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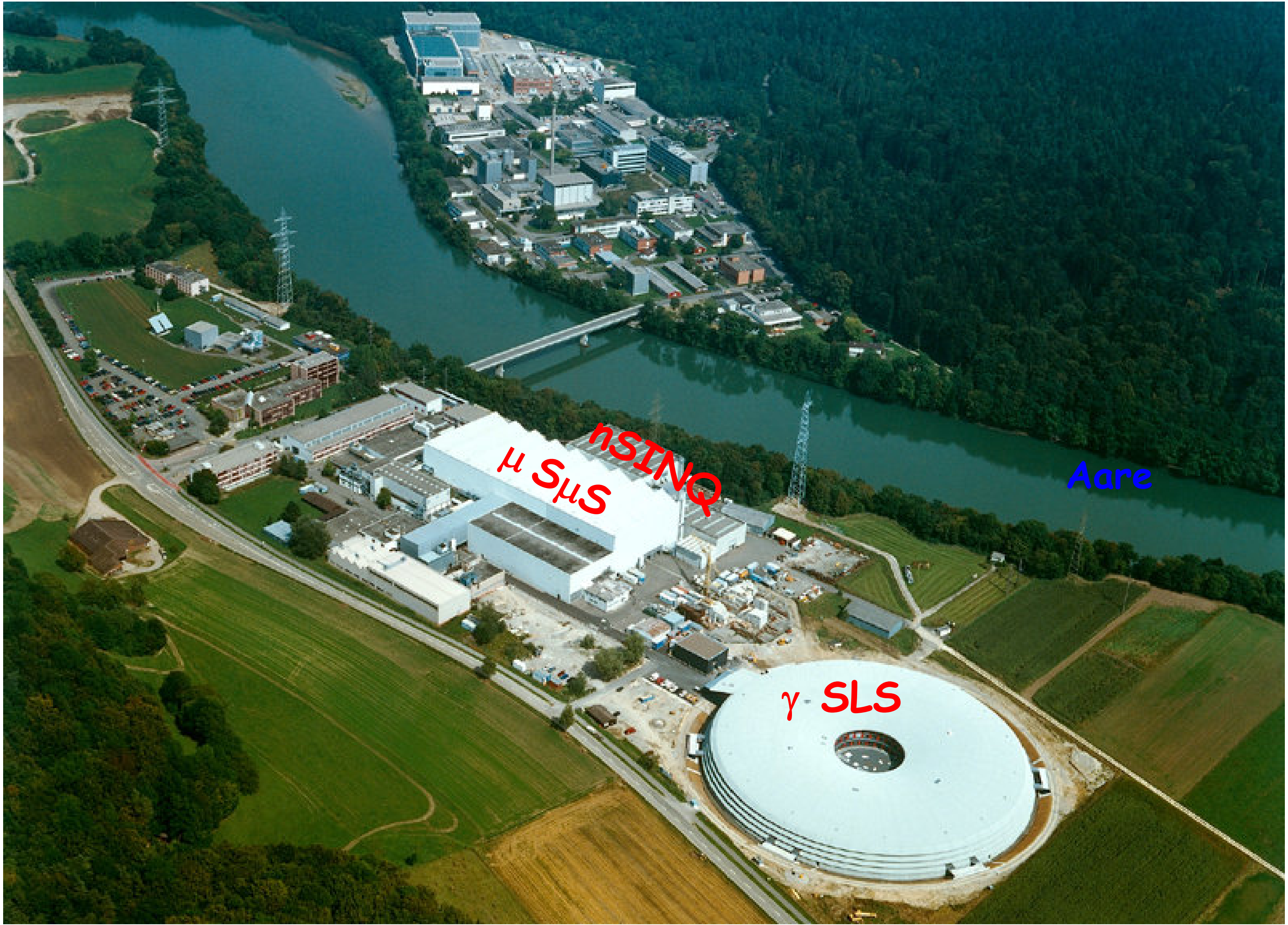
Status of the Low-Energy Muon Project (LEM) at PSI
and
Overview of Experimental Program

T. Prokscha

Paul Scherrer Institute (PSI), Villigen, Switzerland

February 18, 2006, 27th μSR seminar, Repino


nSINQ
μ SμS
Aare
γ SLS

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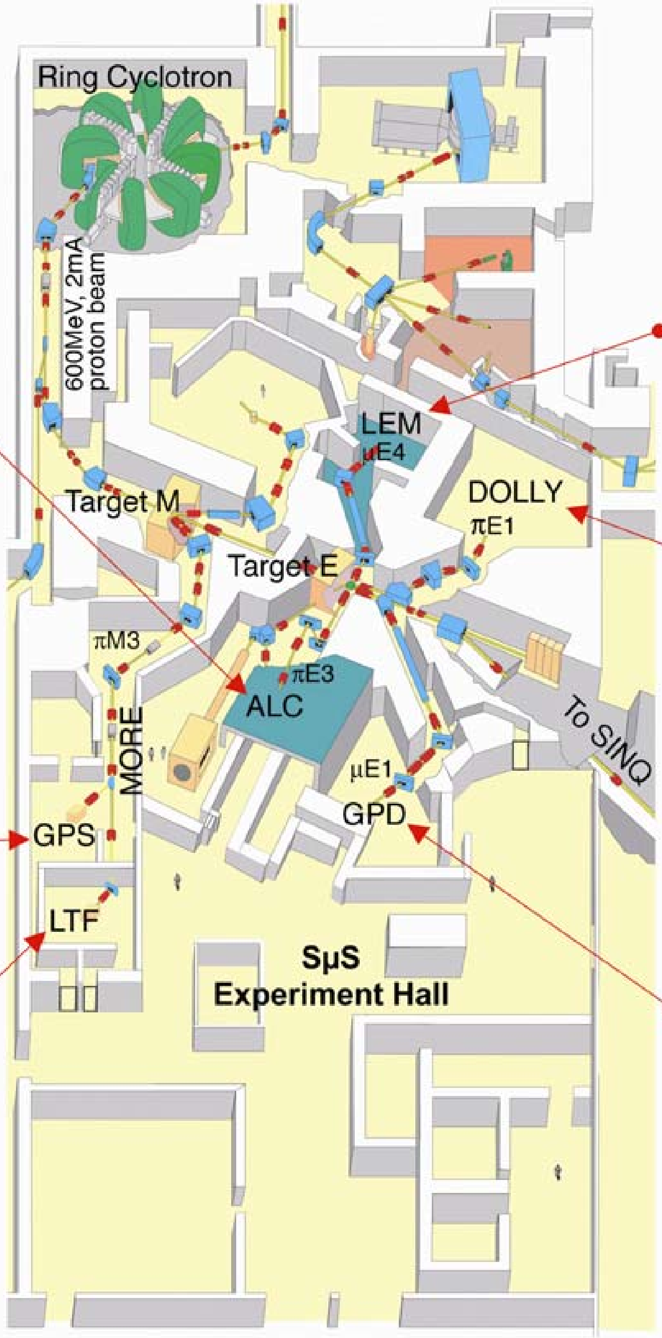
The PSI µSR Facilities

SµS Swiss Muon Source

ALC
Avoided Level Crossing
Resonance Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 4.2 - 600 K
Magnetic Fields: 0 - 5 T

Contact: *A. Stoikov*
alexei.stoikov@psi.ch



LEM
Low Energy Muon Beam and Instrument
Tunable muon energy: 0.5 - 30 keV (μ^+)
Temperatures: 2.5 - 700 K
Magnetic fields: 0 - 0.1 T perpendicular,
0 - 0.03 T parallel to sample surface

Contact: *E. Morenzoni*
elvezio.morenzoni@psi.ch

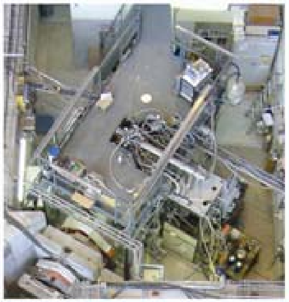
Shared Beam Surface Muon Facility

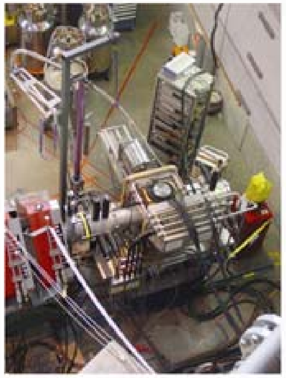
GPS
General Purpose
Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic Fields: 0 - 0.6 T
Muons on Request (MORE)

Contact: *A. Amato*
alex.amato@psi.ch

LTF
Low Temperature Facility
Muon energy: 4.2 MeV (μ^+)
Temperatures: 10 mK - 4.2 K
Magnetic fields: 0 - 3 T
Muons on Request (MORE)

Contact: *C. Baines*
chris.baines@psi.ch





DOLLY
General Purpose
Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic fields: 0 - 0.5 T

Contact: *R. Scheuermann*
robert.scheuermann@psi.ch

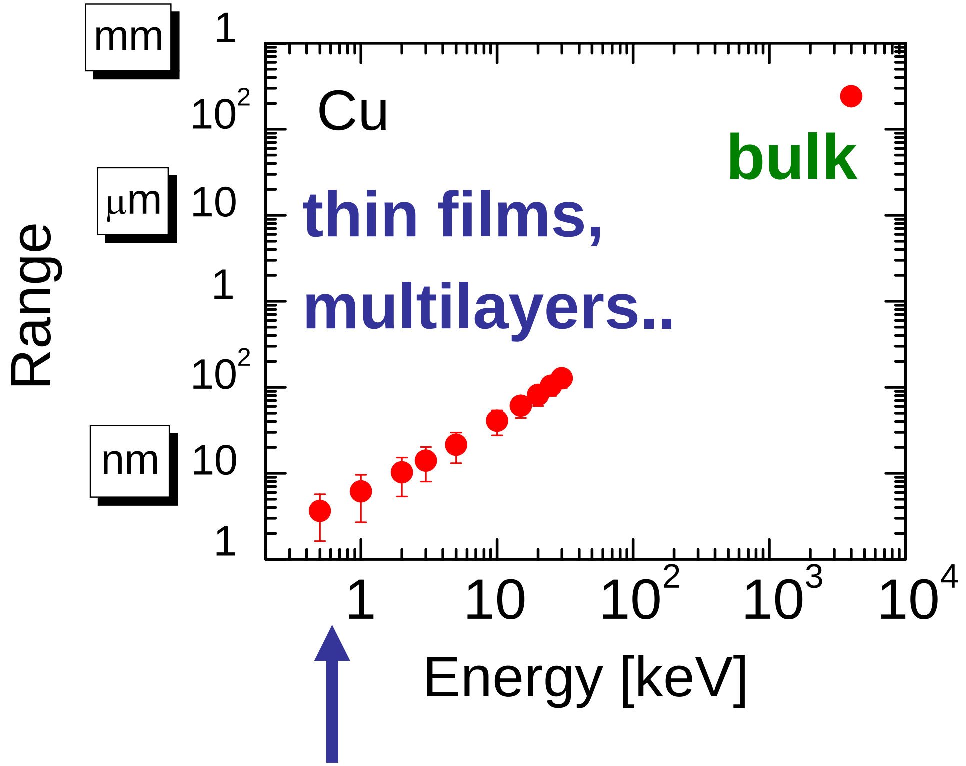
GPD
General Purpose
Decay Channel Instrument
Muon energy: 5 - 60 MeV
(μ^+ or μ^-)
Temperatures: 2 - 500 K
Magnetic Fields: 0 - 0.5 T

Contact: *U.Zimmermann*
ulrich.zimmermann@psi.ch

LMU
Laboratory for Muon Spin Spectroscopy

Contact: D. Herlach - dierk.herlach@psi.ch

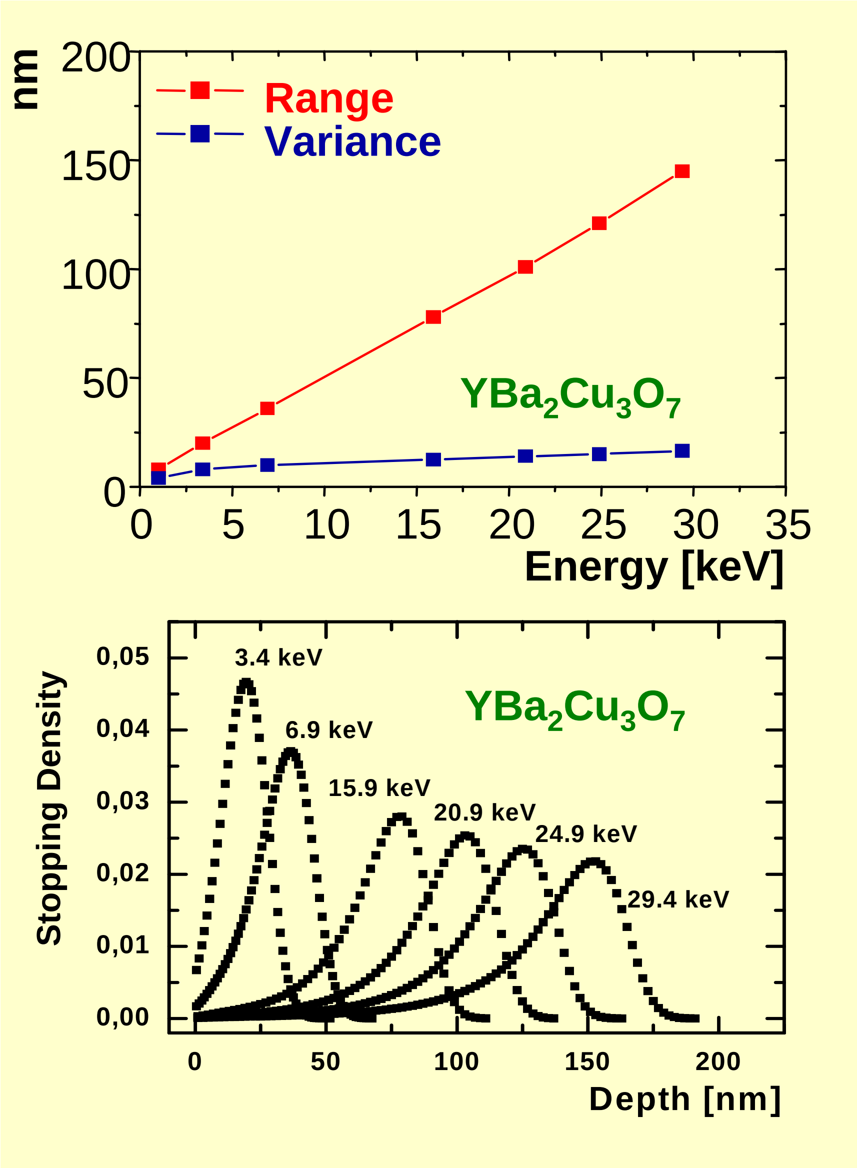
Range of muons in matter



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

- Allow depth-dependent µSR investigations (~ 1 – 300 nm)
- Extend the use of µSR to new objects of investigtions
- New magnetic/spin probe for **thin films**, **multilayers**, **surface regions**, **buried layers**,…

Implantation profiles of LE-μ

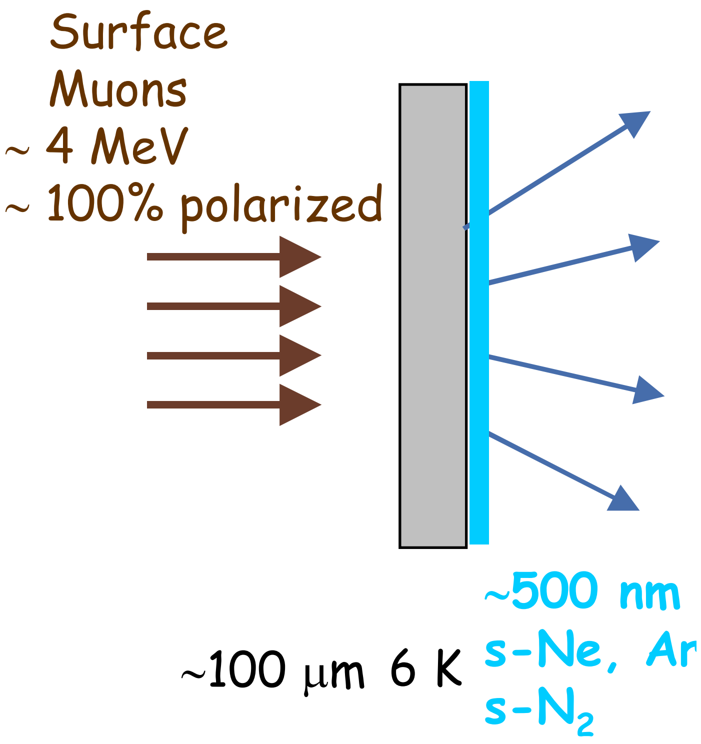


depth sensitive, microscopic, magnetic and spin probe

thin films, near-surface region, multi-layers, buried layers, nano cluster

(stopping profile calculated with Monte Carlo code Trim.SP by W. Eckstein, MPI Garching, Germany; see E.Morenzoni et al., NIM **B192** (2002))

