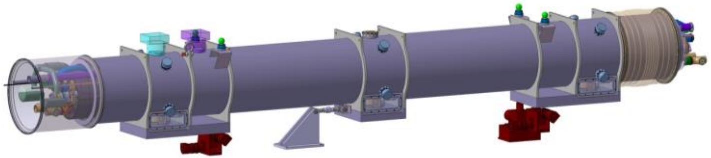
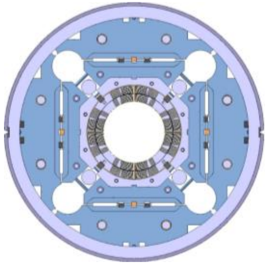
Field quality and integrated gradient in MQXFB





Lucio Fiscarelli, Susana Izquierdo Bermudez, Piotr Rogacki, Mariano Pentella,

Carlo Petrone, Franco Mangiarotti, Guy Deferne, Ricardo Beltron,

and all TE/MSC/TM&LMF colleagues

13th HL-LHC Collaboration Meeting, Vancouver 25-28 September 2023

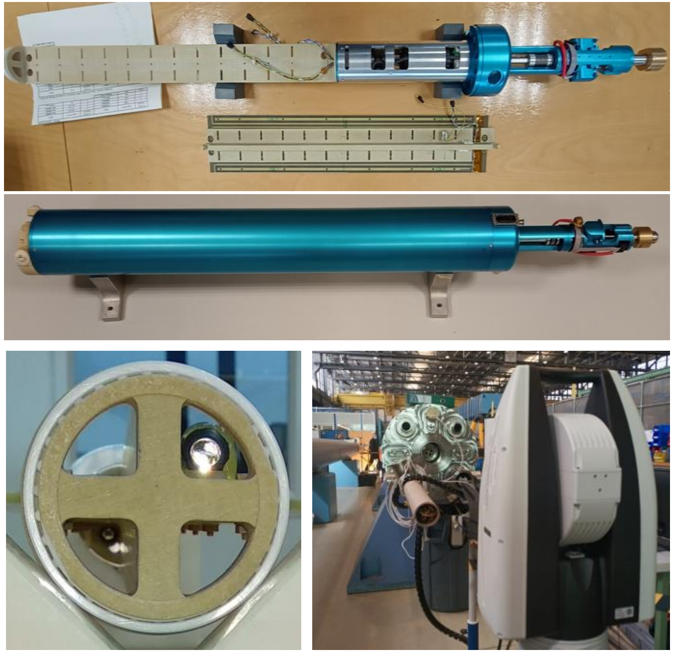
Content

- Magnetic measurement systems
- Standard magnetic tests
- Available measurements
- Main results:
  - Transfer function
  - Field quality
- Additional results

Measurement systems and standard tests

Measurement system at ambient temperature

- Rotating coil scanner
  - Measurement length 600 mm
  - 13 positions to cover the MQXFB
  - Measurement radius 50 mm
  - PCB for the coils
  - On-board tilt sensor and optical targets
- A full scan of the 8-m-long magnet takes 1.5 hours approximately



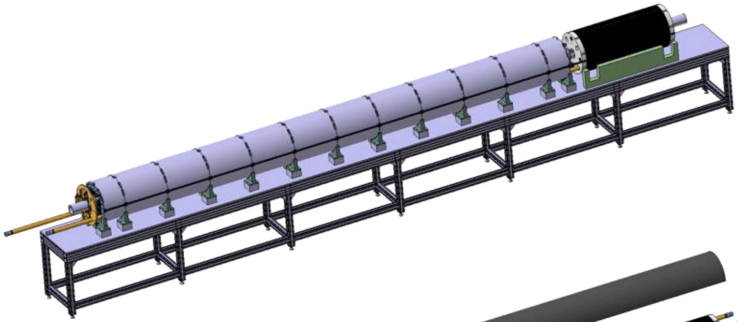
Development of a rotating-coil scanner for superconducting accelerator magnets, https://doi.org/10.5194/jsss-9-99-2020

HiLumi HL-LHC PROJECT CERN

Magnetic tests at ambient temperature

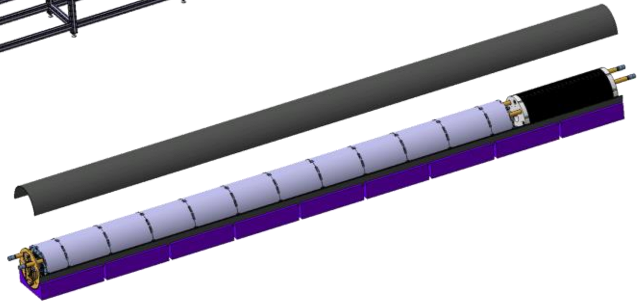
Check during magnet assembly

- Coil-pack
- Centering
- Loading




Alignment during cold-mass assembly

- Angular alignment before welding of end covers and feet

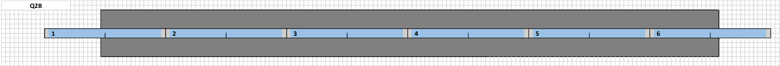



On the final cold-mass assembly

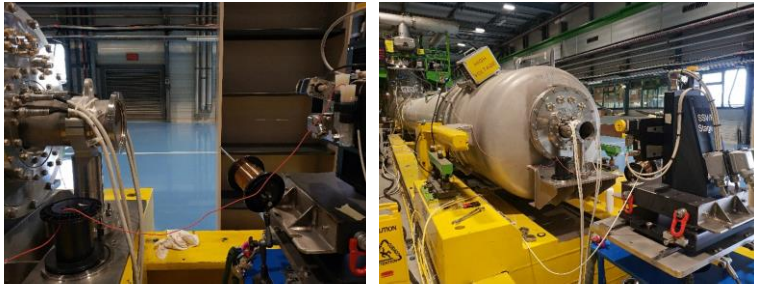
- Final measurement and alignment wrt reference points


Measurement systems at cryogenic temperature

- **Rotating-coil chain**
  - 6 segments measuring in parallel
  - Length 1.3 m each
  - Radius 50 mm
  - PCB for the coils
  - Composite material for the structure

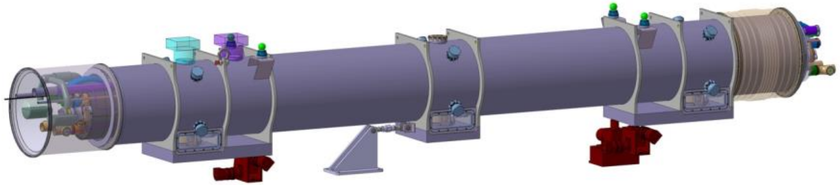


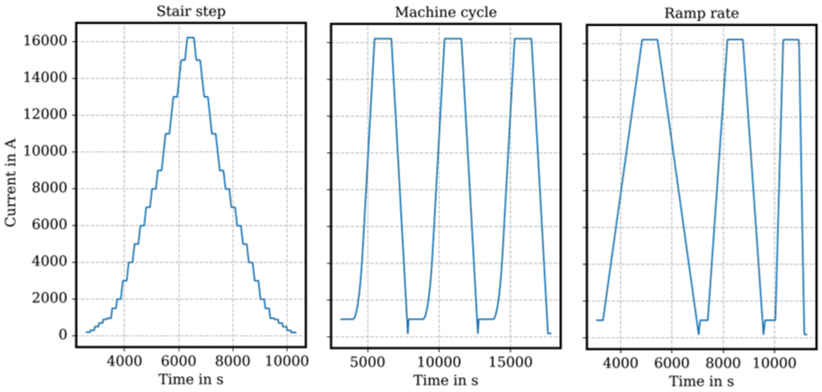
- **Single stretched wire**
  - X-Y tables
  - Wire tension control
  - Positioning accuracy ~1 μm



