PAUL SCHERRER INSTITUT

PSI

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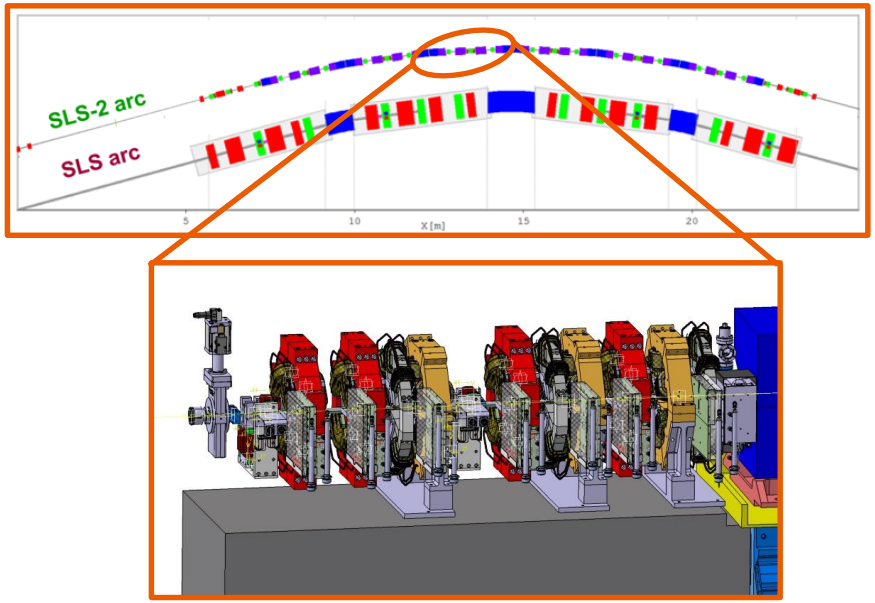
Design and Measurement of the Electromagnets and Permanent Magnets for the Upgrade of the Swiss Light Source (SLS2)

IMMW 22

The SLS2 project

Aim:

- Increase **electron beam energy** from 2.4 GeV to 2.7 GeV → increase photon energy range and flux
- Improvement in **emittance and brightness** by factor 40
- **Maintain locations** of undulator based beam lines and **circumference** 287.25 m

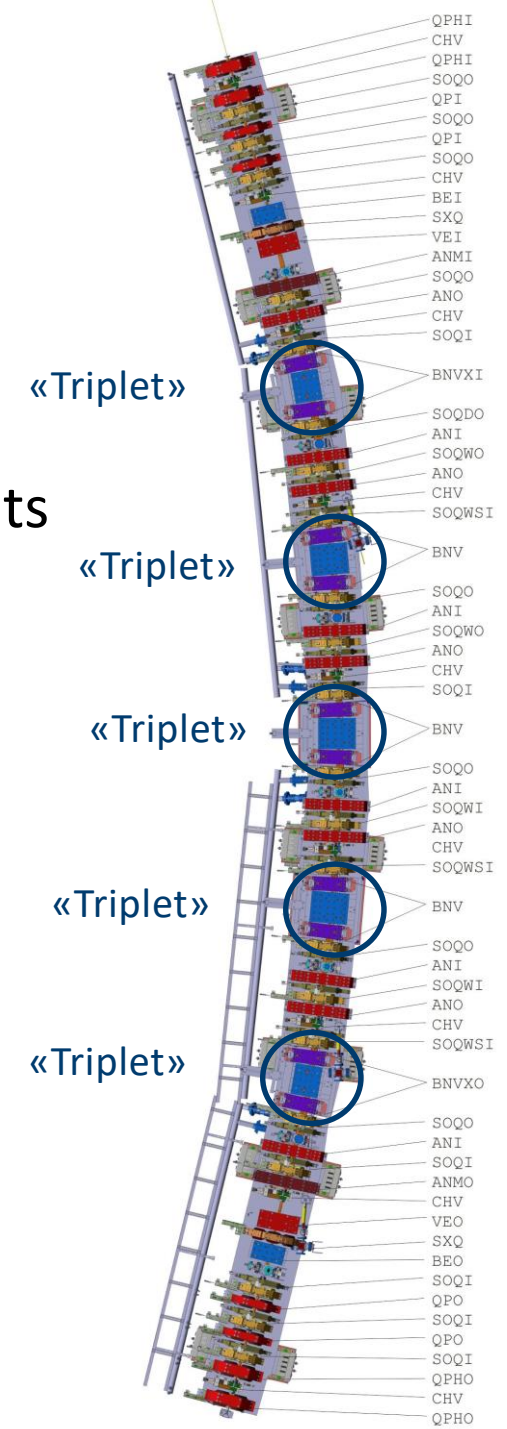


Resulting challenges for magnets:

- **Extremely dense** Multi Bend Achromat lattice arrangement with
  - 888 electromagnets (4 types)
  - 450 permanent magnets (7 types)
  - 2 superconducting magnets (1 type)
- **Measurement of all magnets** until July 2024

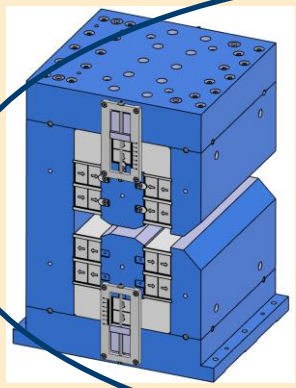
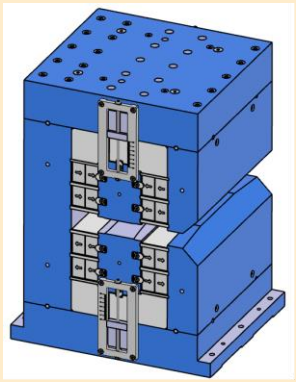
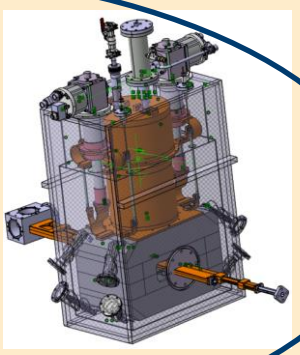
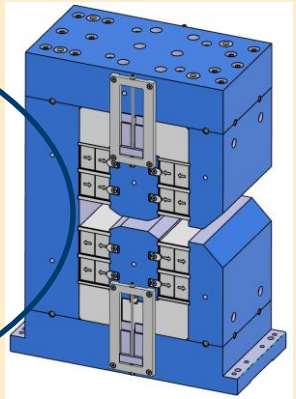
Outline

- **Design of the SLS2 magnets**
  - –Dipole magnets
  - –Combined function and antibend magnets
  - –Electromagnets
- **Magnetic measurement systems for SLS2**
  - –Overview
  - –Rotating Coils
- **Exemplary measurement results**
- **Next challenges**
  - –«Triplet» alignment and measurement
  - –Magnetic axis measurement



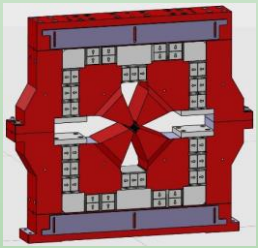
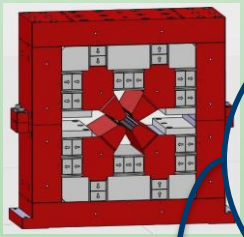
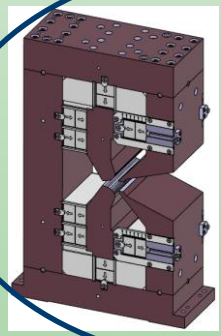
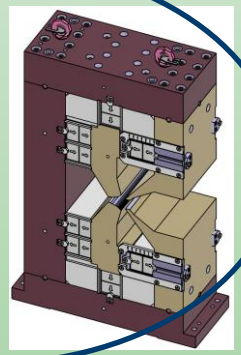
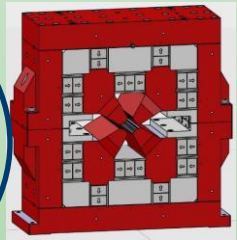
Pure dipole/gradient dipole magnets

Superconducting magnet

Name	AS2A-BN	AS2B-BS2	AS2B-BS5	AS2C-BE
Type	**PM** hom.	**PM** LGB	SC tunable LGB	**PM**
Length / mm	405	405	405	242.5
Peak field / T	-1.35066	-2.099	-3.04….-5.42	-1.141
Amount	56	2 [4]	2 [0]	24
Drawing				

Part of «Triplet» assembly

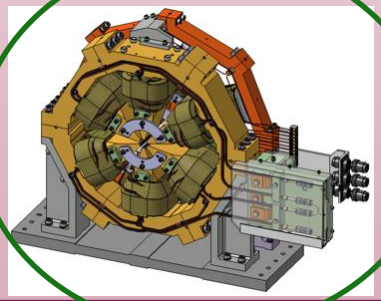
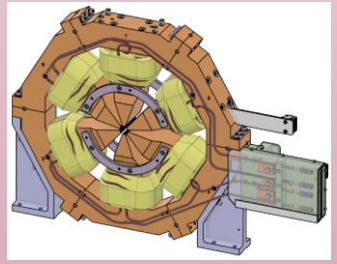
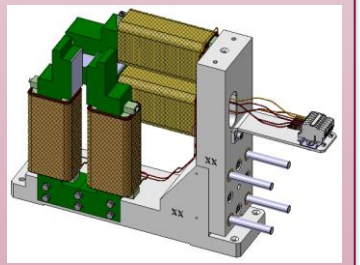
Quadrupole antibend and combined function quadrupole magnets (all PM)

Name	QS2D-AN	QS2C-ANM	QS2E-VB	QS2H-VBX	QS2K-VE
Subtypes	**-I/-O**	**-I/-O**	**-**	**-**	**-I/-O**
Length / mm	140	150	185	185	240
Field / T	+0.26947	+0.27246	-0.84967	-0.84967	-0.65495
Gradient/ T/m	-77.6562	-82.8733	+40.6704	+33.1328	+45.7648
Amount	120 (60+60)	24 (12+12)	96	24	24 (12+12)
Drawing					

