PSI Center for Accelerator Science and Engineering

23th IMMW International Magnetic Measurements Workshop

On-going projects and futur Challenges in the Magnet Section at the Paul Scherrer Institute- an overview

International Magnetic Measurement Workshop
6-11 October 2024, Bad Zurzach

Stéphane Sanfilippo Paul Scherrer Institute

Key points discussed

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- Update of magnet activities and of infrastructure
- Magnet measurements for the upgrade of the Swiss Light Source (SLS2.0)- results and lessons learned
- High Field Superconducting Magnet activities-an overview
- Next challenges:
  - Magnets for the High Intensity Muon Beam Project (HIMB)
  - Superconducting Magnets for low consumption in the High Intensity Proton Accelerator

Magnet section mission

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Magnets in operation maintenance & repair & spares (5%)

Magnet design, construction and tests for PSI projects (40%)

R&D on magnet technologies for Room Temperature and Superconducting Magnets (60%)

Infrastructure development for magnet assembly and measurements (15 %)

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

Current activities and projects

Maintenance & repair& replacement of magnets in operation

- High intensity proton accelerator main line
- SINQ & muons beam lines
- PROSCAN lines + Gantries
- Free Electron Laser lines (2)

Magnet procurement for on-going strategic projects

- Upgrade of the Swiss Light Source (SLS2.0)
- MuH2 and MuH3 High Intensity Muon Beam lines (HIMB-IMPACT)

R&D Measurement techniques

- Power tests –SC magnets
- Field strength
- Field mapping
- Multipoles
- Magnetic axis
- Magnetisation PM magnets

R&D on superconducting magnets

- 14T Nb_3Sn and 20 T hybrid magnets for the **FCC***
- Combined function HTS Short Straight Sections for the **FCee injector***
- HTS coils for **future muon collider magnets***
- HTS coils for **compact stellarators***
- HTS solenoids for **FCCee injector studies** at PSI*
- Advance cyrogenics and LTS/HTS magnets for **energy saving program in PSI large research facilities**
- Fast ramping & low loss magnets for **PSI proton therapy treatment**

* CHART Program

Growing activities in Superconducting Magnet Technologies

PARK innovAARE –Innovation Park at PSI

gegier@parkinnovaare.ch

23,000 square meters of ground surface

Chemistry, Physics, and Biology Laboratories

Mechanical Workshops

20 companies already installed

Magnet section collaboration with VDL and Proxima Fusion

Focus on a strategic PSI project:
The upgrade of the Synchrotron Light Source - SLS2.0

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

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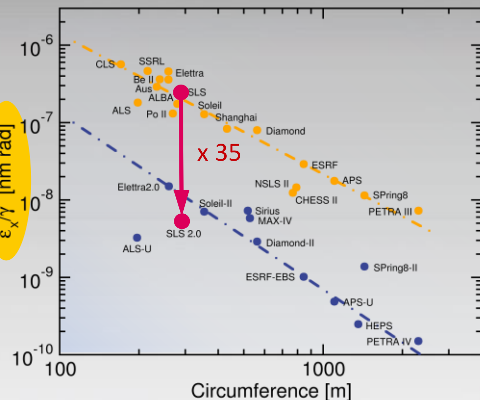
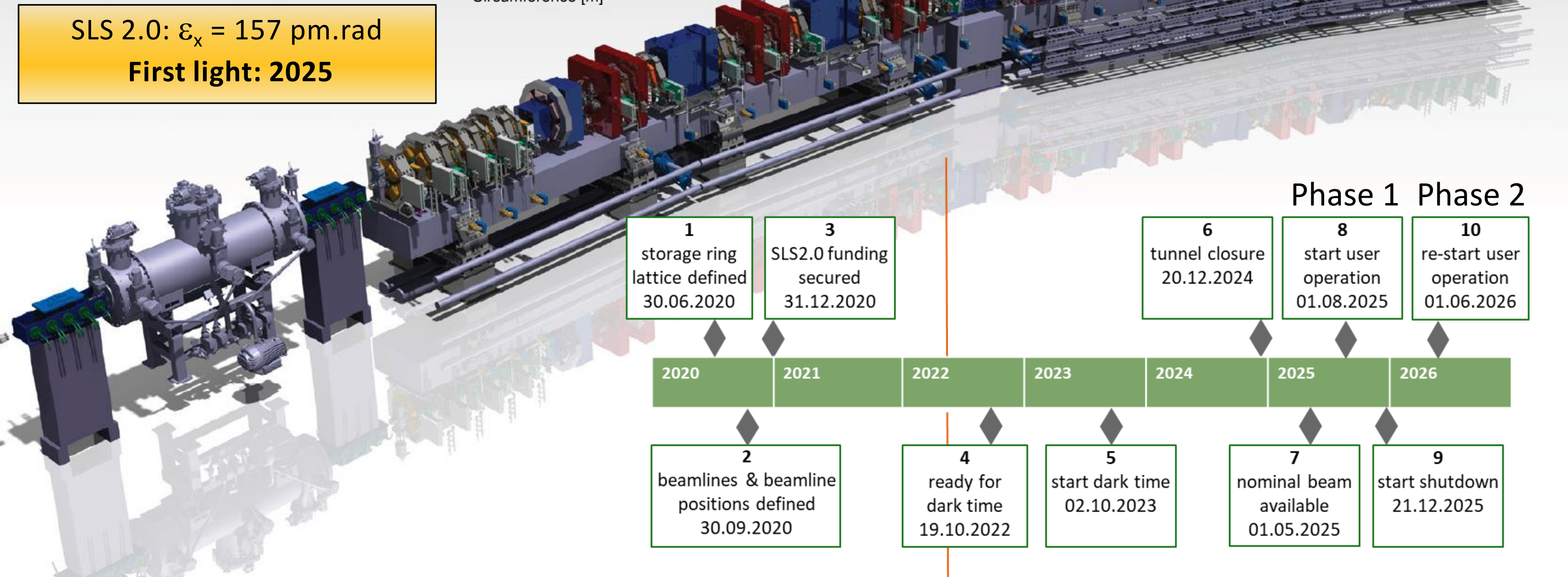
$$\mathcal{B} = \frac{\text{flux}}{\text{emittance}}$$

Brilliance



SLS 2.0: ε_x = 157 pm.rad

First light: 2025



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

First beam in 2025

Magnets for the SLS upgrade - last reminder

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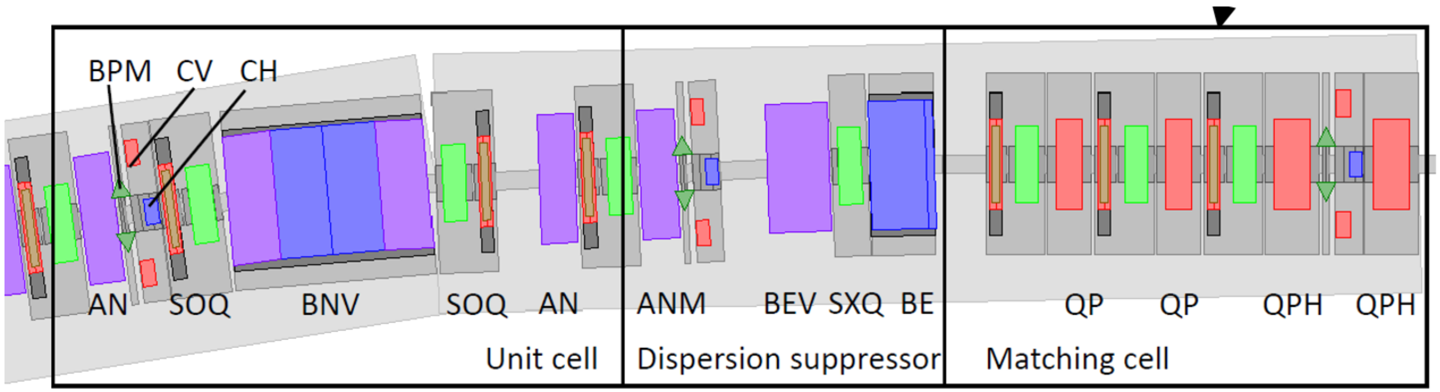
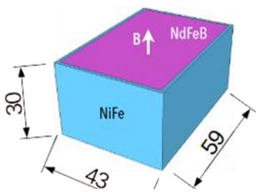
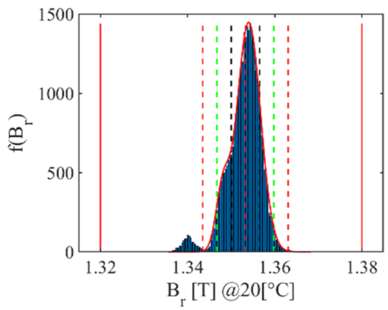


34 000 NdFeB blocks
16.6 tons





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

SLS2.0 magnets : the production path

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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

SLS2.0 permanent magnets- last (individual) pictures

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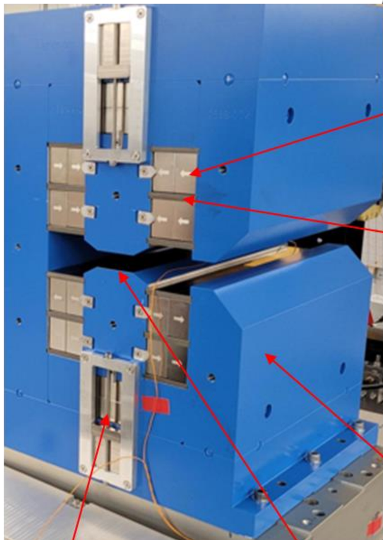
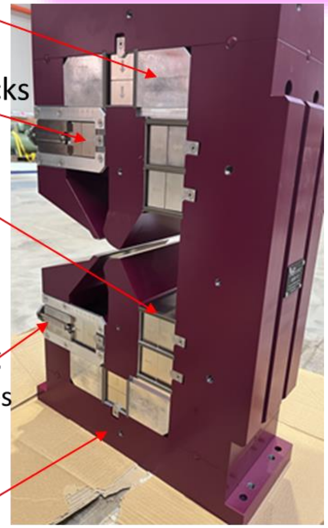
Dipole BN (56)
1.35 T; L=405 mm; G=22 mm

