PSI Center for Accelerator Science and Engineering

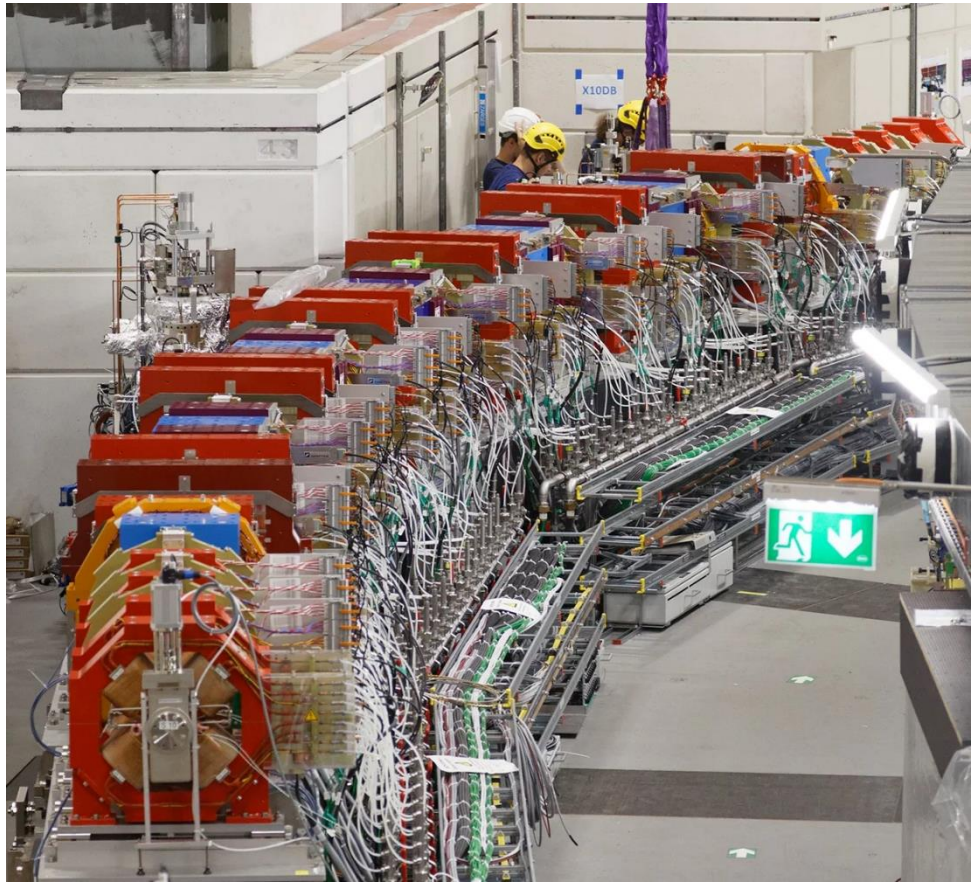
Measurement of Electromagnets and Tuning of Permanent Magnets based on Rotating Coils for the Upgrade of the Swiss Light Source (SLS2)

C. Zoller, M. Duda, T. Ernst, G. Montenero, R. Riccioli, V. van de Vijfeijken

IMMW23, Bad Zurzach, 08/10/2024

Outline

- 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)

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Aim:

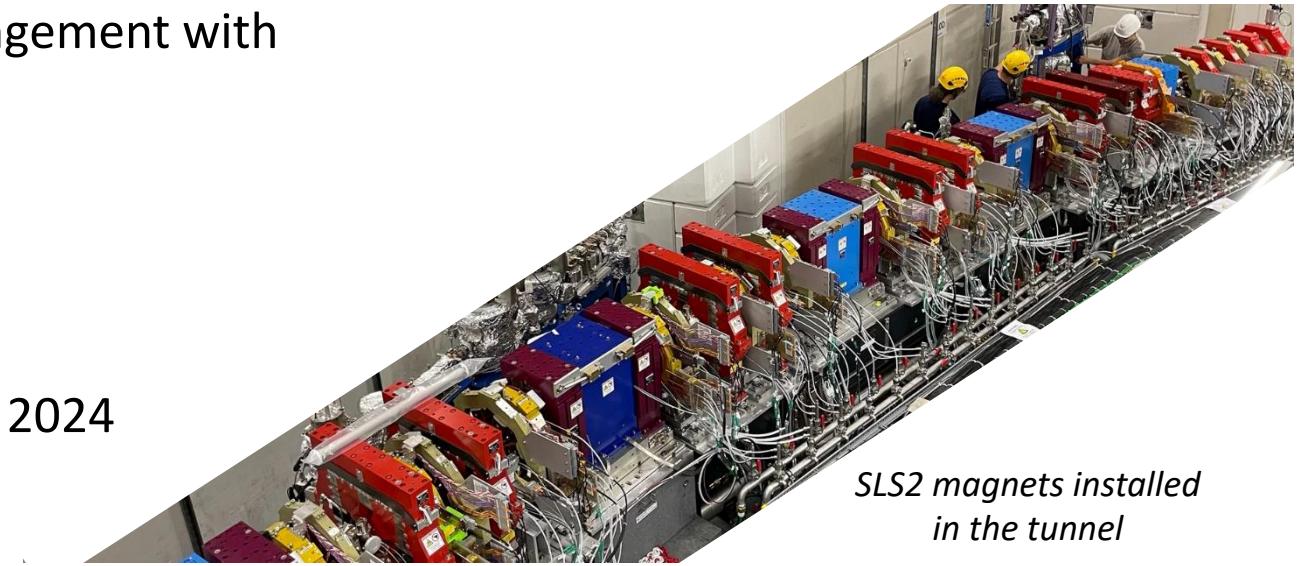
- Increase **electron beam energy** from 2.4 GeV to 2.7 GeV
- Improvement in **emittance and brightness** by factor 40
- **Maintain locations** of undulator based beam lines and **circumference** 287.25 m

More information see presentations of
- S. Sanfilippo
- M. Aiba
- R. Riccioli
- G. Montenero

and visit of SLS2 on Wednesday

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



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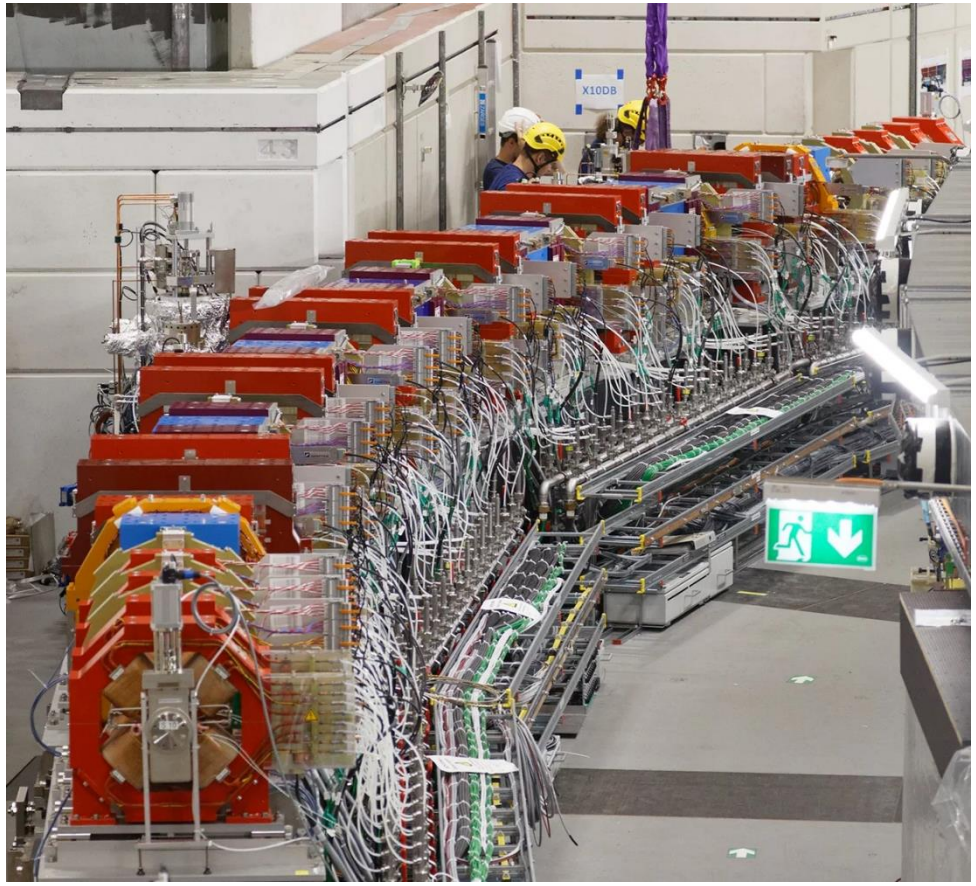
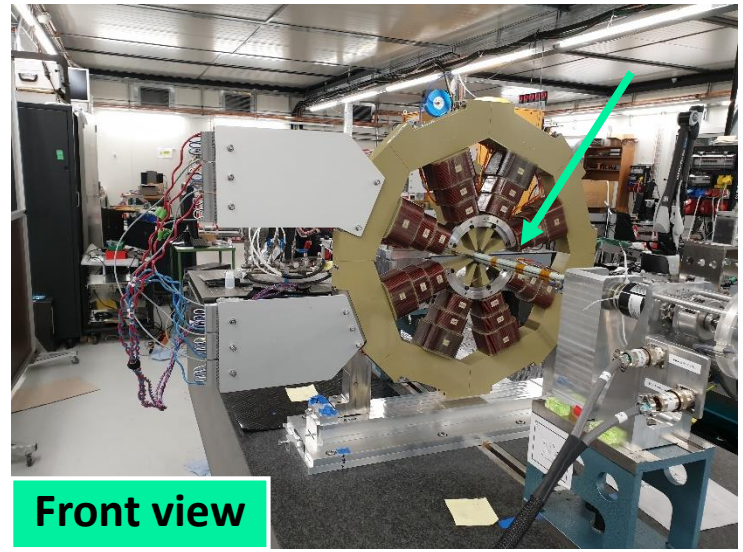
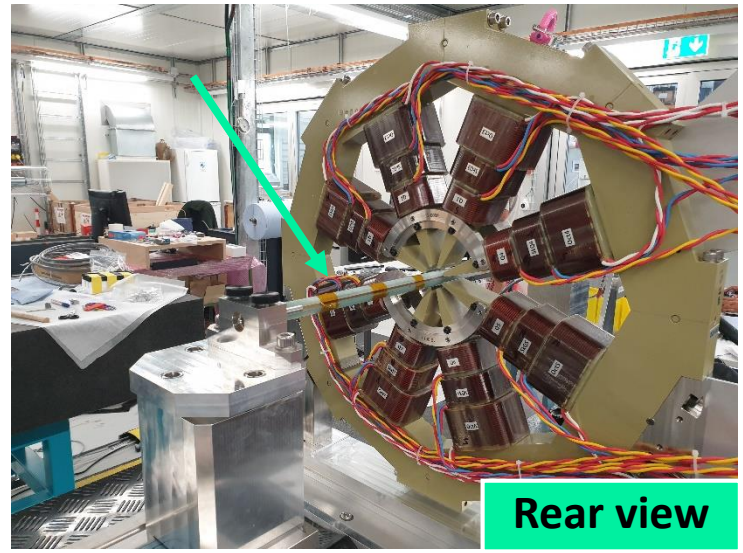


SLS2 magnets installed in the tunnel

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





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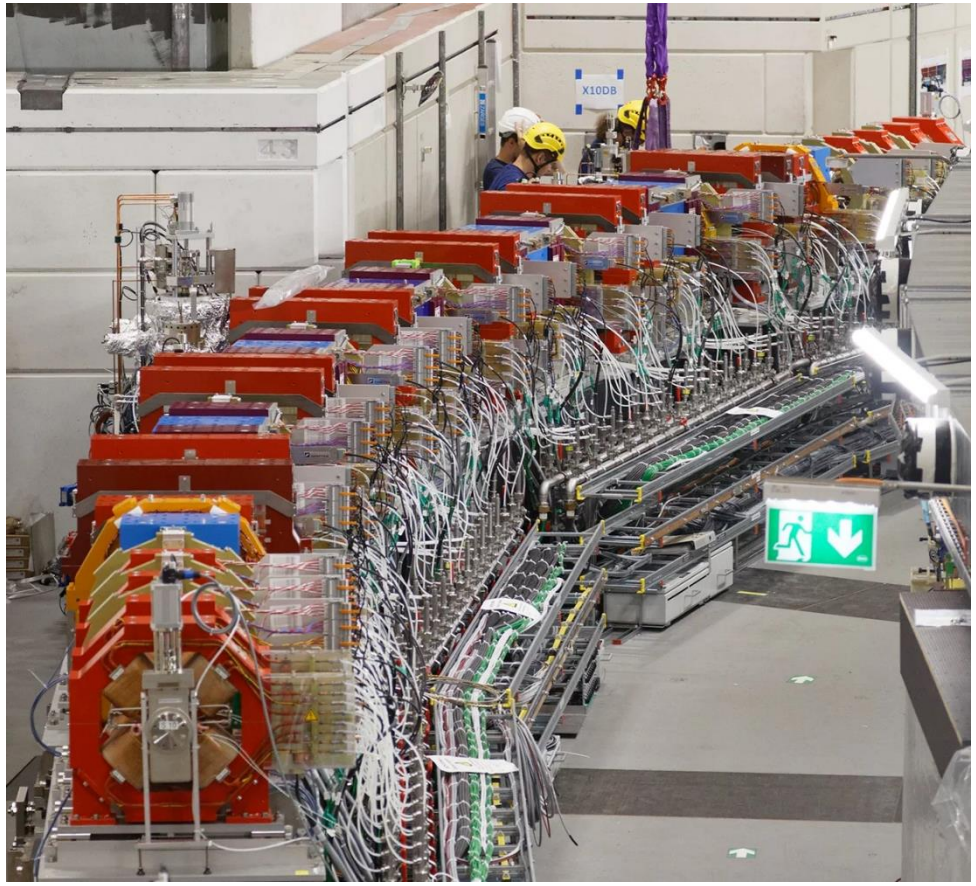
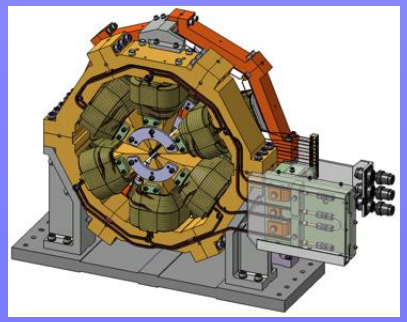
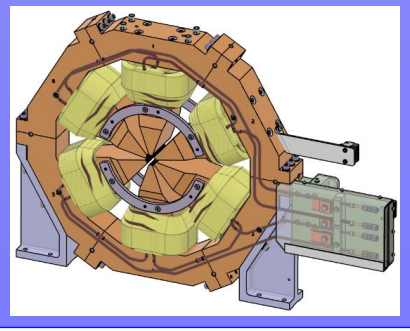
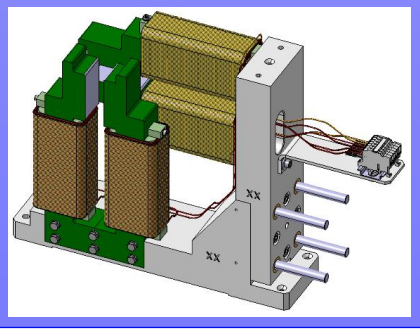