Part of «Triplet» assembly

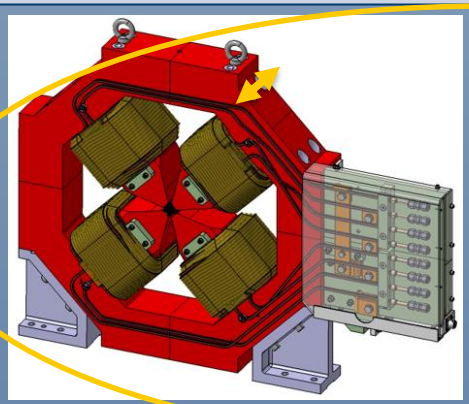
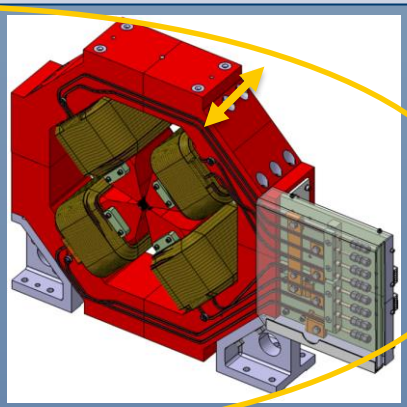
Electromagnets 1

Steerer magnets

Name	HS2A/B/C/D/E and OS2A/B/C/D/E-SOQ	HS2F-SXQ	SS2A-CHV
Subtypes	**-I/-O/-IW/-OW**		**CH/CV**
Length / mm	230 90 (SX) + 50 (OC)	140 90 (SX)	105
$\int \frac{B_Y}{B_X} dl$ / mTm	-	-	3.6
$\frac{B''_Y}{2}$ / T/m^2	5850	5850	-
Amount	264	24	112
Drawing			

Sextupole-Octupole-Module

Electromagnets 2

Name	QS2B/QS2G-QP	QS2A/QS2F-QPH
Subtypes	**-I/-O**	**-I/-O**
Length / mm	**170**	**210**
$\frac{B'_Y}{B'_X}$/ T/m	93/0	98/0
Amount	55 (31+24)	53 (29+24)
Drawing		

Already measured

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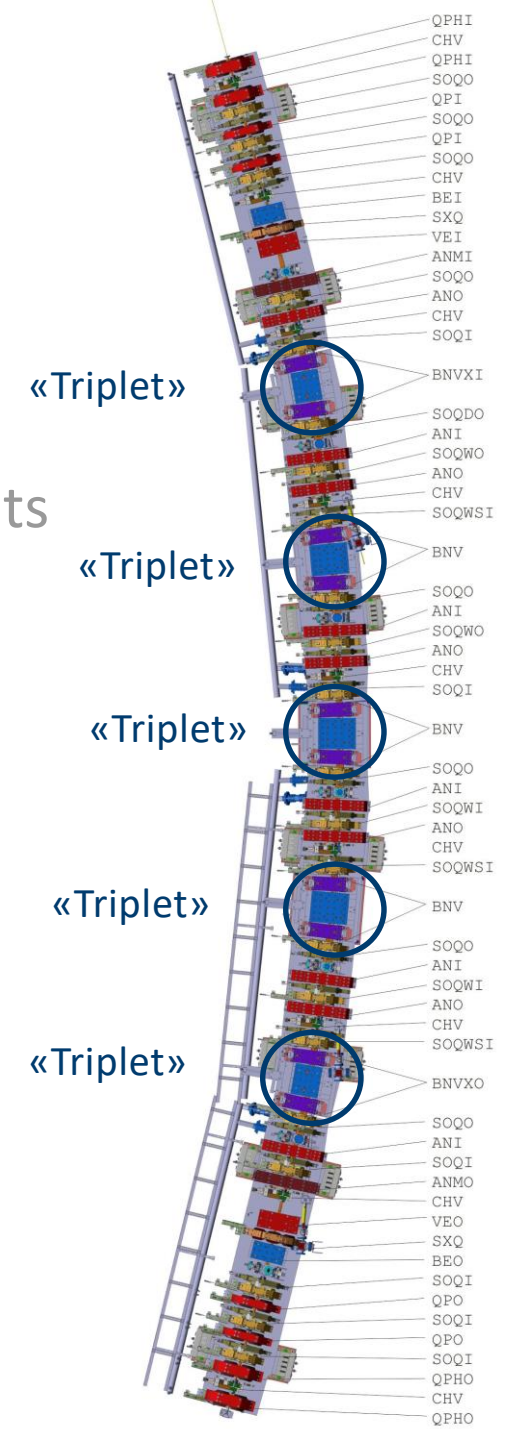
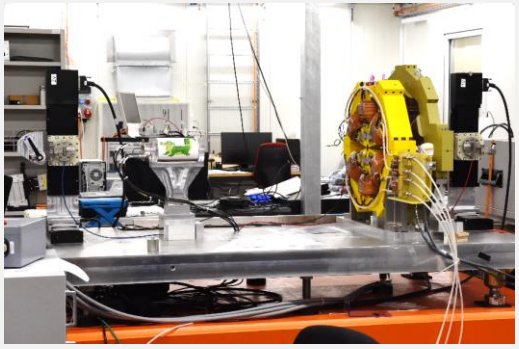


Magnetic measurement systems for SLS2

- Vibrating wire (2x)



➢ For axis measurement of SOQ, SX

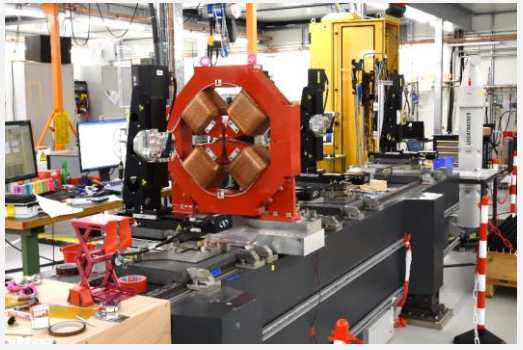
- Helmholtz coils (1x)

➢ For magnetization quality control of PM blocks

- Compact field mapper (1x)

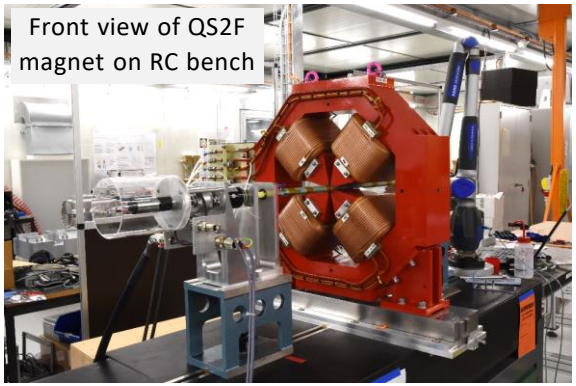
➢ For effective magnetic length and field maps of samples of all SLS2 magnet types

- Moving wire (2x)



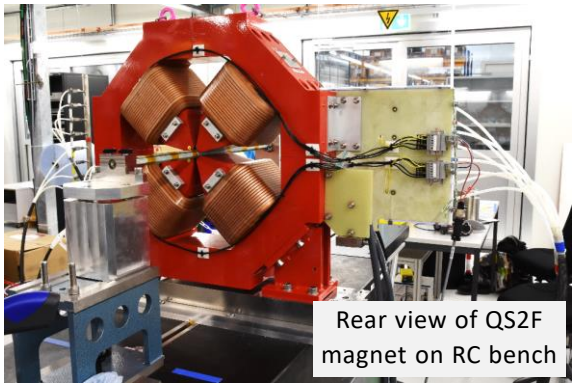
➢ For cross calibration of QP/QPH and measurement of AN/ANM/VE and Triplet

Measurement system: Rotating Coils (RC)


Front view of QS2F magnet on RC bench

Measurement system:

- **PCB** with **5 radial coils** (1 spare), each **120 turns** (in collaboration with Elettra Synchrotron Trieste)
- Reference radius: 18 mm
- Active coil length: 500 mm
- Digital bucking of dipole and quadrupole field components


Rear view of QS2F magnet on RC bench

Measurement program:

- **Inspection control** and **commissioning**
- **Pre-heating** of magnet (cooling water, nominal current 70 A) over night
- Measurement of **magnet position** on bench with FARO
- Measurement of **yoke temperature** with thermal camera
- Measurement of **Loadline** (10 A -> 70 A -> 10 A)
- Measurement of **roll angle**, reference position, 70 A
- Measurement of **roll angle**, flip position, 70 A

➢ Determination of Transfer function (TF), harmonics, magnetic axis, roll angle (1-σ repeatability < 0.05 %)

