High Order Correctors status

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INFN Milano - LASA

7th HL-LHC Collaboration Meeting
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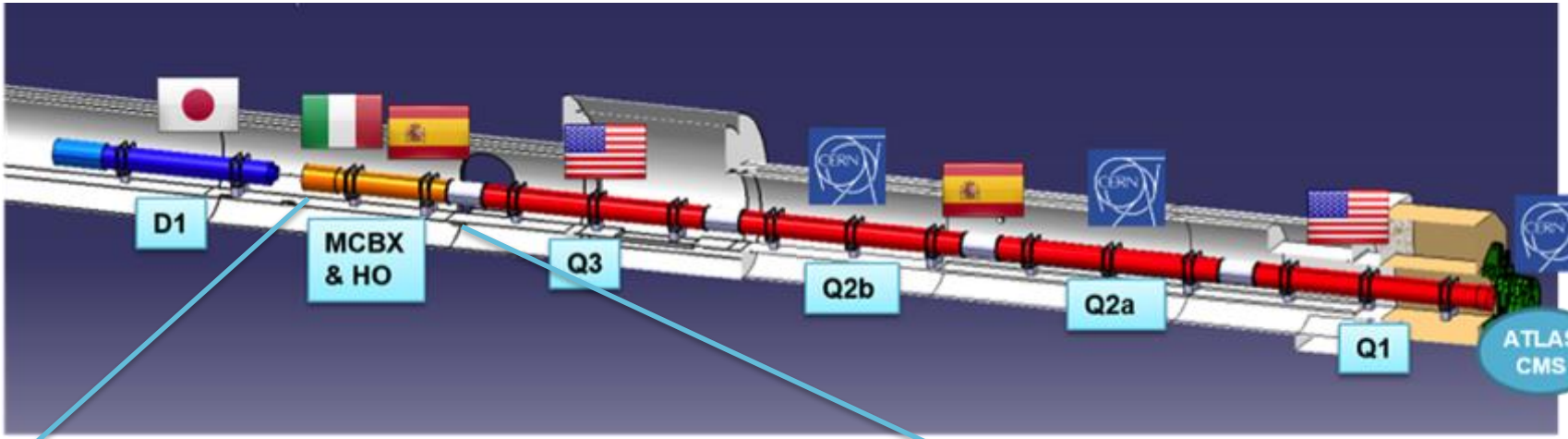
OUTLINE

- Introduction
- Status of work progress
  - MCOXFP1 construction and test
  - MCDXFP1 construction and test
  - next prototypes design and production status
- Integration
- MgB2 demonstrator status
- Test cryostat for next prototypes and for series production
- Conclusions and next steps

SCOPE

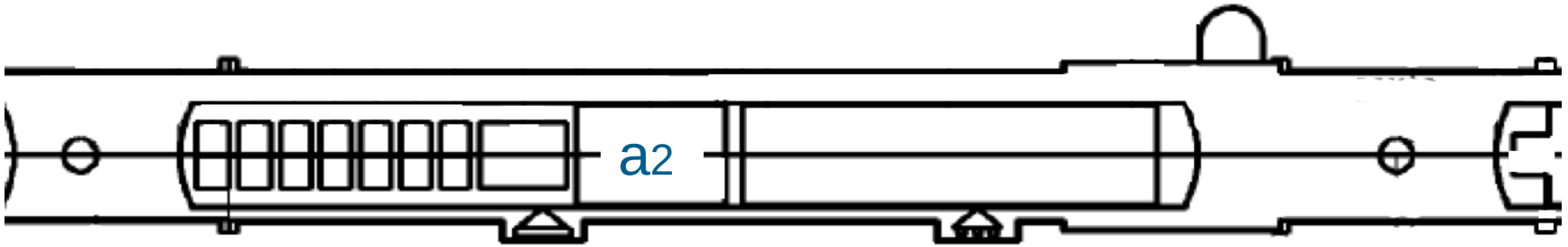
- The INFN-LASA follows the design, construction and test of the 5 prototypes of the High Order (HO) corrector magnets for the HL interaction regions of HL-LHC
- This activity is founded by INFN (Magix “activity”), and with an agreement CERN contributes for about 50%
- The INFN-LASA will follow the series production of the HO corrector magnets for the HL interaction regions of HL-LHC

THE LOW BETA SECTION AND THE HIGH ORDER CORRECTORS



73.6 m

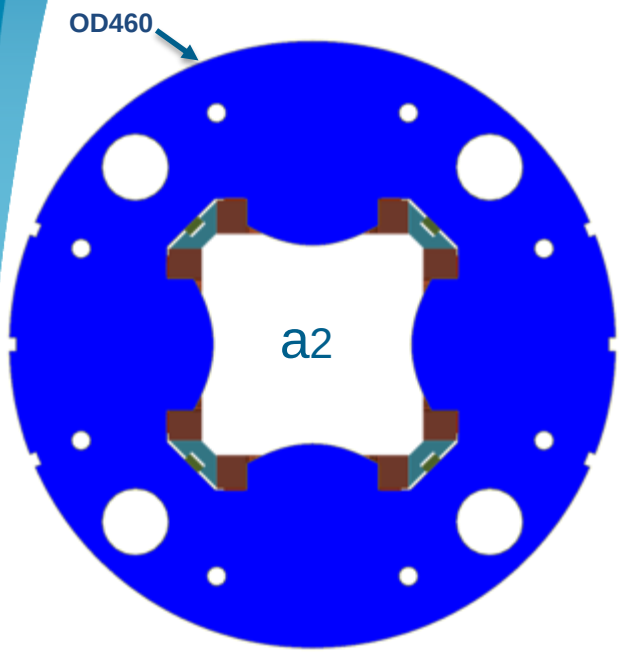
IP



b3 b4 b5 b6
a3 a4 a5 a6

by P. Fessia

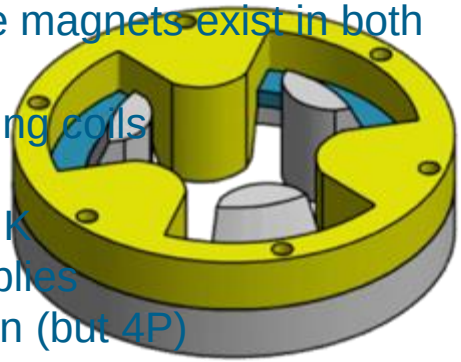
HO CORRECTOR MAGNETS ZOO



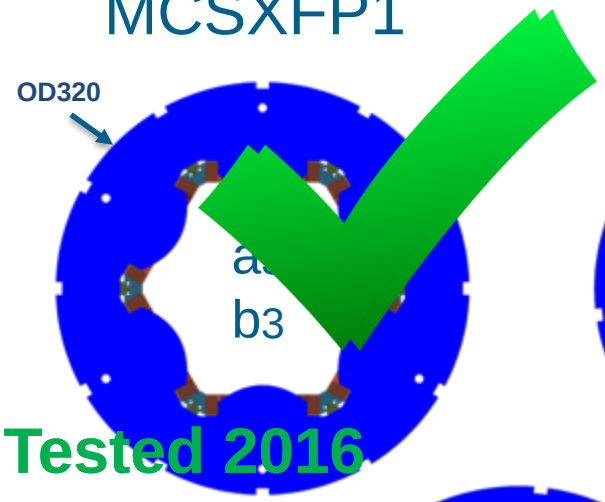
MQSXFP1

From 6-pole to 12-pole magnets exist in both normal and skew form

- NbTi superconducting coils
- superferric design
- 60% margin @ 1.9 K
- existing power supplies
- no energy extraction (but 4P)



MCSXFP1



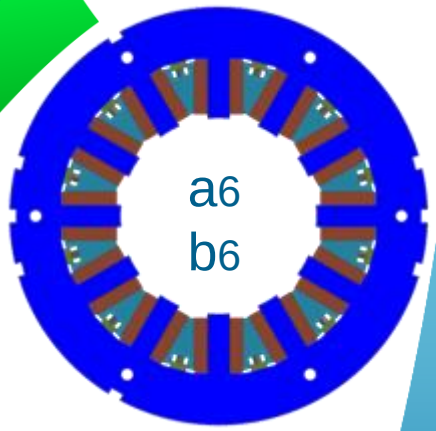
Tested 2016

MCOXFP1

Tested 2017

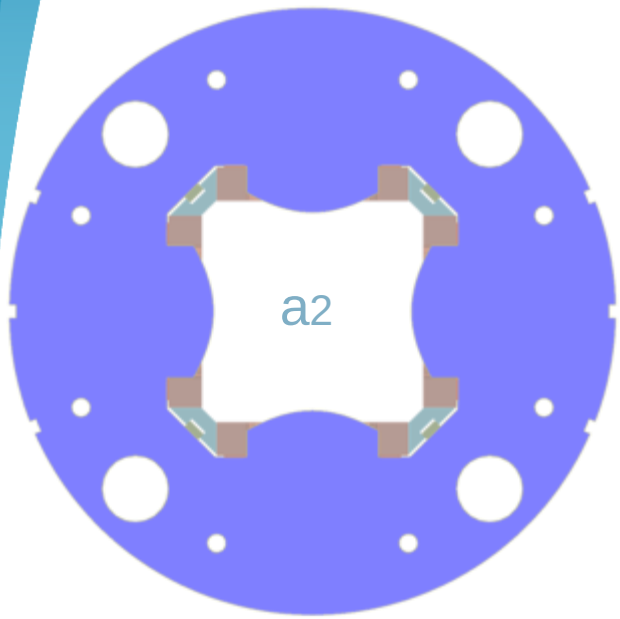
Tested 2017

MCDXFP1



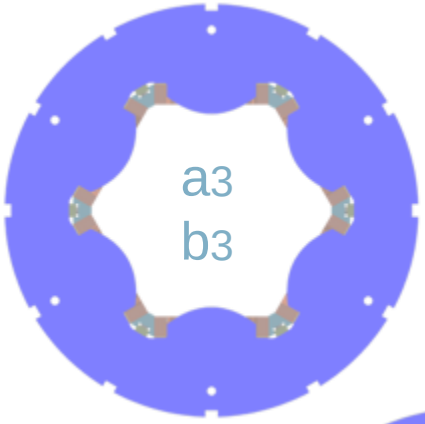
MCTXFP1

MCOXFP1 - THE OCTUPOLE

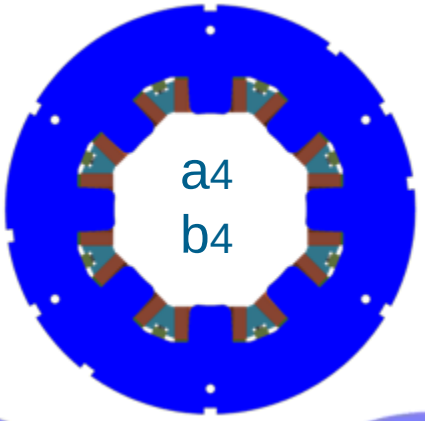


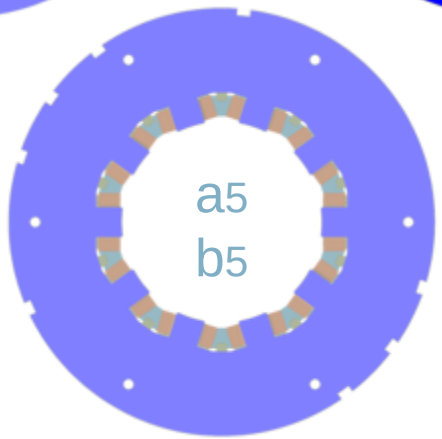
MQSXFP1

MCSXFP1

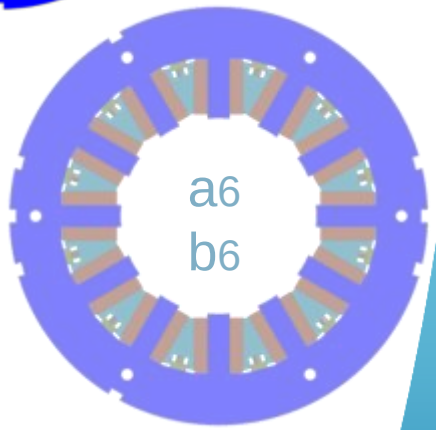


MCOXFP1



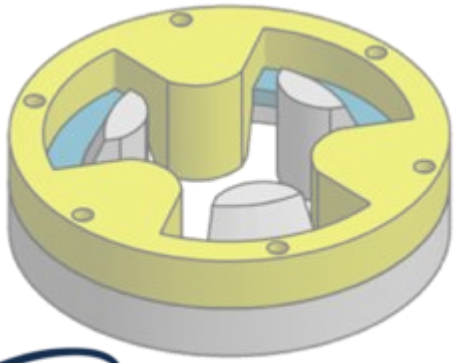


MCDXFP1



MCTXFP1

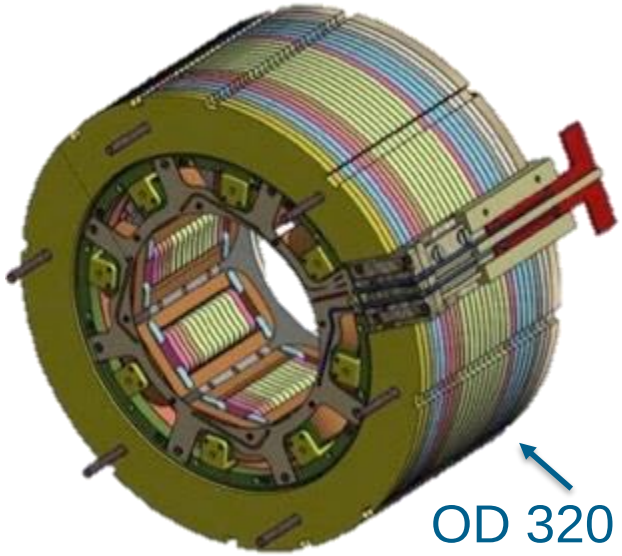
MgB_2 round coil



MCOXFP1

	nominal	design
length	160 mm	183 mm
integrated field @ Iop @ r50 mm	46 Tmm	46 Tmm
magnetic length	87 mm	99 mm
energy @Iop	1.4 kJ	1.07 kJ
harmonics		B12=11.6 B20=-3.0

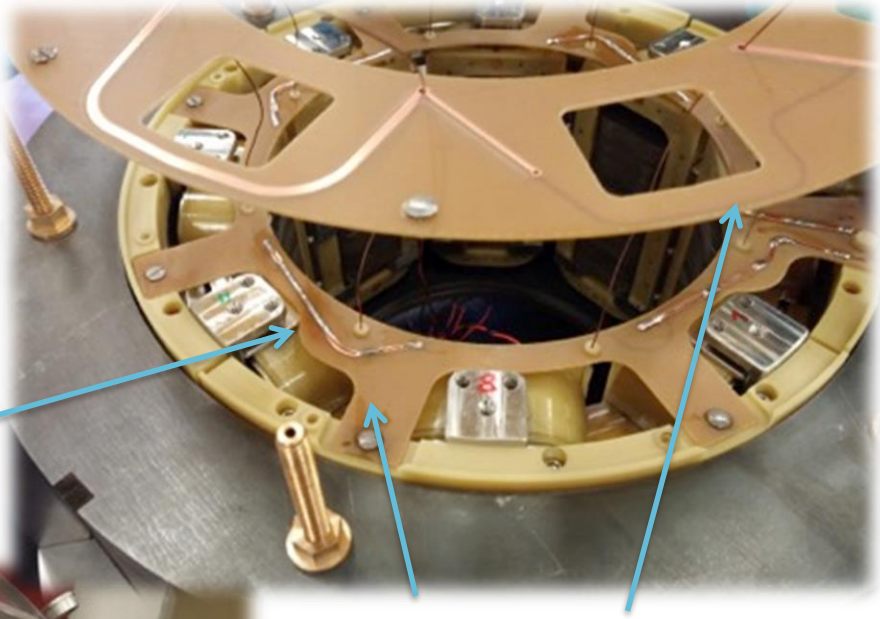
- DURATRON PEI U2300 coils
- electrical connections redesigned



