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Xiaojie Ni :: State Key Laboratory of Particle Detection and Electronics, USTC

The muon facility and μSR instruments at PSI

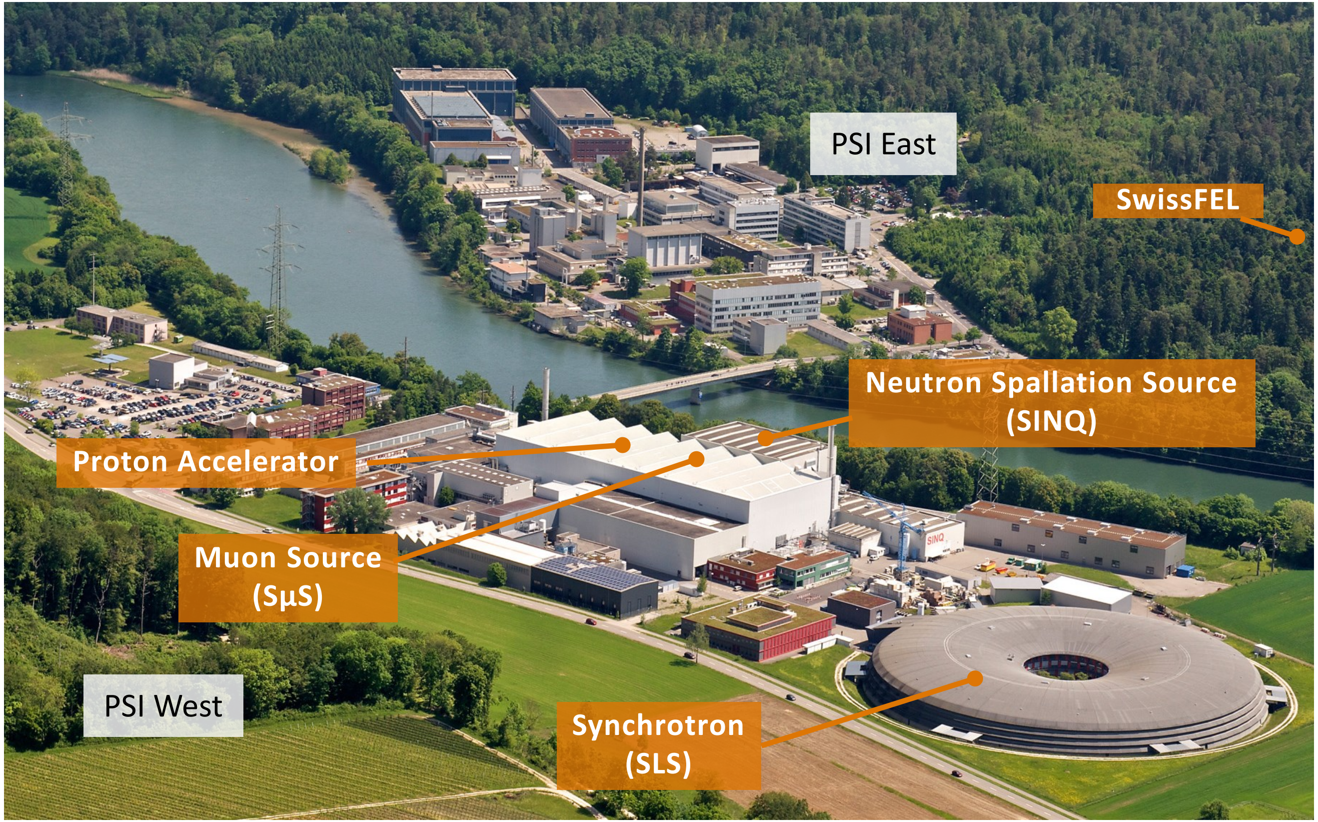
June 7th, 2023 SPeCial4Young: SYSU-PKU Collider Physics forum For Young Scientists

Outline

- Overview
  - Proton accelerator
  - Muon target
  - Muon beamlines
  - Instruments at the SμS (Swiss Muon Source)
- Bulk-μSR Instruments GPD, Dolly, HAL-9500, GPS, and FLAME
  - Experimental capabilities – status quo
  - Scientific examples
- Low energy μSR Instrument: LEM
  - Experimental capabilities – status quo
  - Scientific examples
- Future - High Intensity Muon Beam (HIMB)

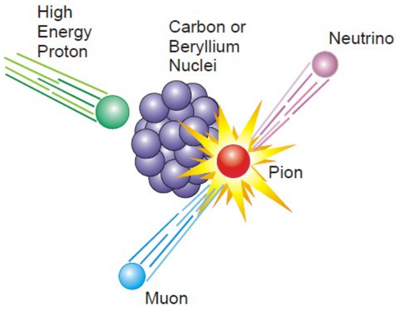
Paul Scherrer Institute

← Basel Germany ↑ Aarau/Bern ↓ Zürich →



Accelerator muons

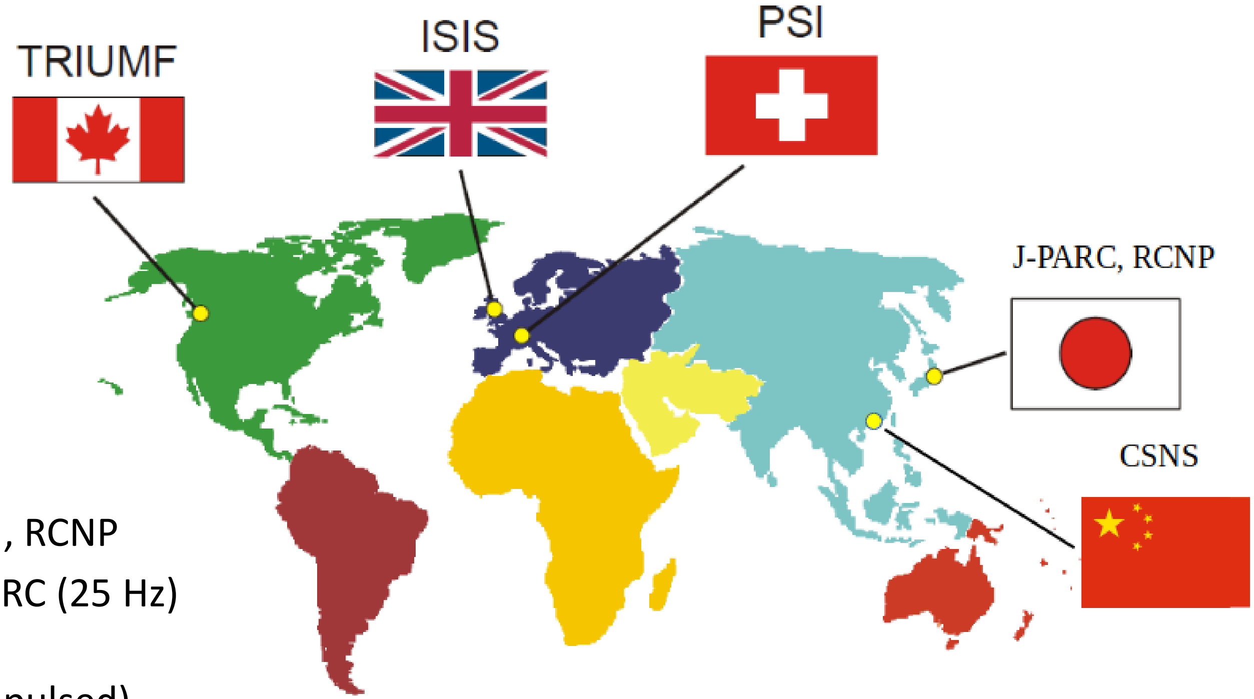
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



continuous µ beams: TRIUMF, PSI, RCNP

pulsed µ beams: ISIS (50 Hz), J-PARC (25 Hz)

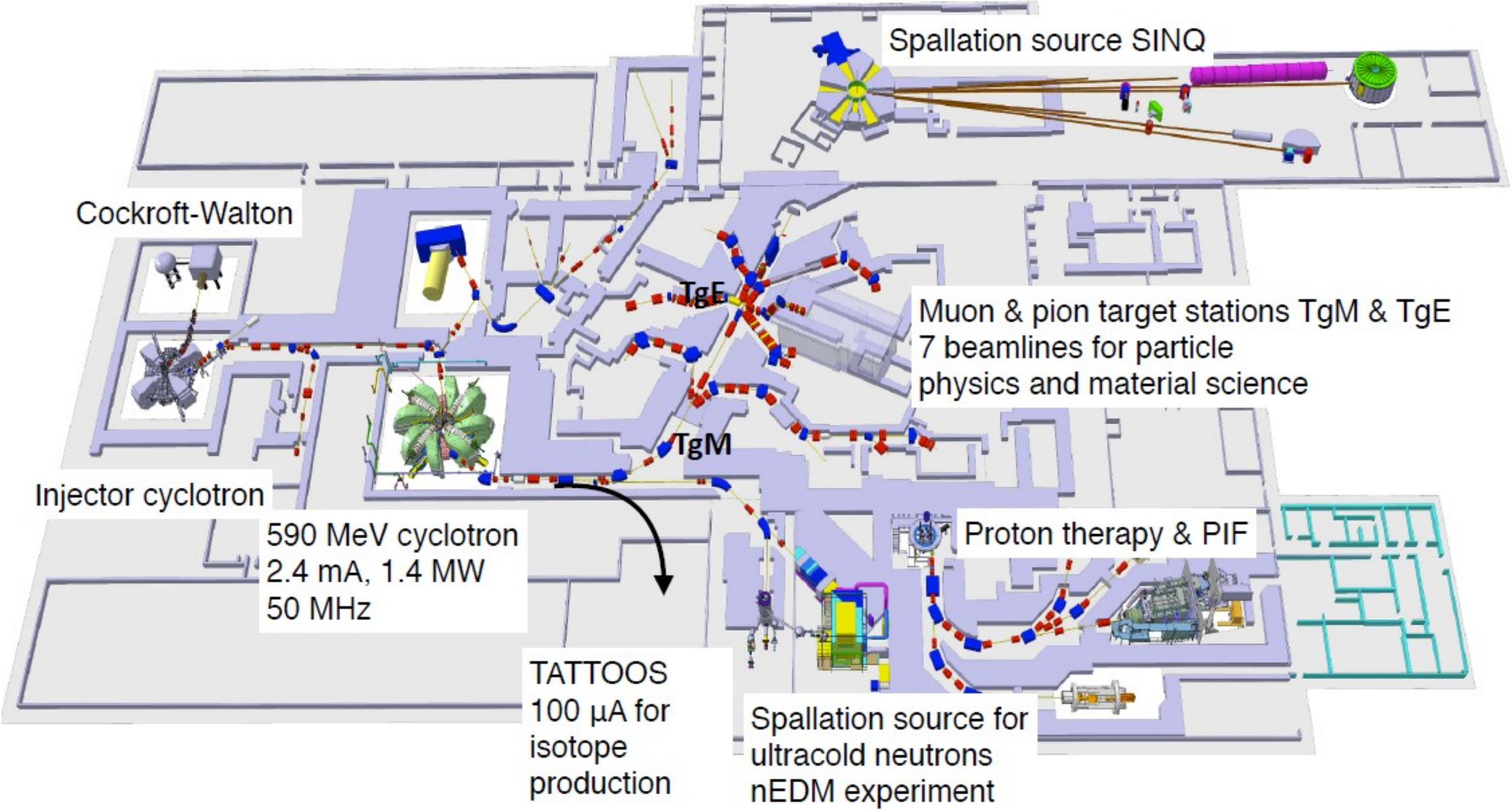
Projects: MELODY, CSNS (China, pulsed)
RAON (South Korea, continuous)



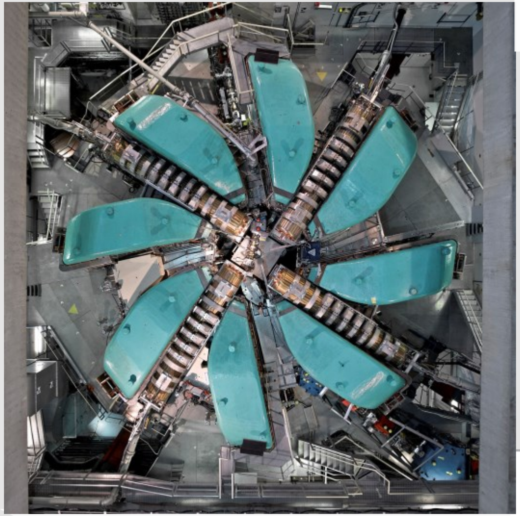
µSR facilities of the world.

http://musr.ca/intro/musr/muSRBrochure.pdf

Proton Accelerator

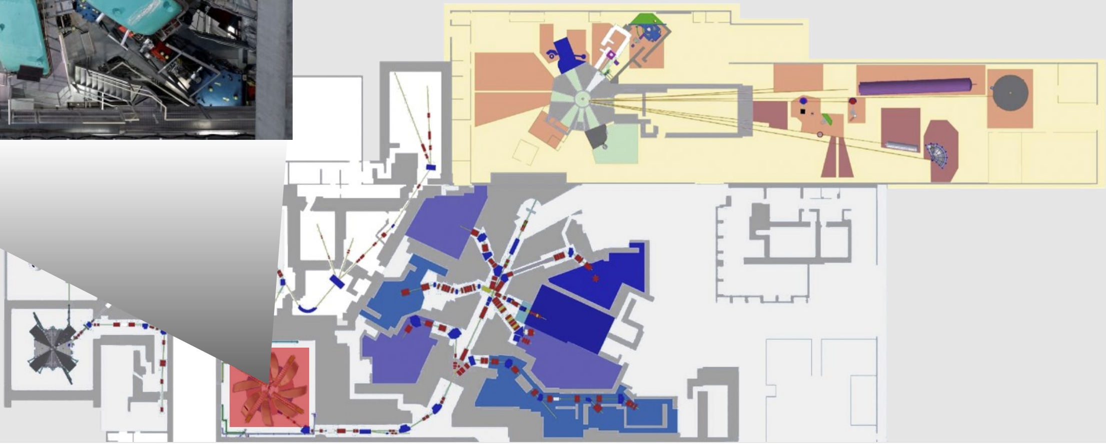


Proton Accelerator



Main Cyclotron

Injection Energy	72 MeV
Extraction Energy	590 MeV
Extraction Momentum	1.2 Gev/c
Energy spread (FWHM)	ca. 0.2 %
Beam Emittance	ca. 2 pi mm x mrad
Beam Current	2.2 mA DC
Accelerator Frequency	50.63 MHz
Time Between Pulses	19.75 ns
Bunch Width	ca. 0.3 ns
Extraction Losses	ca. 0.03 %