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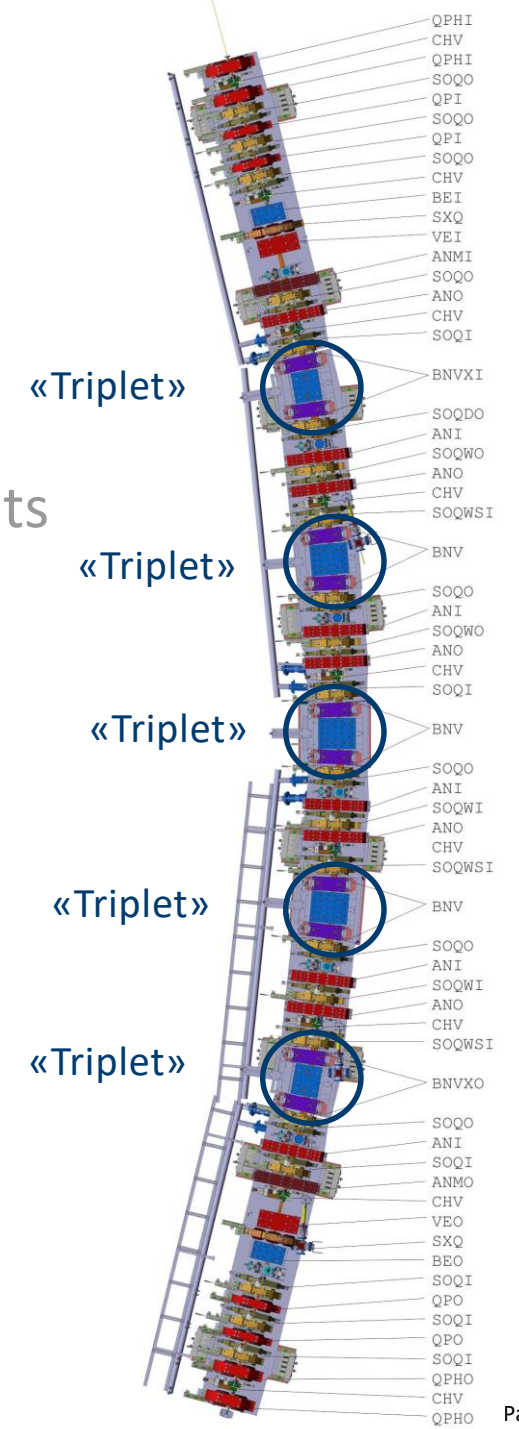
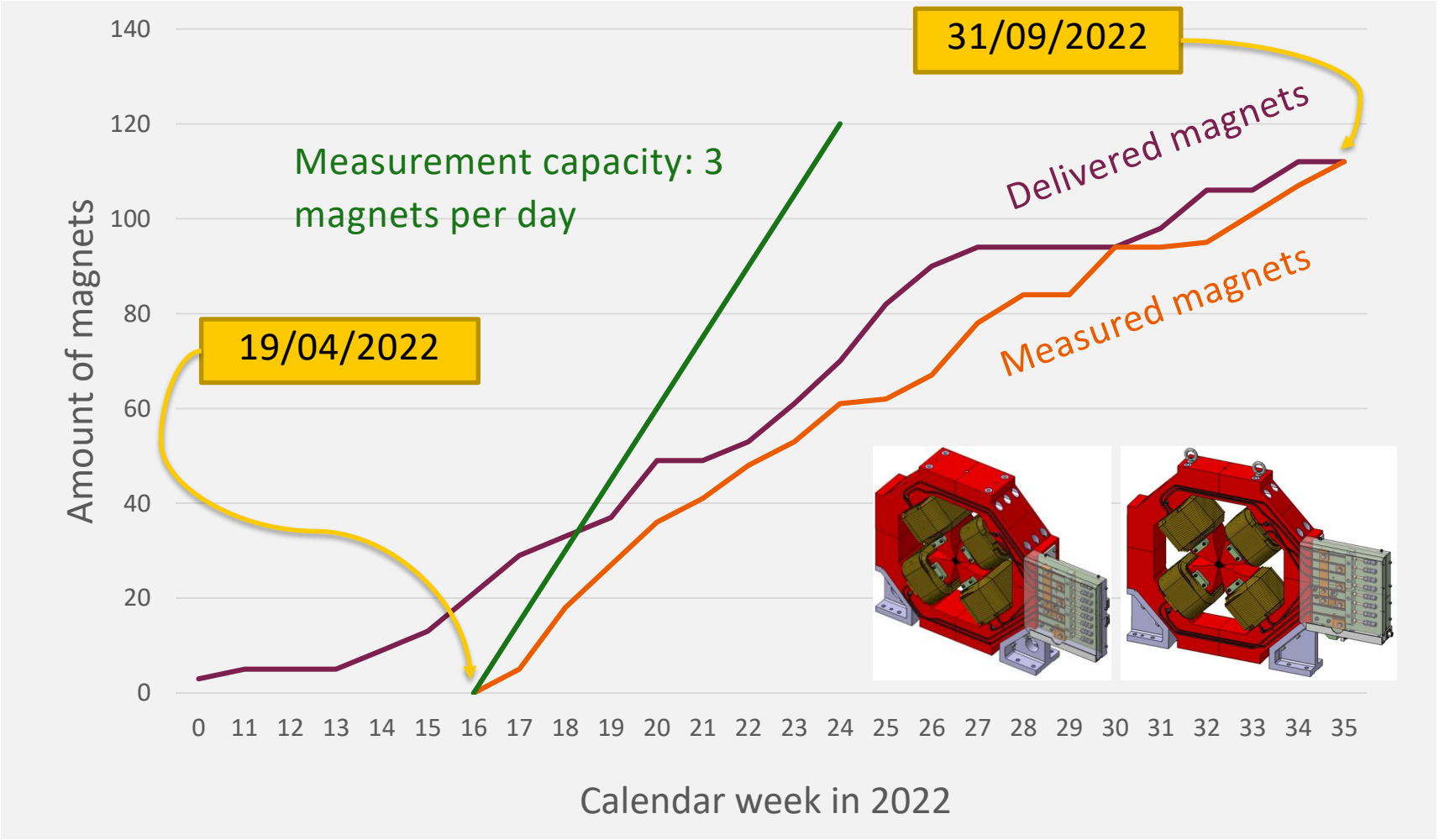
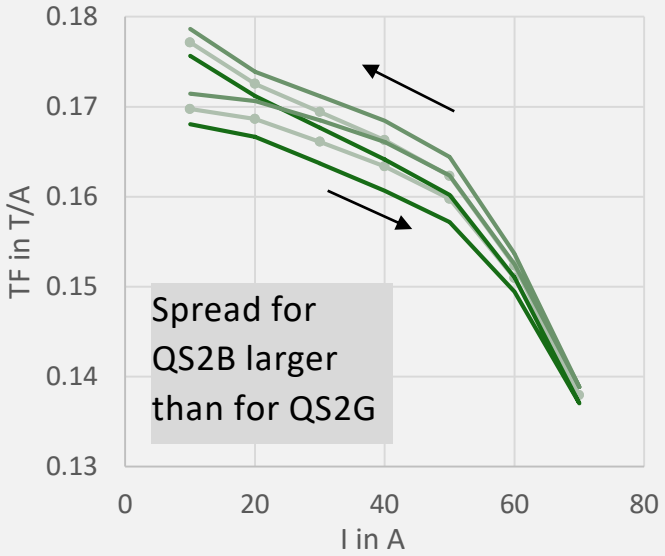
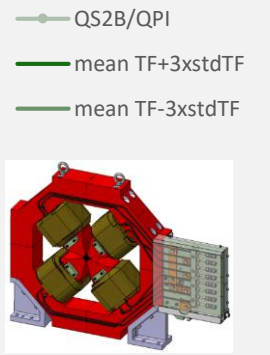


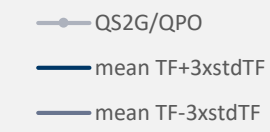
Delivery and measurements per week for QS2A_B_F_G/QP_QPH series

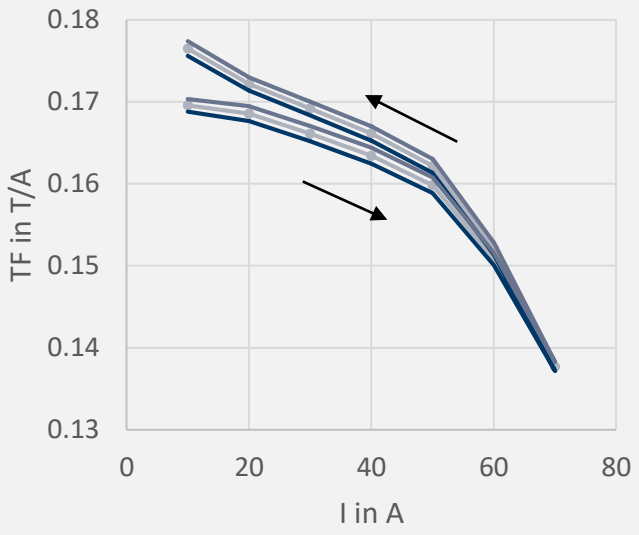


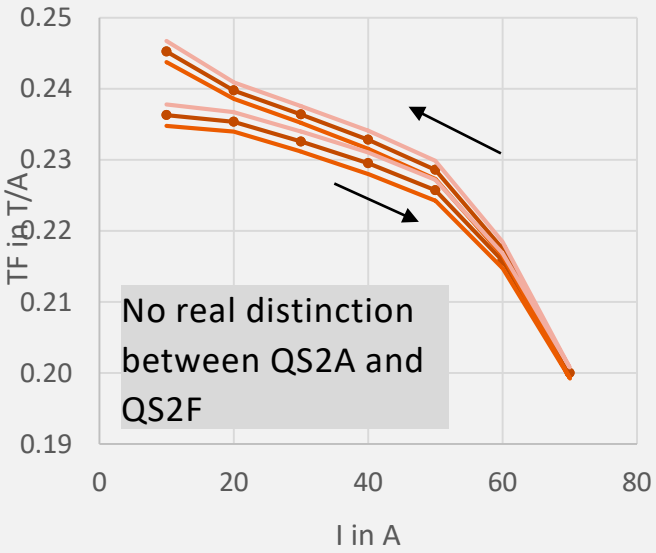
Transfer function (TF) 10 A → 70 A → 10 A

