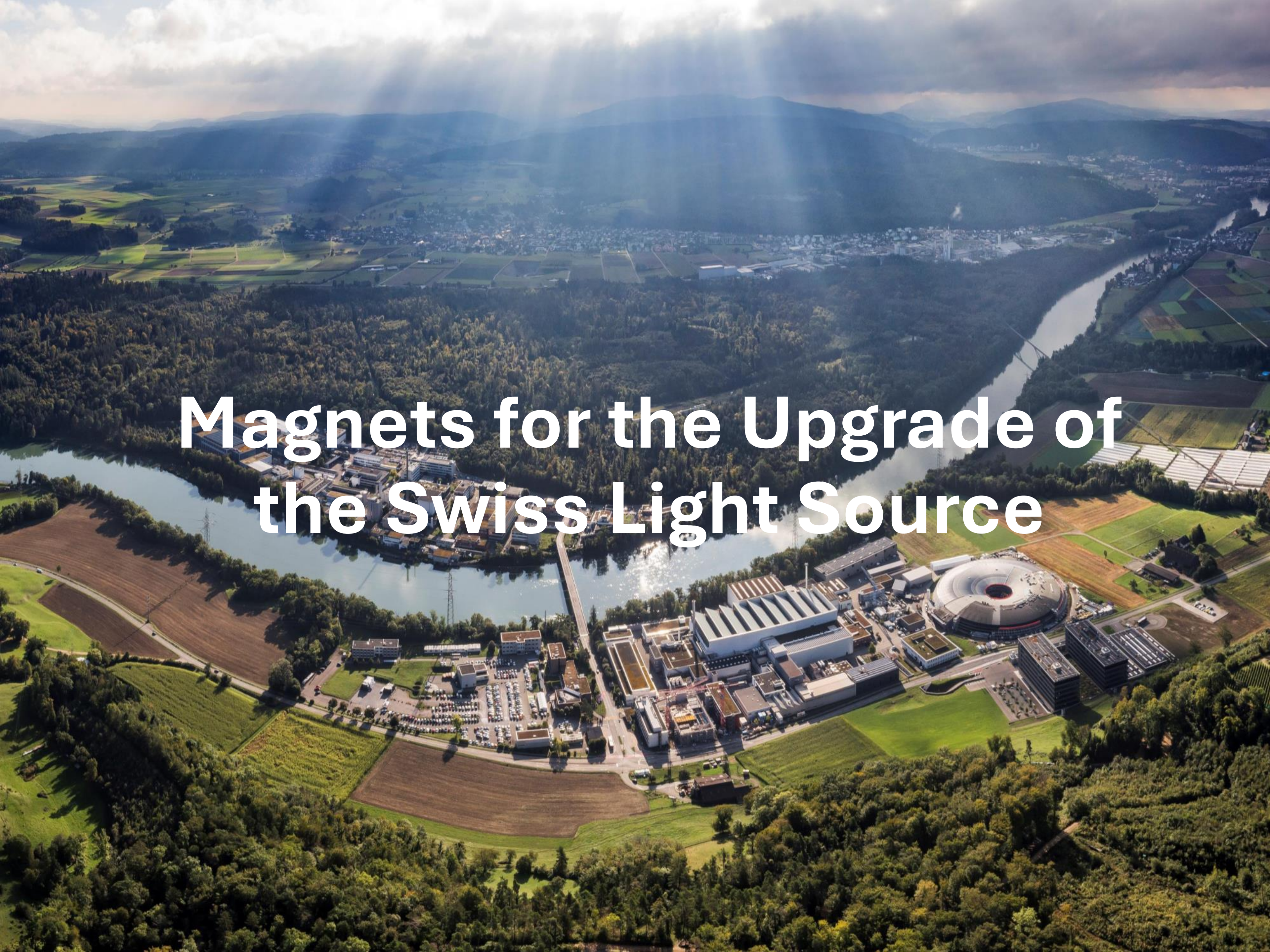
SLS2.0 Series Magnet Qualification
Challenges, results and lessons learned

Stéphane Sanfilippo for the PSI Magnet Section

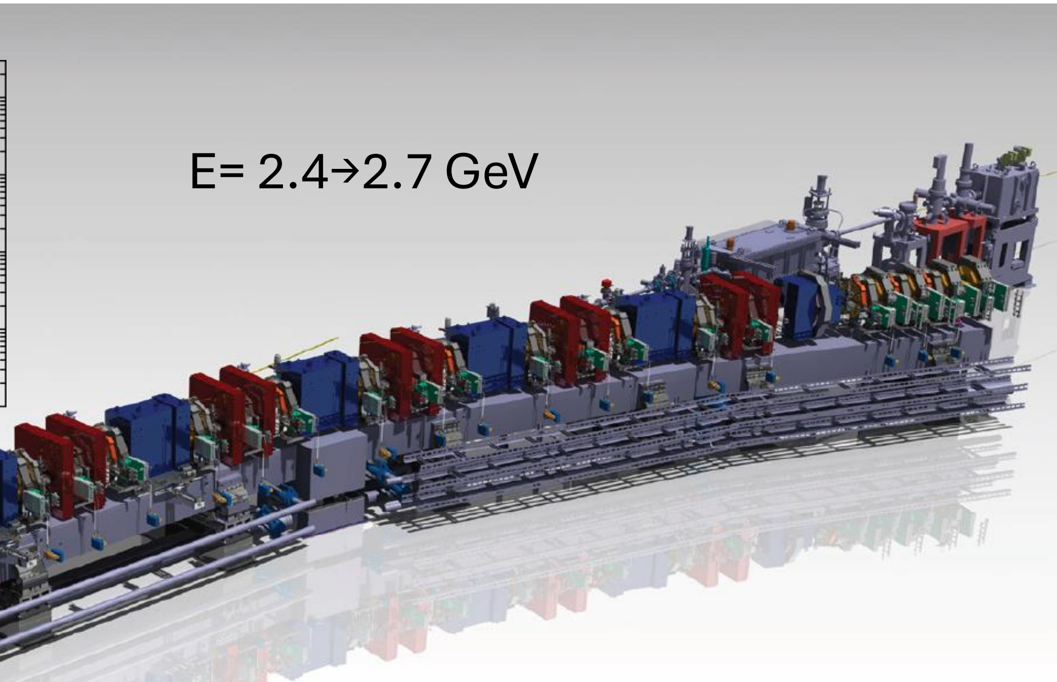
- SLS2.0 series Magnets : Context and the measurement challenge
- The measurement strategy
- Two Selected Results and lessons learned
  – Triplet measurements
  – Magnetic coupling electro & permanent magnets

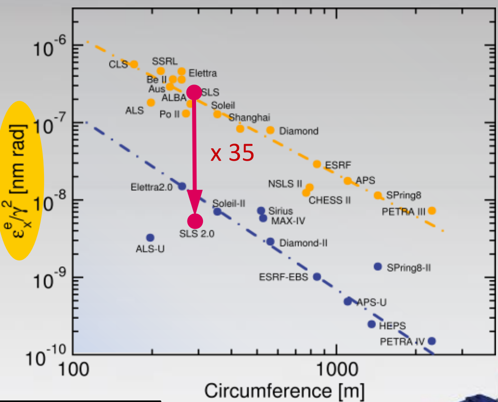
I.FAST Workshop 2025 on Stability of Storage Ring Based Light Sources
Mar 17 – 21, 2025, KIT North Campus


Magnets for the Upgrade of
the Swiss Light Source

The upgrade of the Synchrotron Light Source - SLS2.0

https://www.psi.ch/fr/media/sls-20





$$\mathcal{B} = \frac{\text{flux}}{\text{emittance}}$$

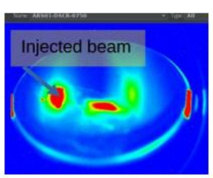
Brilliance

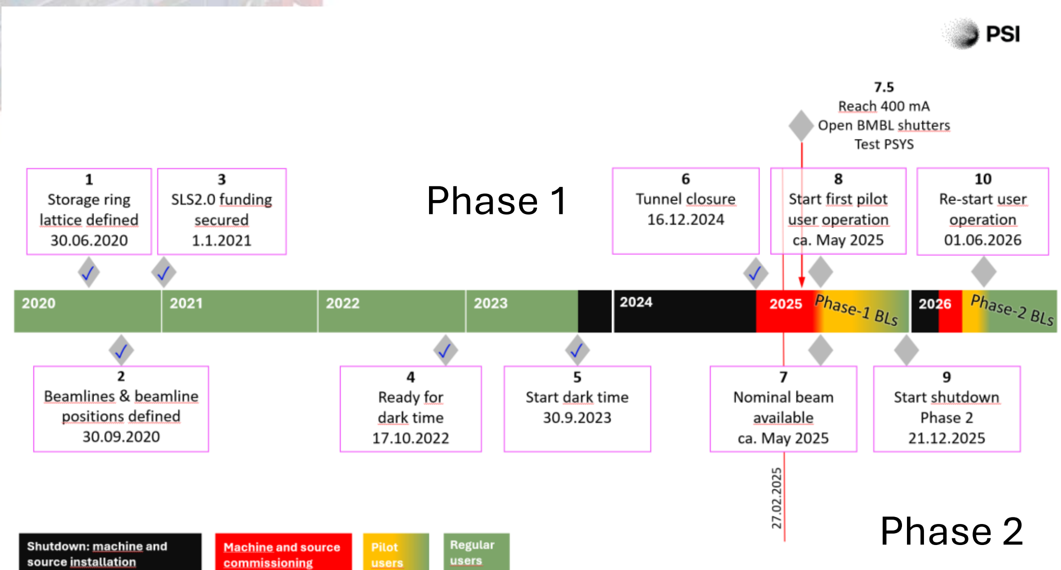
E= 2.4→2.7 GeV

SLS 2.0: ε_x = 157 pm.rad

First light: 2025

Stored beam in January 2025!





