TRIUMF summer school 2011

β-NMR and Low Energy μSR

R.F. Kiefl

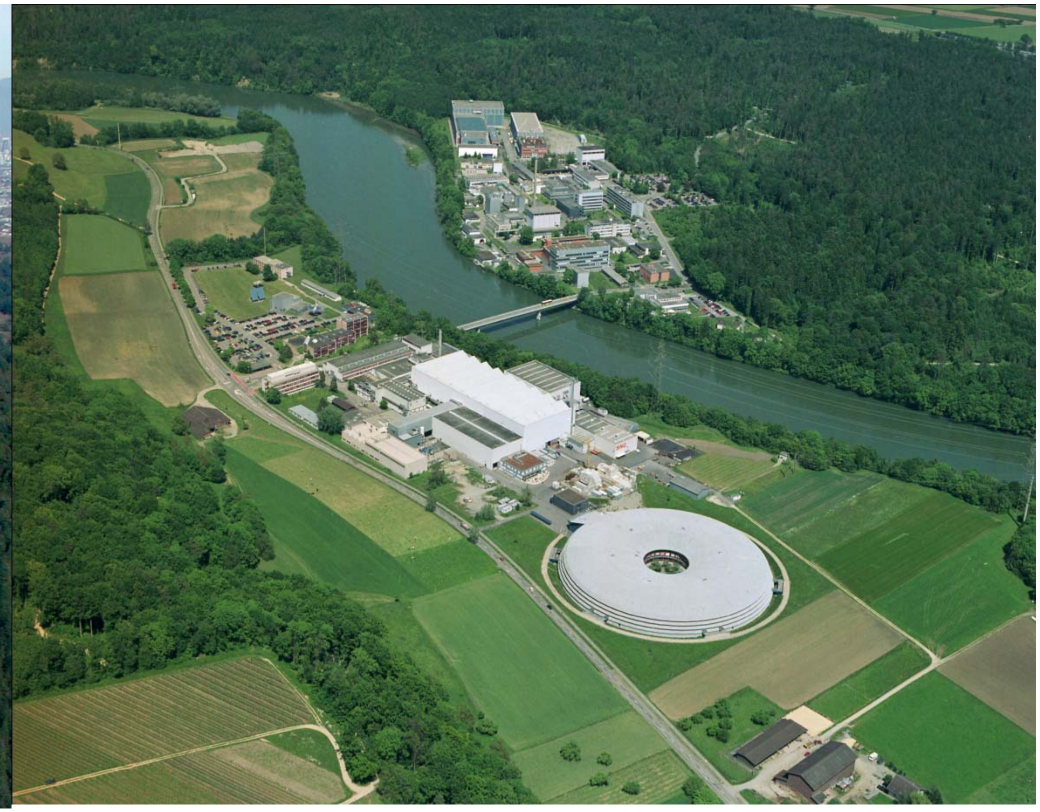


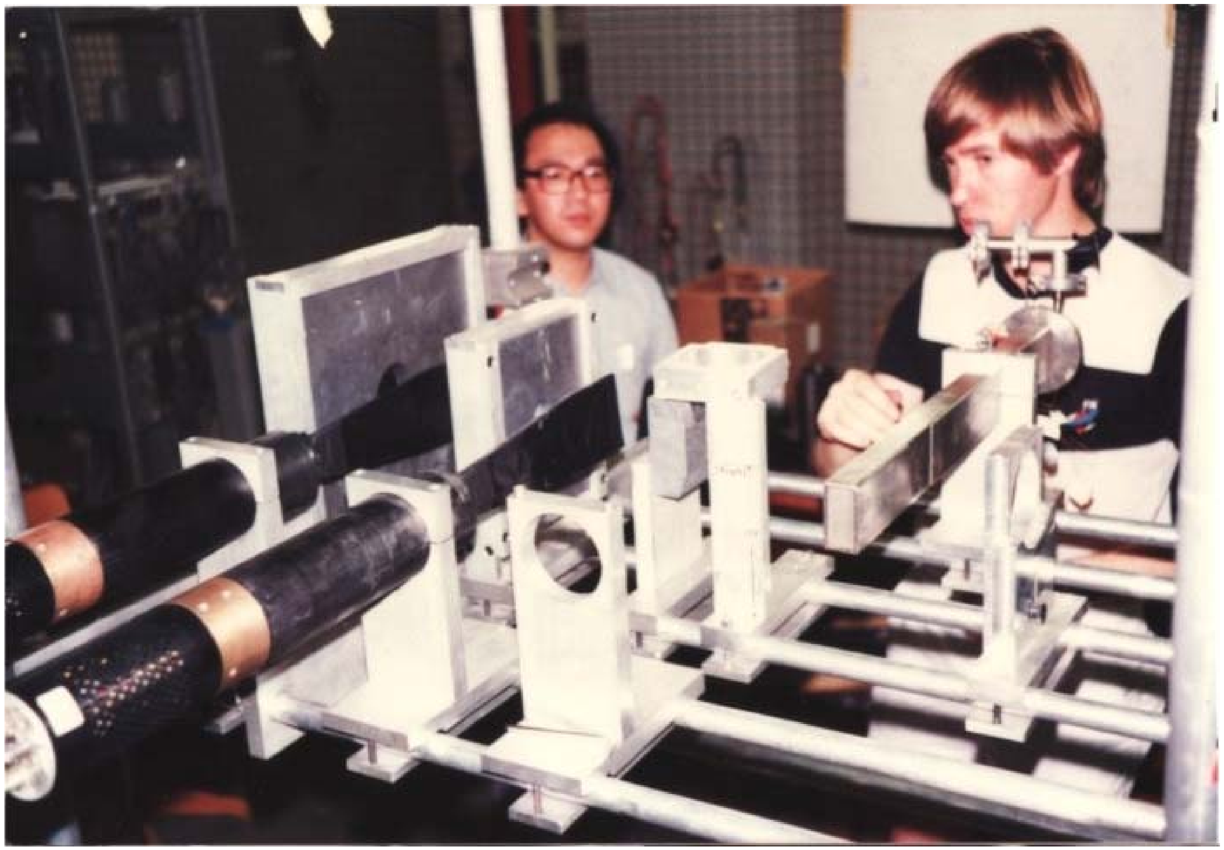
Photo: TRIUMF

Photo: Paul Scherrer Institute

Objective:

be able to write a proposal that is interesting and feasible.

SIN (PSI) 1983



Part I: Principles

-scientific motivation for low energy μSR and β-NMR

-principles of low energy μSR

- -isolated spin ½ particle in a magnetic field
- - ensemble of N spin ½ particles in a crystal at temperature T
- - production and transport of low energy muons
- - stopping distributions
- - LEM spectrometer at PSI

-principles of beta-NMR

- - properties of 8Li in comparison with the muon
- - production of 8Li
- - transport and polarization of 8Li at ISAC
- - beta-NMR spectrometers at ISAC

-Conclusions

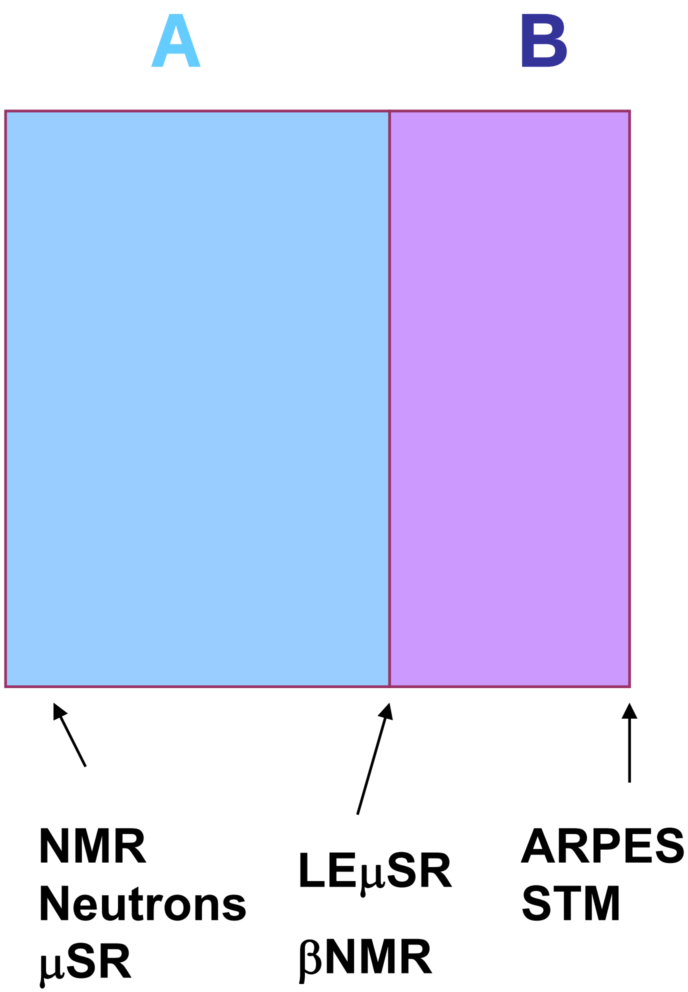
Comparison of conventional NMR with LEμSR and βNMR

	NMR	LEμSR	β-NMR
Polarization	**<**0.01	>0.8	
detection method	**electronic pickup**	**anisotropic β decay**	
Sensitivity	10^{17} **spins**	10^{7} **spins**	
T_1 range (s)	$10^{-5} - 10^{2}$	$10^{-8} - 10^{-4}$	$10^{-3} - 10^{3}$
range	**N/A**	10 **Å** –3000 **Å***	
Applied field (frequency)	**> 1 T**	**any**	**>1mT**

*** Depth Sensitivity!**

General Scientific Motivation:

Exploring the collective behaviour of electrons near an interface.



-superconductor/vacuum, e.g. YBa2Cu3Ox
E1041, E1095, E1100, M1153

-metal/vacuum e.g. Pd, E1042,

insulator/vacuum, SrTiO3 E1094

-semiconductor/vacuum GaAs , Si M1165

-ferromagnet /metal, e.g. Ag/Fe M1093

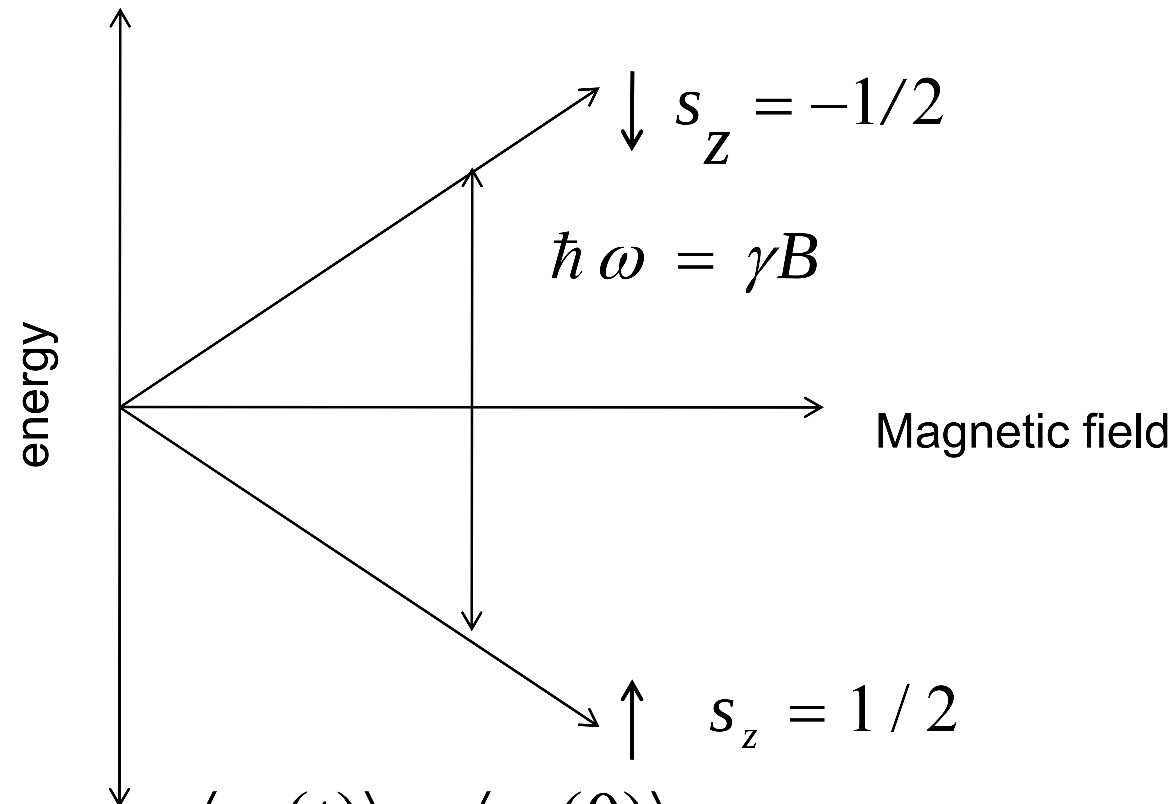
-semiconductor/ferromagnet, spintronics e.g. EuO/Si M1165, M1176,

-insulator/insulator $SrTiO_3$ /LaAlO3 M1226,

- superconductor/metal, proximity effect M1153.