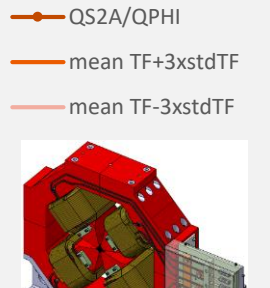


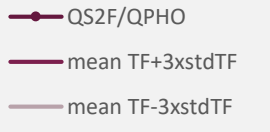


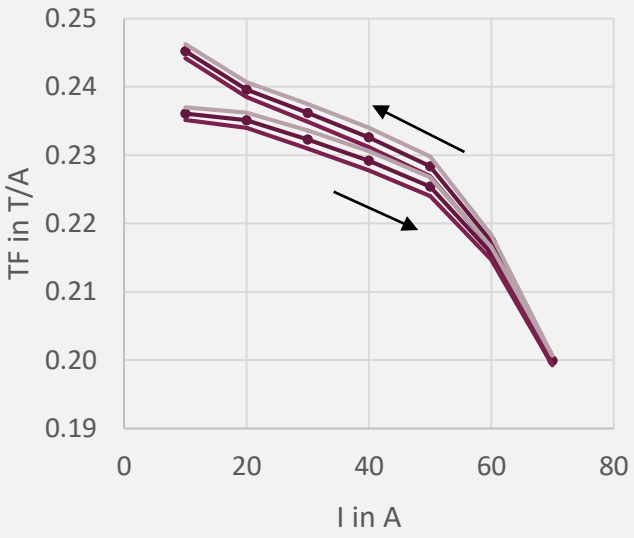




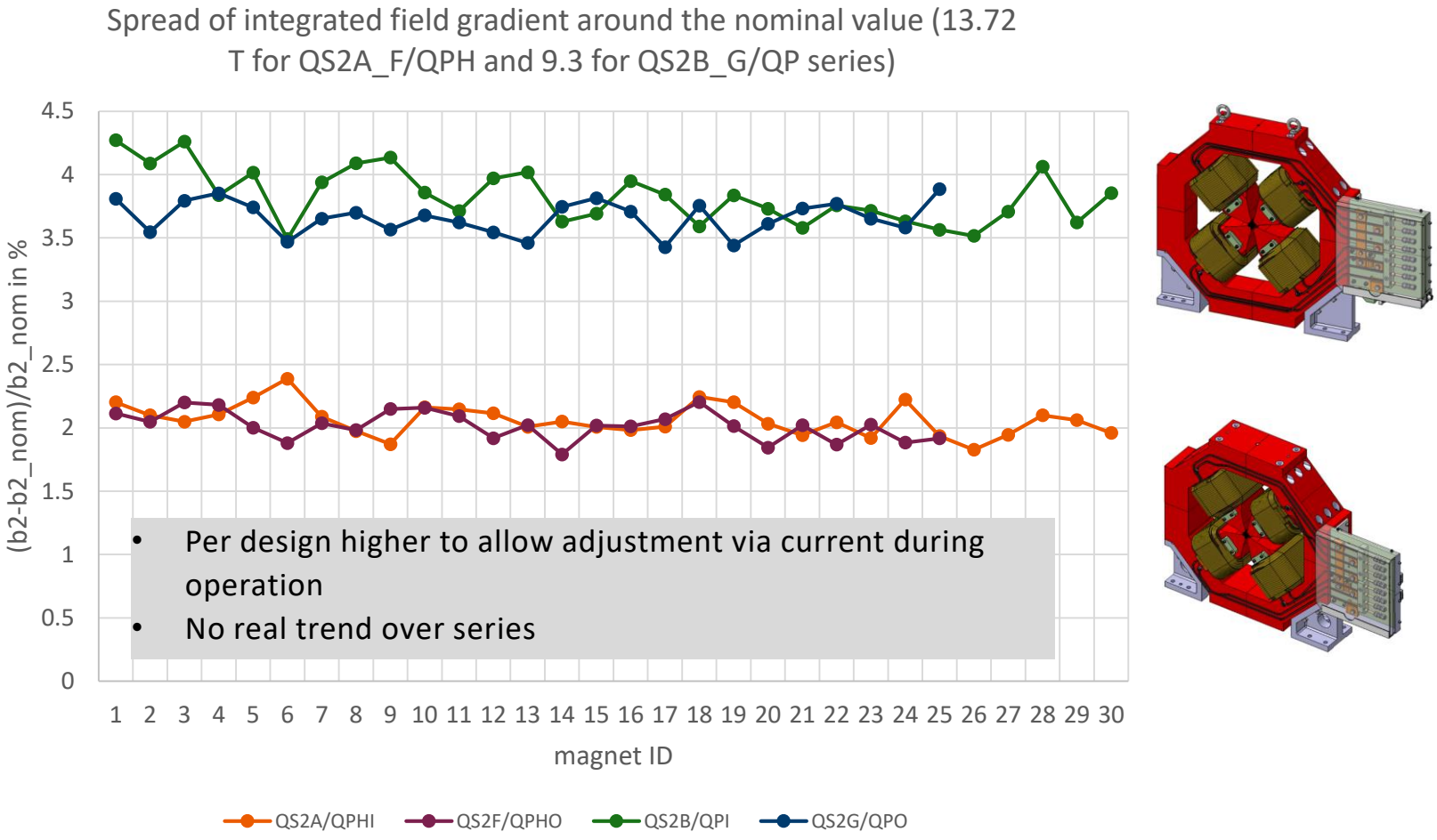






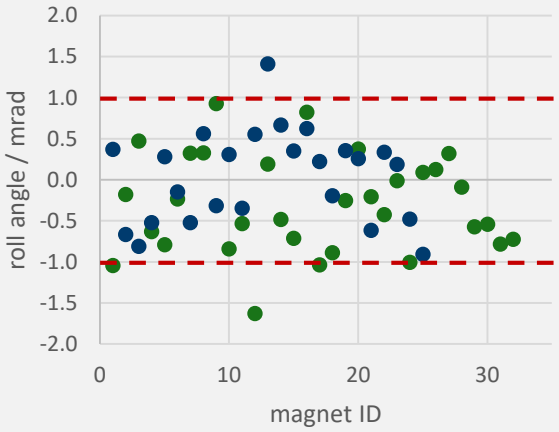


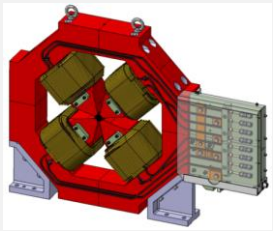
Main field $\int G \, dl$ at 70 A in % of nominal field

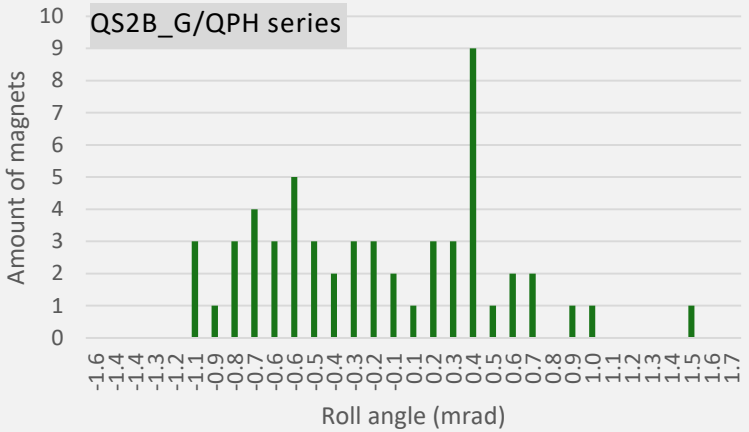


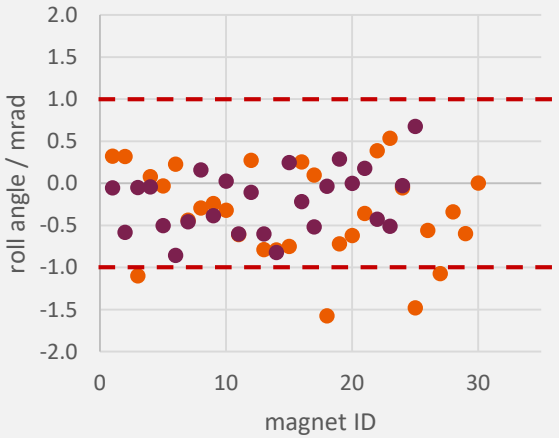
Roll angle

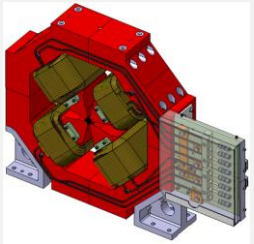
Roll angle distribution

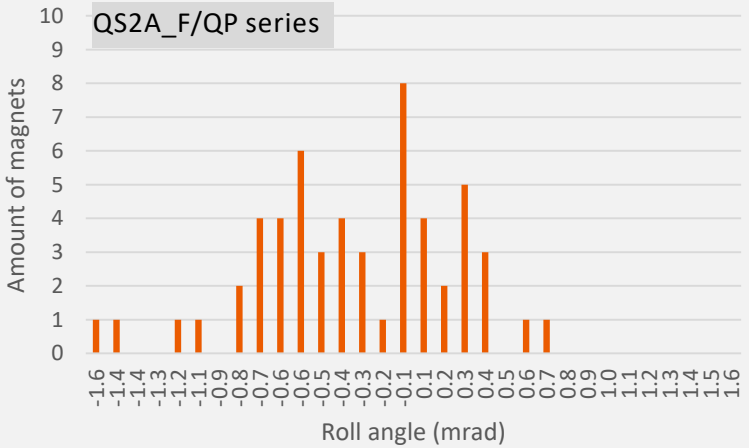












- Spread of roll angle larger for QS2B_G/QPH series than for QS2A_F/QP series
- Roll angle for some magnets outside of Spec, but tolerable with girder adjustment
- Experimental measurement uncertainty 0.3 mrad

Cross-calibration of quads axis (1)

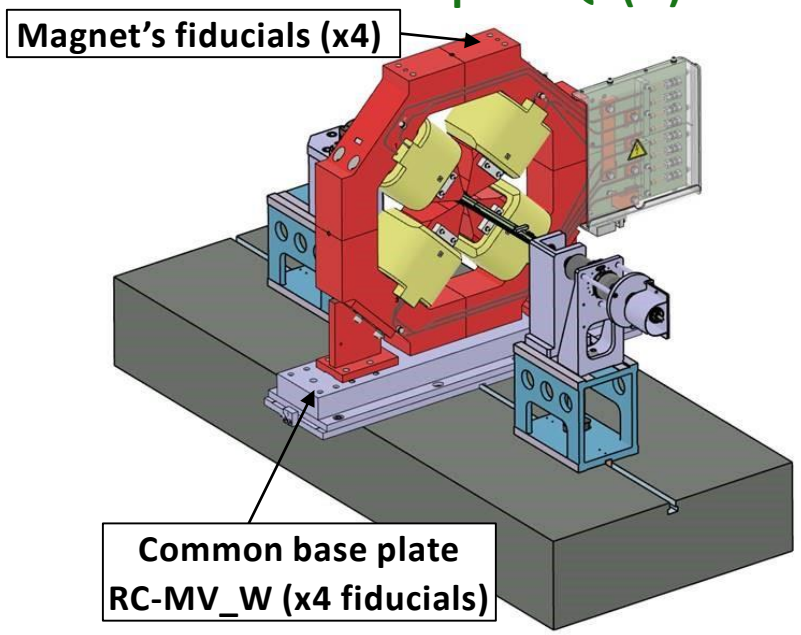
Need for calibration of coils position w.r.t. axis rotation

