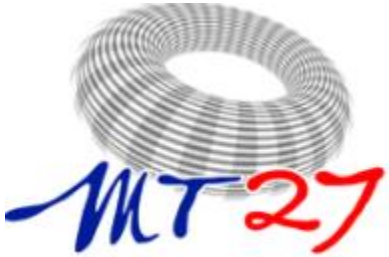


International Conference on Magnet Technology

Fukuoka, Japan
Nov. 15-19, 2021

Magnetic Measurements Results and Analysis of the First Batches of Superferric Magnets for the HL-LHC High Order Field Correction

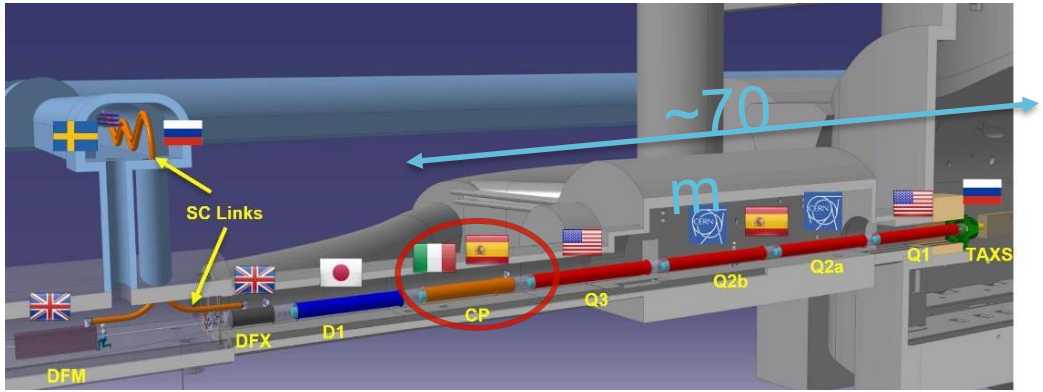
Ernesto De Matteis

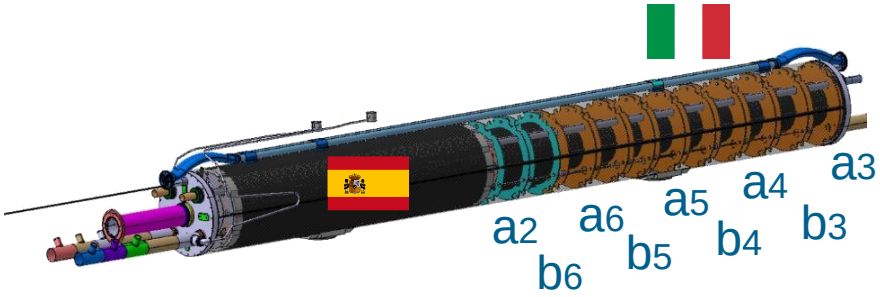
On behalf of INFN Milan – LASA

Outlines

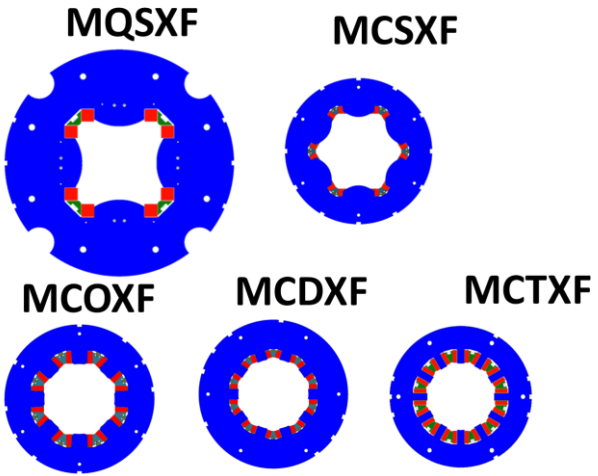
- High Order Correctors for HL-LHC
  - Superferric Design
- Measurement Setup
- Magnet families measurements results
- Results analysis and production monitoring
  - Field integral vs pole length
  - Reassembly effects
- Conclusions

High Order Corrector Magnets for HL - LHC





Five families of the corrector magnets, skew quadrupole, normal/skew sextupole, octupole, decapole and dodecapole order.

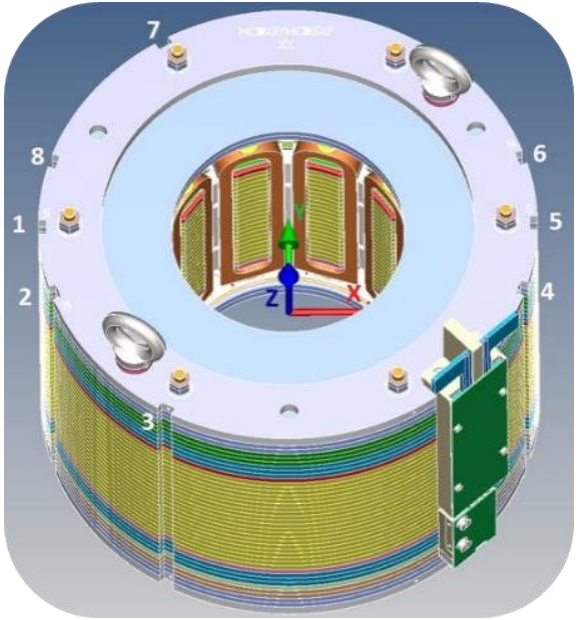


Corrector Package, a "prima" for super-ferric in a collider

Superferric - Magnet Design

- Electromagnetic and mechanical design ‘Superferric’
- Racetrack NbTi coils installed on iron laminations;
- Two different wires used to wind six different types of coils;

- The main advantage of the racetrack windings is to have a shorter fringe field areas considering the required integrated strengths.
- A disadvantage is the saturation of the iron that limits the maximum achievable field.



