PAUL SCHERRER INSTITUT
PSI

Ciro Calzolaio on behalf of the Magnet Section :: Paul Scherrer Institut

PSI experience on design and measurements of series PM Magnets for the upgrade of the Swiss Light Source

Low Emittance Ring - Permanent Magnets Workshop

Elettra Sincrotrone Trieste
1993 - 2023 | 30 years of light

Outline

- The SLS2.0 project

- Status: Magnet production & magnetic measurements-phase 1

- Review and outlook

Upgrade of the SLS - SLS2.0

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

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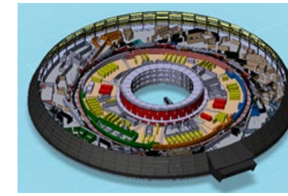
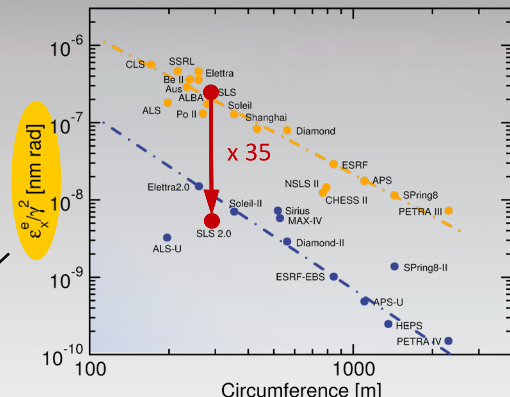


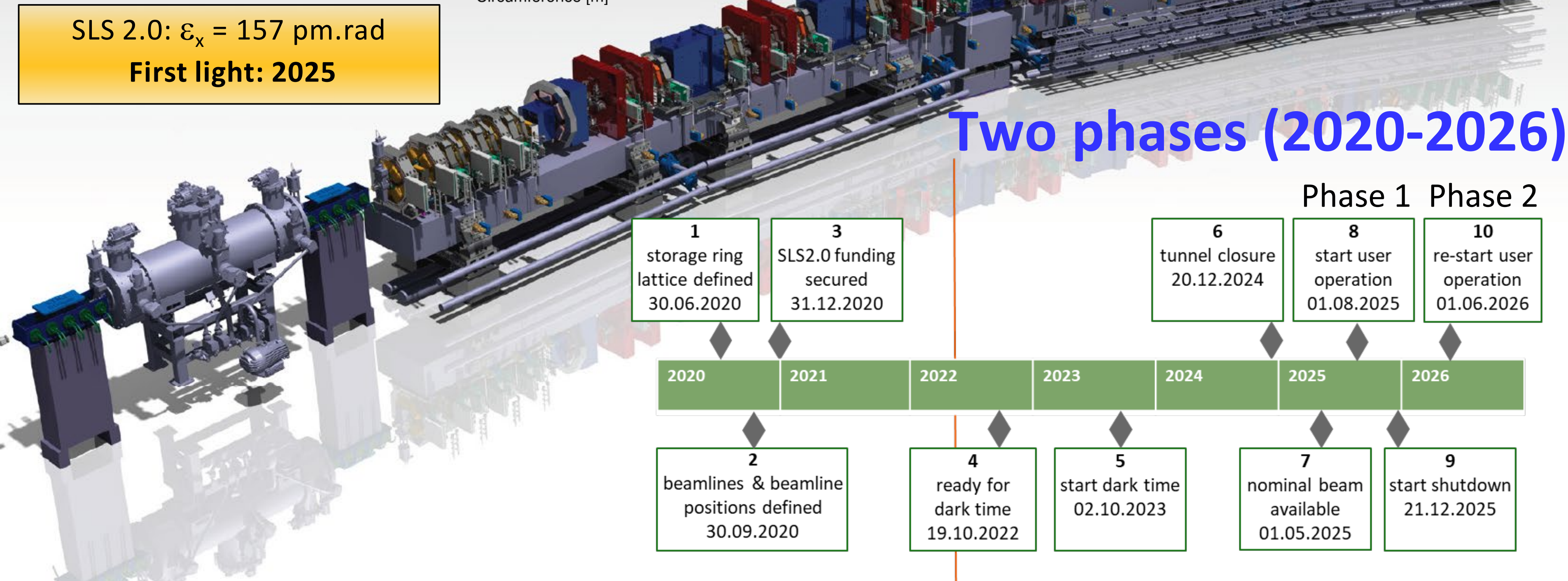


$$\mathcal{B} = \frac{\text{flux}}{\text{emittance}}$$

Brilliance

SLS 2.0: ε_x = 157 pm.rad

First light: 2025



Two phases (2020-2026)

Phase 1 Phase 2

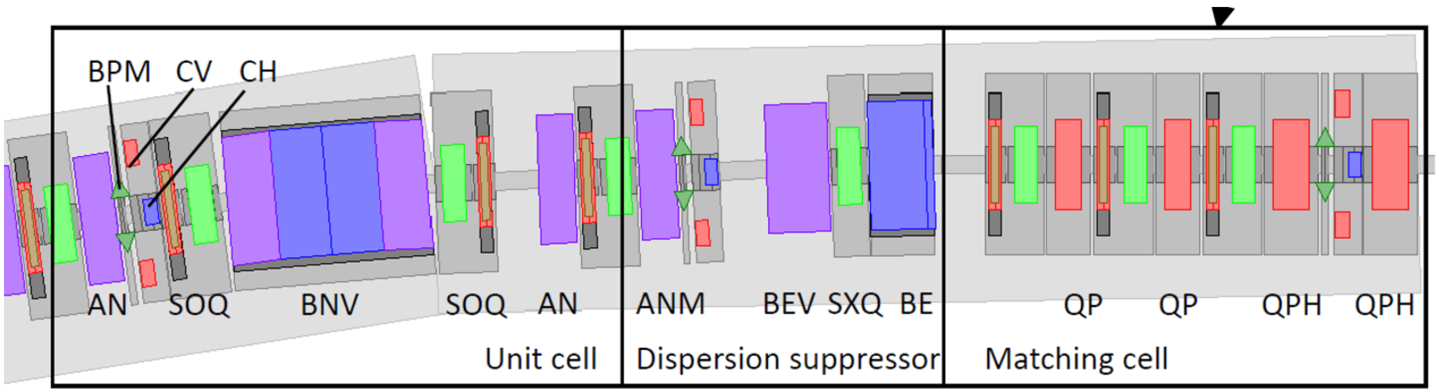
1	storage ring lattice defined	30.06.2020
2	beamlines & beamline positions defined	30.09.2020
3	SLS2.0 funding secured	31.12.2020
4	ready for dark time	19.10.2022
5	start dark time	02.10.2023
6	tunnel closure	20.12.2024
7	nominal beam available	01.05.2025
8	start user operation	01.08.2025
9	start shutdown	21.12.2025
10	re-start user operation	01.06.2026

2020 2021 2022 2023 2024 2025 2026

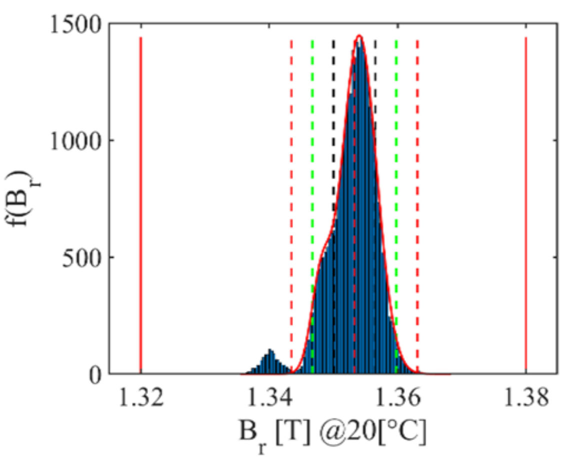
12.4.2022

Tight Schedule

Magnet list 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

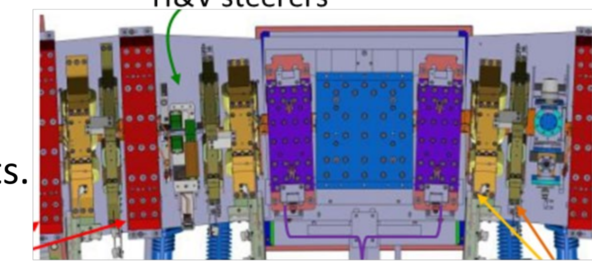
QP	55	Quad
QPH	53	Quad
SXQ	24	6-Poles
SX	264	6-Poles
OC	264	8-poles
	SOQ	264
CHV	112	Steering
	Total: 780	

