurement setup

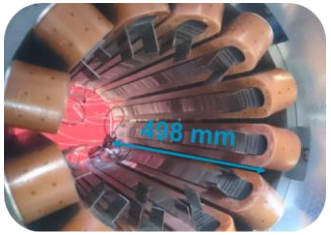
Surge test at $V_0$ = 2 kV to detect internal insulation defects

Voltage to ground tests

Mechanical dimensions

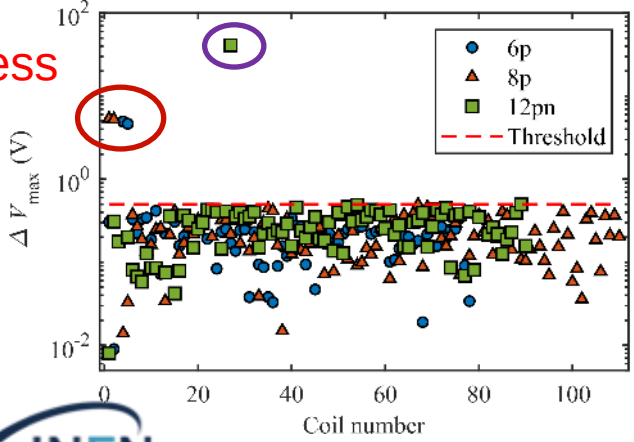


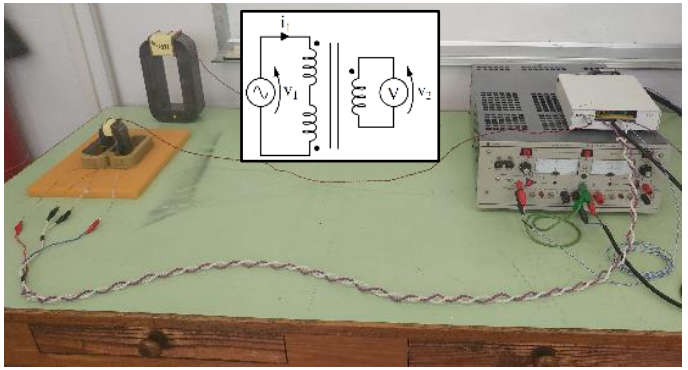




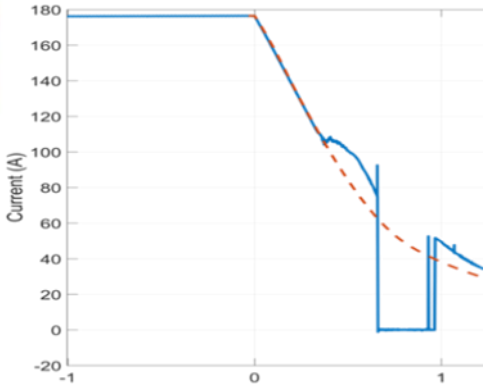

Inter-turn short

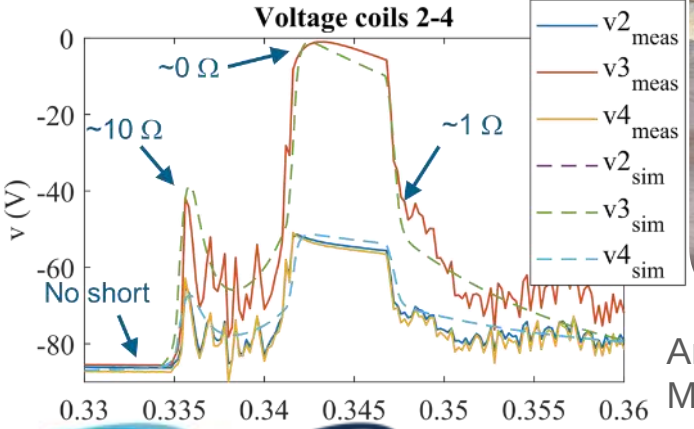
One turn less



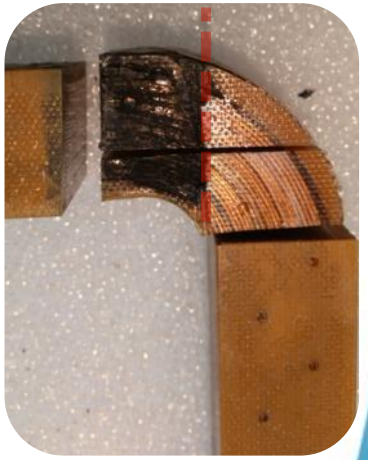



# What happens if something goes wrong?




The quadrupole prototype had an issue on wire to wire insulation during coil construction



Analysis by Sorbi-Prioli-Mariotto
Mitigation: input wire additional protection layer and dedicated test during production