Magnetic tests at cryogenic temperature

- **Powering cycles** by using rotating coils
  - Stair step
  - Machine cycles
  - Variable ramp-rate

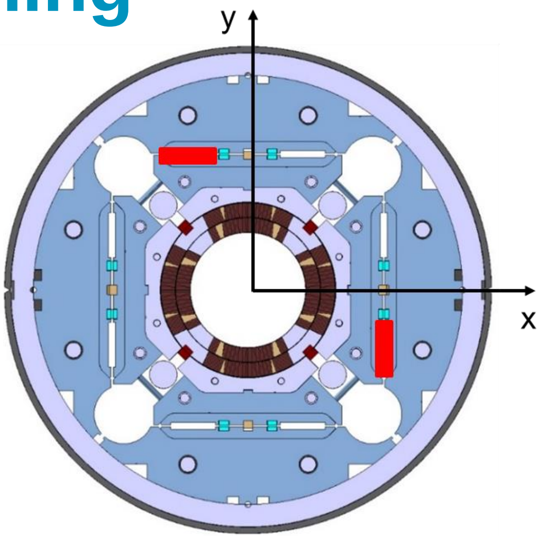




- **TF calibration** and **alignment** at nominal by using the stretched wire

Magnetic shimming

- The field quality of the MQXF magnets can be fine tuned by inserting iron blades in the loading slots.
- The position and the dimension of the iron blades can be computed based on:
  - The results of **magnetic measurements** at ambient temperature during magnet assembly
  - **Numerical calculations** to predict the effect



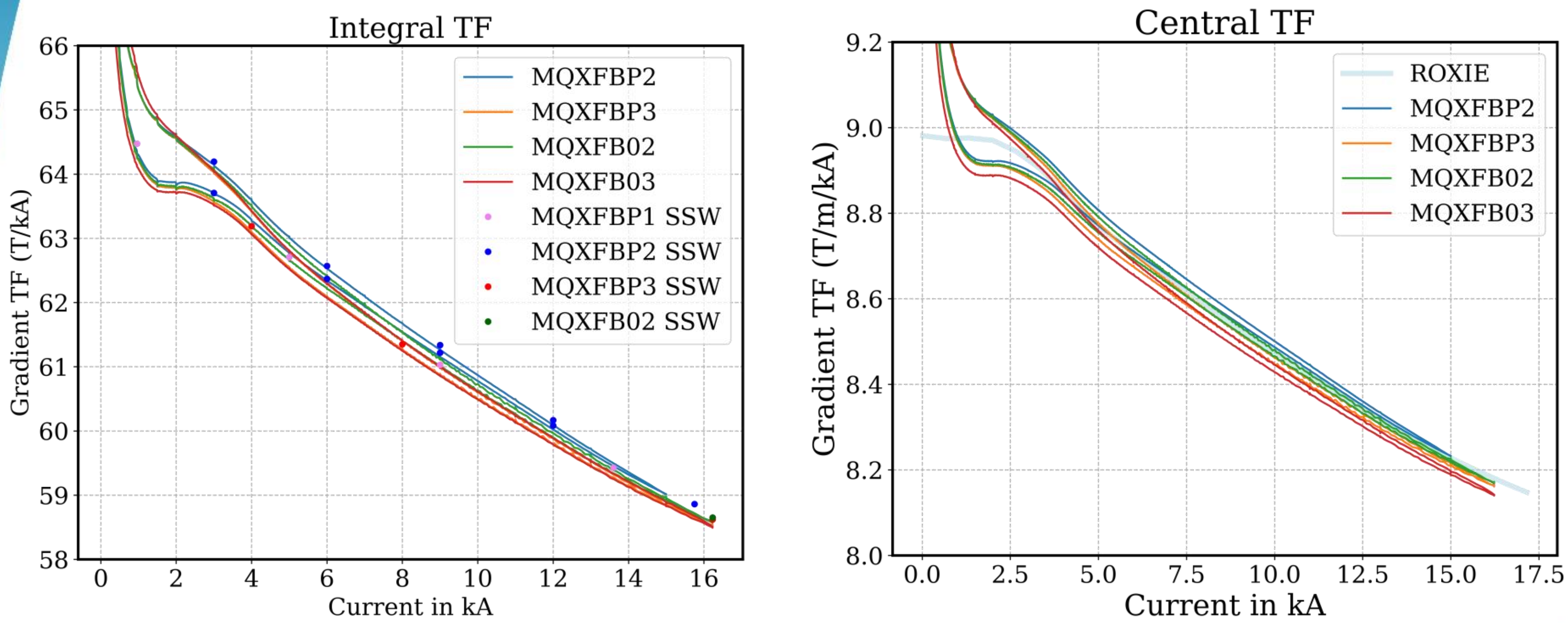
Computed correction using 9x58 mm shims in the bladder slots		
Order	b_n	a_n
3	1.90	-1.90
4	0.00	0.52
5	0.27	0.27

Main results

Performed measurements

	MQXFB**P1**	MQXFB**P2**	MQXFB**P3**	MQXFB**02**	MQXFB**03**	MQXFB**04**
Ambient temperature						
Coil pack	✔	✔	✔	✔	✔	✔
After centering	✔	✔	✔	✔	✔	
After loading	✔	✔	✔	✔	✔	
Cold-mass before	✔	✔	✔	✔	✔	
Cold-mass after	✔	✔	✔	✔		
Final cold-mass		✔	✔	✔		
At 1.9 K						
Stair-step cycle		✔	✔	✔	✔	
Machine cycle			✔	✔	✔	
Ramp-rate cycle			✔	✔	✔	
Stretched wire at nominal	✔	✔	✔	✔		

Transfer function vs current



Integral TF **accurately** measured with stretched wire at **few points.**
Integral and local TF measured **continuously** with rotating coils.

Transfer function

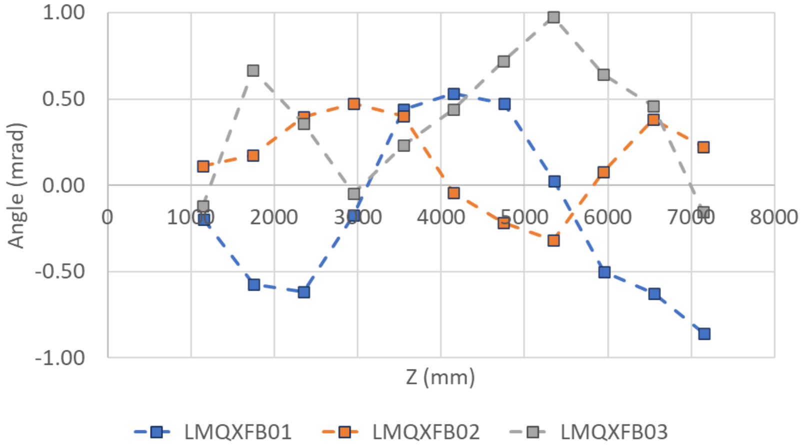
Transfer function of integral gradient (T kA^{-1})									
MQXFB	**P1**	**P2**	**P3**	**02**	**03**	**04**		**Average**	**Max-min**
At ambient temperature									
After coil pack insertion	63.098	62.992	62.949	63.053	62.988	62.965		63.016	24
After centering	63.238	63.122	63.087	63.204	63.103			63.151	24
After loading	63.394	63.359	63.328	63.407	63.458			63.389	20
Cold-mass before cold test		63.400	63.539	63.457	63.407			63.451	22
Cold-mass after cold test	63.432	63.524	63.610	63.598				63.541	28
Final cold-mass		63.646	63.459	63.586				63.564	29
At 1.9 K and nominal current									
At 1.9 K with rotating coils			58.526	58.579	58.500				
At 1.9 K with stretched wire	58.562*	58.708*	58.620	58.649	58.582**			58.624	**25**
Δ to average at amb. temp.	1	-5	-10	3	11				
Δ to average at 1.9 K	-11	14	-1	4	-7				