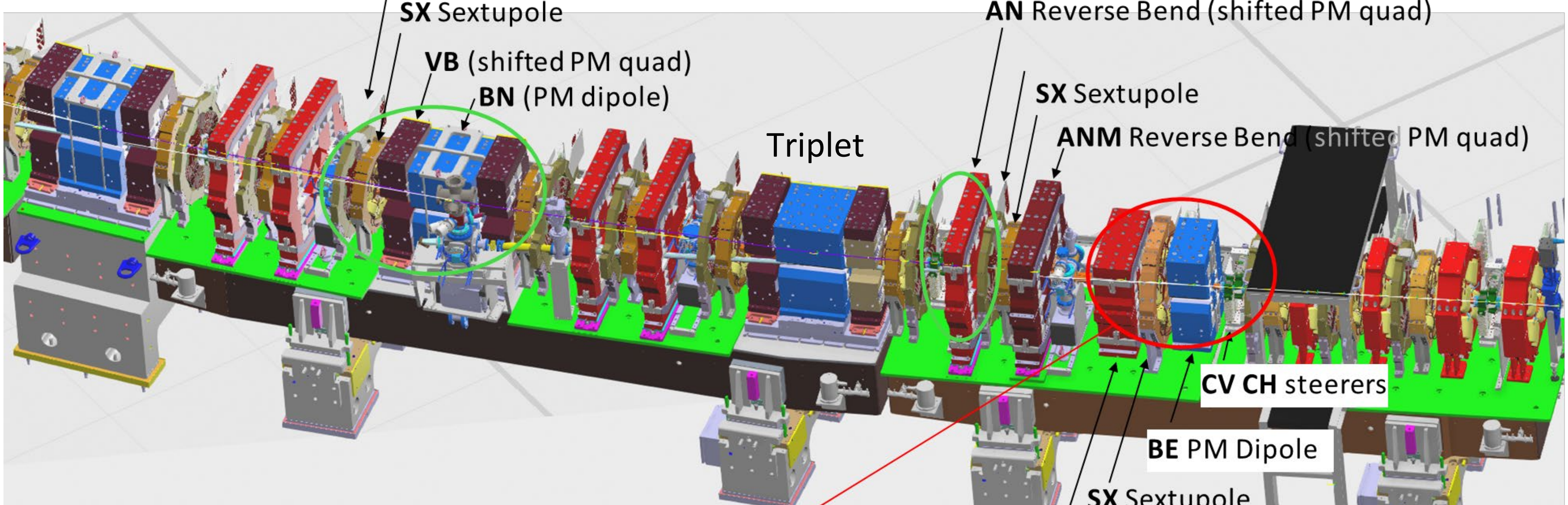
1152 + two 5 T superconducting superbends (phase 2)

SLS2.0 magnets : the challenges

- High field and gradients (>1T).
- **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 issues).
- Tight schedule for the design, the production and the measurements.

Lack of space !





SLS2.0 magnets : the production path

In House | Supplier | In House

Electromagnets

Design + CAD specifications → Magnets manufactured by the supplier → Reception tests & Prototypes & & 100 % magnetic qualifications at PSI

Permanent Magnets (NdFeB)

Specifications for → NdFeB blocks produced and measured by the supplier → few % cross check (Helmholtz)

NdFeB blocks produced and measured by the supplier → Prototypes & 100 % magnet assembly at PSI

Design + CAD+ specifications → Iron yoke, thermal shunts manufactured by suppliers → Prototypes & 100 % magnet assembly at PSI

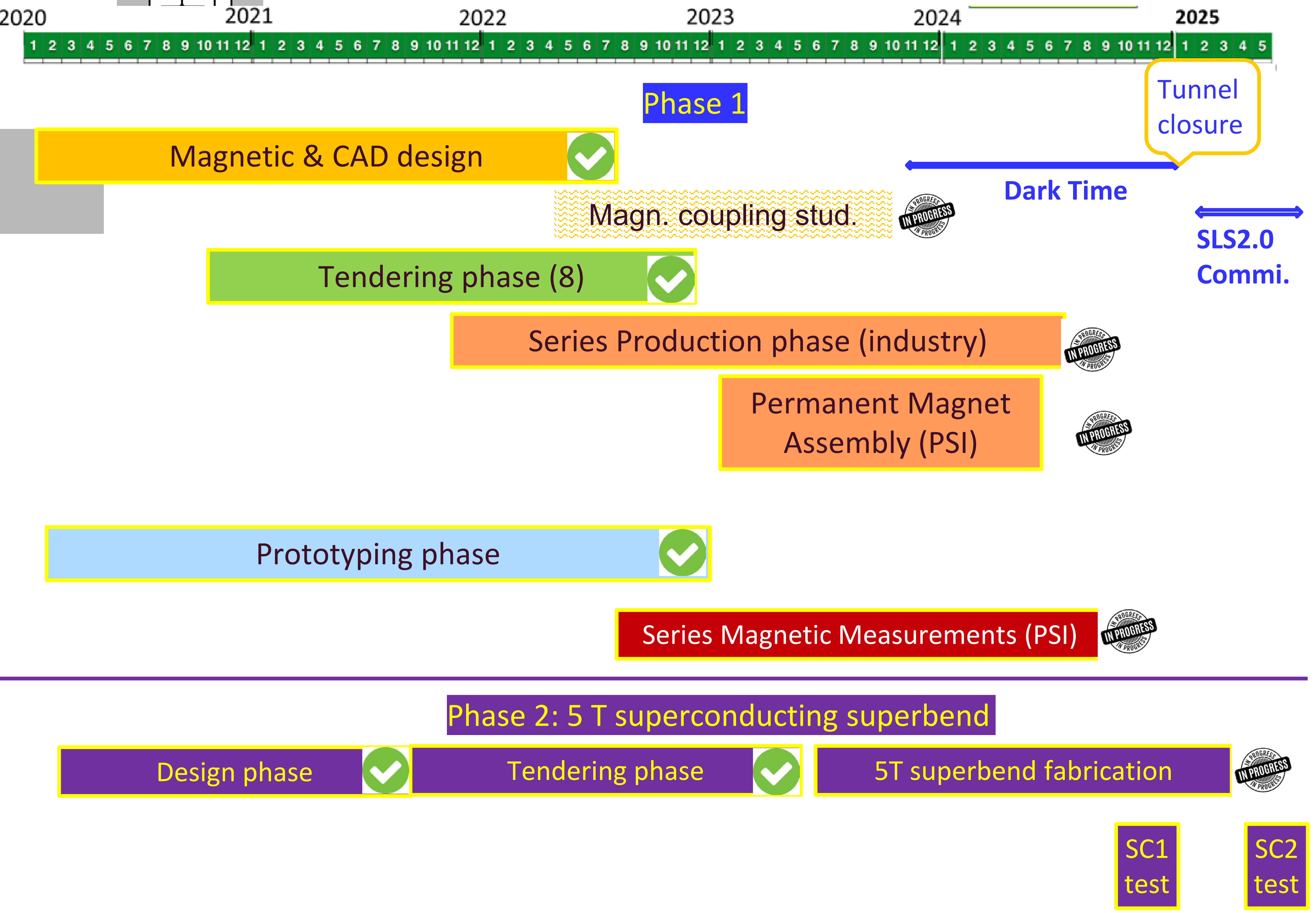
Prototypes & 100 % magnet assembly at PSI → 100 % Magnetic qualifications at PSI

5 T superbends

Design + specifications → Magnets manufactured by the supplier → Power tests at 4.2 K and magnetic tests at PSI

100 % of Permanent Magnets assembly in house
100 % of magnets magnetically measured at PSI

Magnet development Overview (Phase 1+2)

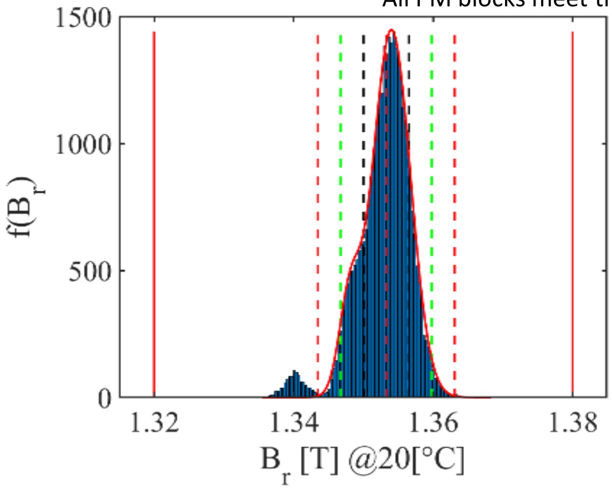


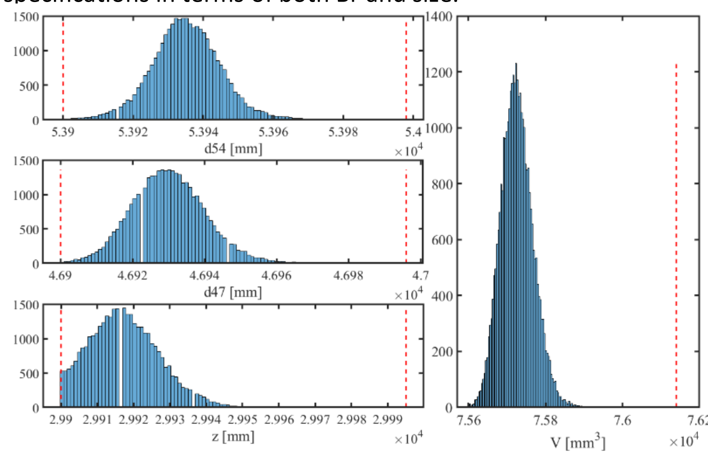
Delivery : permanent magnet blocks

All the permanent magnet blocks were delivered at PSI (34000)

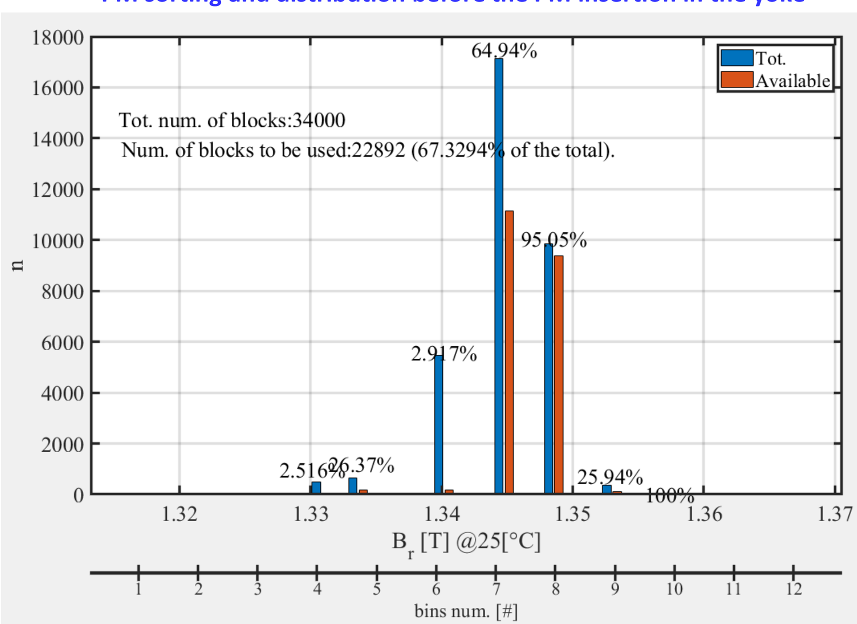
Material: N45SH, H_{cj}=1592 kA/m, $B_{r,\ nominal}$=1.35 T at 20°C.