Isolated spin ½ particle in a magnetic field

$$\mathrm{H}_0 = -\gamma\, \mathbf{s} \cdot \mathbf{B}$$



$$\langle s_z(t) \rangle = \langle s_z(0) \rangle$$

$$\langle s_x(t) \rangle = \langle s_x(0) \rangle \cos \omega t$$

Consider an ensemble of N spin ½ particles in a crystal at temperature T in an external field B

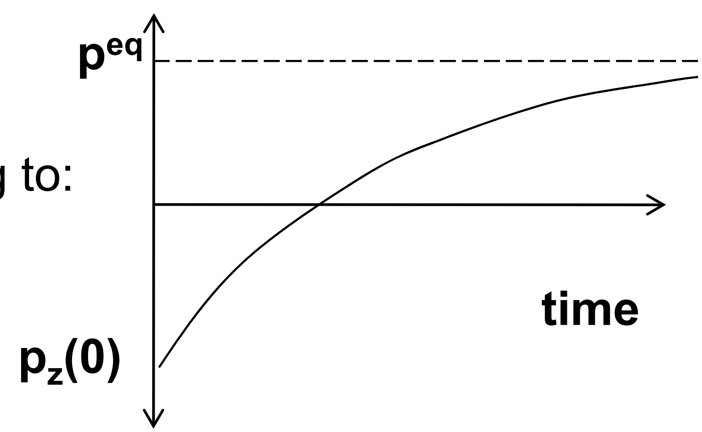
Spin Hamiltonian for each spin $H_0 = -\gamma\, \mathbf{s} \cdot [\mathbf{B} + \mathbf{B}_{loc}(t)]$

In thermal equilibrium the z component of polarization

$$p_z^{eq} \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \frac{1 - N_\downarrow / N_\uparrow}{1 + N_\downarrow / N_\uparrow} = \frac{1 - \exp[-\hbar\omega' / k_B T]}{1 + \exp[-\hbar\omega' / k_B T]} \approx \frac{\hbar\omega'}{2k_B T}$$

With $\omega' = \frac{\gamma}{\hbar}(B + \overline{B}_{loc}) = \omega + \Delta\omega$ and $\overline{B}_{loc}$ Is the time averaged z component of B_{loc}, assuming $B_{loc} \ll B$

whereas $p_x^{eq} = p_y^{eq} = 0$



Now suppose the p_z has some non-equilibrium value at t=0. Then it will evolve toward equilibrium according to:

$$p_z(t) = [p_z(0) - p_z^{eq}]\exp[-t/T_1] + p_z^{eq}$$

$$\frac{1}{T_1} = \frac{2\gamma^2 (\Delta B)^2 \tau_c}{1 + \omega'^2 \tau_c^2}$$

ΔB is the rms component of B_{loc} (t) perpendicular to B.

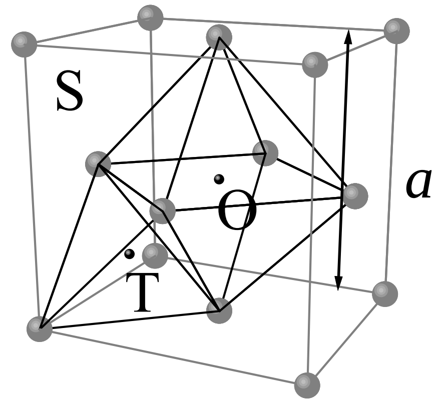
Similarly if the p_x has some non equilibrium value equal to at t=0 Ie. perpendicular to the internal field.

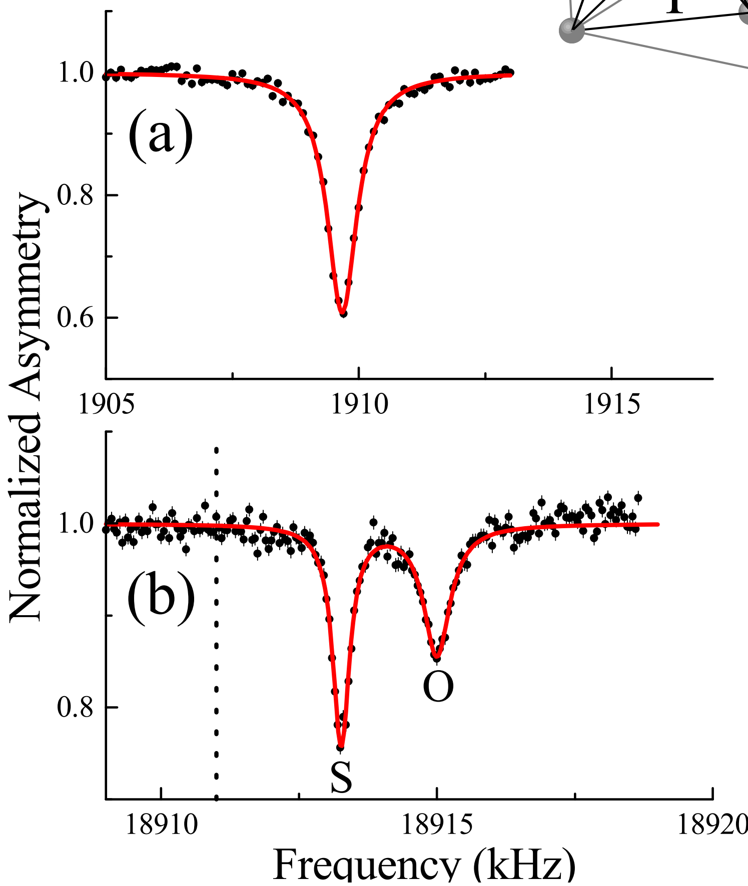
$$p_x(t) = p_x(0)\exp[-t/T_2]\cos(\omega + \Delta\omega)t$$

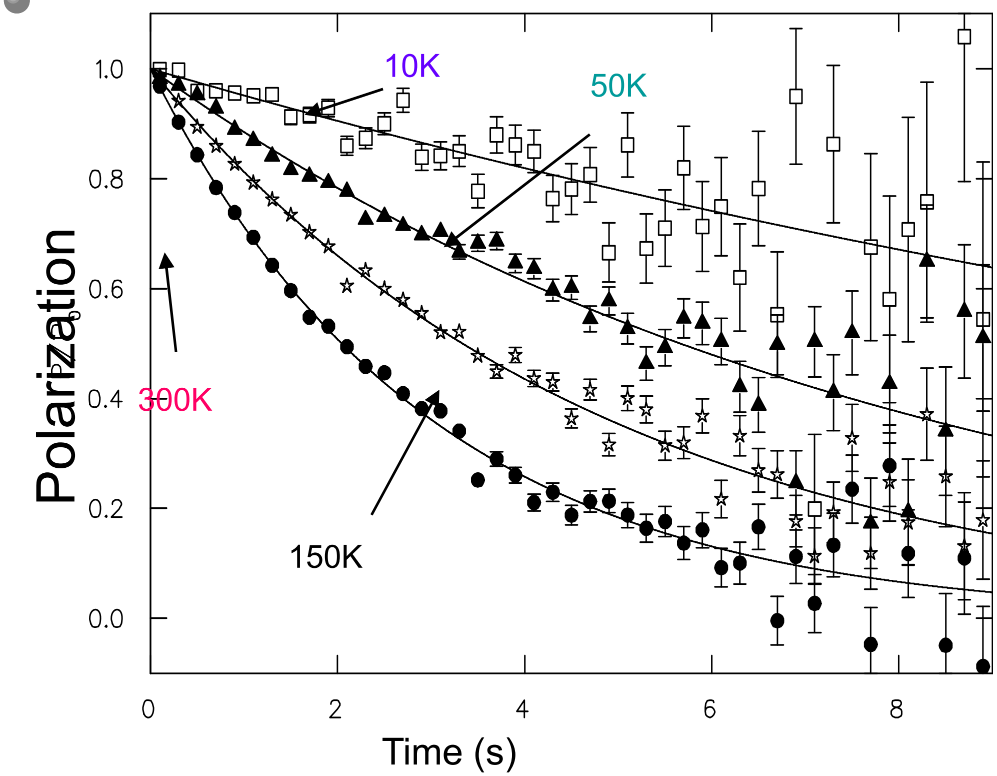
Thus there are three main observables $\Delta\omega$, $1/T_1$, and $1/T_2$ that depend sensitively $B_{loc}(t)$ or more generally on the interaction between the probe spin and the electrons (and host nuclear spins) of the many body system. This allows us to characterize and test models for the electronic state, which is a main theme in condensed matter physics. This is similar to NMR but LE μSR and βNMR can be used to study the collective behaviour of electrons near a surface, interface or thin film.

β-NMR of ^{8}Li in 50nm film of Ag on $SrTiO_3$ at 5 keV

G.D. Morris et al, PRL **73,** 15601 (2004).



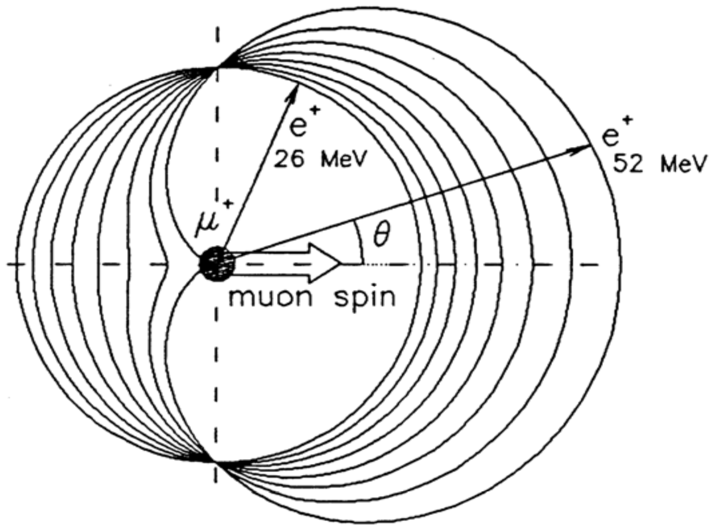


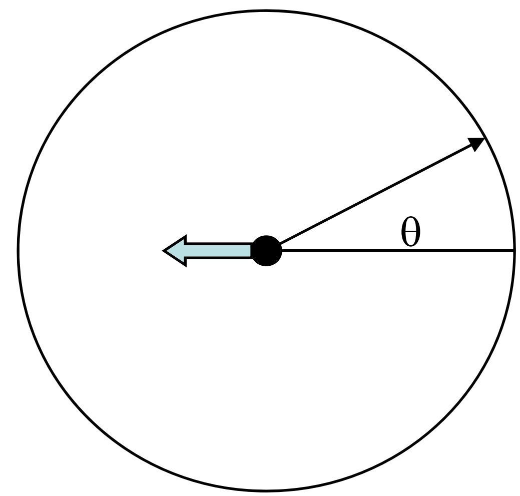


Properties of the muon and ^{8}Li

$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$^8Li \longrightarrow {}^8Be + e^- + \nu_e$