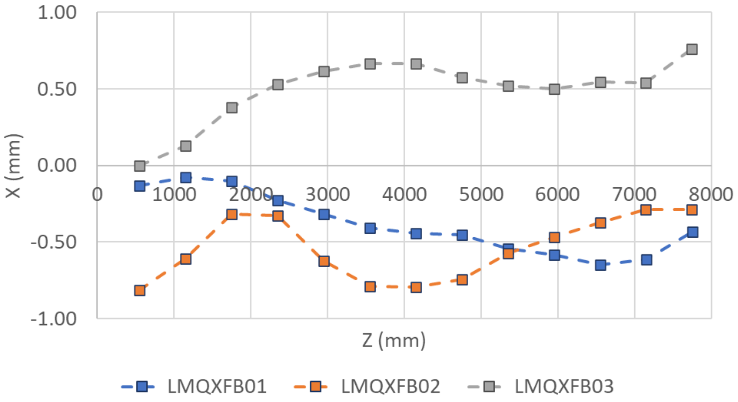
* Extrapolated from a measurement at lower current. ** Measured with rotating coil then cross calibrated.

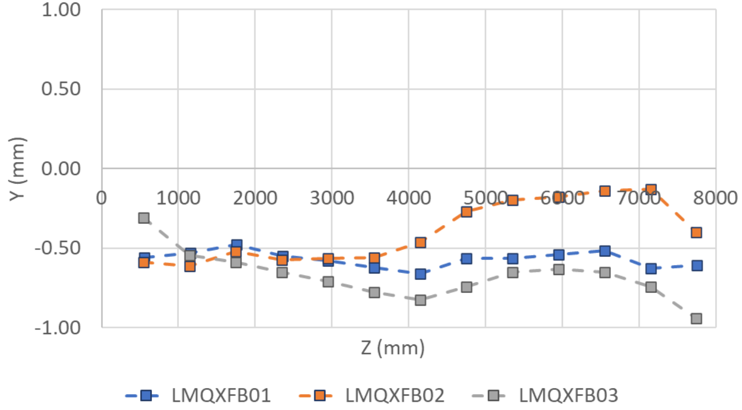
The integrated gradient at the nominal current of **16230 A** is **951.47 T** (35 units more than specification). The integral gradients of all magnets measured so far are **within 25 units**.

Field direction and magnetic axis (final cold-masses at ambient temperature)

LMQXFB	01	02	03
Integrated angle (mrad)	-0.27	0.10	0.30
Integrated x (mm)	-0.39	-0.54	0.50
Integrated y (mm)	-0.57	-0.39	-0.68



