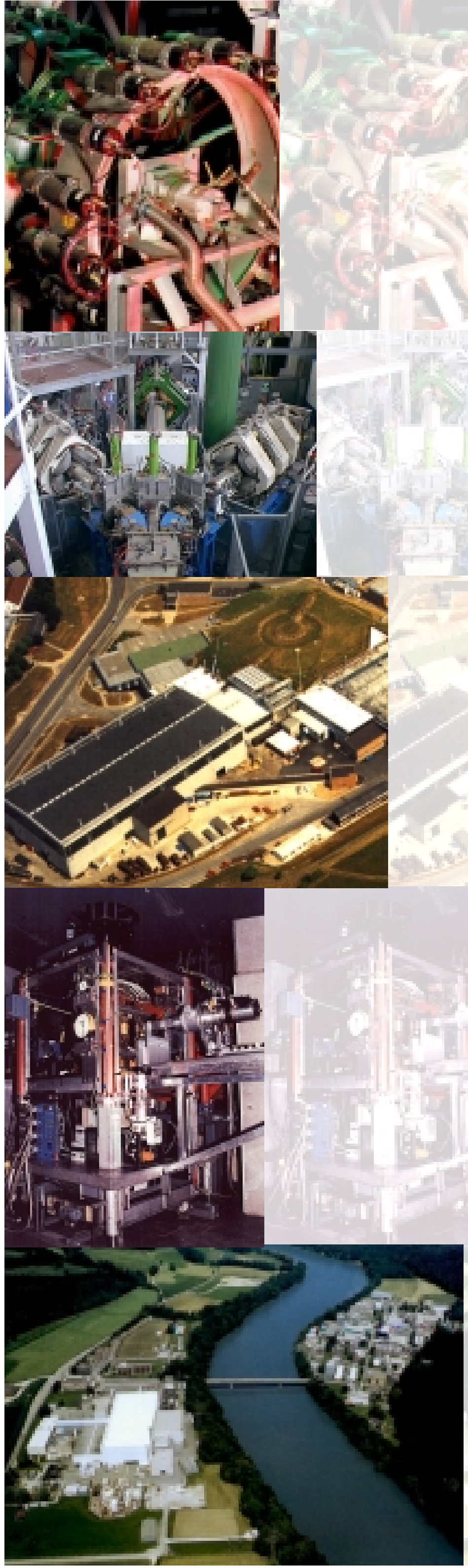

Muon Beam Research in Condensed Matter Science:

achievements and prospects

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Vice President of the International Society for Muon Spectroscopy (ISMS)

President of ISMS-Europe

European Research Infrastructure Symposium - EPS12 Budapest - 27 August 2002

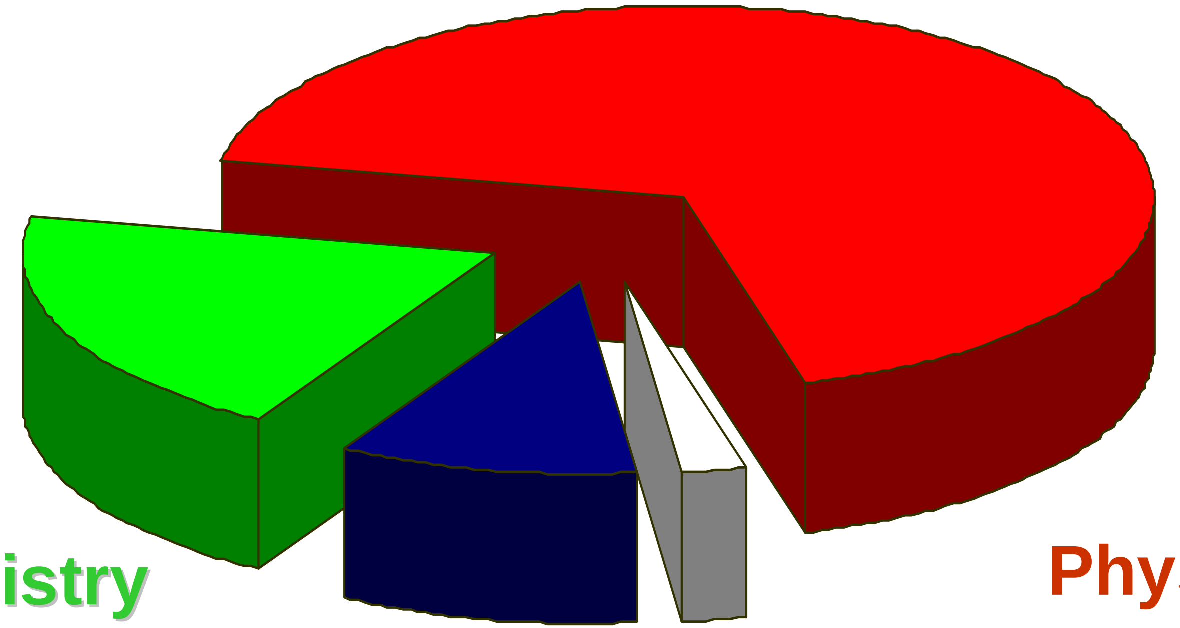
The European Spallation Source

The scientific and technical case for ESS has now been made...

ESS is emerging as *the* “European Source of Science”

…….not just as a world leading source of neutrons but also of exotic nuclei, neutrinos, pions and muons…..

Applications of muon beams



Chemistry

Molecular dynamics
Oxides
Muonium

Materials

Polymers
Semiconductors
Hydrogen in metals

Biology

Proteins

Physics

Magnetism
Superconductivity
Surfaces
Fundamental physics

Some μSR highlights

- First observation of magnetic order in the high T_c cuprate superconductors
- Detailed characterisation of the vortex state in conventional and exotic superconductors
- First direct observation of the predicted evolution of Kohlrausch relaxation in spin glasses above T_g
- Observation of ultra small moment ordering in heavy fermion and organic compounds
- New insights in to the trapping and detrapping of hydrogen in semiconductors
- 1S-2S transitions in muonium and challenges to the Standard Model

μSR - a universal acronym

…..which stands for **Mu**on **S**pin **R**otation,
Relaxation
Resonance

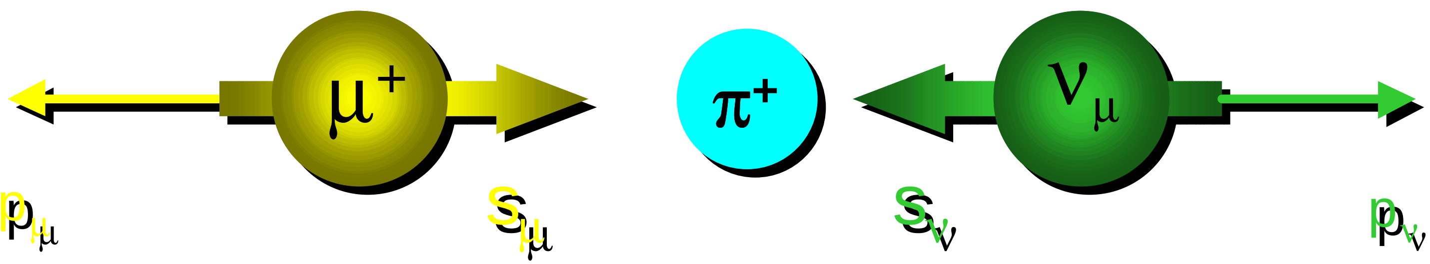
rotation describes the dephasing of muon spins by local magnetic fields with an applied field transverse to the muon spin direction

relaxation describes the time-dependent loss of polarisation of the muon spins by internal fields either in zero applied field or in a field applied parallel to the initial muon spin direction

resonance is associated with RF induced transitions (*cf NMR*)

Muon production from pions

Charge state	π^+	π^-
Mean lifetime (s)	26×10^{-9}	26×10^{-9}
Spin	0	0
Mass (MeV)	139.57	139.57
Decay mode	$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

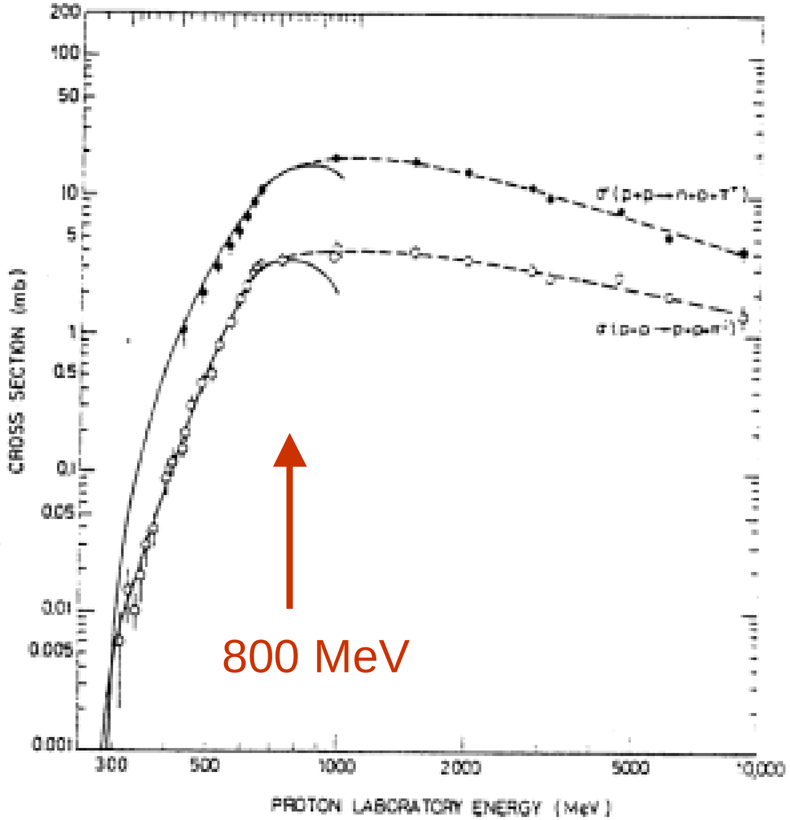


100% polarised "*surface*" positive muons (~4MeV) are generally used for condensed matter studies

