Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

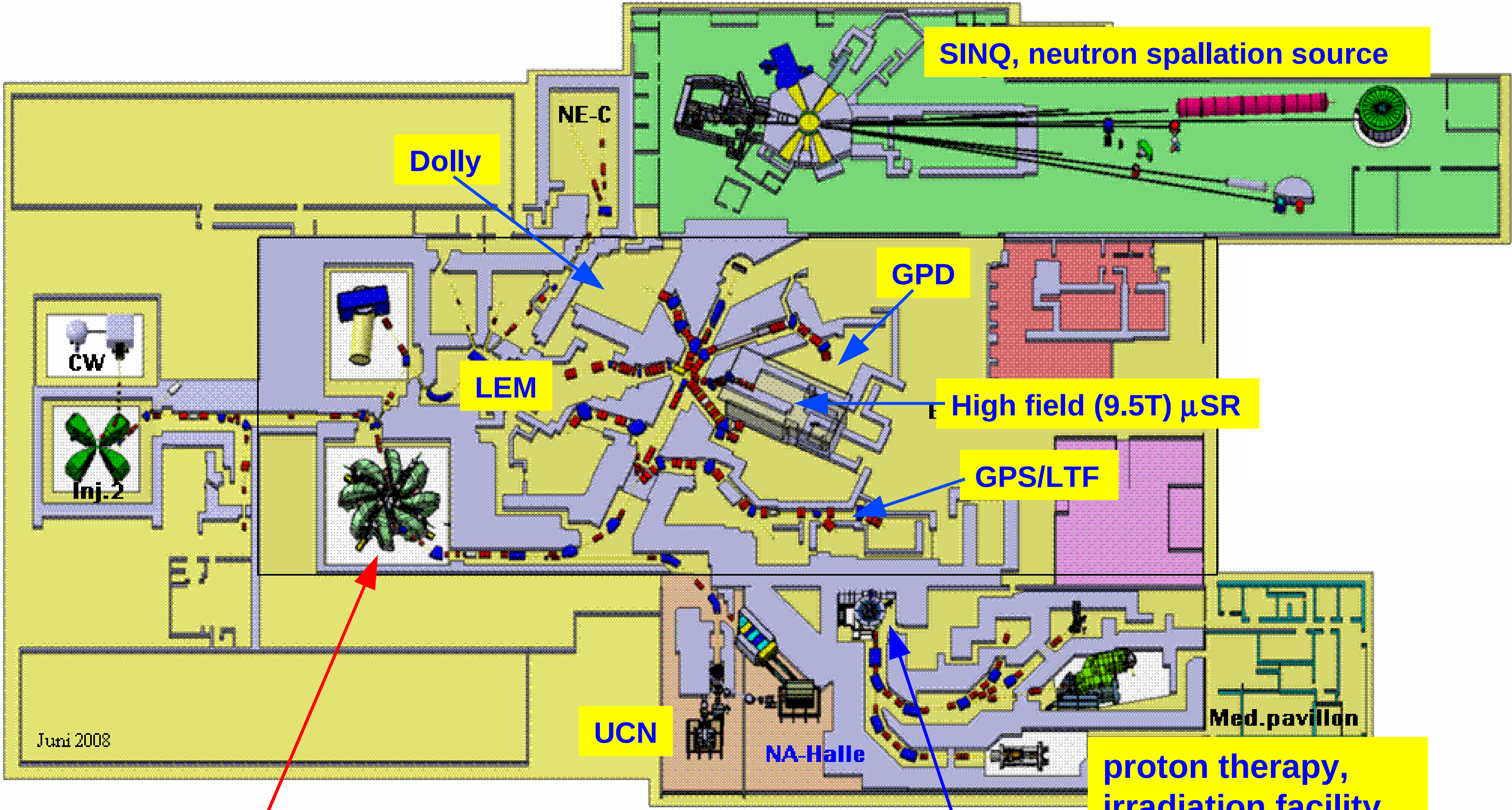
Thomas Prokscha, Laboratory for Muon Spin Spectroscopy

The Low-Energy Muon Facility at PSI

KEK-TRIUMF workshop on Ultra Slow Muons, March 8/9 2012


μSμS
n SINQ
SwissFEL
γ SLS
SINQ

PSI proton accelerator complex



SINQ, neutron spallation source

Dolly

GPD

LEM

High field (9.5T) μSR

GPS/LTF

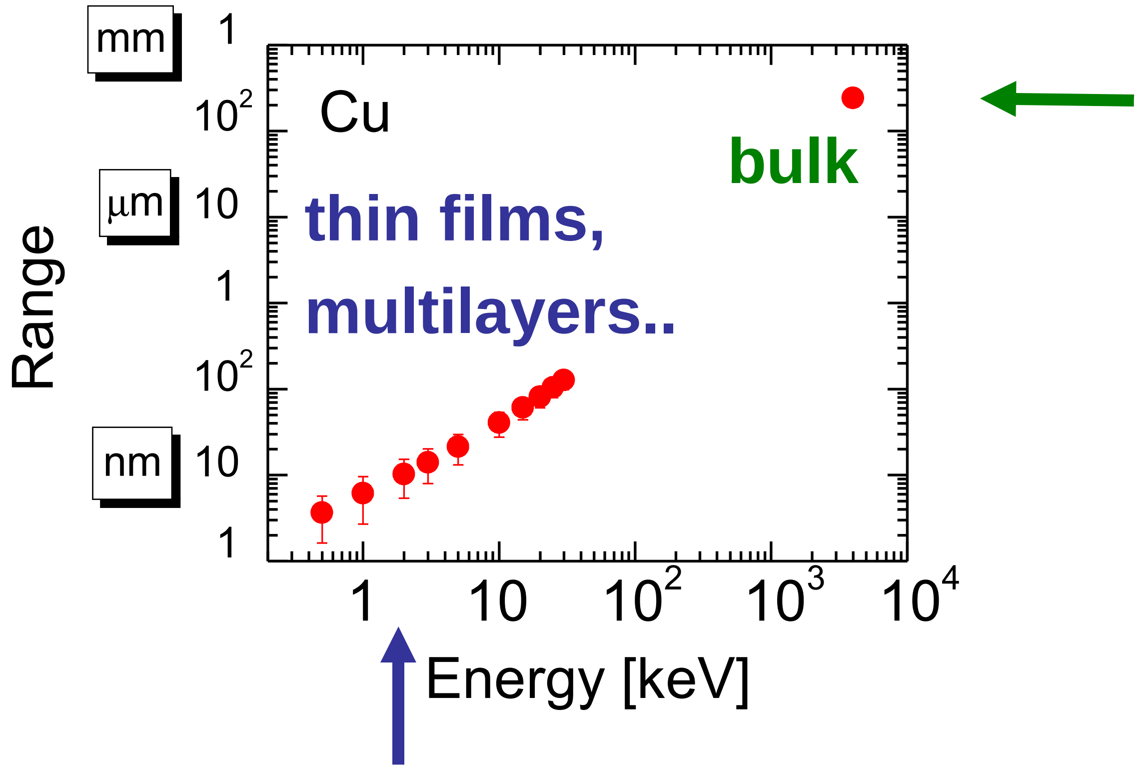
UCN

proton therapy, irradiation facility

50 MHz proton cyclotron, 2.2 mA, 590 MeV, 1.3 MW beam power (2.4 mA, 1.4 MW test operation)

Comet cyclotron (superconducting), 250 MeV, 500 nA, 72.8 MHz

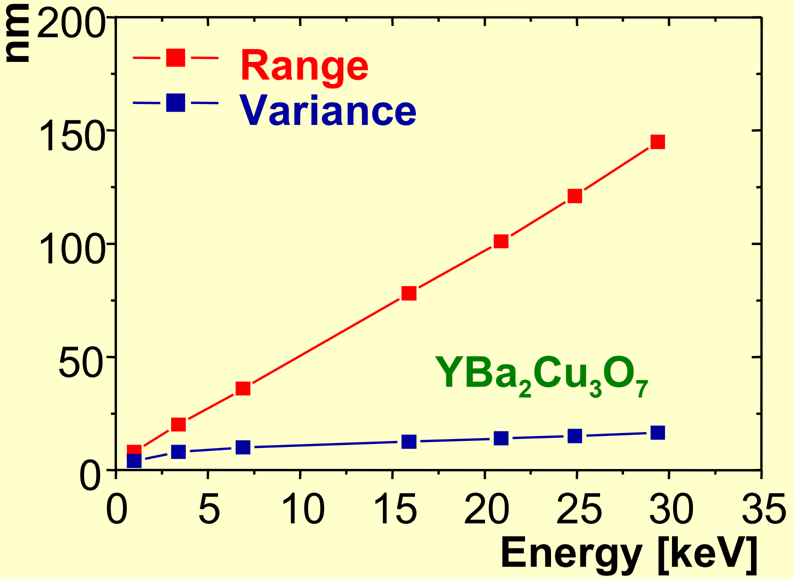
Range of Muons in Matter

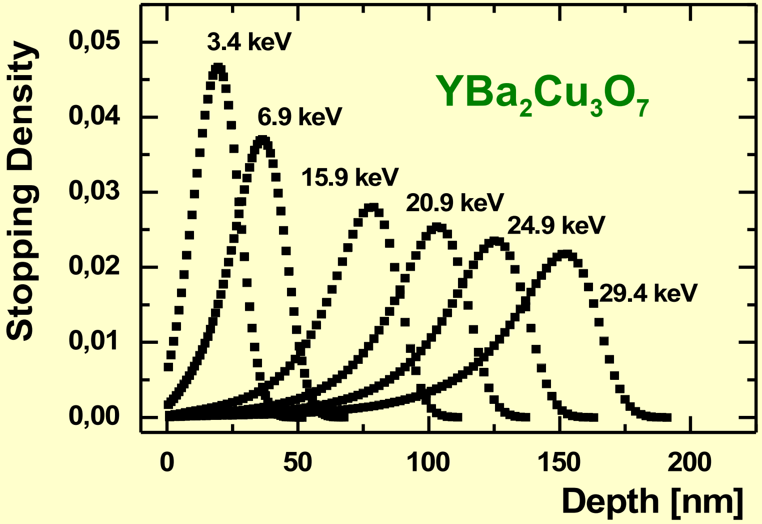


“Surface Muons” from π^+ decay at rest (~ 4 MeV) generally used for bulk studies: **no depth resolution**

- **“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





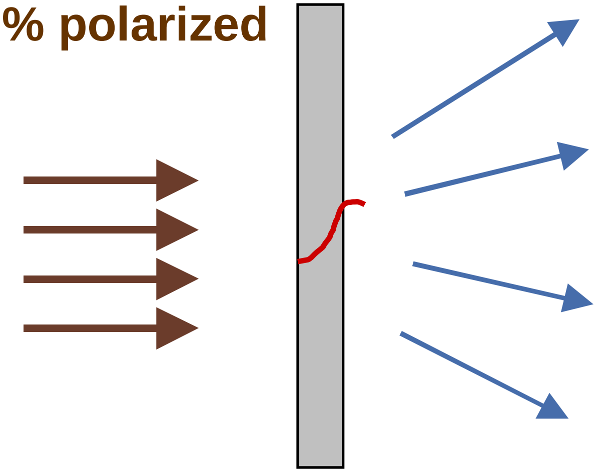
Stopping profiles calculated with Monte Carlo code Trim.SP by W. Eckstein, MPI Garching, Germany.

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

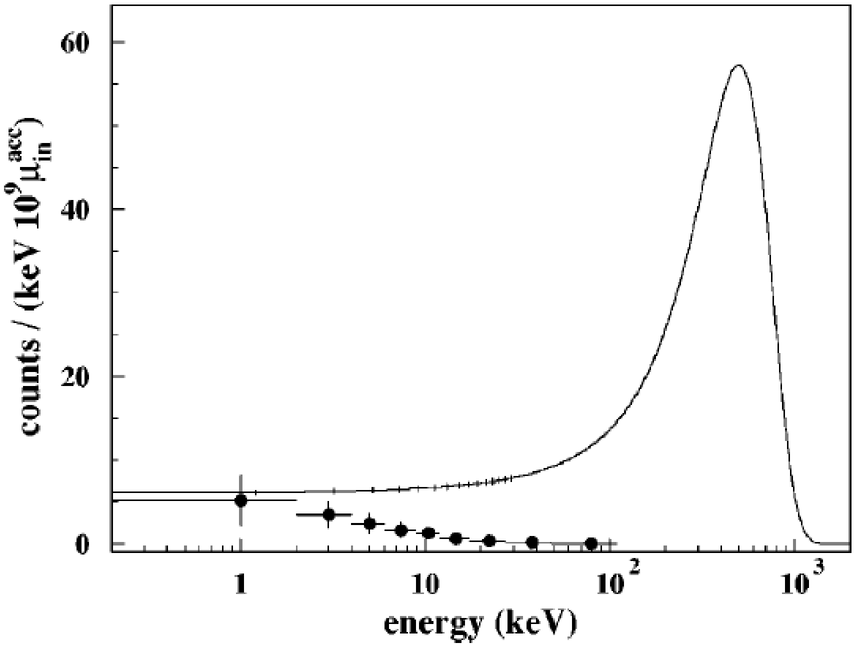
„Surface“ Muons
~ 4 MeV
~ 100% polarized