SLS2 magnets installed in the tunnel

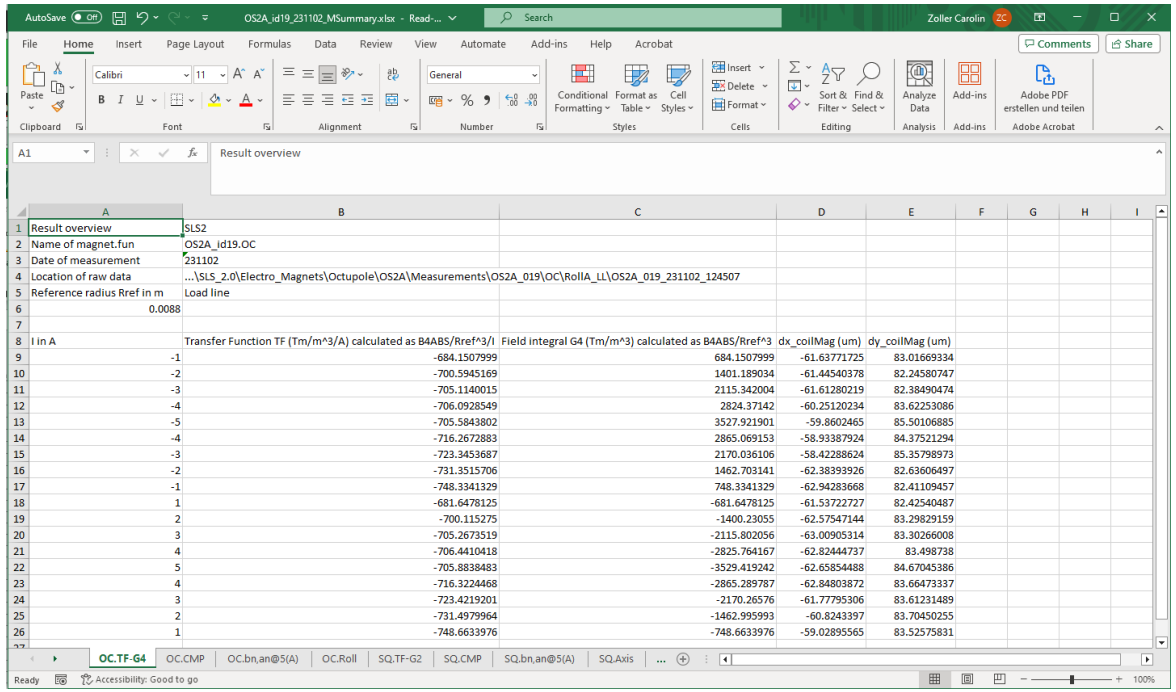
Specs electromagnets (EM)

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
$\int \frac{B_Y}{B_X} dl$ / mTm	-	-	3.6
$\frac{B''_Y}{2}$/ 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

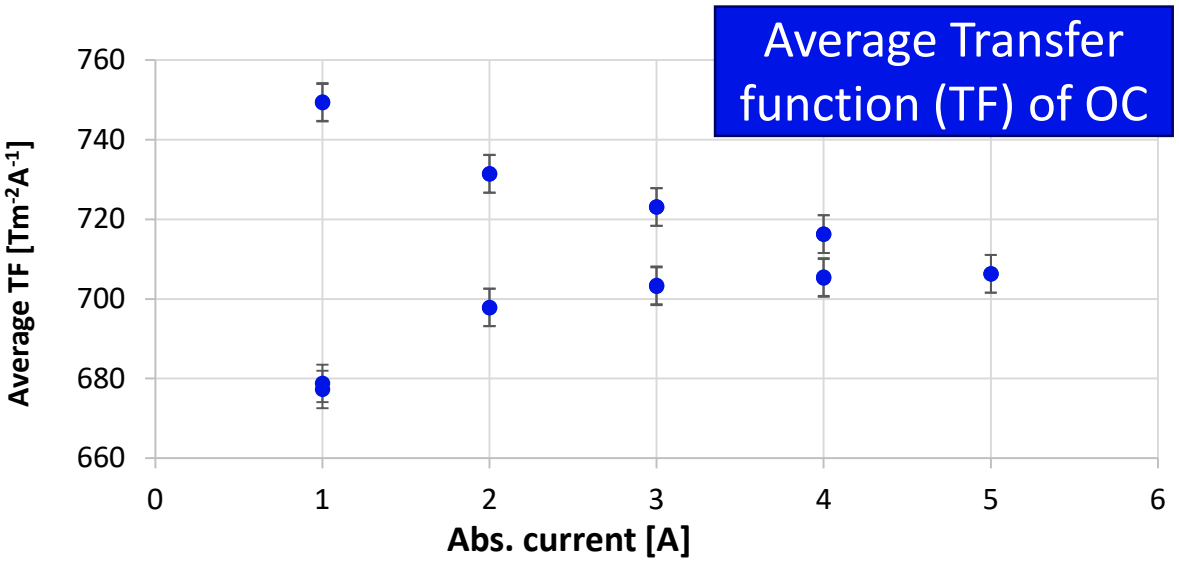


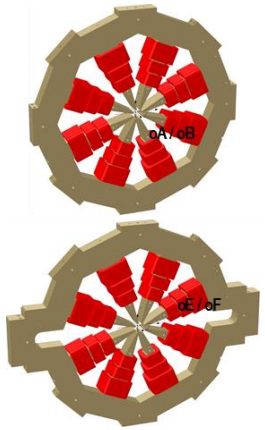
	A	B	C	D	E
1	Result overview	SLS2			
2	Name of magnet.fun	OS2A_id19.OC			
3	Date of measurement	231102			
4	Location of raw data	...\SLS_2.0\Electro_Magnets\Octupole\OS2A\Measurements\OS2A_019\OC\RollA_LL\OS2A_019_231102_124507			
5	Reference radius Rref in m	Load line			
6	0.0088				
7					
8	I in A	Transfer Function TF (Tm/m^3/A) calculated as B4ABS/Rref^3/I	Field integral G4 (Tm/m^3) calculated as B4ABS/Rref^3	dx_coilMag (um)	dy_coilMag (um)
9	-1	-684.1507999	684.1507999	-61.63771725	83.01669334
10	-2	-700.5945169	1401.189034	-61.44540378	82.24580747
11	-3	-705.1140015	2115.342004	-61.61280219	82.38490474
12	-4	-706.0928549	2824.37142	-60.25120234	83.62253086
13	-5	-705.5843802	3527.921901	-59.8602465	85.50106885
14	-4	-716.2672883	2865.069153	-58.93387924	84.37521294
15	-3	-723.3453687	2170.036106	-58.42288624	85.35798973
16	-2	-731.3515706	1462.703141	-62.38393926	82.63606497
17	-1	-748.3341329	748.3341329	-62.94283668	82.41109457
18	1	-681.6478125	-681.6478125	-61.53722727	82.42540487
19	2	-700.115275	-1400.23055	-62.57547144	83.29829159
20	3	-705.2673519	-2115.802056	-63.00905314	83.30266008
21	4	-706.4410418	-2825.764167	-62.82444737	83.498738
22	5	-705.8838483	-3529.419242	-62.65854488	84.67045386
23	4	-716.3224468	-2865.289787	-62.84803872	83.66473337
24	3	-723.4219201	-2170.26576	-61.77795306	83.61231489
25	2	-731.4979964	-1462.995993	-60.8243397	83.70450255
26	1	-748.6633976	-748.6633976	-59.02895565	83.52575831

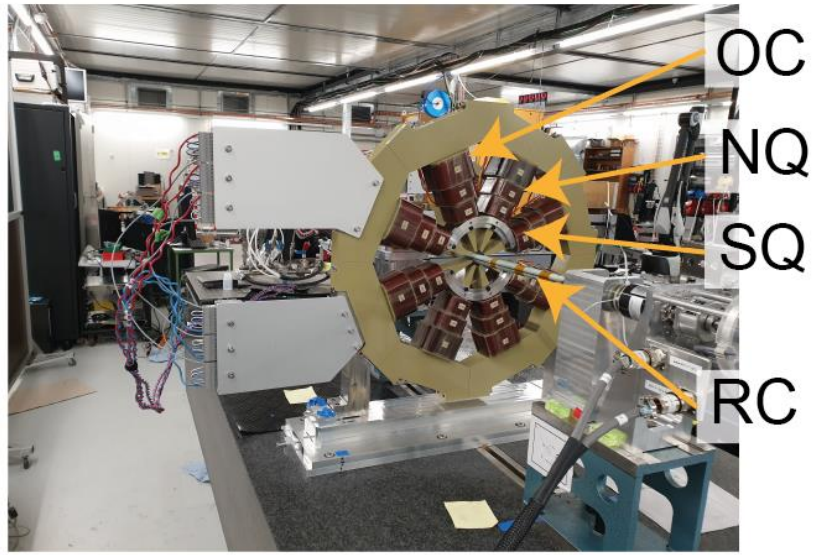
Determination of
- Transfer Function (TF)
- Harmonics
- Magnetic axis
- Roll angle

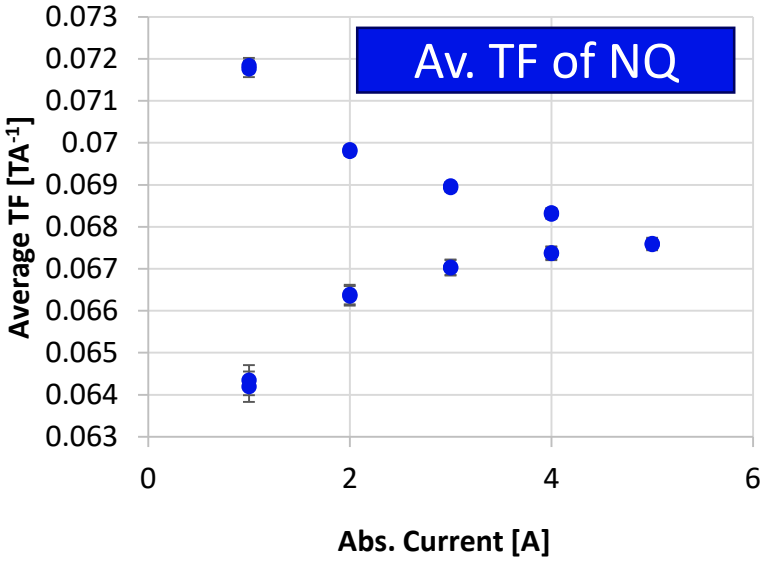
➢ (1-σ repeatability < 0.05 %)

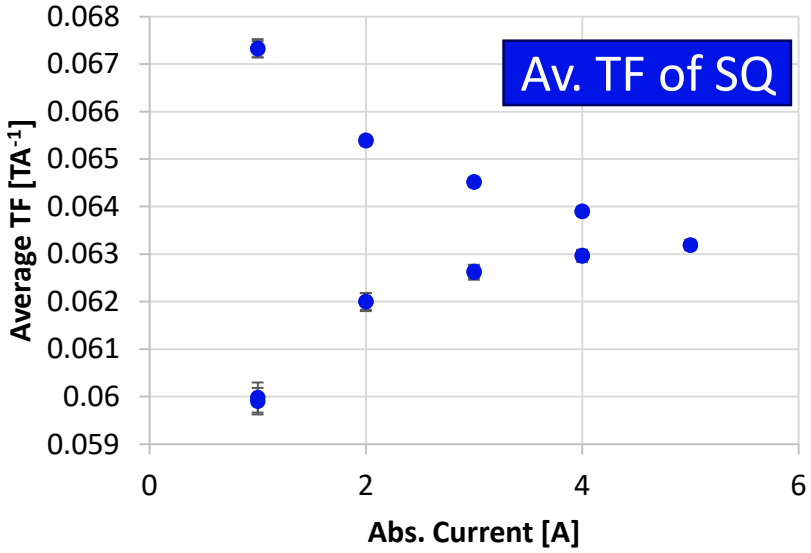
Results 82 OC with RC











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

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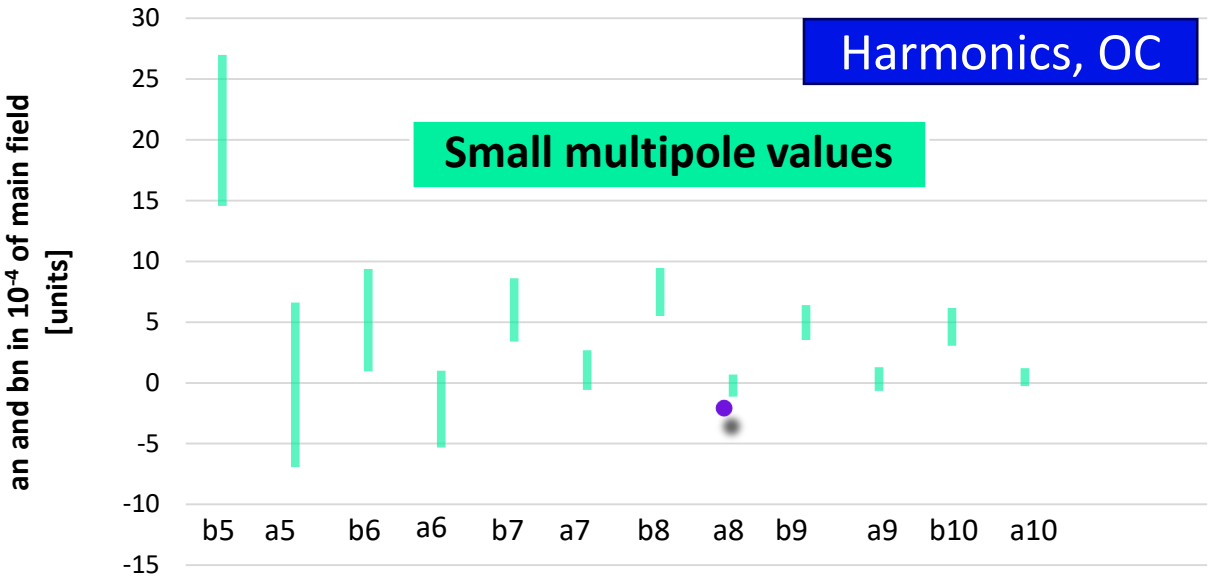