VB (120)
0.84 T
40.6 T/m





Al block

PM blocks

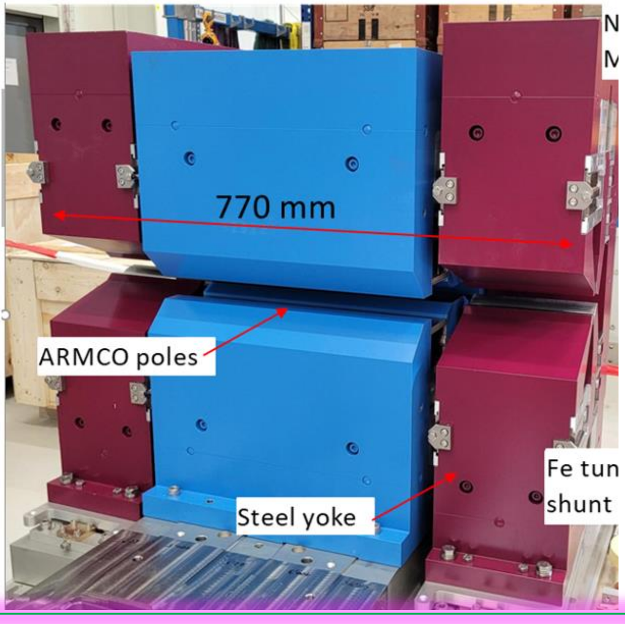
6 mm NiFe strips

Fe tunning Shunt plates

Low C steel 1010

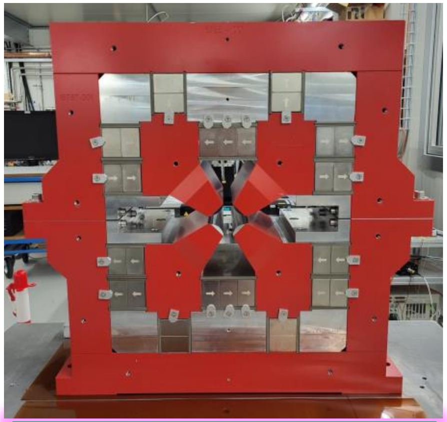
Moderator plates

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
last (individual) pictures

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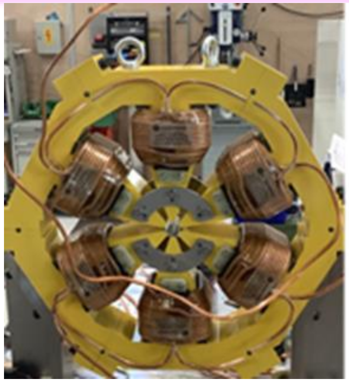
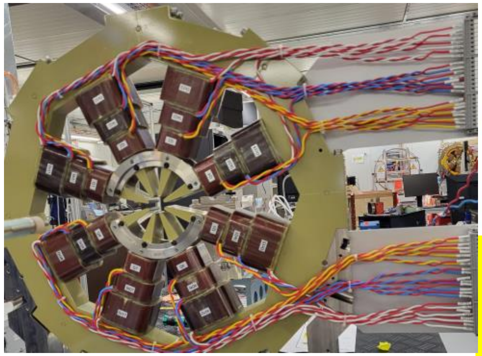
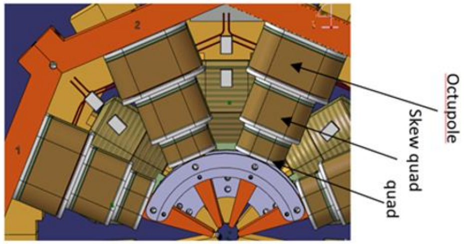
Quadrupoles (110)
93T/m-98 T/m
Ø=21 mm

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

Combined functions
Octupoles (264-2 types)

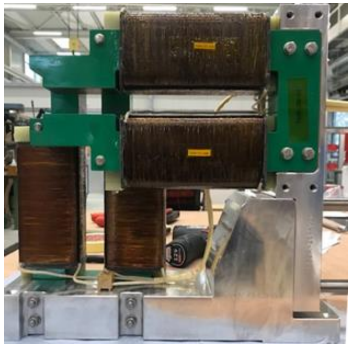






24 coils
ARMCO yokes and poles
Air cooling
3 power supplies (5 A)

Steerers CH/V
44 mT; 31.4 mT



Sextupoles SXQ (24)

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

SLS2.0 Magnet & Yoke deliveries and spares

NdFeB blocks (34000)	
10000	15/9/22
10000	15/11/22
14000	15/01/23
Completed 15/01/23	

QP/QPH quadrupoles		
Scheduled Delivery		
	Date	QTY
Batch 1	**Delivery complete on 24.08.22**	5
Batch 2		4
Batch 3		4
Batch 4		11
Batch 5		28
Batch 6		7
Batch 7		17
Batch 8		16
Batch 9		20
TOTAL MAGNETS		112

Sextupole		
Scheduled Delivery		
	Date	QTY
PO	5/10/2022	Released
Batch 1	28/2/2023	3
Batch 2	30/5/2023	72
Batch 3	30/8/2023	72
Batch 4	30/11/2023	73
Batch 5	01/2/2024	74
Delivery completed the 2.01.2024		
TOTAL MAGNETS		294

BN/BE, VB/VBX Iron yokes		
Scheduled Delivery		
	Date	QTY
PO	13/6/2022	Released
Batch 1	02/12/2022	14
Batch 2	15/2/2023	45
Batch 3	21/4/2023	45
Batch 4	31/6/2023	39
Batch 5	13/9/2023	62
Delivery completed on 30.11.2023		
TOTAL YOKES		205

Steering magnets		
Scheduled Delivery		
	Date	QTY
PO	10/11/2021	Released
Pre-serie	28/11/2022	1
Batch 1	20/12/2022	40
Batch 2	26/1/2023	40
Batch 3	15/2/2023	36
Delivery completed on 02.15.2023		
TOTAL MAGNETS		117

Octupole		
Scheduled Delivery		
	Date	QTY
PO	10/11/2022	Released
Batch 1	30/5/2023	3
Batch 2	17/7/2023	20
Batch 3	18/9/2023	44
Batch 4	3/1/2024	64
Batch 5	15/3/2024	64
Batch 6	15/6/2024	73
Delivery completed on 15/06/2024		
TOTAL MAGNETS		268

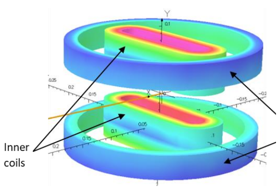
AN/ANM/VE Iron yokes		
Scheduled Delivery		
	Date	QTY
PO	11/17/2022	Released
Batch 1	5/26/2023	3
Batch 2	12/15/2023	57
Batch 3	1/26/2024	54
Batch 4	29/03/2024	30
Batch 5	21/06/2024	27
Delivery completed on 21/06/2024		
TOTAL YOKES		171

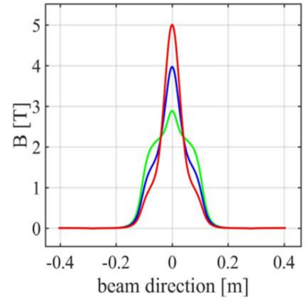
Assembled magnet and yokes were delivered on time !

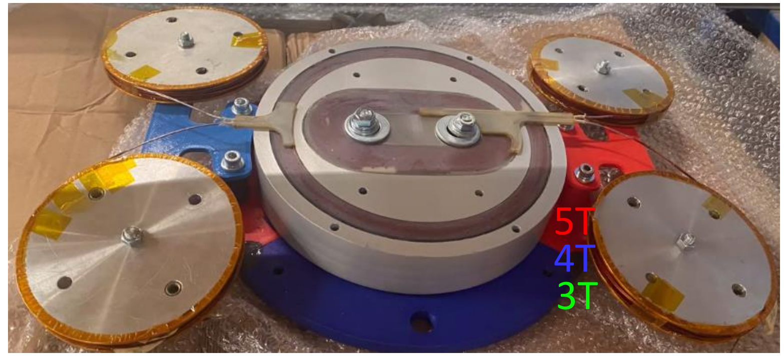
A diligent follow-up of the 7 WTOs

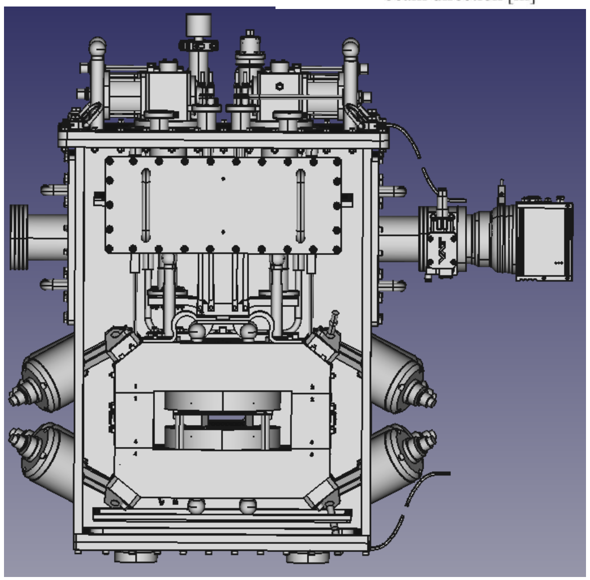


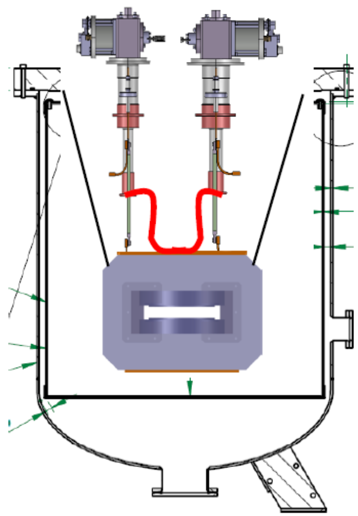
Phase 2: 5T NbTi Superconducting superbend











March 2024
Construction Drawings ready;

1st coils impregnated

September 2024
Design
2 super VBS

October 2024
Cold mass
Test at Manufacturer

January 2025
1st superbend
At PSI

Dec. 2024 – Jan. 2025
Preparation of the compact fiend map

Feb. 2025
Measurement of the SCA

May 2025
2nd superbend
At PSI

Jun. - July 2025
Measurement of SCB

Q1 2026
Superbends
Installation

Installation of SCB 1&2 planed in 2026

Phase 2 : HTS Bulk Undulator (2026)

Marco Calvi with the Insertion Device Group

Contribution from A. Arsenault

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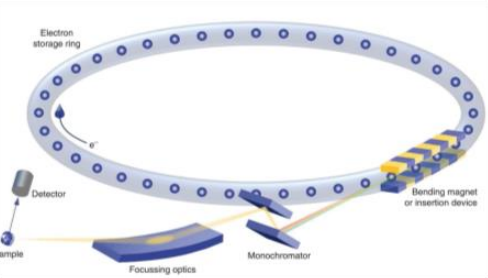
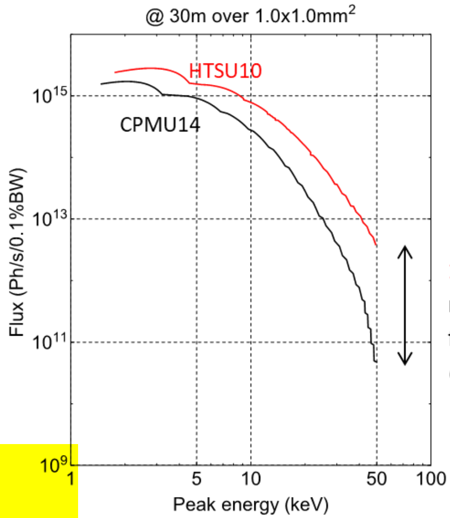


Calculations done for the future iTOMCAT beamline, dedicated to tomographic microscopy



100x more flux @50keV

Total length [m]	< 2
Period length [mm]	10
Magnetic gap [mm]	4.0
Magnetic Field [T]	2.1
Sc Coil Field [T]	12
K	2
HTS temp [K]	10
LTS temp [K]	4.2