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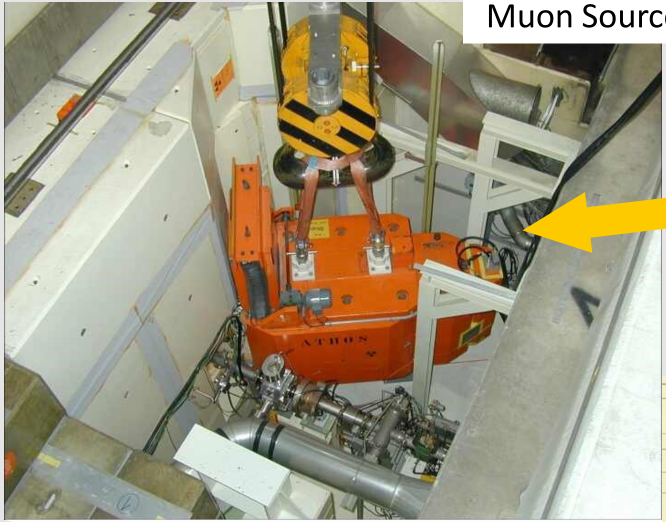
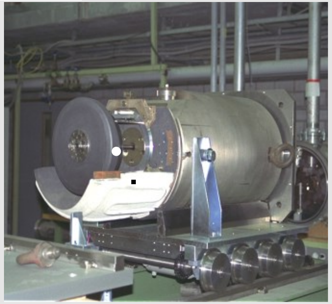
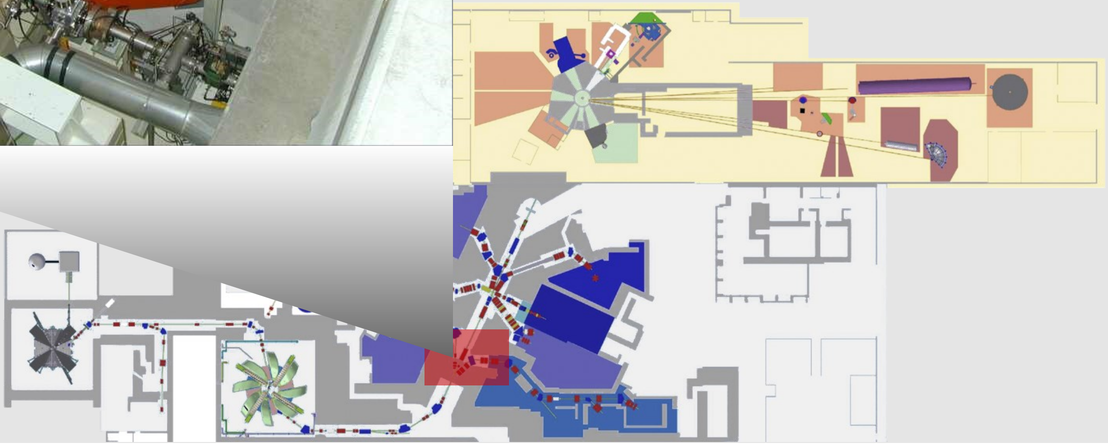
Muon target

Muon Source (Target M)

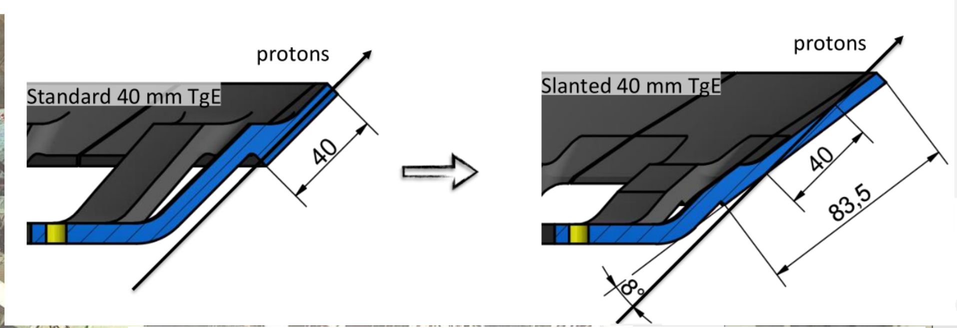


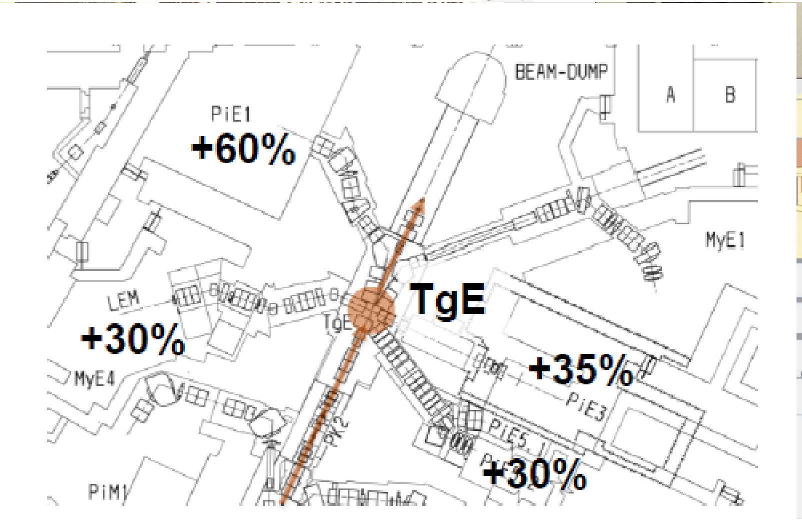


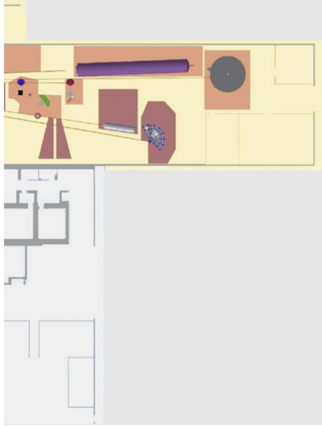
Thin target M ("Mince" in french, 5 mm of graphite)



Muon target





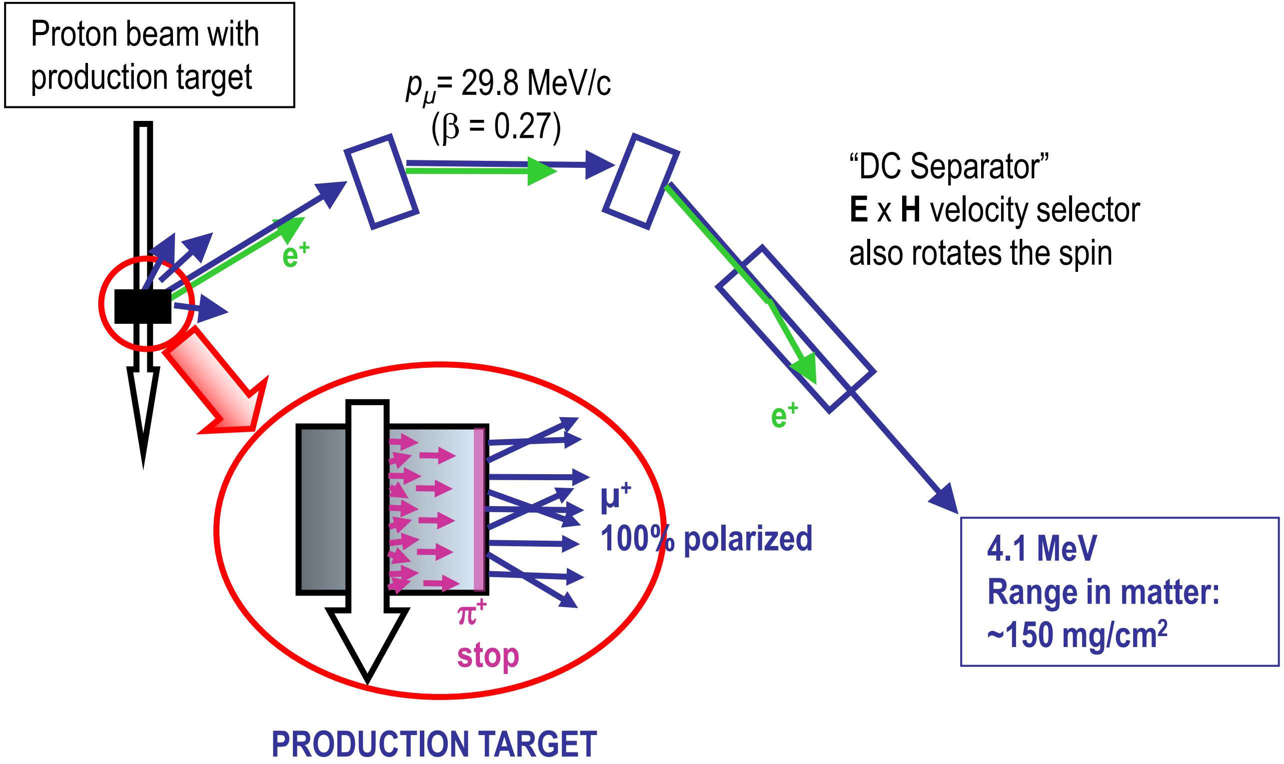


Thick E target 1 Hz
"Epaisse" in french
60 mm or 40 mm of graphite

Slanted E target
30-60% increase in surface muon rate

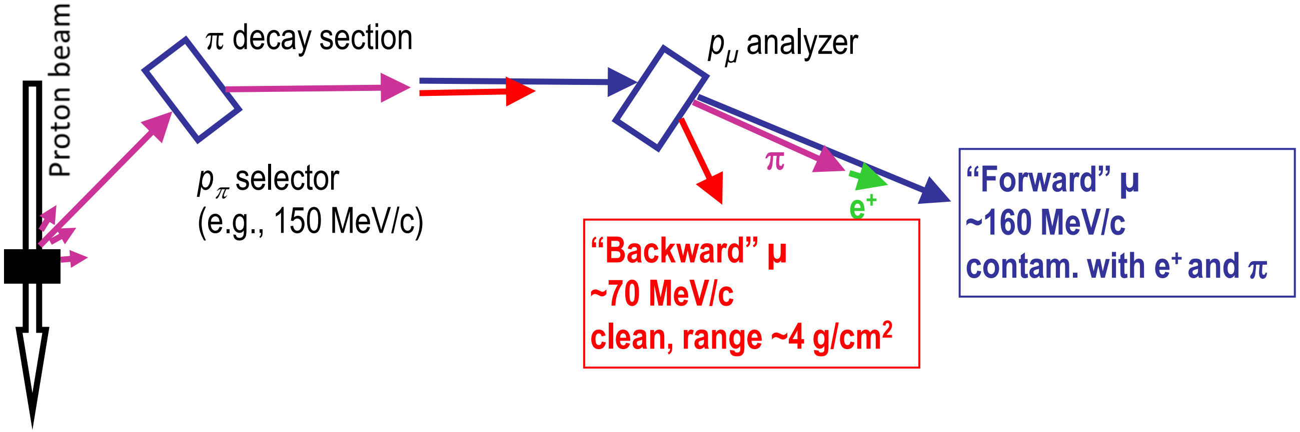
Generation of muon beams

"Arizona" or "Surface Muon Beam" (only μ^+), ~100% polarization



Generation of muon beams

(Traditional) "Decay Muon Beam" (μ^+ or μ^-), ~80% polarization



to select beam momentum *p*: magnetic dipole magnets (bending magnets)

to focus beam: magnetic quadrupole dublets or triplets, solenoids (for «surface muons»)

to vary beam intensity, momentum width *Δp/p*: slits

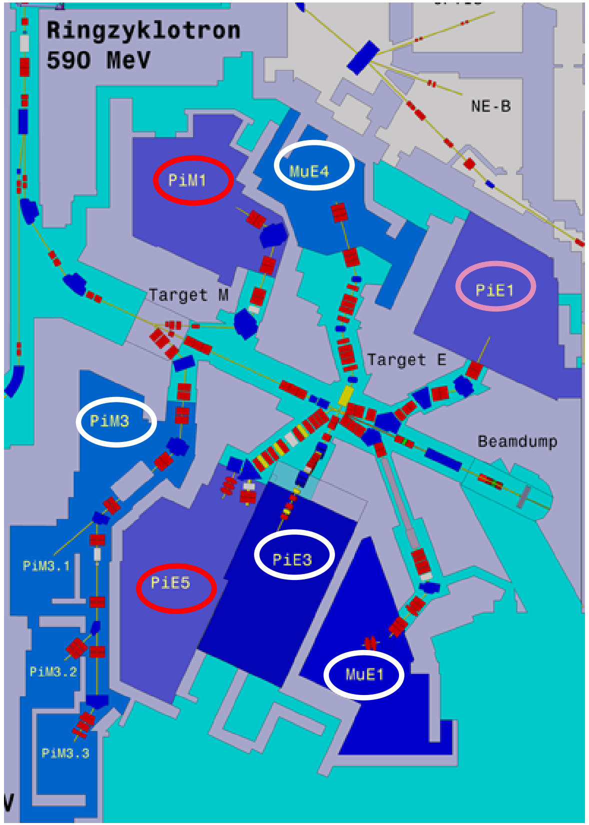
to remove positrons from beam, to rotate muon spin (for «surface muons» only):
ExB velocity filter (separator, spin-rotator)

Muon beamlines

- Particle physics:
  - PiE5
  - PiM1

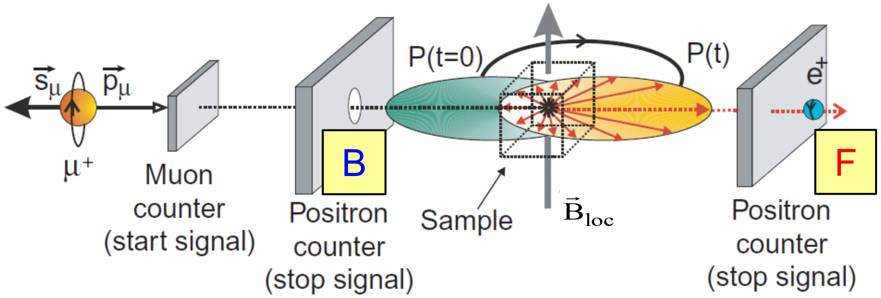
- µSR:
  - PiM3 (GPS & FLAME)
  - PiE3 (HAL-9500)
  - MuE1 (GPD)
  - MuE4 (LEM)

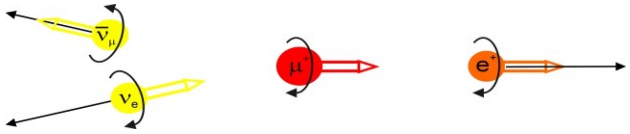
- Shared particle physics/µSR:
  - PiE1 (DOLLY)



https://www.psi.ch/en/smus

Basics of a μSR experiment

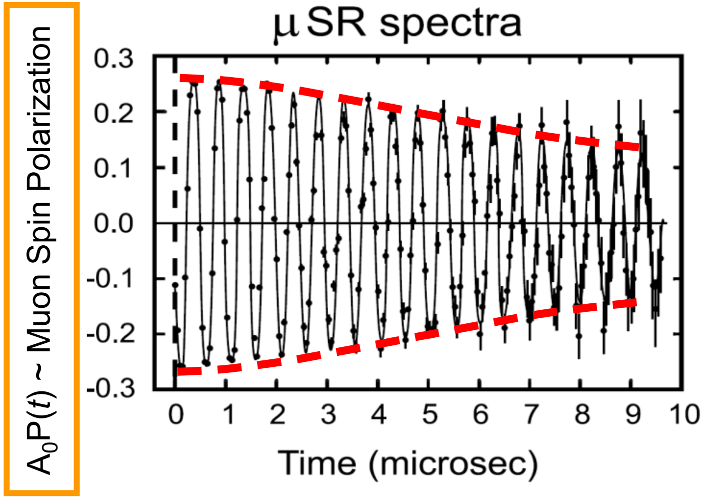




$$N_{e^+}(t) = B_G + N_0 \exp(-t/\tau_\mu)\ [1 + A_0 P(t)]$$

Positron emitted preferentially in the direction of the muon spin:

allows to measure evolution of polarization P(t) of muon ensemble



$A_0P(t)$ contains the physics:

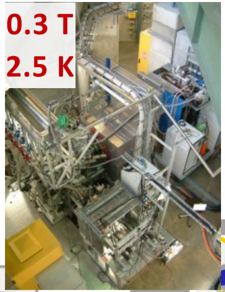
frequency: $\omega_L = \gamma_\mu B_{loc}$ value of field at muon site

damping: width of field distribution, fluctuations

amplitude: magnetic/non-magnetic volume fraction, or muonium fraction

$A_0P(t) = [F(t) – B(t)] / [F(t) + B(t)]$

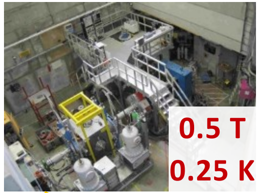
Instruments at the SμS (Swiss Muon Source)



LEM

Low Energy Muon Instrument

Muon Energy: **1-30 keV**



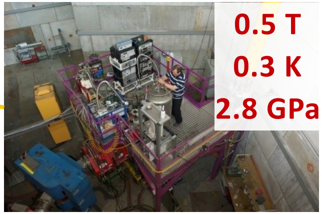
DOLLY

Muon Energy: **4.2 MeV** (μ^+)