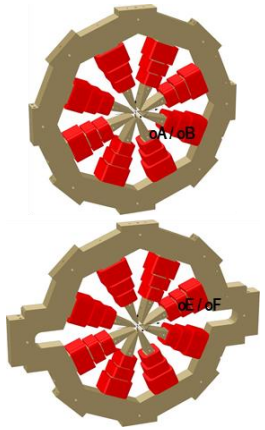

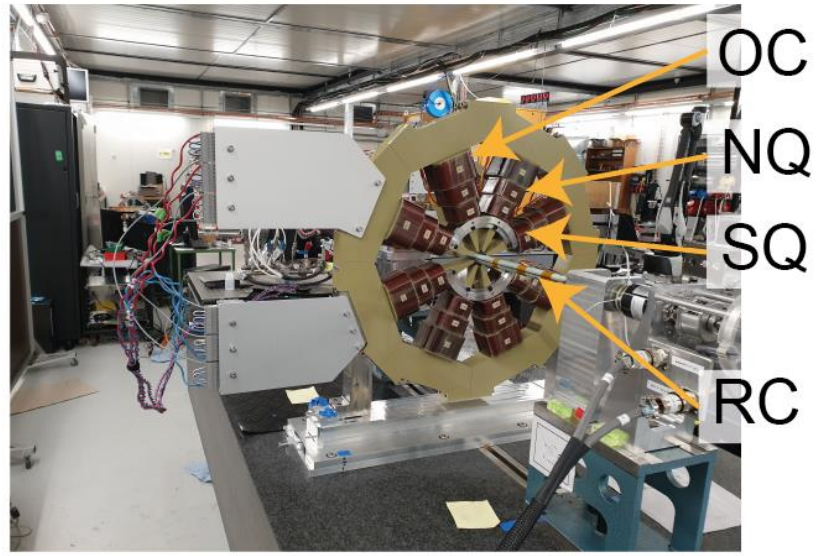

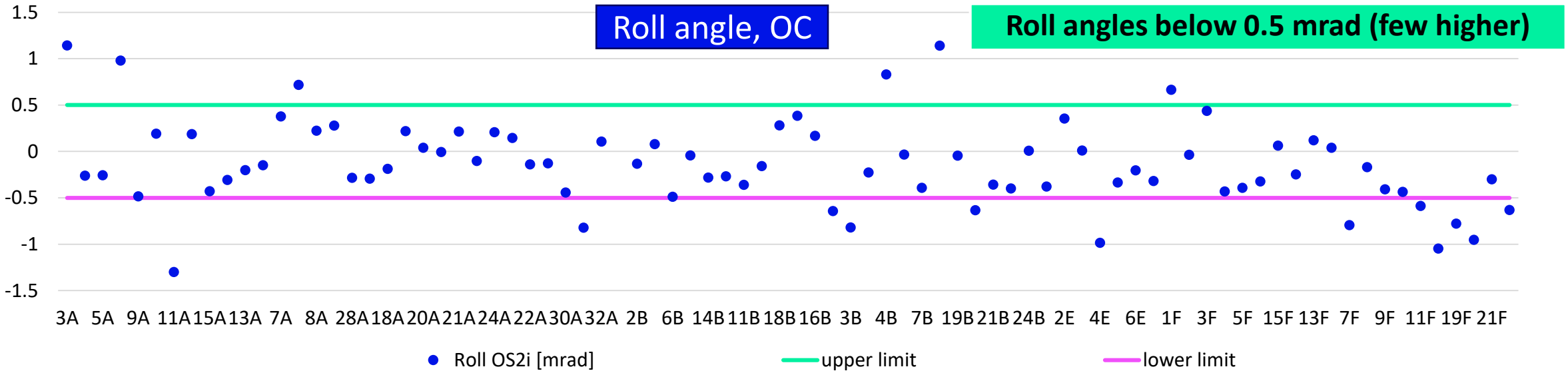

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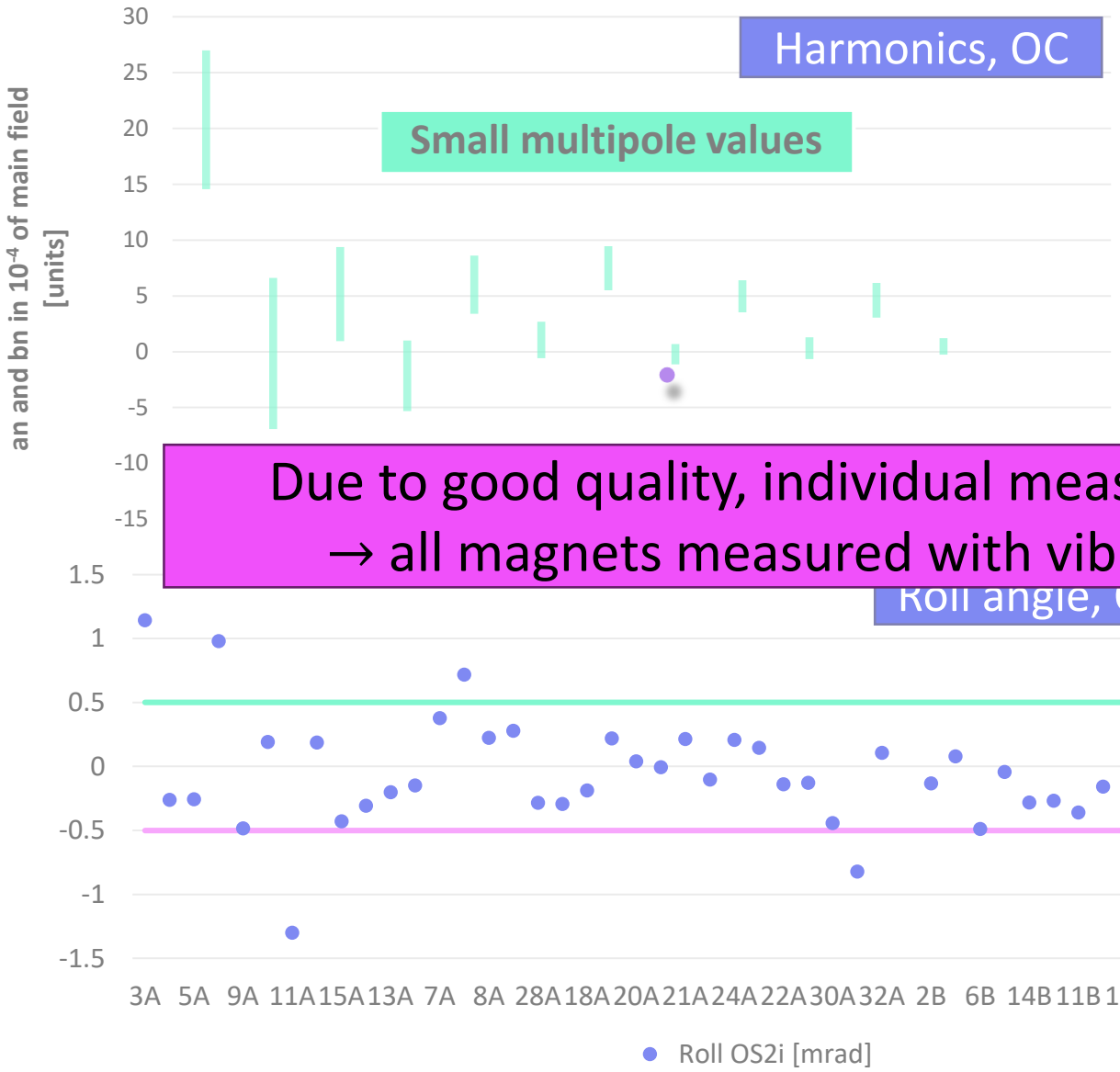
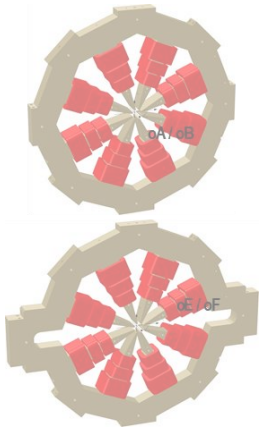
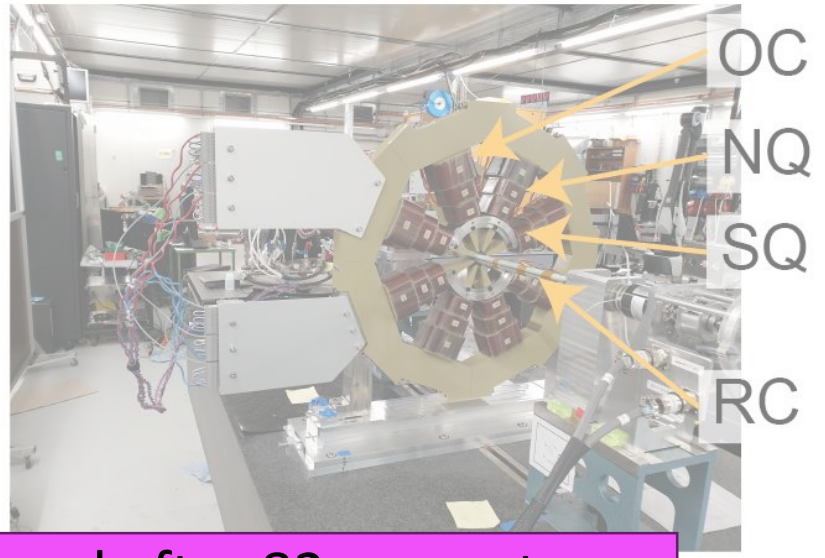
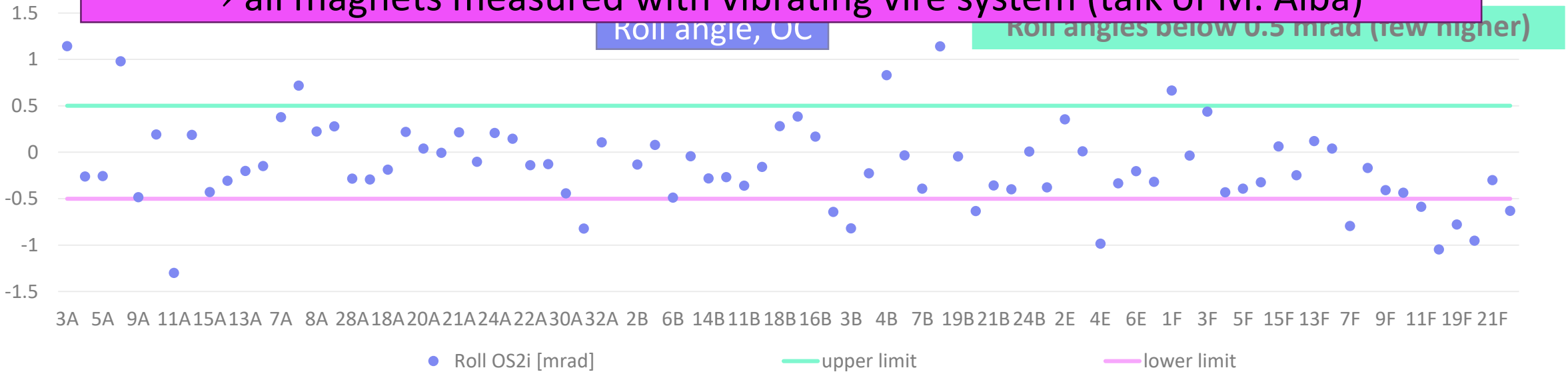


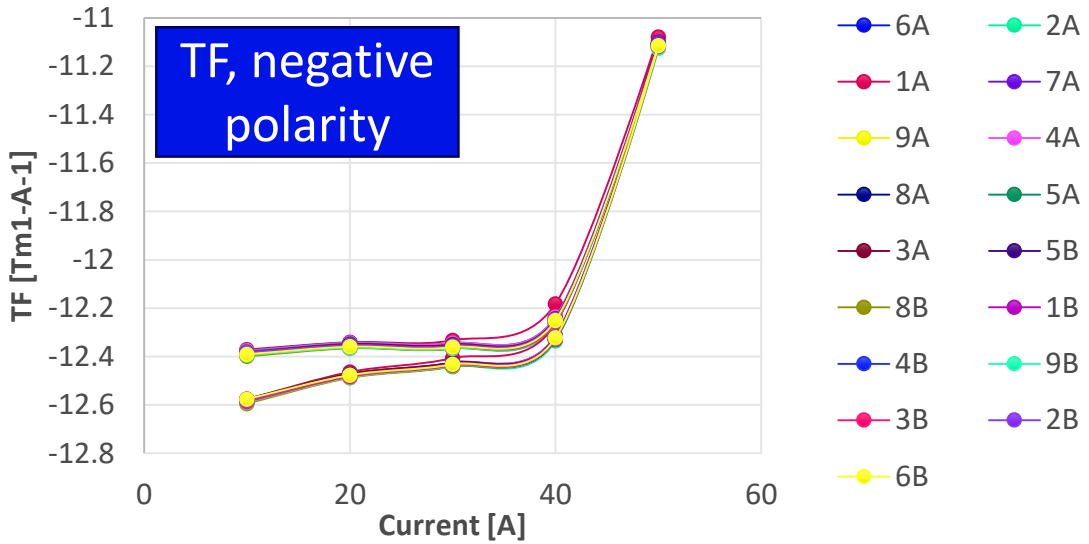


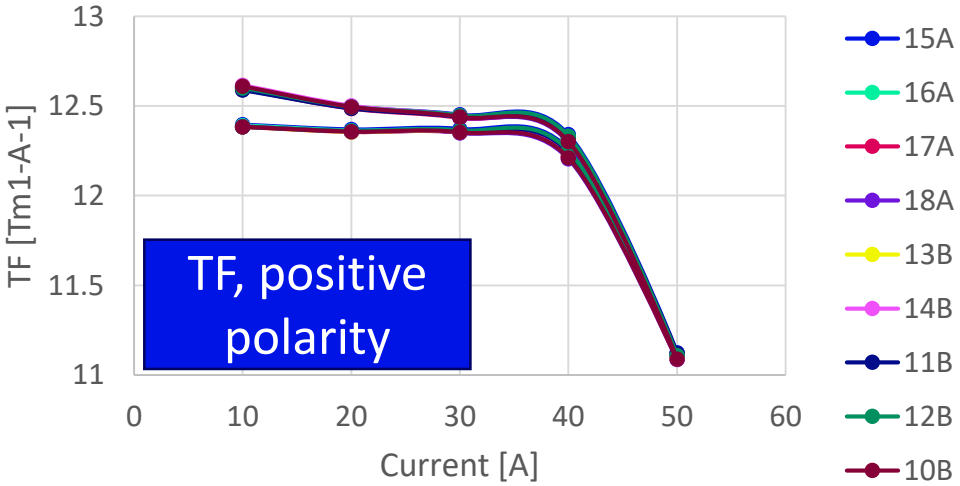


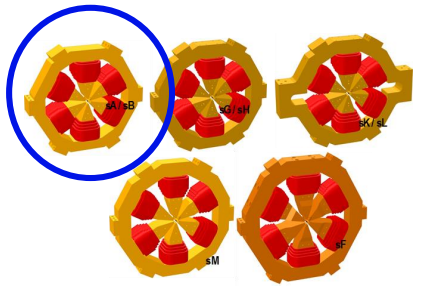
Due to good quality, individual measurements stopped after 82 magnets
→ all magnets measured with vibrating vire system (talk of M. Aiba)

