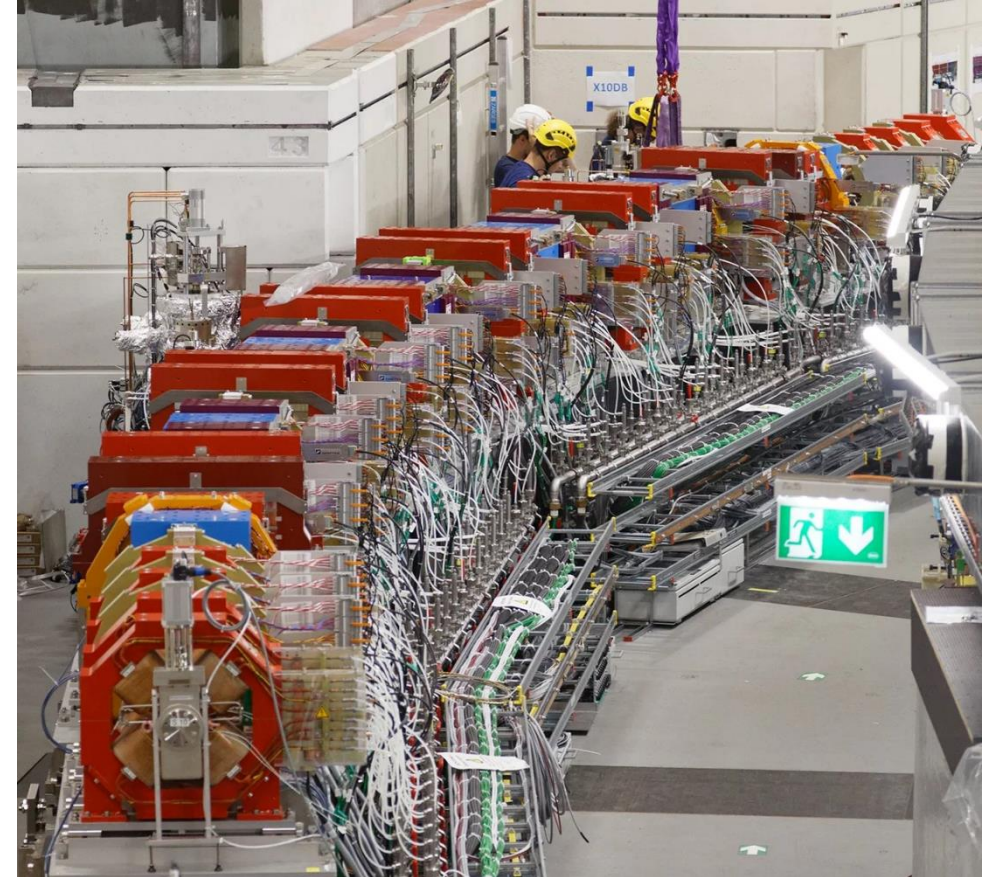


PSI Center for Accelerator Science
and Engineering

Measurement of Electromagnets and Tuning of Permanent Magnets based on Rotating Coils for the Upgrade of the Swiss Light Source (SLS2)

C. Zoller, M. Duda, T. Ernst, G. Montenero, R. Riccioli, V. van de Vijfeijken
IMMW23, Bad Zurzach, 08/10/2024

- Context
- Rotating coils measurement system
- Exemplary results electromagnets
- Exemplary results permanent magnets
- Conclusion



SLS2 magnets installed in the tunnel

Context: Upgrade of the Swiss Light Source (SLS2)



Aim:

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

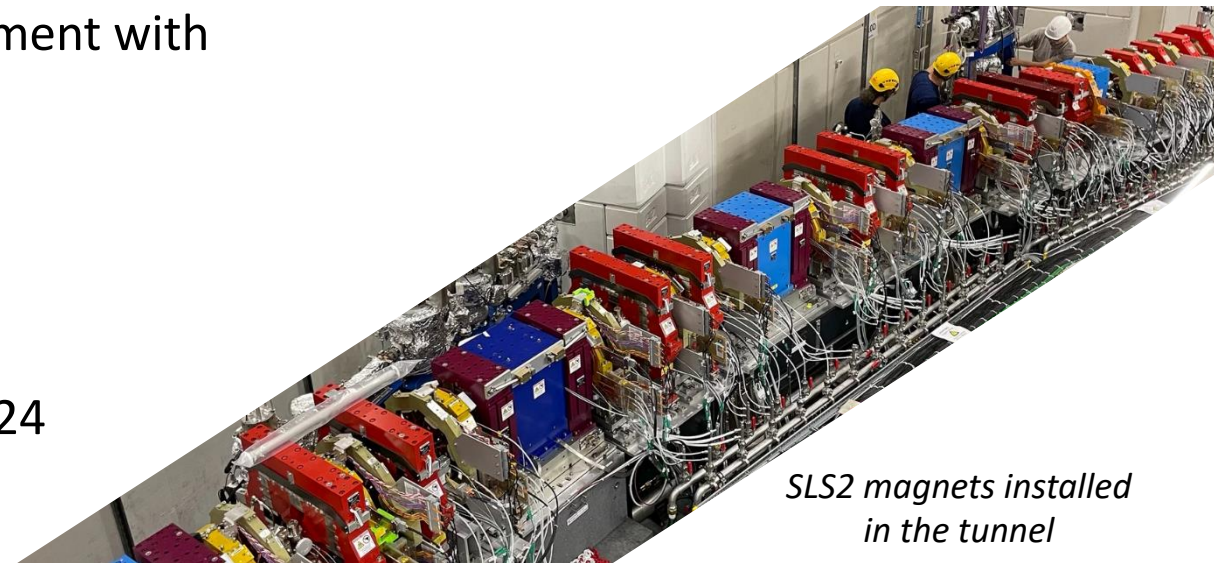
Resulting challenges for magnets:

- **Extremely dense** Multi Bend Achromat lattice arrangement with
 - 888 electromagnets
 - 450 permanent magnets
 - 2 superconducting magnets
- Installation of all magnets in the tunnel until end of 2024

More information see presentations of

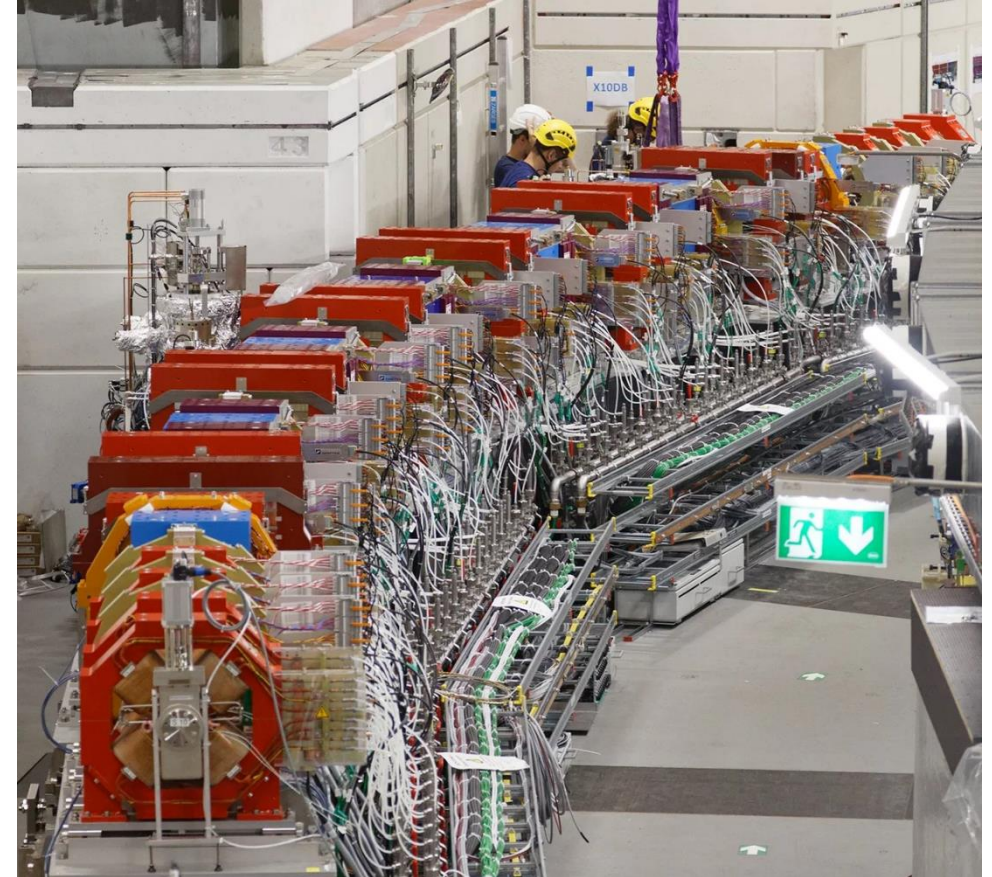
- S. Sanfilippo
- M. Aiba
- R. Riccioli
- G. Montenero

and visit of SLS2 on Wednesday



SLS2 magnets installed in the tunnel

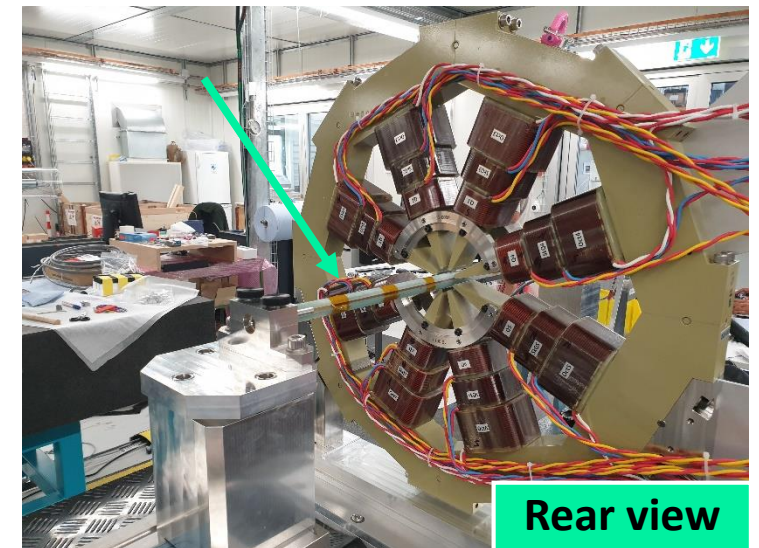
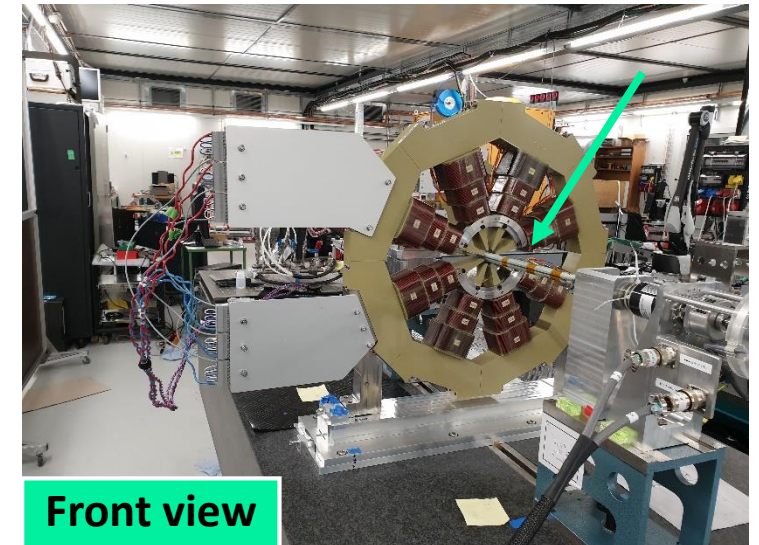
- Context
- Rotating coils measurement system
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- Conclusion



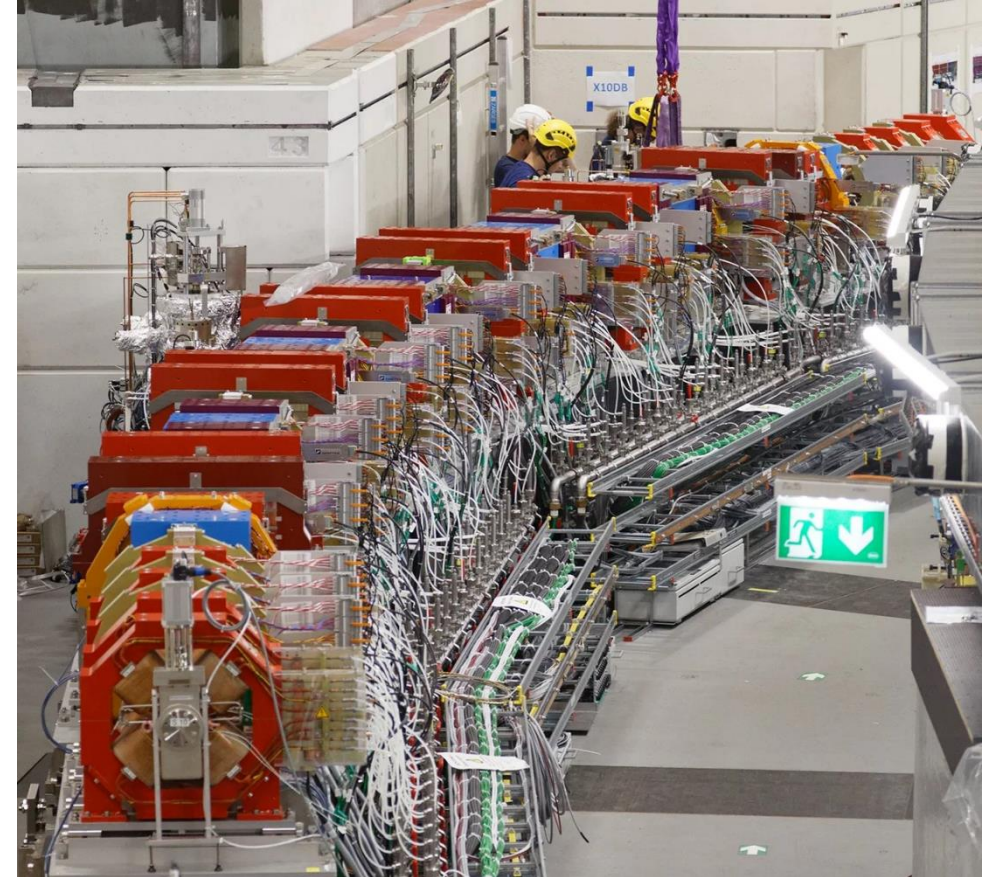
SLS2 magnets installed in the tunnel

Measurement system: Rotating Coils (RC)

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

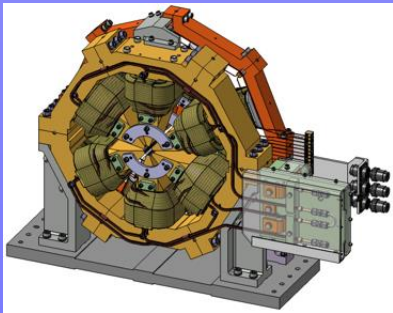


- Context
- Rotating coils measurement system
- Exemplary results electromagnets
- Exemplary results permanent magnets
- Conclusion



