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Wir schaffen Wissen – heute für morgen

Introduction to Muon Spin Rotation and Relaxation
-
Instrumentation and Technique

Hubertus Luetkens

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Paul Scherrer Institut

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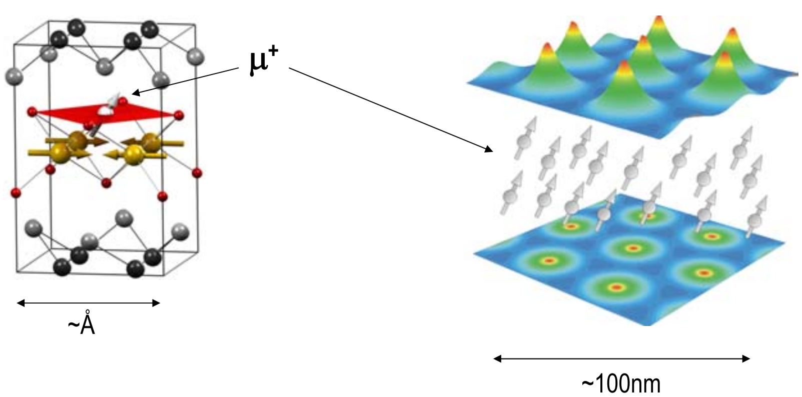
Muon is a Local Magnetic Probe

Muon probes the local magnetism from within the unit cell

Muon probes the local magnetic response of a superconductor (Meissner screening or flux line lattice)



Outline

1. **Principle of a µSR Experiment**
   - Implantation of muons into matter – muon stopping sites
   - Interaction of the muon spin with the environment – muon spin precession
   - Anisotropic decay of the muon
   - Particle detection and data acquisition

2. **Some Characteristics of the µSR Technique**
   - Local probe - volume sensitivity
   - Large magnetic moment – field sensitivity
   - Time window

3. **µSR Instrumentation at SµS**
   - Surface muon instruments
   - Decay muon instrument
   - Low energy muons

Principle of a µSR Experiment

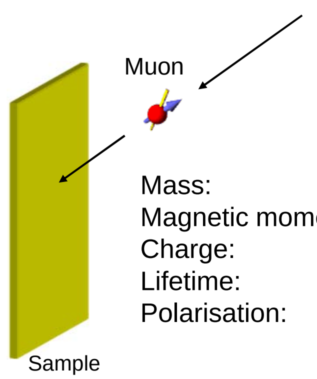
Recapitulation

The three key properties making μSR possible:

1. **The muon is 100% spin polarized.**
2. **The decay positron is preferentially emmitted along the muon spin direction.**
3. **The muon spin precesses in a magnetic field.**

Principle of a μSR Experiment

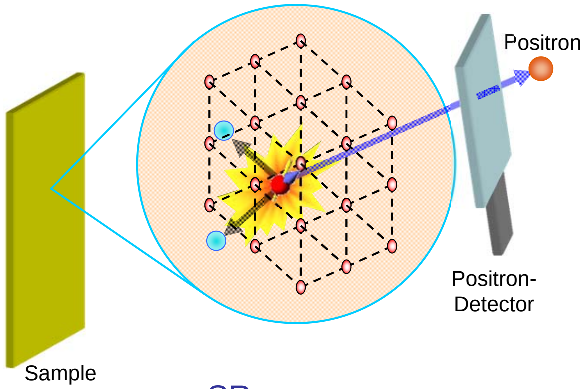
Implantation of muons into the sample



Mass:	$m_\mu \approx 207\, m_e \approx 1/9\, m_p$
Magnetic moment:	$\mu_\mu \approx 3\, \mu_p$
Charge:	+e
Lifetime:	$t_\mu \approx 2.2\ \mu s$
Polarisation:	100 %

Principle of a μSR Experiment

Detection of the decay positron



μSR

2 μs

Static field distribution
Sensitivity: $10^{-3} – 10^{-4}$ μ_B

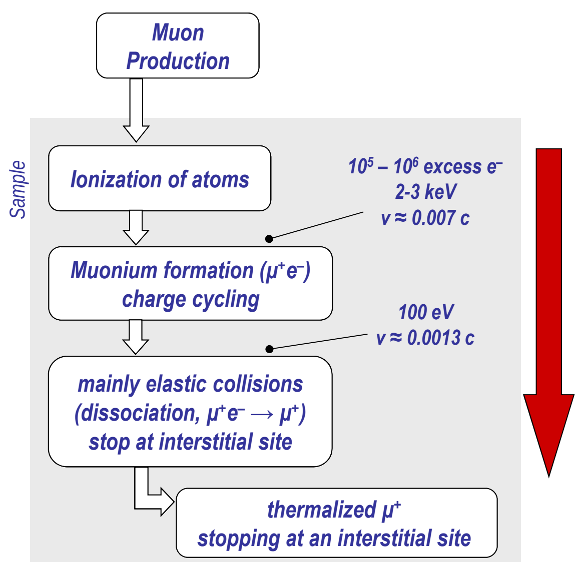
Fluctuation rates
($10^5 – 10^9$ Hz)

Principle of a μSR Experiment

1. Implantation of muons into matter – muon stopping sites
2. Interaction of the muon spin with the environment – muon spin precession
3. Anisotropic decay of the muon
4. Particle detection and data acquisition

Implantation of Muons into Matter
-
Muon Stopping Sites

Muon Implantation into Matter



- *Total stopping time in matter < 0.1 ns*
- *Only electrostatic processes → no loss of polarization!*

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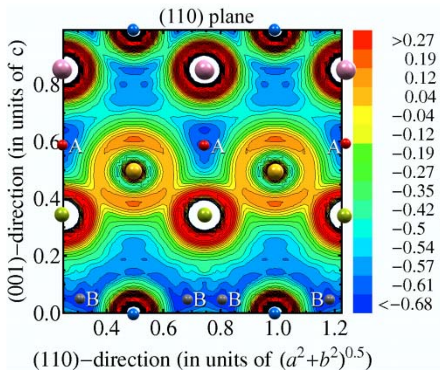
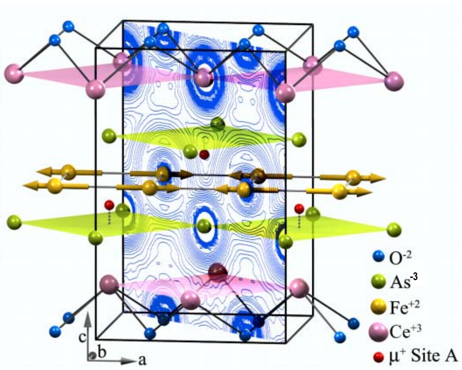
Interstitial Muon Stopping Sites

Electrostatic potential map:



CeOFeAs structure:

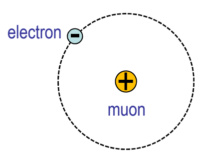


Positive muon likes to stop:

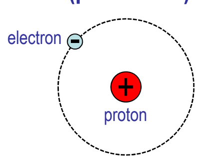
- In the potential minimum
- High symmetry sites
- Near negative ions (e.g. O^{2-}, As^{3-}) (muon hydrogen bond like in OH with ~1 A bond length)
- Large spaces in the crystal structure

More Rare Case: Muonium Formation in Matter

Muonium



Hydrogen (protonium)



- **Muonium**
  - Bound state of electron and positive muon
  - Coupled spin system (electron, muon, nuclei)
  - Muon is a light isotope of proton
    → analogy to hydrogen
- **Possible research with muonium**
  - Hydrogen levels in semiconductors, insulators and organics
  - Light particle diffusion
  - Radical formation
  - Molecular dynamics
  - Chemical reactions (large kinetic isotope effect)