SLS2.0 magnets : the challenges

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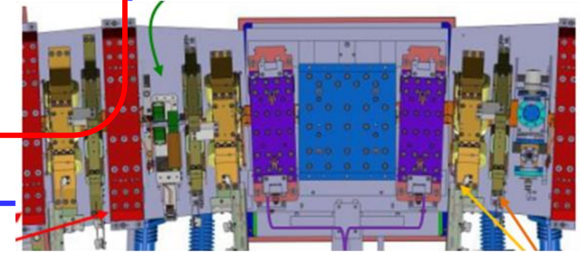
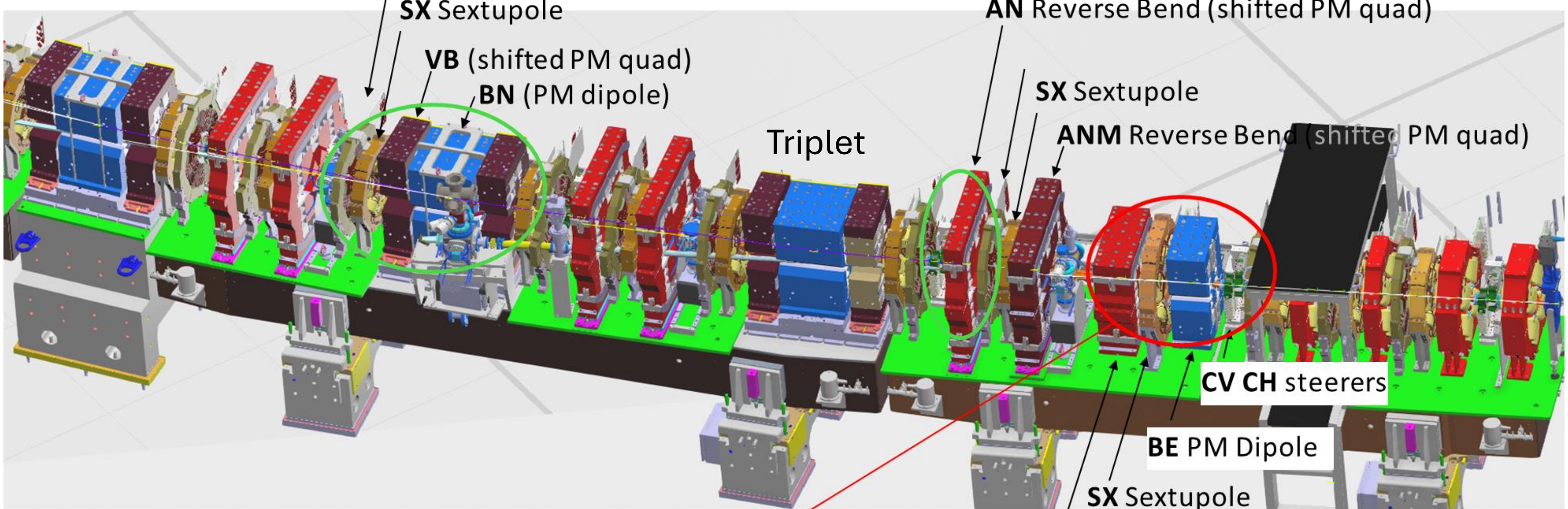
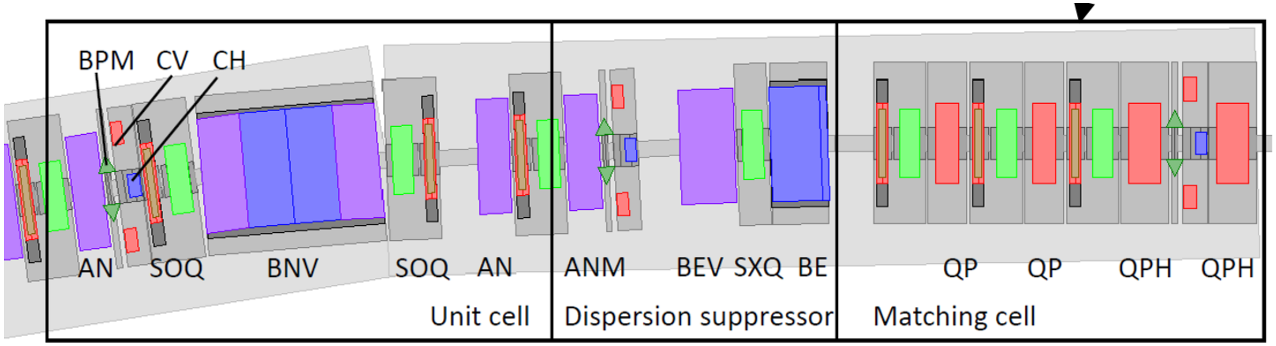
- Fields above 1 T and increased field gradients
- **Combined function magnets**
- **Tight tolerances** (field quality 0.01....0.1 %; aligment below 30 micrometers)
- Three types of magnets (electro/**permanent**/superconducting)
- High number of magnets , **16 different types**
- **Dense packing of magnets** (Cross-talk effects).
- Tight schedule for the design, production and measurements.

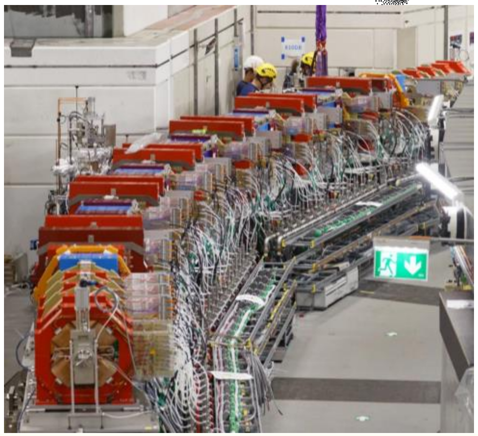
Lack of space !



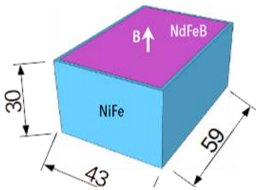


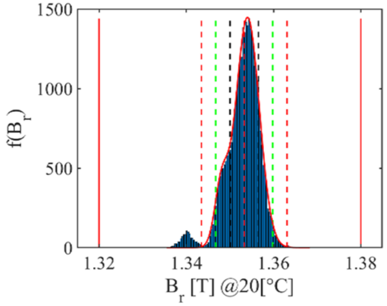
Magnets for the SLS upgrade





34 000 NdFeB blocks
16.6 tons





Permanent Magnets*

BN	56	Dipole
BS	4	Dipole
VB	96	Quad
VBX	24	Quad
	Triplet	60
AN	120	Quad
ANM	24	Quad
BE	24	Dipole
VE	24	Quad
	Total : 372	

Electromagnets

QP	55	Quad
QPH	53	Quad
SXQ	24	6-Poles
SX	264	6-Poles
OC	264	8-poles
	SOQ 264	
CHV	112	Steering
	Total: 780	

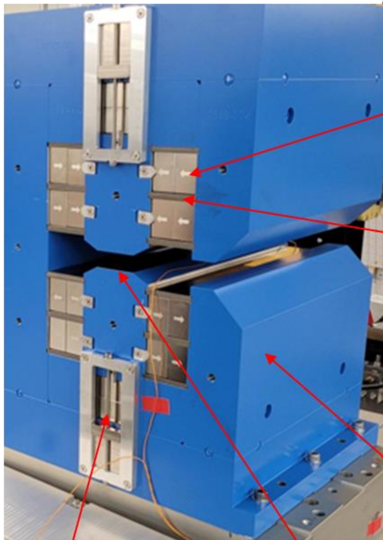
**** Reduction of the magnet power consumption ~60 %***

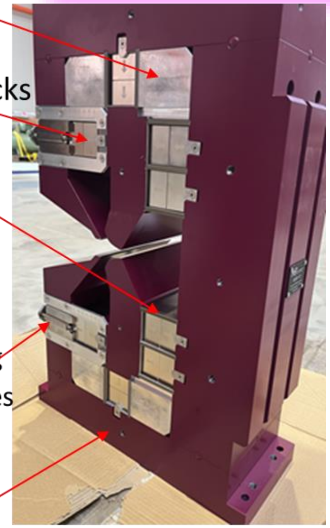
1152 (phase 1)+ two 5 T superconducting superbends (phase 2)

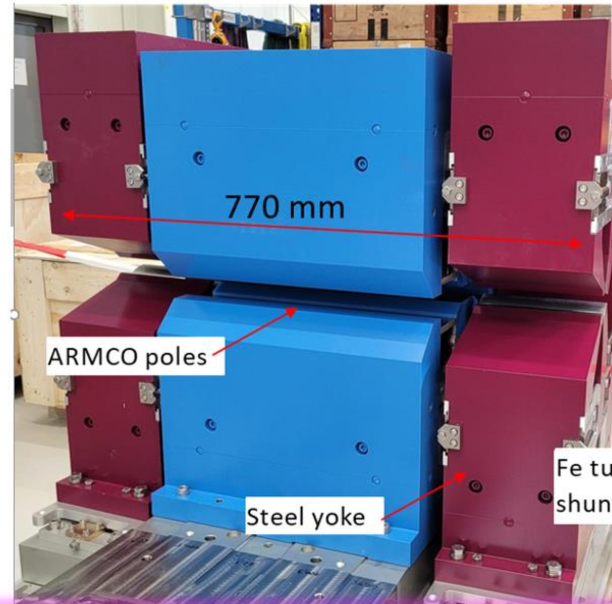
SLS2.0 permanent magnets

Dipole BN (56)
1.35 T; L=405 mm; G=22 mm

VB (120)
0.84 T
40.6 T/m

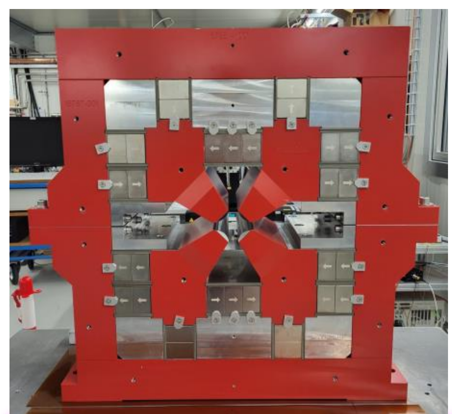




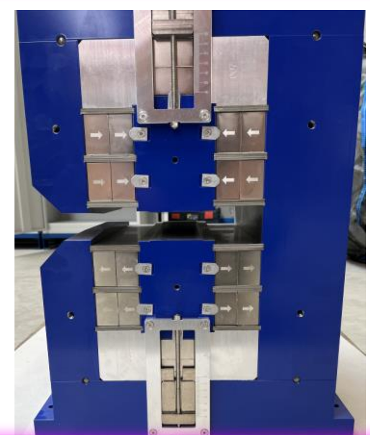


Triplet VB/BN/VB (60) , 0.861 Tm

Quadrupole AN(M) (148)
72.5-78 T/m ; Ø=22 mm



Quadrupole VE (24)
45.8 T/m; Ø=22 mm



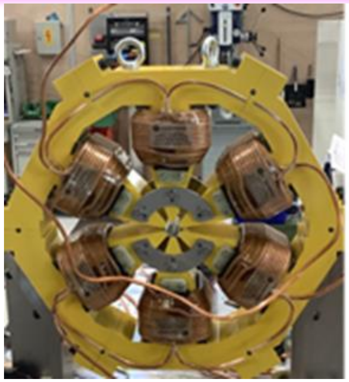
2.1 T Superbend (4)
Gap =14 mm; L=405 mm

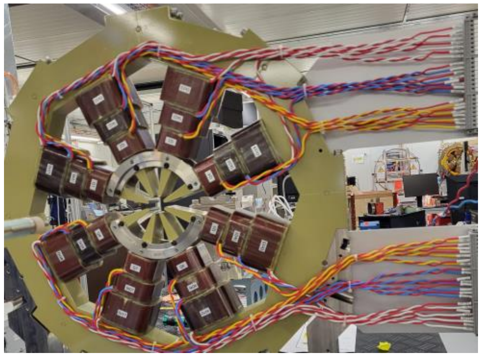
SLS2.0 electromagnets

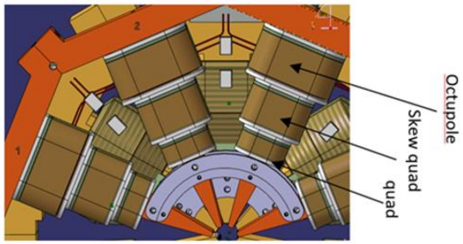
Quadrupoles (110)
93T/m-98 T/m
Ø=21 mm

Sextupoles (288-6 types)
5093T/m^2-5840 T/m^2
Ø=22 mm

Combined functions
Octupoles (264-2 types)

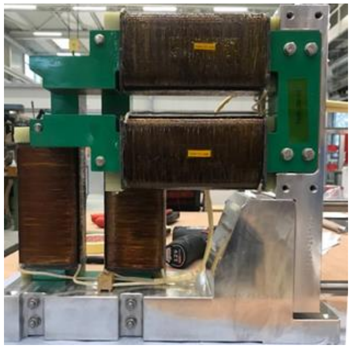






- 30 coils (8+8+8+6)
- ARMCO yoke and poles
- Water cooling for 6-poles
- air cooling for 4-poles and 8-poles
- 4 power supplies 5 A (3) & 50 A (1)
- Mass: 260 kg

Steerers CH/V
44 mT; 31.4 mT

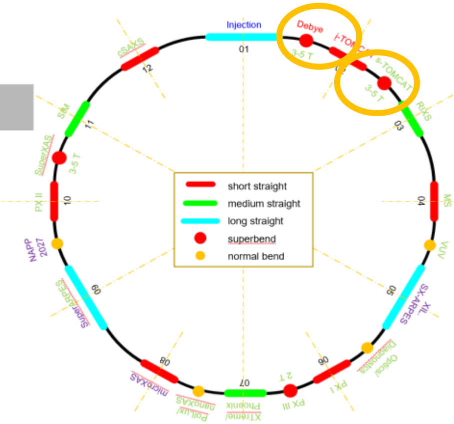


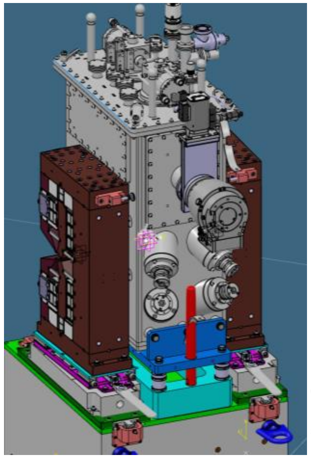
Sextupoles SXQ (24)