Pion production

Single pion production

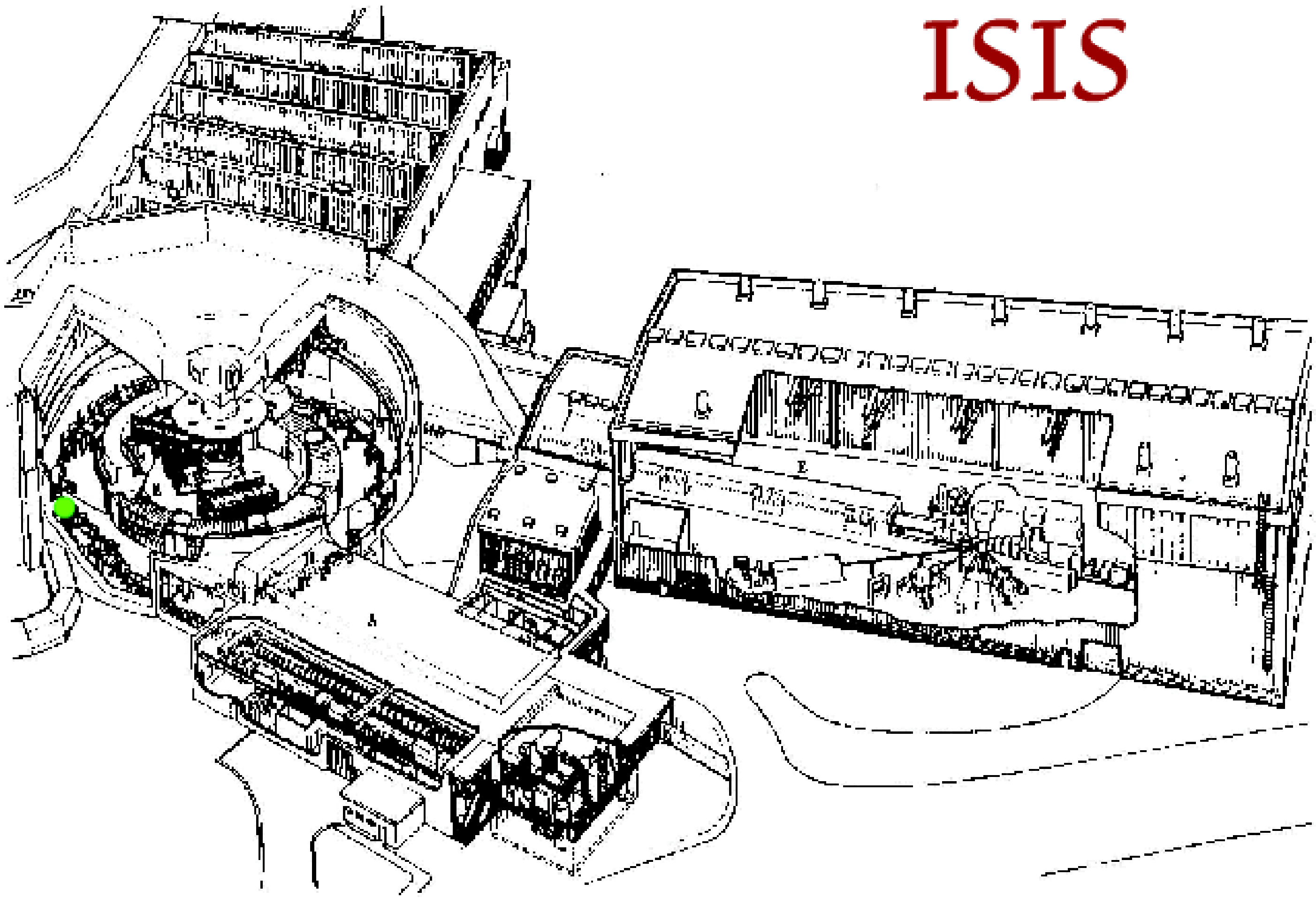
$$p + p \rightarrow p + n + \pi^{+}$$
$$\rightarrow p + p + \pi^{o}$$
$$p + n \rightarrow p + n + \pi^{o}$$
$$\rightarrow p + p + \pi^{-}$$
$$\rightarrow n + n + \pi^{+}$$



eg, proton bombardment of a graphite target

See Eaton and Kilcoyne in "Muon Science" eds Lee, Kilcoyne and Cywinski, 1998

Pulsed muon production at ISIS

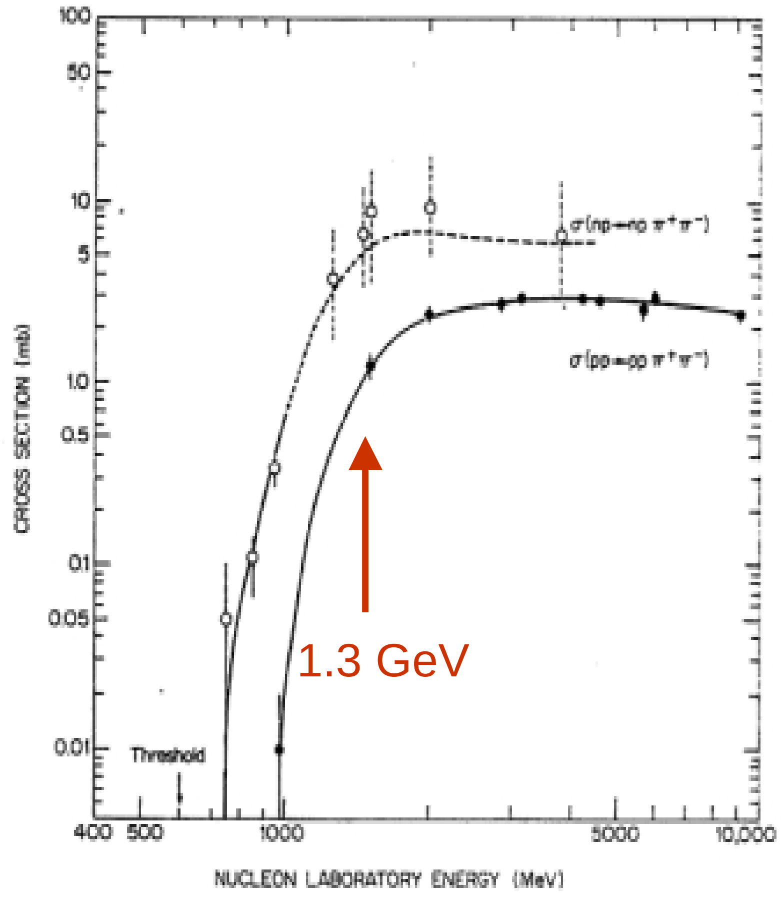


RAL's 800MeV, 200mA proton accelerator-based pulsed neutron and muon facility (UK)

Pion production

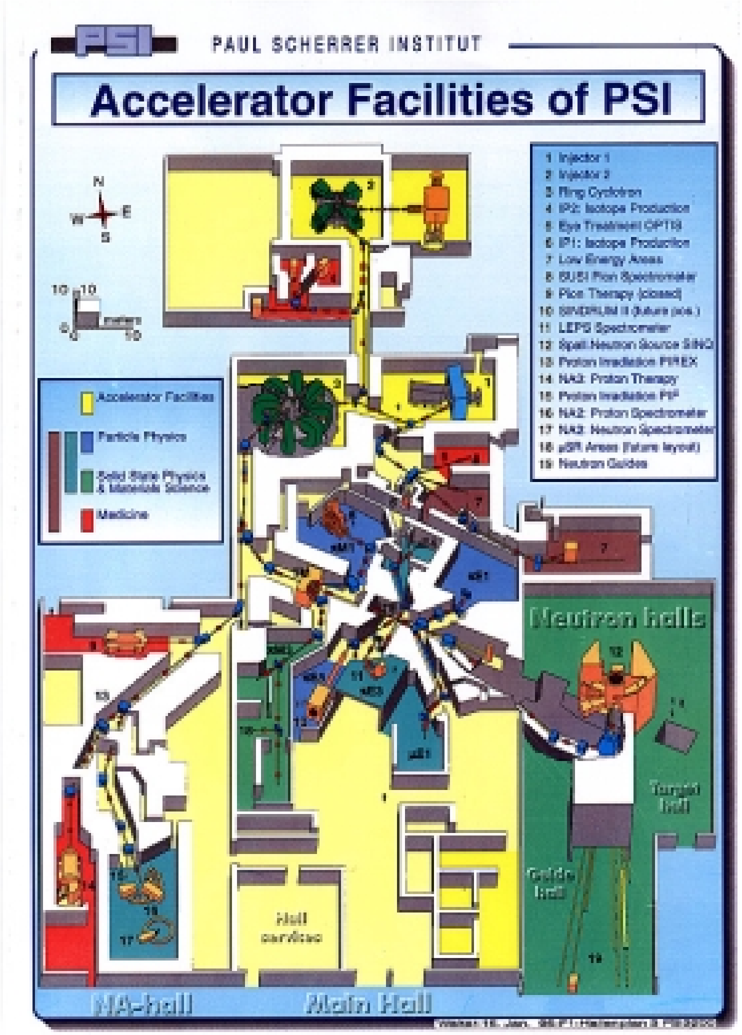
Double pion production

$$p + p \rightarrow p + p + \pi^{+} + \pi^{-}$$
$$\rightarrow p + p + \pi^{o} + \pi^{o}$$
$$\rightarrow n + \pi + \pi^{+} + \pi^{+}$$
$$\rightarrow n + p + \pi^{+} + \pi^{o}$$
$$p + n \rightarrow p + n + \pi^{+} + \pi^{+}$$
$$\rightarrow p + n + \pi^{o} + \pi^{o}$$
$$\rightarrow n + n + \pi^{+} + \pi^{o}$$
$$\rightarrow p + p + \pi^{+} + \pi^{-}$$