MCOXFP1 ASSEMBLY 1

assembly procedure

- same as 6pole
- new electrical connections

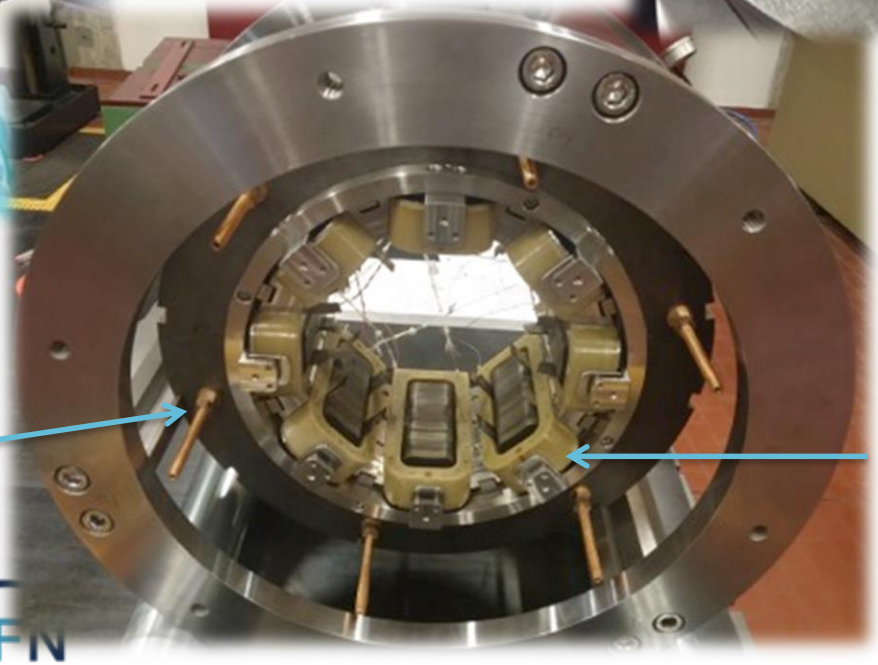


Copper 2 mm wide
0.035 mm thick

two printed circuit boards

- coils' connections
- signals

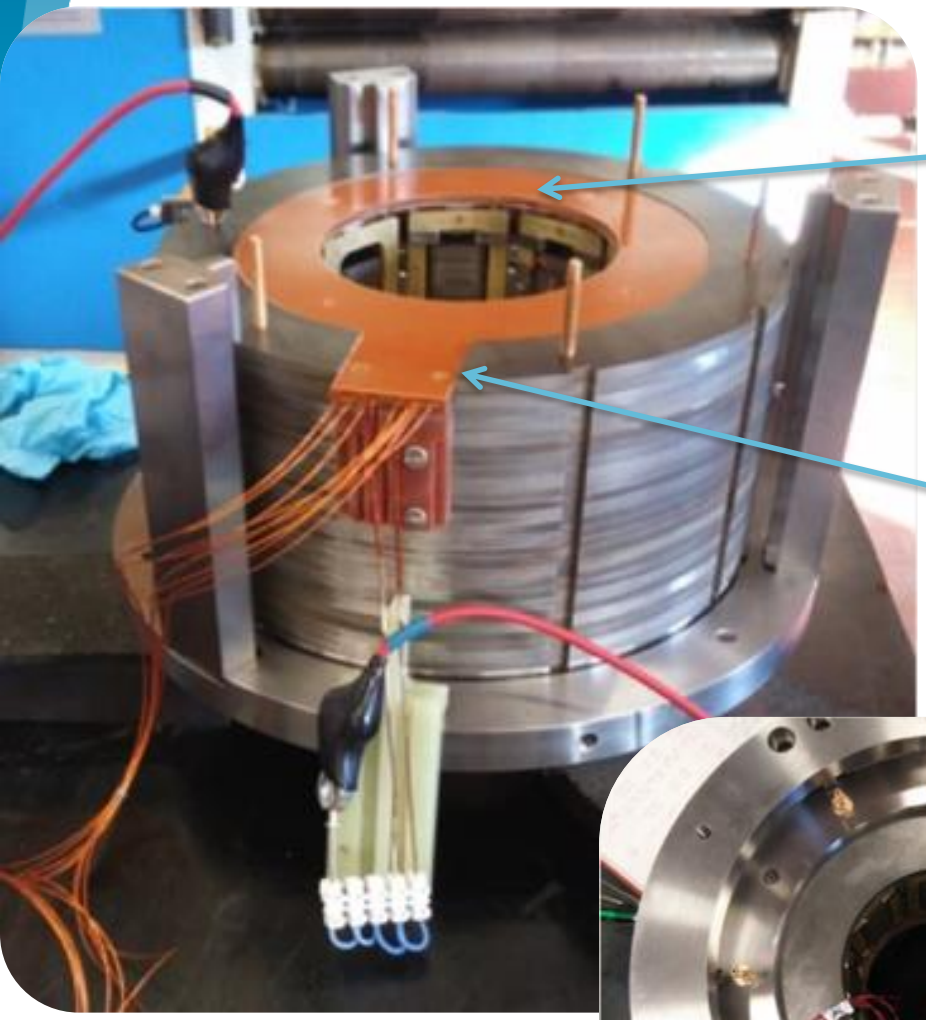
alignment frame

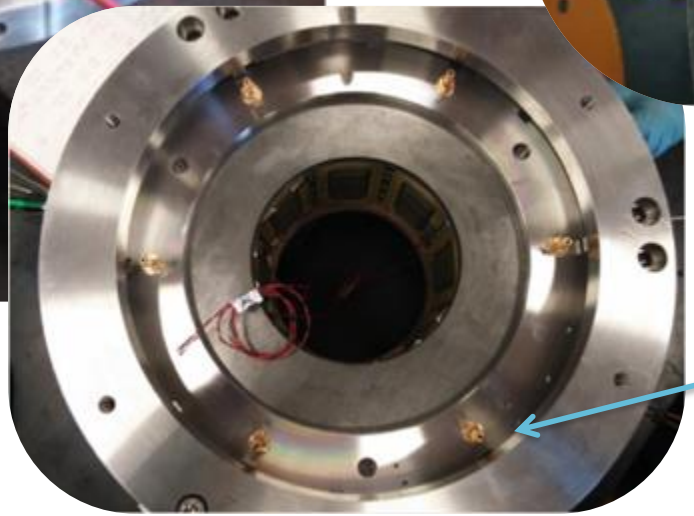


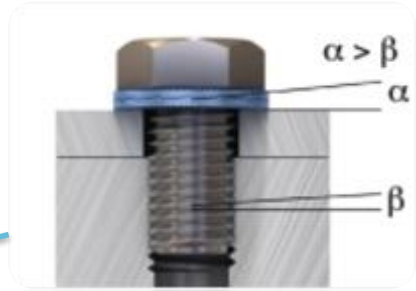
CuBe rods

- spacers
- fixed longitudinally
- wedges in position
- the wedges are fixed

MCOXFP1 ASSEMBLY 2



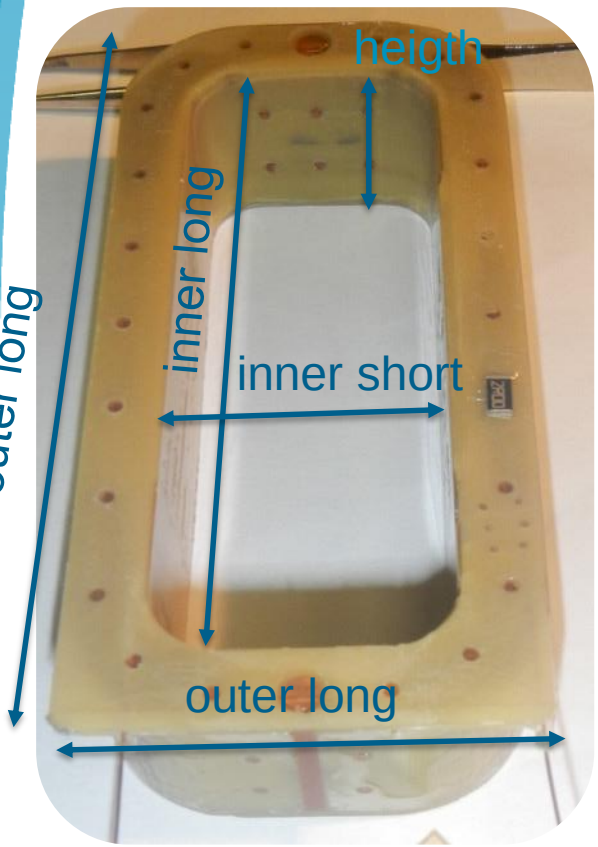


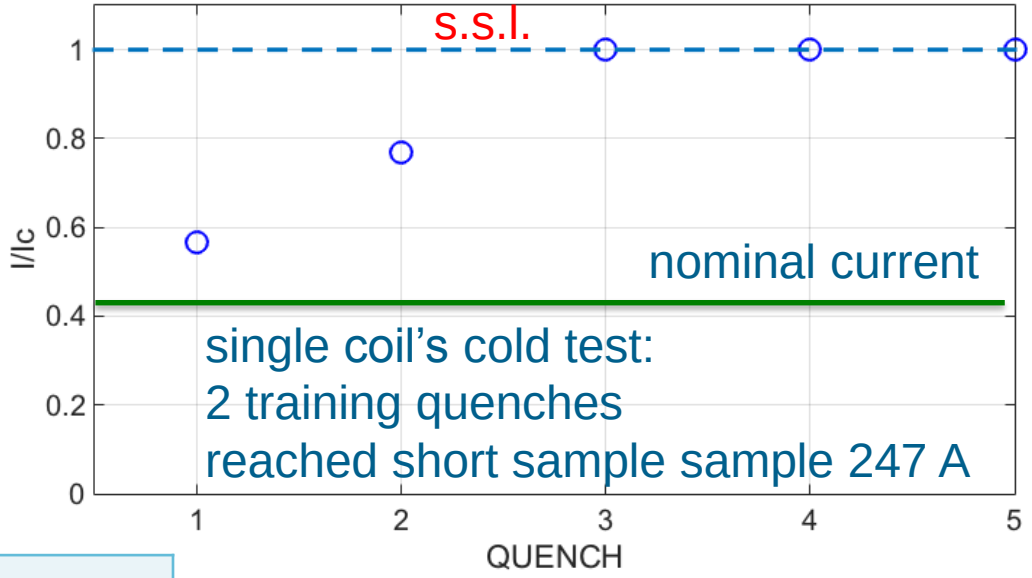


MCOXFP1 COILS

12 coils produced

HCMCOXFC01-I1000001





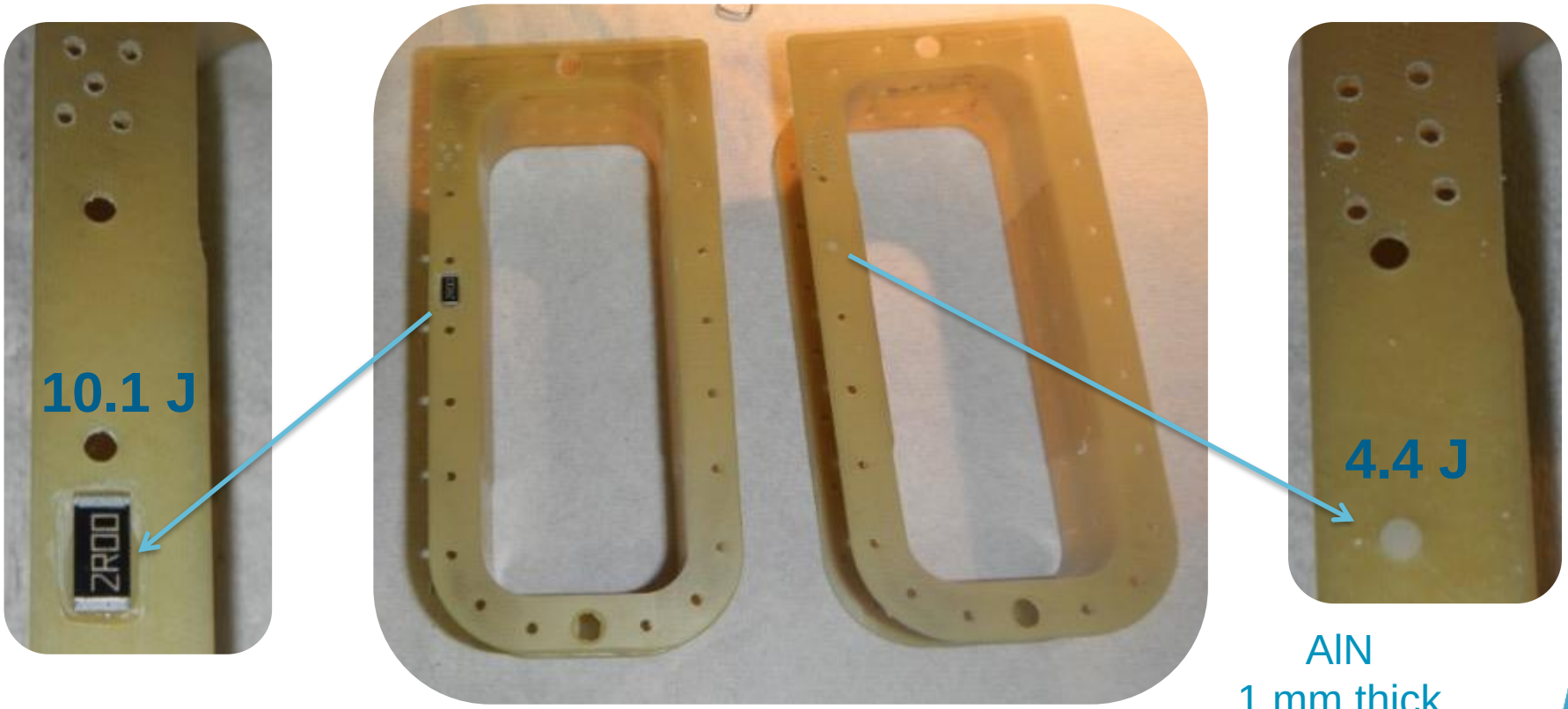
B1	M08-01
B2	M08-08
B3	M08-07
B4	M08-06
B5	M08-09
B6	M08-10
B7	M08-11
B8	M08-12

coils' assessment

- **Geometry**
  6pole average σ 0.09 mm
  8pole average σ 0.13 mm
- **Resistance**
  number of turns
- **HV insulation**
  all coils above 1.8 TΩ at 5 kV

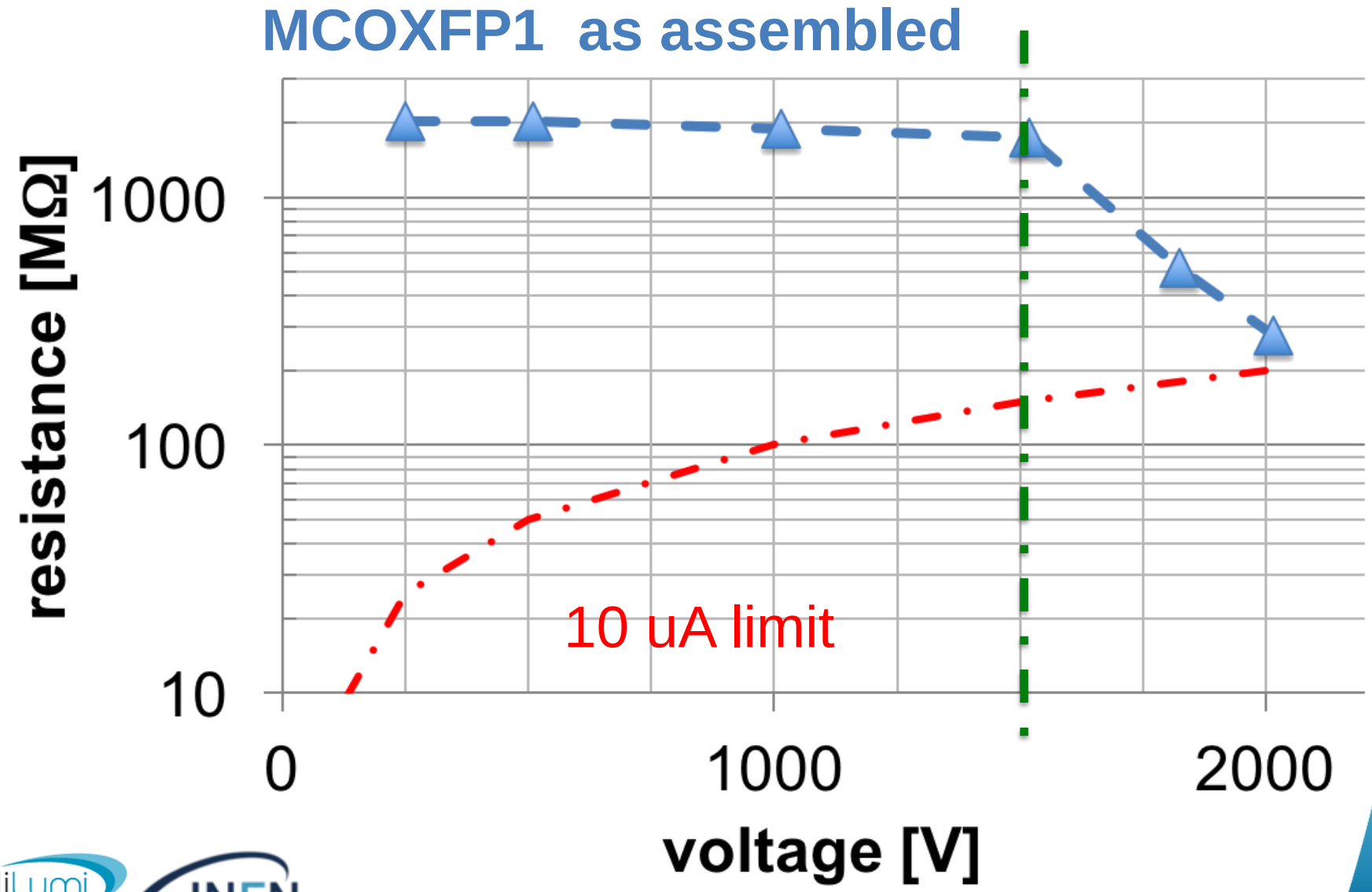
HEATERS

- Two heaters are installed
- DURATRON thickness reduced by hand in coil **B5**
- A Φ 2 mm Aluminum nitride (AlN) ceramic insert in one hole of coil **B6**
- quench induced at 4.2 K, I= 73 A



AlN
1 mm thick
By INTELLION S.a.r.l.