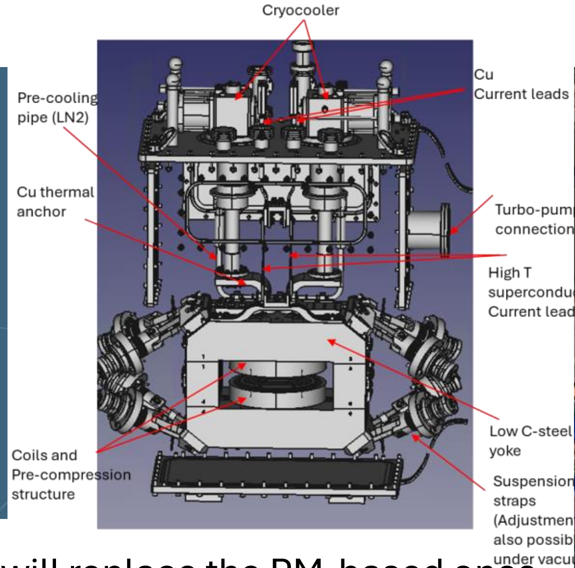
SOQ (264)

B''/2, T/m^2	5850
Aperture (Ø) sextupole, mm	22
Yoke Length, mm	84
Yoke mass, kg	93
Current, A	50
B'''/6, T/m^3	63000
B' , T/m	2.8
A' , T/m	5.6
Aperture (Ø) octupole, mm	29
Yoke Length, mm	44
Yoke mass, kg	40
Current, A	5

5T NbTi Superbend – phase 2

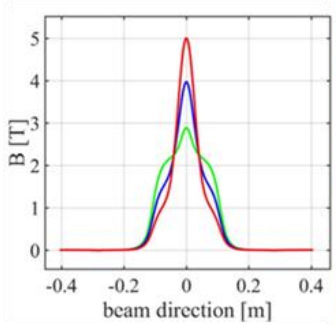


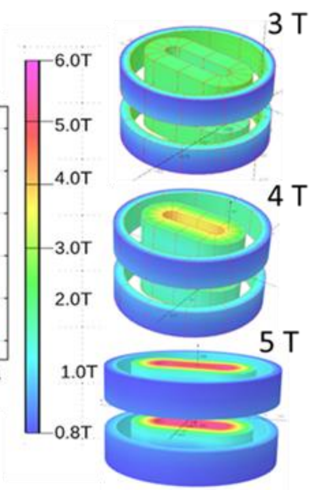


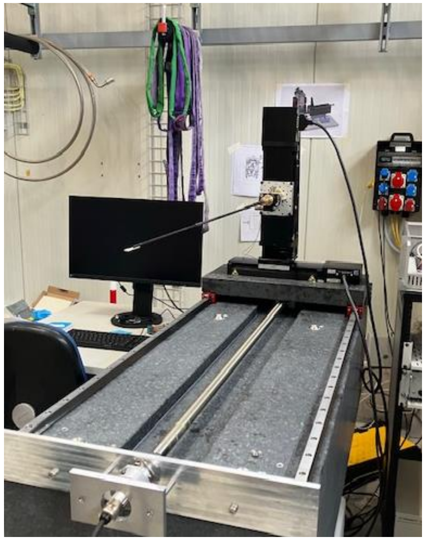


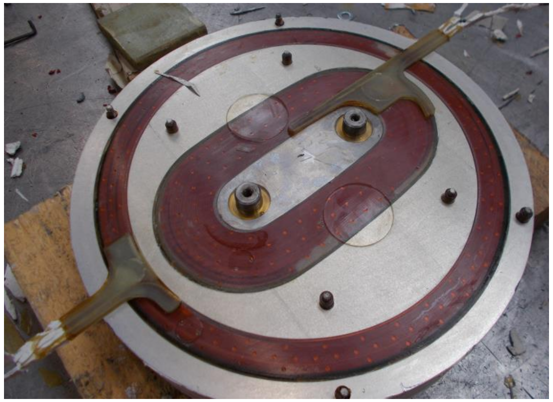
Cold mass test at SIGMAPHI

- 2 superconducting Superbend magnets will replace the PM-based ones.
- 2 operating scenarios: 3T and 5T peak field.
- Superbend delivery planned between July and fall 2025
- 2 new VBS yokes are required (normal VBs are too weak);
- Power tests and magnetic measurements with till end of 2025









Measurement strategy and implementation

SLS2.0 Magnet qualification

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Challenge : 100 % of magnets are measured at PSI

7 measuring test benches operational since September 2023

Systems (X benches)	Electro magnets	Permanent Magnets	3-5T superbend
Rotating coils (2)	Field Strength Multipoles	Field Strength Multipoles Magnetic axis	
Moving Wires (2)	Magnetic axis (reference magnet)	Triplet: Field Strength alignment	
Vibrating Wires (2)	Magnetic Axis (SOQ)		
3D Field Mapper	Field Strength & Maps (cross talk)	Field Strength & Maps (BE & cross talk)	Field Strength Maps

Accuracy (wire) : 1-2 units

Reproducibility : 1 unit

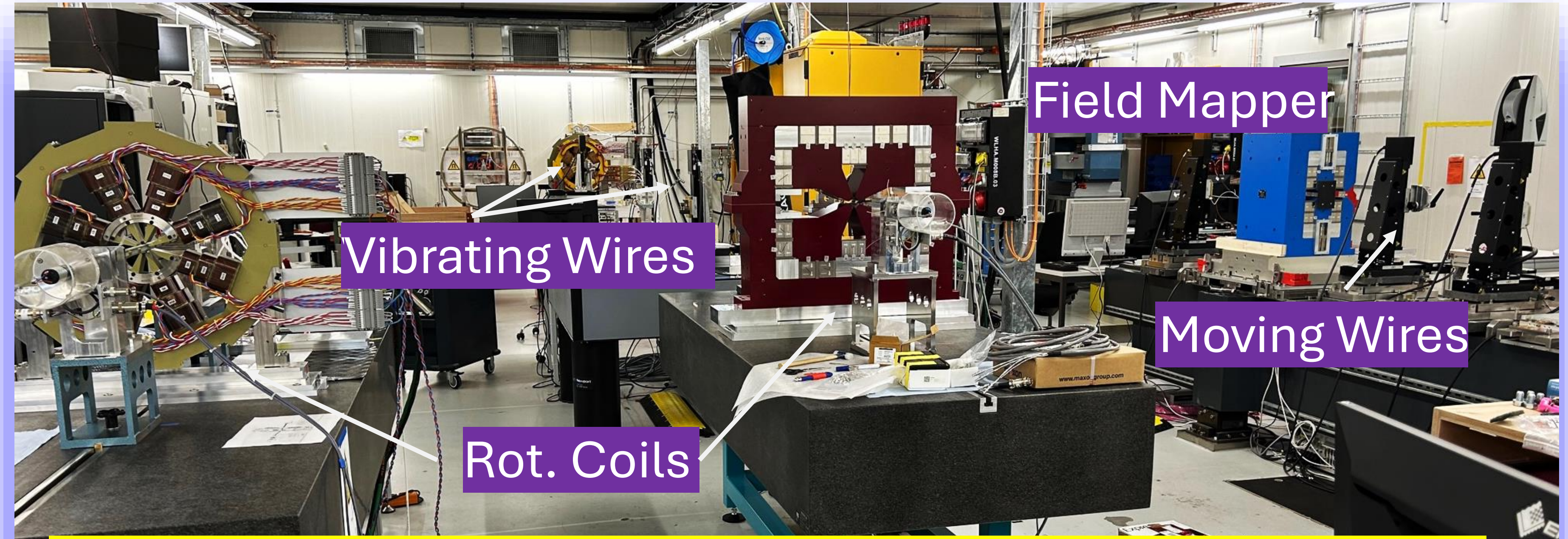
Axis : < 30 micrometers

Integrated Field Strength	**Moving Wire**	**Rotating Coil**	**Compact Field Mapper**
Uncertainty vs ref. (units)	Reference	**<5 units**	**~10 units**

Reliable and accurate measurement systems

Infrastructure for SLS2.0 magnets: Magnetic Measurement Lab

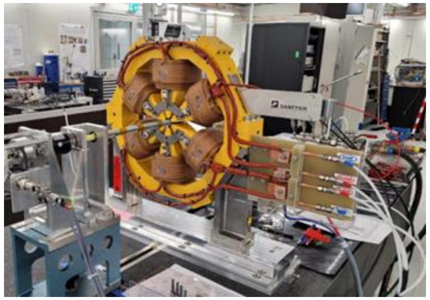
PSI

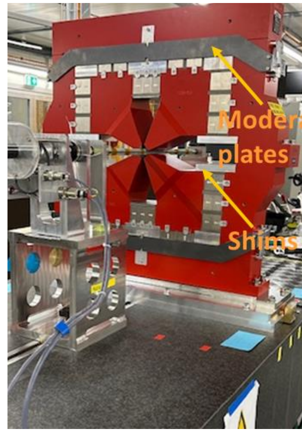


Seven magnetic measurement benches are operational since september 2023

Assembly & Measurement & Support teams for SLS2.0 in 2024 ~ 22 people

Magnetic measurements (phase 1)

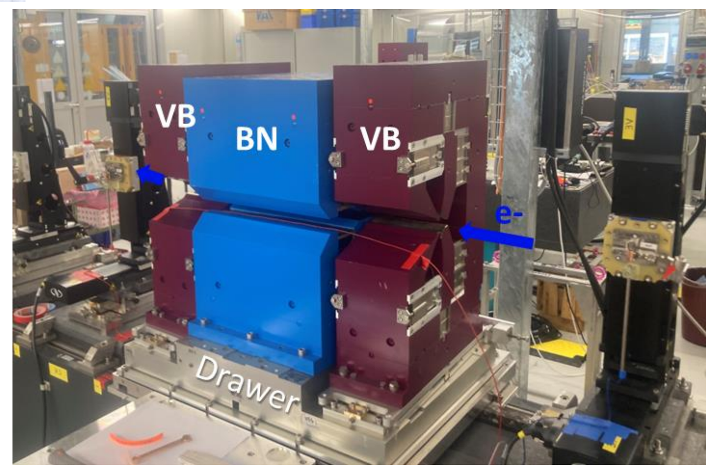




One team of 4 persons

Sextupoles &Octupoles axis measurement
with vibrating wires
Team of 4 persons

Magnetic coupling studies with Hall mapper
Team of 2 persons



Triplet measurements and alignment
with Moving Wires
Team of 4 persons

Two challenging measurements results & lessons learned

- Triplets measurements
- Magnetic coupling

Alignment and tuning of the triplets : a multi step process

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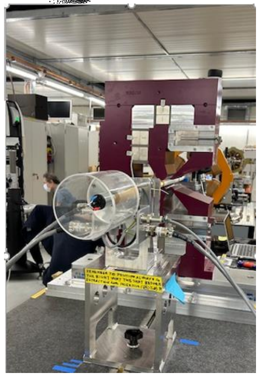
PSI

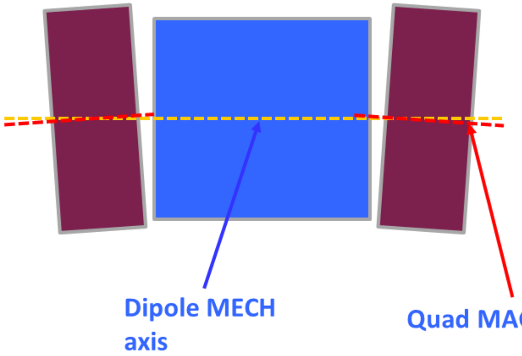
Simulation including cross-talk (once for all)

a. Extract the nominal field integral of the stand alone dipole for magnet shimming
b. Extract the horizontal & vertical field gradient components Ghor, Gver and the nominal integrated field gradient G for stand alone quads.



