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# *HTS technology development for energy efficient magnets in PSI Large Research Facilities*

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Motivation and context
Projects and R&D programs
Technological bricks and infrastructure
Overview of the on-going R&D PSI activities

**IPAC'26 – the 17th International Particle Accelerator Conference**

# Motivation and context

# Improved performance and energy transition: a major challenge

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The energy transition of key components in large research infrastructure is essential : Future facilities = high performance, economically viable and environementally sustainable

## Several ambitious programs and events in Europe

- Innovation Fostering in Accelerator Science and Technology (**I.FAST**)
  Work Package 11: Sustainable Concepts and Technologies
  **https://www.psi.ch/en/scat**

- ESABLiM project, Energy Saving Accelerator and Beam Line Magnets
  INFN- LASA (Laboratori Acceleratori e Superconduttività Applicata)- Milano

  UNIONE EUROPEA Fondo Sociale Europeo PON

- SuperEML : HTS magnets for very high fields with energy reduction- EU project H2020-INFRADEV-01-2019-2020 with 10 partners, coordinated by the LNCMI.

- EPITA (Enabling Partnerships for Innovation & Accelerator Technology advancement) : Enabling + emerging technologies for accelerators including HTS , prototype systems, energy efficiency and sustainability- EU project consortium with 16 countries+ CERN+ESS, 43 beneficiaries.

- iRIS (Intelligent Research Infrastructure sustainability ): Sustainability methodology + pilots in Resarch Infrastructure components with AI- HORIZON-INFRA-2025-01-TECH-01 (2026-2029)

- ESSRI : Series of workshops for Energy for Sustainable Science at Research Infrastructures workshops

# Large Research facilities & CPT at PSI

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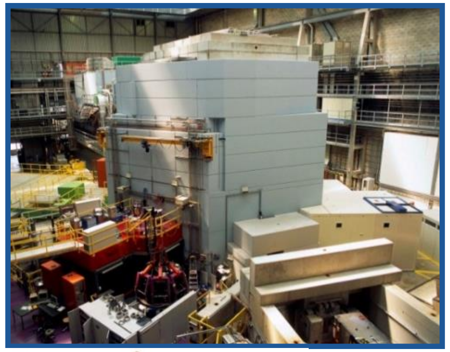
**Engines of discovery= *Machine generating “probes” to examine the matter structure***

## High Intensity Proton Accelerator Complex

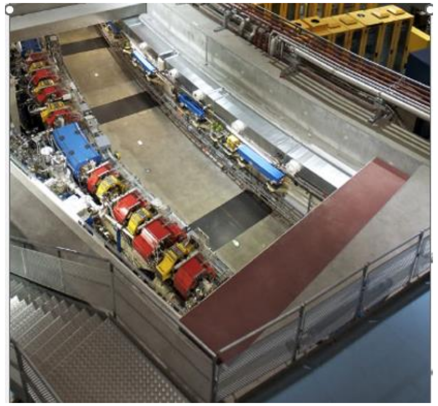
**590 MeV Proton Cyclotron**

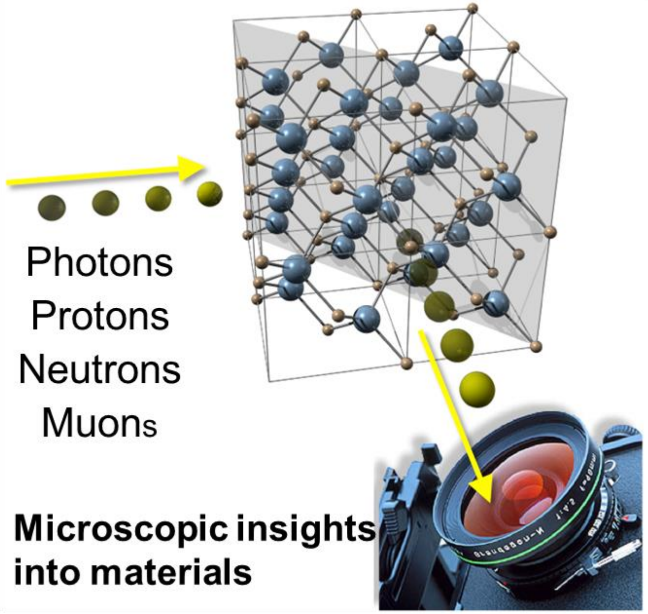
**Spallation Neutron Source (SINQ)**



**Swiss Muon Source (SμS)**

**Swiss Light Source (SLS 2.0)**

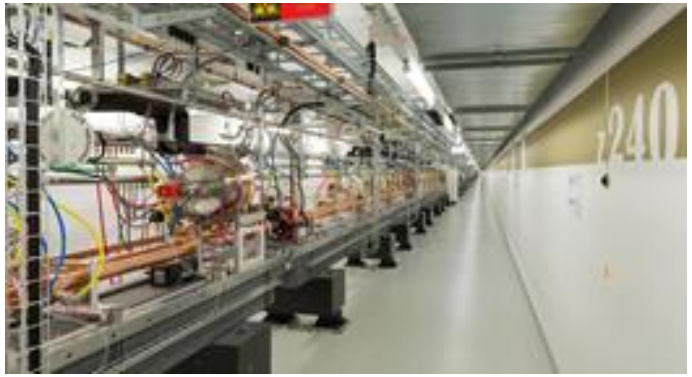





**Microscopic insights into materials**

**Protons beam therapy**

**Swiss Free Electron Laser (SwissFEL)**



# Energy Management in PSI Large Research Facilities – Operation and Upgrade

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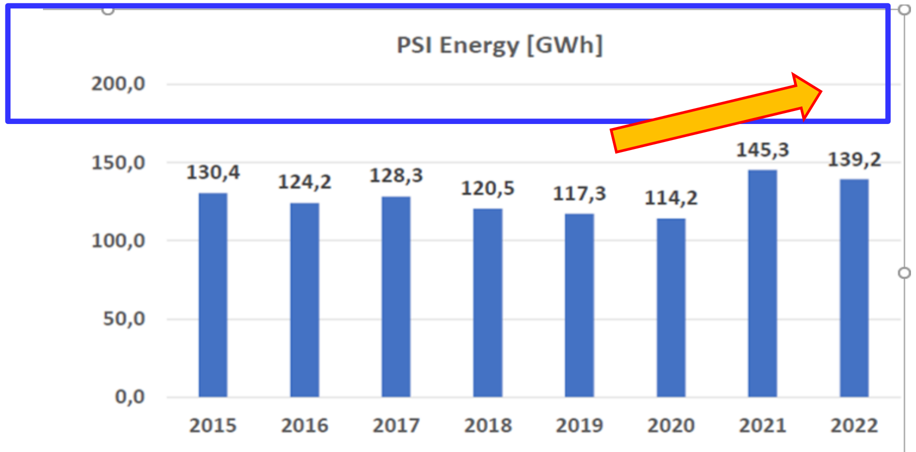
## High Energy Demand of PSI Large Research Facilities:

- High Intensity Proton Accelerator (HIPA)
- Swiss Free Electron Laser (SwissFEL)
- Swiss Light Source (till October 2023)
- PROSCAN- Tumor treatment facility using protons (2 beamlines with gantries)

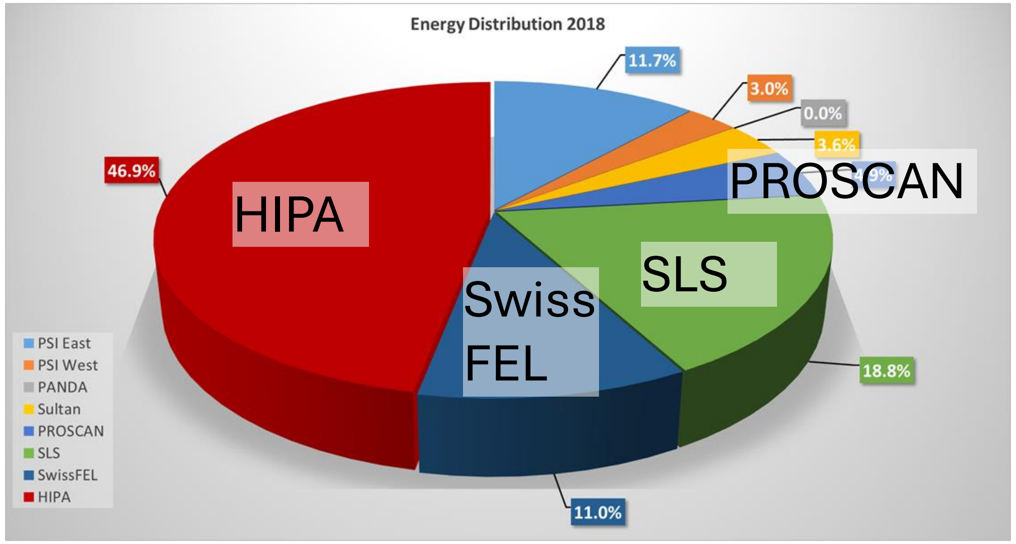
Strong contribution from resistive magnets to power consumption (HIPA -2.6 MW, 26 %)

## Trends

- Expected Increase in electricity cost
- Growing $CO_2$ Footprint

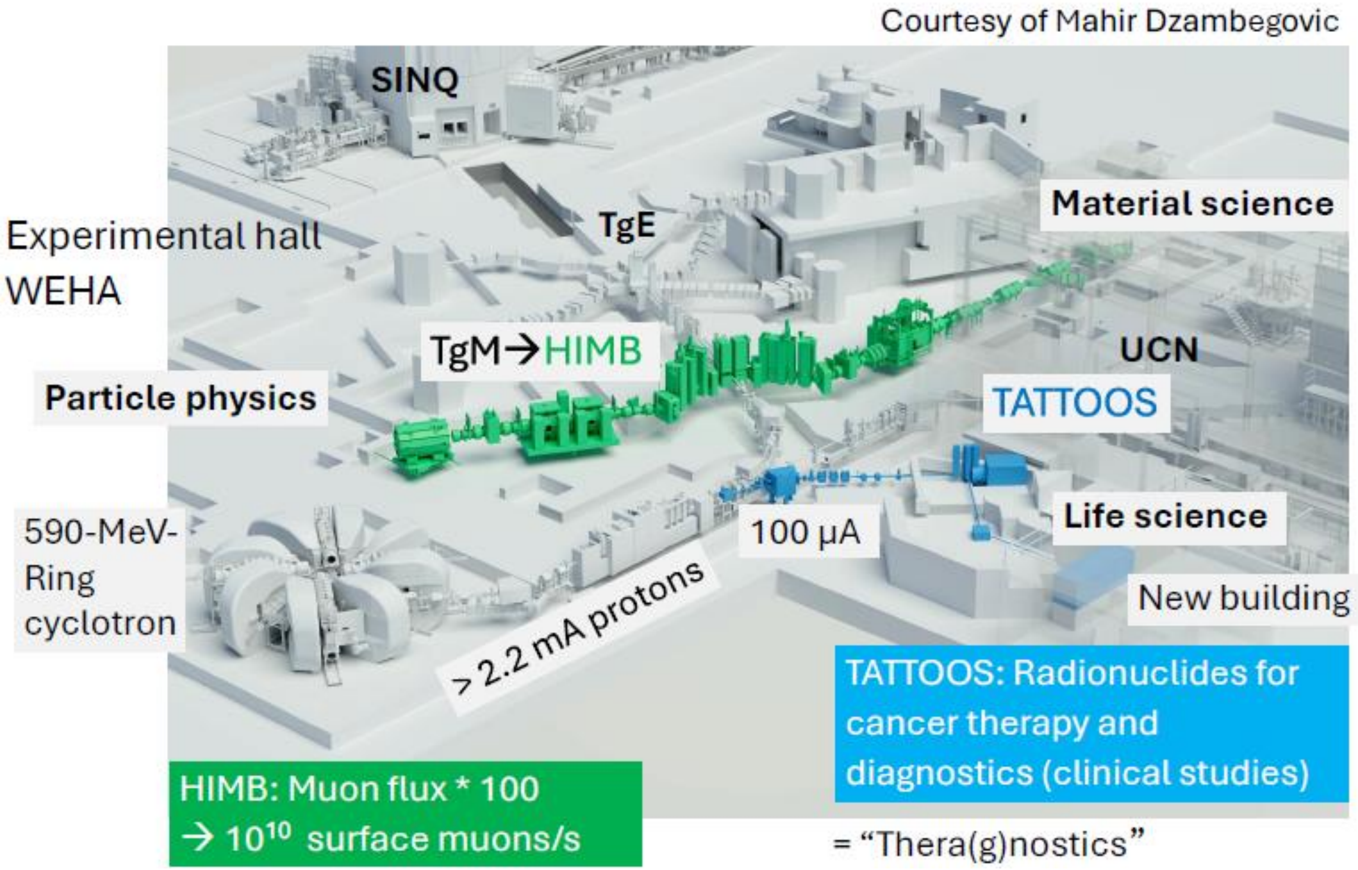



PSI peak power: 22.5 MW




***PSI energy / year ~ 140 GWh***

# Upcoming upgrade of HIPA
# Project IMPACT = HIMB + TATTOOS





https://www.dora.lib4ri.ch/psi/dload/psi:78449/PDF/Aeschbacher-2025-IMPACT_technical_design_report-(published_version).pdf

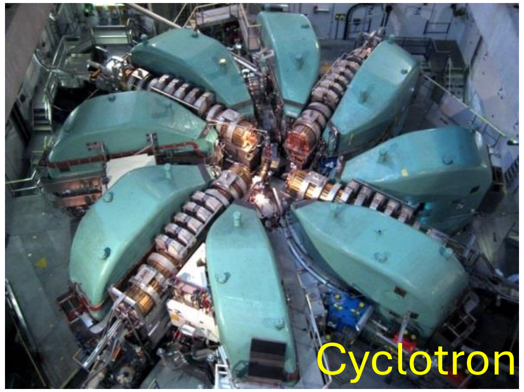
**Timeline of IMPACT:** 2027/28 HIMB installation ; 2029/30 TATTOOS installation