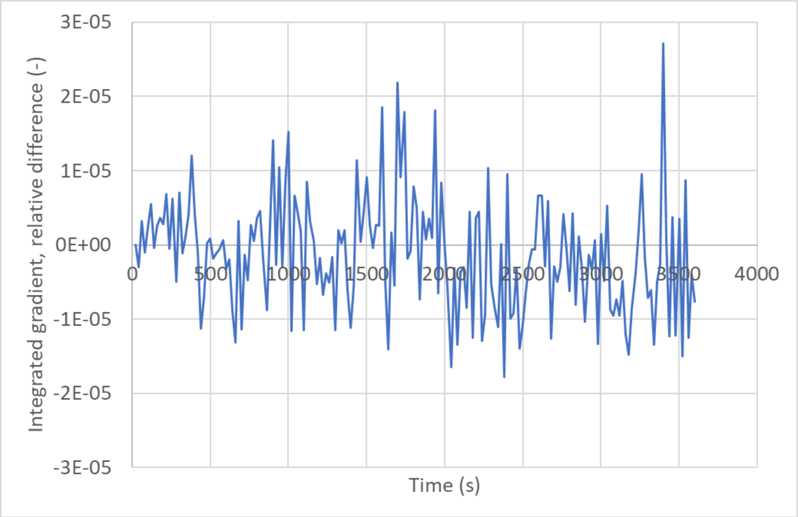


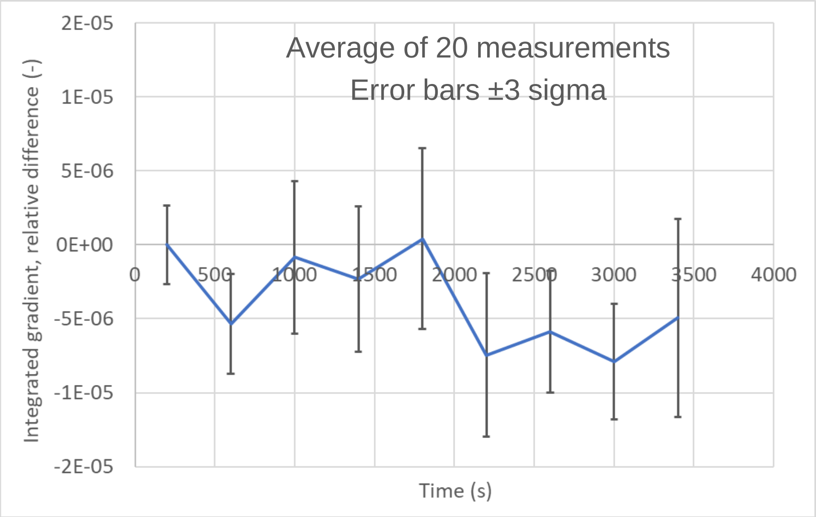


Field direction and magnetic axis under control

Stability of main field at nominal

- Plateau of 1 hour measured with stretched wire

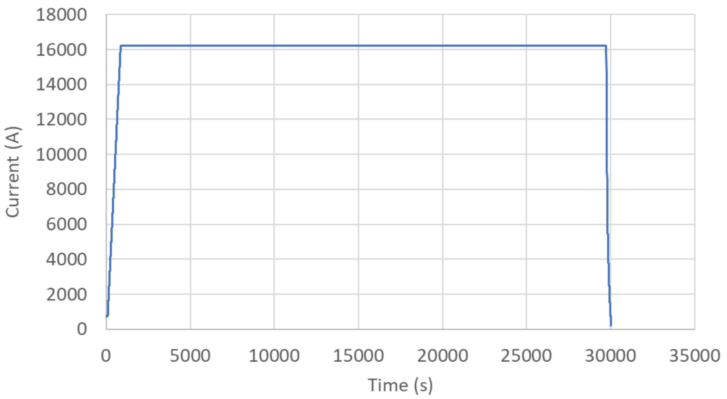


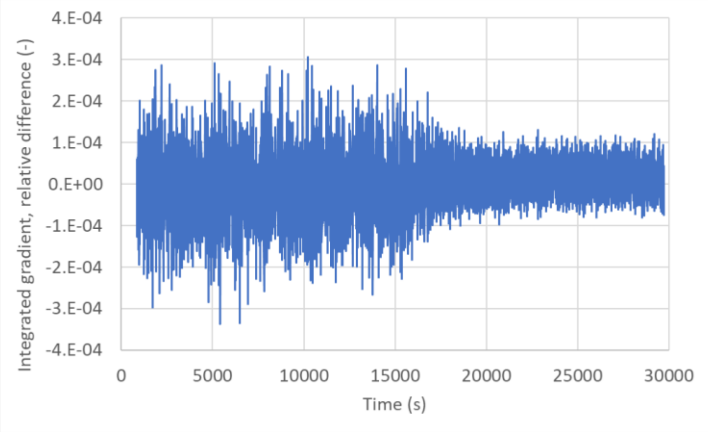


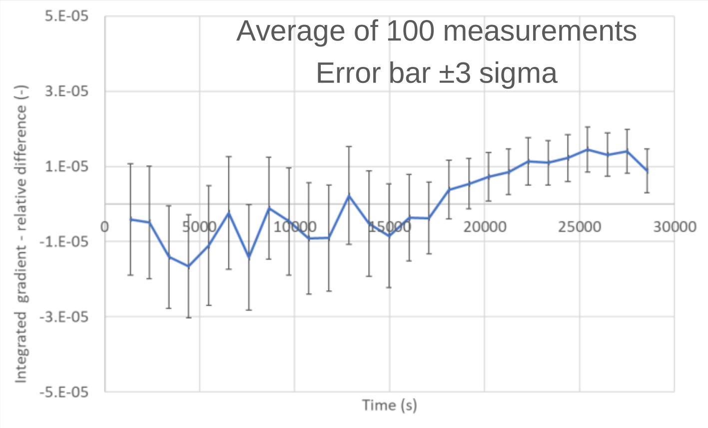
Field stability better than ±0.5 10^{-5}
(limited by measurement precision)

Stability of main field at nominal

- Plateau of 8 hours at nominal with rotating coils



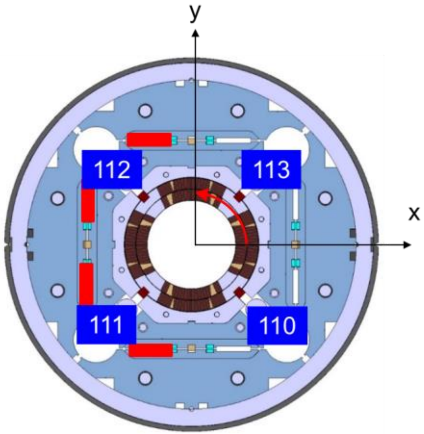




Field stability better than ±1 10^{-5}

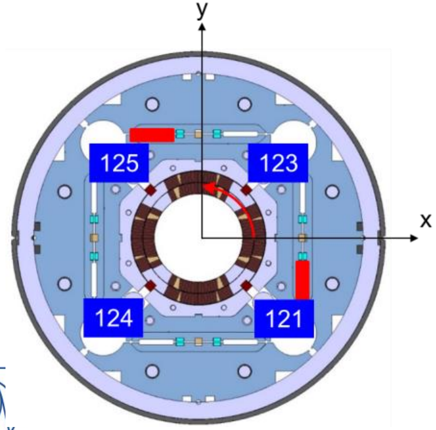
(limited by the measurement precision)

Magnetic shimming



MQXFBP2

Computed correction		
Order	b_n	a_n
3	-3.37	0.00
4	0.00	0.00
5	-0.11	0.00



MQXFB02

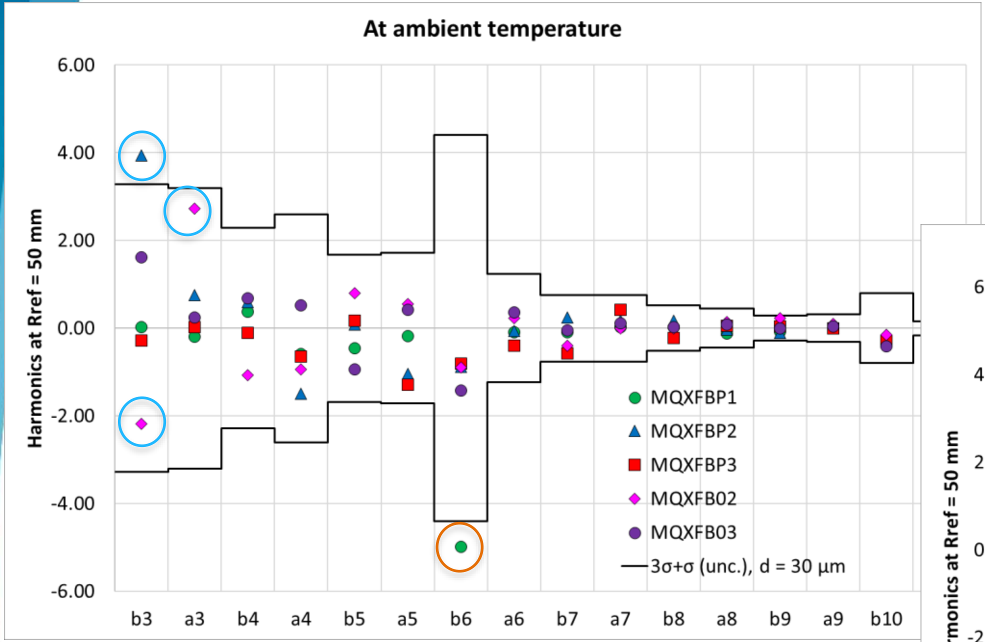
Computed correction		
Order	b_n	a_n
3	1.90	-1.90
4	0.00	0.52
5	0.27	0.27

Integral field quality at nominal

	MQXFBP2*		MQXFBP3		MQXFB02		MQXFB03			Average				STD		
n	bn	an	bn	an	bn	an	bn	an		n	bn	an		n	bn	an
3	1.11	-1.71	-1.08	-0.23	-0.15	0.46	1.61	0.27		3	0.37	-0.30		3	1.22	0.98
4	0.93	1.25	0.40	-0.88	-0.39	-0.79	1.04	0.55		4	0.49	0.03		4	0.65	1.04
5	-0.20	1.43	0.23	-1.50	1.21	0.97	-1.01	0.47		5	0.06	0.34		5	0.92	1.29
6	0.32	-0.04	-0.95	-0.27	0.15	0.22	-1.39	0.57		6	-0.47	0.12		6	0.83	0.36
7	0.26	-0.27	-0.67	0.61	-0.47	0.04	-0.08	0.15		7	-0.24	0.13		7	0.41	0.36
8	0.02	0.06	0.17	0.25	-0.19	0.16	0.02	0.13		8	0.00	0.15		8	0.15	0.08
9	0.23	-0.11	0.08	-0.14	-0.24	0.05	-0.01	0.06		9	0.02	-0.03		9	0.20	0.10
10	-0.34	0.03	-0.41	-0.03	-0.18	0.01	-0.54	0.01		10	-0.37	0.00		10	0.15	0.02
11	0.01	-0.03	-0.09	0.06	0.01	0.00	-0.01	-0.02		11	-0.02	0.00		11	0.05	0.04
12	0.06	0.01	-0.05	0.00	-0.01	0.02	-0.02	0.07		12	-0.01	0.03		12	0.05	0.03
13	-0.05	-0.03	-0.02	0.00	0.00	0.01	0.00	0.00		13	-0.02	0.00		13	0.02	0.02
14	-0.92	0.03	-0.90	0.01	-0.87	0.01	-0.85	0.01		14	-0.89	0.02		14	0.03	0.01
15	0.00	-0.01	-0.01	0.00	0.01	0.00	0.00	-0.01		15	0.00	0.00		15	0.01	0.01