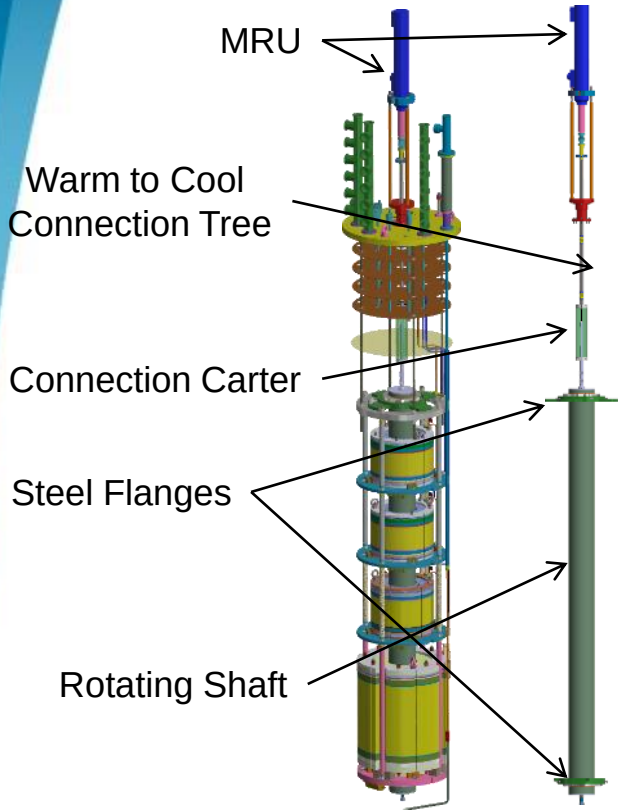
See also M. Statera presentation (WED-OR2-103-05)

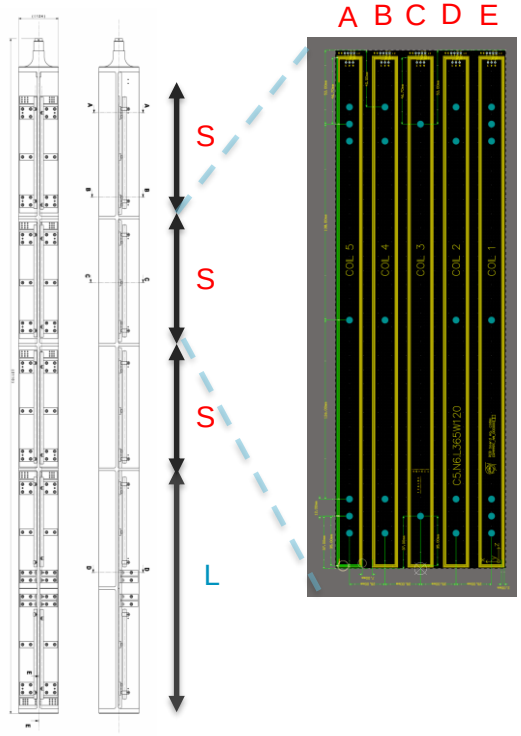
Measurement setup (1/2)

Rotating coil system (from CERN):

- Electronic rack
- 2 FDI (Fast digital Integrator)
- MRU motor unit (motor + encoder + slip rings)
- FFMM software (Flexible Framework for Magnetic Measurements)
- Magnetic meas. shaft

Measurement setup (2/2)





Tests at 4.2 K

Series Shaft (CERN)