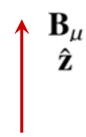
Muonium is not topic of this school

Interaction of the Muon Spin with the Environment – Muon Spin Precession

Muon Spin Precession – Larmor frequency

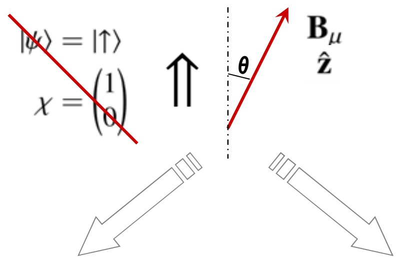
$$|\psi\rangle = |\uparrow\rangle$$

$$\chi = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \Uparrow$$



- Field axis: quantization axis
- Spin-state eigenvalue of S_z
- Stationary state

Muon Spin Precession – Larmor frequency



- Field axis: quantization axis
- ~~Spin-state eigenvalue of S_z~~
- ~~Stationary state~~

Quantum Mechanics:

$\mathbf{B}_\mu$ quantization axis

χ in the new base $\Rightarrow \chi = \begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}\end{pmatrix}$

Calculation of $\chi(t)$
with time dependent Schrödinger Eq.

Calculation expectation values of S_α

$\langle S_\alpha\rangle = \chi^\dagger S_\alpha \chi$

Project back to the ref. frame of the lab.

Classically:

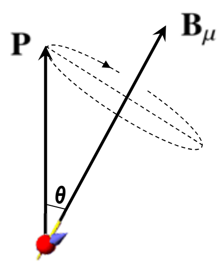
Torque: $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}_\mu = \gamma_\mu \mathbf{S} \times \mathbf{B}_\mu$

Euler's Eq.: $\frac{d\mathbf{S}}{dt} = \boldsymbol{\tau}$

$\Rightarrow \frac{d\mathbf{S}}{dt} = \gamma_\mu \mathbf{S} \times \mathbf{B}_\mu$

Muon Spin Precession – Larmor frequency

$$\mathbf{P} = \frac{\langle \mathbf{S}\rangle}{\frac{\hbar}{2}}$$

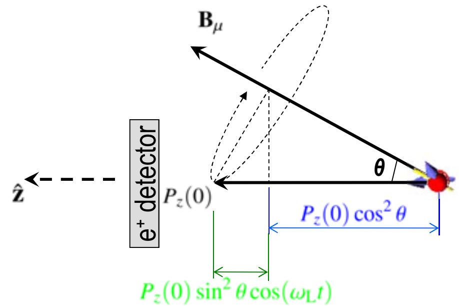


Larmor precessions with angular velocity: $\omega_\mathrm{L} = \gamma_\mu B_\mu$

with $\gamma_\mu = \frac{e}{2m_\mu} g_\mu = 8.51615 \times 10^8$ rad/sT

Frequency: $\frac{\gamma_\mu}{2\pi} = 135.539$ MHz/T

Field Direction -- Field Distribution



$$P_z(t) = \cos^2\theta + \sin^2\theta\cos(\gamma_\mu B_\mu t)\;)\;\Big]d\mathbf{B}_\mu$$

- Static part
- Oscillating part

θ angle between magnetic field and muon polarization at *t = 0*

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Particle Detection and Data Acquisition

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Particle Detection and Data Acquisition

Plastic scintillators

- **Plastic scintillator detectors**
  - Particle → Light

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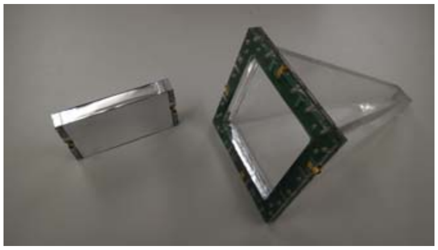
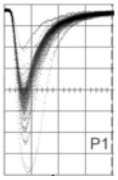
Particle Detection and Data Acquisition

Plastic scintillators + SiPM



Amplified analog signal



Scale:
5ns, 200mV

- **Plastic scintillator detectors**
  - Particle → Light
- **Silicon photomultiplier (SiPM)**
  - Light → electric analog signal

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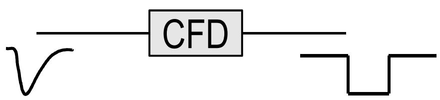
Particle Detection and Data Acquisition

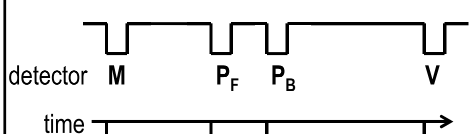
Constant fraction discriminator



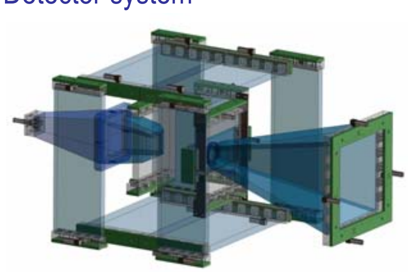
- **Plastic scintillator detectors**
  - Particle → Light
- **Silicon photomultiplier (SiPM)**
  - Light → electric analog signal
- **Constant fraction discriminator (CFD)**
  - Analog signal → digital signal

Particle Detection and Data Acquisition

Time to digital converter (TDC, clock)

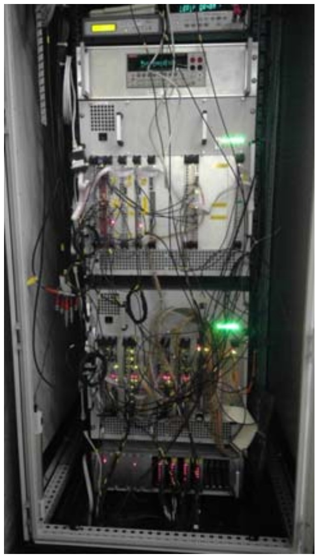


Detector system



- **Plastic scintillator detectors**
  - Particle → Light
- **Silicon photomultiplier (SiPM)**
  - Light → electric analog signal
- **Constant fraction discriminator (CFD)**
  - Analog signal → digital signal
- **Time to digital converter (TDC, clock)**
  - Digital signals → time stamp
  - Continuous stream of events

Particle Detection and Data Acquisition



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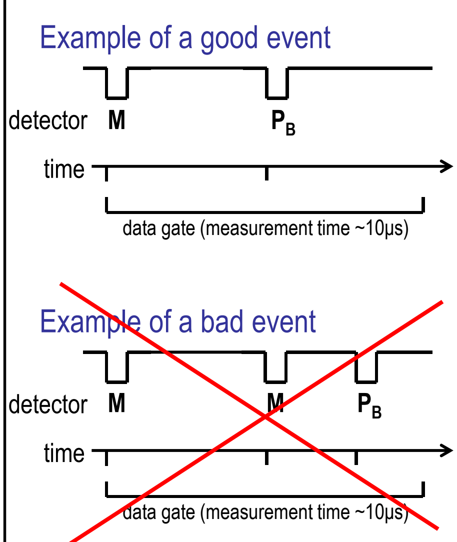
Particle Detection and Data Acquisition



- **Plastic scintillator detectors**
  - Particle → Light
- **Silicon photomultiplier (SiPM)**
  - Light → electric analog signal
- **Constant fraction discriminator (CFD)**
  - Analog signal → digital signal
- **Time to digital converter (TDC, clock)**
  - Digital signals → time stamp
  - Continuous stream of events
- **Linux PC (analyser), MIDAS**
  - µSR logic (selects only good events)
  - data storage