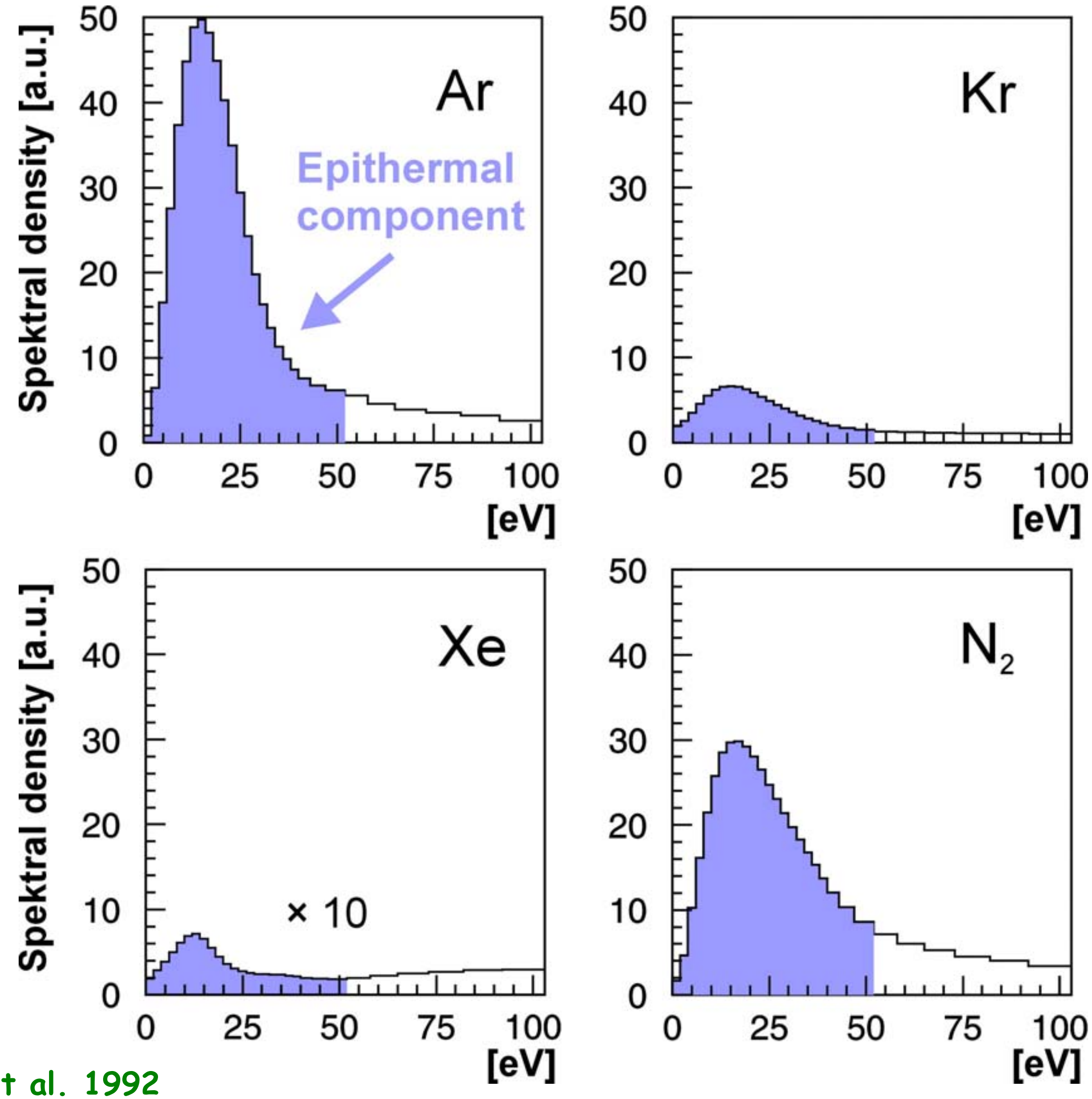
Generation of epithermal muons



Surface
Muons
~ 4 MeV
~ 100% polarized

~500 nm
s-Ne, Ar
s-N_2

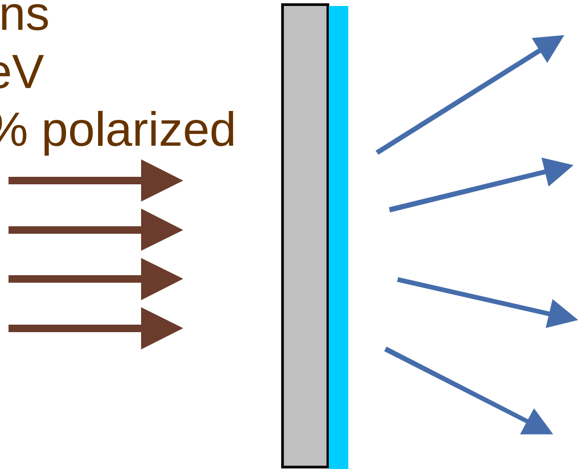
~100 μm 6 K



D. Harshmann et al. 1987, E. Morenzoni et al. 1992

Characteristics of epithermal μ^+

Surface
Muons
~ 4 MeV
~ 100% polarized



~100 μm
6 K

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

Mechanism of epithermal μ^+ production in weakly bound insulators:

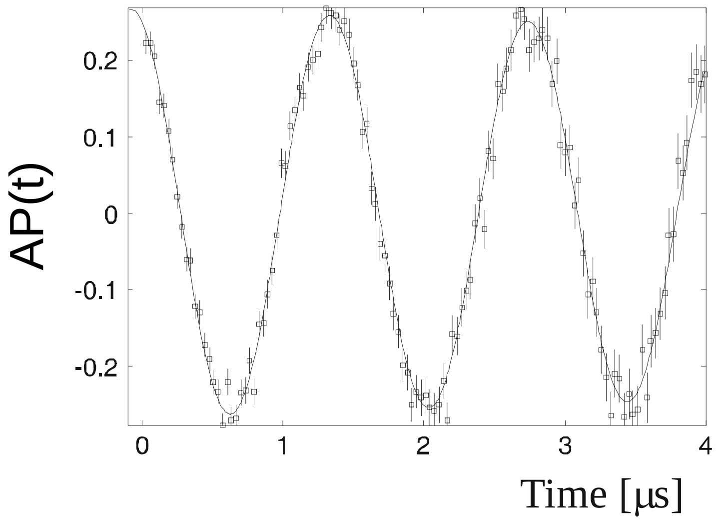
-Suppression of electronic energy losses
-Soft elastic collisions in the eV region
→ escape before thermalization

LE-muons source:

- 100% polarized
- peak energy: ~ 15 ± 10 eV
- moderation efficiency ~ 10^{-4}
- escape depth : 15-100 nm
- angular distribution: dN ~ cosθdW

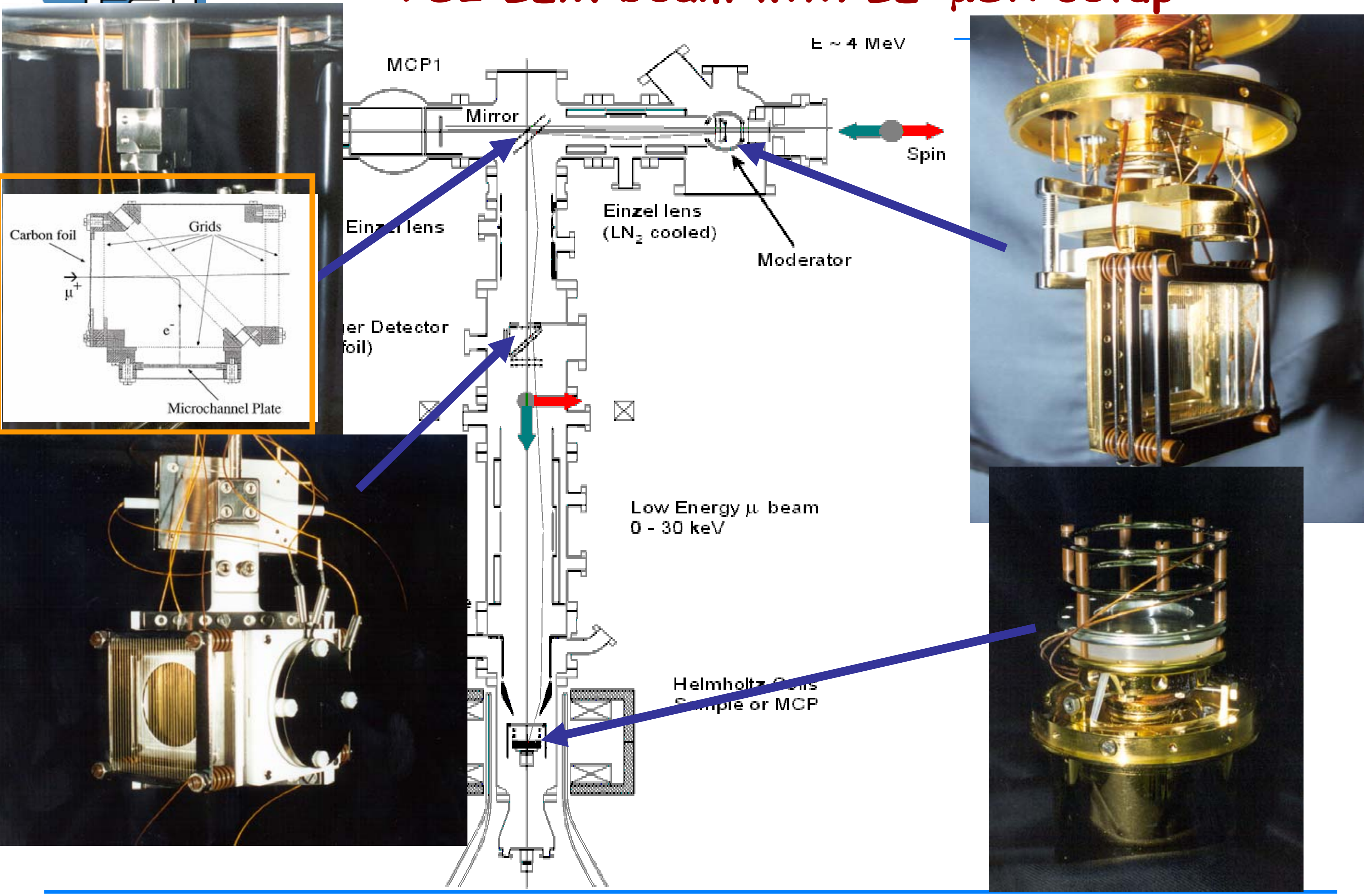
$$\varepsilon_{\mu^+} \cong \frac{d_{\mu^+}}{\Delta R}$$

Polarization: ~ 100%

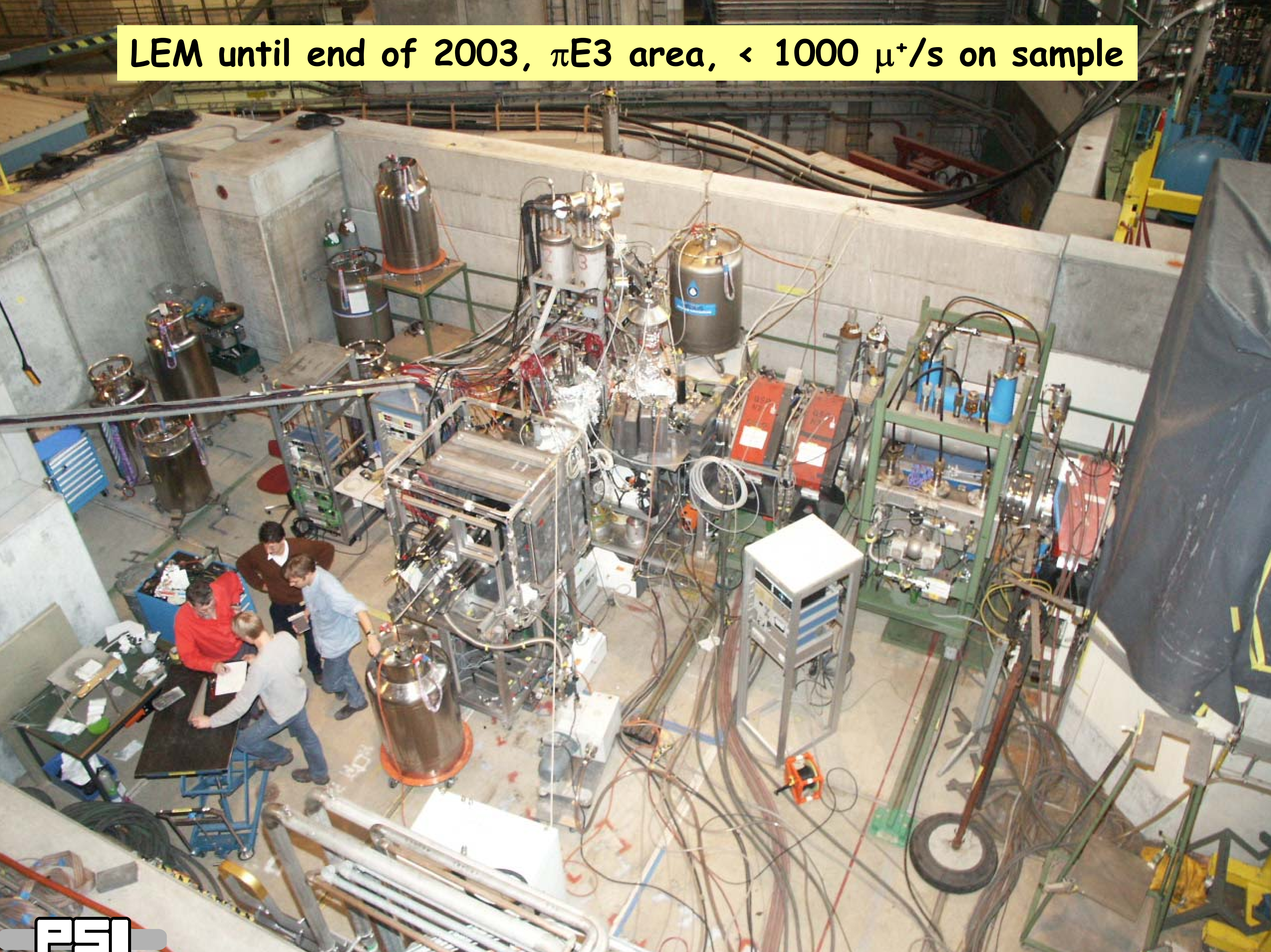


E. Morenzoni, F. Kottmann, D. Maden, B. Matthias, M. Meyberg, Th. Prokscha, Th. Wutzke, U. Zimmermann, Phys.Rev.Lett. 72, 2793 (1994).

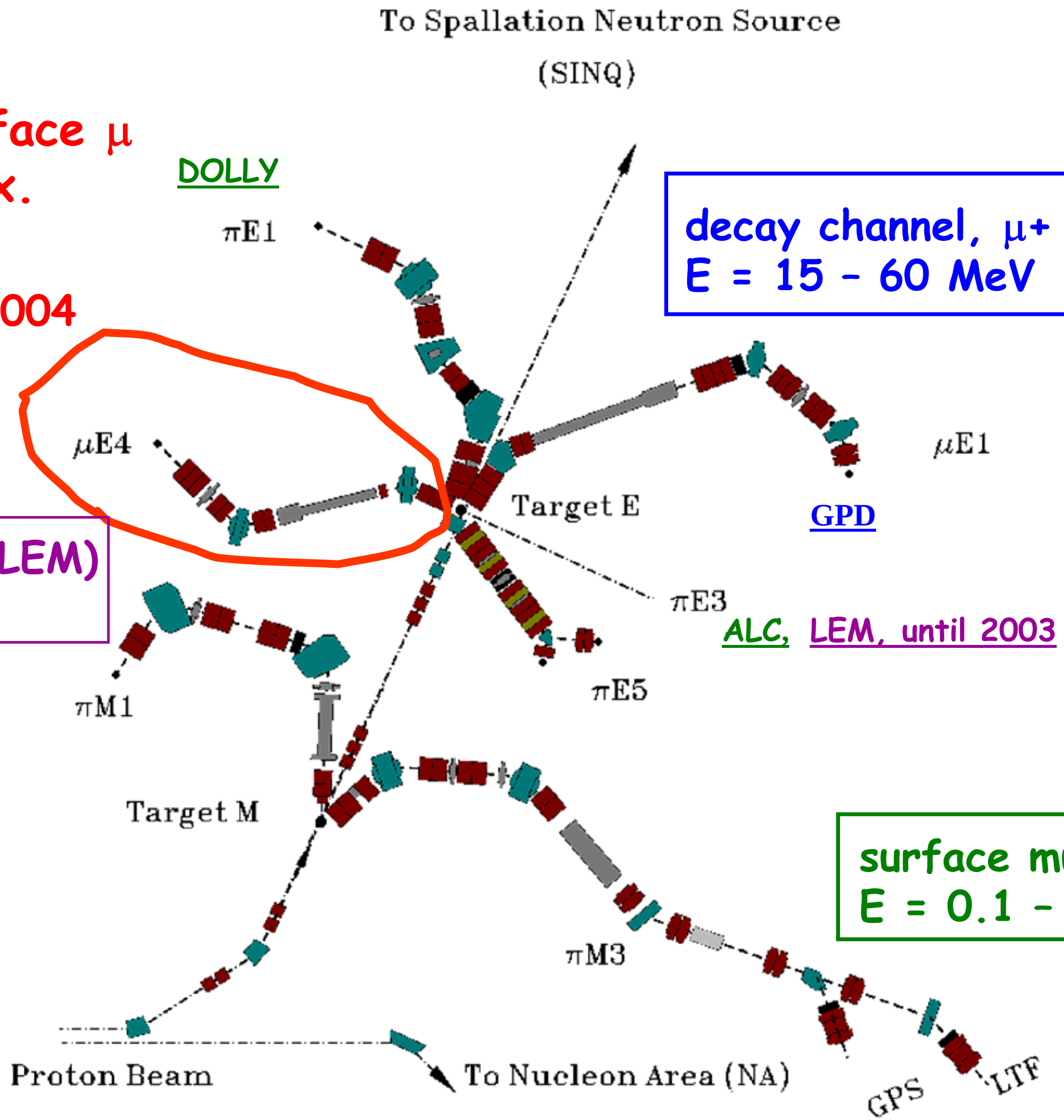
PSI LEM beam with LE-μSR setup



LEM until end of 2003, πE3 area, < 1000 μ^+/s on sample



To fully exploit LE-μSR a 5-10 times higher intensity is required



dedicated surface μ beam with max. intensity:

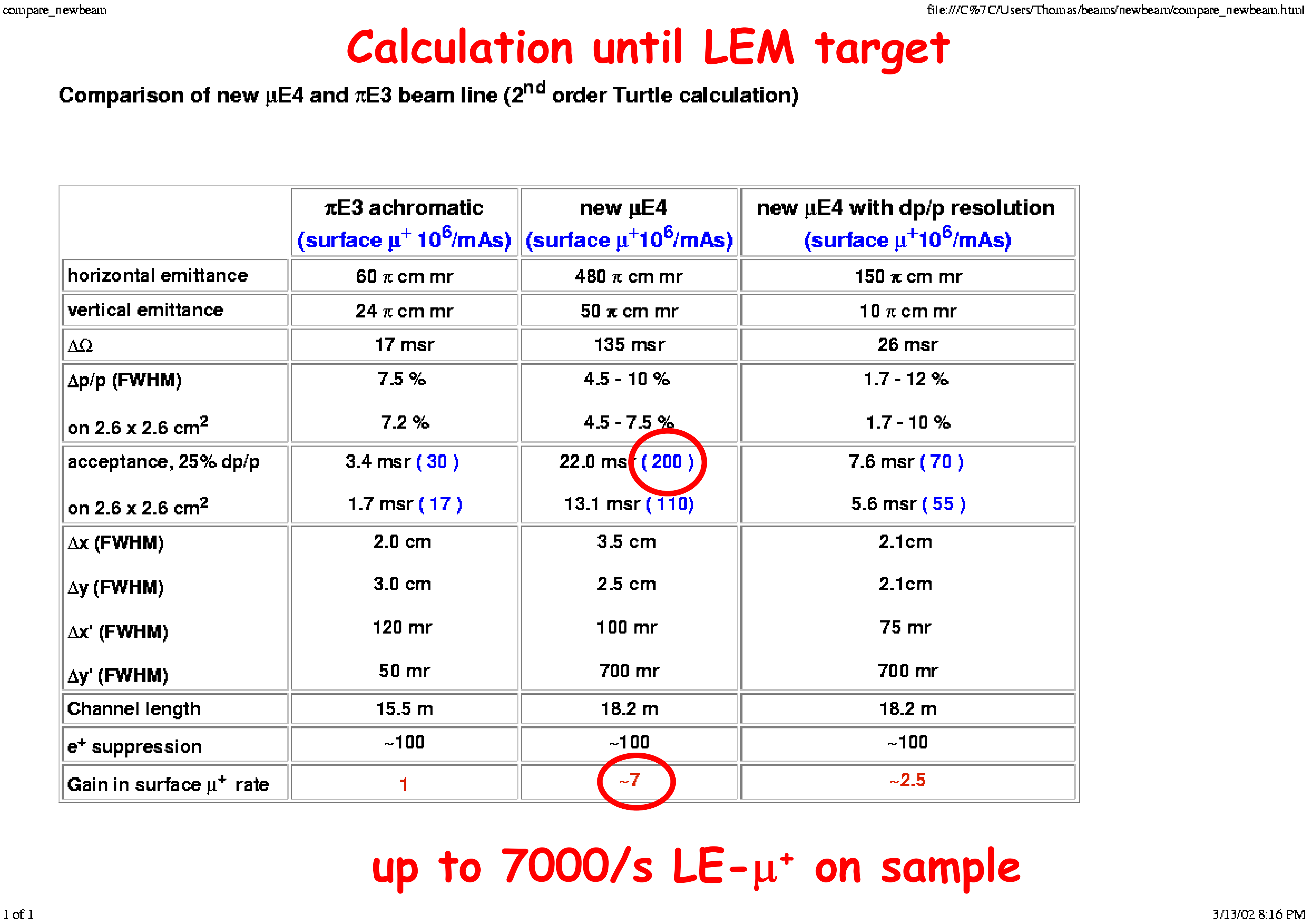
reconstruction 2004

decay channel, μ+ and μ-
E = 15 – 60 MeV

low-energy μ+ (LEM)
0.5 – 30 keV

surface muon beam, μ+
E = 0.1 – 4.2 MeV

Calculation until LEM target

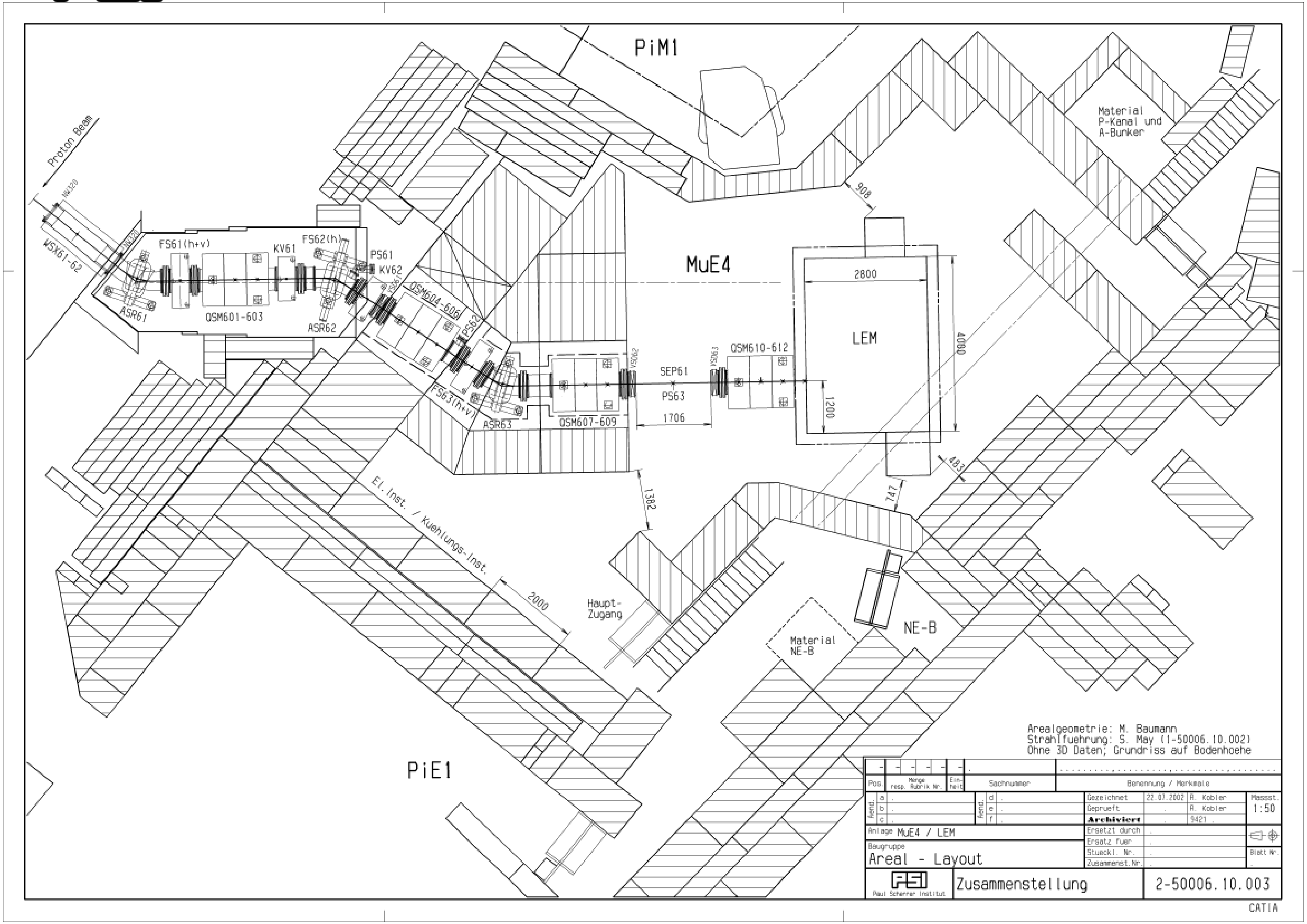


Comparison of new μE4 and πE3 beam line (2nd order Turtle calculation)

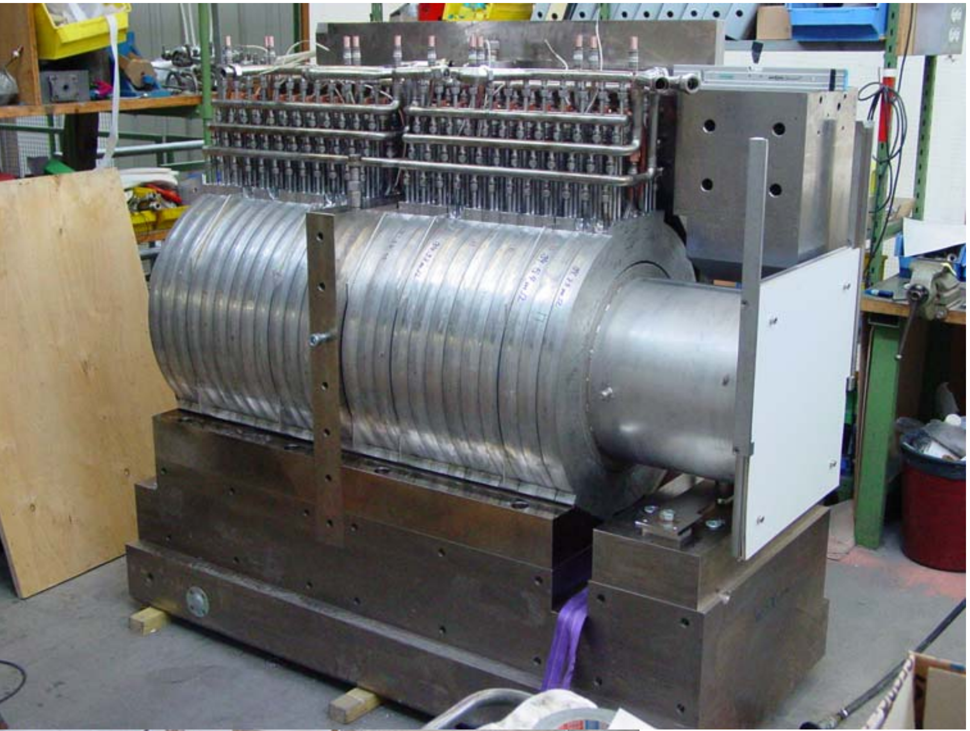
	πE3 achromatic (surface μ$^+$ 10^6/mAs)	new μE4 (surface μ$^+$10^6/mAs)	new μE4 with dp/p resolution (surface μ$^+$10^6/mAs)
horizontal emittance	60 π cm mr	480 π cm mr	150 π cm mr
vertical emittance	24 π cm mr	50 π cm mr	10 π cm mr
ΔΩ	17 msr	135 msr	26 msr
Δp/p (FWHM) on 2.6 x 2.6 cm^2	7.5 % 7.2 %	4.5 - 10 % 4.5 - 7.5 %	1.7 - 12 % 1.7 - 10 %
acceptance, 25% dp/p on 2.6 x 2.6 cm^2	3.4 msr (30) 1.7 msr (17)	22.0 msr (200) 13.1 msr (110)	7.6 msr (70) 5.6 msr (55)
Δx (FWHM) Δy (FWHM) Δx' (FWHM) Δy' (FWHM)	2.0 cm 3.0 cm 120 mr 50 mr	3.5 cm 2.5 cm 100 mr 700 mr	2.1cm 2.1cm 75 mr 700 mr
Channel length	15.5 m	18.2 m	18.2 m
e^+ suppression	~100	~100	~100
Gain in surface μ$^+$ rate	1	~7	~2.5

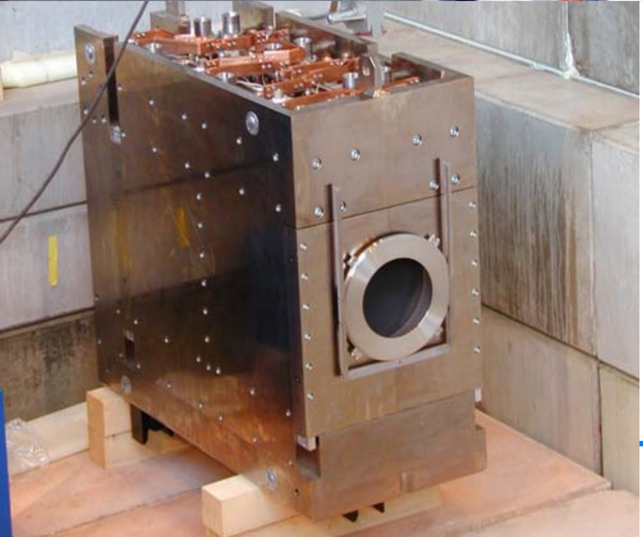
up to 7000/s LE-μ^+ on sample

Layout of the new μE4 beam line

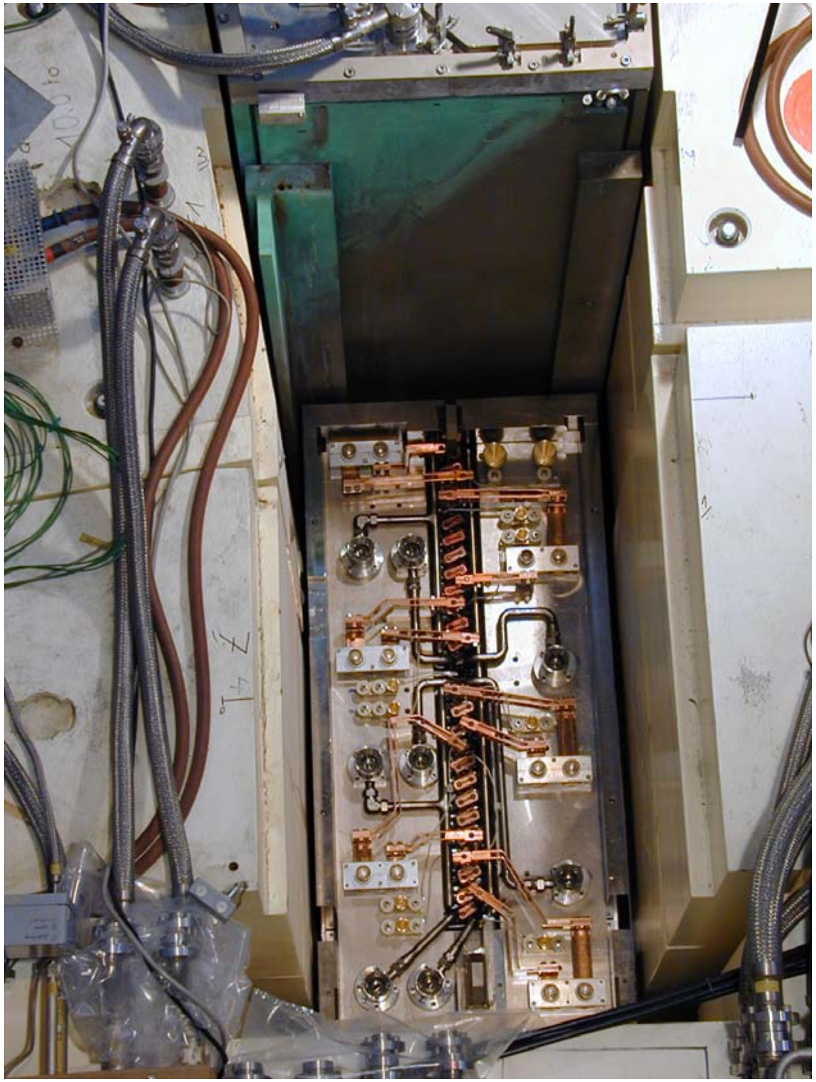


Large acceptance double solenoid (WSX)