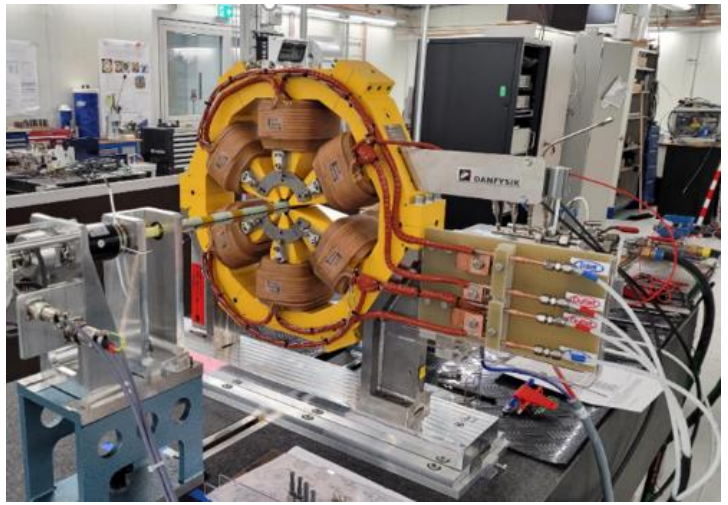


Results 116 SX/SXQ with RC: exemplary HS2A and -B









	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

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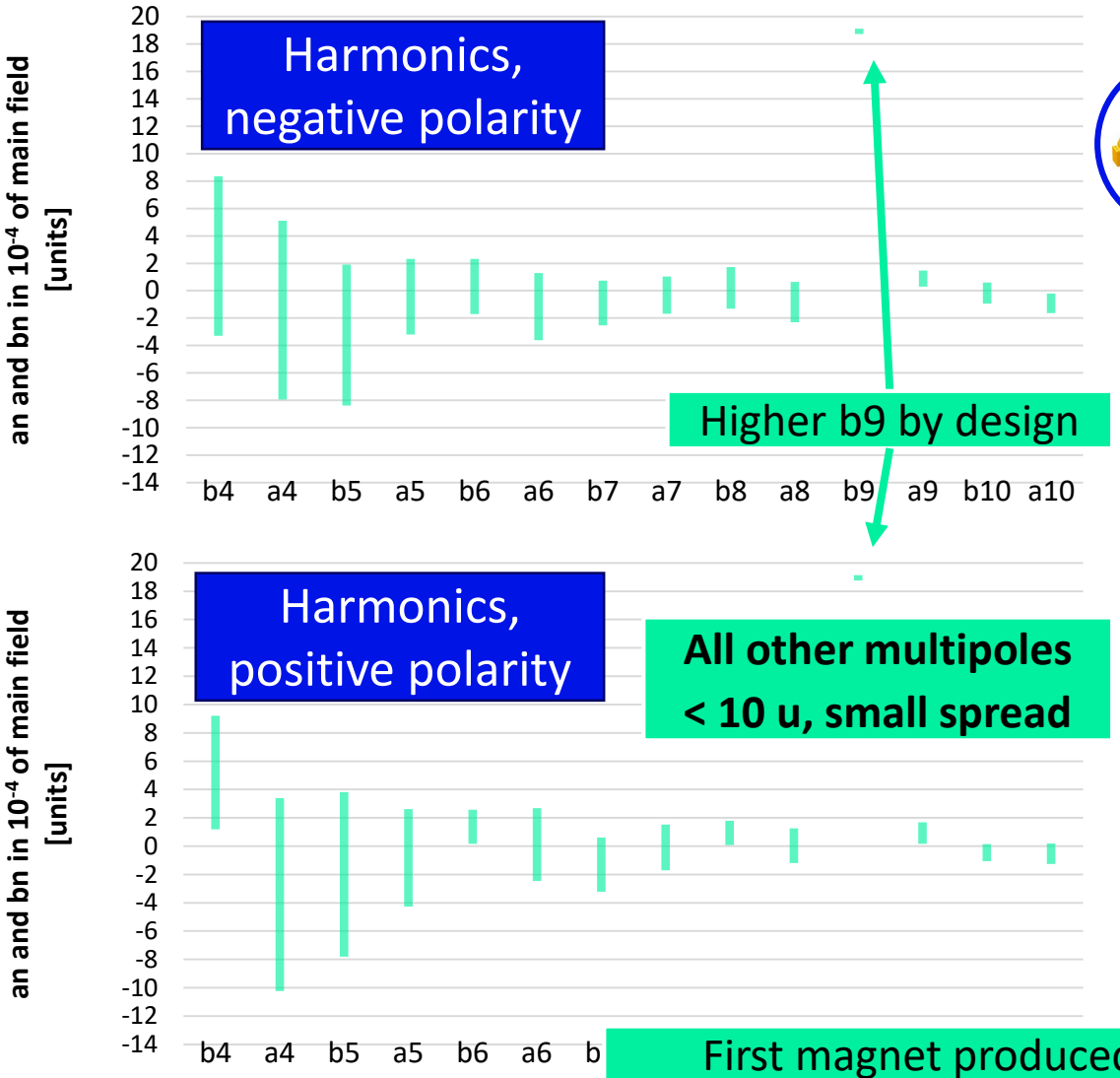

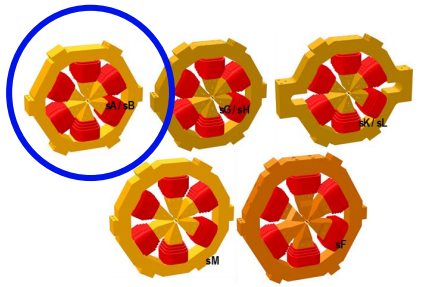

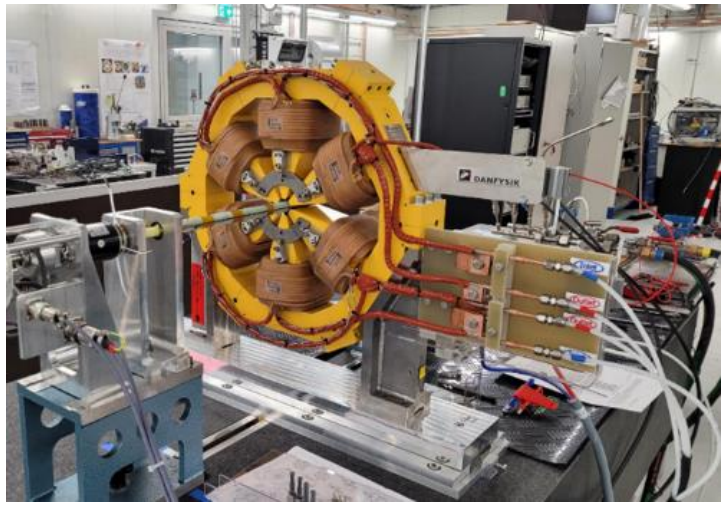

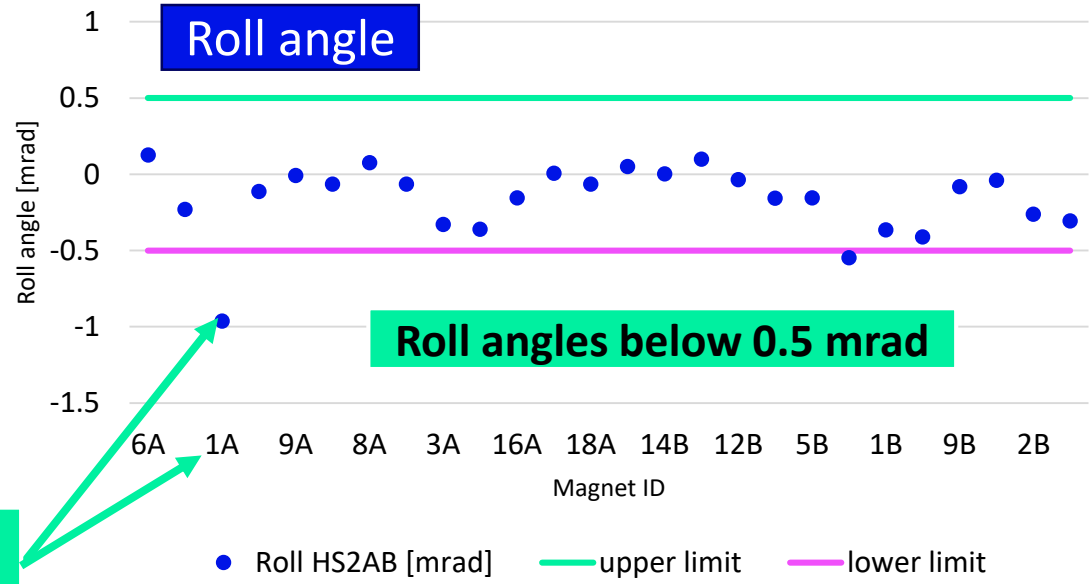

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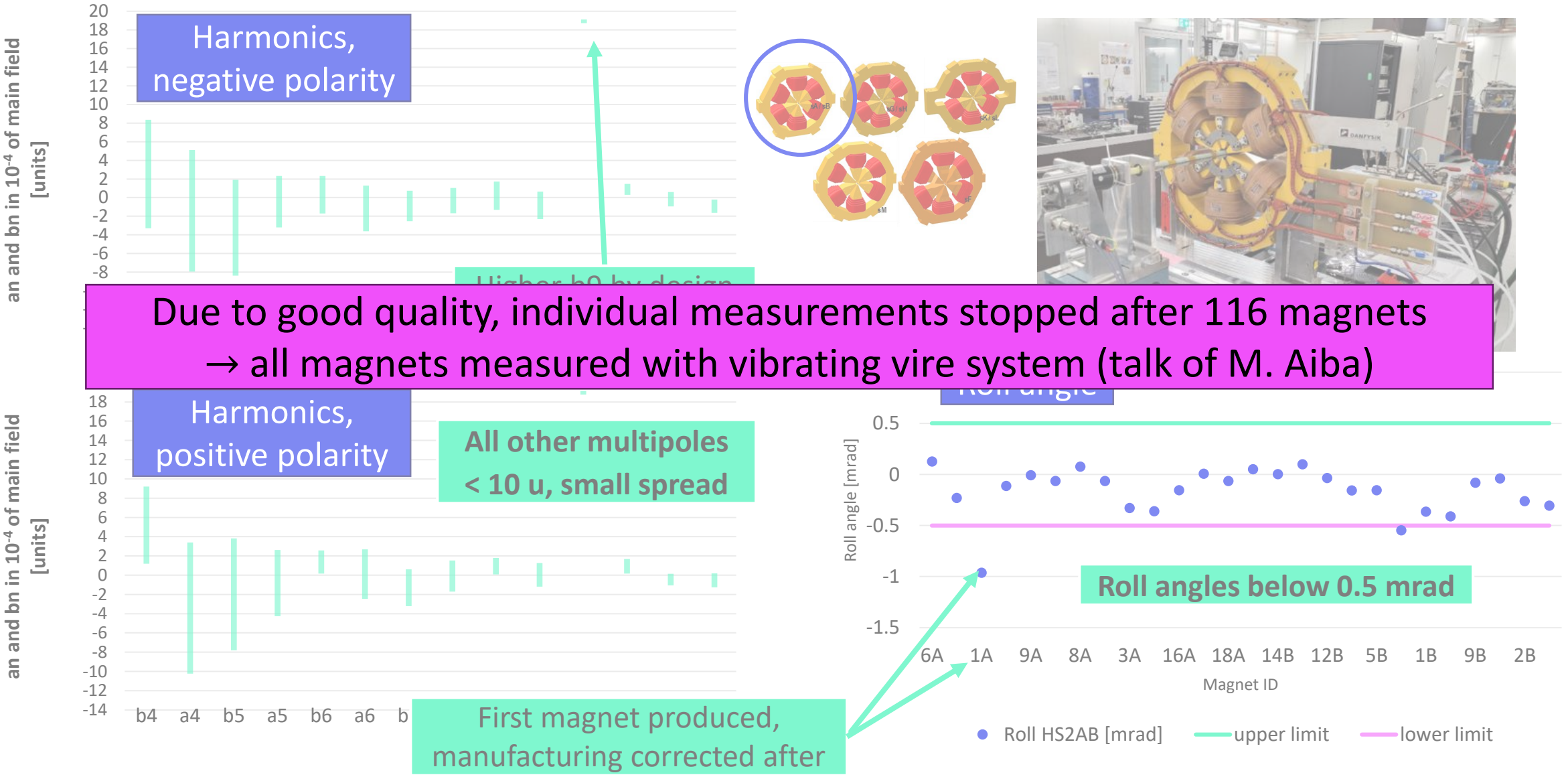
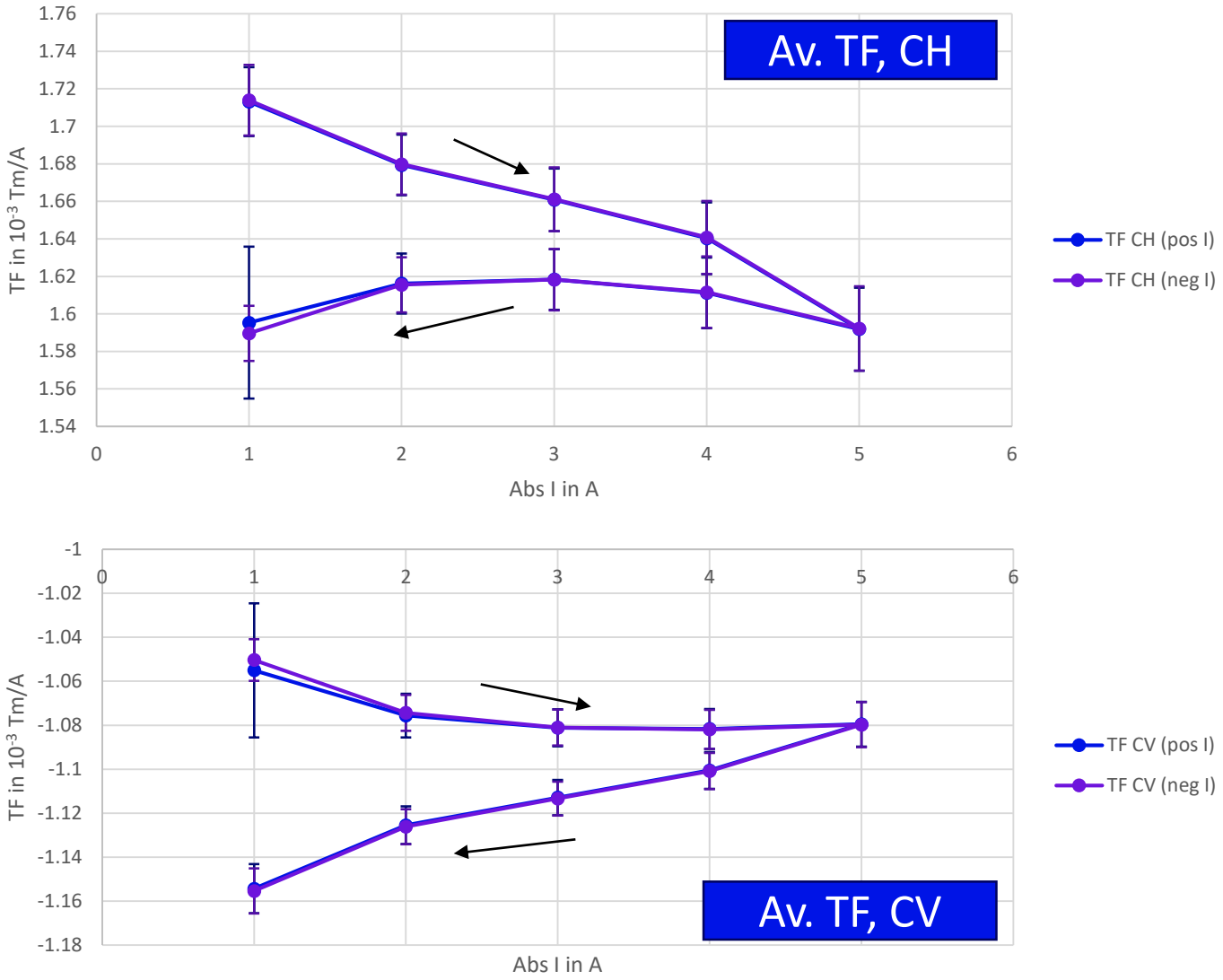
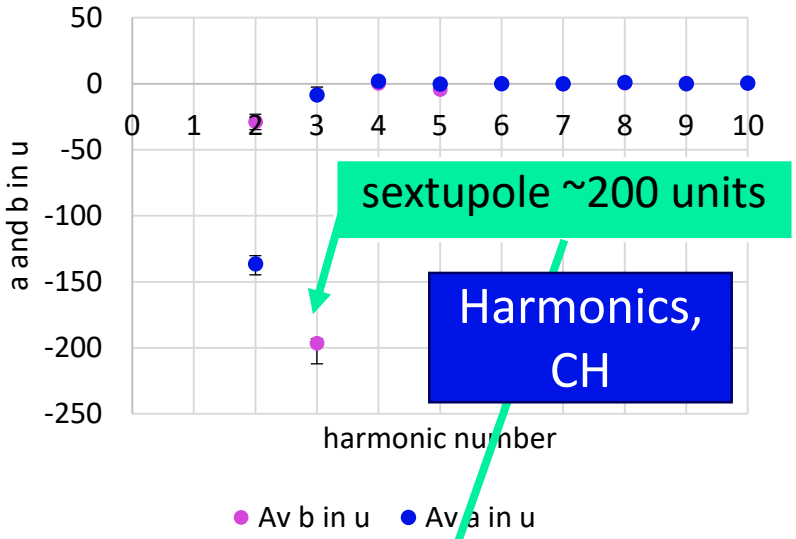