LEAPS INNOVATION

SLS 2.0

CHART

Swiss Accelerator Research and Technology

UNIVERSITY OF CAMBRIDGE

Fermilab

Kyoto University

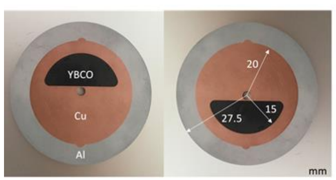
SPring-8

ESRF

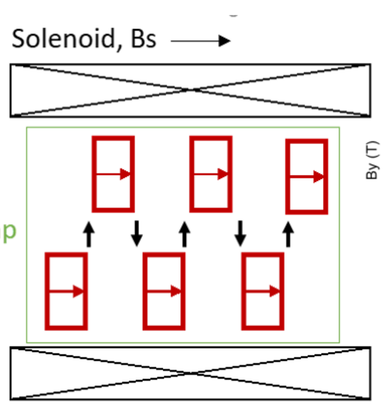
Bulk HTS sample : Cambridge
Ø : 30 mm; Thickness : 4 mm

10 mm period, 4 mm gap, 2 T
Tmag~10 K

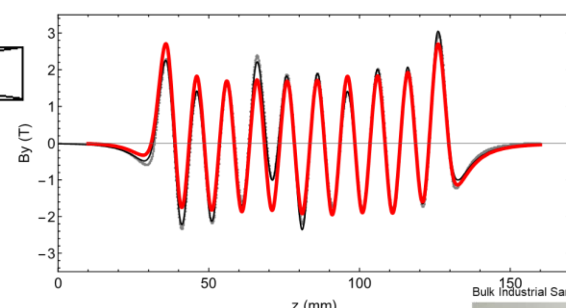
Nb_3Sn solenoid (10T): Fermilab



mp



GdBCO Tc=92K



B (z) for a prototype

(FC @ 10T to 0)

Bulk Industrial Sample

SLS2.0 Permanent Magnets Assembly in PSI

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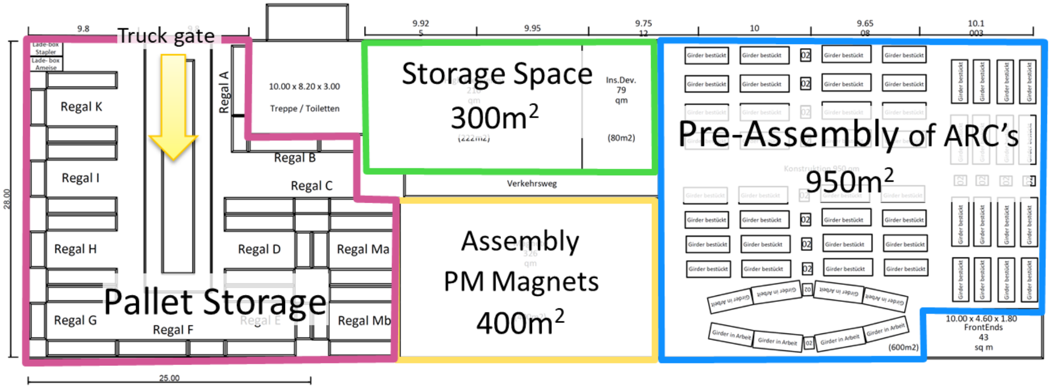
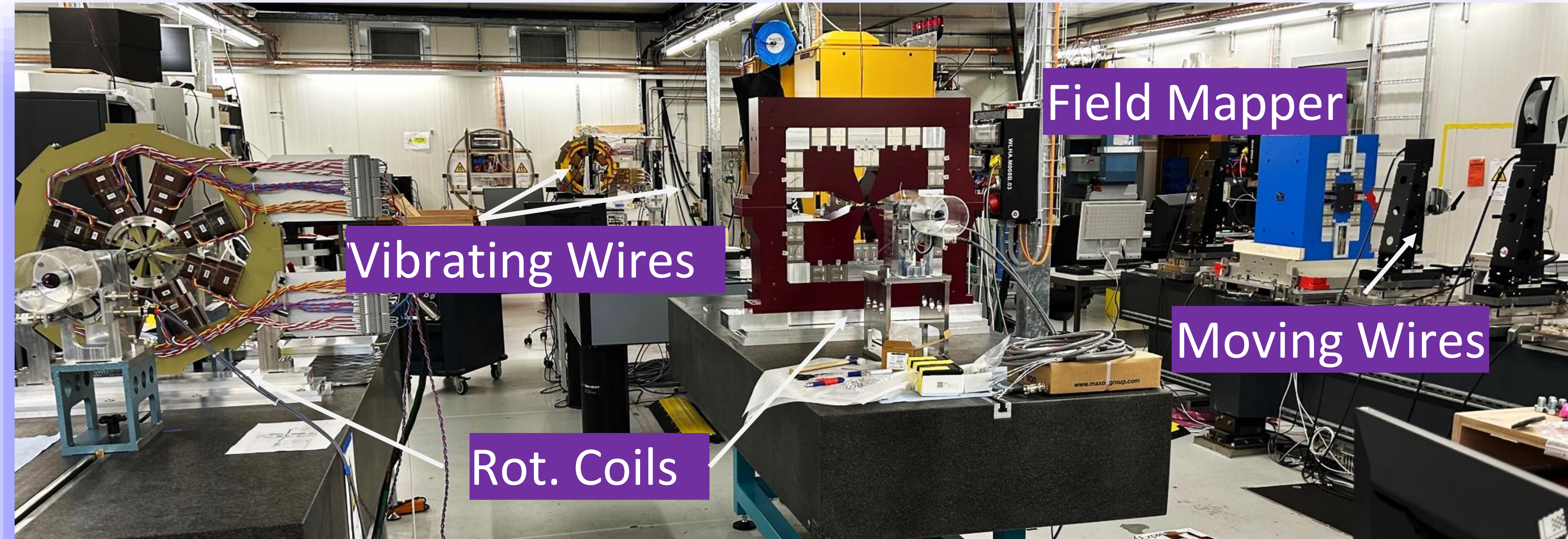
Challenge: Assembly of the 372 Permanent Magnets by PSI staff !



All the magnets are assembled

Infrastructure for SLS2.0 magnets: Magnetic Measurement Lab



Seven magnetic measurement benches are operational since september 2023

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

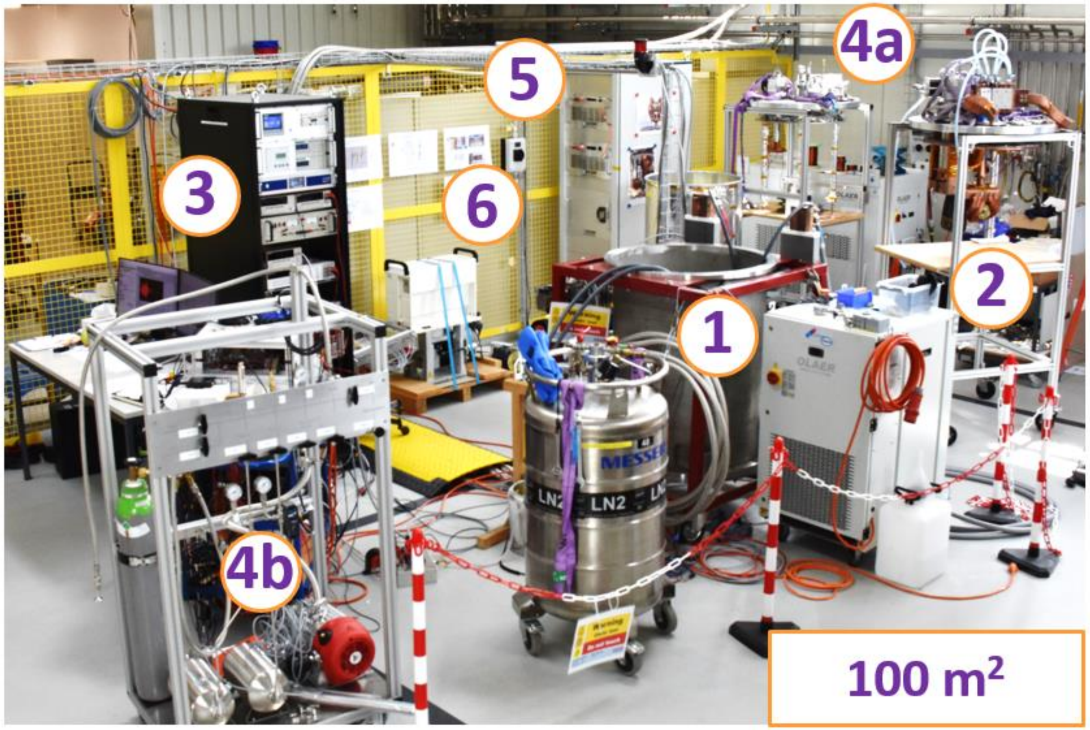
Test stand for superconducting magnets cooled with cryocoolers

CHART
Swiss Accelerator Research and Tec

PSI

Projects : SLS2.0 Superbends & HTS; PhP; P^3, HTS4…..

michal.duda@psi.ch



1: Cryostat

- Thermal radiation shield
- Vacuum pumps
- 3 Cryocoolers (RDK-415D/418D and RDK-500B)

2: Test setup for superconducting HTS and LTS coils

- RRR, T_C and th. cond. test
- NI HTS coils test (18.2 T)

3: Electronic rack

- vacuum control/monitoring
- temperature control/monitoring (16 Cernox/ Pt1000 sensors, PID controller)
- voltage signals recording (2 nanovolt/64 high precision/64 fast sampling channels)
- quench detection system (CERN uQDS with PSI modification)

4: Test setup for cryogenic pulsating heat pipes (PHP)

- 10 and 20 tube neon PHP (with VDL ETG)