All PM blocks meet the specifications in terms of both Br and size.

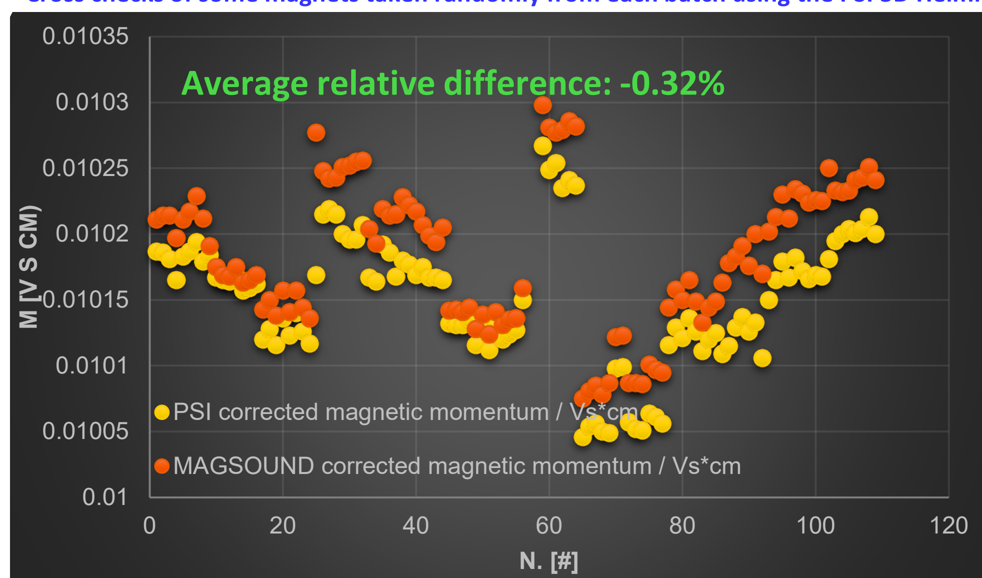




PM sorting and distribution before the PM insertion in the yoke



Cross checks of some magnets taken randomly from each batch using the PSI 3D Helmholtz



NiFe thermal shunts

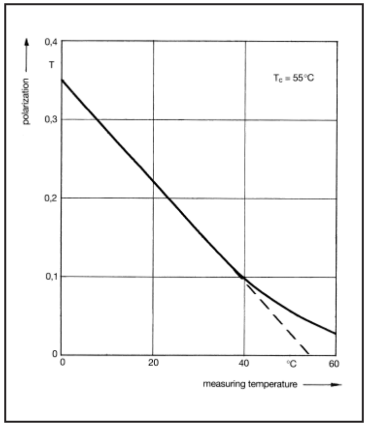


Fig. 12: Polarization Temperature Curve of THERMOFLUX 55/100 G

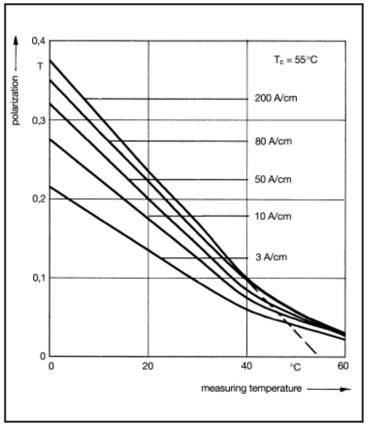
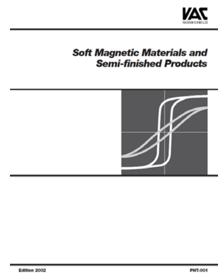
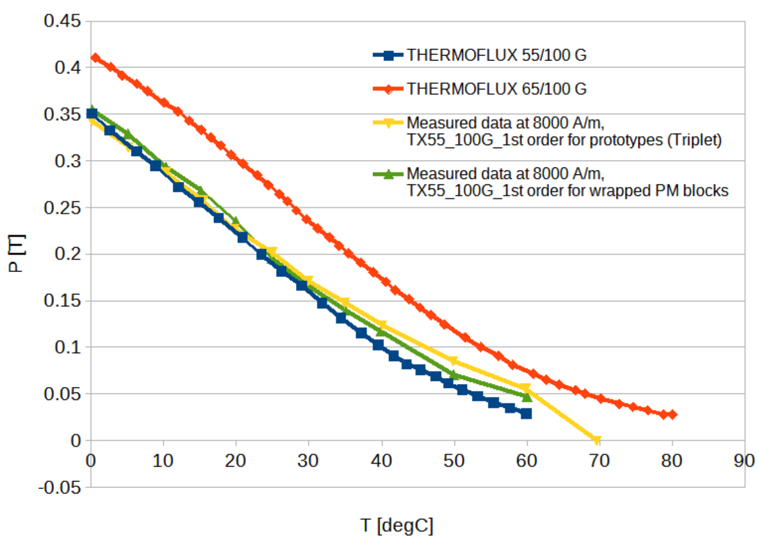
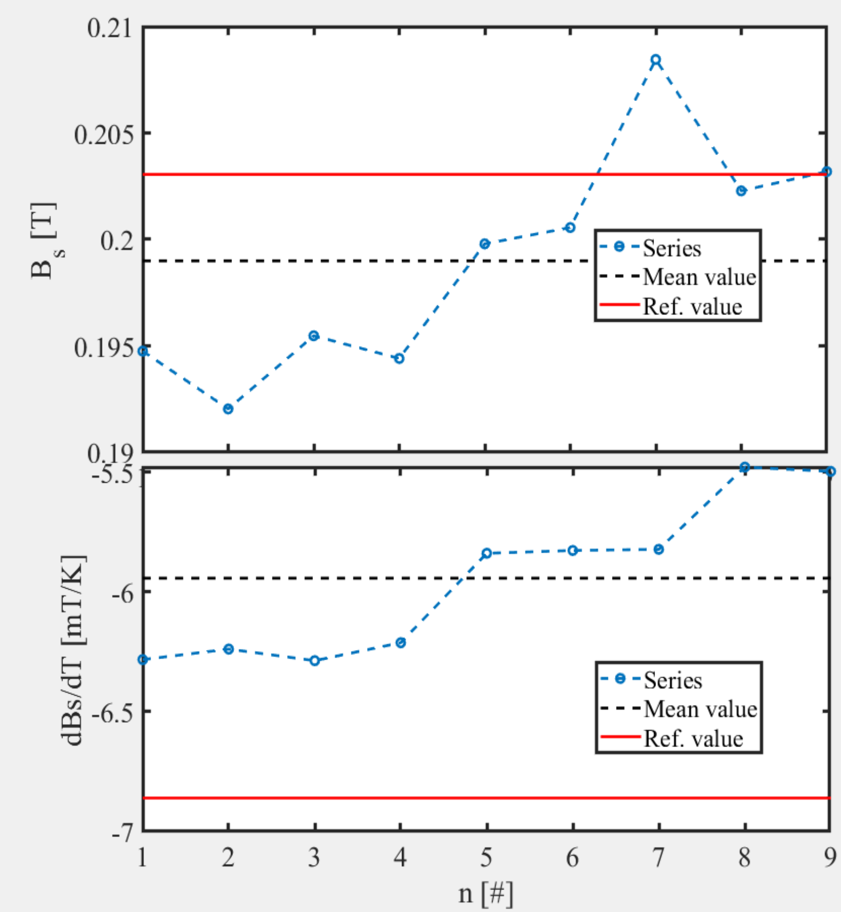


Fig. 13: Polarization Temperature Curves of THERMOFLUX 55/100 G as a Function of Field Strength (f = 50 Hz)