~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

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~ 4 MeV
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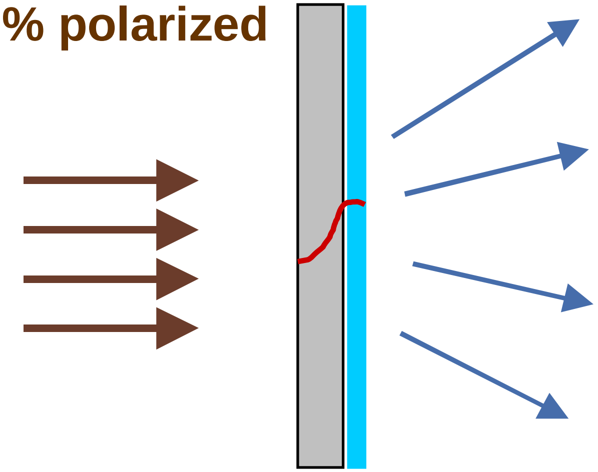
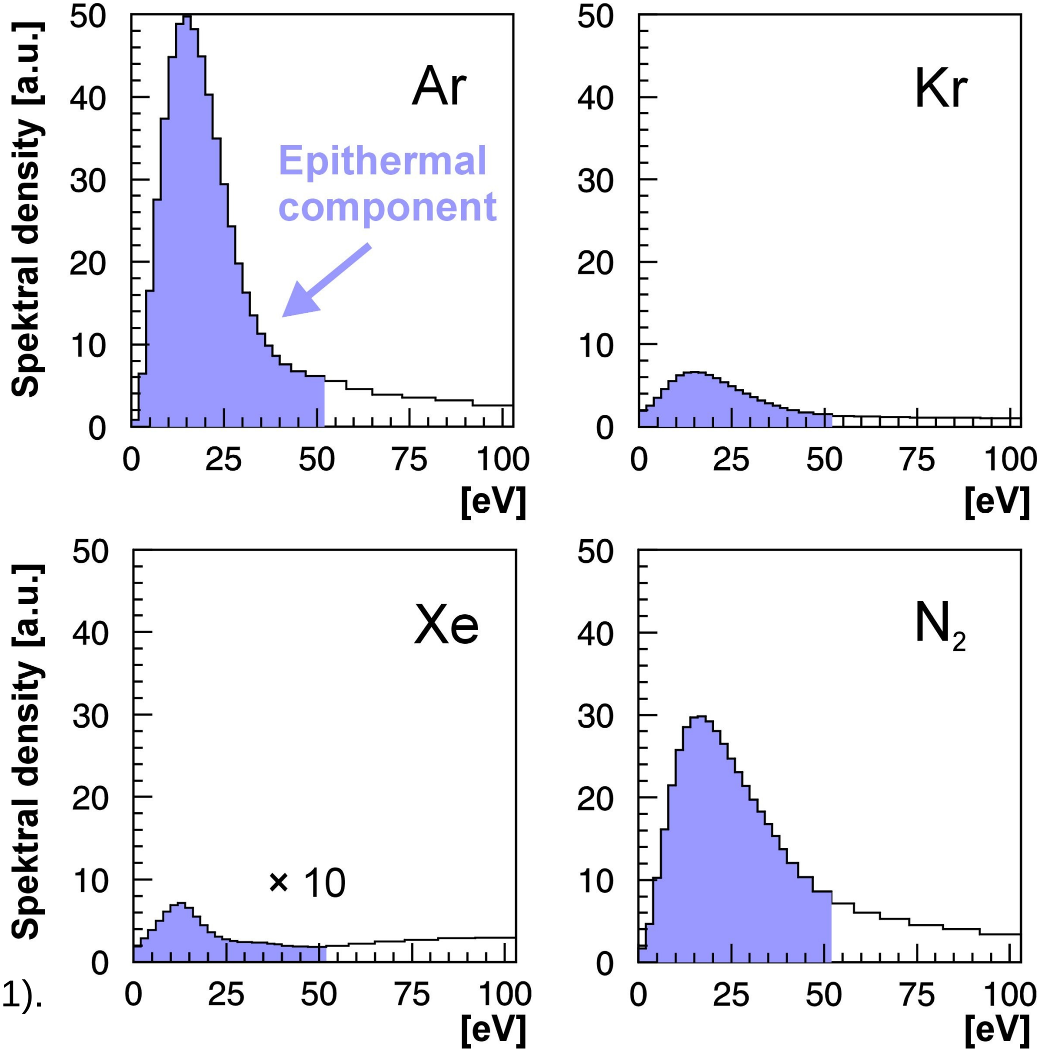


~100 µm Ag
6 K

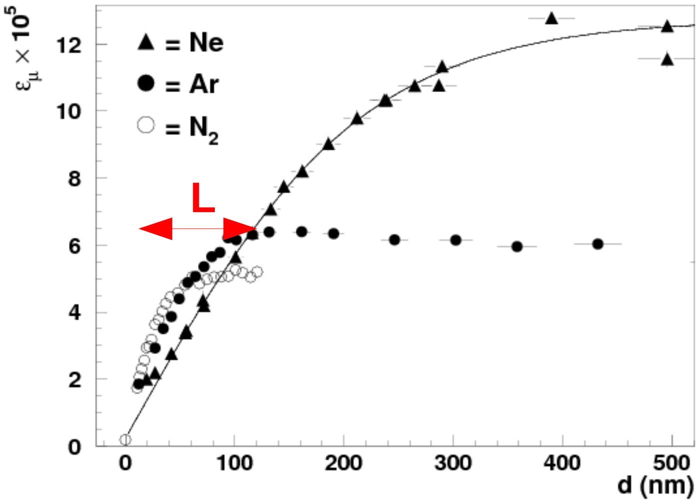
~500 nm s-Ne, Ar, s-N$_2$

motivated by experiments for positron moderation

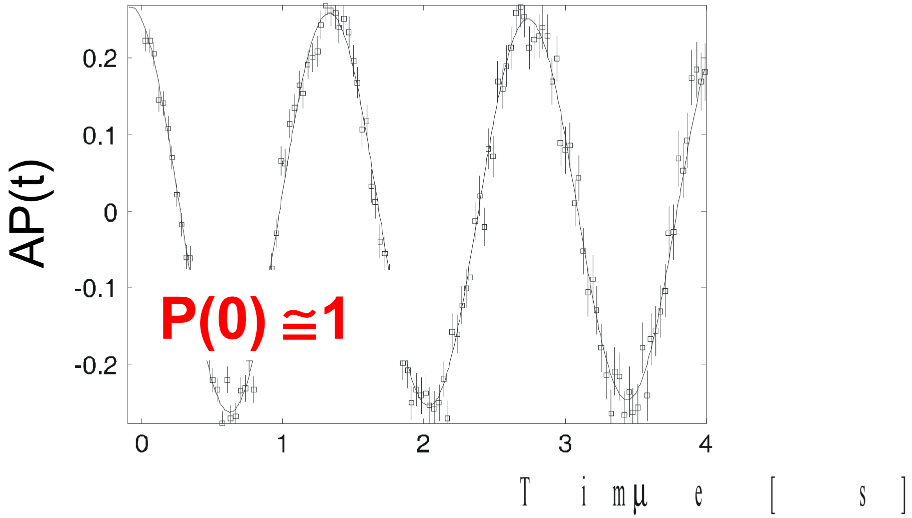


T. Prokscha et al., Appl. Surf. Sci. **172**, 235 (2001).
T. Prokscha et al., Phys. Rev. **A58**, 3739 (1998).
E. Morenzoni et al,. J. Appl. Phys. **81**, 3340 (1997).
D. Harshmann et al., Phys. Rev. **B36**, 8850 (1987).

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):**

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

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

Constraints for a high-intensity μ beam at PSI

- 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

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:**

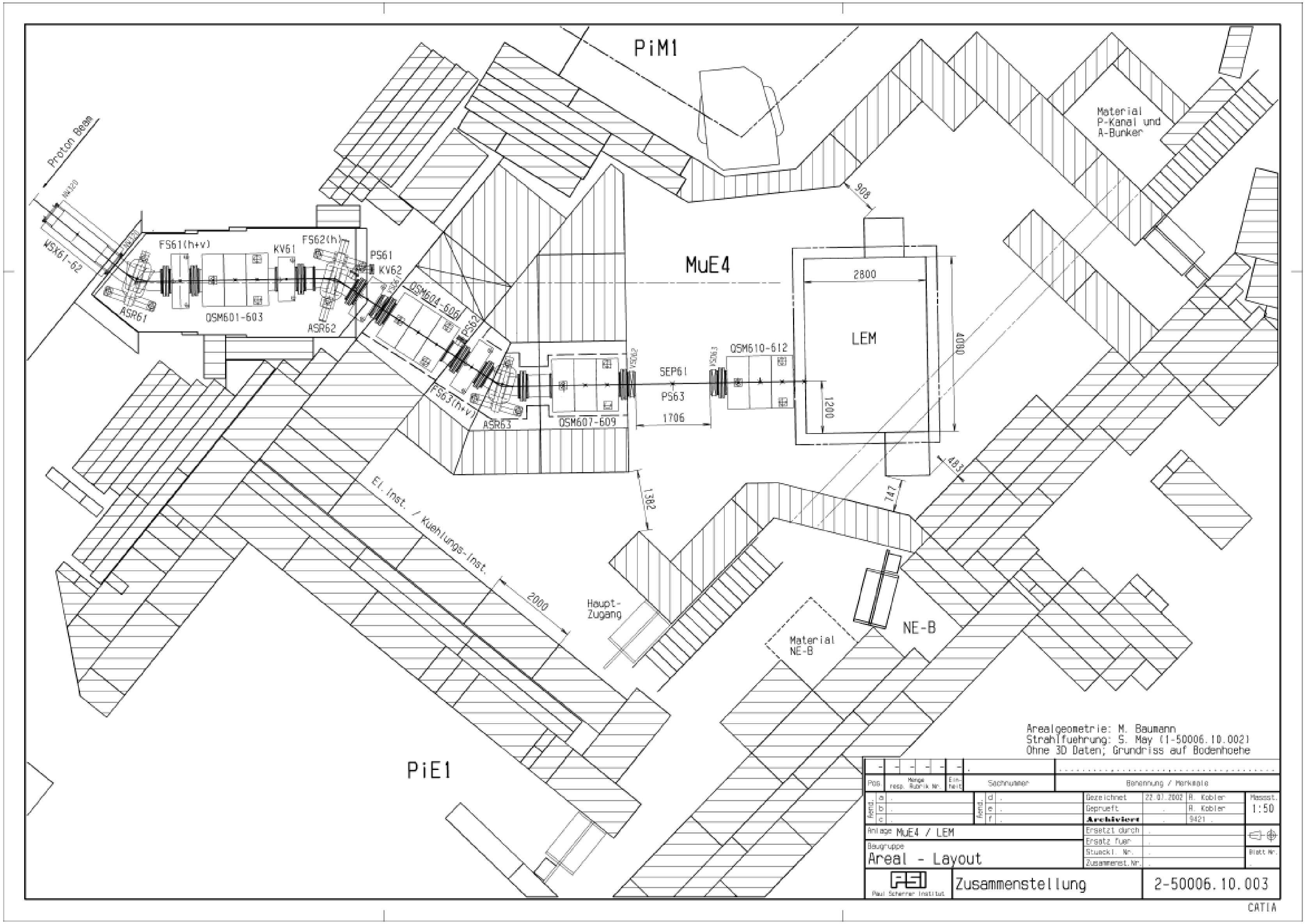
$$\mathbf{R} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} & \dots & R_{16} \\ 0 & 0 & R_{23} & R_{24} & \dots & R_{26} \\ R_{31} & R_{32} & 0 & 0 & \dots & \dots \\ R_{41} & R_{42} & 0 & 0 & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

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

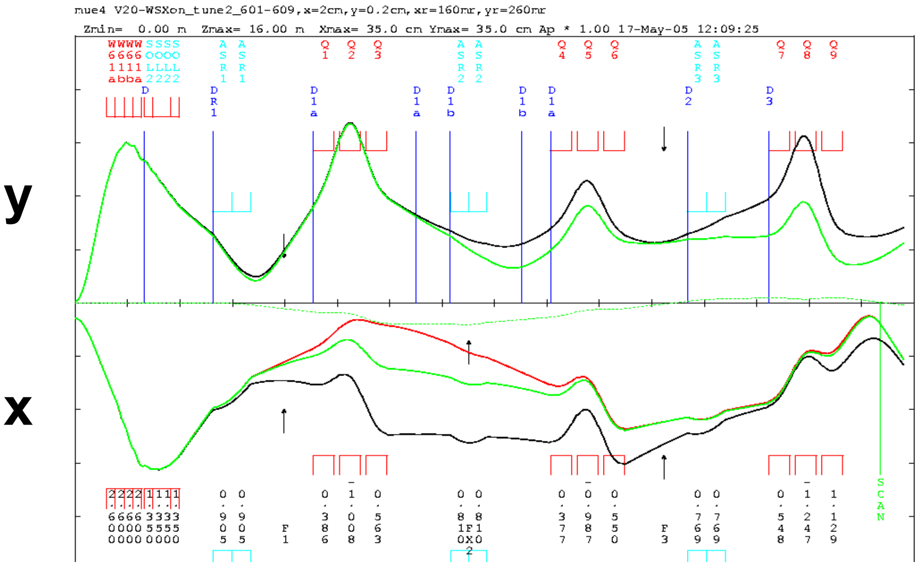
$$\begin{gathered} 1/f = P \\ P_T = P_S \cdot [l_{eff}^2/(2a^2)] \\ P_T > P_S \quad \text{if} \quad l_{eff} > \sqrt{2}a \end{gathered}$$

Azimuthal symmetry of solenoids leads to larger acceptance

Layout of the μE4 high-intensity μ beam



Transport and TRACK calculations



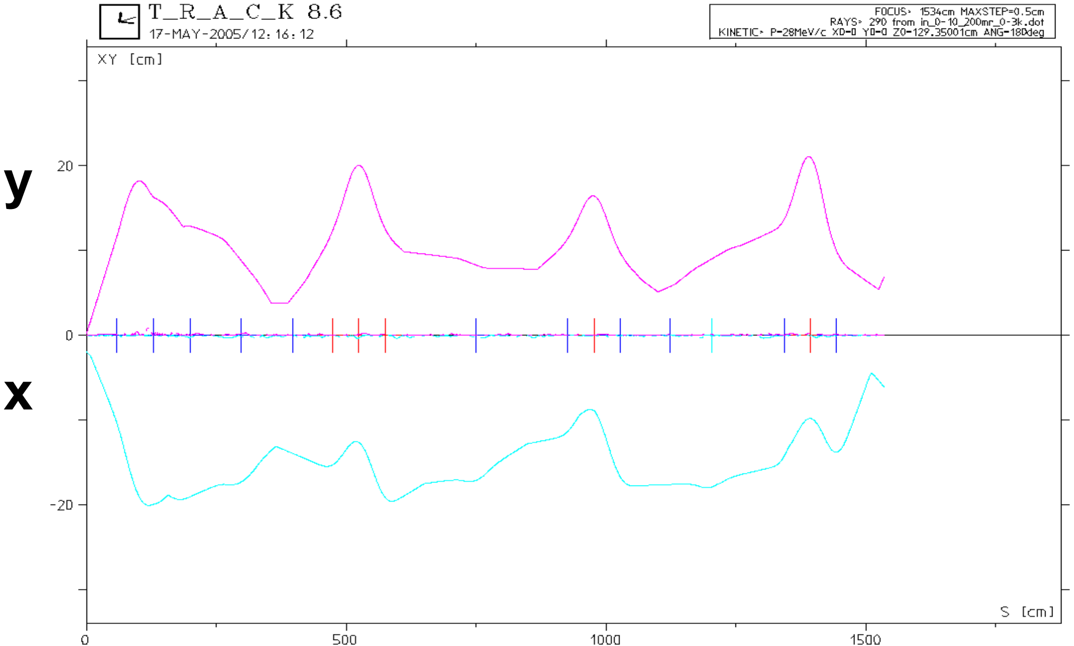
TRANSPORT: ***PSI Graphic Transport framework*** **by U. Rohrer, based on a CERN-SLAC-FermiLab version by K.L. Brown et al.**