New target two new beam Lines at HIPA
- to increase the Muon rate production by a factor 100 **(HIMB)**
- create radioisotopes suitable for advanced cancer treatments **(TATTOOS)**

# Magnets in operation at PSI end of 2025

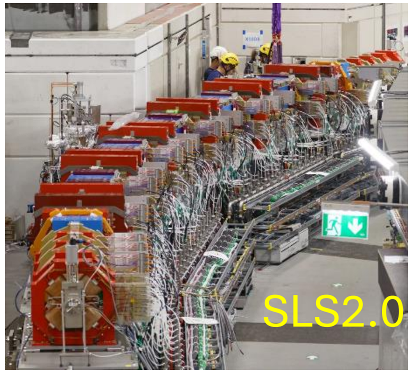
## Magnets in Operation at PSI

| *Machine* | *Magnet number* | *In operation since* |
|---|---|---|
| HIPA | 300 | 1974 (Ring)<br>1984 (Inj. II)<br>1996 (SINQ) |
| PROSCAN | 100 | 2004 |
| *Gantry 3* | *13* | *2017* |
| *SwissFEL* | *373* | *2017&2021* |
| *SLS2.0* | *1019* | 2025 |
| *Total* | *1805* | |
| *HIMB*<br>*TATTOOS* | *34* | *2027 & 2029* |



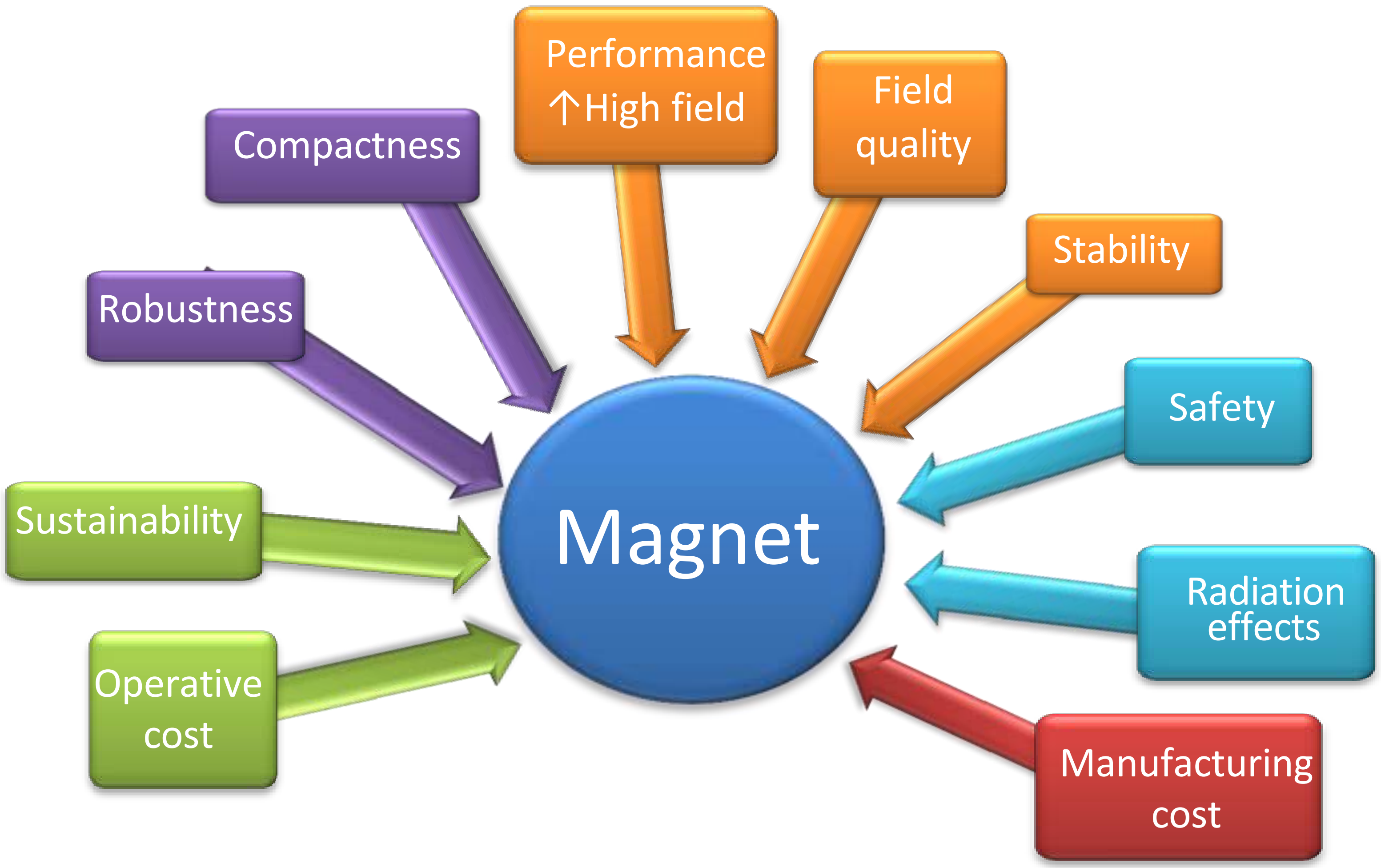





80 % are Electromagnets - 385 Permanent Magnets (SLS2.0)+ one superconducting cyclotron

# Requirements for Accelerator Magnets in 21st-Century Research Facilities




***Operative cost : Electricity and maintenance***

***Robustness : Manufacturing quality + radiation damage***

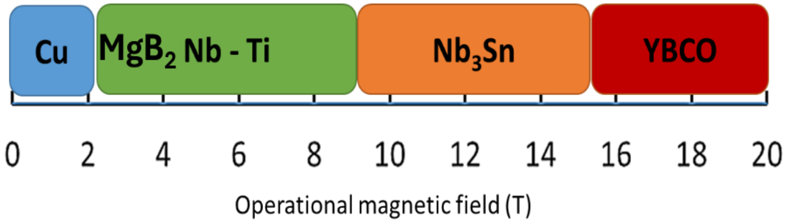
# Energie Transition for the PSI accelerator magnets: The proposed strategy

| Starting Situation | Proposed Solution |
|---|---|
| Low field<br>High magnetic density<br>Low radiation (e.g. Light Sources) | **Permanent magnets (NdFeB)**<br>(applied in SLS2)-PROkW program |
| Moderate/high field<br>High energy consumption<br>Highly radiation-exposed environment | **Superconducting magnets-conduction cooled** |

Copper → LTS → HTS

No ohmic losses

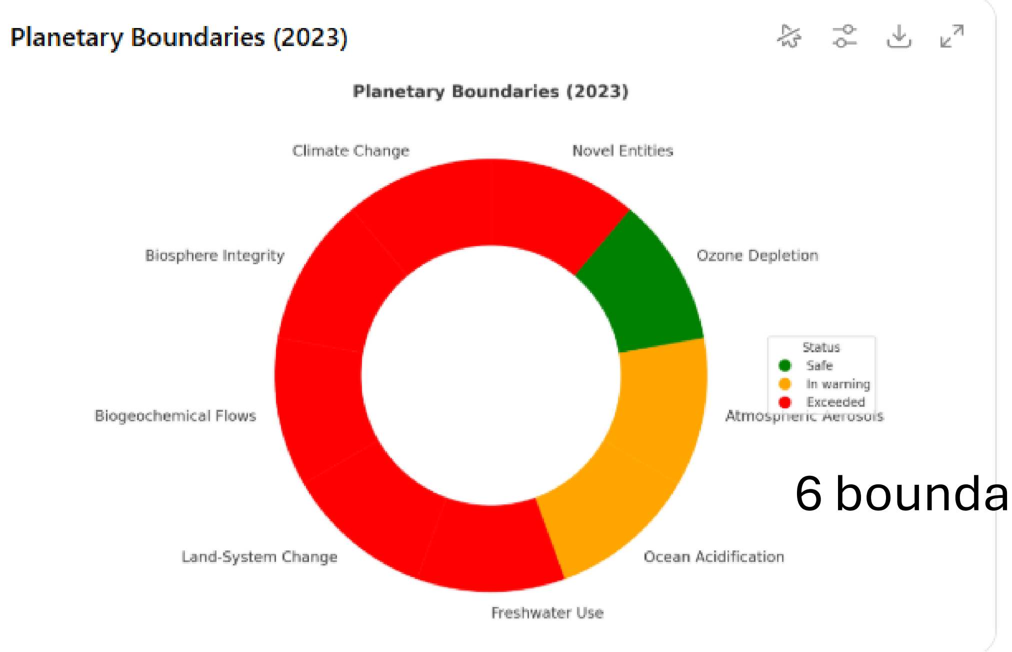
Reduced cooling costs
Higher magnetic fields




***Factors:***

1. **Operating conditions:**
   - Field strength
   - Beam energy deposition
   - Space
2. **Economics:**
   - Initial capital cost
   - Cost saving in electricity
   - $CO_2$ emission reduction
3. **Radiation damage**
   - Superconductors
   - Insulation

# Energy Transition for the PSI accelerator magnets
# And …. sustainability?




6 boundaries exceeded (2023)

*Johan Rockström et al, Nature 2009*

- **Production phase**→ negative impacts on planetary boundaries (water, materials, extraction pollution….)
- **Use phase**→ positive impacts, energy savings, footprint reduction, supporting medical application

The choice of REBCO tapes, insulation, impregnation, soldering, coatings, copper stabilizers and cryogenic components should also be evaluated through **LCA**

***Factors:***

1. **Physics and performance:**
   - Operating conditions ($J_{ce}$, $T_{op}$)
   - Field strength beam energy deposition
   - AC losses &Field Quality
   - Space
2. **Economics & strategic**
   - Conductor cost and availability
   - lifecycle costs (CAPEX vs OPEX)
   - long-term compatibility with upgrades.
3. **Environmental &Reliability**
   - Radiation dammage
   - Quench protection
   - Cooling & powering
4. **Sustainability**
   - LCA on raw materials
   - Process and manufacturing
   - Recyclability
   - Reduced waste protocols

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# HTS (conduction cooled) superconducting magnets Versus resistive and LTS ones

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| Advantages | Drawbacks |
|---|---|

**Resistive magnets**

**Advantages**

- Increased performance
- Compact design
- Saving electric consumption
- Reduced cost for power supply

**Drawbacks**

- Higher capital cost
- Cryogenics
- Quench detection system

**LTS magnets**

**Advantages**

- Thermal stability
  *Large temperature margin*
  *(including beam deposited energy)*
- Top>20 K
  - *Smaller $P_{electric}$ /$P_{cryogenic}$ ratio*
  - *Reduced thermal losses*

**Drawbacks**

- Not multi-filamentary architecture
  *Reduced field quality*
- AC losses in time varying field
  - *Hysteresis loss*
  - *Eddy currents*
  - *Coupling currents*
- Radiation damages
  - *Limits for superconductor operation?*
  - *No organic insulation*

# LTS & HTS technology development : The fundational diagram

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Vision

Performance & compactness
Energy savings & sustainability ($C0_2$ reduction)
Cryogen free →Helium free ?

Technology bricks

ReBCo tapes technology &Low loss cables
Radiation hardness & impregnation
Stress management structure
Efficient quench protecion
Cryocoolers +Pulsating Heat Pipes
Cryogenic power supply

Projects & Programmes

CHART
SMILE, HTS4SRI

Sub-scale Prototytpes

High field coils & magnets
Radiation hard dipoles
HTS solenoids
Efficient combined function magnets
Low field superferric HTS magnets
Infrastructure (fabrication & tests)

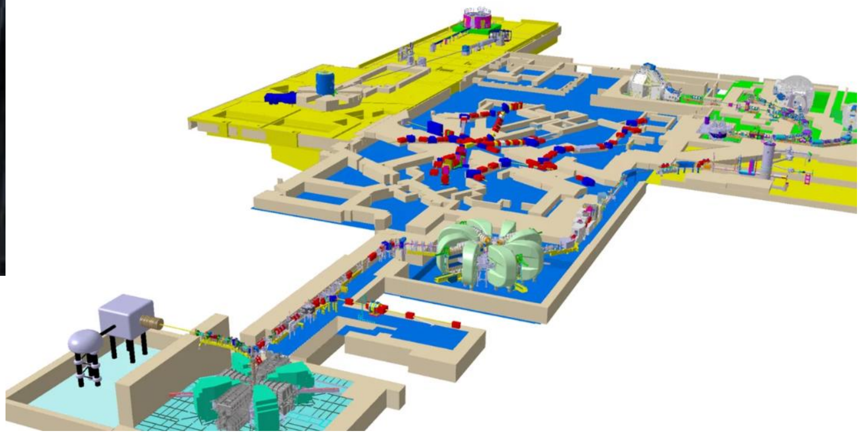
Machine Integration

SLS2.0, IMPACT
PSI beam lines

*Inspired from J.F Becquaert*

# Efficient Magnets in the High Intensity Proton Accelerator

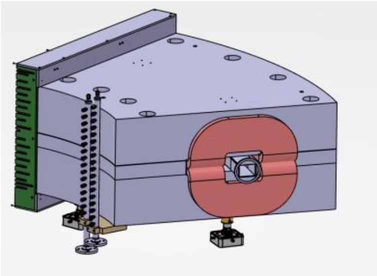




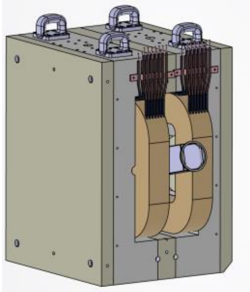
3 Accelerators and 4 Users facilities
Power from the magnets : 2.6 MW- 26 %

**Long term plan : Replace progressively high consumption resistive magnets with HTS magnets**

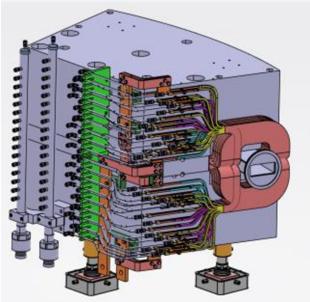
# Efficient Superconducting Magnets in the High Intensity Proton Accelerator