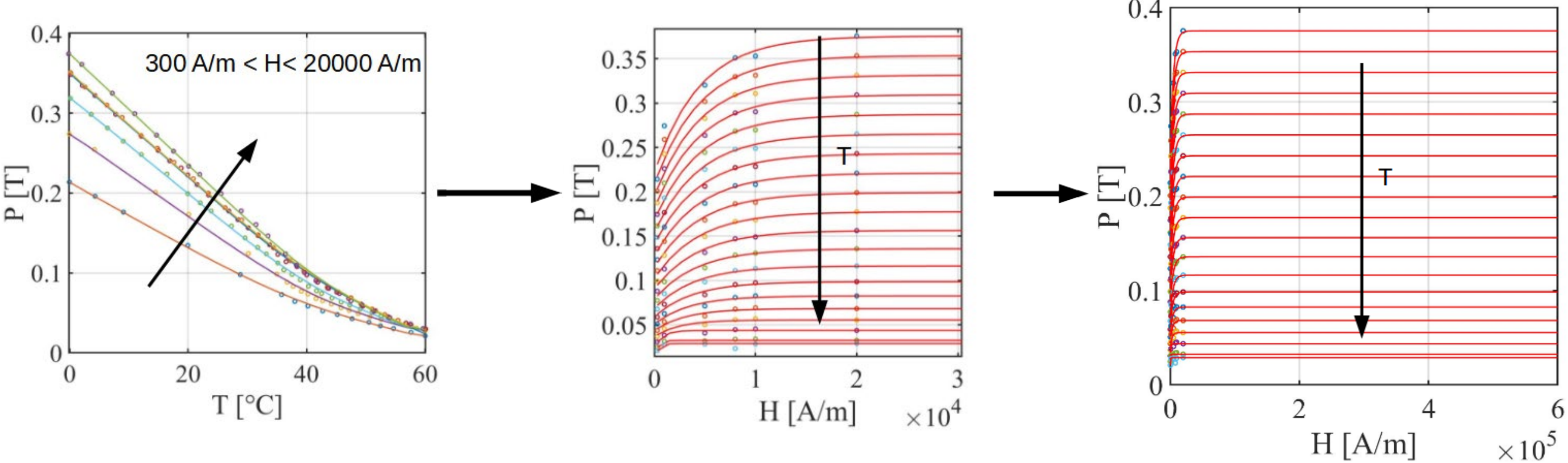




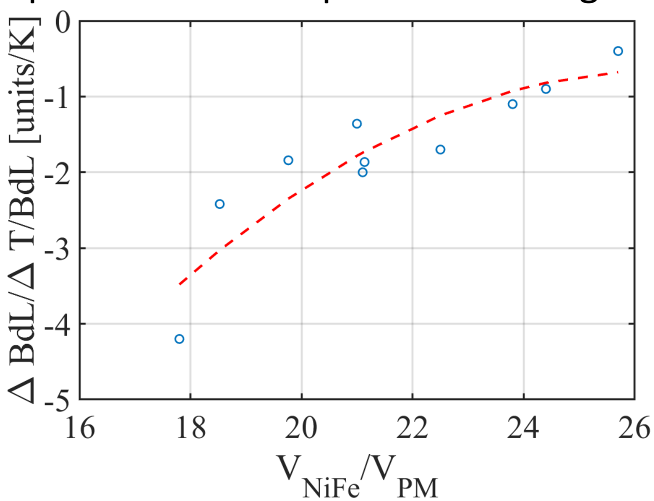
NiFe thermal shunts

$$\vec{B} = \mu_0 \mu_r(T, H)\vec{H} = \mu_0 \vec{H} + \vec{P}(T, H)$$

$$P(H) = B_s(T) \cdot (1 - ae^{-bH})$$



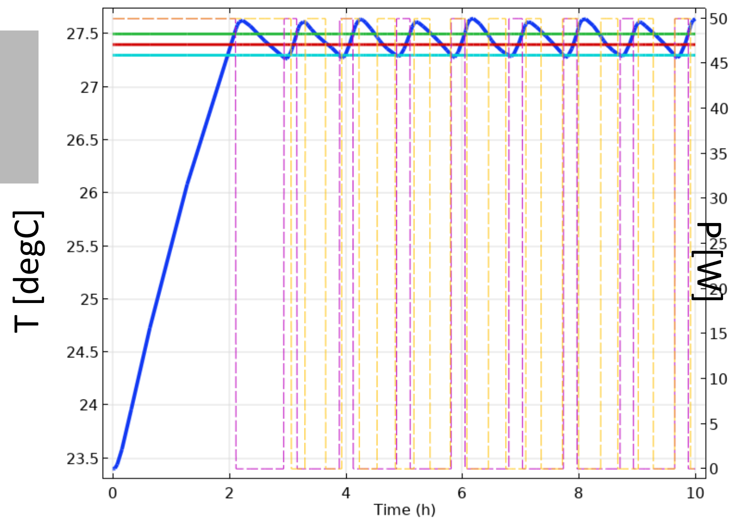
The temperature in the tunnel won't be uniform: we try to minimize as much as possible the temperature dependence of the permanent magnets. Goal: d $\int Bdl$ /dT/$\int Bdl_{ref}$ ≈ -1 units/K.

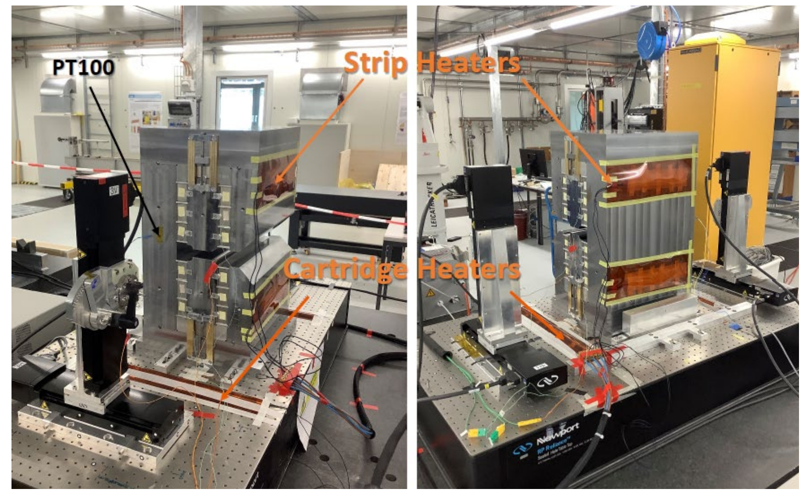


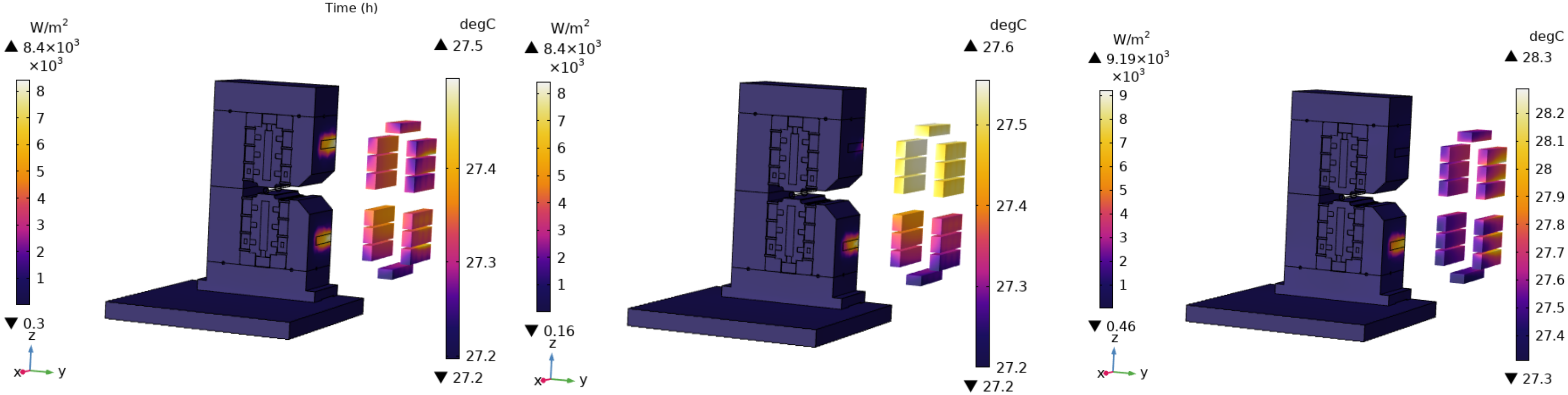
Temperature derivative of the field integral against the volume ratio of NiFe and PM in the magnet, normalized wrt nominal field. The data points have been calculated and measured for different types of magnets.