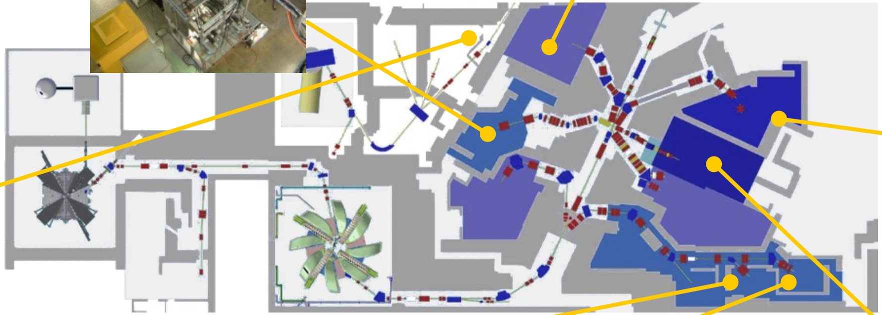
GPD

General Purpose Decay Channel Instrument (for Pressure Studies)

Muon Energy: **5-60 MeV** (μ^+/ μ^-)



MIXE, μ-



HAL-9500

High Field and Low Temperature

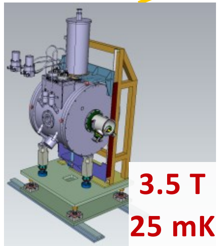
GPS

General Purpose Surface Muon Instrument

Shared Surface Muon Beam

Muon on Request (MORE)

Muon Energy: **4.2 MeV** (μ^+)

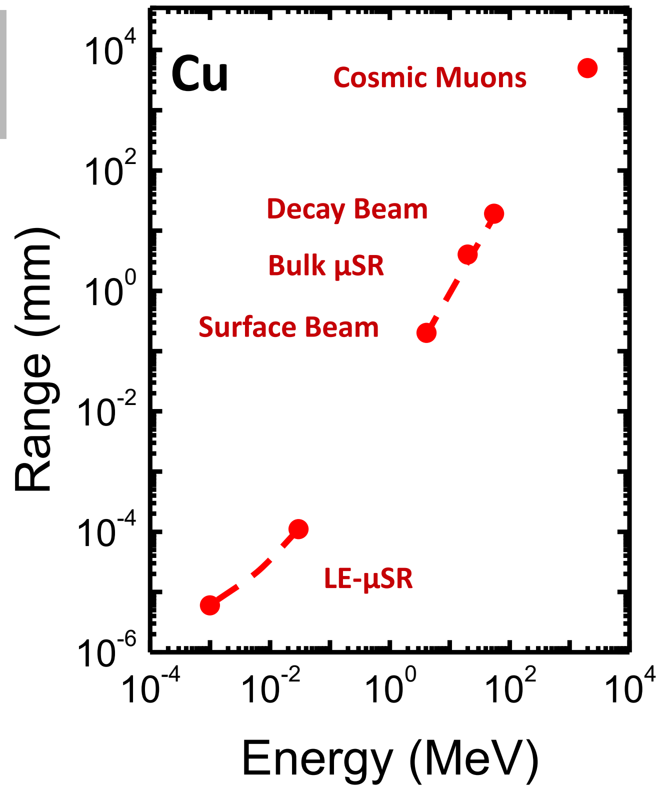


FLAME

FLexible and Advanced MuSR Environment

First Experiments 2022

Different Muon Energies for Different Studies



Bulk µSR (MeV muons):

- ‘‘normal’’ samples (sub-mm)
- bulk samples in pressure cells or containers (e.g. liquids)
- MeV muons delivered by the “secondary beam lines” connected to the proton beam (“primary beam line”) target

Low-energy µSR (LE-µSR, keV µ+):

- depth-dependent investigations (≈ 1 – 300nm)
- Cannot be extracted from the proton beam target
- Needs an efficient conversion (“moderation”) of MeV muons to keV muons, “tertiary beam line” of keV muons

- Strategy: Convert MeV muons to epithermal (eV) energies and re-accelerate up to 30 keV

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Bulk-μSR Instruments

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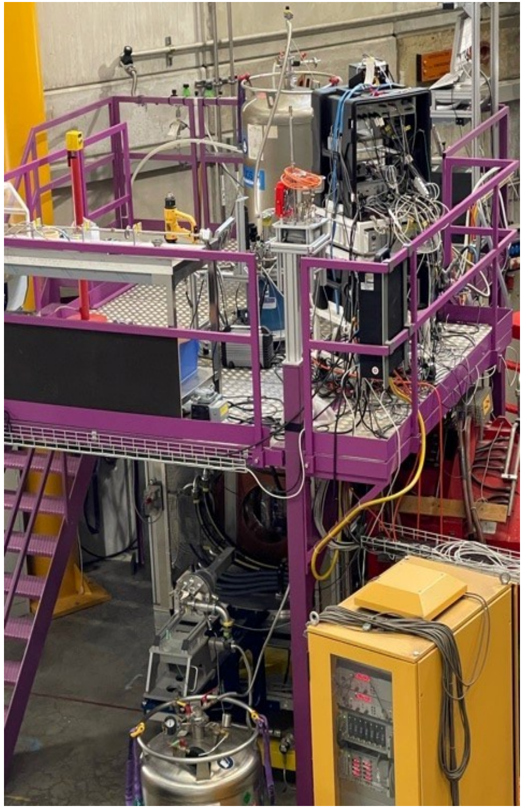
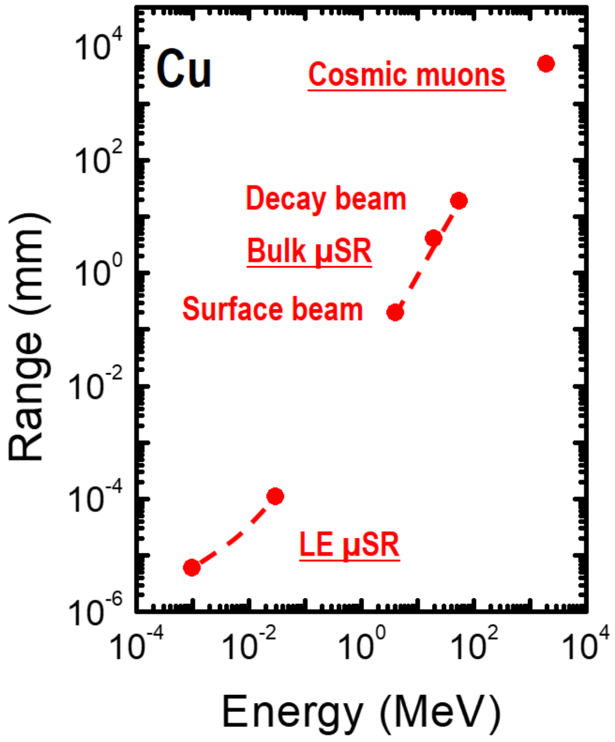
General Purpose Decay Muon Instrument (GPD)

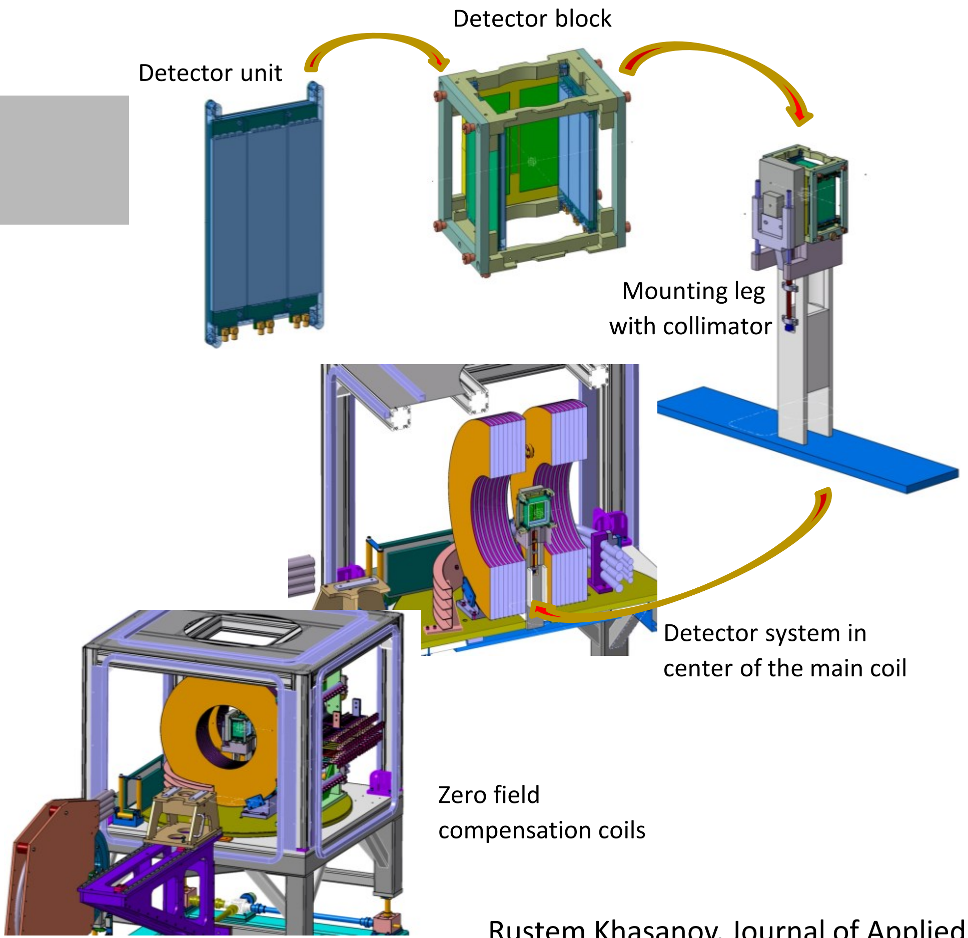


General Purpose Decay Muon Instrument (GPD)



- High energy muons from pion decay in flight
- Energy: 10 – 60 MeV (60 – 125 MeV/c)
  - Stopping range: 1 mm – 2 cm (steel)

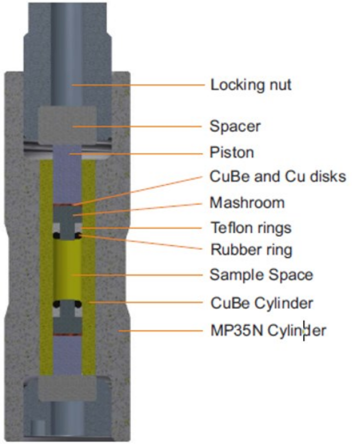
General Purpose Decay Muon Instrument (GPD)

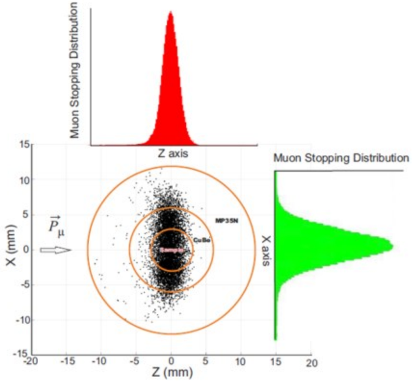


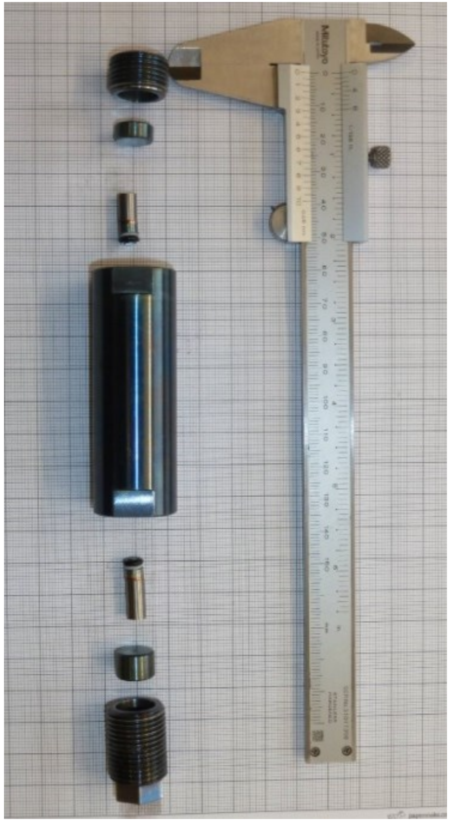
- High energy muons from pion decay in flight
- Energy: 10 – 60 MeV (60 – 125 MeV/c)
  - Stopping range: 1 mm – 2 cm (steel)
- Detector system
  - Plastic scintillators with SiPM readout
  - Time resolution: 160 ps
- Magnetic field: 2 μT (ZF) – 0.5 T

Rustem Khasanov. Journal of Applied Physics, **132** (19),190903, (2022)

General Purpose Decay Muon Instrument (GPD)







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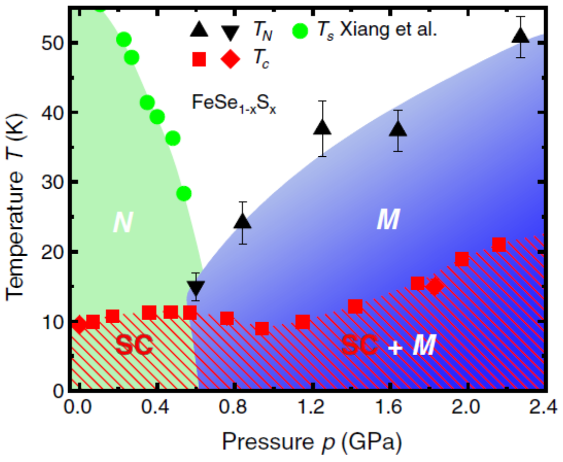
- Energy: 10 – 60 MeV (60 – 125 MeV/c)
  - Stopping range: 1 mm – 2 cm (steel)
- Detector system
  - Plastic scintillators with SiPM readout
  - Time resolution: 160 ps
- Magnetic field: 2 μT (ZF) – 0.5 T
- Temperature range: 250 mK – 475 K
  - ^{3}He, ^{4}He flow, CCR and N_2 cryostats
- Hydrostatic pressure: 2.8 GPa
  - Double wall CuBe or MP35 clamp cells
  - 40% sample and 60% cell signal

Rustem Khasanov, Journal of Applied Physics, **132** (19),190903, (2022)

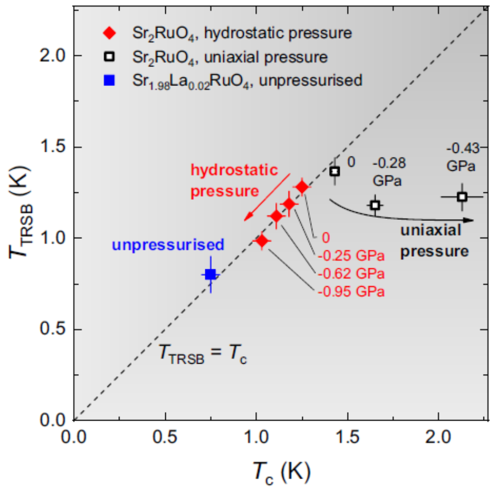
GPD Instrument – Research Examples

Extended magnetic dome induced by low pressures in superconducting $FeSe_{1-x}S_x$



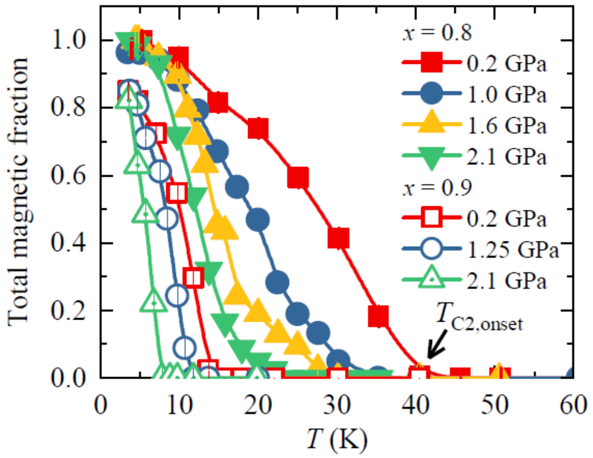
S. Holenstein *et al.*,
Phys. Rev. Lett. **123**, 147002 (2019)