# Production and test (magnets)

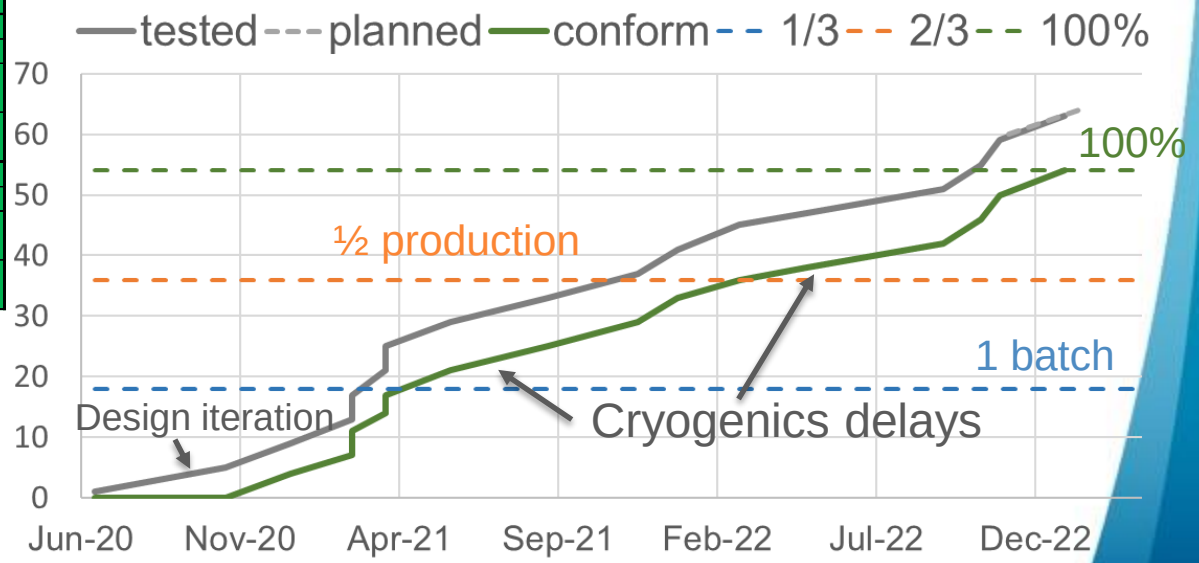
Produced magnets

| | Batch | Serial | TEST |
|---|---|---|---|
| M06 | 1a | 1 2 | |
| | 1b | 3 4 | |
| | 2 | 5 6 7 8 | |
| | 3 | 9 10 11 12 | |
| M08 | 1a | 1 2 | |
| | 1b | 3 4 | |
| | 2 | 5 6 7 8 | |
| | 3 | 9 10 11 12 | |
| M04 | 1a | 1 | |
| | 1b | 2 | |
| | 2 | 3 4 | |
| | 3 | 5 6 | |

| | Batch | Serial | TEST |
|---|---|---|---|
| M10 | 1a | 1 2 | |
| | 1b | 3 4 | |
| | 2 | 5 6 7 8 | |
| | 3 | 9 10 11 12 | |
| M12 | 1a | 1 | |
| | 1b | 2 | |
| | 2 | 3 4 | |
| | 3 | 5 6 | |
| M13 | 1a | 1 | |
| | 1b | 2 | |
| | 2 | 3 4 | |
| | 3 | 5 6 | |