5: 2 kA ± 10V power converter

6: Quench protection

- mechanical switch (~4 ms) with varistor

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

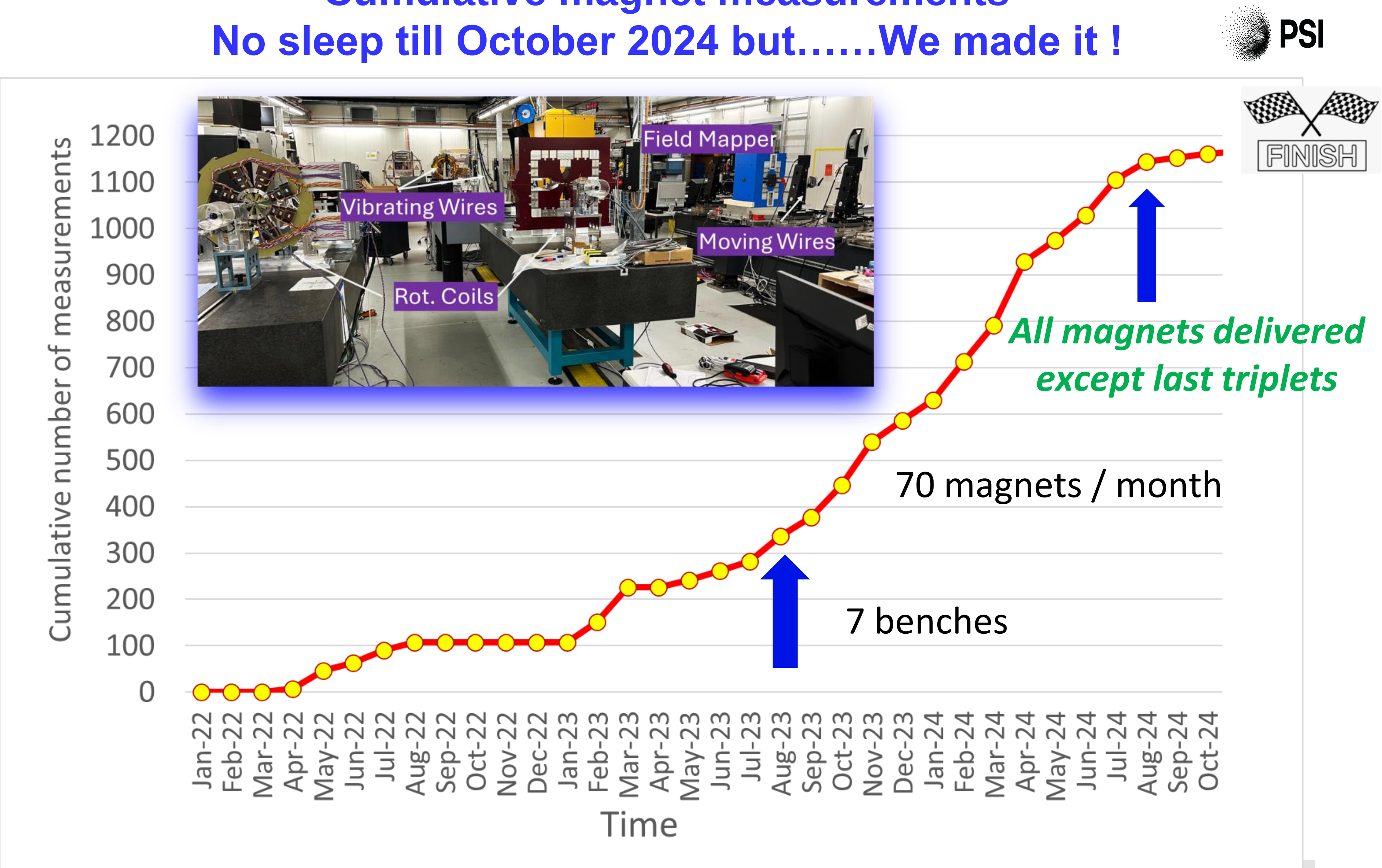
Reproducibliy : 1 unit

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

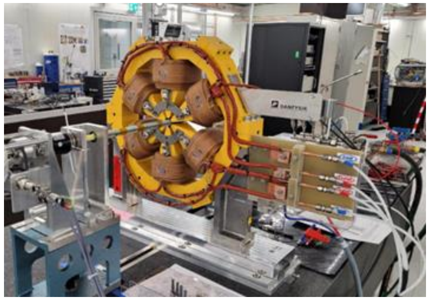
Cumulative magnet measurements
No sleep till October 2024 but……We made it !

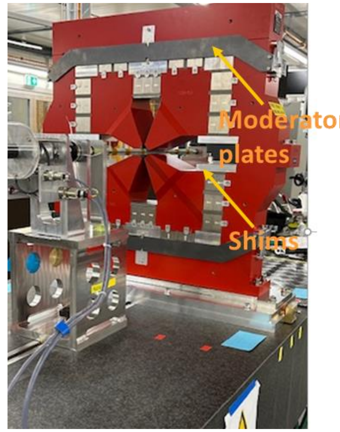


From September 2023 : all the 7 magnetic measurement benches operational

………Measurements completed end of October 2024 (6 triplets to be measured)

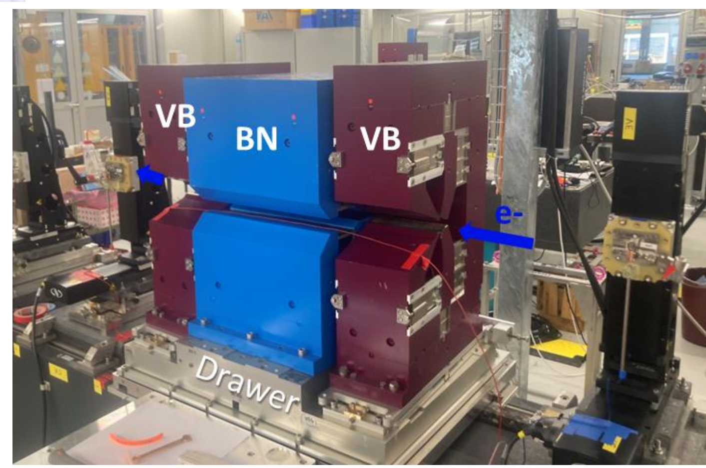
Magnetic measurements results (phase 1)





Sextupoles &Octupoles axis measurement
with vibrating wires:
Contribution M. Aiba

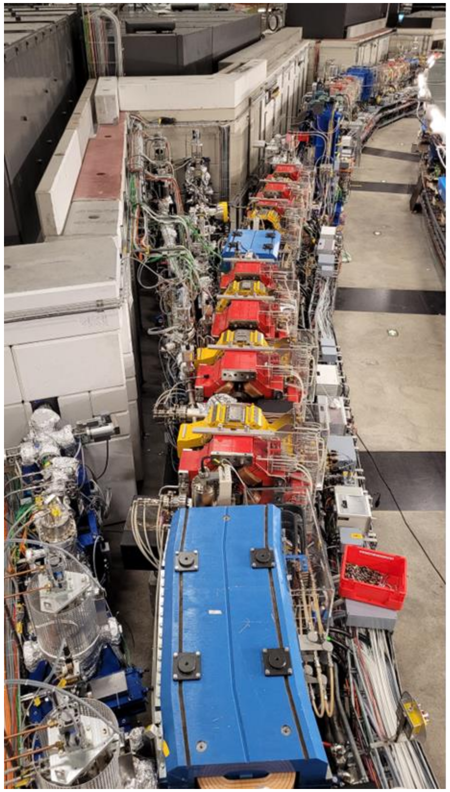
Field Quality and Field Integral tuning
with Rotating Coils:
Contribution C. Zoller

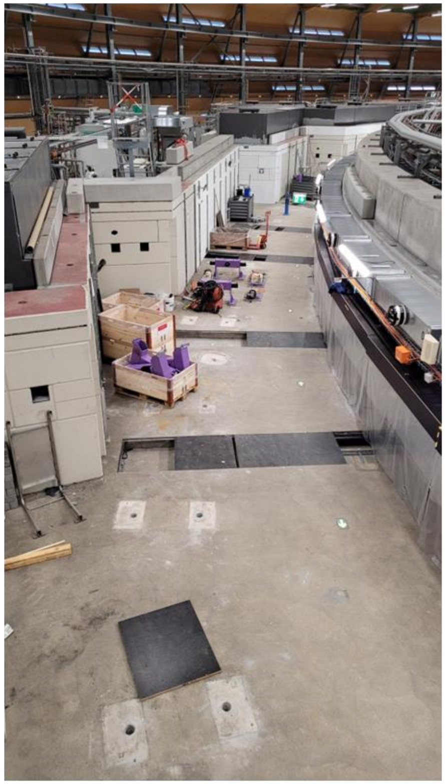


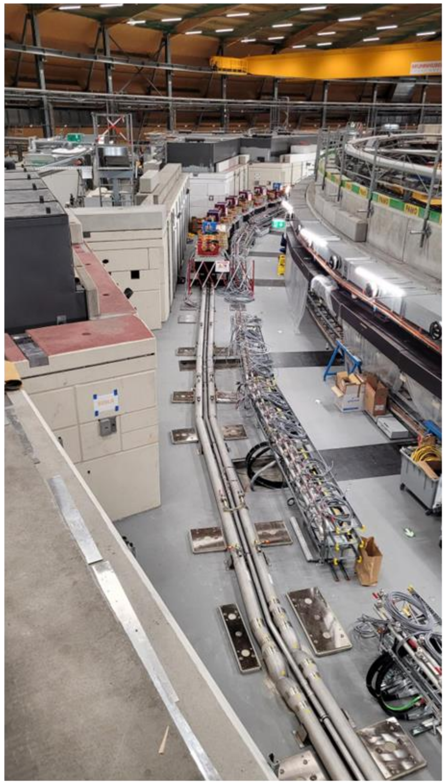
Magnetic coupling studies with Hall mapper
Contribution R. Riccioli

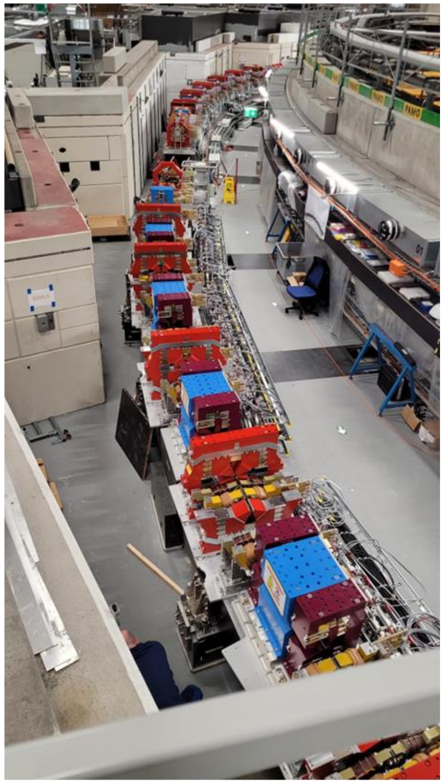
Triplet measurements and alignment
with Moving Wires
Contribution G. Montenero

SLS upgrade-the progress









03.10.2023	28.11.2023	07.03.2024	September 2024
Dark time start	End of dismantling	Installation Start	10 Arcs

Last triplet delivered and installed 1.11.2024

Visit of the SLS2.0 storage ring on Wednesday

Courtesy Romain Ganter

SLS2.0 with permanent magnets: 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 number of test benches: 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 in 2022)