Unsplit superconducting and time reversal symmetry breaking transitions in Sr_2RuO_4 under hydrostatic pressure and disorder



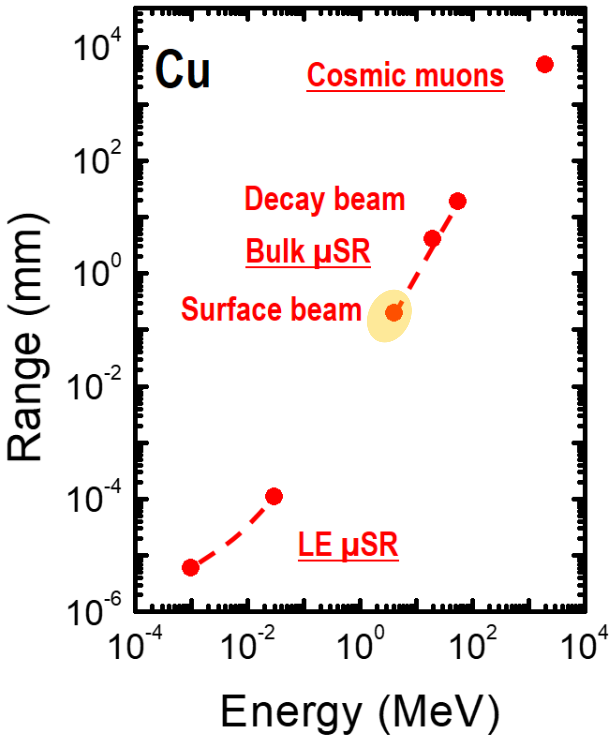
V. Grinenko *et al.*,
Nat. Commun. **12**, 3920 (2021)

Multiple quantum phase transitions of different nature in the topological kagome magnet $Co_3Sn_{2-x}In_xS_2$



Z. Guguchia *et al.*,
npj Quantum Materials **5**, 50 (2021)

Surface Muon Instruments (Dolly, HAL-9500, GPS, and FLAME)

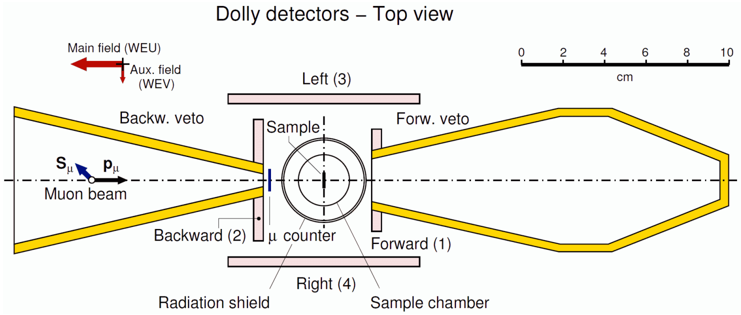


- Surface muons from pion decays at the surface of the production target
- Energy: 4 MeV (28 MeV/c)
  - Stopping range: ~100 – 300 µm

Muon is a local probe in the bulk of the specimen

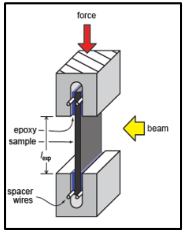
Multi Purpose Surface-Muon Instrument (Dolly)

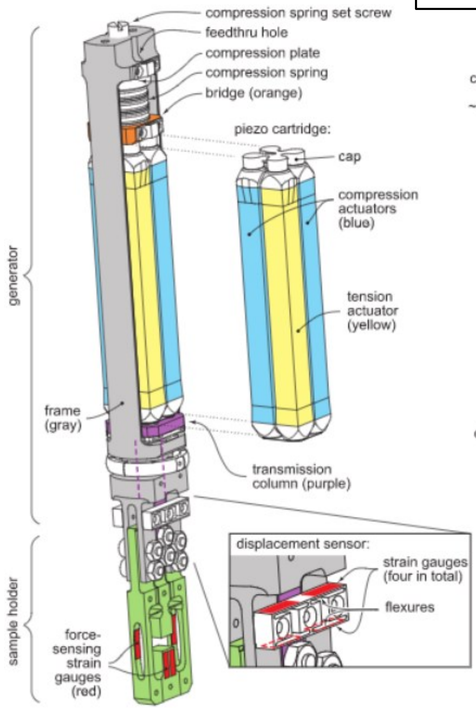
Multi Purpose Surface-Muon Instrument (Dolly)

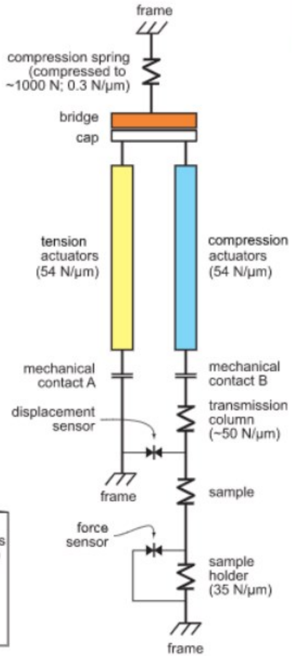


- Detector system
  - Plastic scintillators with conventional PM
  - Time resolution: 700 ps
  - Active forward-and backward veto systems for measuring small samples (>2x2 mm^2)
- Magnetic field: 2 μT (ZF) – 0.5 T (LF and TF)

Multi Purpose Surface-Muon Instrument (Dolly)





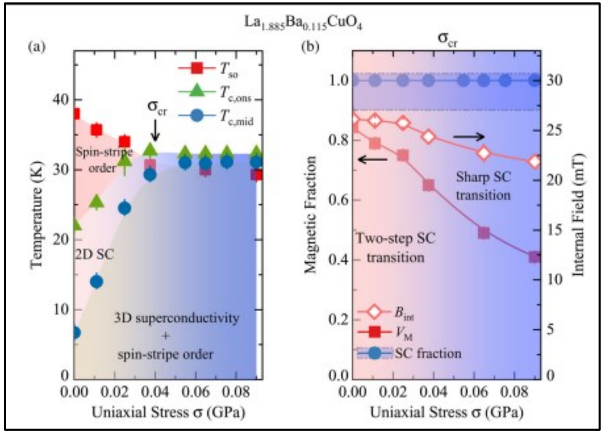


- Detector system
  - Plastic scintillators with conventional PM
  - Time resolution: 700 ps
  - Active forward-and backward veto systems for measuring small samples (>2x2 mm^2)
- Magnetic field: 2 µT (ZF) – 0.5 T (LF and TF)
- Temperature range: 250 mK – 300 K
  - ^{3}He and ^{4}He cryostats
- Uniaxial pressure: 1 GPa
  - Piezoelectrically driven force generator
  - In-situ modification of stress at mK temperatures
  - 50% sample and 50% cell signal

S. Ghosh, et al., Rev. Sci. Instrum., 91 (10): 103902, (2020)

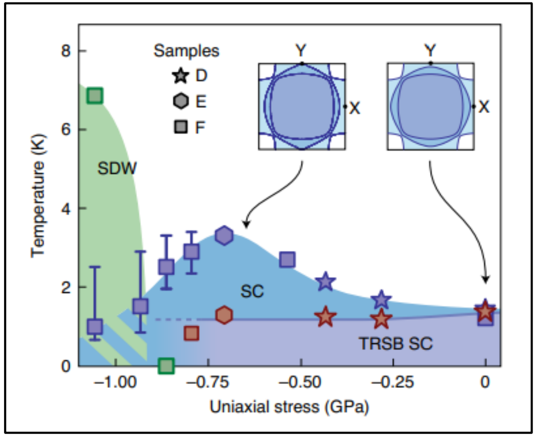
Dolly μSR spectrometer – Research Examples

Using Uniaxial Stress to Probe the Relationship between Competing Superconducting States in a Cuprate with Spin-stripe Order



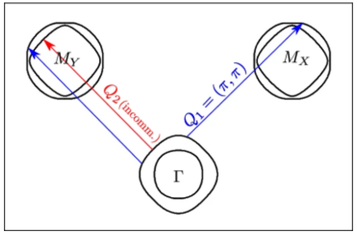
Z. Guguchia *et al.*,
Phys. Rev. Lett. **125**, 097005 (2020)

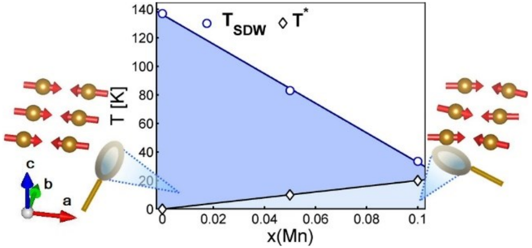
Split superconducting and time-reversal symmetry-breaking transitions in Sr_2RuO_4 under stress



V. Grinenko *et al.*,
Nat. Phys. **17**, 748 (2021)

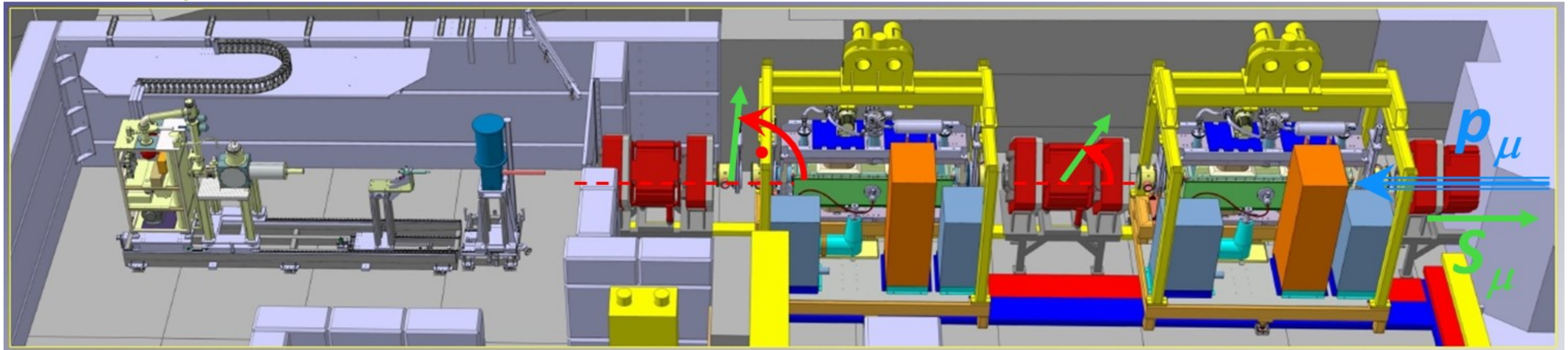
Mn-induced Fermi-surface reconstruction in the SmFeAsO iron-based parent compound



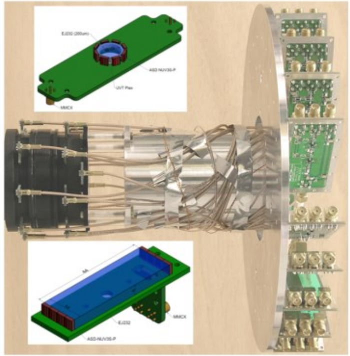


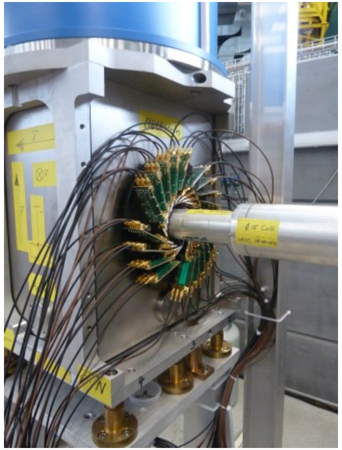
M. Meinero *et al.*,
Sci. Rep. **11**, 14373 (2021)

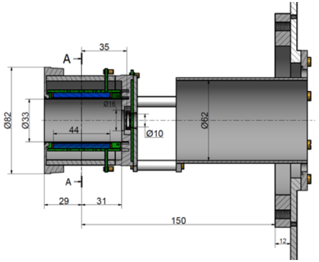
High-Field And Low-Temperature Instrument (HAL-9500)



HAL-9500 Instrument

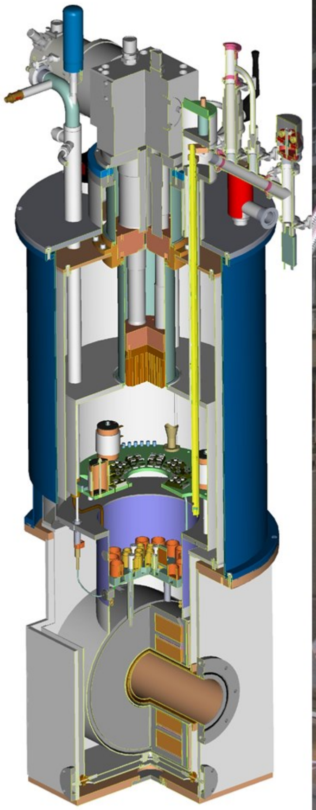






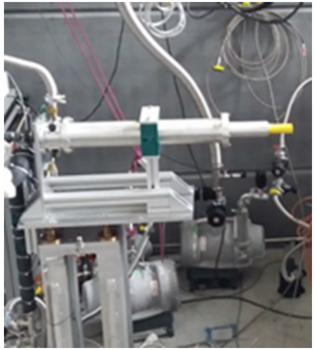
- Detector system
  - Plastic scintillators with SiPM
  - Time resolution: 60 ps

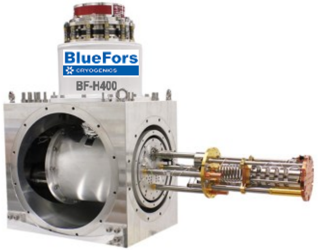
HAL-9500 Instrument



- Detector system
  - Plastic scintillators with SiPM
  - Time resolution: 60 ps
- Magnet (TF)
  - 9.5 T warm bore magnet
  - ΔB < 0.1 mT (sample)

HAL-9500 Instrument

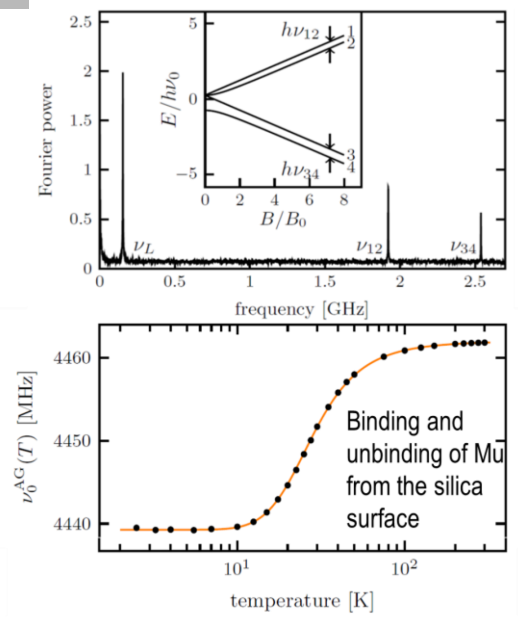




- Detector system
  - Plastic scintillators with SiPM
  - Time resolution: 60 ps
- Magnet (TF)
  - 9.5 T warm bore magnet (recondens.)
  - $\Delta B < 0.1$ mT (sample)
- Temperature range: <20 mK (12 mK) – 300 K
  - Cryogen-free ‘true’ horizontal dilution refrigerator
  - ^{4}He flow cryostat cryostat