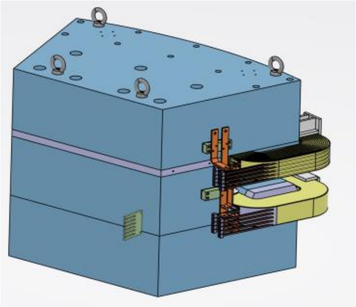
| AHC | |
|---|---|
| Power | 128 kW |
| Field | 1.564 T |
| Integral | 2.8 Tm |
| Size | 2x1.5x0.8 m |
| Weight | 12.5 t |



| AHM, AHN | |
|---|---|
| Power | 67 kW |
| Field | 1.5 T |
| Integral | 3.75 Tm |
| Size | 2x1.5x1.2 m |
| Weight | 22 t |



| AHB | |
|---|---|
| Power | 189 kW |
| Field | 1.8 T |
| Integral | 2.9 Tm |
| Size | 1x0.7x0.7 m |
| Weight | 4.2 t |



| AHD1, AHD2 | |
|---|---|
| Power | 32 / 74 kW |
| Field | 1.2 / 1.15 T |
| Integral | 2.2 / 2.3 Tm |
| Size | 2x1.2x1.5 m |
| Weight | 19 t |

Saved Energy (MW/y per magnet)

*481MWh* *238 MWh* *725 MWh* *267 MWh*

Minimum time of operation: 20 years

**Saved energy with one SC magnet from 4.5 GWh (183 Tons $CO_2$e) to 14.5 GWh (590 Tons $CO_2$e) after 20 years of operation**

# Support from projects and programs

# Support for this development

**1. PSI projects and R&D programs**

- SLS2.0 , IMPACT
- Swiss Accelerator Research and Technology (CHART)
- Superconducting Magnet to Improve the Efficiency of Large research facilities (SMILE)
- EU project HTS4SRI (HTS For Sustainable Research Infrastructure)

*These activities are complementary and are being developed in a synergistic manner.*



**2. Infrastructure development and beam line upgrade**

- Supporting infrastructure, testing, and integration capabilities
- PSI Positron Project (P3) (SwissFEL) , Muon beam line, Neutron scattering…

**3. International Collaboration and Innovation Ecosystem**

- Collaborations with CERN, research institutes, and industry partners.
- Co-development with the partners of the innovation environment "Park Innovaare".

# CHART : Swiss Accelerator for Research and Technology

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CHART — Swiss Accelerator Research and Technology

CHART is an umbrella for Swiss contributions to the science and technology of the FCC accelerator, **a Swiss national science priority**

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

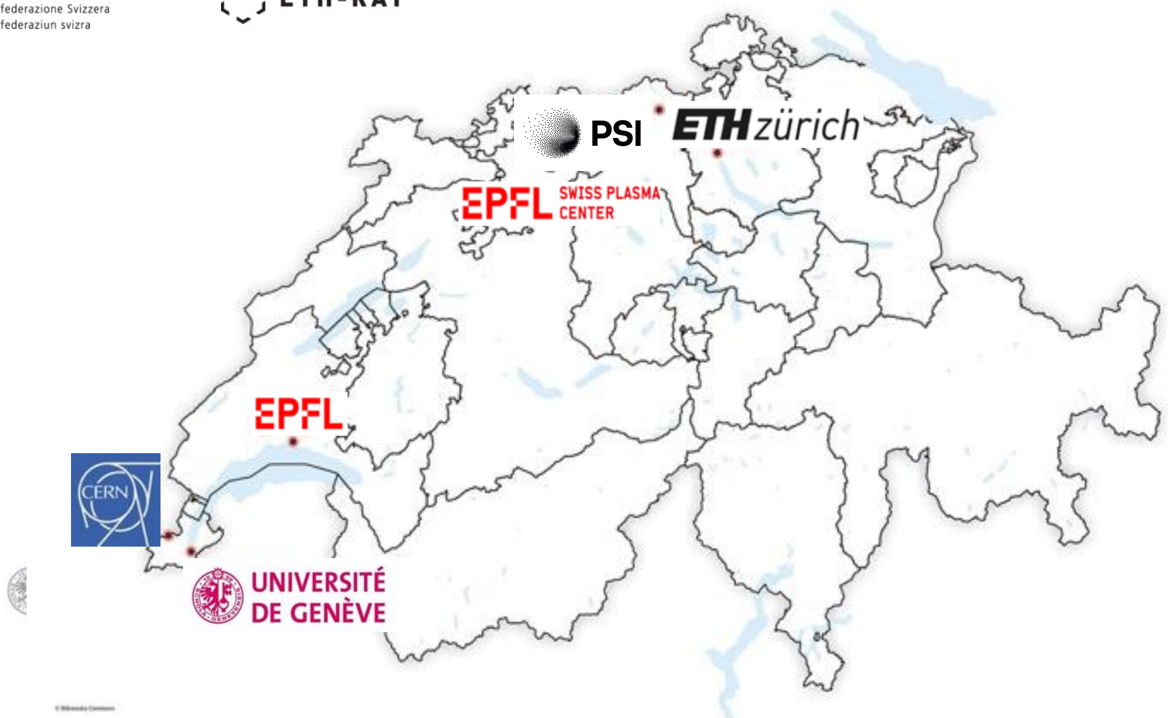
ETH-RAT

**Initial agreement in October 2015**

- Co-funded by SERI, ETH-domain and partners CERN, PSI, EPFL, ETHZ, UniGE
- Home institute : PSI
- **> 30 projects**

**Goals:**

- development and innovation of future accelerator technologies **for the Future Circular Collider**;
- synergy with synchrotron light sources, medical, industrial, and energy/fusion applications;
- emphasis: technologies and demonstrators for **high field magnets and FCC-ee injector.**

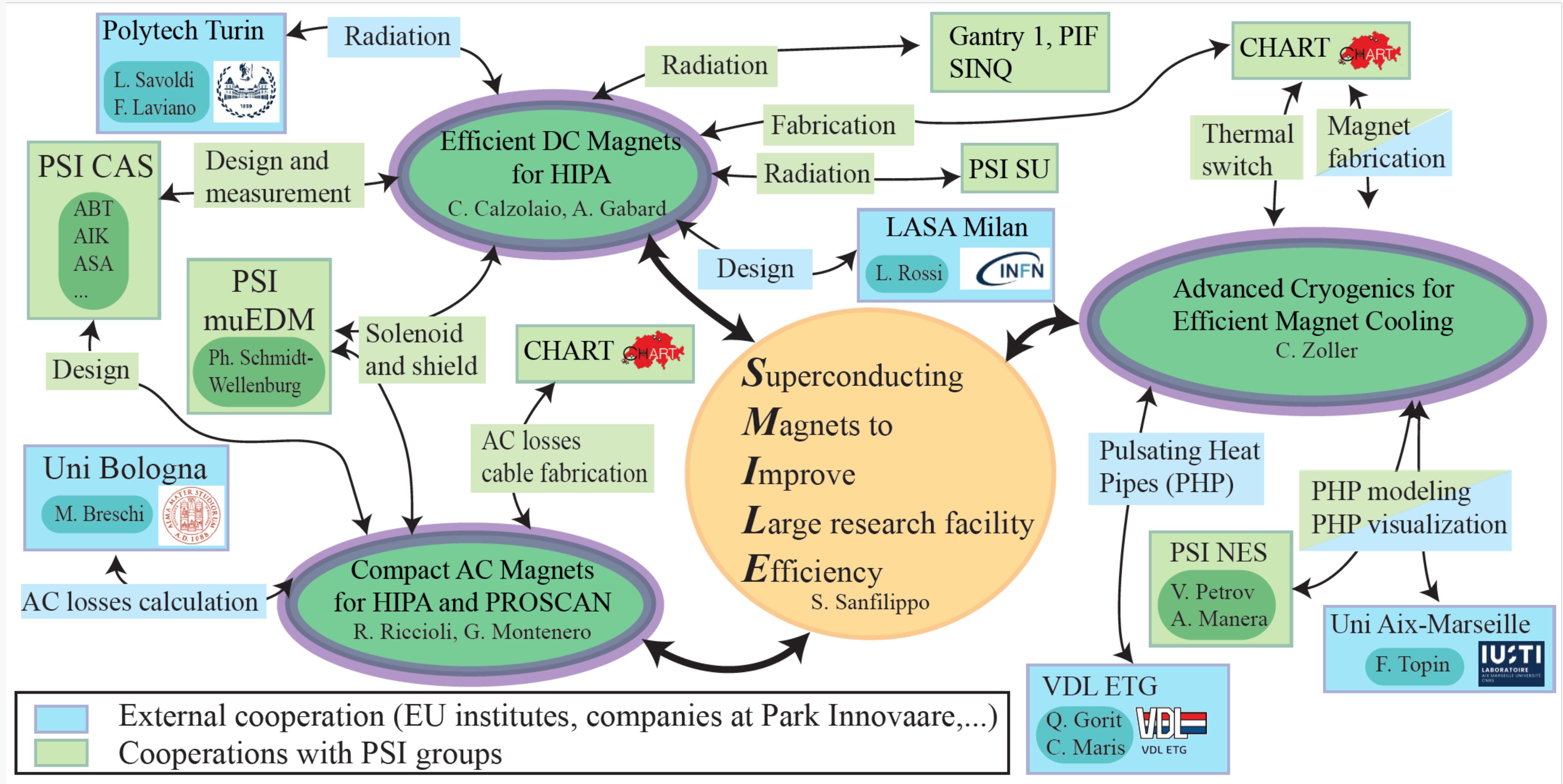



http://chart.ch

FUTURE CIRCULAR COLLIDER · CERN · EPFL · ETH zürich · PAUL SCHERRER INSTITUT PSI · UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES · HFM High Field Magnets

**PSI MAGDEV program : High field magnet technology, design, manufacturing process & infrastructure for demonstrator construction using LTS and HTS**

# SMILE initiative (2025-2026)



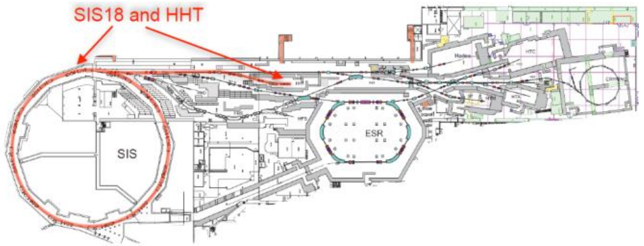

Three poles of activities (partially funded) : DC magnets, AC magnets and Efficient cooling

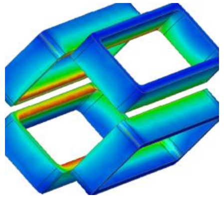
Pole 1: Irradiation effect on HTS magnet (March 2026)
Pole 2: Numerical and experimental studies of CORC conductors (2026)
Pole 3: Pulsating Heat Pipes with HTS coils
and....... the EU funded project HTS4SRI (2026-2029)

# HTS4SRI- 5 MiEuros EU grant HTS coils and demonstrators

**HORIZON-INFRA-2025-01-TECH-01: New technologies and solutions for reducing the environmental and climate footprint of research infrastructures**

## Efficient and sustainable HTS accelerator magnets



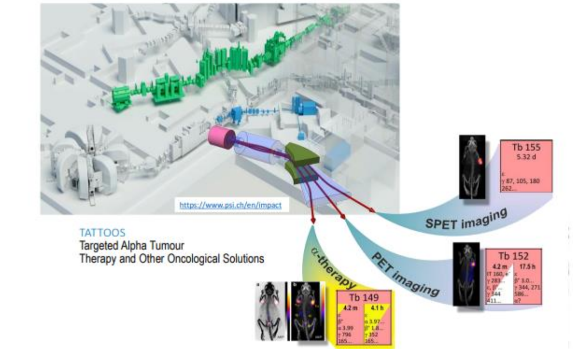



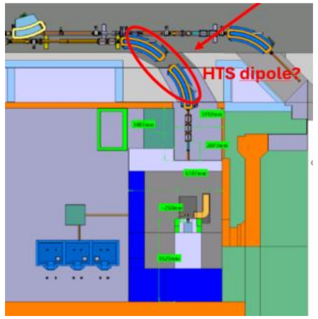
normal conducting magnet focusing quad consuming a lot of energy (~ 60 kW)
→ HTS one

## FFQ coils : HTS Final Focusing Magnet System at GSI heavy ion synchrotron SIS18

| FFQ coils | |
|---|---|
| **Magnetic Field peak** | 4 T |
| **Aperture** | 200 mm |
| **Operating Temperature** | 20-40 K |
| **Energy Saving** | ~ 50 % |

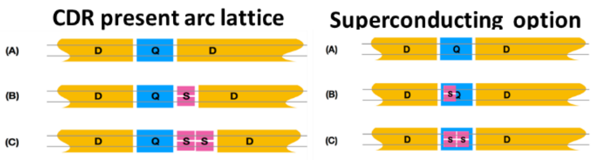
## ADHTS : 4 T HTS dipole demonstrator for the TATTOOS beam line




| ADHTS dipole | |
|---|---|
| **Magnetic Field** | 4 T |
| **Bending Angle** | 80 ° |
| **Gap** | 100 mm |
| **Expected Energy Saving / per year** | 0.2 GWh (~50 %) |