- Even if PCB coils are precisely manufactured (geometry pretty close to the nominal design, surface area < 0.1% difference->calibrated at CERN), careful assembly of the measurement shaft can still introduce misalignment between PCB axis and shaft rotation axis (tens of µm)
- That turns into an error that can hit % level for main field component (here we consider quads)
- Distance between coil axis and magnet axis is marginally affected (few µm)

Strategy for QP(H) series measurements

- The 112 magnets are measured on the Rotating Coil (RC) bench: nominal sensitivity coil factors
- For each magnet type a reference magnet is selected (QPI_2, QPO_9, QPHI_4, QPHO_6)
- Each reference magnet is measured repeatedly during the series to monitor repeatability of i) the mechanical assembly and ii) relative axis position PCB coil to magnet axis
- The four magnets later on are measured with the moving wire (MV_W) and the PCB coil is in situ calibrated
- Using base plate (x4) and magnet (x4) fiducials, axis coordinates are transferred to moving wire reference system

RC meas. setup for QP(H)



- Fiducials on the RC bench are measured with a 2.7 m Faro arm CMM (fixed positon during the whole series measurements)
- Fiducials on the MV_W bench are measured using a Leica laser tracker (AT960-M)
- Transformation matrix is then available

Cross-calibration of quads axis (2)

Wire position w.r.t. measurement reference frame

- To minimize the uncertainty on the cross calibration process the wire position in a give reference frame has to be carefully determined (MV_W stages aligned against this frame using AT960 M)

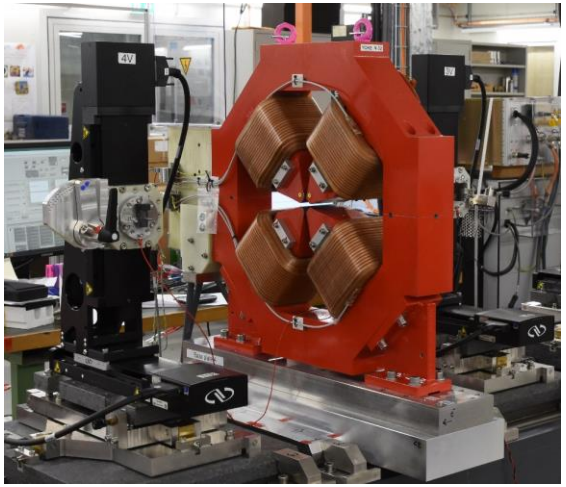
We are going to calibrate the wire using 3 steps

- Digital Imaging through high-resolution 3D scanner (GOM-ATOS Compact Scan)
- Validate results through CMM measurements
- Transfer the above info on field using the available laser tracker (AT960 M)

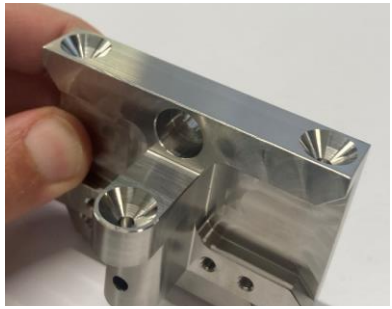
Preliminary results QS2B

- Gradient +0.5% difference MV_W-RC (relative to MV_W)
- Equivalent to 40 µm misalignment coil axis-shaft rotation axis

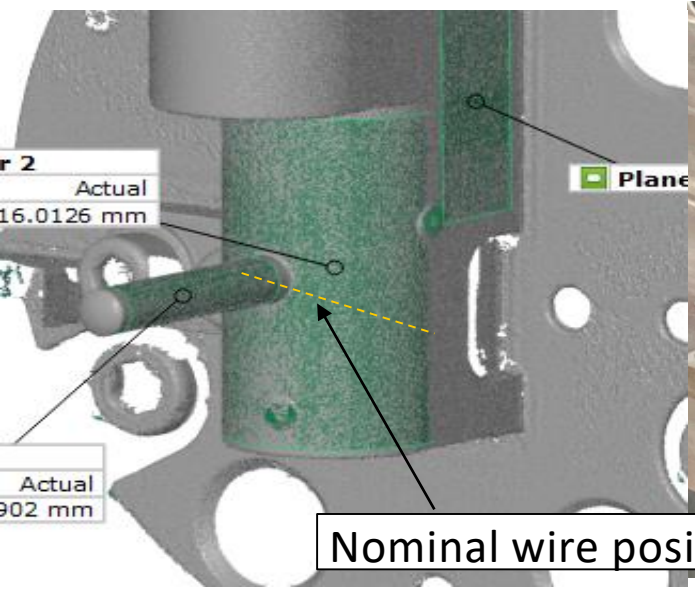
QS2B MV_W B1 for cross calibration



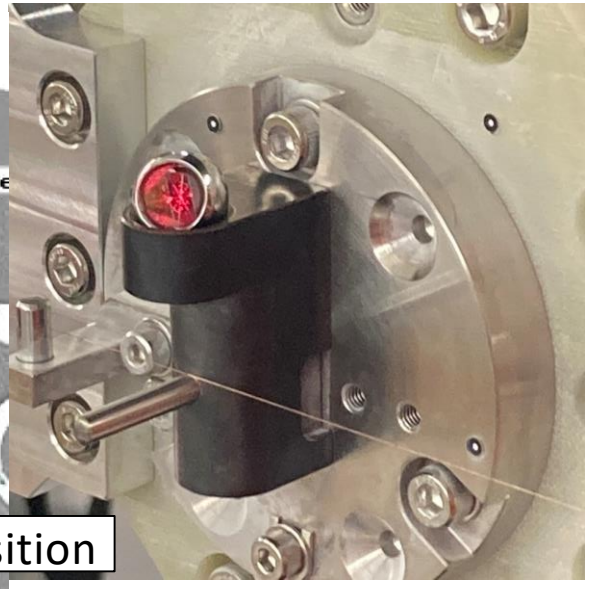
Wire holder V1



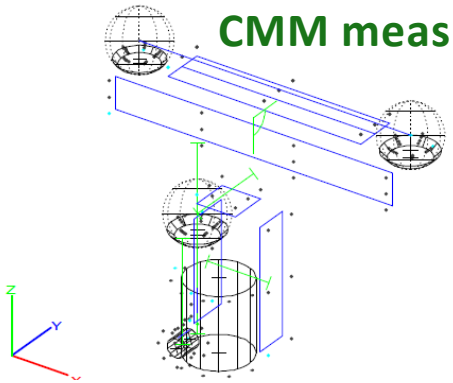
Wire holder V0 (3D Scan)



Wire holder V0



CMM meas.



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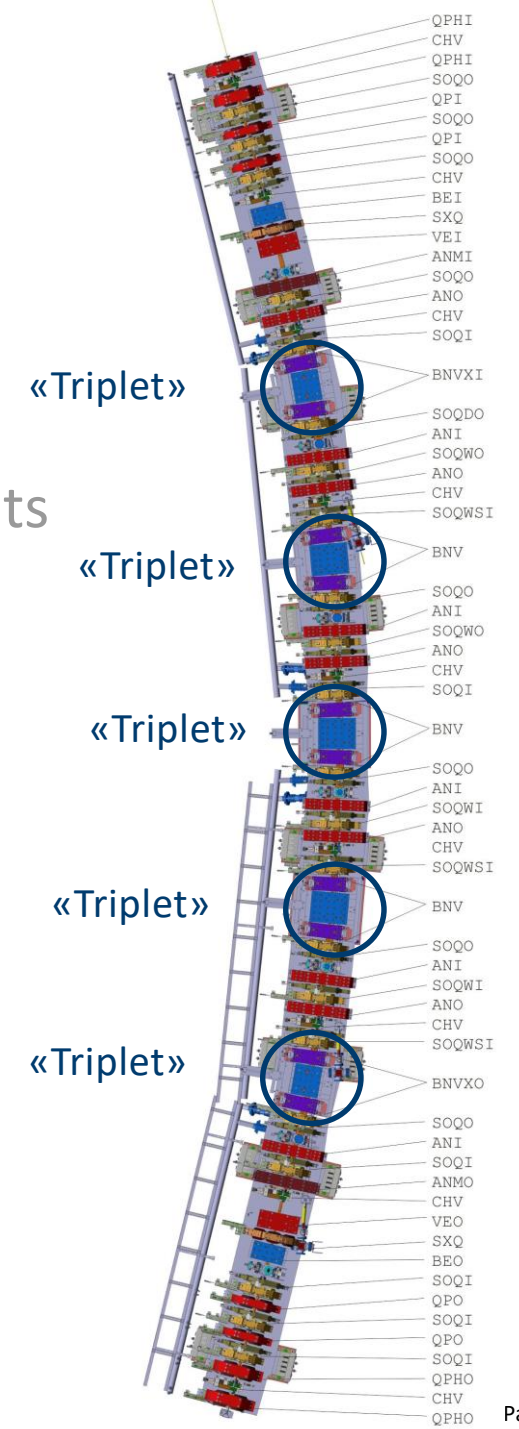
  - –«Triplet» alignment and measurement
  - –Magnetic axis measurement



«Triplet» alignment and measurement

Main machine requirements

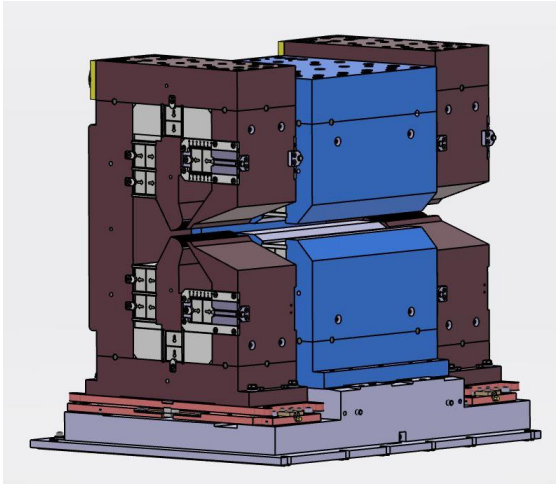
- **+/-0.2% relative integral field error for each PM magnet**
- **Alignment of magnets in the assembly with +/- 30 µm**

Measurement challenges (120 VB(x)s; 60 BN(BS2,BS5)s; 60 Triplets → March 2023/June 2024)

- Adjust integral field within machine specs (C-shape magnets → mechanical distortions)
- Remember: VB(X) is a combined quadrupole/dipole magnet (determination of the magnetic axis….)
- Assembly of the 3 magnets together and align them within +/- 30 µm
- Measurement of the triplet field integral: cross talk issues

Assembly of the first proto

Final design



AND ALL OF THAT TAKES TIME!