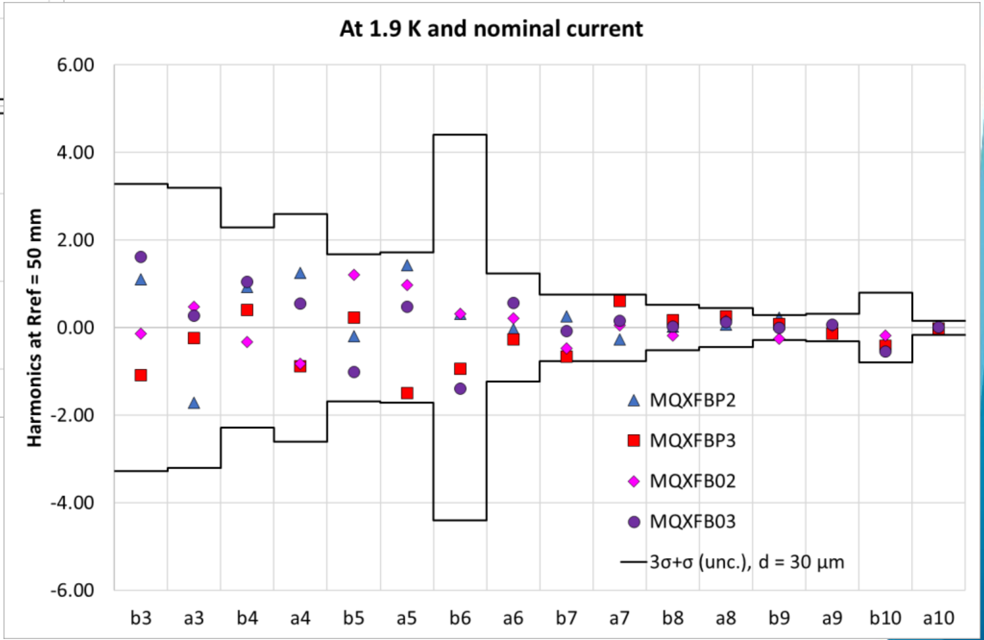
Field quality fully under control for both systematic and random components.

Integral field quality



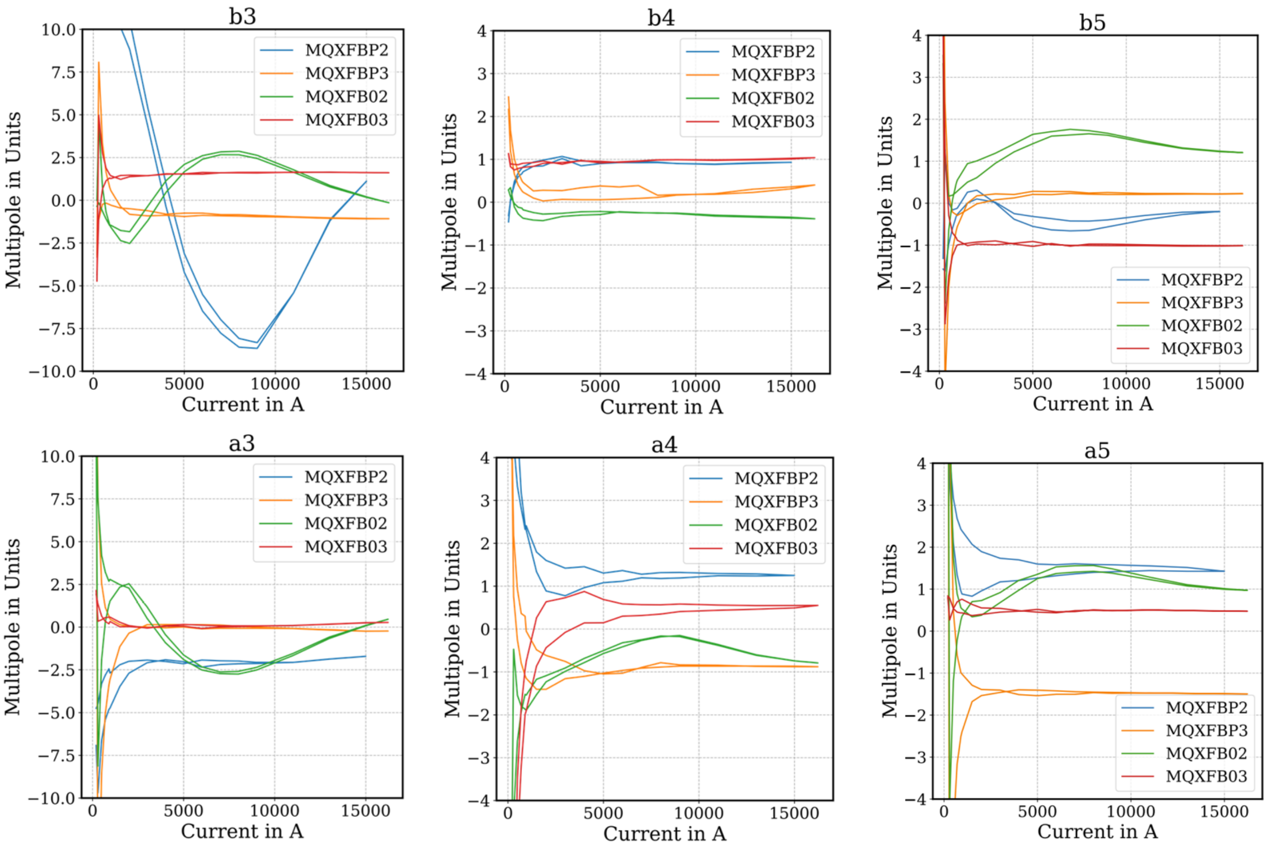
Multipole corrected by applying magnetic shimming

