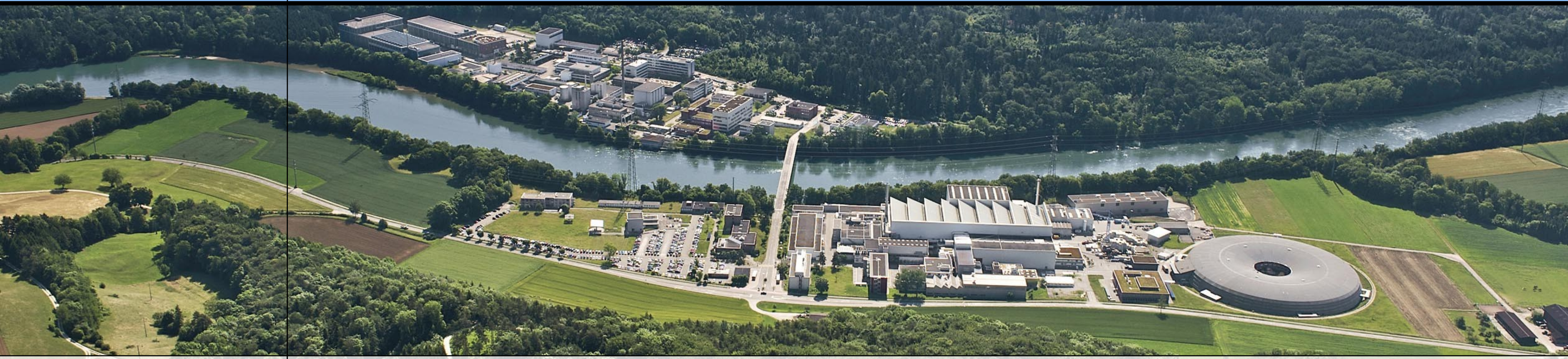


Wir schaffen Wissen – heute für morgen

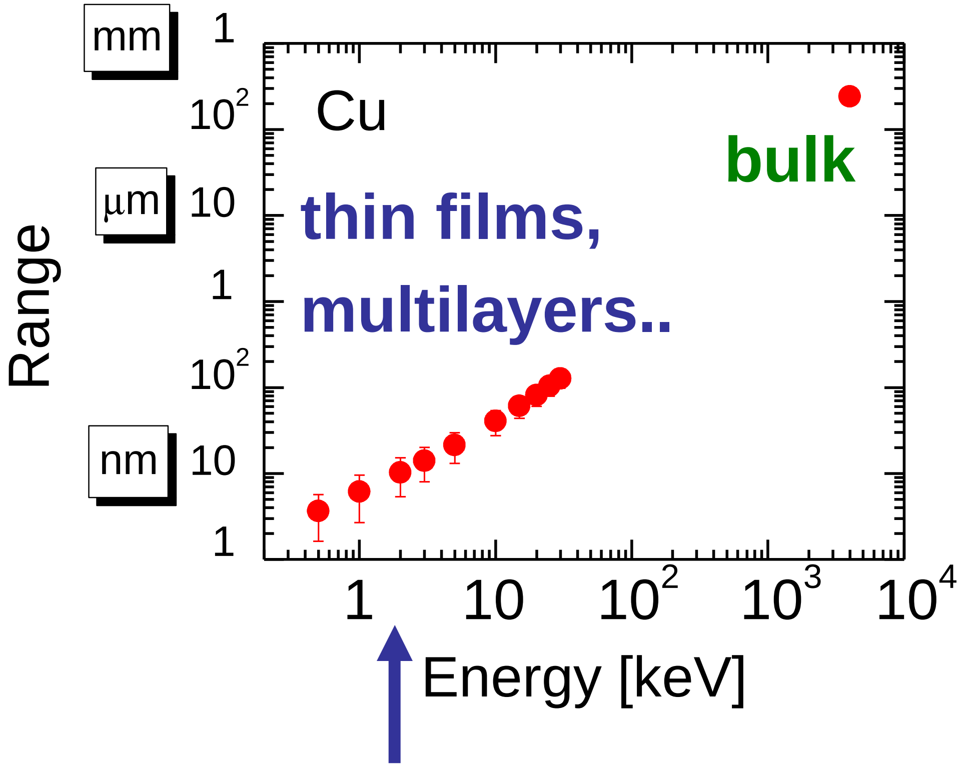
Paul Scherrer Institut

Thomas Prokscha, Laboratory for Muon Spin Spectroscopy

Low energy muons at PSI

Future Muon Sources, Univ. Huddersfield, January 13, 2015

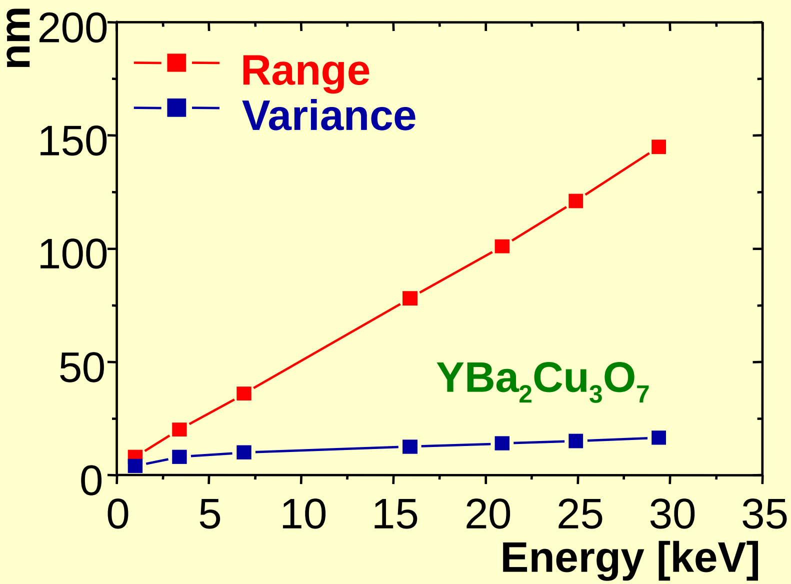
Range of Muons in Matter

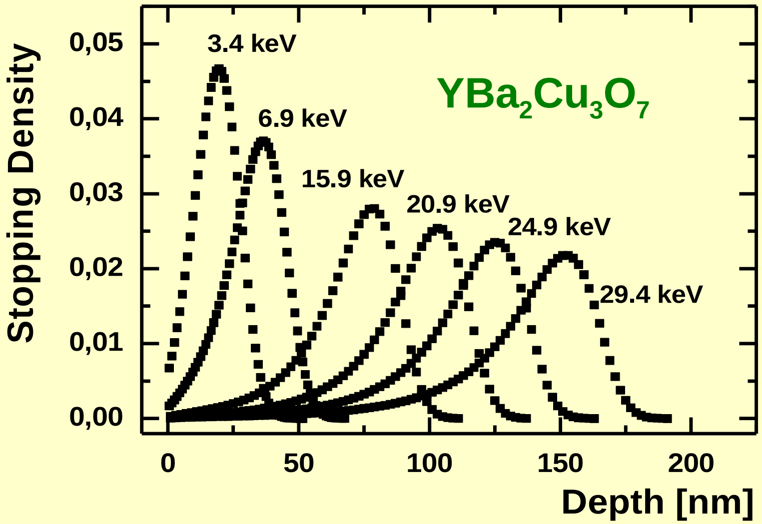


"Surface Muons" from π^+ decay at rest (~ 4 MeV) generally used for bulk studies: **no depth resolu-tion**

- **"Low-energy muons": 0.5 – 30 keV**
- Allows depth-dependent μSR investigations (~ 1 – 300 nm)
- Extends the use of μSR to new objects of investigtions
- New magnetic/spin probe for **thin films, multilayers, surface regions, buried layers**

Implantation Profiles of Low Energy Muons





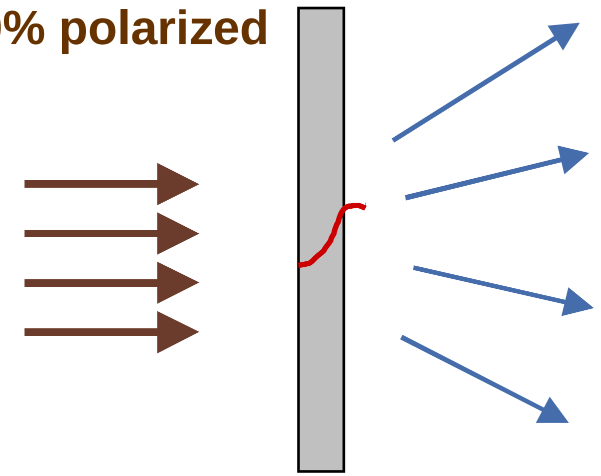
Stopping profiles calculated with Monte Carlo code Trim.SP by W. Eckstein, MPI Garching, Germany.

Experimentally tested for muons:

*E. Morenzoni, H. Glückler, T. Prokscha, R. Khasanov, H. Luetkens, M. Birke, E. M. Forgan, Ch. Niedermayer, M. Pleines, NIM **B192**, 254 (2002).*

Generation of polarized epithermal muons

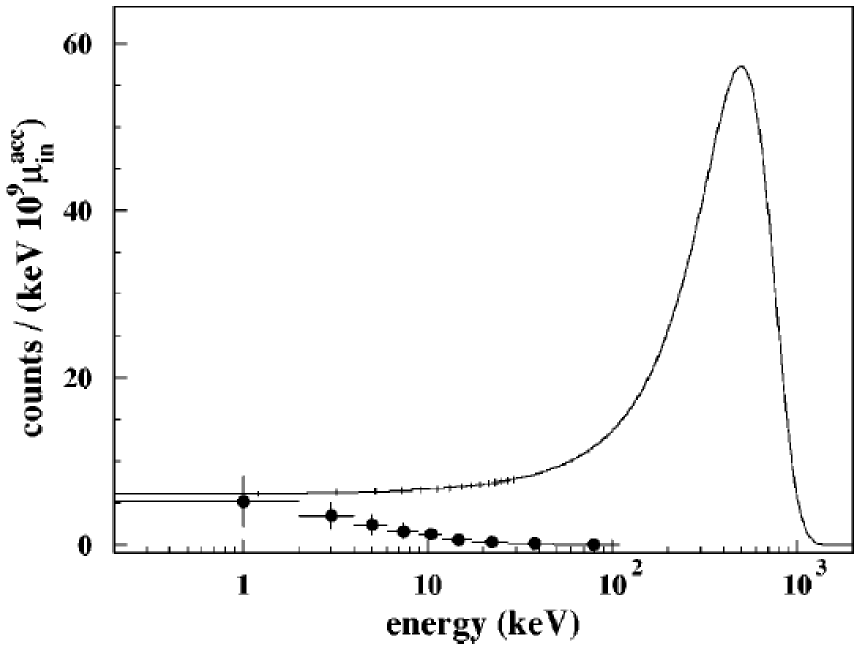
„Surface“ Muons
~ 4 MeV
~ 100% polarized



~100 µm Ag

Using a proper moderator:
motivated by experiments for positron moderation, a solid film of a rare-gas should work!