0% $\Delta p/p$ 1^{st}

3% $\Delta p/p$ 1^{st}

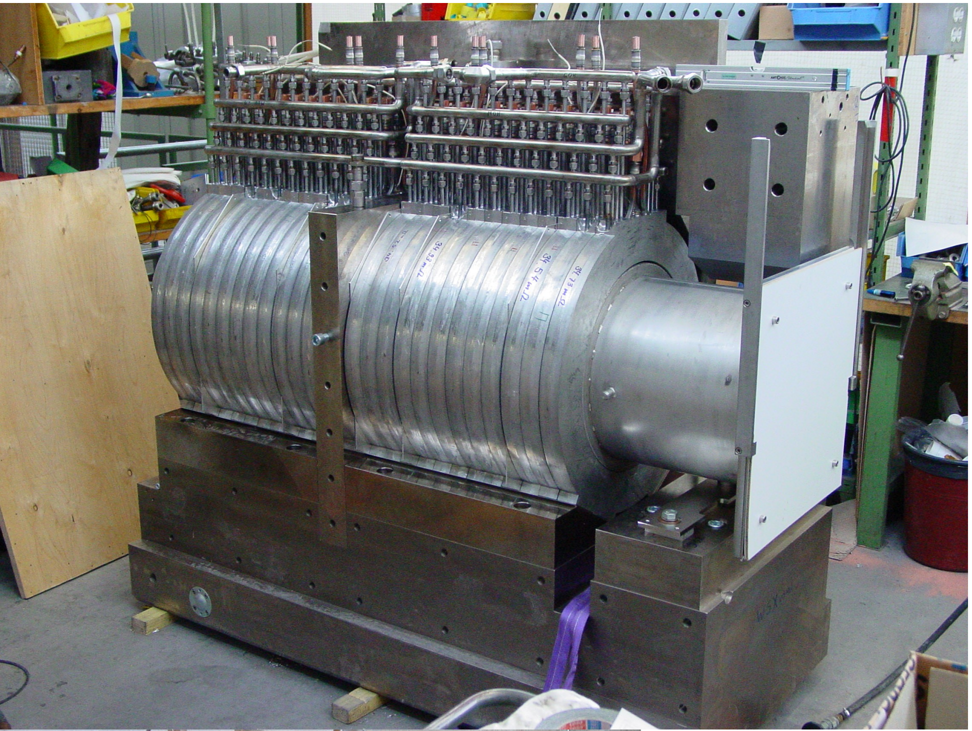
3% $\Delta p/p$ 2^{nd}

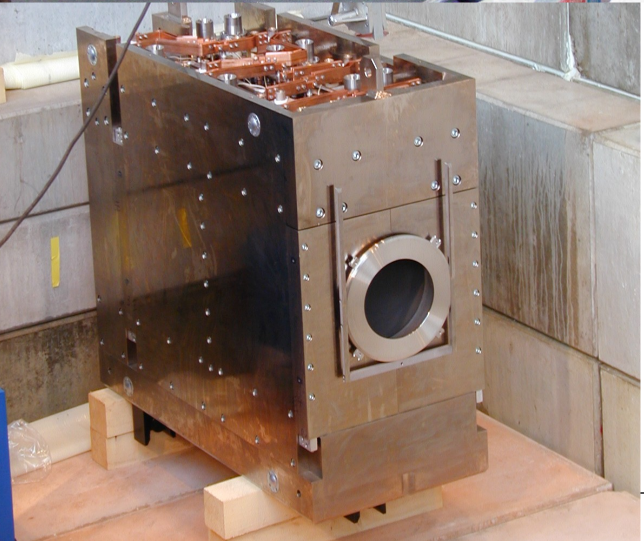
$\Delta p/p$ (FWHM): 4.5% - 9.5%

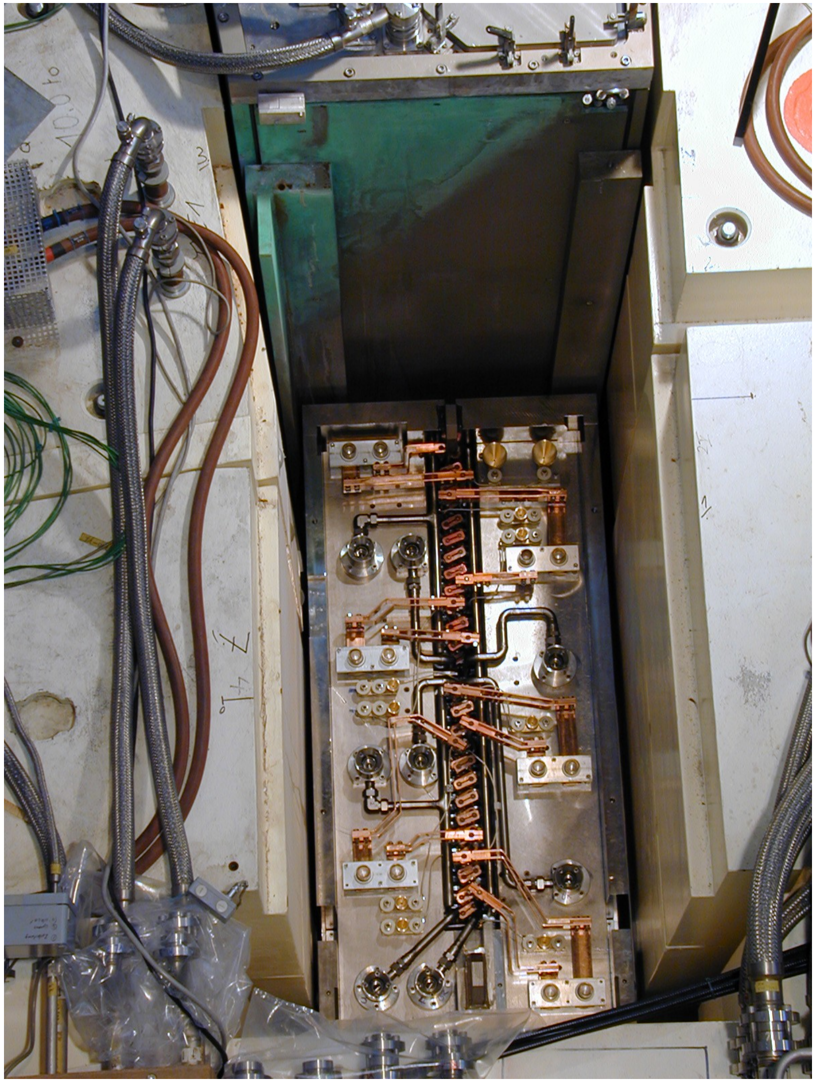


TRACK: ***Three-dimensional Ray Tracing Analysis Computational Kit*****, developed by PSI magnet section (V. Vrankovic, D. George)**

Double-solenoid WSX61/62





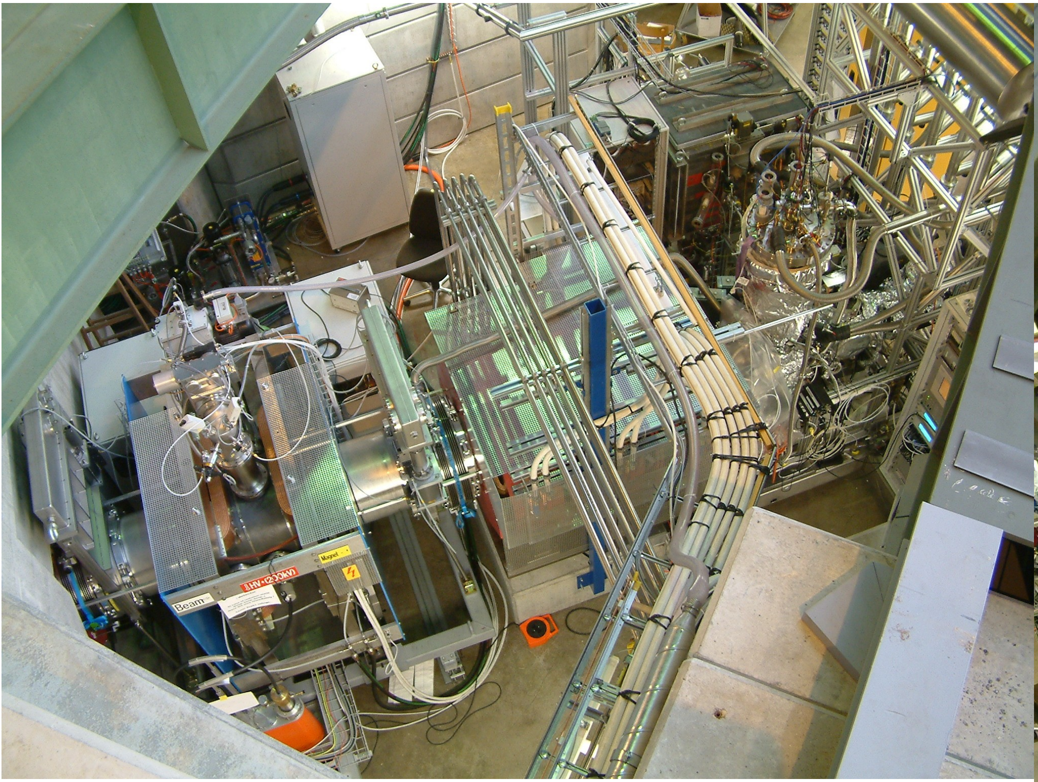


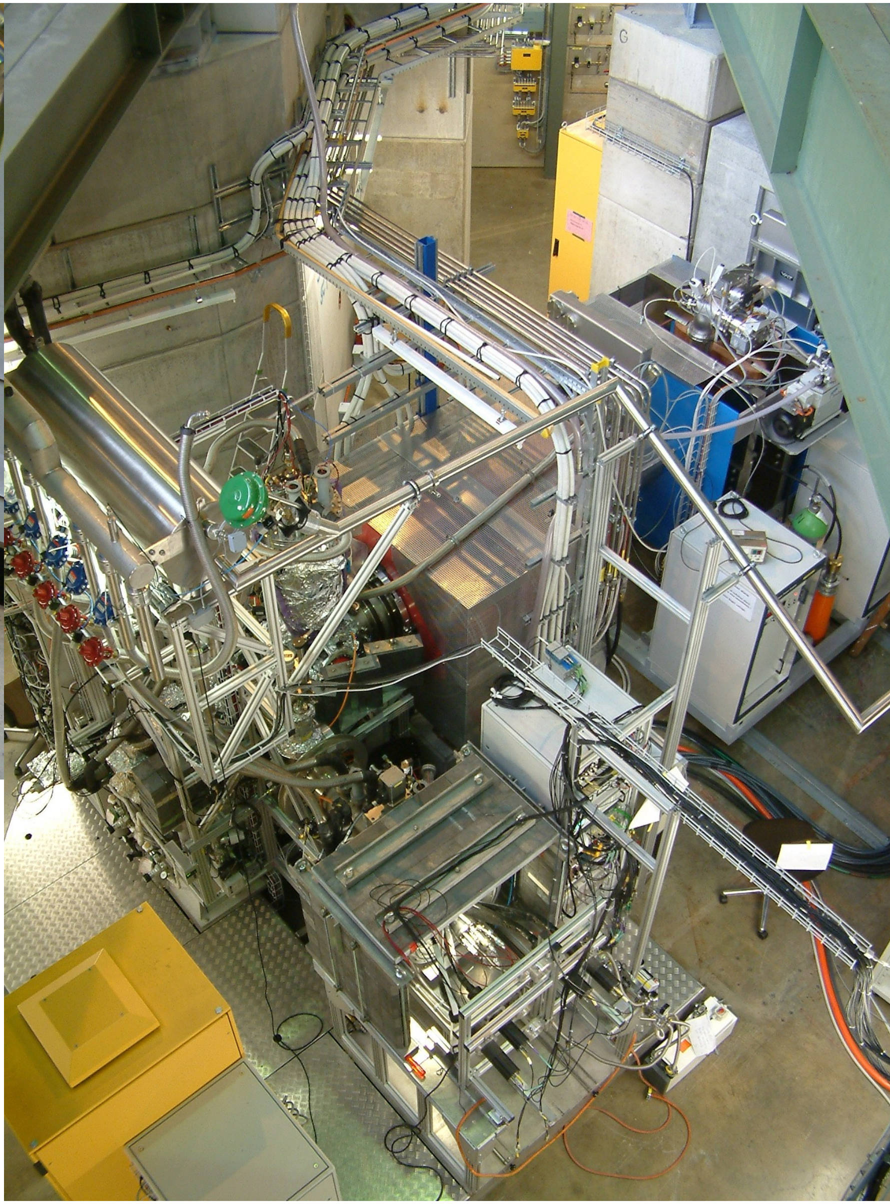
B_{max} = 3.5 kG

$\O_i$ = 500 mm

Installation of a section of μE4 in 2004

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





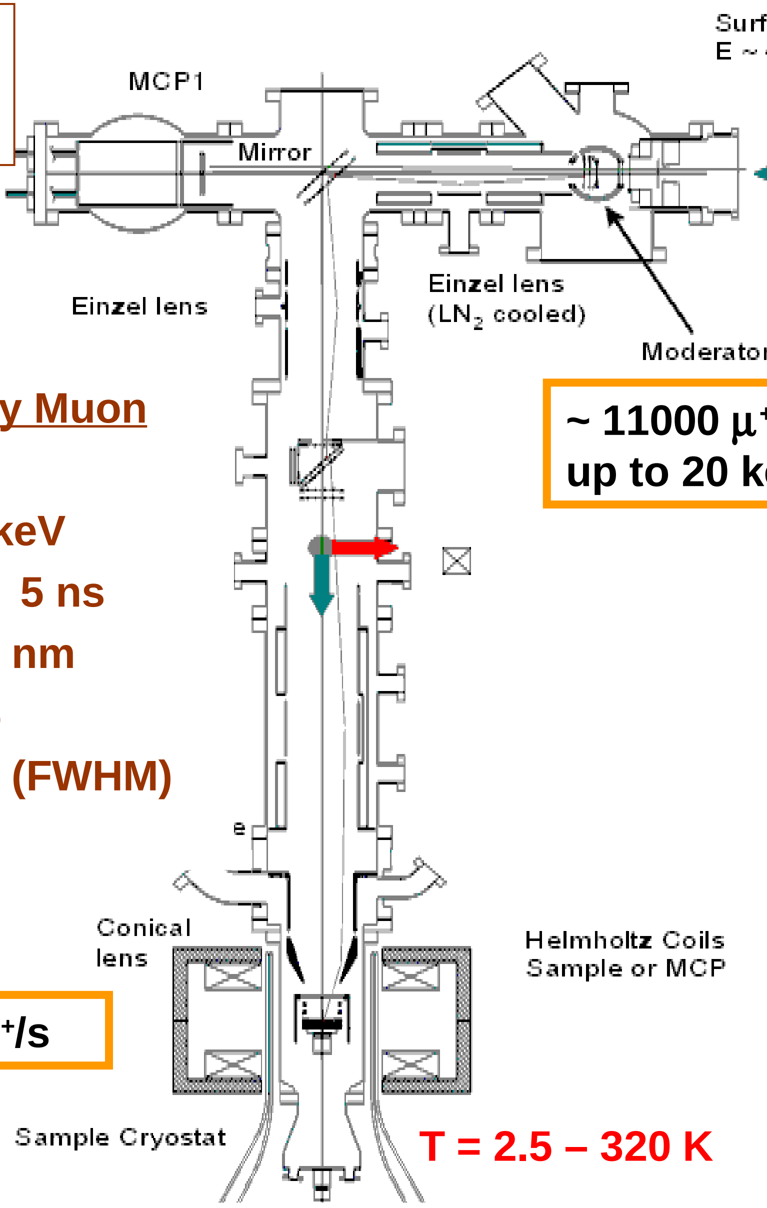
At 2.2 mA proton current:

~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

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



~1.9 •10^8 μ⁺/s

rebuilt μE4 beam line

~ 11000 μ⁺/s; accelerate up to 20 keV

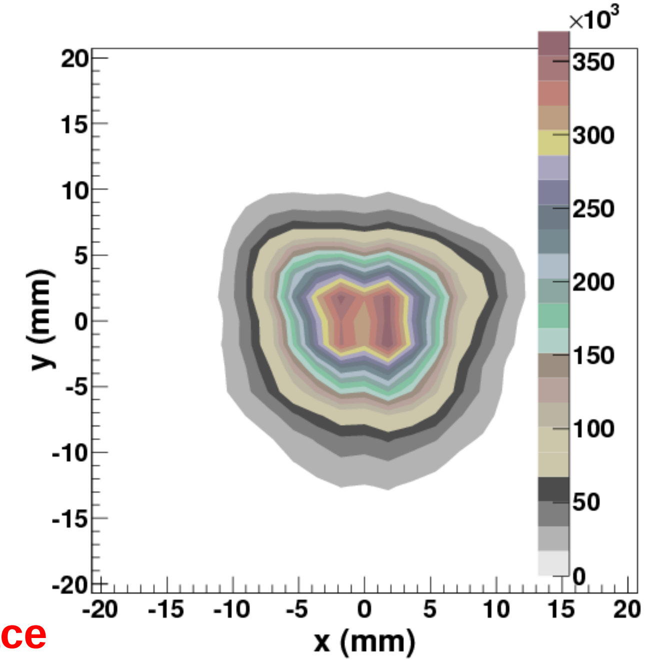
Polarized Low Energy Muon Beam

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

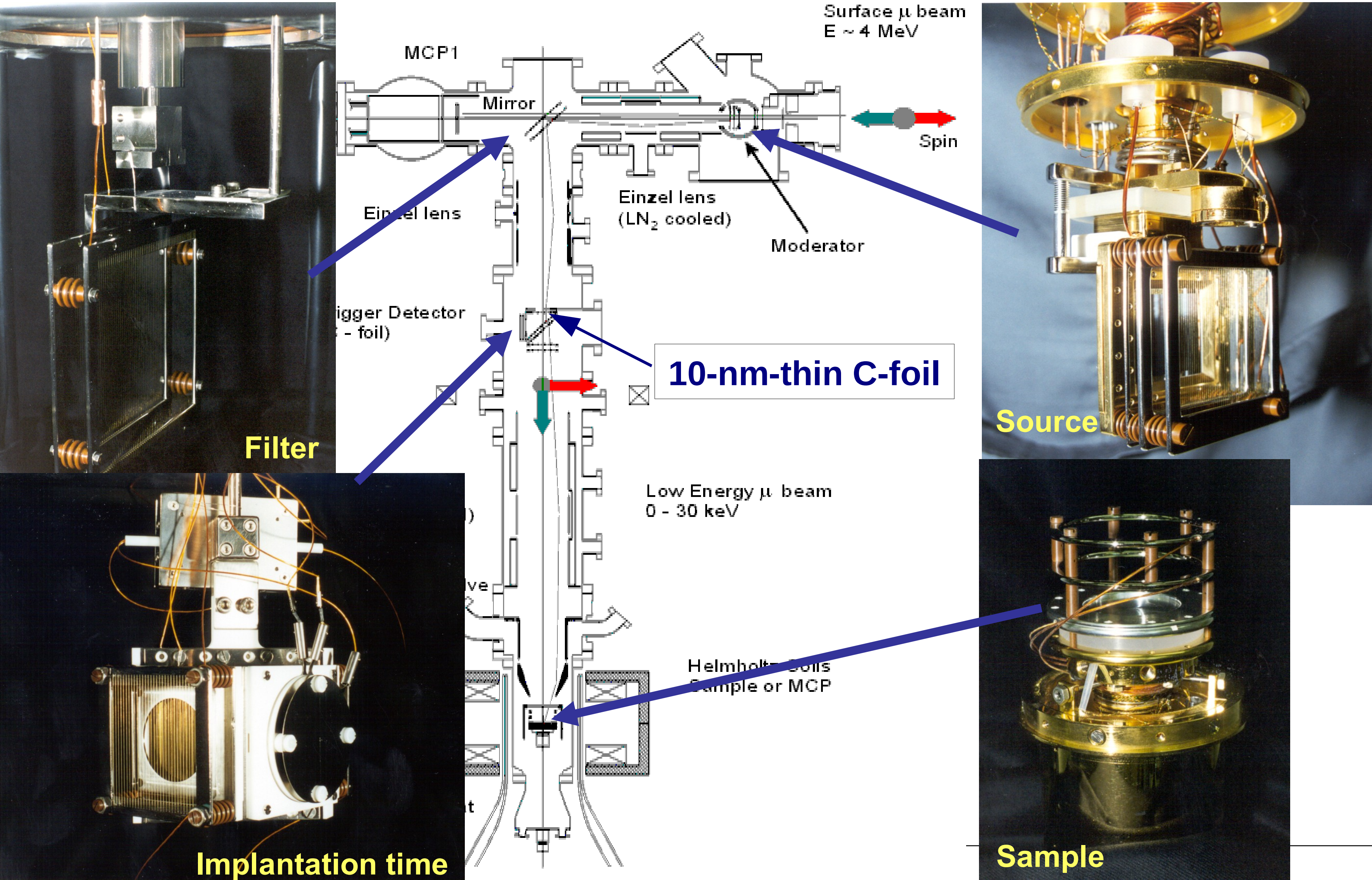
up to ~ 4500 μ⁺/s

T = 2.5 – 320 K

B = 0 – 0.3 T ⊥ , 0 – 0.03 T ∥ sample surface



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



10-nm-thin C-foil

Filter

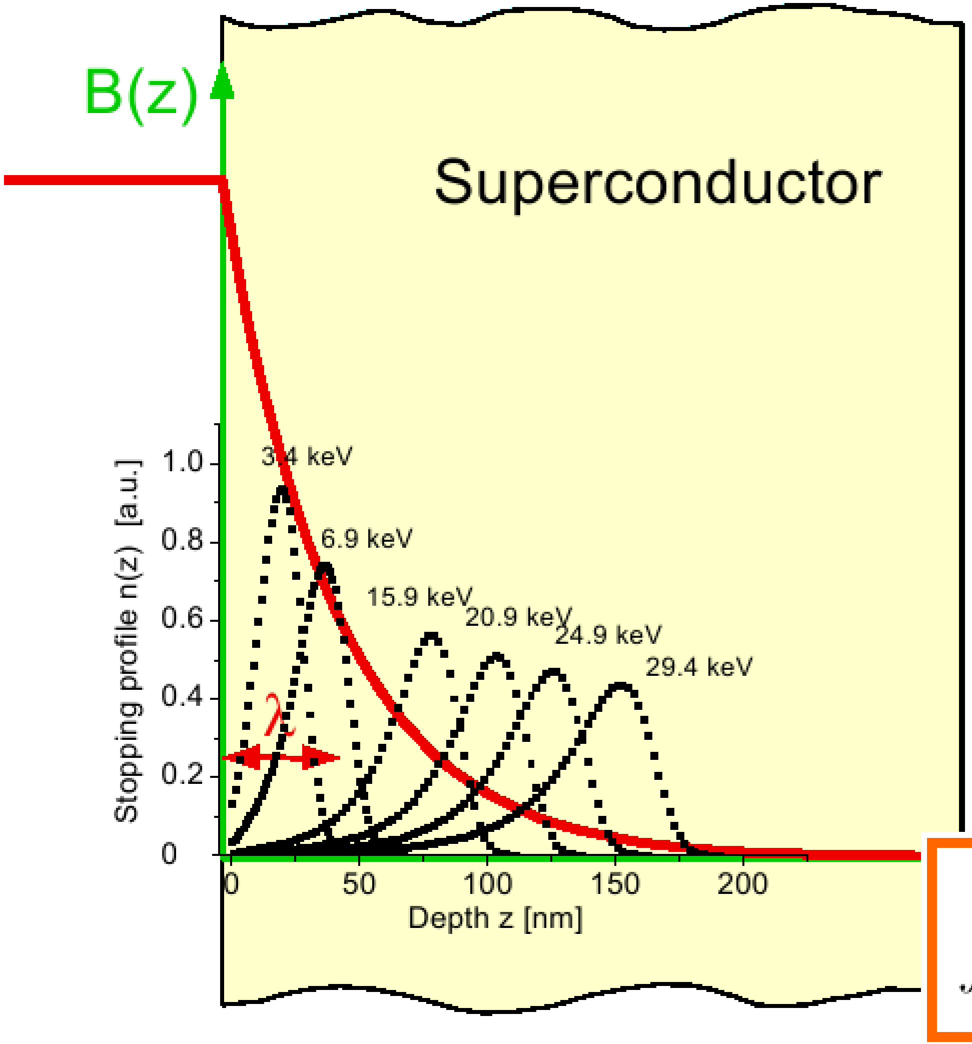
Source

Implantation time

Sample

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

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

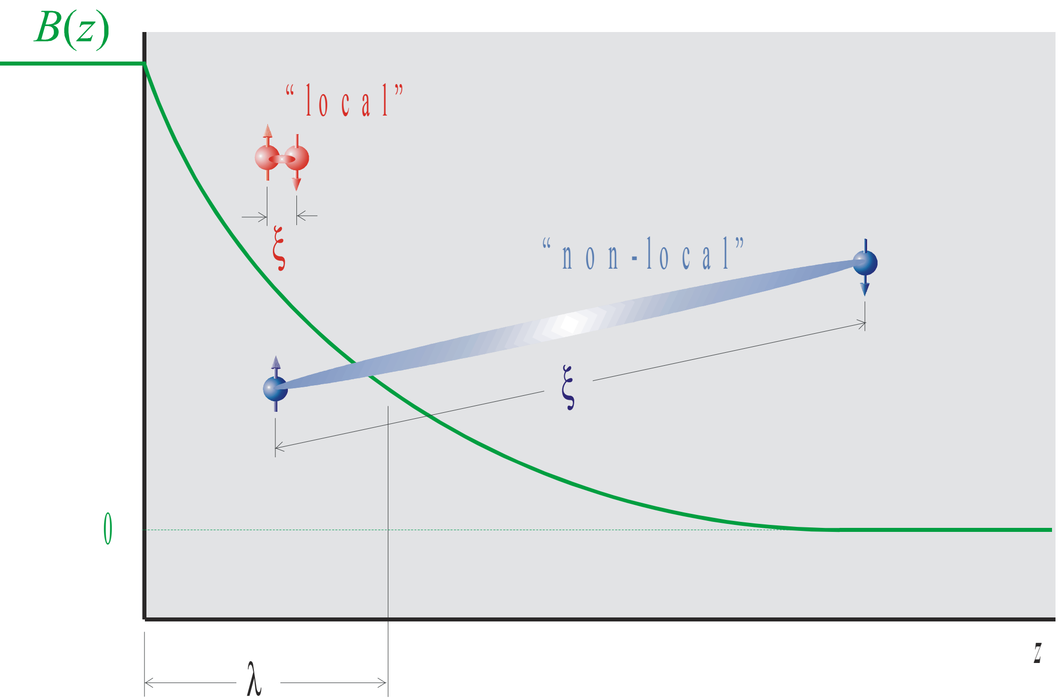
$$\int_0^z n(\zeta,E)\,\mathrm{d}\zeta = \int_{B(z)}^{\infty} p(\beta,E)\,\mathrm{d}\beta$$

⇒ B(z)

→ Magnetic field profile B(z) over nm scale

→ Characteristic lengths of the sc λ, ξ

Magnetic field profiles in superconductors



- ➔ Local, non-local response
- ➔ Determination of the coherence length ξ, κ=λ/ξ

- ➔ Direct, absolute measurement of **magnetic penetration depth**

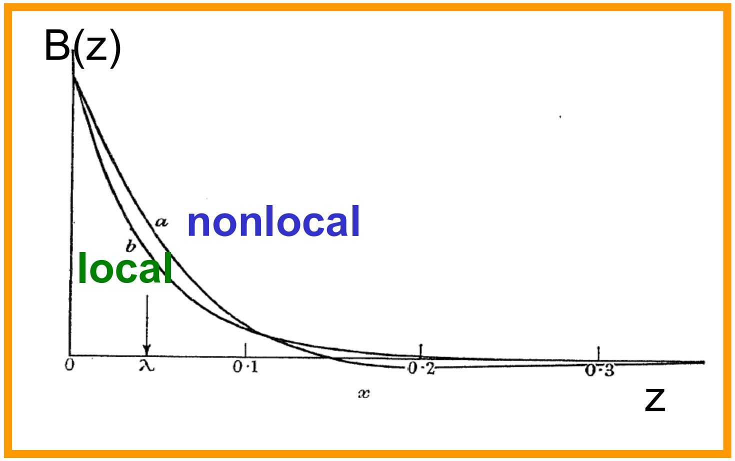
$$\lambda(T) \propto \sqrt{\frac{m^*}{n_s(T)}}$$

←effective mass

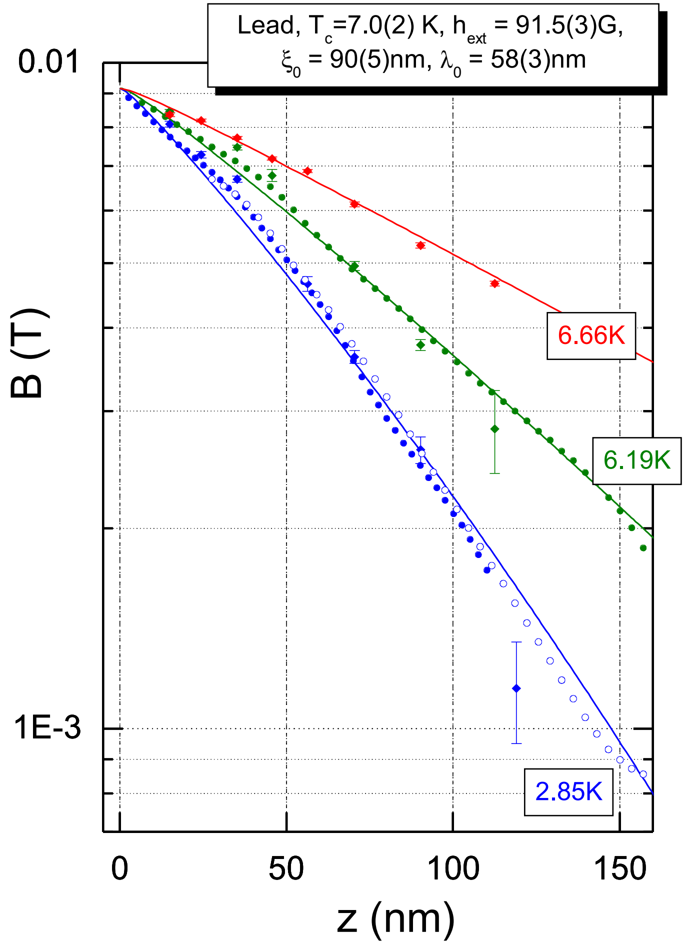
←density of supercarriers

- ➔ Direct Test of theories (London, BCS)