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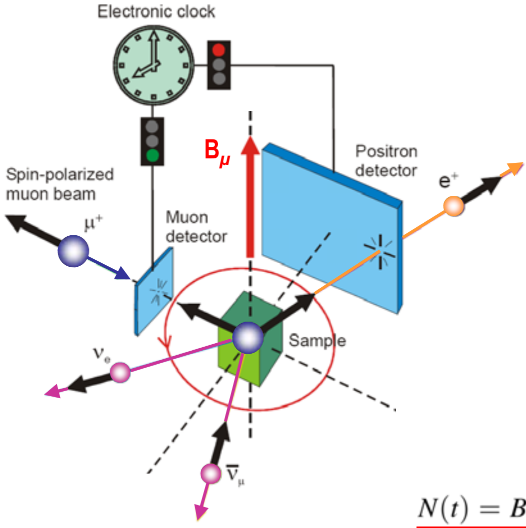
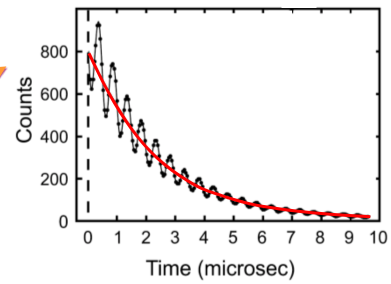
Principle of a μSR Experiment





$$N(t) = Bkg + N_0 \exp(-t/\tau_\mu)$$

$\hat{\mathbf{n}}$: direction of detector

$\mathbf{B}_\mu$ internal or external field

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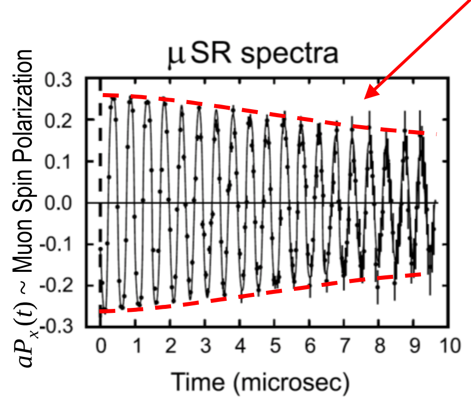
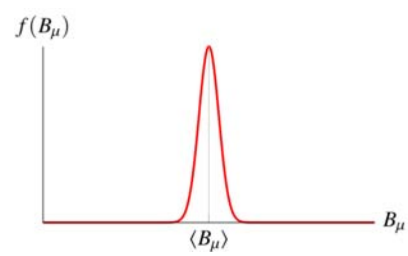
μSR Spectra

$$N(t) = Bkg + N_0 \exp(-t/\tau_\mu)\left[1 + a\,\hat{\mathbf{n}} \cdot \mathbf{P}(t)\right]$$





Frequency ▶ *Value of field at muon site ($\omega_L = \gamma_\mu B_\mu$)*

Damping ▶ *Field distribution and/or dynamics*

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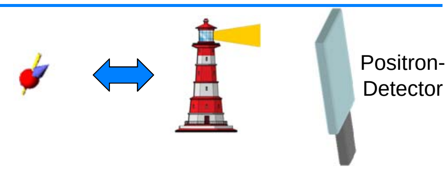
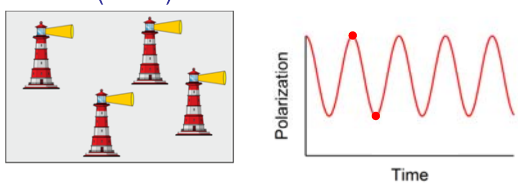
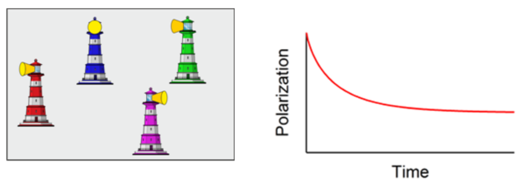
Simple illustration of μSR



Uniform (static) fields



Random fields



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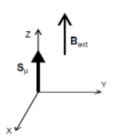
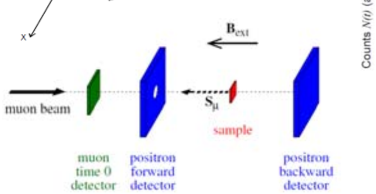
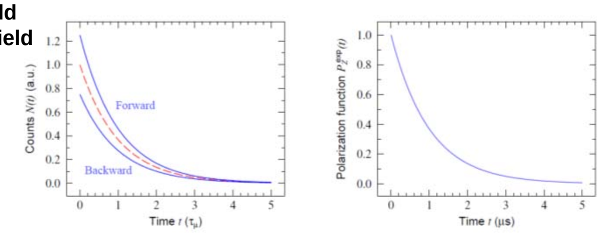
Different Measurement Geometries



ZF and LF: Zero field and Longitudinal Field geometry





Typically used for the study of:

- Static magnetism
  - Temperature dependence of the magnetic order parameter
  - Determination of the magnetic transition temperature
  - Homogeneity of the sample
- Dynamic magnetism
  - Determination of magnetic fluctuation rates
  - Slowing down of fluctuations near phases transitions

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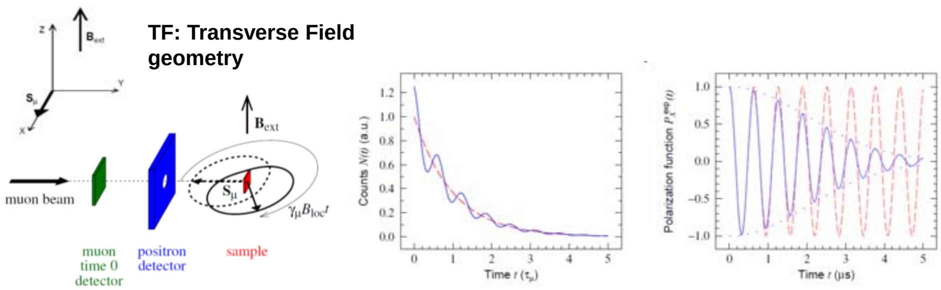
Different Measurement Geometries

TF: Transverse Field geometry



Typically used for the study of:

- Magnetism
  - Determination of the magnetic transition temperature
  - Homogeneity of the sample
  - Knight shift (local susceptibillity)
- Superconductivity
  - Absolute value and temperature dependence of the London penetration depth
  - Coherence length, votex structure, vortex dynamics, …

Some Characteristics of the μSR Technique

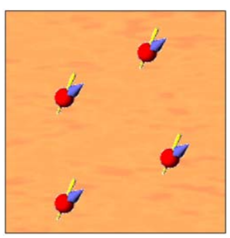
Some Characteristics of the μSR Technique

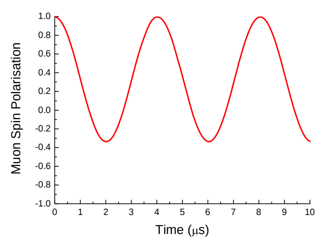
1. Local probe - volume sensitivity
2. Large magnetic moment – field sensitivity
3. Time window

Local Probe – Volume Sensitivity (e.g. Magnetism)

Homogen:

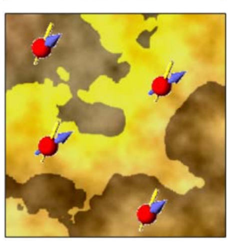
M_{hom}

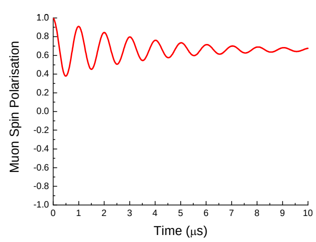




Inhomo-
geneous:

$M_{inhom} = M_{hom}$





Amplitude = Magnetic volume fraction
Frequency = Size of the magnetic moments (order parameter)
Damping = Inhomogeneity within the magnetic areas