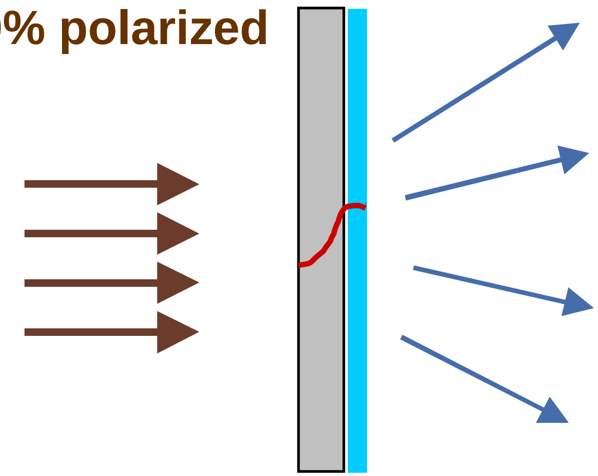
Energy spectrum after a degrader
Solid line: muon energy spectrum
Solid circles: energy spectrum of muonium



T. Prokscha et al., Phys. Rev. **A58**, 3739 (1998).

Generation of polarized epithermal muons

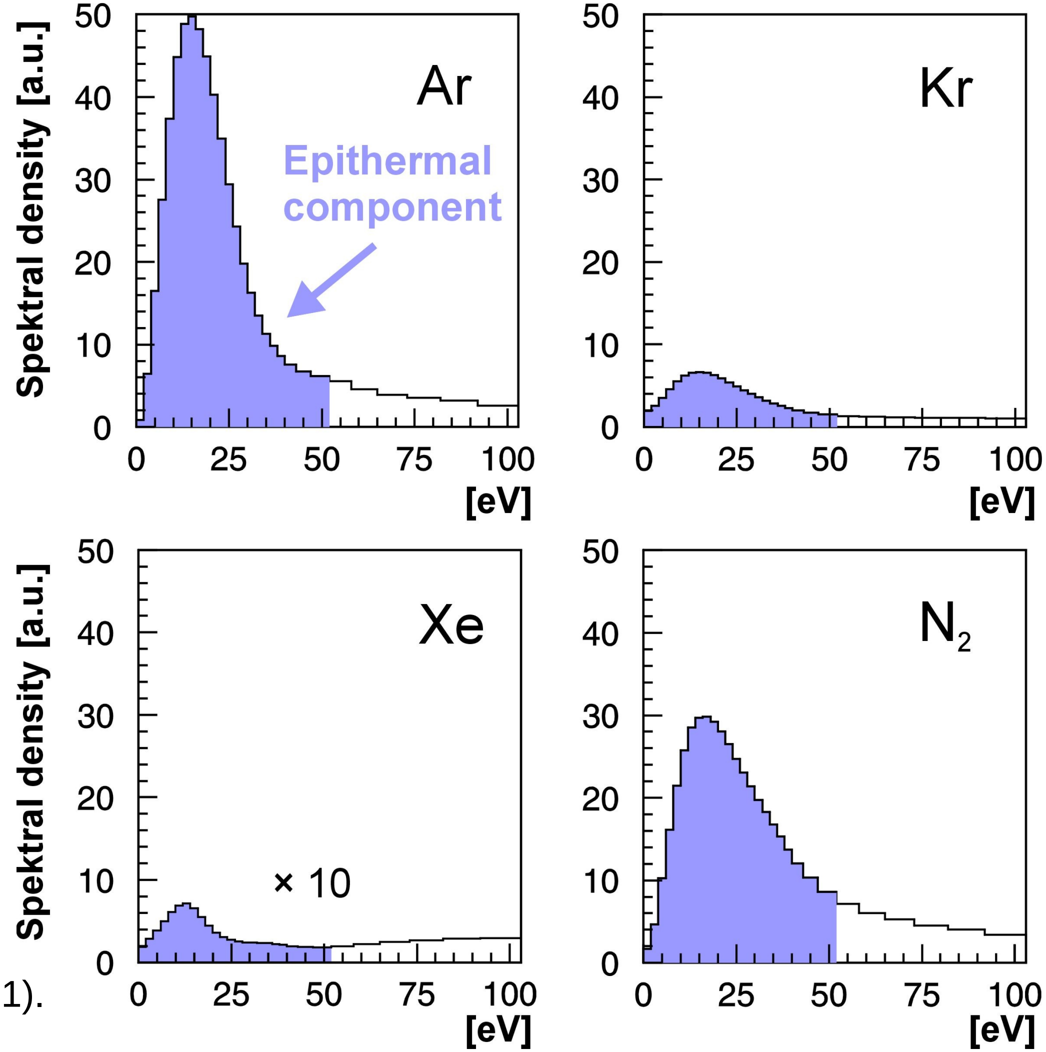
„Surface“ Muons
~ 4 MeV
~ 100% polarized



~100 µm Ag
6 K

~500 nm s-Ne, Ar, s-N_2

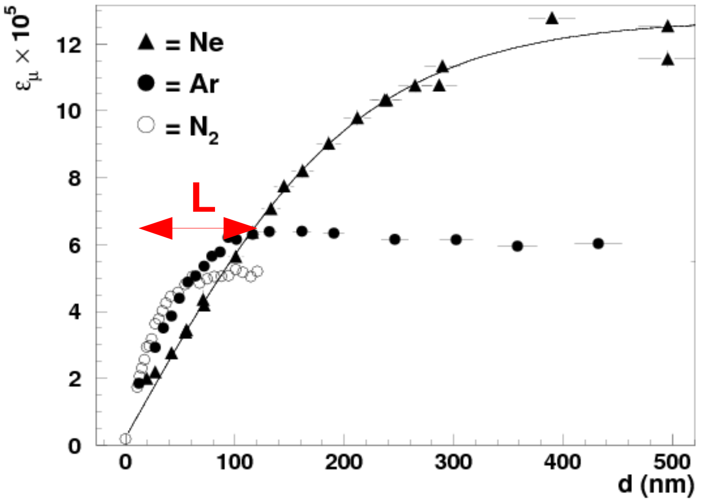
motivated by experiments for positron moderation

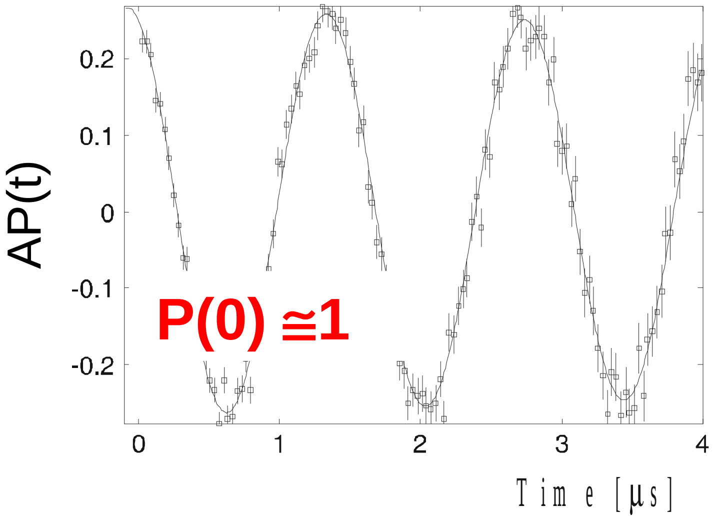


A. Hofer, PhD thesis, U Konstanz (1998).

T. Prokscha et al., Appl. Surf. Sci. **172**, 235 (2001).
T. Prokscha et al., Phys. Rev. **A58**, 3739 (1998).
E. Morenzoni et al,. J. Appl. Phys. **81**, 3340 (1997).
D. Harshmann et al., Phys. Rev. **B36**, 8850 (1987).

Characteristics of epithermal muons





E. Morenzoni, T. Prokscha, A. Suter, H. Luetkens, R. Khasanov, J.Phys.: Cond. Matt. **16**, S4583 (2004).

E. Morenzoni, F. Kottmann, D. Maden, B. Matthias, M. Meyberg, T. Prokscha, T. Wutzke, U. Zimmermann, PRL **72**, 2793 (1994).

→ suppression of electronic energy loss for $E > E_g$, large band gap E_g (10-20 eV) „soft, perfect“ insulators

→ large escape depth L (10-100 nm), no loss of polarization during moderation (~10 ps)

→ **moderation efficiency is low (requires high intensity μ^+ beam, > 10^8 μ^+/s):**

$$\varepsilon_{\mu+} = N_{epith}/N_{4MeV} \approx \Delta\Omega\,(1-F_{Mu})\,L/\Delta R \approx 0.25\,L/\Delta R \approx 10^{-4} - 10^{-5}$$

$\Delta\Omega$: probability to escape into vacuum (~50% for isotropic angular distribution)
F_{Mu}: muonium formation probability

High-intensity μE4 beam for LE-μ^+ production

- Goal: >10^8 μ^+/s on moderator target (3x3 cm^2)
- no modification of the pion/muon target region
- no modification of the main shielding of proton beam, i.e. reconstruct existing beam line
- to obtain maximum acceptance at limited space: use a solenoid as the first focusing element (normal conducting, limiting p)
- use large aperture radius (200 mm) quadrupole triplets for subsequent transport to obtain large transmission
- use large vacuum tubes (diameter 500 mm)
- first solenoid and bending magnet: radiation hard coils

- Completed in 2005. LEM user operation since 2006

Solenoid versus quadrupole

First order transfer matrix for static magnetic system with midplane symmetry:

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & \dots & R_{16} \\ R_{21} & R_{22} & 0 & 0 & \dots & R_{26} \\ 0 & 0 & R_{33} & R_{34} & \dots & \dots \\ 0 & 0 & R_{43} & R_{44} & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \end{pmatrix}$$

➡

$$\begin{aligned} x_1 &= R_{11}x_0 + R_{12}x_0' + R_{16}\frac{\Delta p}{p} \\ x_1' &= R_{21}x_0 + R_{22}x_0' + R_{26}\frac{\Delta p}{p} \\ &\vdots \end{aligned}$$

First order transfer matrix for a solenoid, mixing of horizontal and vertical phase space:

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & \dots & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & \dots & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & \dots & \dots \\ R_{41} & R_{42} & R_{43} & R_{44} & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

➡

$$\begin{aligned} x_1 &= R_{11}x_0 + R_{12}x_0' + R_{13}y_0 + R_{14}y_0' + R_{16}\frac{\Delta p}{p} \\ x_1' &= R_{21}x_0 + R_{22}x_0' + R_{23}y_0 + R_{24}y_0' + R_{26}\frac{\Delta p}{p} \\ &\vdots \end{aligned}$$

Mixing of phase space might lead to an increase of beam spot size

Rotation Θ of phase space: $\Theta = \frac{B \cdot l_{eff}}{2(B\rho)}$ $\tan(\Theta) = -\frac{R_{31}}{R_{11}} = \frac{R_{13}}{R_{33}}$ **Θ = 90° x-y PS exchanged**