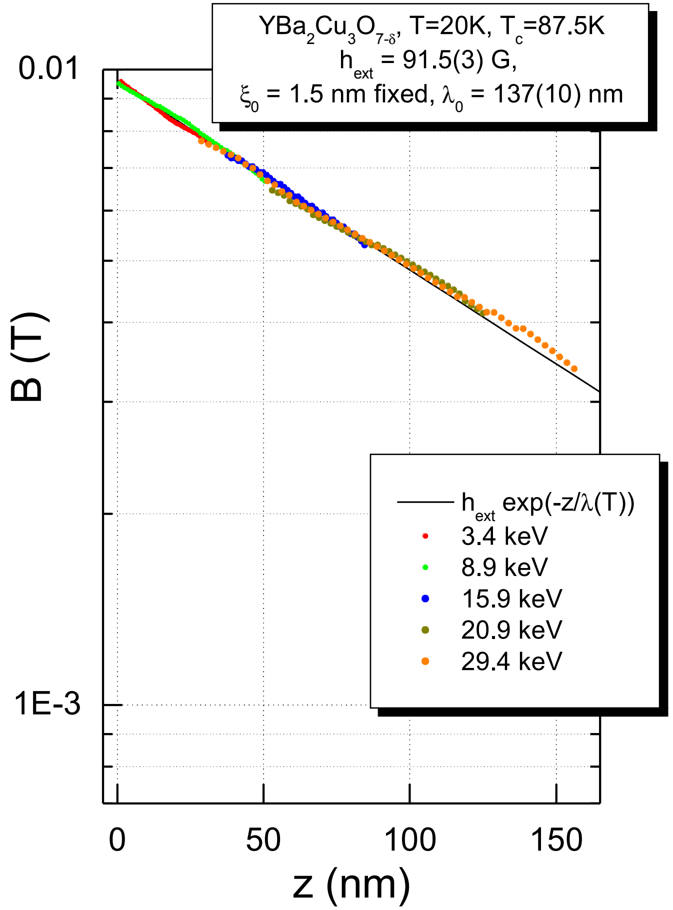
$$\rightarrow B(z) = B_0 e^{-\frac{z}{\lambda_{ab}(T)}}$$



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



Non-local: non- exponential

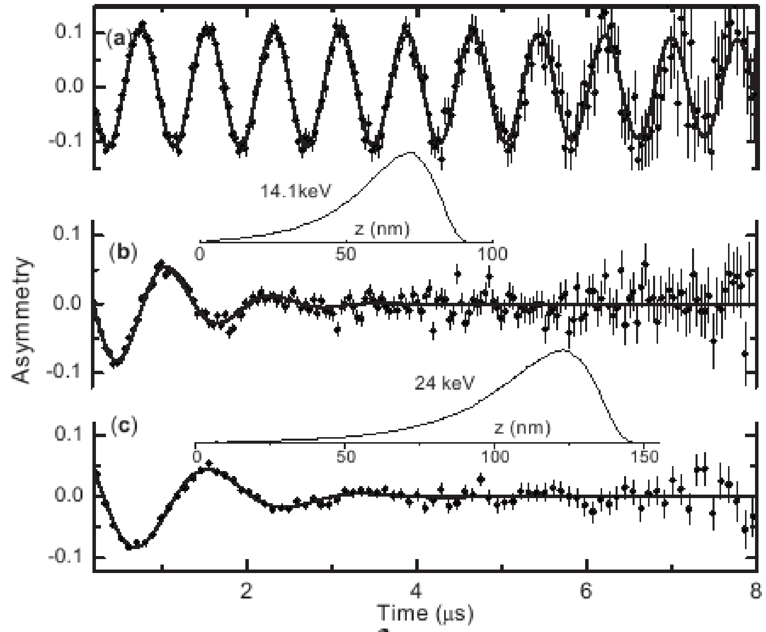


local: exponential

A. Suter, E. Morenzoni, R. Khasanov, H. Luetkens, T. Prokscha, and N. Garifianov, PRL **92**, 087001 (2004)

A. Suter, E. Morenzoni, N. Garifianov, R. Khasanov, E. Kirk, H. Luetkens, T. Prokscha, M. Horisberger, PRB**72**, 024506 (2005)

Detwinned $YBa_2Cu_3O_{6.92}$, T_c = 94.1 K, B = 9.47 mT



100 K

8 K

8 K

$$\mathcal{A}(t) = A\,\exp[-\sigma^2 t^2/2]\int \rho(z)\cos[\gamma_\mu B(z)t+\phi]dz, \qquad (2)$$

$$\lambda(T) \propto \sqrt{\frac{m^*}{n_s(T)}}$$

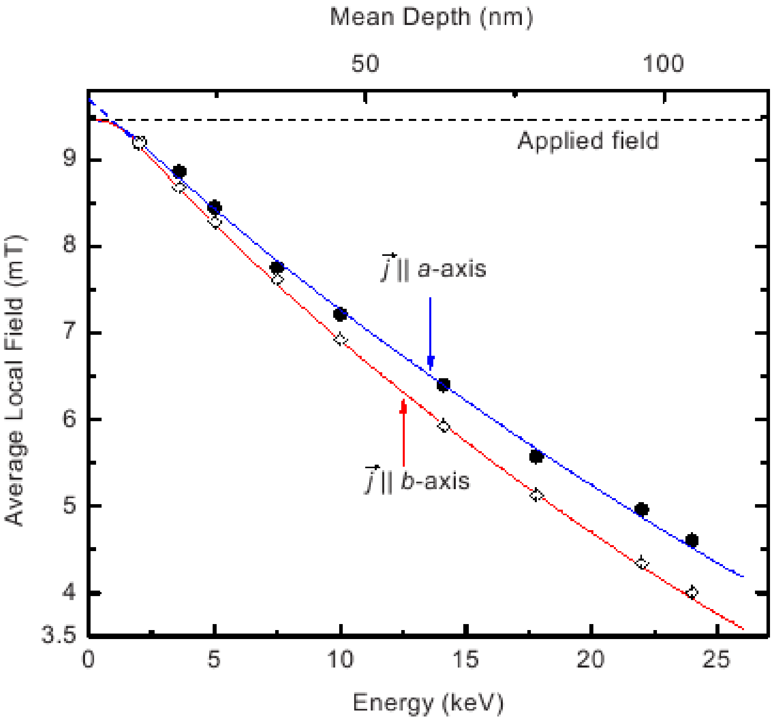
←**effective mass**

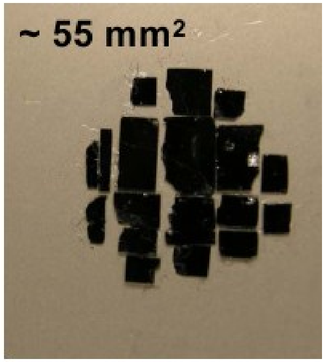
←**density of super carriers**

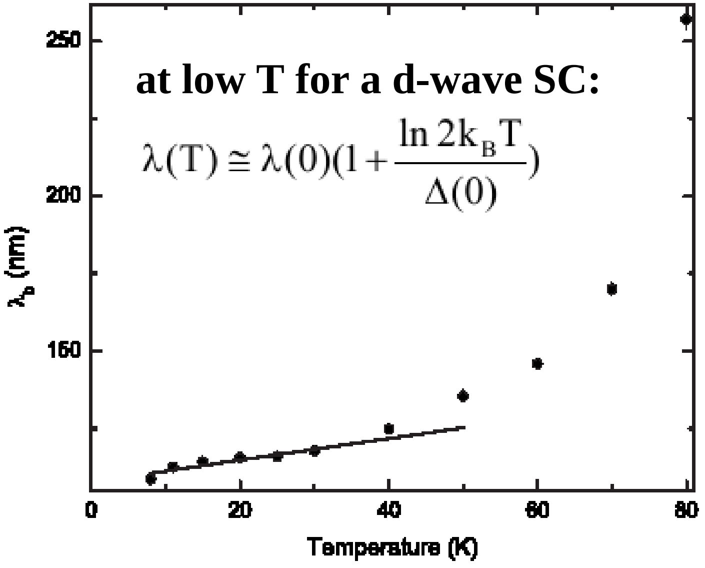
λ_a **= 126(1.2)nm,** λ_b **= 105.5(1.0) nm,**

λ_a/λ_b **= 1.19(1)**

R.F. Kiefl et al, PRB **81**, 180502(R), (2010)







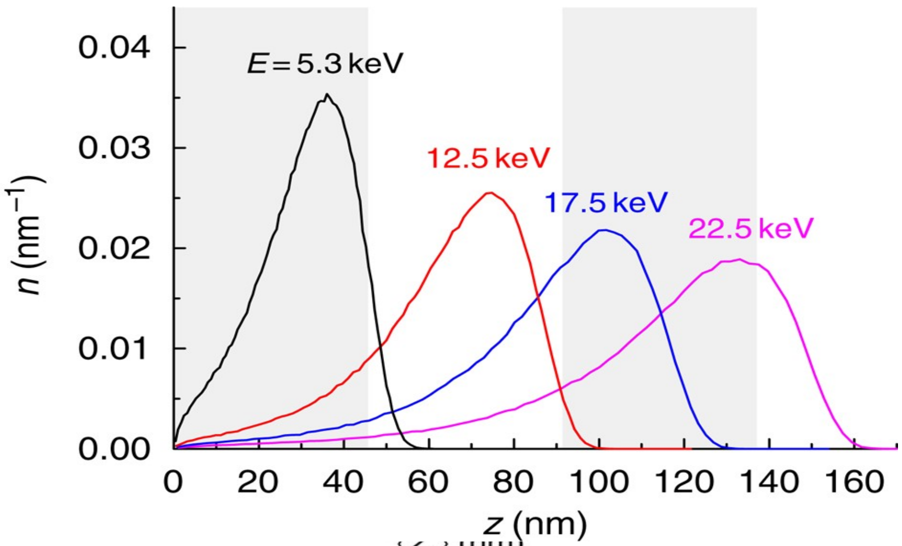
at low T for a d-wave SC:

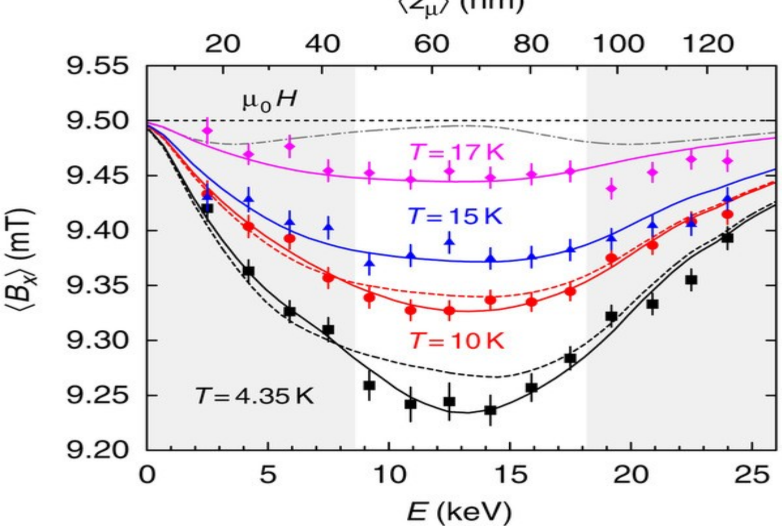
$$\lambda(T) \cong \lambda(0)\left(1+\frac{\ln 2 k_B T}{\Delta(0)}\right)$$

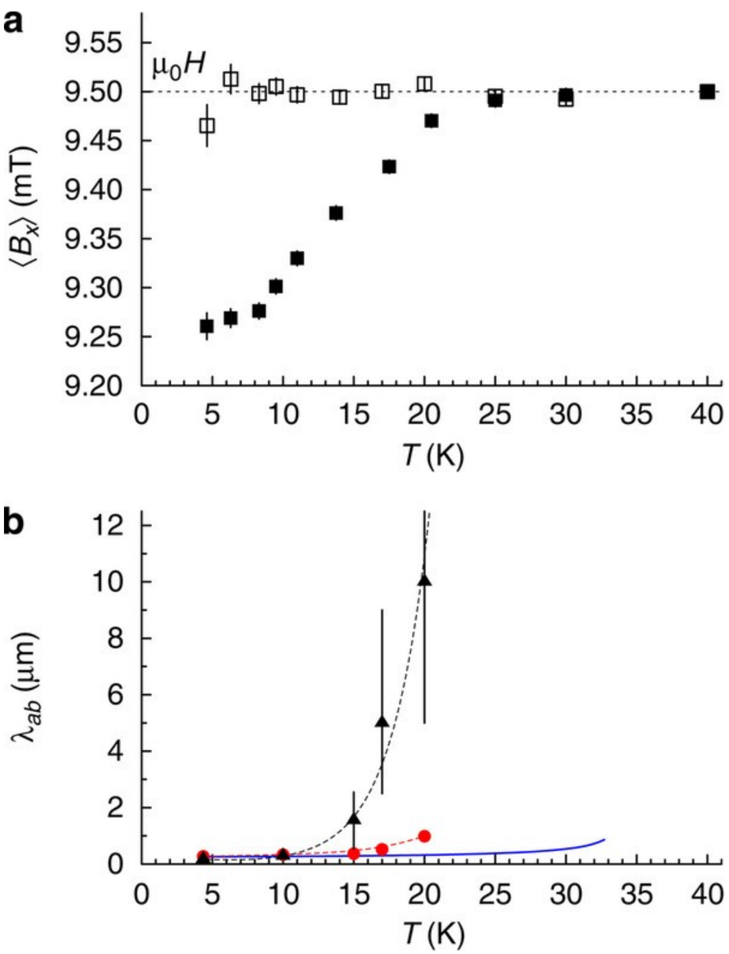
Meissner effect in a strongly underdoped cuprate

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

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







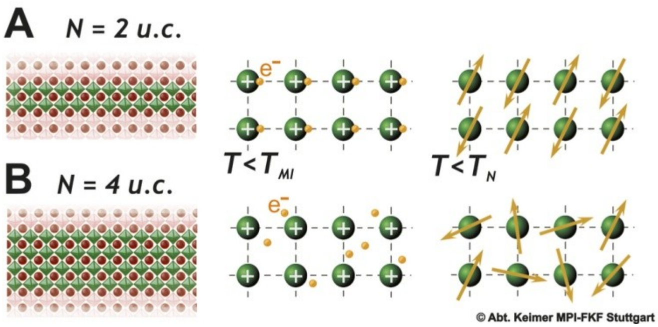
induced superfluid density disappears at T_{eff} >>T'_c. This result is not expected within the conventional proximity effect theory.