SLS2 magnets installed in the tunnel

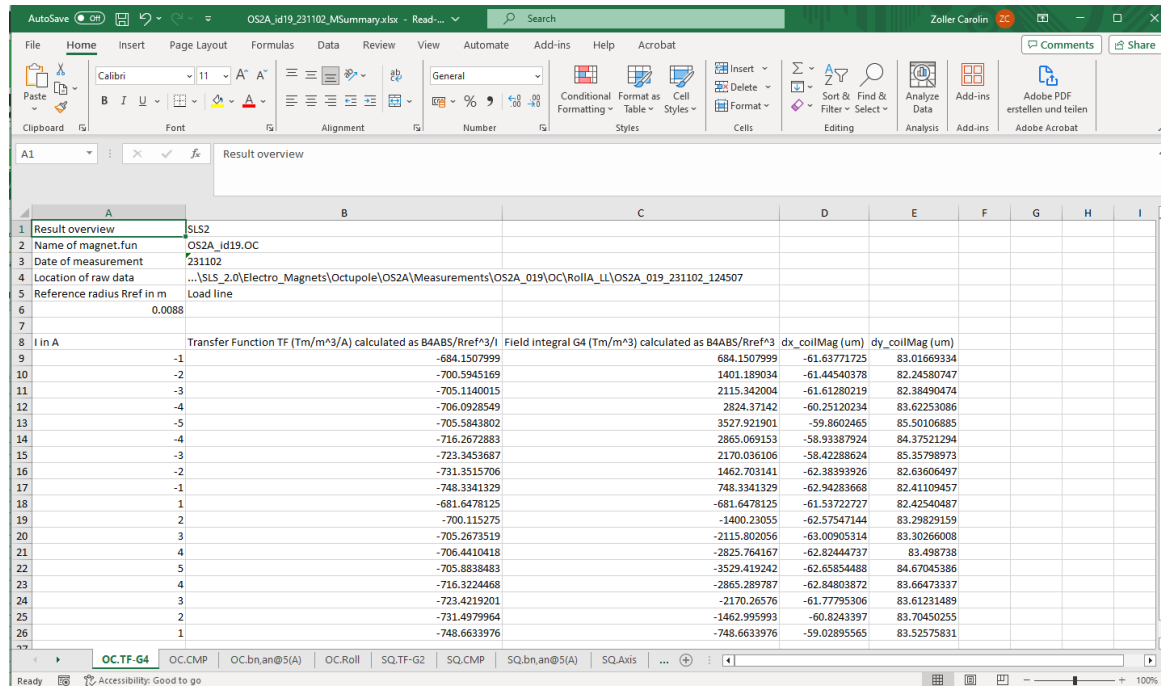
Specs electromagnets (EM)

Name	SOQ = HS2-A/B/G/H/K/L/M and OS2- A/B/E/F	HS2F-SXQ	SS2A-CH(S)/CV
Subtypes	8 HS2i and 4 OS2i		2 CH(S) and 1 CV
Length / mm	230= 90 (SX) + 50 (OC)	140, 90 (SX)	105
$\int \frac{B_Y}{B_X} dl / \text{mTm}$	-	-	3.6
$\frac{B''_Y}{2} / \text{T/m}^2$	5850	5850	-
Amount	264	24	112
Drawing			

Measurement program EM:

- Some magnets: **Pre-heating** of magnet (cooling water, nominal current) over night
- Some magnets: Measurement of **magnet position** on bench with FARO or laser tracker
- Some magnets: **Degaussing**
- Measurement of **Loadline** (0 A -> +/- nominal current -> 0 A)
- Measurement of **roll angle**, reference position, nominal current
- Measurement of **roll angle**, flip position, nominal current

In case of combined-function- OC-NQ-SQ

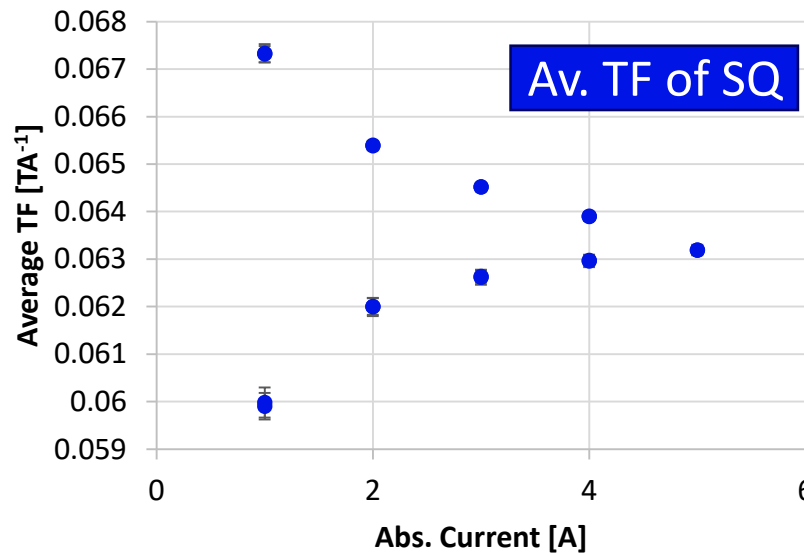
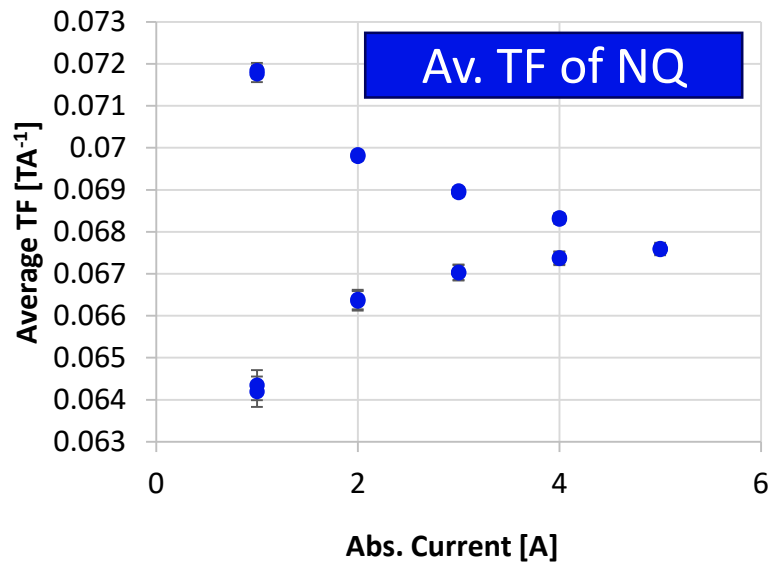
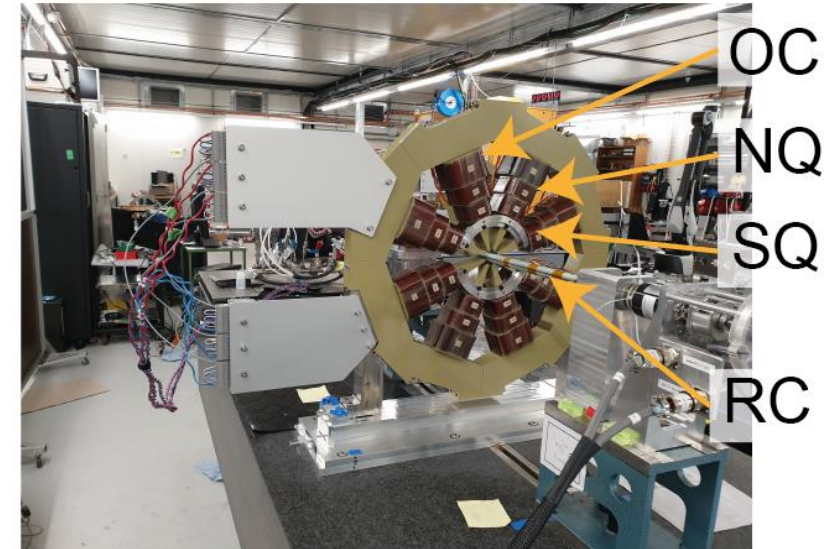
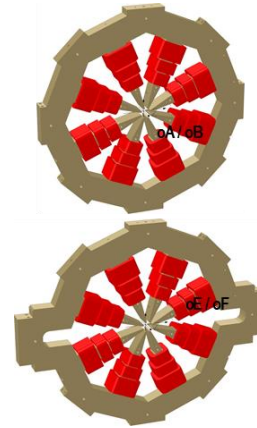
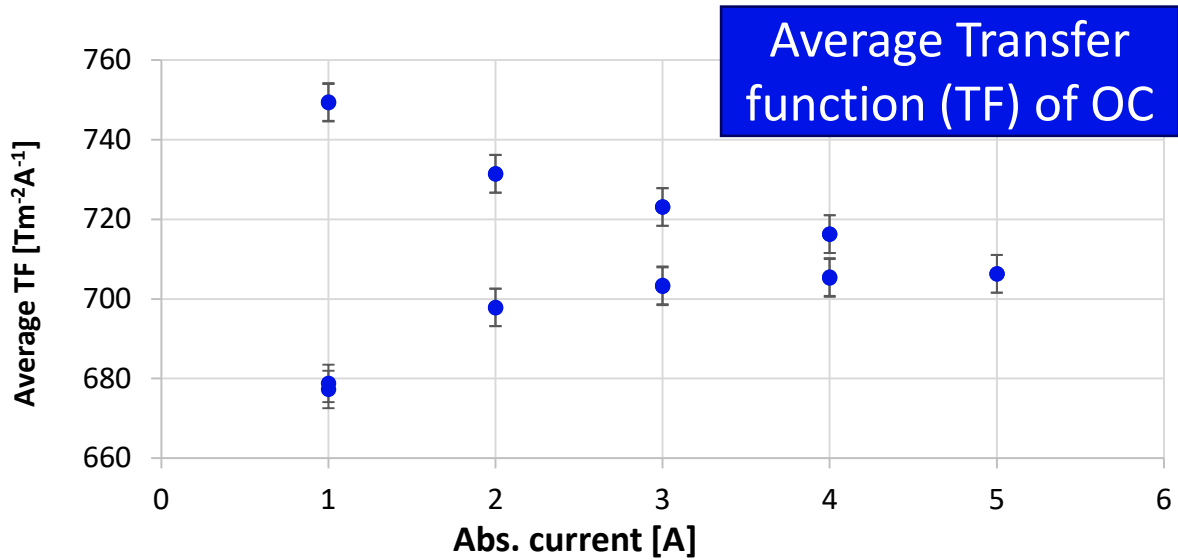


I in A	Transfer Function TF (Tm/m³/A) calculated as B4ABS/Rref³/3	Field integral G4 (Tm/m³) calculated as B4ABS/Rref³	dx_coilMag (um)	dy_coilMag (um)
-1	-684.1507999	684.1507999	-61.63771725	83.01669334
-2	-700.5945169	1401.189034	-61.44540378	82.24580747
-3	-705.1140015	2115.342004	-61.61280219	82.38490474
-4	-706.0928549	2824.37142	-60.25120234	83.62253086
-5	-705.5843802	3527.921901	-59.8602465	85.50106885
-4	-716.2672883	2865.069153	-58.93387924	84.37521294
-3	-723.3453687	2170.036106	-58.42288624	85.35798973
-2	-731.3515706	1462.703141	-62.3833926	82.63606497
-1	-748.3341329	748.3341329	-62.94283668	82.41109457
1	-681.6478125	-681.6478125	-61.53722727	82.42540487
2	-700.115275	-1400.23055	-62.57547144	83.29829159
3	-705.2673519	-2115.802056	-63.00905314	83.30266008
4	-706.4410418	-2825.764167	-62.82444737	83.498738
5	-705.8838483	-3529.419242	-62.65854488	84.67045386
4	-716.3224468	-2865.289787	-62.84803872	83.66473337
3	-723.4219201	-2170.26576	-61.77795306	83.61231489
2	-731.4979964	-1462.995993	-60.8243397	83.70450255
1	-748.6633976	-748.6633976	-59.02895565	83.52575831

- Determination of
- Transfer Function (TF)
 - Harmonics
 - Magnetic axis
 - Roll angle
- (1-σ repeatability < 0.05 %)



