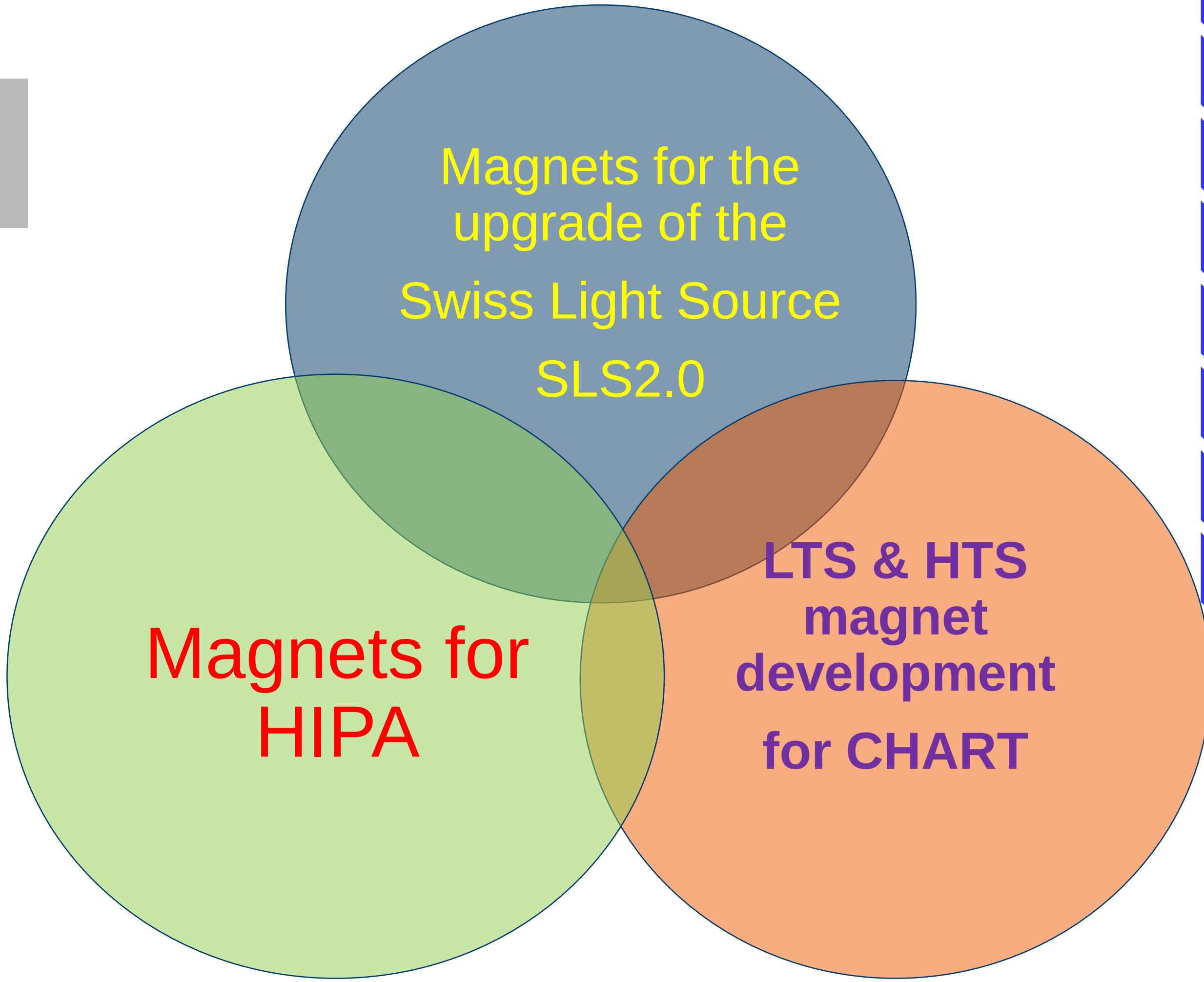

Stéphane Sanfilippo on behalf of the Magnet Section &CHART Team :: Paul Scherrer Institut

# Magnet Section Activities at the Paul Scherrer Institute: Status and future challenges

International Magnetic Measurement Workshop 22 @Brazilian Center for Research in Energy and Materials (CNPEM)

PAUL SCHERRER INSTITUT

# Main activities (2019-2024)

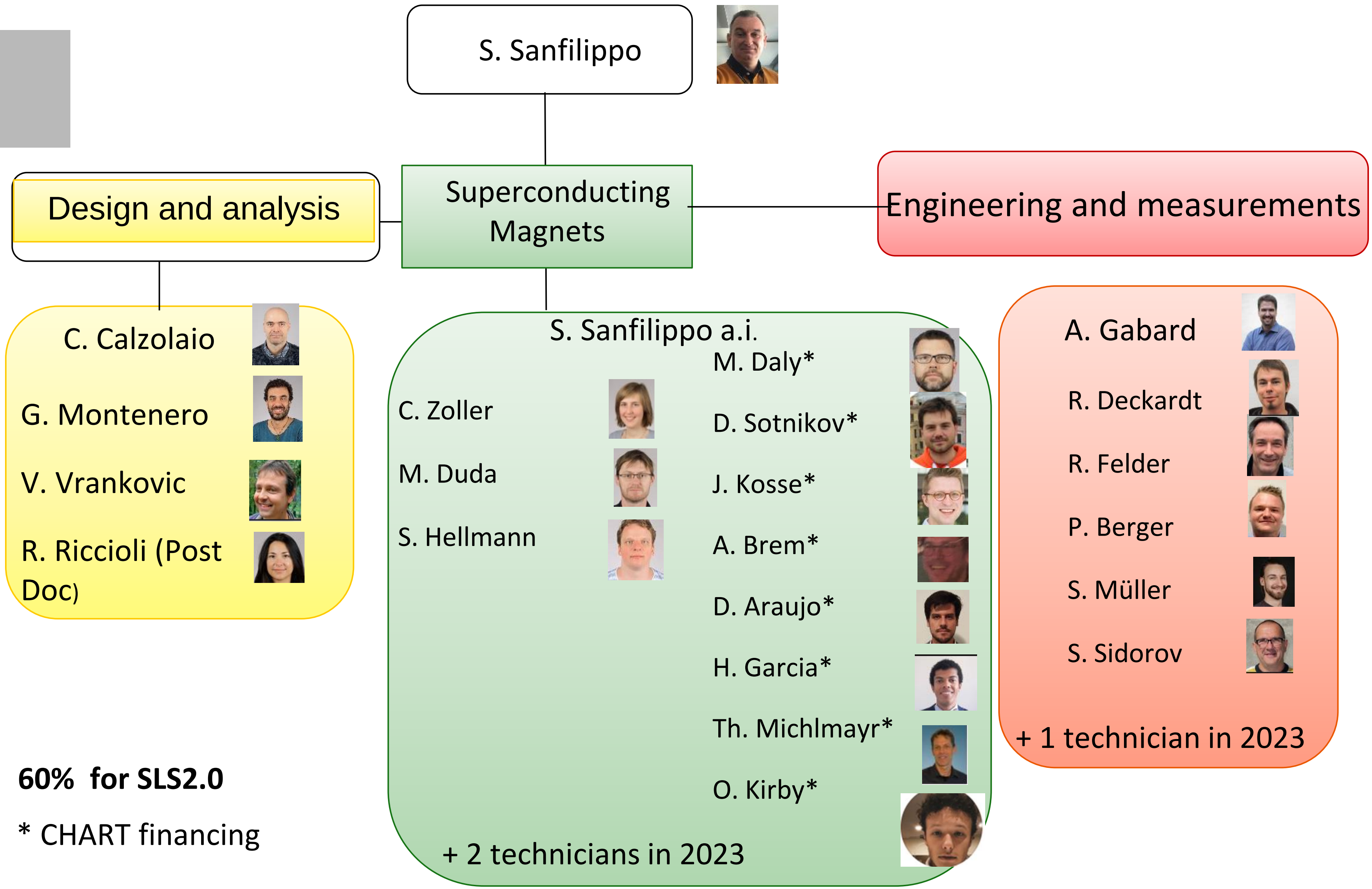



- Magnetic design
- CAD design
- Procurement
- Assembly (PM &SC magnets)
- Tests @ 4.2 K and 10 K
- Magnetic measurements
- Maintenance &Repair
- Spare