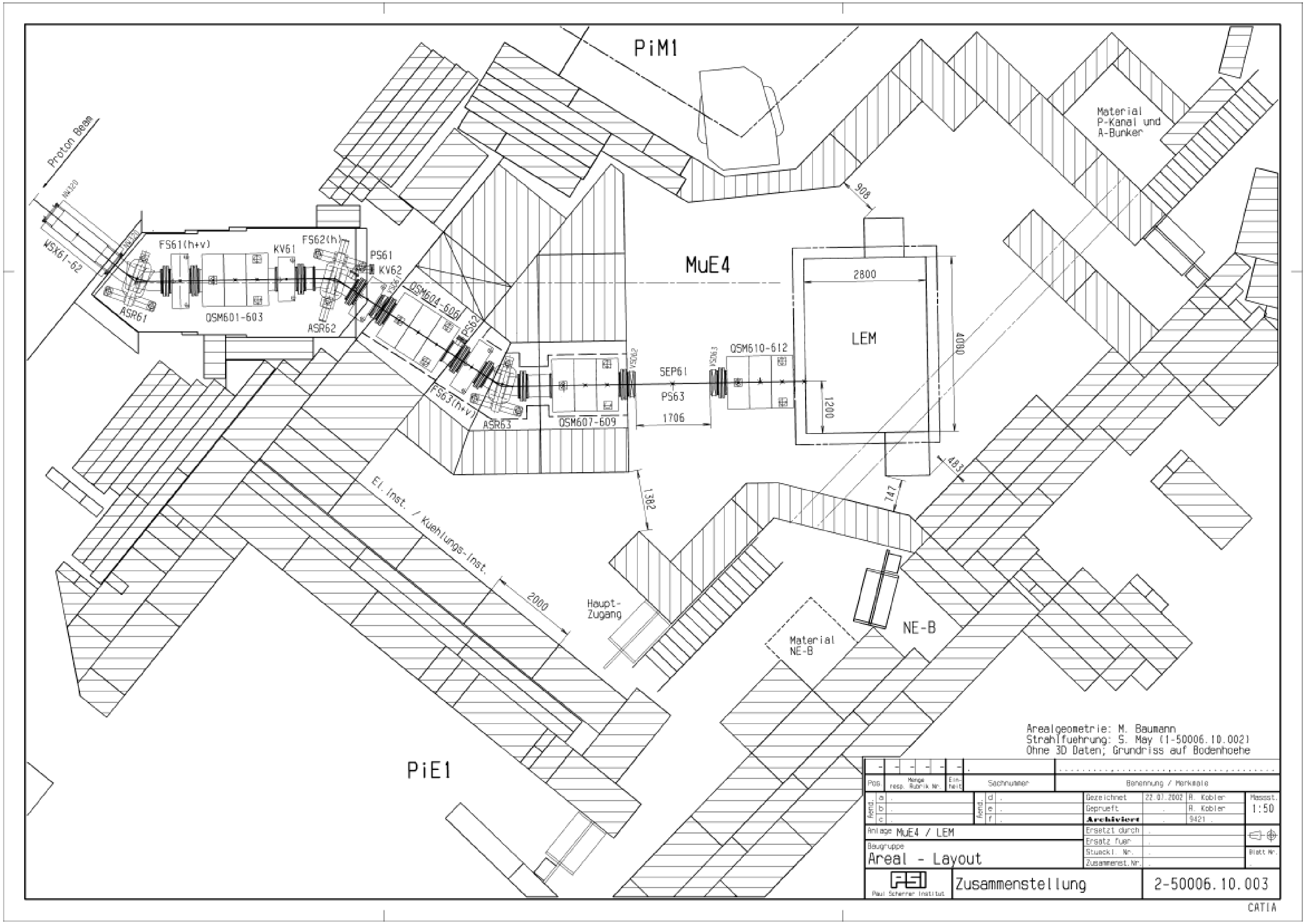
$$\mathbf{R} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} & \dots & R_{16} \\ 0 & 0 & R_{23} & R_{24} & \dots & R_{26} \\ R_{31} & R_{32} & 0 & 0 & \dots & \dots \\ R_{41} & R_{42} & 0 & 0 & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

Focusing powers $P_{S,T}$ of solenoid and triplet at same power dissipation in device:

$$\begin{aligned} 1/f &= P \\ P_T &= P_S \cdot [l_{eff}^2/(2a^2)] \\ P_T &> P_S \quad \text{if} \quad l_{eff} > \sqrt{2}a \end{aligned}$$

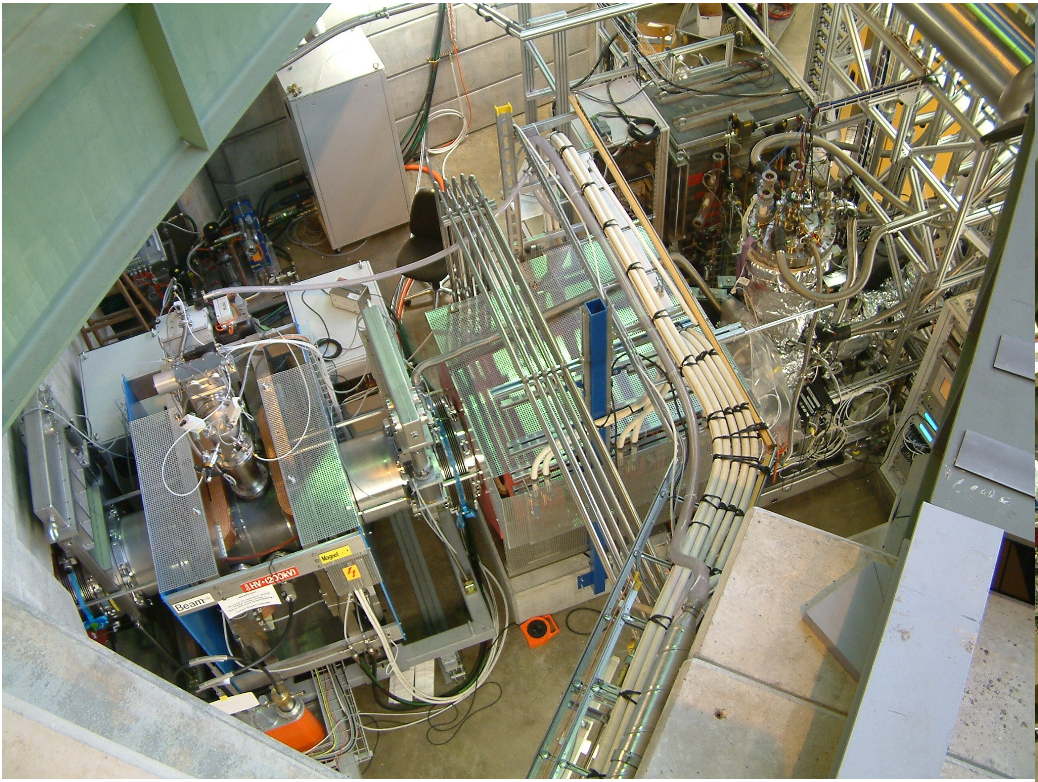
Azimuthal symmetry of solenoids leads to larger acceptance

Layout of the μE4 high-intensity μ beam



PAUL SCHERRER INSTITUT PSI

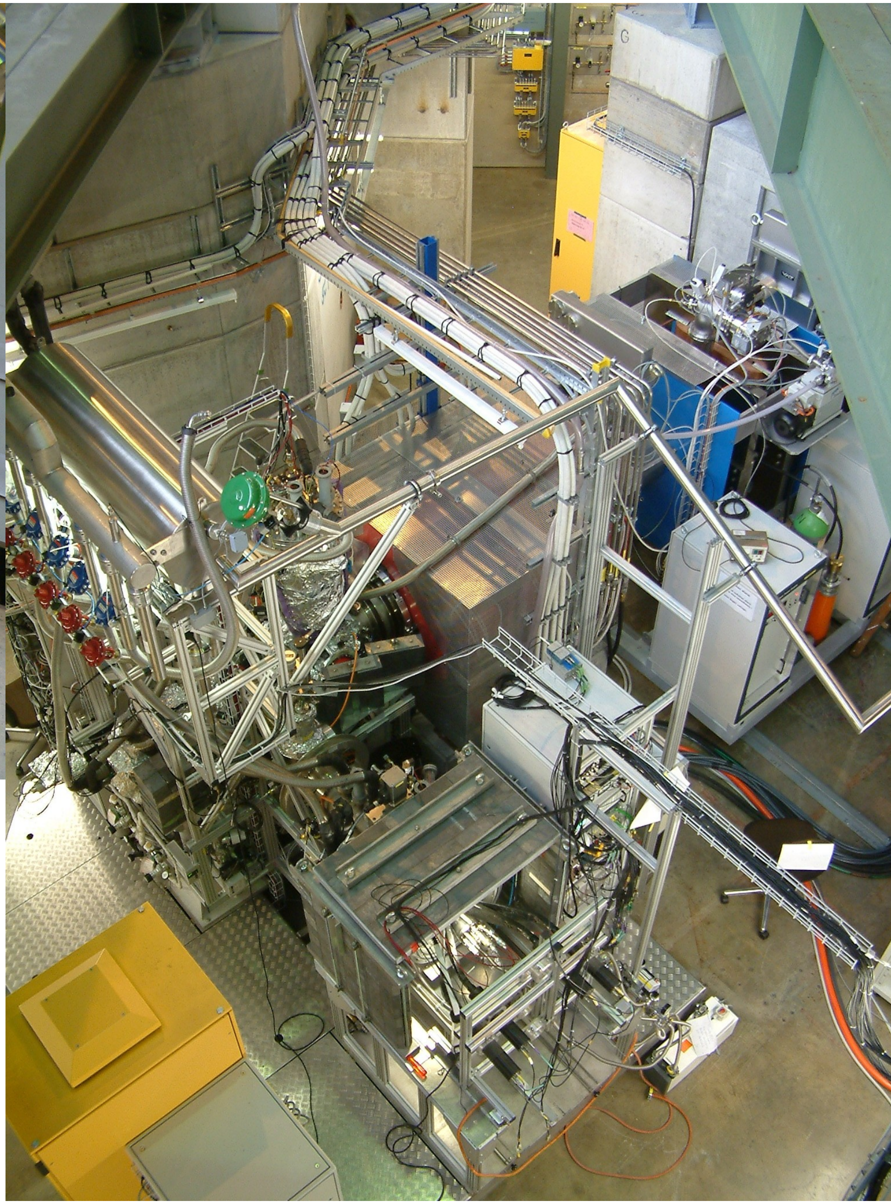
2005: LE-μ+ Apparatus @ rebuilt μE4 beam line



At 2.2 mA proton current:

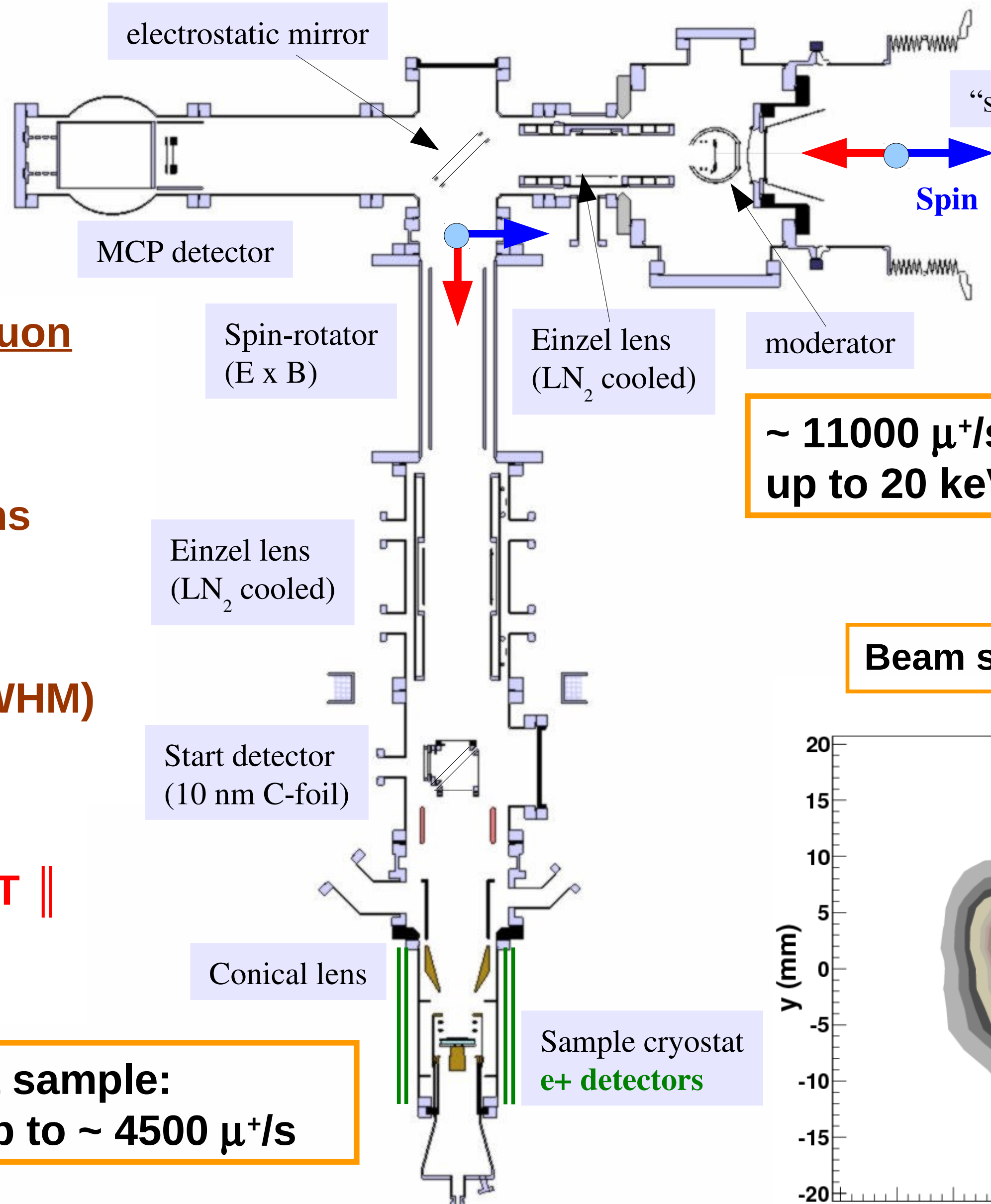
~4.6 • 10^8 μ^+/s total, $\Delta p/p$ = 9.5% (FWHM)
~1.9 • 10^8 μ^+/s on LEM moderator
~1.1 • 10^4 μ^+/s moderated (solid Ar)

T. Prokscha, E. Morenzoni, K. Deiters, F. Foroughi, D. George, R. Kobler, A. Suter and V. Vrankovic
Nucl. Instr. Meth. **A 595**, 317 (2008).



Low energy μ^+ beam and set-up for LE-μSR (LEM)

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



~1.9 • 10^8 μ^+/s

~ 11000 μ^+/s; accelerate up to 20 keV

<u>**Polarized Low Energy Muon Beam**</u>

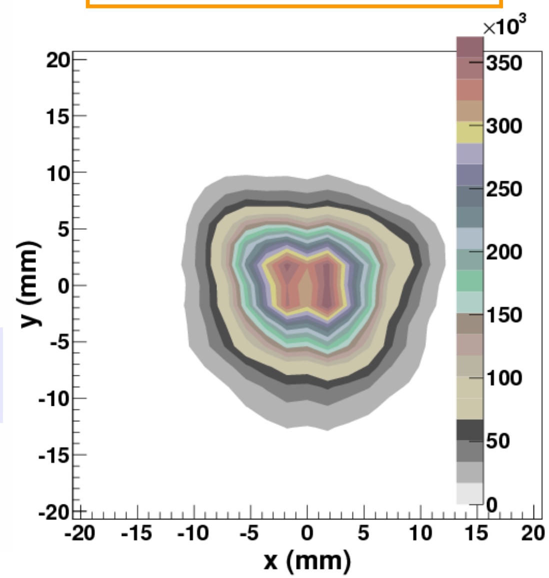
Energy: 0.5-30 keV
ΔE, Δt: 400 eV, 5 ns
Depth: 1 – 300 nm
Polarization ~100 %
Beam Spot: 12 mm (FWHM)

Sample environment:

B = 0 – 0.3 T ⊥ , 0 – 0.03 T ‖ sample surface
T = 2.5 – 600 K

at sample:
up to ~ 4500 μ^+/s

Beam spot at sample

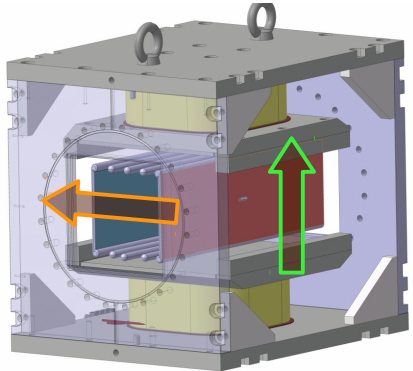


LEM spin-rotator for LF-μSR

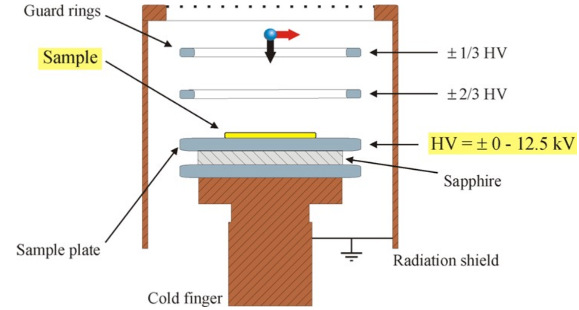
Muon momentum

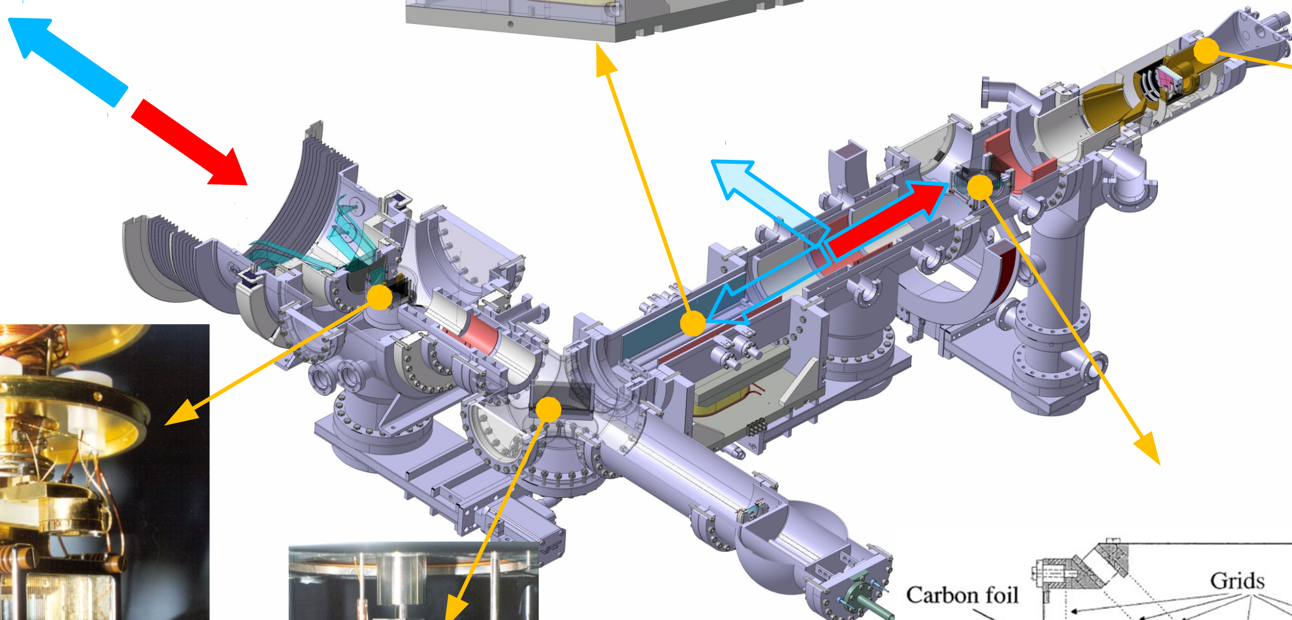
Muon spin

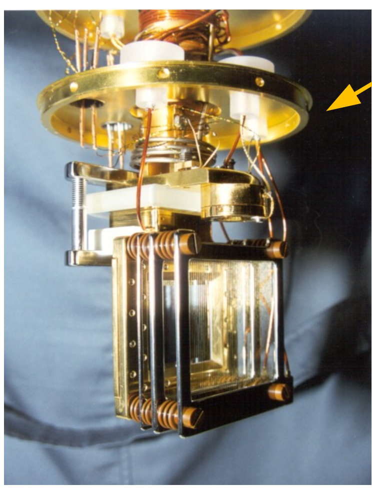
E-Field

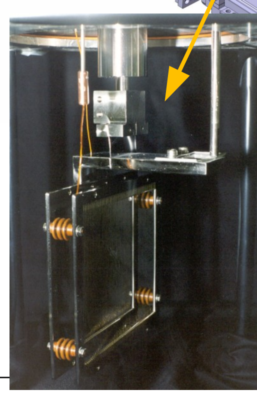


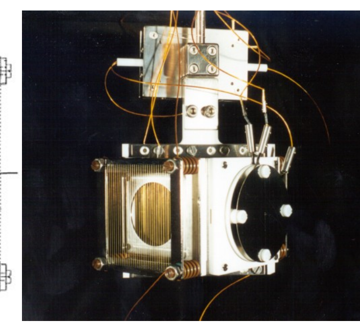
B-Field

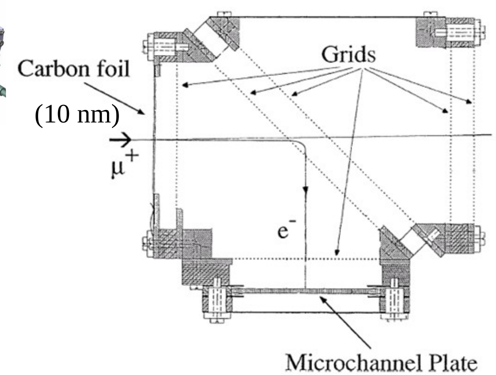




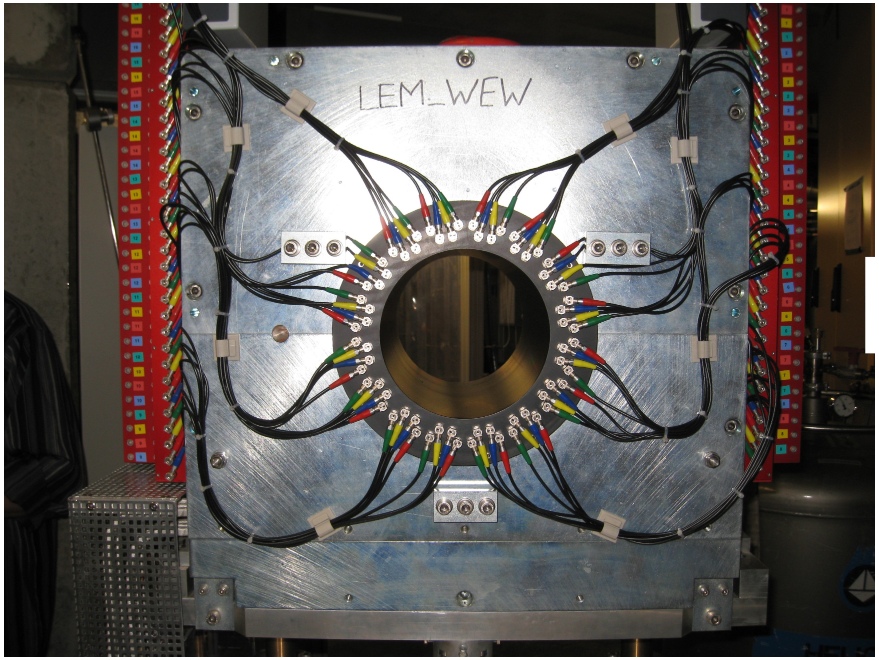


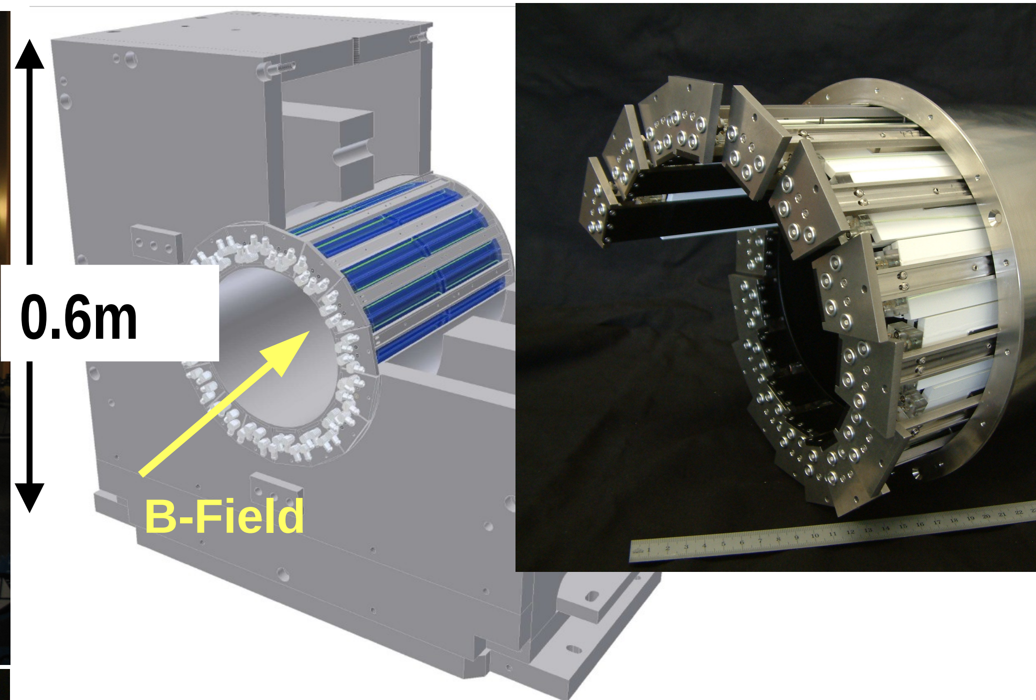


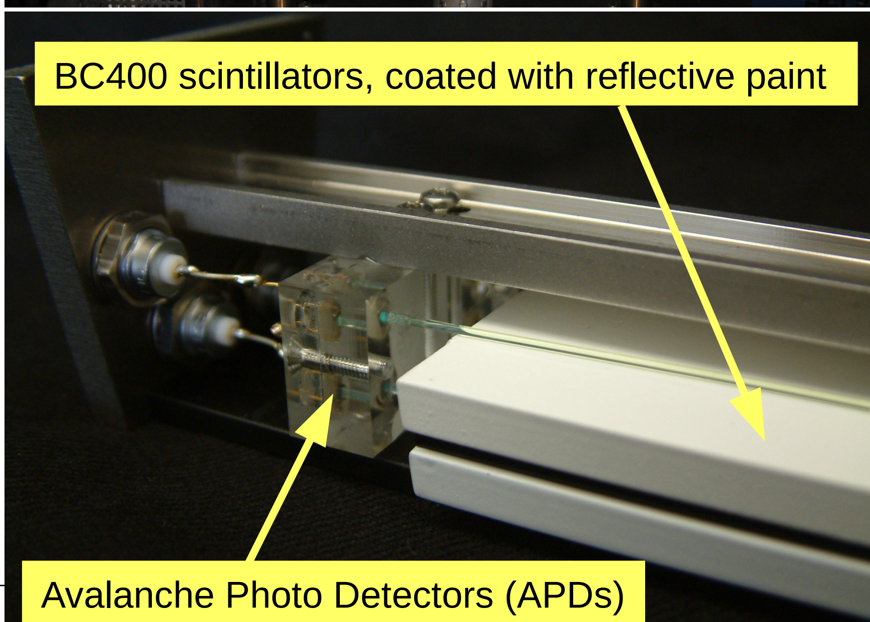




LEM spectrometer for TF/LF-μSR







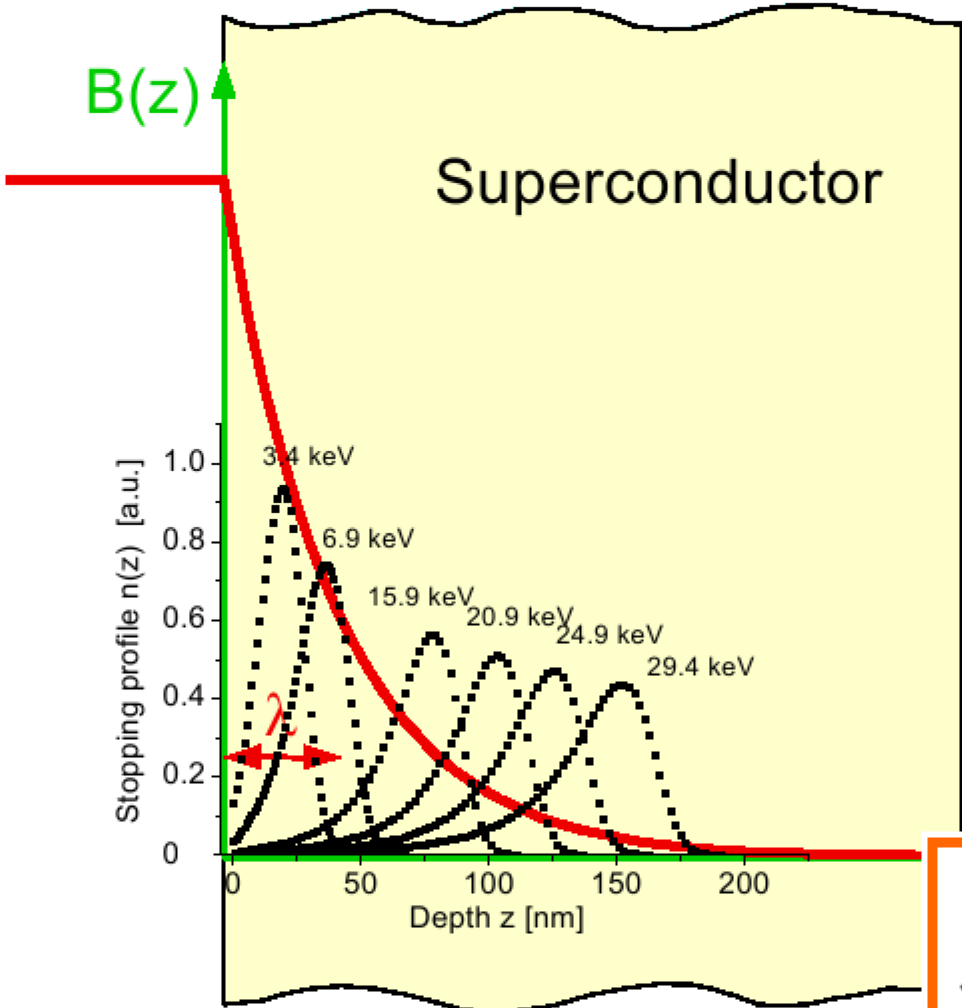
B = 0 – 0.34 T. Positron (e^+) scintillators split in upstream and downstream detectors; use wave-length shifting fibres (blue-to-green) to guide the light to green-sensitive APDs ($1mm^2$, Photonique SSPM 0810G).

Solid angle and e^+ rates optimized with ***musrSim***:

- Use 1-mm Ti vacuum tube containing the sample
- Shape of the scintillators
- Use carbon-fibre support structure for the e^+ counters

LEM science, some selected topics

Depth dependent LE-μSR measurements



n(z,E): muon implantation profile for a particular muon energy E

μSR experiment ⇒ magnetic field probability distribution p(B, E) sensed by the muons

$$n(z,E)\,\mathrm{d}z = p(B,E)\,\mathrm{d}B$$

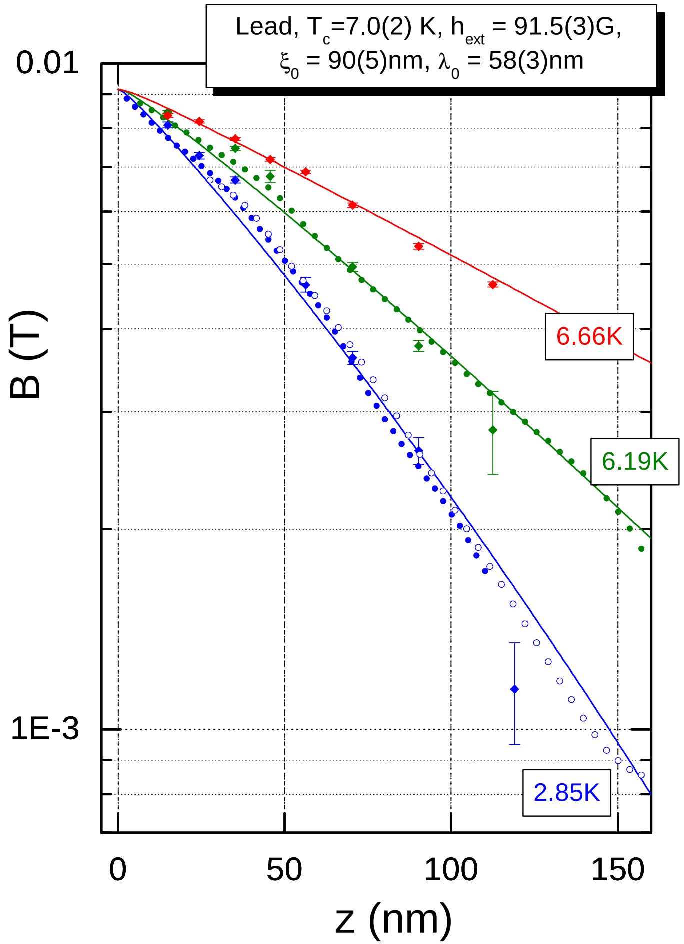
$$\int_0^z n(\zeta,E)\,\mathrm{d}\zeta = \int_{B(z)}^{\infty} p(\beta,E)\,\mathrm{d}\beta$$