E. Morenzoni et al, Nature Communications **2**, 272 (2011)

Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices

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

MPI Solid State Research - MPI Metals Research – Univ. Fribourg - PSI



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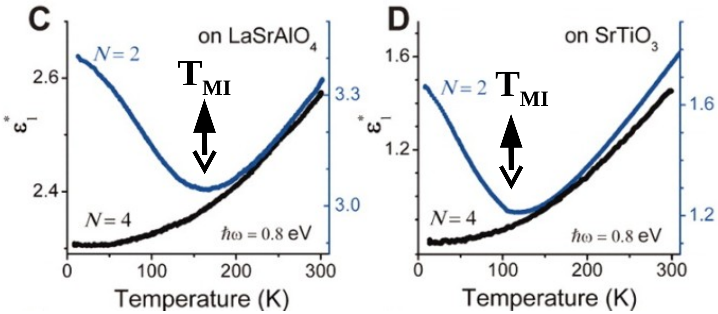
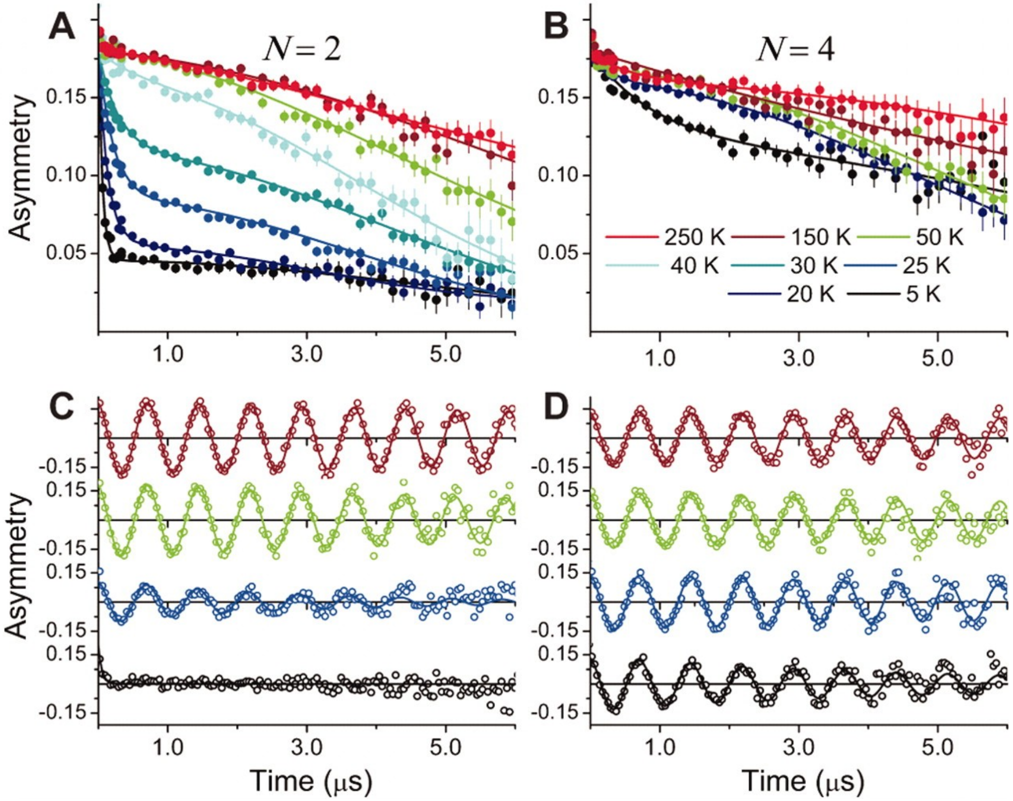
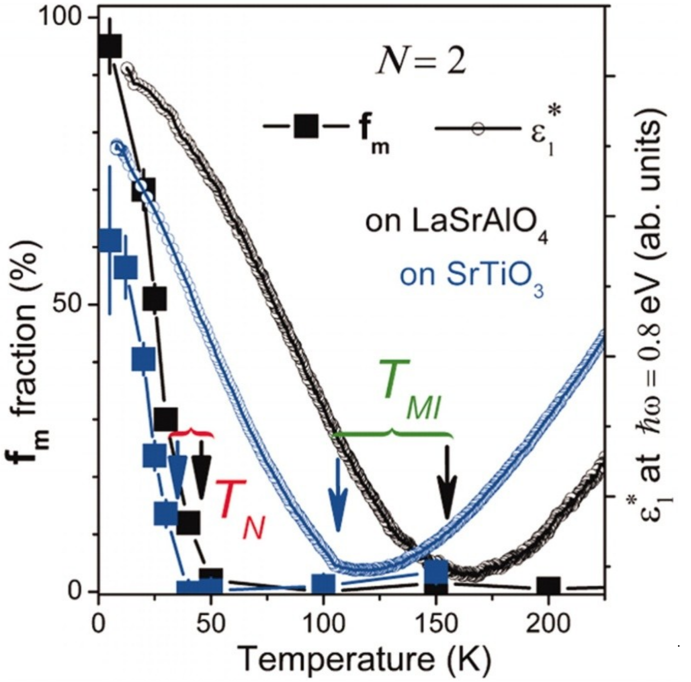
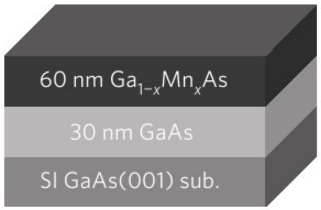
- 100-nm-thick NxN u.c. $LaNiO_3/LaAlO_3$ superlattices
- **2 u.c. $LaNiO_3$: MI and AF transitions at T < 150 K**
- **4 u.c. $LaNiO_3$: metallic and paramagnetic at all T**

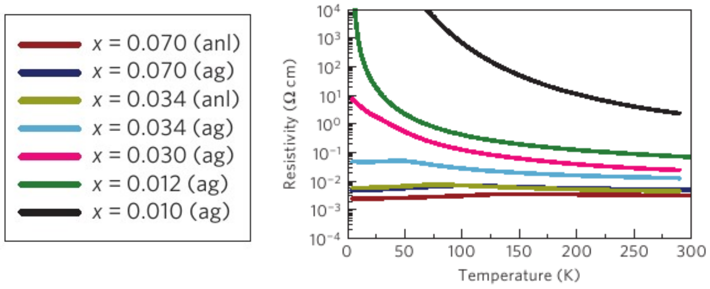


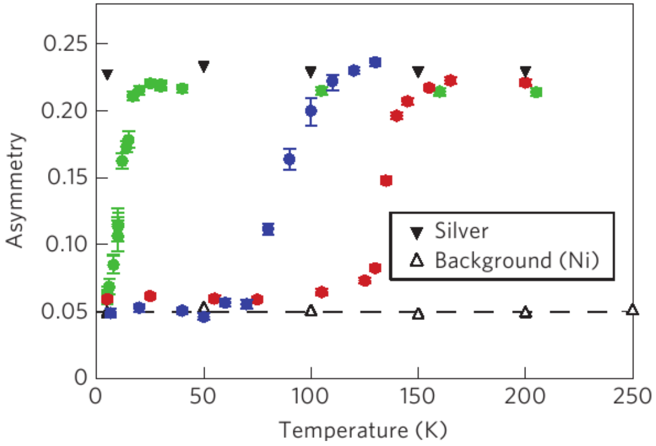




Spatially homogeneous ferromagnetism of (Ga,Mn)As



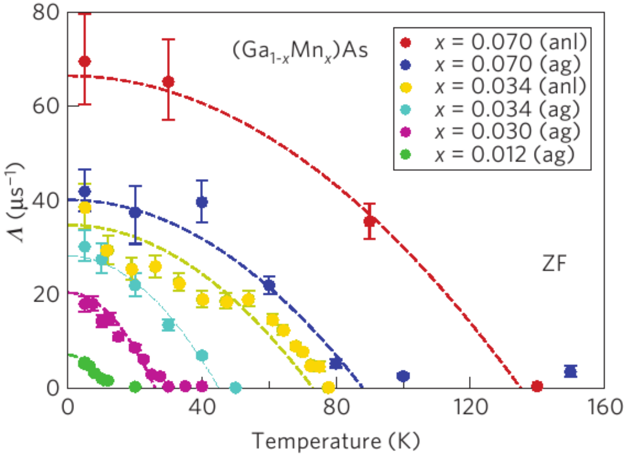




- Mn-doped GaAs potential **‘spintronics’ material**
- great interest in fundamental research: **evolution from a paramagnetic insulator to ferromagnetic metal**
- **controversy** if FM is associated with **intrinsic spatial inhomogeneity**

Low-energy μSR **(in combination with conductivity and DC/AC magnetization)** **results:**

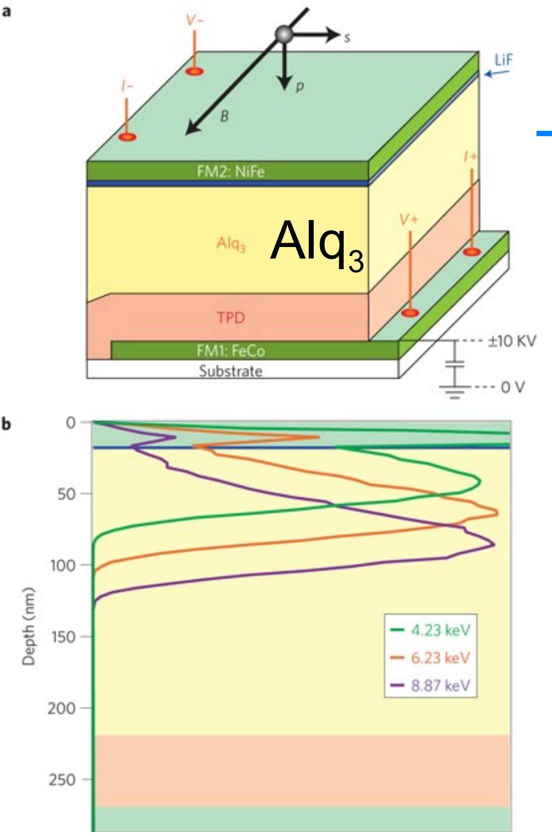
- **sharp onset of FM order, developing homogeneously in the full volume fraction, in both insulating and metallic films.**
- **smooth evolution of ordered moment size across metal-insulator transition at x ~ 0.03**
- **FM coupling between Mn before full emergence of itinerant hole carriers**



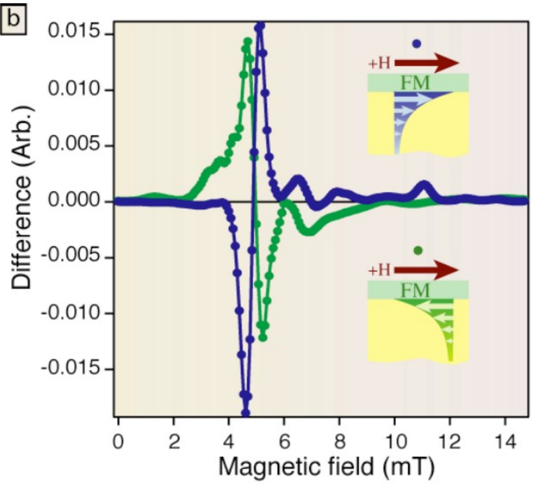
muon decay asymmetry (10 mT TF top) and zero field (ZF) relaxation rate (bottom) as a function of temperature and doping

S.R. Dunsiger, J.P. Carlo, T. Goko, G. Nieuwenhuys, T. Prokscha, A. Suter, E. Morenzoni, D. Chiba, Y. Nishitani, F. Matsukara, H. Ohno, J. Ohe, S. Maekawa, Y.J. Uemura, Nature Materials ***9,*** *299 (2010).*

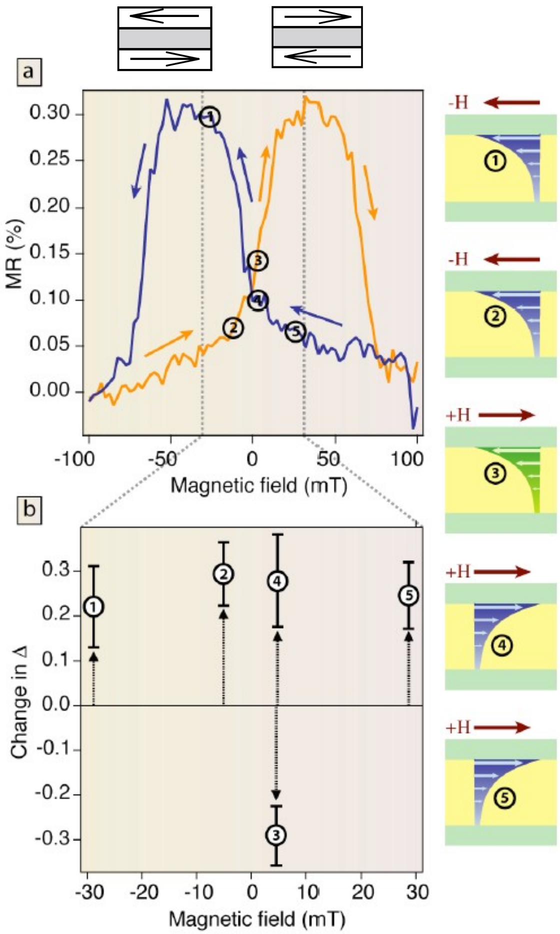
Spin diffusion length in organic spin valve



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



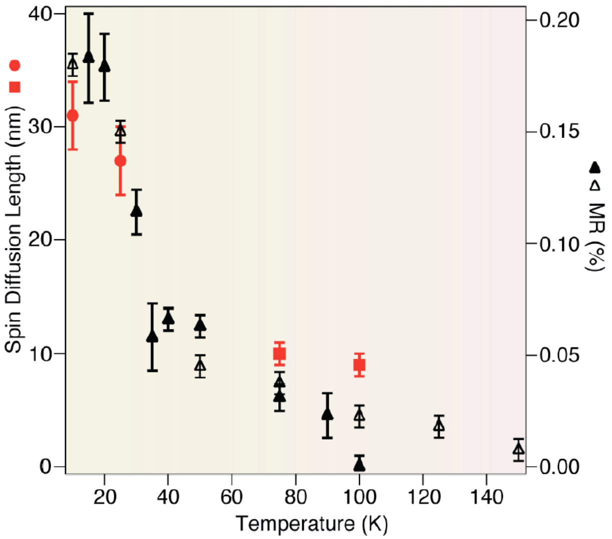
Magnetoresistance vs B



Skewness

Long coherence time of injected spins ~10^{-5} s ➔ measurable static fields

Spin diffusion length vs T correlates with magneto-resistance

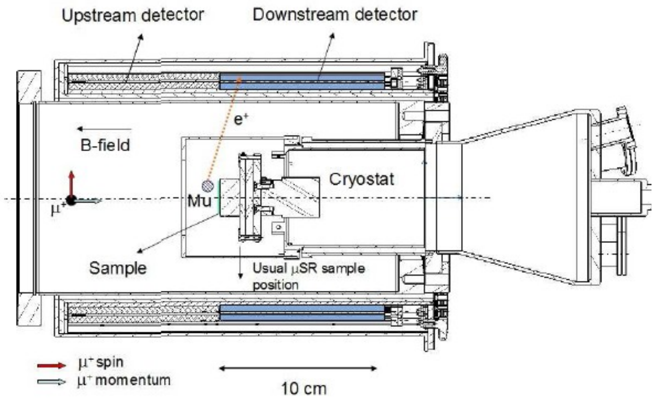


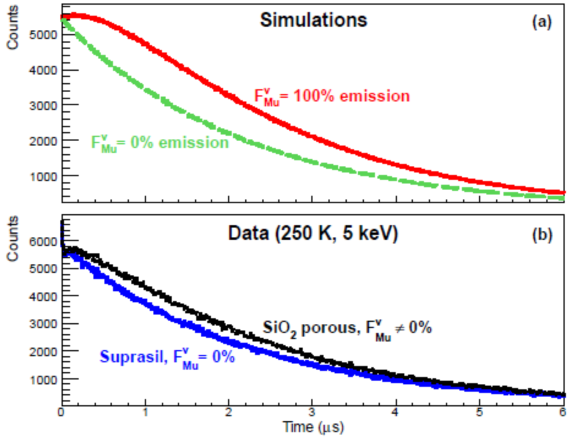
First direct measurement of spin diffusion length in a working spin valve.