SQO and SXQ magnetic axis measurement

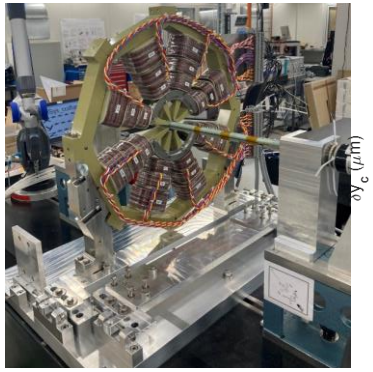
Main machine requirements:

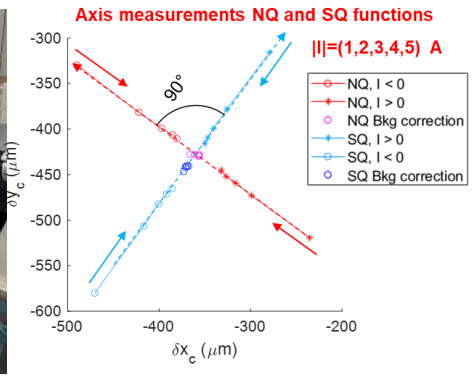
- **SXQ: magnetic axis know with +/- 30 µm**
- **SOQ assembly: alignment of the quadrupole correction function to the sextupole axis with +/- 30 µm**

Measurement challenges (264 SQOs and 24 SXQs)

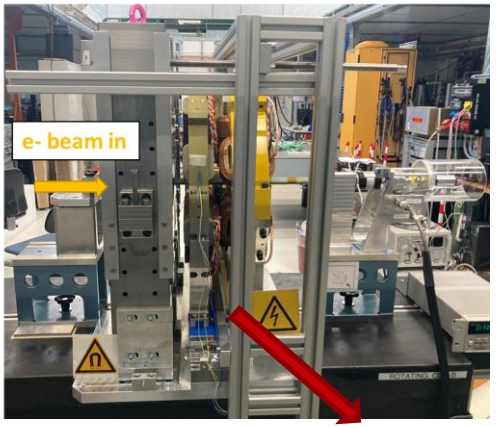
- Idea Vibrating Wire method for axis determination
- PSI Vibrating Wire system as of today optimized for quadrupole magnets
- Sextupole axis measurements intrinsically challenging->Literature available but PSI vibration detection system (based on pick up coils and lock in amplifier) has to be reviewed
- Quadrupole functions of the octupole magnet weak → background field during measurements not negligible
- Magnets cross talk increase uncertainty of the axis localization → new OC design (wider yoke)

2ND OC prototype



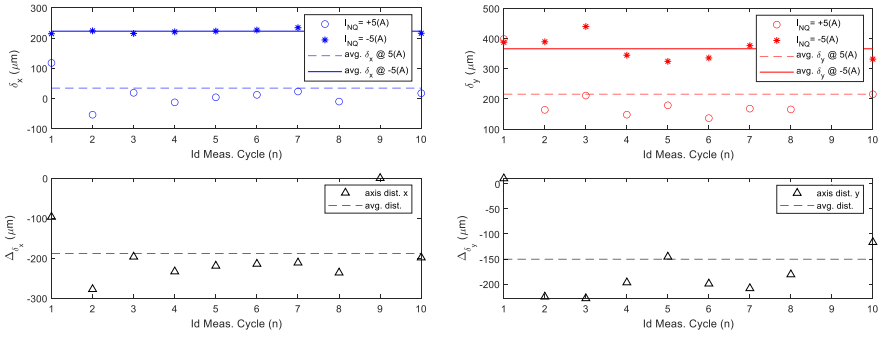


ANM-SOQ (2ND OC) prototype RC



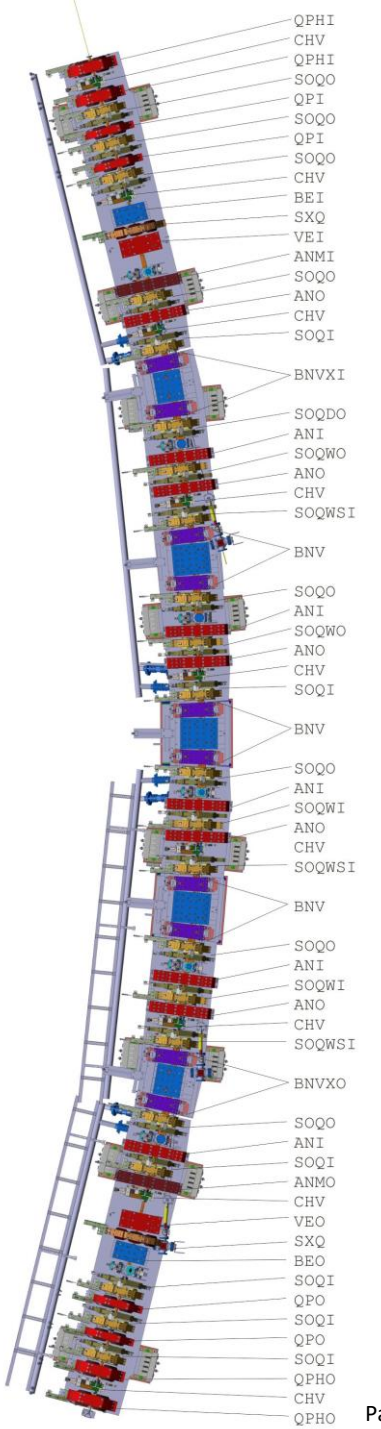
3rd OC Design

Cross talk effect



Summary and Conclusions

- SLS2 huge project, but «we are in good shape»
  - **All magnets** designed and ordered
  - **Measurement systems** getting ready for series measurement (**mid 2023**)
  - **Rotating coils** work fine with good reproducibility of results
  - First series QP/QPH magnets successfully measured with RC
  - First results show that not everything within specs, but tolerable for machine
- Next challenges:
  - Preparation of alignment and measurement of **«Triplets»**
  - Preparation of **Sextupole and Octupole** magnetic axis measurement
- **Completion** of all magnetic measurements **July 2024**



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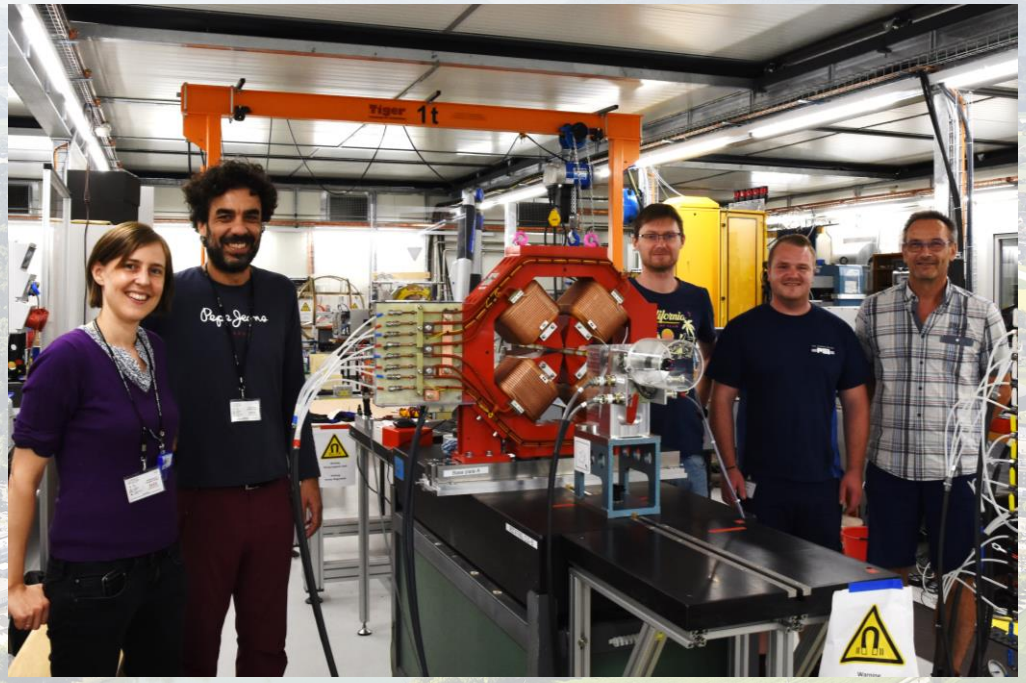
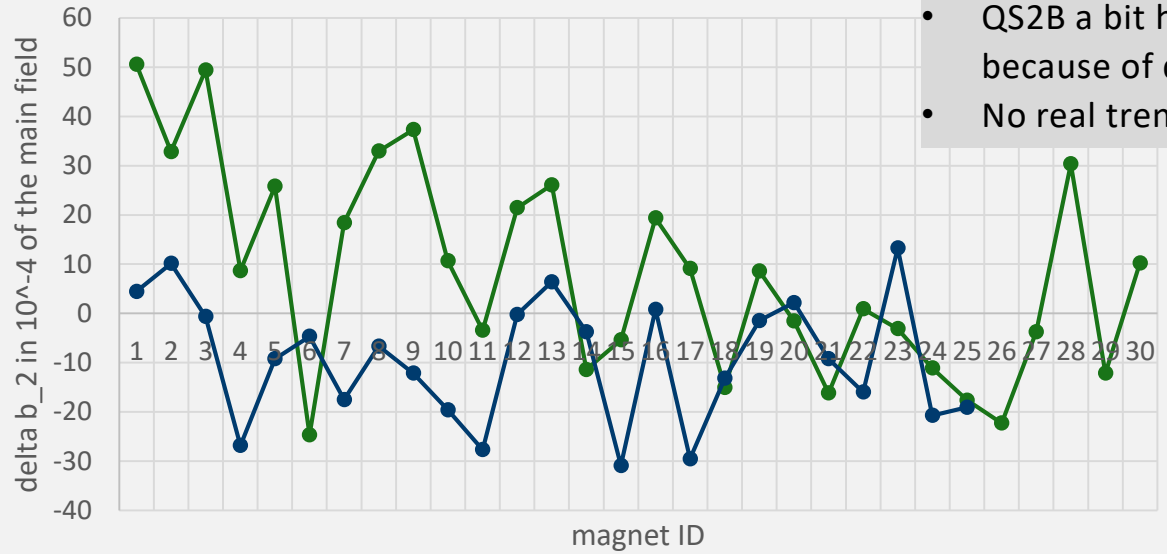
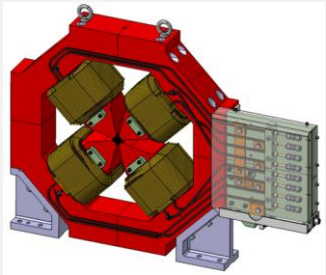
- S. Sidorov
- H. Garcia Rodrigues