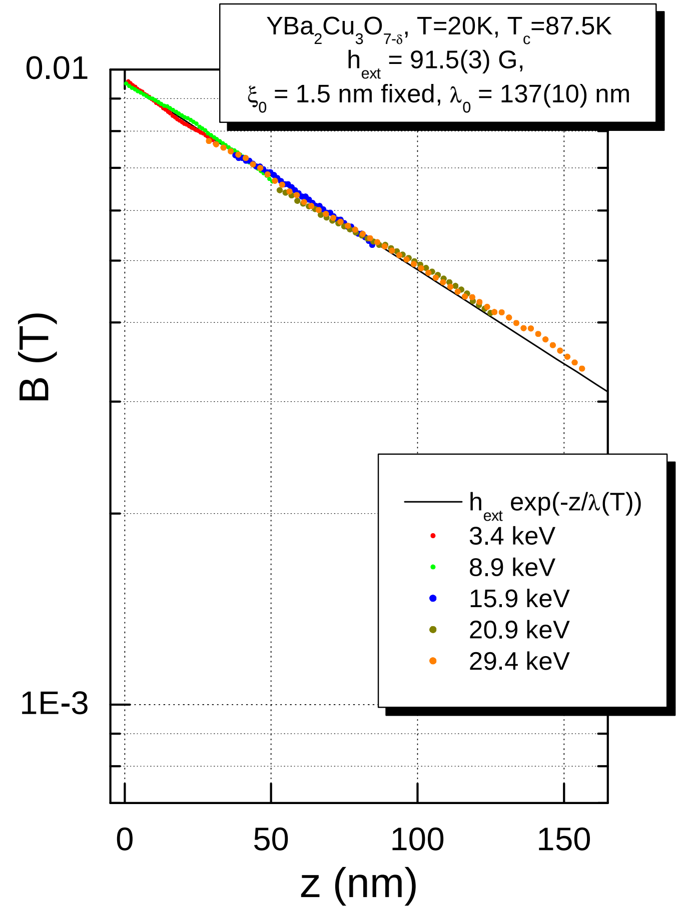
⇒ B(z)

→ Magnetic field profile B(z) over nm scale

→ Characteristic lengths of the sc λ, ξ

Magnetic field profiles in Pb and $YBa_2Cu_3O_{7-\delta}$





Non-local: non- exponential

local: exponential

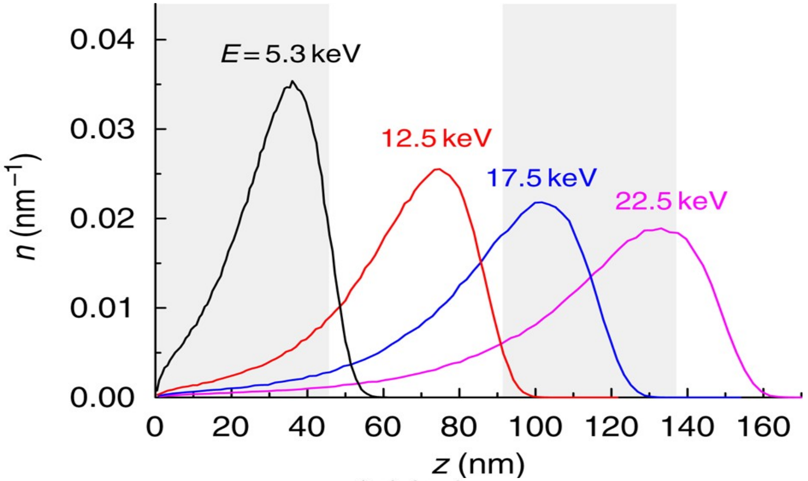
T.J. Jackson et al., PRL **84**, 4958 (2000).
A. Suter et al., PRL **92**, 087001 (2004).
A. Suter et al., PRB **72**, 024506 (2005); *V. Kozhevnikov et al.,* PRB **87**, 104508 (2013).

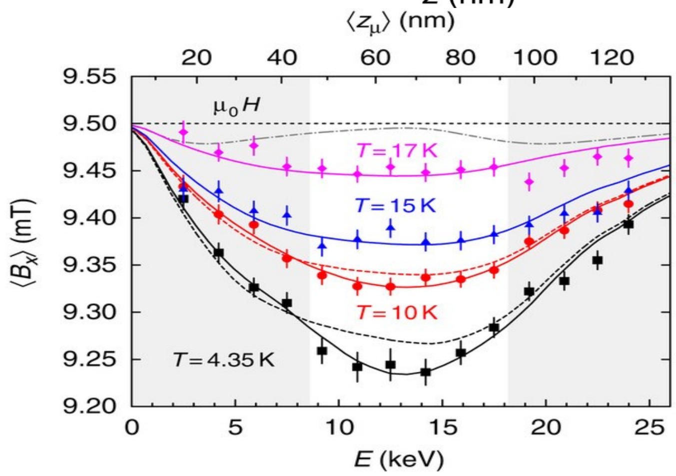
Low Energy Muon Applications

Meissner effect in strongly underdoped cuprate

$La_{1.84}Sr_{0.16}CuO_4$ - $La_{1.94}Sr_{0.06}CuO_4$ - $La_{1.84}Sr_{0.16}Cu_4$

T_c = 32 K T'_c < 5 K T_c = 32 K

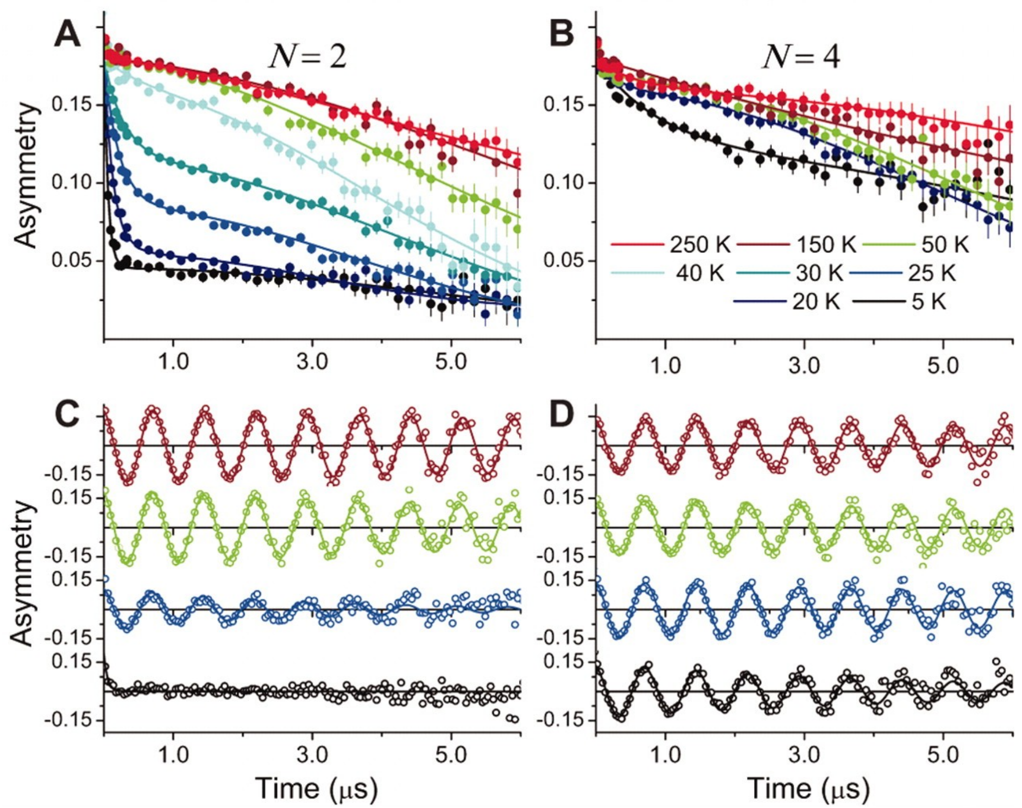




E. Morenzoni et al., *Nat. Comm.* ***2***, *272 (2011)*

Dimensionality control of electronic phase transition in Ni-oxide superlattices

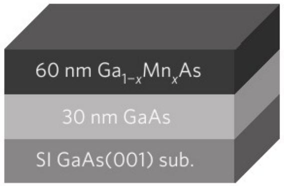
- 100-nm-thick NxN u.c. $LaNiO_3/LaAlO_3$ superlattices
- **2 u.c. $LaNiO_3$: MI and AF transitions at T < 150 K**
- **4 u.c. $LaNiO_3$: metallic and paramagnetic at all T**

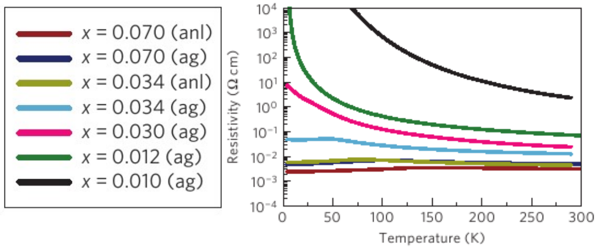


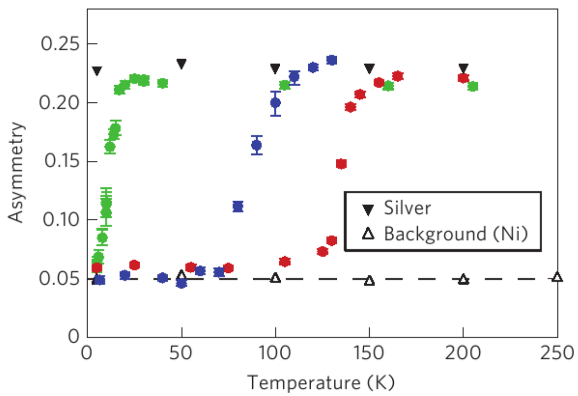
A.V. Boris et al., *Science* ***332***, *937 (2011)*