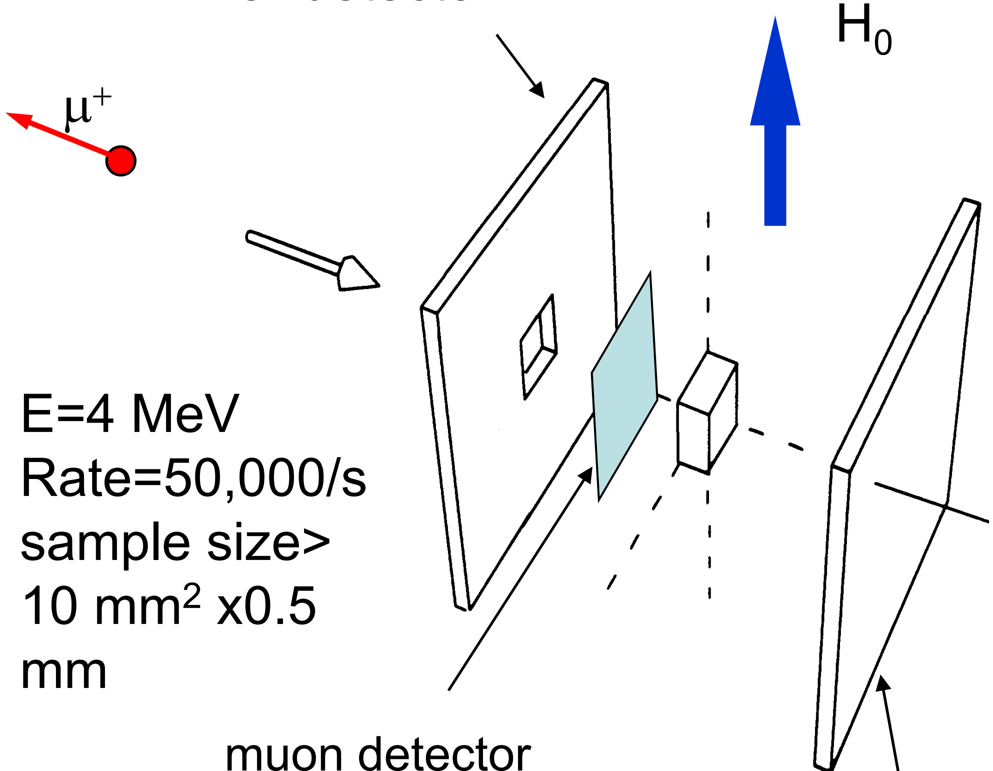


Spin = 1/2
γ = 135.55MHz/T
<A>= 0.33
Polarization = 95%
Lifetime = 2.19714(7) μs

Spin=2, Q=33 mb
γ =6.30 MHz/T
<A>=-0.30
Polarization= 70%
Lifetime= 1.2s

Schematic of a conventional μSR Experiment

backward
e^+ detector

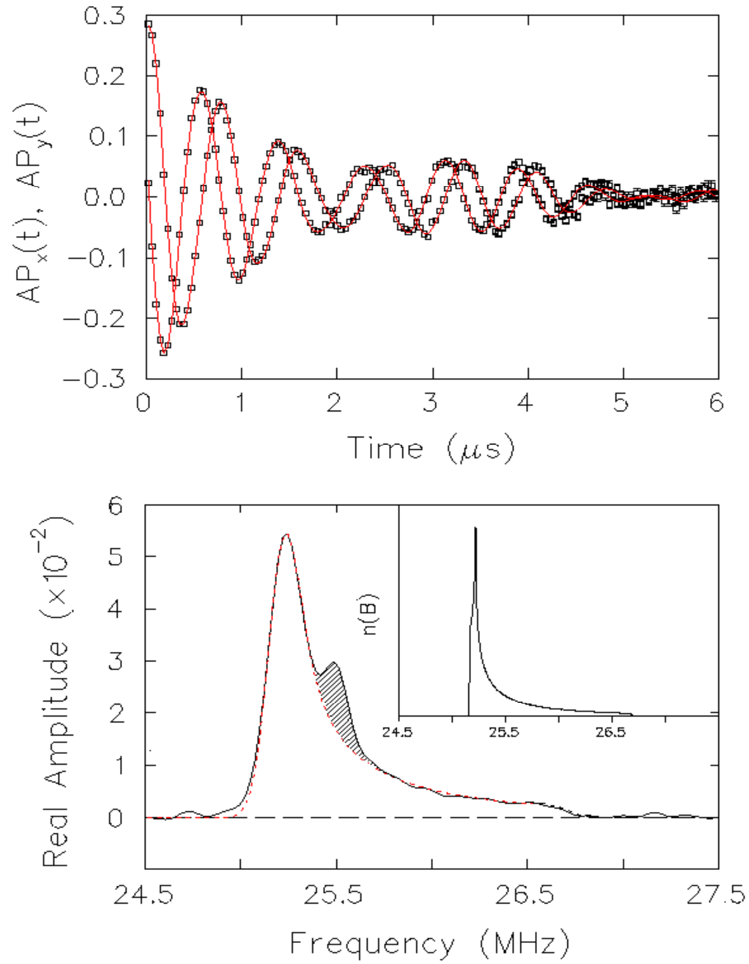


E=4 MeV
Rate=50,000/s
sample size>
10 mm^2 x0.5
mm

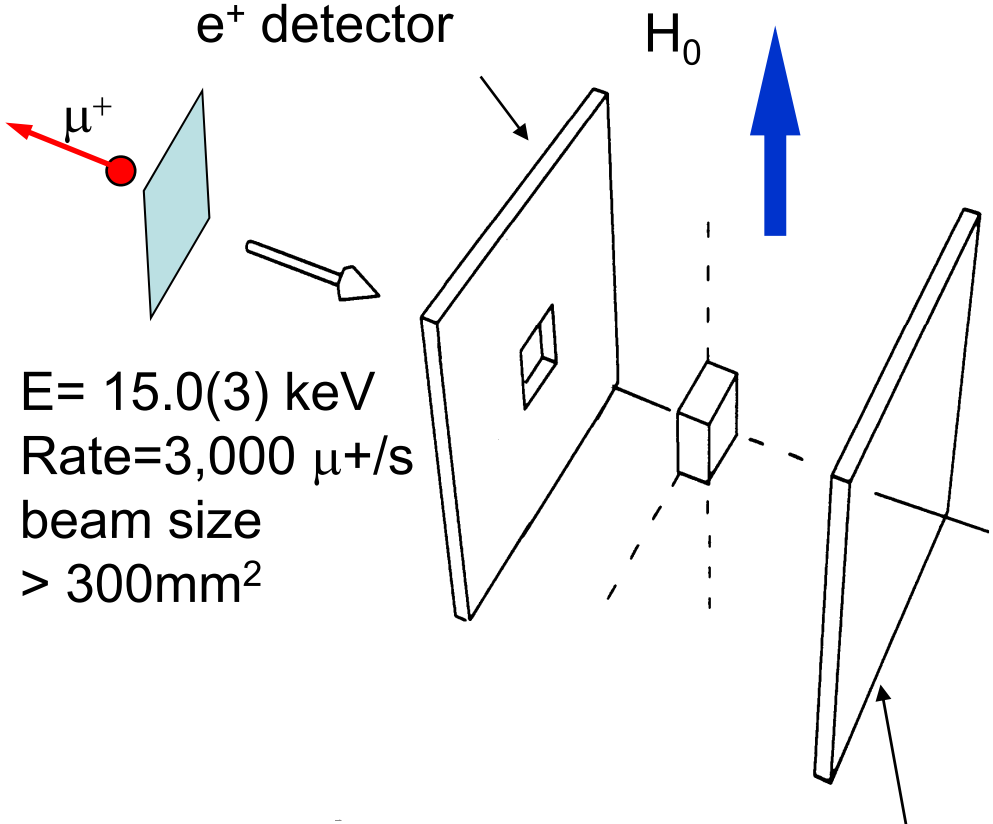
muon detector

forward
e^+ detector

$NbSe_2$ $T=0.33T_c$, H=1.9 kOe

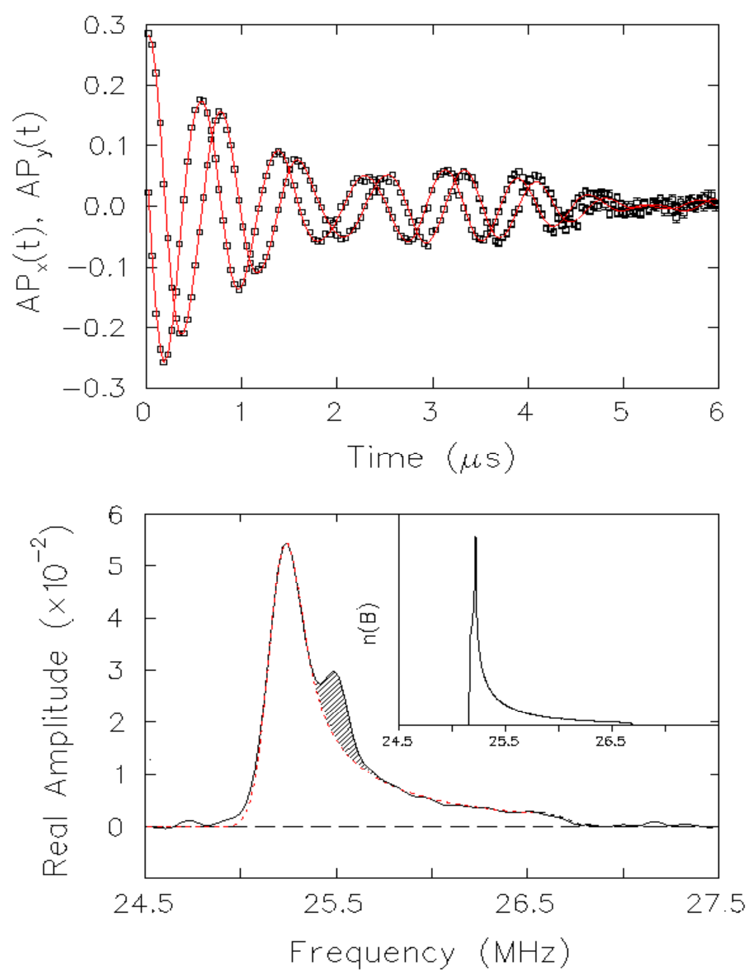


Schematic of a low energy μSR Experiment



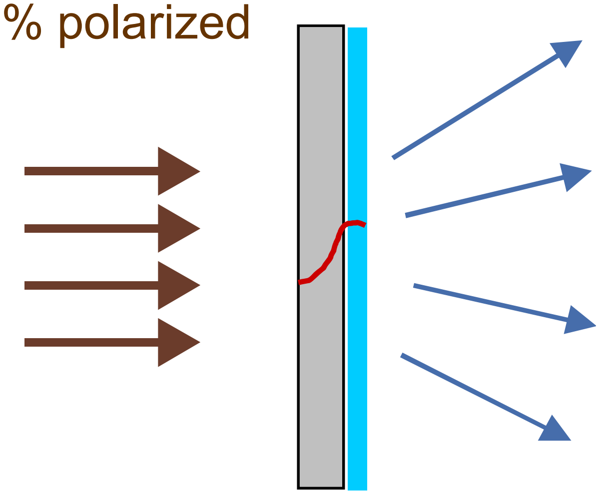
E= 15.0(3) keV
Rate=3,000 μ+/s
beam size
> 300mm^2

$NbSe_2$ $T=0.33T_c$, H=1.9 kOe



Production of low energy muons

a lot of muons
~ 4 MeV
~ 100% polarized

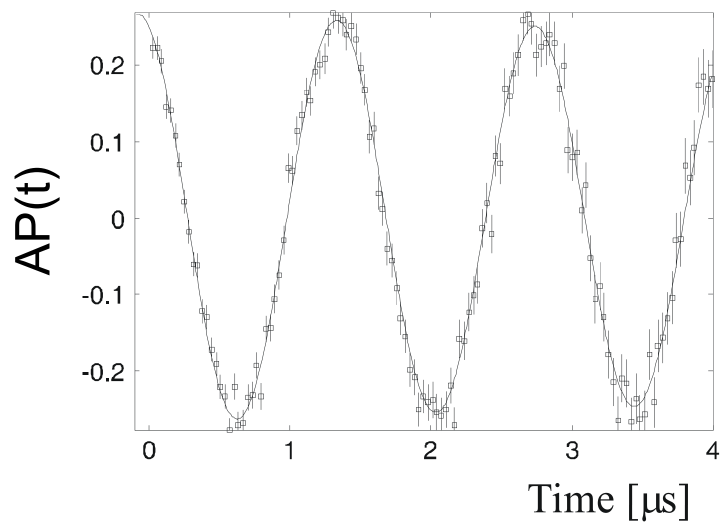


~100 μm ~ 500 nm
6 K s-Ne, Ar,
s-N_2

LE-muons source:

- **100% polarized**
- **peak energy: ~ 15 ± 10 eV**
- **moderation efficiency ~ 10^{-5}**

Polarization: ~ 100%

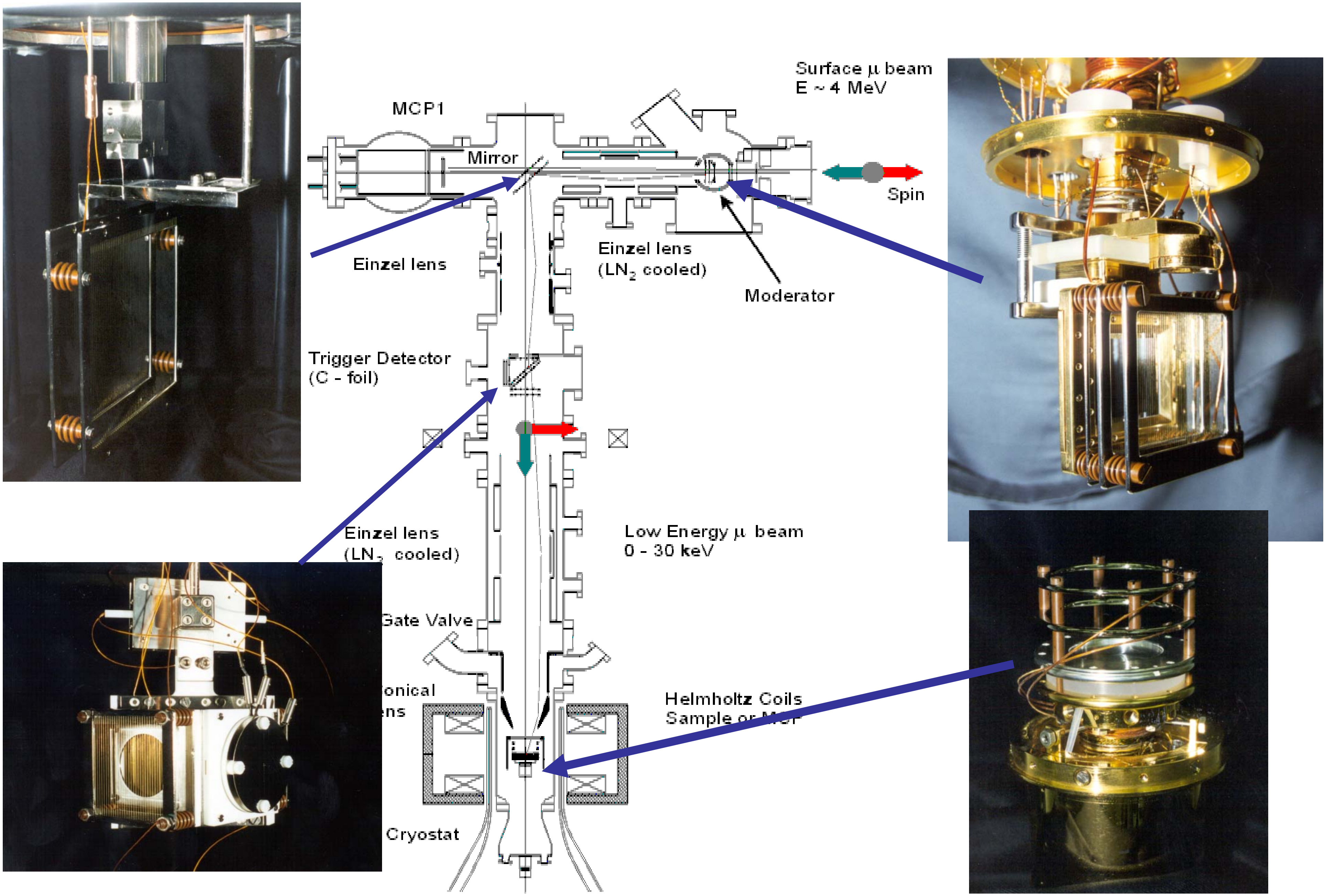


Mechanism:
Suppression of electronic energy loss and soft elastic collisions in the eV region during slowing down in van der Waals cryosolids

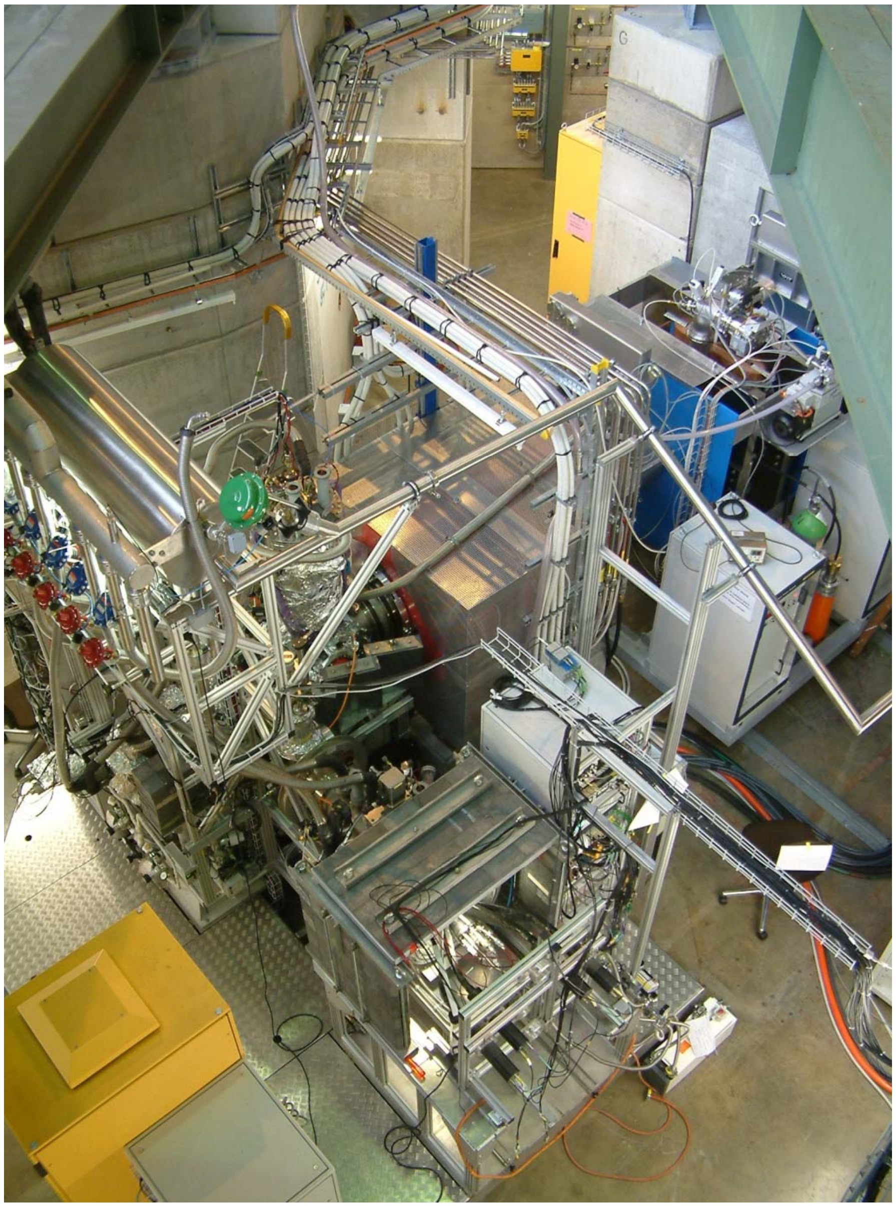
→ escape before thermalization
→ very fast no polarization loss

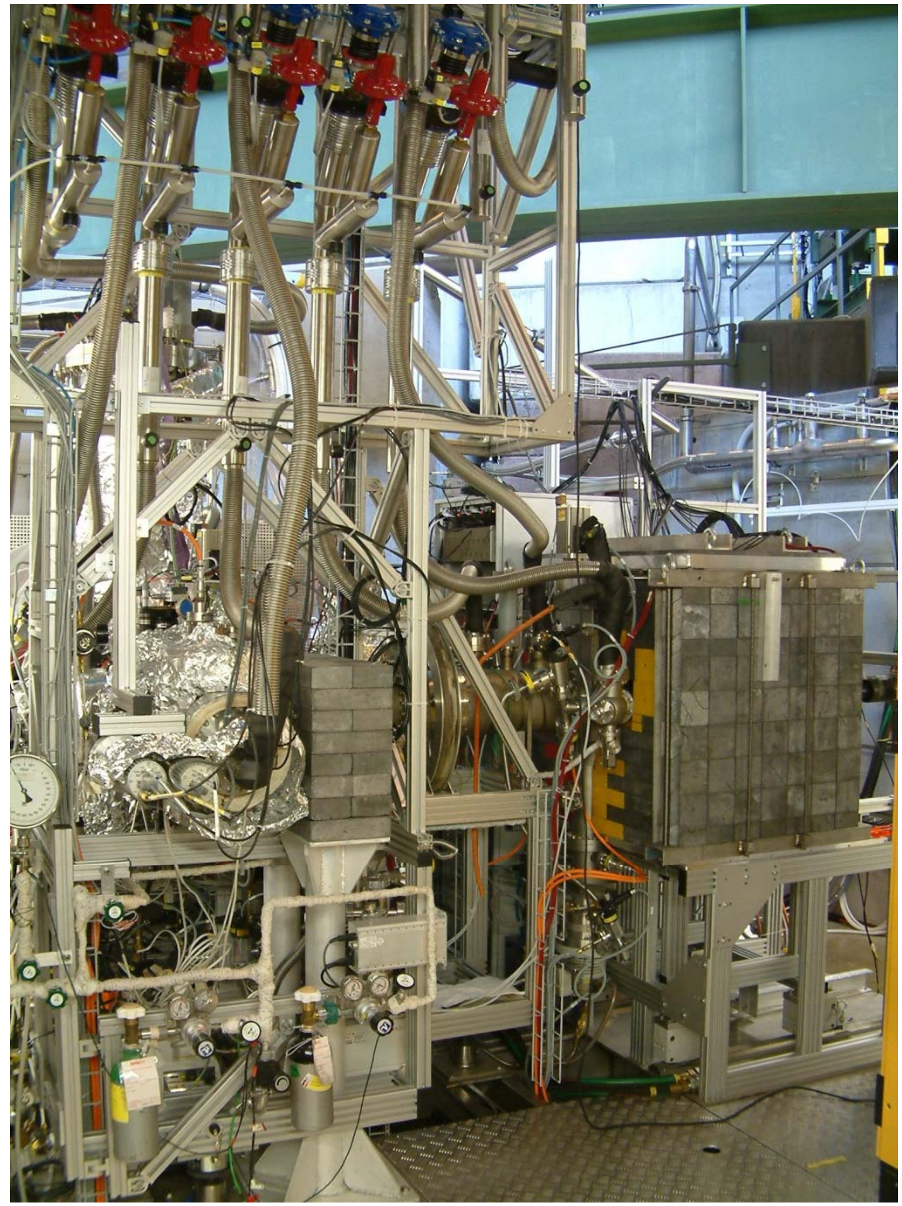
E. Morenzoni, F. Kottmann, D. Maden, B. Matthias, M. Meyberg, Th. Prokscha, Th. Wutzke, U. Zimmermann, Phys.Rev.Lett. **72**, 2793 (1994).