Systematic b6 corrected by modifying the coil shims

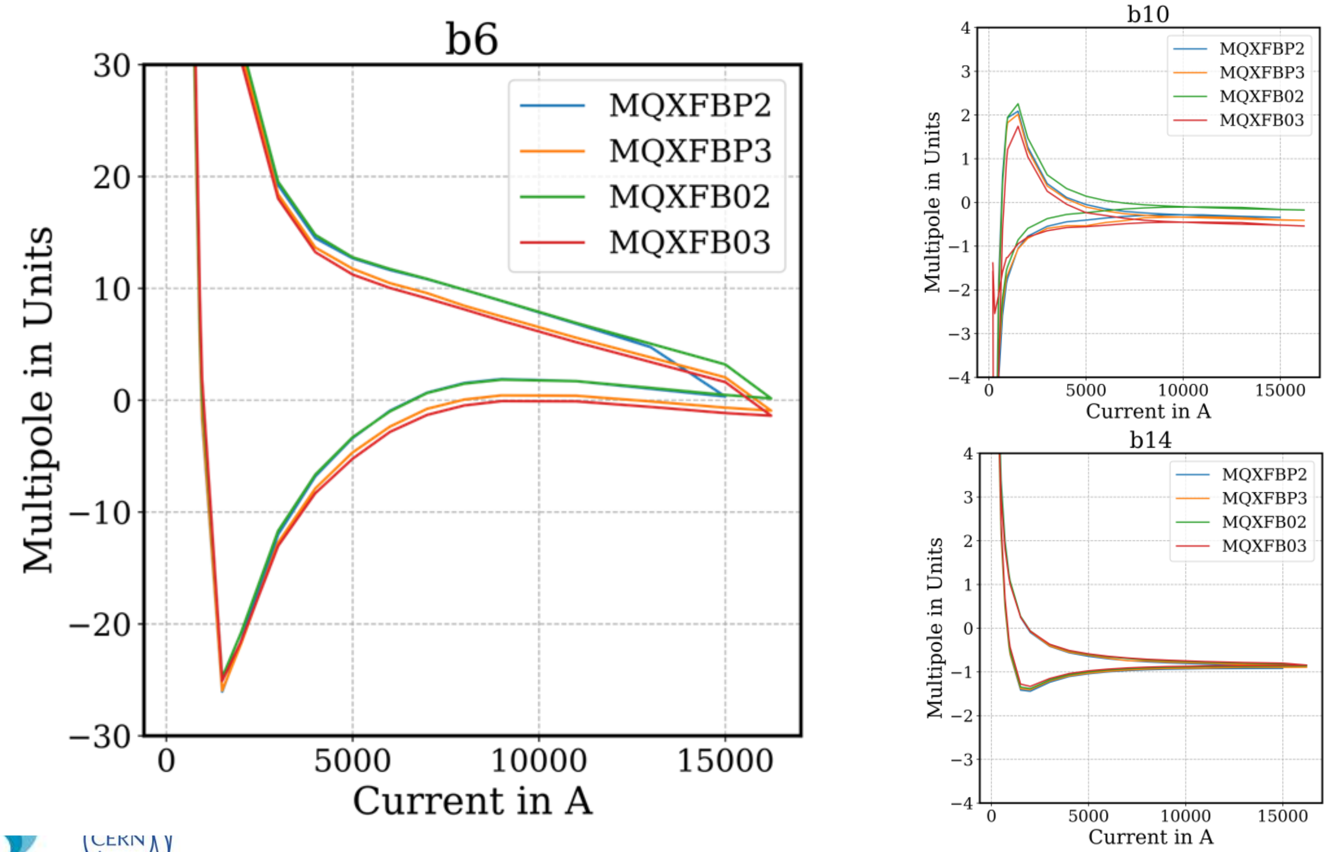


Field quality well within the expected range

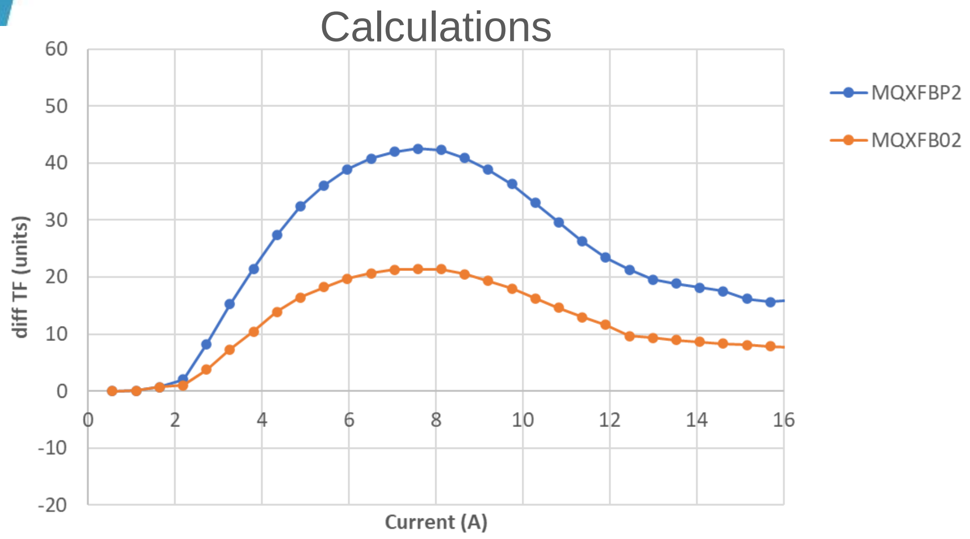
Multipoles vs current

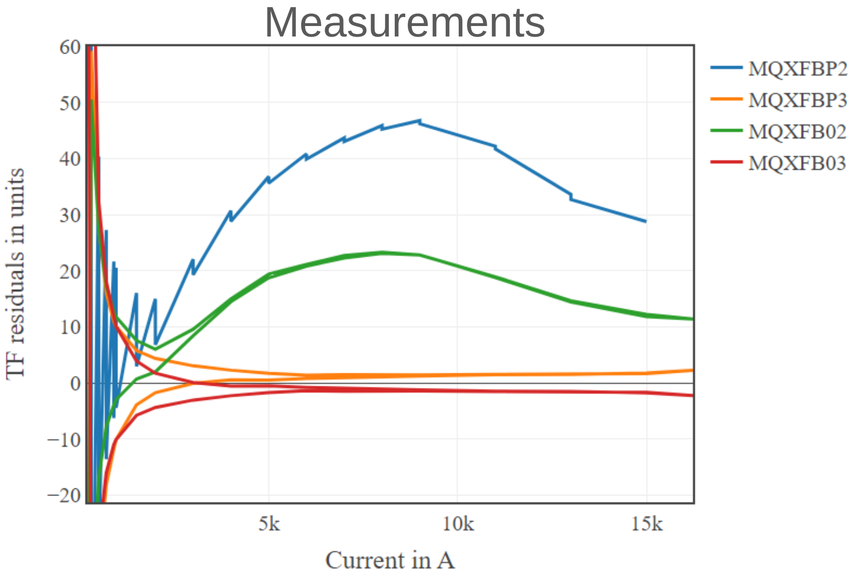


Allowed multipoles vs current



Effect of magnetic shimming on the TF





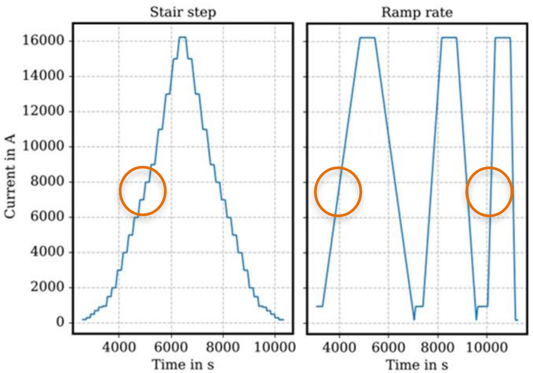
Magnetic shimming has a slight effect on the main field (~10 units).

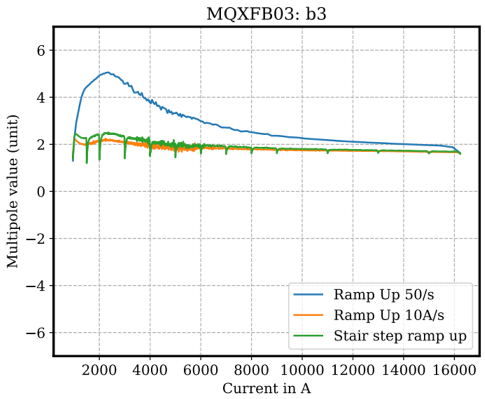
To be taken into consideration when the shimming is evaluated.