Complementary Method to Scattering Techniques

Scattering techniques:
(neutrons, X-rays)

Local probes:
(μSR, NMR, …)

One strength of muon spin rotation / relaxation:

Investigation of magnetically inhomogeneous materials:

- Chemical inhomogeneity ("dirty samples")
- **Competing interactions, coexistence of different magnetic orders, short range order, magnetic frustration**
- **Magnetism and superconductivity (competition and coexistence)**

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Sensitivity of the μSR Technique

Internal field at the muon site:

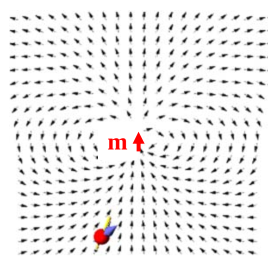
$$\mathbf{B}_\mu = \mathbf{B}_c + \mathbf{B}_{\rm dip}$$

- Contact field $\propto e|\Psi(\mathbf{r}_\mu)|^2$
- Dipolar contribution

$$\mathbf{B}_{\rm dip} = \sum_i \frac{1}{r_i^3}\Big[\frac{(3\mathbf{m}_i \cdot \mathbf{r}_i)}{r_i^2}\mathbf{r}_i - \mathbf{m}_i\Big]$$

$$B_{\rm dip} \simeq \frac{m}{r^3}$$

For $m = 1\,\mu_{\rm B}$ and $r = 1\,\text{Å} \Rightarrow B_{\rm dip} \simeq 1\,\text{T}$



μSR time window: 10-20 μsec

➡ Frequencies down to 50 kHz detectable
Fields of few Gauss (10^{-4} T)

➡ ***static moments as low as 0.001 μ_B can be detected by μSR***

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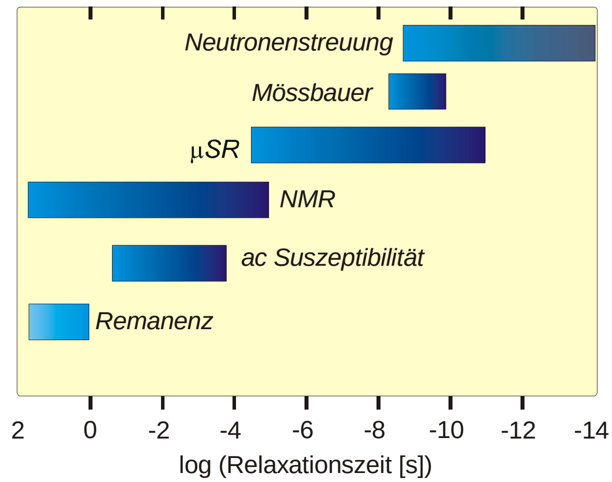
Time Window of the μSR Technique



The time window is given by muon lifetime, data gate, time resolution and the availability of external magnetic fields.

μSR Instrumentation at SμS

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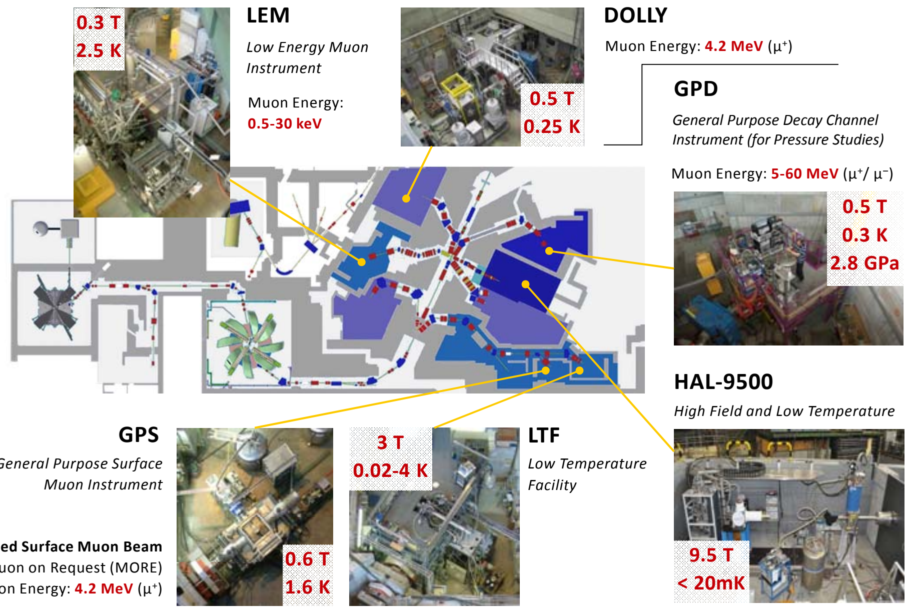
Instruments at the SμS (Swiss Muon Source)



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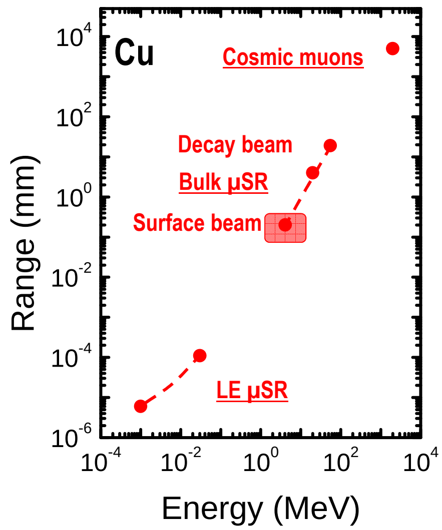
Surface Muon Instruments

Surface Muon Instruments



- **GPS, LTF, Dolly, HAL-9500**
- **Energy: 4 MeV**
  - Stopping range: 140 mg/cm^2 (~100 – 300 μm)
  - Bulk probe

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Surface Muon Instruments

- **GPS, LTF, Dolly, HAL-9500**
- **Energy: 4 MeV**
  - Stopping range: 140 mg/cm^2 (~100 – 300 μm)
  - Bulk probe
- **Temperature: 12 mK – 1000 K**

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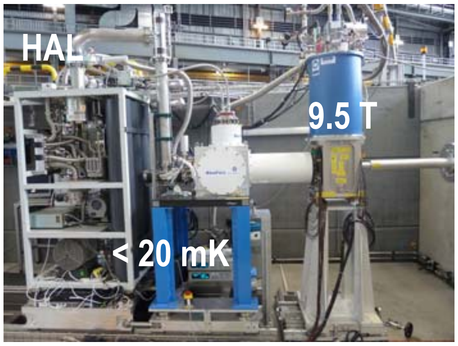
Surface Muon Instruments



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  - Active ZFC

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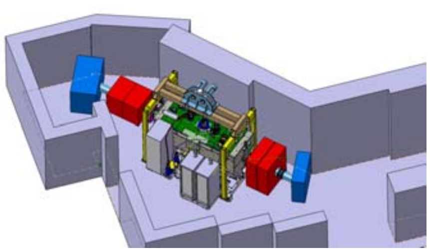
Surface Muon Instruments



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  - Active ZFC
- **Spin rotator**
  - ZF, LF and TF µSR possible

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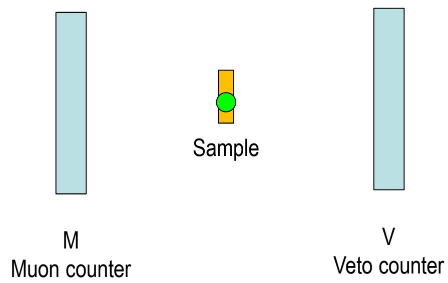
Surface Muon Instruments