HIPA= High Intensity Proton Accelerator

CHART = Swiss Accelerator and Technology

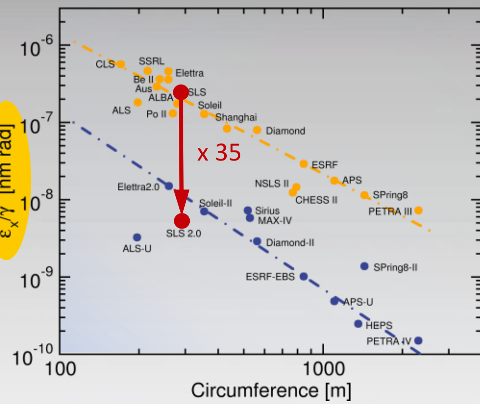
# Magnet section organigram




**60% for SLS2.0**

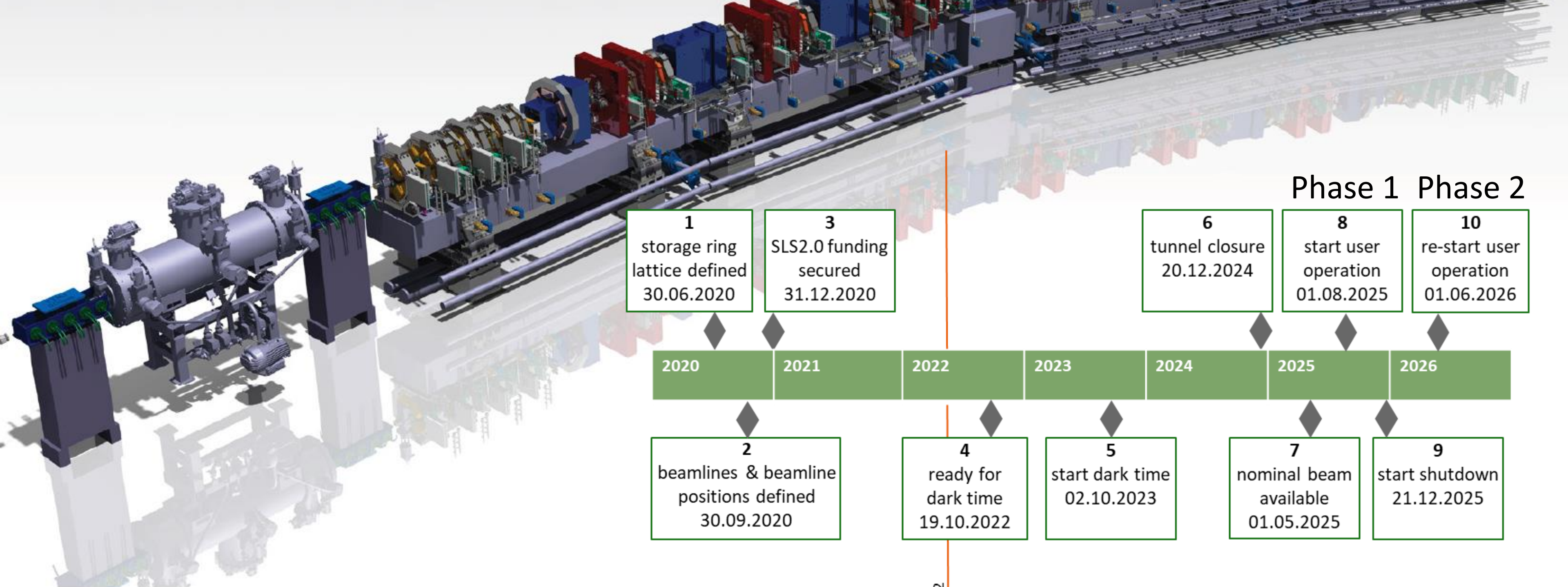
* CHART financing

# Project SLS 2.0




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

Brilliance



Phase 1 Phase 2

| | | | | | | |
|---|---|---|---|---|---|---|
| 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |

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

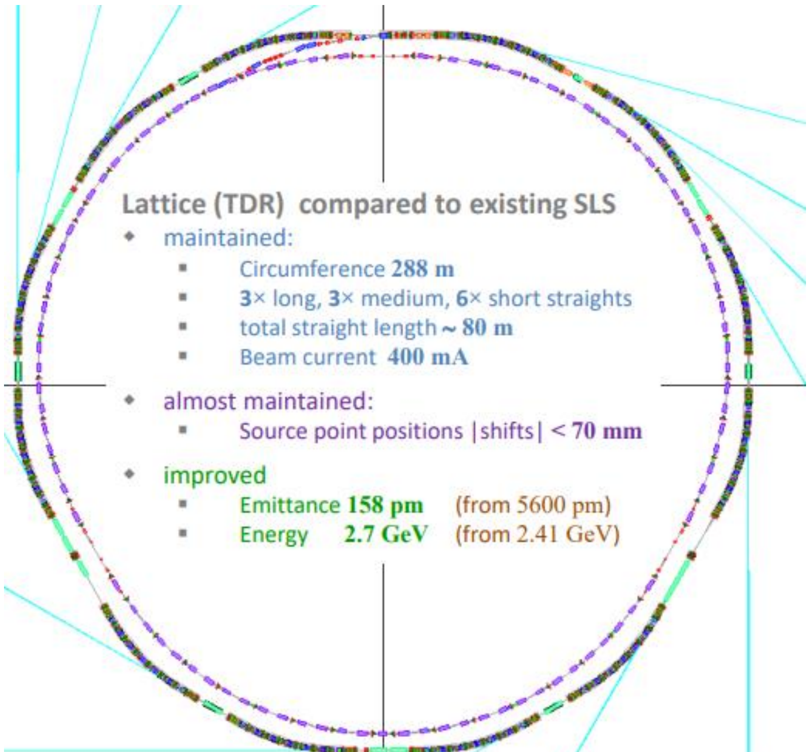
10 re-start user operation 01.06.2026

12.4.2022

# SLS now … to SLS 2.0 in 2025

## SLS 2.0

**288 m** circumference = **80 m** straights + **208 m** arcs

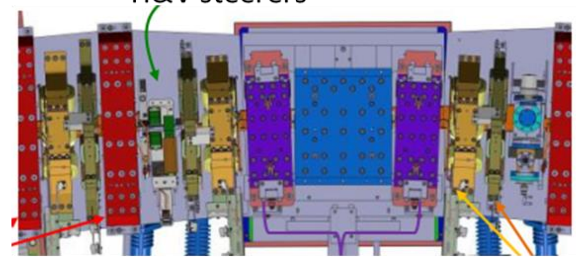


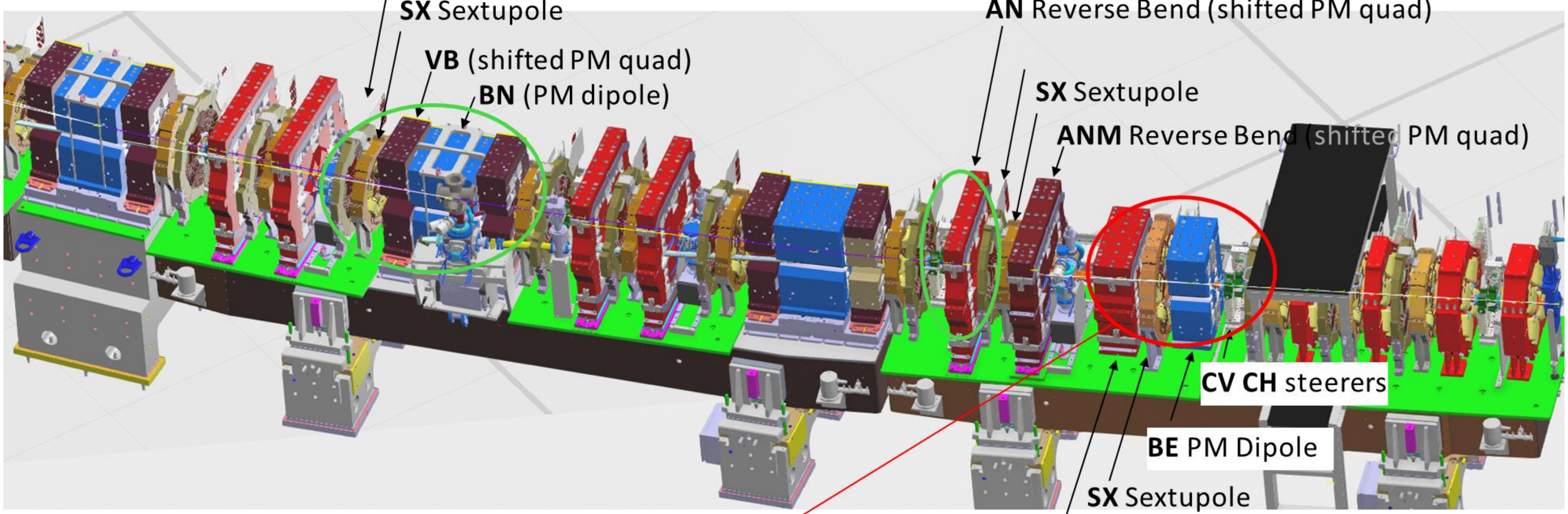

- 12 Multi-bend achromatic arcs
- 7BA best compromise: low emittance, nonlinear dynamics and magnet feasibility.
- Energy increase from 2.4 to 2.7 GeV
- Re-use of the SLS injector