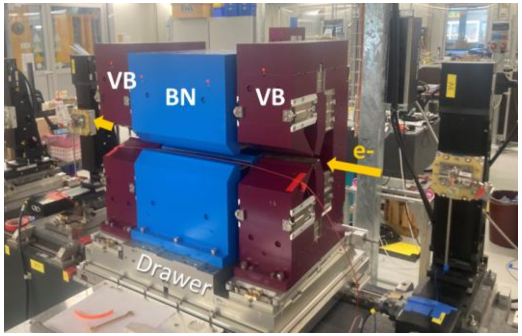
Single magnet measurement and optimization

a. Dipole field integral (wire1) and shimming to **$\int B_1 dl=-0.5699$ (Tm)**
b. Nominal integrated field gradient and shimming to **$\int G dl=7.0184$ (T)** and multipoles **(Rotating coil)**
c. Magnetic axis position of each Quad (wire 1)



Triplet assembly and alignment

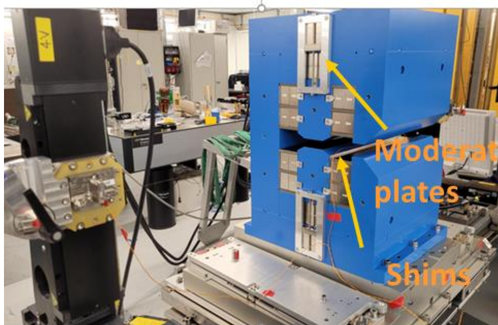
1. **The dipole mechanical axis (MECH) define the nominal axes of triplet magnets**
2. Quads are positioned on the drawer; a **preliminary alignment** is carried out on the two Quads vs. the nominal axes (wire 2)
3. **Dipole is installed** on the triplet; **final tuning** of the drawer and Quads (wire 2)- error less than 20 μm
4. The resulting integral of the assembled triplet is recorded as control parameter (wire 2)

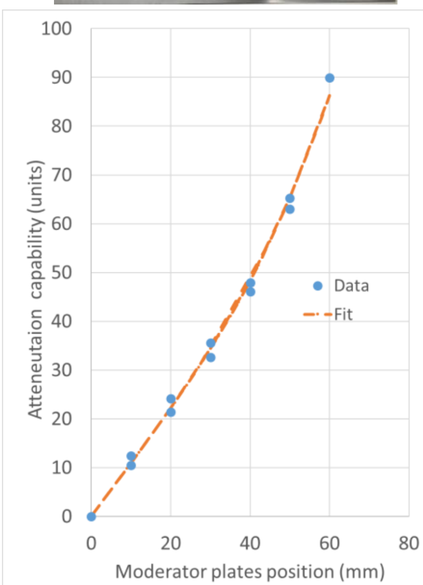


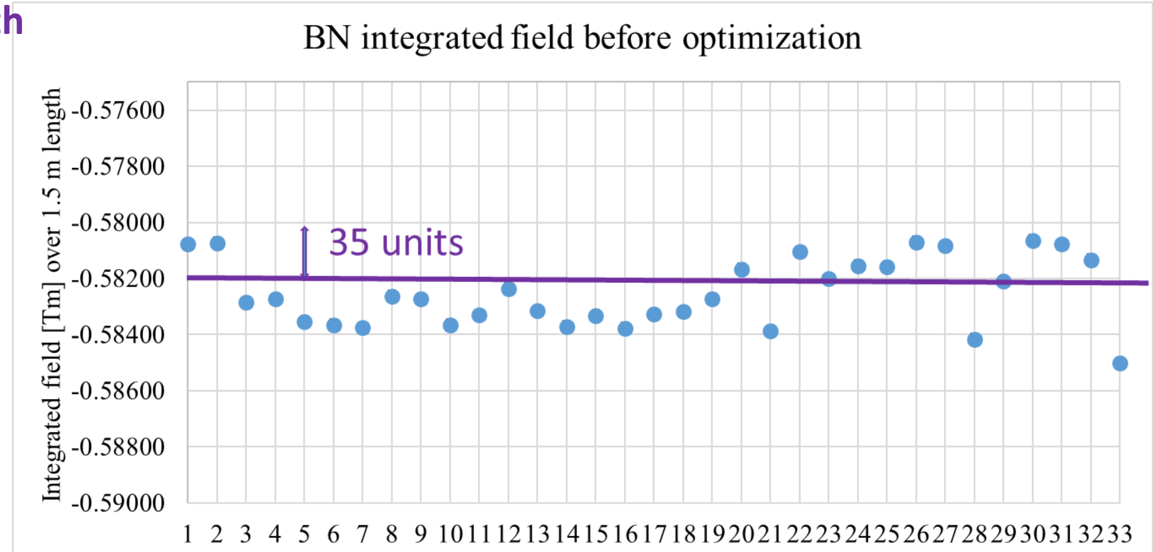
Machine specifications: max 0.2 % relative uncertainty of the triplet field

Individual measurements
Dipole optimization with moving wire

Single magnets measured/optimized with the moving wire (Field Strength)







Total tuned BN at target value: 33
Total BN tuned for VBXI/VBXO: 7

Field Integral	Not Optimized (BN for VB)	Optimized (BN for VB)	Attenuation
Average	-0.5823 Tm	-0.5724 Tm	174 units
σ (unit)	22	1.5	

Integrated field strength before optimization : 1.74 % above the machine value in average and spread of 22 units- very good manufacturing quality and efficient PM blocks sorting!

Optimization with (0.75 -1 mm thick) shims +moderator plates successful – ~1 unit level

Individual measurements (2)
VB measurements with rotating coil (48 magnets)

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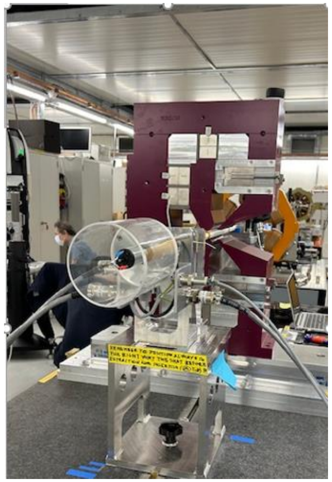
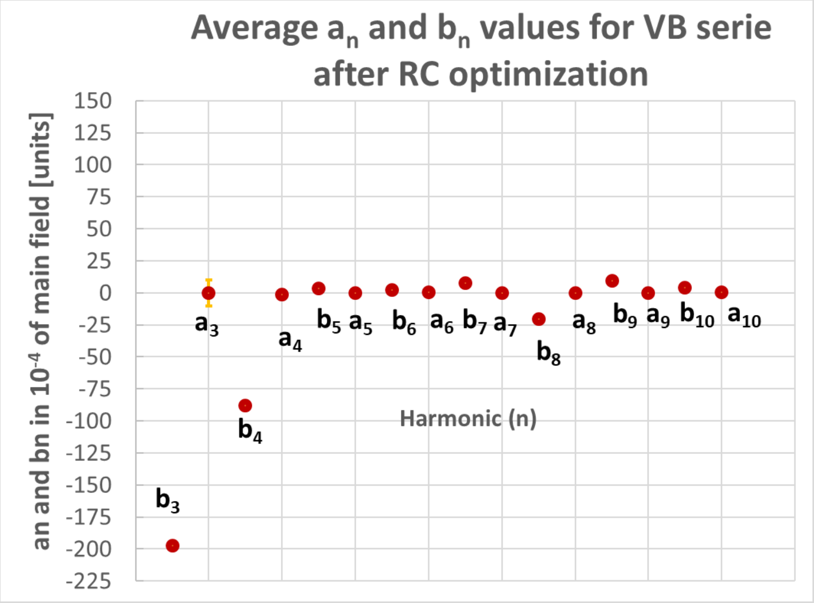
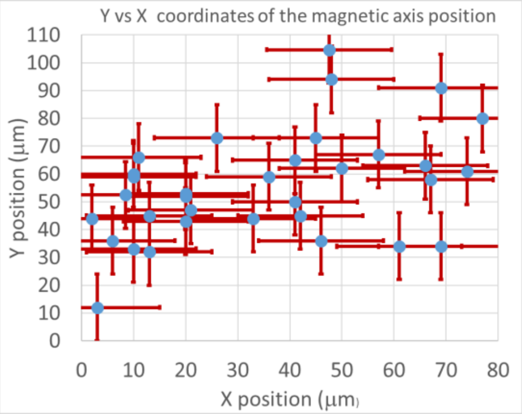
Single magnets Field Strength optimized with the rotating coils

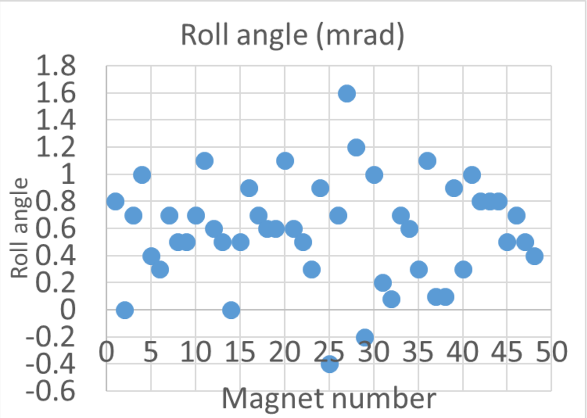


2 mm low C steel shims



Field integral	Before optimization	After optimization
Δ (average) (meas. vs target) (unit)	+ 769	
σ (unit)	26	<2





Strength : 7.7 % above the target value but optimization works (shims, mod.plates)

Field Quality : b_3 and b_4 as high as expected, small skews, stable during production

Roll angles up to 1.6 mrad; large uncertainty of the mag. axis position with the Rot. Coils

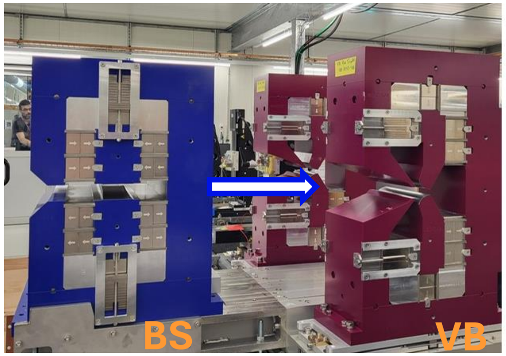
Optimization of the axis position with the moving wire mandatory!

Triplet assembly, alignment and Field Integral tuning

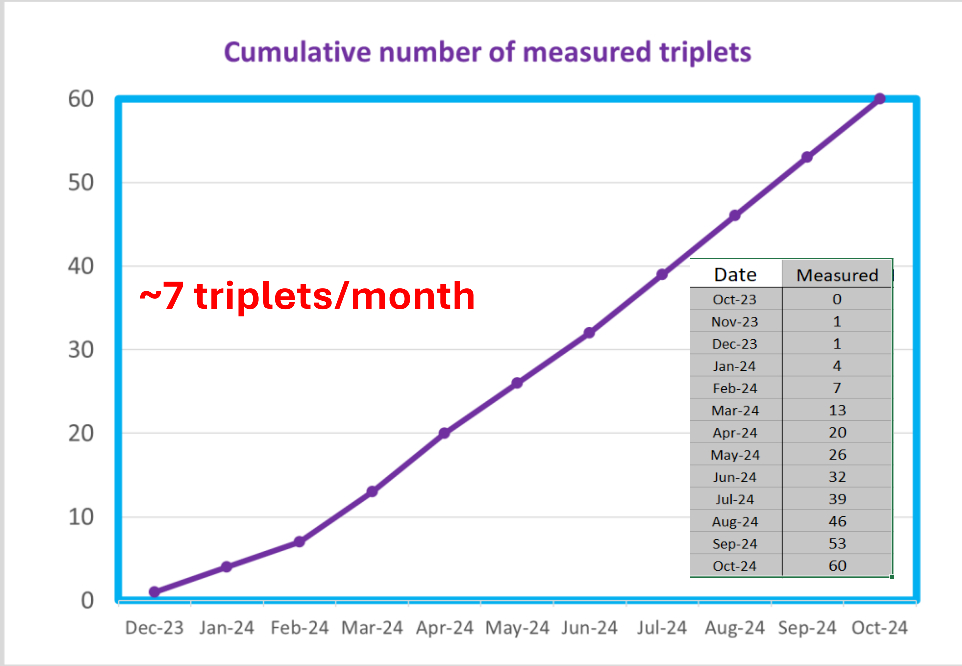
Assembly, Alignment according individual meas.