Results 112 CH(S)/CV with RC: exemplary CH/CV



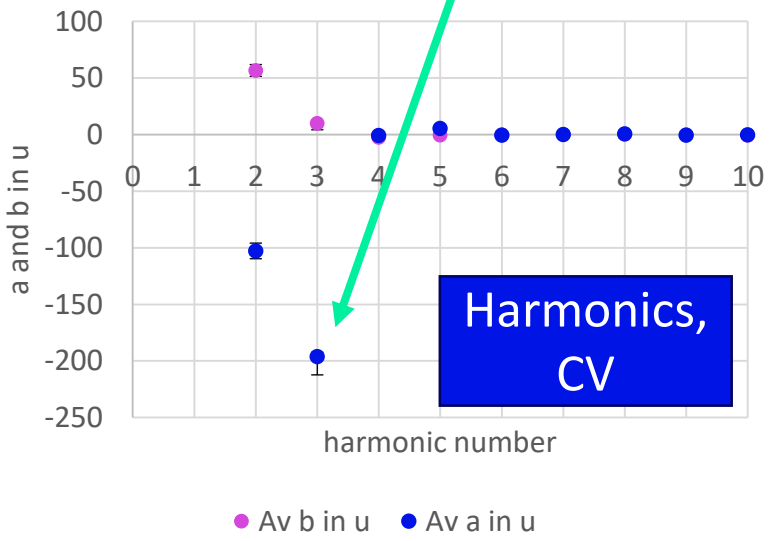
Vertical steering & horizontal steering strength as expected

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



sextupole ~200 units

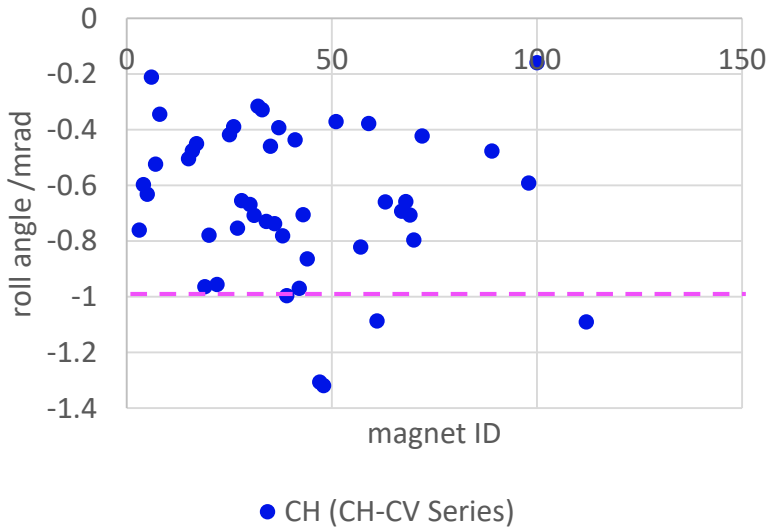
Harmonics, CH

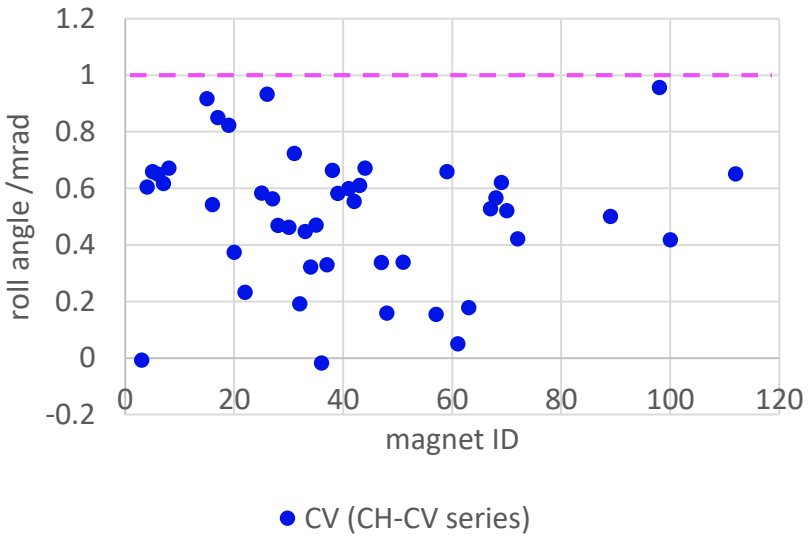


Harmonics, CV

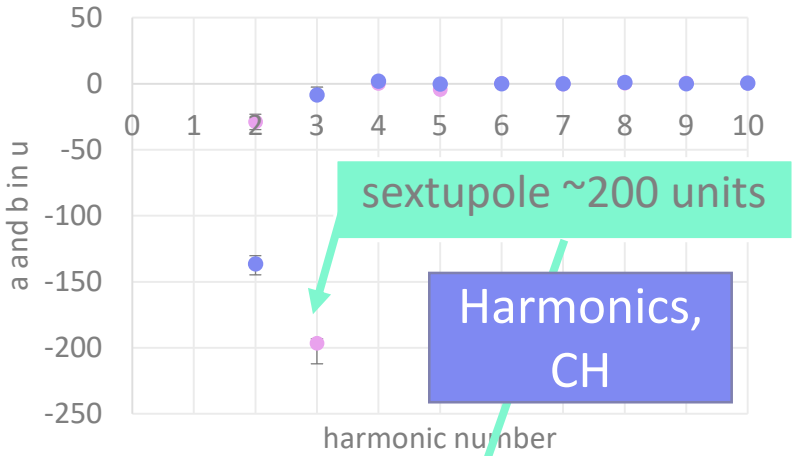
Multipoles as expected

Roll angles between +/- 1 mrad (few higher)



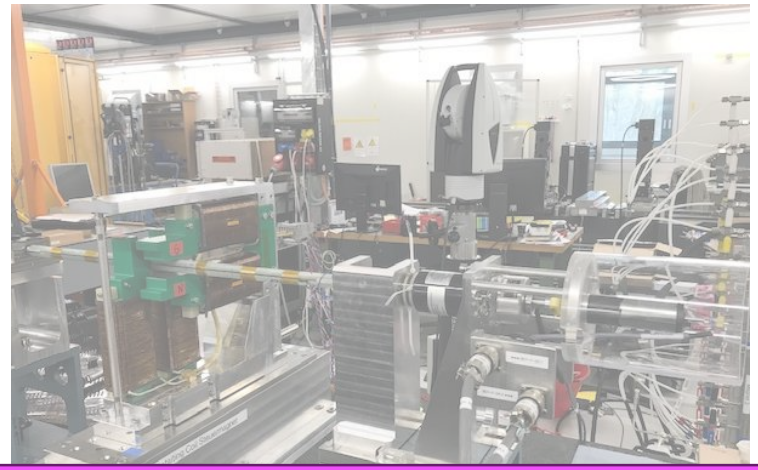


Results 112 CH(S)/CV with RC: exemplary CH/CV



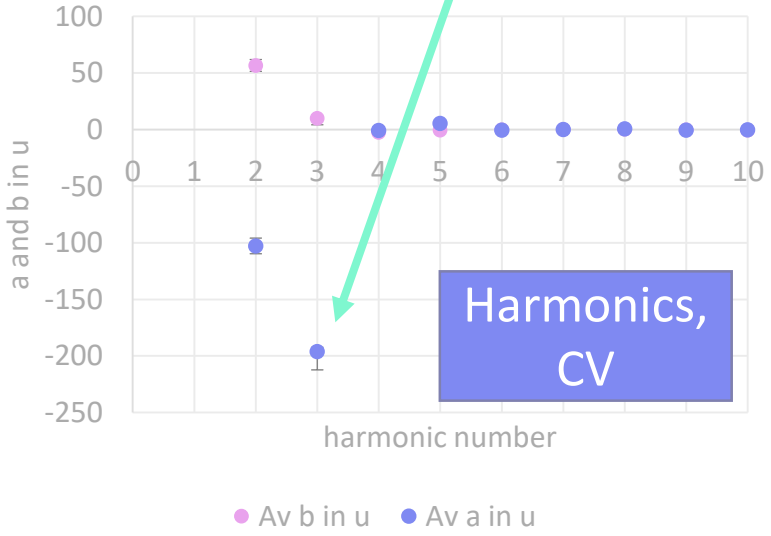
Harmonics, CH

Multipoles as expected

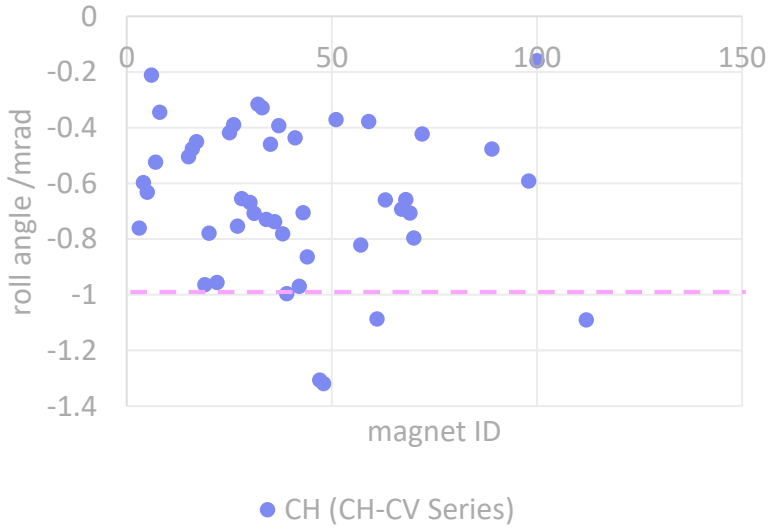


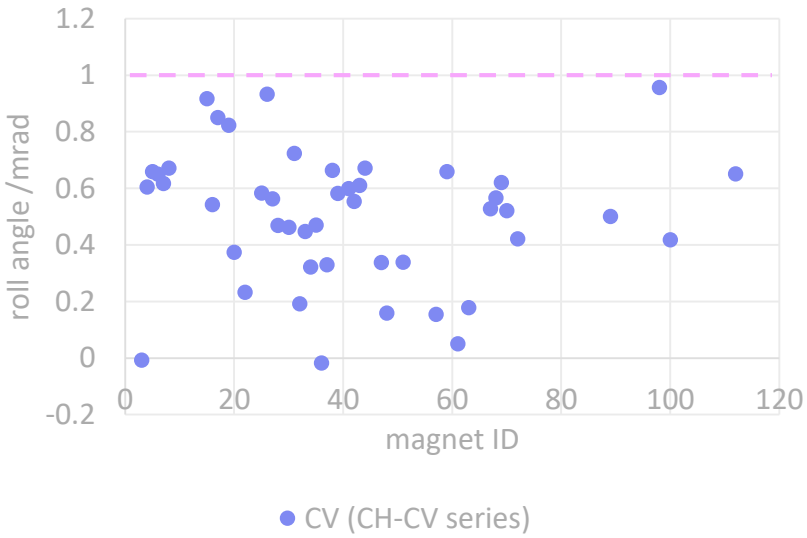
Roll angles between +/-

Good quality of magnets delivered



Harmonics, CV





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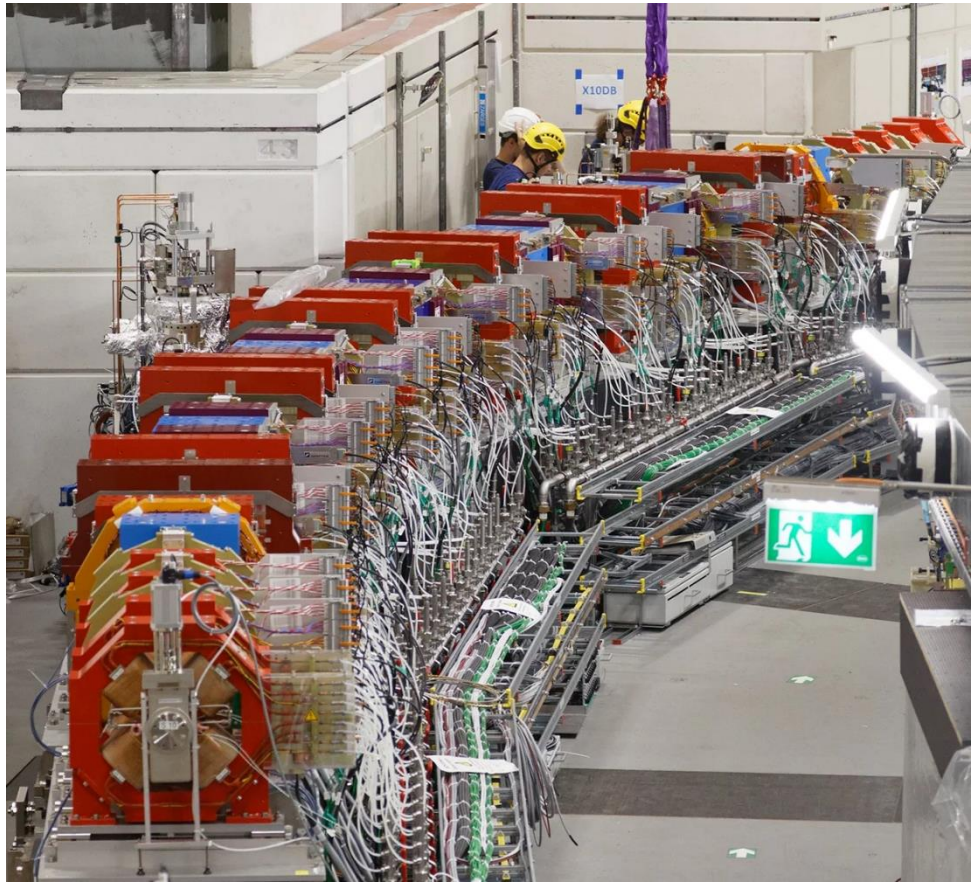
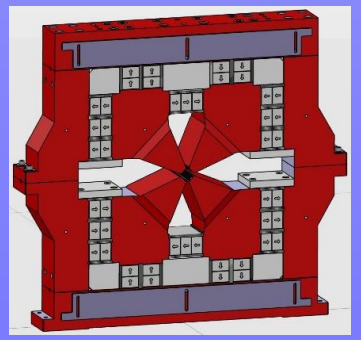
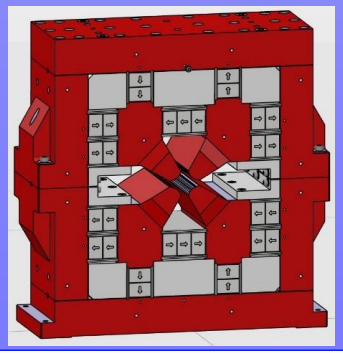
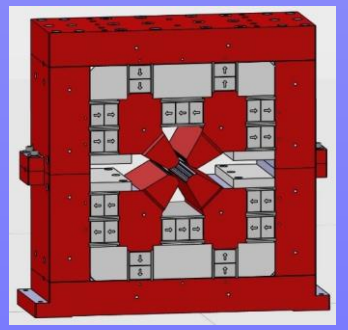