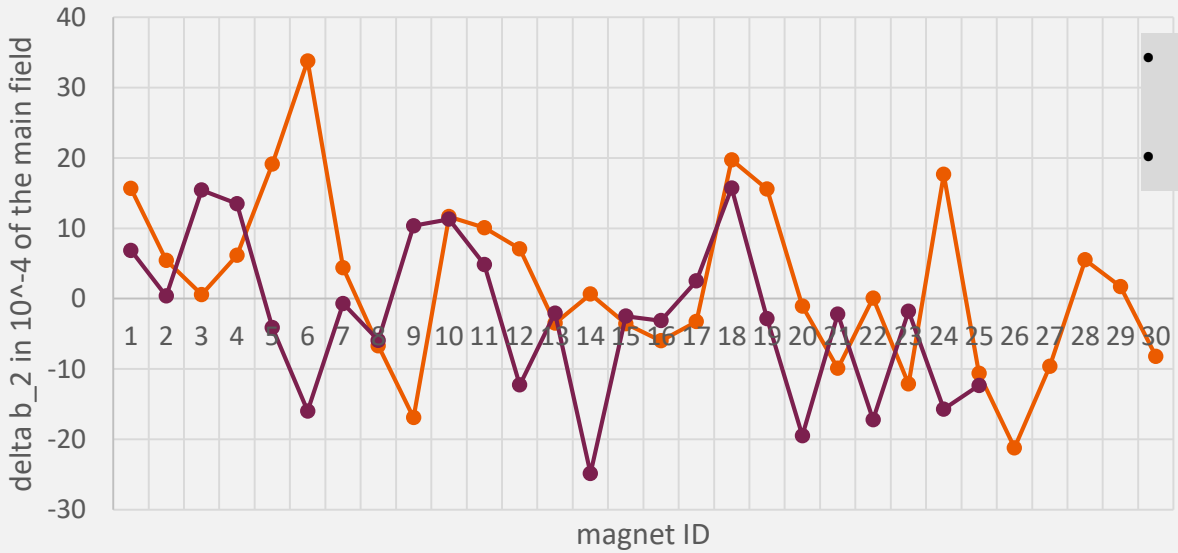


Spread of integrated field gradient around the average at 70 A

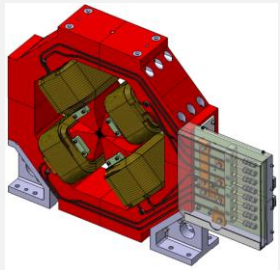


- QS2B a bit higher than QS2G, possibly because of different batch of iron for yoke
- No real trend over series

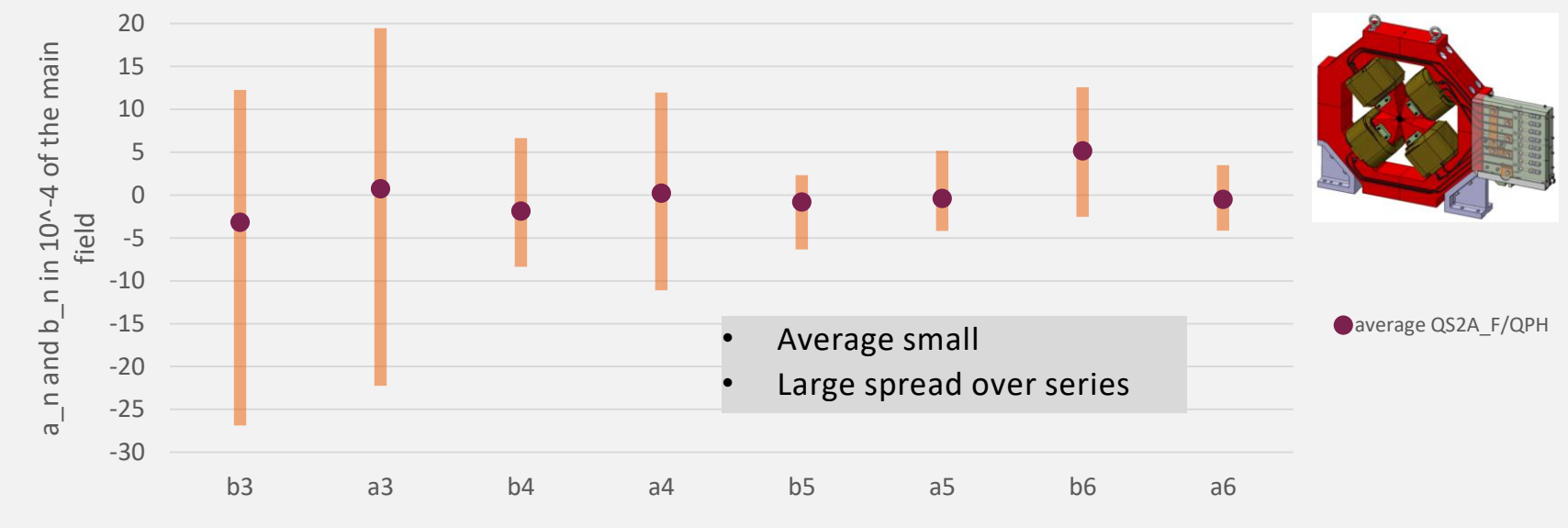


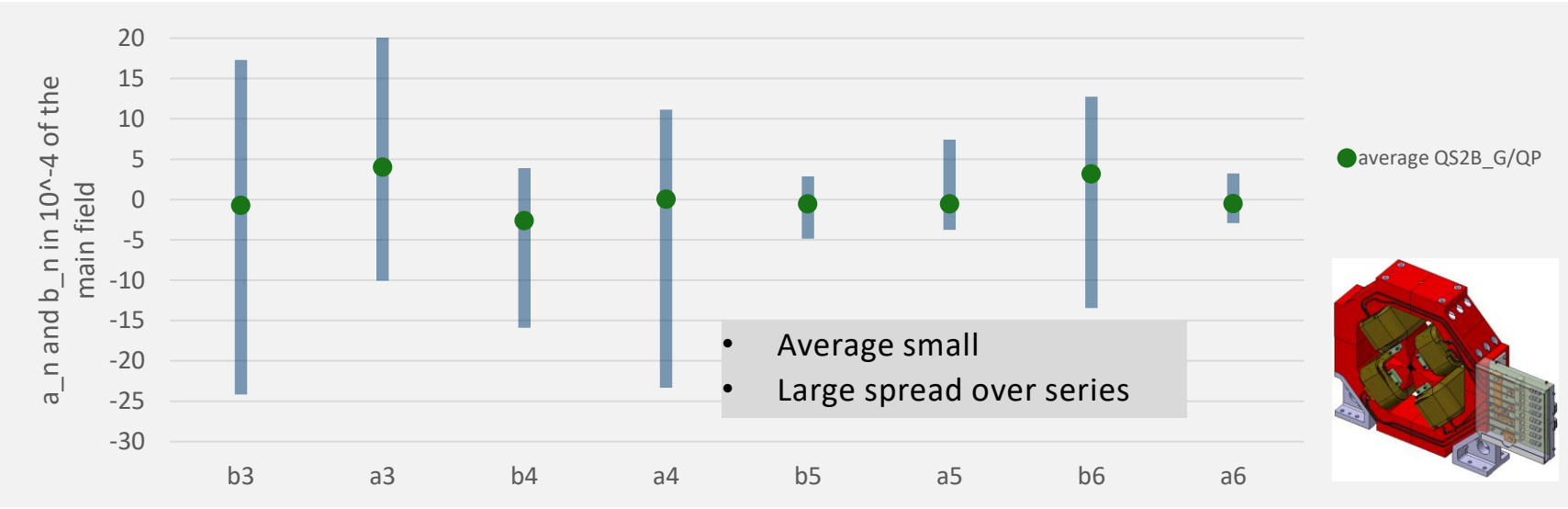


- No real distinction between QS2A and QS2F
- No real trend over series

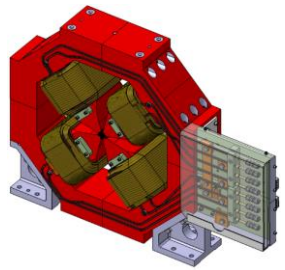


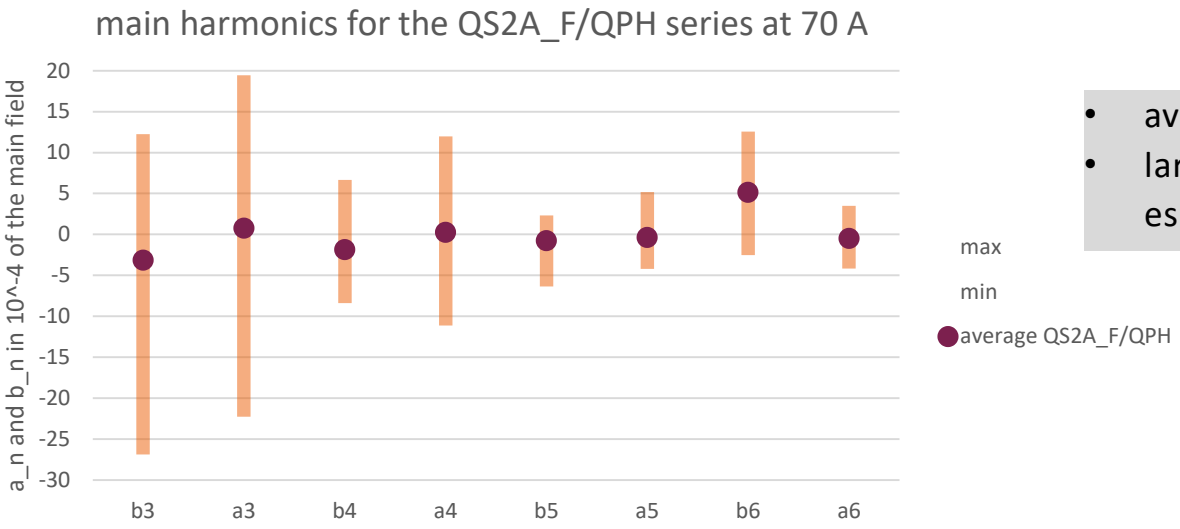
Average and spread of main harmonics at 70 A