Final tuning on the whole assembly

VB(X) Mag axis Measurement (x2)



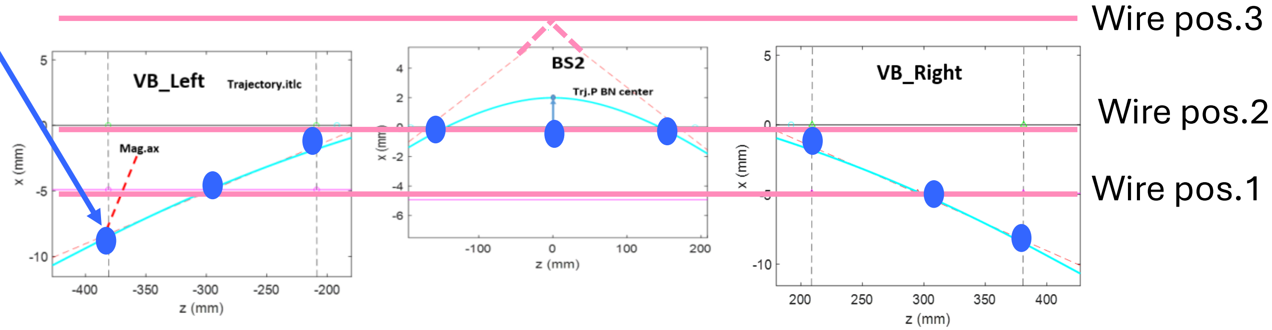
Assembly of the triplet



Date	Measured
Oct-23	0
Nov-23	1
Dec-23	1
Jan-24	4
Feb-24	7
Mar-24	13
Apr-24	20
May-24	26
Jun-24	32
Jul-24	39
Aug-24	46
Sep-24	53
Oct-24	60

Triplet alignment vs. the nominal axes (survey group) + **final tuning**

Mag. axis coordinates



VBs quad strength stronger than computed

up to 60 units (coupling effect under-estimated)

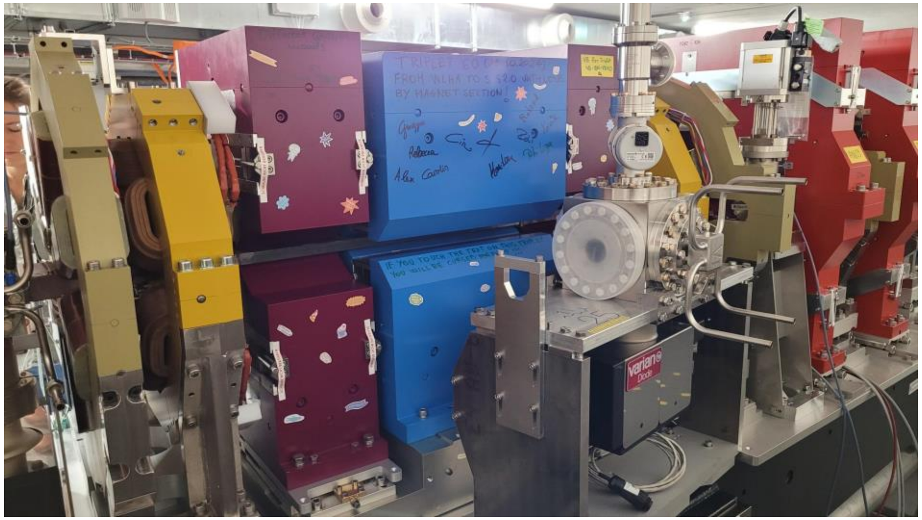
Reduction of the triplet strength with the VBs moderator plates

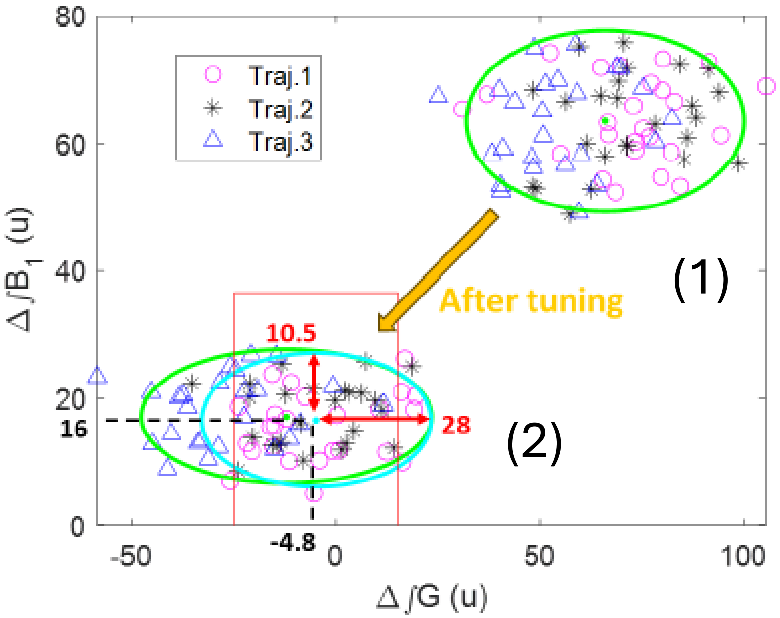
Average measurement rate today : 3 Triplets every 2 weeks

Series measurements in Schedule : Last triplet delivered End of October 2024

Triplets field strength before and after tuning

PSI





(1) : **Single magnet** measurements and assembly on the girder

(2) : After fine tuning with moving wire measurements on the fiducialised **triplets**

Without triplet measurements : error of about 0.5 % in $\int B1dl, \int Gdl$

Measurements on assembled and aligned triplet is mandatory !

Triplet: major difficulties

- Measuring various types of triplets reveal that **each triplet is unique**, making it imperative to follow each step of the process meticulously, especially the **individual assessments of the Vertical Bends (VBs)** in terms of field quality and axis alignment.

- The primary bottleneck is due to the complexities involved with the VBs. The employment of Rotating Coils (RC) and Moving Wire techniques is essential for achieving the target strength value and for determining the magnetic axis (initially RC as starting point and subsequently, moving wire).

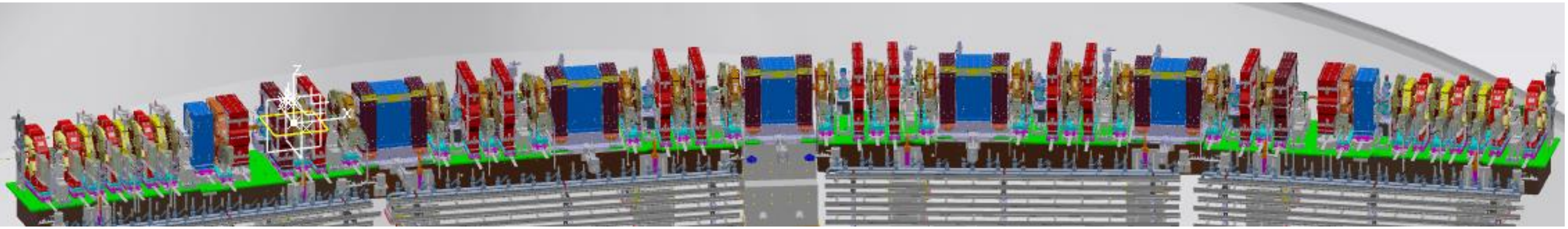
- The quality of the positioning of the BN between the two VBs is crucial →survey group expertise for alignment

- **The computed magnetic coupling effect on the VBs strength was underestimated** : a fine tuning process reduction up to 50 units for integrated field strengths

- Achievable : **uncertainty of 20 units** in the field strength and **3 triplets every two weeks**

- **Last Triplet was measured in schedule: End of October 2024**

Computed magnetic coupling of PM dipoles and quadrupoles with <u>next neighbors</u>



Tuning values for each PM dipoles and Quads

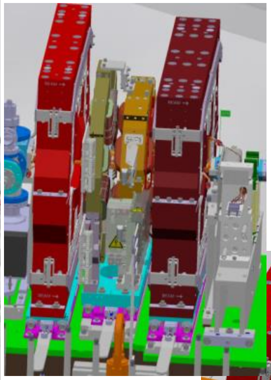
Account for the crosstalk effect **BUT**

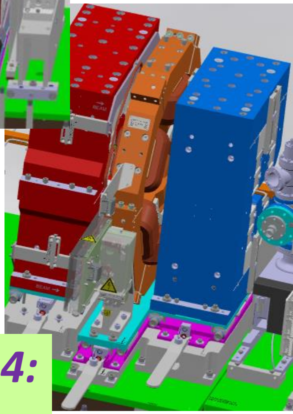
$BH_{curve, simulations}$ ≠ $BH_{curve, real\ magnets}$

⇩

lag. coupling needs to be corrected

		Integrated Field Strength		
Scenario	Magnet sequence	Magnet alone (T or Tm)	Magnet with next neighbors (T or Tm)	Attenuation due to coupling %
1	BEI-SXQ	0.258	0.249	3.83
2	SXQ-BEO	0.253	0.245	3.16
3	ANMI-HS2G-OS2A	11.577	11.313	2.28
4	HS2G-OS2A-ANO1-CHV	8.559	8.293	3.11
5	ANI2-HS2K-OS2E	8.427	8.221	2.44
6	HS2K-OS2E-ANO3-CHV	8.545	8.276	3.15
7	ANI4-H2SK-OS2E	8.482	8.241	2.84
8	HS2K-OS2E-ANO5-CHV	8.548	8.278	3.16
9	ANI6-OS2F-HS2L	8.496	8.253	2.86
10	OS2F-HS2L-ANO7-CHV	8.535	8.262	3.20
11	ANI8-OS2F-HS2L	8.496	8.253	2.86
12	OS2F-HS2L-ANO9-CHV	8.506	8.241	3.12
13	ANI10-OS2B-HS2H	8.466	8.230	2.79
14	OS2B-HS2H-ANMO-CHV	11.680	11.350	2.83
15	VEO-SXQ	9.897	9.723	1.76
16	SXQ-VEI	9.876	9.658	2.21





Computed coupling effect :

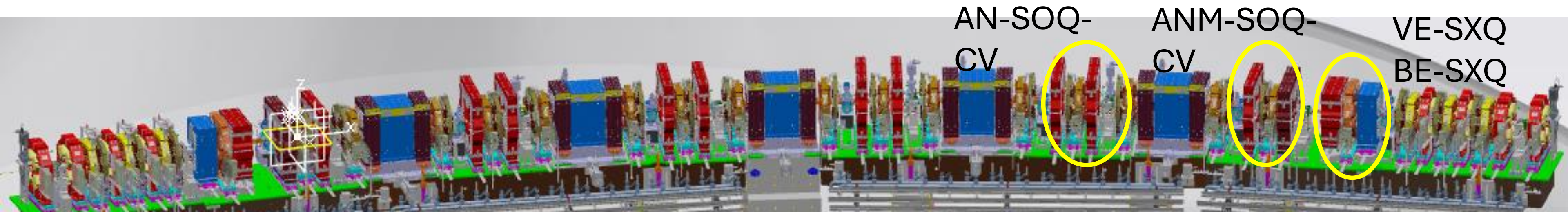
Attenuation of Integrated Field Strength ranging between 2.5-3.9 %