Idea of the veto system



Muon stopped in sample

- **GPS, LTF, Dolly, HAL-9500**
- **Energy: 4 MeV**
  - Stopping range: 140 mg/cm^2 (~100 – 300 µm)
  - Bulk probe
- **Temperature: 12 mK – 1000 K**
- **Magnetic field: 2 µT (ZF) – 9.5 T**
  - Active ZFC
- **Spin rotator**
  - ZF, LF and TF µSR possible
- **Veto system – small samples**
  - 2x2 mm^2 (better 4x4 mm^2)
  - > 12 mg (better 50 mg, optimally 200 mg)

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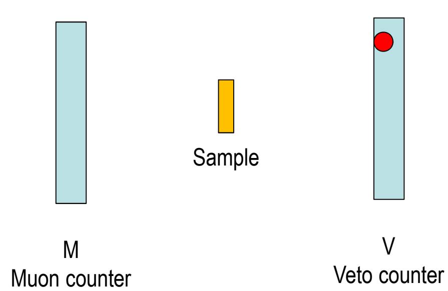
Surface Muon Instruments

Idea of the veto system



Muon missed the sample

- **GPS, LTF, Dolly, HAL-9500**
- **Energy: 4 MeV**
  - Stopping range: 140 mg/cm^2 (~100 – 300 µm)
  - Bulk probe
- **Temperature: 12 mK – 1000 K**
- **Magnetic field: 2 µT (ZF) – 9.5 T**
  - Active ZFC
- **Spin rotator**
  - ZF, LF and TF µSR possible
- **Veto system – small samples**
  - 2x2 mm^2 (better 4x4 mm^2)
  - > 12 mg (better 50 mg, optimally 200 mg)

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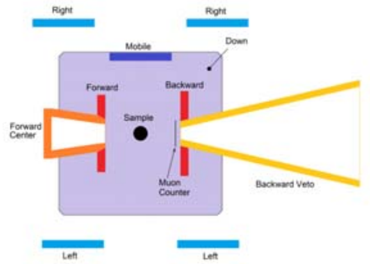
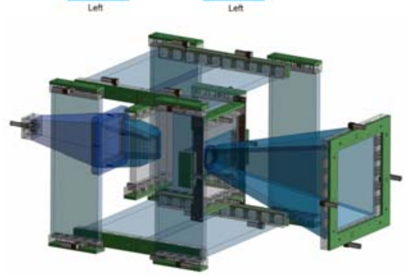
Surface Muon Instruments

Idea of the veto system

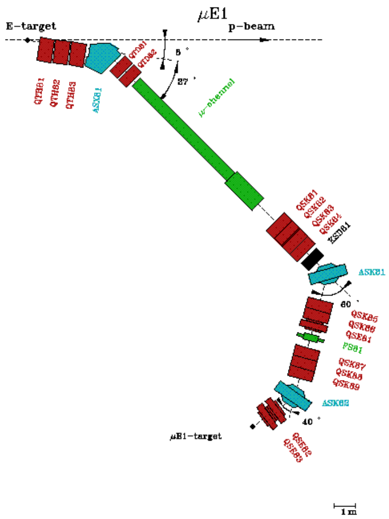




- **GPS, LTF, Dolly, HAL-9500**
- **Energy: 4 MeV**
  - Stopping range: 140 mg/cm^2 (~100 – 300 µm)
  - Bulk probe
- **Temperature: 12 mK – 1000 K**
- **Magnetic field: 2 µT (ZF) – 9.5 T**
  - Active ZFC
- **Spin rotator**
  - ZF, LF and TF µSR possible
- **Veto system – small samples**
  - 2x2 cm^2 (better 4x4 cm)
  - > 12 mg (better 50 mg, optimally 200 mg)

Decay Muon Instrument

Decay Muon Instruments



- **GPD**
  - **G**eneral **P**urpose **D**ecay channel muon instrument

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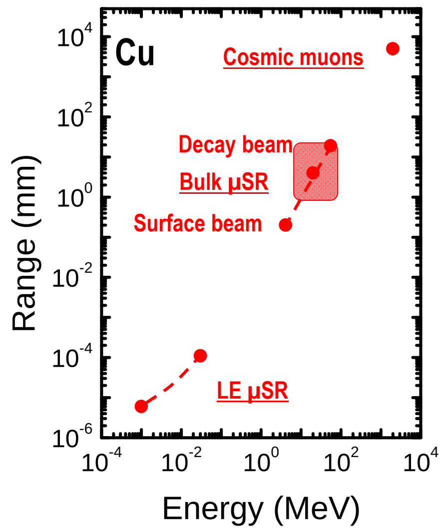
Decay Muon Instruments



- **GPD**
  - **G**eneral **P**urpose **D**ecay channel muon instrument
- **Energy: 10 - 60 MeV**
  - Stopping range: ~1mm – 2 cm (steel)

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Decay Muon Instruments

- **GPD**
  - **G**eneral **P**urpose **D**ecay channel muon instrument
- **Energy: 10 - 60 MeV**
  - Stopping range: ~1mm – 2 cm (steel)
- **Temperature: 250 mK – 475 K**
- **Magnetic field: 5 μT (ZF) – 0.5 T**

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Decay Muon Instruments

- **GPD**
  - **G**eneral **P**urpose **D**ecay channel muon instrument
- **Energy: 10 - 60 MeV**
  - Stopping range: ~1mm – 2 cm (steel)
- **Temperature: 250 mK – 475 K**
- **Magnetic field: 5 μT (ZF) – 0.5 T**
- **High Pressures: 2.8 GPa**
  - 2.8 GPa at 4 K
  - 4.0 GPa at 300 K
  - Sample mass: ~1 – 2 g
  - Material: CuBe or MP35
  - Double wall cells

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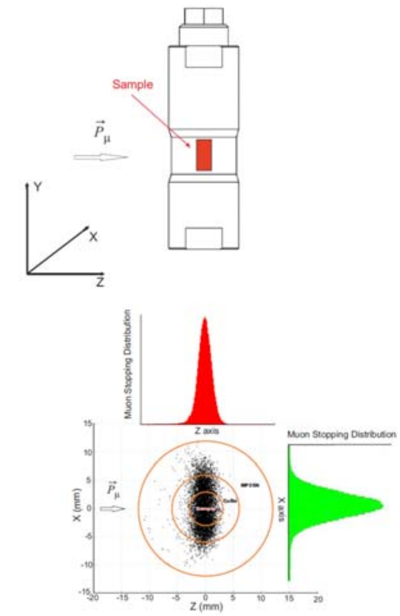
Decay Muon Instruments



- **GPD**
  - **G**eneral **P**urpose **D**ecay channel muon instrument
- **Energy: 10 - 60 MeV**
  - Stopping range: ~1mm – 2 cm (steel)
- **Temperature: 250 mK – 475 K**
- **Magnetic field: 5 µT (ZF) – 0.5 T**
- **High Pressures: 2.8 GPa**
  - 2.8 GPa at 4 K
  - 4.0 GPa at 300 K
  - Sample mass: ~1 – 2 g
  - Material: CuBe or MP35
  - Double wall cells
  - 40% sample and 60% cell signal

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Low Energy µSR Instrument

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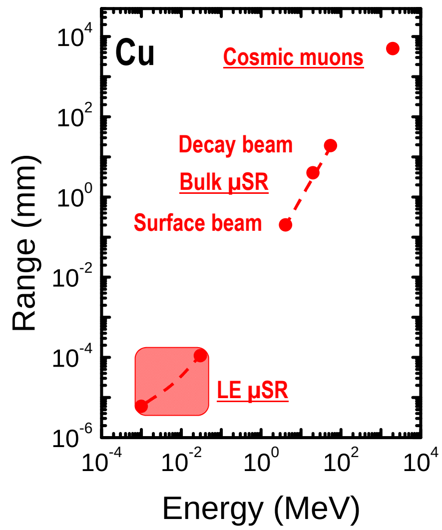
Low Energy μSR