MCOXFP1 GROUND INSULATION

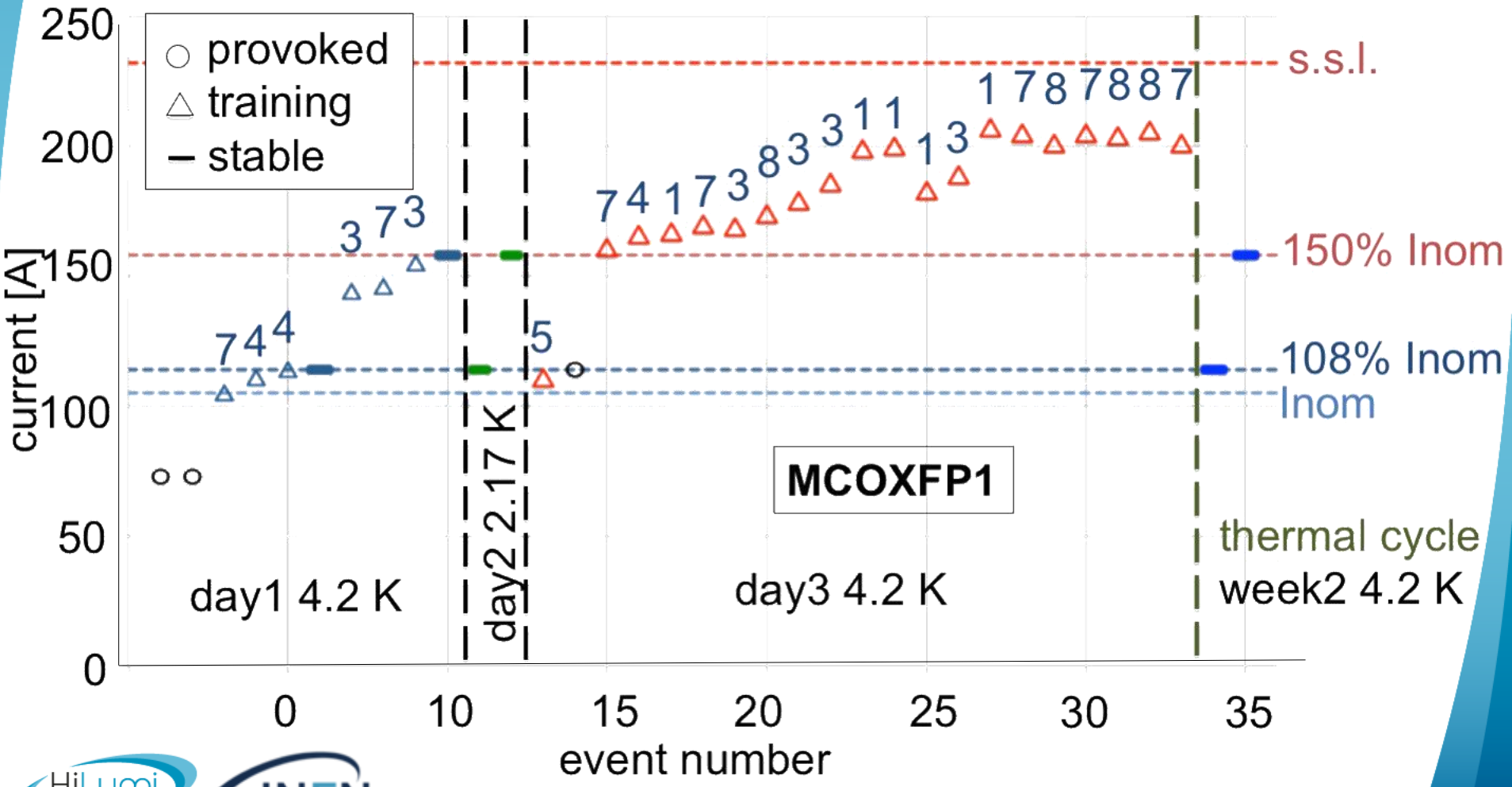


8POLE TEST

- qualification @ 4.2 K
- qualification 1h @ 108% @2.17 K
- training @4.2 K
- working condition test
  w/o energy extraction
- thermal cycle
- qualification @ 4.2 K

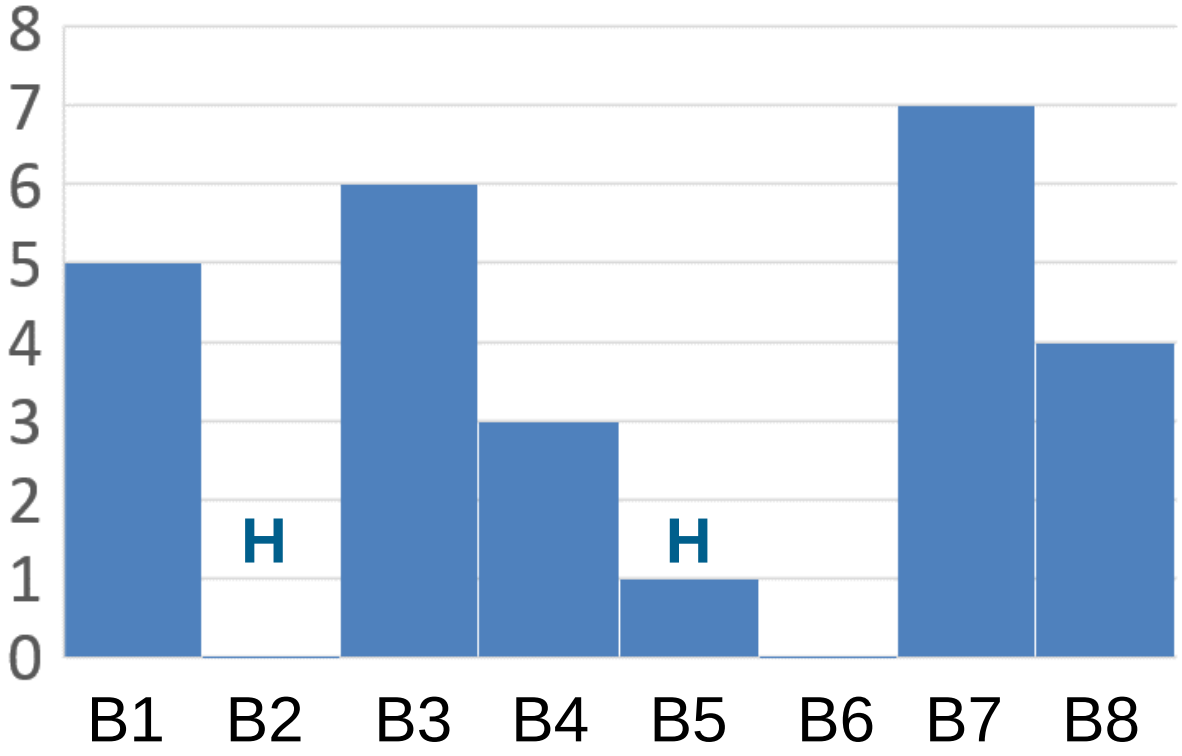
8POLE COLD TEST RESULTS

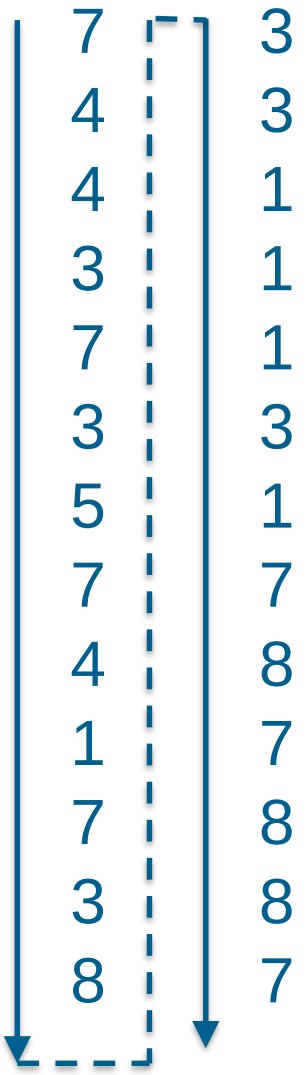
- stable at ultimate current (108% Inom) and at 150% Inom
- 26 quenches – I_{max}= 207 A (89.2 % s.s.l.)



QUENCH SEQUENCE

- Not all coils had training
- Single tested coil (B1) has training I> 150% Inom
- No evidence of induced quench effect

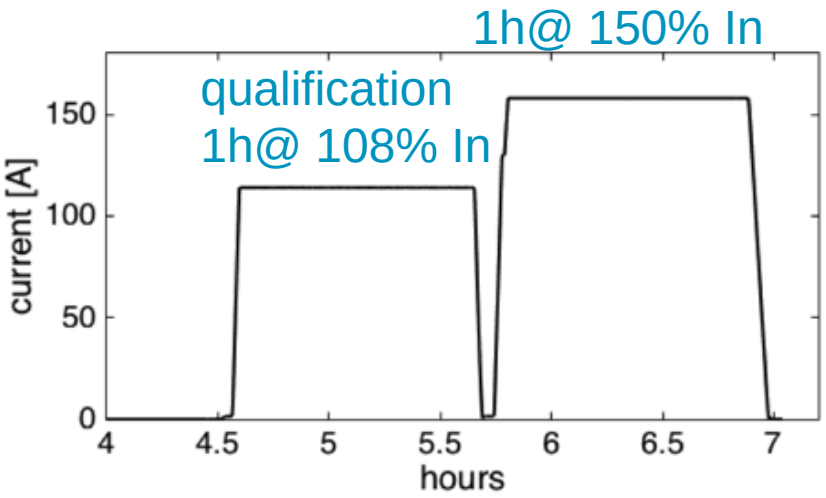


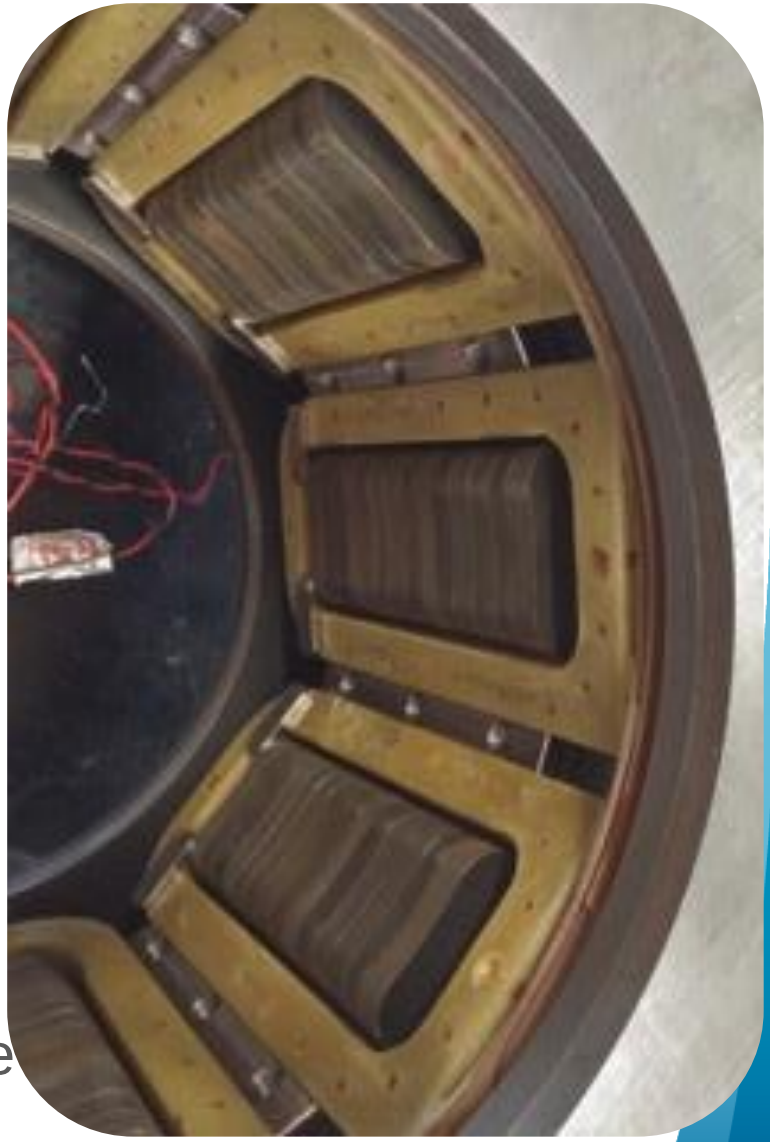


8POLE COLD TEST RESULTS - 2

He II test: 2.17 K

- 1h @ 108% Inom (114 A)
- 1h @ 150% Inom (158 A)
- no quenches occurred





tests @ 4.2 K

- full training: Imax 89% of s.s.l.
- working condition test
- qualification @4.2 K after a thermal cycle

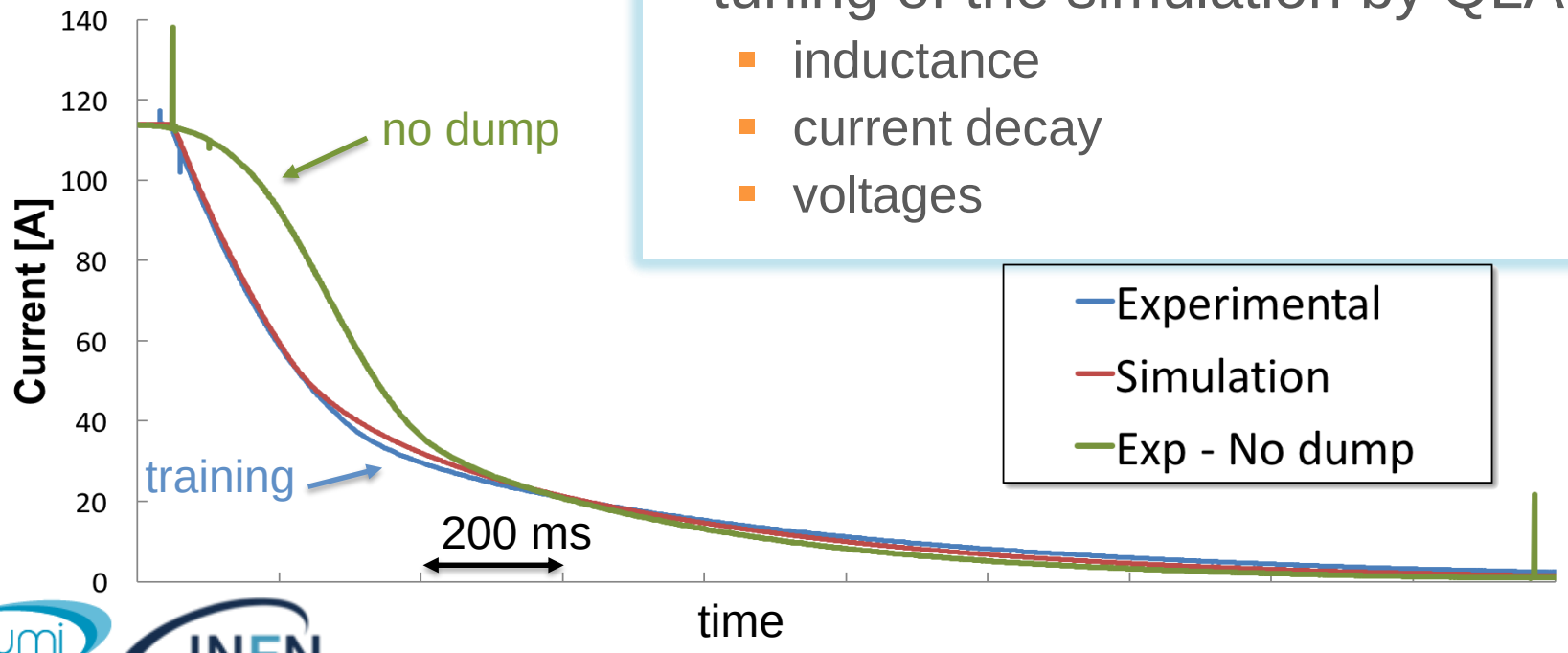
QUENCH PROTECTION IN LHC

- Protection in LHC
  - Existing power supplies
  - Measuring current
  - Time range 60-180 ms
  - Max current: ultimate current (114 A)
- Protection at LASA
  - Total voltage and differential voltage (half magnet)
  - Quench induced by heater (and AlN insert)

QUENCH PROTECTION (no ENERGY EXTRACTION)

- Quech induced by heater (and AlN insert)
- threshold up to 5.0 V
- total time before relay opening: 145 ms
- ΔI = 8 A @ 145 ms PS dependent