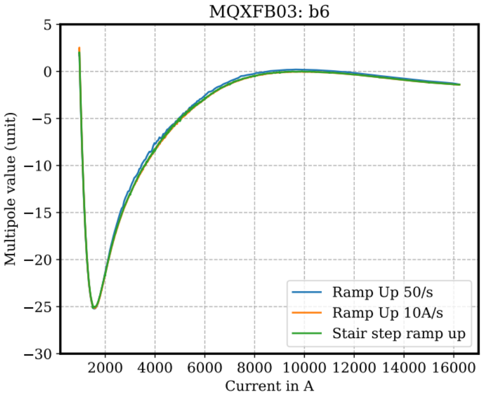
Additional results

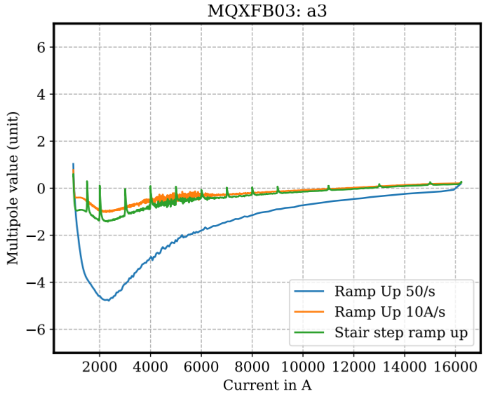
Not important for the MQXFB but interesting for the understating of NB_3Sn technology

Ramp-rate effects









Some dynamic effect due to induced currents are visible.

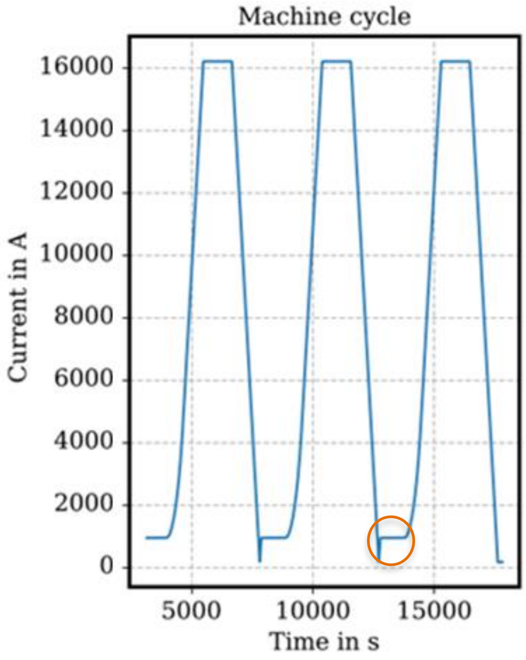
The effect can vary from magnet to magnet and along the same magnet.

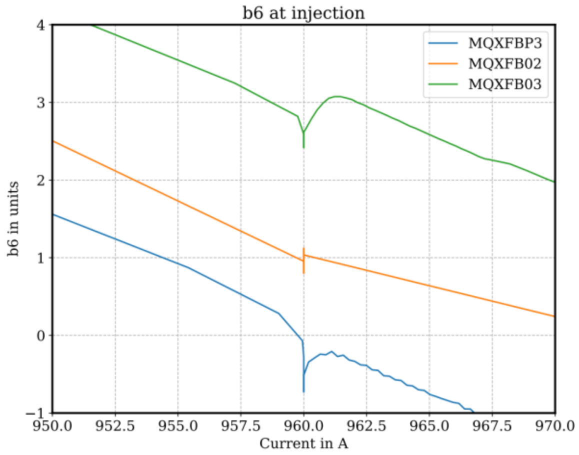
Overall, it is a small effect (~1 unit).

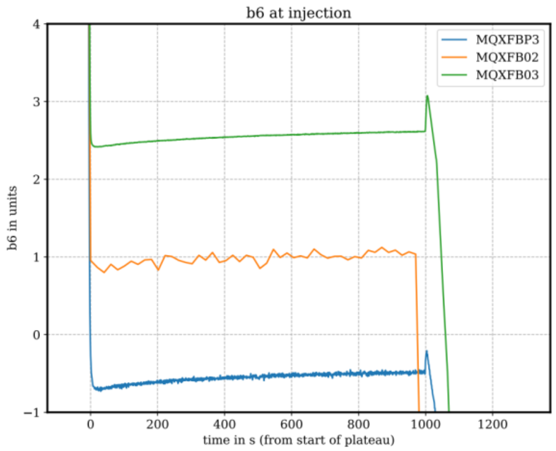
Much larger ramp rate to see significant effects

(50 A/s vs 14 A/s)

Dynamic effects at injection level



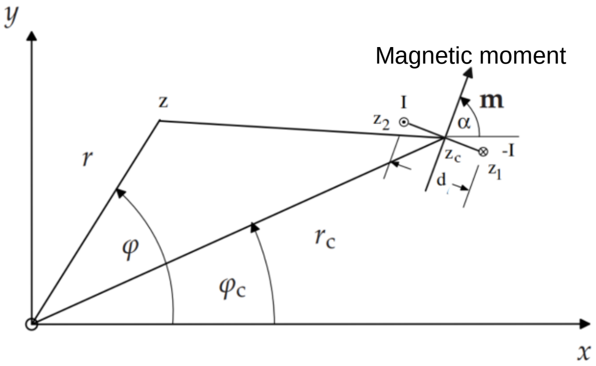




The decay during the injection plateau, and the subsequent snapback, is ~10 times smaller than NbTi magnets.

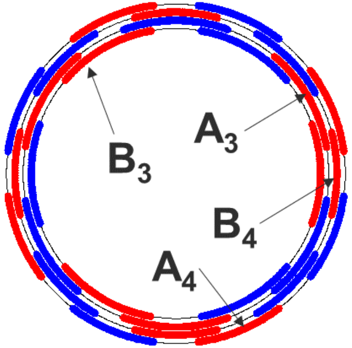
Decay and Snapback in Nb3Sn Dipole Magnets
10.1109/TASC.2016.2633980

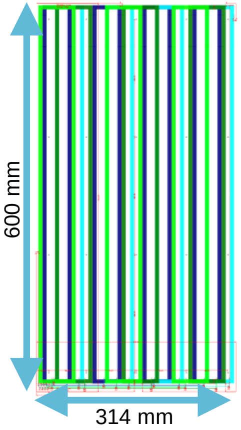
Quench antenna

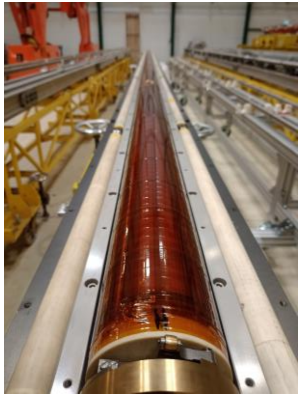


$$C_n = m\frac{i\mu_0 n}{2\pi}\frac{e^{i\alpha}}{z_c^2}\left(\frac{r}{z_c}\right)^{n-1}$$

$$z_c = \frac{4}{3}\frac{C_3}{C_4}\,\mathrm{r} = \frac{4}{3}\frac{B_3 + i\,A_3}{B_4 + i\,A_4}\,\mathrm{r}$$