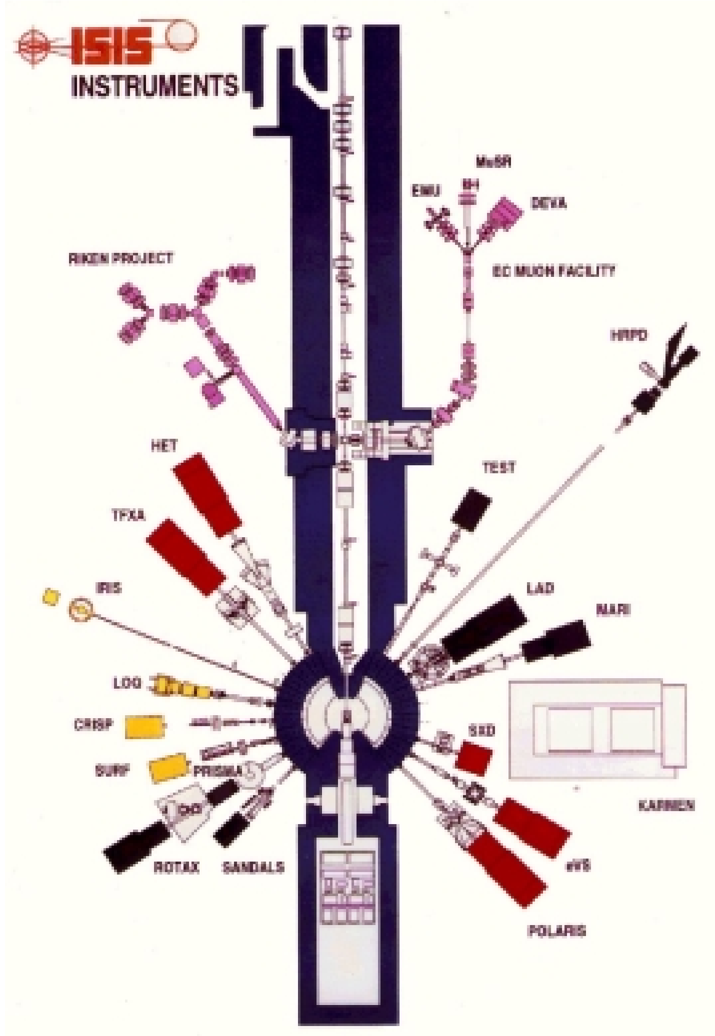


See Eaton and Kilcoyne in "Muon Science" eds Lee, Kilcoyne and Cywinski, 1998

Europe’s muon facilities



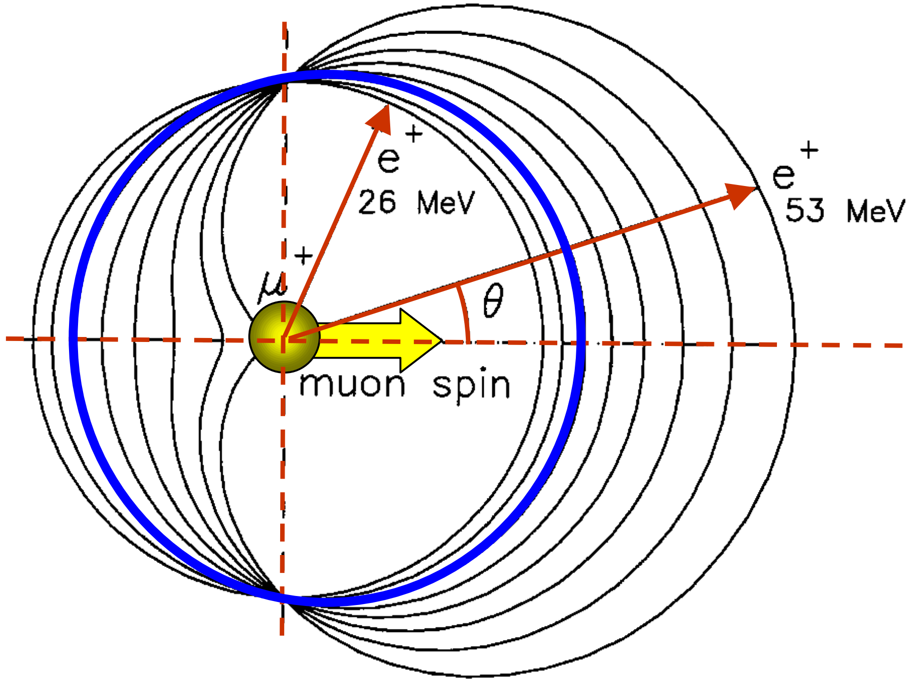
PSI, (Villigen, Switzerland)
- a continuous muon source



ISIS, (RAL, UK)
- a pulsed muon source

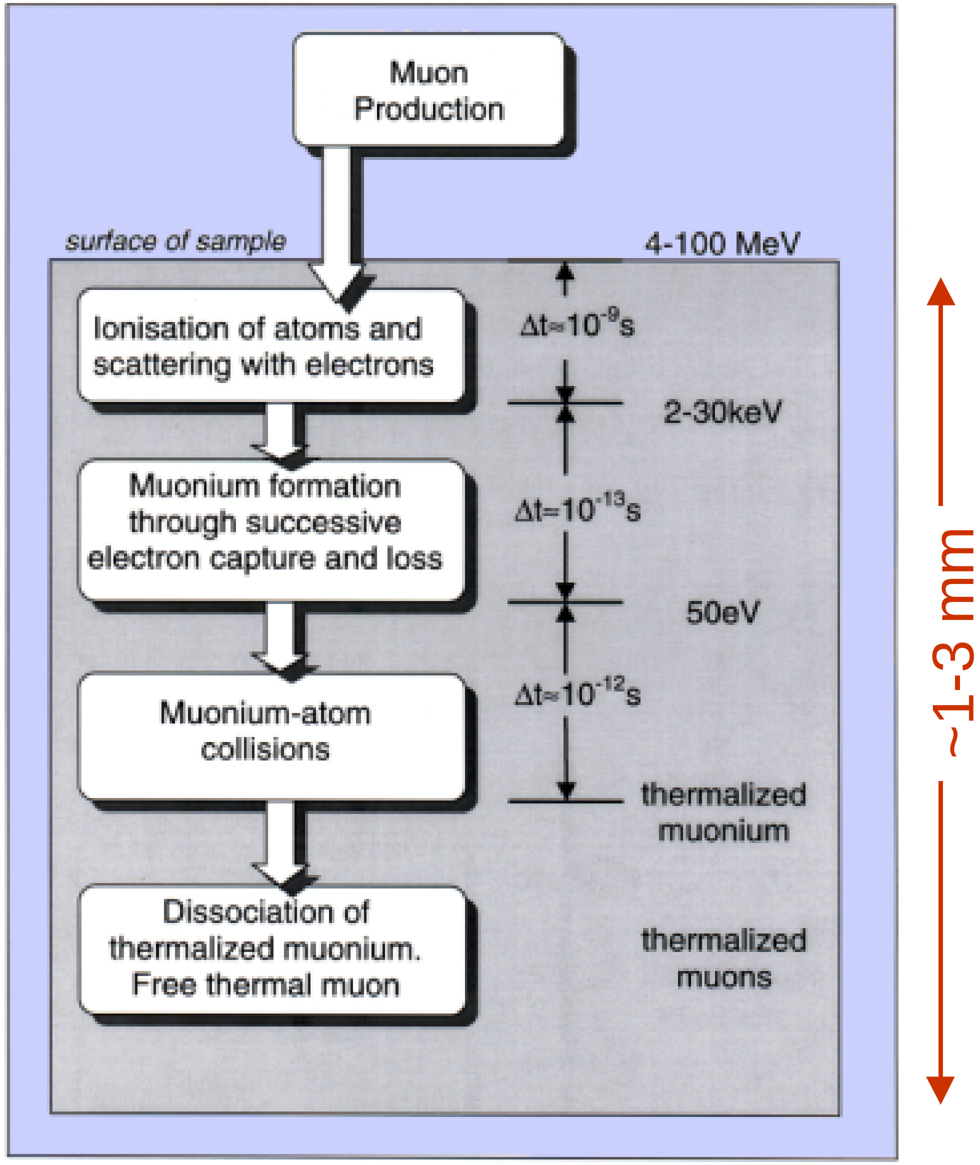
Properties of the muon

Mass:	0.1126 x M_p
Charge:	+ (-)
Gyromagnetic ratio:	$1.355342\times10^{8}\ s^{-1}T^{-1}$
Lifetime:	2.19714μs
Decay asymmetry:	$W(\theta) = 1+a_0\cos\theta$