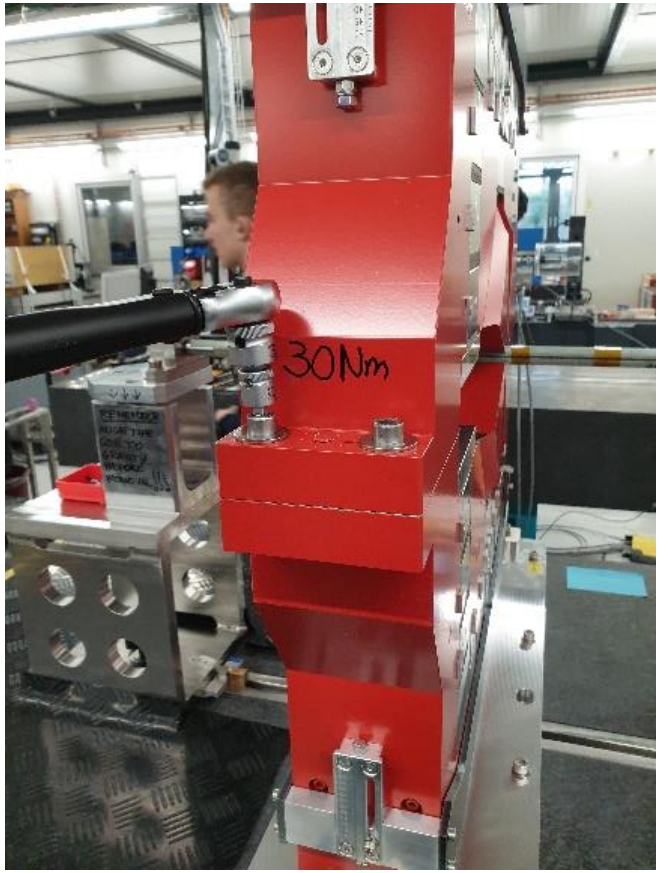
SLS2 magnets installed in the tunnel

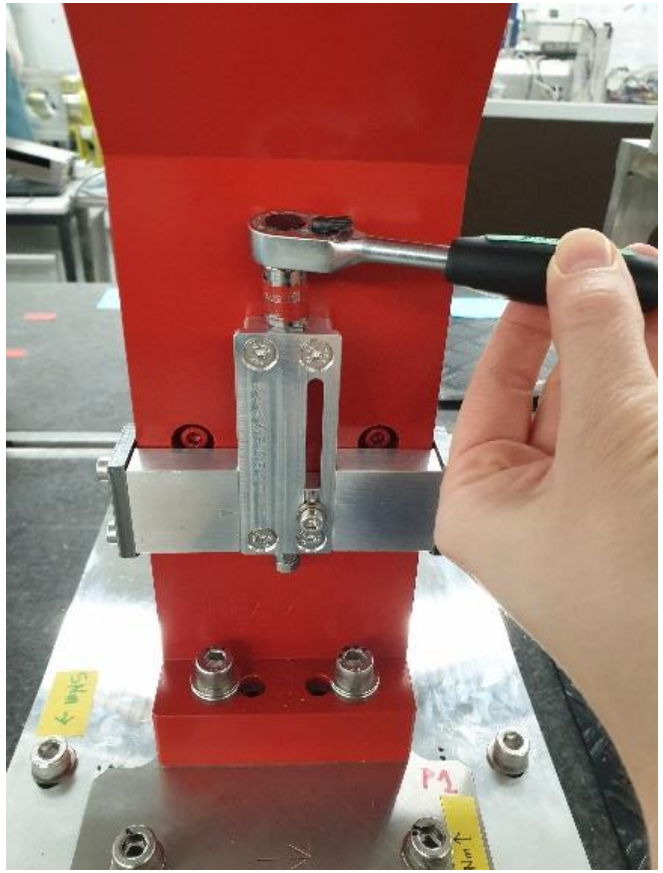
Specs permanent magnets (PM)

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

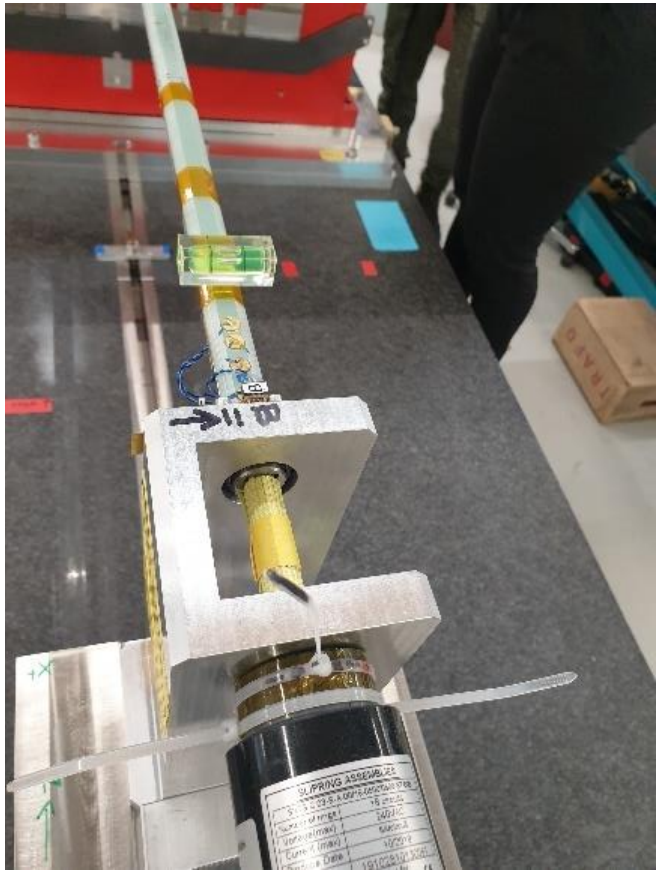
- **Pre-warming** of magnets for 3 days in building, 1 night in hutch
- Mechanical preparation of magnets

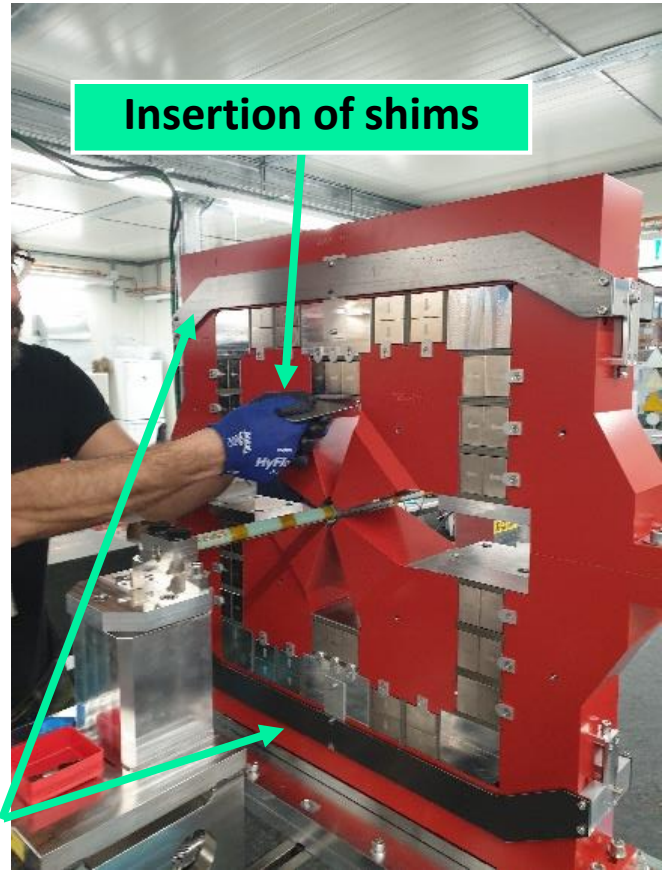




Measurement program PM

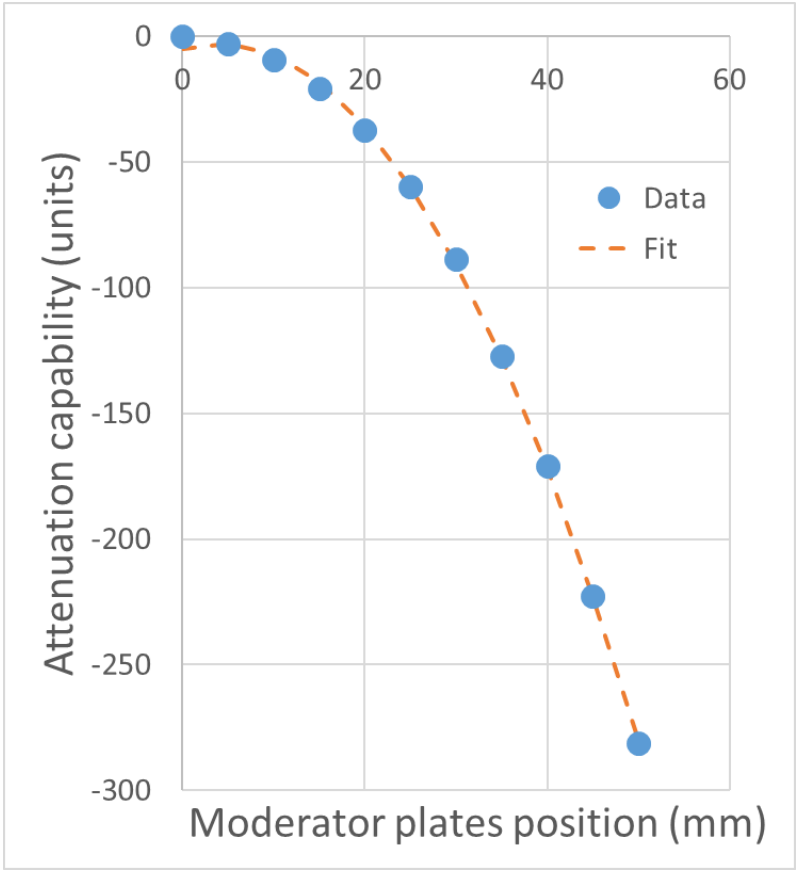
- **RC measurement with moderator plates at 0-position**
- RC measurement with shims





Measurement program PM

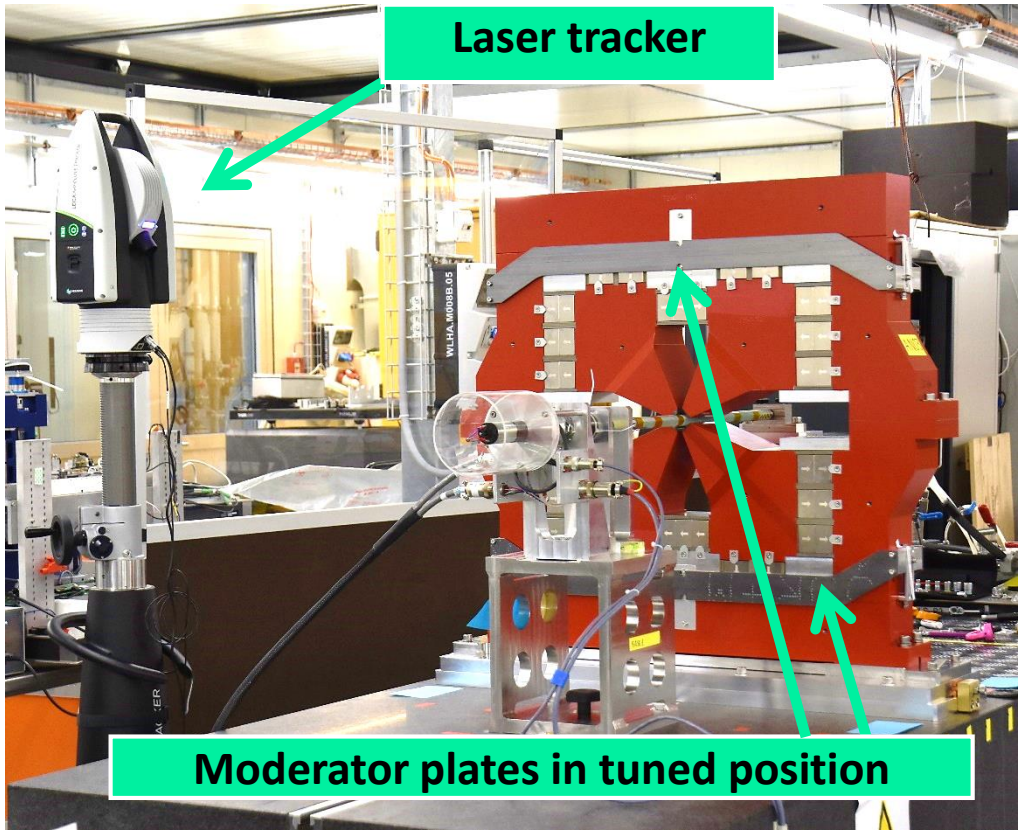
- **Tuning of magnet** (closing moderator plates) to target value **+/- 3 u** (10 types)
- **RC measurement** of harmonics, magnetic axis and roll angle in reference position



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

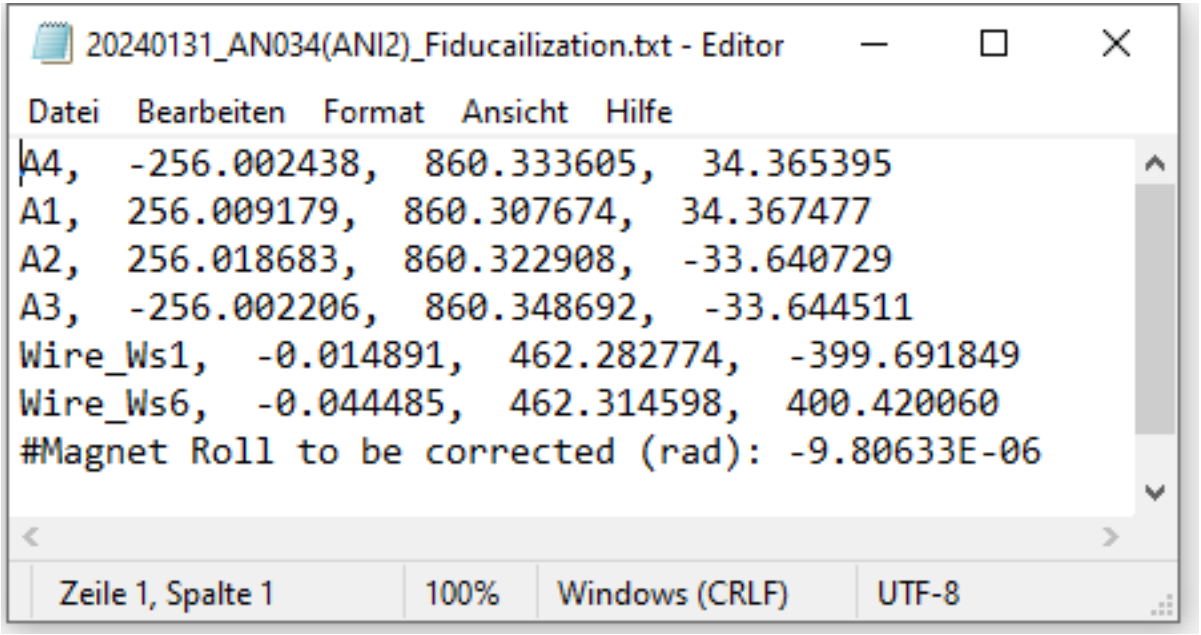
Measurement program PM

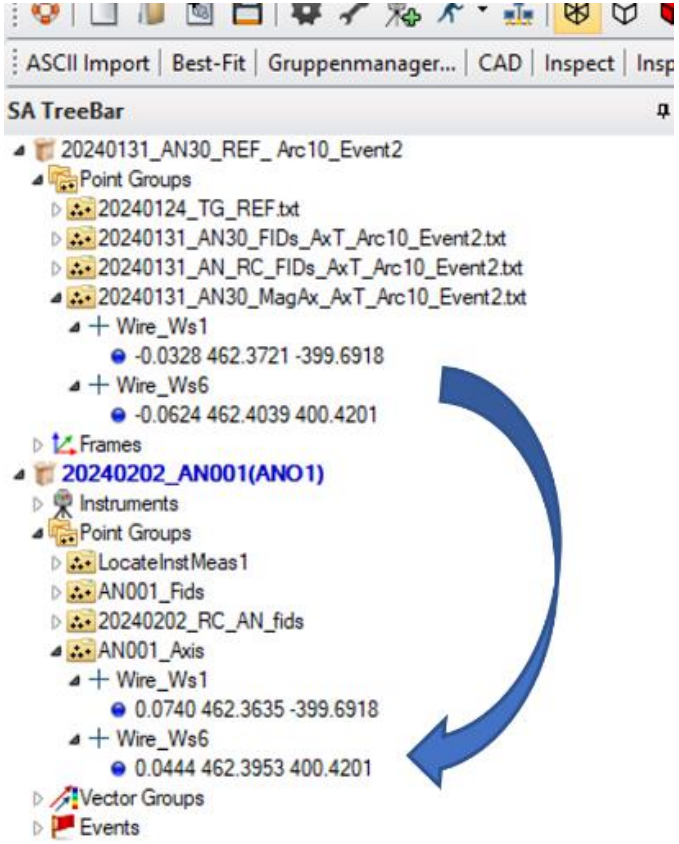
- Measurement of **magnet position** on bench with AT500 laser tracker
  - Level laser w.r.t. gravity
  - Adjust measurement template in Spatial Analyzer
  - Align instrument -> Measure the fiducial of the bench -> check RMS < 10 um compared to reference magnet measurement
  - Measure magnet fiducials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