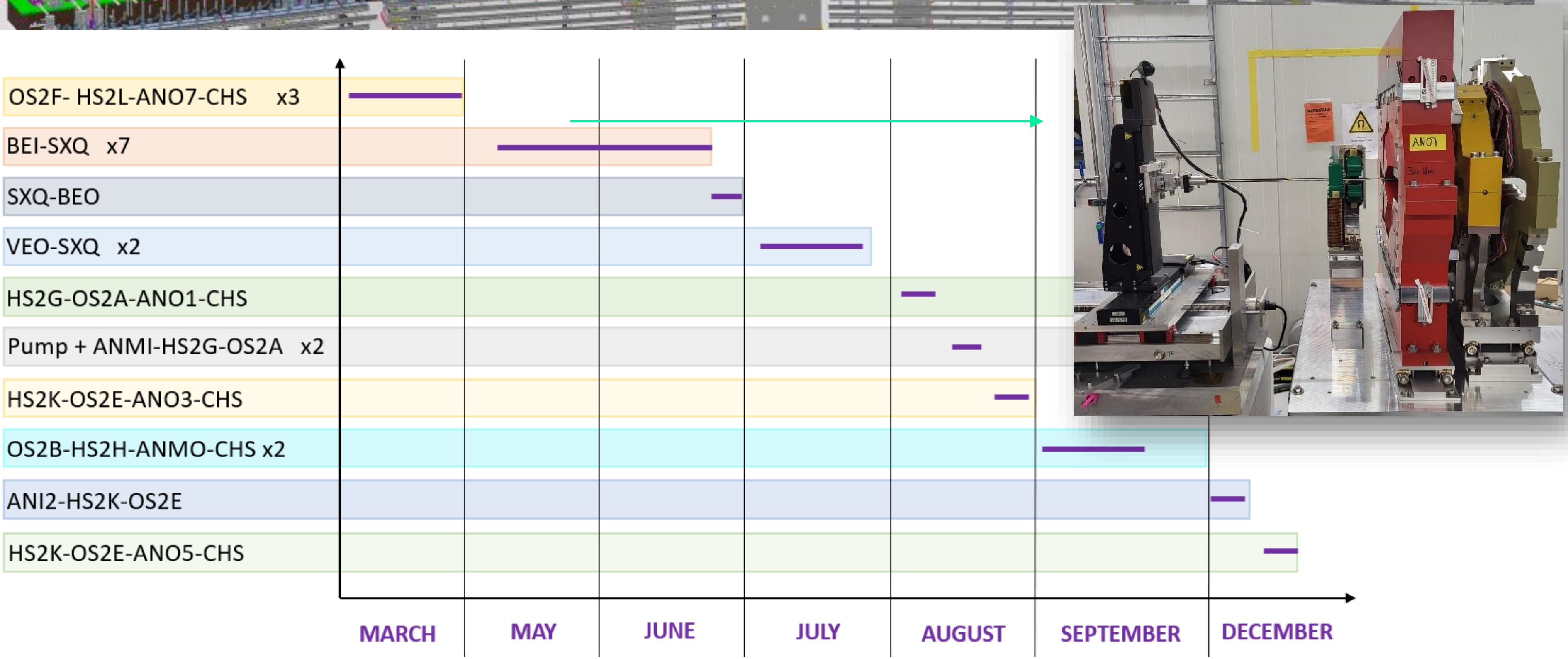
+

Experimental program till December 2024:

- **differences between the computed values and the measurements**
- **Fine tuning of the PM field integral <u>if needed</u> (discrepancies above 20 units)**

Coupling measurements program
October 2023-December 24

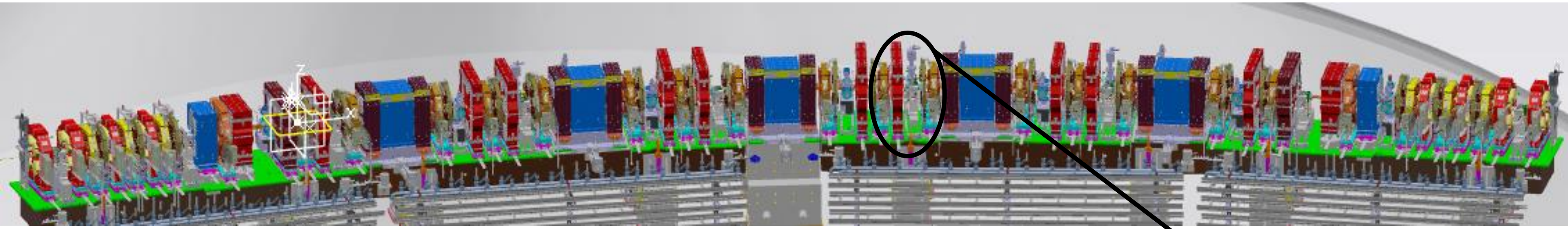




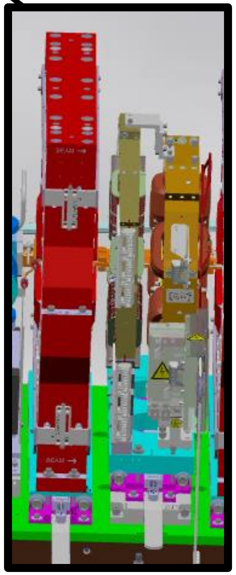
Experimental program during one year and before the closing of the tunnel based on selected critical magnet groups

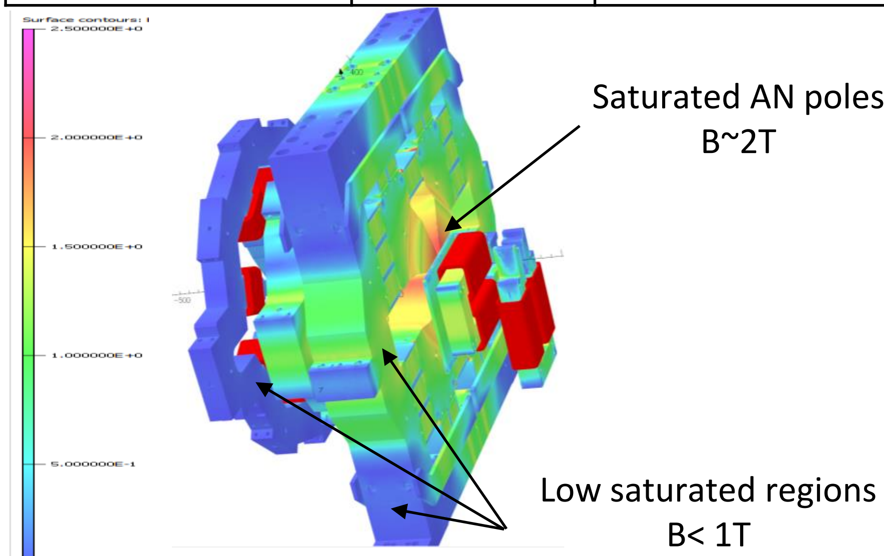
Statistic is performed for selected configurations based on PM type

Coupling measurements – the example of CHV-AN-SOQ
AN=PM quad, SOQ=Sext+Oct,CHV=steerers



AN-Field integral	AN Alone	CHV+AN+SOQ on (28 A, 1.75 A)	Attenuation %
Computed (T)	-10.111	-9.7881	-3.2
Measured (T)	-10.115	-9.7534	-3.6
Δ [units]	**-4**	**40**	



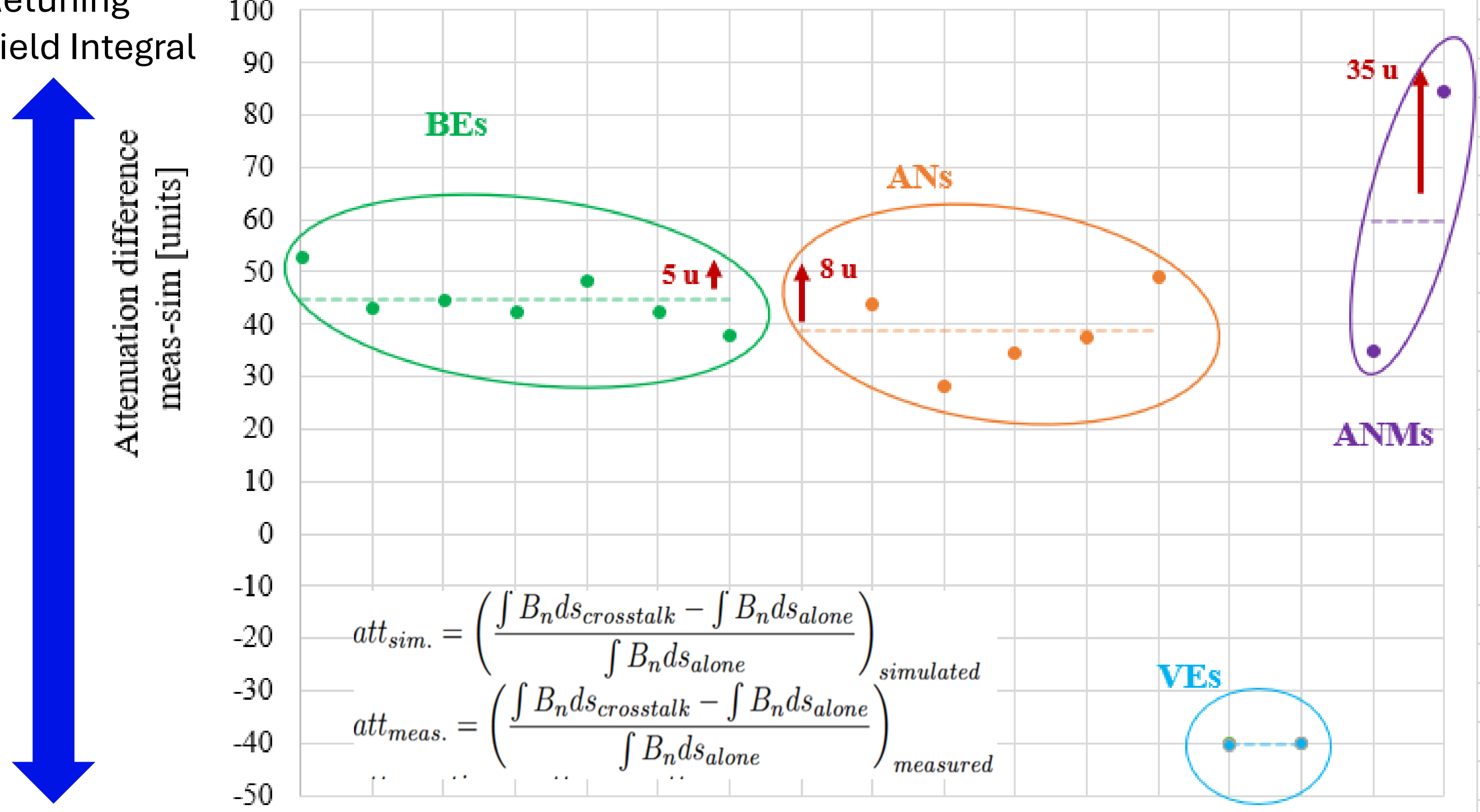


OPERA simulation

AN Quad alone : OK
AN measured with CHV+SOQ : 3.6 % of attenuatio
Calculated effect : 3.2 %
Coupling under-estimated by 40 units (0.4 %)