## SQCM: HTS sextupole & quadrupole for FCC-ee (~7,600 NC magnets → ~2,900 combined QSCMs)



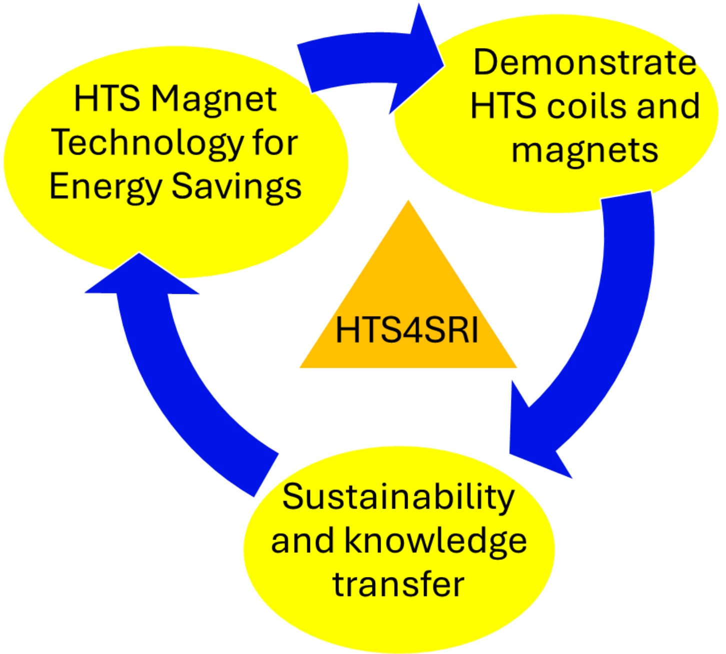

| Magnet | Quadrupole–Sextupole Combined Magnet |
|---|---|
| **Design type** | Superferric, flat REBCO racetrack coils, dodecapole iron yoke (2T peak field) |
| **Op. Temp** | 50–65 K (cryocooler-based refrigeration); extendable to 65 K -77 K ($LN_2$-derived cooling) |
| **Cooling Approach** | Conduction-cooled, distributed cryocoolers (FCCee-CPES compatible) |
| **Manufacturing strategy** | Planar coil geometry , robotic winding, AI field quality optimization |
| **Scalability** | 20 ‘000 coils for FCC-ee |
| **Energy savings** | 0.25 TWh per year |

# HTS4SRI Identity Kit

**Duration:** 4 years (2026–2030)
**Start : 01 September 2026**
**Participants:** 8 institutions
**Budget:** 7.57 M€ total – EU contribution 5.0 M€ – In-kind 2.57 M€ (52 % of the EU contribution)
Work Packages: 6 (WP1–WP6)

| Partner | Role / WP leadership |
|---|---|
| **PSI (CH)** | Coordinator, WP1 & WP3 lead |
| **Bruker Biospin (CH)** | Co-lead WP2 |
| **CEA (FR)** | Co-lead WP1 & WP5 |
| **CIEMAT (ES)** | Co-lead WP2 |
| **CERN (CH)-Int. Org.** | Lead WP6 |
| **GSI (DE)-ESFRI** | Co-lead WP4 |
| **INFN (IT)** | Co-lead WP4 & WP5 |
| **Univ. Milano UMIL (IT)** | Co-lead WP4 & WP5 |

**WP1: Coordination & dissemination**
**WP2: LCA & Sustainability**
**WP3: HTS conductor tests and subscale coils**
**WP4: Design and Engineering**
**WP5: Coils & demonstrator manufacturing**
**WP6: Qualification and testing**




***Kick off meeting: 7-8 October 2026 at PSI***

# Technological building bricks and infrastructure

Conductors and cable
Conduction cooling and Pulsating Heat Pipes
Laboratories for superconducting magnet development and tests

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# Enabling Efficient HTS Magnets for PSI Large Research Facilities: Technology Pathways

## Conductor, cable architectures
REBCO stacked tapes, non-insulated tapes, CORC, CORT, low-loss cable design

## Magnet design, manufacturing & assembly processes
Mechanical design & stress management, thermo-mechanical behavior, field quality
Coil winding, soldering, impregnation, mechanical assembly, instrumentation

## Cryogenic systems & thermal management
Conduction cooling with cryocoolers+ Pulsating heat Pipes

## Reduction of the thermal losses from current leads
Cryogenic power supply (CPES)

## Radiation hardness
HTS tapes and full coil test under radiation

## Efficient magnet design & integration
Compactness, operating conditions to reduce energy consumption,
full design-to-demonstrator value chain

## Quench detection & protection
Adapted to HTS and NI coil behavior

## Sustainability
Life cycle assessment of the magnet design and construction

CHART Swiss Accelerator Research and Technology

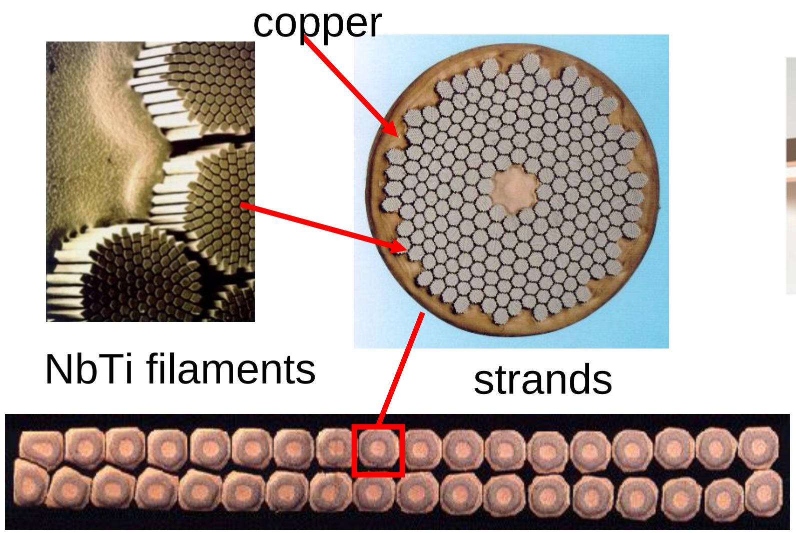
SMILE SUPERCONDUCTING MAGNETS TO IMPROVE THE EFFICIENCY OF LARGE RESEARCH FACILITIES

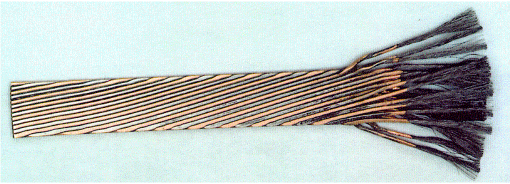
HTS4SRI HIGH-TEMPERATURE SUPERCONDUCTORS FOR SUSTAINABLE RESEARCH INFRASTRUCTURES

**Integrated value -chain approach**

# Practical superconductors used for PSI magnets

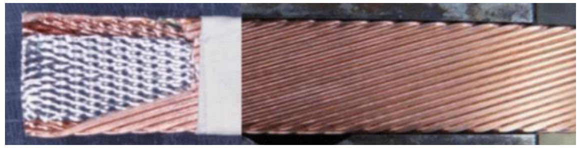
## NbTi rutherford cables



**Rutherford cable**

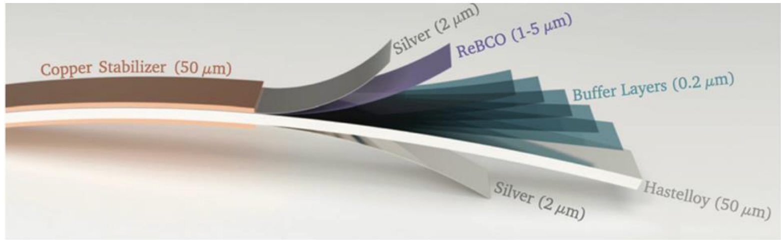
## Nb$_3$Sn cable



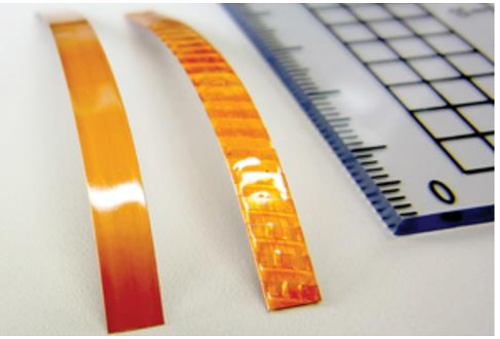
**Rutherford cable**

**(21 high-current-density strands)**

## ReBCO: Insulated and non insulated tapes

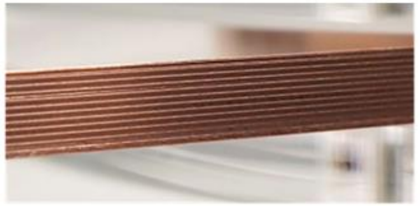



***4 mm width***
***Non Insulated***
***ReBCO tape***



**Tape and stack of tapes**

**Striated tapes**



Coated conductors :
- ReBCO
- HTS film of 1-2 mm thickness deposited on one side of the substrate

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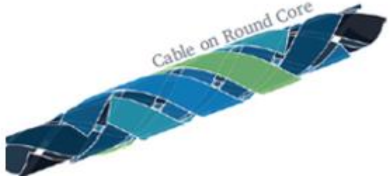
## ReBCO cable with CORC(T) or twisted stack of tapes

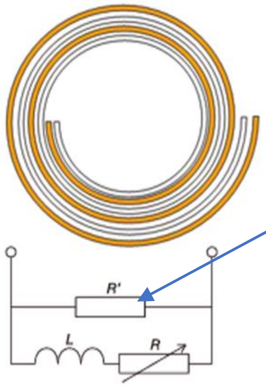



**Twisted stack of tapes**

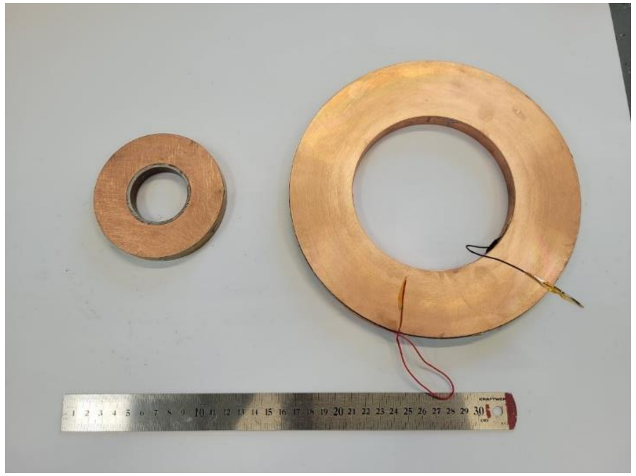
**CORC or CORT:** Cable On a Round Copper Core (Tube)
- Increasing the current;
- Allowing current sharing between tapes;
- Reducing AC losses;
- Improving mechanical properties.

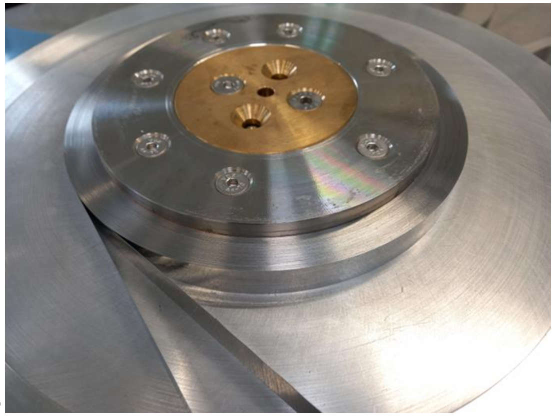
# One example of synergy: Non insulated HTS technology for high field magnets in PSI beam lines

Swiss Accelerator Research and Technology




Turn to turn

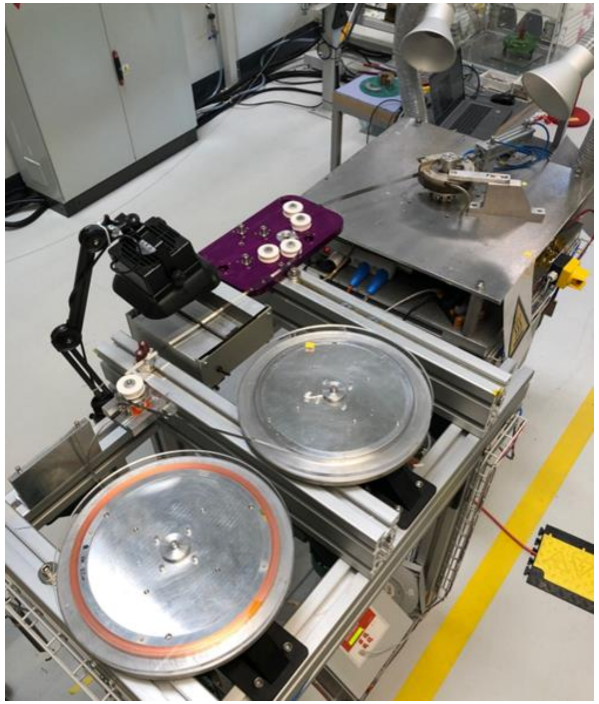




Insulated coil: R'~∞
Metal-insulated coil: R'>>0
Non-insulated coil: R'~0

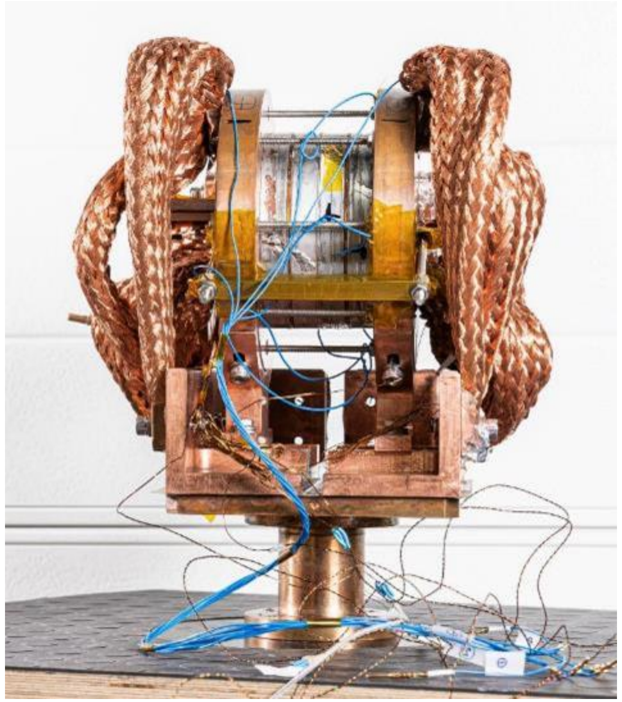
\+ Very high current density,
→ compact winding, lower cost
→ better mechanical and thermal conductivity
→ Simpler passive protection

\- Slow charging and discharging for large L, $\tau = L/R$
-Need to control turn-to-turn contact resistance
-screening-current effects



Rapidly developed infrastructure at PSI, & parts of soldering technology via license agreement with

Tokamak Energy



4 coils demonstrator
18 T @50 mm cold bore, 10 K

NI HTS technology used for high field solenoids in future PSI beam lines

# Conduction cooled magnets (SHI GM cryocoolers)

Choice for single PSI LTS & HTS magnets

| Advantages (+) | Disadvantages (–) |
|---|---|
| No liquid helium plant required | Limited cooling capacity (very low COP) |
| Compact and modular system | Long cooldown time |
| Simplified installation | Mechanical vibrations |
| Small helium consumption | Limured by the thermal contact between the coil, thermal links, and cryocooler cold head. |
| Lower operational complexity | Failure impacts operation |
| Ideal for HTS (T>20 K) | Not suited for large heat loads |
| Improved safety (no liquid helium) | Requires redundancy |
| Potential cost reduction | Compressor maintenance |

***https://shicryogenics.com/product-finder/***

**Use of dual inverter** for energy-saving operation of GM SHI cryocoolers, with regulation frequency of compressor allowing cooling control and reduced electricity consumption.