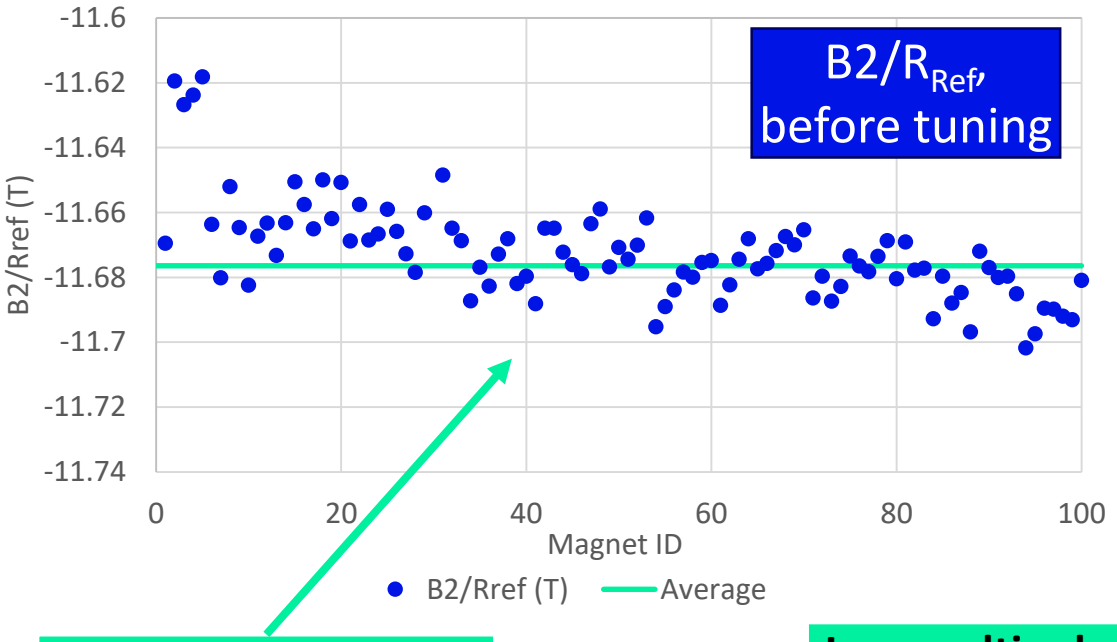
Measurement program PM

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



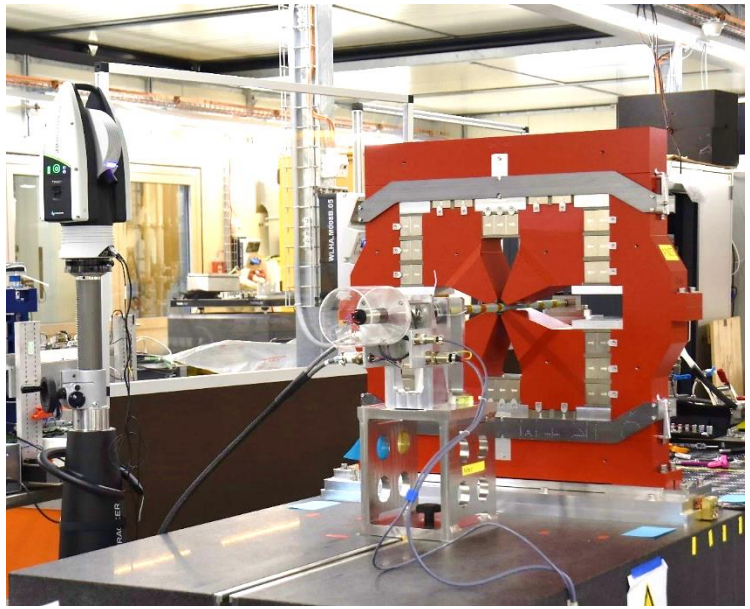


Results PM, exemplary for AN



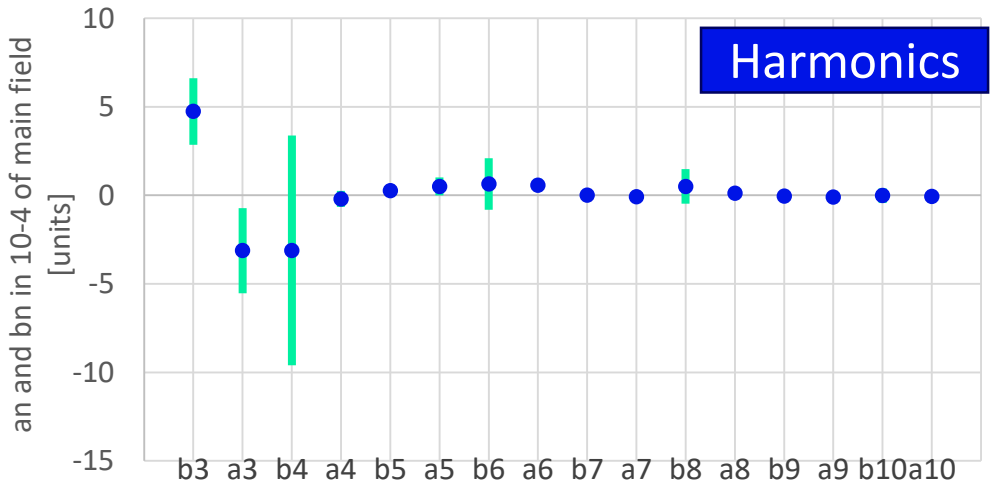
Field strength getting lower with time due to adjustment of PM block assembly plan (10 charges) → as expected

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



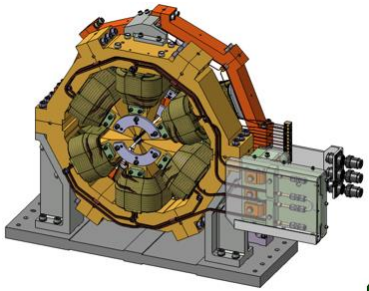
Low multipole values <10 units, small spread

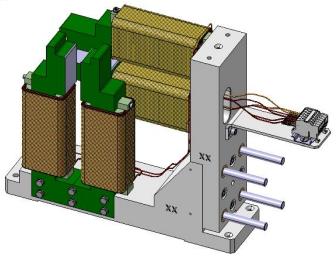
Roll angles below 0.5 mrad

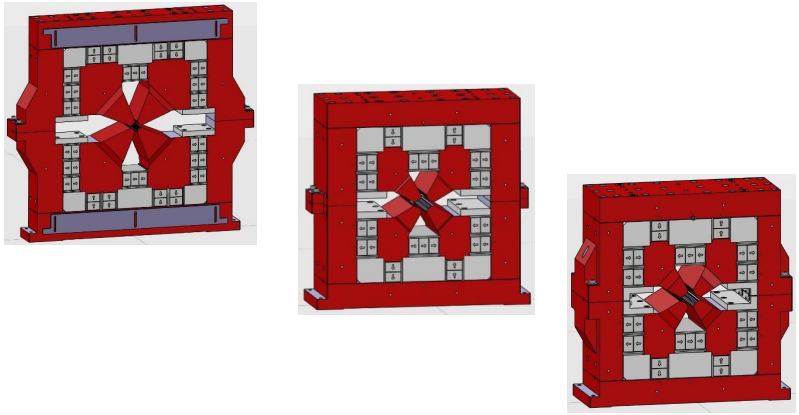


Conclusion

- **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)







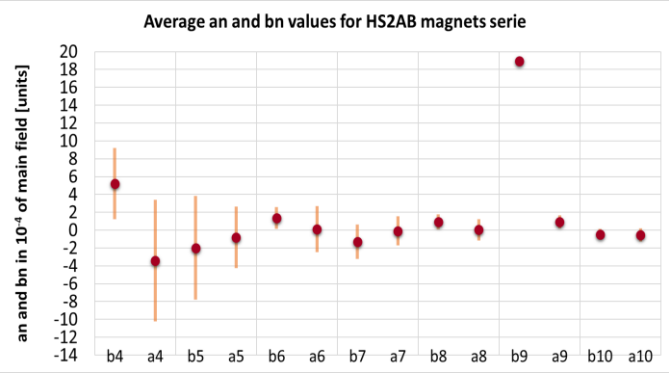
PSI Center for Accelerator Science and Engineering

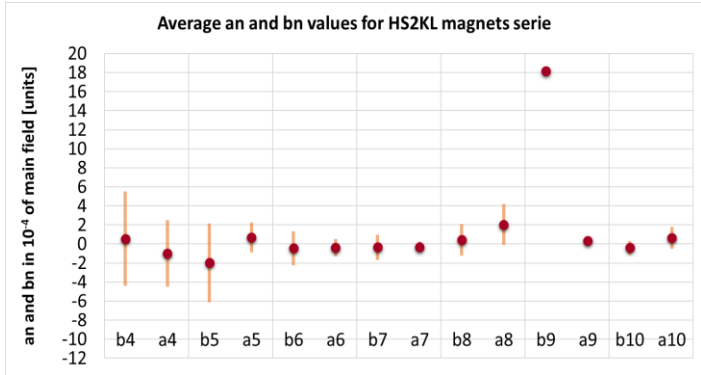
We would like to thank:

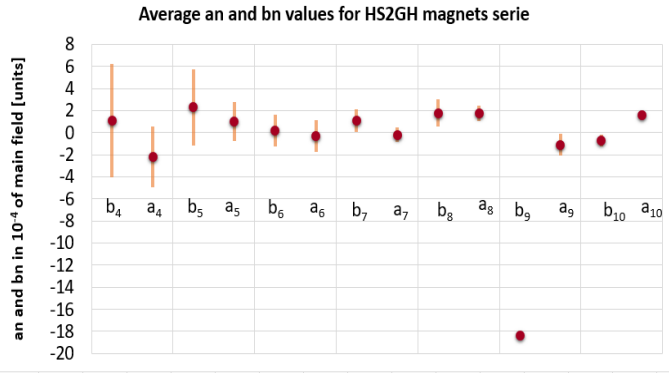
- **PSI line managers** for their support during this massive undertaking
- **PSI technicians** for their highly valued contributions in manufacturing parts, assembly, crane operation, …
- **Logistics team** for making in-time deliveries and pre-warming possible

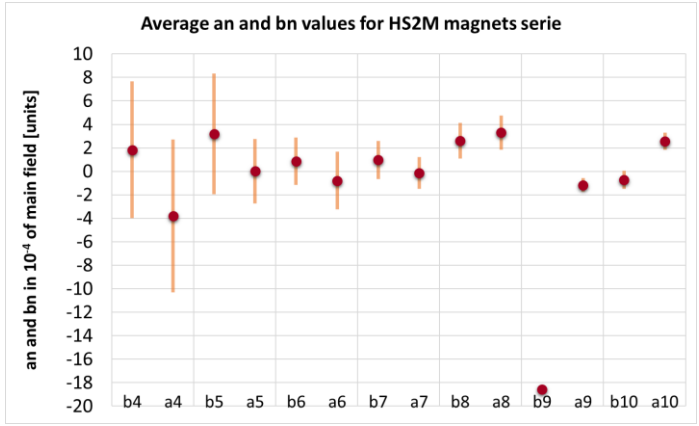
C. Zoller, M. Duda, T. Ernst, G. Montenero, R. Riccioli, V. van de Vijfeijken