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

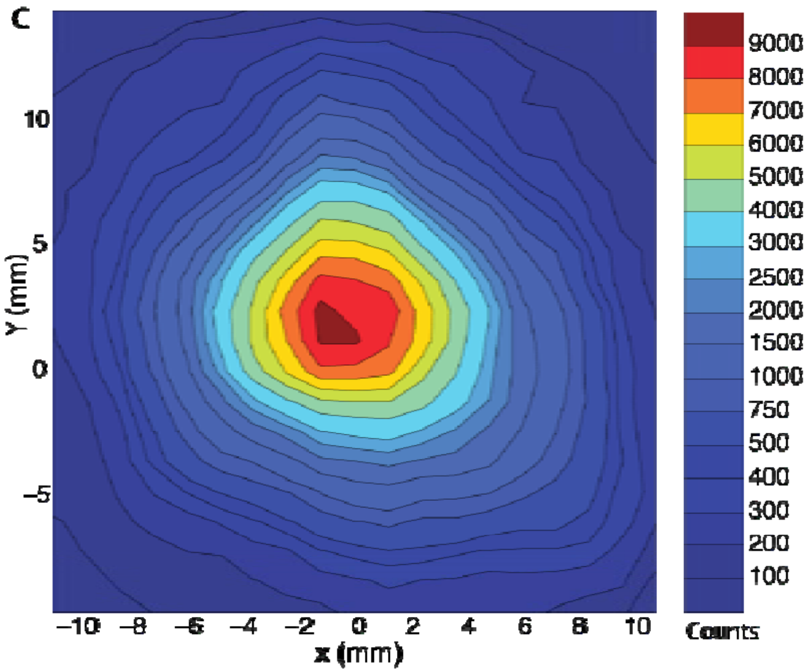


LEM Beam line and apparatus



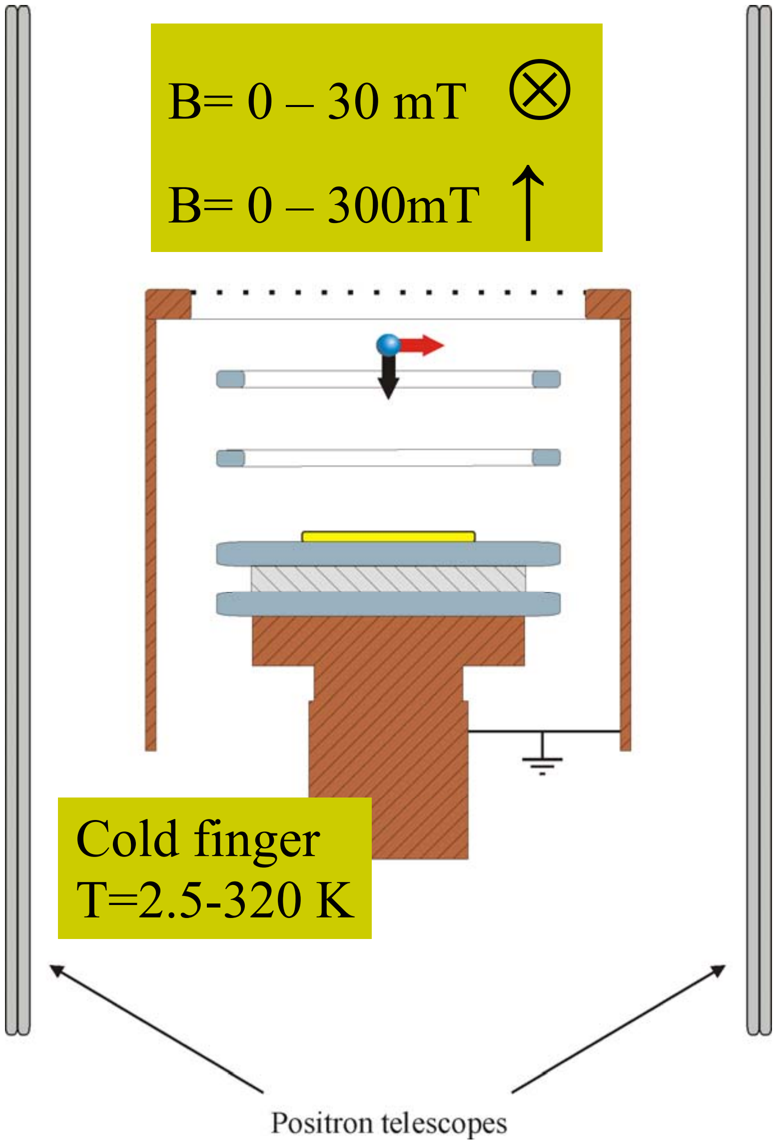


Low energy muon beam properties at PSI



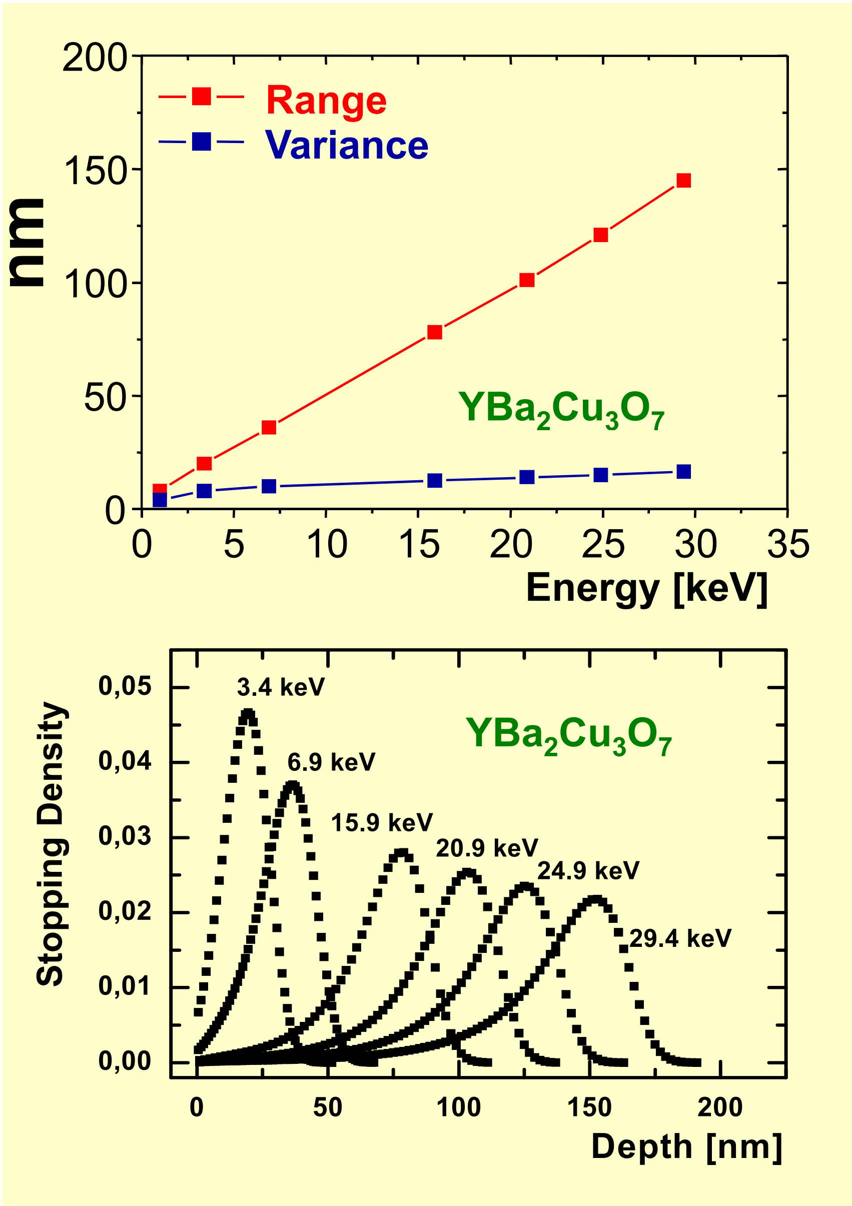
- Initial intensity (4 MeV): $1.9 \cdot 10^{8}$ /s
- LE-μ intensity at moderator: 11000 /s
- LE-μ intensity at the sample: 4500 /s
- Tunable LE-μ energy: 1 – 30 keV
  - Implantation depth: 2 – 200 nm
- Energy spread (RMS): 450 eV
- Beam spot size 200 mm^2

Low Energy Muons (LE-μSR) Spectrometer



- T = 2.5 – 320 K
- B = 0 – 30 mT (0.3 T)
- 2 or 32 positron detectors
- Time resolution: ~ 5 ns
- Event rate : ~ 700 or 1600 /s

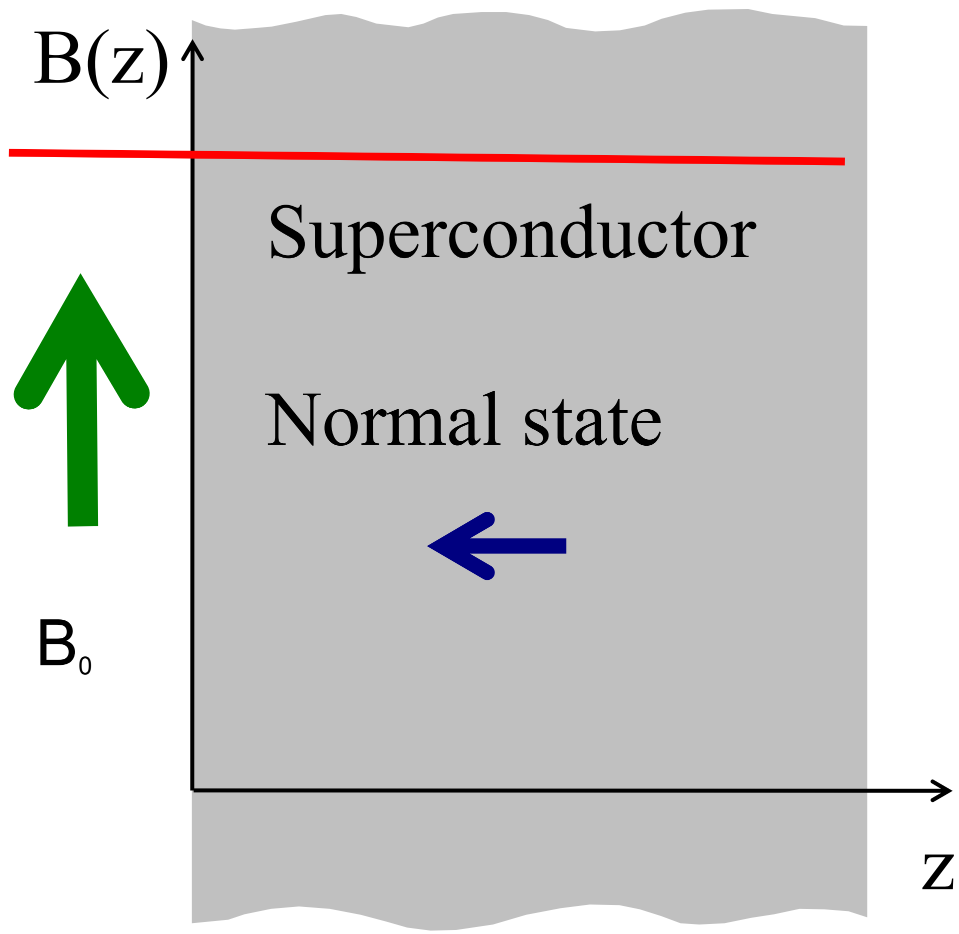
Implantation profiles of LE-μ $YBa_2Cu_3O_7$

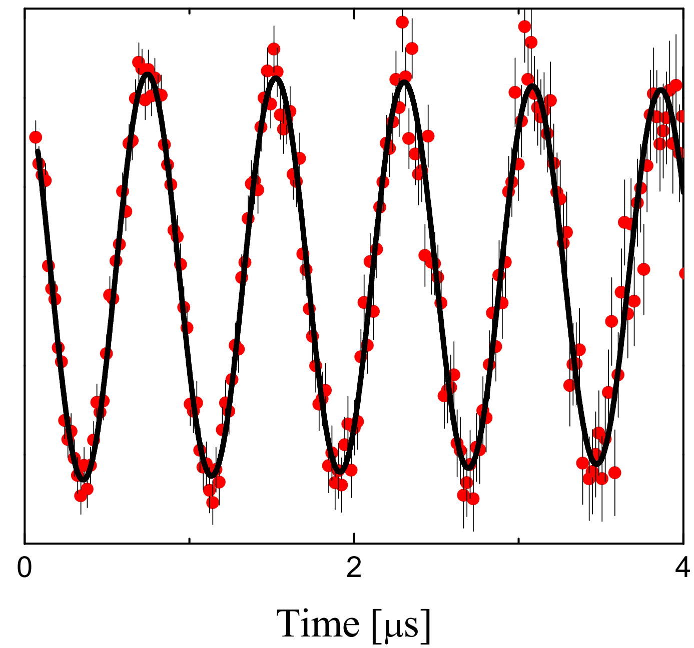


stopping profile calculated with Monte Carlo code Trim.SP by W. Eckstein, MPI Garching, Germany

see E.Morenzoni et al., NIM **B192** (2002)