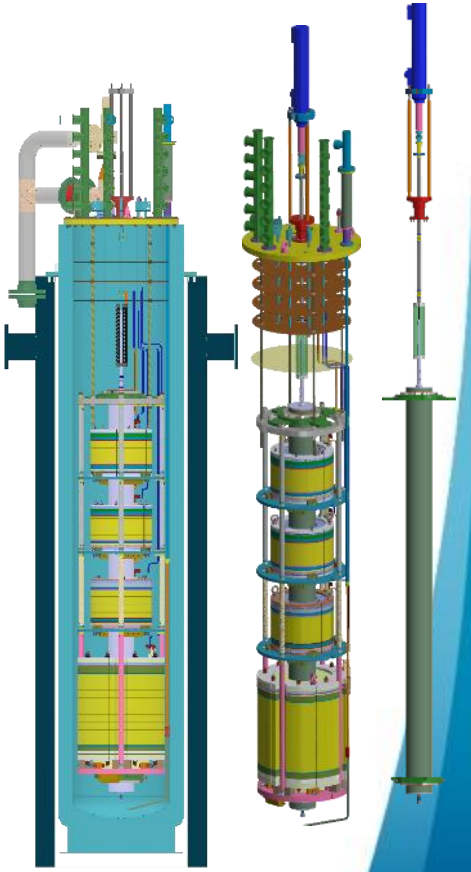
Legend
done/tested
Test ongoing
re-assembly

Contract signed in
Coils produced at SAES Getters Lainate (Milano, I)
Last coils delivered in July 2021
Magnets Assembled at SAES Rial Vacuum (Parma, I)
Last 10 produced magnets delivered to LASA in Oct 2021
End of tests Feb 2023



# The test station

- Four HO correctors cooled
  - Each magnet powerd individually
  - Magetic Measurements
- New power converter 600 A
  - Dump resistance 1 Ω or 1.5 Ω
  - IGBT polarity switch by LASA
  - IGBT for quench protection
- Field probe for the series
  - Each magnet measured individually
  - No cross talk

# Measurements

Powering **100%** (M. prioli)

- Training (both polarities)
- Endurance test 1h at ultimate

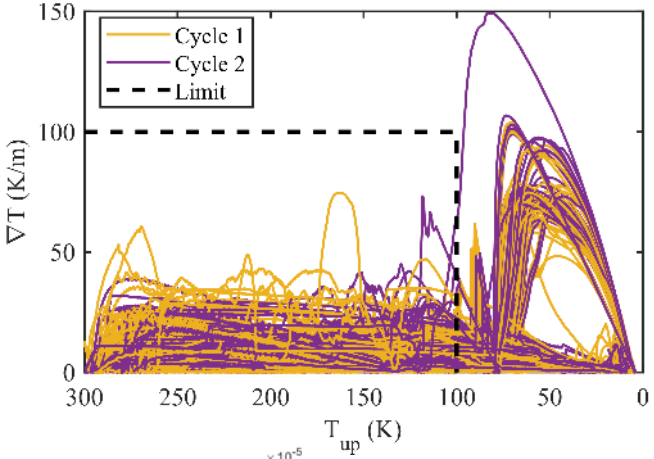
Magnetic field measurement **96%**

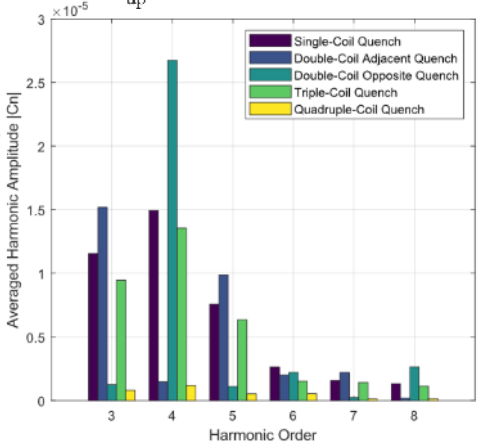
(E. De Matteis, S. Mariotto)