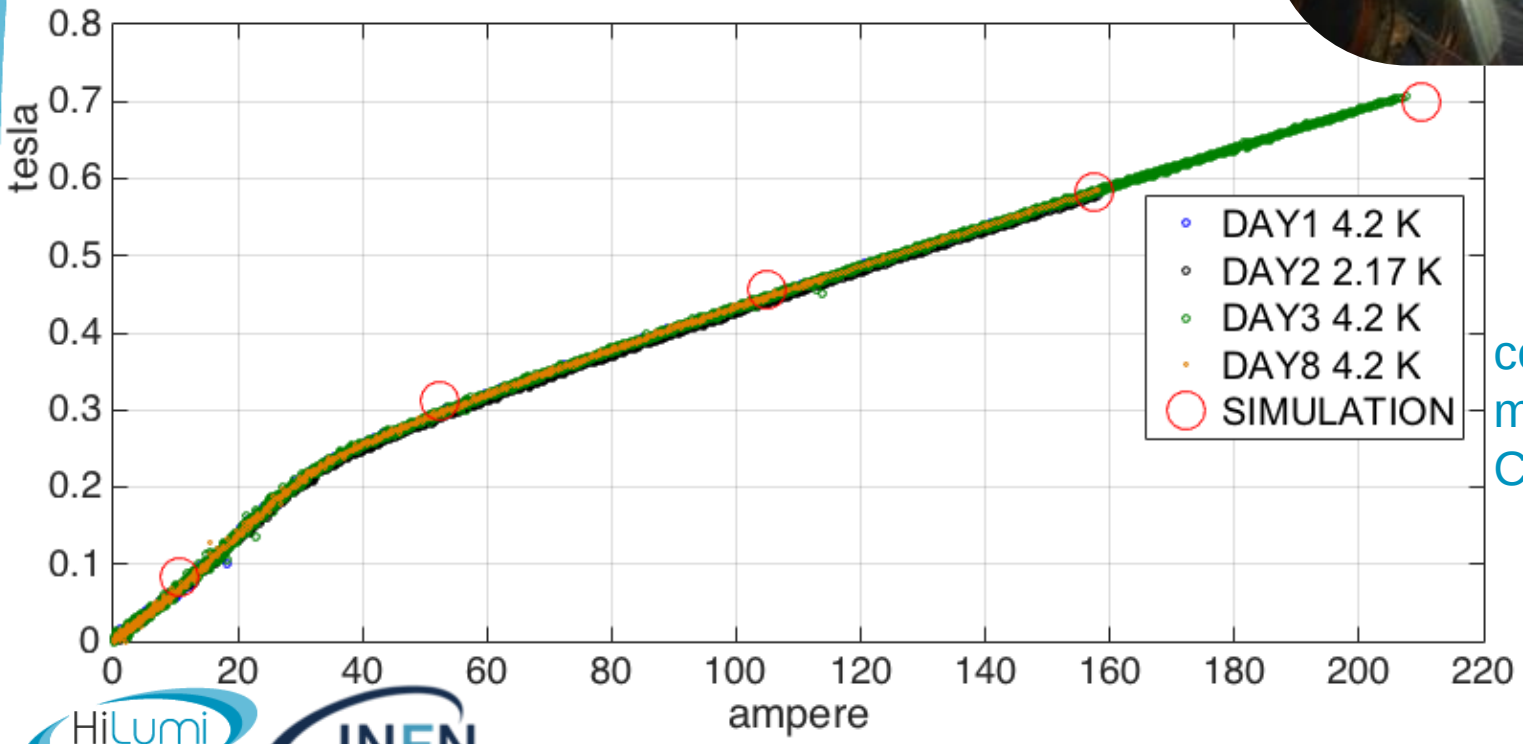
- tuning of the simulation by QLASA
  - inductance
  - current decay
  - voltages



PRELIMINARY FIELD MEASUREMENT

preliminary measurement of the field

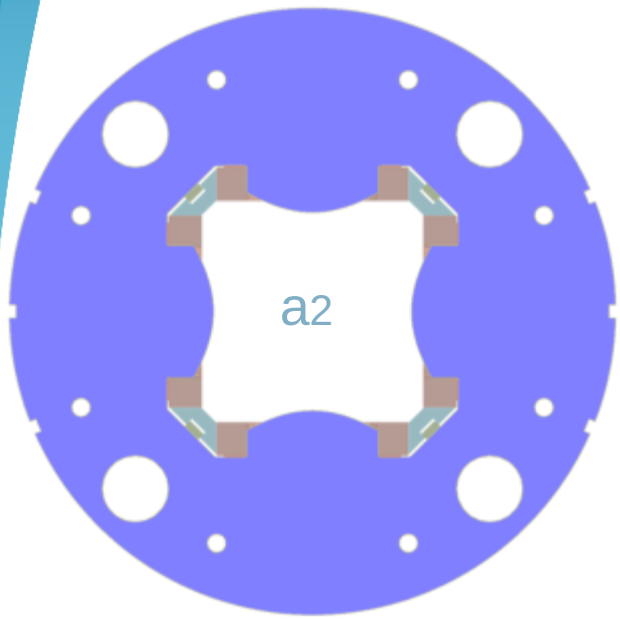
- single point
- in front of a pole
- radius of 50±1 mm (correction applied)



reproducible
5 mT
saturation 30 A

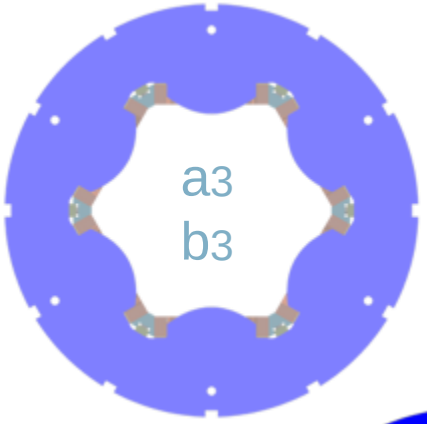
complete measurement at CERN (2017?)

MCDXFP1 THE DECAPOLE

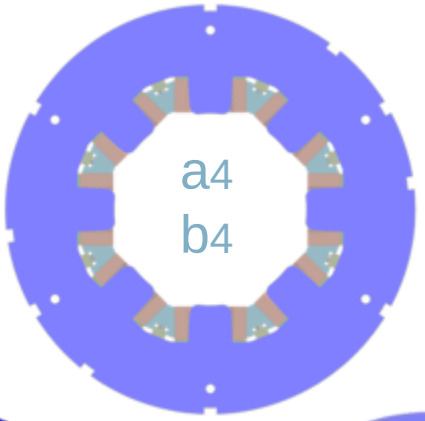


MQSXFP1

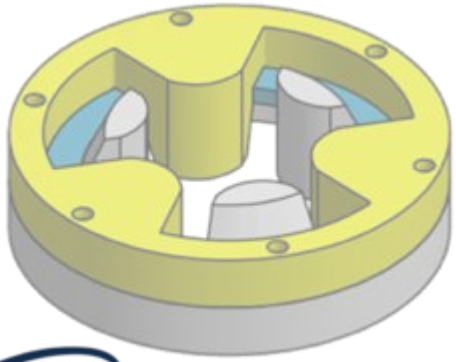
MCSXFP1

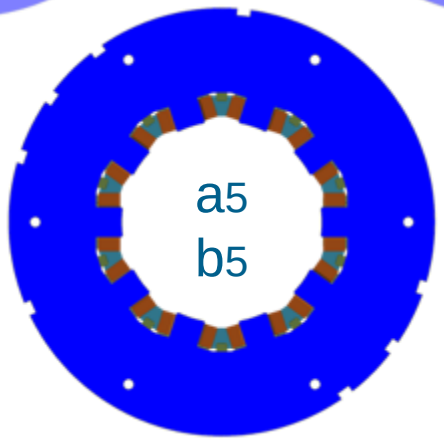


MCOXFP1

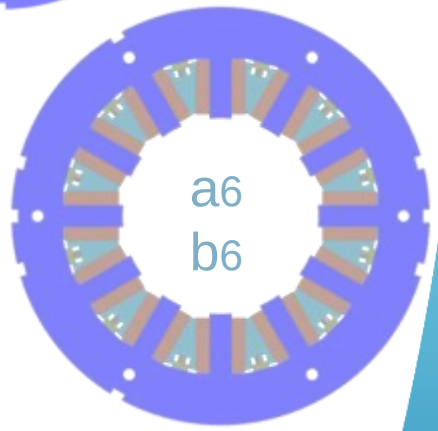


MgB_2 round coil





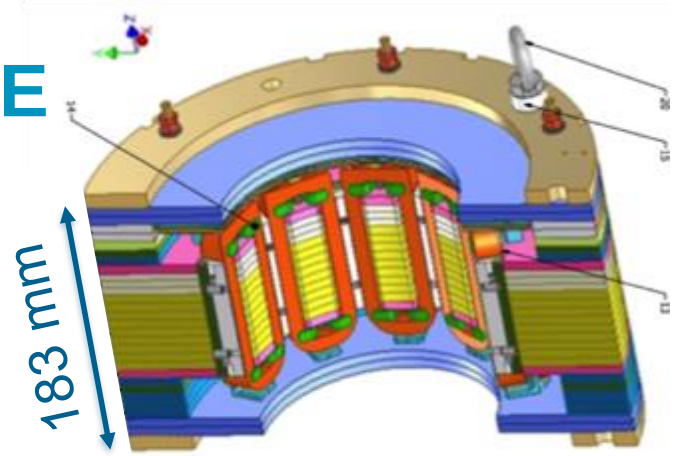
MCDXFP1

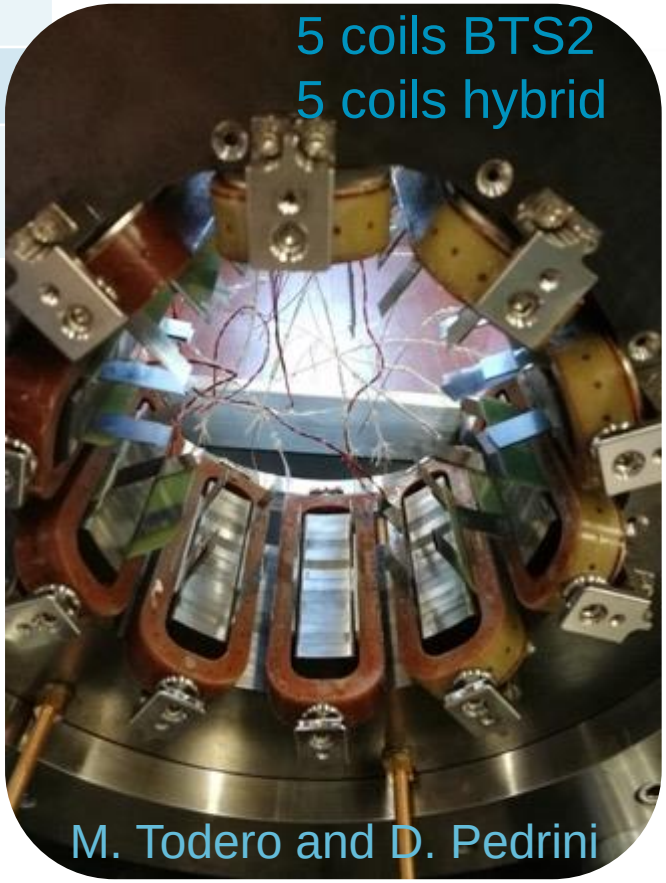


MCTXFP1

MCDXFP1 10POLE

	nominal	design
length	172 mm	183 mm
integrated field @ Iop @ r50 mm	25 Tmm	26 Tmm
magnetic length	95 mm	97 mm
harmonics		B15=11.6 B25=-0.7





- COILS
  - Updated BTS2 Arisawa design
  - Hybrid BTS2/DURATRON
- Improved electrical connection design, pcbs supporting and integration with connection box

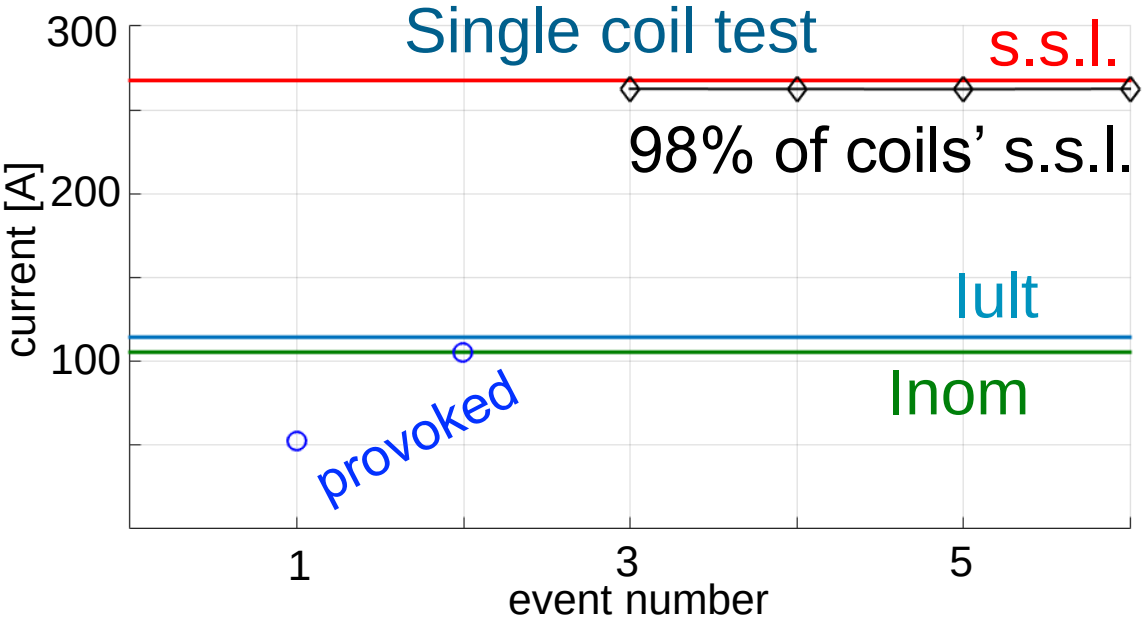
MCDXFP1 COILS' ASSESSMENT

16 coils produced

- 4 batches

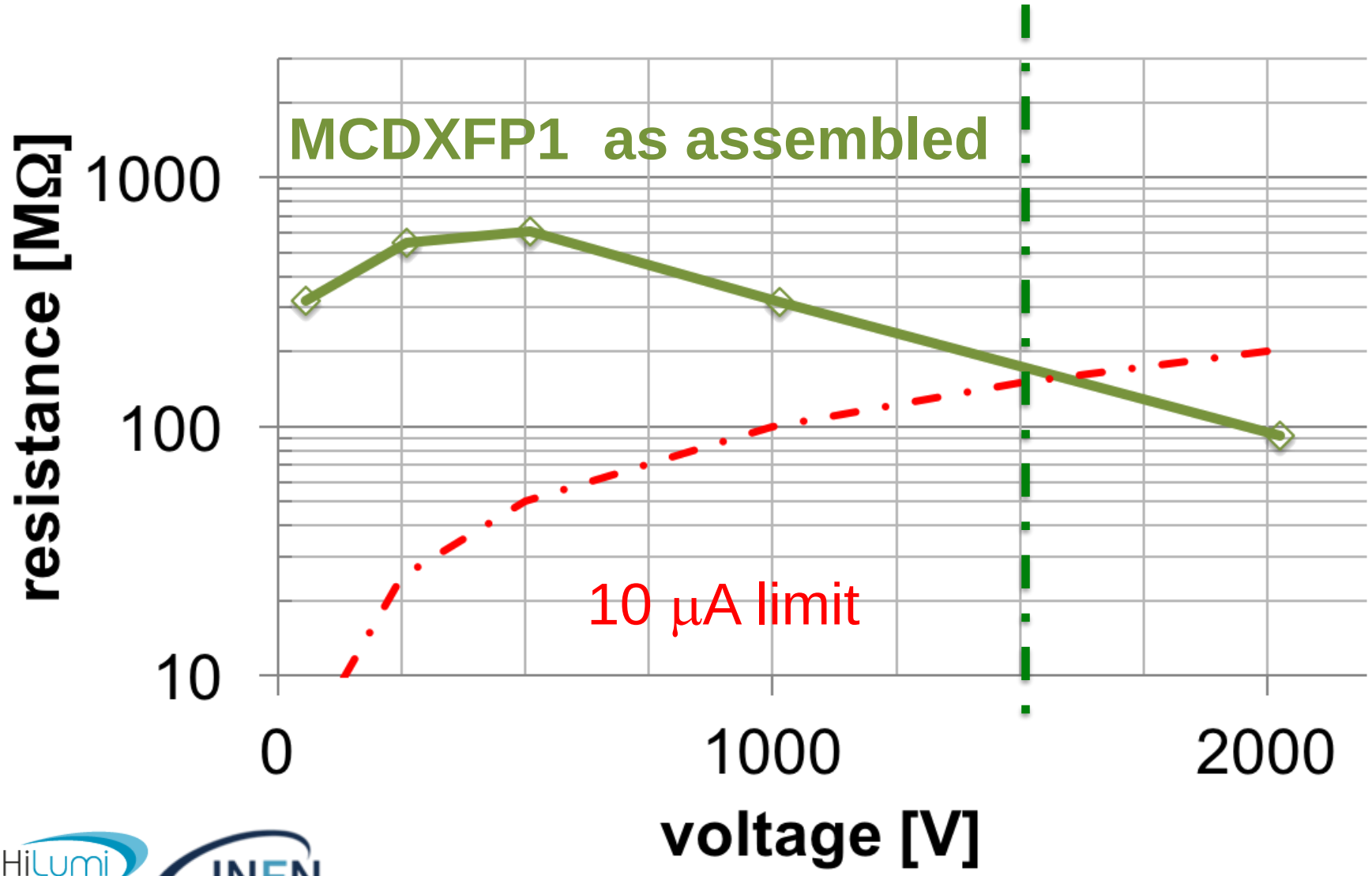
1st batch single coil test and LHe cooldown
2nd batch LN_2 cooldown