- Energy of 2.4 GeV
- 288 m circumference
- 12 × TBA (triple bend achromat) lattice
- straight: 6 × 4 m, 3 × 7 m, 3 × 11.5 m
- 3 NC 3T super-bends
- Horizontal emittance 5.5 nm
- Vertical emittance ≈ 5 pm
- User operation since June 2001
- 18 beam lines in operation

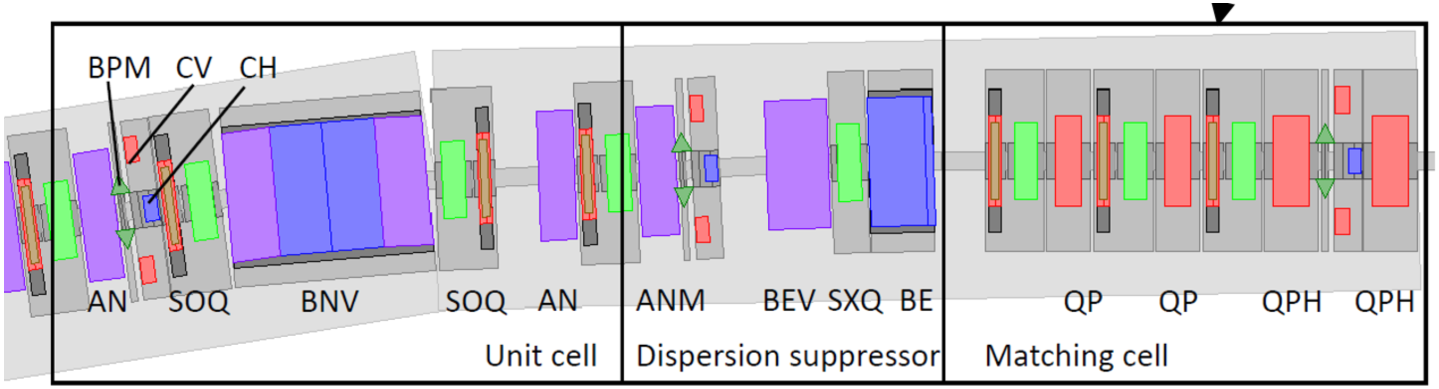
# Challenges for the SLS 2.0 magnet design & production & measurements

- High field and gradients (>1T)
- Combined function magnets (OC+Nquad+SkewQuad)
- Tight tolerances (field quality 0.01….0.1 %; aligment below 30 micrometers)
- Three types of magnets (electro/permanent/superconducting)
- High number of magnets
- Dense packing of magnets (Cross-talk effects)
- Tight schedule for the design, production and measurements



# Magnet list




| 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 | Steerer |
| | Total: 780 | |

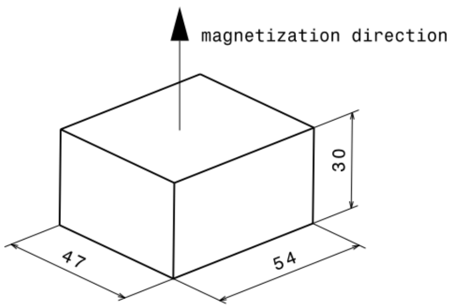
+ two 5 T superconducting superbends (phase 2-2026)

# Status of the SLS2.0 magnet production (September 2022)

- Magnetic and CAD design completed
- Calls for tender completed (including the SC superbends)
  almost all the purchase orders are signed
- Infrastructure & Magnetic systems : completed at 80 %
- Magnetic measurements : 112 electro-quadrupoles were measured

(Zoller & Montenero talk)

# Permanent Magnet Material for the blocks

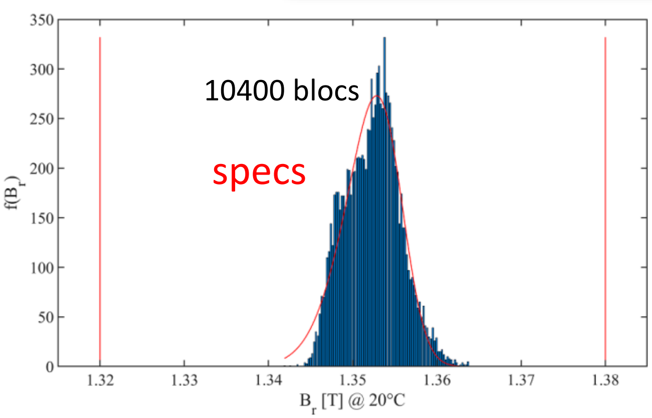



- 1 block size for all magnet types: 30 mm x 47 mm x 54 mm
- Rare earth : **$Nd_2Fe_{14}B$** ( Remanent field $B_r$: ~1.35 T @ 20°C)
- Weight : 0.57 kg
- Coercive field : 1015 kA/m
- Temperature dependence : -0.12 %/°C
  (thermal stabilization needed)

| Description | Value | |
|---|---|---|
| Nominal size of Permanent Magnet block | 30 mm x 47 mm x 54 mm | |
| Direction of magnetization | Along 30 mm block size | |
| Max. deviation of the magnetization direction wrt the orthogonal to the surface of the block [degree] | 2.5 | |
| Remanent flux density at 20°C, Br [T] | $B_r$ = 1.35 | $B_{r,max}$ = 1.38 |
| | | $B_{r,min}$ = 1.32 |
| Coercive field (typical value), HcB [kA/m] | $H_{cB}$ = 1015 | $H_{cBmax}$ = 1050 |
| | | $H_{cBmin}$ = 979 |
| Intrinsic coercive field, $H_{cJ,min}$ [kA/m] | 1592 | |
| Energy product at 20°C (typical value), $BH_{max}$ [kJ/m³] | 350 | |
| Reversible temperature coefficient of induction, α(Br) [%/°C] | -0.120 | |
| Reversible temperature coefficient of intrinsic coercitivity, α(HcJ) [%/°C] | -0.535 | |
| Heat treatment temperature [°C] | 100 | |
| Weight of one block [kg] | 0.57 | |

We need about 34 000 blocks
16.6 Tons

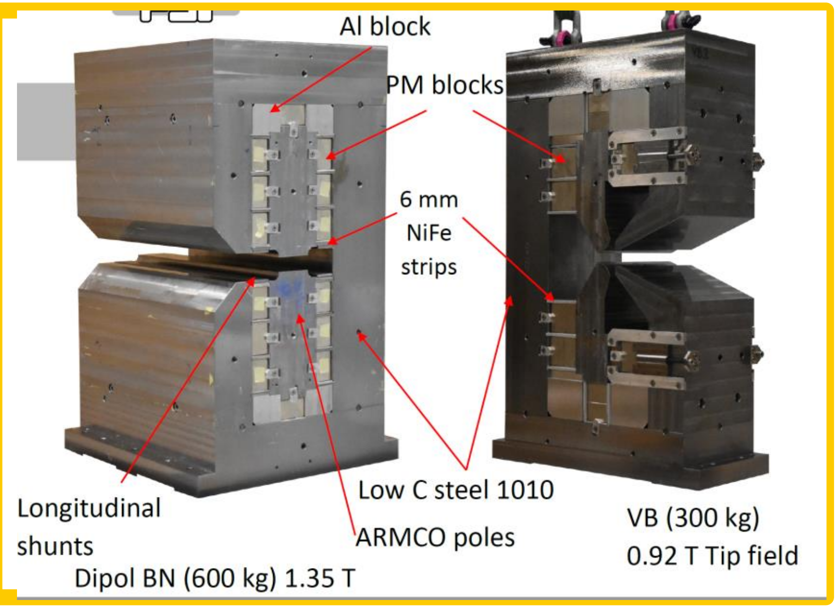
| Number of permanent magnet blocks (54 x 47 x 30 mm³) | | | | | |
|---|---|---|---|---|---|
| Magnet | N. of magnets for SLS2.0 | N. of spare magnets | N. of PM blocks per magnet | N. of spare PM blocks per magnet | TOTAL |
| BN | 56 | 1 | 98 | 2 | 5700 |
| VB | 96 | 2 | 48 | 2 | 4900 |
| VBX | 24 | 1 | 48 | 2 | 1250 |
| BE | 24 | 1 | 56 | 2 | 1450 |
| BS2 | 4 | 1 | 98 | 2 | 500 |
| VE | 24 | 1 | 60 | 2 | 1550 |
| AN | 120 | 1 | 88 | 2 | 10890 |
| ANM | 24 | 1 | 108 | 2 | 2750 |
| TOTAL NUMBER | | | | | 28990 |
| TOTAL [kg] | | | | | 16555 |