G-10 t-beam internal support

- Diameter ~130 mm
- Measurement radius 55 mm

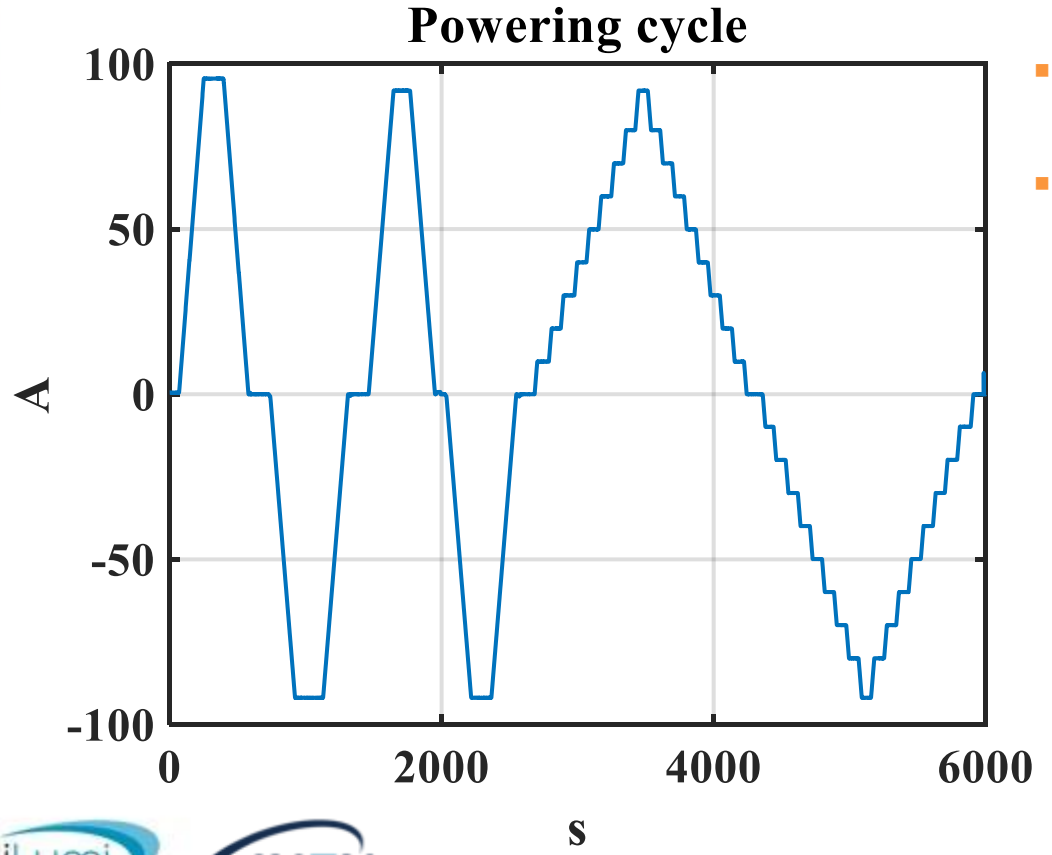
5 equal PCB

- 1 segment for each short magnet
- 2 segments for long magnets
- Active length of 355 mm
- Compensation of vibrations by averaging the measurements from coils in opposite position (A and E) except for the quadrupole (compensation scheme A, A-B-C+D)

Measured Magnets Families

- 5 magnet families:
  - Skew quadrupole (MQSXF);
  - Normal and skew sestupole (MCSXF/MCSSXF);
  - Normal and skew octupole (MCOXF/MCOSXF);
  - Normal and skew decapole (MCDXF/MCDSXF);
  - Normal and skew dodecapole (MCTXF/MCTSXF).
- First magnet batches already manufactured by industry and tested at LASA.
- Magnetic measurements during cold tests at 4.2 K (18 magnets).

Powering cycle for MM



- Two cycles up to +/- nominal current
- One stairs cycle up to +/- nominal:
  - 20 A steps for the quadrupoles;
  - 10 A steps for the others.

Quantity to be measured:

- Integrated field (BdL)
- Transfer function (bipolar)
- Field quality (<100 units)

MM Results - BdL

	Order	Magnet		Model	Measured at LASA	
			Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
Quadrupoles	2	MSQXF1	174	700.0	718.8	2.7
		MSQXF2			720.36	2.8
		MSQXF3			719.6	2.8
Sestupoles	3	MCSXF02	99	93.5	95.22	1.8
		MCSXF03			95.22	1.8
		MCSXF05			95.31	1.9
		MCSXF06			95.27	1.9
		MCSXF07			95.34	2.0
Octupoles	4	MCOXF03	102	70.7	71.59	1.3
		MCOXF04a			71.54	1.2
		MCOXF04b			71.48	1.1
		MCOXF07			71.59	1.3
Decapoles	5	MCDXF03	92	38.7	39.56	2.2
		MCDXF07			39.60	2.3
		MCDXF08			39.62	2.4
Long Dodecapoles	6N	MCTXF2	85	86.1	88.82	3.1
		MCTXF3			88.20	2.4
Short Dodecapoles	6S	MCTSXF01	84	17.2	17.33	0.6
		MCTSXF02			17.39	0.9

Field integral repeatability <0.2%

Field integral 1% to 3% w.r.t. model

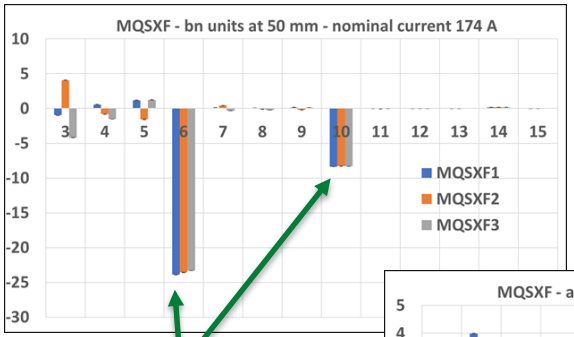
Field quality well below 100 units (max spec.)

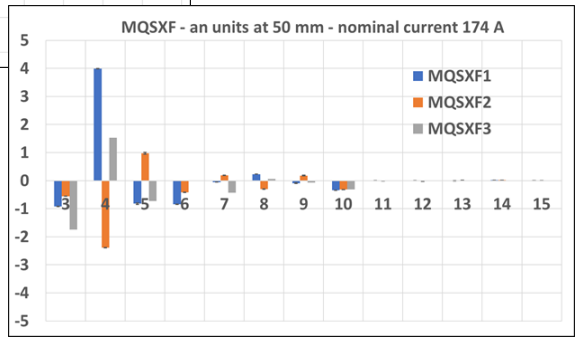
Field quality high reproducibility: few units

Quadrupoles – Results

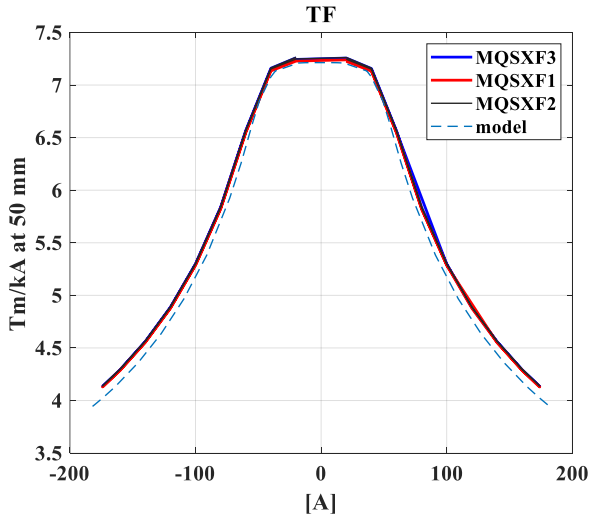
- Magnet-to-magnet repeatability among quadrupoles is 0.1%
- Difference wrt the model bigger than 2%
- Field quality within specs (<100 units)

Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
2	MSQXF1	174	700.0	718.8	**2.7**
	MSQXF2			720.36	**2.8**
	MSQXF3			719.6	**2.8**





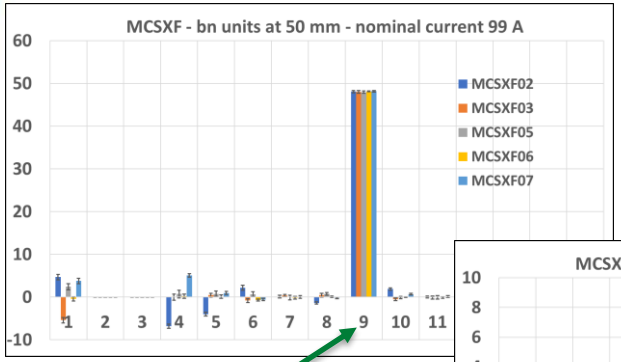
b6 and b10 well reproduced (+/- 1 units)

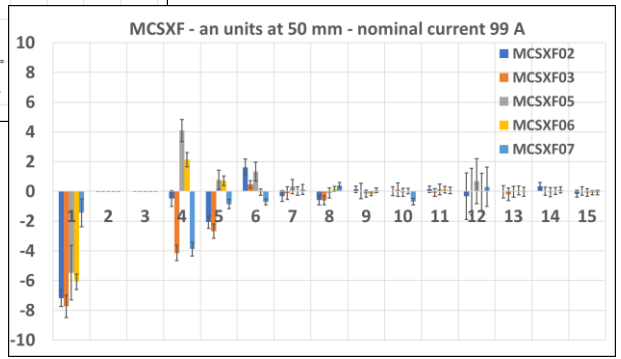


Sestupoles – Results

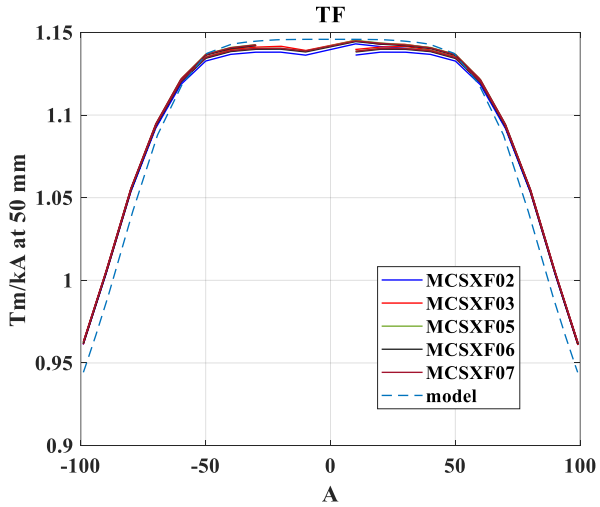
- Magnet-to-magnet repeatability among sestupoles is 0.2%
- Difference wrt the model of about 2%
- Field quality within specs (<100 units)

Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
3	MCSXF02	99	93.5	95.22	1.8
	MCSXF03			95.22	1.8
	MCSXF05			95.31	1.9
	MCSXF06			95.27	1.9
	MCSXF07			95.34	2.0



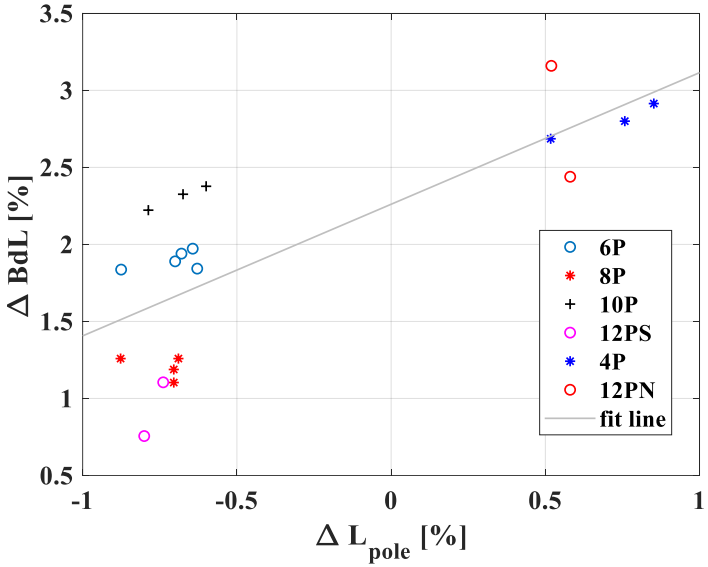


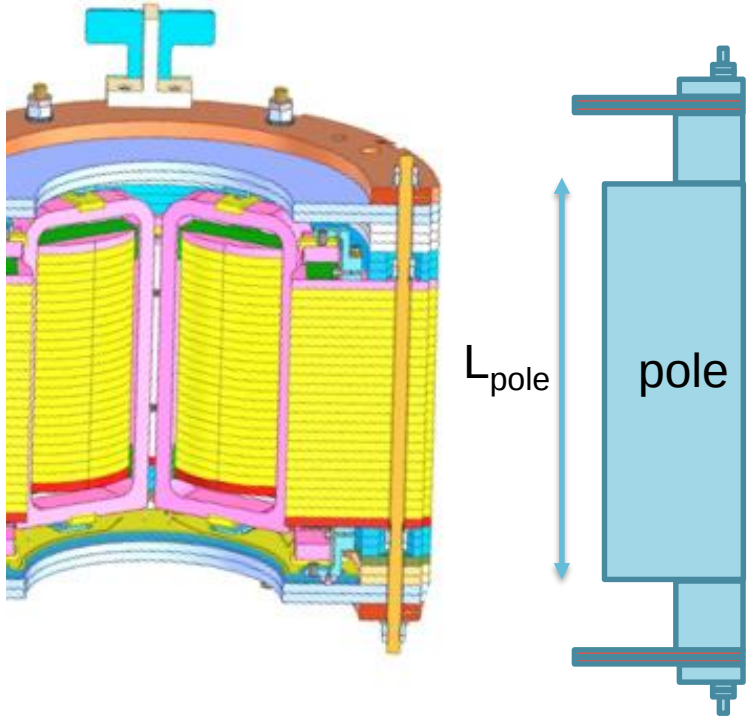
b9 well reproduced (<1 unit)