B1	M10-05	BTS2
B2	M10-08	
B3	M10-09	
B4	M10-11	
B5	M10-13	
B6	M10-06	DURATRON
B7	M10-10	
B8	M10-12	
B9	M10-14	
B10	M10-15	



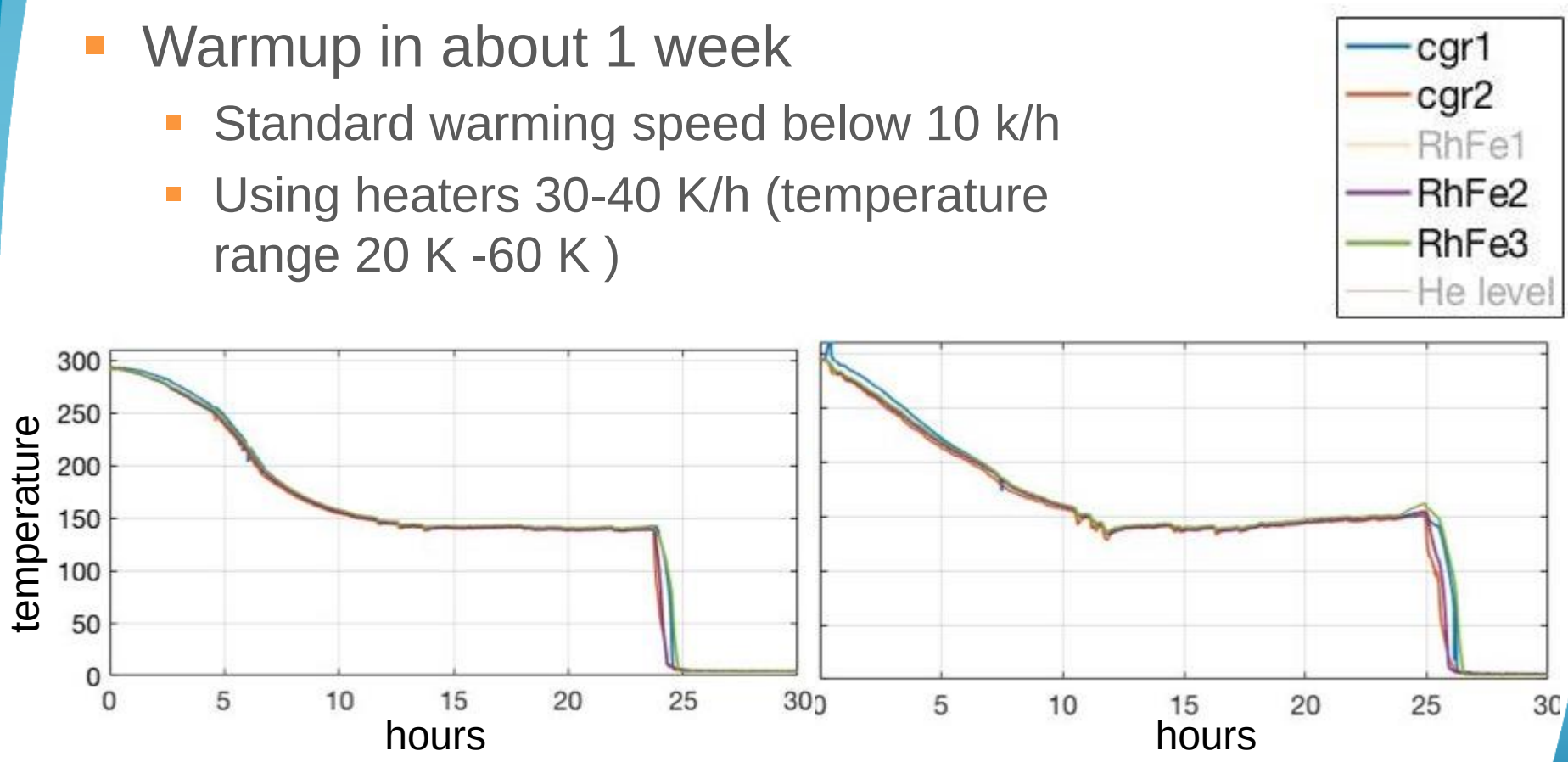
- **Geometry**
  8pole average σ 0.13 mm
  10pole average σ 0.11 mm
- **Resistance**
  number of turns
- **HV insulation**
  (Al wrap) all coils above 36 GΩ at 2.5 kV

MCDXFP1 GROUND INSULATION



THERMAL CYCLES

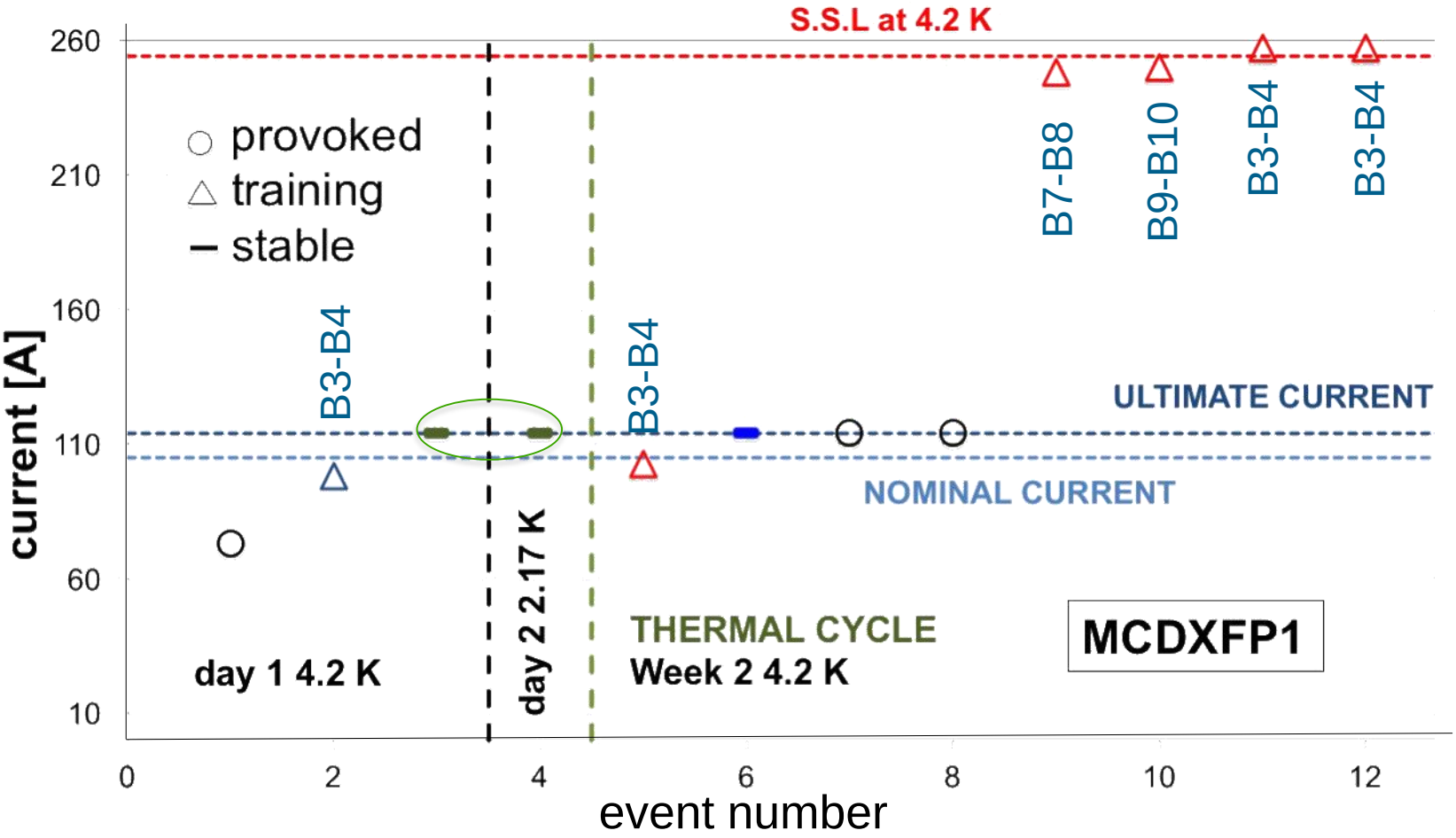
- Cooldown in about 1 day
  - Nitrogen heat exchanger
- Warmup in about 1 week
  - Standard warming speed below 10 k/h
  - Using heaters 30-40 K/h (temperature range 20 K -60 K)



MCDXFP1 TEST

- Week 1
  - 4.2 K 1h @ I_{ult} , 121 A (115% I_{op})
  - 2.17 K 1h @ I_{ult} , 121 A
- Week 2
  - 4.2 K 1h @ I_{ult} , 121 A (115% I_{op})
  - no energy extraction quench test (operating conditions simulation)
  - training

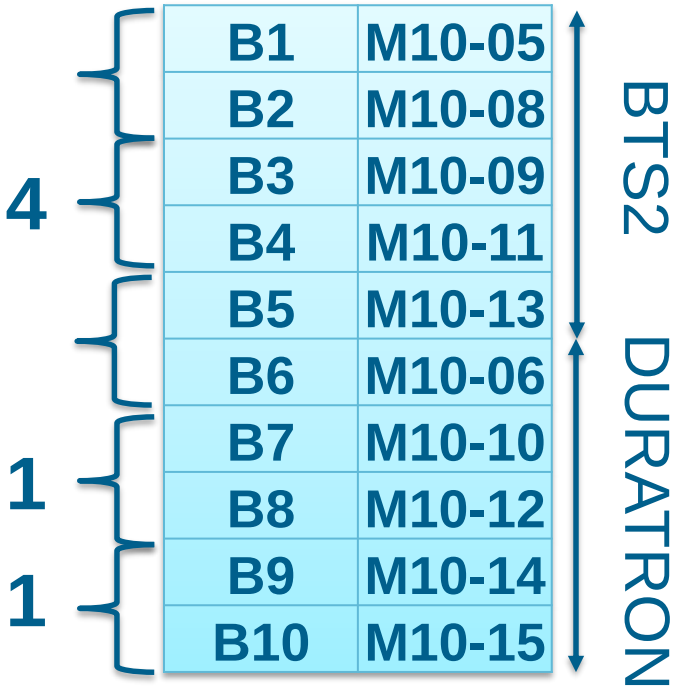
MCDXFP1 QUENCH SEQUENCE



- One provoked
- One 98 A quench
- Ultimate 114 A -1 h test (4.2 K and 2.17 K)
- Reached 100% S.S.L at 4.2 K

QUENCH vs COILS TECHNOLOGY

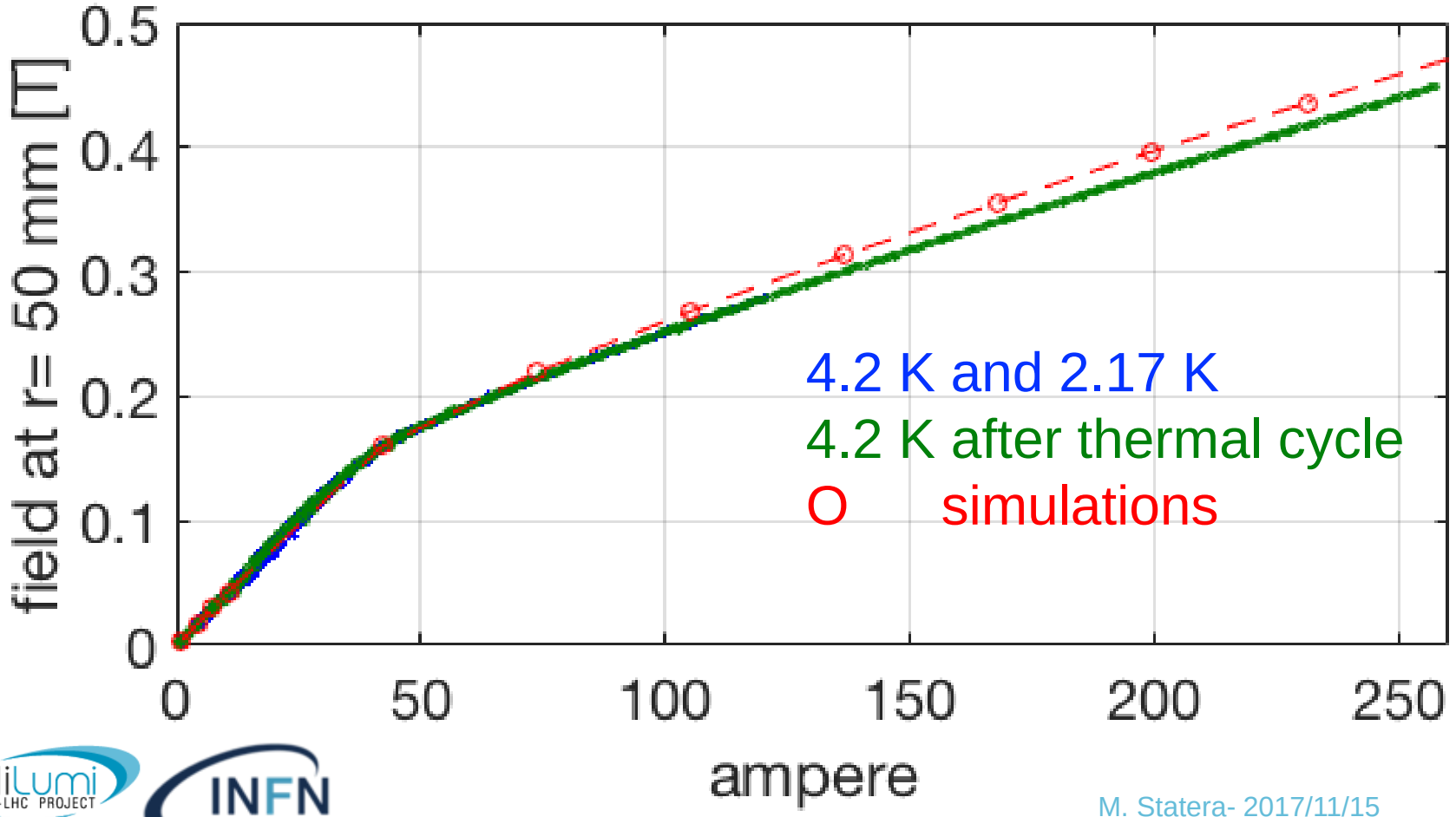
- Quench detection detects 2 coils
- Quench heater on coil B3 (3 provoked)
- 4 quenches on B3-B4
- 1 quench on B7-B8
- 1 quench on B9-B10



- No sensitive difference between coils' technology

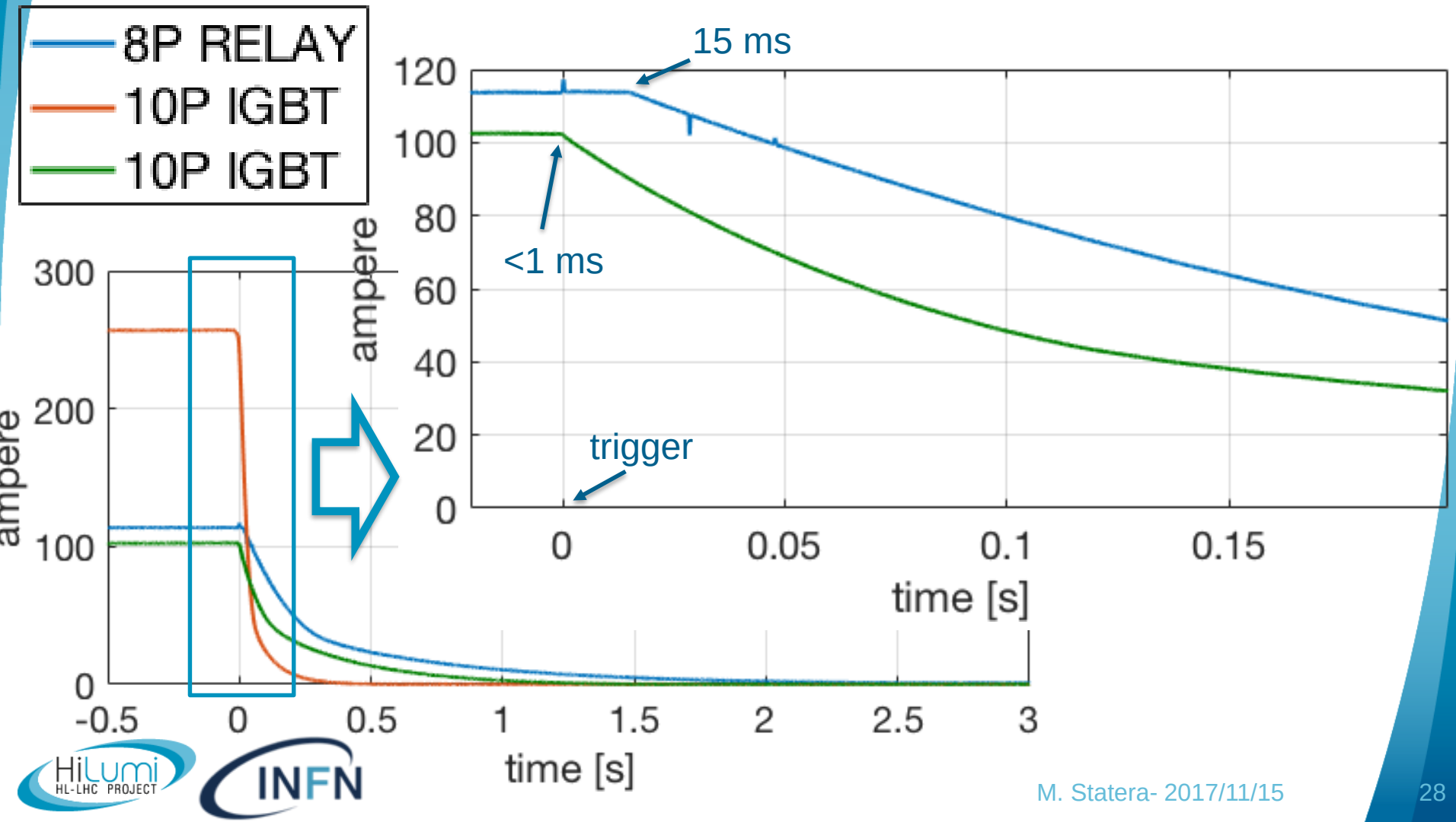
SINGLE POINT MAGNETIC FIELD

- Single Hall probe
- r_{ref}= 50 mm
- Errors not shown
- Good reproducibility
- Harmonic measurements at CERN (2017?)