Test of BN magnet

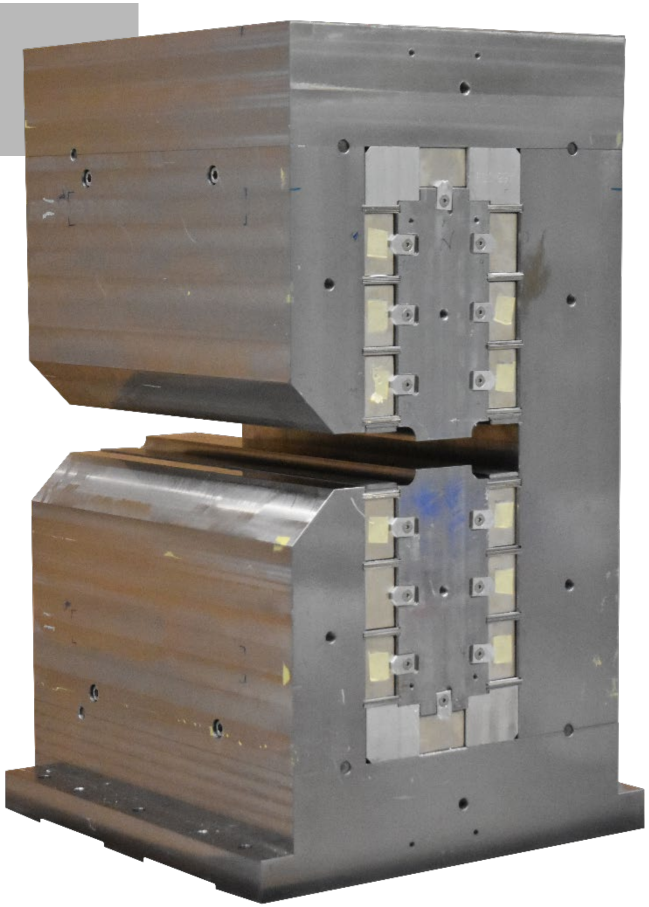
BN Prototype



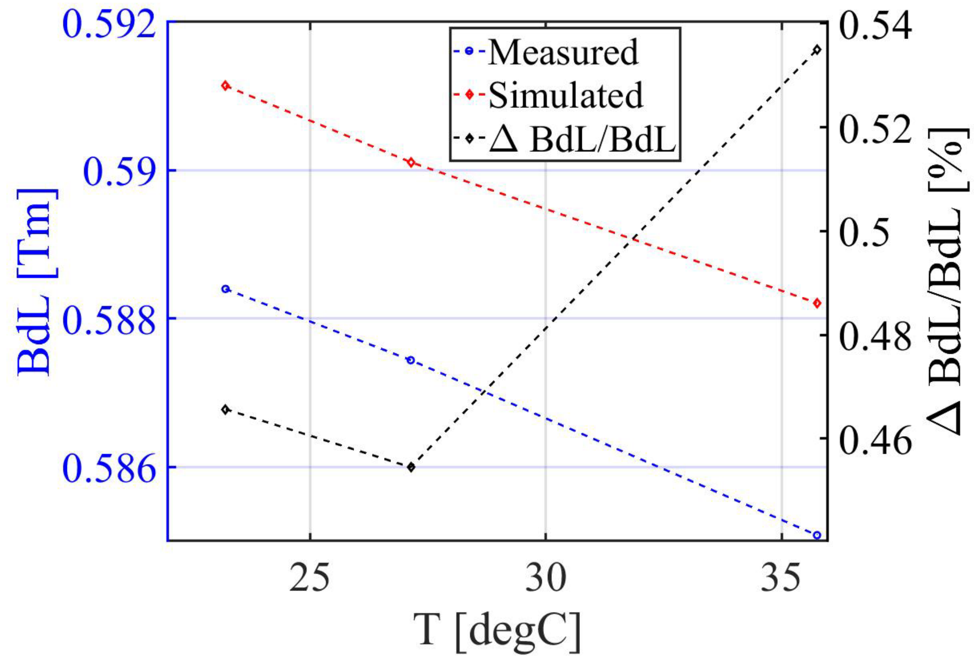




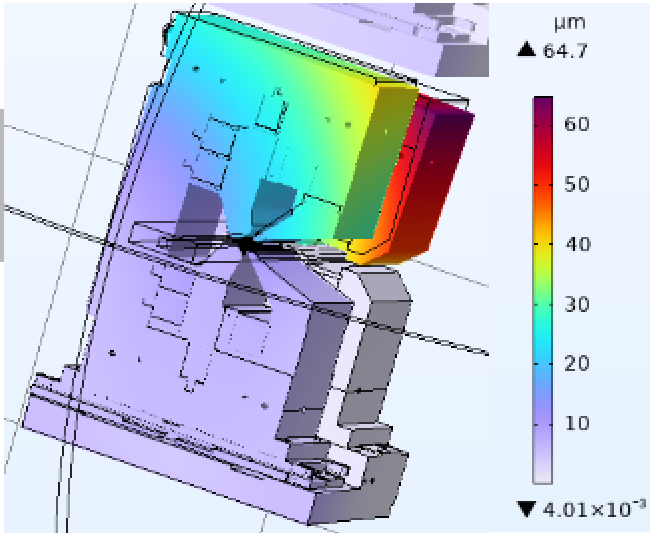
Test of BN magnet

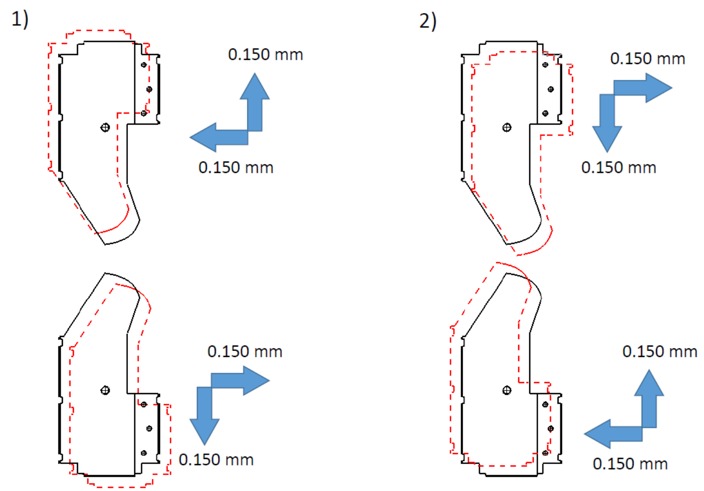


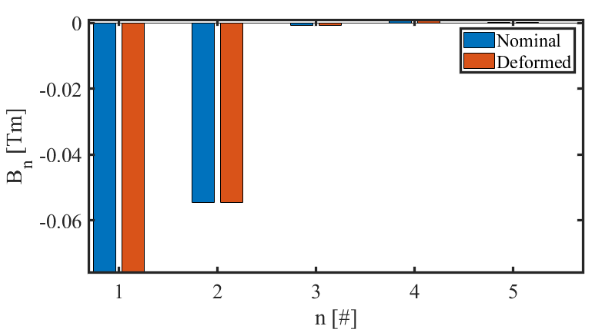
BN Prototype

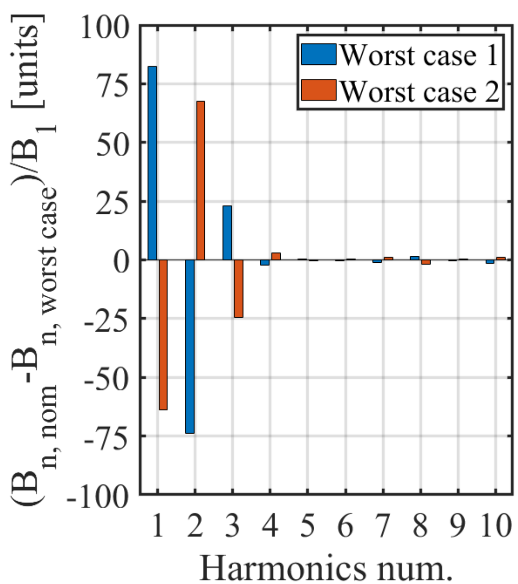


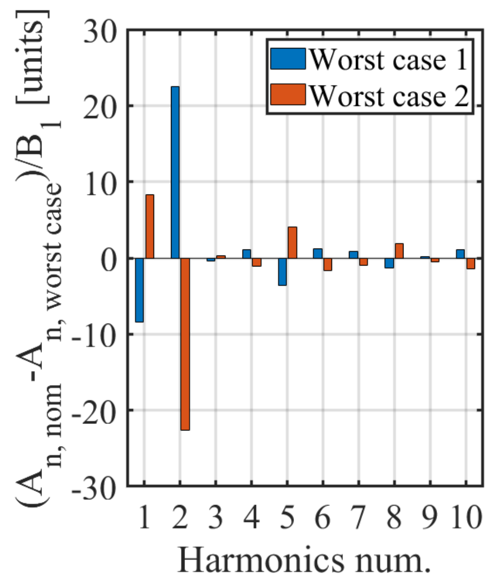
Mechanical deformation & tolerances

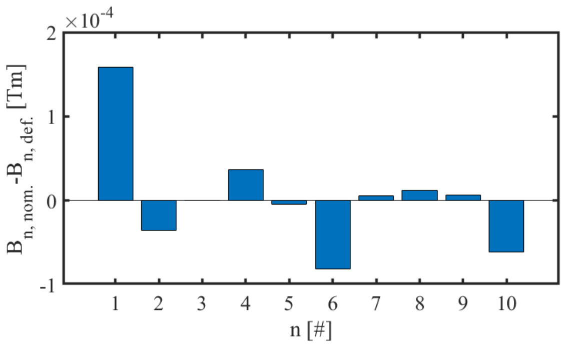






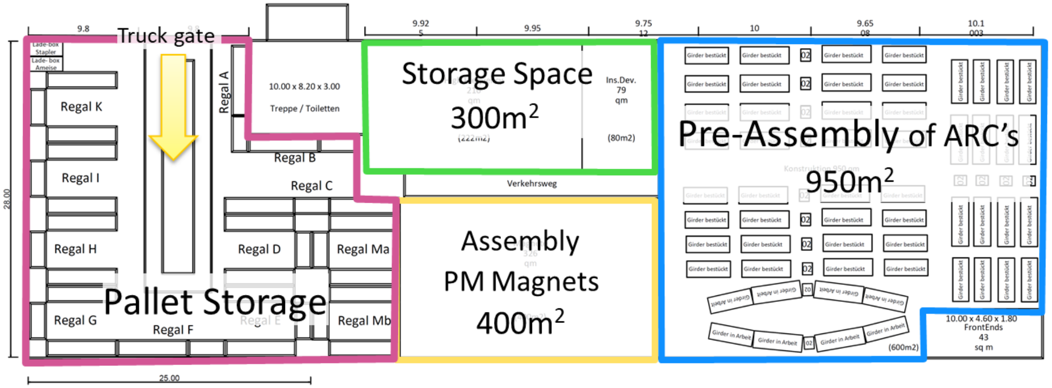


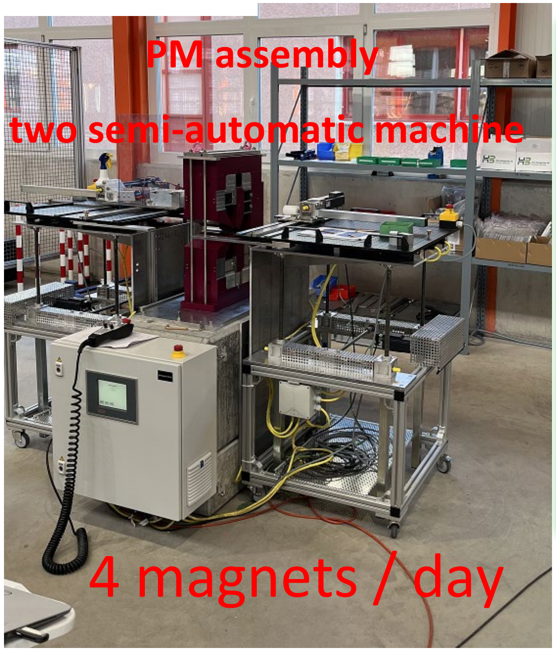




Assembly facility for permanent magnets in PSI

Challenge: Assembly of the 372 Permanent Magnets by PSI staff !