Harmonics for QS2A and QS2F

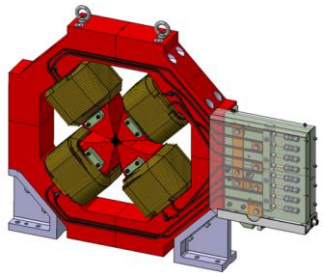


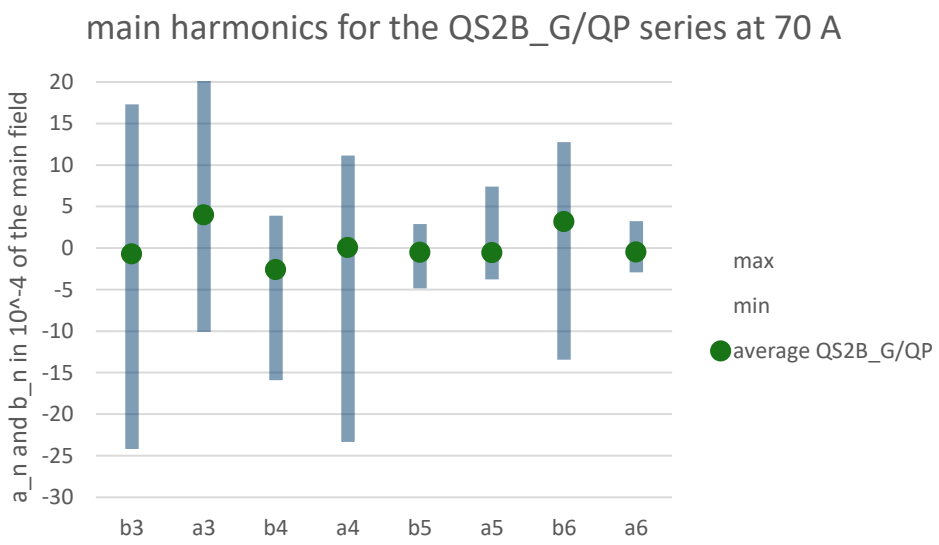


- average small
- large spread over series, especially b3, a3, a4, b6

Harmonic	b3	a3	b4	a4	b5	a5	b6	a6
Average	-3.16	0.73	-1.88	0.22	-0.80	-0.41	5.13	-0.51
Standard deviation	7.14	8.32	3.12	3.43	1.60	2.13	3.89	1.34
max	12.24	19.46	6.65	11.96	2.31	5.17	12.57	3.49
min	-26.87	-22.26	-8.38	-11.12	-6.36	-4.19	-2.53	-4.16

Harmonics for QS2B and QS2G

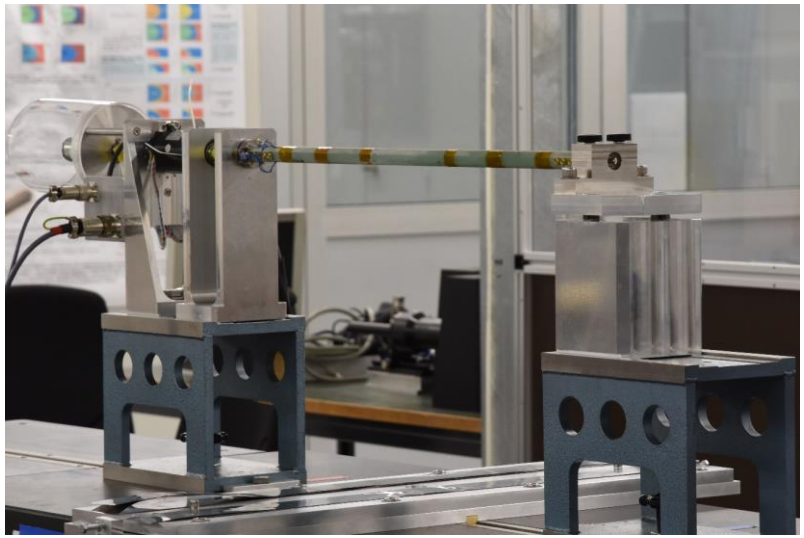


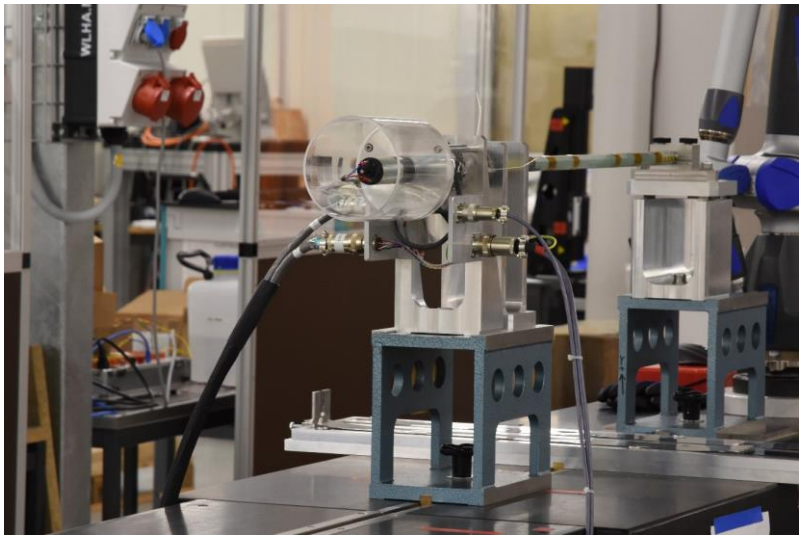


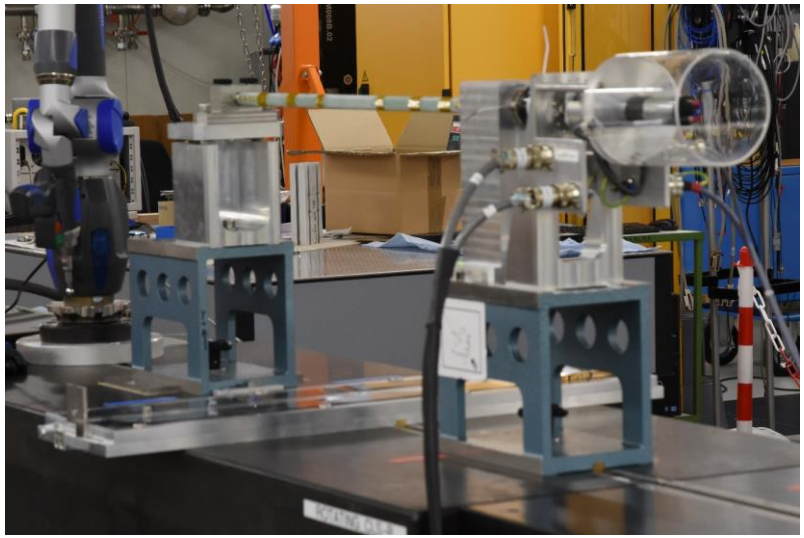
- Average small
- Large spread over series, especially b3, a3, b4, a4, b6

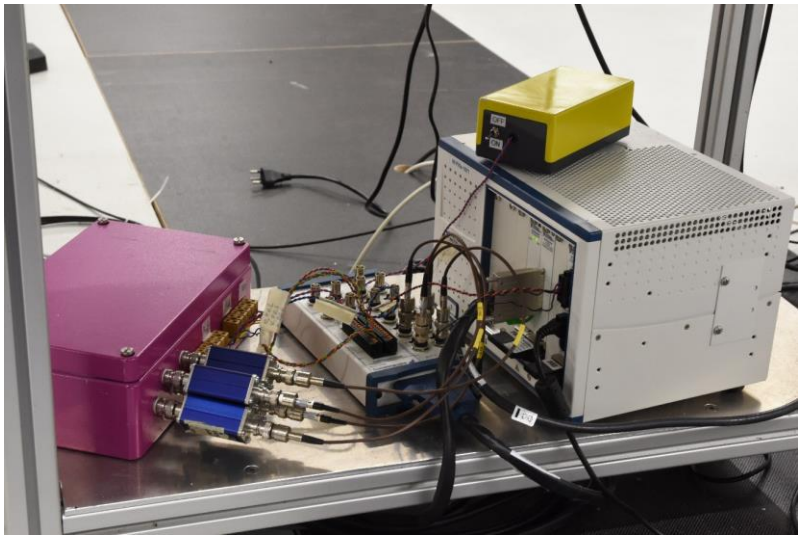
Harmonic	b3	a3	b4	a4	b5	a5	b6	a6
Average	-0.71	4.01	-2.60	0.05	-0.53	-0.56	3.17	-0.49
Standard deviation	7.96	7.10	3.67	4.89	1.90	1.87	4.27	1.18
max	17.29	24.24	3.88	11.15	2.88	7.42	12.76	3.25
min	-24.17	-10.08	-15.92	-23.33	-4.85	-3.78	-13.45	-2.93

Rotating Coils









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