Coupling measurements – results overview

Retuning
Field Integral



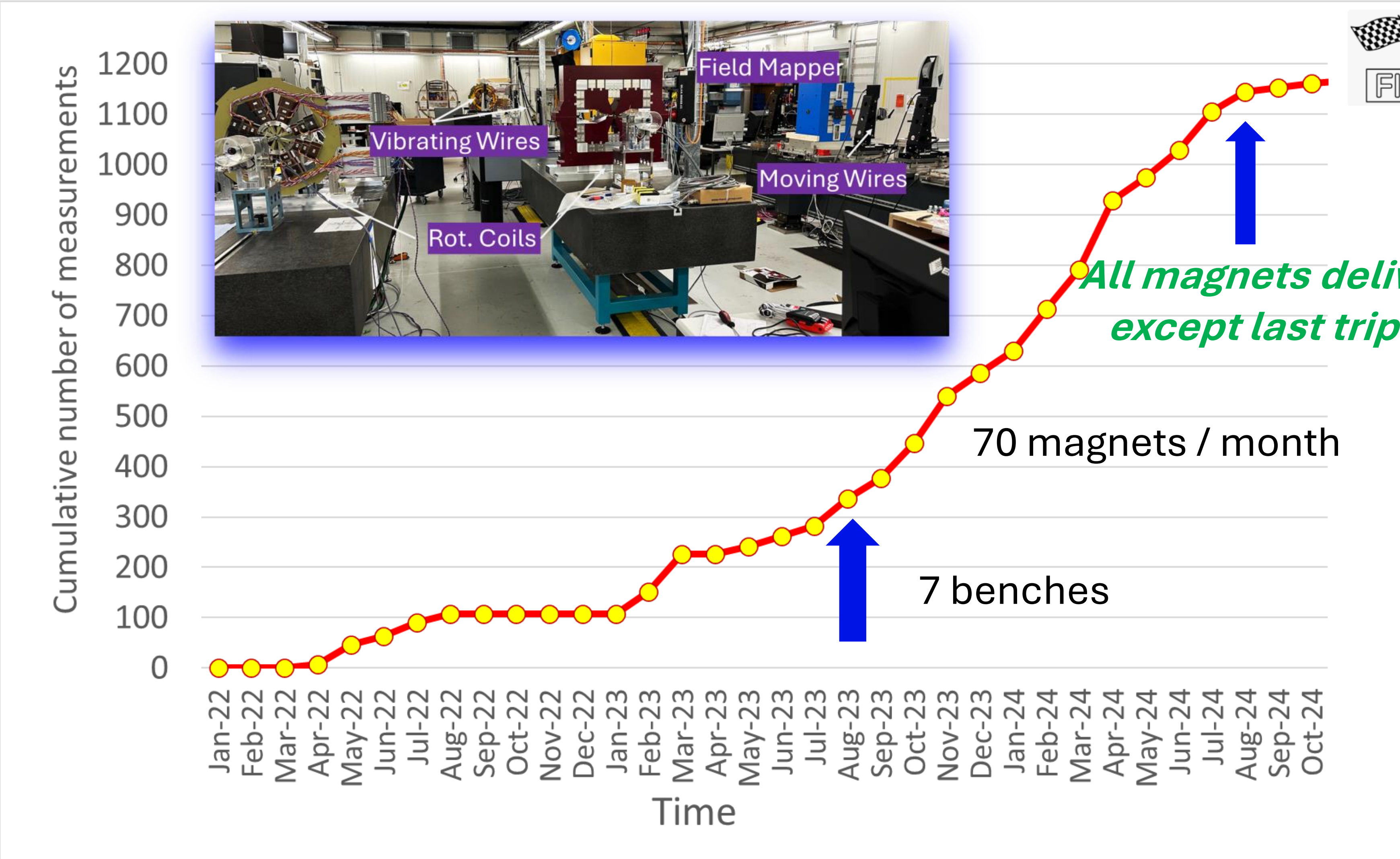
$$att_{sim.} = \left(\frac{\int B_n ds_{crosstalk} - \int B_n ds_{alone}}{\int B_n ds_{alone}} \right)_{simulated}$$

$$att_{meas.} = \left(\frac{\int B_n ds_{crosstalk} - \int B_n ds_{alone}}{\int B_n ds_{alone}} \right)_{measured}$$

All the field integral of permanent magnets retuned in the tunnel to guarantee an uncertainty below 0.1 % required by beam optics
Tuning amplitude ~ 0.5 %

Cumulative magnet measurements
No sleep till October 2024 but……We made it !

PSI



From September 2023 : all the 7 magnetic measurement benches operational
Highest ramp rate : ~70 magnets per week
………Measurements completed end of October 2024

SLS2.0 series measurements: (preliminary) lessons learned

- Characterize all the material used for the fabrication : permeability, hysteresis, also at various temperatures→ minimize discrepancies calculated vs. measured values (specialized companies? Lab consortium?)

- Include in the magnet design phase and the measurement time plan the magnetic coupling measurements of most sensitive sub-sets of machine magnets assemblies

- Perform the commissioning of all the test benches ***with pre-series magnets*** and not during the series

- Do not under-estimate the <u>number of test benches</u>: the magnetic measurement equipment and the delivery plan are coupled with the installation plan in the machine and the complexity of the measurements (upgrade from 5 → 7 benches)

- Include the impact of neighboring magnetic components in the field integral tunning

- Careful follow up of the logistics (assembly pieces, thermal shunts, moderator plates…) and the safety issues

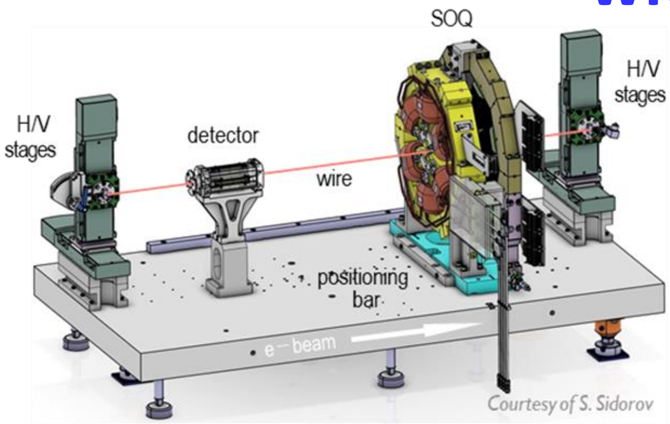
Key elements for a successful mass production testing

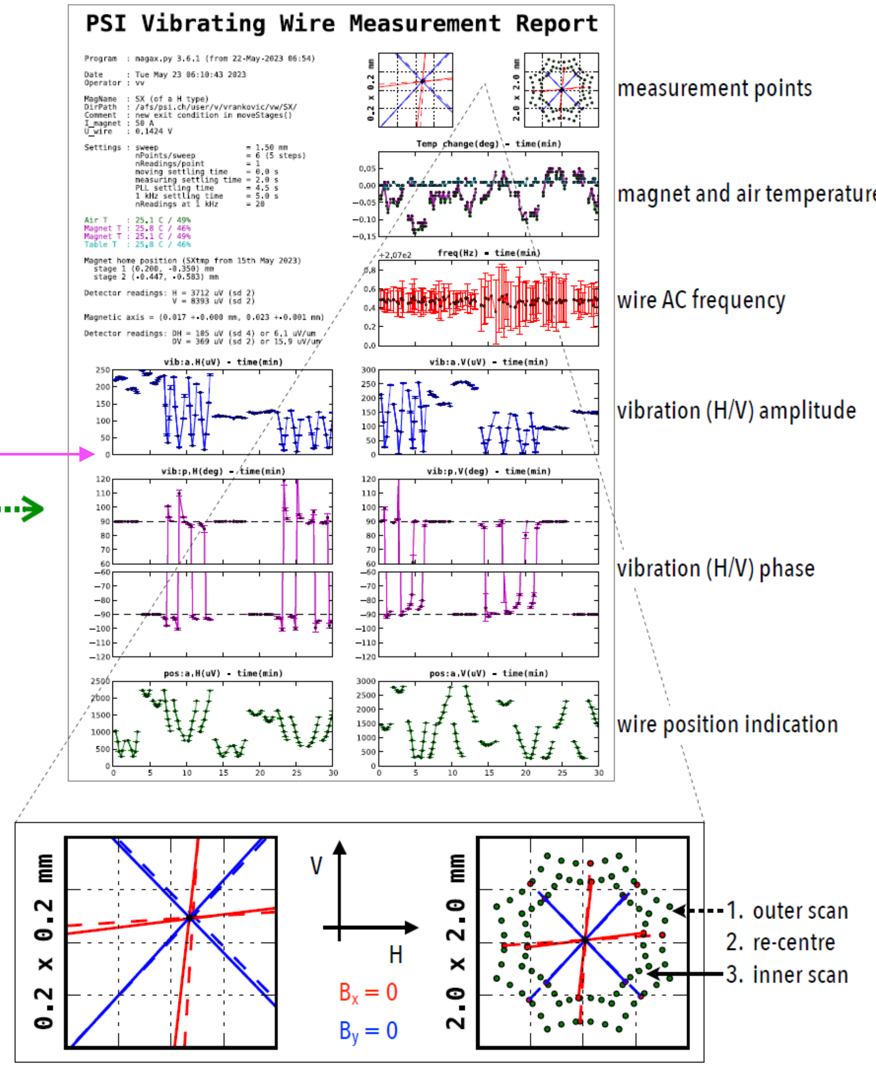
- Successful design and modeling phase of each magnet including the magnetic coupling and various operating scenarios.
- Efficient tendering process to select competent and reliable manufacturers
- Adaptative management strategy to prioritize the type of tested magnets
- The financial support from the management line for a sufficient test benches number and the staff to operate them.
- Competent team leaders to produce measurements protocols and train the measurement teams
- Close collaboration between expert teams (power supply, beam optic…) to analyse and give a rapid feedback on the measurement results


Thank you for your attention

Supplementary Slides

SOQ : magnetic axis alignment with the vibrating wire





|error| < 2 μm

MEASUREMENT PROCEDURE:

➞ SOQ on the measurement bench positioning bar

➞ determine the sextupole magnetic axis

➞ determine the octupole magnetic axis (through auxiliary quad excitation)

➞ adjust the sextupole vertically (V) if magnetic axes misalignment >30 μm

repeat until <30 μm is achieved

➞ adjust the octupole horizontal (H) position to align to the sextupole magnetic axis

➞ fasten the sextupole-octupole fixing bracket

➞ verify the sextupole and octupole magnetic axes (with octupole quad and skew-quad functions)

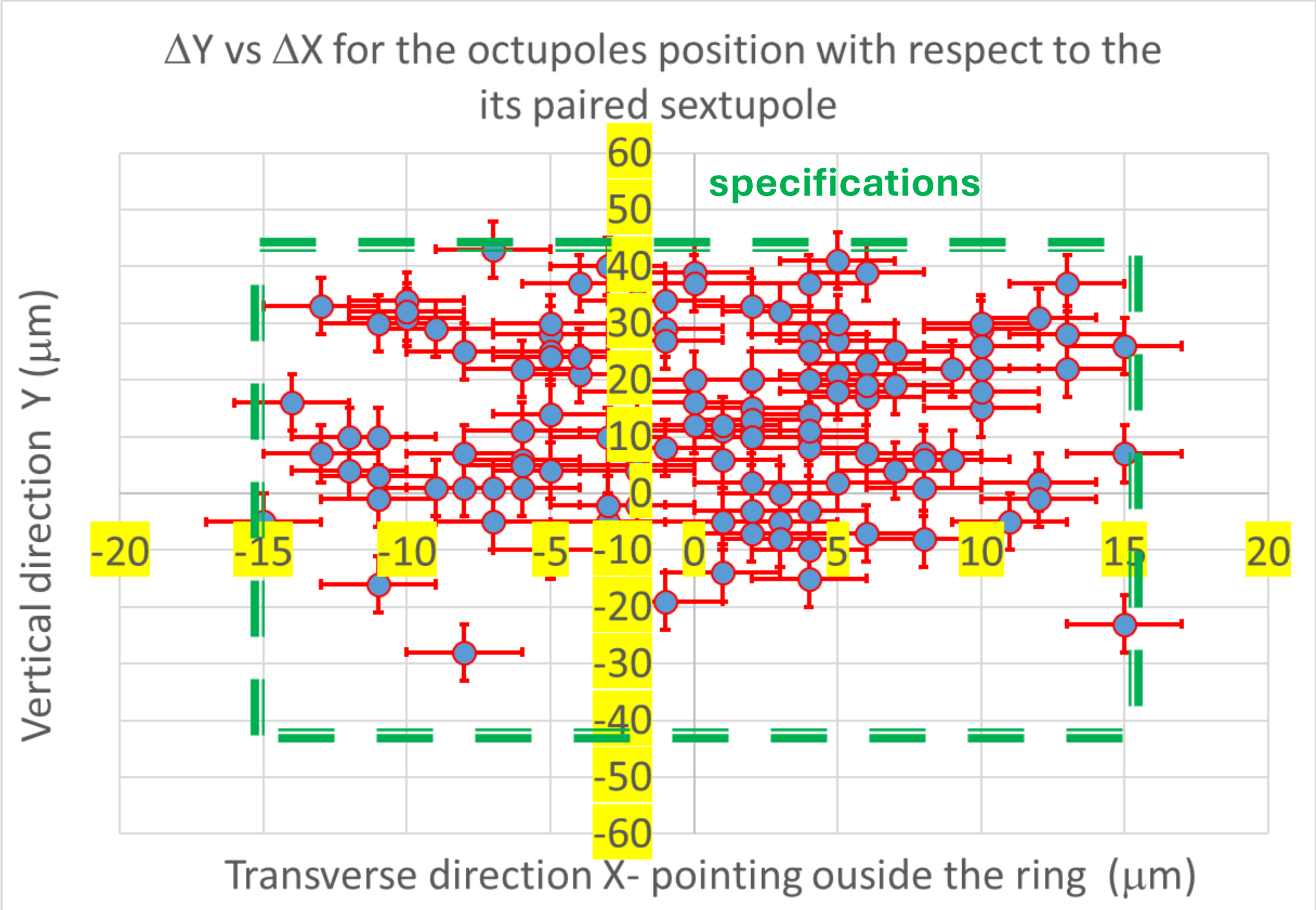
➞ laser tracker fiducialisation

First results Δ MECH-MAG successful on two SX: within 30 um (as expected)