Integrated field vs pole length

- Clear Correlation between BdL and Pole length
- Same family, same region

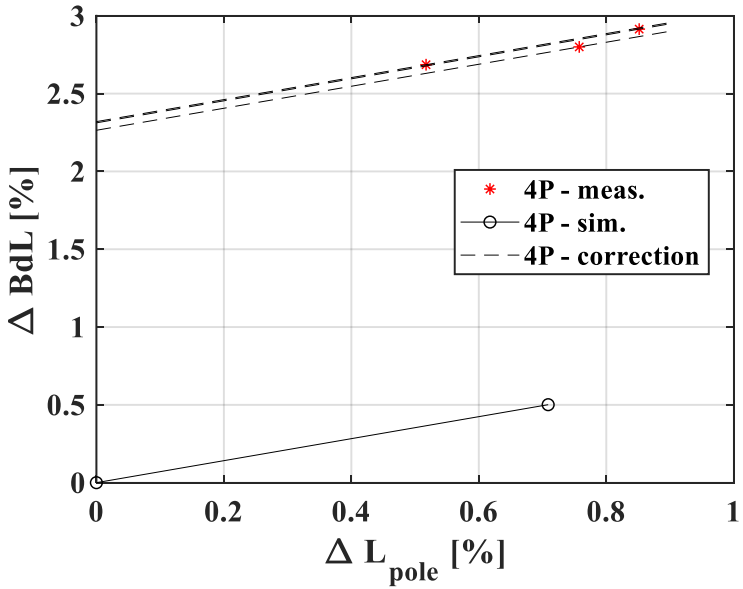




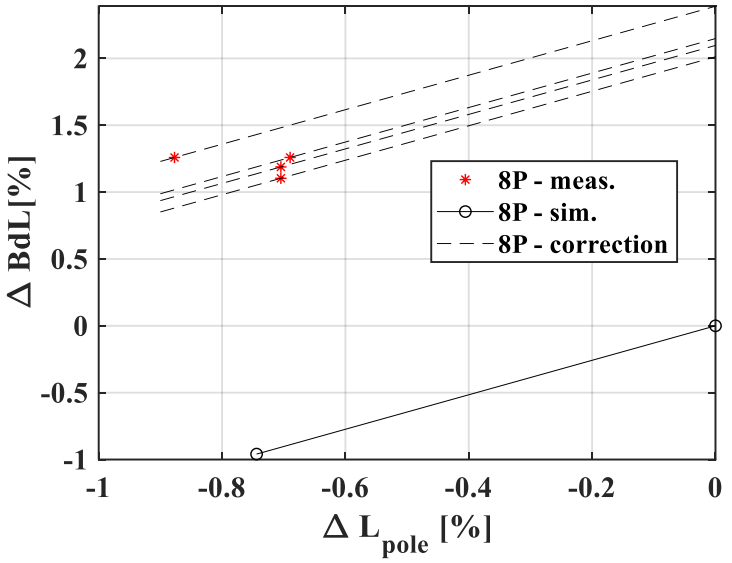
Integrated field vs pole length

- After correction: ~2% residual discrepancy measurement-simulations
- First candidate: BH curve of Iron (to be measured)

Quadrupoles MQSXF



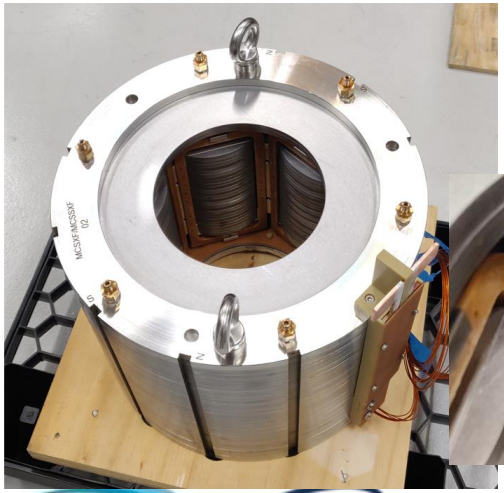
Octupoles MCOXF

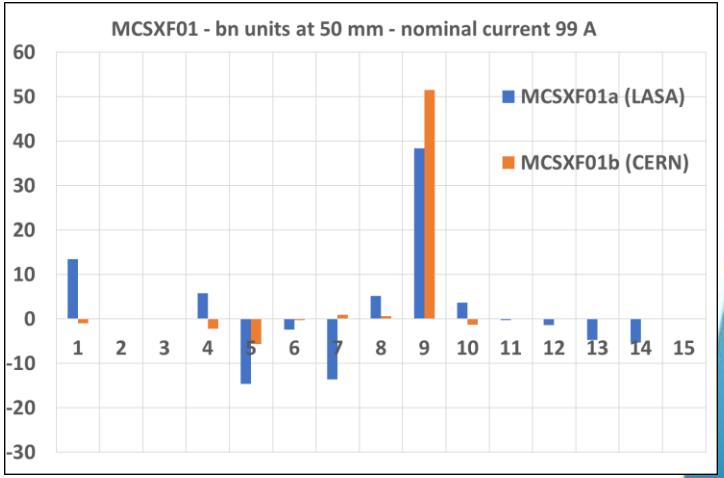


Reassembly effects

- First series sestupole, MCSXF01, reassembled for wedges preload modification
- MCSXF01a – tested at LASA
- MCSXF01b – tested at CERN
- Negligible effects of the reassembly for the BdL and the field quality