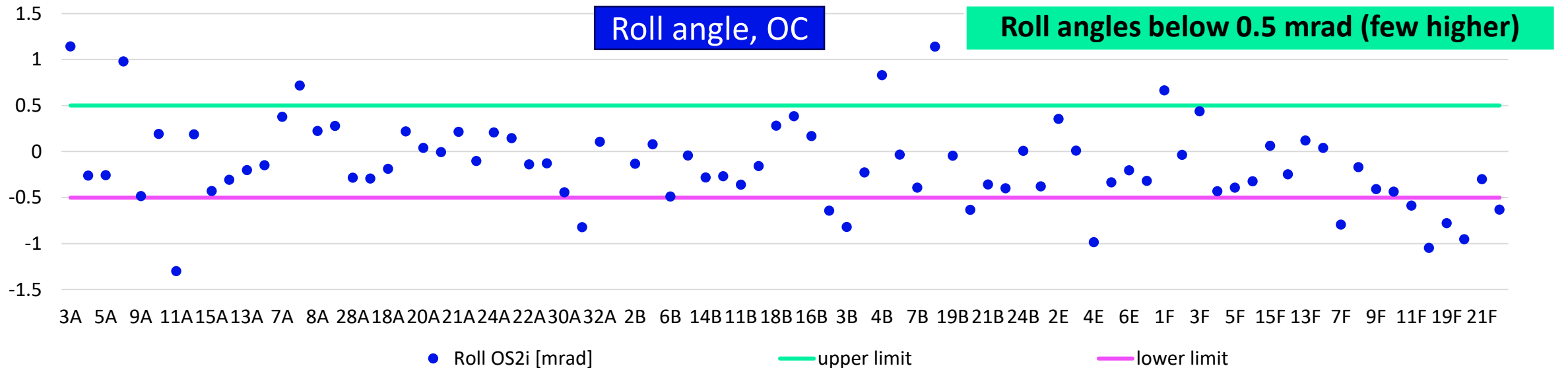
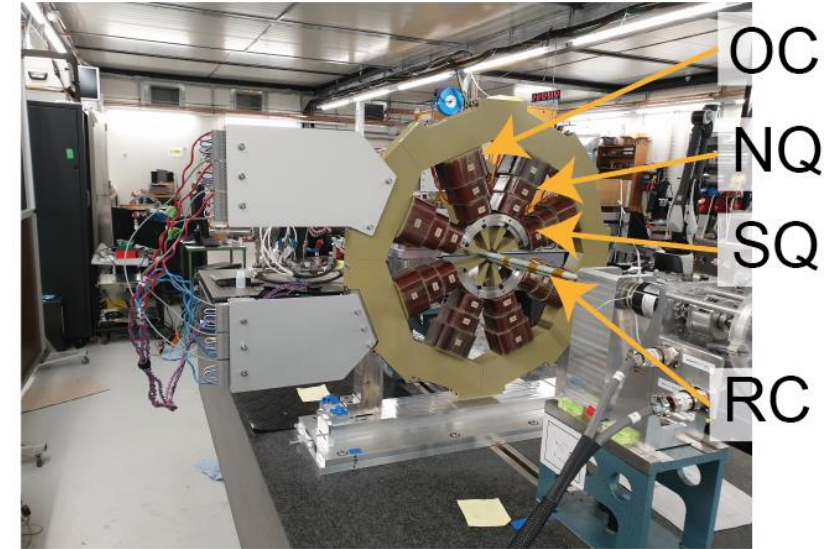
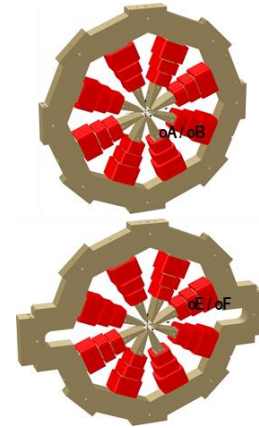
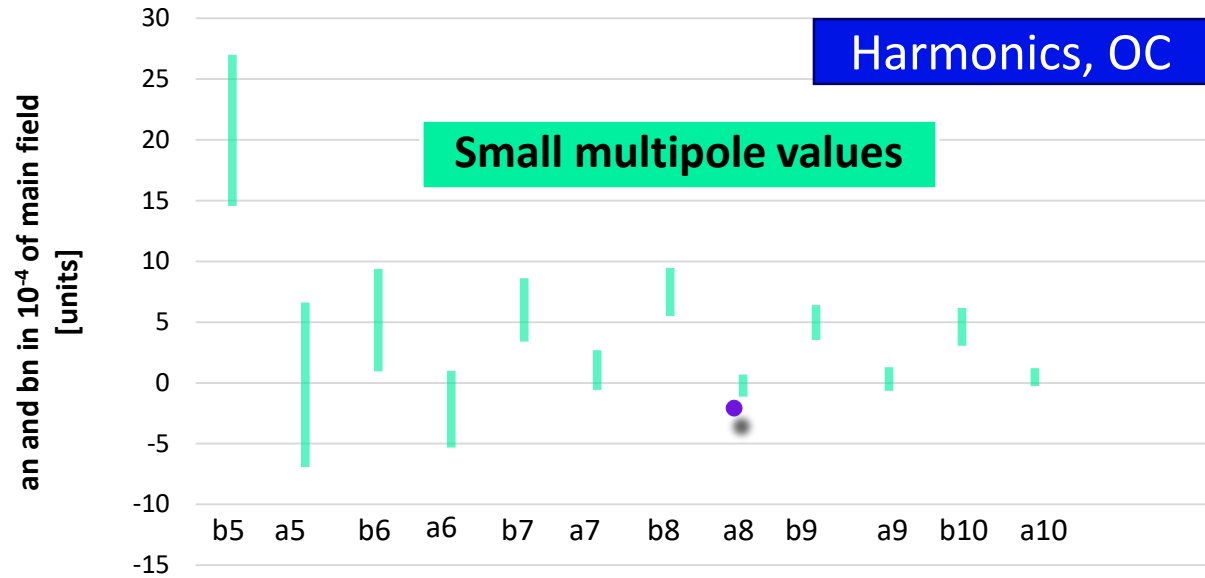
Results 82 OC with RC



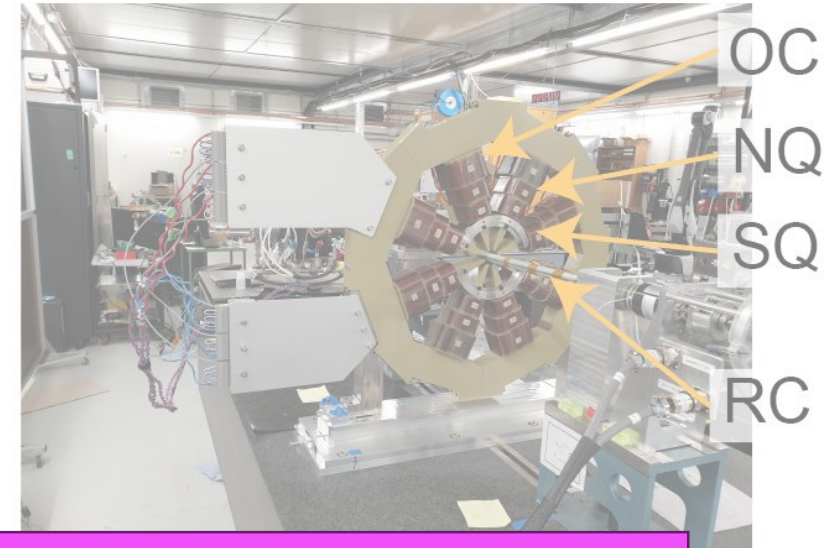
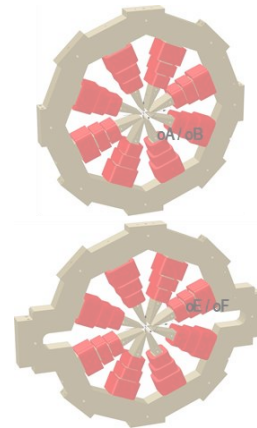
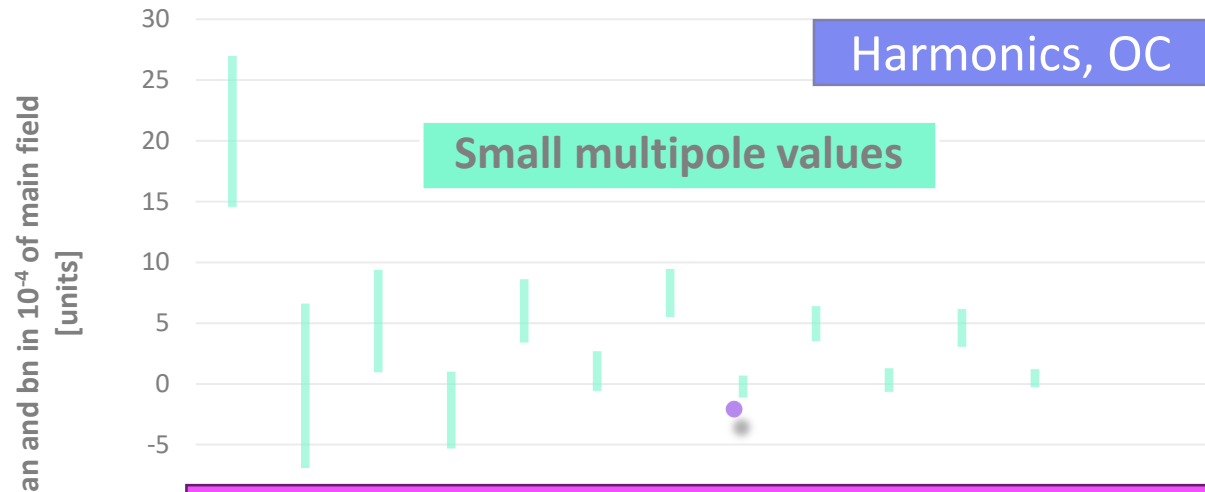
Integr. Strength	Meas. Average (T/m ²)	σ (unit)	Meas. vs. Sim. (%)
OA/OB	3530	23	+1.5
OE/OF	3531	25	+1.7

Integrated field strength: small spread, discrepancies with simulation ~1.6 %

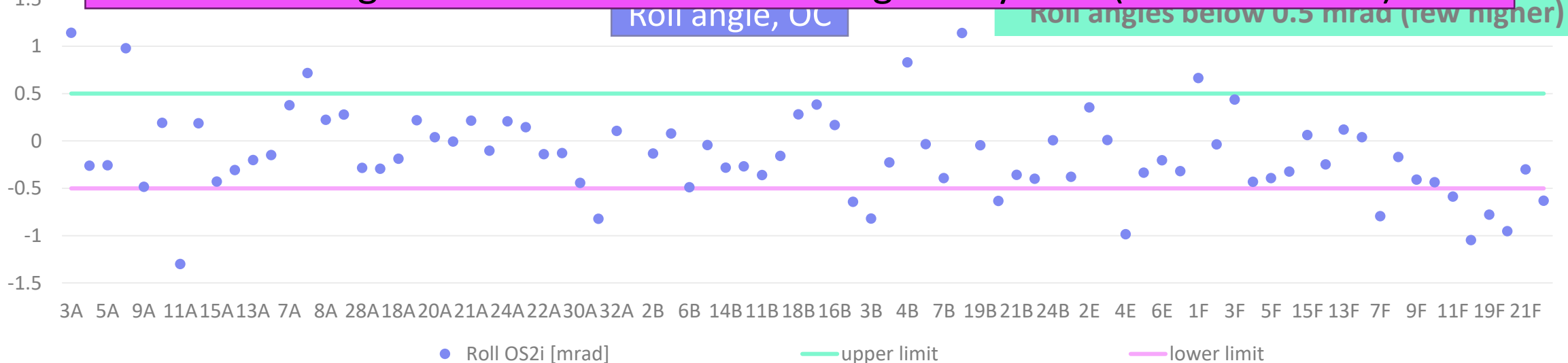
Results 82 OC with RC



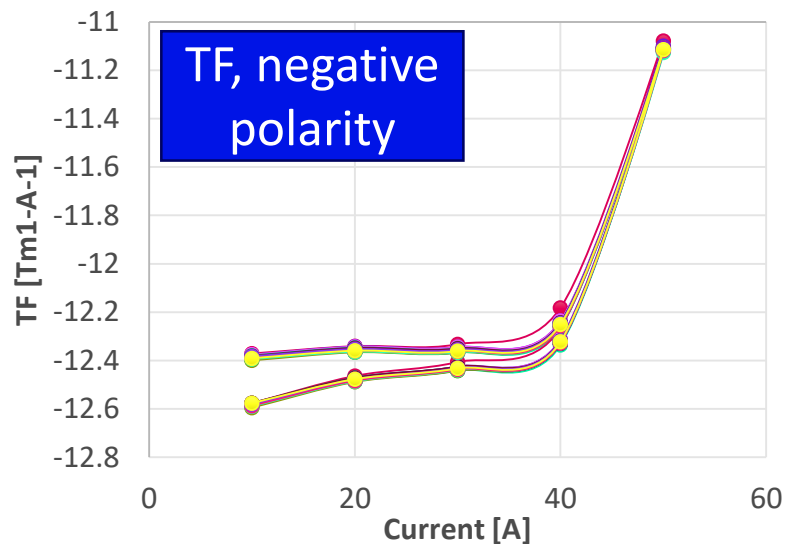
Results 82 OC with RC



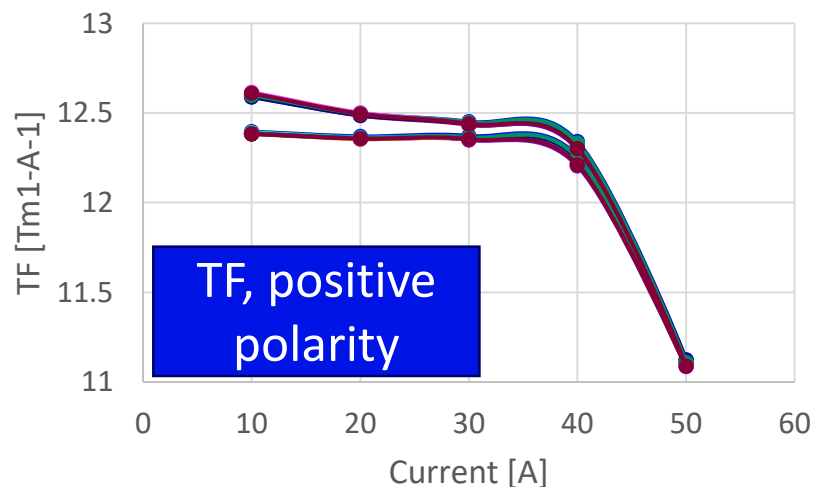
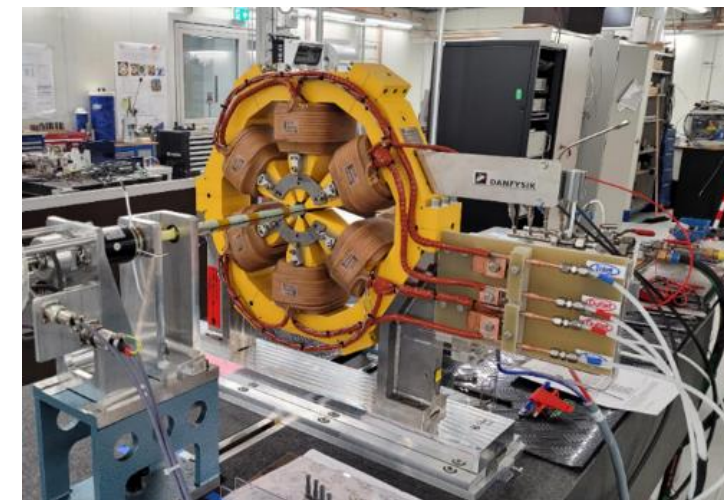
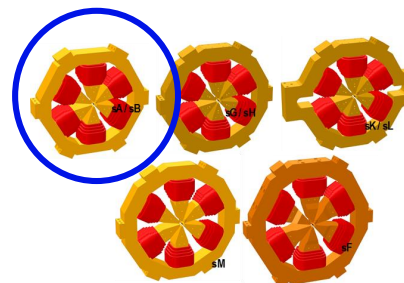
Due to good quality, individual measurements stopped after 82 magnets
 → all magnets measured with vibrating wire system (talk of M. Aiba)