Variable muon energy: 0 – 30 keV

▼

Depth-sensitive local magnetic spin probe on the nm length scale

- Thin films
- Near-surface regions
- Multilayers
- Buried interfaces

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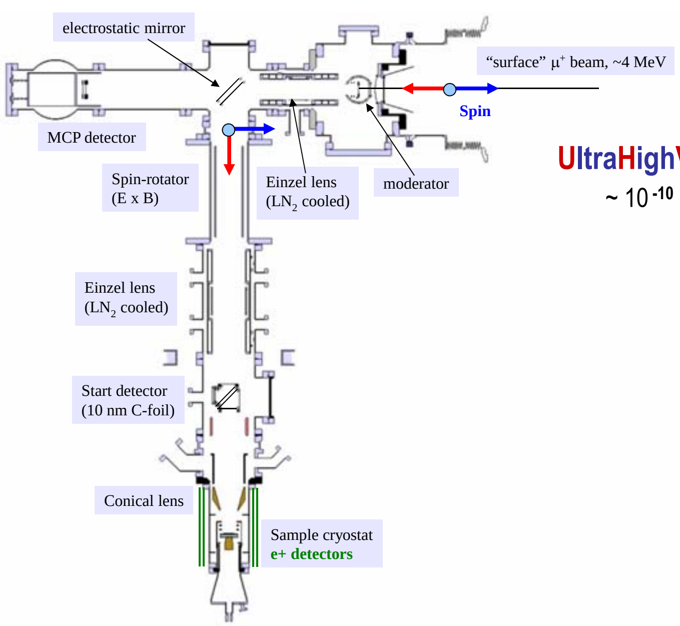
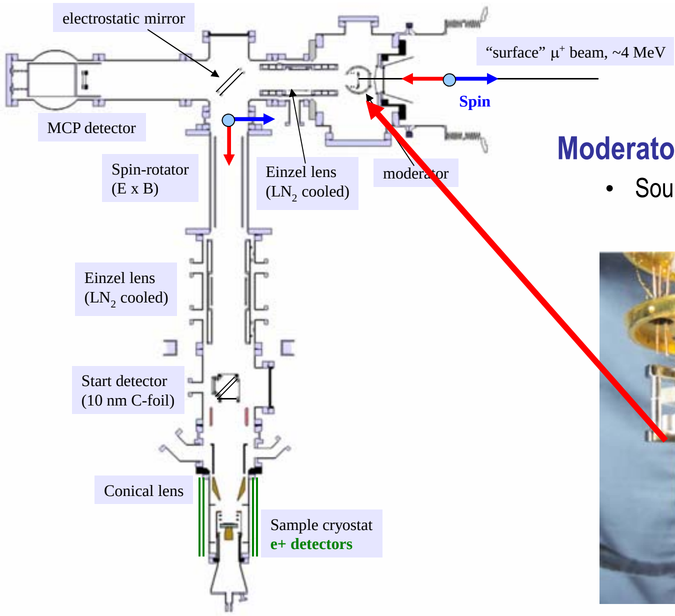
Low Energy μSR Apparatus