Order	Magnet		Model	Measured	
		Current [A]	BdL [T mm]	BdL [T mm]	Diff [%]
3	MCSXF01a (LASA)	99	93.5	95.29	1.9
	MCSXF01b (CERN)			95.84	2.4

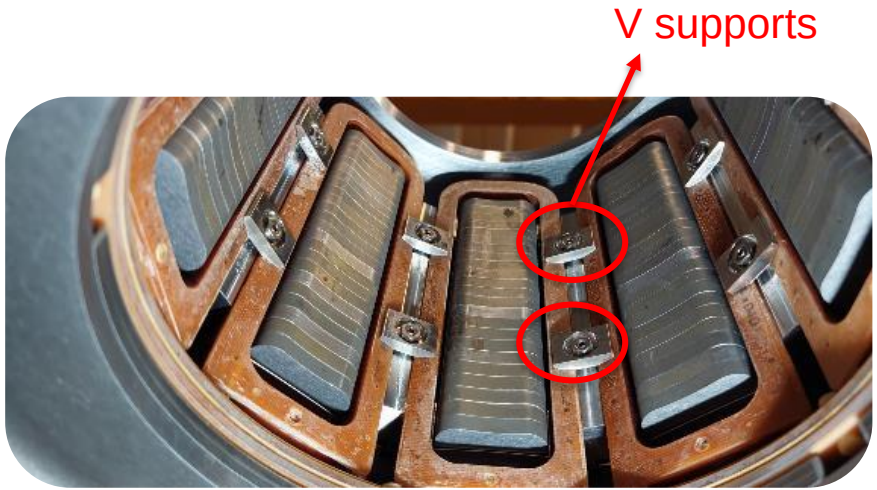


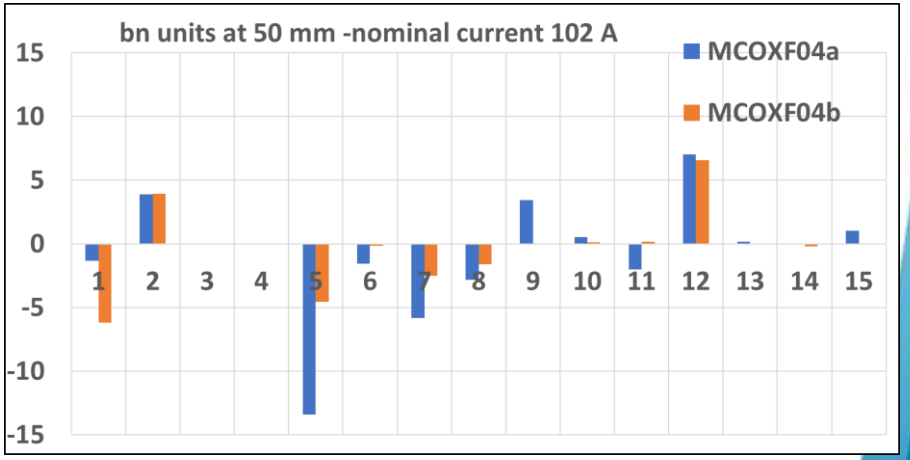


Reassembly effects

- Octupole MCOXF04 – additional V supports
- MCOXF04a and MCOXF04b tested at LASA
- Negligible effects on the BdL and on the field quality

Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
4	MCOXF04a	102	70.7	71.54	1.2
	MCOXF04b			71.48	1.1





Conclusions

- Magnetic measurements of the first HO corrector series magnet batches:
  - 18 magnets measured at LASA
  - Field integral repeatability <0.2%;
  - Field integral 1% to 3% w.r.t. model;
  - Field quality is well within specs (multipoles<100 units) for all the magnets.
- Results Analysis:
  - Clear Correlation between BdL and Pole length
  - 2% residual discrepancy measurement-simulations after correction (BH curve of Iron is the candidate)
- Production monitoring:
  - Negligible effects of the reassembly on the magnetic performance.
- 27 magnets still to be tested out of the 54 total (8 tested at CERN).

Thanks for your attention!

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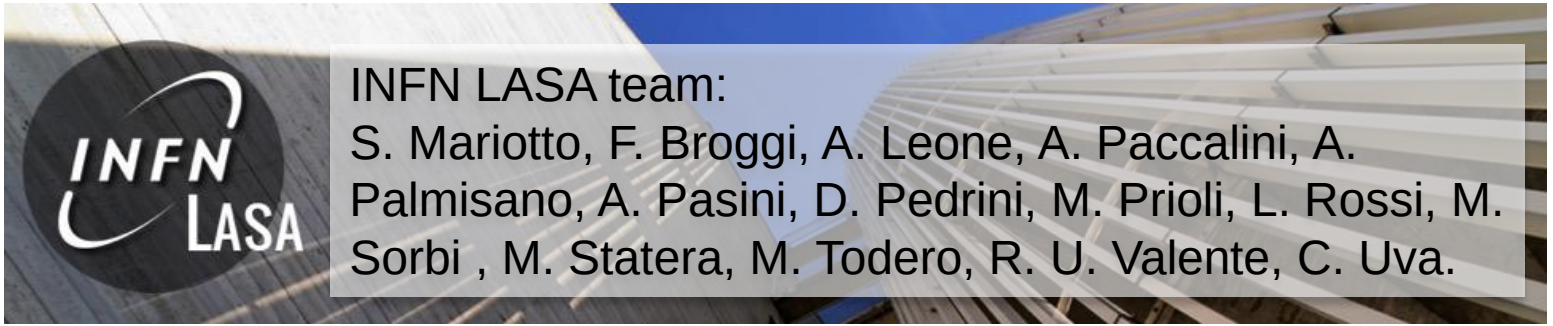


INFN LASA team:
S. Mariotto, F. Broggi, A. Leone, A. Paccalini, A. Palmisano, A. Pasini, D. Pedrini, M. Prioli, L. Rossi, M. Sorbi , M. Statera, M. Todero, R. U. Valente, C. Uva.