RDEK-500B +F70 compressor
Single stage
Power capacity : 45 W @ 20 K (50Hz)
Power consumption :6.6-6.9 kW at 50 Hz


RDE418D4 + E77 compressor- 2 stages
Dual inverter: f ~40-60 Hz
Power capacity :
*1st stage : 42 W @ 50 K (50Hz),50W (60Hz)*
*2nd stage : 1.8 W @ 4.2 K (50Hz), 2W (60Hz)*
Power consumption :

- 6.5 kW at 50 Hz
- 7.5 kW at 60 Hz

# Pulsating Heat Pipes for HTS magnet cooling
## (partnership with VDL ETG-ParkInnovaare)

IPAC26

PSI

SMILE — Superconducting magnets

VDL ETG

Switzerland Innovation Park Innovaare

## Context

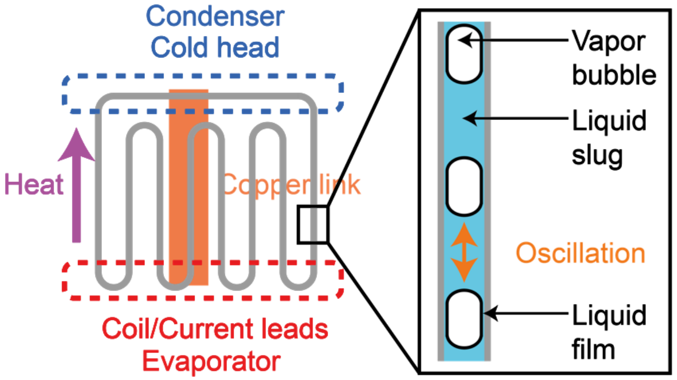
PSI beam lines: SC magnets cooled with cryocoolers can be installed (space problem)

Challenge: Transport heat efficiently from HTS and LTS coils to cryocooler

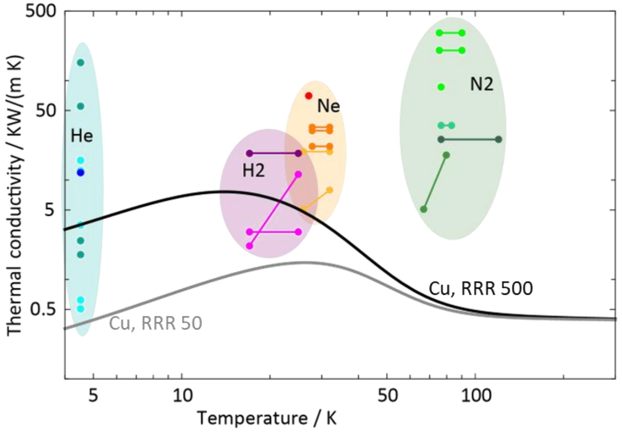
Proposed solution: Use Pulsating Heat Pipes (PHP) filled with neon or nitrogen (for HTS) and helium (for LTS)

Principle: 1) Highly efficient **passive** device **transferring latent heat** from "warm" evaporator (HT coils) to cold condenser using thermally induced two-phase flow

2) **Convection**: Oscillation of liquid slugs and vapor bubbles



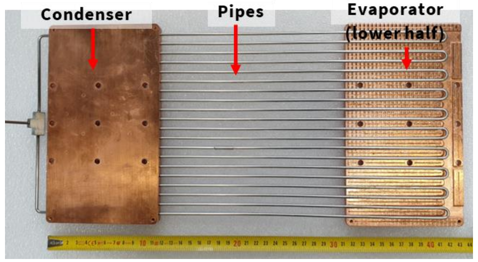

$$k = \frac{power\ transferred}{temperature\ difference} \times \frac{distance}{fluid\ cross\ sectional\ area}$$



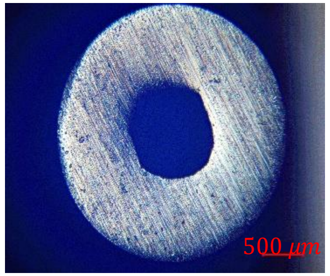

## Highlights

- Fabrication of PhPs working with Neon and $N_2$ connected to HTS coils (evaporator) and cryocoolers (condenser)
- Experimental campaigns with Ne and $LN_2$
- Successful cooldown and operation of HTS coils with a non-insulated coil (DC operation) and with an insulated coil (AC operation)

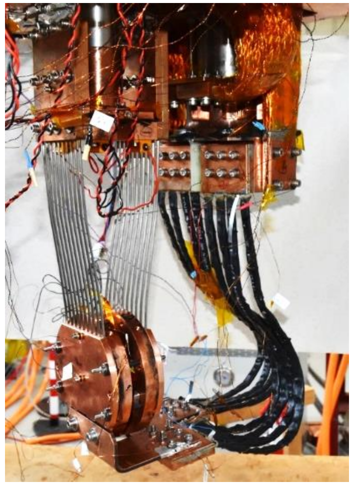
Heat transfer improved compared to copper thermal link :
Thermal resistance between the cryocooler and the coil decreased of nearly **80%**




Test with 2 copper plates




Pipe cross-section



Two PHPs in parallel embedded in an insulated HTS coil

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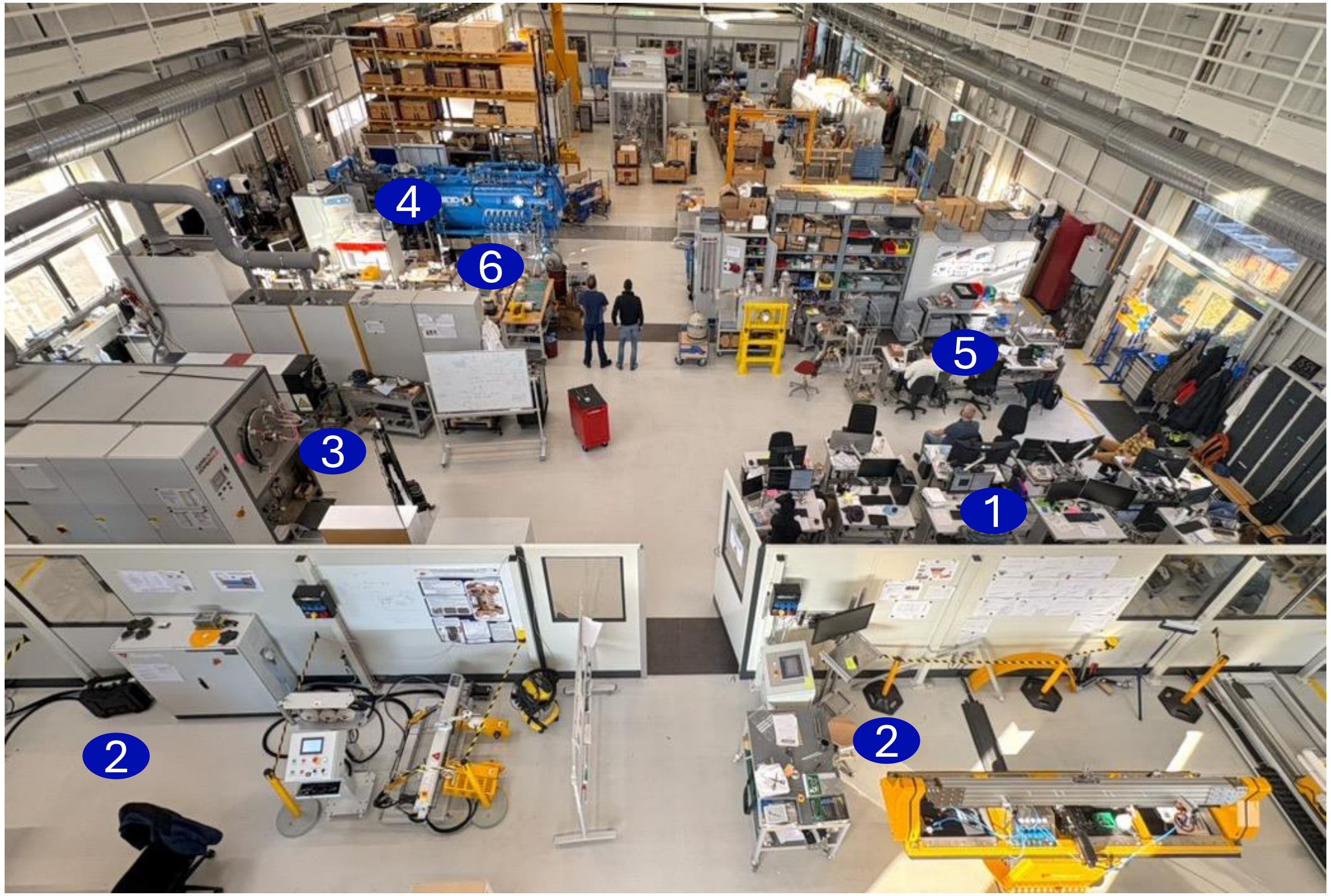
# Synergy with CHART : MagDev laboratory for superconducting magnets (2020-2026)

CHART Swiss Accelerator Research and Technology

PSI




Design (1), coil winding (2), heat treatment (3), impregnation (4), magnet assembly (5) , instrumentation (6)

1

Financed by CHART 2 & 3 program

Courtesy Bernhard Auchmann

Douglas Araujo
*Engineer LTS*

André Brem
*Material Scientist*

Jaap Kosse
*Engineer ReBCO*

Anna Stampfli
*Technician Process*

Dmitry Sotnikovs
*Design Engineer ReBCO*

Jürgen Schmidt
*Technician HTS*

Inês S. P. Peixoto
Magnet Engineer

Christian Lindner
*Technician HTS*

Kirtana Puthran
*Engineer ReBCO*

Colin Müller
*Mechanic LTS*

Thomas Michlmayr
*CAD, Technical Design*

Nicolas Kehl
*Technician LTS*

Alejandro Carlòn Zurita
Technician HTS, CAD

Sascha Röthlisberger
Laboratory technician

Joep Van den Eijnden
*PhD Student*

Matteo Crescenti
*PhD Student*

# PSI infrastructure (2) :Test stand for cryogen free superconducting magnets (2019-2026)

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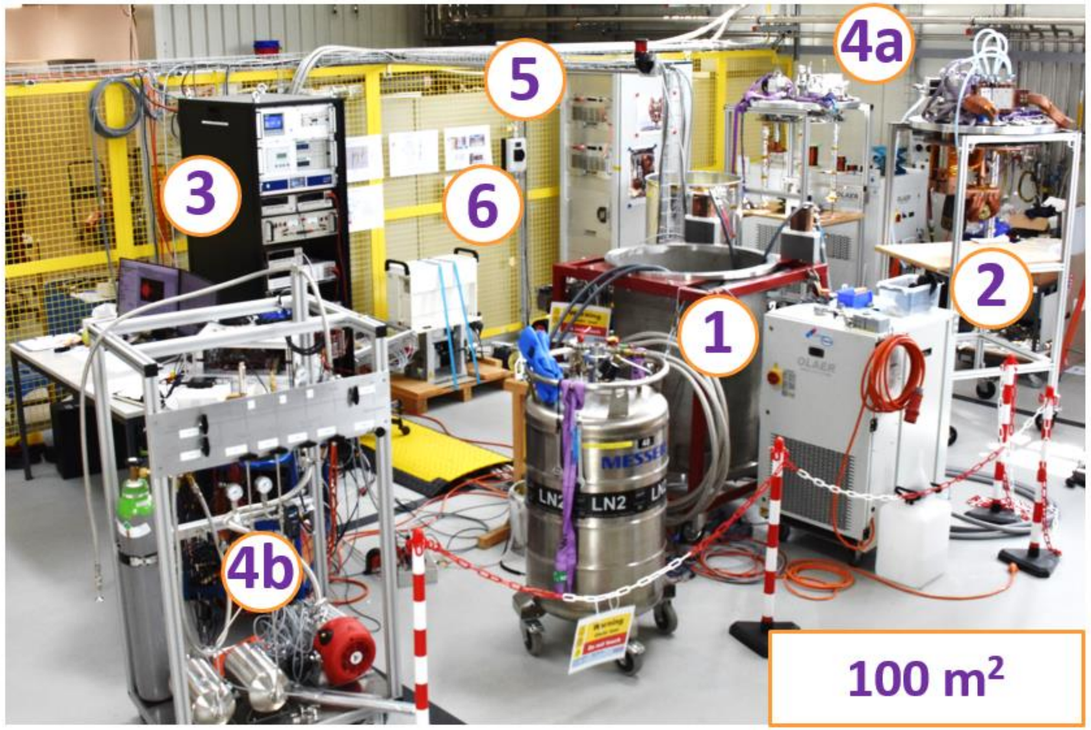
PSI




## 1: Cryostat

- Thermal radiation shield
- Vacuum pumps
- 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)