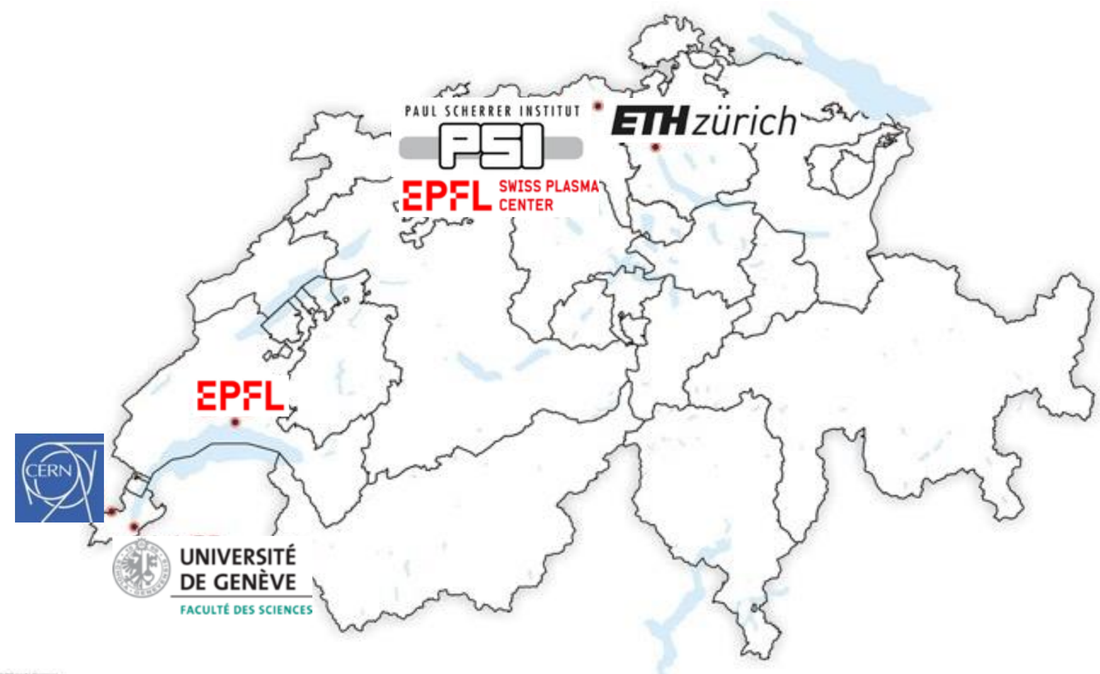
- Include the impact of neighboring magnetic components in the field integral tunning

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

R&D on very high field magnet technologies - CHART

mike.seidel@psi.ch

"CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of **advanced accelerator concepts in Switzerland beyond the existing technology**. […] The high field magnet R&D has strong synergies with PSI projects […]"
[Application for support of the Swiss Accelerator Research and Technology Initiative, 2018]



http://chart.ch

- Funded in **2016** as umbrella organization for accelerator research in switzerland
- **support FCC and develop future accelerator technologies**
- co-funded by **CERN, PSI, ETHZ, EPFL and University of Geneva**
- Support of the State Secretariat for Education and the ETH Board
- Home Institut : PSI
- PSI : **High field magnet technology and demonstrator design and construction**

CHART activities at PSI

bernhard.auchmann@psi.ch

Swiss Accelerator Research and Technology

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

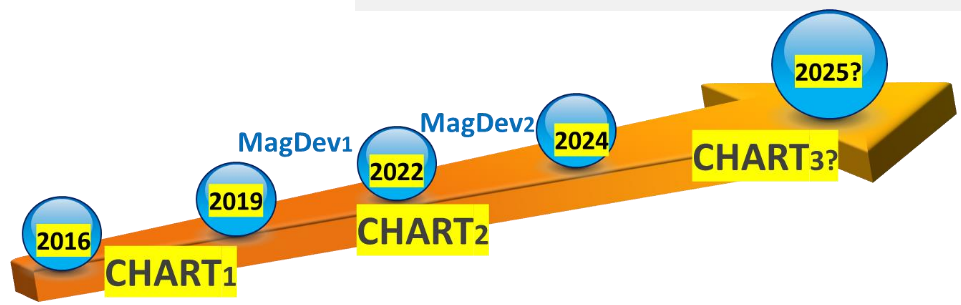
- T3.1: Manufacturing trials
  Partners: PSI
  Sub-contractors:
- T3.2: Subscale design, construction, and test
  Partners: PSI, LBNL
  Sub-contractors: EPFL-SPC
- T3.3: CDx construction and test
  Partners: PSI, LBNL, CERN
  Sub-contractors:
- T3.4: LTS HFM design studies
  Partners: PSI, CERN
  Sub-contractors:

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:

Technologies & demonstrators of High Field Magnets

- Magnet design
- R&D in LTS and HTS materials (key technologies)
- Coil winding and magnet assembly
- Infrastructure for LTS and HTS magnet assembly and test
- Synergies with technological development for Large Research Facilities at PSI



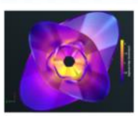
MagDev1 / MagDev2

Superconducting Accelerator Magnet R&D

Project MagMu

MagMu

Enabling Technologies for the Stable Operation and Protection of Final Cooling Solenoids in a Muon Collider

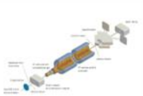


FCCee HTS4

FCC-ee High-Temperature-Superconducting Short Straight Section

HTS Bulk Undulator

High Temperature Superconducting Undulator for SLS2 Upgrade



FCCee Injector

Design and positron production test program for FCC-ee Injector

https://chart.ch/psi/

Achievements since 2018 : MagDev Laboratory

Visit on Wednesday

3: Thermal Treatment

- **Argon-furnace** (2-m-long coils)
- **Research tubular furnace**
  1-m-long, 14 cm diam.
  Quartz tube, vacuum or gas atmosphere up to 1100ºC

4: Chemistery workplace

- Spray-coating equipment.
- Ultrasonic cleaning
- Diamond wire saw.
- Polishing equipment.
- Optical microscope

5: Impregnation tools

- **Vacuum-impregnation vessel** for 1-m-long coils, vertical impregnation.
- **Autoclave** for 2-m-long coils, horizontal impregnation.
  250ºC, 10 bar.
  Mixing, degassing set-up
- **Box oven** for wax crystallization / epoxy curing

1: Magn. & Mech & CAD Design (7 mobile desks)

2: HTS & LTS coil manufacturing workplace

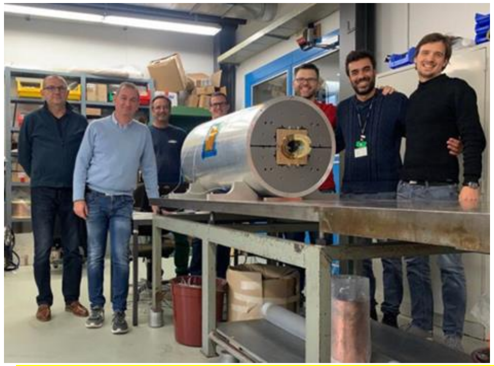
2 winding machines

6: Assembly tables

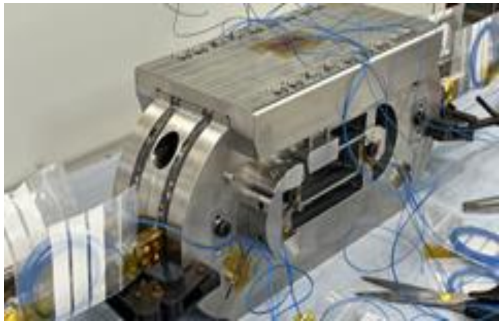
- Loading, welding
- Instrumentation
- 3D scanning metrology

Selected achievements since 2018 (2)

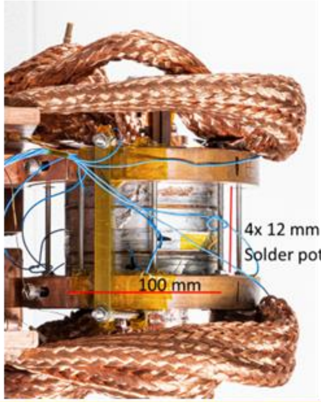
Swiss Accelerator Research and Technology



Canted Cosθ Nb_3Sn dipole

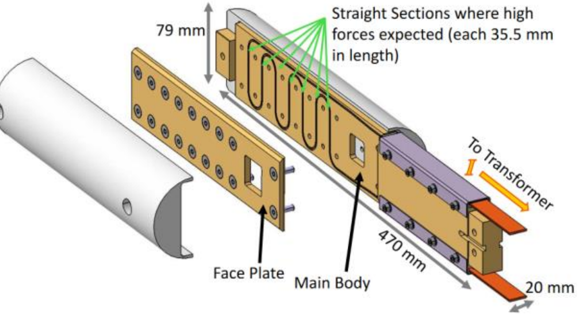


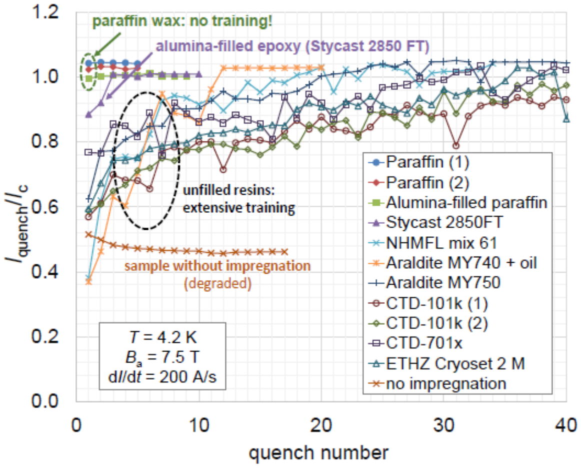
Subscale Nb_3Sn SM Common Coil

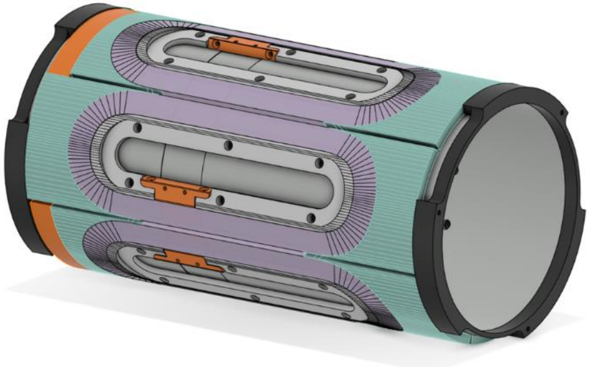


HTS Non Insulated coils

LTS Powered Samples BOX:
BOnding eXperiment (2019-2022)







Sextupole demonstrator, cosine-theta type with HTS coils for energy-efficient FCC-ee

And many mores at : https://chart.ch/chart-projects/ ….