UltraHighVacuum

~ 10^{-10} mbar

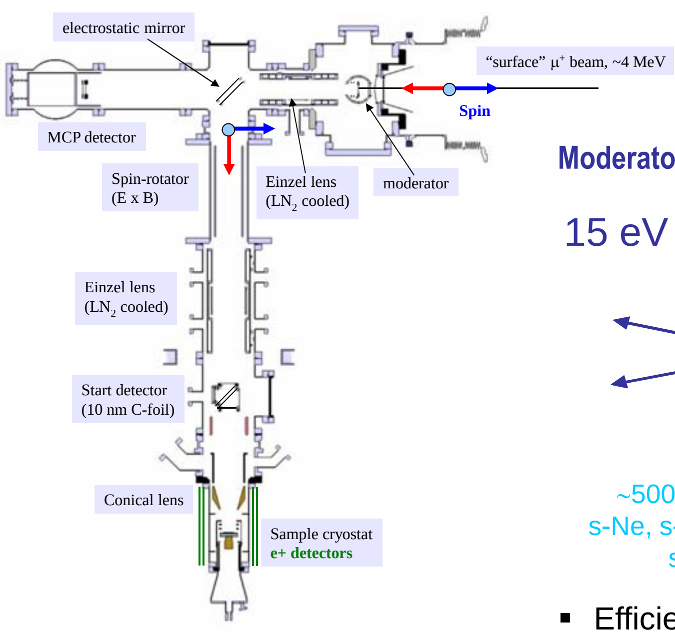
Low Energy μSR Apparatus



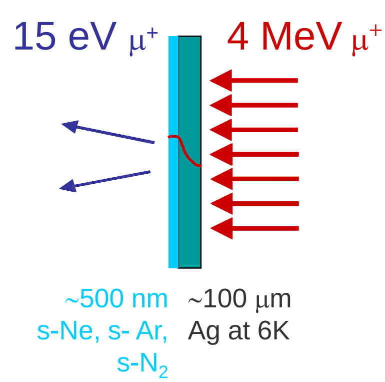
Moderator

- Source of low energy muons

Low Energy μSR Apparatus

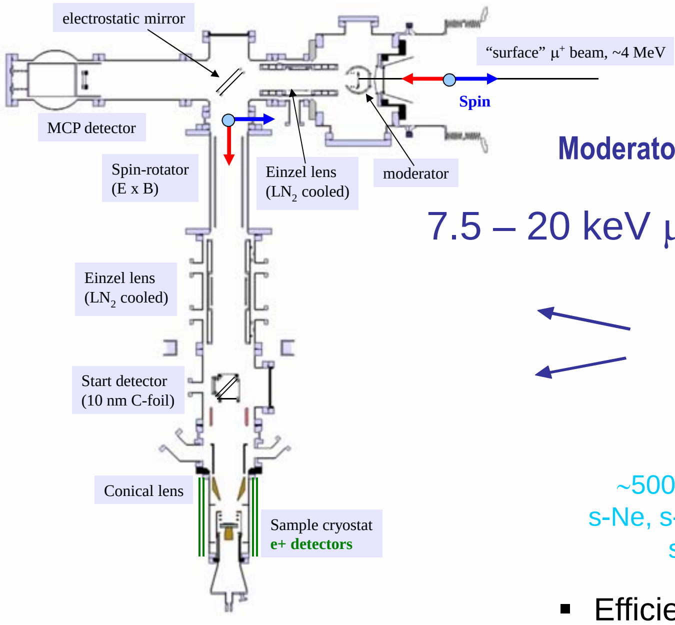


Moderator

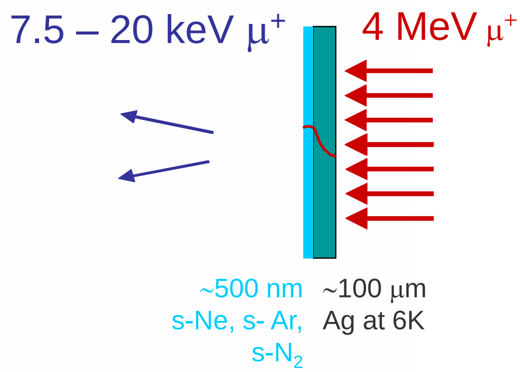


- Efficiency ~ $10^{-4} - 10^{-5}$

Low Energy μSR Apparatus

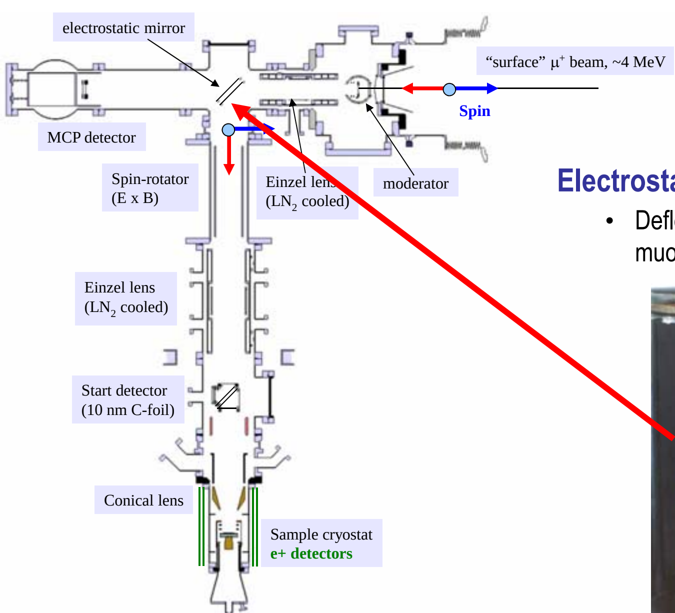


Moderator



- Efficiency ~ 10^{-4} – 10^{-5}

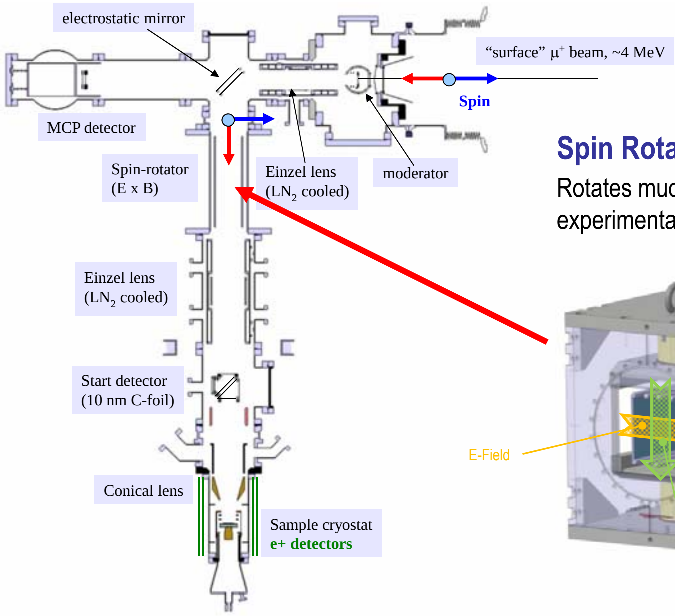
Low Energy μSR Apparatus



Electrostatic mirror

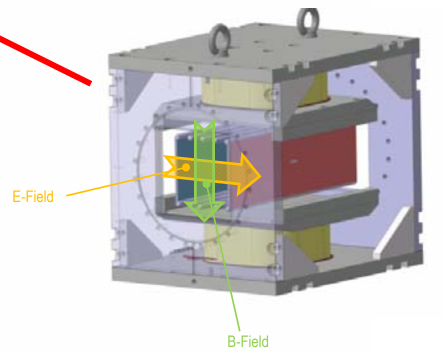
- Deflection of the low energy muons

Low Energy μSR Apparatus

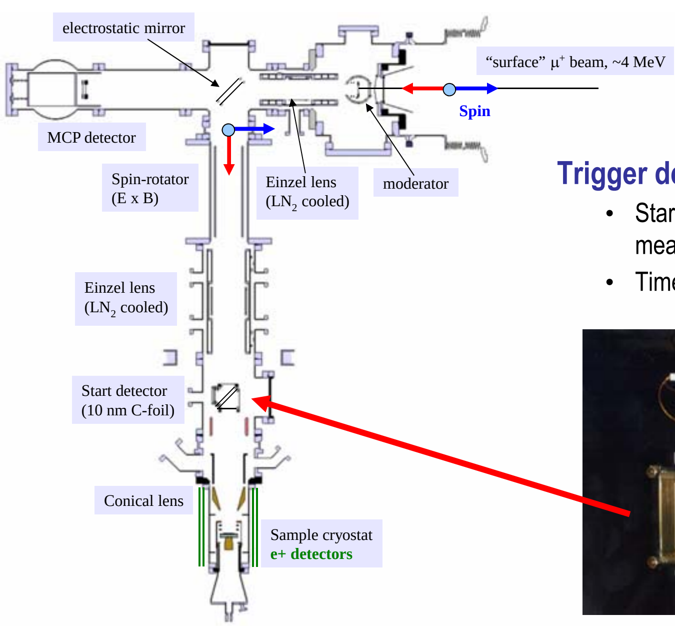


Spin Rotator

Rotates muon spin for different experimental conditions

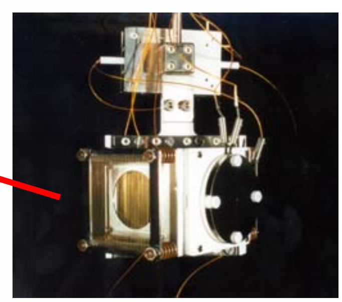


Low Energy μSR Apparatus

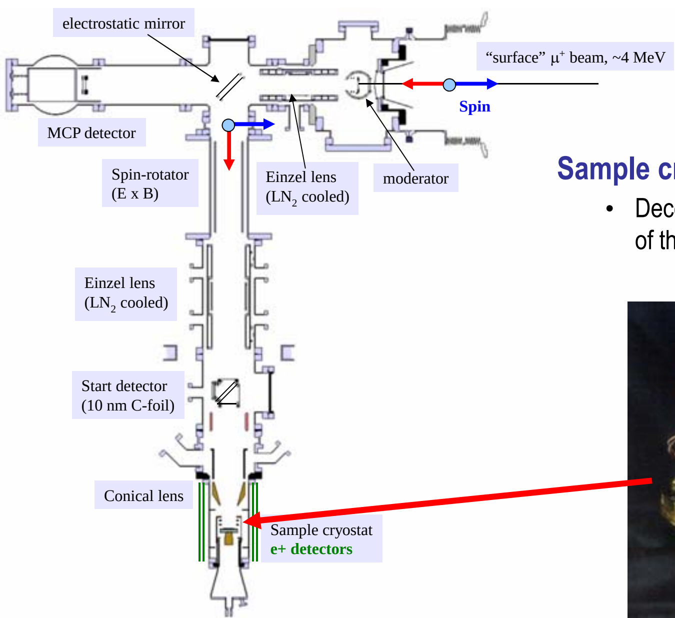


Trigger detector

- Start of the LE-μSR measurement
- Time-of-flight measurements



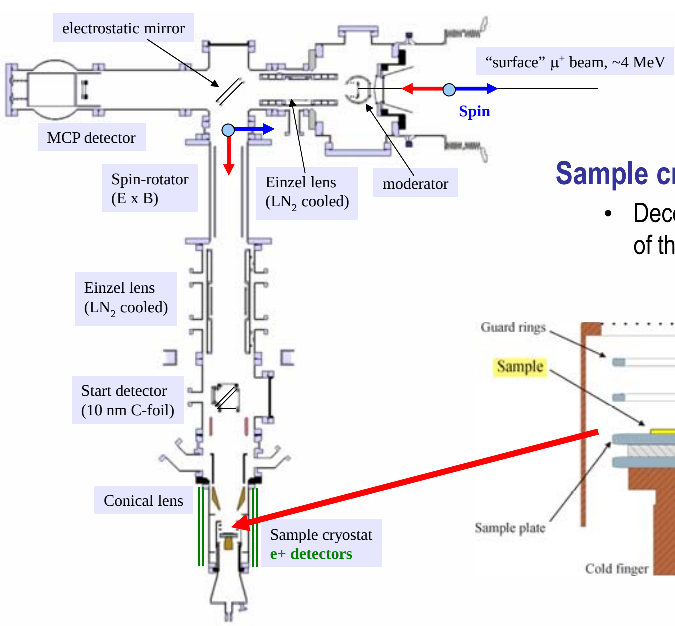
Low Energy μSR Apparatus



Sample cryostat

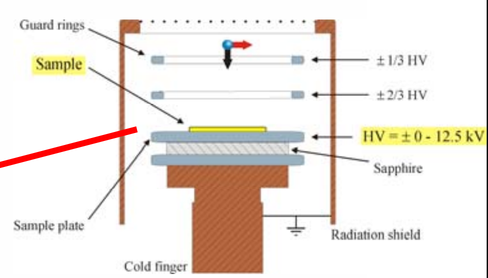
- Deceleration and acceleration of the μ^+