First 10’000 blocks (september 2022)

# Permanent magnets for SLS2.0

## Triplet VB/BN(S)/VB




## BN

| | |
|---|---|
| Yoke Length (iron), mm | 384 |
| Aperture, mm | 22 |
| Field, T | 1.35 |
| Bending angle, degree | 3.48 |
| PM blocks/unit | 84 |
| Weight, kg | 600 |
| Quantity of magnets | 60 |

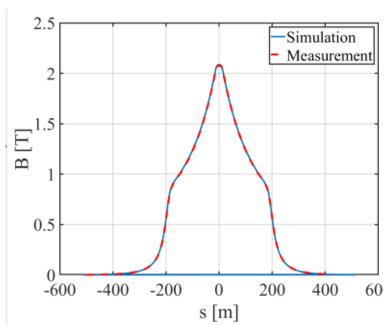
## VB

| | |
|---|---|
| Yoke Length (iron), mm | 172 |
| Aperture (Ø), mm | 22 |
| Field, T | 0.849 |
| Field Gradient, T/m | -40.643 |
| Bending angle, degree | 1.000 |
| Tip Field, T | 0.919 |
| Shift, mm | -20.891 |
| PM blocks/unit | 36 |
| Weight, kg | 300 |
| Quantity of magnets | 96 |

focusing
quadrupole

Triplet VB/BN/VB

## 2T superbend

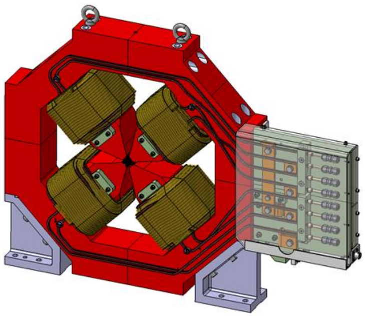


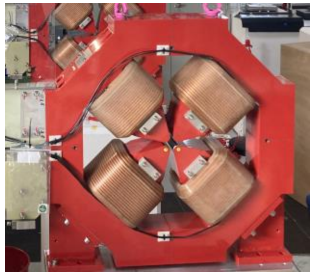

## ANM

| | |
|---|---|
| Yoke Length (iron), mm | 150 |
| Aperture (Ø), mm | 22 |
| Field, T | 0.272 |
| Field Gradient, T/m | 82.61 |
| Bending angle, degree | -0.26 |
| Tip Field, T | 1.051 |
| Shift, mm | --3.55 |
| PM blocks/unit | 88 |
| Quantity of magnets | 24 |

# SLS2.0 electro magnets

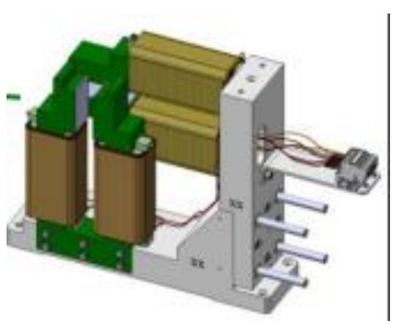
## SLS-2 Q- Poles

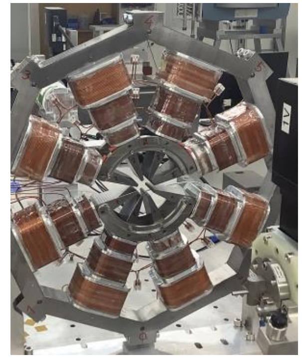


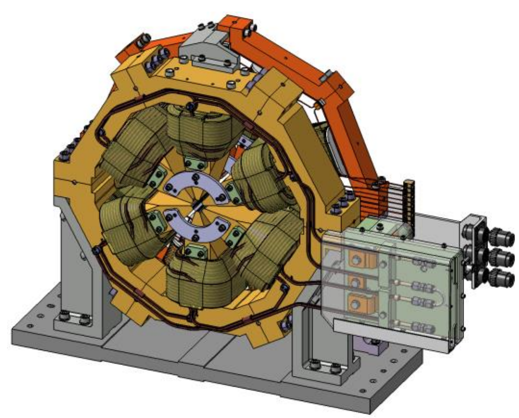


| | | |
|---|---|---|
| ø (mm) | 18 | 18 |
| Mag. Lenth (mm) | 100 | 140 |
| Nom. Gradient (T/m) | 93 | 98 |
| Pole Tip Field (T) | 0.98 | 1.03 |

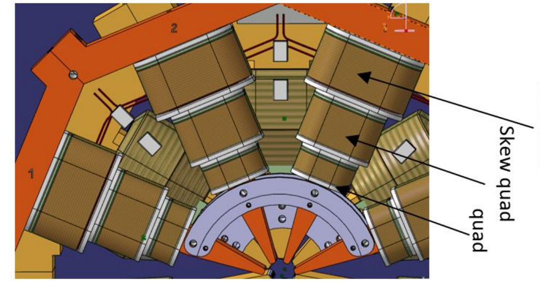
## H&V correctors







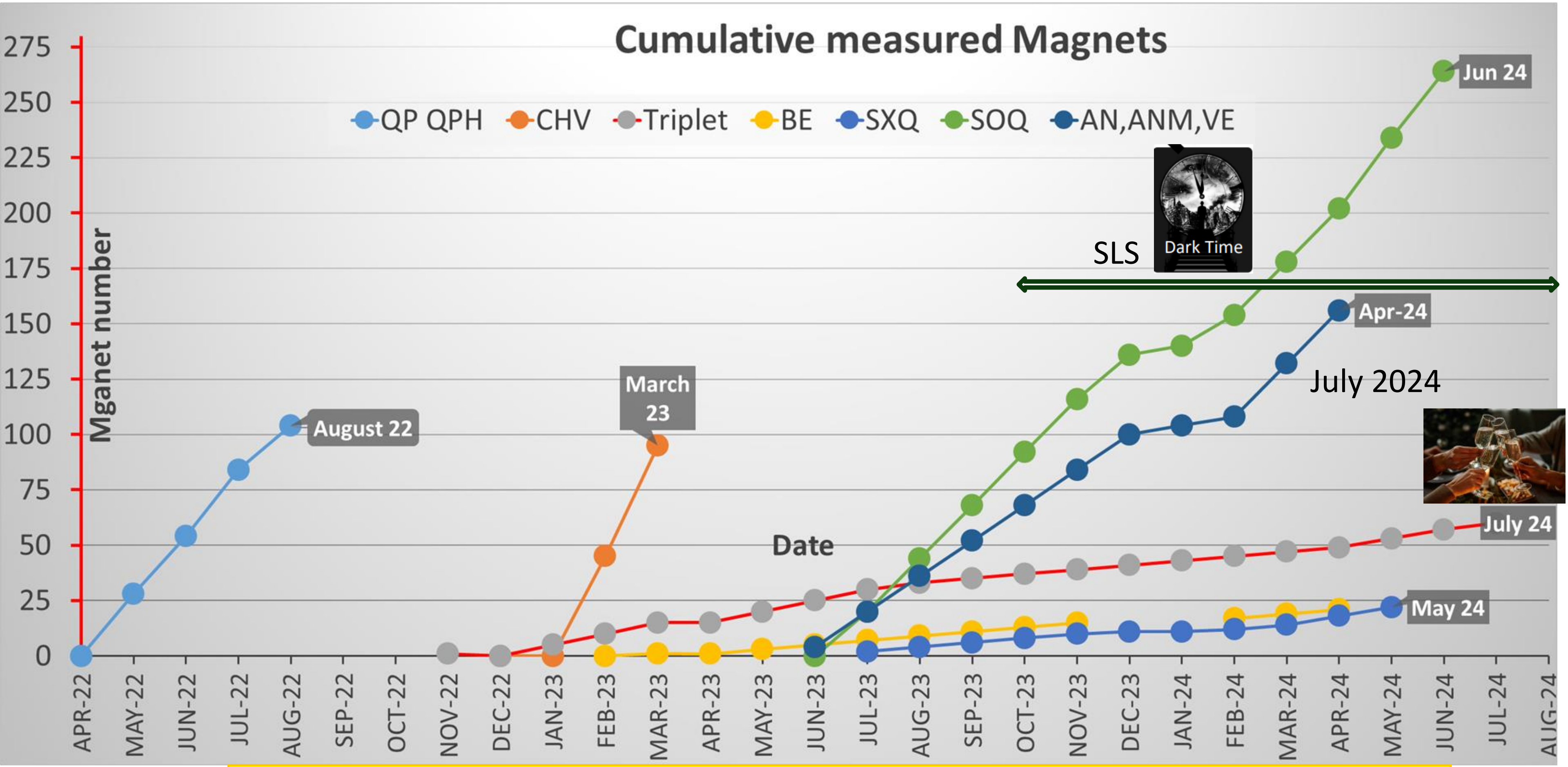
## Sextupole and octupole module




- 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

| | |
|---|---|
| $B''/2$, 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 |