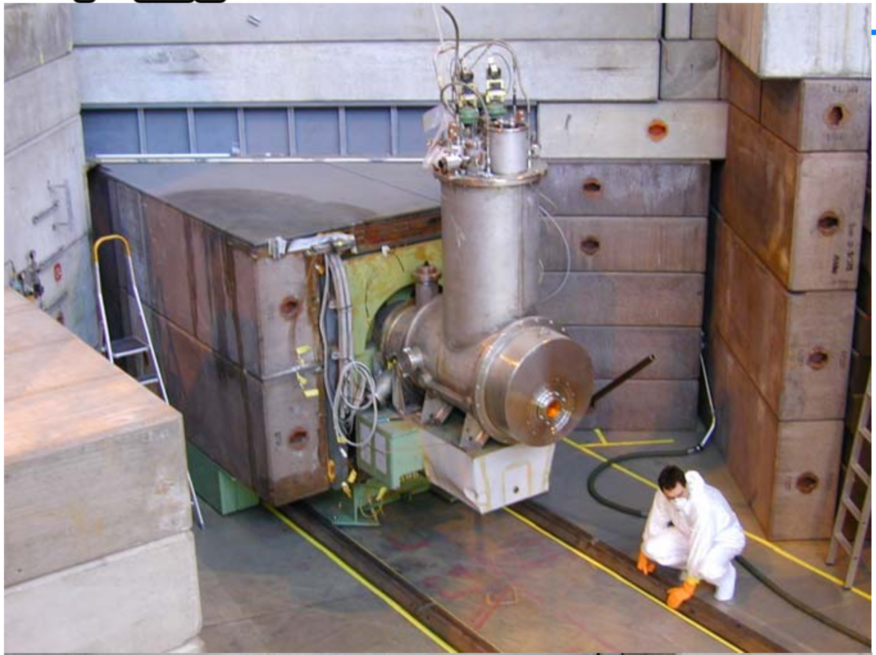




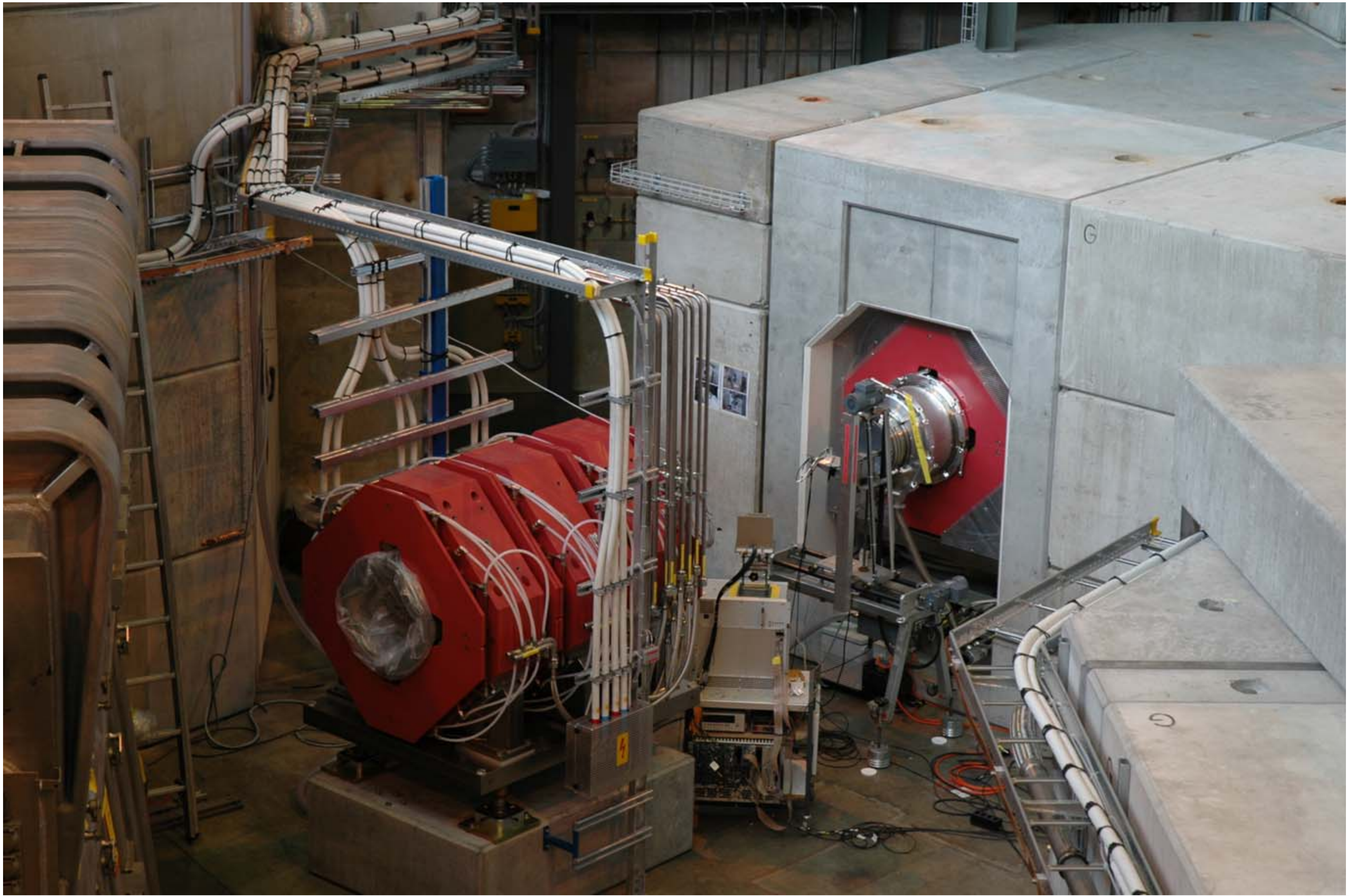
B_{max} = 3.5 kG
$Ø_i$ = 500 mm



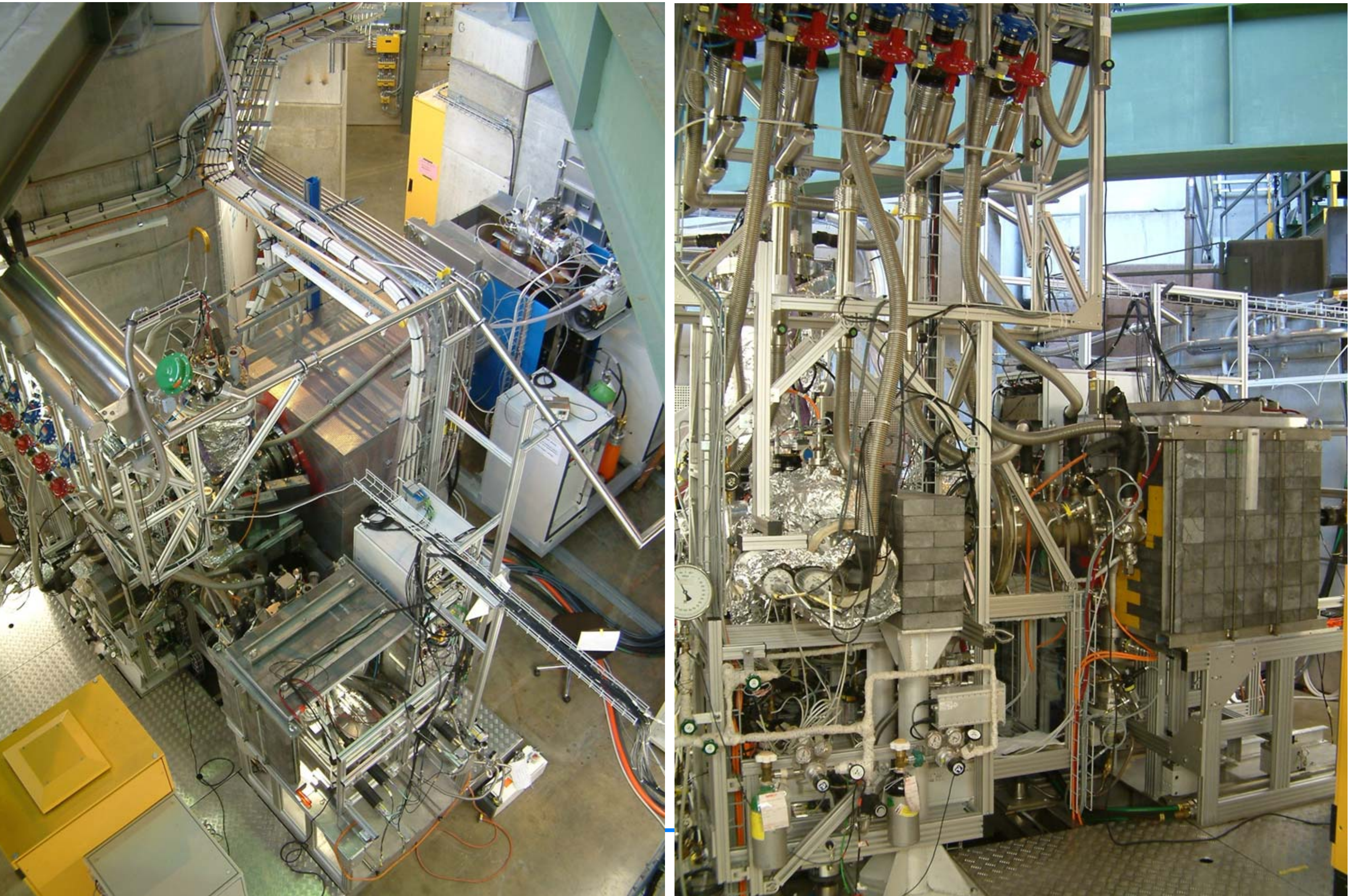
Installation



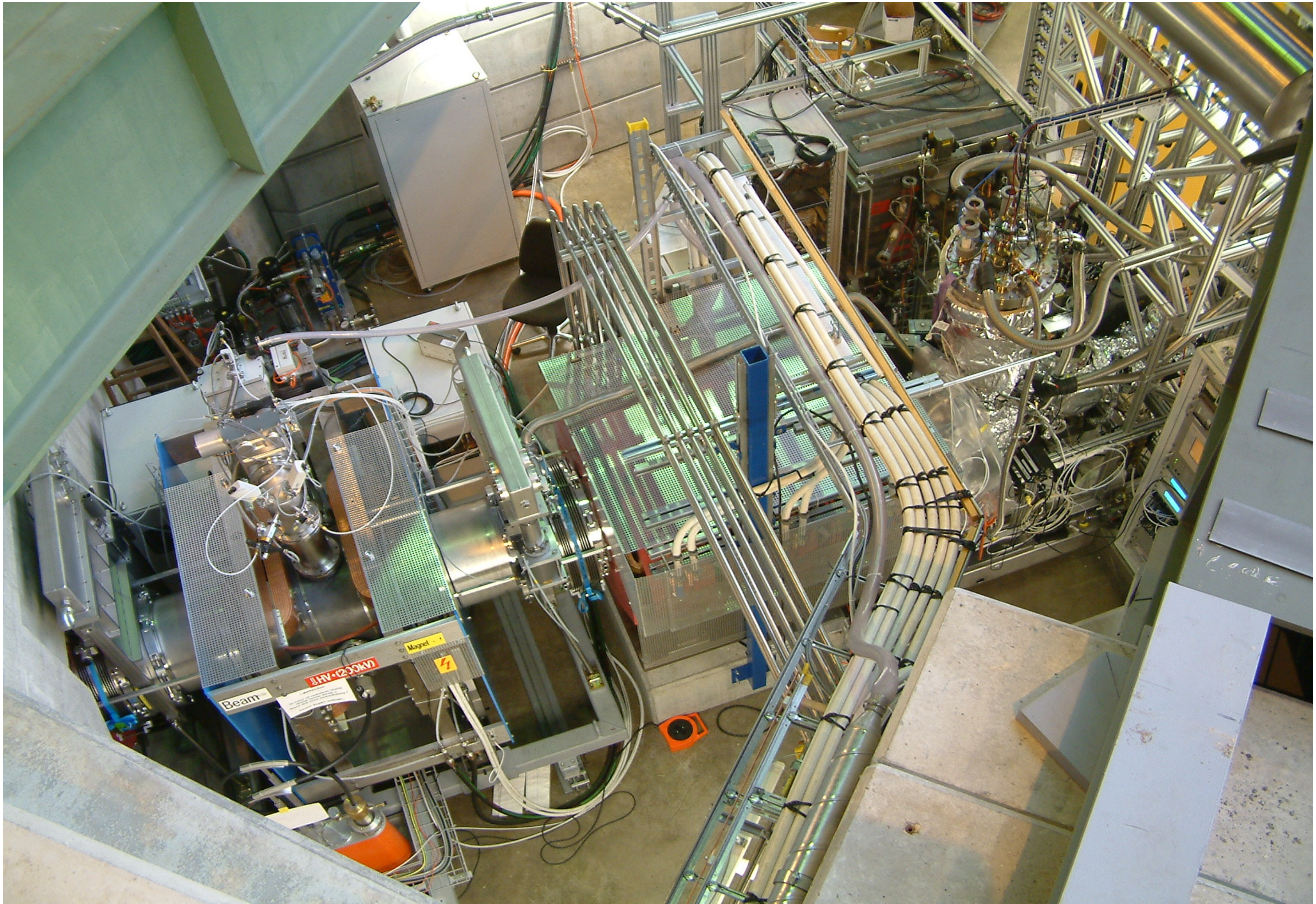
μE4 area in January 2005



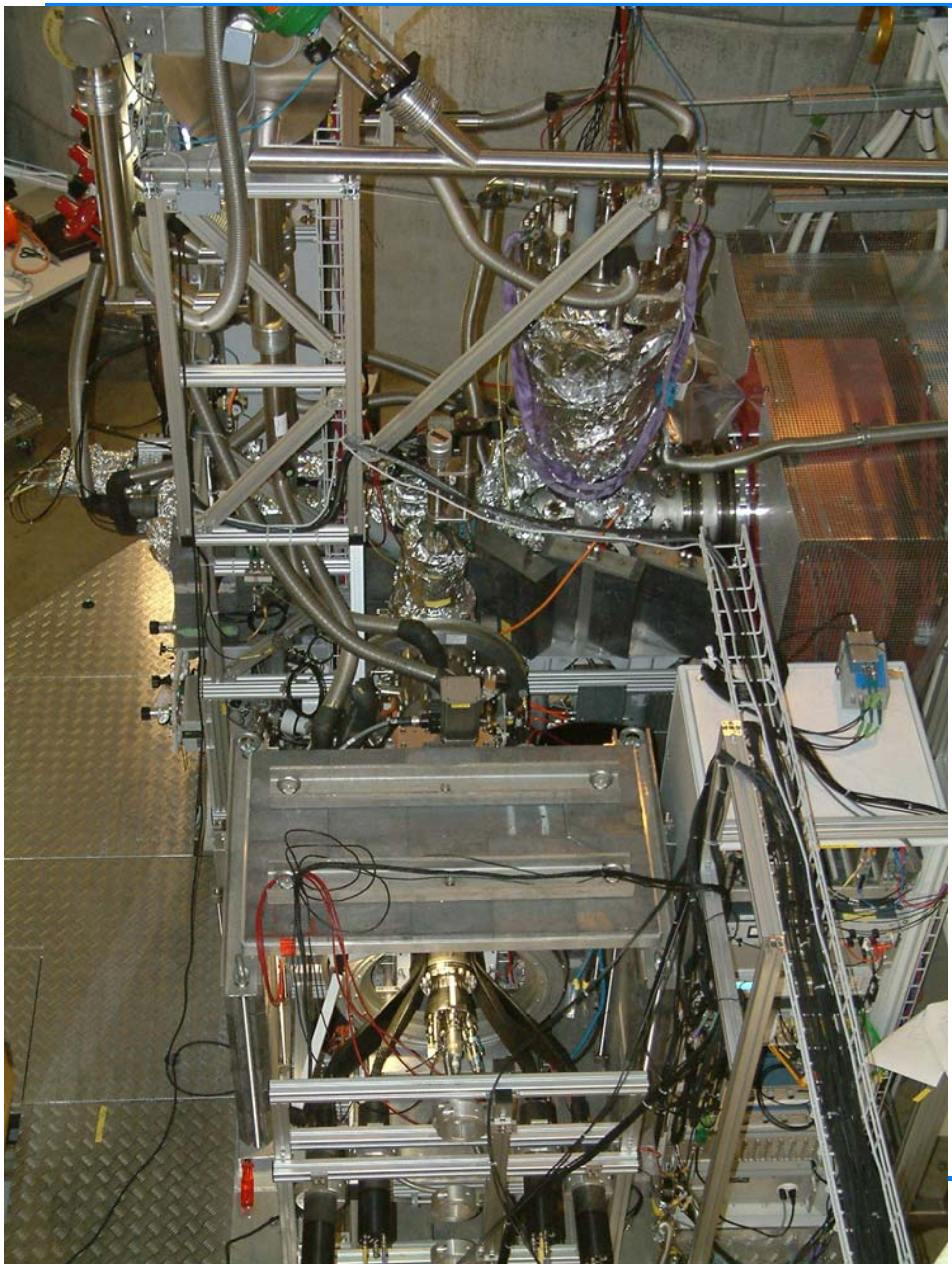
LEM in μE4, since November 2005

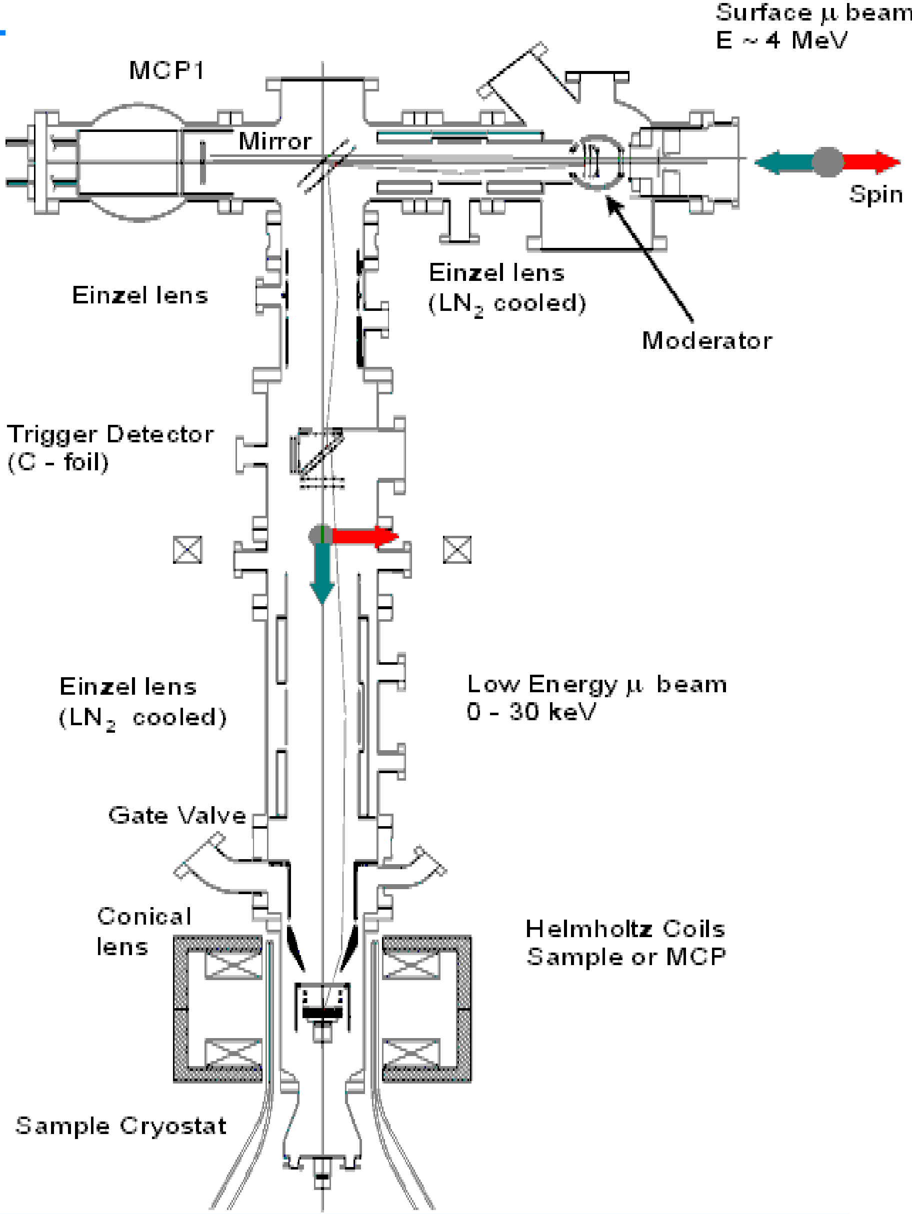


LEM in μE4, since November 2005

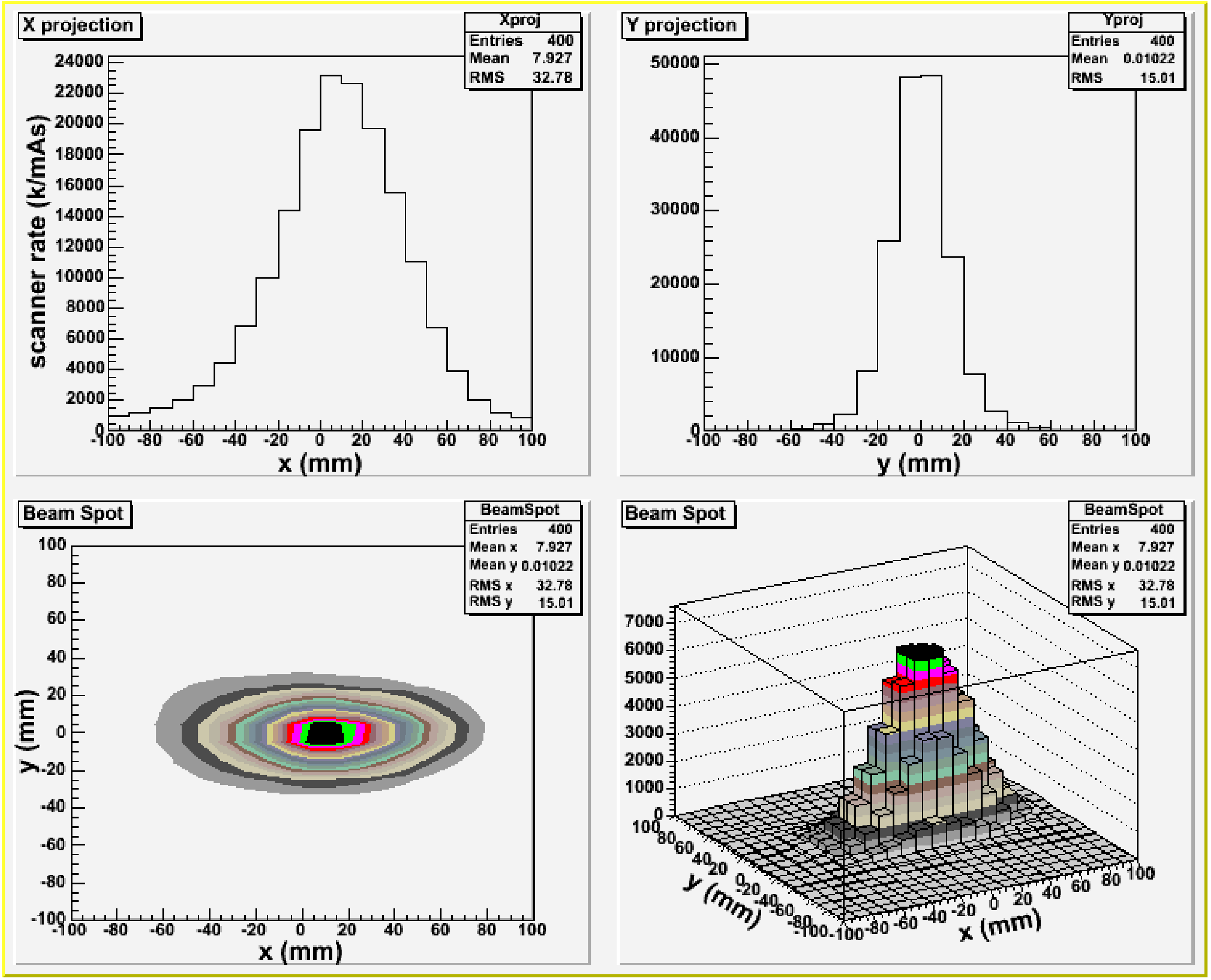


New LEM Apparatus





WSXon beam spot, LEM moderator position, 4cm target E NO separator (replaced by straight vacuum tube)