Next challenges (2025-2030)

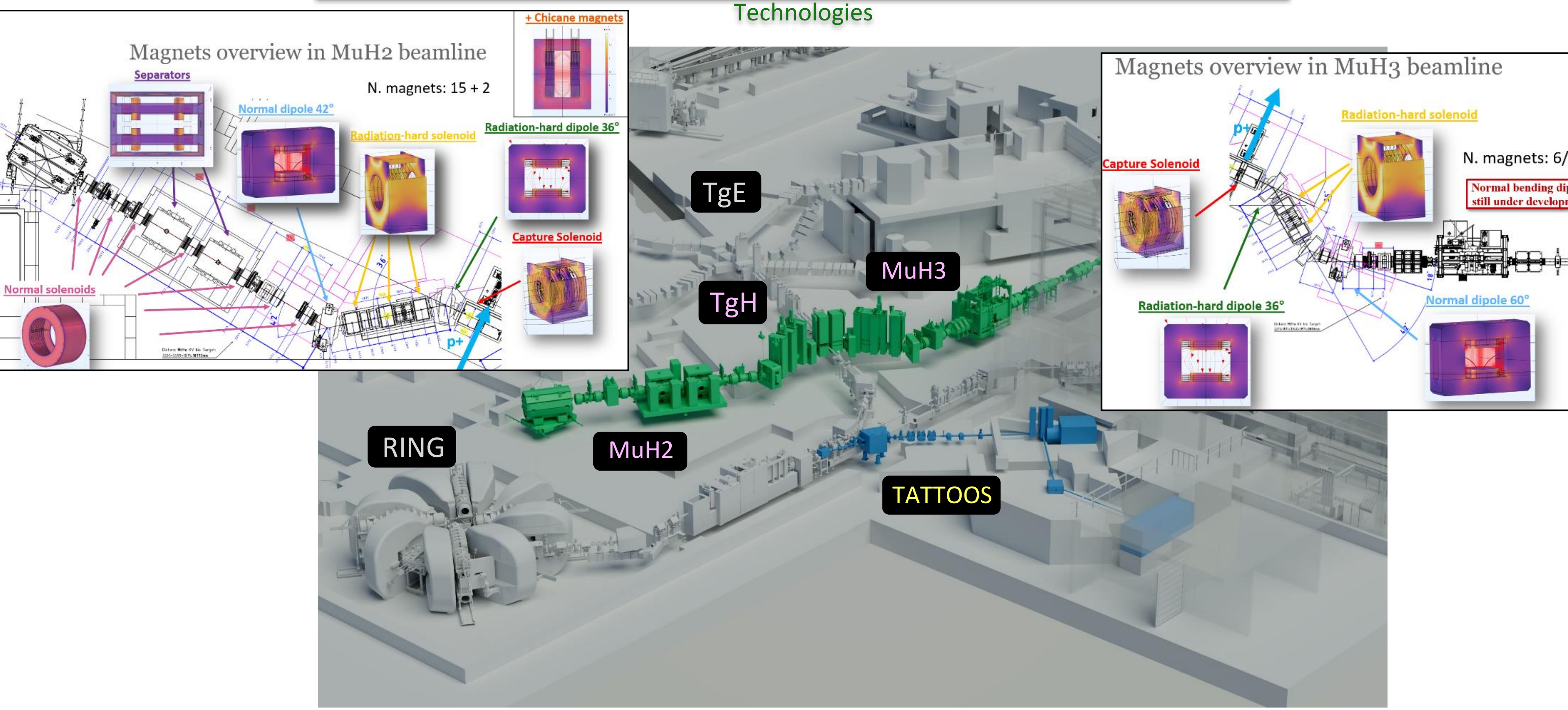
Project IMPACT

SMILE : Superconducting Magnets
Improving Large research facility Efficiency

HIPA Upgrade : magnets for the IMPACT Project

https://www.dora.lib4ri.ch/psi/islandora/object/psi%3A41209

IMPACT = Isotope and Muon Production using Advanced-Cyclotron and Target Technologies



- **HIMB : High Intensity Muon Beam Line (flux X 100)-2 lines (2027)**
- **TATTOOS: Radionucleïde for cancer therapy and diagnostics ($^{149/152}$Tb, ^{165}Er, ^{175}Yb,…..)- 2029**

~ 100 people from 5 PSI divisions are involved

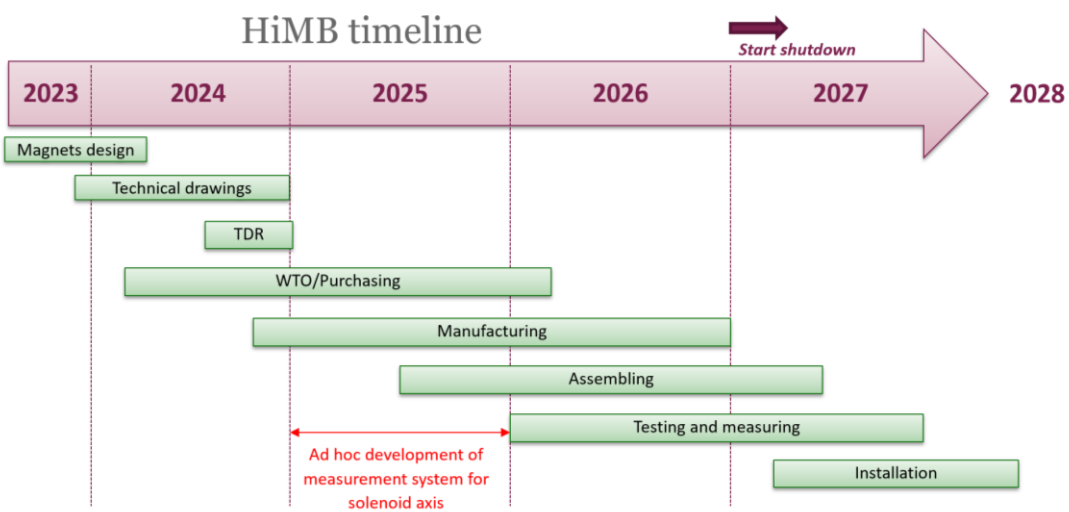
9 subprojects and 35 working groups

HIMB magnets status overview

PSI

	EM design	Mechanical design	Next Steps
Capture solenoid	Completed	In progress : 60 % (Coils 75%, yoke 50%)	1) Cooling calculation 2) WTO for coils
Rad.-hard transport solenoid	Completed	Concept: 20% (coils: 75%)	WTO for coils (together with capture Solenoid)
Normal transport solenoid	Completed	In progress : 90 %	3 2D drawings (coil, yoke, assembly)
Rad.-hard dipole 36°	Completed	In progress : 80 %	1) 2D drawings (ongoing) 2) Final definition of connections (coil is defined →WTO)
Normal dipole 40° and 60°	Completed	In progress : 90 %	3 2D drawings (coil, yoke, assembly)
Chicane magnets	Completed	In progress : 90 %	3 2D drawings (coil, yoke, assembly)
Separator	In progress : 80 %	X	Waiting for confirmation of magnetic design and max. field value

"Magnet designs for the High-Intensity Muon Bea Project (HIMB) at PSI's Accelerator Complex HIPA"
R. Riccioli et al., IEEE Transactions on Applied Superconductivity (2024)

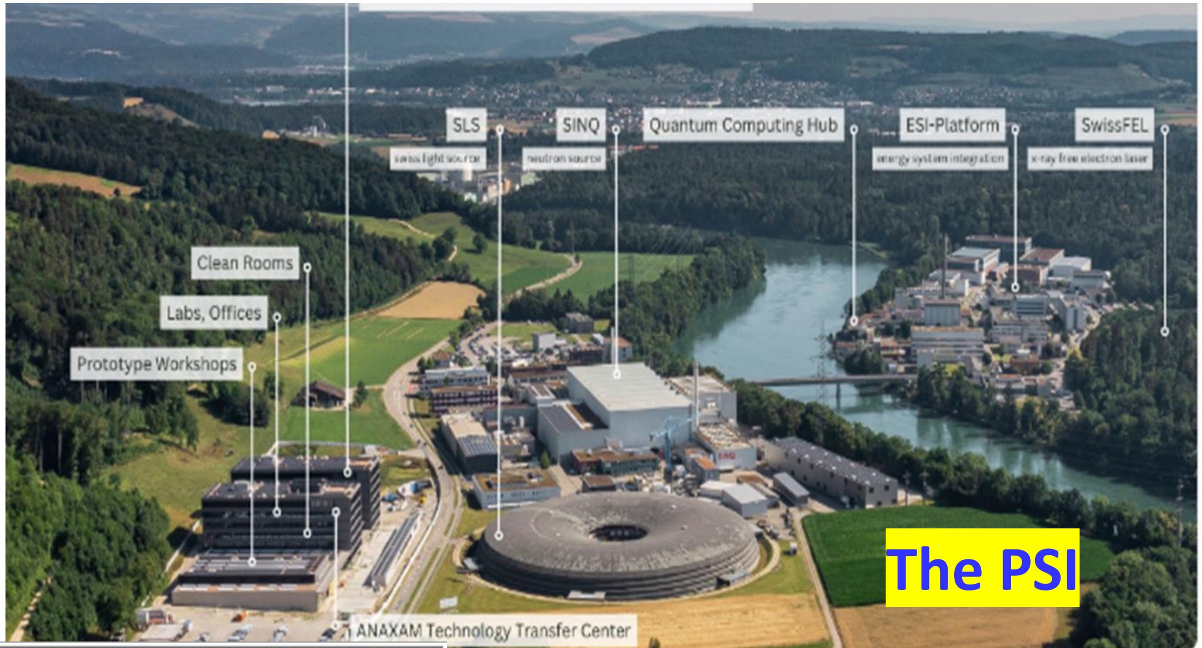


Magnet caracteristics

- Large aperture solenoids (diameter~0.5 m)
- Resistive magnets-first option
- Radiation hard conductors
- Field quality specs (0.1 % of uncertainty)
- Magnetic axis measurements?

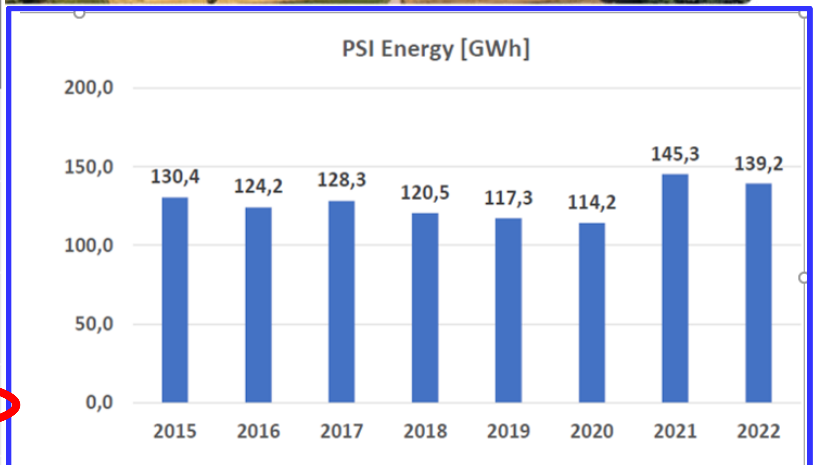
Superconducting magnets in PSI large Research Facilities: context

PSI

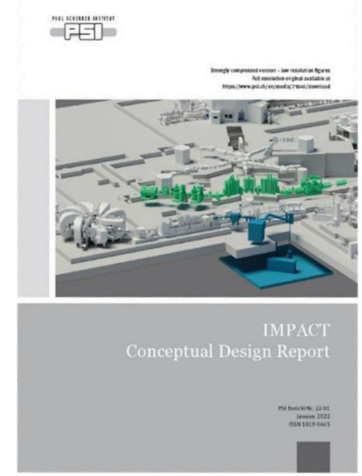


SLS2.0 2.4->2.7 GeV (2025)

European RI	per year
CERN	1300 GWh
ESS (S)	280 GWh
DESY (D)	175 GWh
PSI (CH)	140 GWh
ISIS (UK)	70 GWh



PSI peak power: 22.5 MW



IMPACT- HIMB (2027)

5 large-scale research facilities: the Swiss Spallation Neutron Source (SINQ), the Swiss Synchrotron Light Source (SLS), the Swiss Muon Source (SμS), the X-ray Free Electron Laser (SwissFEL) and Proton Therapy center with 2 upgrades (SLS2.0 and HIMB)-1384 Magnets