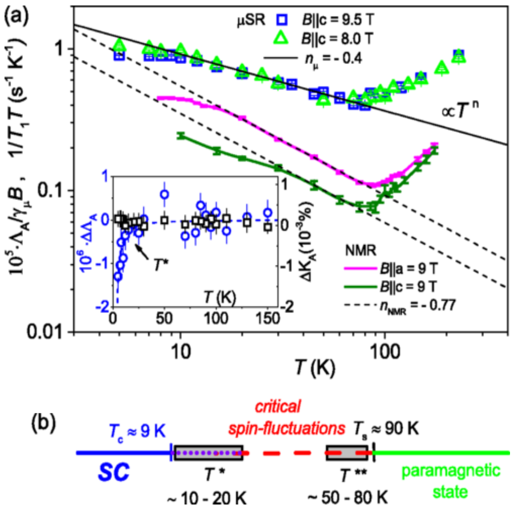
HAL-9500 Instrument – Research Examples

Precision measurement of the Mu hfc in mesoporous aerogel



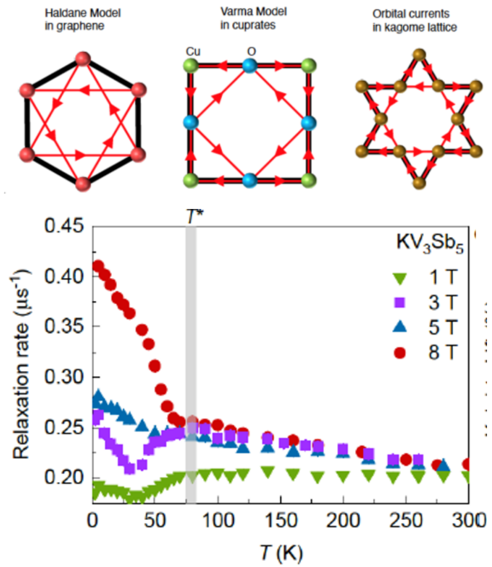
M. Dehn *et al.*,
Phys. Rev. Res. **3**, 013029 (2021)

Low-temperature breakdown of antiferromagnetic quantum critical behavior in FeSe



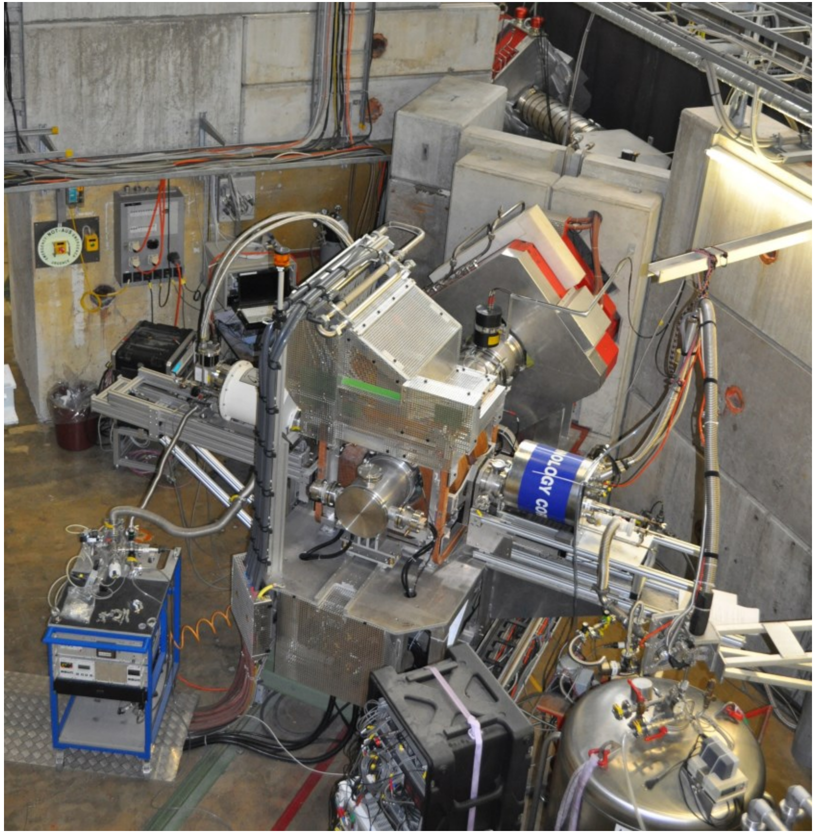
V. Grinenko *et al.*,
Phys. Rev. B **97**, 201102 (2018)

Time-reversal symmetry-breaking charge order in a correlated kagome superconductor

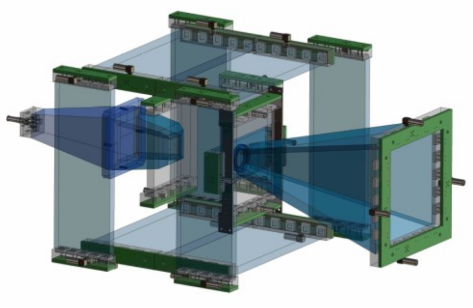


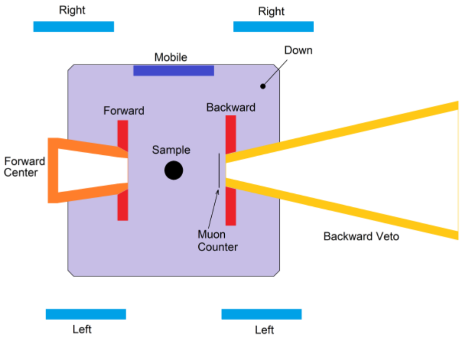
C. Mielke III *et. al.*,
Nature **602**, 245-250 (2022)

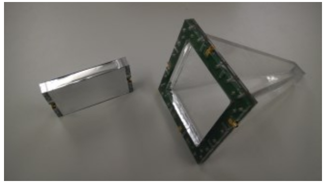
General Purpose Surface-Muon Instrument (GPS)



General Purpose Surface-Muon Instrument (GPS)







A. Amato, et al., Rev Sci Instrum **88**, 093301 (2017)

- «Working horse» of the facility
- Detector system
  - Plastic scintillators with SiPM readout
  - Time resolution: 160 ps
  - Active forward-and backward veto systems for measuring small samples (>2x2 mm^2)
- Magnetic field: 2 µT (ZF) – 0.8 T (LF and TF)
  - Active ZF compensation
- Temperature range: 1.5 K – 1000 K
  - Fast ^{4}He cryostat (at 1.5 K in 15 min)
  - CCR cryostat (4 – 475 K)
  - Oven (300 – 1000 K)

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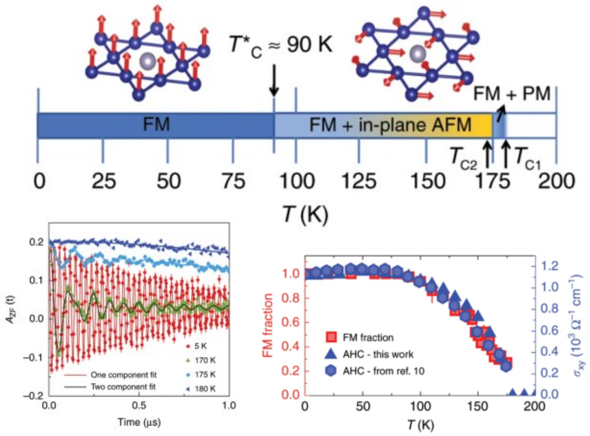
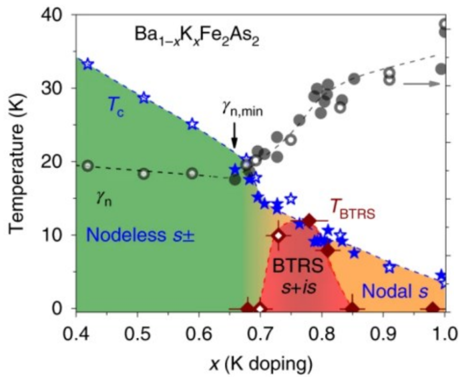
GPS μSR spectrometer – Research Examples

Tunable anomalous Hall conductivity through volume-wise magnetic competition in a topological kagome magnet



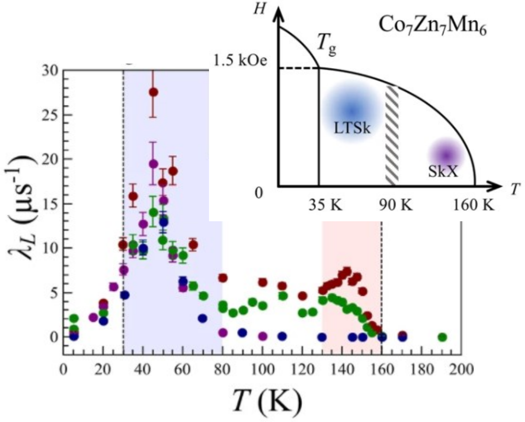
Z. Guguchia *et al.*,
Nat. Commun. 11, 559 (2020)

Superconductivity with broken time-reversal symmetry inside a superconducting s-wave state



V. Grinenko, *et al.*,
Nat. Phys. 16, 789 (2020)

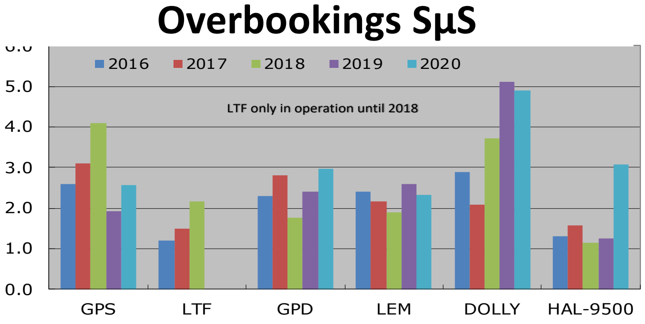
Frustration-driven magnetic fluctuations as the origin of the low-temperature skyrmion phase in $Co_7Zn_7Mn_6$

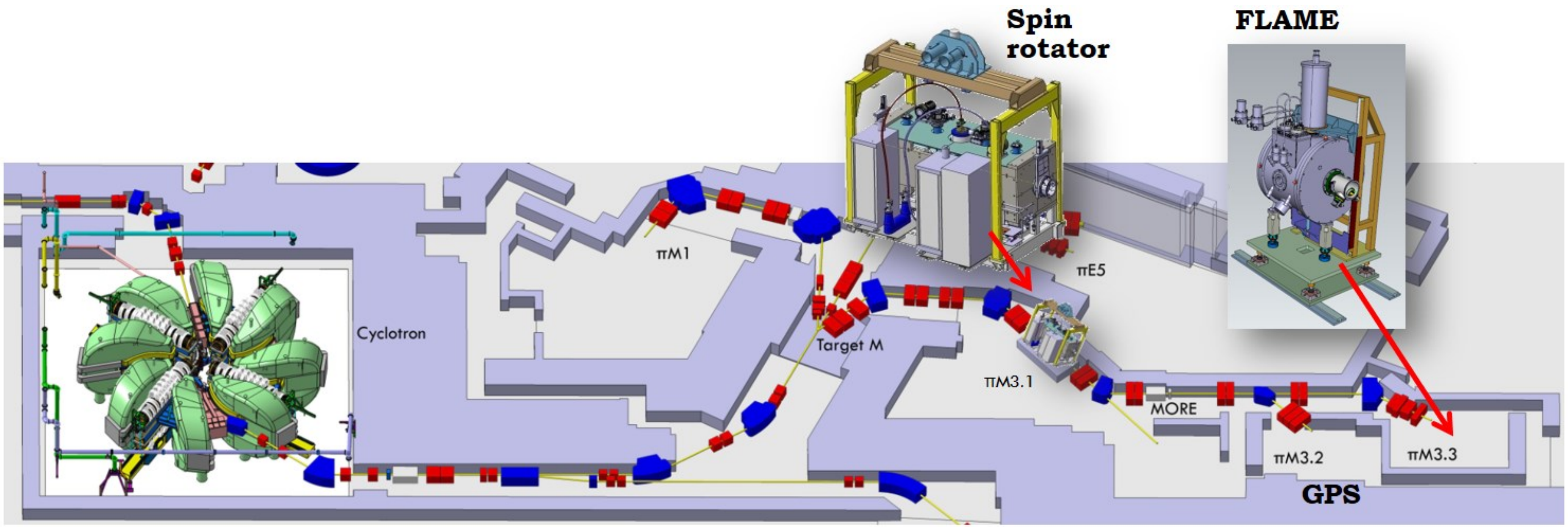


V. Ukleev *et al.*,
npj Quantum Materials 6, 40 (2021)

FLexible Advanced MuSR Environment (FLAME)

Enable new research directions by the extension of experimental capabilities at the SµS user facility



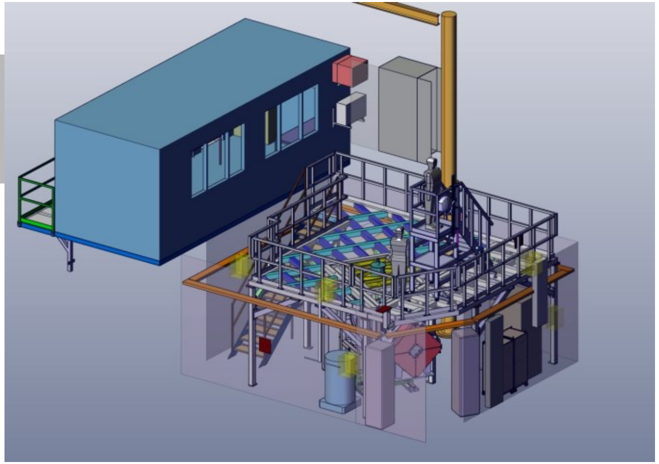
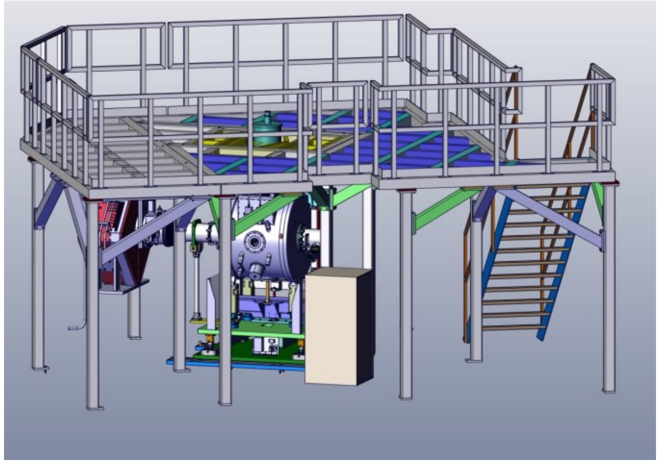
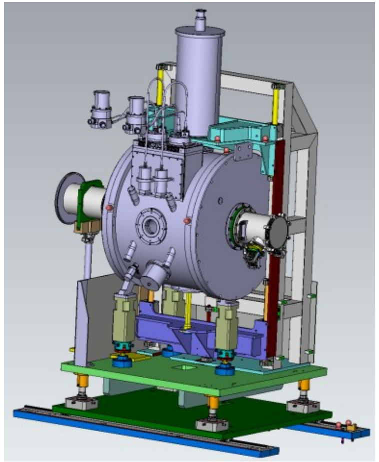


FLexible Advanced MuSR Environment (FLAME)

Design Specifications for FLAME

- Temperature range 20 mK – 300 K (possibly 1000 K)
- Magnetic field up to 3.5 T (TF & LF)
- Zero field option B < 5 µT
- Small samples with practically no background
  → improvement of factor 100 in data quality
- In-situ modification of the sample by external stimuli (uniaxial pressure, …)
- Multiple sample stage
  → high throughput and reference sample