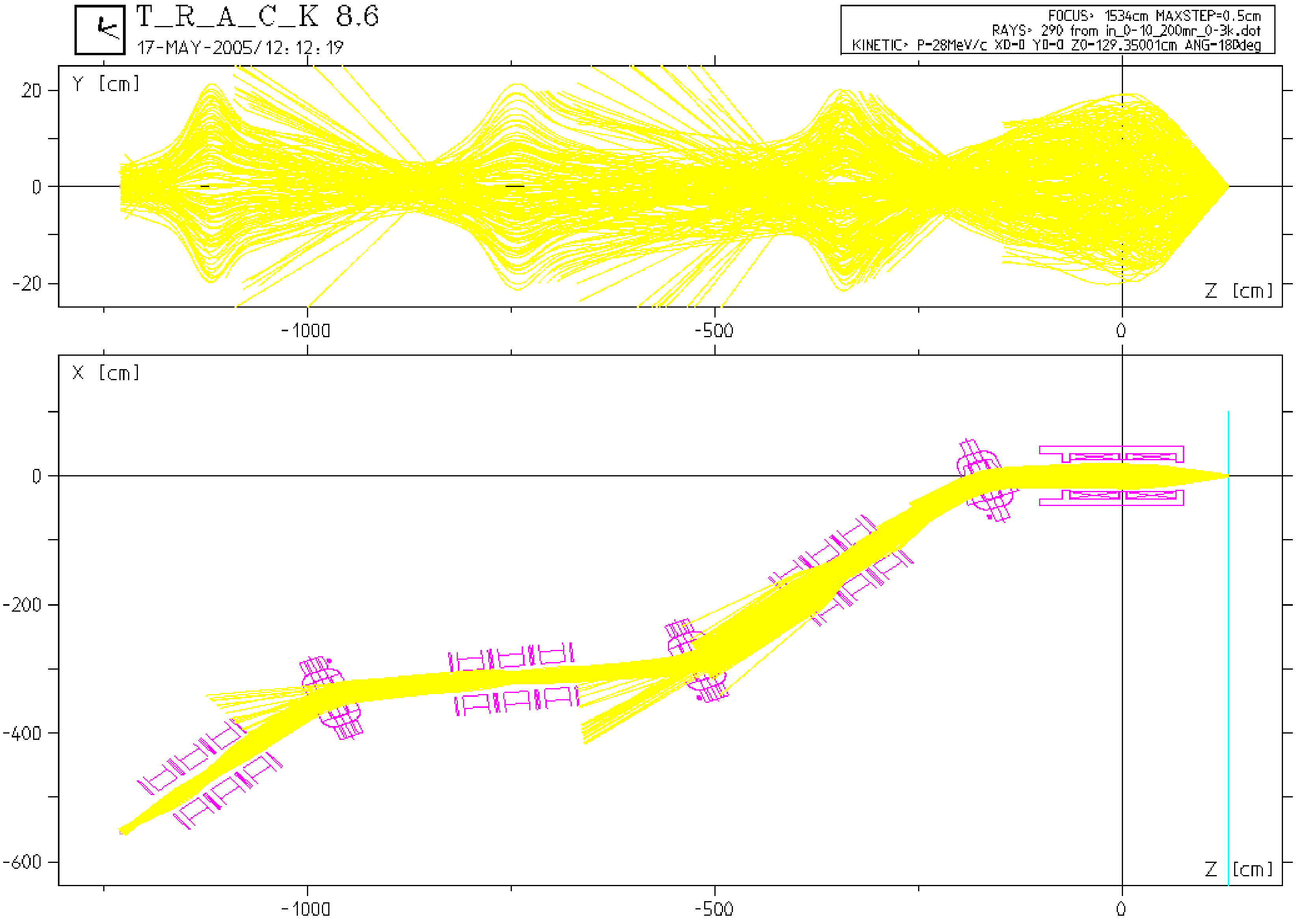
I_μ = 300M/mAs
(I_μ = 115M/mAs
on moderator)
On axis:
15 M/(mAs cm^2)

$\Delta p/p$ ~ 8.5% FWHM

FS61 = 500
FS62 = 555
FS63 = 500

Δx = 7.0 cm FWHM
Δy = 3.5 cm FWHM

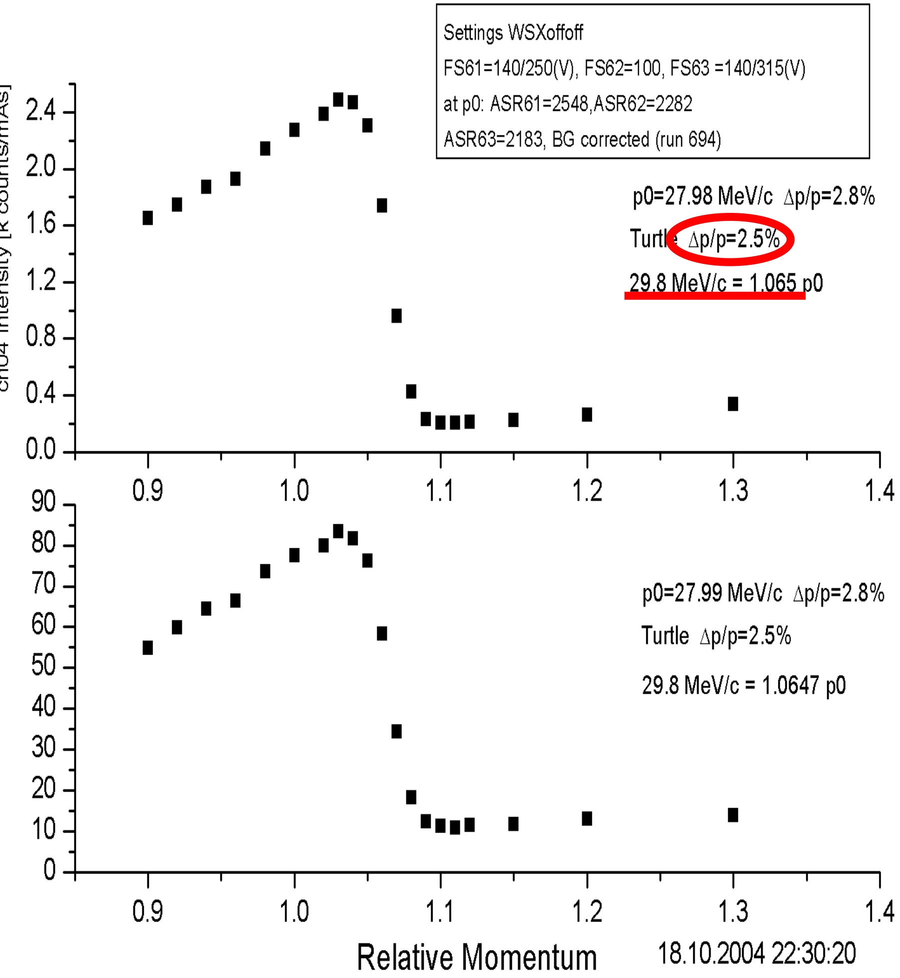
TRACK calculation, WSXon



T. Prokscha, V. Vrankovic

Δp/p for WSX off

σ_x = 1.0 cm, σ_y = 1.2 cm

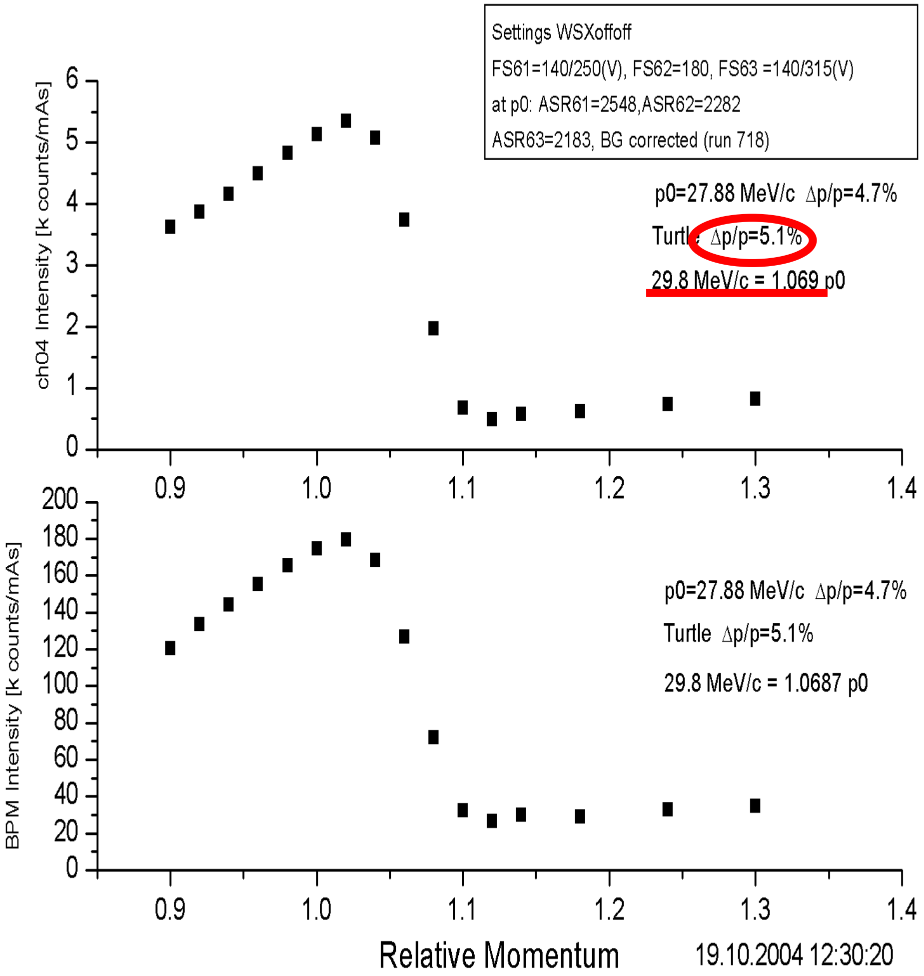


Settings WSXoffoff
FS61=140/250(V), FS62=100, FS63 =140/315(V)
at p0: ASR61=2548,ASR62=2282
ASR63=2183, BG corrected (run 694)

p0=27.98 MeV/c Δp/p=2.8%
Turtle Δp/p=2.5%
29.8 MeV/c = 1.065 p0

p0=27.99 MeV/c Δp/p=2.8%
Turtle Δp/p=2.5%
29.8 MeV/c = 1.0647 p0

18.10.2004 22:30:20



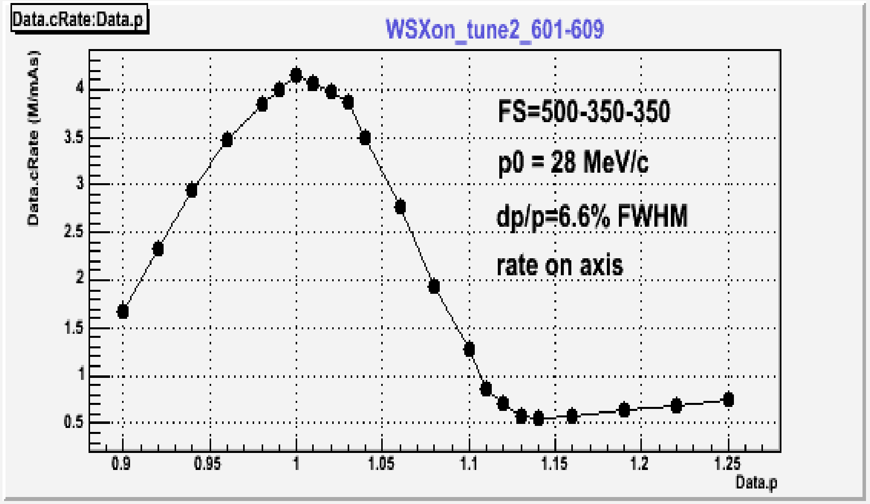
Settings WSXoffoff
FS61=140/250(V), FS62=180, FS63 =140/315(V)
at p0: ASR61=2548,ASR62=2282
ASR63=2183, BG corrected (run 718)

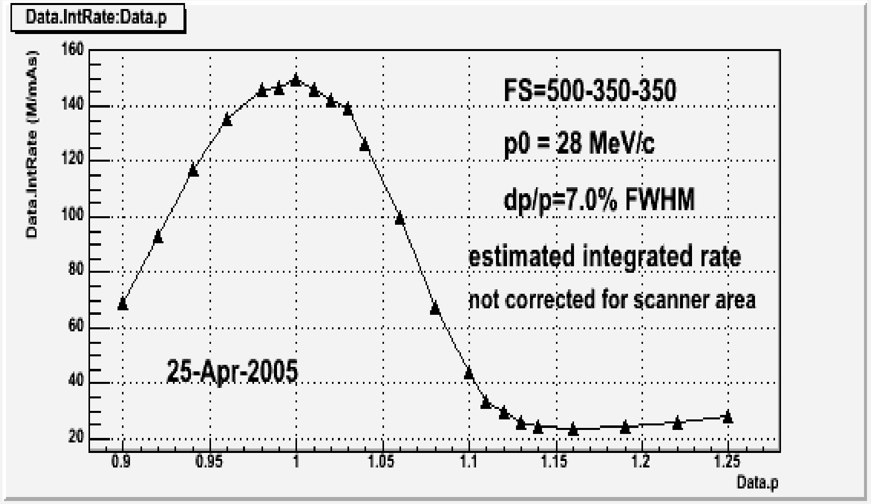
p0=27.88 MeV/c Δp/p=4.7%
Turtle Δp/p=5.1%
29.8 MeV/c = 1.069 p0

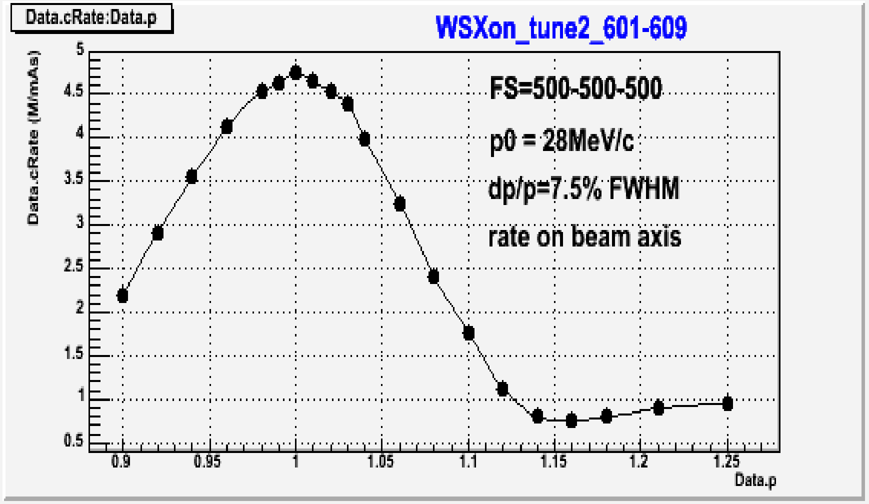
p0=27.88 MeV/c Δp/p=4.7%
Turtle Δp/p=5.1%
29.8 MeV/c = 1.0687 p0

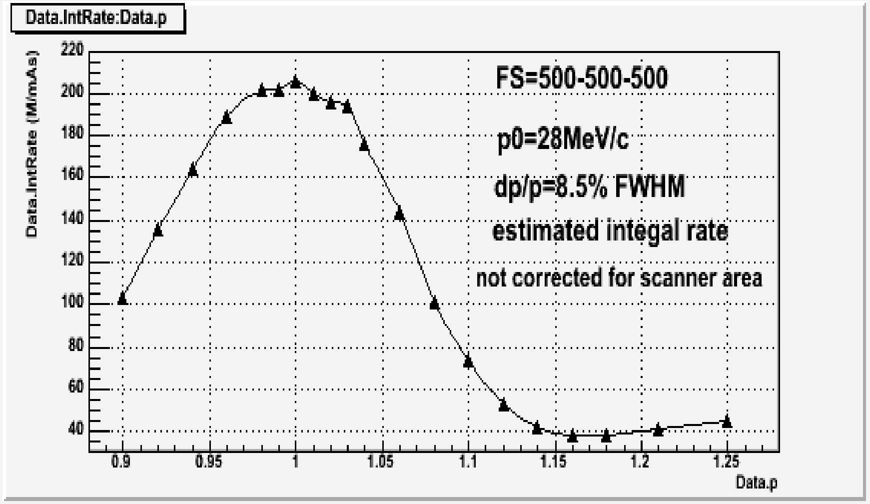
19.10.2004 12:30:20

Δp/p for WSX on









Results for new μE4 (4-cm Tgt E, 28 MeV/c):

- Accepted solid angle: 150 msr
- $\Delta p/p$ (FWHM): 4.5% – 8.5% (1.5% – 11% for WSX-off)
- Max. Intensity (at Sep entry): 700 M/s (@1.9mA) (40 M/s for WSX-off, e+/μ+ = 5)

  on LEM Moderator (Sep off): 185 M/s (@1.9mA) (25 M/s for WSX-off)

  on LEM Moderator (Sep on): 160 M/s (@1.9mA)
- Low-energy μ^+ rate: 20000/s (at moderator)
- Low-energy μ^+ rate: up to 7000/s (on sample, 7x more compared to πE3)
- x-y beamspot (FWHM): 7.0 x 3.5 cm^2 (2.5 x 3.5 cm^2, WSX-off)
- x-y beam divergence: 135 x 320 mr^2 (from TRACK calculation)

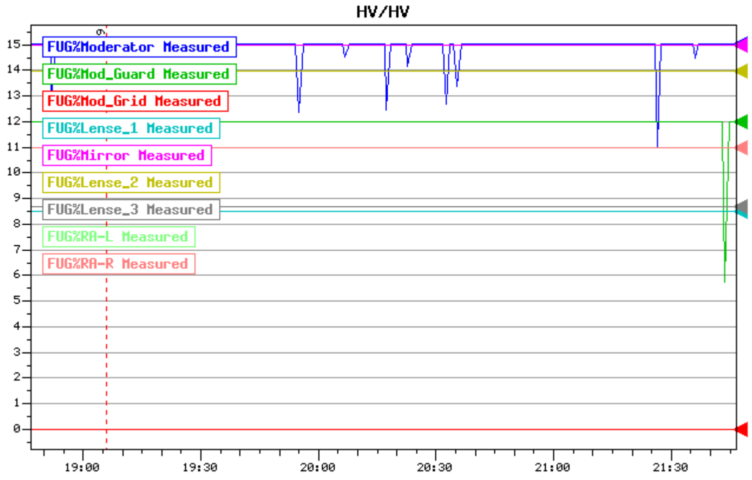
Intensity on moderator as proposed. Good agreement between experiment and TRACK ray-

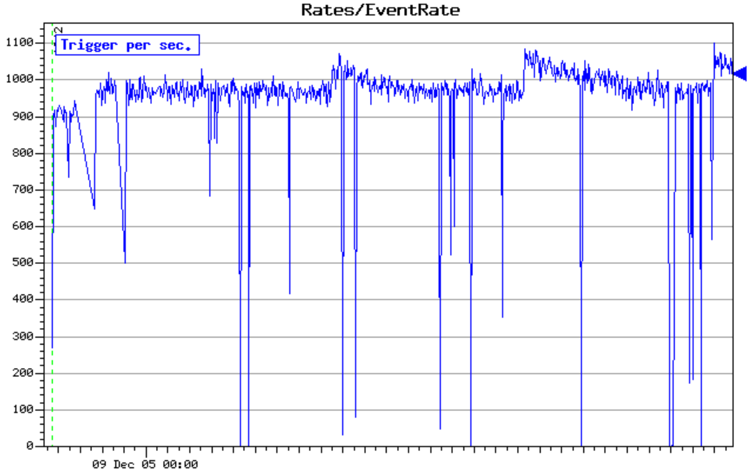
Total cost: ~ 2.3 MFr. (Financial support by TU Braunschweig + U Konstanz (BMBF), U Birmingham (UK EPSRC), U Zürich, U Leiden)