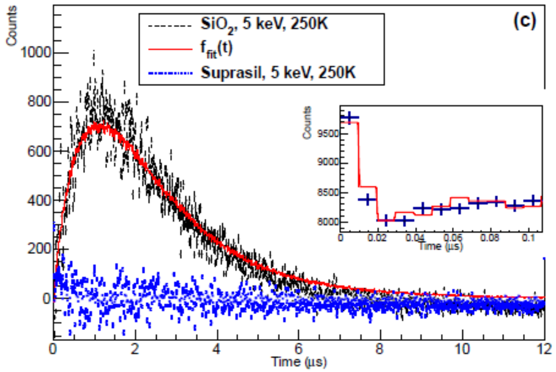
*A.J. Drew et al., Nature Materials **8**, 109 (2009)*

“Cold” muonium from mesoporous SiO_2 in vacuum

Motivated by recent results on Ps emission from mesoporous SiO_2 films

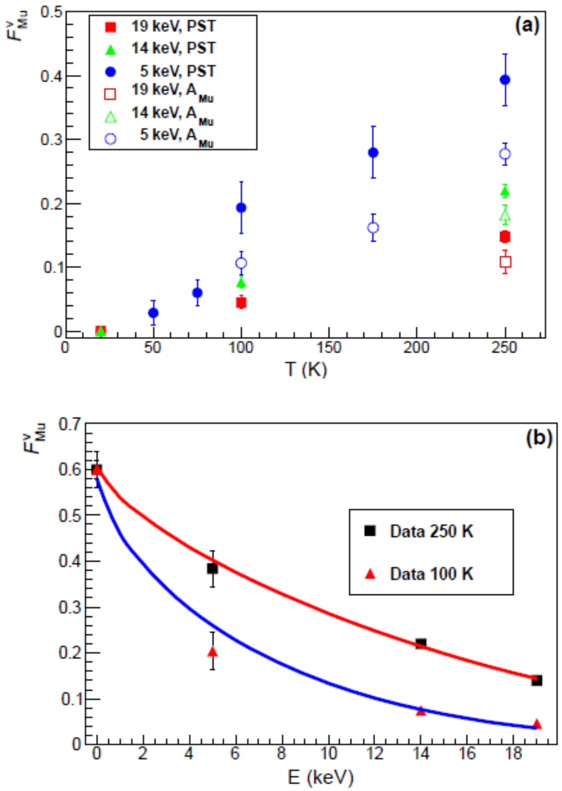






250 K, 5 keV: **40% emission of thermal Mu in vacuum**

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

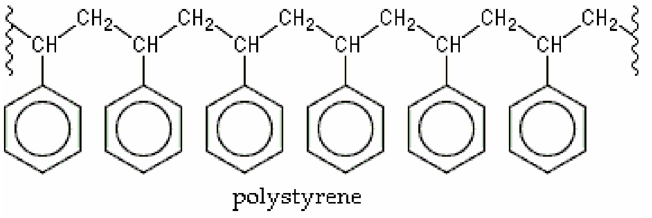


Vacuum Mu fraction F^{V}_{Mu} as a function of temperature and energy; solid lines are a fit of a diffusion model to the data.

A. Antognini, P. Crivelli, T. Prokscha, K.S. Khaw, B. Barbiellini, L. Liszkay, K. Kirch, K. Kwuida, E. Morenzoni, F.M. Piegsa, Z. Salman, A. Suter, arXiv:1112.4887v1, accepted by PRL (2012)

Some More Low Energy Muon Applications

Surface dynamics of polymers

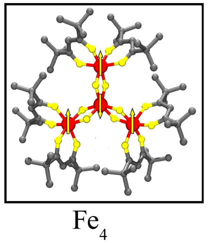


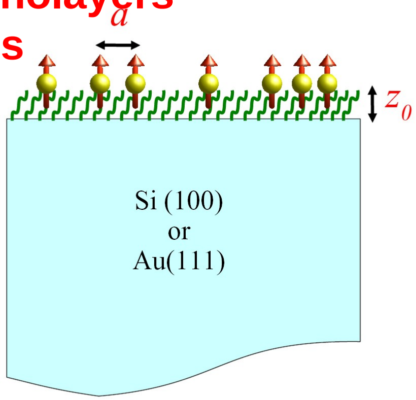
polystyrene

F.L. Pratt et al., *PRB* ***72****, 121401(R) (2005)*

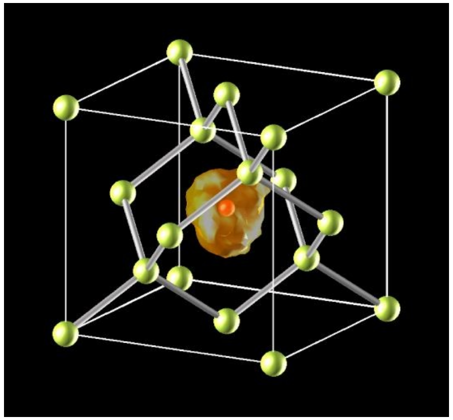
Magnetic properties of monolayers of single molecule magnets

Z. Salman et al.





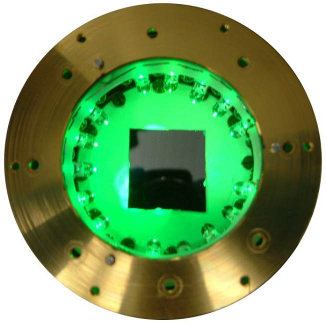
Formation of hydrogen impurities in semiconductors at low energies

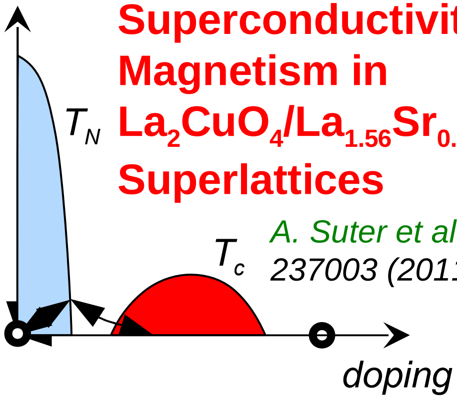


T. Prokscha et al., *PRL* ***98****, 227401 (2007)*
T. Prokscha et al., *Physcia* ***B 404****, 866 (2009)*
D.G. Eshchenko et al., *Physica* ***B 404****, 873 (2009)*
H.V. Alberto et al., *Physica* ***B 404****, 870 (2009)*

Photo-induced effects in semiconductors

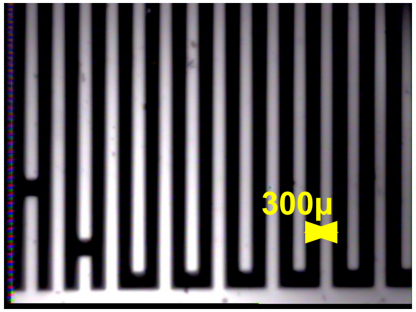
T. Prokscha et al.





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

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



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)*

Superfluid density in high and low T_c heterostructures

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

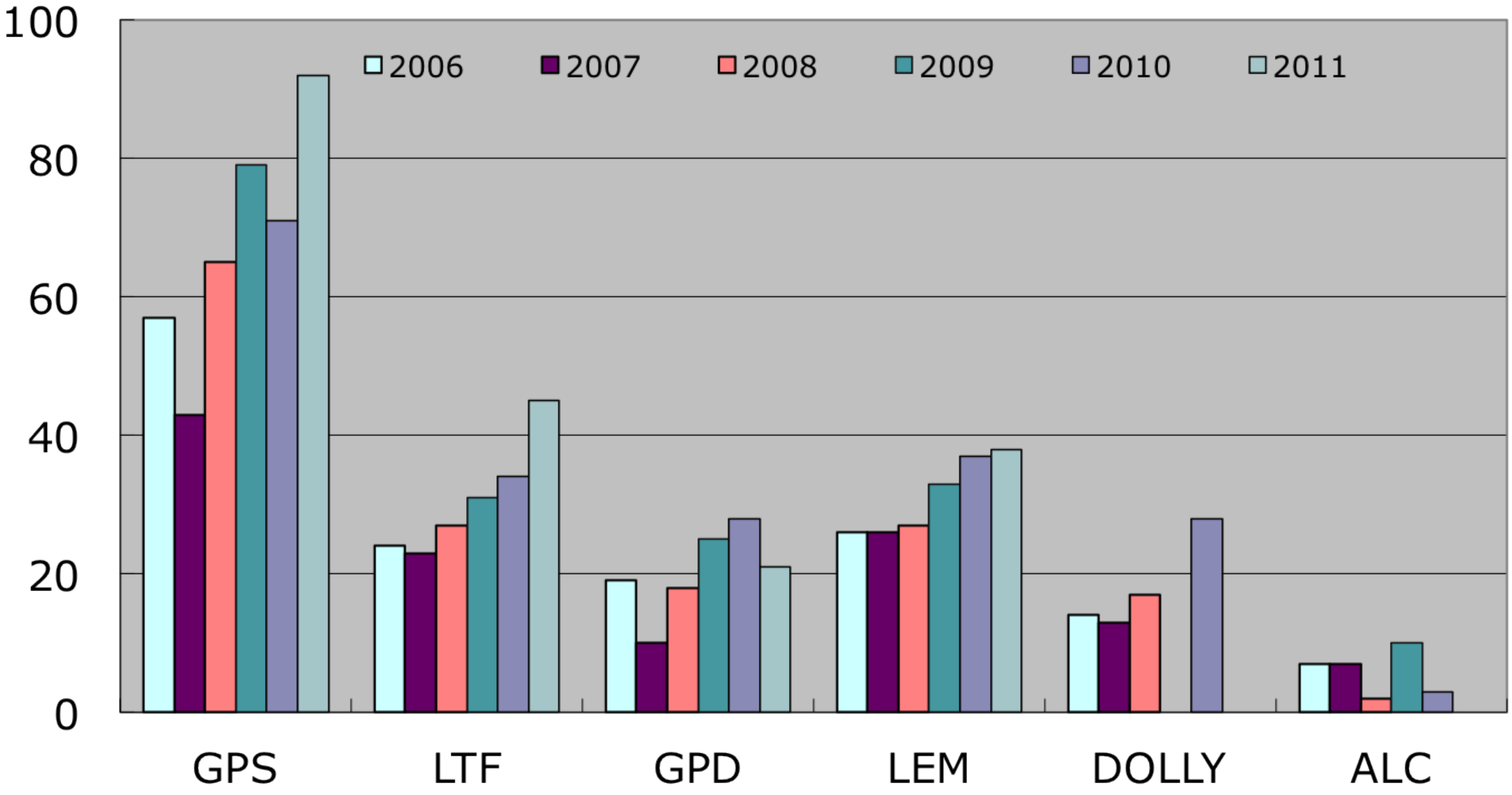
Superconductivity and magnetism in electron doped cuprates and pnictide films

H. Luetkens et al.

Developments

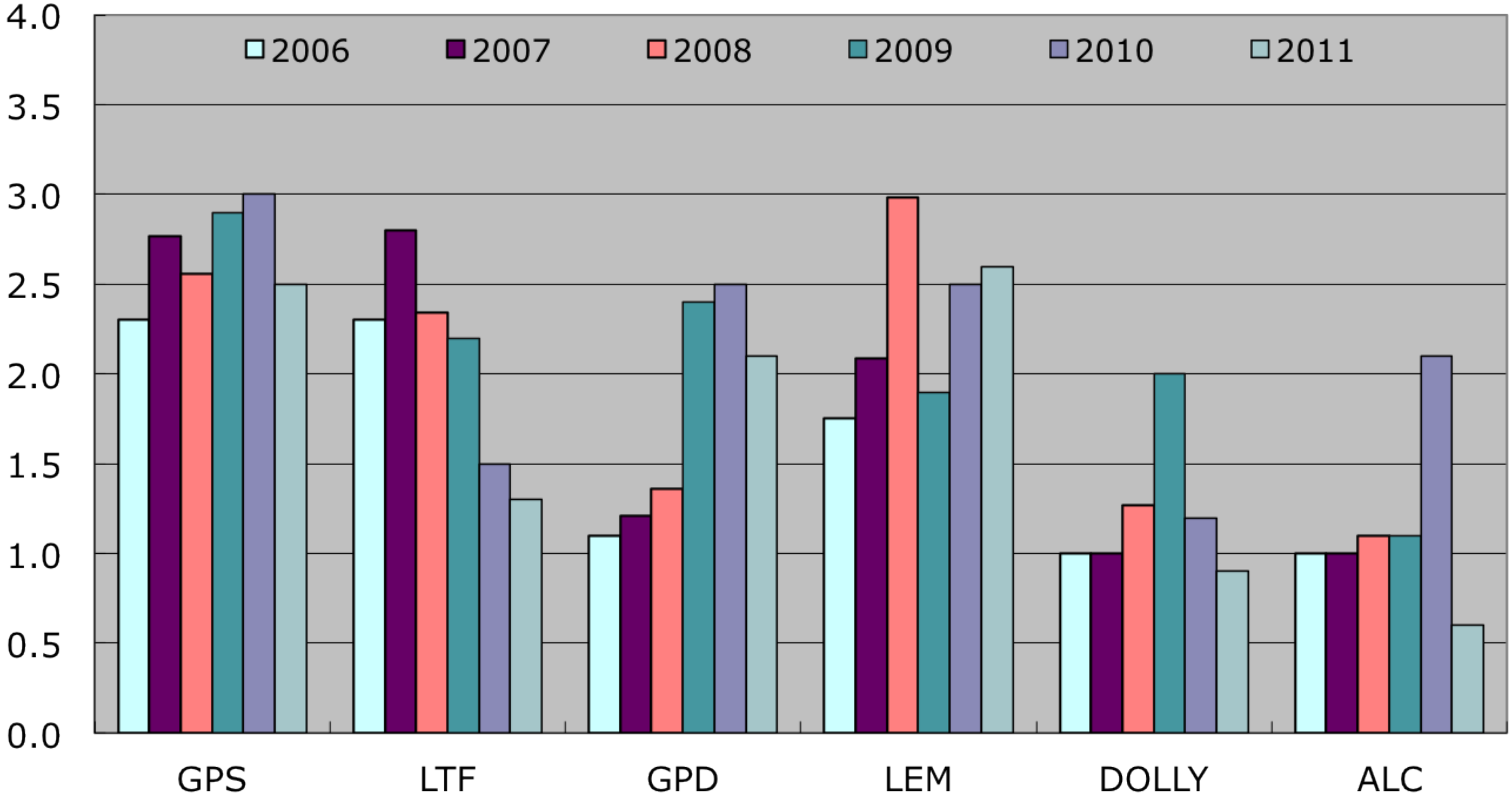
- Spin-rotator for LF-μSR, commissioning started in Feb-2012; will give factor 2 better time resolution (σ ~ 2.5 ns) compared to old setup
- Increasing LEM rate, solid Ne moderator
- A new APD positron spectrometer for the “B-parallel” magnet
- Extension to lower temperatures (from 2.7 K to <~2.0 K)
- External stimulus: ongoing developments on E-field, illumination, current
- Feasibility of a vector magnet at the sample
- Improve beam spot at sample, or active tracking detector system