Normal sate of $YBa_2Cu_3O_7$, T=110K, B_0=9.3mT

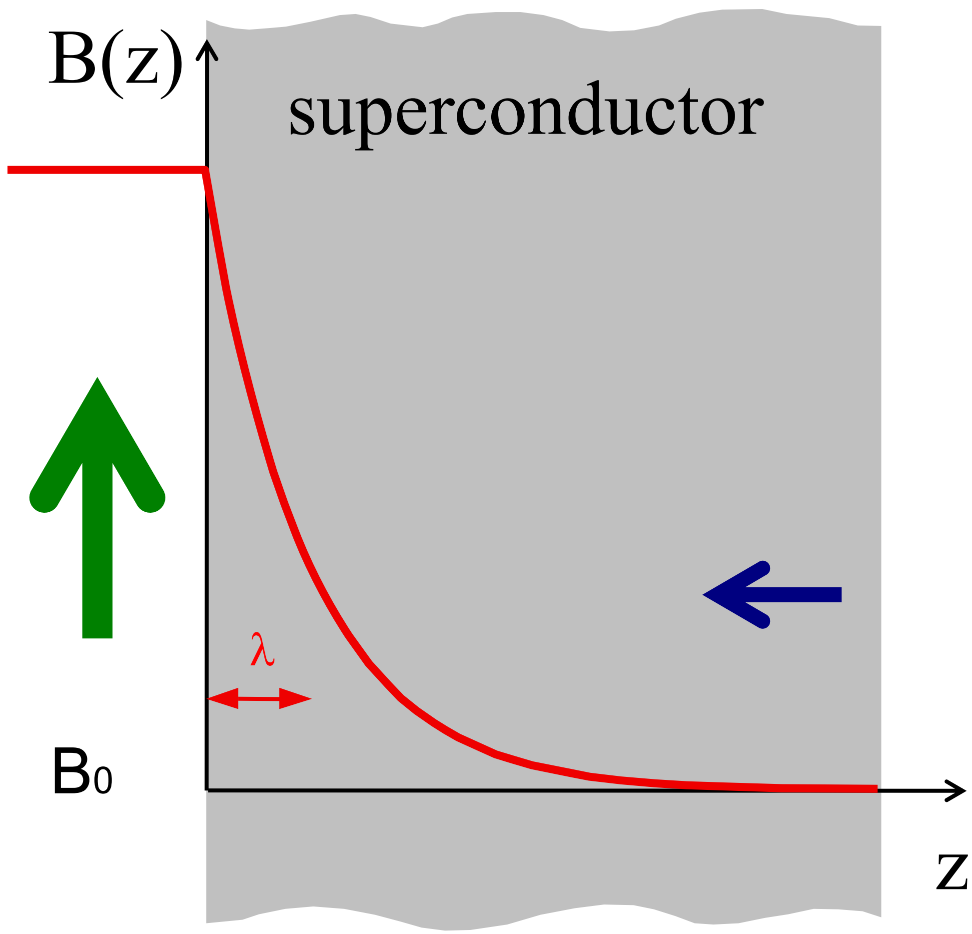


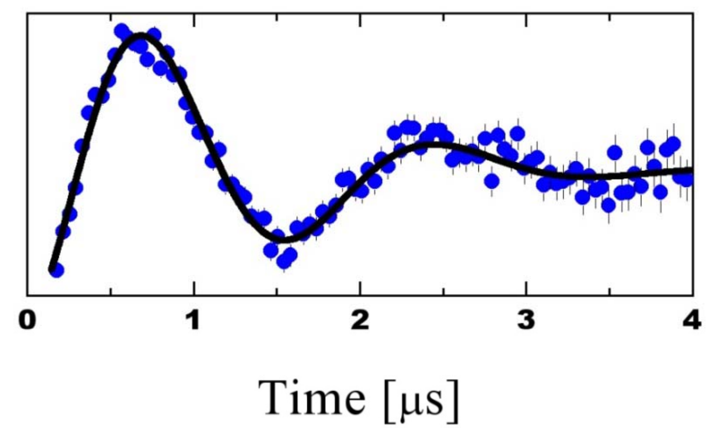


T=110 K > T_c=94.1 K

B~10 mT

Superconducting sate of $YBa_2Cu_3O_7$ B_0=9.3mT

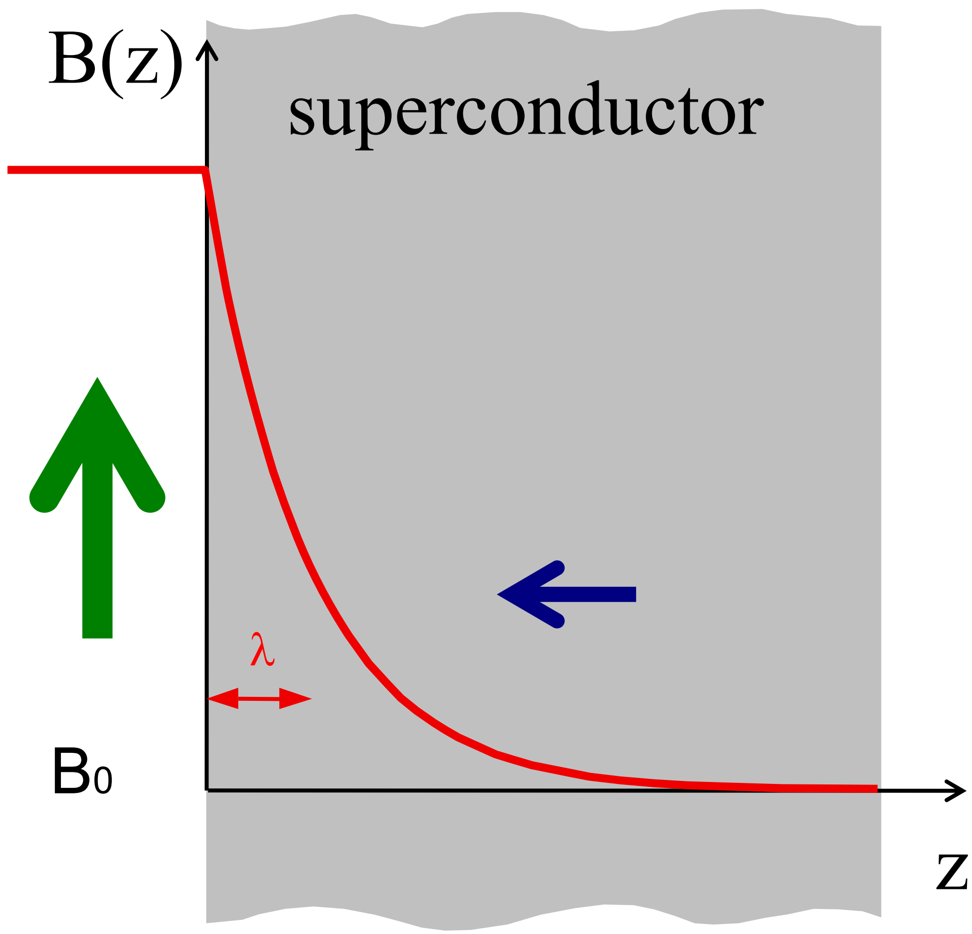


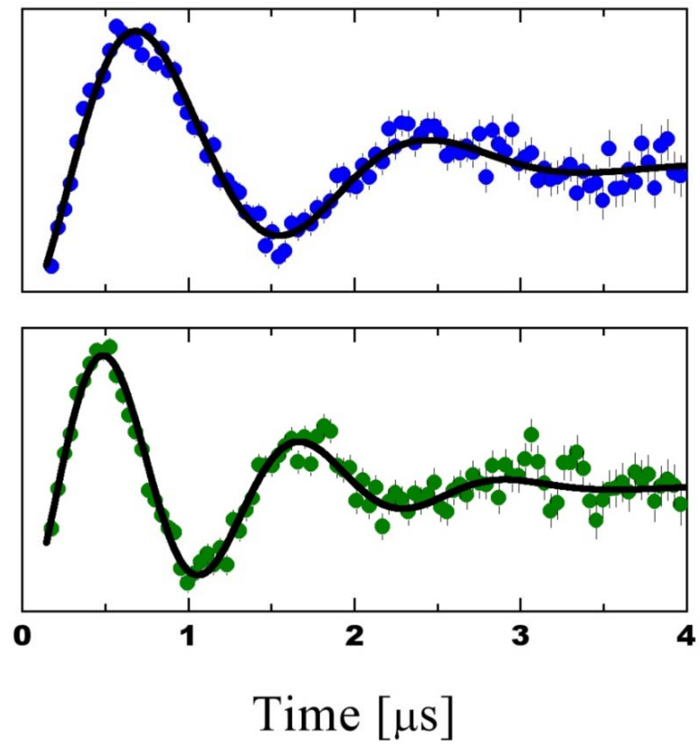


Kiefl et al. PRB 81, 180502(R) (2010)