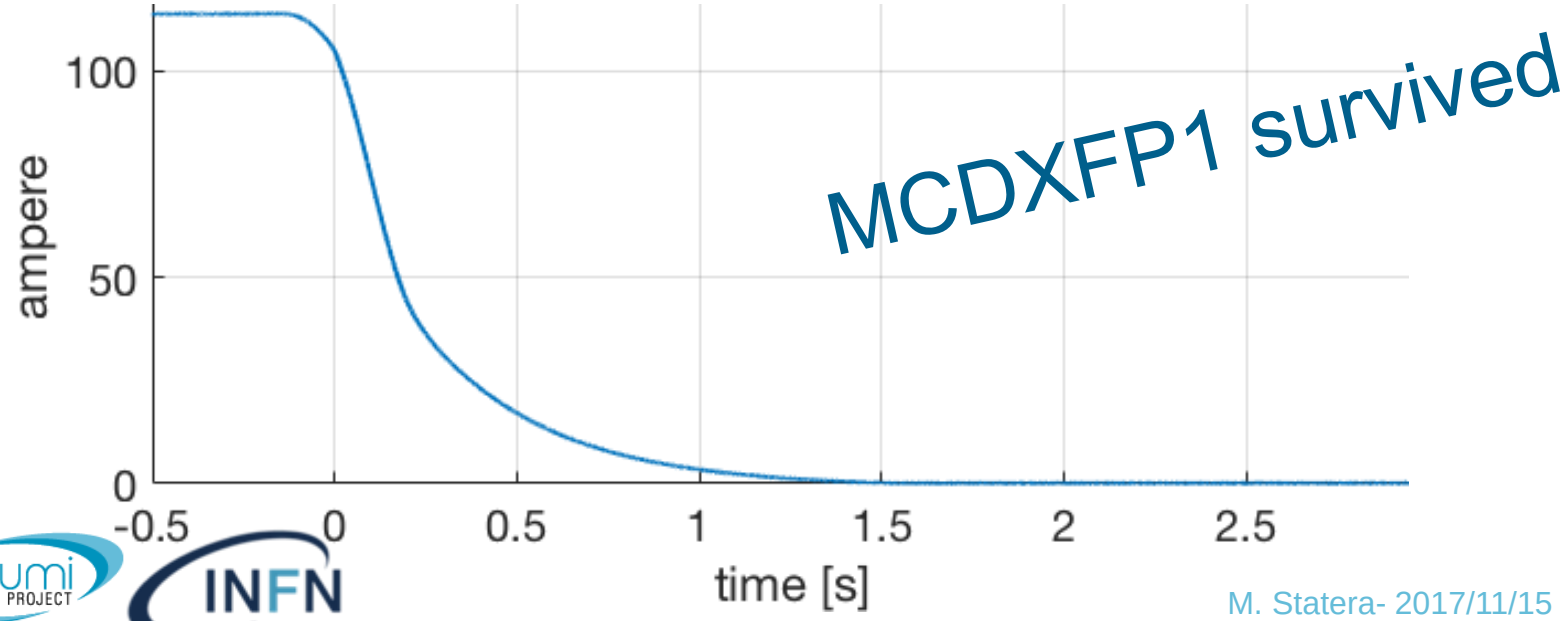
QUENCH PROTECTION SYSTEM UPGRADE

- 2 IGBTS working in parallel
- Same components as 10 kA switch (by A. Paccalini and M. Quadrio)

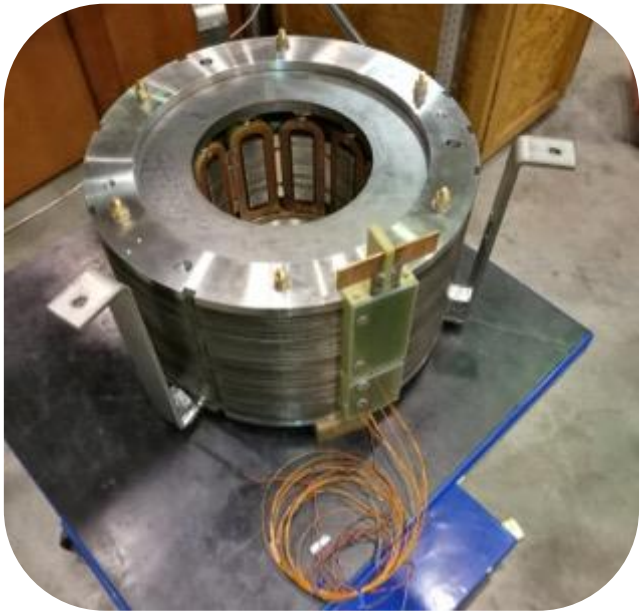


QUENCH PROTECTION (no ENERGY EXTRACTION)

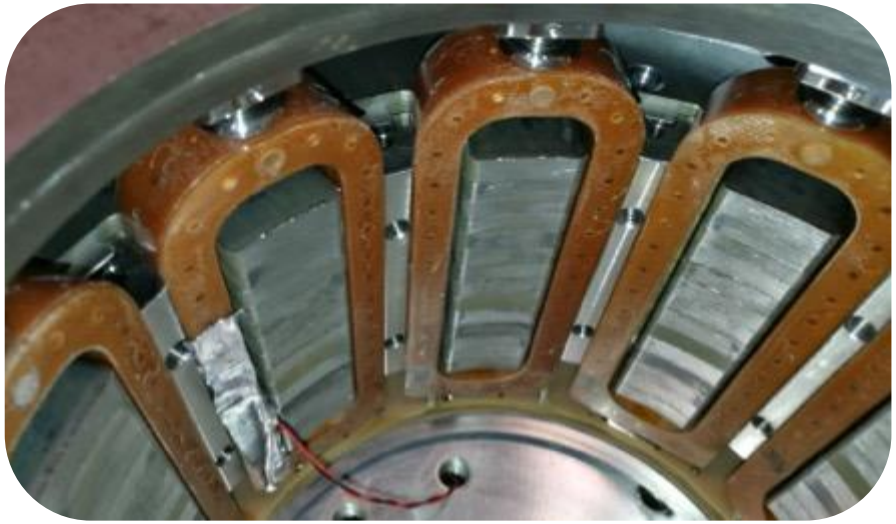
- Protection in LHC
  - Measuring current
  - Time range 60-180 ms
  - Max current: ultimate current (114 A)
- Protection at LASA
  - Quech induced by heater (and AlN insert)
  - Increase validation time
  - Reached **120 ms** and **140 ms** at **ultimate current**



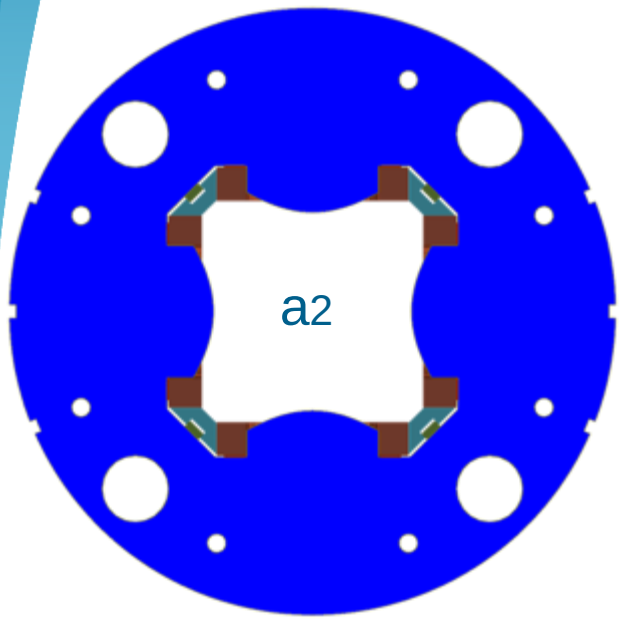
AFTER THERMAL CYCLE



- Detailed inspection on one side
- One defect on coil M10-14
- No detached wedges

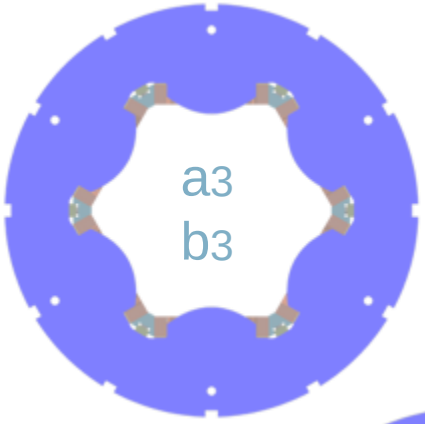


NEXT STEPS: MCTXFP1 AND MCQSXFP1

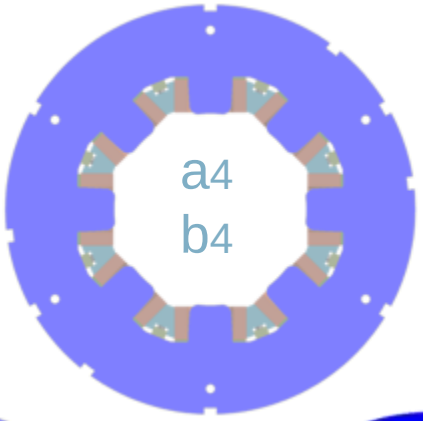


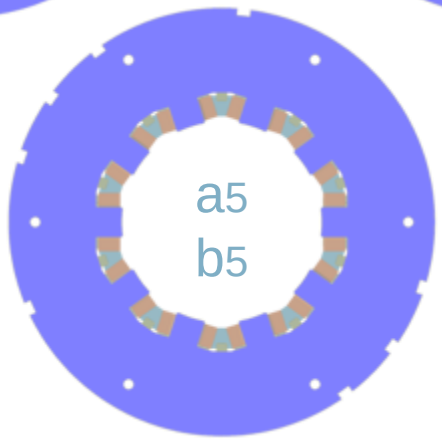
MQSXFP1

MCSXFP1

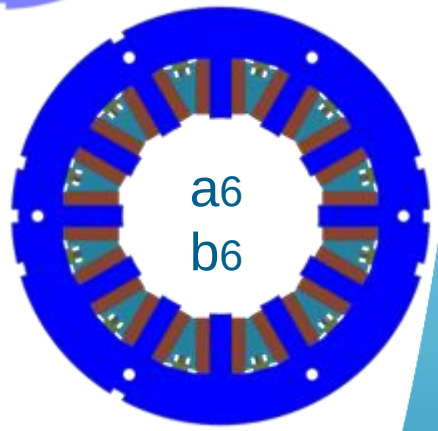


MCOXFP1



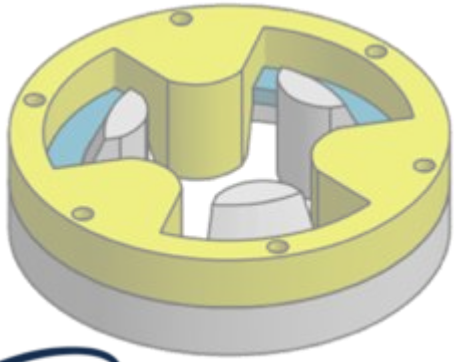


MCDXFP1



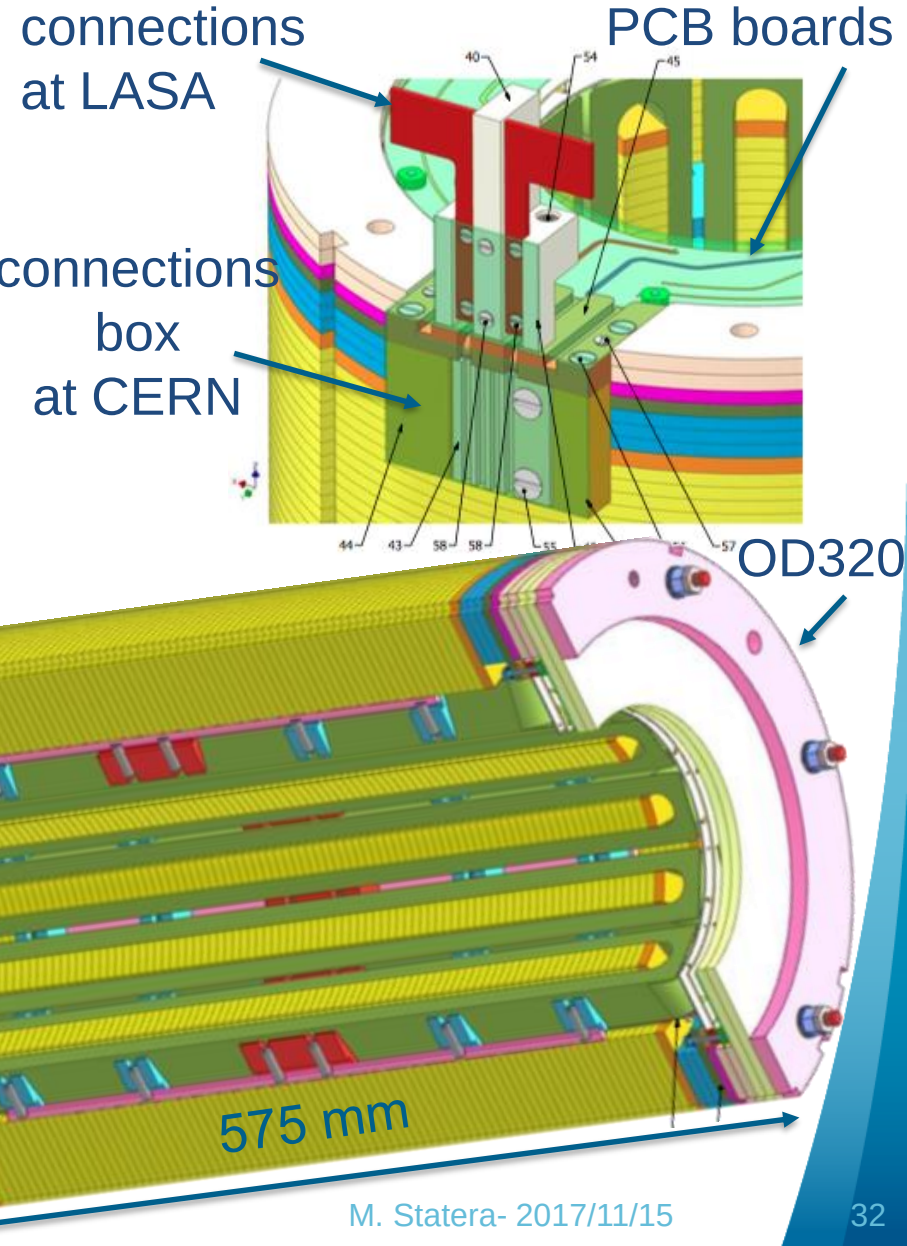
MCTXFP1

MgB_2 round coil



DODECAPOLE MCTXFP1

Normal (Skew)	nominal	simulation
length plate to plate	514 mm (166 mm)	575 mm (200 mm)
integrated field @ I_{op} @ r50 mm	0.086 Tm (0.017 Tm)	0.086 Tm (0.017 Tm)
magnetic length	430 mm	471 mm
energy @I_{op}	4.35 kJ	7,78 kJ
harmonics @I_{op}		B18= -6.2 B30= -3.5