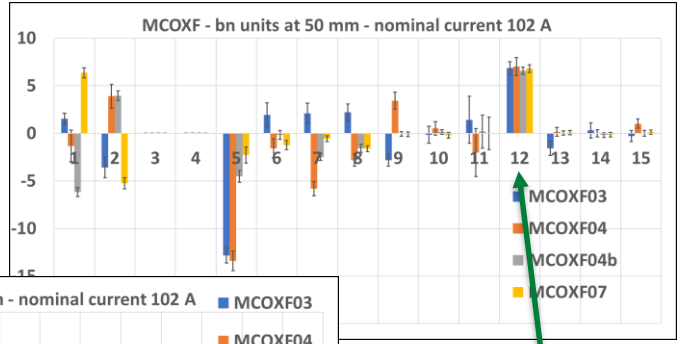
CERN colleagues:
L. Fiscarelli, E. L. Gautheron, A. Musso, E. Todesco

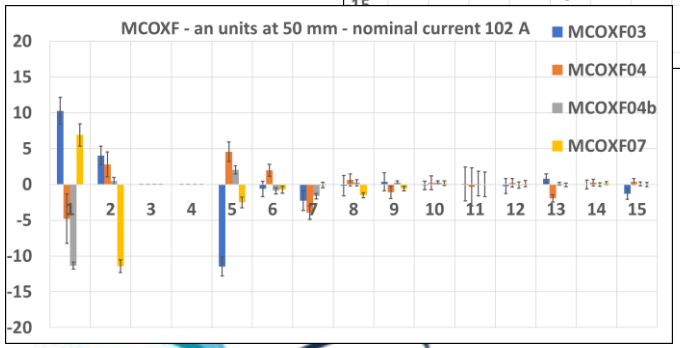
Spare slides

Octupoles – Results

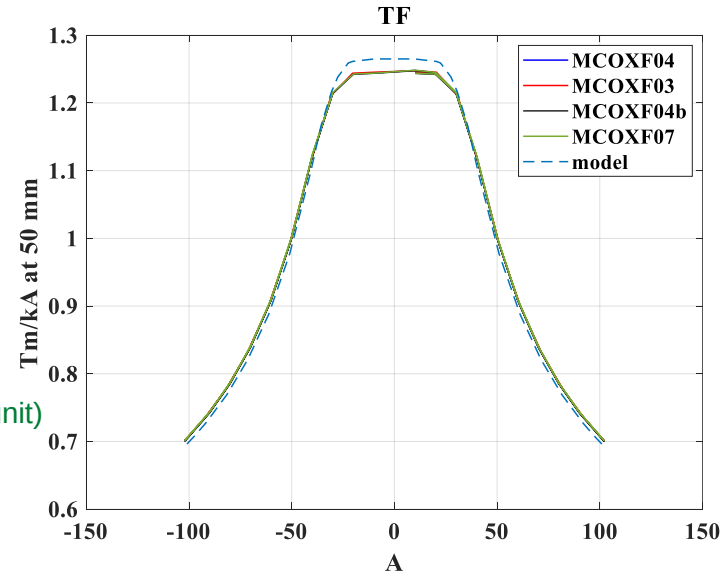
- Magnet-to-magnet repeatability among octupoles is 0.1%
- Difference wrt the model bigger than 1%
- Field quality within specs (<100 units)

Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
4	MCOXF03	102	70.7	71.59	**1.3**
	MCOXF04			71.54	**1.2**
	MCOXF07			71.59	**1.3**





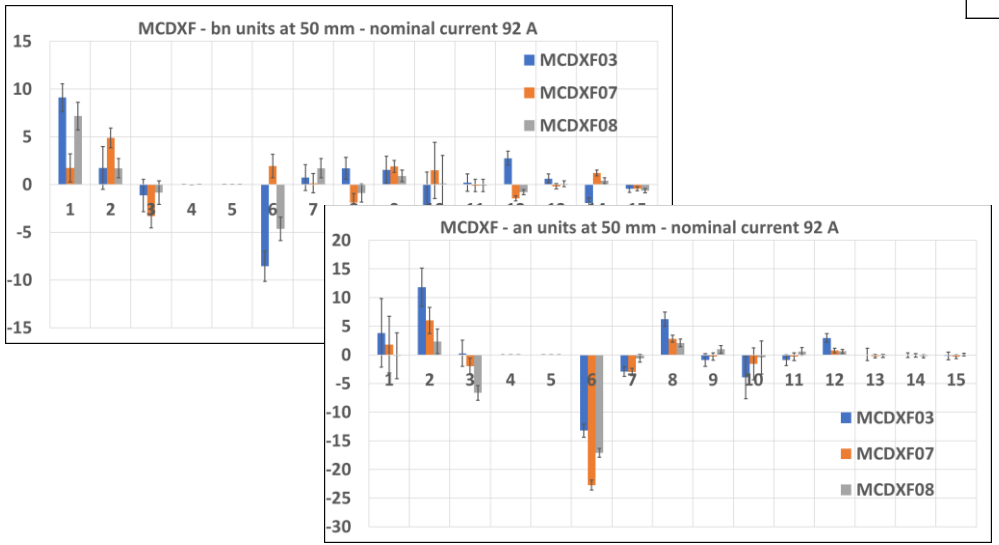
b12 well reproduced (<1 unit)