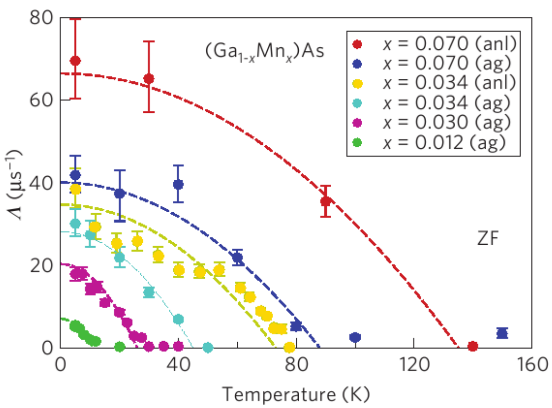
Low Energy Muon Applications

Spatially homogeneous ferromagnetism in (Ga,Mn)As



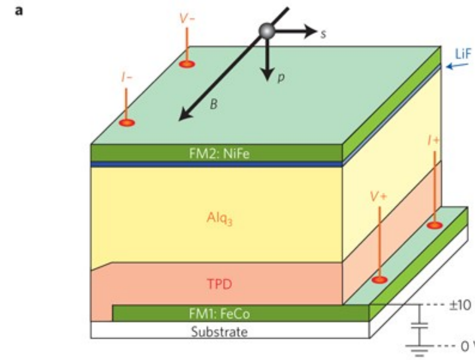


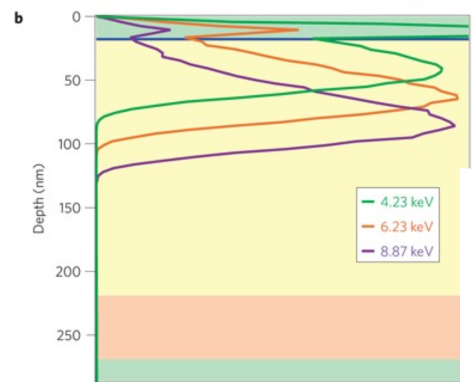




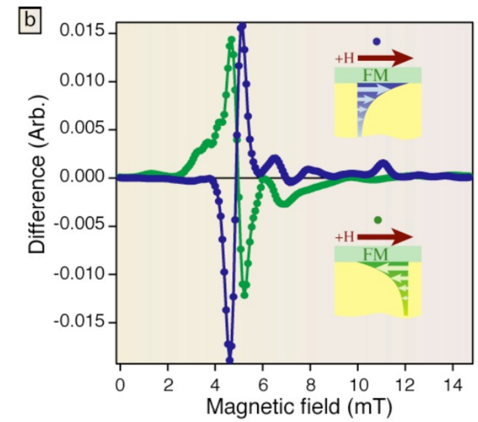
S.R. Dunsiger et al., *Nat. Mat.* **9**, 299 (2010)

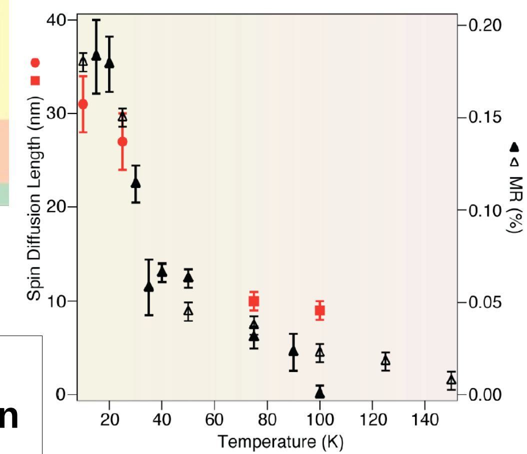
Spin diffusion length in organic spin valves





Field distribution: $I_{on} - I_{off}$



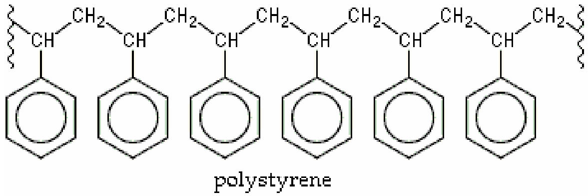


First direct measurement of spin diffusion length in a working spin valve.

A.J. Drew et al., *Nat. Mat.* **8**, 109 (2009)

Some More Low Energy Muon Applications

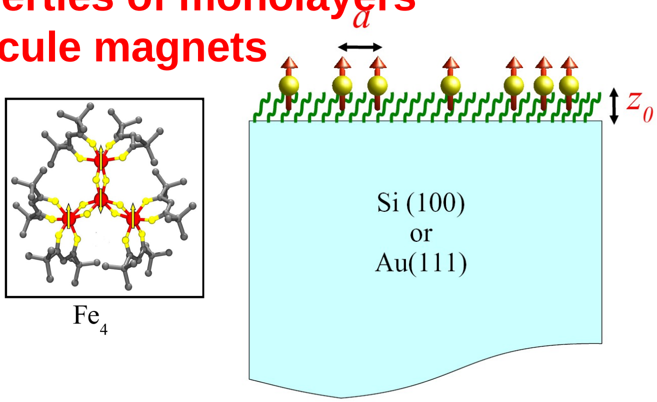
Surface dynamics of polymers



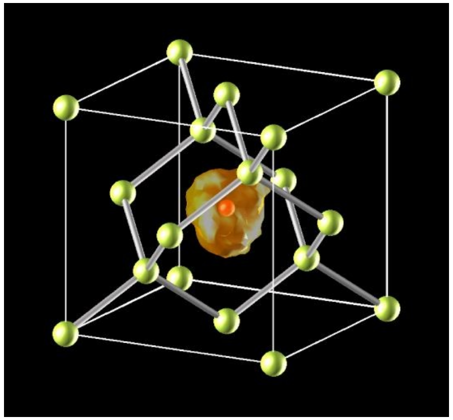
F.L. Pratt et al., PRB **72**, 121401(R) (2005)
I. McKenzie et al., PRE **89**, 022605 (2014)

Magnetic properties of monolayers of single molecule magnets

Z. Salman et al.

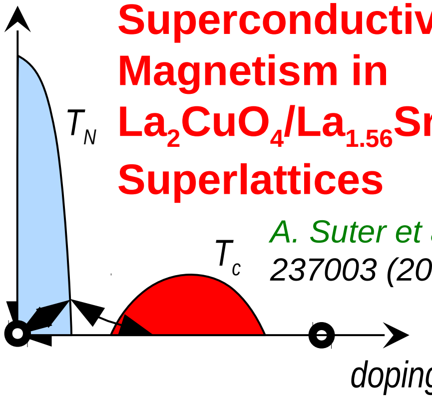


Formation of hydrogen impurities in semiconductors at low energies



T. Prokscha et al., PRL **98**, 227401 (2007)
T. Prokscha et al., PRB **90**, 235303 (2014)
D.G. Eshchenko et al., Physica **B 404**, 873 (2009)
Z. Salman et al., PRL **113**, 156801 (2014)

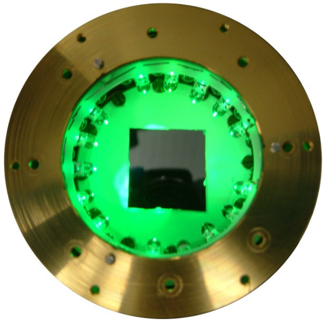
Superconductivity and Magnetism in $La_2CuO_4/La_{1.56}Sr_{0.44}CuO_4$ Superlattices



A. Suter et al., PRL **106**, 237003 (2011)

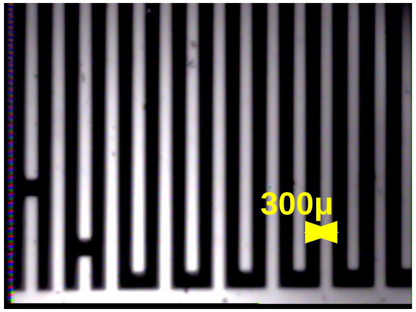
Photo-induced effects in semiconductors

T. Prokscha et al. Sci. Rep. **3**, 2569 (2013)



Superfluid density in high and low T_c heterostructures

B. Wojek et al., PRB **85**, 024505 (2012)



Current effects on magnetism and superconductivity in a thin $La_{1.94}Sr_{0.06}CuO_4$ wire

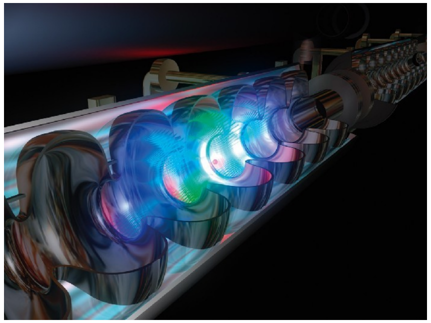
M. Shay et al., PRB **80**, 144511 (2009)

Superconductivity and magnetism in electron doped cuprates films

H. Saadaoui et al., Nat. Comm. accepted

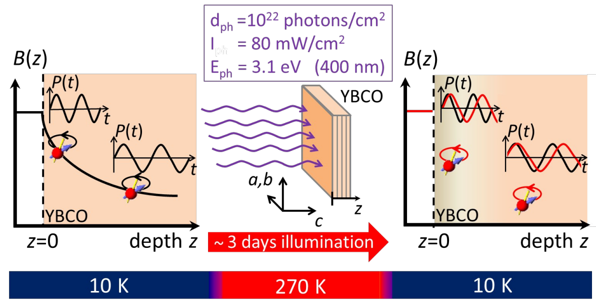
Low Energy Muon Applications

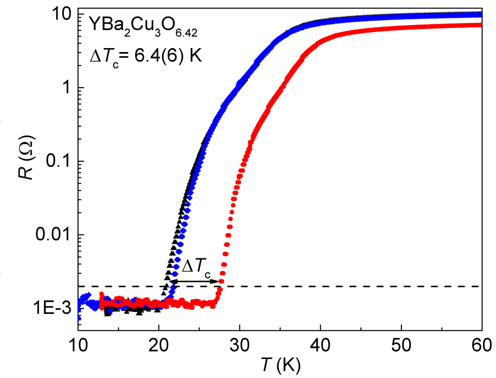
Superconducting Nb RF-cavities



A. Romanenko et al., *APL* ***104****, 072601 (2014)*

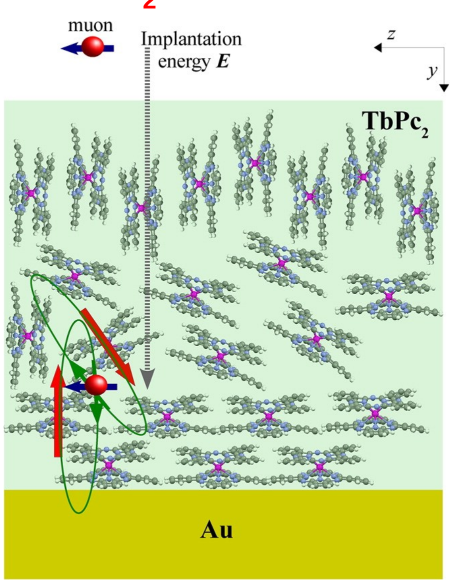
Photo-persistent change of Meissner screening in $YBa_2Cu_3O_{6+x}$





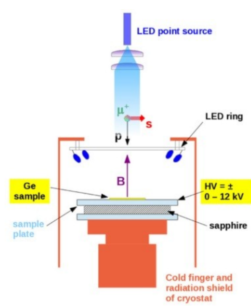
E. Stilp et al. Sci. Rep. ***4****, 6250 (2014)*

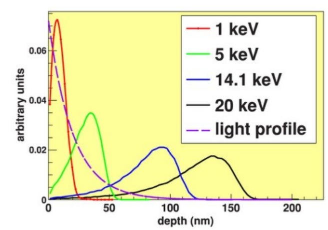
Depth-dependent spin dynamics in $TbPc_2$ thin films



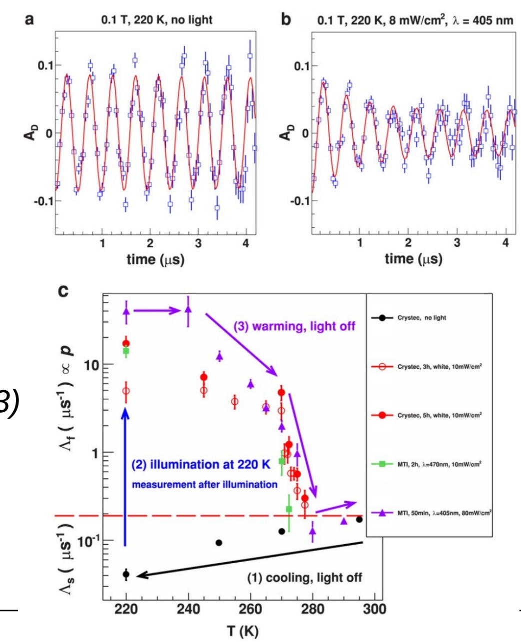
A. Hofmann et al., *ACS NANO* ***6****, 8390 (2012)*