**Versatile infrastructure for tests:**

- 4.5K ≤T ≤65 K (cold heads)
- In a 77 K $LN_2$ bath

## 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)

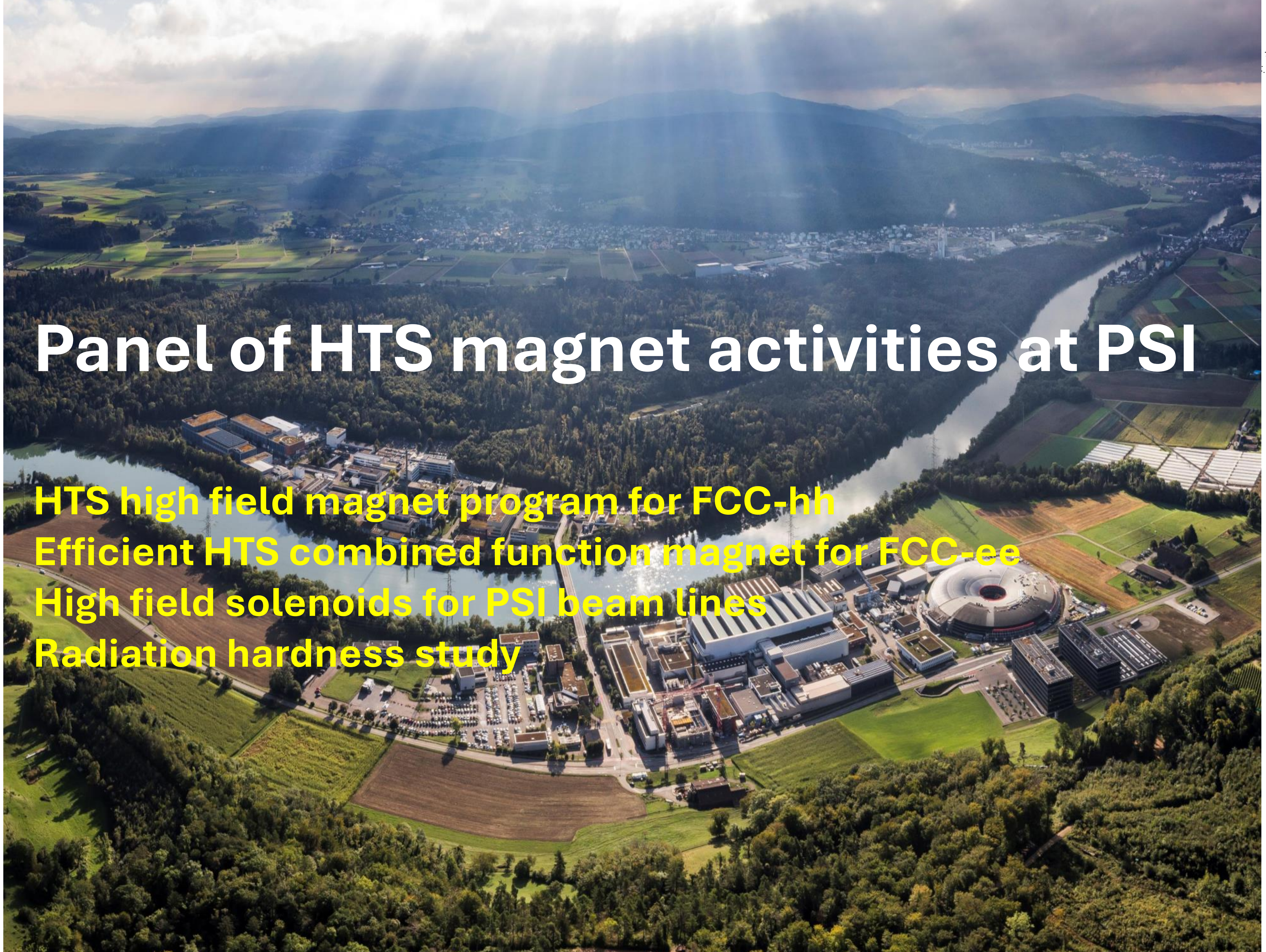
## 5: 2 kA ± 10V power converter

## 6: Quench protection

- mechanical switch (~4 ms ) with varistor

*Magnetic measurement system 3D hall probe*

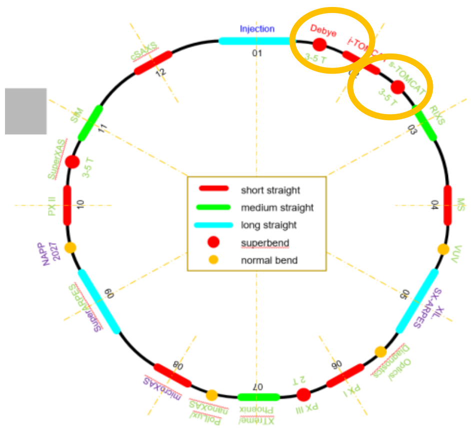
# Panel of HTS magnet activities at PSI

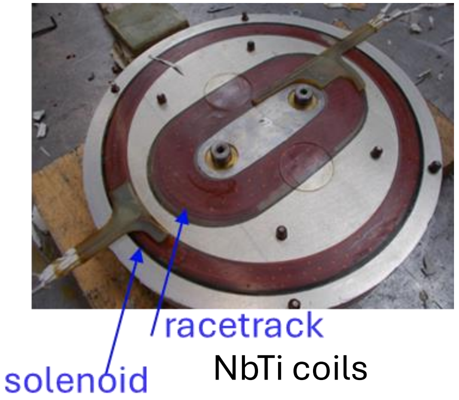


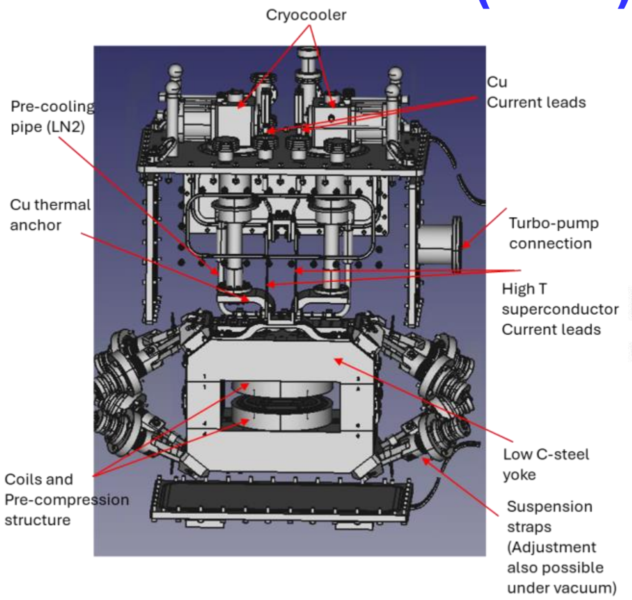
- HTS high field magnet program for FCC-hh
- Efficient HTS combined function magnet for FCC-ee
- High field solenoids for PSI beam lines
- Radiation hardness study

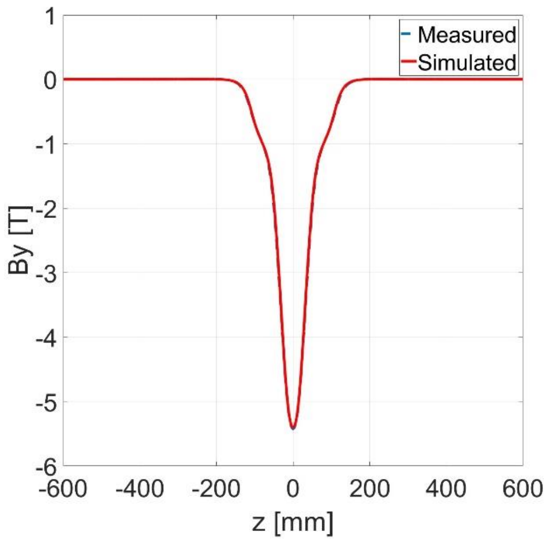
# Useful experience : Two 5T NbTi Superbends for SLS2.0 (2026)

PSI



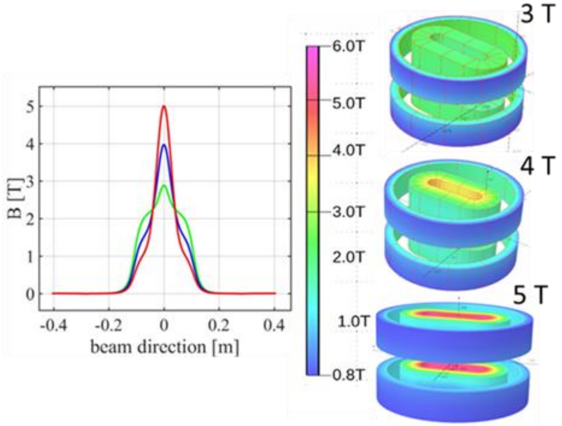



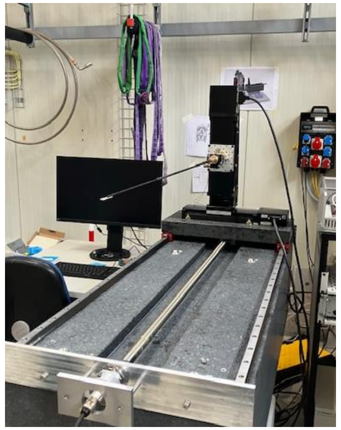



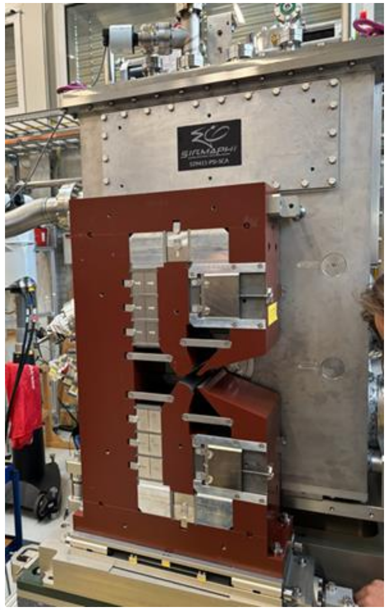




SCA field profile, peak field at 5.4 T

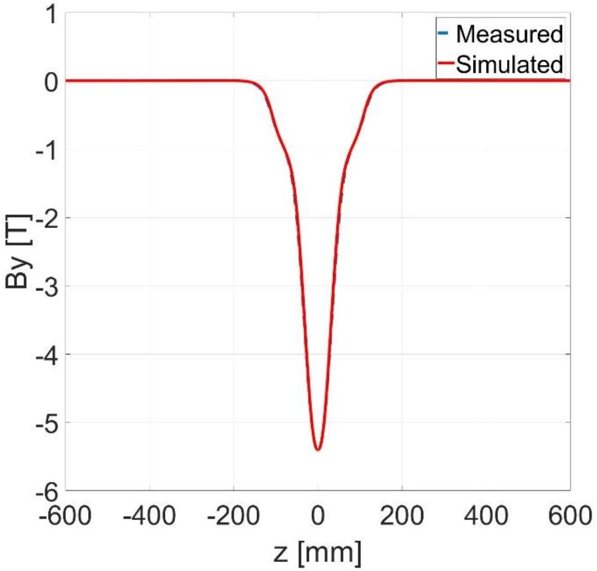
- 2 superconducting Superbend magnets will replace the 3.1 T one of SLS.
- 2 operating scenarios: 3T and 5T peak field.
- Electromagnetic design & magnet qualification at PSI
- Cryostat design and magnet manufacturing by the company SIGMAPHI (F)
- Power tests and magnetic measurements on-going
- Installation foreseen end of 2026





Cold test with quadrupole



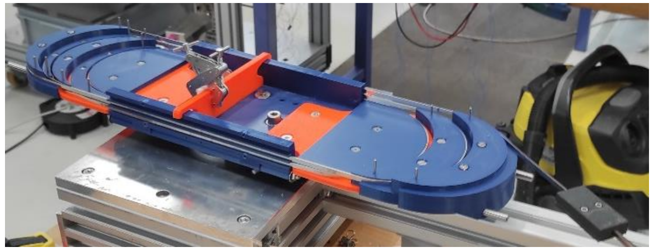

SCB field profile, peak field at 5.4 T

SLS2 vs SLS SB: 170kW x 6800 operating hours ; 0.6 GWh per year
Savings for 15 Years : 9 GWh

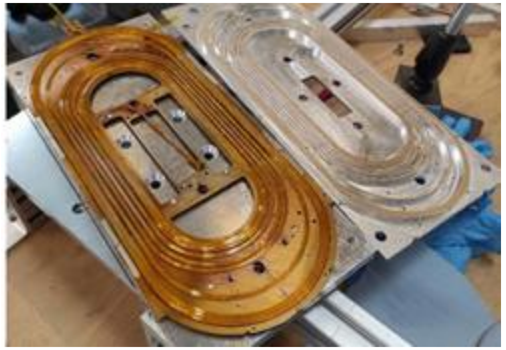
# HTS (ReBCO) magnet development for FCC-hh

MagDev2, MagDev3 (RS1, RS2)

Prototype



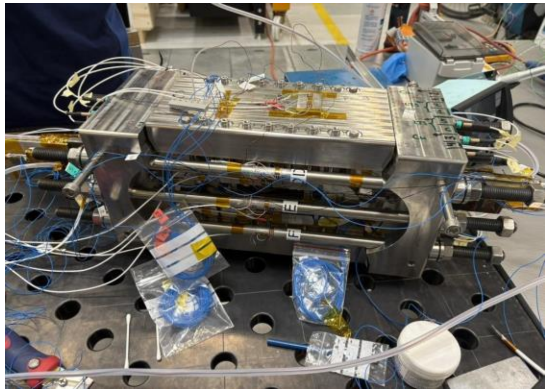
Racetrack winding – cosine θ geometry with elliptical ends