Status October 2023

BN	54/56	Dipole
BS	4/4	Dipole
BE	12/24	Dipole
VB (X)	101/120	Quad
AN(M)	6/144	Quad
VE	3/24	Quad

SLS2.0 permanent magnets

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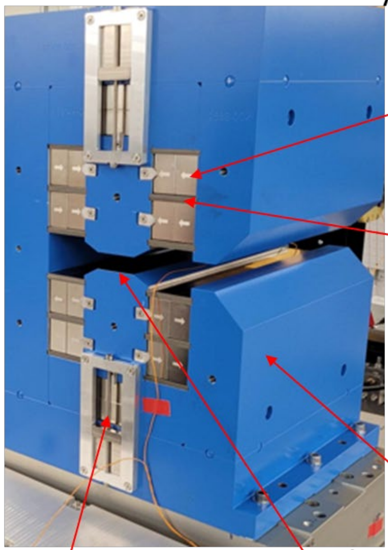
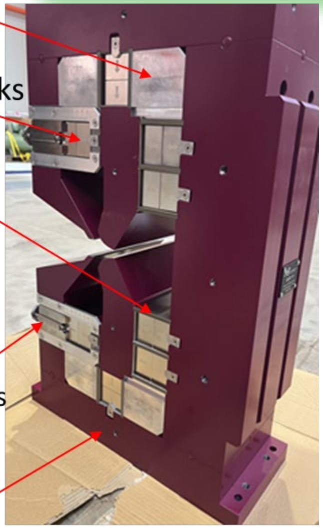
Dipole BN (56)
1.35 T; L=405 mm; G=22 mm

VB (120)
0.84 T
40.6 T/m





Al block

PM blocks

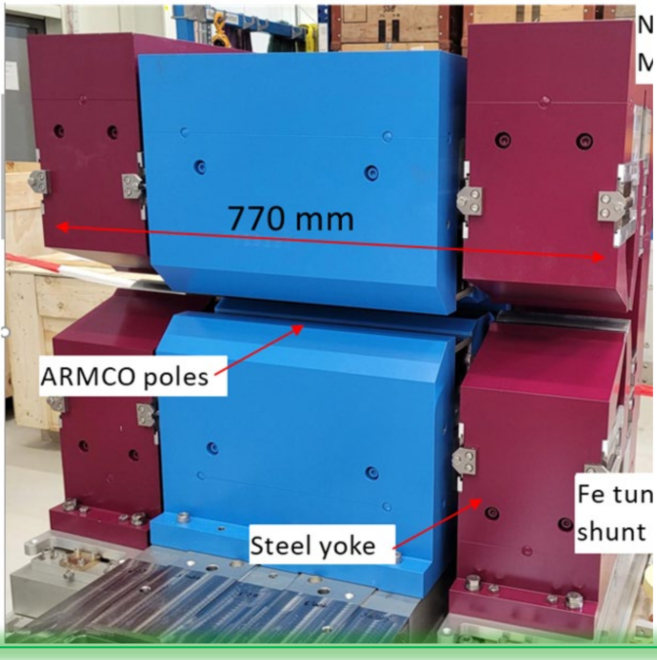
6 mm NiFe strips

Fe tunning Shunt plates

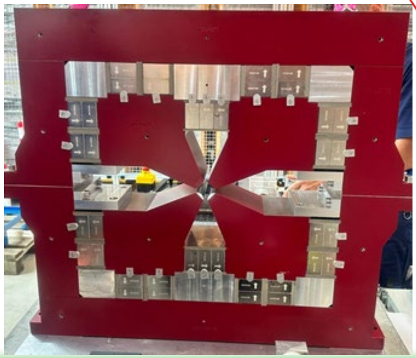
Moderator plates

Low C steel 1010

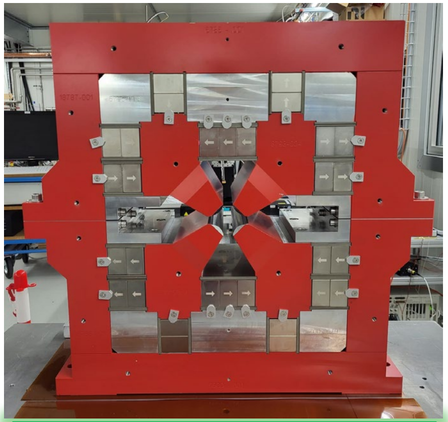
ARMCO poles



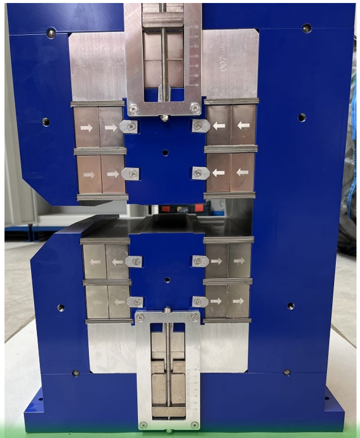
Triplet VB/BN/VB (60) , 0.861 Tm



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

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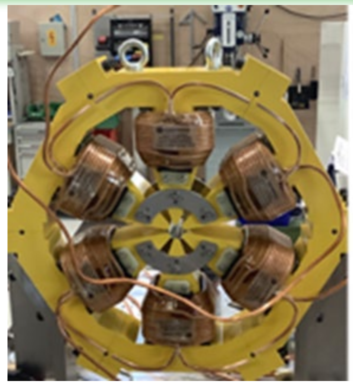
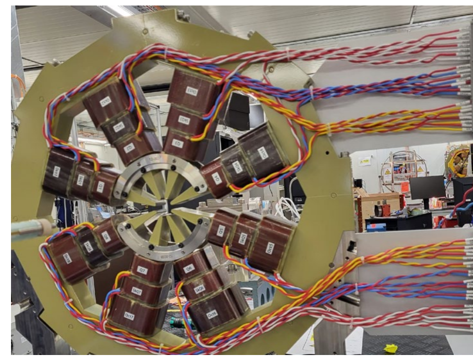
Quadrupoles (110)
93T/m-98 T/m
Ø=21 mm

Sextupoles (288-6 types)
5093T/m²-5840 T/m²
Ø=22 mm

Combined functions
Octupoles (264)





24 coils
ARMCO yokes and poles
Air cooling
3 power supplies (5 A)

Steerers CH/V
44 mT; 31.4 mT

SOQ (264)

B''/2, T/m²	5850
Aperture (Ø) sextupole, mm	22
Yoke Length, mm	84
Yoke mass, kg	93
Current, A	50
B'''/6, T/m³	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

Magnet qualification

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Challenge : 100 % of magnets will be measured at PSI

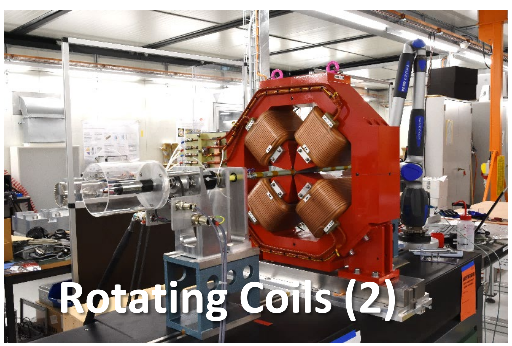
7 measuring test benches operational-80 magnets/month

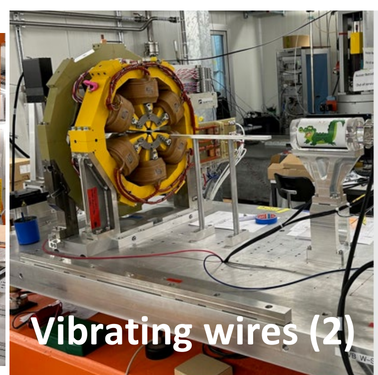
Systems (X benches)	Electro magnets	Permanent Magnets	3-5T superbend
Rotating coils (2)	Field Strength Multipoles	Field Strength Multipoles	
Moving Wires (2)		Field Strength, Magnetic axis	
Vibrating Wires (2)	Magnetic axis		
3D Field Mapper		Field Strength Maps (Few %)	Field Strength Maps

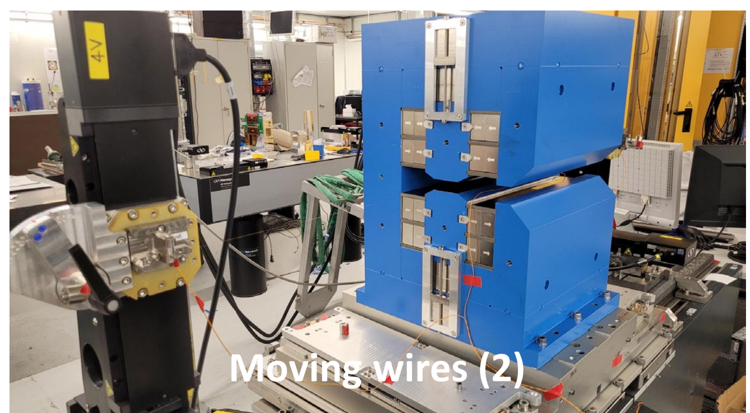
Accuracy : 1/1000

Reproducibility : 1/10000

Axis : < 30 micrometers







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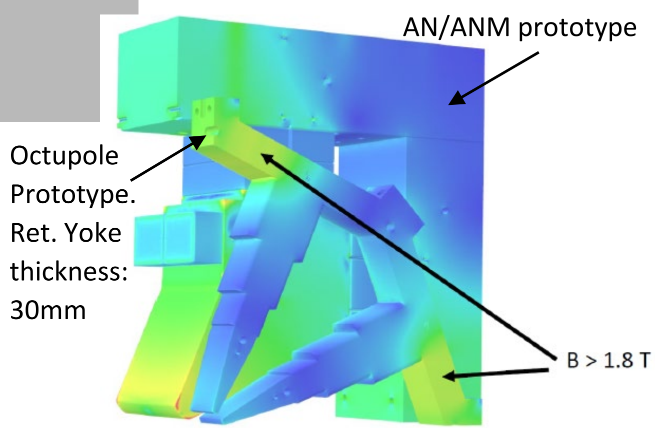
OC magnet