FLAME Overview


LE-μSR Instruments

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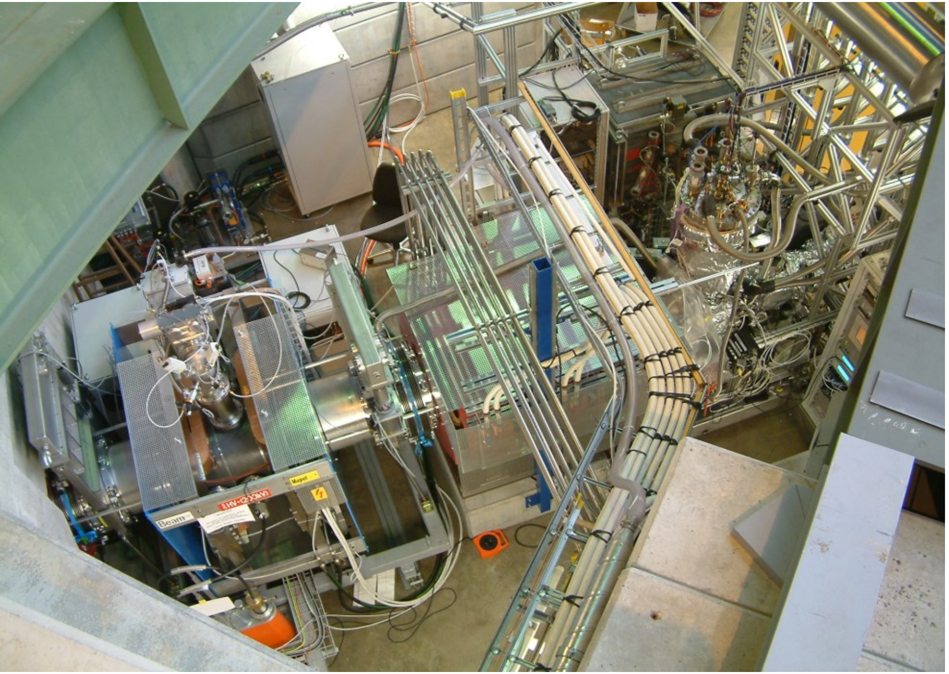
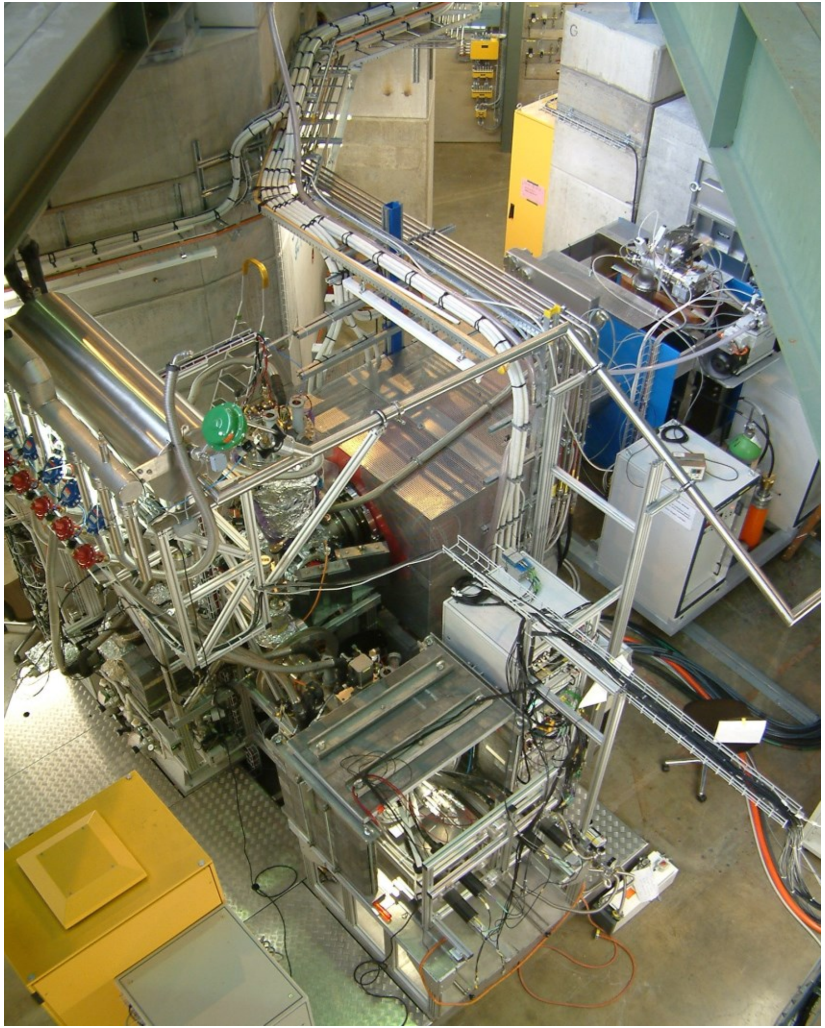
LEM facility





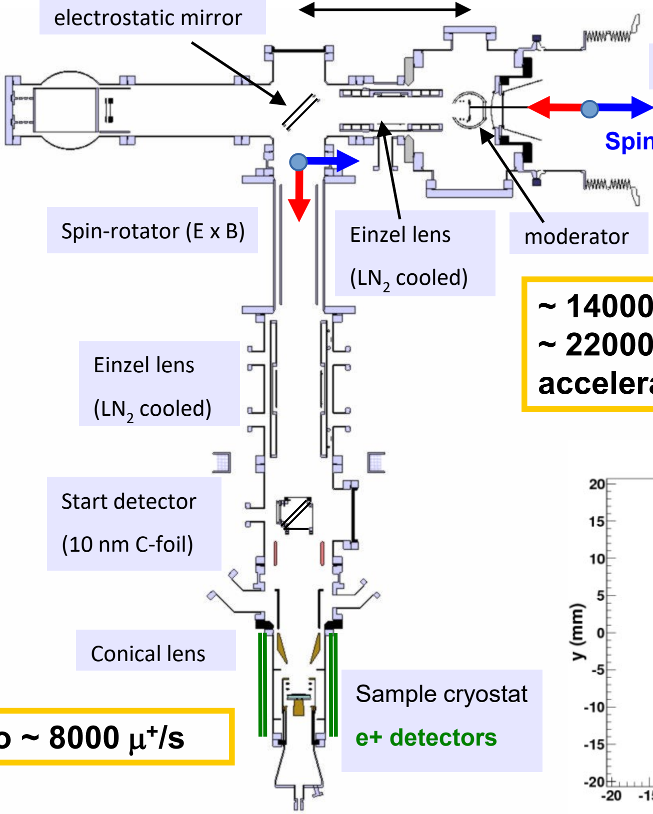
At 2.0 mA proton current, “slanted” muon target E

~5.4 • 10^8 μ^+/s total, $\Delta p/p$ = 9.5% (FWHM)
~2.3 • 10^8 μ^+/s on LEM moderator
~1.4/2.3 • 10^4 μ^+/s moderated (solid Ar/solid Ne)

Low-energy muon facility LEM

- UHV system, 10^{-10} mbar
- some parts LN_2 cooled

Rates are for 4-cm "slanted" target E and 2.0 mA proton current (2021)



~2.3 • 10^8 μ^+/s

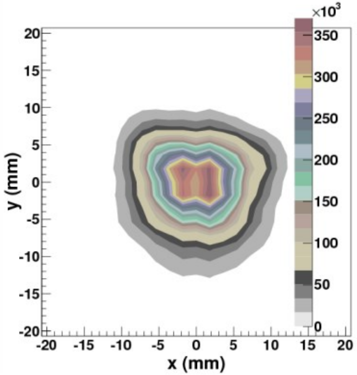
~ 14000 LE-μ^+/s, s-Ar;
~ 22000 LE-μ^+/s, s-Ne;
accelerate up to 20 keV

Polarized Low Energy Muon Beam

Energy:	1-30 keV
ΔE, Δt:	400 eV, 5 ns
Depth:	1 – 300 nm
Polarization	~100 %
Beam Spot:	12 mm (FWHM)

at sample: up to ~ 8000 μ^+/s

Beam spot at sample



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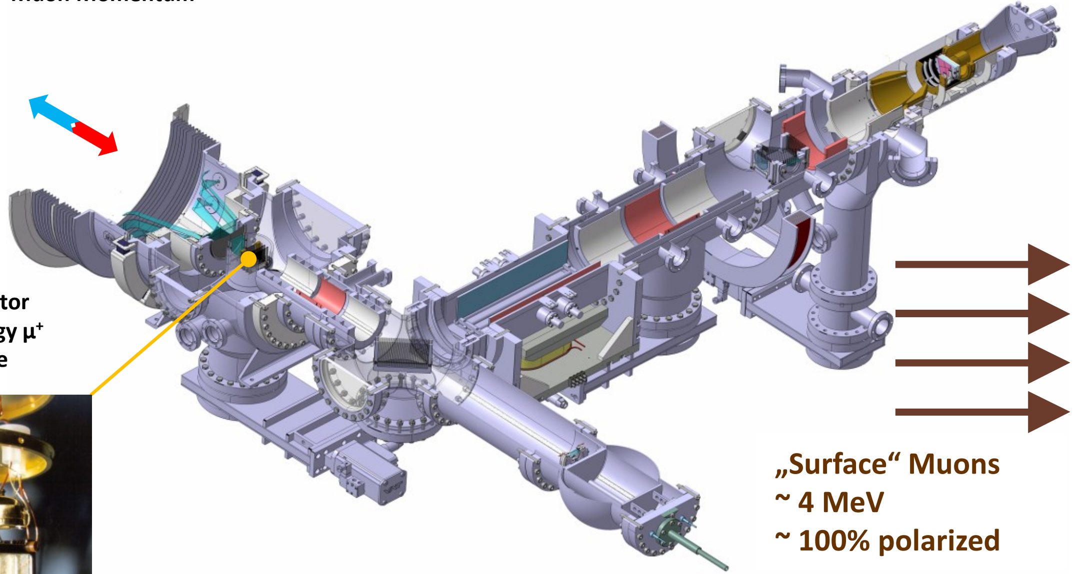
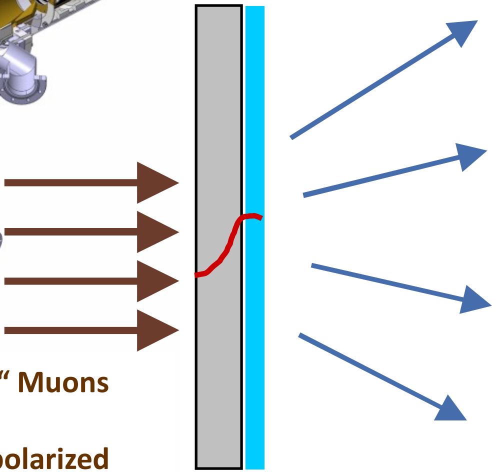
Low Energy μ⁺ Beam and Setup for LE-μSR

Muon Spin
Muon Momentum



Moderator
low energy μ^+
source

Typical re-acceleration
voltage at the moderator:
15kV



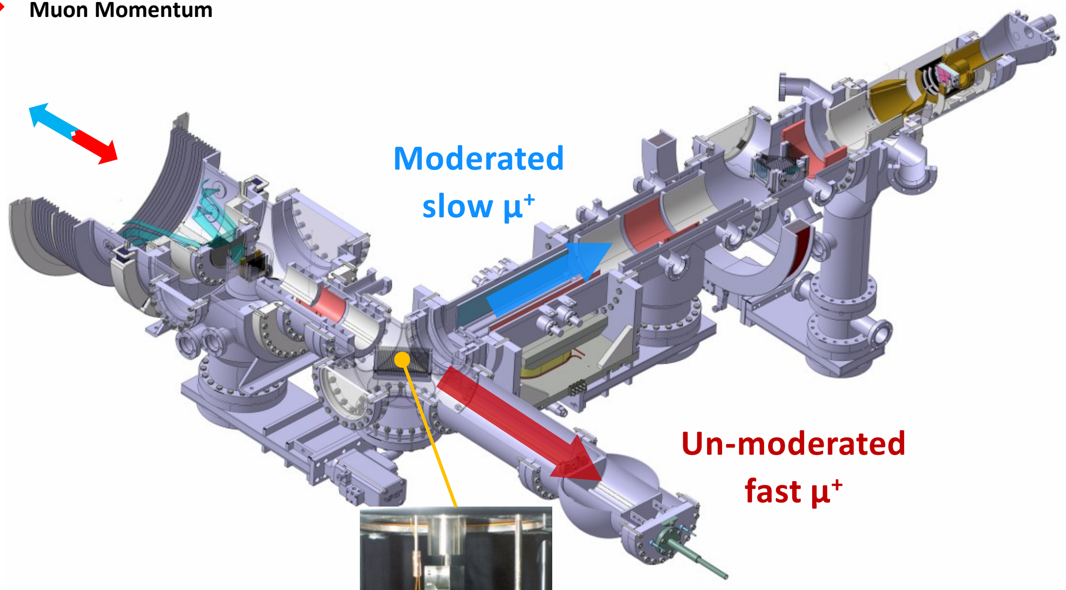
„Surface“ Muons
~ 4 MeV
~ 100% polarized

~100 µm Ag

~500 nm
s-Ne, Ar,
$s\text{-}N_2$

Low Energy μ^+ Beam and Setup for LE-μSR

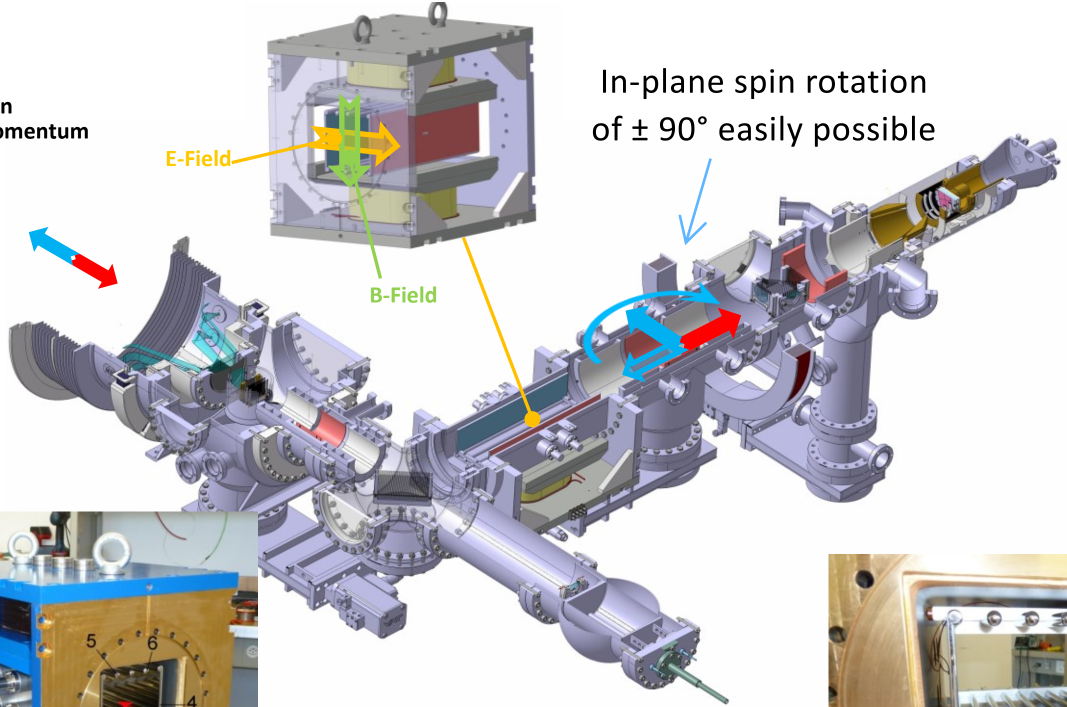
Muon Spin
Muon Momentum

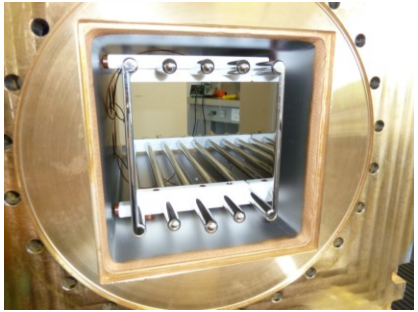


Mirror
energy filter

Mirror at the same high voltage as the moderator. Typically 15kV

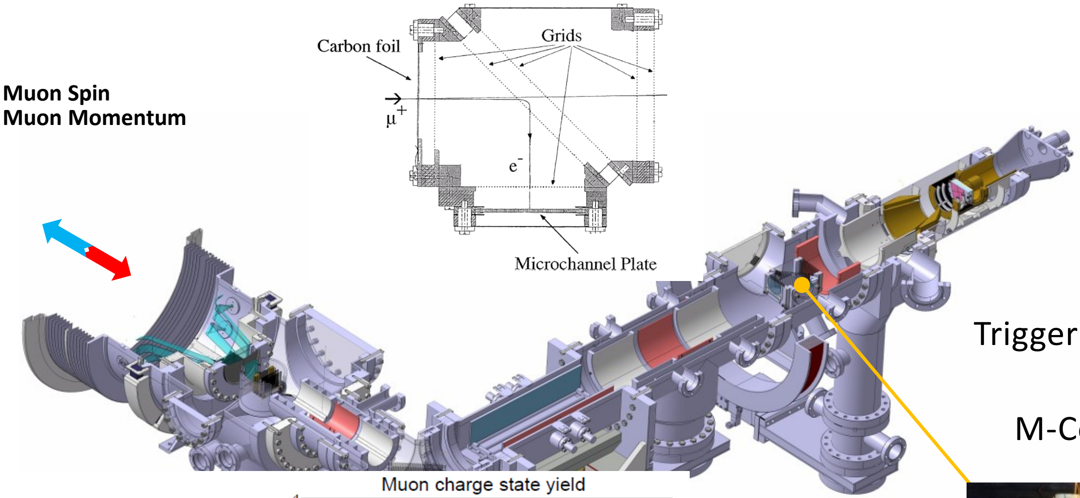
Low Energy μ^+ Beam and Setup for LE-μSR