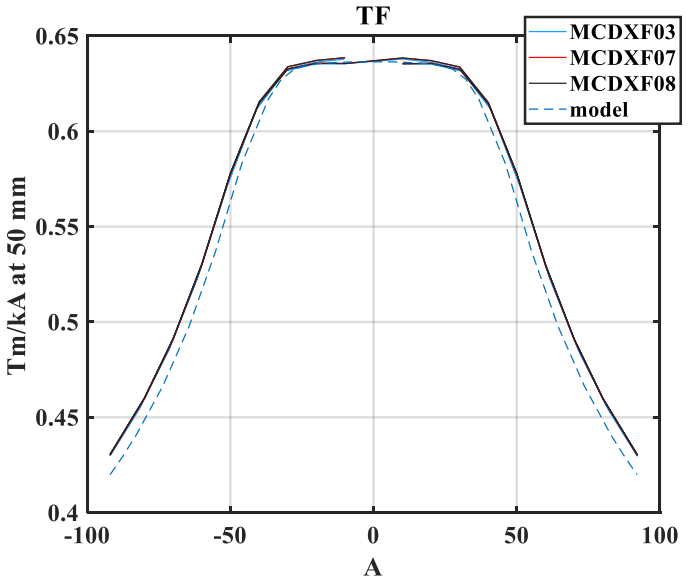


Decapoles – Results

- Magnet-to-magnet repeatability among decapoles is 0.2%
- Difference wrt the model bigger than 2%
- Field quality within specs (<100 units)

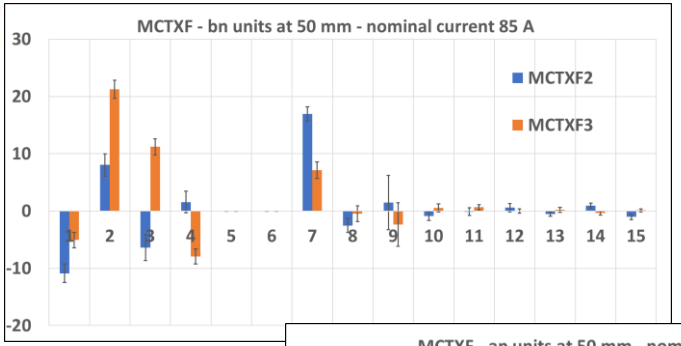
Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
5	MCDXF03	92	38.7	39.56	**2.2**
	MCDXF07			39.60	**2.3**
	MCDXF08			39.62	**2.4**

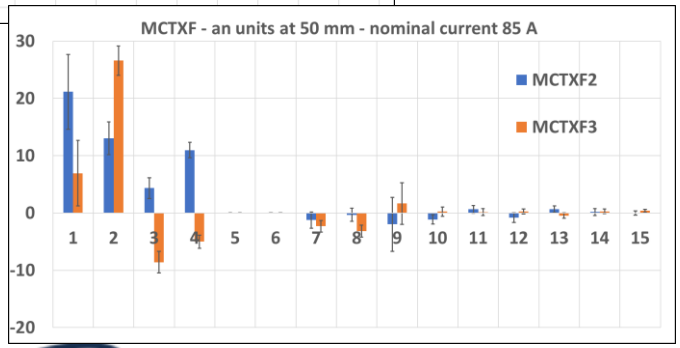




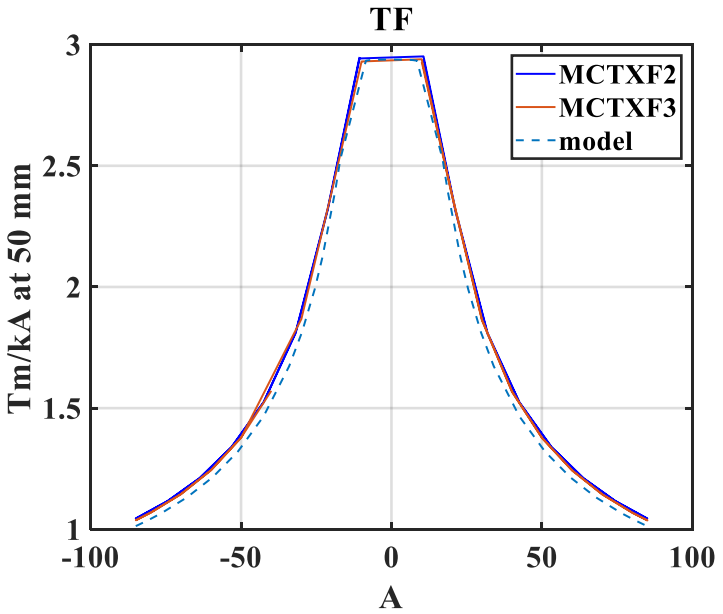
Normal Dodecapoles – Results

- Difference wrt the model bigger than 2%
- Field quality within specs (<100 units)





Order	Magnet		Calculations	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
6L	MCTXF2	85	86.1	88.82	**3.1**
	MCTXF3			88.20	**2.4**



Skew Dodecapoles – Results

- Difference wrt the model less than 1%
- Field quality within specs (<100 units)

Order	Magnet		Model	Measured at LASA	
		Current [A]	BdL [T mm]	BdL [T mm]	diff [%]
6S	MCTSXF01	84	17.2	17.33	**0.6**
	MCTSXF02			17.39	**0.9**