New LEM apparatus results

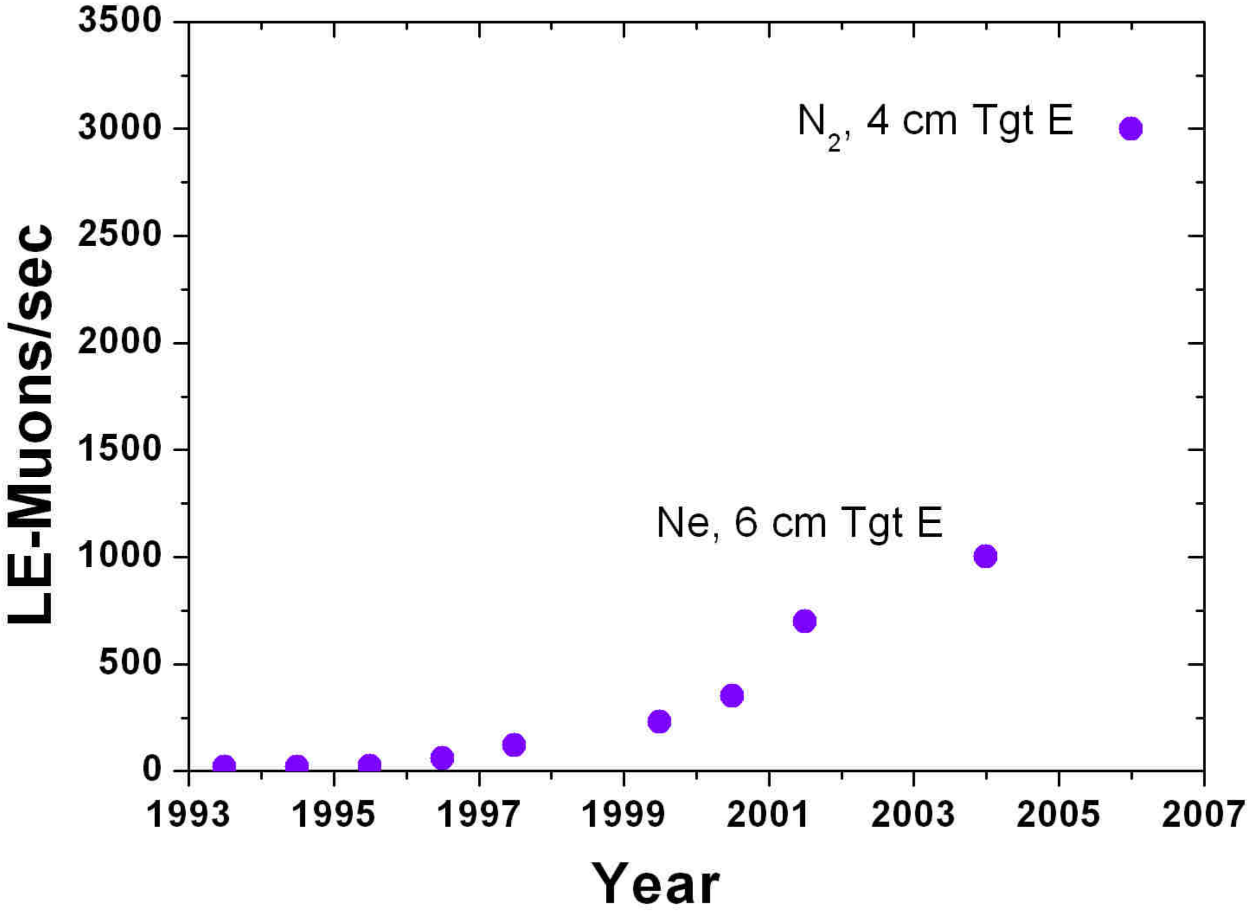
- LE μ intensities at sample:

Moderator	**Muons /sec (@1.9 mA)**	**Remarks**
s-N$_2$	**3000** **(1000 events/s** **3.6 Mev/h)**	**Tested for experiments,** **Not yet optimum**
s-Ar	**4500**	**Tested with Beam**
s-Ne	**7500**	**Not yet tested with beam**

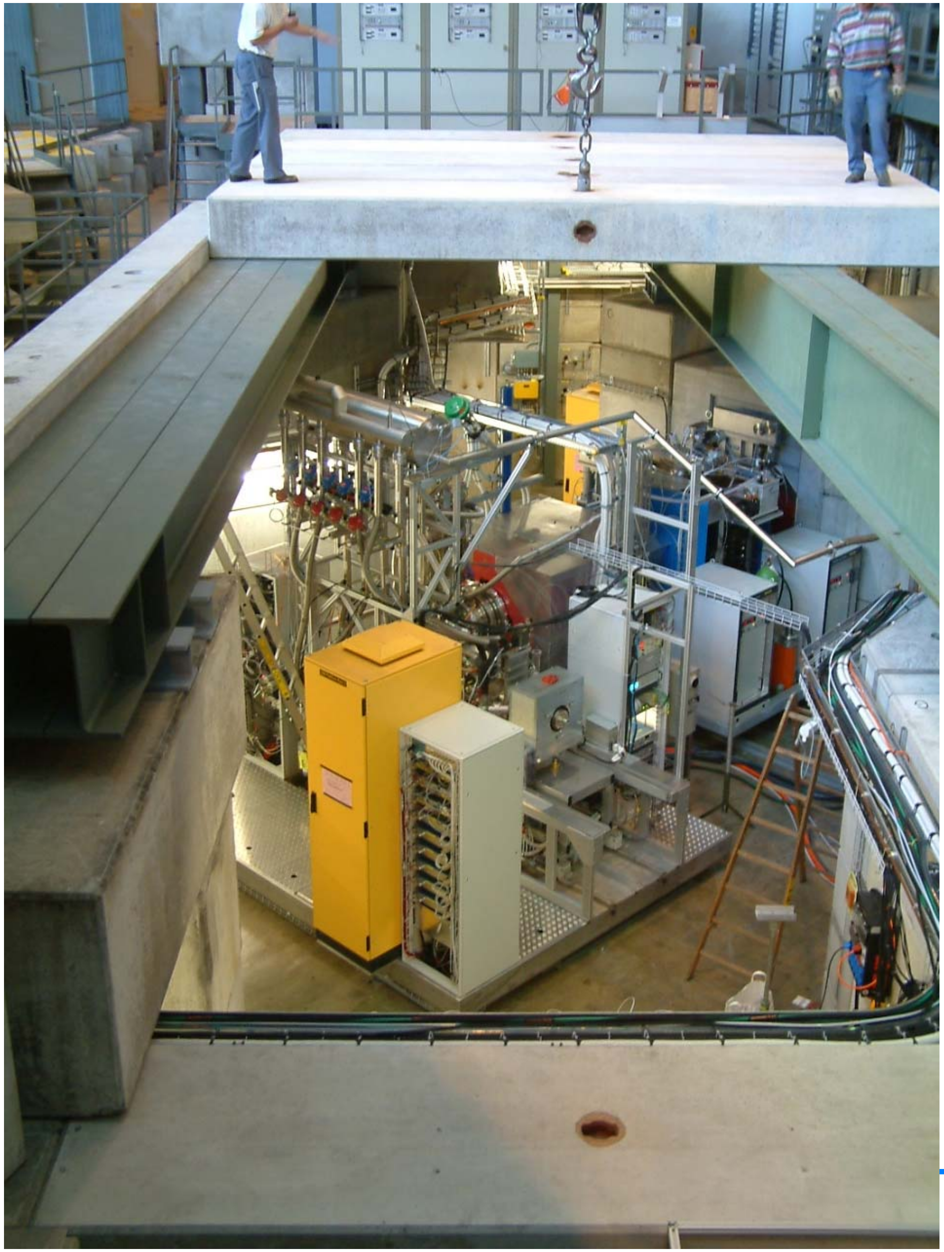




LE muons at sample



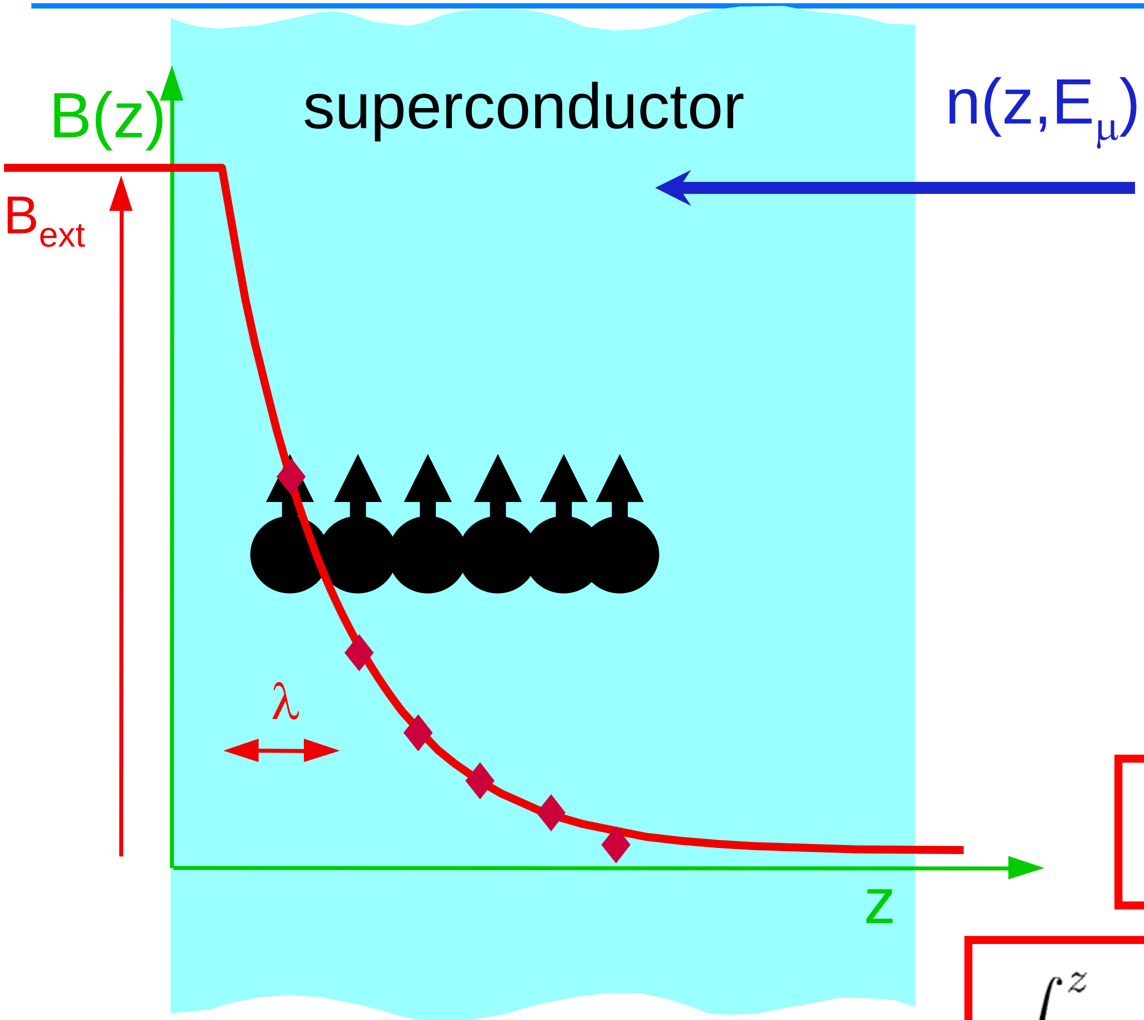
μE4 shielding roof



LEM Experimental Program

- **Magnetism**
  - **Interlayer exchange coupling** in multilayers, superparamagnetism in mass selected nanoclusters, Magnetic ordering in buried, strained/stressed films, surface vs bulk magnetism in LaCoO$_3$
- **Superconductivity (near surface)**
  - **Non-local effects, Isotope effects**, Vortices across surface, Vortex motion and pattern formation in 2D
- **Interplay/Coexistence Magnetism/Superconductivity**
  - YBCO/SRO superlattices, **Fe/Pb multilayers**, YBCO/PBCO/YBCO multilayers, Spin glass transition /sc in LSCO meanderfilms, Surface magnetism/superconductivity in La$_{1.9}$Ce$_{0.1}$CuO$_4$, search for spontaneous magnetization at the surface of YBCO110
- **Dimensional or surface effects**
  - Surface polymer dynamics, Finite size effects in spin glass freezing,
  - Surface vs bulk magnetism in LaCoO$_3$
- **Hydrogen states and dynamics in semiconductors and dieletrics**
  - Low k-materials (nanoporous silica), hydrogen states in semiconductor and insulating films
- **Basics of LE-μSR**
  - Implantation studies, behavior at surfaces, diffusion at interfaces, muon moderation studies

Depth dependent LE-μSR studies



muon implantation profile for a particular muon energy E_μ

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

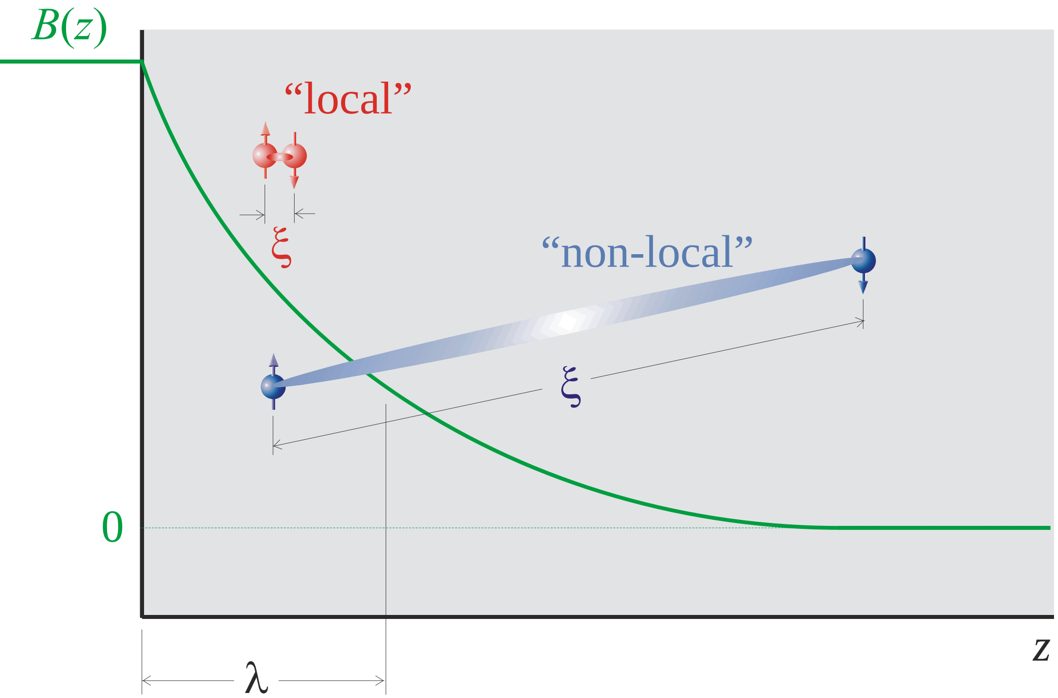
$$n(z,E)\,\mathrm{d}z = p(B,E)\,\mathrm{d}B$$

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

→magnetic field profile B(z)

→Characteristic lengths of the sc λ, ξ

Magnetic field profiles in superconductors



→ Direct, absolute measurement of **magnetic penetration depth**

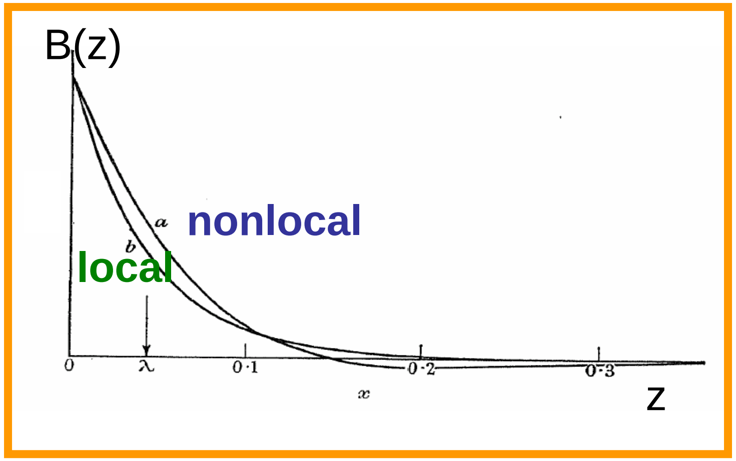
$$\lambda(T) \propto \sqrt{\frac{m^*}{n_s(T)}}$$

←effective mass

←density of supercarriers

→ Direct Test of theories (London, BCS)

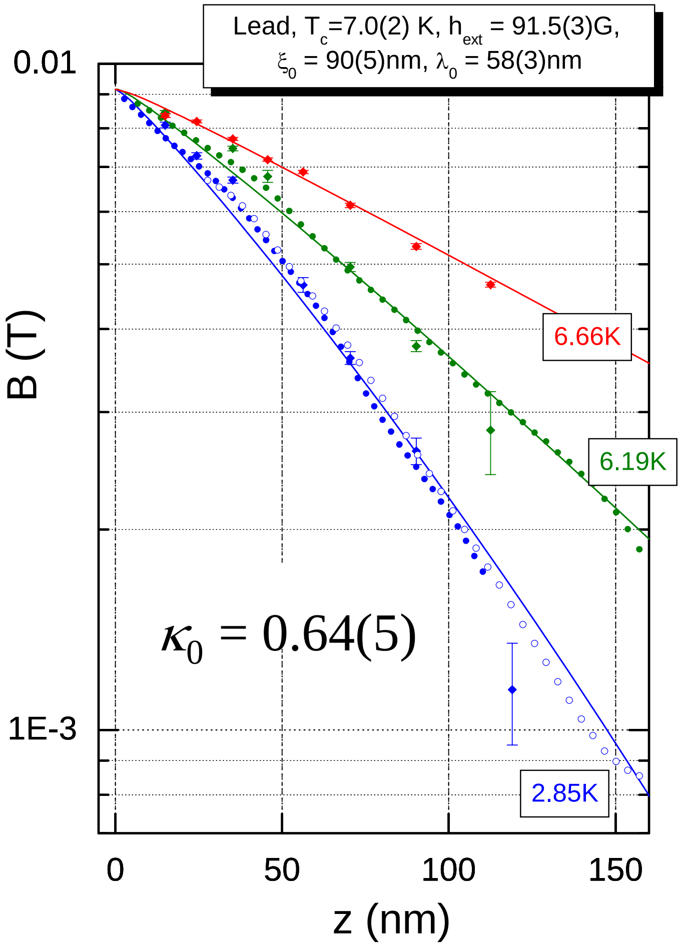
$$\rightarrow B(z) = B_0 e^{-\frac{z}{\lambda_{ab}(T)}}$$