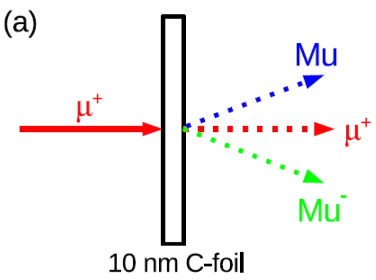


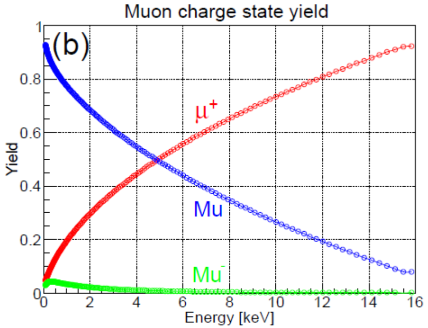
Low Energy μ⁺ Beam and Setup for LE-μSR

Muon Spin
Muon Momentum

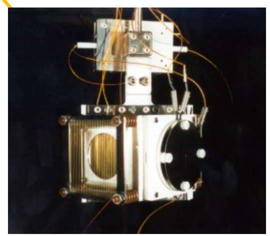


Trigger Detector
or
M-Counter



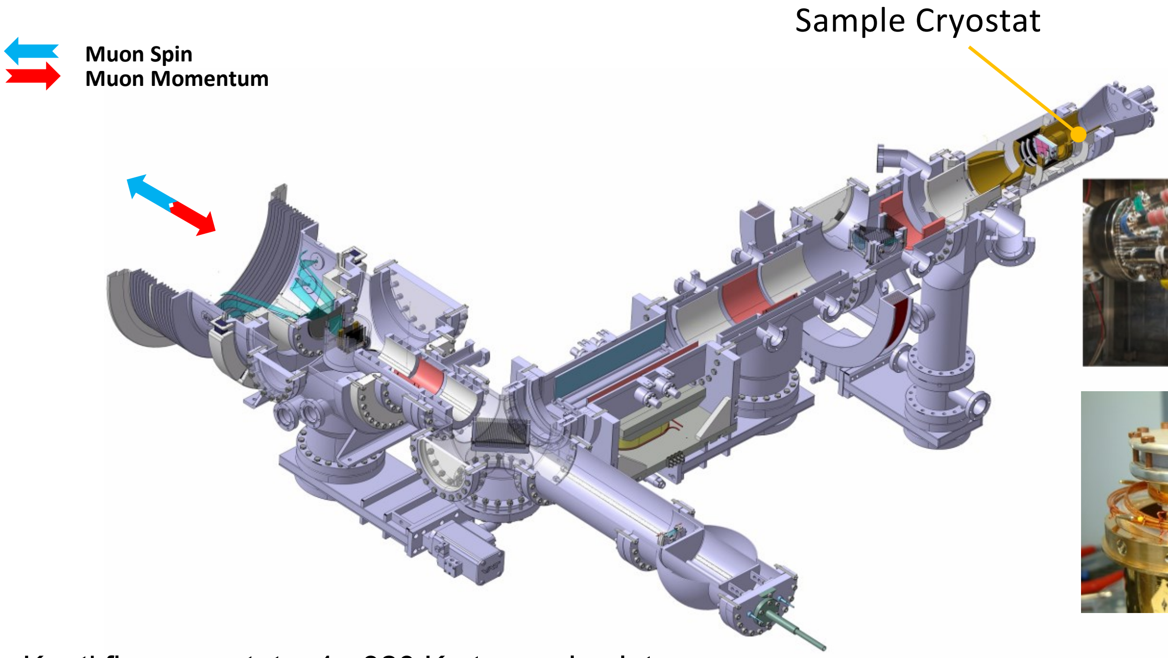


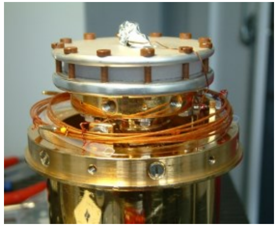
Trigger
implantation time



A. Hofer, PhD Thesis (98)
K.S. Khaw, *et al.*, JINST **10**, P10025 (15).

Low Energy μ^+ Beam and Setup for LE-μSR



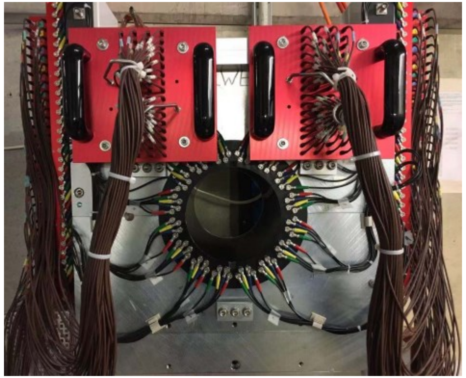


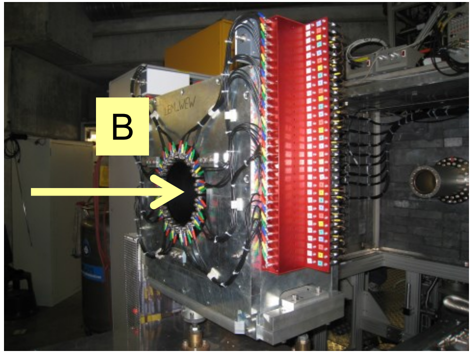
- Konti flow cryostats: 4 - 320 K at sample plate
- LowTemp cryostat: 2.4 - 300 K with sample plate, 2.2 - 300 K without sample plate
- Furnace: -50 - 300°C (can be cooled by LN_2)
- Sample size: Ideally 25x25 mm^2 or ∅ = 25 mm, mosaic of four pieces of 10x10^{2}mm

Low Energy μ^+ Beam and Setup for LE-μSR

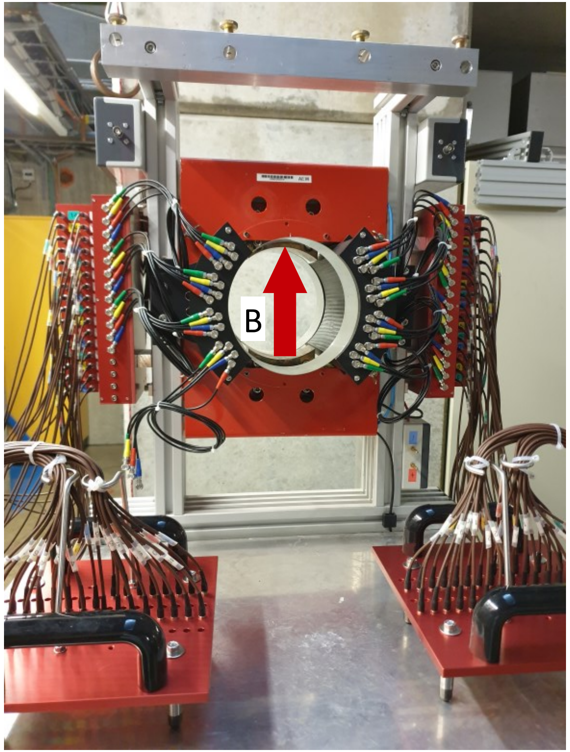
Magnets with APD Positron Spectrometer

WEW: 0-0.34 T



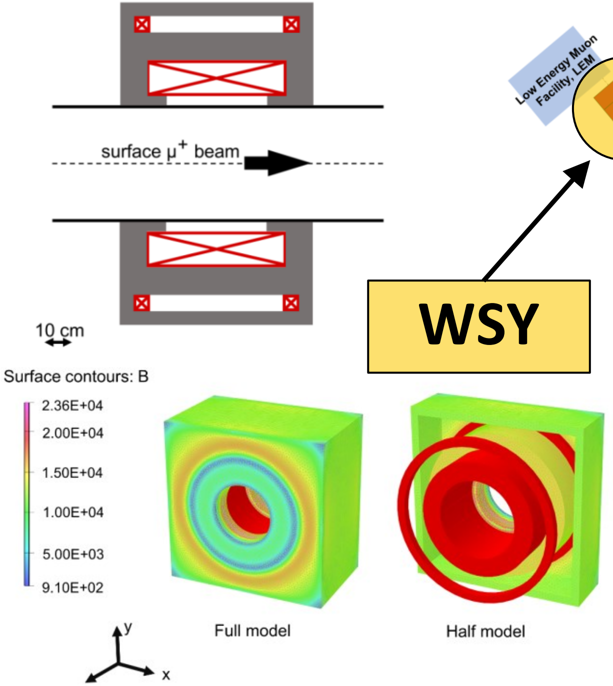


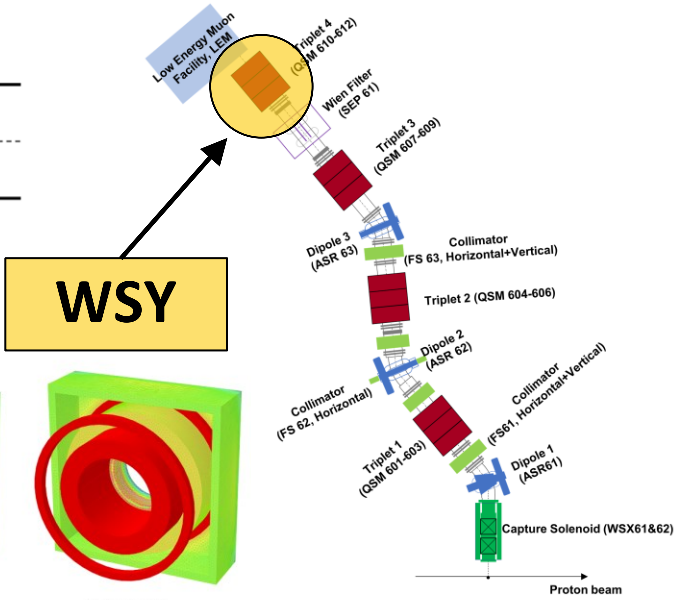
AEW: 0-300 G

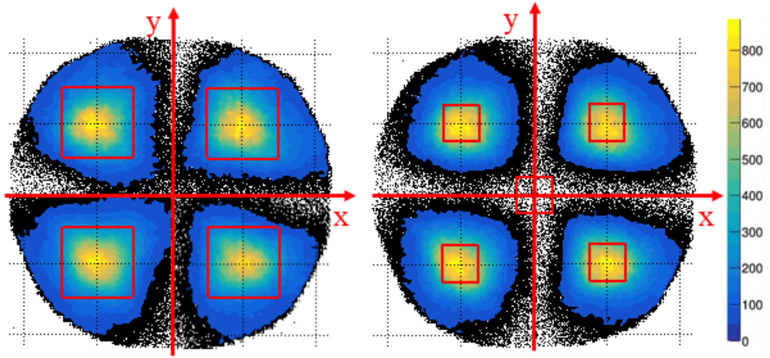


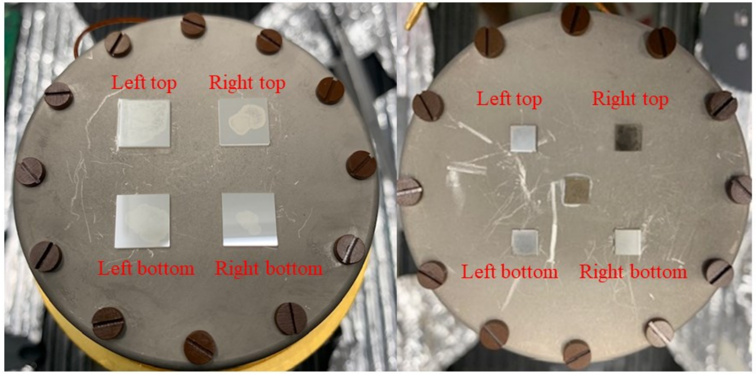
Upgrade of LEM

- Increase LEM rate by 50%
- Small sample measurements (5×5 mm²)







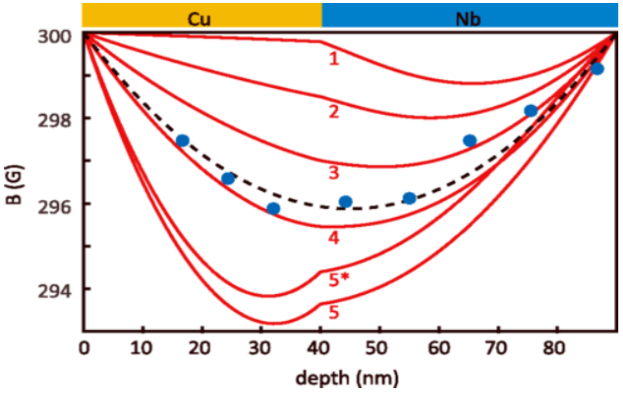


L. P. Zhou, **X. J. Ni**, et al., *Phys. Rev. Accel. Beams* 25, 051601, (2022)

X. J. Ni., et al., *NIM-A*, accepted; *arXiv preprint arXiv:2302.06773*, (2023)

LE-μSR – Research examples

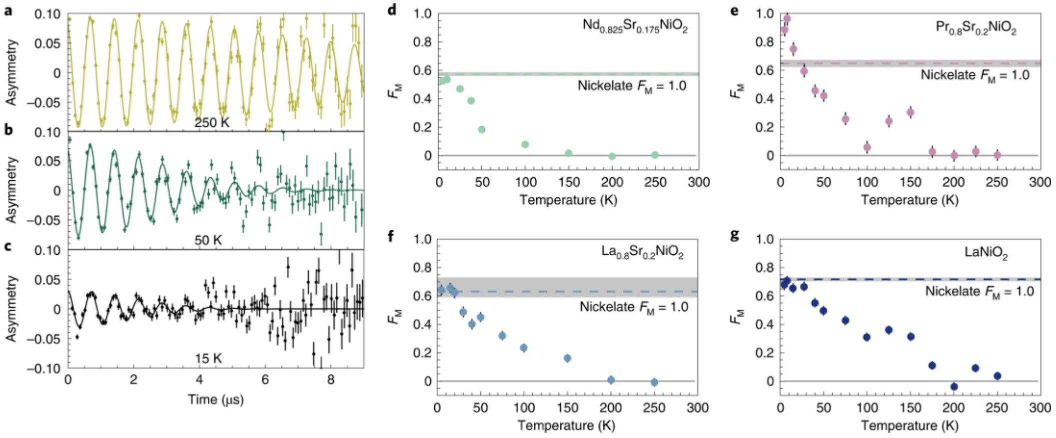
Observation of Anomalous Meissner Screening in Cu/Nb and Cu/Nb/Co Thin Films