Approach for an energy transition of PSI magnets

PSI

- Low field, high density of magnets & low radiation (Light sources) → **permanent magnets**
- Moderate/high fields & ***high consumption*** magnets ***in highly radiative environment*** (proton accelerator) → **cryogen free superconducting magnets**

Normal condutors

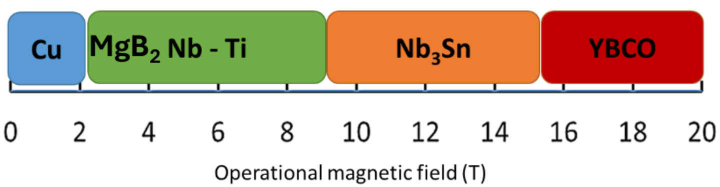
Omitting resistive loss

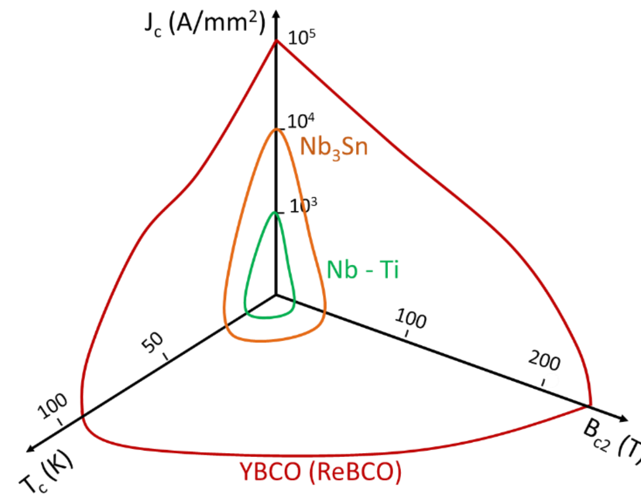
LTS

Lowering cooling cost

Higher magnetic fields

HTS





From Samira Fatehi, KIT, Germany

Aspects to consider :

1. Economical study (capital cost, power consumption,CO_2…)
2. Operating conditions (Field and Thermal budget -incl. beam deposited energy)
3. Radiation damages on superconductor and insulation

Power consumption management for the upgrades SLS 2.0 and High Intensity Proton Accelerator

PSI

Power economy SLS2.0 vs. original SLS (2019-2024)

ProKilowatt Programm des Bundesamts für Energie

Swiss Federal Program „ProKw“

- More radiated X ray power for users (2.4 GeV→2.7 GeV)
- Less electricity consumption:
  30 % of electricity reduction (24 W→17 kW)
- Key Savings: **Electromagnets → Permanent magnets**
  Klystrons → Solid state amplifiers
  standard pumps → modern pumps for cooling

372 permanent magnets (one third)

reduction of 60 % of the magnet consumption

High Intensity Proton Accelerator (SMILE project 2025-?)

- Required for the proton beam : 7.8 MW
- 350 resistive magnets in operation: 34 % power consumption (2.6 MW)
- On going upgrade → increase power consumption
- Magnets in operation (future replacement):

Study : High power consumption dipole in Operation AHO →Cryogen-free SC one

collaboration with LASA Milano

SMILE : Superconducting Magnets
Improving Large research facility Efficiency

PSI

Implement cost-efficient and sustainable superconducting magnets in PSI's large-scale facilities: High-Intensity Proton Accelerator and PROSCAN (proton therapy)

- Work-packages (numerical & experimental aspects & technology development)

  - DC Magnet design & construction (including radiation impact on HTS conductor)
  - AC Magnet design and production using selected low loss superconductors
  - Advance cryogenics study and implementation (Pulsating heat Pipes, efficient cyrocoolers…)

- ***Possible*** external partners (Institutions and companies)
  - University Alma Matter Bologna- AC losses numerical studies
  - CERN (cryostats for AC losses conductor studies)
  - Politechnico di Torino- radiation effects calculation and experimental tests
  - LASA UNI Milano – Magnet design
  - University of Aix Marseille – numerical calculation on PhP mechanisms
  - VDL company- Pulsating heat Pipes development

Program in preparation (not approved yet) – submitted to the PSI direction at the end of 2024

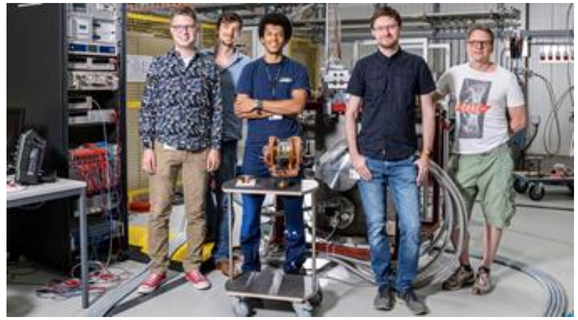
Summary

PSI

- The production and measurement of a massive number of magnets for the SLS upgrade Phase 1 were successful, and the magnet production for Phase 2 is currently ongoing.
- A tremendous effort was made to develop the infrastructure and parallelize magnetic measurements to comply with the specifications and meet the tight schedule.
- This project required meticulous planning and coordination, and a number of valuable lessons were drawn from this extraordinary scientific and human experience.
- As we move forward, the development of technologies for the design, assembly, and testing of superconducting magnets is becoming an increasingly significant part of our activities.
- Future challenges we are focusing on include the development of high-field, compact, low-consumption, and sustainable magnets.
- Bright prospects are on the horizon, particularly through our collaboration with our partners at Park Innovaare.

PSI

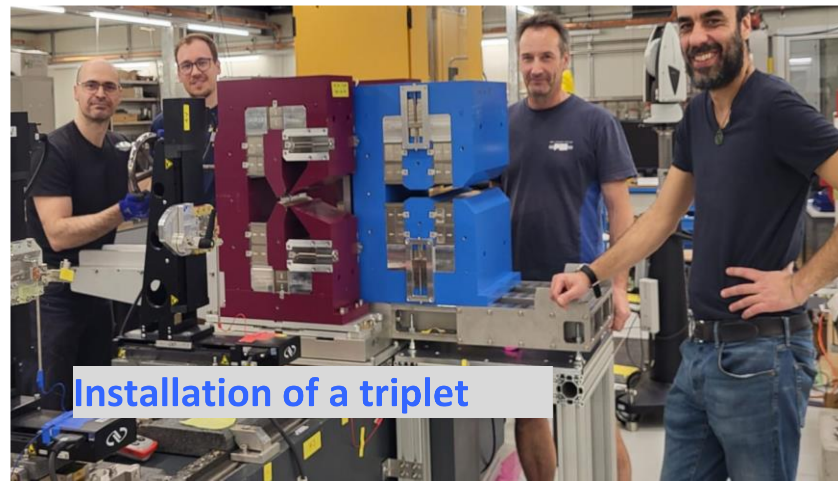
Training of the team for rotating coils



18 T@10 K with 4 NI HTS coils

Celebrating the Nb_3S_n Subscale

Successful measurement of Sextupoles Octupoles axis



Installation of a triplet

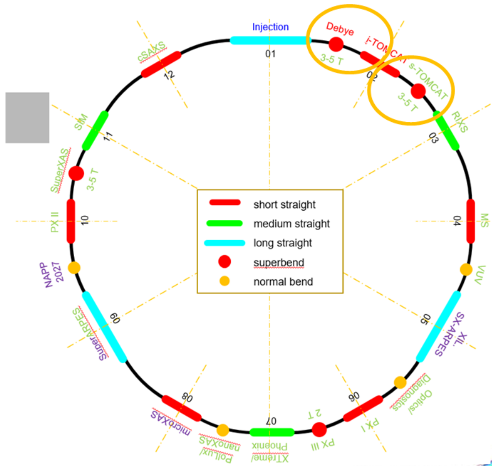
Dedication, Setbacks, Unexpected Turns, Achievements, and…. Challenges

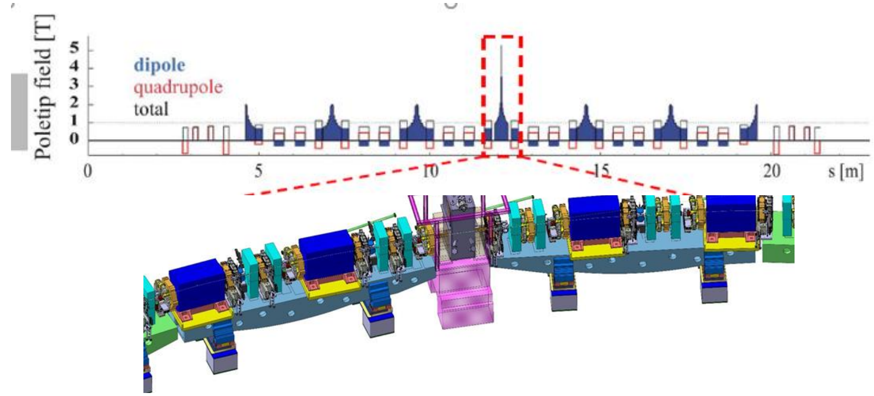
Join the magnet section

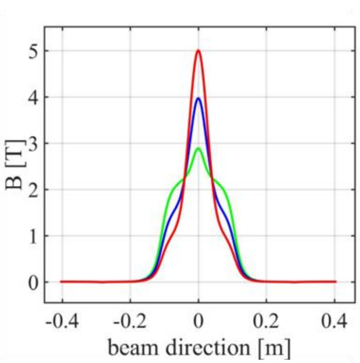
Thank you for your attention

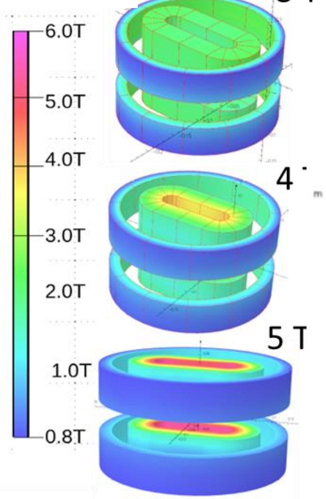
Additional slides

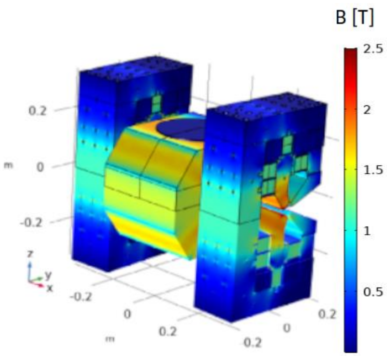
5 T superbends- phase 2 (2026)