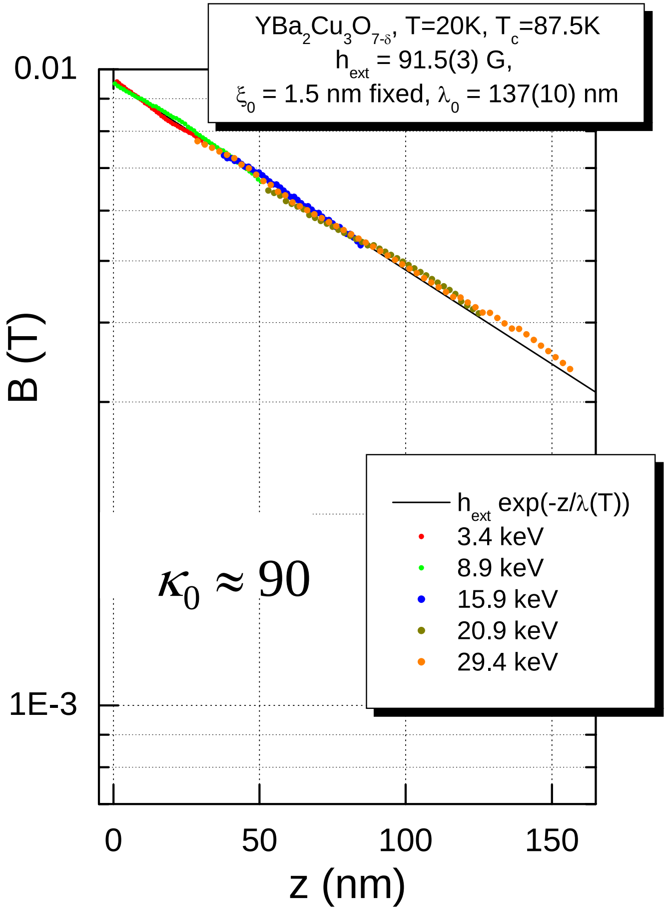


→ Local, non-local response

→ Determination of the coherence length ξ, and $\kappa = \lambda/\xi$

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





non-local ←→non- exponential

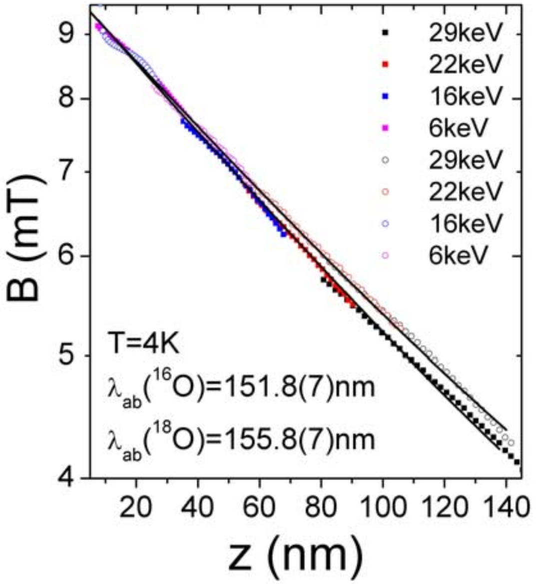
local ←→ exponential

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

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

Isotope effect $YBa_2Cu_3O_{7-\delta}$

$YBa_2Cu_3O_{7-\delta}$ Film



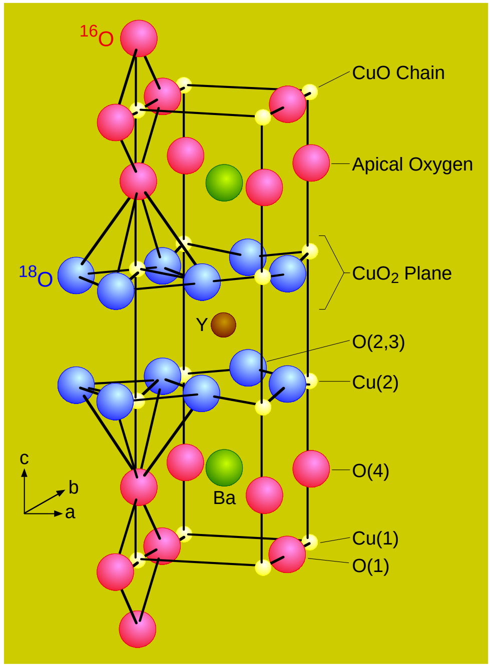
Oxygen isotope effect on the magnetic penetration depth.

$$2.8\,\% = \frac{\Delta\lambda_{ab}}{\lambda_{ab}} = \frac{1}{2}\left(\underset{\substack{\Downarrow\\ 5.6\,\%}}{\frac{\Delta m_{ab}}{m_{ab}}} - \underset{\substack{\Downarrow\\ \cong 0}}{\frac{\Delta n_s}{n_s}}\right)$$

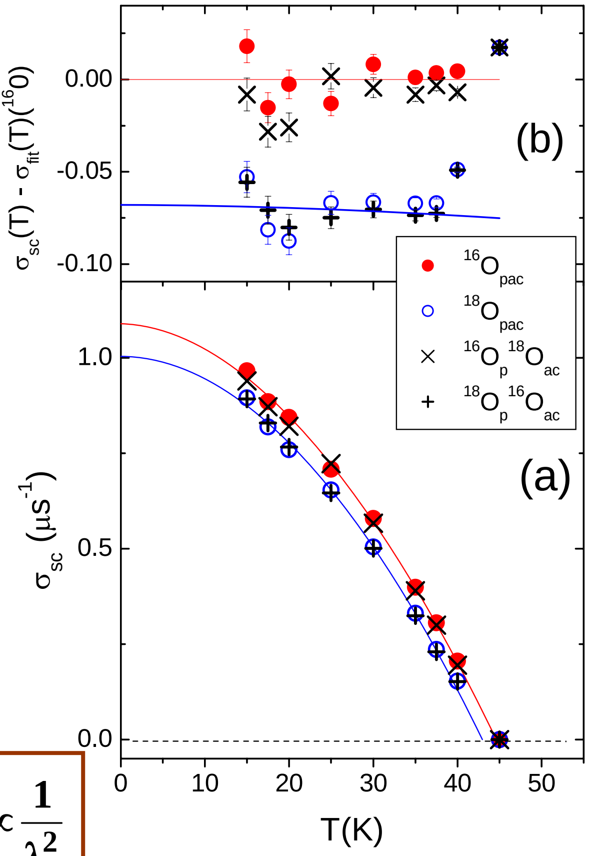
Which Oxygen in the crystal lattice mainly contributes to the effect?

→ Selective site substitution

Structure of $YBa_2Cu_3O_{7-\delta}$



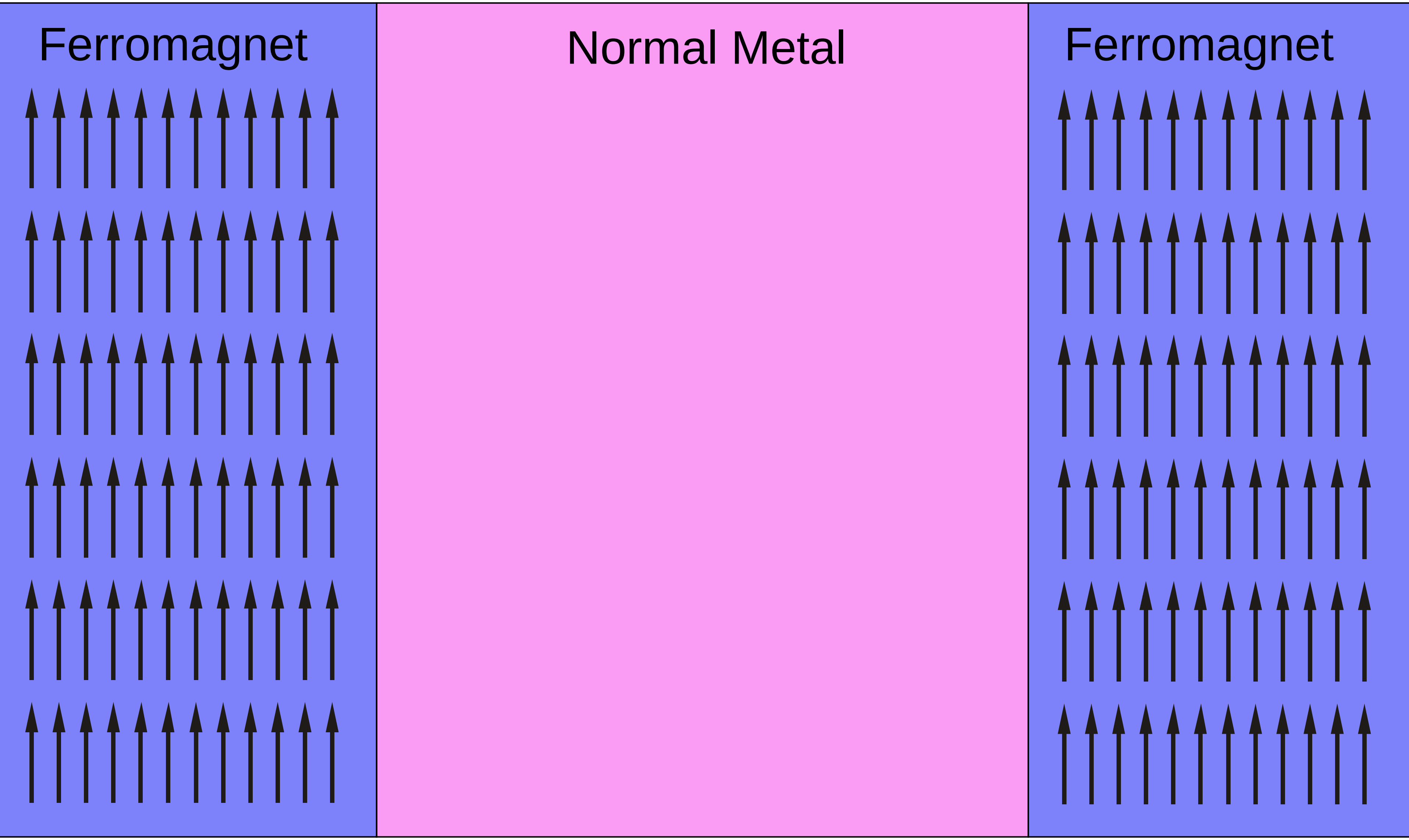
$Y_{0.6}Pr_{0.4}Ba_2Cu_3O_{7-\delta}$ Powder



$$\boxed{\sigma \propto \frac{1}{\lambda^2}}$$

R. Khasanov, D.G. Eshchenko, H. Luetkens, E. Morenzoni, T. Prokscha, A. Suter, N. Garifianov, M. Mali, J. Roos, K. Conder, and H. Keller Phys. Rev. Lett. **92**, 057602 (2004)

Magnetic/non-magnetic Multi-layers

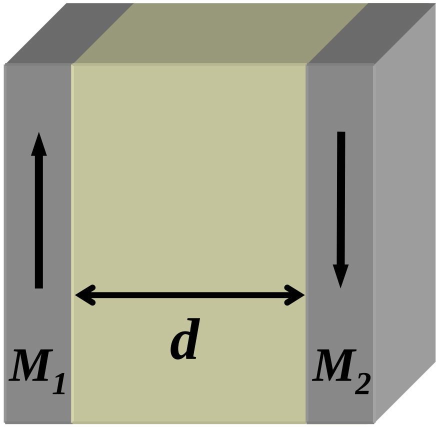


Ferromagnet

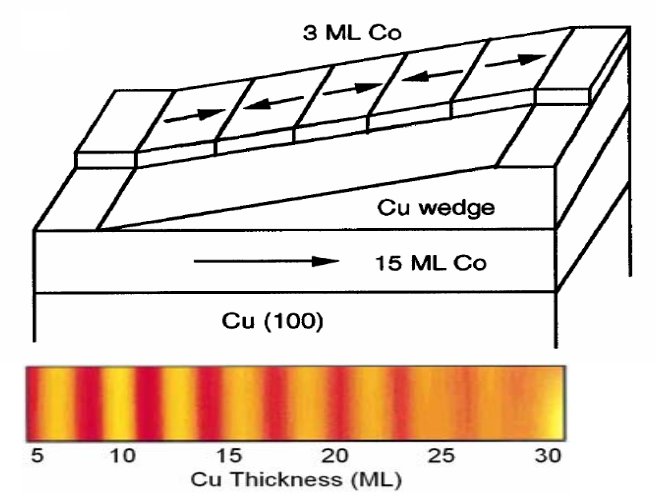
Normal Metal

Ferromagnet

Interlayer exchange coupling in magnetic ML



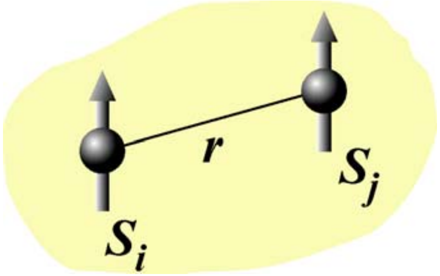
$$\mathcal{H}_{\mathrm{IEC}} = -J(d)\, \boldsymbol{M_1} \cdot \boldsymbol{M_2}$$



- IEC oscillates with spacer thickness (RKKY or Quantum-well models)
- Different techniques to probe the FM layer (polarization of secondary electrons, MOKE, …)
  → oscillation period, coupling strength
- It is **much more difficult to measure the polarization in the non-magnetic spacer layer**
- Muons can locally probe **the polarization of the non-magnetic spacer mediating the coupling**

RKKY Model

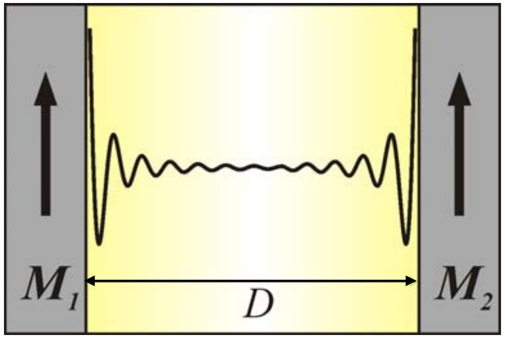
Magnetic Atoms:



$$\mathcal{H}_{\mathrm{RKKY}} = -J(r)\, \boldsymbol{S_i} \cdot \boldsymbol{S_j}$$

$$J(r) \propto \frac{1}{r^3} \cos(2k_F r + \phi)$$

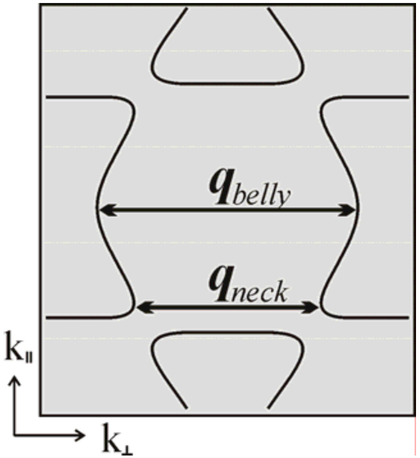
Magnetic Films:



$$E = -J(D)\, \boldsymbol{M_1} \cdot \boldsymbol{M_2}$$

$$J(D) \propto D^{-2} \sin(qD + \phi)$$

Non-spherical Fermi-surfaces:

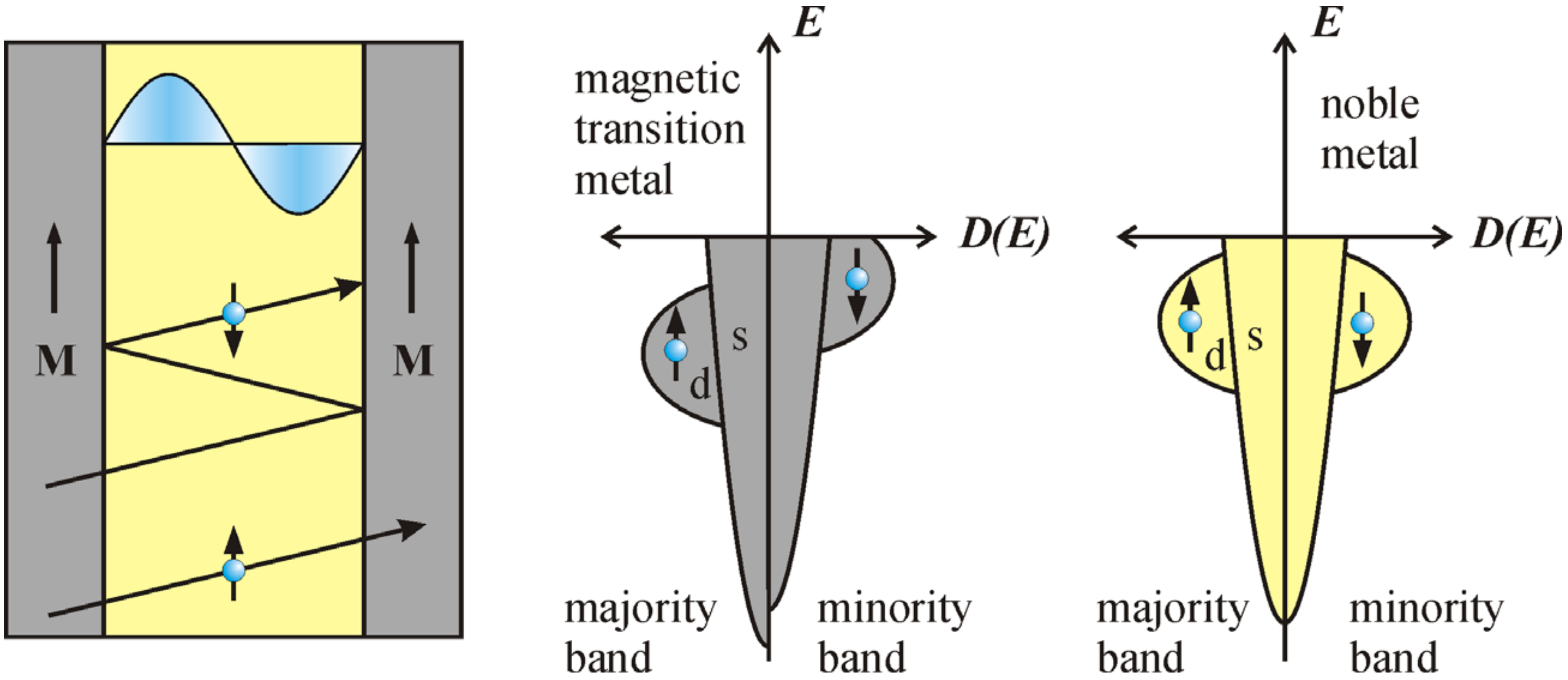


Extremal spanning vectors dominate the coupling

$$(\mathrm{Ag}: \ \Lambda_{\mathrm{belly}} = 1.2\,\mathrm{nm}, \ \Lambda_{\mathrm{neck}} = 0.47\,\mathrm{nm})$$

→ $$J(D) \propto \sum_i A_i\, D^{-2} \sin(q_i D + \phi_i)$$

Quantum Well States



Minority electrons are reflected at the interface

⇓

Minority electrons are confined within the spacer

Predictions of the models

IEC oscillates as a function of spacer thickness D

IEC is dominated by extremal spanning vectors in the Fermi surface of the spacer

Coupling strength varies like D^{-2}

Both models imply a spatially oscillating electron spin polarization $M(x)$ within the spacer (implicitly or explicitly)