Results 116 SX/SXQ with RC: exemplary HS2A and -B



- 6A
- 1A
- 9A
- 8A
- 3A
- 8B
- 4B
- 3B
- 6B
- 2A
- 7A
- 4A
- 5A
- 5B
- 1B
- 9B
- 2B

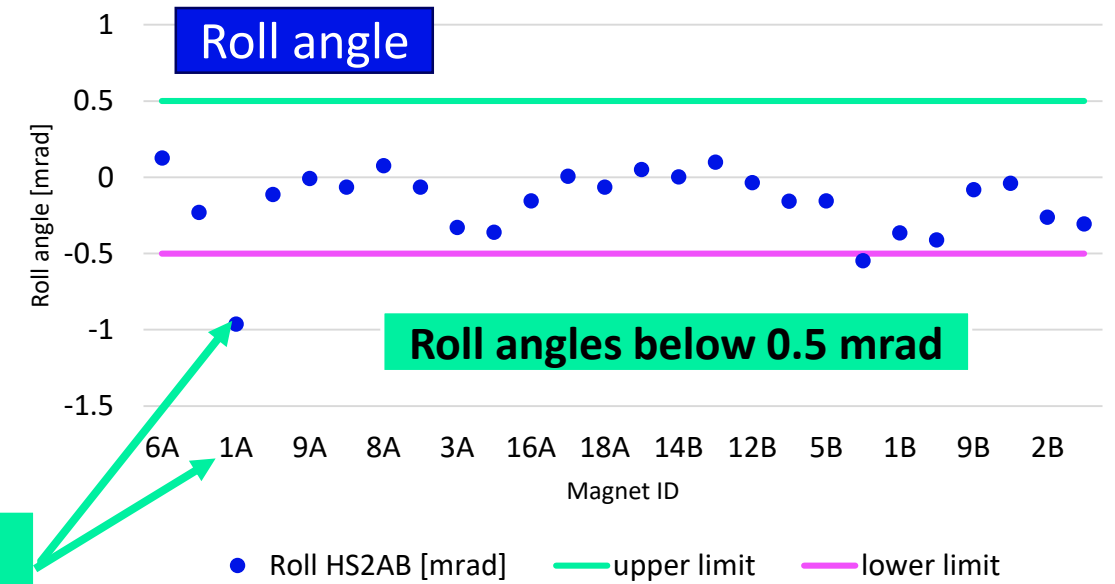
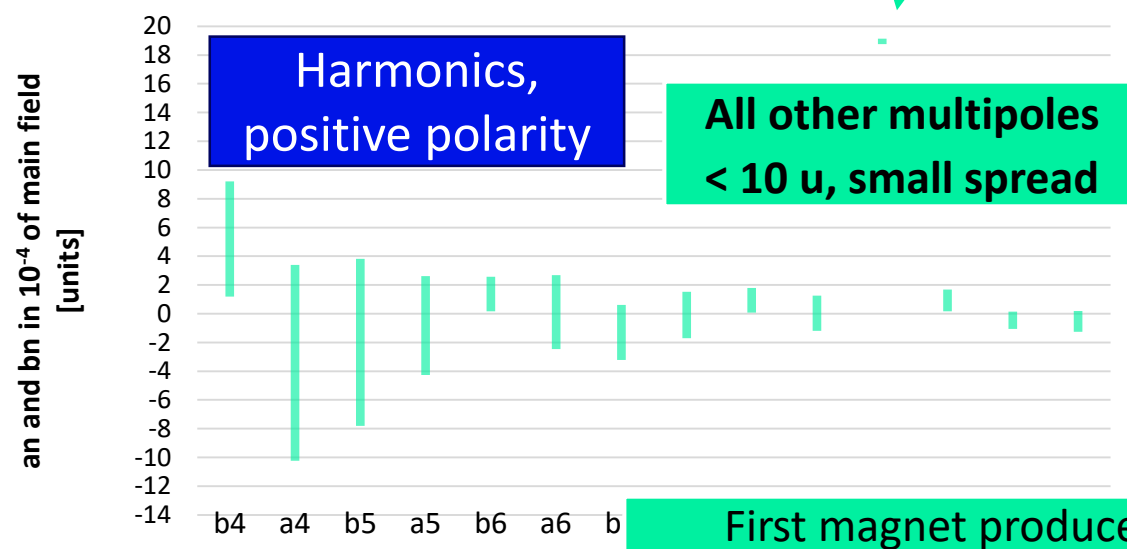
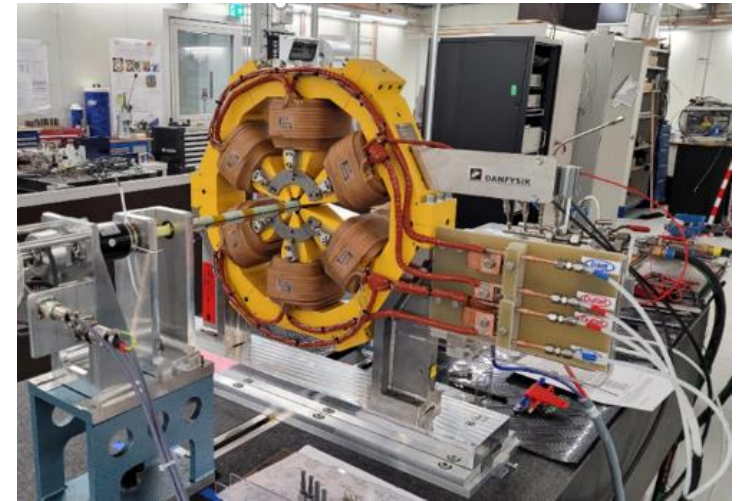
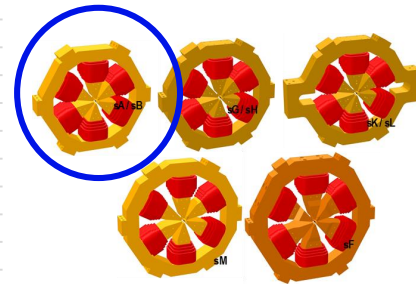
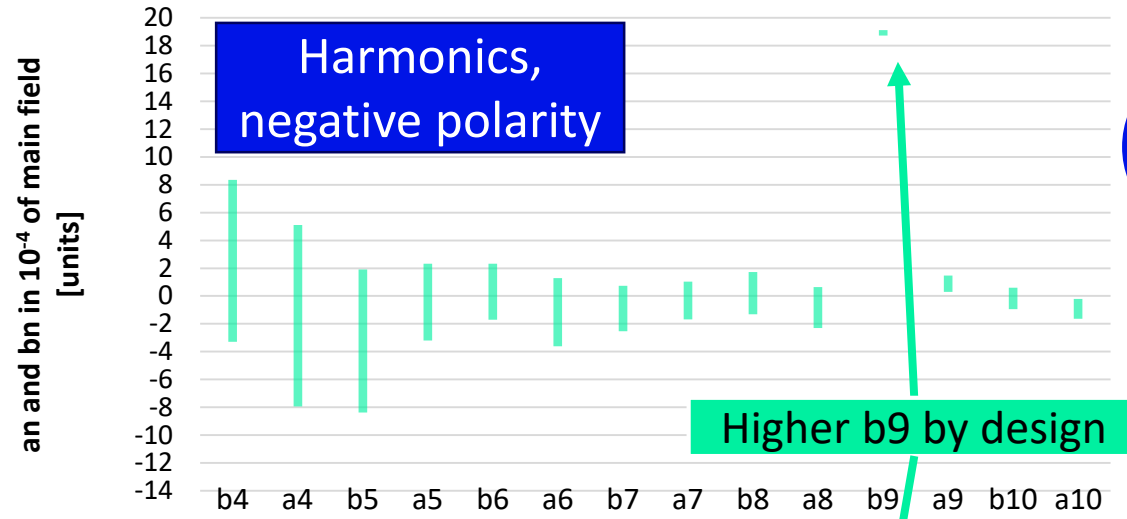


- 15A
- 16A
- 17A
- 18A
- 13B
- 14B
- 11B
- 12B
- 10B

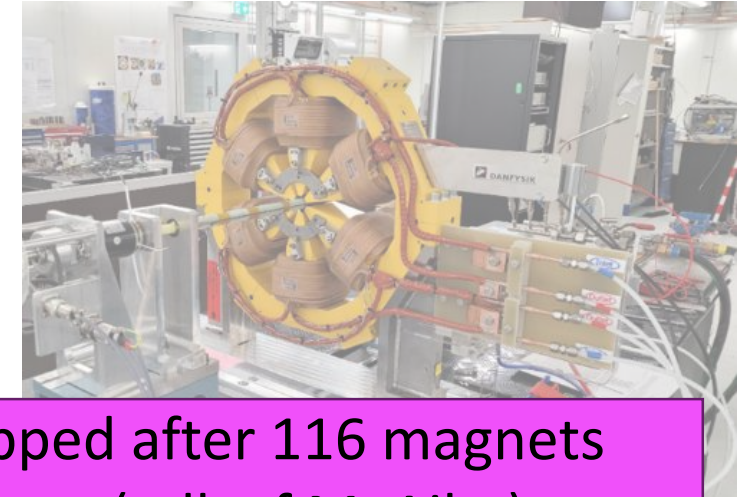
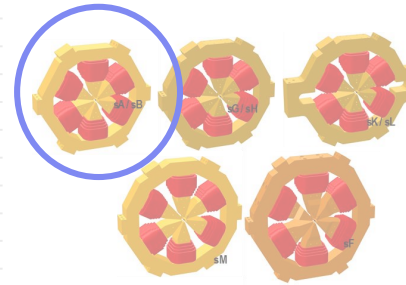
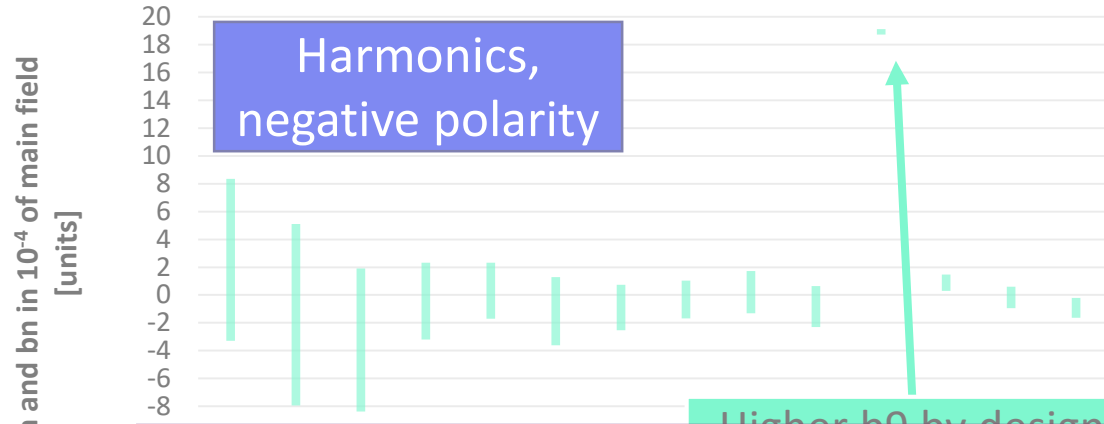
	Strength @50 A		
	Average (T/m)	Spread (unit)	Mea. vs exp.(%)
H2SA&H2SB	555.557	9.2	2.30
H2SG&H2SH	487.082	5.7	3.2
H2SF	480.857	7.8	2.9
H2SKL	487.173	12.7	3.2
H2SM	482.493	8.6	2.9

Integrated field strength: small spread – Meas. values ~3 % above the computed ones

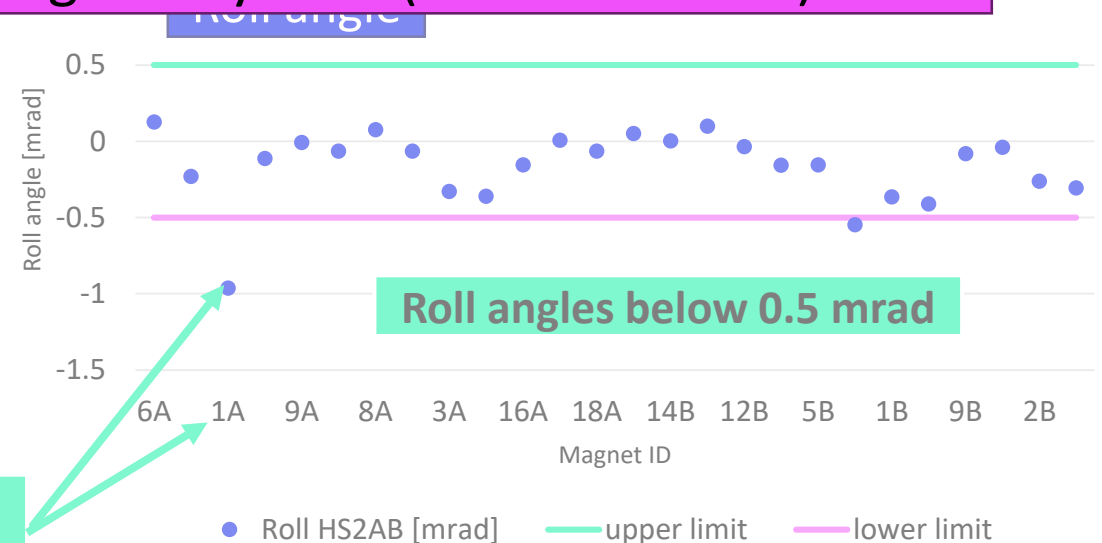
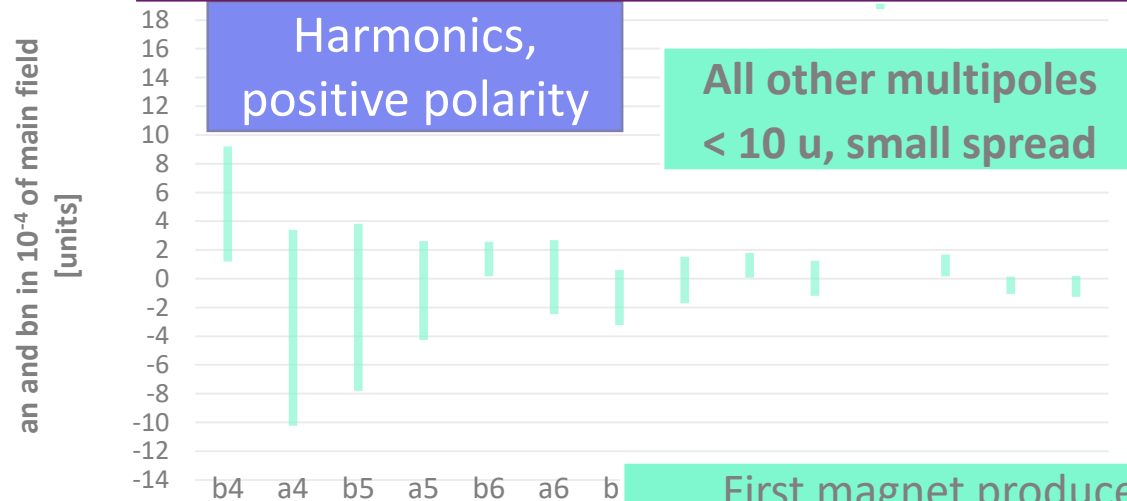
Results 116 SX/SXQ with RC: exemplary HS2A and -B



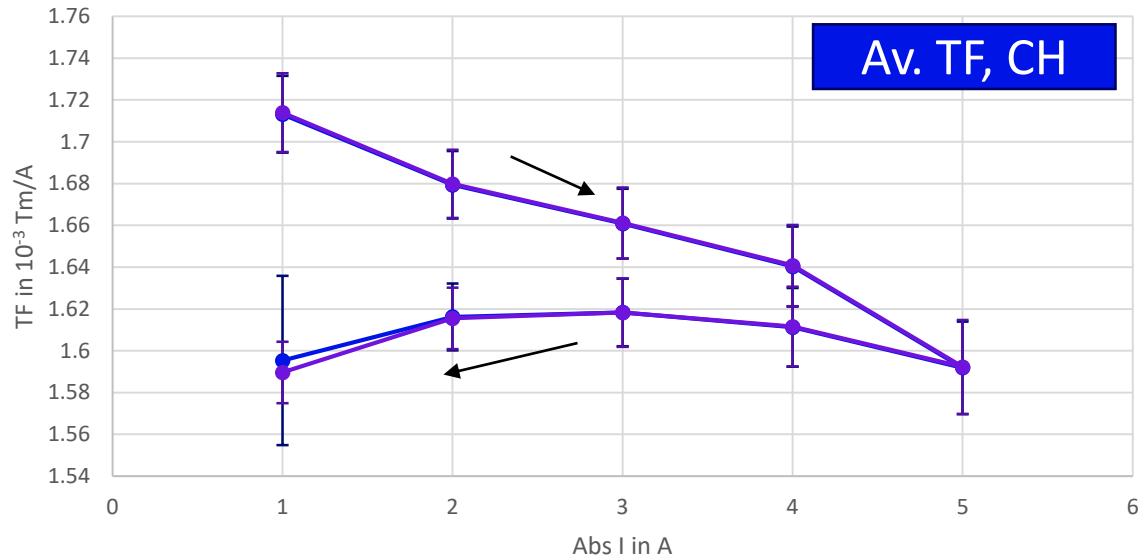
Results 116 SX/SXQ with RC: exemplary HS2A and -B