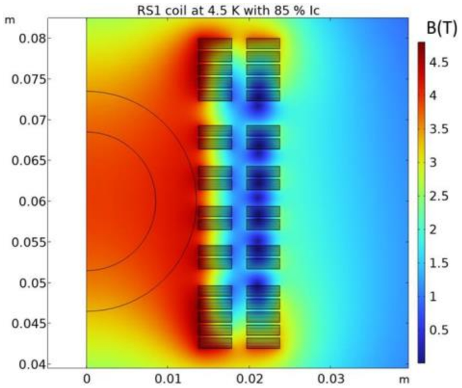
Race-track coil

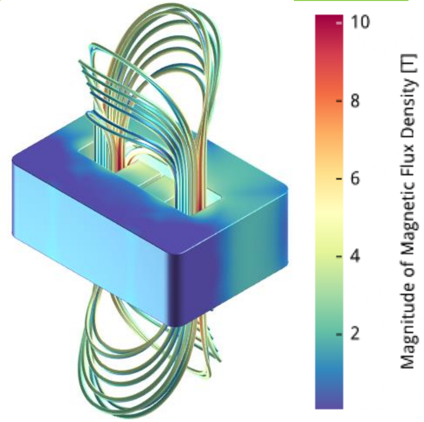
| | |
|---|---|
| HTS sub-scale RS1 | Magnet Assembly and Tests at PSI ($LN_2$) and CERN - 2026 (4.5 K and 20 K) |
| HTS sub-scale RS2 | Conceptual Design Finalization, Coil Manufacturing Development, and $LN_2$ Testing |
| REBCO Cable Develop. | Short-Length Sample Production and $LN_2$ Testing |

Double Racetrack of HTS (ReBCO) insulated (soldered) tape-stack cable tested at PSI



REBCO Subscale magnet 1




REBCO Subscale magnet 2 optimized coil geometry

Stress management of the lorentz forces by the geometry

**Assess: engineering current density, AC losses, field quality**
**Synergies for PSI magnets: coil fabrication, stress management, fast ramping operation**

# HTS magnet for energy saving : FCCee-HTS4 project (CHART/CERN/PSI)

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CERN

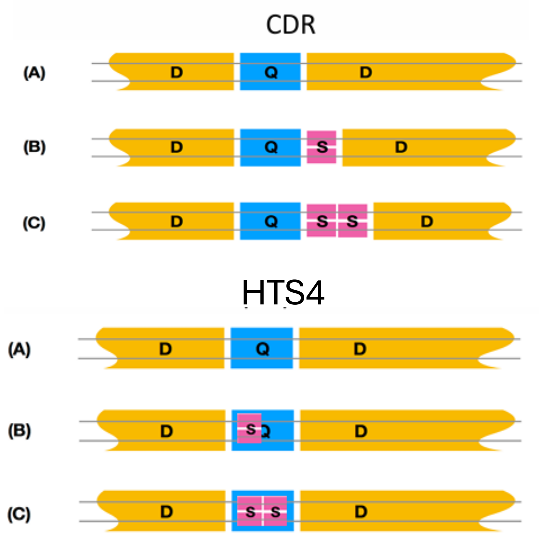
CHART Swiss Accelerator Research and Technology

Replace all arc normal conducting quadrupoles and sextupoles of the FCC-ee arcs (89 MW), with superconducting ones using HTS technology

Design, fabricate and test a cryocooled HTS combined function (quadrupole & sextupole) working at 40 K for energy saving in FCC-ee short straight section magnets

- *HTS technology : reduce the consumption by 20 % i.e. 2.9 TWh*
- *Nested geometry : only one type of neighbouring dipoles →increase the packing factor and the luminosity*
- *Sister CHART project : FCC-ee cryogenic power converter (CPES) developed with ETHZ*

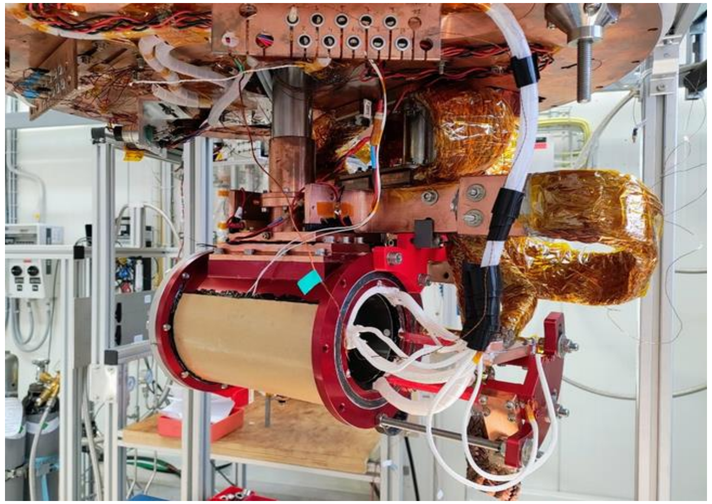
Two prototyping geometries : Canted Cosine Theta (CERN) and Cosine Theta (PSI)




M. Koratzinos (CERN)

**PSI sextupole (cosine Theta) prototype fabricated and tested**


Sextupoles made of 6 racetrack HTS coils (coated HTS tapes at PSI)



Cryogenic test of the sextupole at PSI

**Perspectives 2026 : Fabrication of a full nested magnet and test between 30-70 K**
**Synergies : conduction cooled HTS magnet construction, field quality, compactness, and reduced power consumptior**

# NI HTS technology for a high field solenoid of the PSI Positron Production ($P^3$) Experiment

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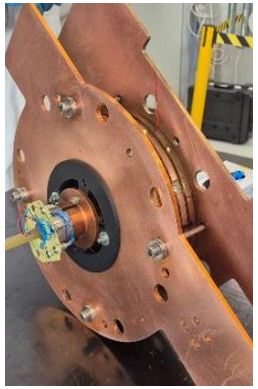
CHART Swiss Accelerator Research and Technology

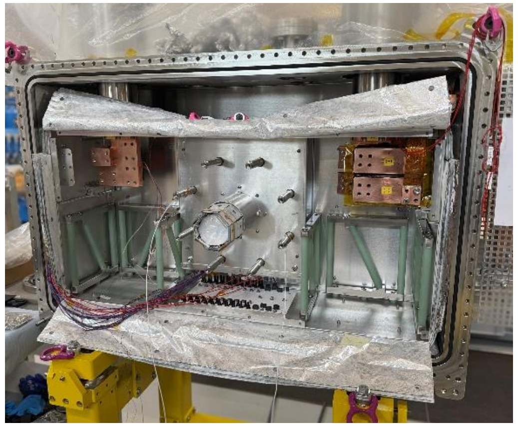
$P^3$ PSI PRODUCTION

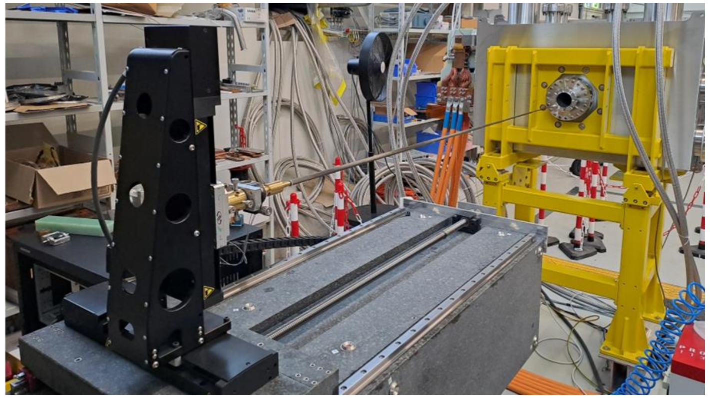
P3 final assembly, cryogenic tests up to 1 kA (~10 T,21 K), and installation in the SwissFEL beam line

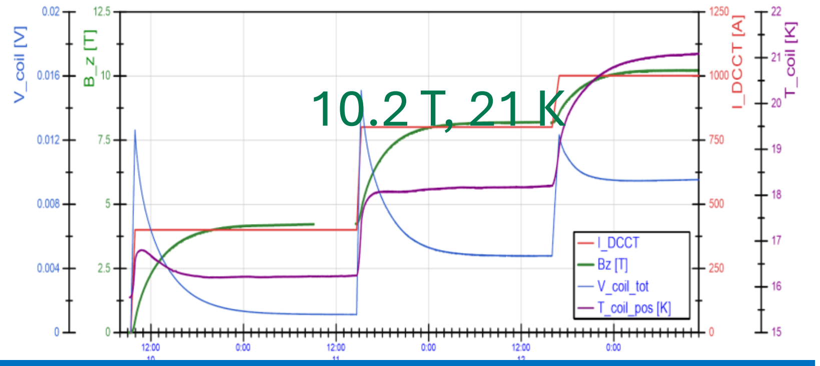


5x 12 mm wide

Non insulated HTS coils



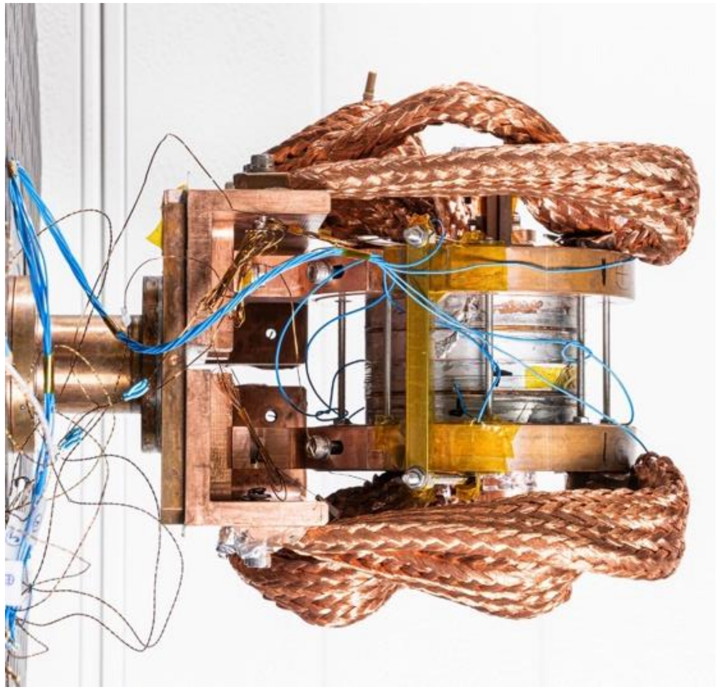


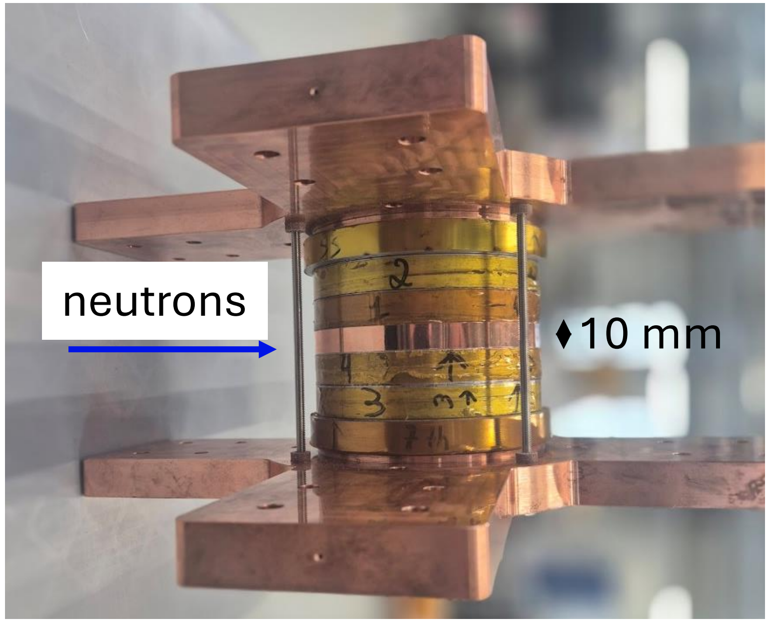



**Direct application : HTS solenoid will be installed into an accelerator beam line (2026) !**

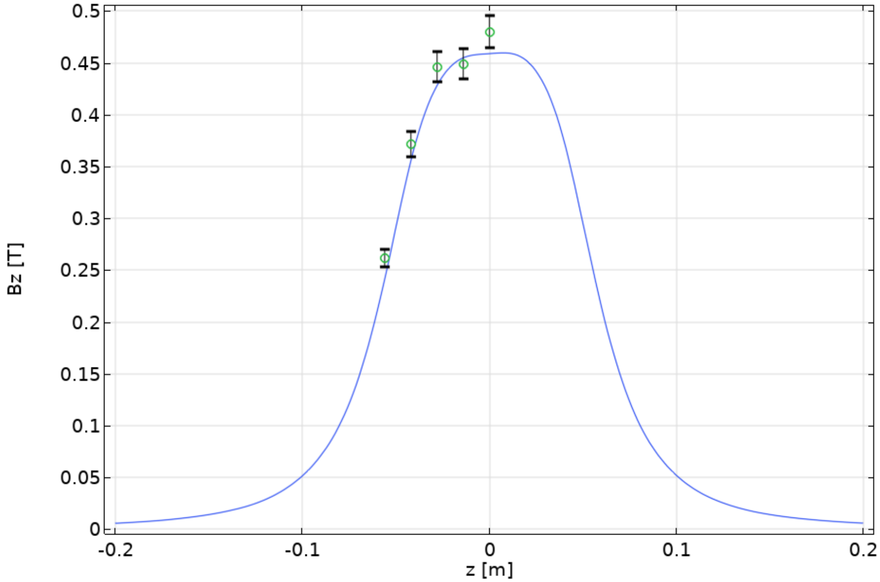
# Split HTS Solenoid for Neutron Scattering experiment in SINQ (CHART-PSI)