# Magnetic measurements schedule




Very aggressive schedule (>1000 magnets in 26 months)

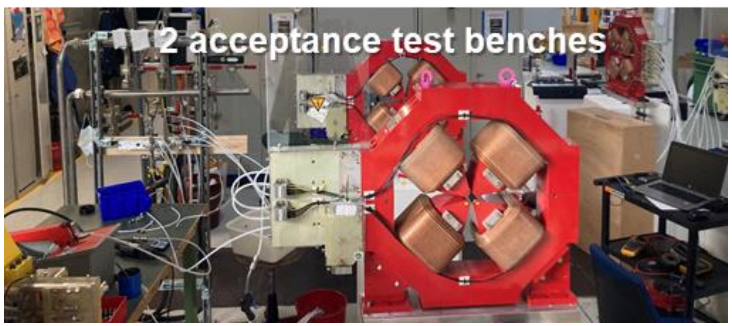
Parallelization of the measurements after June 2023

Last measured magnets : July 2024

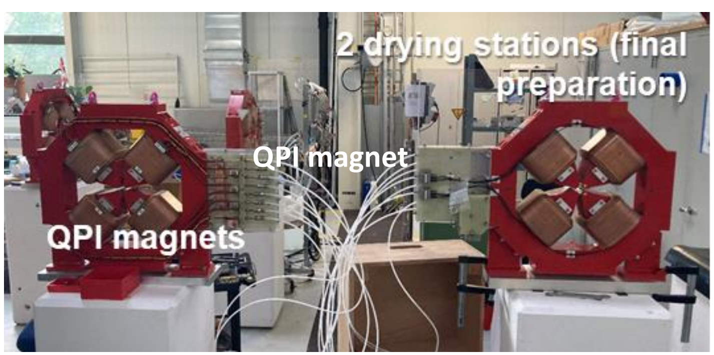
# Infrastructure : 2 buildings
# (Mag. Lab & Assembly Facility)

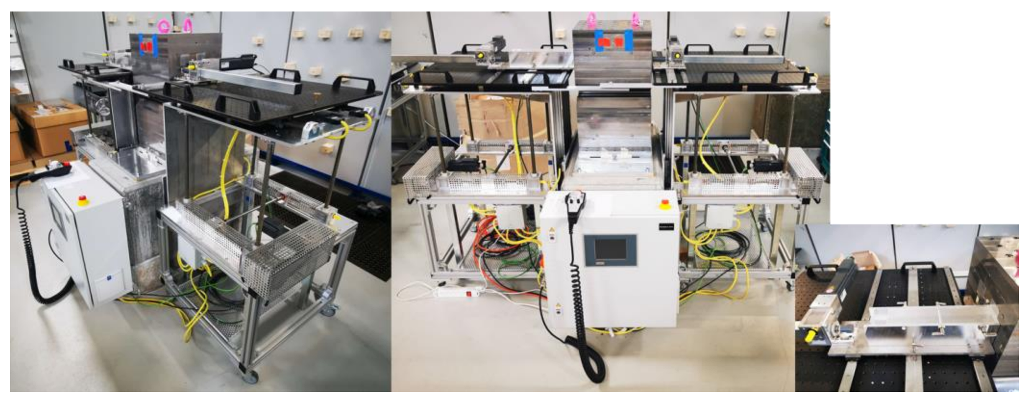
***Mag.Lab***
- Electromagnet delivery
- Electromagnet inspection and acceptance tests (2 workstations)
- Magnetic measurements (all the magnets)

***Assembly facility***
- PM blocks and yokes delivery
- PM dipoles and quadrupoles assembly (2 benches)
- PM dipoles and quadrupoles assembly ready for measurements
- Storage or magnet assembly (all) in the girders



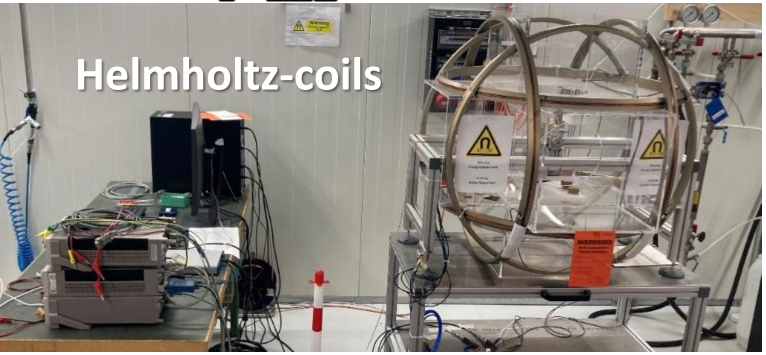




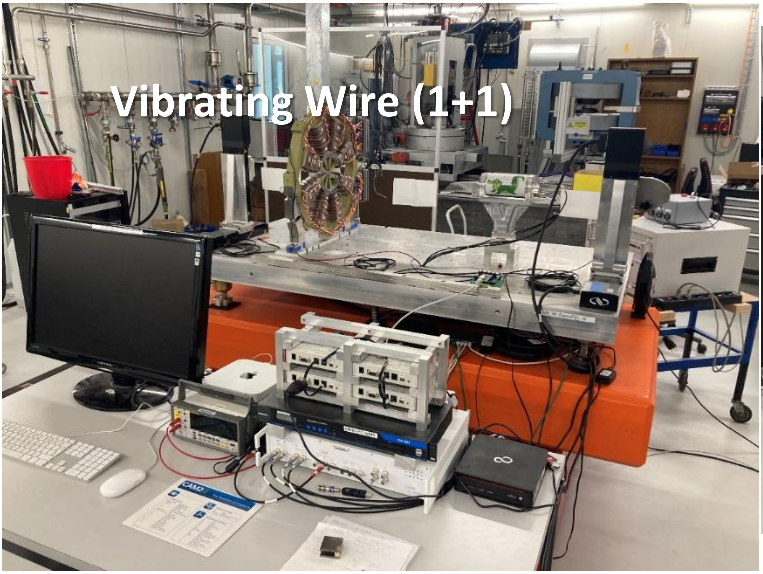



PM magnets assembly benches

# Measurement systems (Mag.Lab)







Dipole Field Integral →Moving wires (2)

CHV, Quadrupoles, Sextupoles, Octupoles (Field Integral, Multipoles) →Rotating coils (2)

Axis (SOQ) → Vibrating wires (2)

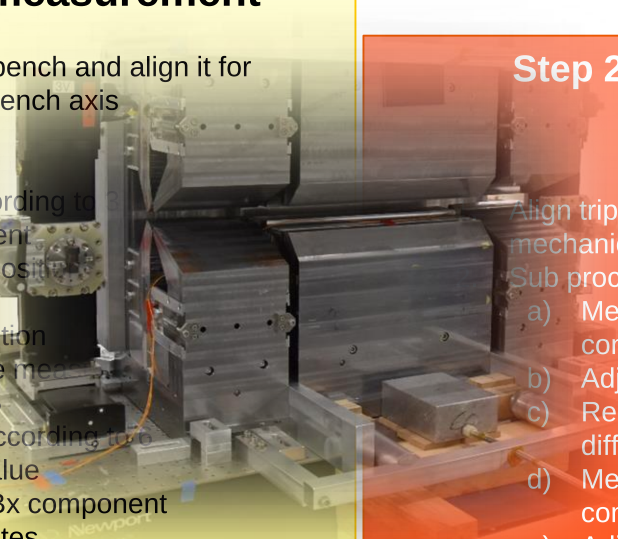
100 % operational July 2023

PAUL SCHERRER INSTITUT PSI

# Challenge (1): Triplet measurements and alignment

## Step 1 : 2 VB(X) Alignment and measurement

1. Install VB magnet support on the measurement bench and align it for matching nominal VB axis to the measurement bench axis
2. Install VB magnet on the measurement bench
3. Measurement of the vertical axis offset
4. Set new vertical starting position of the wire according to 3
5. Sub procedure-Horizontal axis offset measurement
   a) Horizontal measurement in the reference position
   b) Flip the magnet 180 degrees w.r.t. y axis
   c) Horizontal measurement in the flipped position
   d) Flip back the magnet and repeat reference measurement
6. Calculate horizontal axis offset using data from 5
7. Set new horizontal starting position of the wire according to 6
8. Sub procedure-Field adjustment to the design value
   a) Measure the integral field gradient due to Bx component
   b) Adjust the field gradient with moderator plates
   c) Repeat a) and b) until integral measured gradient differs for design <0.06%
9. Repeat from 3. to 7. for final refinement
10. Measure integral field tilting the wire according to final position of the VB(x) on the triplet (used at Step2.4)