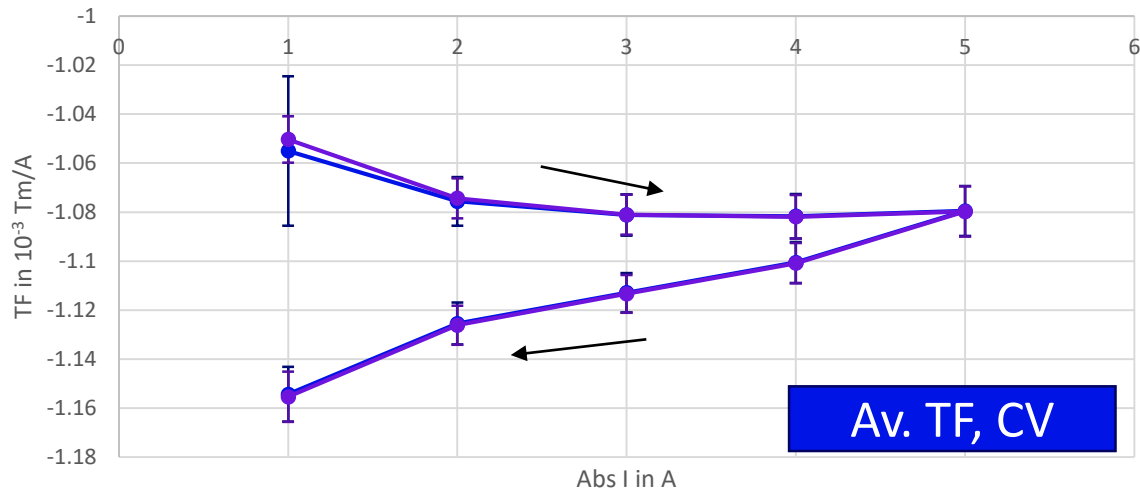
Due to good quality, individual measurements stopped after 116 magnets
 → all magnets measured with vibrating wire system (talk of M. Aiba)



Results 112 CH(S)/CV with RC: exemplary CH/CV



● TF CH (pos I)
● TF CH (neg I)

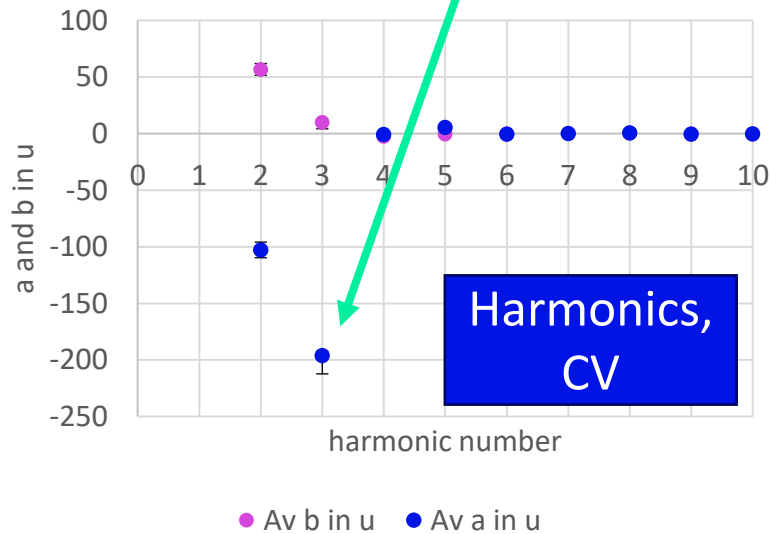
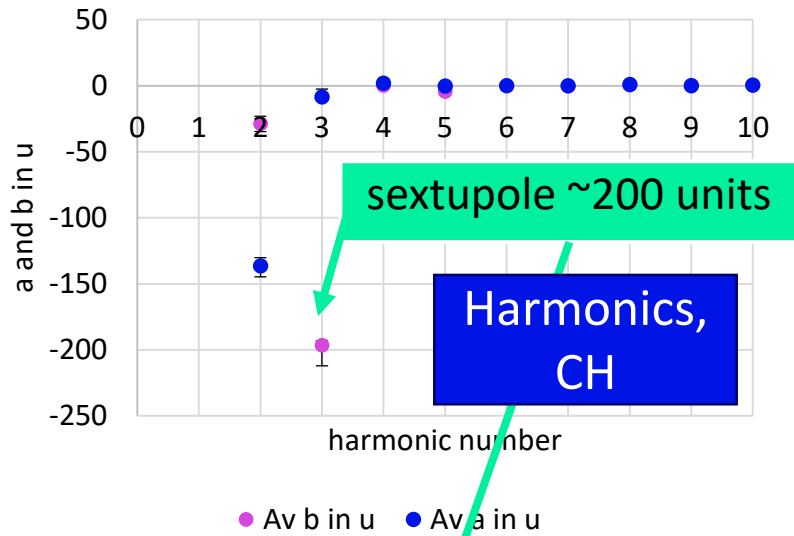


● TF CV (pos I)
● TF CV (neg I)



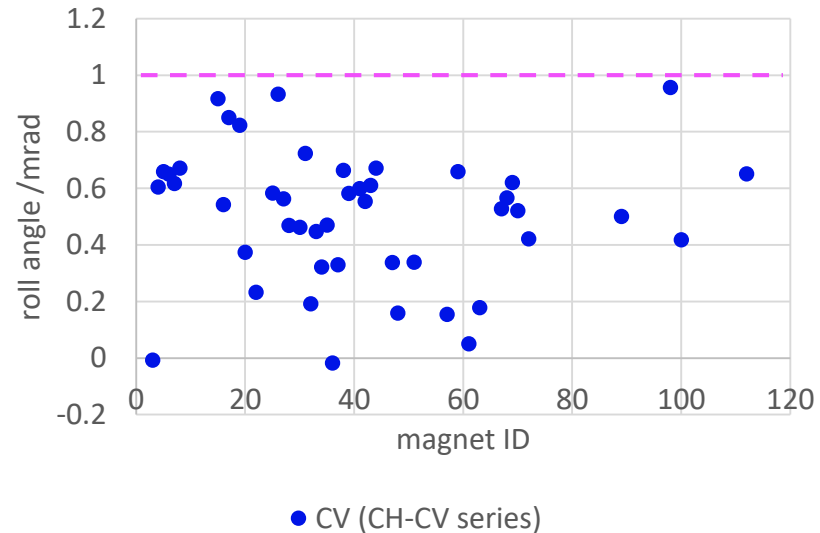
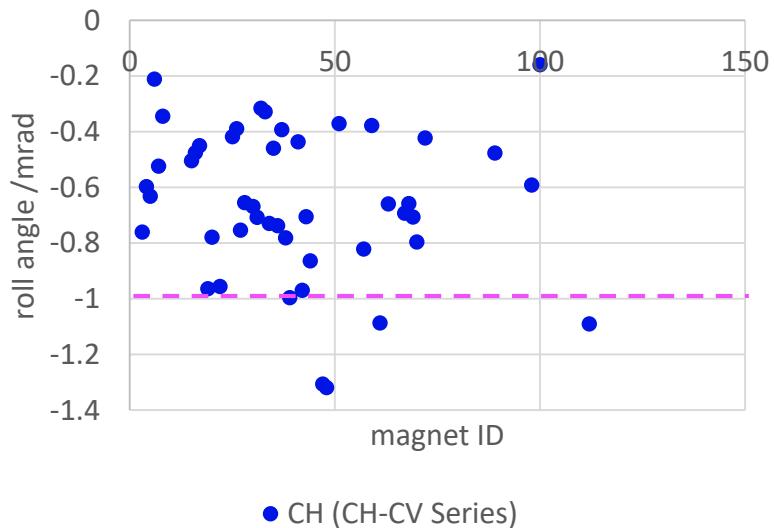
Vertical steering & horizontal steering strength as expected

Results 112 CH(S)/CV with RC: exemplary CH/CV

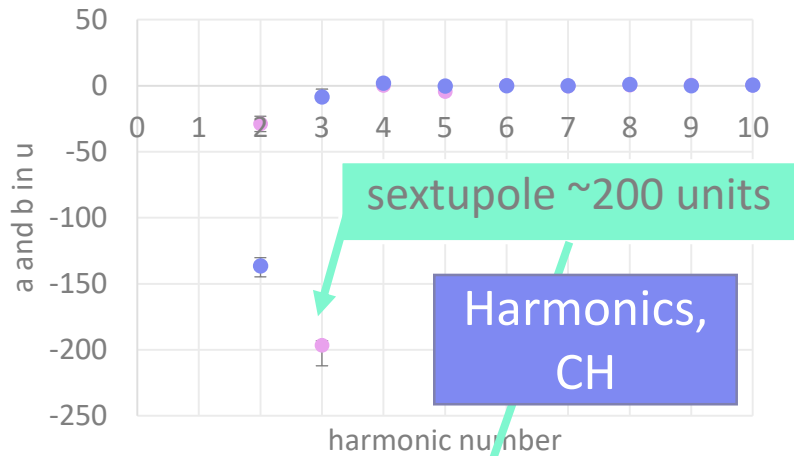


Multipoles as expected

Roll angles between ± 1 mrad (few higher)



Results 112 CH(S)/CV with RC: exemplary CH/CV

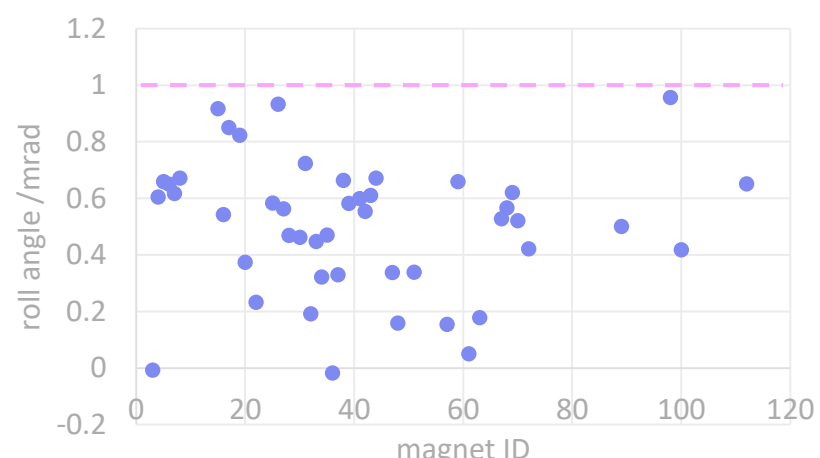
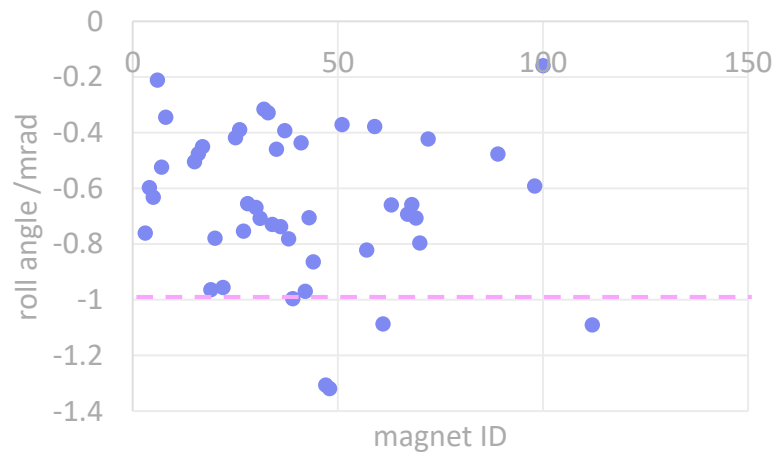
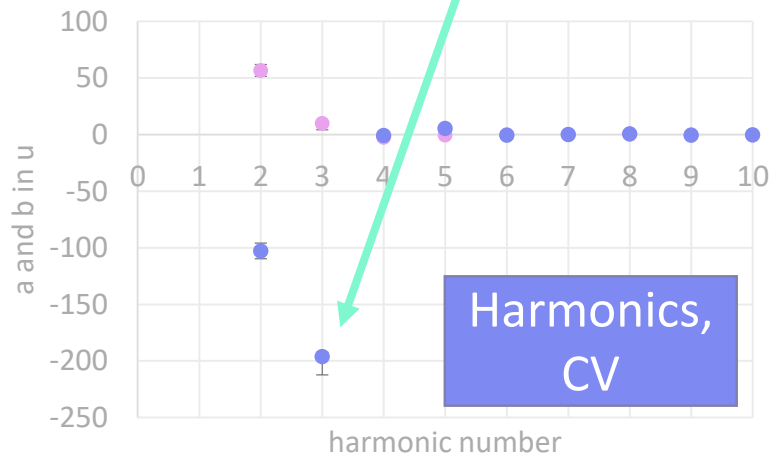