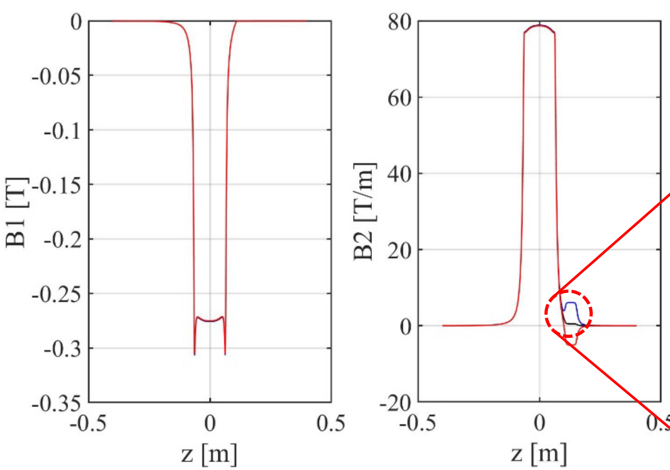


AN(M) prototype alone: 83.9 T/m

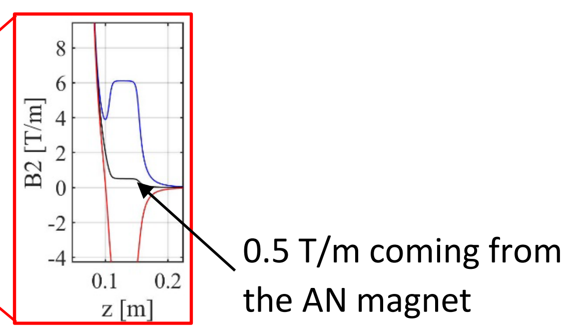
AN(M) + OC (30 mm iron to iron distance): 79.7 T/m (-5%)

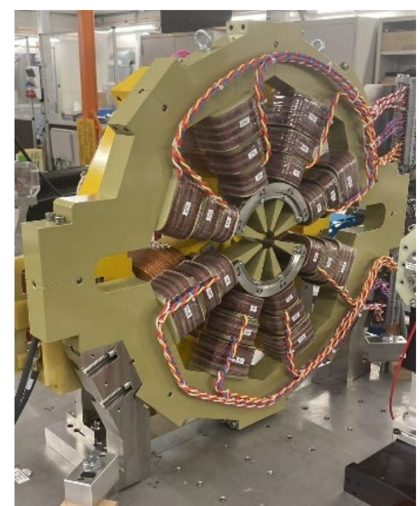
Nominal quadrupole in OC: 5.6 T/m

Quadrupole in the OC magnet coming from the AN(M) magnet: 8.8 T/m.



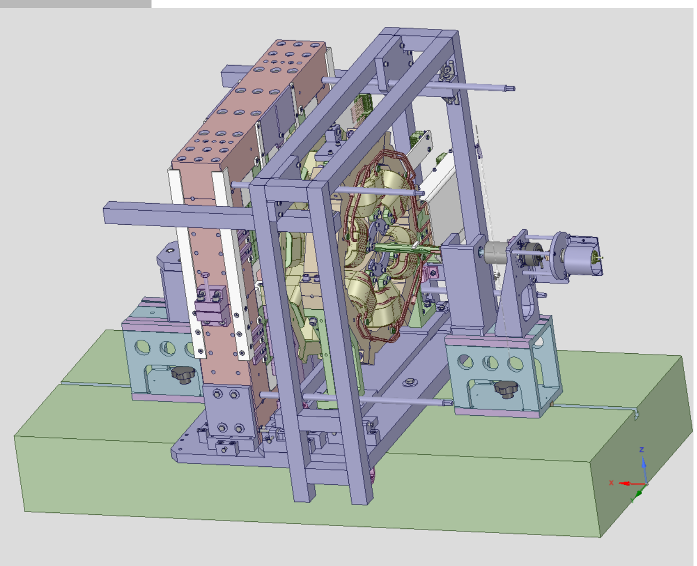
By increasing the OC return yoke thickness to 72.7 mm the quadrupole in the OC magnet coming from the cross-talk with the AN magnet dropped to 0.5 T/m.

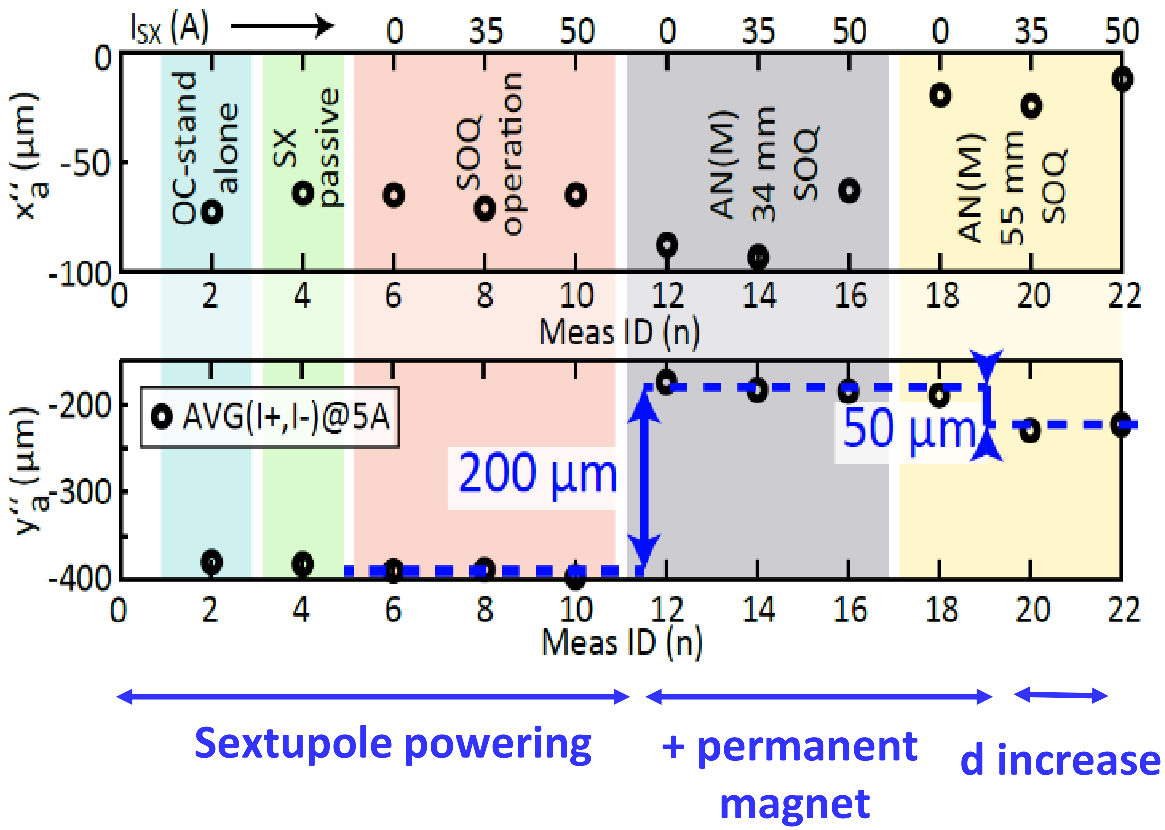




Challenge : Magnetic Coupling effect (Octupole axis)

→ OC magnetic axis position dependence with the sextupole powering and the neighboring permanent magnet (in that case AN(M) quadrupole)
→ test of an increase distance d=OC-ANM yoke on the axis shift





- Magnetic axis (x”,y”) measured using the Normal or Skew Quad function

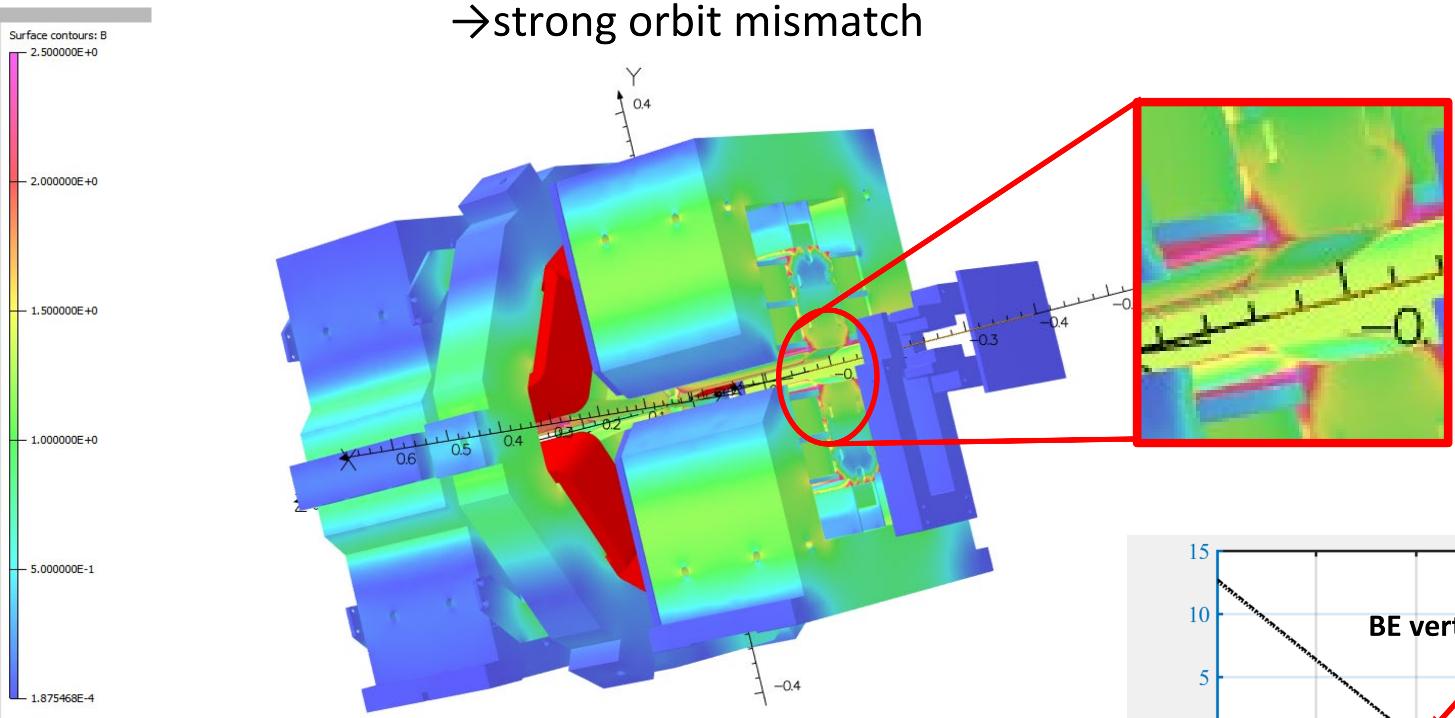
- Sextupole powering : almost no effect
- Permanent magnet influence: shift ~200 µm
- Reduced shift to ~150 µm, increasing the distance d by 20 mm