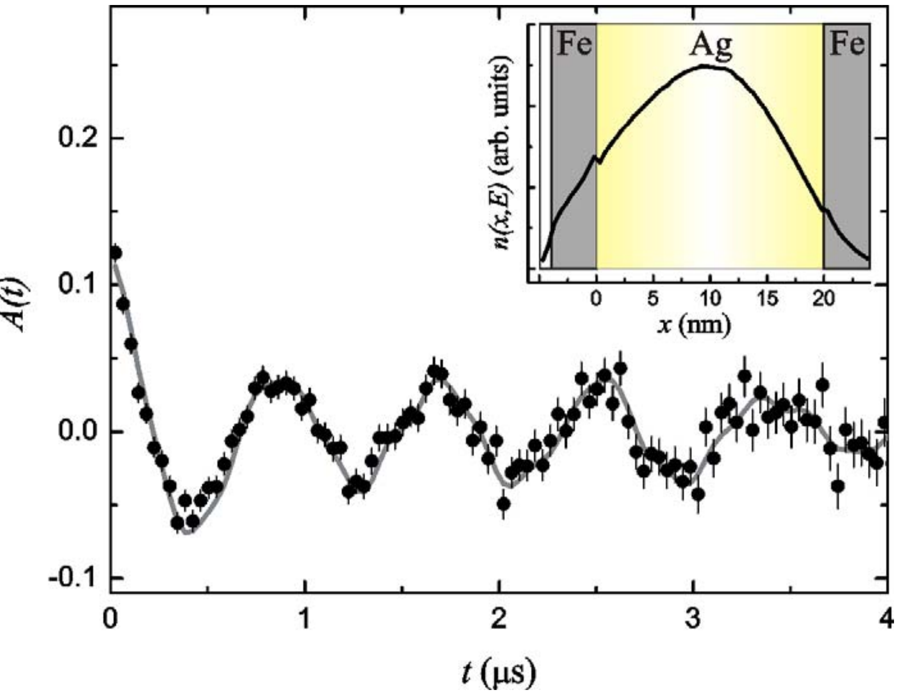
Problem:

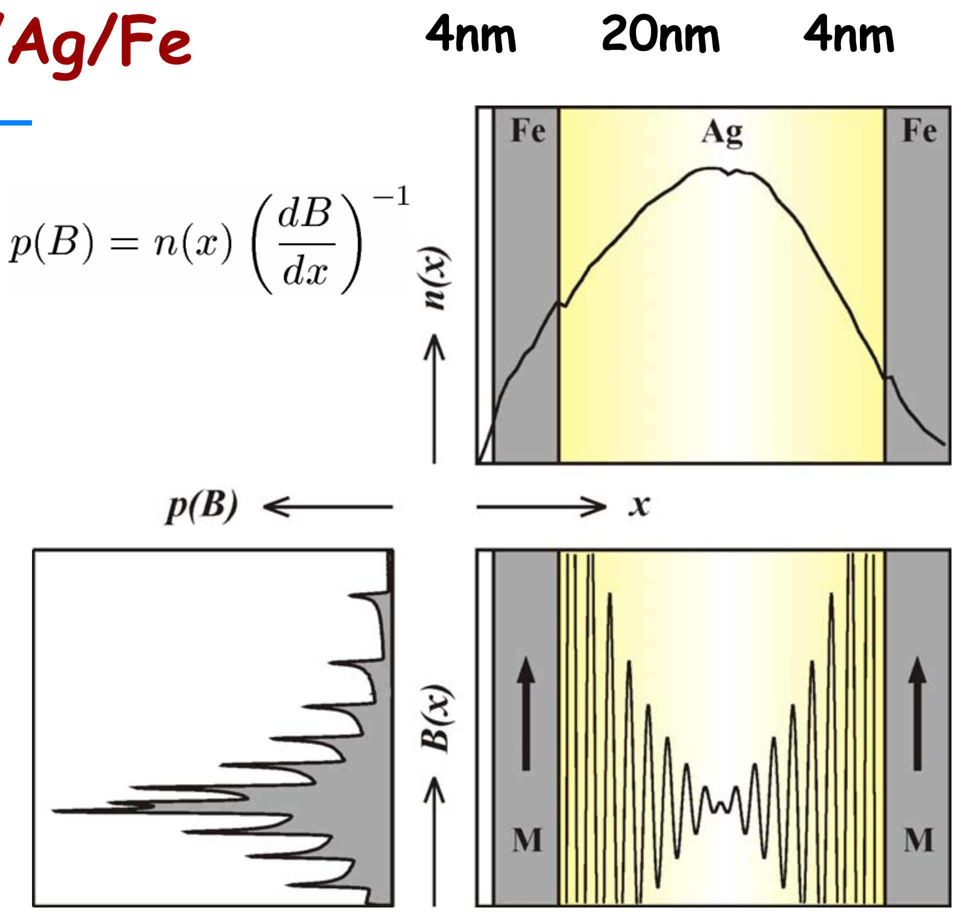
There is no general analytic theory for $M(x)$ including the confinement of electron states in the spacer

- For Co/Cu/Co (Mathon *et al.*):
  - $M(x)$ oscillates with the same periods as the IEC
  - Non-confined electron states: $M(x) \propto x^{-2}$
  - Totally confined electron states: $M(x) \propto x^{-1}$

LE-μSR in Fe/Ag/Fe

B_{ext} = 87 G, 20 K, 3 keV





$$p(B) = n(x) \left(\frac{dB}{dx} \right)^{-1}$$

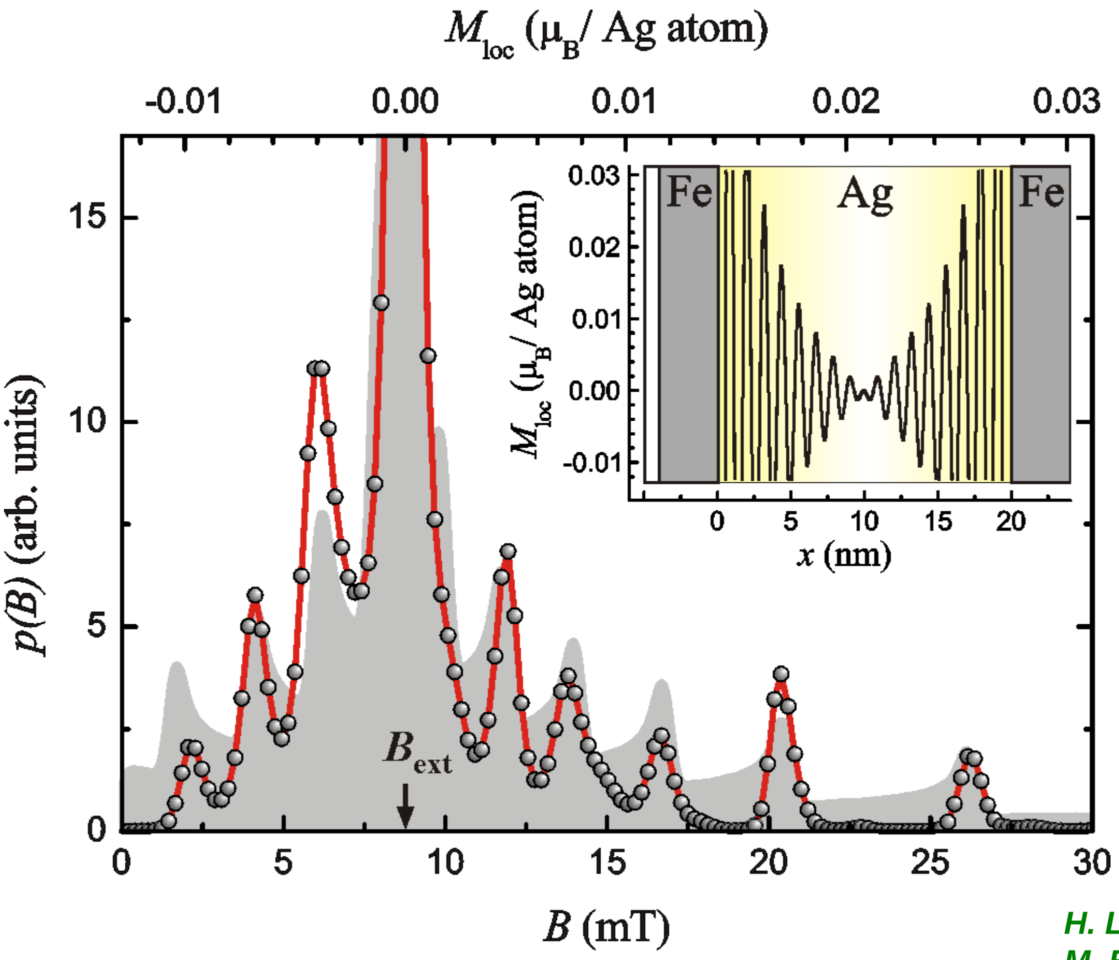
$$A(t) = A_0 \int p(B) \cos(\gamma B\, t)\, dB \implies$$

Field distribution *p(B)*

Fit-model: $B(x) \propto M(x) = \sum C_i\, x^{-\alpha_i} \sin(q_i x + \phi_i)$

Free parameters: $C_i\ ,\ \alpha_i$

LE-muons in Ag/Fe/Ag



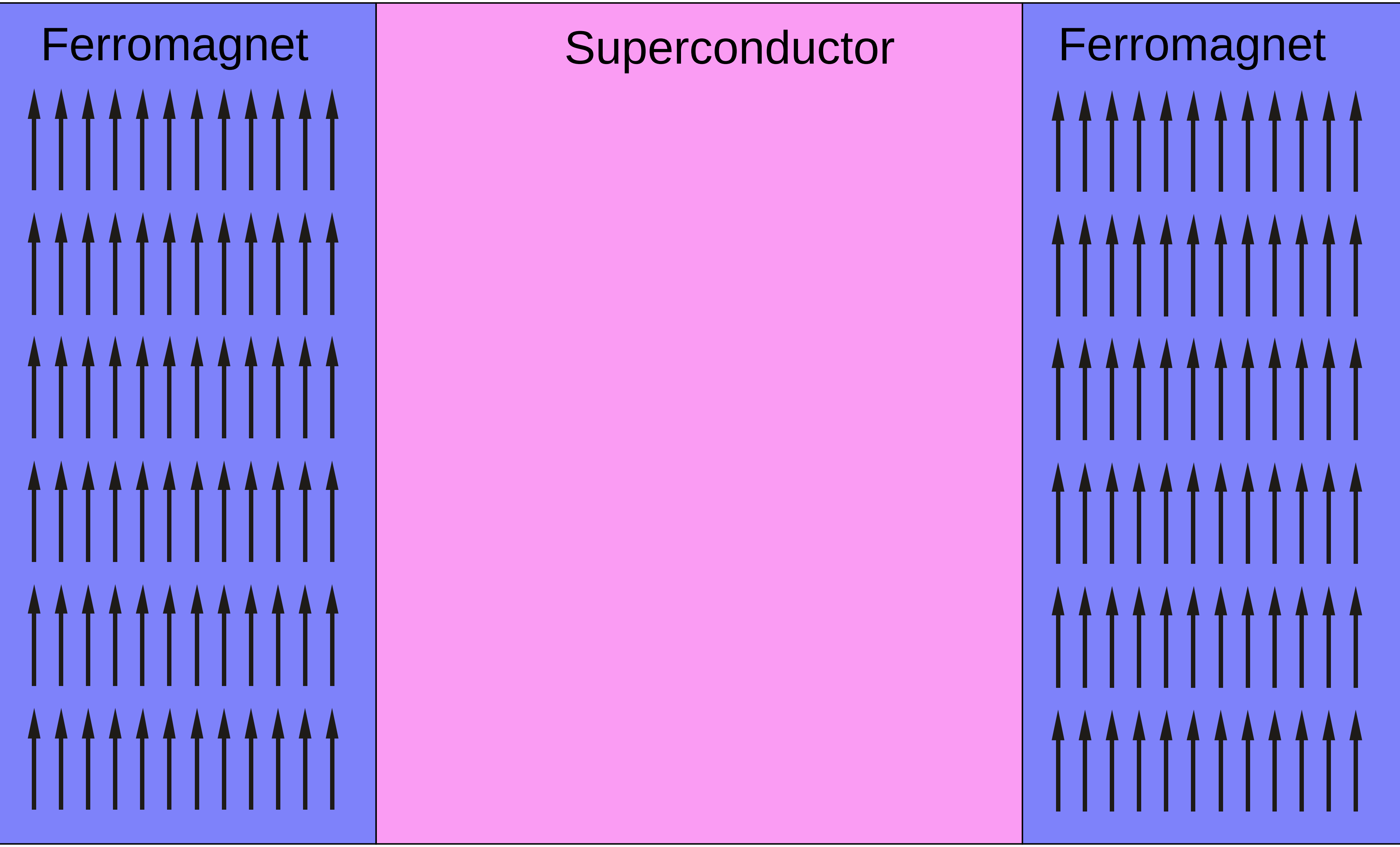
Observation of the spatially oscillating spin density in Ag !

B(x) and IEC oscillate with the same period but attenuation with distance from interface different !

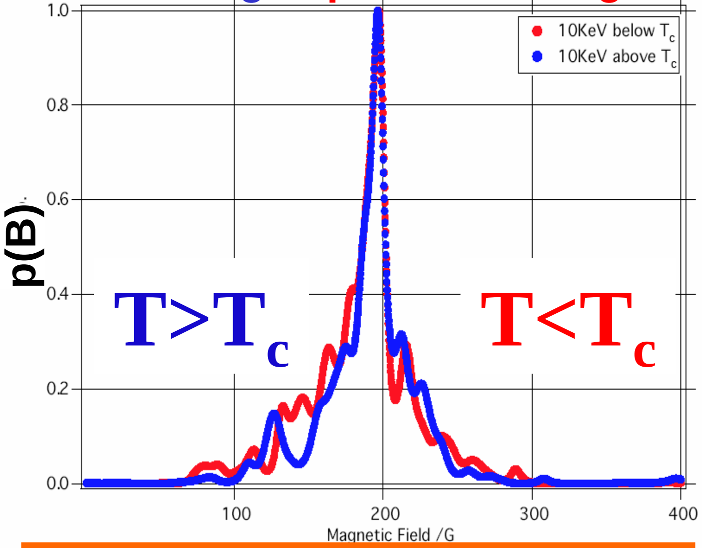
Fit: $B(x) = C\, x^{-0.8(1)} \cos(q_{belly} x + \phi)$

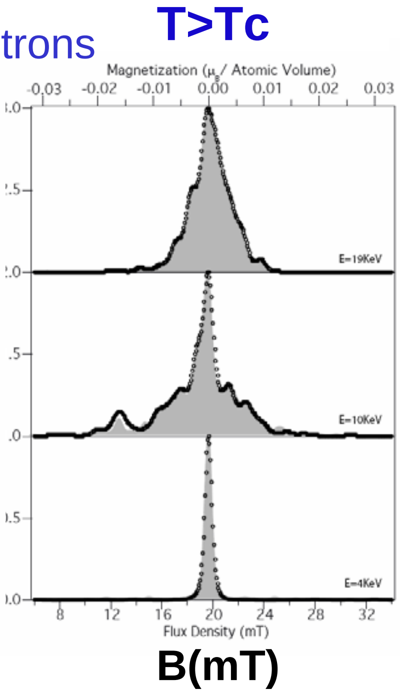
H. Luetkens, J. Korecki, E. Morenzoni, T. Prokscha, M. Birke, H. Glückler, R. Khasanov, H.-H. Klauss, T. Slezak, A. Suter, E. M. Forgan, Ch. Niedermayer, and F. J. Litterst Phys Rev. Lett. **91**, 017204 (2003).

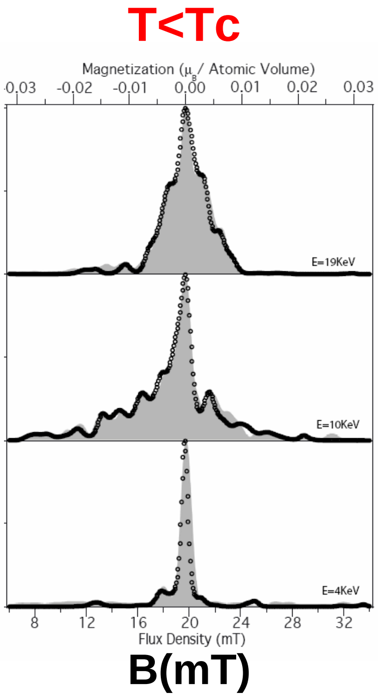
Magnetism/Superconductor ML

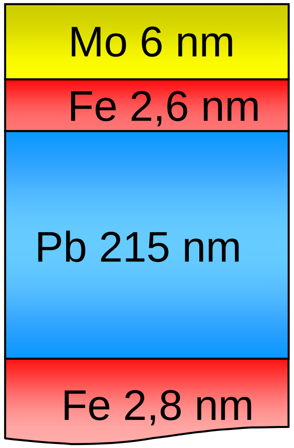


Oscillating polarisation of **conducting/superconducting** electrons









$$M(x) = \sum_i A_i \frac{\sin(2k_i x + \phi_i)}{x^{n_i}}$$

$$k_1 = 2.3(2)nm^{-1}$$
$$\phi_1 = \frac{3\pi}{2}$$
$$k_2 = 15.8(2)nm^{-1}$$
$$\phi_2 = \frac{\pi}{2}$$

$$k_1 = 2.3(2)nm^{-1}$$
$$\phi_1 = 2\pi$$
$$k_2 = 15.8(2)nm^{-1}$$
$$\phi_2 = \frac{\pi}{2}$$

- **Spin Density Wave in Pb induced above and below T_c with same wave vectors (values consistent with deHaas- van Alphen measurements of spanning vectors)**
- **Below T_c: enhancement of SDW and 90^0 phase shift of long wave length component**
- **Coexistence of the SDW with bulk superconductivity in the fm/sc tri-layer and interaction between the two forms of order.**

$A(T<T_c) / A(T>T_c) = 1.25$

A. J. Drew, S. L. Lee, D. Charalambous, A. Potenza, C. Marrows, H. Luetkens, A. Suter, T. Prokscha, R. Khasanov, E. Morenzoni, D. Ucko E. M. Forgan Phys Rev. Lett. **95**, 197201 (2005).

LEM collaboration

PSI: E. Morenzoni, T. Prokscha, A. Suter, H. Luetkens(50%), H.P. Weber (technical support)

U Leiden: G. Nieuwenhuys (guest at PSI at the moment), S. Vongtragool (Post-Doc at PSI)

U Zurich: H. Keller, D.G. Eshchenko (Post-Doc at PSI), T. Paraïso (PhD student at PSI)

TU Braunschweig: J. Litterst, M. Dubman (PhD student at PSI)

U Birmingham: E.M. Forgan, S. Ramos (Post-Doc), R. Lycett (PhD student)

new μE4 beam: R. Kobler, K. Deiters, S. May and support groups of GFA/PSI

PAUL SCHERRER INSTITUT