Multipoles as expected



Roll angles between +/-

Good quality of magnets delivered

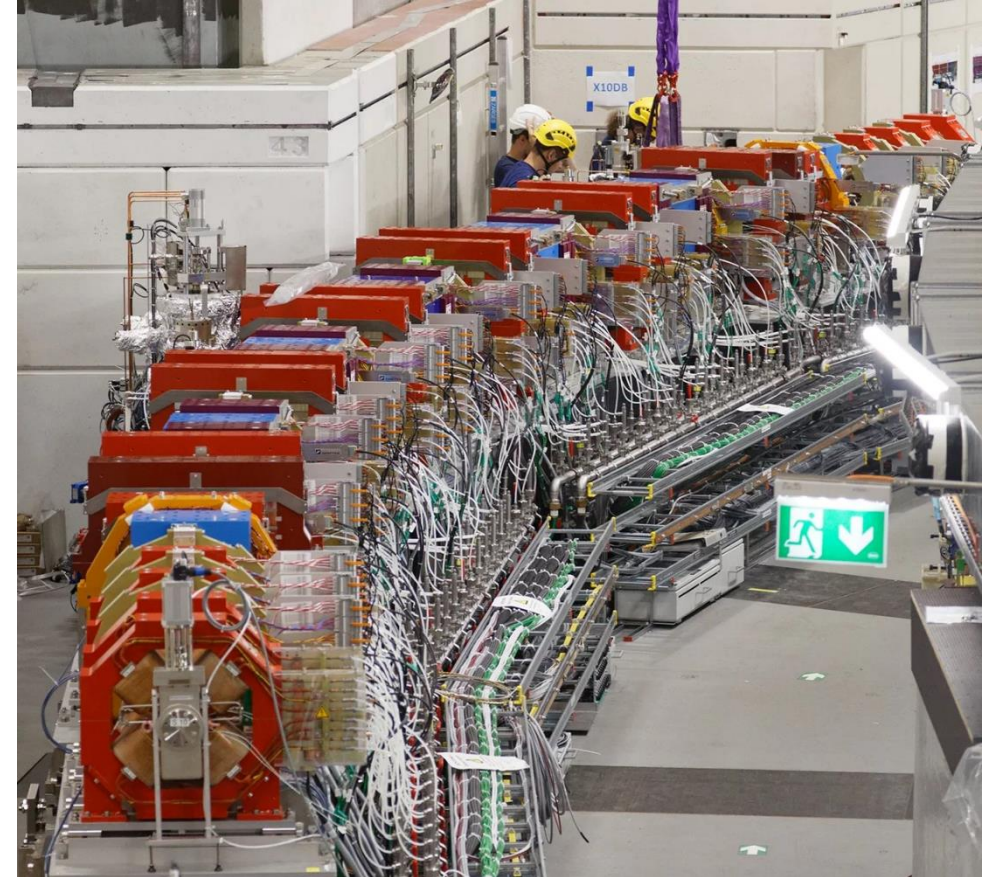


● Av b in u ● Av a in u

● CH (CH-CV Series)

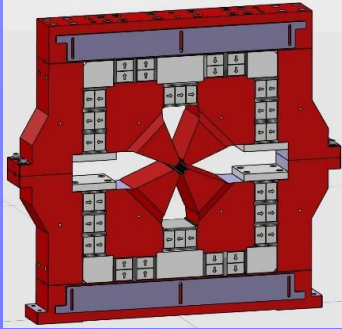
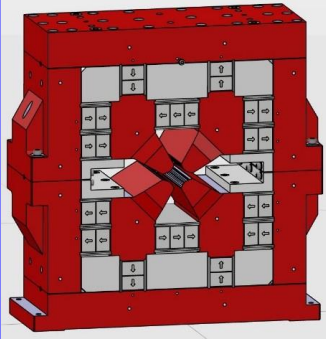
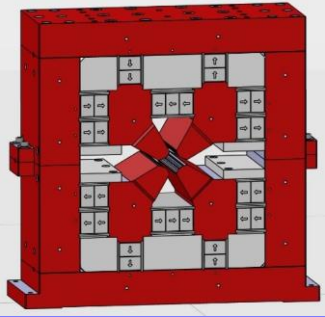
● CV (CH-CV series)

- Context
- Rotating coils measurement system
- Exemplary results electromagnets
- Exemplary results permanent magnets
- Conclusion



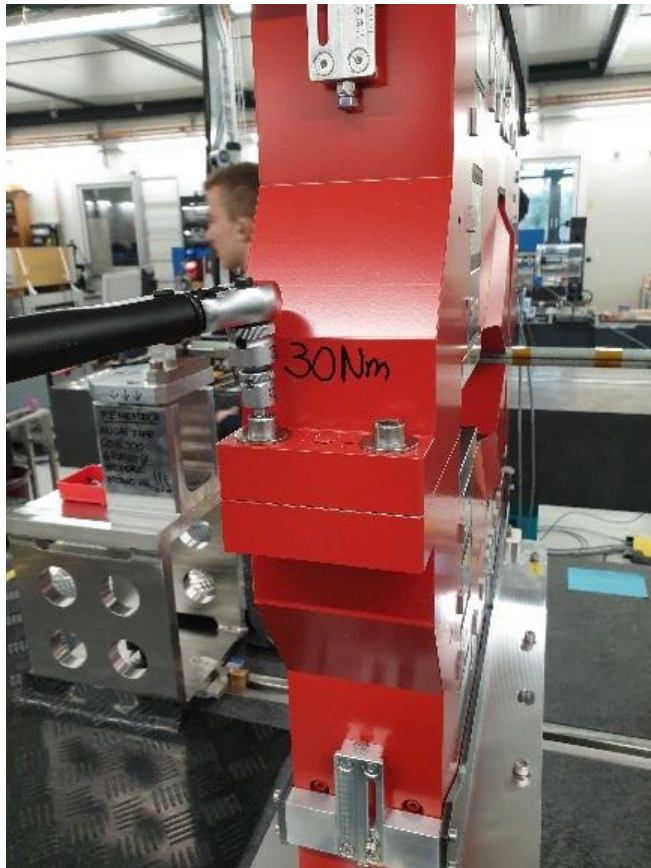
SLS2 magnets installed in the tunnel

Specs permanent magnets (PM)

Name	AN (QS2D)	ANM (QS2C)	VE (QS2K)
Subtypes	10	2	2
Length / mm	140	150	240
Field / T	+0.26947	+0.27246	-0.65495
Gradient/ T/m	-77.6562	-82.8733	+45.7648
Amount	120 (10x12)	24 (12+12)	24 (12+12)
Drawing			

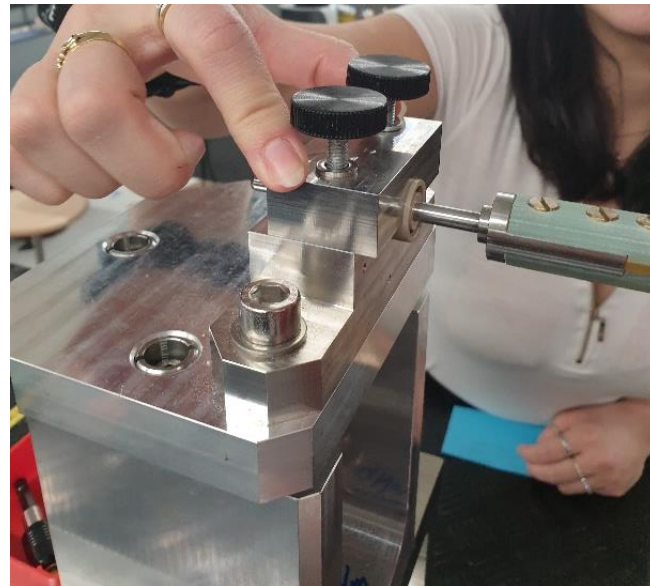
Measurement program PM

- **Pre-warming** of magnets for 3 days in building, 1 night in hutch
- Mechanical preparation of magnets



Measurement program PM

- RC measurement with moderator plates at 0-position
- RC measurement with shims

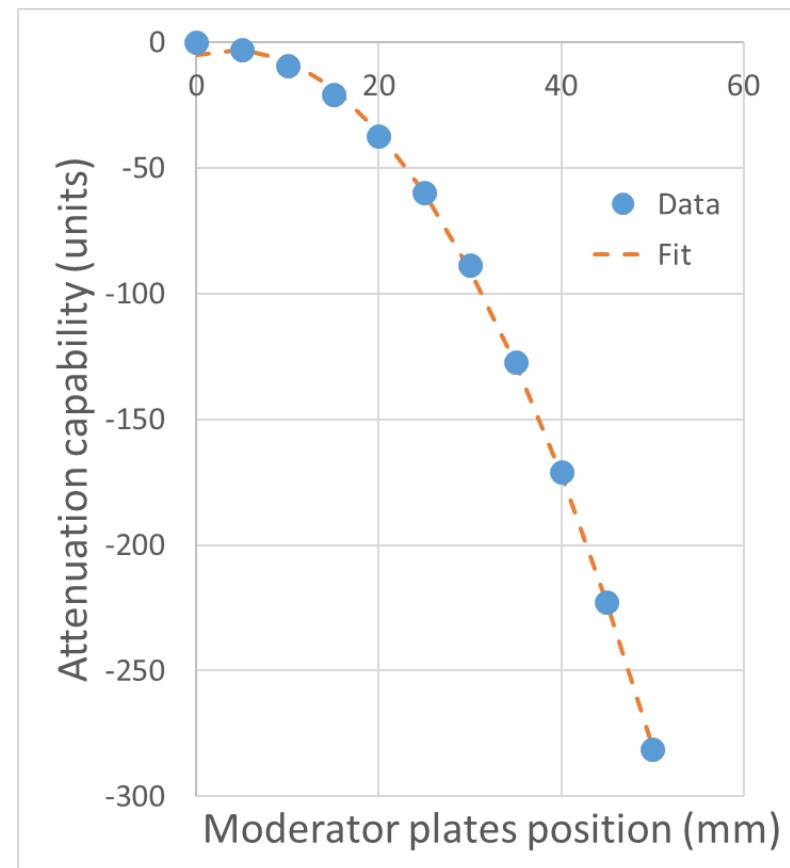


Moderator plates at 0-position



Measurement program PM

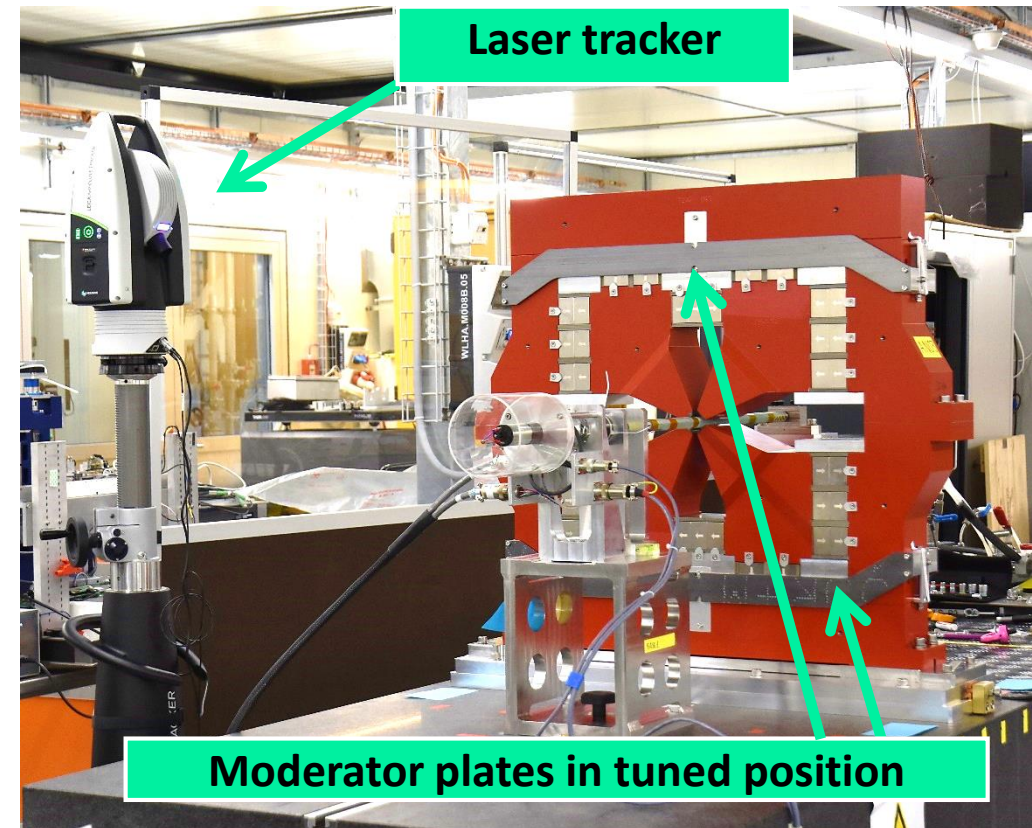
- **Tuning of magnet** (closing moderator plates) to target value $\pm 3 \text{ u}$ (10 types)
- **RC measurement** of harmonics, magnetic axis and roll angle in reference position



Magnet Type (AN label)	B2_Nominal (T)	Shim (mm)
ANO1	-11.43486087	NO
ANI2	-11.26424458	4.5
ANO3	-11.41488081	NO
ANI4	-11.33068781	2.5
ANO5	-11.4197839	NO
ANI6	-11.35074981	2
ANO7	-11.40144712	NO
ANI8	-11.348197	2
ANO9	-11.36359016	2
ANI10	-11.31130482	2.5

Measurement program PM

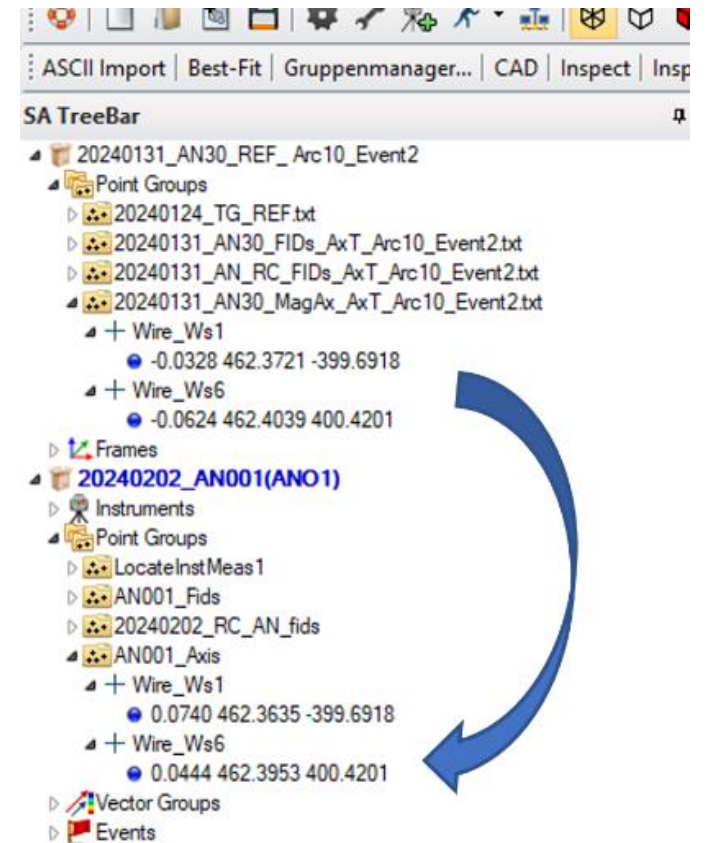
- Measurement of **magnet position** on bench with AT500 laser tracker
 - Level laser w.r.t. gravity
 - Adjust measurement template in Spatial Analyzer
 - Align instrument -> Measure the fiducial of the bench -> check RMS < 10 μm compared to reference magnet measurement
 - Measure magnet fiducials
 - Measure base plate fiducials -> check AVG Mag < 10 μm and Max Mag < 15 μm compared to reference magnet measurement