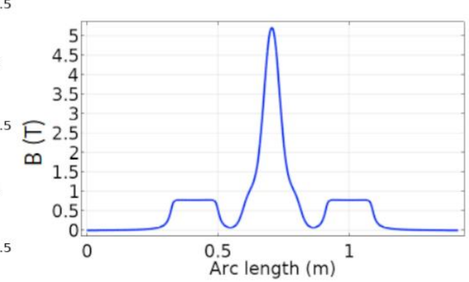


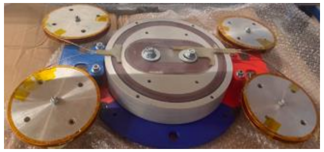


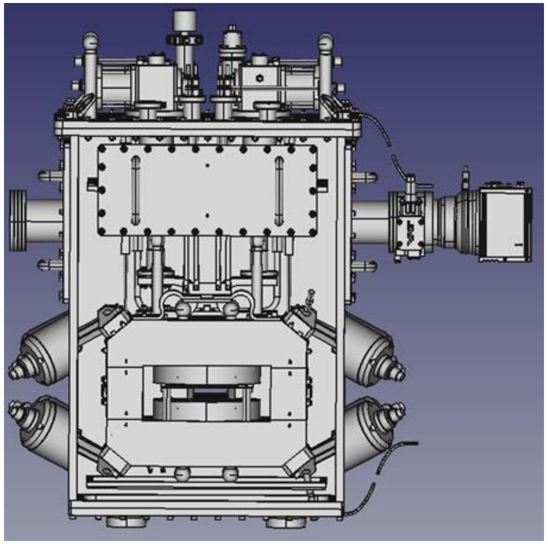












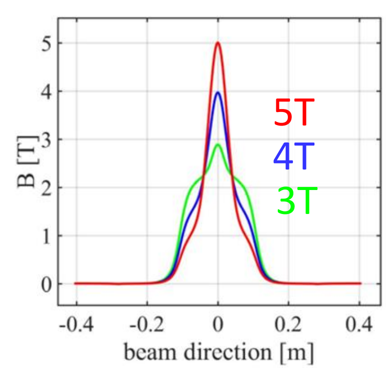
- 2 superconducting dipoles to provide hard X-rays at two beam lines
- Operating fields between 3 T and 5 T
- 2 pairs of Nb-Ti coils (racetrack, solenoid)
- Close yoke with soldered vacuum chamber
- *SC test coils in Fall 2024*
- *Magnet delivery (Jan-June 2025)*
- *Power and Magnetic tests (Hall Mapper) in 2025*

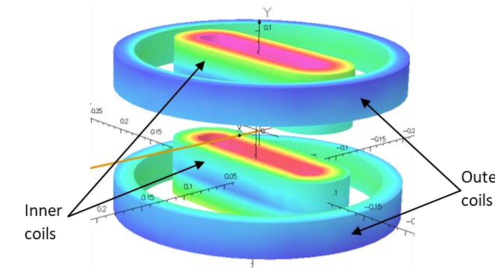
Phase 2: 5 T superconducting superbend

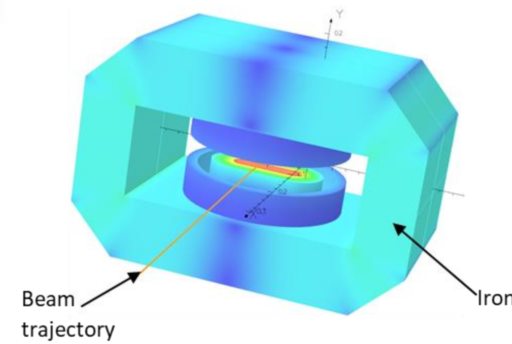
ciro.calzolaio@psi.ch

PSI

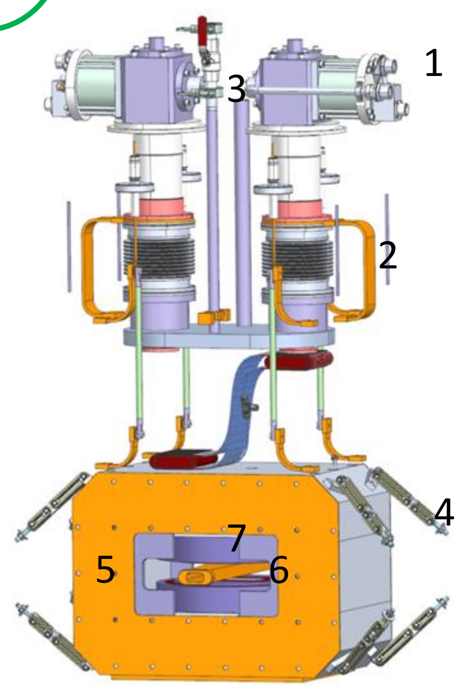
- Conduction cooled concept (2 cryocoolers)
- 2 pairs NbTi coils (racetrack, solenoidal)
- Two 200 A power supplies to adjust current (field)
- T_{op}~4.5 K
- 2 HTS -110 current leads (500 A@64K)
- ARMCO yoke (close geometry)
- Beam pipe included in the magnet assembly



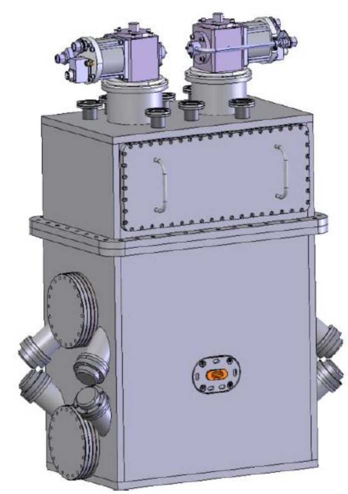




	Main magnet components
1	2 cryocolers RDK-415D
2	Thermal connections
3	Current leads (Cu+HTS)
4	Suspension straps
5	Armco Yoke
6	Vacuum chamber
7	Pair of NbTi coils inside the Al precompression ring



Cold mass



Cryogenic power tests and magnetic measurements @ PSI in a dedicated test stand

Example : Impact of the vacuum pump

PM Quadrupole

Vacuum pump

(ferrite magnets)

Reduction of 0.3 % of the Field Integral

Vertical shift of the magnetic axis position by 60 micrometers

Practical example: High Intensity Muon Beam project: Estimated Magnet Consumption (MuH2&3)

PSI

Location	Magnet	Number of magnets	Power per magnet	Total power
MuH2	Capture Solenoid	1	142.5 kW	142.5 kW
	Dipole	1	3.2 kW	3.2 kW
	Transport Solenoid (A-B)	3	37.5 kW	112.5 kW
	Dipole	1	2.4 kW	2.4 kW
	Transport Solenoid (C)	6	17.9 kW	107.4 kW
	Separator	2	0.45 kW	0.91 kW
MuH3	Capture Solenoid	1	142.5 kW	142.5 kW
	Dipole	1	2.3 kW	2.3 kW
	Transport Solenoid (A-B)	2	35.5 kW	71 kW
	Dipole	2	3.1 kW	6.2 kW
	Transport Solenoid (C)	2	15.4 kW	30.8 kW
General	Other magnets	2	5 kW	10 kW
	Cable resistance	3%		
TOTAL				632 kW

Power consumption goes from 120 kW to 632 kW of the new lines

1) Capture solenoid : Superconducting HTS tentative **not successful** because of lack of space for thick radiation shields

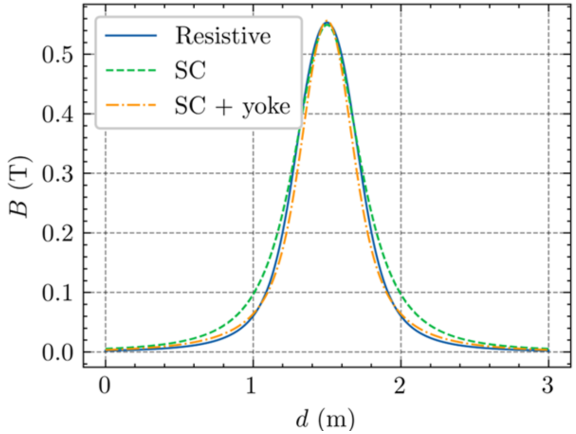
2) Second choice**: transport solenoids** (13 in the two lines positions A,B,C)

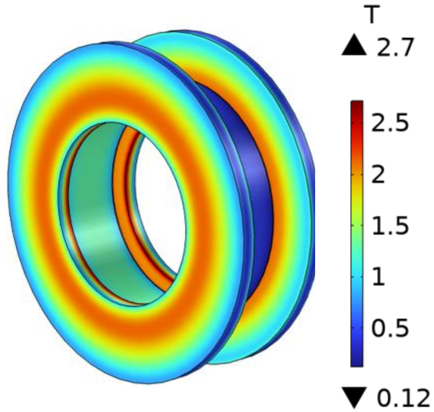
Study for a NbTi (and HTS) superconducting option

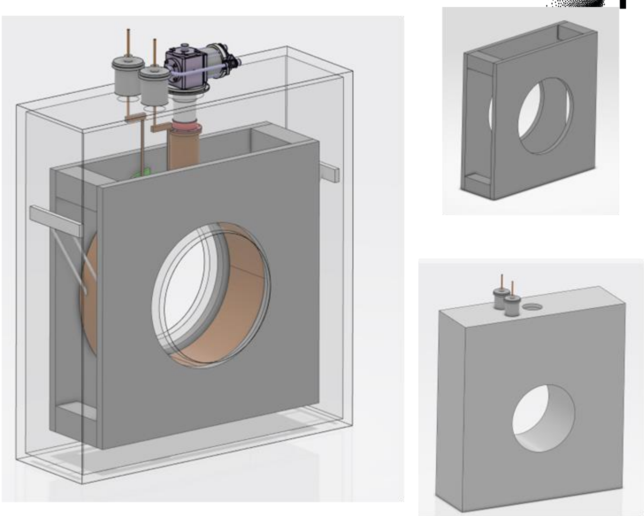
L-Università ta' Malta
https://www.um.edu.mt

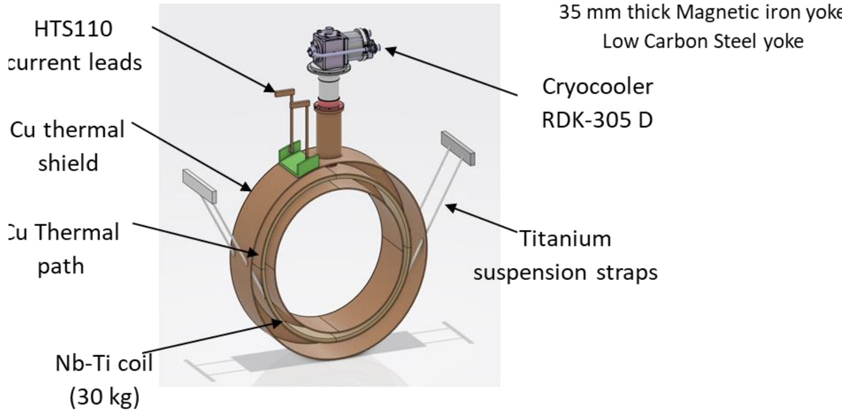
HIMB Transport solenoids- NbTi option study

Aperture (inner)/length	650 mm/300 mm
Max current (80 MeV/c)	93 A (with yoke)
Max Mag. Field (80 MeV/c)	0.55 T
Field Integral/Peak field	0.310 Tm / **1.46 T**
Turns number	2760
Operating Temperature	**4.5 K**
Cryocooler RDK-305D	**1** (3.6 kW)
Load-line and Temp. margin @1T	**72 %, 3-4 K**









Problematics in PSI facilities :

- Energy deposited by beam (T-margin)
- Radiation damage on insulation and superconducting coils (>20 years)
- Energy savings (Capital cost vs electricity savings)
- Sustainability (CO_2 emission reduction)

Decision for a potential implementation by the direction end of 2024