T=8 K << T_c
Zero field cooled
B~10 mT

Superconducting sate of $YBa_2Cu_3O_7$ B_0=9.3mT





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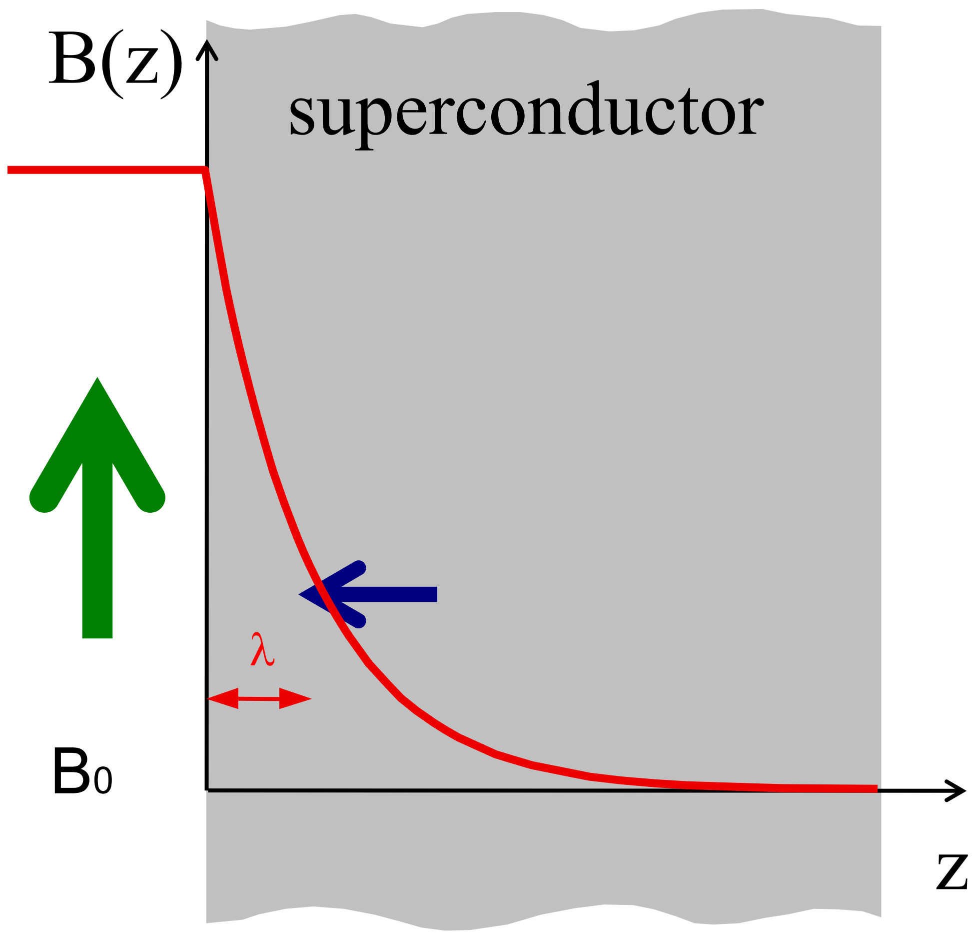
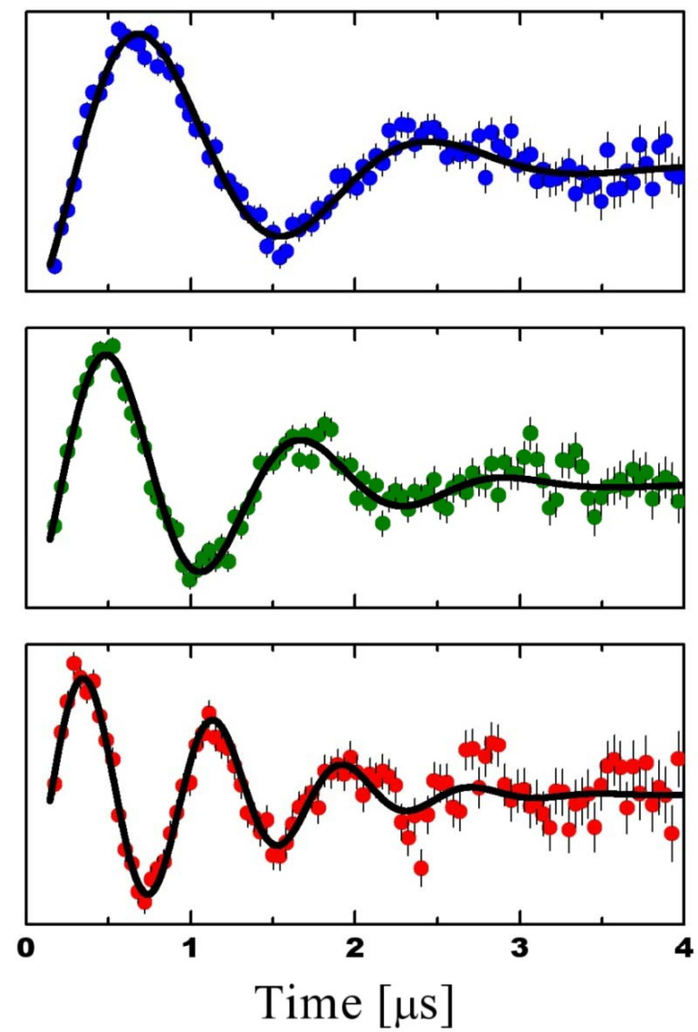
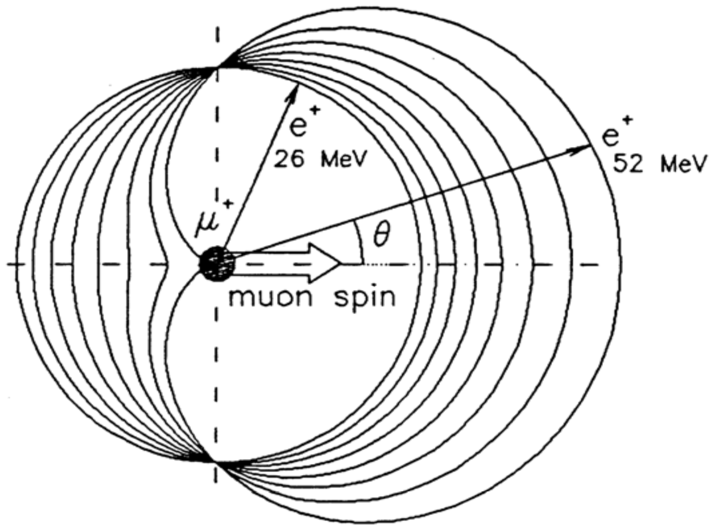


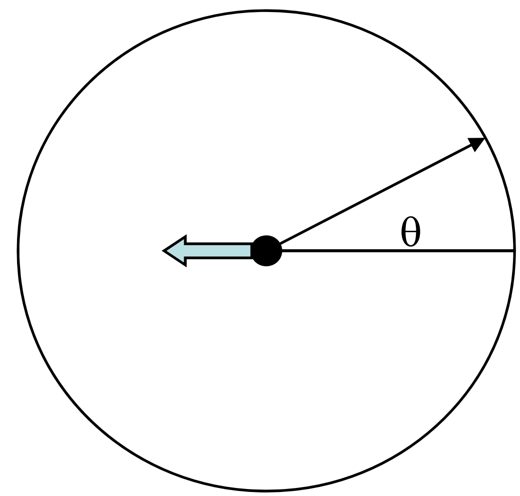


Kiefl et al. PRB 81, 180502(R) (2010)

Properties of the muon and ^{8}Li

$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$ $\quad$ $^8Li \longrightarrow {}^8Be + e^- + \nu_e$





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<A>= 0.33
Polarization = 95%
Lifetime = 2.19714(7) μs

Spin=2, Q=33 mb
γ =6.30 MHz/T
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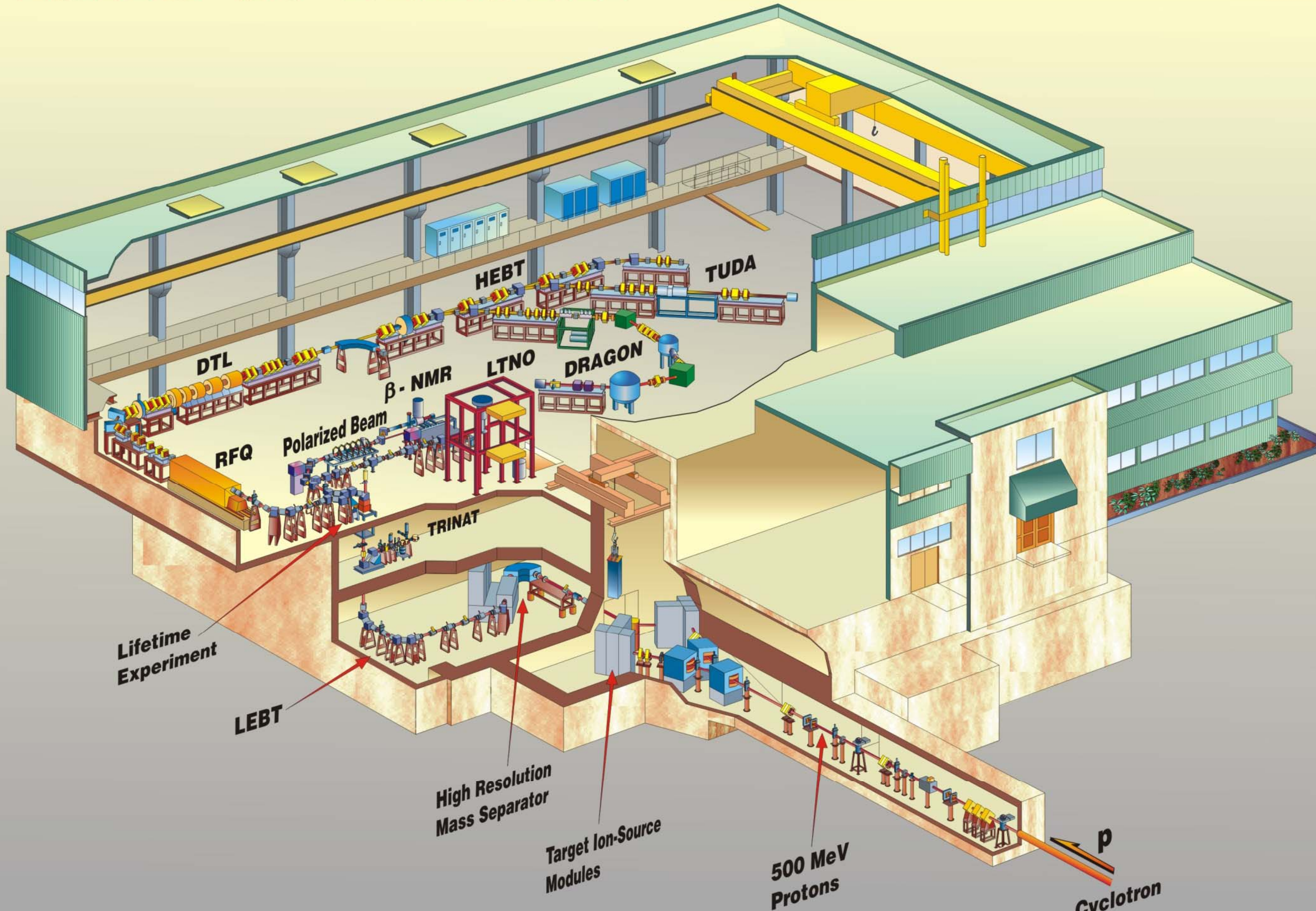
Polarization= 70%
Lifetime= 1.2s