Measurement program PM

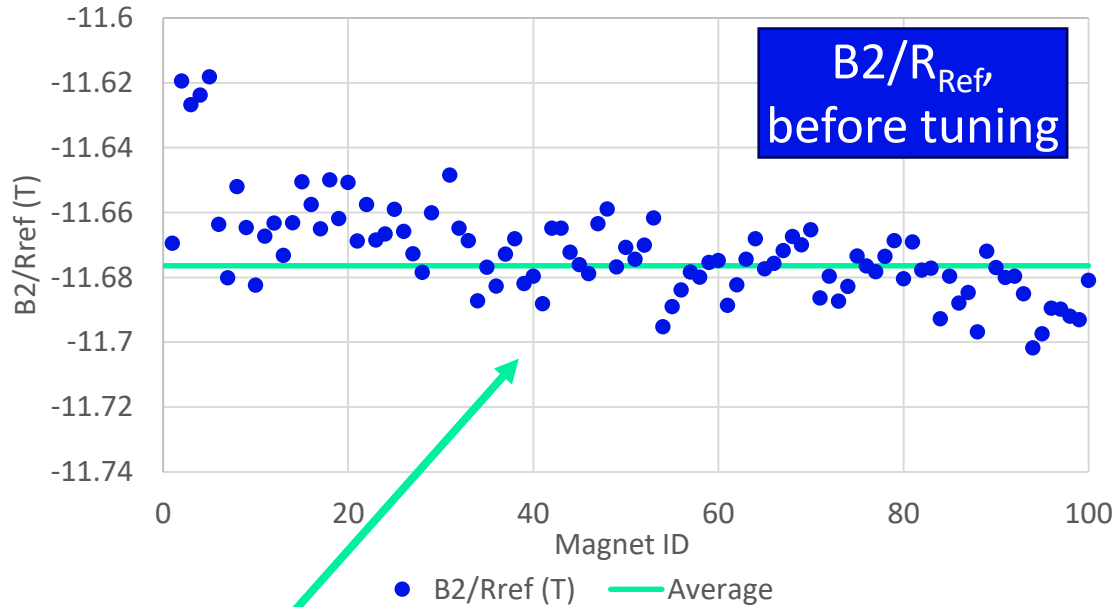


- RC Measurement of **roll angle**, flip position
- Perform **axis transfer** compared to moving wire measurement
- Export fiducialization file
- Upload information on inventory database

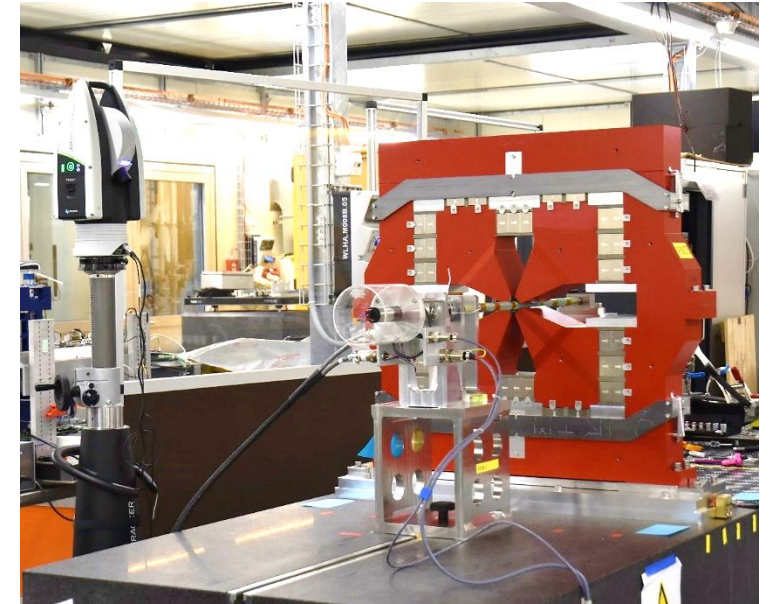


```
20240131_AN034(ANI2)_Fiducailization.txt - Editor
Datei Bearbeiten Format Ansicht Hilfe
A4, -256.002438, 860.333605, 34.365395
A1, 256.009179, 860.307674, 34.367477
A2, 256.018683, 860.322908, -33.640729
A3, -256.002206, 860.348692, -33.644511
Wire_Ws1, -0.014891, 462.282774, -399.691849
Wire_Ws6, -0.044485, 462.314598, 400.420060
#Magnet Roll to be corrected (rad): -9.80633E-06
Zeile 1, Spalte 1 | 100% | Windows (CRLF) | UTF-8
```


Results PM, exemplary for AN



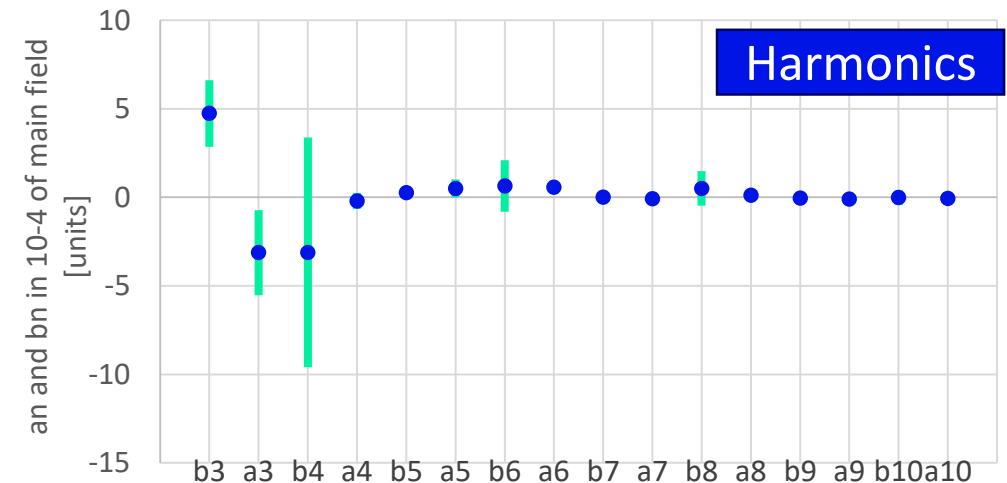
Successful tuning for each spec to below +/- 3 u



Field strength getting lower with time due to adjustment of PM block assembly plan (10 charges) → as expected

Low multipole values <10 units, small spread

Roll angles below 0.5 mrad

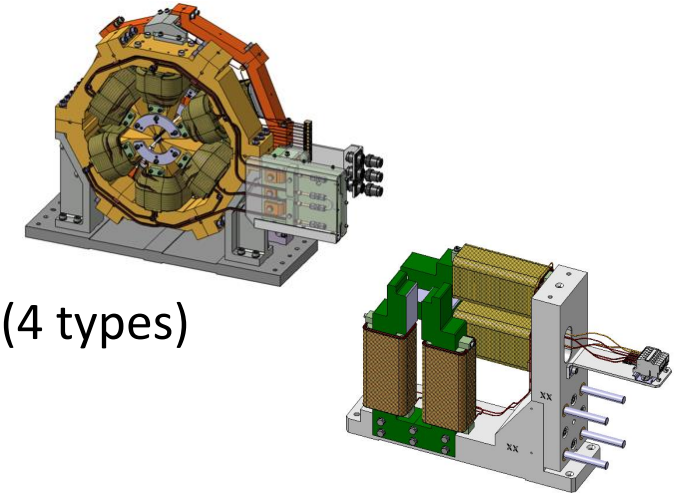


Conclusion

- **Rotating coils** have proved to be the «**working horse**» for the SLS2 magnetic measurements
- **Successful series measurement** with this RC system of

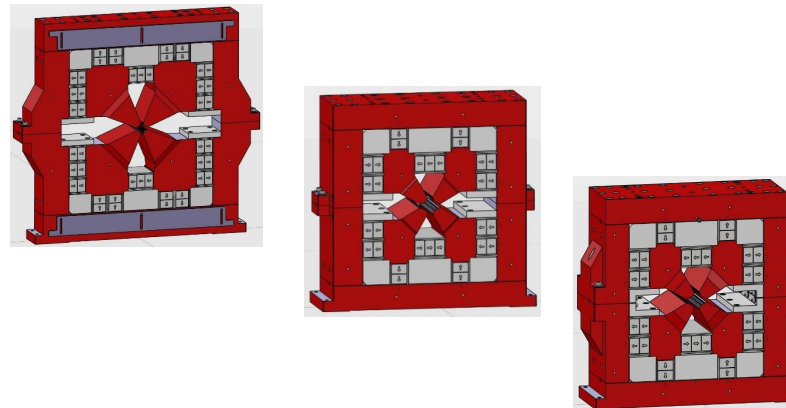
- **Electromagnets:**

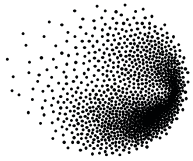
- 116 Sextupoles (8 types)
- 82 combined-function Octupoles (with Normal Quad and Skew Quad) (4 types)
- 112 steerers (i.e. 112 CH(S)+112 CV)
- 55 QP+53 QPH magnets (presented during last IMMW)



- **Permanent magnets:**

- 120 AN (10 types)
- 24 ANM (2 types)
- 24 VE (2 types)





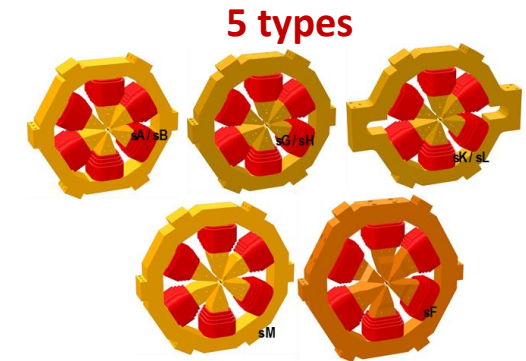
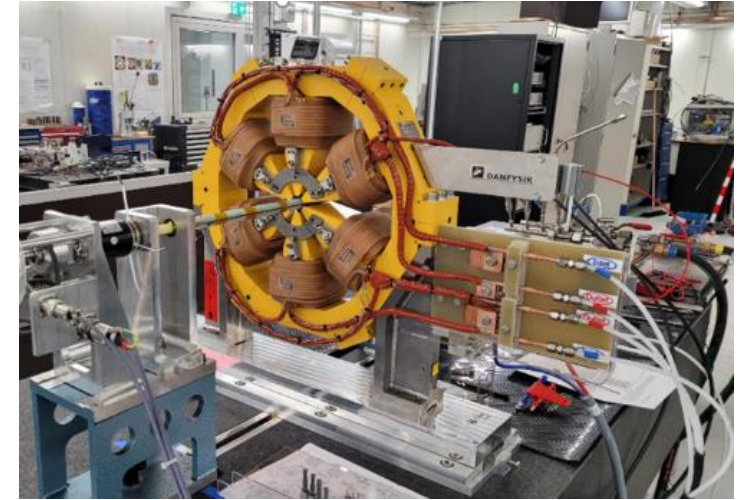
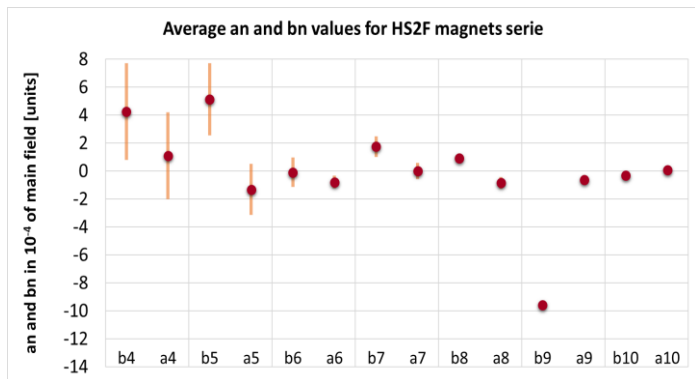
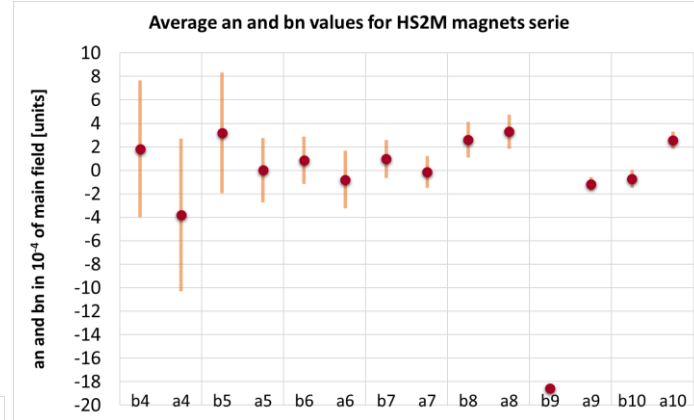
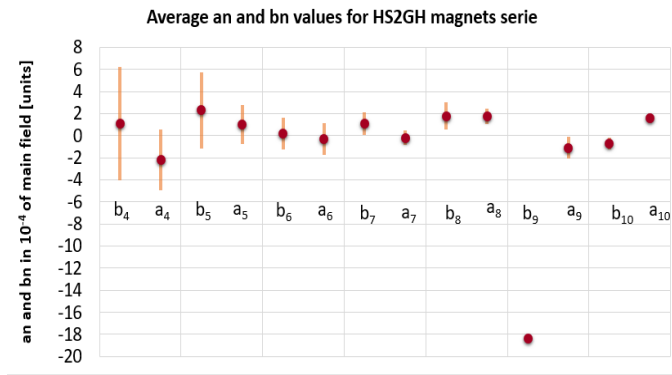
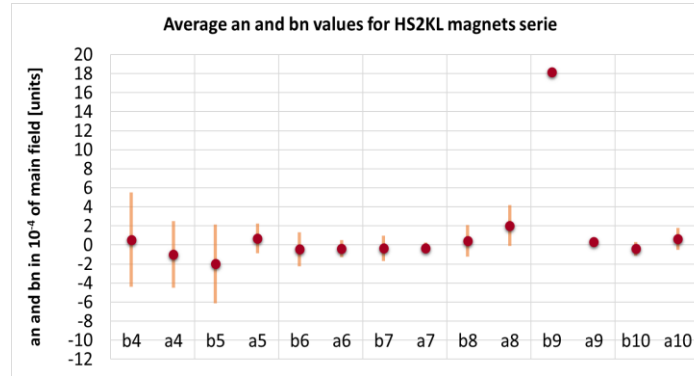
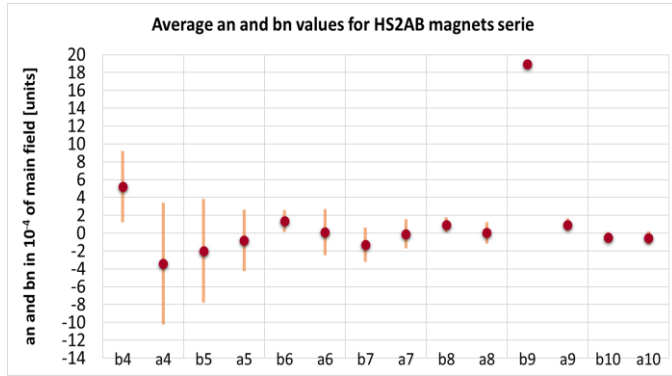
Thank you for your interest

We would like to thank:

- **PSI line managers** for their support during this massive undertaking
- **PSI technicians** for their highly valued contributions in manufacturing parts, assembly, crane operation, ...
- **Logistics team** for making in-time deliveries and pre-warming possible