## Step 2 :BN (BS2) alignment and measurement

1. Align triplet drawer in order to have BN nominal mechanical axis aligned with measurement bench axis
2. Sub procedure-Field adjustment to the design value
   a) Measure the integral field gradient due to By component
   b) Adjust the field gradient with shimming plates
   c) Repeat a) and b) until integral measured field differs for design <0.2%
   d) Measure the integral field gradient due to By component
   e) Adjust the field gradient with moderator plates
   f) Repeat d) and e) **until integral measured field differs for design <0.06%**

## Step 3 : measurements of the triplet

1. Remove BN(BS2) from triplet drawer
2. Install 2 x VB(x) with support on the drawer
3. Slide in the BN(BS2) magnets between the 2 x VB(x) on the triplet drawer
4. Measure integral field of the triplet and compare with the sum of the integrals of single magnets: the ratio has to match FEM simulations
5. Adjust VB position if ratio from 4 is off more than 0.2%

**Complicated**

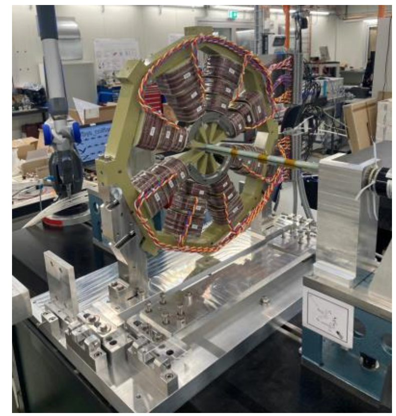
**1 triplet /week**

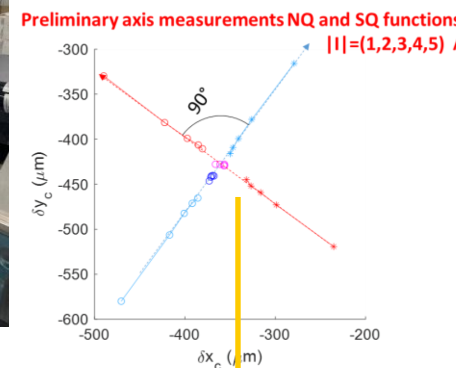
# Challenge (2): Alignement of the SOQ (sextupole & octupole)

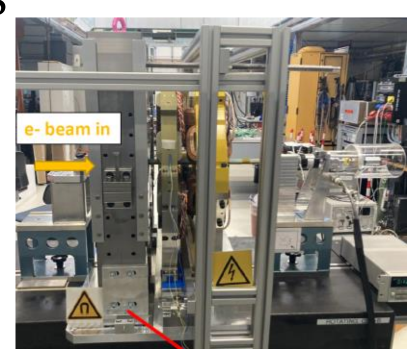
Align the SOQ within 30 micrometers

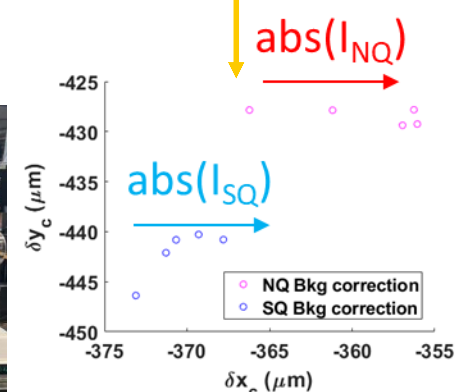
- Axis position of the sextupoles (magnetic, mechanic?)- RC, v.wire?

- Multi-function octupoles:
  - axis position using the normal (NQ) skew quad (SQ)- no octupole powering
- Position change :
  - ✓ when all the functions are powered
  - ✓ Cross talk coming from the neighbors (sextupole, big permanent magnet)





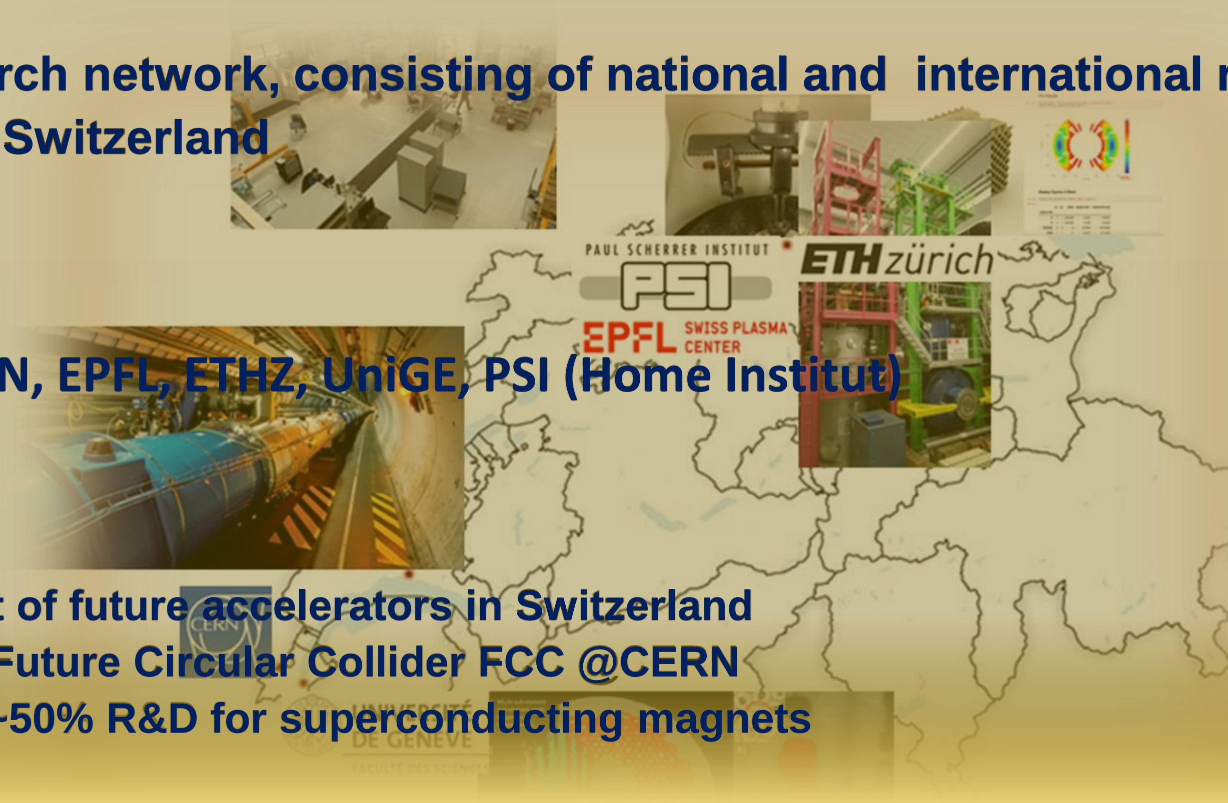



# CHART activities at PSI

**CHART = "Swiss Accelerator Research and Technology"**

- **Swiss research network, consisting of national and international research institutes in Switzerland**




**Members : CERN, EPFL, ETHZ, UniGE, PSI (Home Institut)**

- **Goal: Support of future accelerators in Switzerland**
  **Main task: Future Circular Collider FCC @CERN**
  **~50% R&D for superconducting magnets**

- **Funding by the participating institutes**
  **(CERN ~40% of the total budget)**
  **Support of the State Secretariat for Education and the ETH Board**