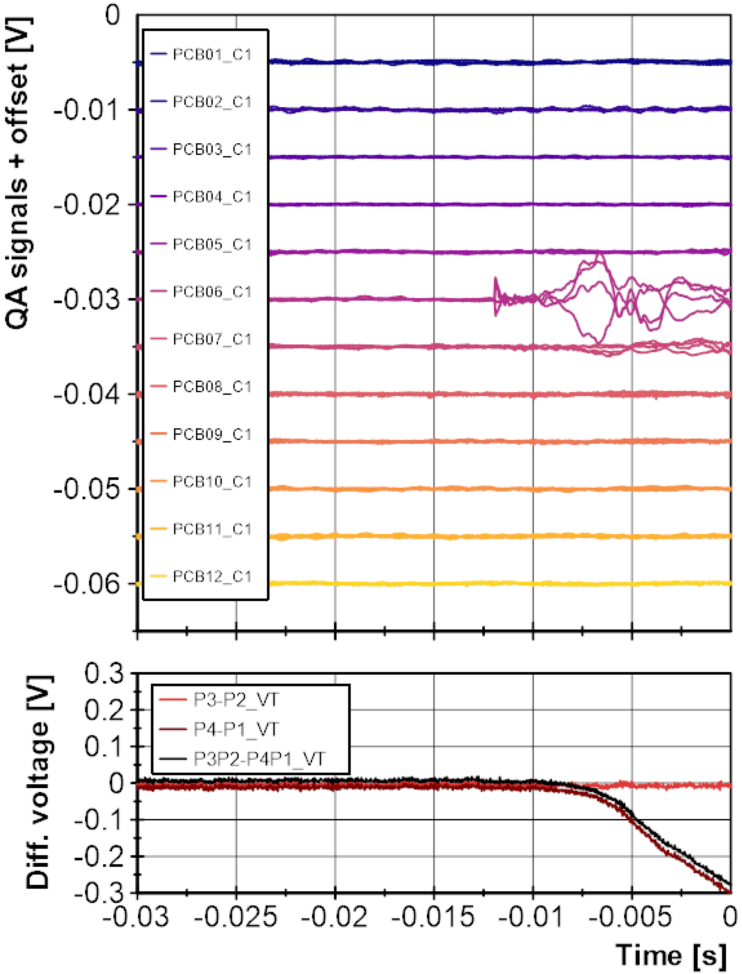


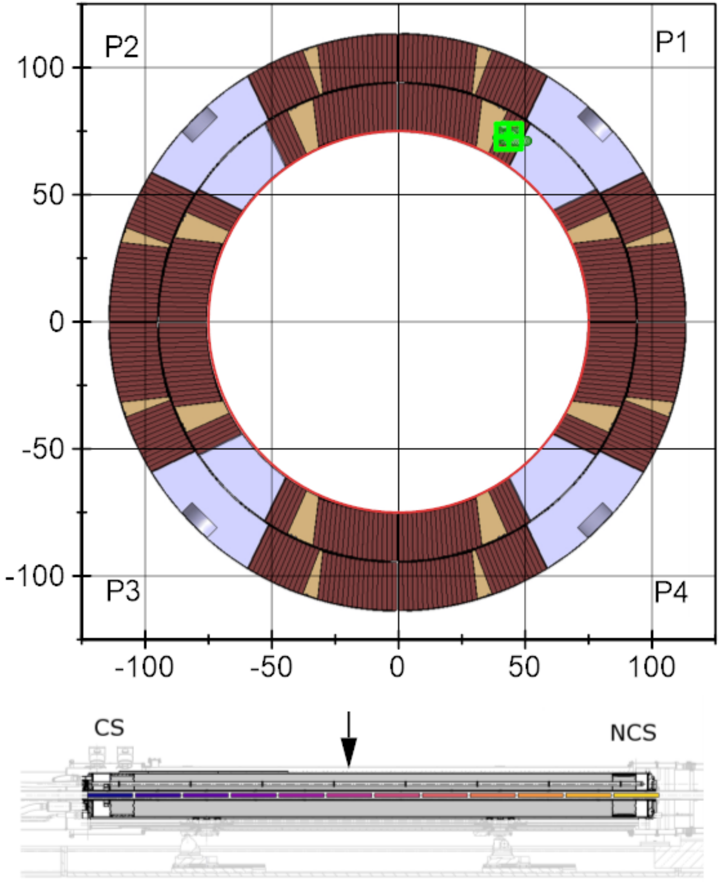




Quench antenna development at CERN

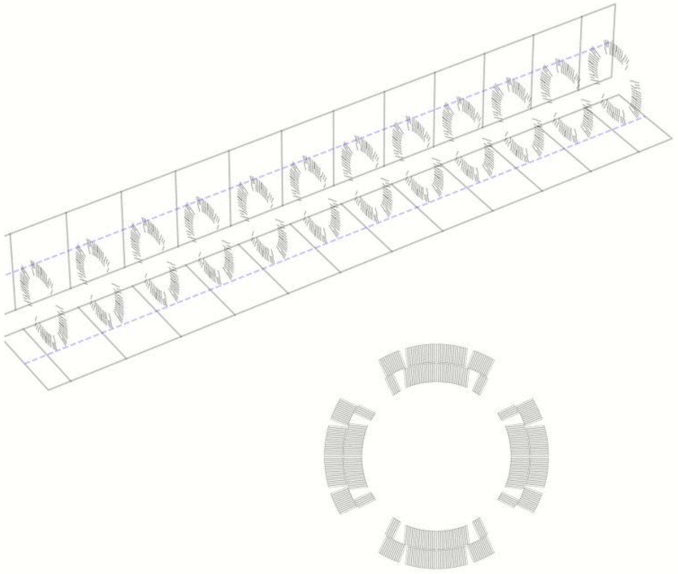
[Instrumentation and Diagnostics for Superconducting Magnets Workshop (IDSM)]

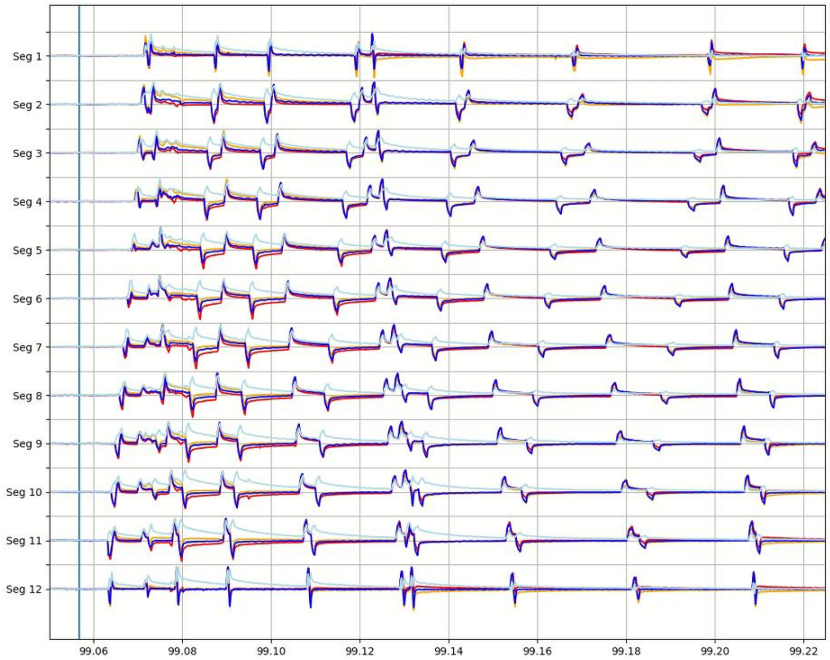




Current: 16.39 kA
File: HCLMQXFBT01-CR000005__G202211291432_na001(0).tdms

Quench antenna to measure flux-jumps





The instrument is suitable for the measurement of flux-jumps in terms of magnitude, direction, position, propagation, and impact on field quality (work in progress…).

Conclusions

Main results of magnetic tests on MQXFB's

- 5 magnets already measured at 1.9 K
- A comprehensive set of results is available
- Transfer function within 25 units
- Multipoles within specifications

Thank you!