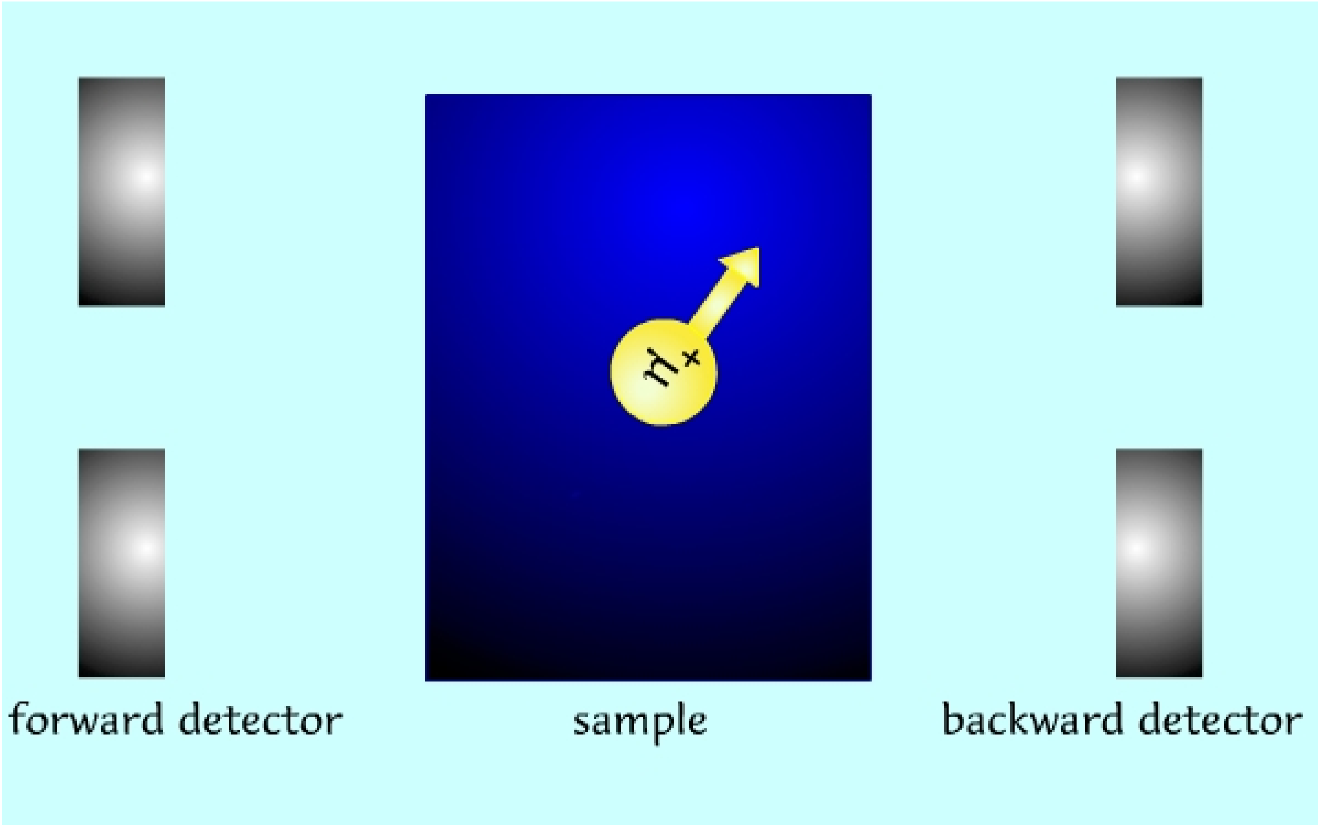
a_o~0.25

Implanting the muon in a sample



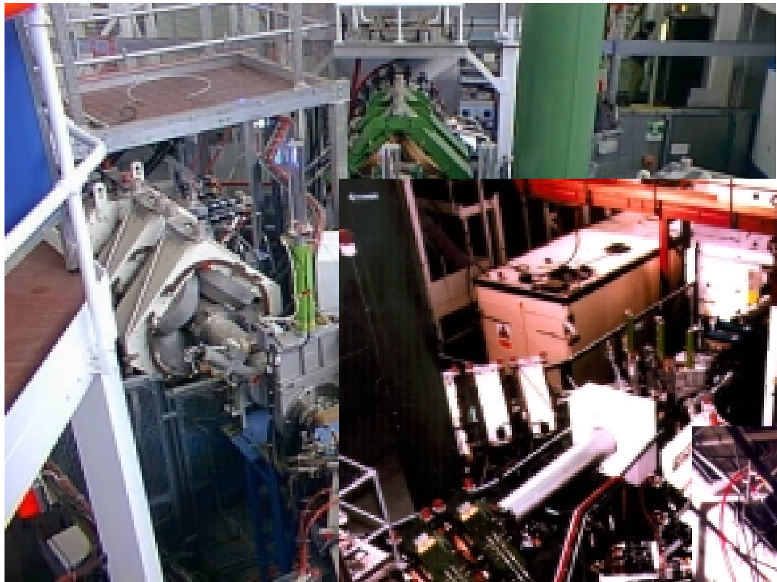
Implantation is rapid and occurs without loss of muon polarisation

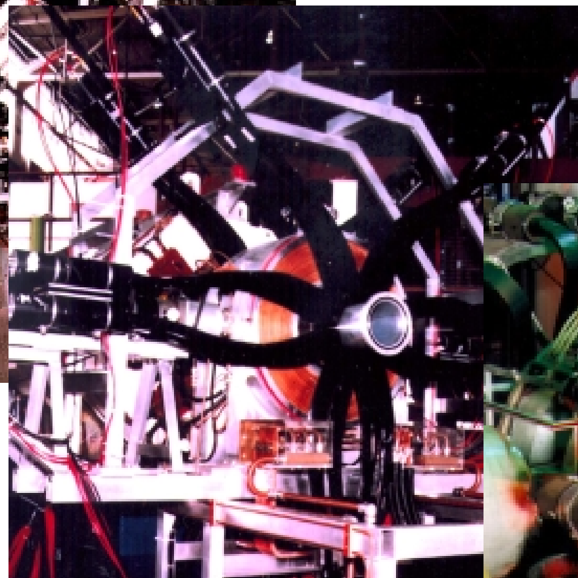
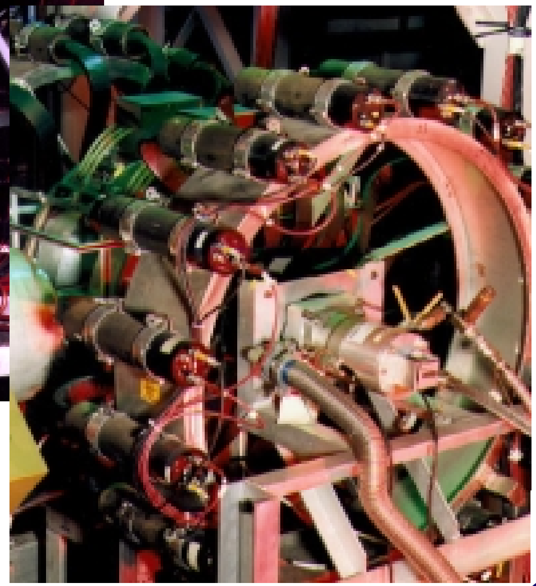
Muon precession and decay



$$P(t) = \frac{F(t) - B(t)}{F(t) + B(t)}$$

Muon spectrometers

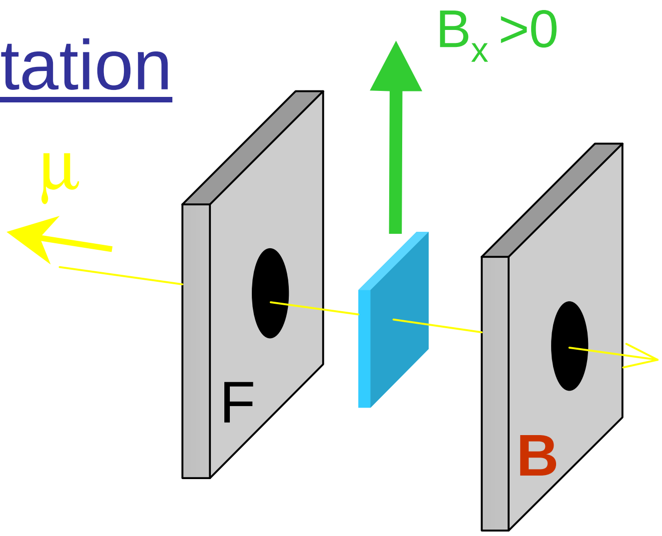


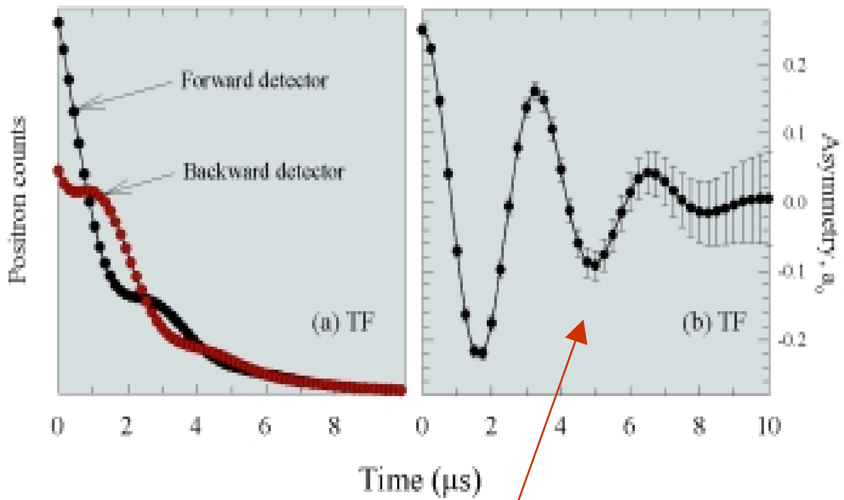



MuSR and Emu,
ISIS
(*EU sponsored muon facility*)