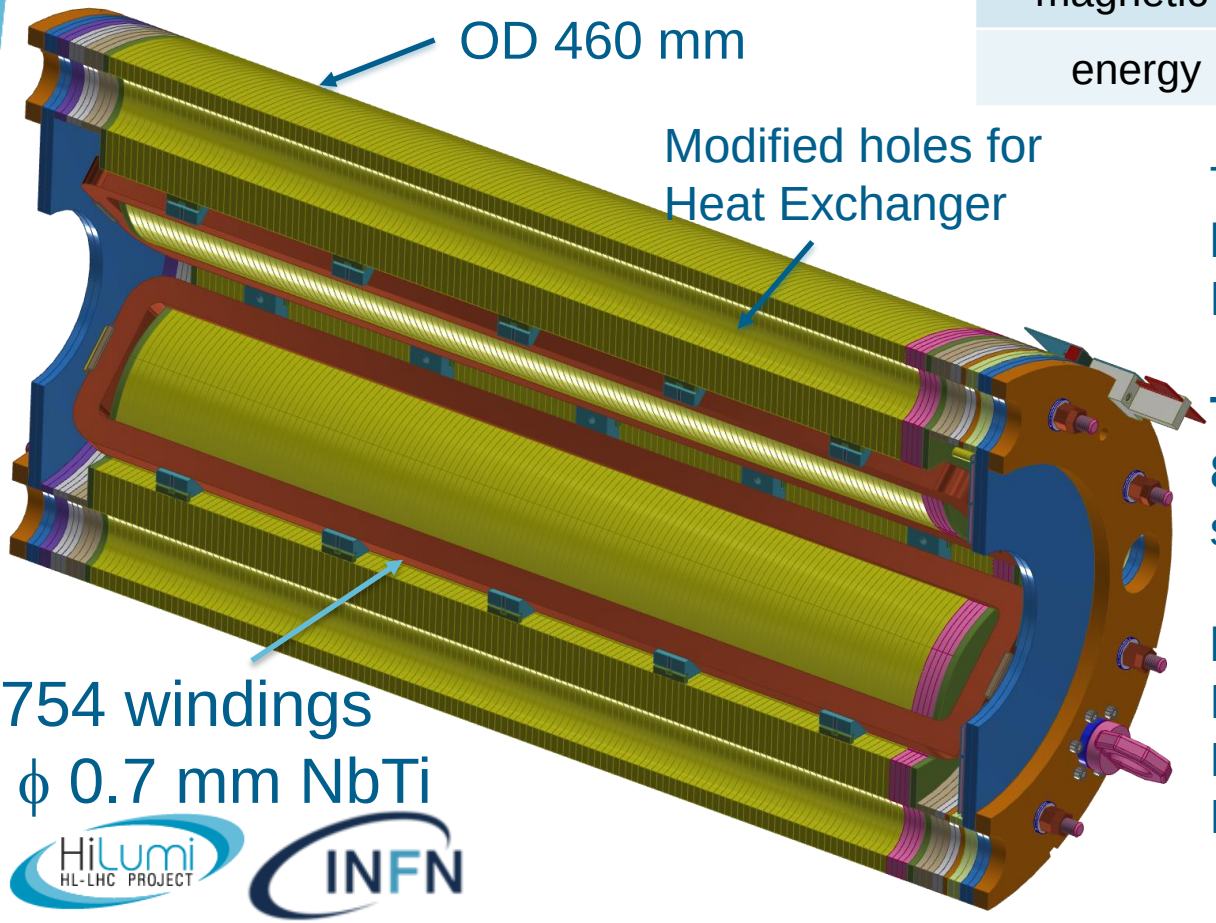
coils

- 432 windings
- Φ 0.5 mm NbTi
- 500 mm long
- Full BTS2 technology

SKEW QUADRUPOLE MCQSXFP1

- I_{op}=182 A - ϕ 0.7 mm NbTi
- protection: 1.5 Ω dump
- 50% energy extracted

	nominal	simulation
length plate to plate	903	814
integrated field @ I_{op} @ r50 mm	1.0 Tm	1.016 Tm
magnetic length	807 mm	671 mm
energy @I_{op}	24 kJ	36 kJ



The poles are modified hyperbolas
B(@z=0,r=50 mm) = 1.5 T

Transfer Function
8.86 Tm/kA ÷ 5.58 Tm/kA
saturation at ~0.3 I/Inom

harmonics
B6= -30 U at low current
B6= 30 U at I_{op}
B10= -8 U ÷ -12 U

DELIVERY AND TEST

- Tender approved by INFN
- contract sent to company – **arrived 4 weeks later**
- Start end of October (T_0)
- Updated schedule
  - 4/6/2018 MCTXFP1 delivered to LASA (T_0 + 7 months)
  - 4/9/2018 MCQSXFP delivered to LASA (T_0 + 10 Months)
- Test at LASA 2 months

INTEGRATION

Cold mass

- Magnet length vs magnetic d
- Position in the cold mass
- Alignment
- Electrical connections (box d
- Fix threads and nuts by resi
- Position and diameter for the

Power supply and protection

- Reduction of nominal current
  - But MCQSXFP1 (4P)
  - MCSXFP1 (6P) to be updated
- Quench protection w/o energ

Documentation

- All produced magnets are in
- Test reports and test summa
- Acceptance procedures
- Workflow
- MIPs in preparation

MCSXFP1 test report

Test summary of sextupole MCSXFP1

M. Statera, M. Sorbi
EDMS n. 1856594

Nominal superconductor current density	A/mm^2	2250
Nominal differential inductance	mH	122
Stored energy	kJ	1.434

I.! TEST SUMMARY

The test of the MCSXFP1 magnet [1-2] included:

- Qualification test at 2.17 K;
- Training at 4.2 K to ultimate current;
- Ramp rate tests;
- Transfer function measurement;
- Dynamic inductance measurement;
- Field quality at room temperature and at 1.9 K.

Summary of different phases is given in Table I.

TABLE I
PHASES OF TEST AND TIME NEEDED

Test phase	Date	Hours
Start date	15.February 2016	
End dateTotal time	26.February 2017	
Cool-down		**12 h**
Training		1 day
Protection studies		1 day
Magnetic measurements		~1 wk
Warm-up		~1 wk

II.! MAGNET AND TEST FEATURES

A.! General magnet features

This is the first prototype of the High Order corrector magnets; main parameters are given in Table II. Coil were manufactured at LASA with Nb-Ti 0.5 mm wire insulated by S2 (supplied by Bruker). The ground insulation of the coils is composed by G10 layers 0.2 mm and 1.0 mm thick; G10 is not qualified for HiLumi due to its low radiation hardness and will be replaced by qualified materials for the series. The update does not affect the electromechanical design. The magnet design also went through an iteration to reduce current at

B.! Test configuration

Main features of the test

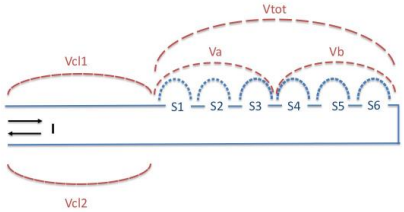
- Vertical test;
- LASA – small magnets facility;
- LASA, Milano, I.

Main features of protection

- Energy extraction with 0.5 W dump resistor;
- Detection threshold: differential 200 mV – total 1.5 V;
- Validation time of 20 ms;
- Relay closing time about 60 ms.

Voltage taps (see Fig. 1)

- On each coil;
- Total voltage;
- Current leads;
- All voltage taps fully operational.



QUENCH PROTECTION

No dump	Quadrupole	Sextupole I_{nom}=134 A	Octupole	Decapole	Dodecapole
Peak voltage to ground	633 V	135 V	70 V	36 V	251 V
Hot spot temperature	132 K	164 K	131 K	122 K	147 K

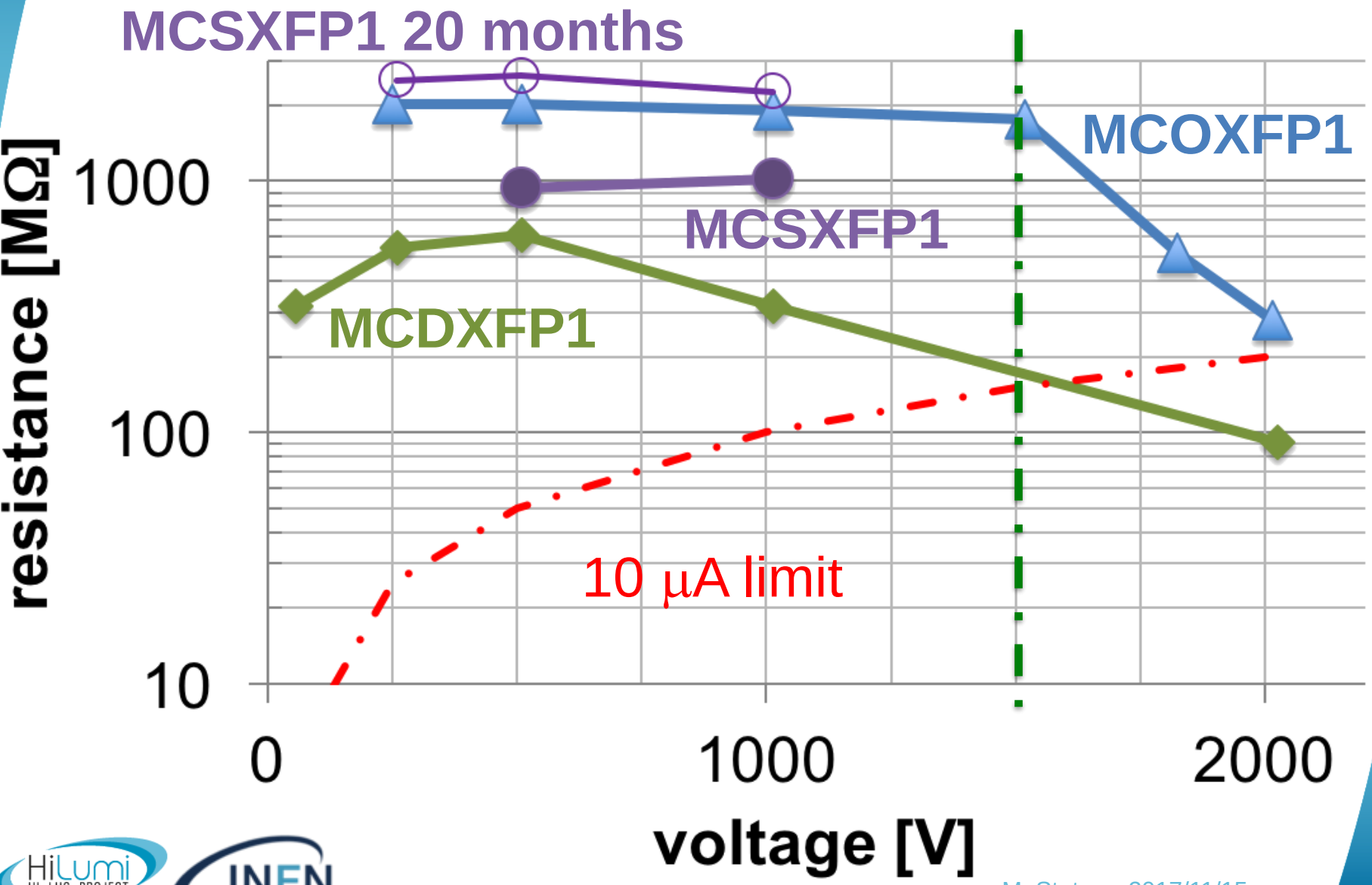
4P	Ground at magnet end	Ground at half dump	Ground at half magnet
0 Ω	633 V	633 V	422 V
0.5 Ω	474 V	447 V	316 V
1 Ω	407 V	357 V	271 V
1.5 Ω	358 V	287 V	238 V

QLASA simulations by V. Marinozzi

Room Temperature test
$V_{test}=(2 \times V_{mx} + 500) \times 2$

HO correctors tested
V_{test} 1.5 kV at RT
But 4P
6p to be reviewed

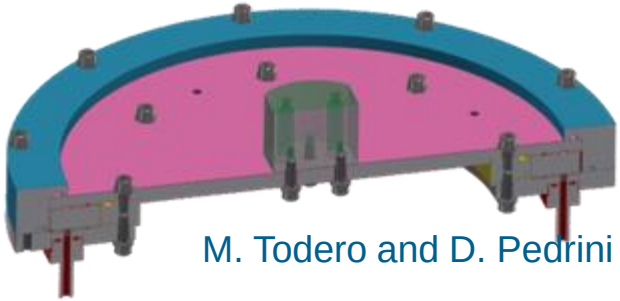
GROUND INSULATION



ROUND COIL MAGNET

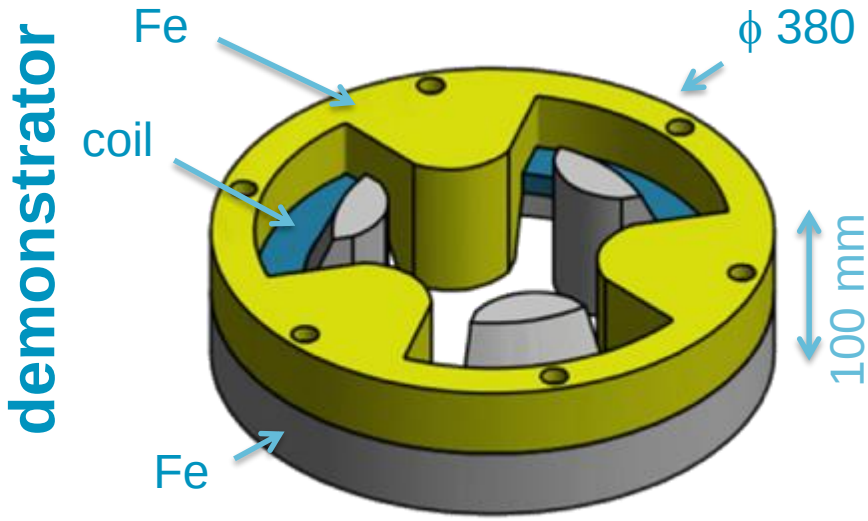
Demonstrator

- Mechanics design ongoing
- Winding machine **done**
- mould construction **done**



M. Todero and D. Pedrini

- First batch of insulated MgB_2 wire delivered at LASA

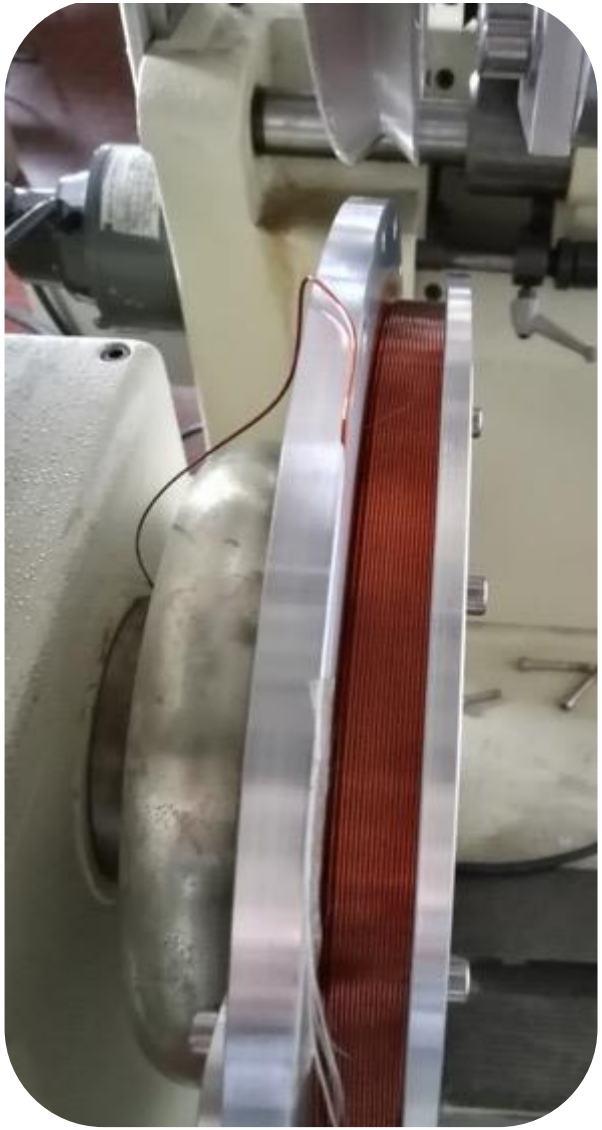


C. Uva

ROUND COIL MAGNET II

Test Cu coil

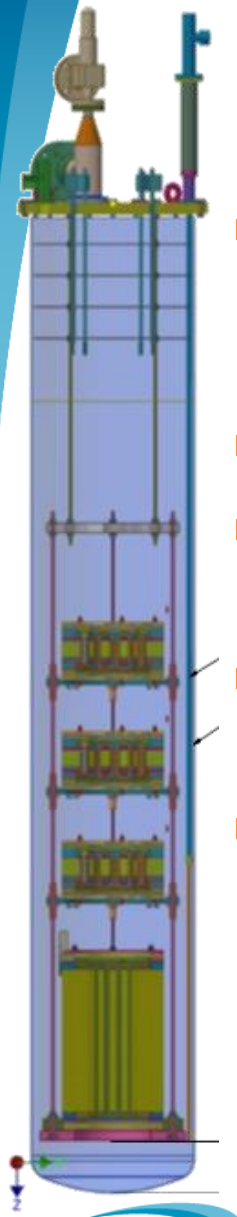
M. Quadrio and A. Paccalini



SCHEDULE

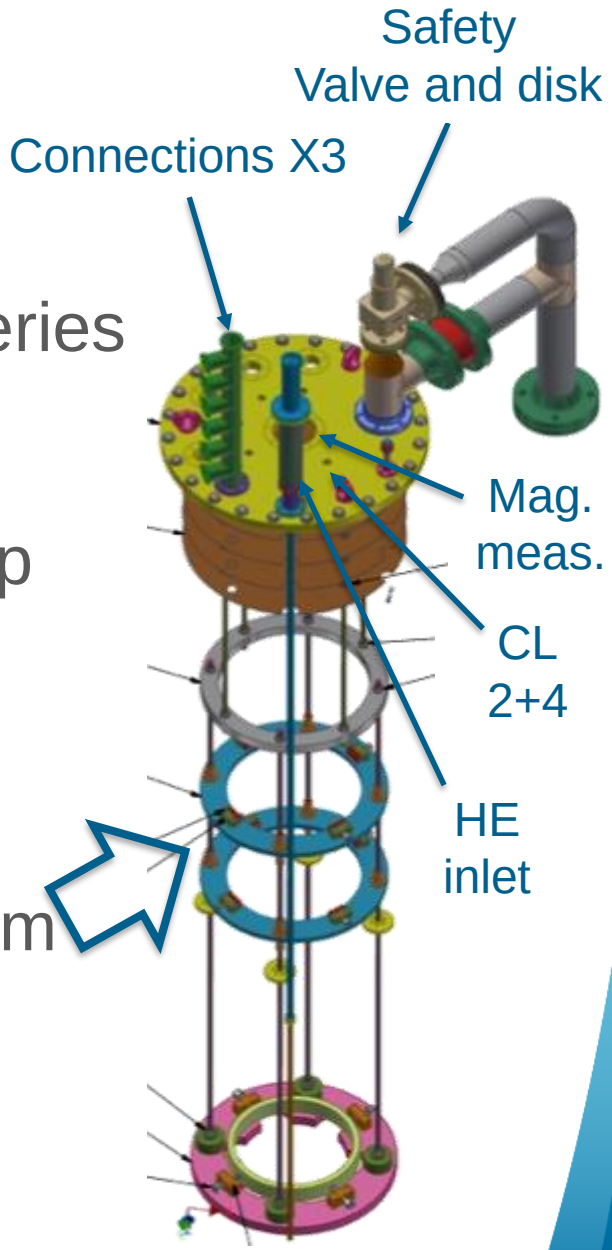
- Winding MgB_2 wire in 2017
- Impregnation in 2017
- Cold test of the coil 1Q2017
- Magnet assembly 2Q 2018

NEW CRYOSTAT



- Cryostat for testing MCTXFP1 (12P), MCQSXFP1 (4P) and series magnets
- 520 mm inner diameter
- About 3 m cold volume (with top flange insulation)
- Up to 4 magnets (3 possible configurations)
- Flange modification, thermal insulation, magnet support, room temperature connections.