18 T solenoid → 17 T @10 K 1700 A ,10 mm split






LN2 test

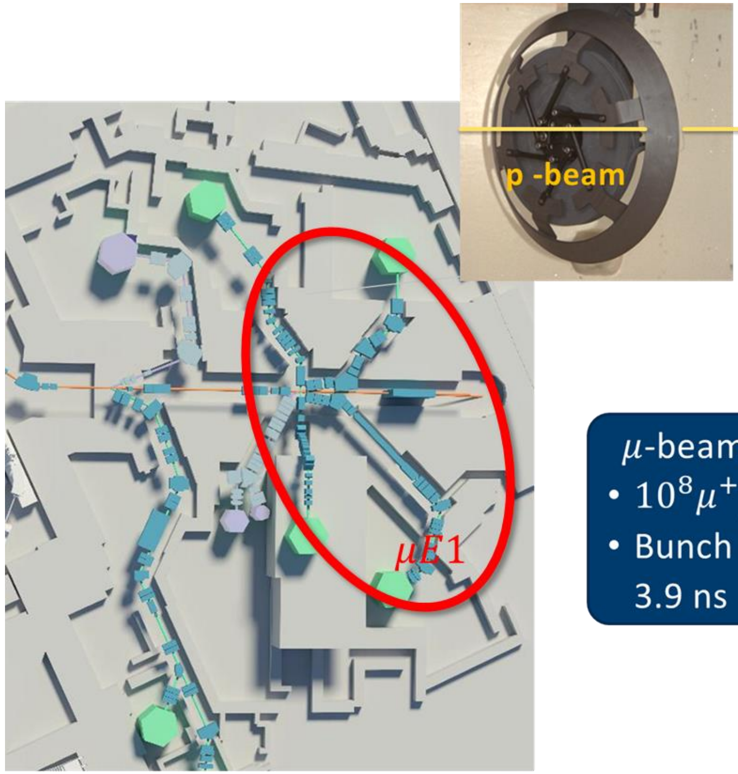


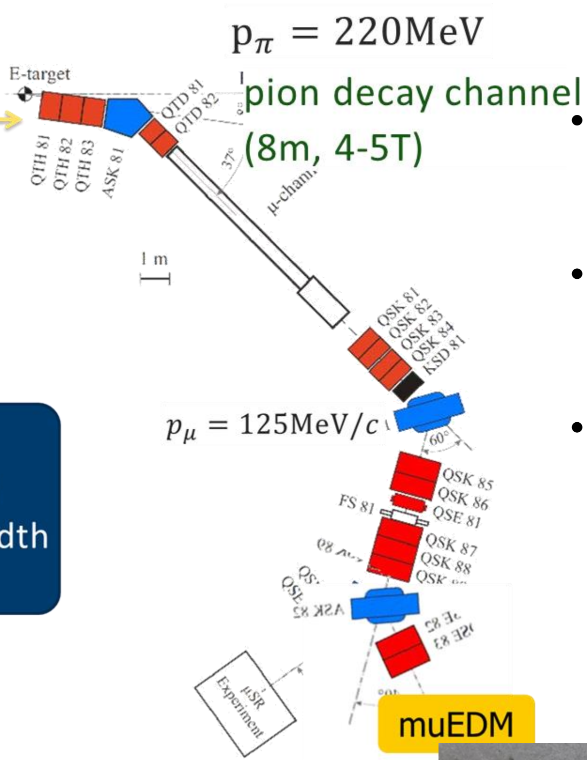

- Split coils with NI HTS double tapes;
- Operating temperature: ~12 K;
- Cooling provided by a two stages GM cryocooler;
- Current leads cooled with liquid nitrogen.

- 2025: Stack assembled
- 2025: Initial LN2 tests
- 2026: Integration in dedicated cryostat

# HTS solenoid for the PSI Muon EDM experiment in the μE1 beam line (HIPA)-2030?

*https://www.psi.ch/en/ltp/muedm-experiment*

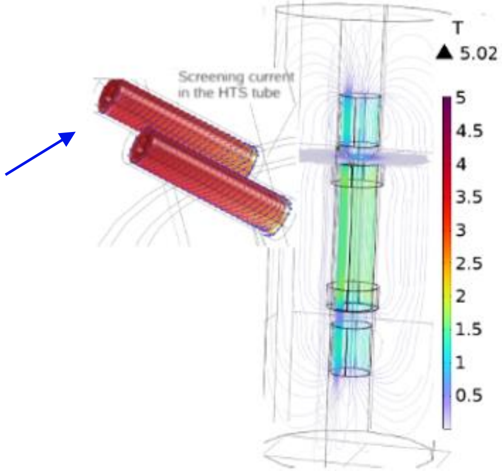



**μ-beam:**
- $10^8 \mu^+/s$
- Bunch width 3.9 ns

- Design of a superconducting solenoid for measurement of muons Electric Dipole Moment (muEDM)
- Development of a zero-field superconducting injection channel into solenoid→ use of HTS bulk/tape (2024)
- High peak field (5 T), large aperture (0.5 m) solenoid for magnetic storage muons trap (highly uniform magnetic field required to control muon spin dynamics)

YBCO tape Helix




Higher field → better signal-to-noise → improved EDM sensitivity
HTS : working above 20 K possible, cost efficiency

**Design of a 5T HTS solenoid from mid-2026 to mid-2030: Ph.D. student with SNFS grant**

# Radiation hardness study (SMILE –pole1)

**70 magnets with Mineral Insulated Cables (MIC) (highly radiative environment)**

Replacement of high-energy-consumption magnets with LTS and HTS magnets

Cost-effectiveness & performance including ***thermal stability and radiation effects***

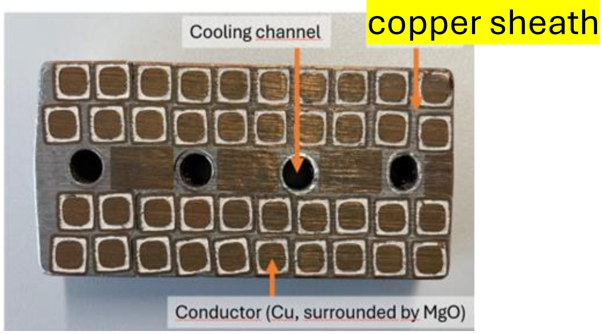
AHL with MIC coils

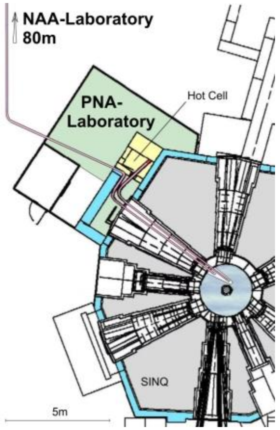
## Program 2025-2029

- **Modeling** of the radiation effects on HTS tapes & coils
- **Test of HTS samples** in PSI facilities (Gantry 1, PIF, NIS…)
- **Produce am HTS coil without organic insulation**
- **Build an HTS magnet demonstrator** to test the changes in superconducting properties under radiation exposure online in **HIPA** → 2026
- **Validation numerical model** on experimental data on HTS irradiated samples and coils
- **Pilot Magnet design and assembly** to be installed in a PSI beam line?

**Activity linked with EU HTS4SRI project**

Typical MIC cross-section




Proton Irradiation Facility

***Irradiation (n, p) of HTS tapes and coils***

# Irradiation effect on HTS magnet demonstrator

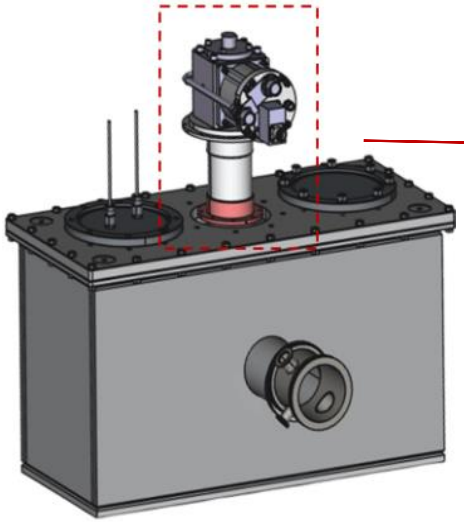
IPAC26

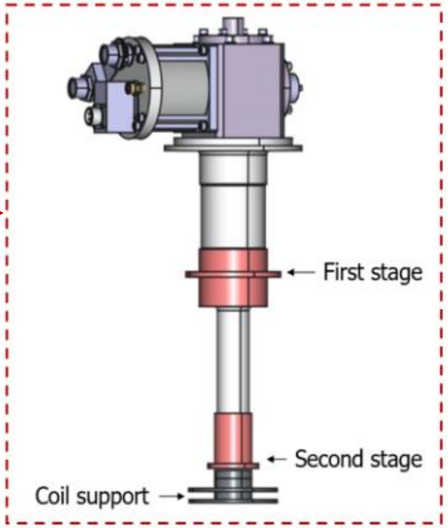
Politecnico di Torino International University 1859

SMILE SUPERCONDUCTING MAGNETS

PSI

Experiment set-up:



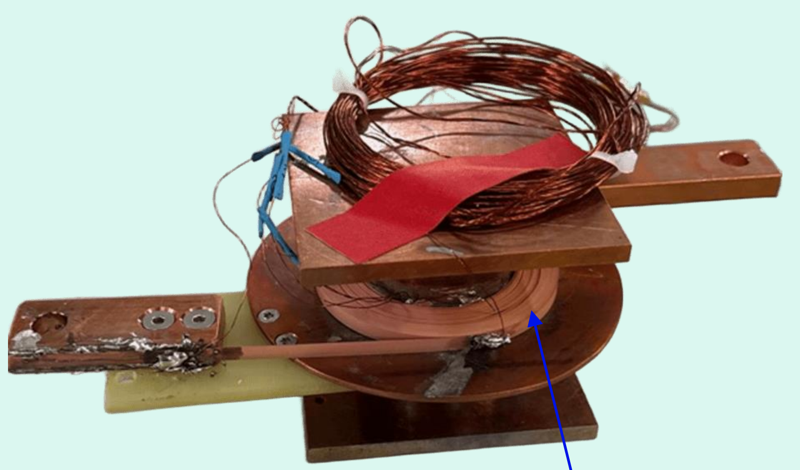



## Aluminum Cryostat

The cryostat features inner and outer **aluminum** shields

## Cryocooler head

The cooling system is based on a RDK-415D2 cryocooler, which provides about 1.5 W at 4 K

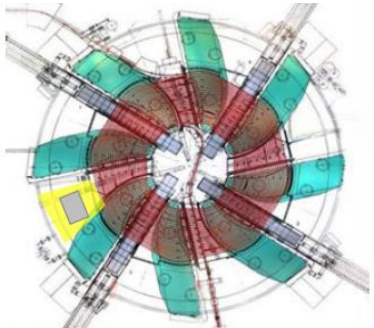


## HTS Coil on a copper support

The HTS coil consists of **150 turns of 4 mm Faraday Factory tape**, in **dry-wound configuration**.

Dose rate: ~5e-4 Gy/s

Neutron fluence after 4000 h: $10^{18}$ n/m$^2$



➡ The final demonstrator will be installed in the cryostat near the cyclotron and operated between 10 K and 40 K to monitor its critical parameters.

➡ Neutron flux will be measured using activation foils and beam loss monitors to correlate radiation exposure with coil performance and assess its long-term reliability.

**<u>Perspectives 2026 :</u> Installation of the HTS demonstrator close to the PSI ring.**
**Monitoring of the irradiation effect on superconducting properties.**
**Information for the possible replacement of the AHC magnet in the PSI ring**

# Conclusions

- The increasing energy demand of more powerful accelerators requires a more efficient and sustainable approach to magnet technologies.

- PSI benefits from a strong ecosystem of ambitious strategic projects, of an FCC-oriented R&D program (CHART) and innovative industrial environment , creating a unique opportunity to drive the energy transition through HTS magnet technology.

- SMILE and HTS4SRI are developing key technological building blocks for cryocooled HTS magnets tailored to the needs of current and future PSI large research facilities.

- The future use of HTS magnets—combining high performance, energy savings, reduced operational costs, and lower environmental impact—is progressively gaining momentum.

Join us in shaping the future of efficient and sustainable HTS magnet technologies

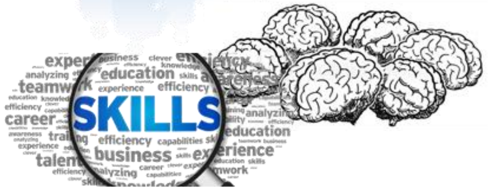
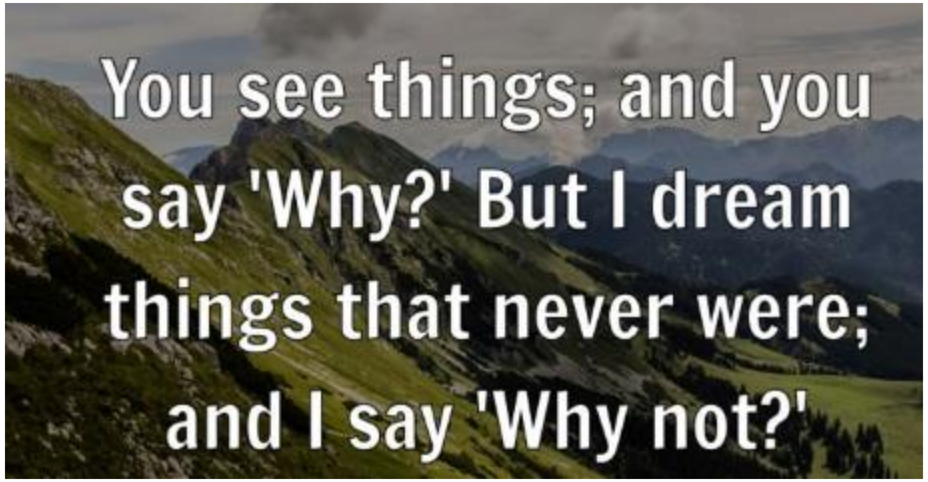
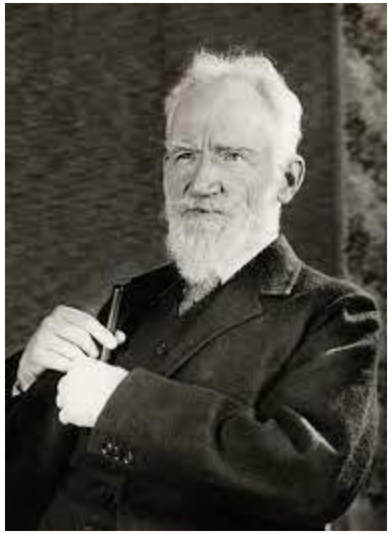



CHART
Swiss Accelerator Research and Technology

SMILE
SUPERCONDUCTING MAGNETS

HTS4SRI
HIGH-TEMPERATURE SUPERCONDUCTORS FOR SUSTAINABLE RESEARCH INFRASTRUCTURES



George Bernard Shaw (1856–1950)
Irish playwright, critic, dramatist and polemist
Nobel Prize in Literature in 1925

**Thank you**

**for your attention**