Low Energy μSR Apparatus

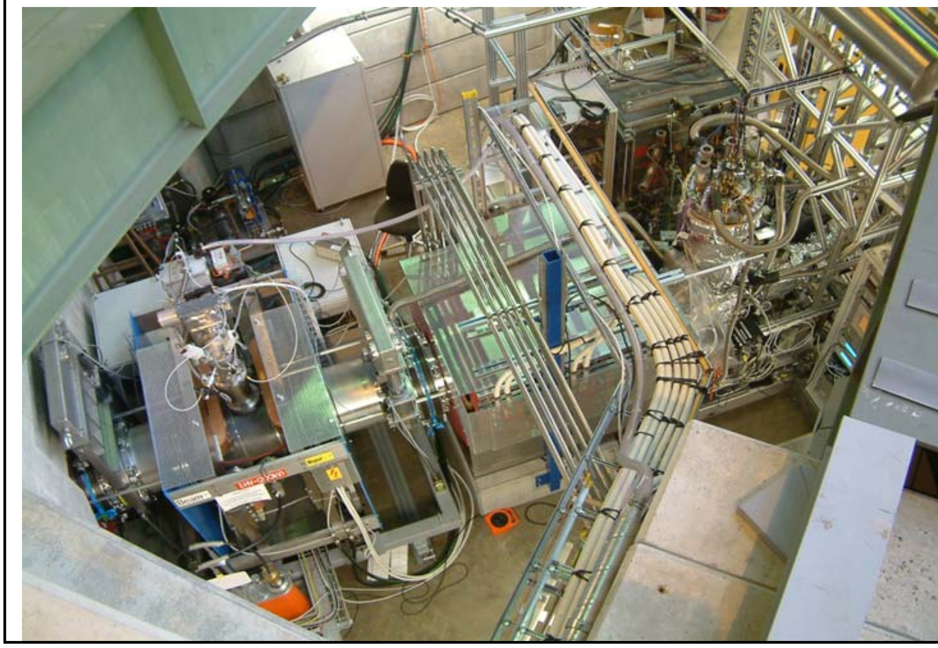


Sample cryostat

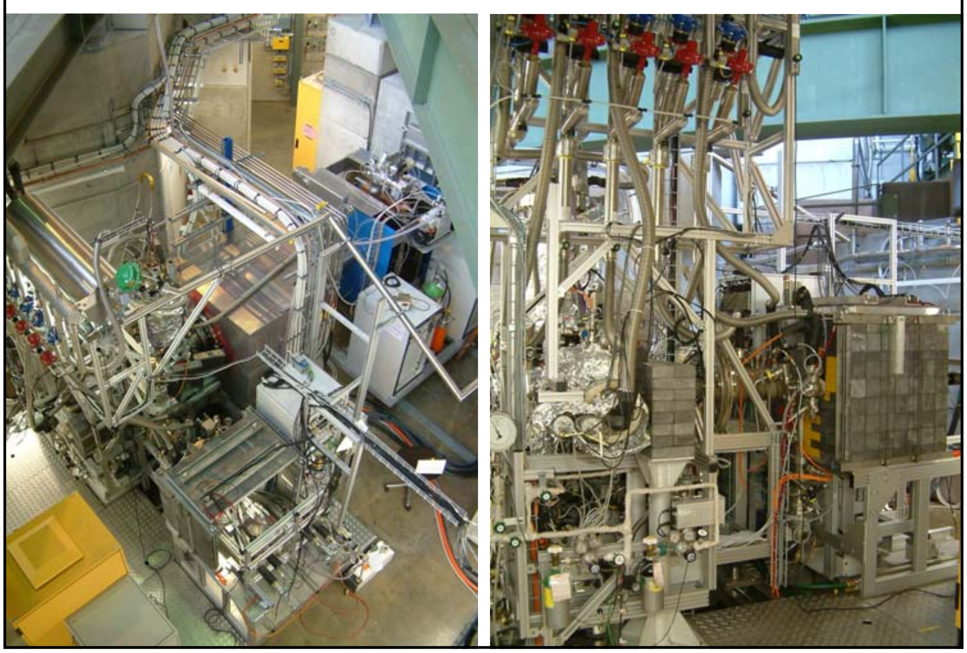
- Deceleration and acceleration of the μ^+



LE-μSR Apparatus



LE-μSR Apparatus



Examples of LEM Research – Physicist's Lego

Magnetic properties: P, FM, AFM

CMR, MF

Electric properties: M, I, FE, SC, AFE

Combinations

Fundamental Science

- Competition of ground states
- Coexistence of ground states
- Coupling of different ground states
- (Giant) proximity effects
- Electric field effects (2D-electron gas, ...)
- …

Applications

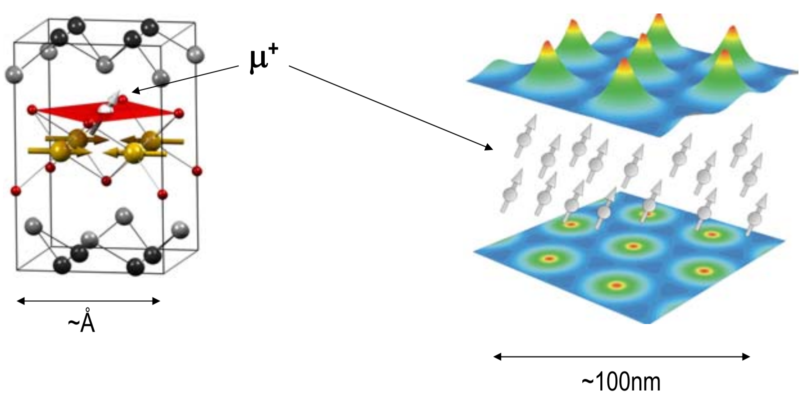
- Spintronics (Switching of currents with magnetic fields)
- Sensors (Magnetism, pressure, temperature, gases, …)
- Actuators
- Non-volatile memory (MRAM, …)
- …

FM	AFM	FM	AFM	P	CMR
P	P	SC	SC	SC	SC
FM	AFM	FM	AFM	P	CMR

Next Two Lectures by A. Amato

Muon probes the local magnetism from within the unit cell

Muon probes the local magnetic response of a superconductor (Meissner screening or flux line lattice)



Thanks

Figures, slides, and ideas taken from:

A. Amato, A. Suter, T. Prokscha, E. Morenzoni, R. Scheuermann, *PSI*

B. Cywinski, *University of Huddersfield*

A. Yaouanc, *CEA Grenoble*

S. J. Blundell, *University of Oxford*

Thank you for your attention!

Hubertus Luetkens