Muon Spin Rotation and Relaxation

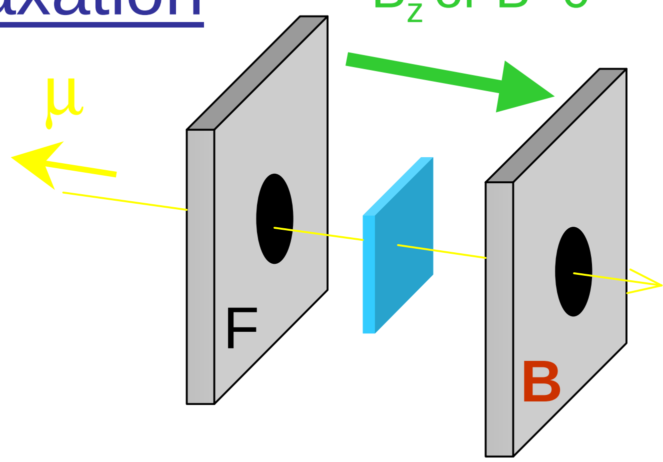
Rotation

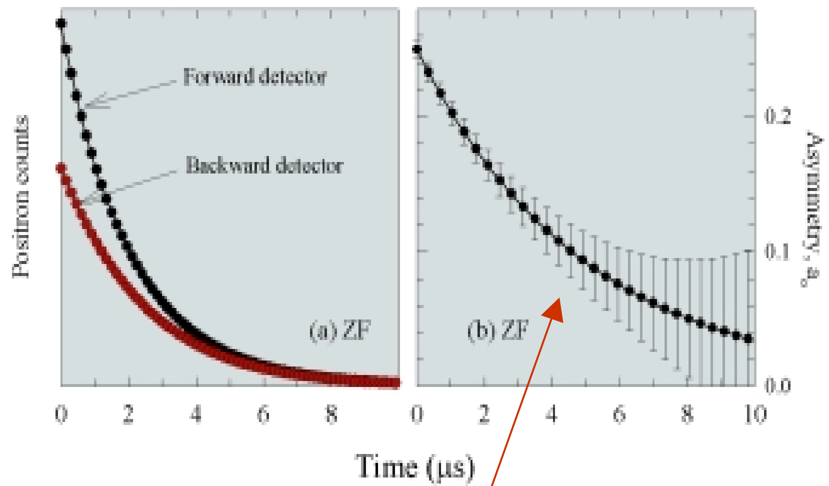




$$P_x(t) = \frac{F(t) - B(t)}{F(t) + B(t)} = a_o G_x(t) \cos(\omega_L t)$$

Relaxation





$$P_z(t) = \frac{F(t) - B(t)}{F(t) + B(t)} = a_o G_z(t)$$

Some science……muon spin rotation

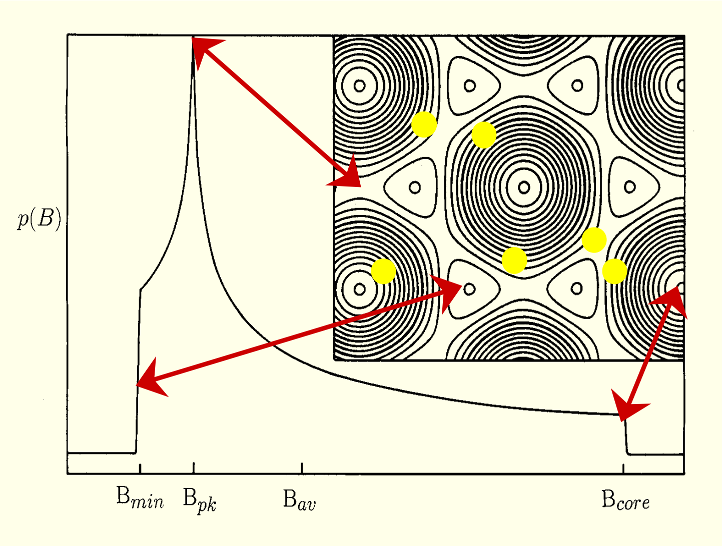
The time evolution of the muon polarisation in a transverse field B is

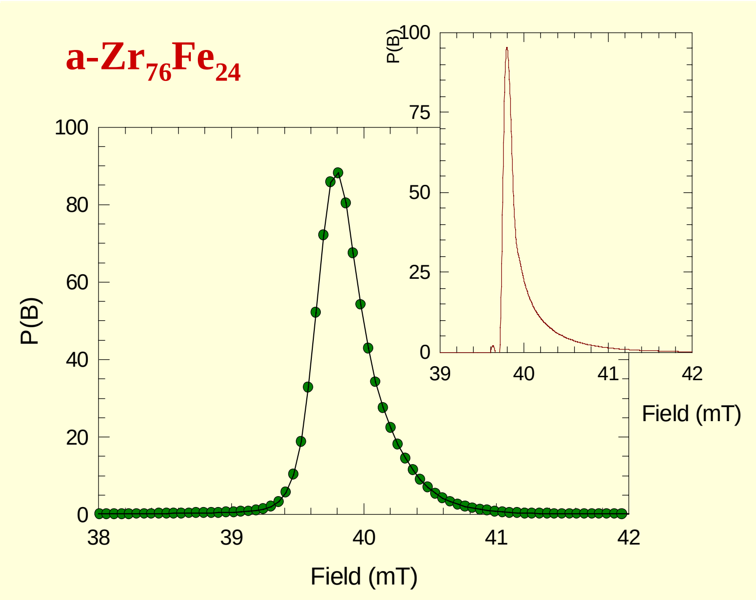
$$P_x(t) = a_o G_x(t) \cos(\omega_L t)$$

where $\omega_L = \gamma B$

$G_x(t)$ is simply the Fourier transform of the field distribution averaged over all muon sites.

Muon spin rotation has provided remarkable insights into the nature of the superconducting flux line lattice



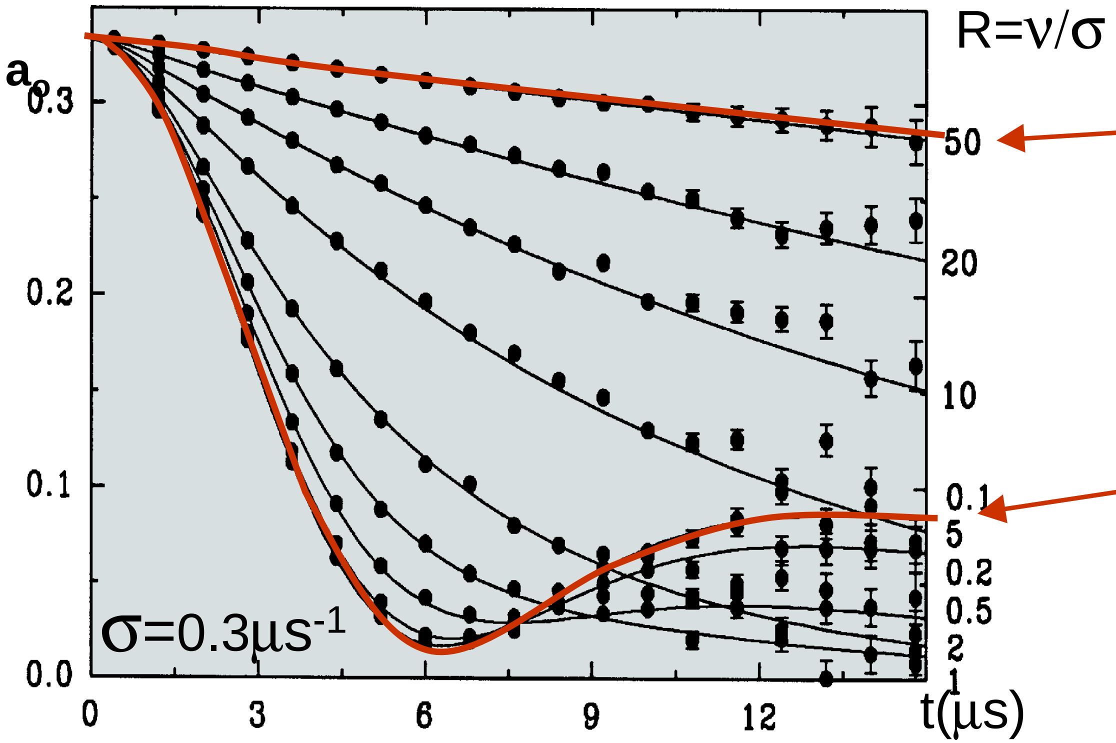


λ=500nm, ξ= 29nm, T_C=1.7K

Muons in Condensed Matter Science

Some science....muon spin relaxation

$G_z(t)$ depends upon the distribution and dynamics of internal fields at the muon site - usually in the absence of applied fields - eg for dynamic Gaussian fields of rms width σ and a fluctuation rate ν:



Dynamic (exponential) limit

$$G_z(t) = \exp\left(-\frac{2\sigma^2 t}{\nu}\right) = \exp(-\lambda t)$$

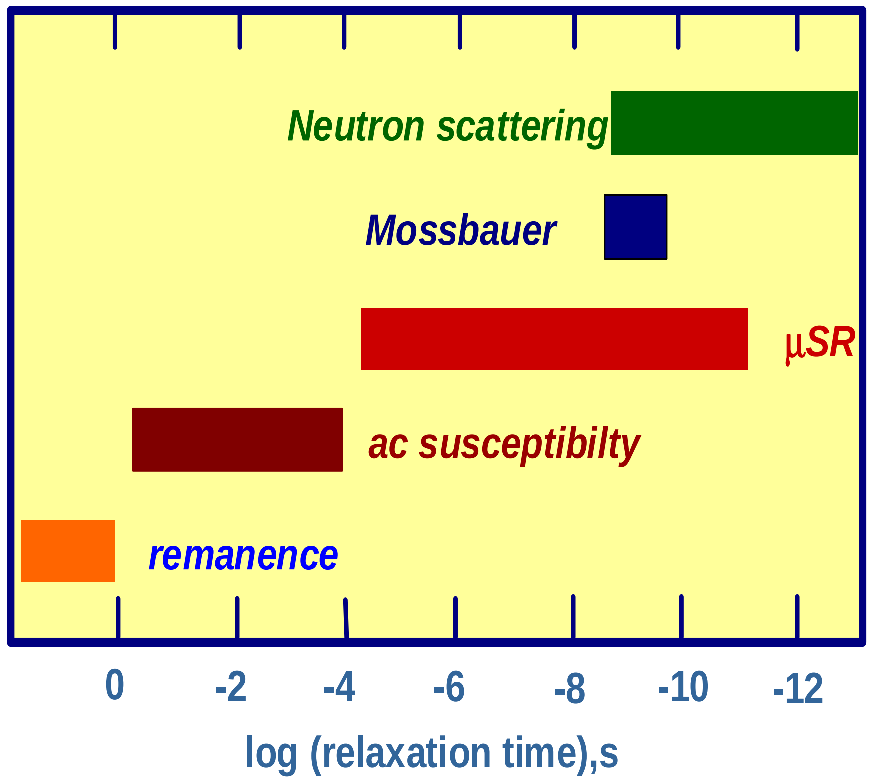
Static (Kubo-Toyabe) limit

$$G_z(t) = \frac{1}{3} + \frac{2}{3}\left(1 - \sigma^2 t^2\right)\exp\left(-\frac{\sigma^2 t^2}{2}\right)$$

Muon spin relaxation - time scales

A time window sufficiently wide for studies of fast itinerant electron spin fluctuations through to slow distributed spin relaxation in spin glasses

…or of fast muon hopping through to slow diffusional processes….

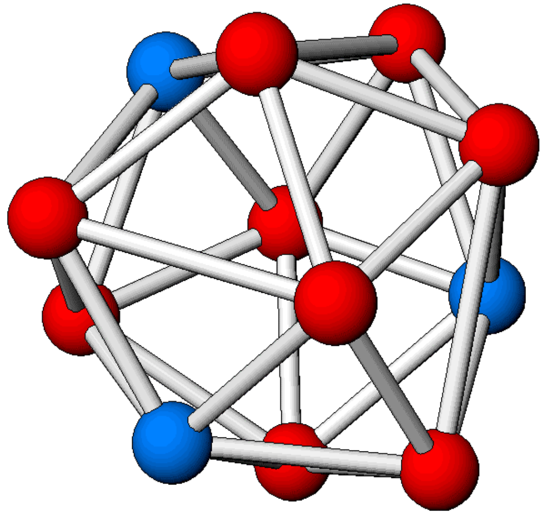


…..and µSR is sufficiently sensitive for ultra-small magnetic moments (~$10^{-3}\mu_B$) to be detected

Muons in Condensed Matter Science

Spin dynamics in itinerant magnets

β-Mn
an elemental
spin fluctuator

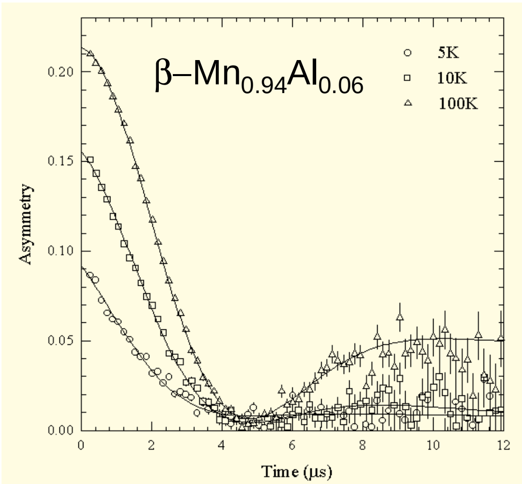


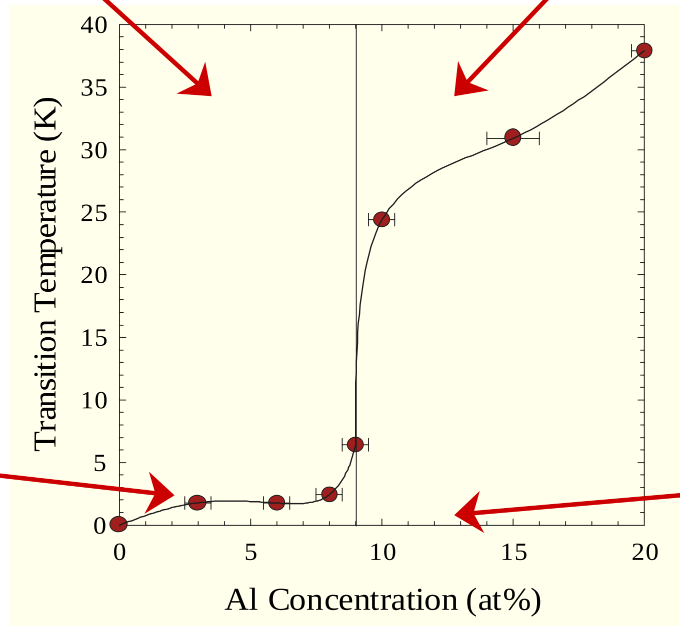
Stewart and Cywinski PRB59 (1999) 4305

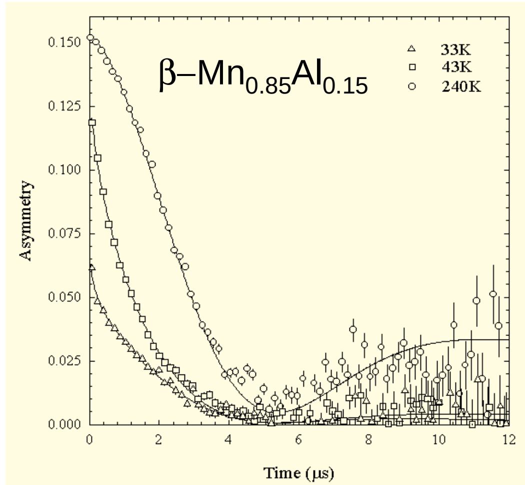
Campbell, Cywinski et al PRL 72 (1994) 1291