C. Zoller, M. Duda, T. Ernst, G. Montenero, R. Riccioli, V. van de Vijfeijken
IMMW23, Bad Zurzach, 08/10/2024

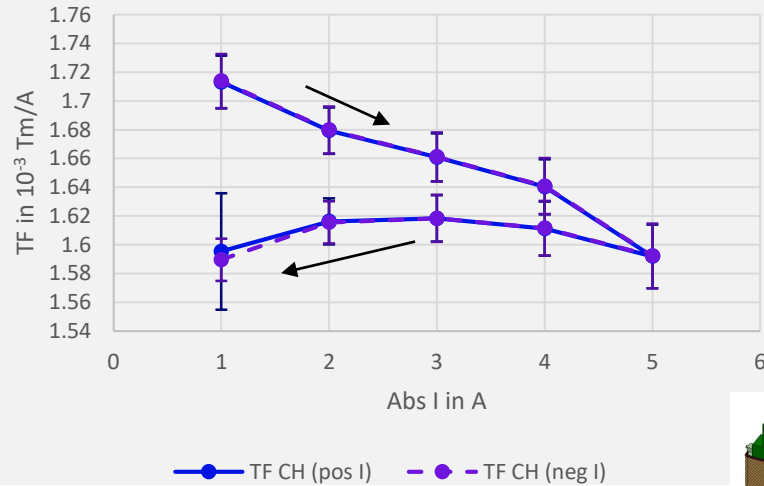
Results 116 SX/SXQ with RC: harmonics



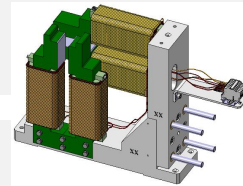
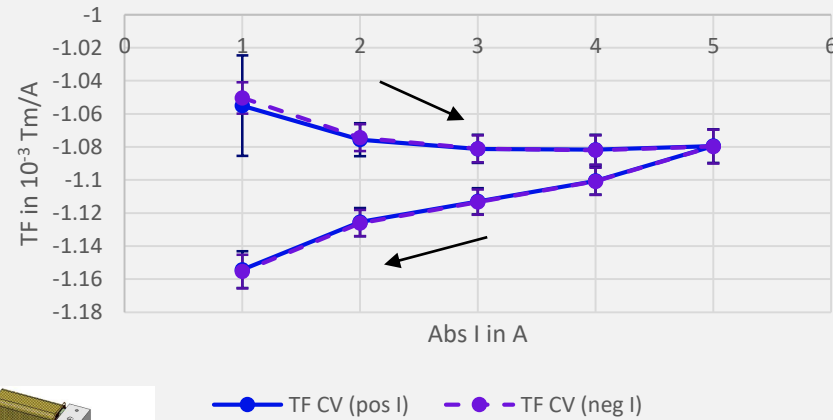
Transfer function $1A \rightarrow 5A \rightarrow -5A \rightarrow -1A$ with 3σ



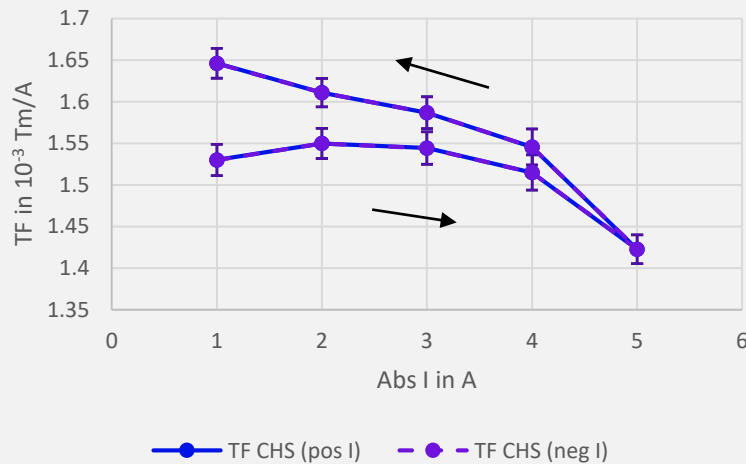
CH (CH-CV series)



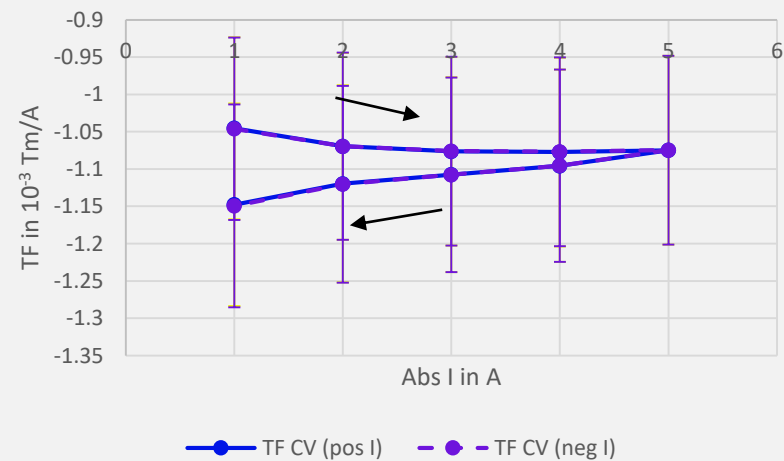
CV (CH-CV series)



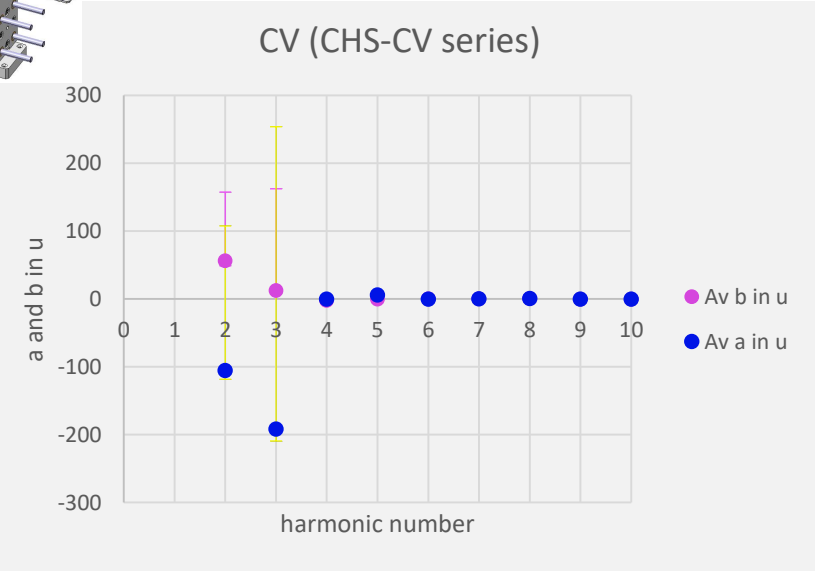
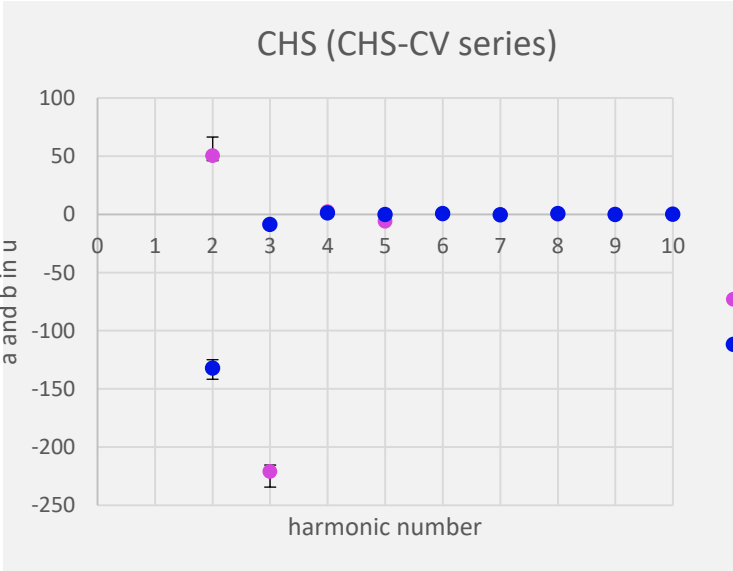
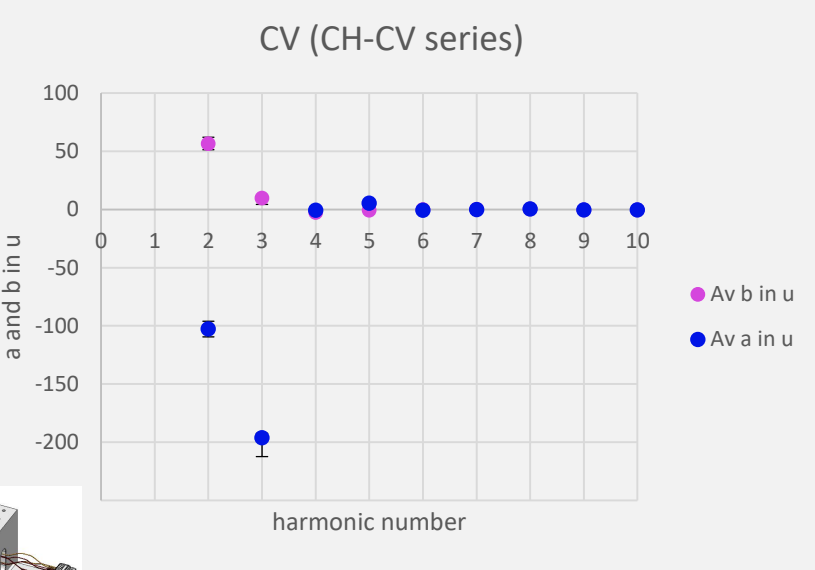
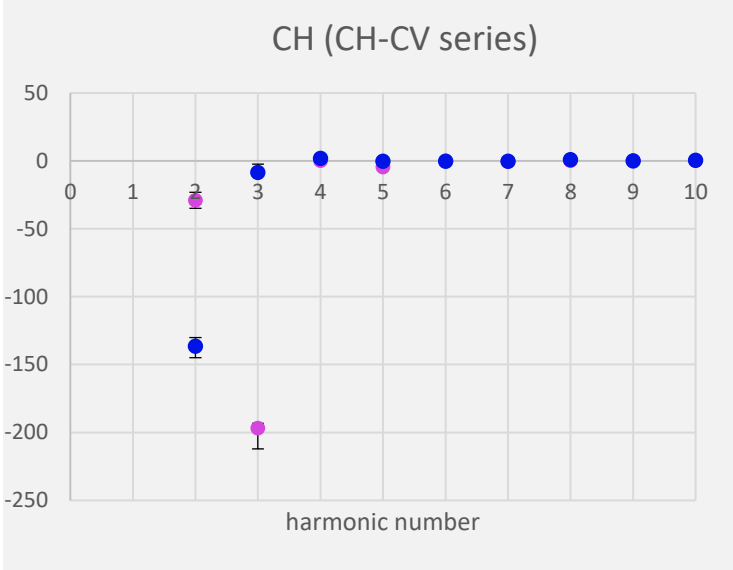
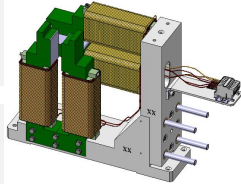
CHS (CHS-CV series)



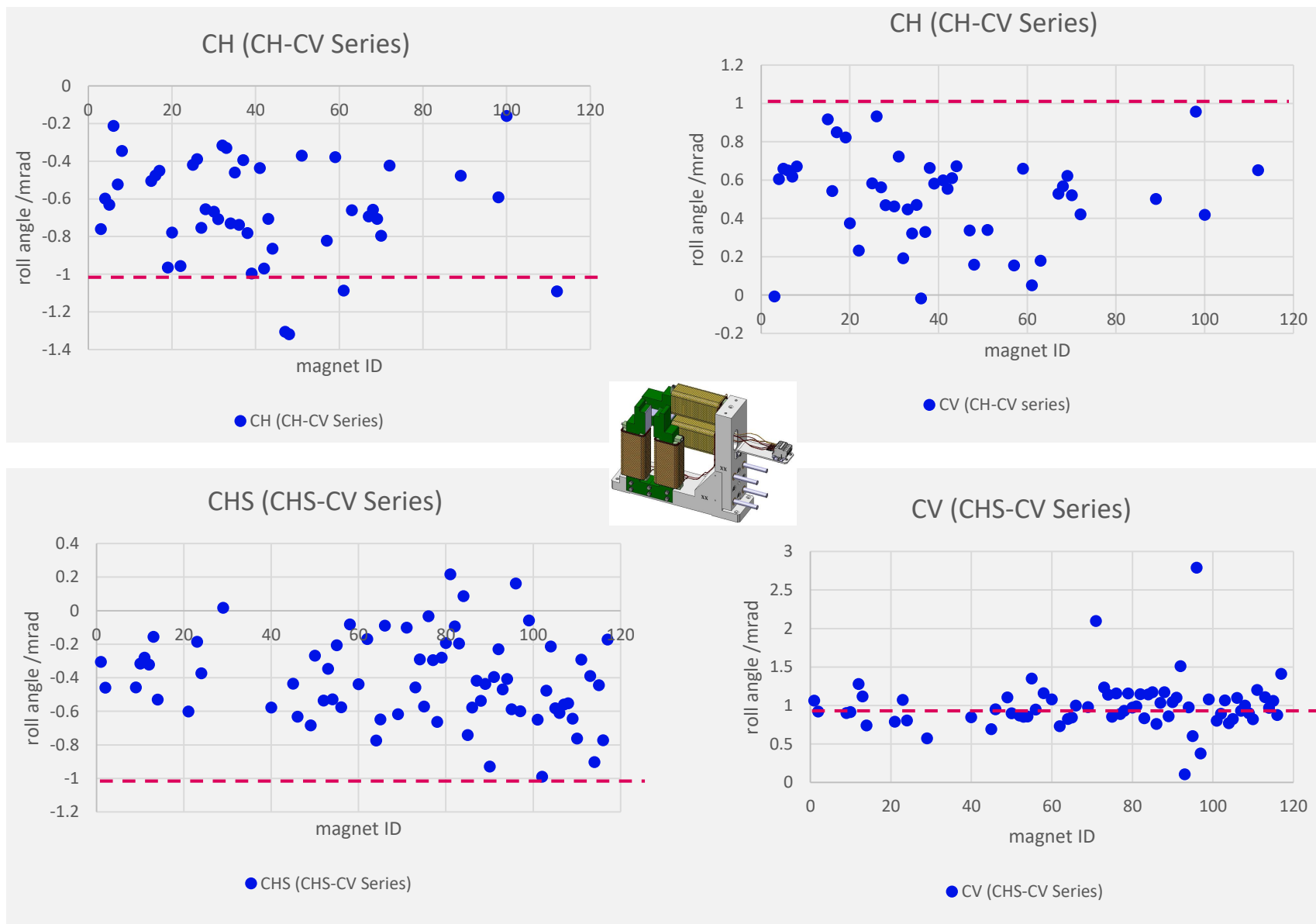
CV (CHS-CV series)



Average harmonics at 5 A with min and max



Roll angle at 5 A



Measurement system: Rotating Coils (RC)

- **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
- Shaft with hexagonal cross section