# CHART goals

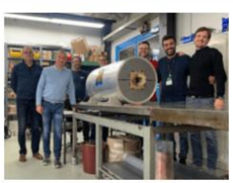
B. Auchmann

**CHART2: Accelerator Magnets**

- **WP0: Management, coordination**
- **WP1: Infrastructure**
  - T1.1: CHART2 facility specification and construction follow-up — Partners: PSI — Sub-contractors:
  - T1.2: CHART1 move — Partners: PSI — Sub-contractors:
  - T1.3: CHART2 equipment spec., procurement, commissioning — Partners: PSI, CERN — Sub-contractors:
  - T1.4: Cryogen-free test station upgrade — Partners: PSI, CERN — Sub-contractors:
- **WP2: Enabling Technologies**
  - T2.1: Adhesion and impregnation techniques — Partners: ETHZ, PSI, CERN — Sub-contractors:
  - T2.2: Advanced manufacturing — Partner: — Sub-contractors: : Inspire (ETHZ), commercial partner
  - T2.3: Full and partial insulation schemes — Partners: PSI, CERN — Sub-contractors: von Roll, Oerlikon Metco
  - T2.4: Mechanical coil interfaces — Partners: PSI, CERN, ETHZ — Sub-contractors:
  - T2.5: Winding and stress relief — Partners: PSI, CERN — Sub-contractors:
  - T2.6: Splicing and solder impregnation — Partners: PSI, CERN, KIT — Sub-contractors:
- **WP3: LTS Magnet R&D**
  - T3.1: Manufacturing trials — Partners: PSI — Sub-contractors:
  - T3.2: Subscale design, construction, and test — Partners: PSI, LBNL — Sub-contractors: EPFL-SPC
  - T3.3: CDx construction and test — Partners: PSI, LBNL, CERN — Sub-contractors:
  - T3.4: LTS HFM design studies — Partners: PSI, CERN — Sub-contractors:
- **W45: HTS Magnet R&D**
  - T4.1: Non-insulated technology coil design, construction, and testing — Partners: PSI, CERN, KIT — Sub-contractors:
  - T4.2: Coil stack construction and testing — Partners: PSI, CERN, KIT — Sub-contractors:
  - T4.3: Partially-insulated technology coil construction and testing — Partners: PSI, CERN, KIT — Sub-contractors:
  - T4.4: HTS applications design studies — Partners:: PSI, CERN, KIT — Sub-contractors:

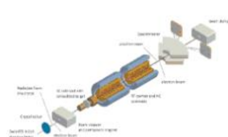
- **Design and construction of superconducting magnets**
- **Coil winding and magnet assembly**
- **R&D in LTS and HTS materials (key technologies)**
- **Development of an infrastructure for LTS and HTS magnet assembly (MagDev Lab) and test**
- **Promote synergies (competences, topics, personnel, equipment) with PSI projects (HTS Superbends, $P^3$ experiment, superconducting gantry...)**

CHART project at PSI https://chart.ch/psi/



**MagDev1**

Superconducting Accelerator Magnet R&D



**FCCee Injector**

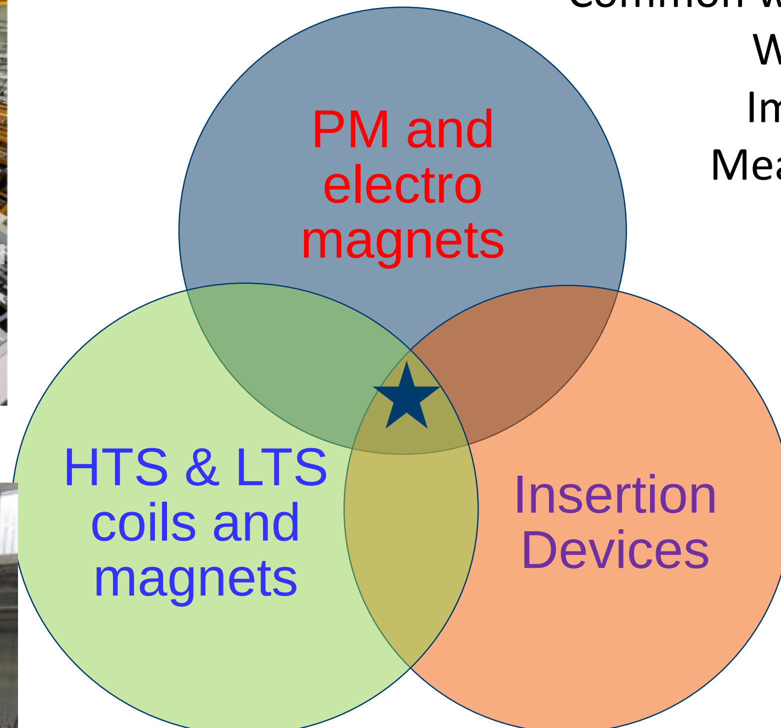
Design and positron production test program for FCC-ee Injector

**HTS Bulk Undulator**

High Temperature Superconducting Undulator for SLS2 Upgrade

# Competence center : Magnets & Insertion Devices

Know-how

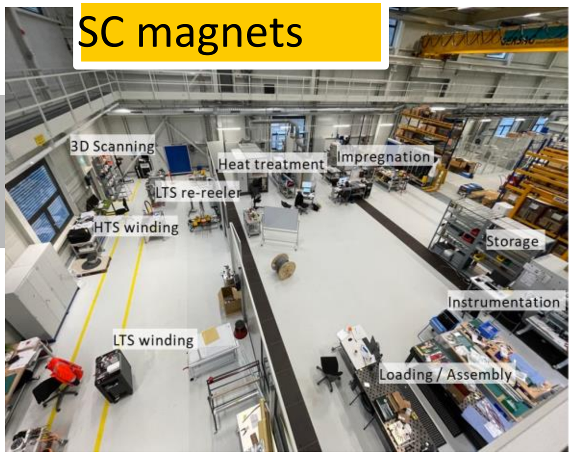



Resource

## Infrastructure

Common workshop, production tools
Winding machines
Impregnation oven
Measurement systems

SC magnets




Cryogenic test station

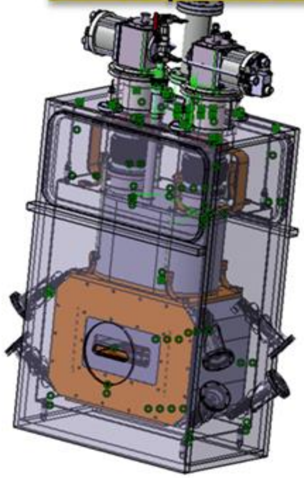
Measurement hutch

Workshop

1100 m² for Insertion Devices & Magnets

# Examples: superconducting magnet activities

## 5T superbend



SLS2.0 (in preparation)

## PSI CCT magnet

CHART (in test at CERN)

## Stack of HTS coils

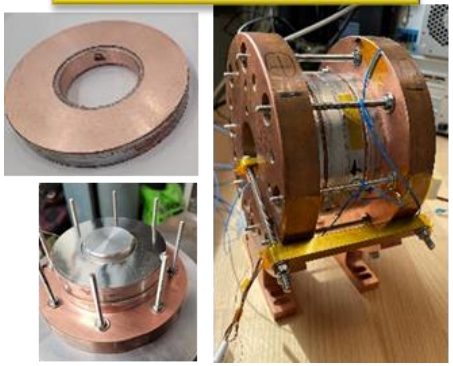
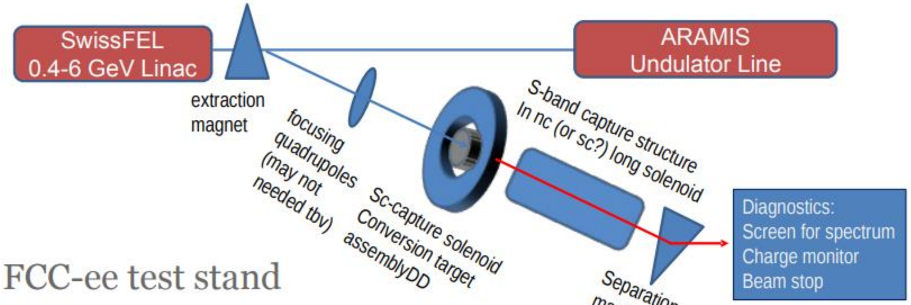


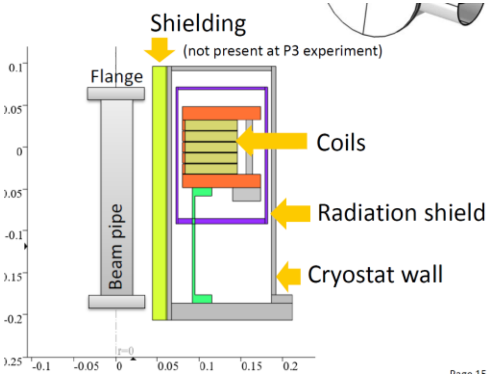
CHART 18 T@10 K

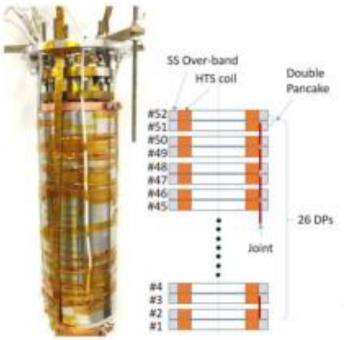
## Building and test of a positron source at PSI ($P^3$ experiment)