Proposals SμS 2006-2011

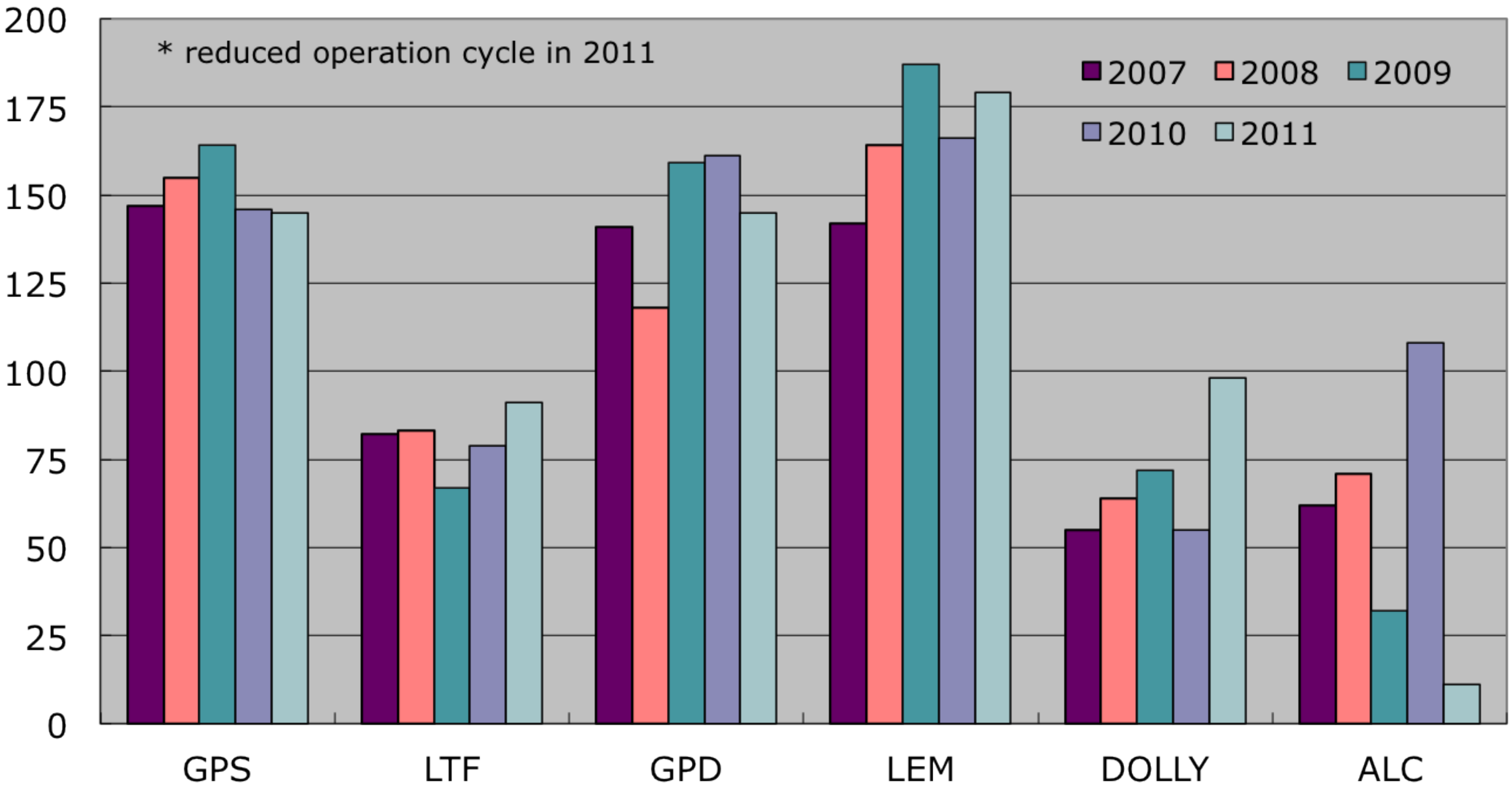


LEM publications 2007-2011 in high impact journals: 9
1 Science, 3 Nature Materials, 1 Nature Communications, 4 PRL

Overbookings SμS 2006-2011



Experimental days per SμS instrument 2007-2011*



LEM group at PSI

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

Part time: H. Luetkens, E. Morenzoni

Ph. D. students: G. Pascua (part time), E. Stilp (PSI/U Zurich)

Computing support: A. Raselli (part time)

People, funding of LEM over the past 20 years

Paul Scherrer Institute: H. Luetkens (part time), E. Morenzoni, T. Prokscha, H. Saadaoui (MaNEP PostDoc), Z. Salman, A. Suter, H.P. Weber (techn.)

Ph.D students: G. Pascua (part time), E. Stilp (PSI/ U Zurich)

former members:

Ph.D students: Th. Wutzke, A. Hofer, R. Khasanov, M. Birke, M. Pleines, B. Wojek

PostDocs, research scientists, computing support:
D. Eshchenko, H. Glückler, M. Meyberg, S. Vongtragool, U. Zimmermann
F. Kottmann, D. Maden, A. Raselli

from **PSI** technical divisions: R. Kobler, D. George, V. Vrankovic, K. Deiters, S. May and many other

Technische Universität Braunschweig: J. Litterst, A. Schatz

University of Birmingham: T. Forgan, T. Jackson, T. Riseman, D. Ucko, S. Ramos, R. Lycett

Universität Konstanz: C. Niedermayer (now PSI), G. Schatz

Universität Zürich: H. Keller

University Leiden: G. Nieuwenhuys

University of Heidelberg: B. Matthias, K. Jungmann, G. zu Putlitz

Kazan Physicotechnical Institute: N. Garifianov

Funding:

PSI, German BMBF, UK EPSRC, MaNEP, Univ. Zurich, Leiden Univ.

Milestones of new µE4 beam

08/2000: proposal to PSI Research Commission

2002: design finished (except separator SEP61), start of fabrication

2003: most elements finished, pre-assembly, problems with radiation hard coils

10/2003: dismantling of old µE4 elements started

12/2003: change supplier for radiation hard coils (Novosibirsk)

03/2004: trolley with ASR61/62, 1st triplet QSM601-603, KV61/62, FS61/62

04/2004: double solenoid WSX61/62

05/2004: 2nd triplet QSM604-606, FS63

08/2004: ASR63, 3rd triplet QSM607-609, design SEP61 completed

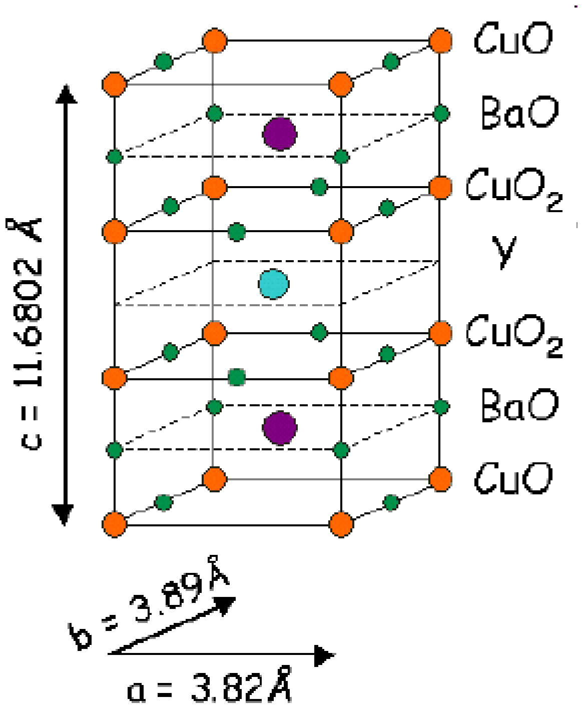
09/2004: beam measurements started, 0.7 m downstream of QSM609, at SEP61 position

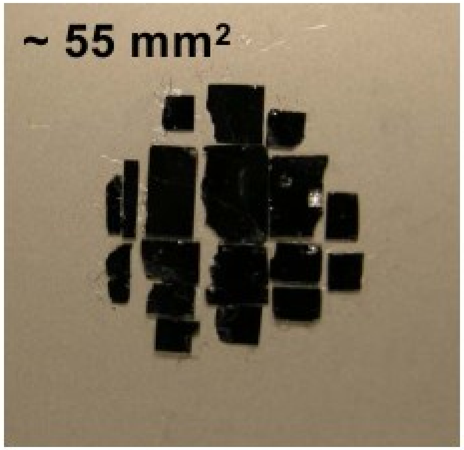
11/2004: last triplet QSM610-612

07/2005: SEP61 installed, first separated beam at 350kV at 19-Jul-2005

09/2005: first low-energy muons in µE4

In-plane Anisotropy in detwinned $YBa_2Cu_3O_{6.92}$





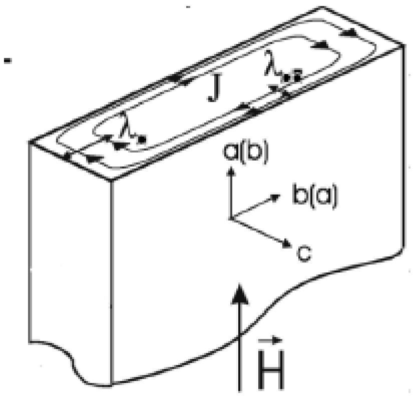
samples produced by R. Liang, W. Hardy, D. Bonn, Univ. of British Columbia

Detwinned (>95%) $YBa_2Cu_3O_{6.95}$ crystals optimally doped
(T_c= 94.1 K, $\Delta T_c \leq$ 0.1K)

$$\lambda(T) \propto \sqrt{\frac{m^*}{n_s(T)}}$$

← effective mass

← density of super carriers

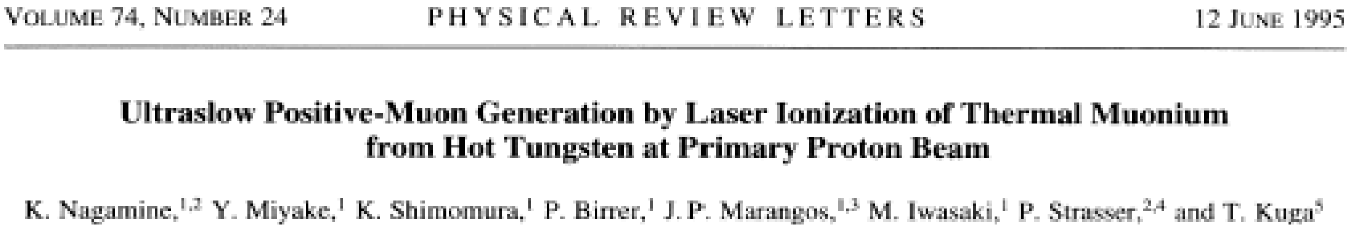


$$\vec{H}_{ext} \parallel \hat{a}\text{-axis} \rightarrow \lambda_b$$

$$\vec{H}_{ext} \parallel \hat{b}\text{-axis} \rightarrow \lambda_a$$

$1/\lambda^2 \sim n_s/m^* \equiv \rho_s$, superfluid density
Test of theories (London, BCS), symmetry of the sc gap

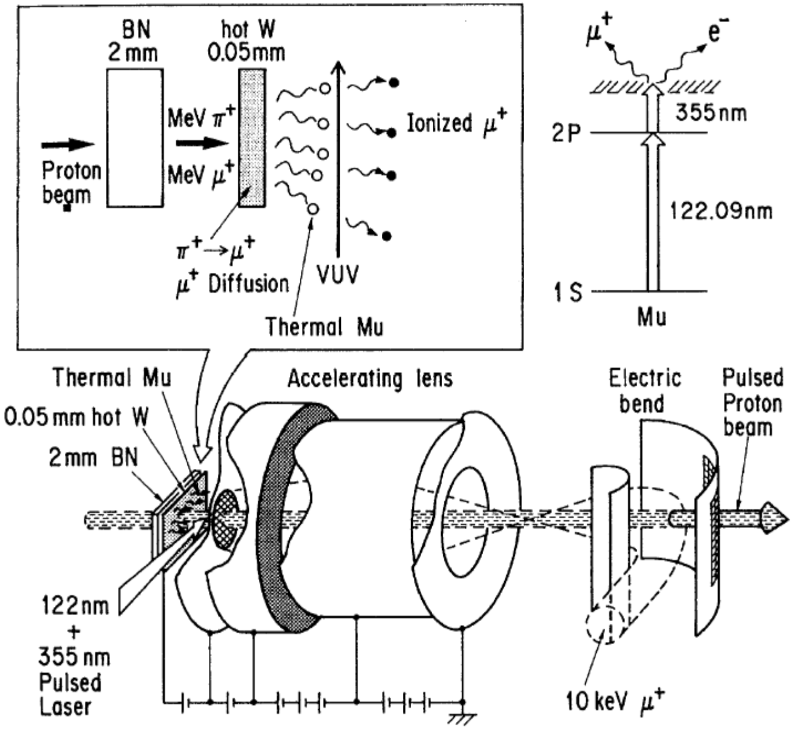
Generation of thermal μ^+ at a pulsed muon beam

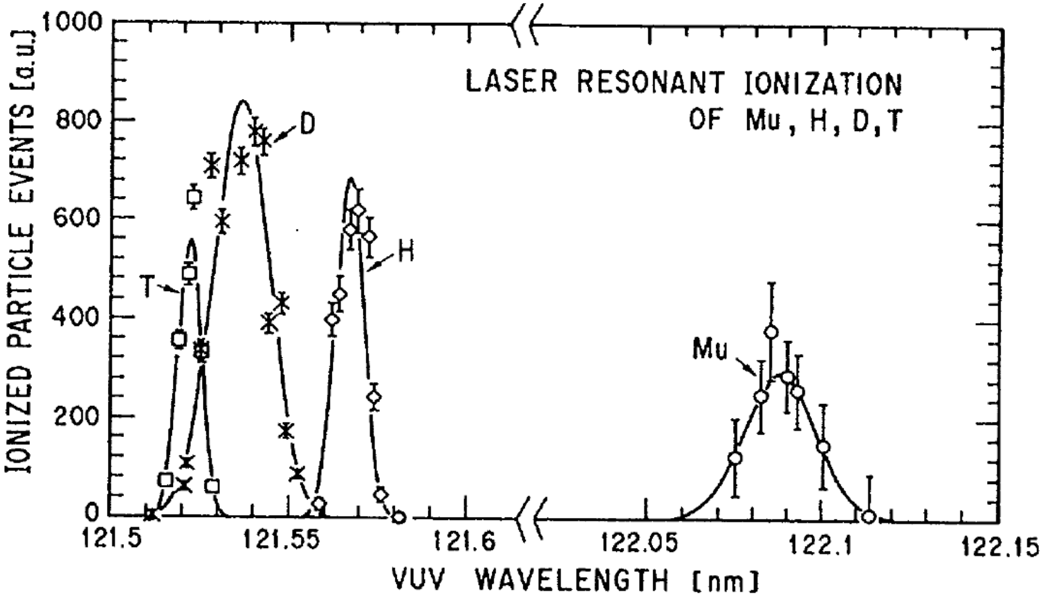


VOLUME 74, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1995

Ultraslow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot Tungsten at Primary Proton Beam

K. Nagamine,[1,2] Y. Miyake,[1] K. Shimomura,[1] P. Birrer,[1] J. P. Marangos,[1,3] M. Iwasaki,[1] P. Strasser,[2,4] and T. Kuga[5]





P. Bakule, Y. Matsuda, Y. Miyake, K. Nagamine, M. Iwasaki, Y. Ikedo, K. Shimomura, P. Strasser, S. Makimura
*Nucl. Instr Meth. B **266**, 335 (2008)*

Pulsed beam (25Hz) @ RIKEN-RAL:

Intensity: ~15 LE-μ^+/sec
Polarization: ~ 50%
Beam spot: 4 mm