M. G. Flokstra, et al.,

Phys. Rev. Lett. **120**, 247001 (2018)

Intrinsic magnetism in superconducting infinite-layer nickelates

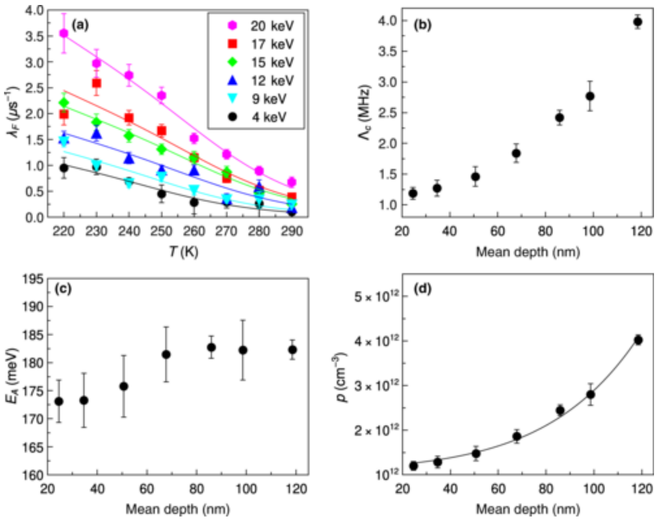


Fowlie J., et al.,

Nat. Phys. 18, 1043–1047 (2022)

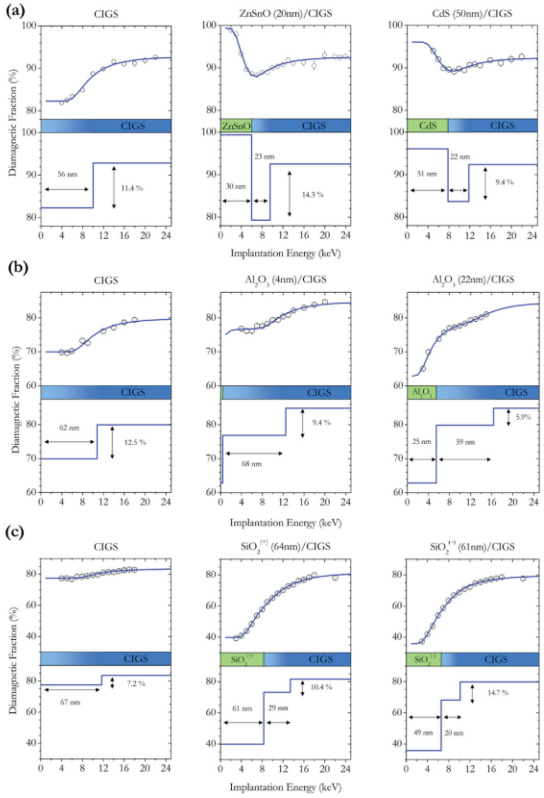
LE-µSR – Research examples

Direct observation of hole carrier-density profiles and their light-induced manipulation at the surface of Ge



T. Prokscha, et al.,

Phys. Rev. Applied. **14**, 014098 (2020)



Characterization of the Interfacial Defect Layer in Chalcopyrite Solar Cells by Depth-Resolved Muon Spin Spectroscopy

H. V. Alberto, et al.,

Adv. Mater. Interfaces **9**, 2200374 (2022)

LE-μSR – Research examples

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Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells

Akihiro Kojima[†], Kenjiro Teshima[‡], Yasuo Shirai[§], and Tsutomu Miyasaka[*†‡∥]

View Author Information

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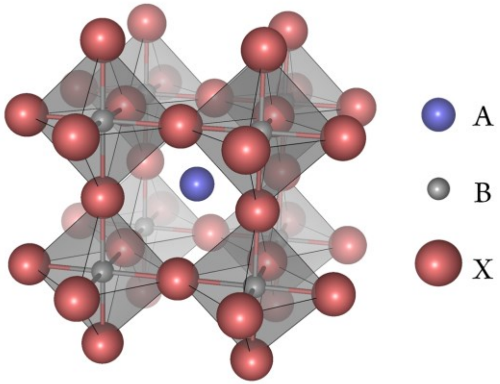
Cite this: *J. Am. Chem. Soc.* 2009, 131, 17, 6050–6051
Publication Date: April 14, 2009
https://doi.org/10.1021/ja809598r

Journal of the American Chemical Society

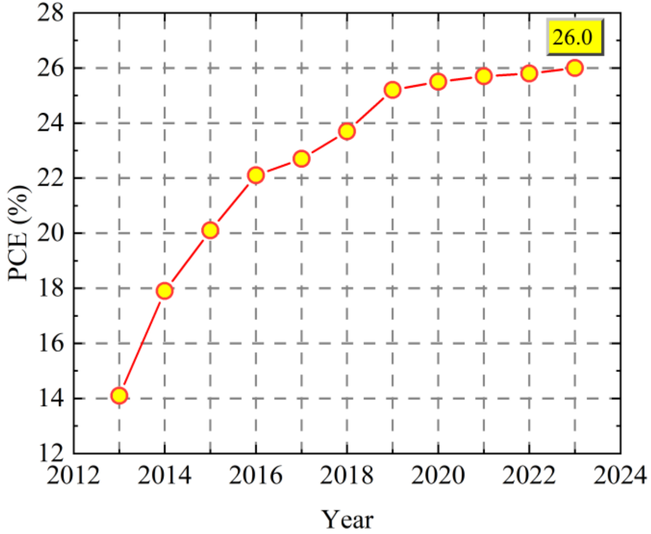


A: $CH_3NH_3^+$ (MA), $CH_2(NH_2)_2^+$ (FA), or Cs^+

B: Pb^{2+}

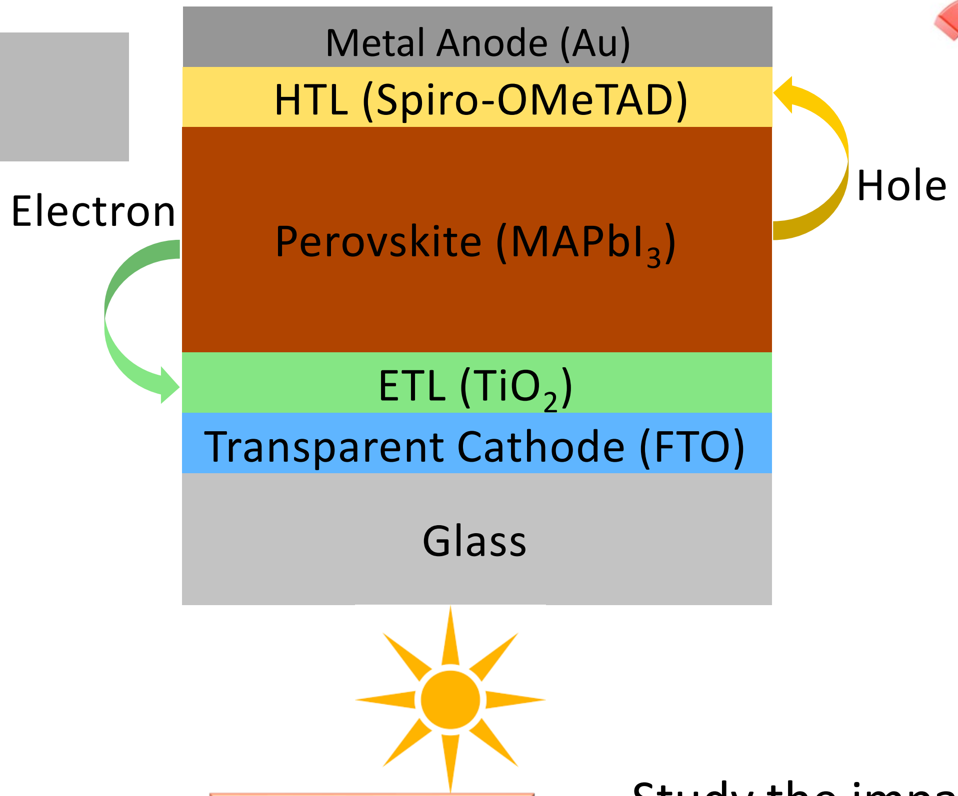
X: I^-, Br^-, Cl^-

Perovskite solar cell efficiency certified by NREL



https://www.nrel.gov/pv/cell-efficiency.html (National Renewable Energy Laboratory)

LE-μSR – Research examples



How to further improve the efficiency?

Passivate defects,
Suppress carrier recombination

Well-controlled growth conditions can effectively improve the interfaces and reduce internal defects

Motivation

Study the impact of different growth conditions on the perovskite solar cells

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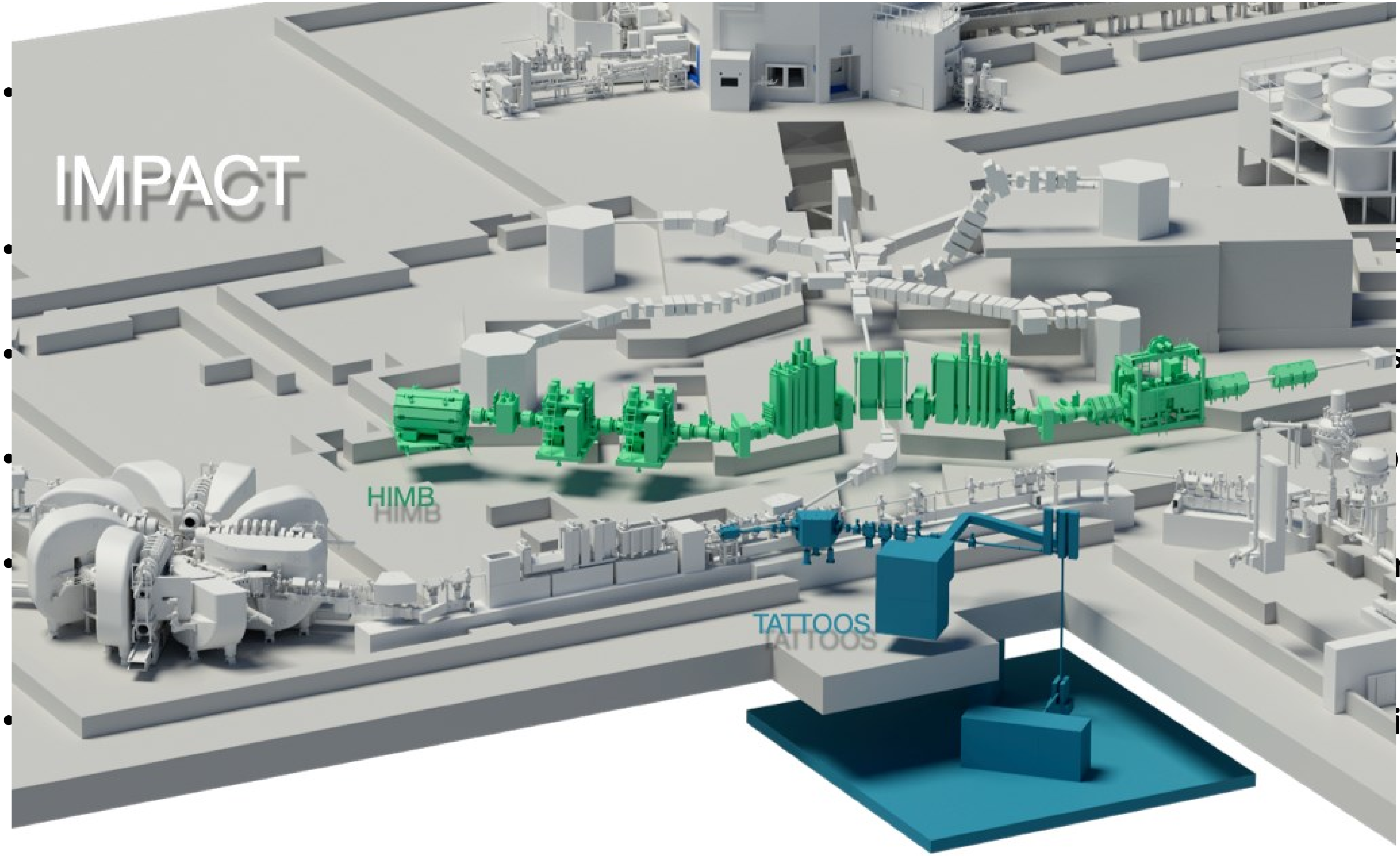
High Intensity Muon Beam

IMPACT – a major upgrade proposal for HIPA



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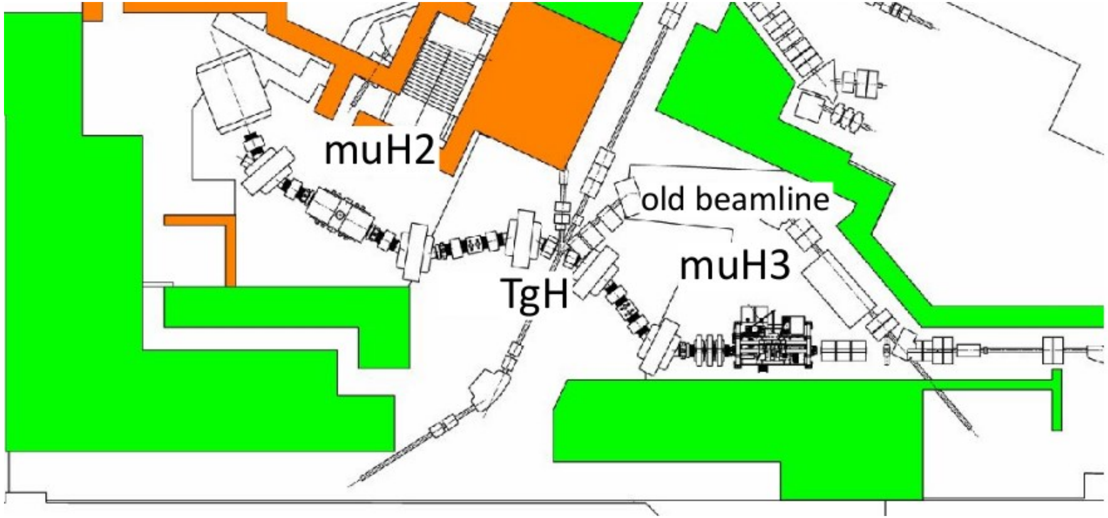
High Intensity Muon Beam (HIMB)

- Vertex reconstruction with ≤1 mm resolution to fully exploit the >20 times higher beam intensities made available by HIMB (**in collaboration with LTP and U Zurich**).
- **A «game changer» for μSR! (HIMB Science Case: https://arxiv.org/abs/2111.05788)**



10^8 μ^+/s

GPS + FLAME

High Intensity Muon Beam (HIMB)

Current limitations of μSR at PSI:

- Maximum rate 40k muons/s
- Sample area > 4x4 mm^2
- Thickness > ~200 μm, < 200 nm

Vertex Reconstruction

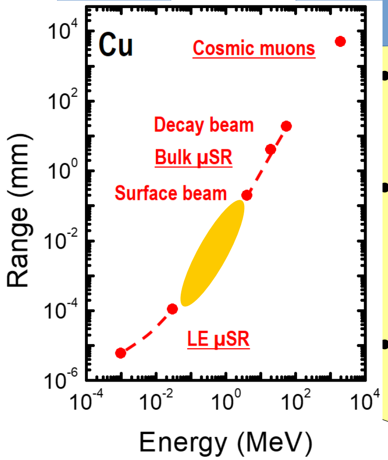
- Novel small samples
- Multi samples in parallel
- >10x faster measurements
- 10x higher pressure/strain

High Rate

- Extend muon range to 200 nm – 200 μm ("sub-surface muons")
- 10x more low energy muons for thin-film and device applications (< 200 nm)
- Elemental analysis tomography (mm sized objects)

Pulsed beam

- Pump-probe measurements
- Multiple stations in parallel
- Semi-integral measurements



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Wir schaffen Wissen – heute für morgen

Thank you for your attention!

I am happy to answer questions.