- Field integral 1% to 3%  wrt simulations
- Field integral reproducibility <0.1%
- Field quality high reproducibility
- Transfer function very good agreement with simulations, high reproducibility

Quenched coil recostruction via Magnetic Measurements (S. Mariotto)

- Number of quenched coils
- Position of the quenched coils



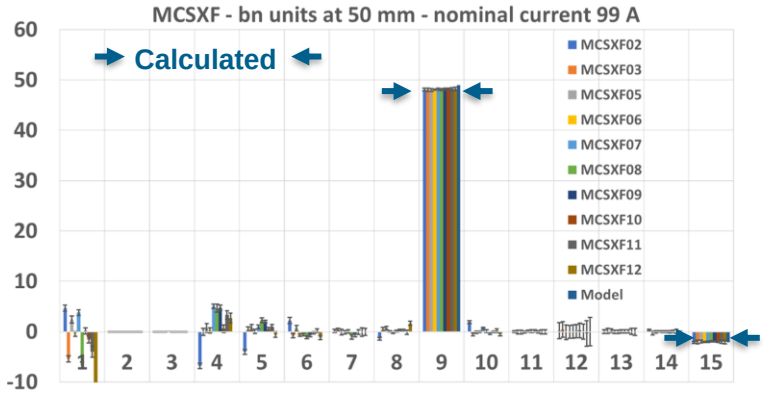

S. Mariotto and M. Sorbi. SuST, 35(1):015006, nov 2021.

# Magnetic measurements of HOC magnets

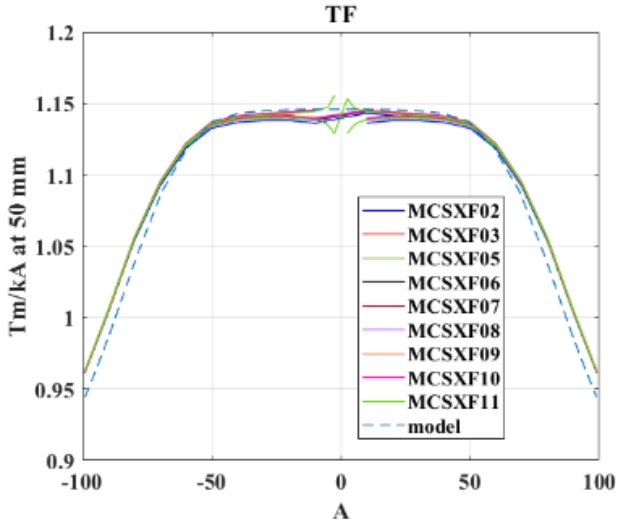
HOC magnets have been very challenging to measure:

- very important to have a good Magnetic Measurement system with software tools for a fast analysis