FCC-ee test stand

**Timescale: Sep. 2020 – Dec. 2024**



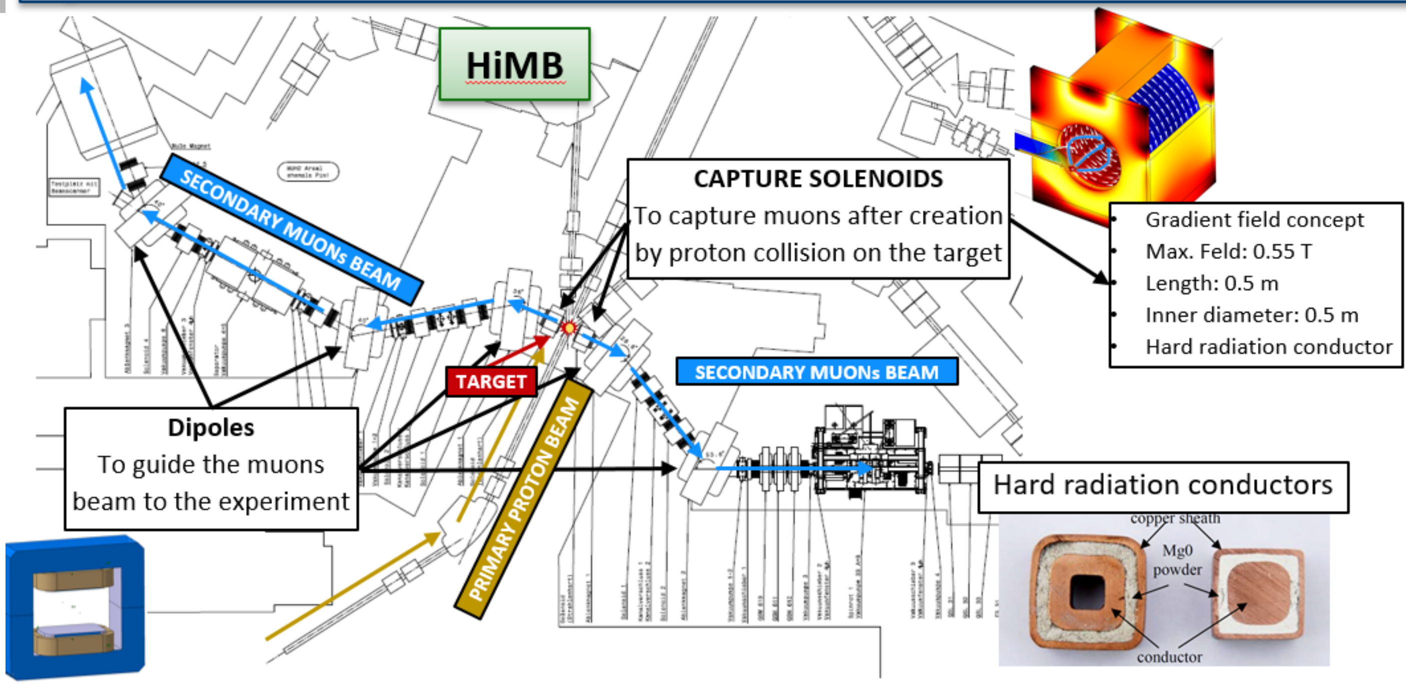

HTS SC solenoid

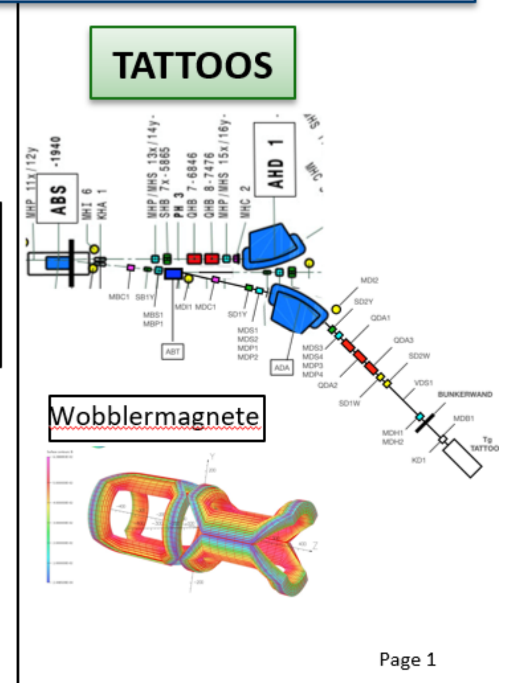
2 NC or SC long solenoids around the 3 GHz cavities

# What 's next : Project IMPACT

To produce and fully exploit **unprecedented intensities** and quantities of muons (factor 100: $5 \cdot 10^8$#/s → $10 \cdot 10^{10}$#/s) and radionuclides (produced with 50 times higher proton current than CERN) **at HIPA** for advancements in particle physics, chemistry, material and life sciences.

Two **new target stations** will boost the existing infrastructure: **HIMB** (High-Intensity Muon Beamlines) **will provide two orders of magnitude higher muon intensities** and **TATTOOS** (Targeted Alpha Tumour Therapy and Other Oncological Solutions) **unrivalled quantities of a wide range of radionuclides.**

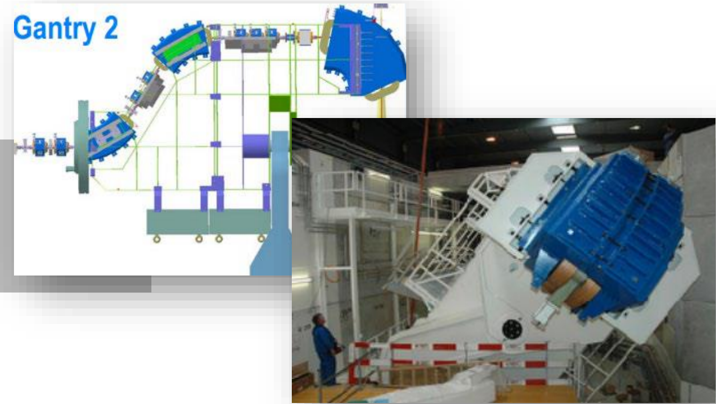



| 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|---|
| Mag. Design & simulations | Simulations II Mech. Design | TDR tender preparation | Tendering phase | Assembly & tests | Installation |

# Superconducting Dipole for compact gantry

PAUL SCHERRER INSTITUT PSI

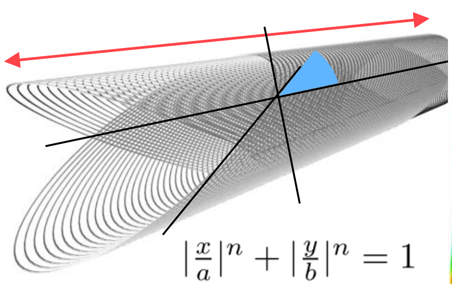


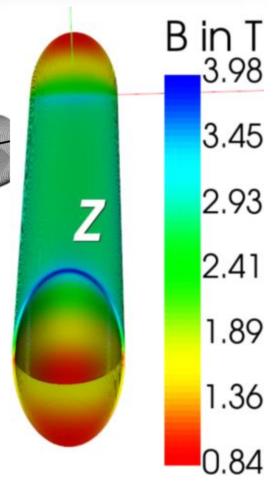

PSI gantries: Volumetric Rescanning (5MeV/100ms)
→ Fast field ramps and energy changes

Upgrade with new concepts

| Items | Gantry 2 | SC Gantry | + |
|---|---|---|---|
| Weight | 45 t (AMF3): 2 T Cu dipole | 4-5 t 3 T SC dipole | Compact, lighter |
| Scanning aperture | 12x20 cm$^2$ | 27x22 cm$^2$ | Reduced patching |
| Power supply | 85 kW | 20 kW | cost |

Magnet-geometry CCT:




Lamé-Kurve for rectangular apertures

**Operating parameters**

- Geometrie: Canted Cosine Theta (CCT)
- conductor: REBCO tapes
- $T_{op}$ >10 K
- Cooling: Cryo-cooler

FuSuMaTech

CHART Swiss Accelerator Research and Technology

| 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|---|
| Design pre-study | EU proposal demonstrator | demonstrator construction and test at PSI | | | Gantry magnet |

# Challenges - summary

- Production and measurement of a massive number of magnets for the SLS upgrade : the main priority for the next two years

- Triplet measurements and SOQ alignment are measurements challenges

- A huge effort is developed for the infrastructure and the parallelization of magnetic measurements to comply with the tight schedule

- Development of the technologies for superconducting magnets design, assembly and test is taking an increasing part of the activities within the CHART program

- A competence center for PSI magnets and Insertion devices is now operative

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PSI


# Thank you for your attention

S. Sanfilippo, P. Berger, C. Calzolaio, R. Deckardt, M. Duda, R. Felder, A. Gabard, S. Hellmann, G.Montenero, S. Müller, R. Riccioli, S. Sidorov, V. Vrankovic, C. Zoller;
D. Araujo, A. Brem, M. Daly, H. Garcia, O. Kirby, J. Kosse, Th. Michlmayr, D. Sotnikov and B. Auchmann :: Paul Scherrer Institut