Photo-induced persistent inversion of Ge in a 200-nm-deep surface region



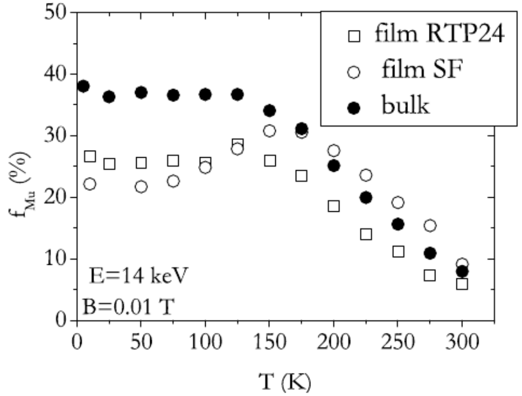


T. Prokscha et al., Sci. Rep. ***3****, 2569 (2013)*



Low Energy Muon Applications

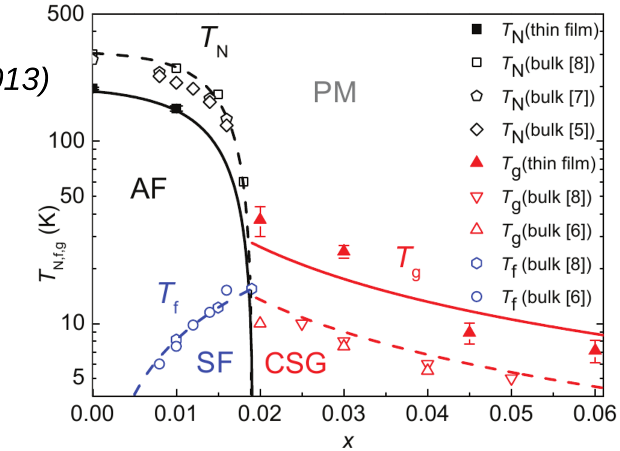
Mu states in CZTS solar cell material



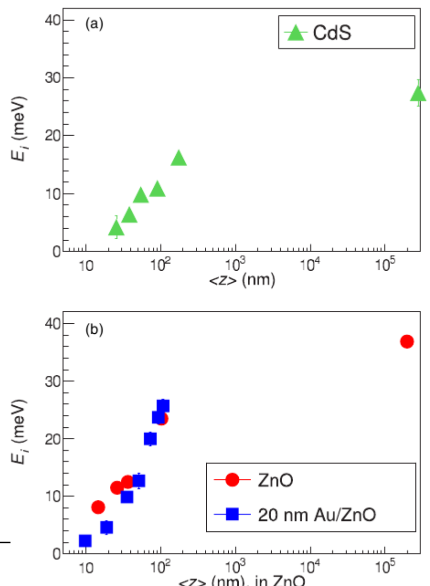
H.V. Alberto et al., *J.Phys.: Conf. Ser.* ***551***, *012045 (2014)*

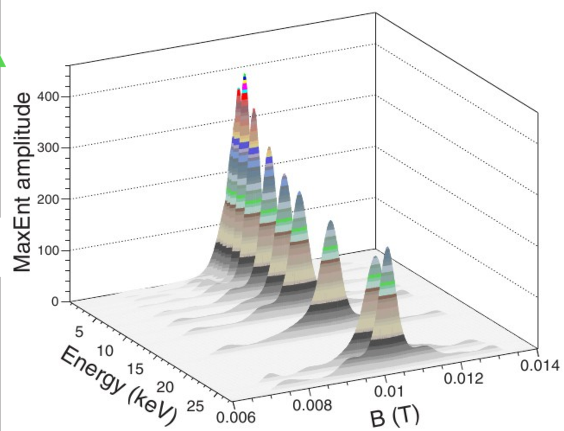
Magnetic phase diagram of low-doped $La_{2-x}Sr_xCu_2O_4$ thin films

E. Stilp et al., *PRB* ***88***, *064419 (2013)*



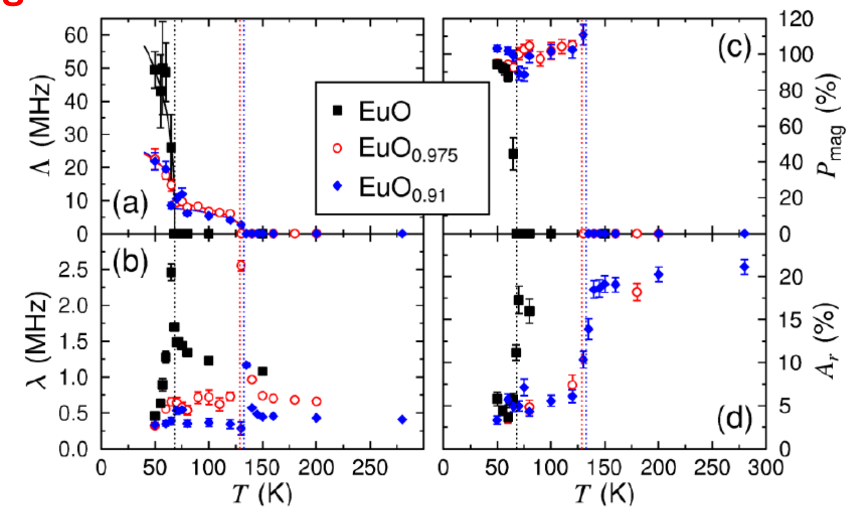
Depth-dependent ionization energy of shallow hydrogen in ZnO and CdS





T. Prokscha et al., *PRB* ***90***, *235303 (2014)*

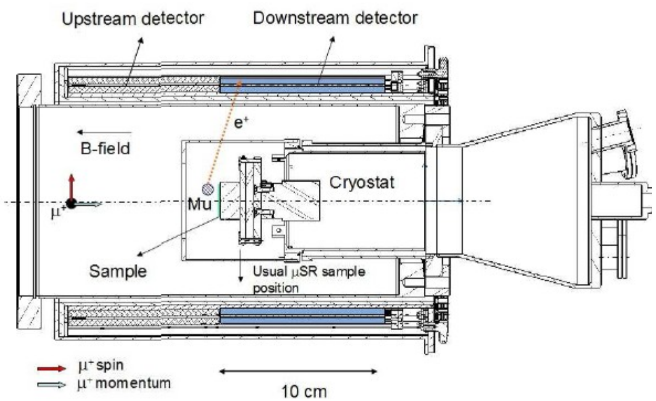
Spatially homogeneous ferromagnetism in EuO_{1-x} thin films

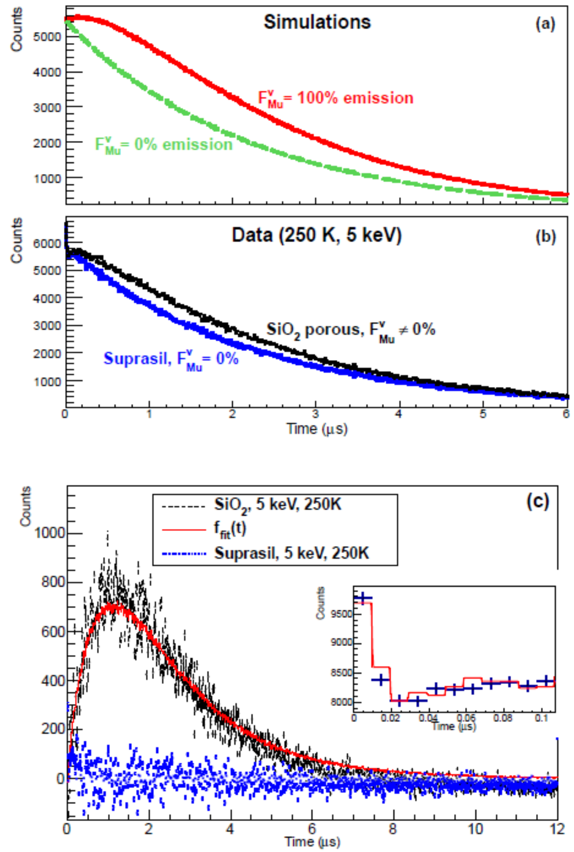


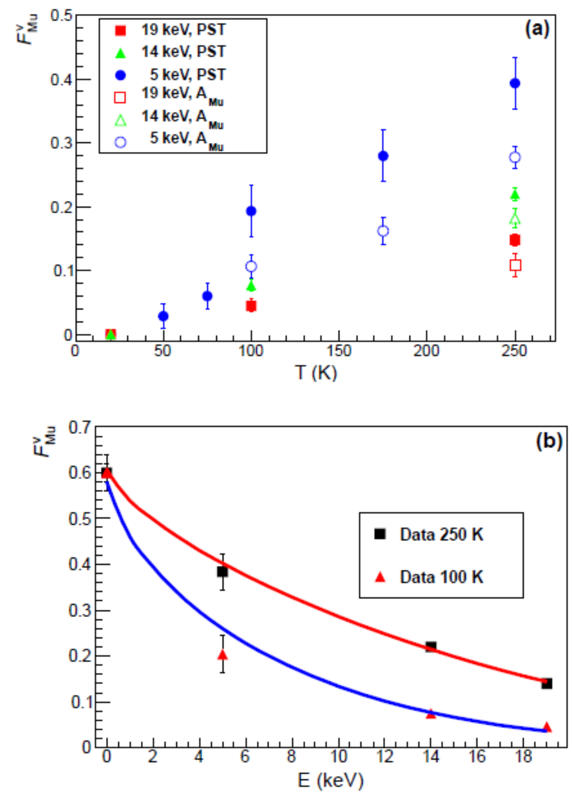
P. Monteiro et al., *PRL* ***110***, *217208 (2013)*

“Cold” muonium from mesoporous SiO_2 in vacuum

Motivated by recent results on Ps emission from mesoporous SiO_2 films







Vacuum Mu fraction F^V_{Mu} as a function of temperature and energy; solid lines are a fit of a diffusion model to the data.

250 K, 5 keV: **40% emission of thermal Mu in vacuum**

100 K, 5 keV: 20% emission of thermal Mu in vacuum; expect 40% at 2 keV (to be confirmed)

A. Antognini et al., PRL **108**, 143401 (2012): “cold” Mu enables cw precision spectroscopy on Mu_{1S-2S} transition.

Developments

- Increasing LEM rate, solid Ne moderator
- Sample transfer chamber
- Extension to lower temperatures (from 2.7 K to < 2.0 K)
- External stimulus: ongoing developments on E-field, illumination, current, RF
- Feasibility of a vector magnet at the sample
- Improve beam spot on moderator, at sample, tracking detector system
- Computing: use of graphics cards and MICs for faster fitting and simulation

LEM group at PSI

T. Prokscha, A. Suter, Z. Salman, H.P. Weber (technician)

Part time: H. Luetkens

PhD student: E. Stilp (PSI/U Zurich), just finished

Guest: R. Xiao (PhD student at USTC), U. Locans (PhD student U Riga)

Computing support: A. Raselli (part time)