Assembly non-conformities detection and cross-check after re-assembly



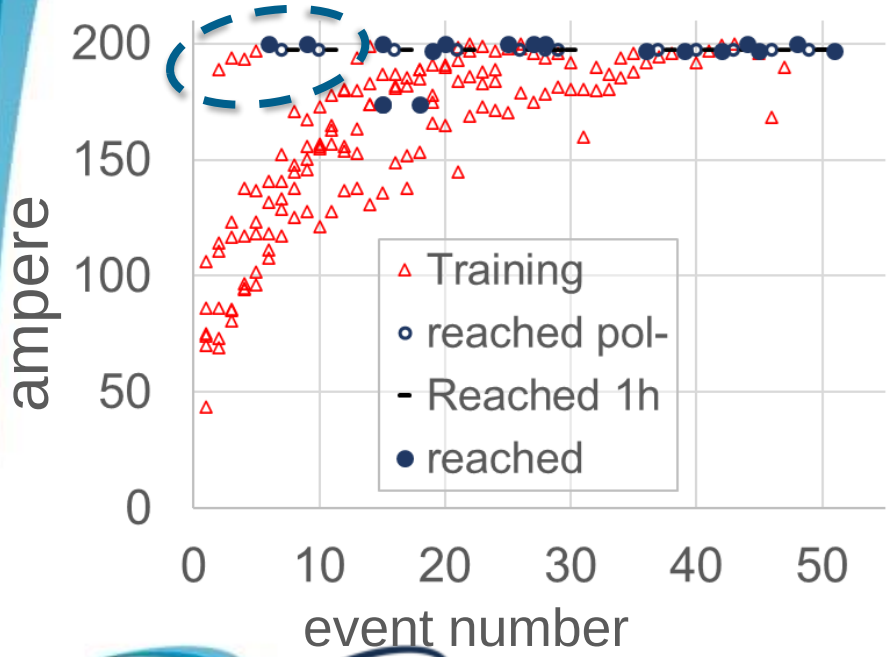

Reproducibility 0.2%

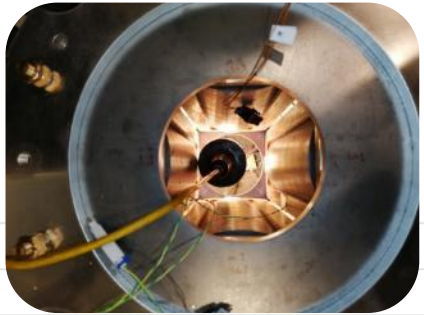


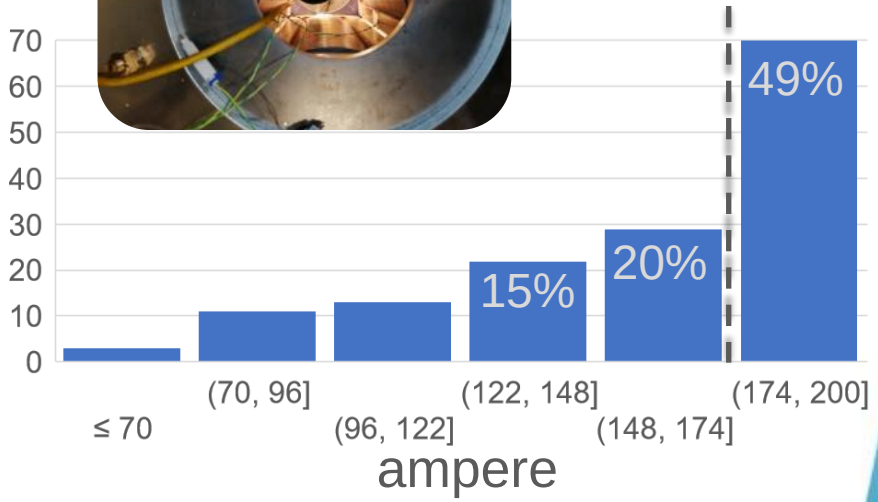

Allowed harmonics 100 U

# Training history of quadrupoles

Second assembly
Coils already trained



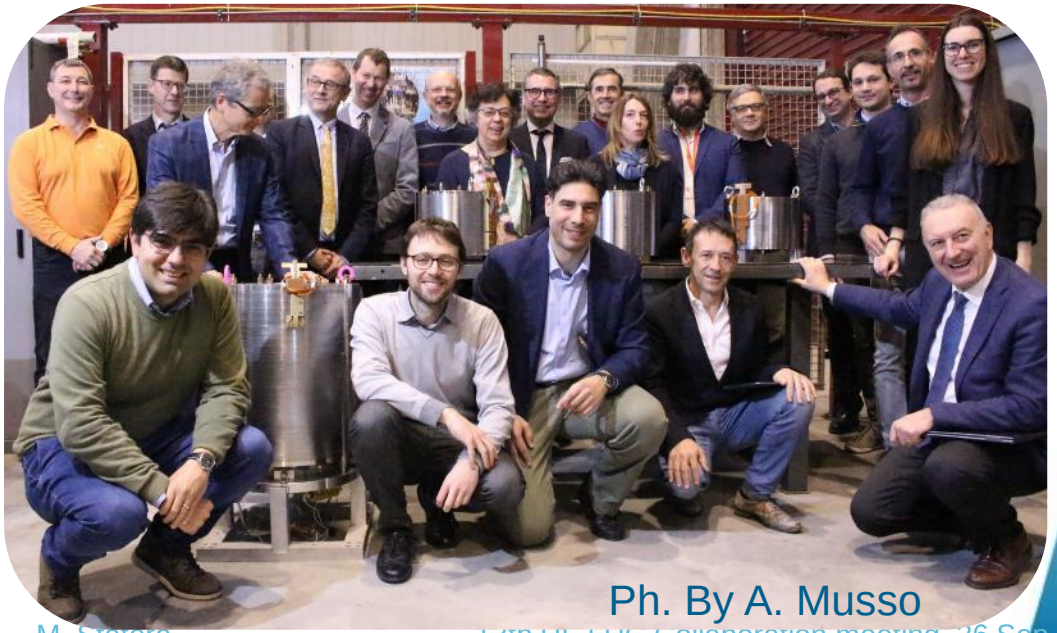



- Half quenches above nominal current
- Most quenches are coil training


**HL-LHC: HIGH-ORDER CORRECTOR MAGNETS ARRIVED AT CERN**
https://home.infn.it/en/infn-news/5607-hlc-hl-high-order-corrector-magnets-delivered-to-cern

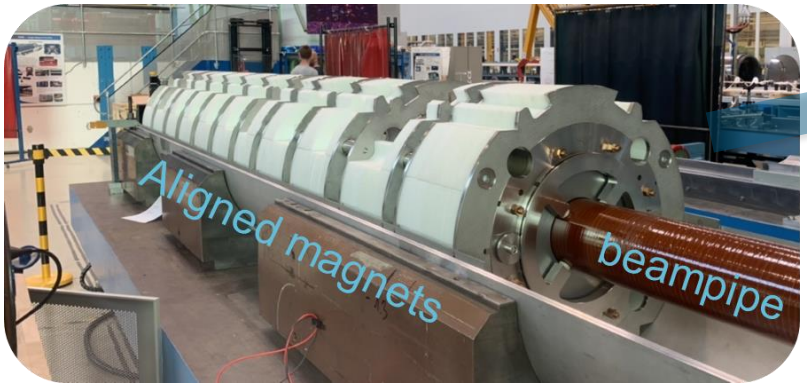
ANSA.IT '**Cern, consegnati i magneti per la versione super di LHC**'
https://www.ansa.it/canale_scienza_tecnica/notizie/fisica_matematica/2023/03/02/cern-consegnati-i-magneti-per-la-versione-super-di-lhc-_573bce19-c93e-41ca-9c60-1bed780725d0.html

Accelerating news
**54 magnets: The High-Luminosity LHC receives its first in-kind contribution**
The completion of the High Order Corrector Magnet project was only made possible by the collaborative efforts of INFN, CERN, and industry.



Ph. By A. Musso

# Integration




# CONCLUSIONS

- The corrector design is solid
- Developed several techniques for coils, electrical connections, assembly, quench reconstruction, quality control…
- Commissioned a multipolar accelerator magnet based on $MgB_2$ that is suitable with operation at 20 K
- The in house development of technologies and the involvement of industry since prototype phase were good practices
- The solution oriented interaction with company solved the issues raised during series production
- Installation, commissioinign and deployment are ongoing

INFN LASA

Istituto Nazionale di Fisica Nucleare

Laboratorio Acceleratori e Superconduttività Applicata


# THANK YOU

**LASA team**
F. Broggi, E. De Matteis,
S. Mariotto, A. Paccalini, A. Pasini, D. Pedrini, A. Leone,
A. Palmisano, M. Prioli, M. Quadrio, M. Sorbi,
M. Statera, M. Todero, C. Uva, R.U. Valente
**CERN** A. Musso, E. Gautheron, E. Todesco
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