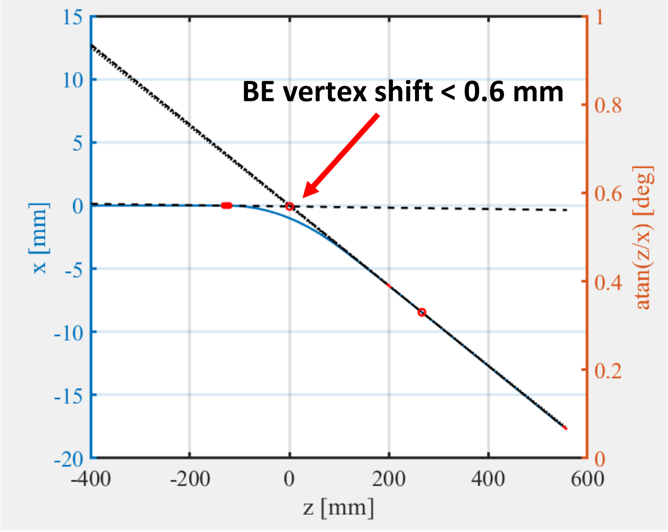
Example : Case of the VE-SXQ-BE

BE fringe field is strongly reduced at SXQ side

→BE vertex point shift longitudinally >3 mm

→strong orbit mismatch

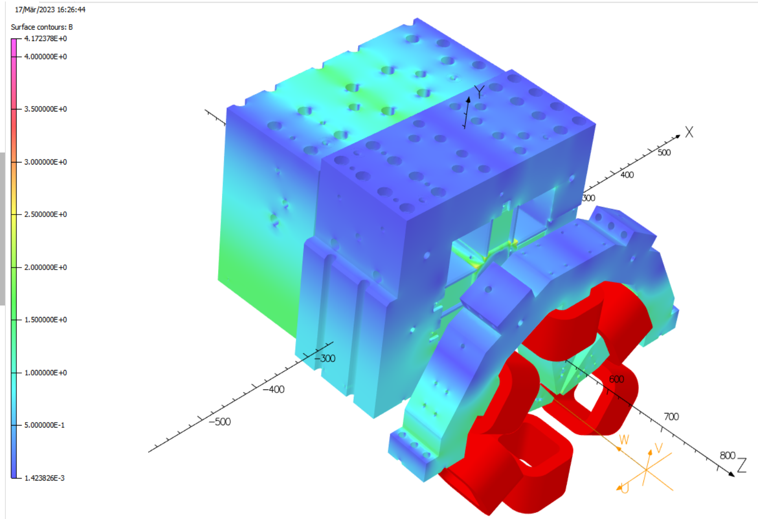


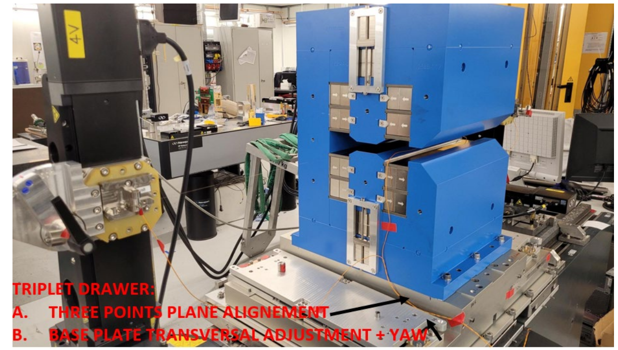


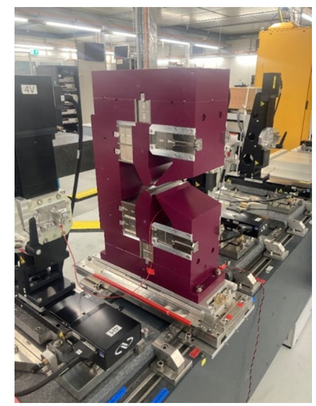
<u>Dipole BE at the arc exit</u> : addition of a chamfer (30 mmH, 12 mmV) to produce an asymmetric field profile and to reduce the longitudinal shift of the magnet (< 1mm)

Implemented for 12 produced yokes (2 types of BE)

Challenge : Alignment and tuning of the triplets with the moving wires







3D full model: Tuning the strengths of BN/VBs to meet machine specs (cross-talk taken into account)

3D model of BN stand alone from triplet

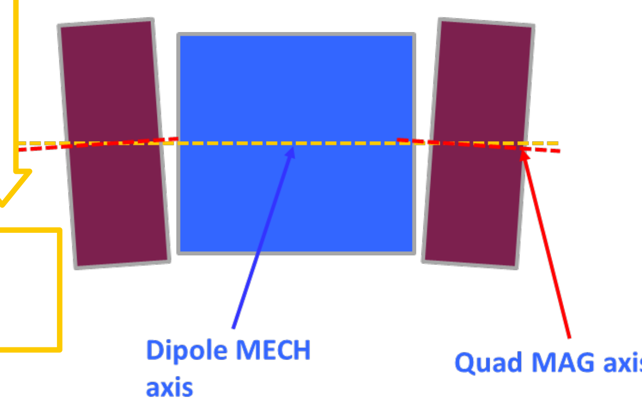
3D model of VB stand alone from triplet

3D map

3D map

3D map

Moving wire (MV_W) simulation using 3D maps



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Challenge : Alignment and tuning of the triplets with the moving wires

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 G_{hor}, G_{ver} and the nominal integrated field gradient G for stand alone quads.

Single magnet measurement and optimization

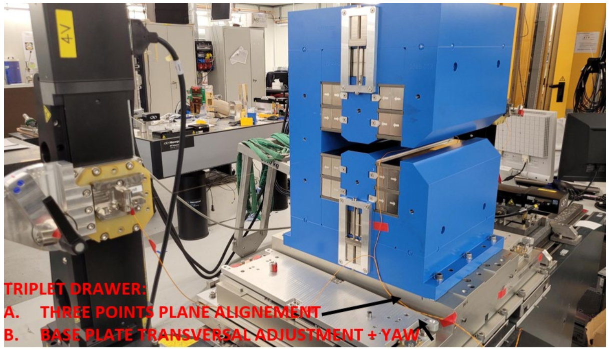
a. Dipole field integral (wire1) and shimming to **$\int B_1 dl$=-0.5699 (Tm)**

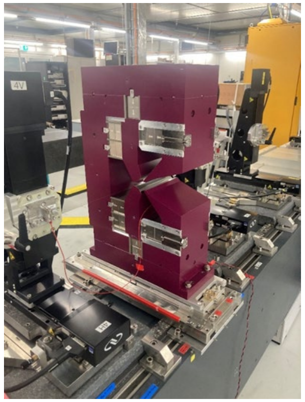
b. Nominal integrated field gradient and shimming to **$\int G dl$=7.0184 (T)** and multipoles **(Rotating coil)**

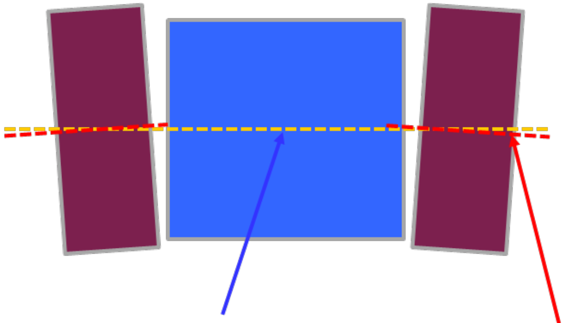
c. Magnetic axis position of each Quad (wire 1)

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)
4. The resulting integral of the assembled triplet is recorded as control parameter







Summary and perspectives

Challenges

- More than 1000 magnets of three types are designed, produced and measured of the upgrade of the Swiss Light Source at the Paul Scherrer Institut.
- The use of series permanent magnets, the density of the magnets and the combined function make the magnetic design and the measurement complicated .
- The tight schedule imposes the construction of an infrastructure at PSI for the assembly, magnetic measurements and the cryogenic tests.

Status- October 2023

- The design and tendering phases are over; contracts signed.
- 45 % of the magnets are delivered at PSI.
- Aggressive magnetic measurement plan – **80** individual magnets per month starting fall 2023.
- All the seven test benches are operational.
- The magnetic qualification is on-going.

Next important milestones

- Series measurements of the SOQ magnetic axis.
- All magnets qualified till **September 2024**
- Phase 2: Test of the first superconducting superbend Fall 2024.

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Thank you

for your attention

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