Simple exponential μSR
$P(t) = a_o e^{-(\lambda t)}$

Stretched exponential μSR
$P(t) = a_o e^{-(\lambda t)^{\beta}}$



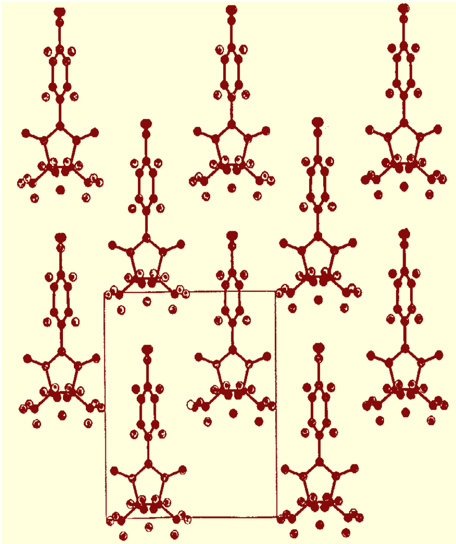




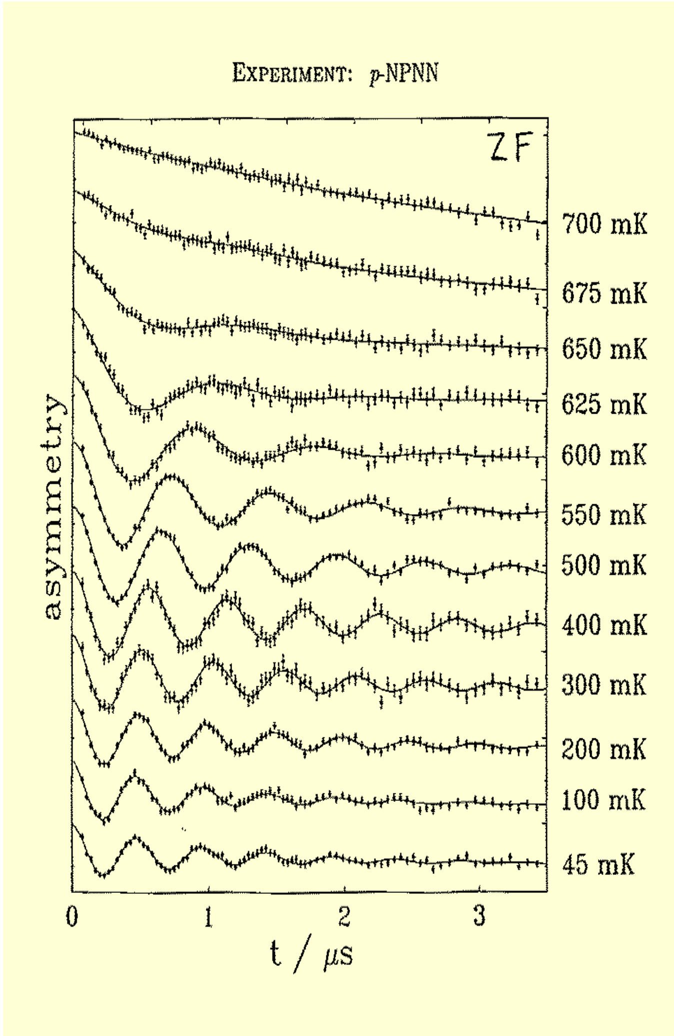
Spin liquid phase

Spin glass phase

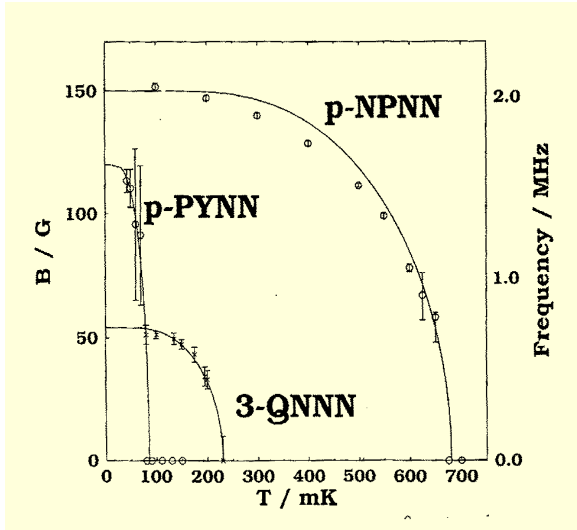
Magnetic order in organic magnets



Blundell et al
Europhysics Letters
31 (1995) 573

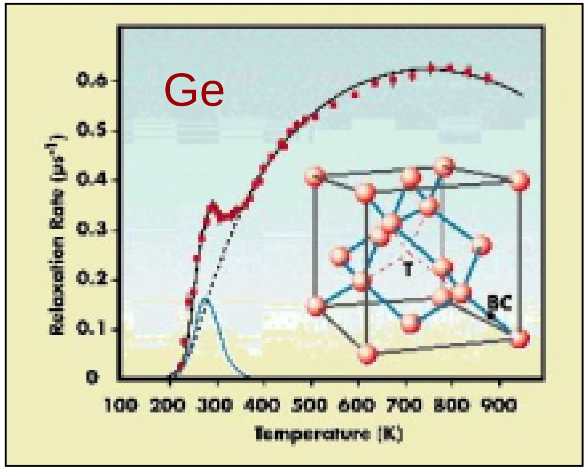


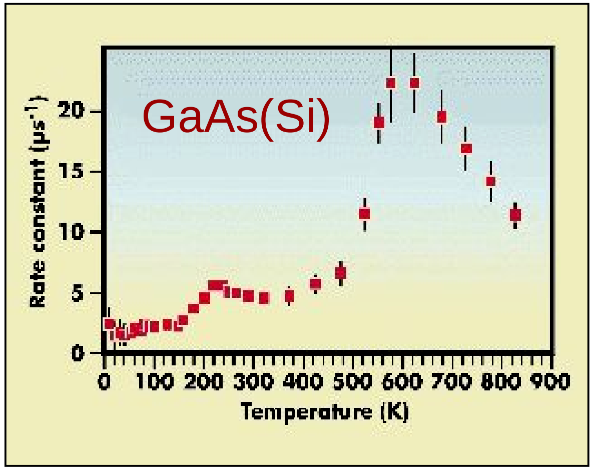
Spontaneous muon precession in a coherent internal field at mK temperatures

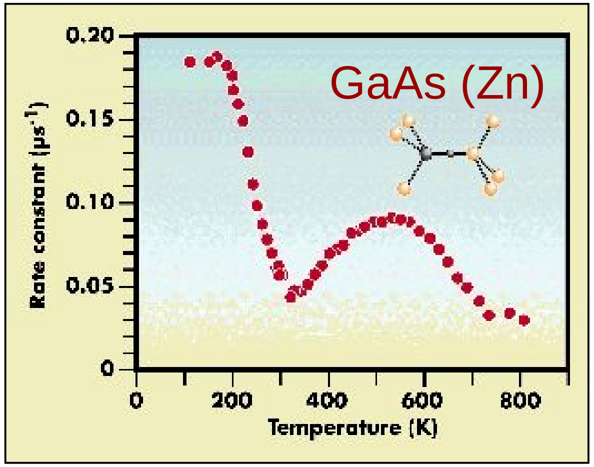


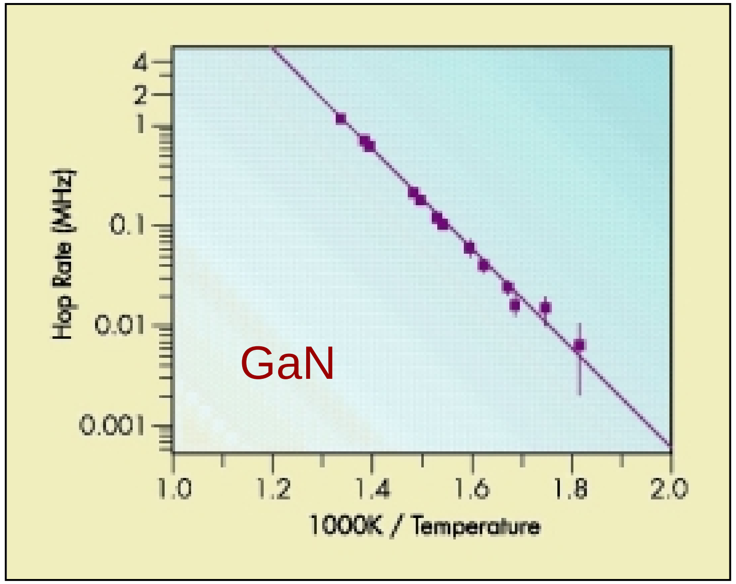
Muons in Condensed Matter Science

Modelling Hydrogen in Semiconductors









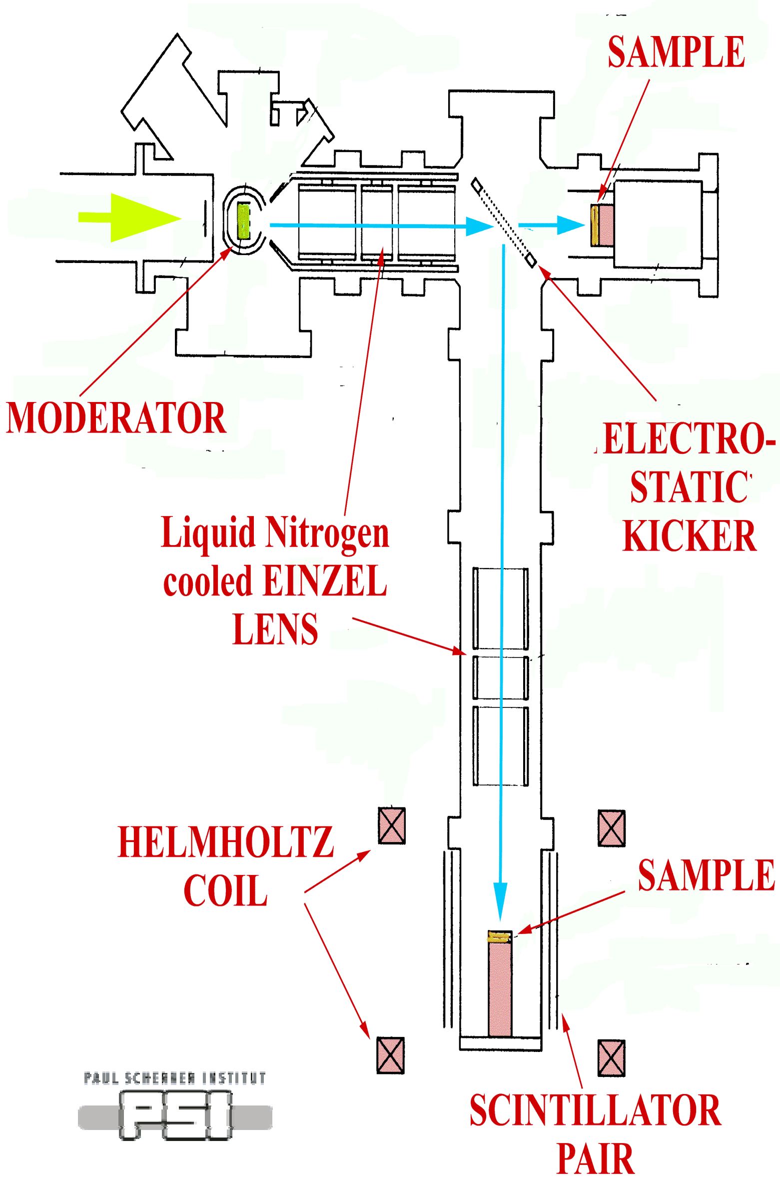
Muon hopping rates measured over three decades in frequency in Ge, GaAs, GaN and Si-based semconductors

Cox, Davis et al, PRL 2001

The future ? - “cold” muons

Muons are cryogenically moderated and energy selected to tune localisation depth within the sample:

E(keV)	R(nm)	ΔR(nm)
0.010	0.5	0.3
0.100	2.1	1.3
1.0	13.1	5.4
10.0	75.0	18.0
30.0	244.0	36.0