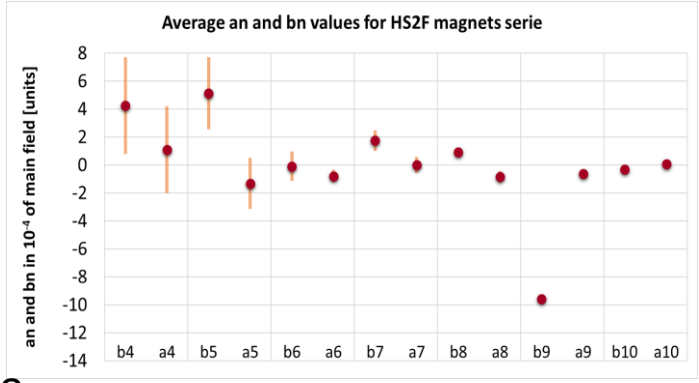
Results 116 SX/SXQ with RC: harmonics

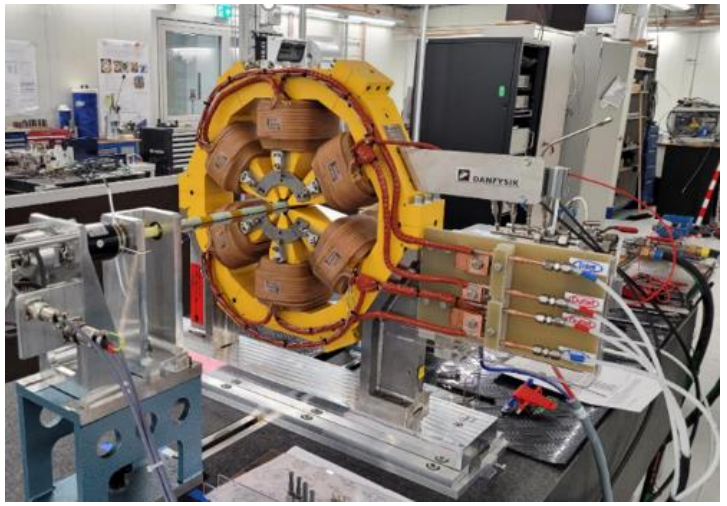


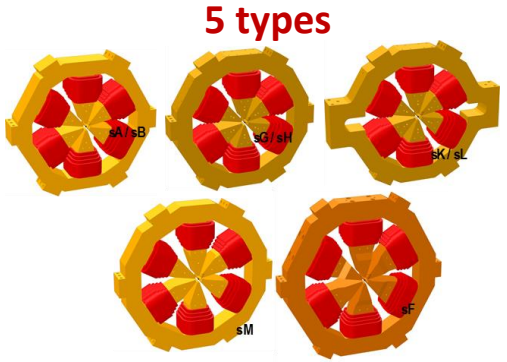




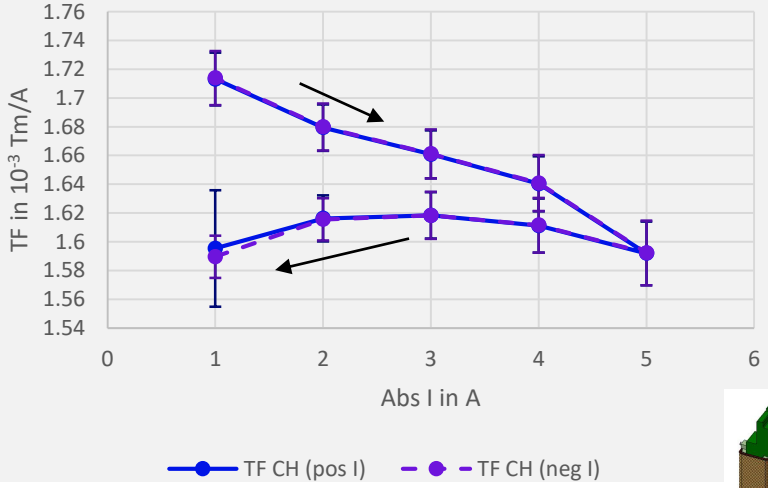


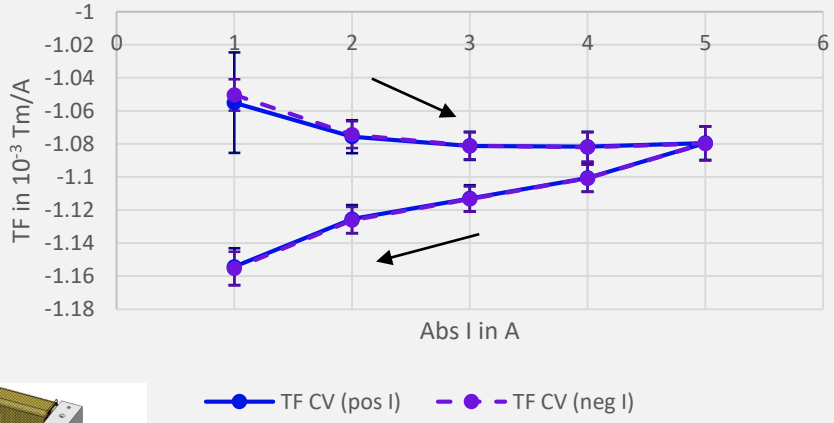


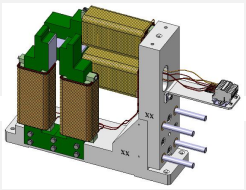


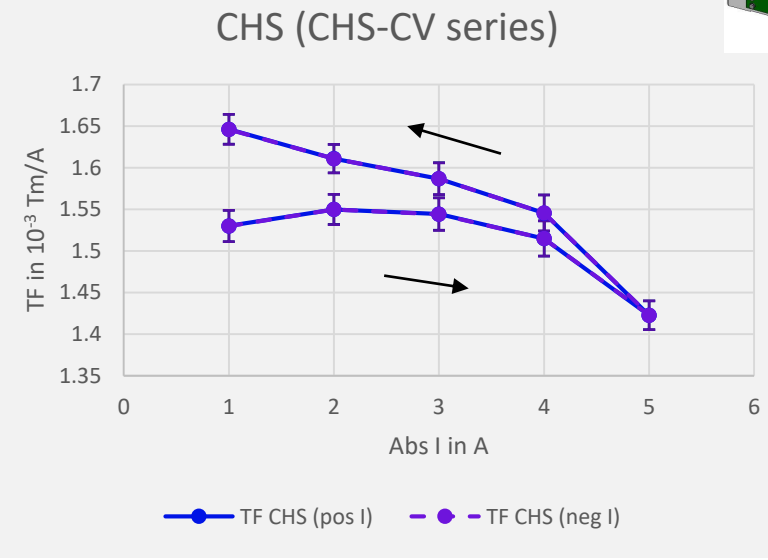


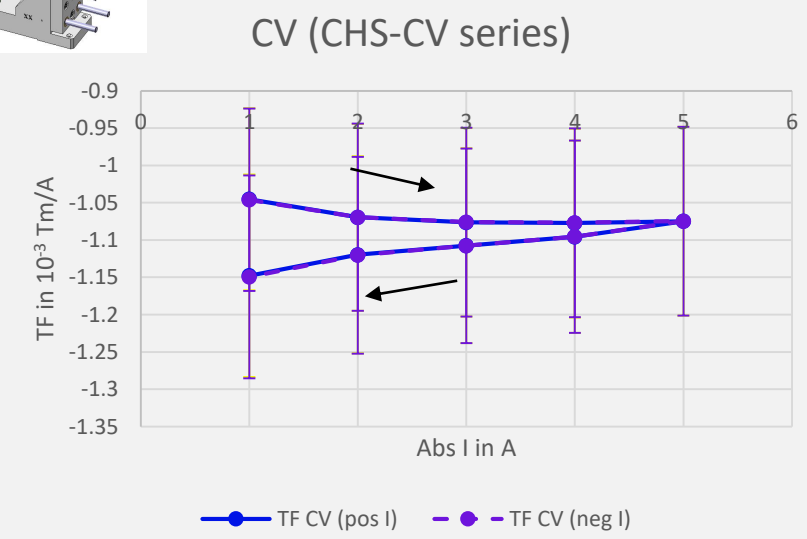
Transfer function $1\mathrm{A} \rightarrow 5\mathrm{A} \rightarrow -5\mathrm{A} \rightarrow -1\mathrm{A}$ with 3 σ



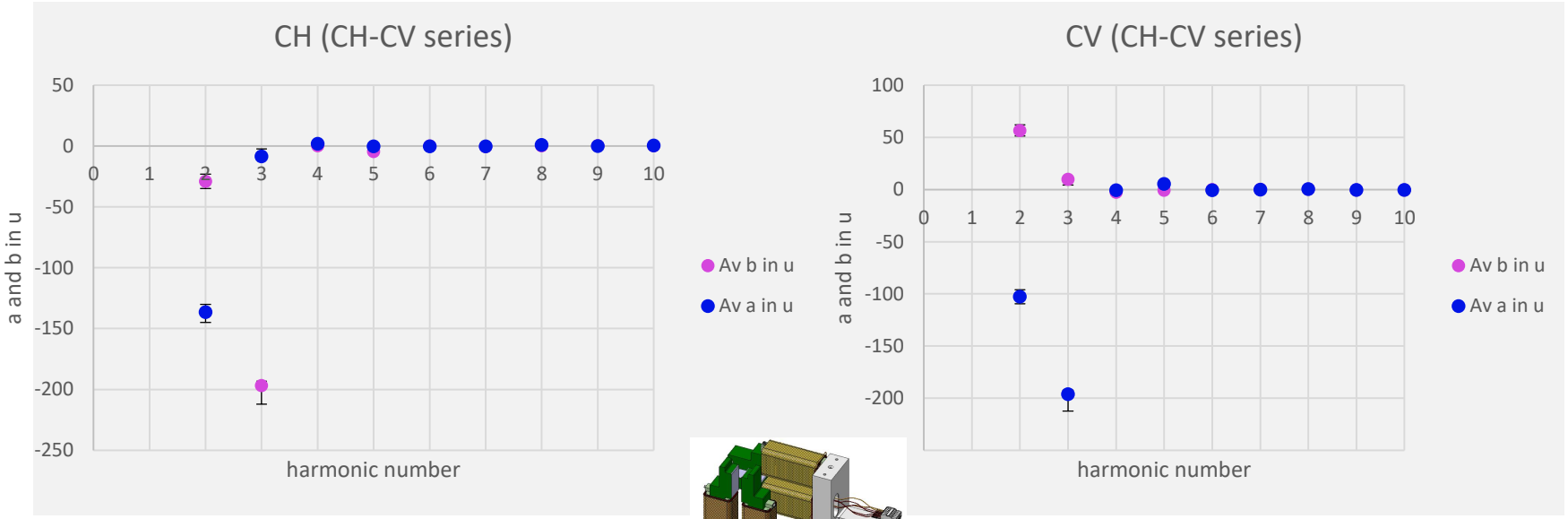


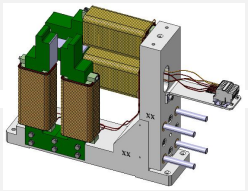


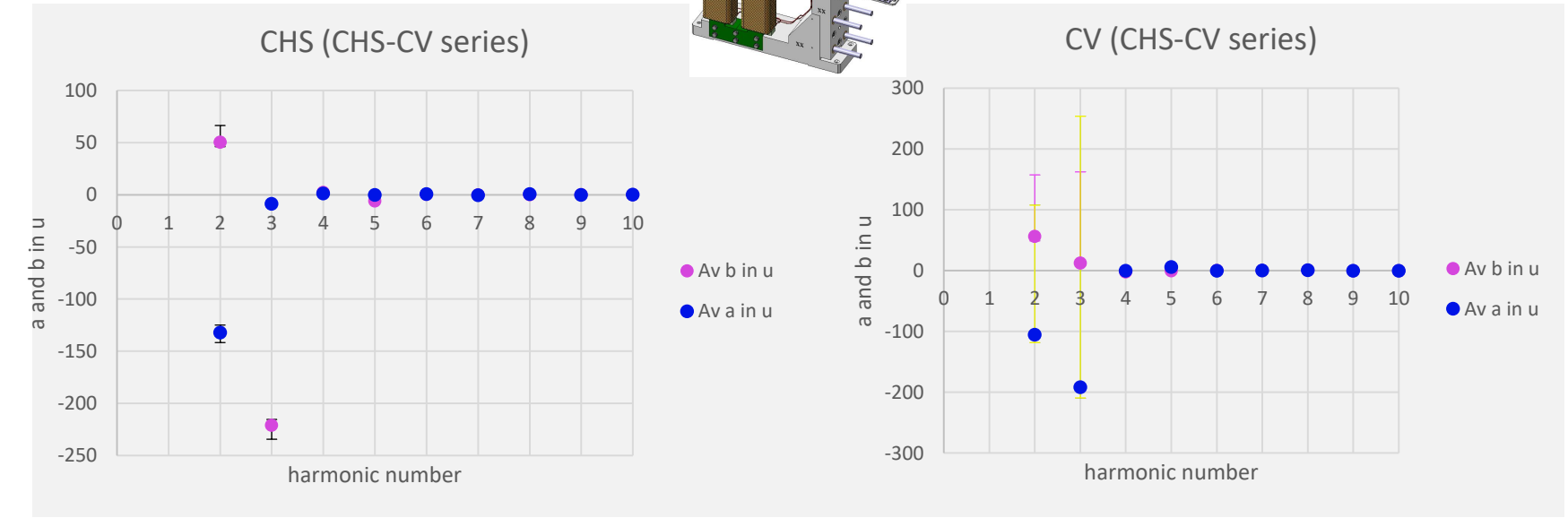




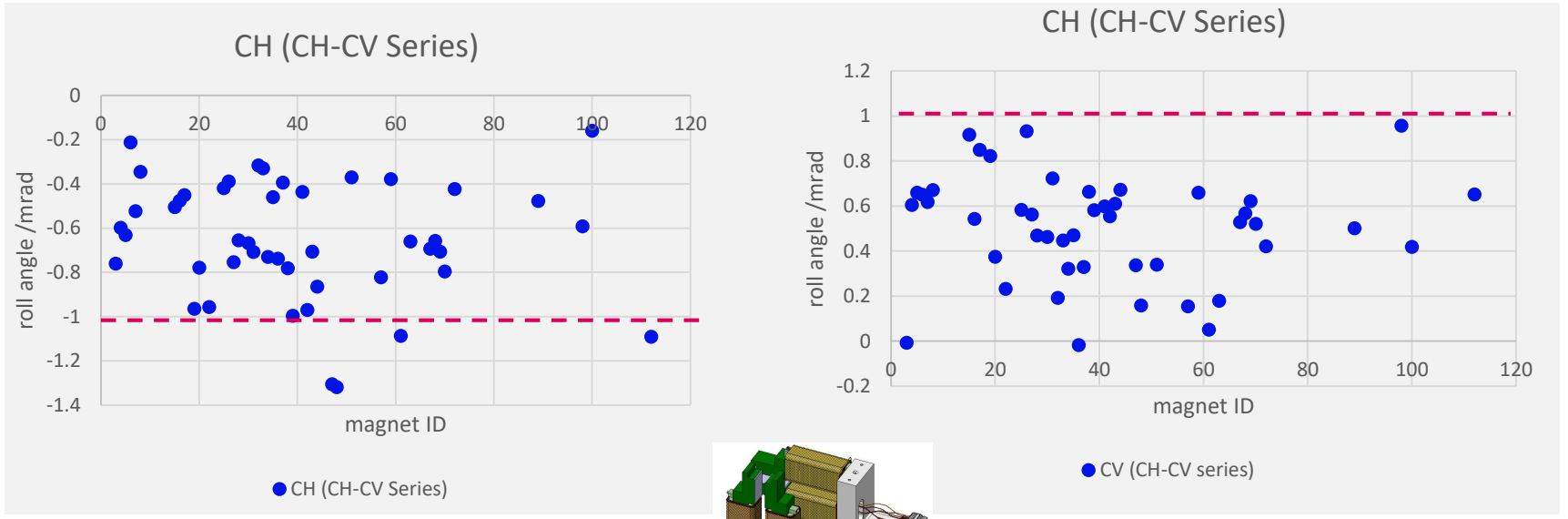
Average harmonics at $5\ A$ with min and max

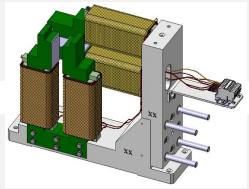


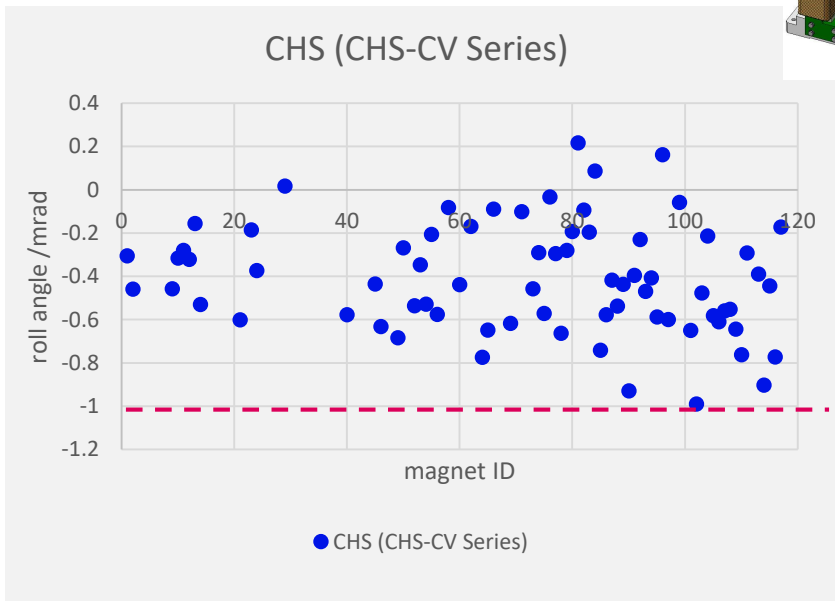


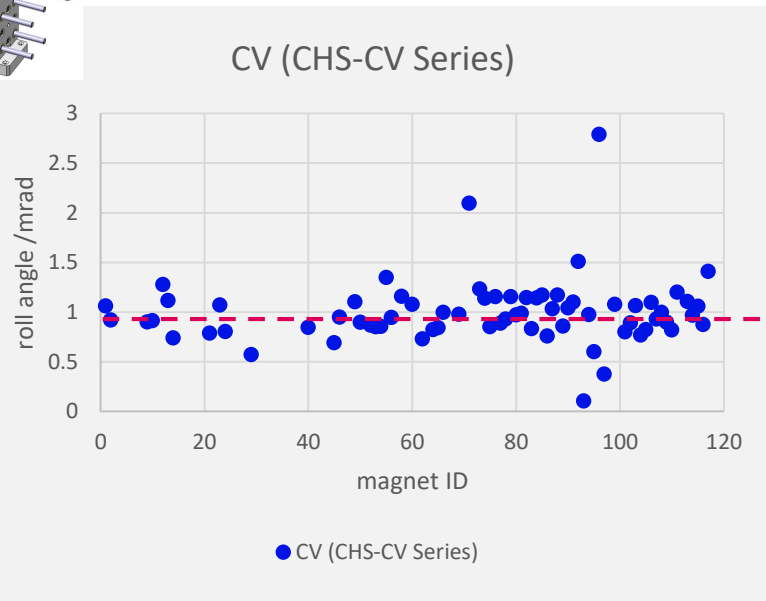


Roll angle at 5 A









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