SOQ axis

Position of the octupole with its paired sextupole

PSI



Repeteability : 2/5 μm in X/Y

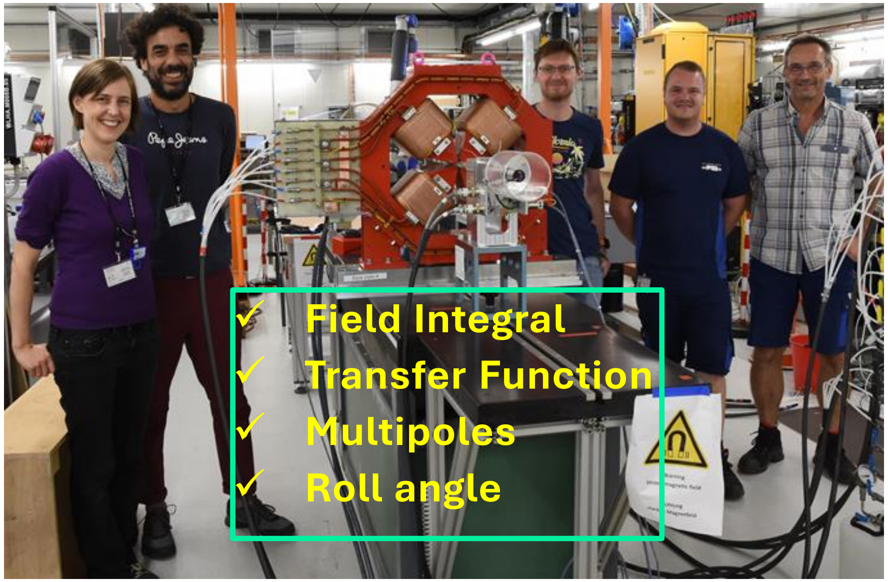
The SOQ magnetic axis measurement process allows to align the octupole with its paired sextupole inside the tolerances (+/- 015; +/-45 μm)

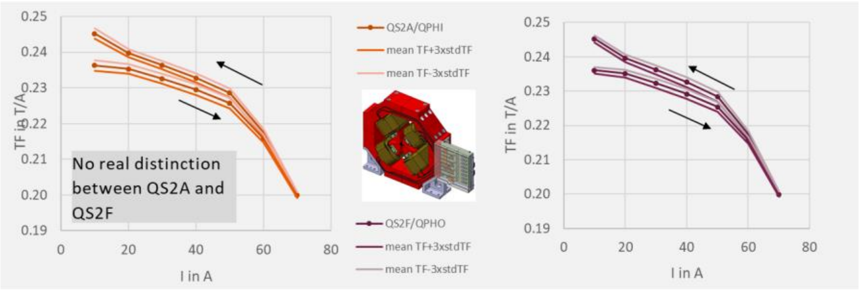
Meet the specifications

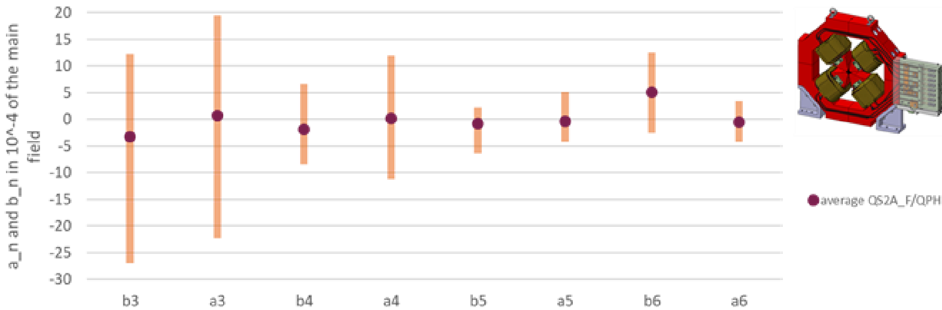
Magnetic measurements
Electroquadrupoles QP, QPH

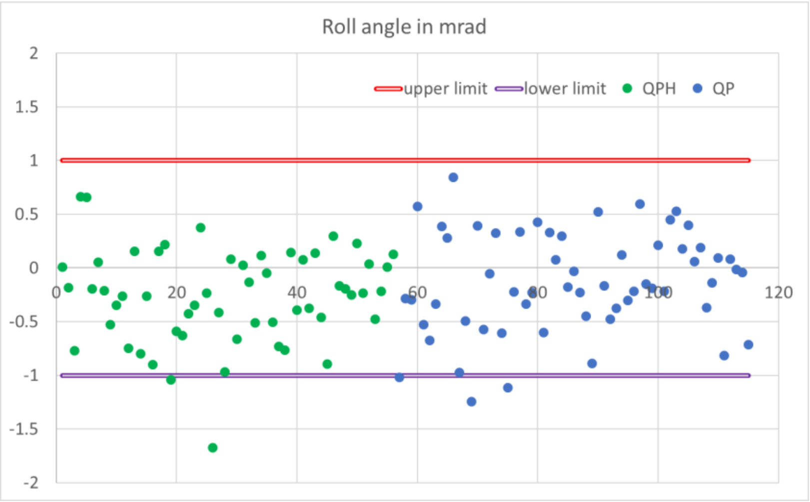
08.22

115 electro-quadrupoles delivered & measured with rotating coils







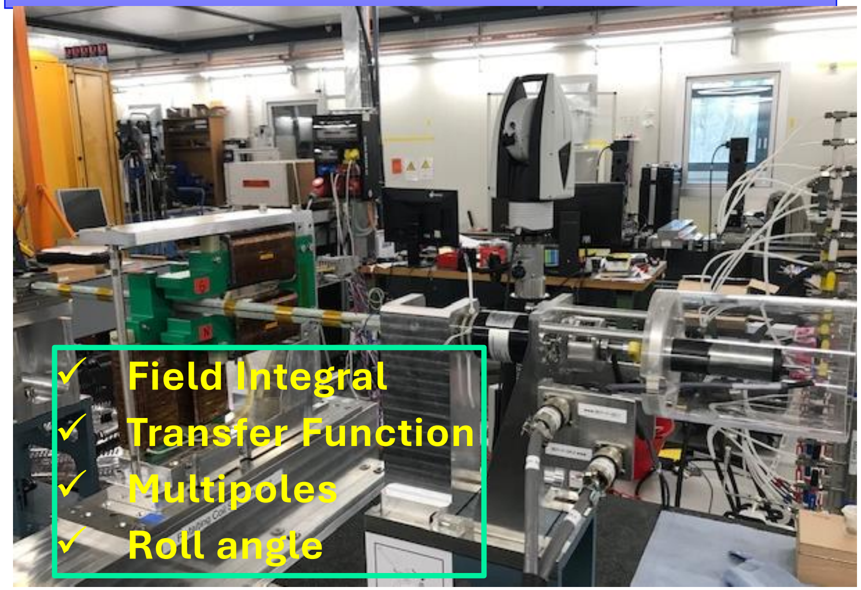


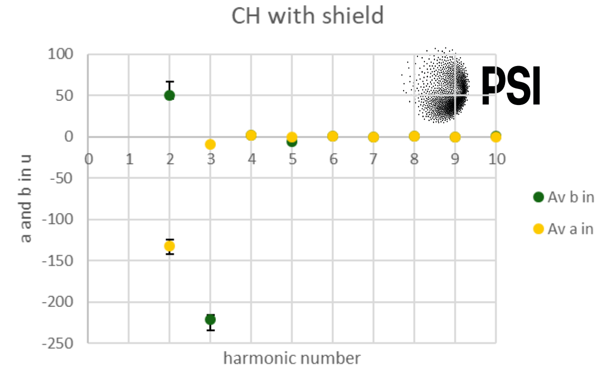
- Field integrals with comfortable margin above the nominal values (3-4 %-designed for +3%) spread 0.15 % - 0.2% (at 70 A)
- Multipoles below the 20 units
- Roll angles below 1 mrad- few outliners

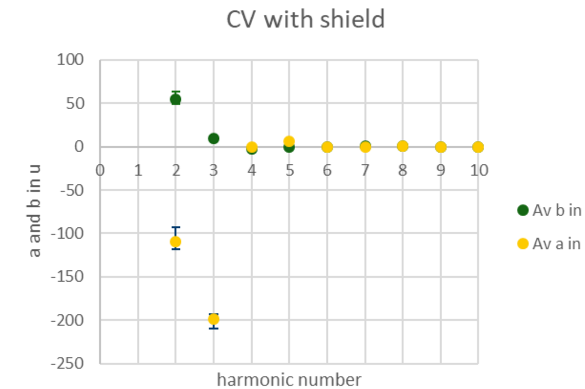
Magnetic measurements steerers

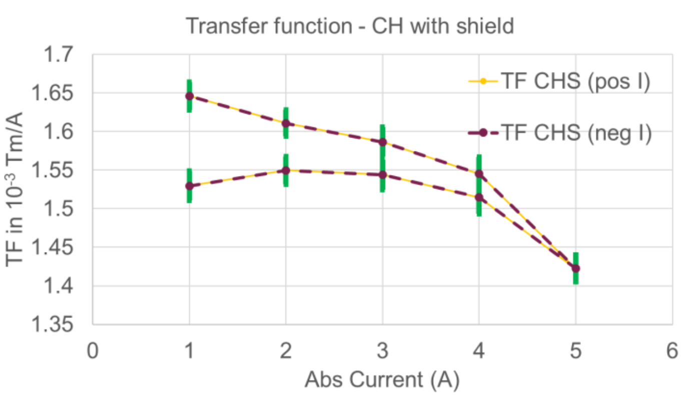
117 Steerer magnets measured

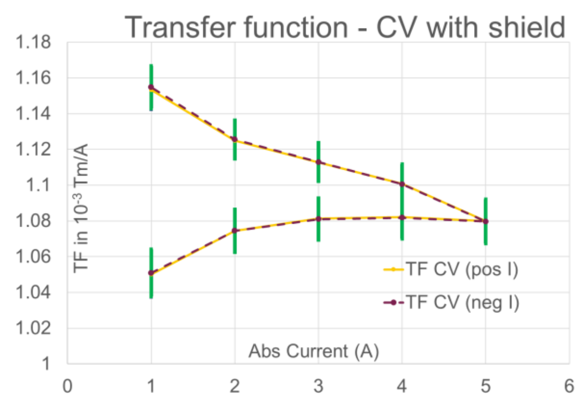
04.23

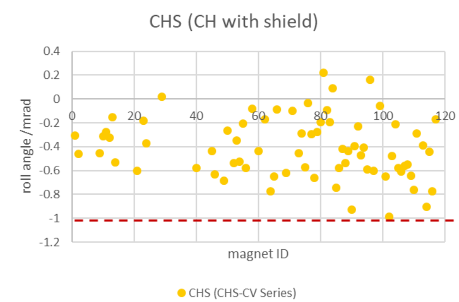


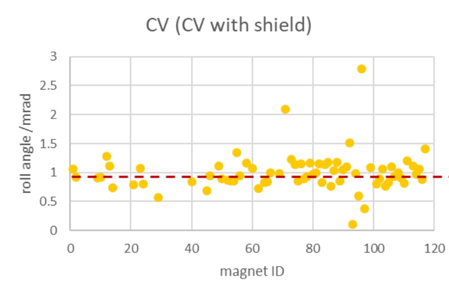












- Vertical steering & Horizontal steering strength : OK;
- Multipoles : OK , sextupole between 200 and 250 units
- Roll angles between +/-1 mrad- few outliners