Ordered end 2017



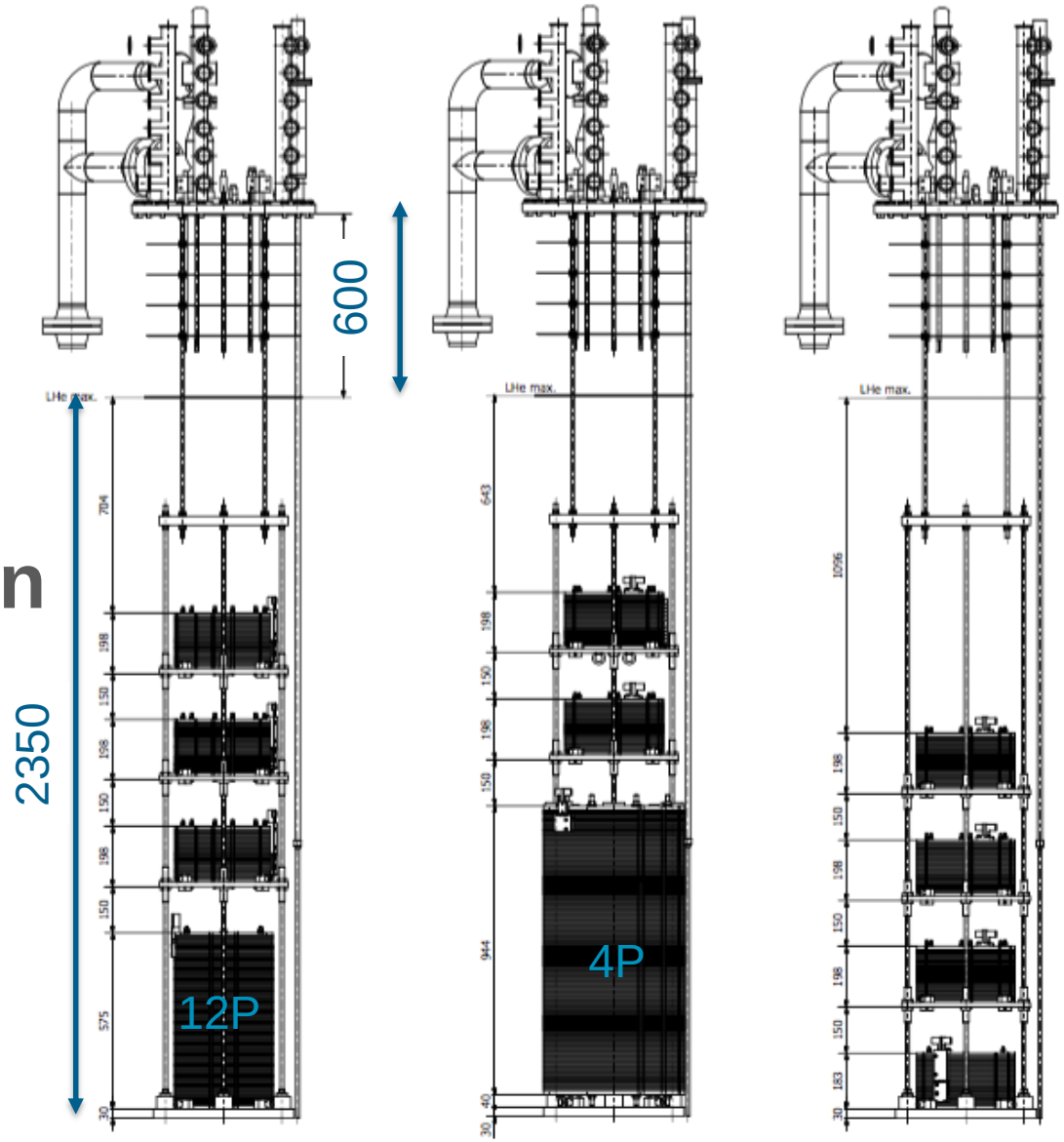
TEST CONFIGURATIONS

Prototypes

- Single magnet test

Series production

- 3 batches
  - 18 magnets
  - 2X12P 2X4P
  - 5 cooldowns



TEST STATION UPGRADE

- New cryostat all components ordered
- New main switch for power supply (fast solid state switch, $\Delta t<1$ ms) DONE
- New power supply for magnet test (200 A, 50 V)

  ORDER ONGOING
- New acquisition system for test monitoring

  ORDER ONGOING
- Installation of system for magnetic measurement at low/room temperature (supplied by CERN)

CONCLUSIONS

magnet		assembly	Cold test	Field measurement
MCSXFP1	6P	2015	2016	2016
MCOXFP1	8P	2016	2017	2017?
MCDXFP1	10P	2017	2017	2017?
MCTXFP1	12P	2018	2018	2018
MCQSXFP1	4P	2018	2018	2018

CONCLUSIONS AND NEXT STEPS

- MCOXFP1
  - Tested
- MCDXFP1
  - Assembled
  - First cooldown and thermal cycle results
- MCQSXFP1 and MCTXFP1: 2018
- MgB_2 RCSM
  - Winding end 2017
  - Test 2018
- New cryostat (MAGIX)
  - Flange and magnet support 1Q 2018

THANK YOU

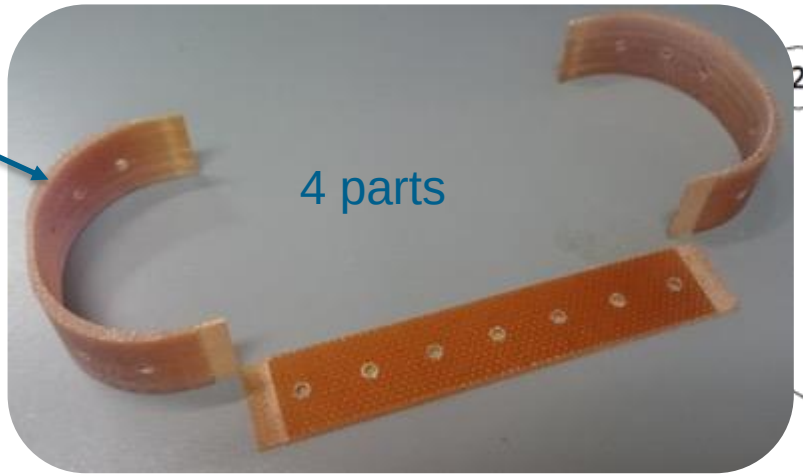
LASA team

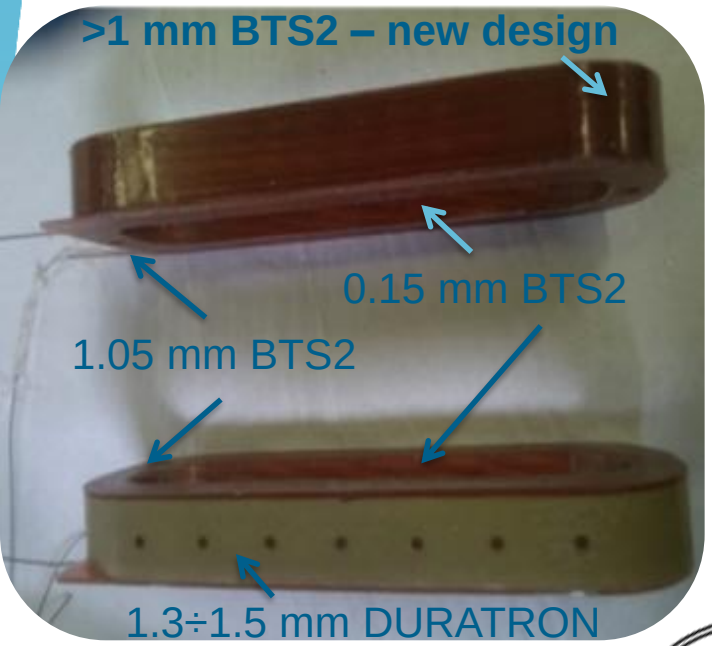
F. Alessandria, G. Bellomo, F. Broggi, S. Mariotto, A. Paccalini, D. Pedrini, A. Leone, V. Marinozzi, M. Quadrio, M. Sorbi, M. Statera, M. Todero, C. Uva

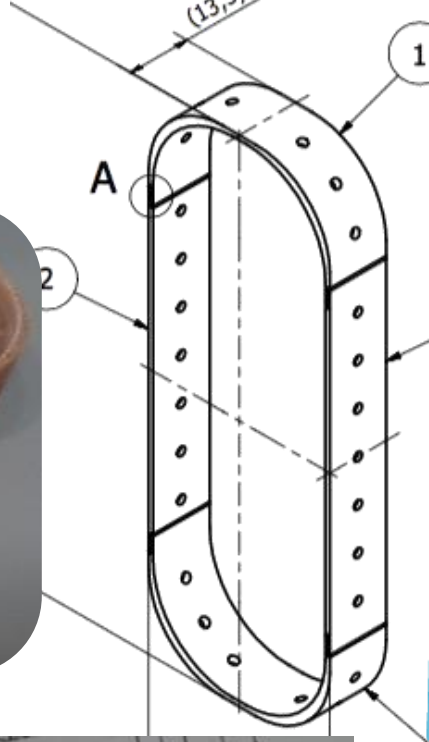
SPARE

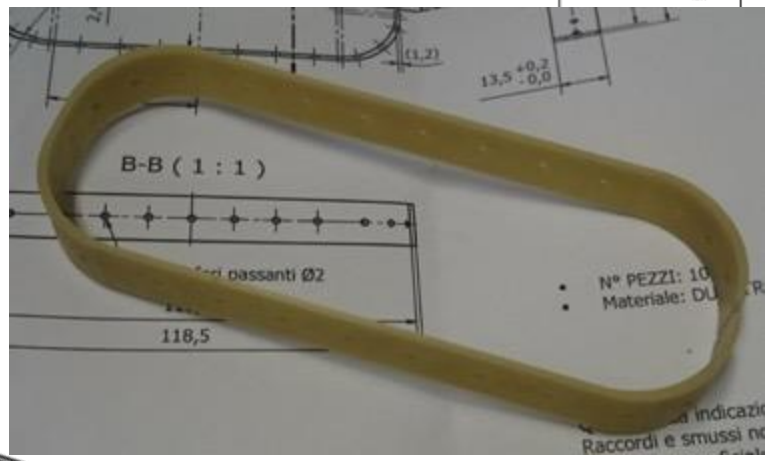
MCOXFP1 COILS - spares

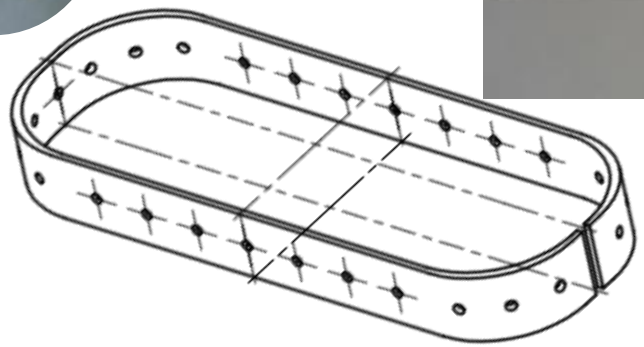
machined from bulk



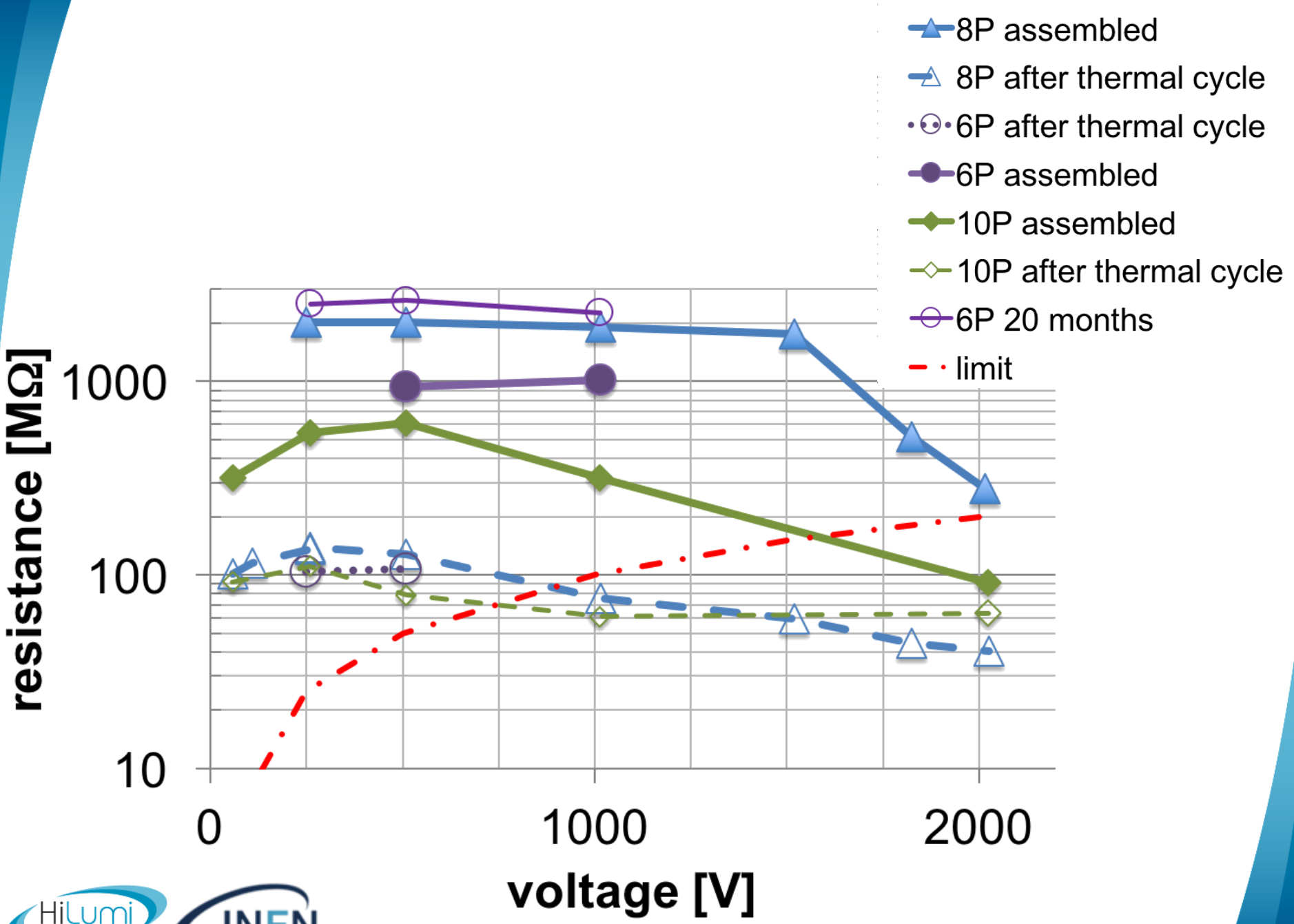








machined from bulk


8P assembled
8P after thermal cycle
6P after thermal cycle
6P assembled
10P assembled
10P after thermal cycle
6P 20 months
limit
resistance [MΩ]
1000
100
10
0
1000
2000
voltage [V]