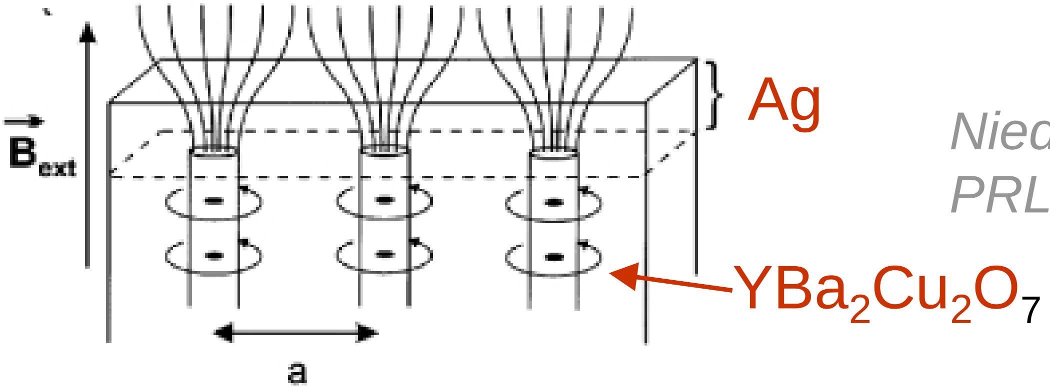
See Morenzoni in “Muon Science”
eds Lee, Kilcoyne and Cywinski, 1998

Cold muons at PSI

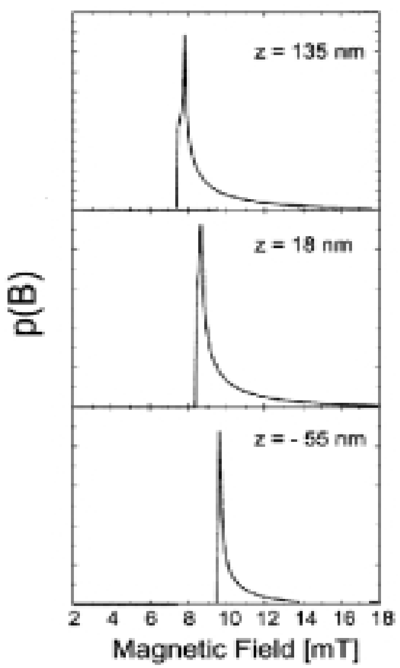
….but the efficiency is still very low (~10^{-5})

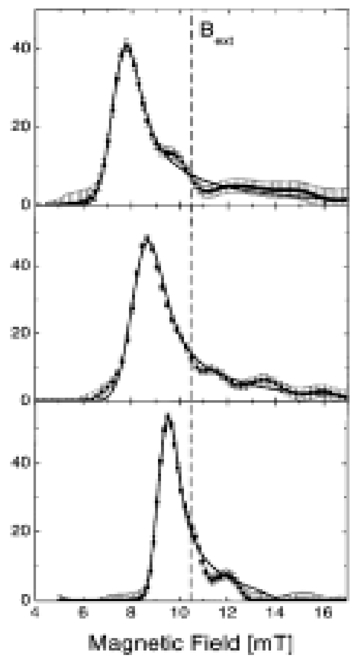
Muons in Condensed Matter Science

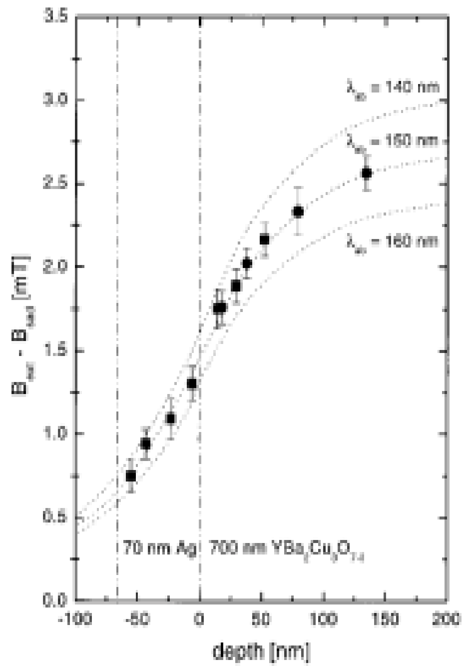
Flux distribution at surface of $YBa_2Cu_3O_7$



Niedermayer, Forgan et al
PRL83, 3935, 1999



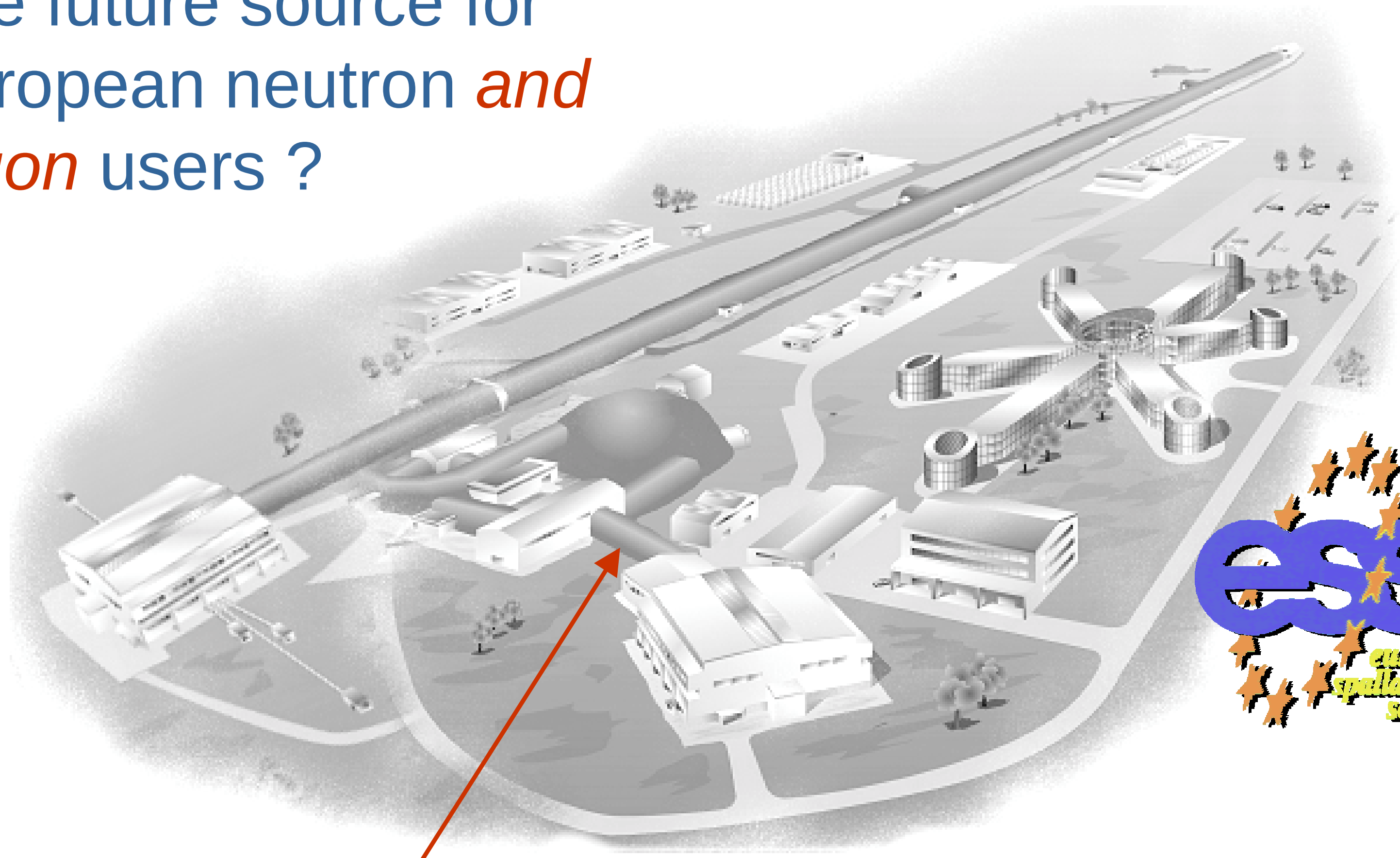




simulated *measured*

The European Spallation Source

The future source for European neutron *and* *muon* users ?



High power (12kW) target for pulsed muon production serving two surface muon channels (several instruments) with only 1.6% beam loss to short pulse target *~ISIS x 100*

Muons at ESS

ESS offers:

- *High intensity, small beams for high countrate (kinetic?) studies*
- *Ultra-small beam size for tomographic studies*
- *High intensity for development of analogue counting methods*
- *Sufficient intensities for development of rapid scanning RF techniques*
- *Routine application of cold muon techniques…….*

The newly constituted European Chapter of the International Society for Muon Spectroscopy has placed the development of a world leading muon facility at the ESS high on its agenda ……

Conclusions

μ**SR** is making an increasingly significant contribution to condensed matter science research

Emerging techniques, such as cold muon spectroscopy are extending the already broad range of applications…...

…and ESS will extend the possibilities still further

The European muon community therefore strongly supports the speedy construction of ESS

There is already strong competition to host the ESS from *Lund (Scandinavia), Julich* and *Halle-Leipzig (Germany)* and *Yorkshire (UK)….*

YESS!

bringing the

European Spallation Source

to

Yorkshire

a world class
science facility
for a world class
region

Yorkshire Forward and the White Rose University Consortium

www.yorkshire-ess.org.uk