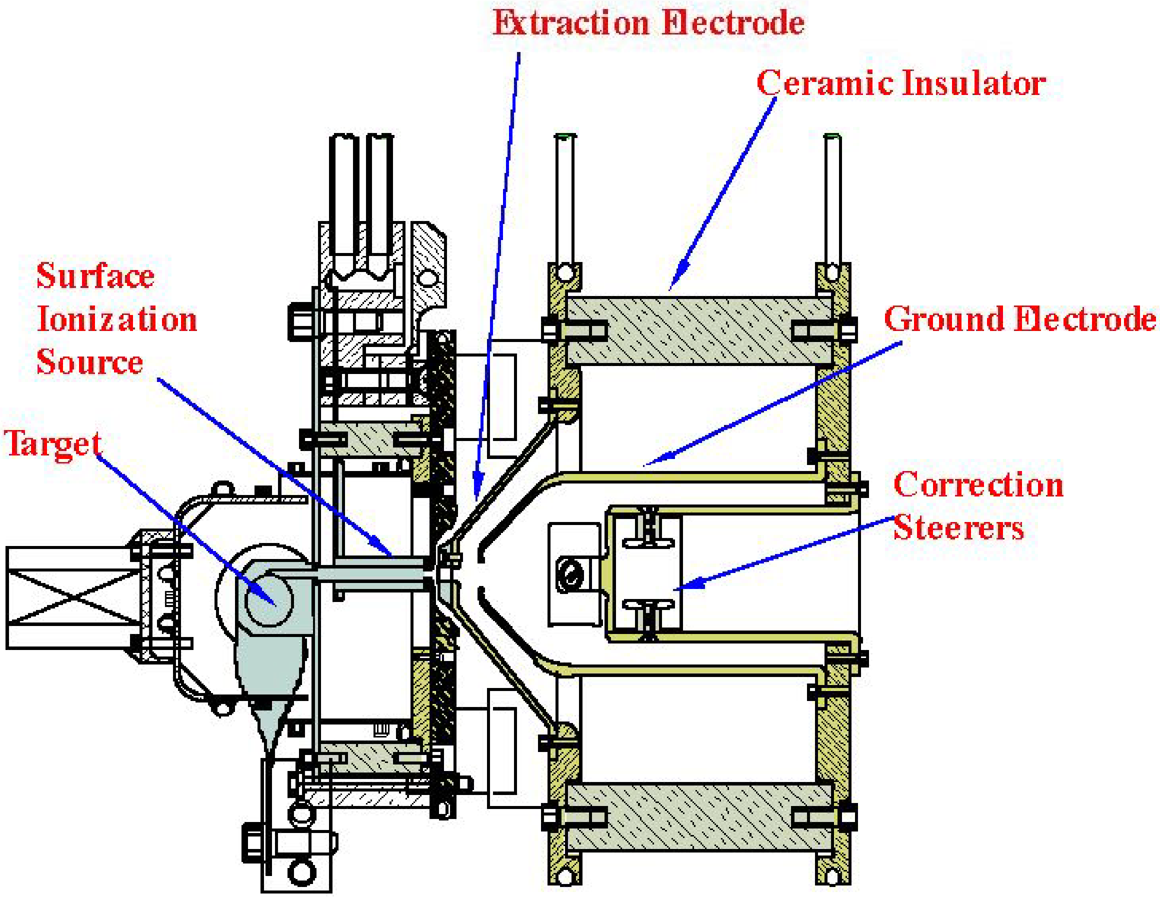
ISAC at TRIUMF



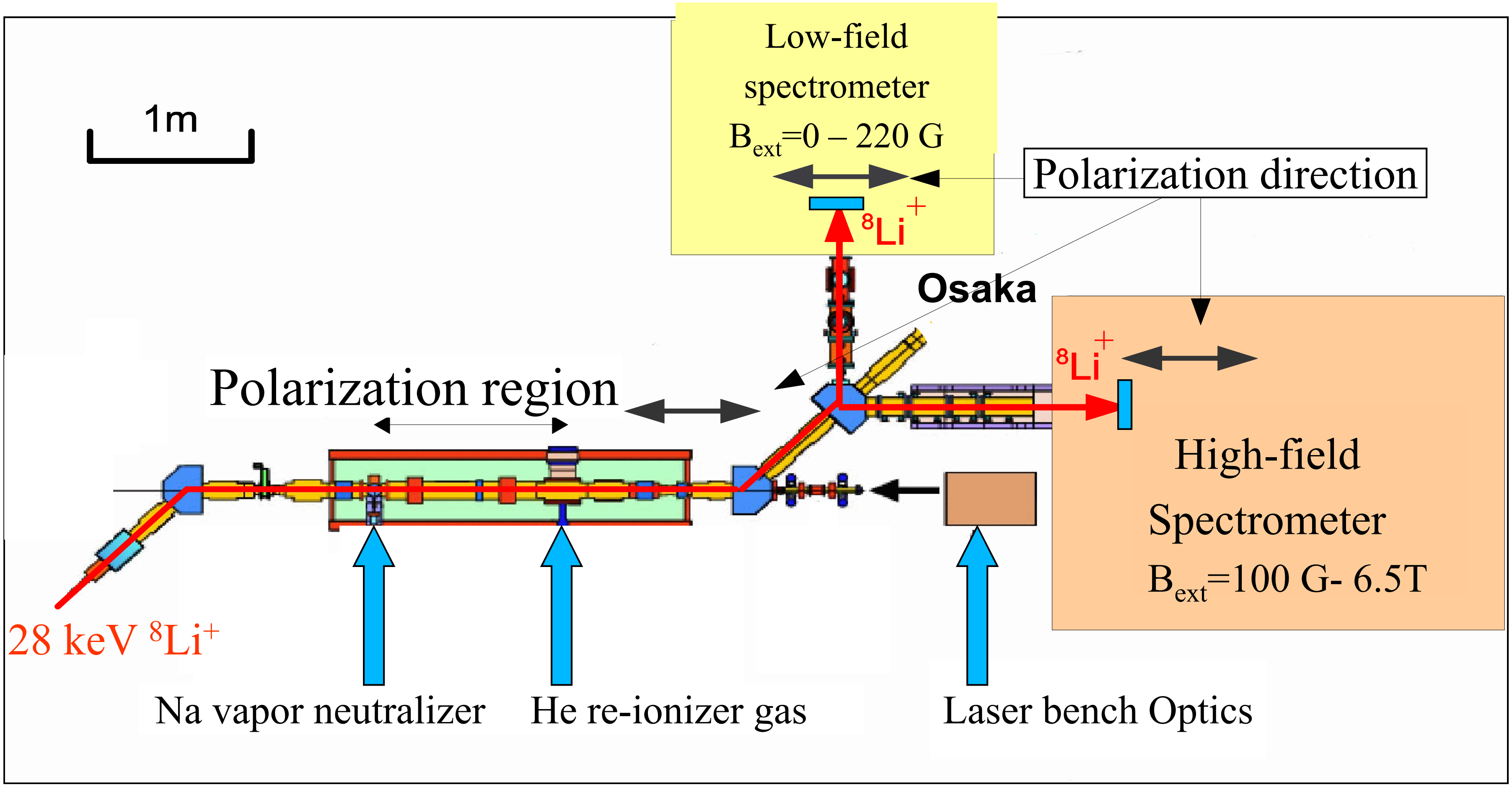
Some Suitable Isotopes for βNMR at ISAC

Isotope	Spin	$\tau_{1/2}$ s	γ (MHz/T)	β-Decay Asymmetry	Estimated Rate (s^{-1})
^{8}Li	2	0.8	6.3	0.33	10^{8}
^{11}Be	1/2	13.8	22	~0.3	10^{7}
^{15}O	1/2	122	10.8	0.66	10^{8}

Production of $^8Li^+$ Ion (M. Dombsky, TRIUMF)

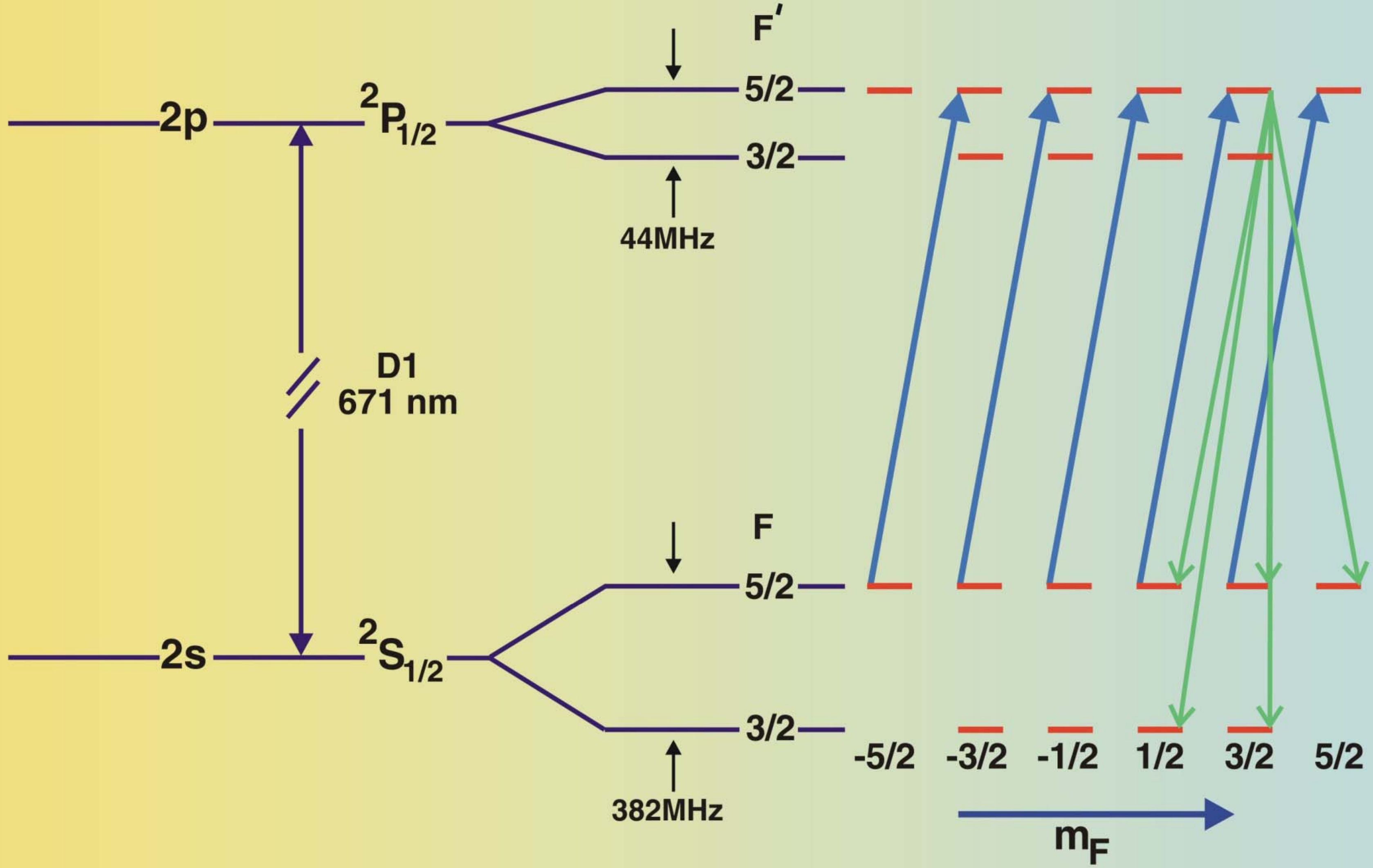


β-NMR setup at ISAC

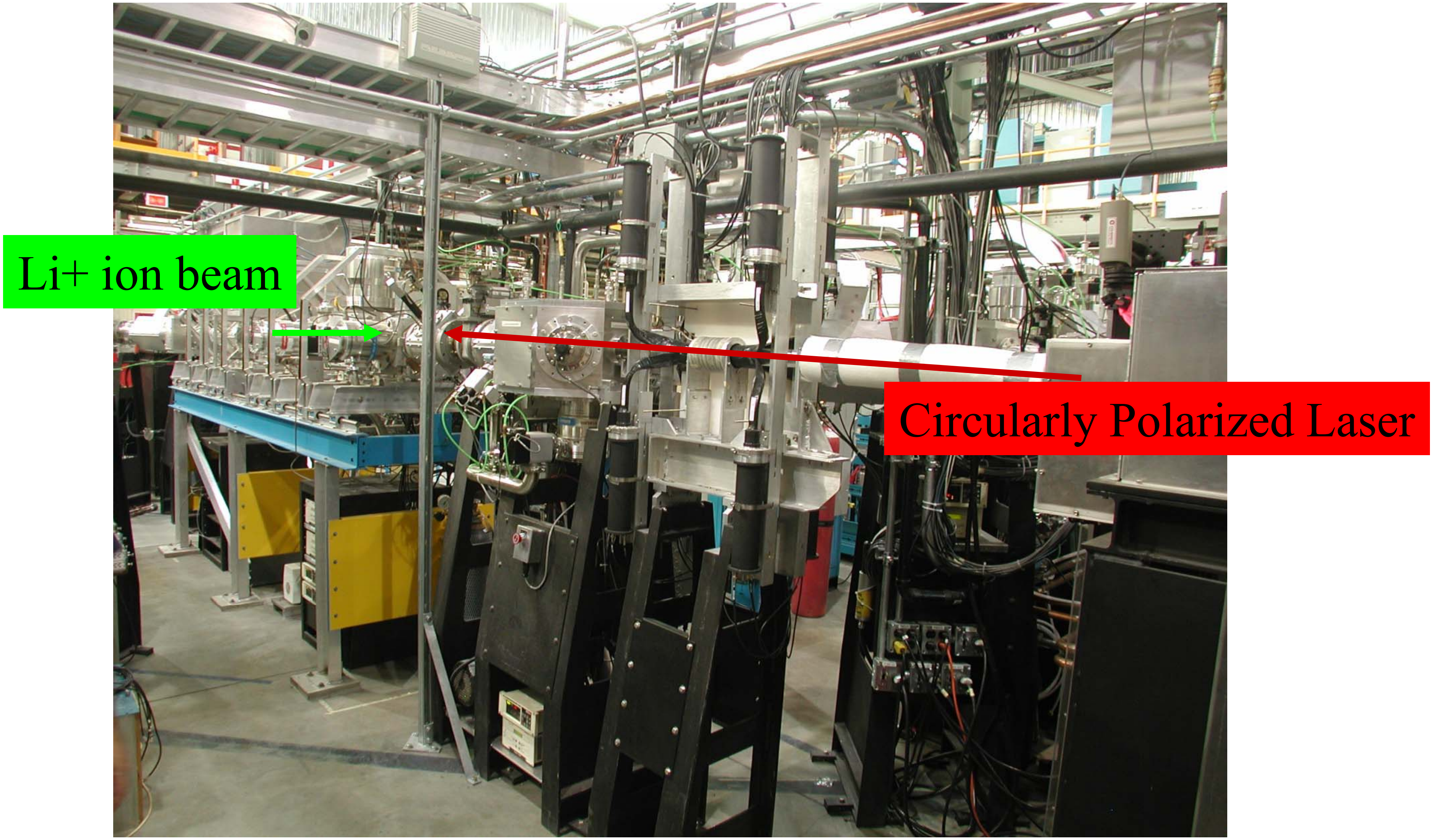


- Optical pumping with a tuned laser is used to achieve ~70% of spin polarization.
- Electrostatic deceleration is used to control the depth of the implanted ions (2-500nm)

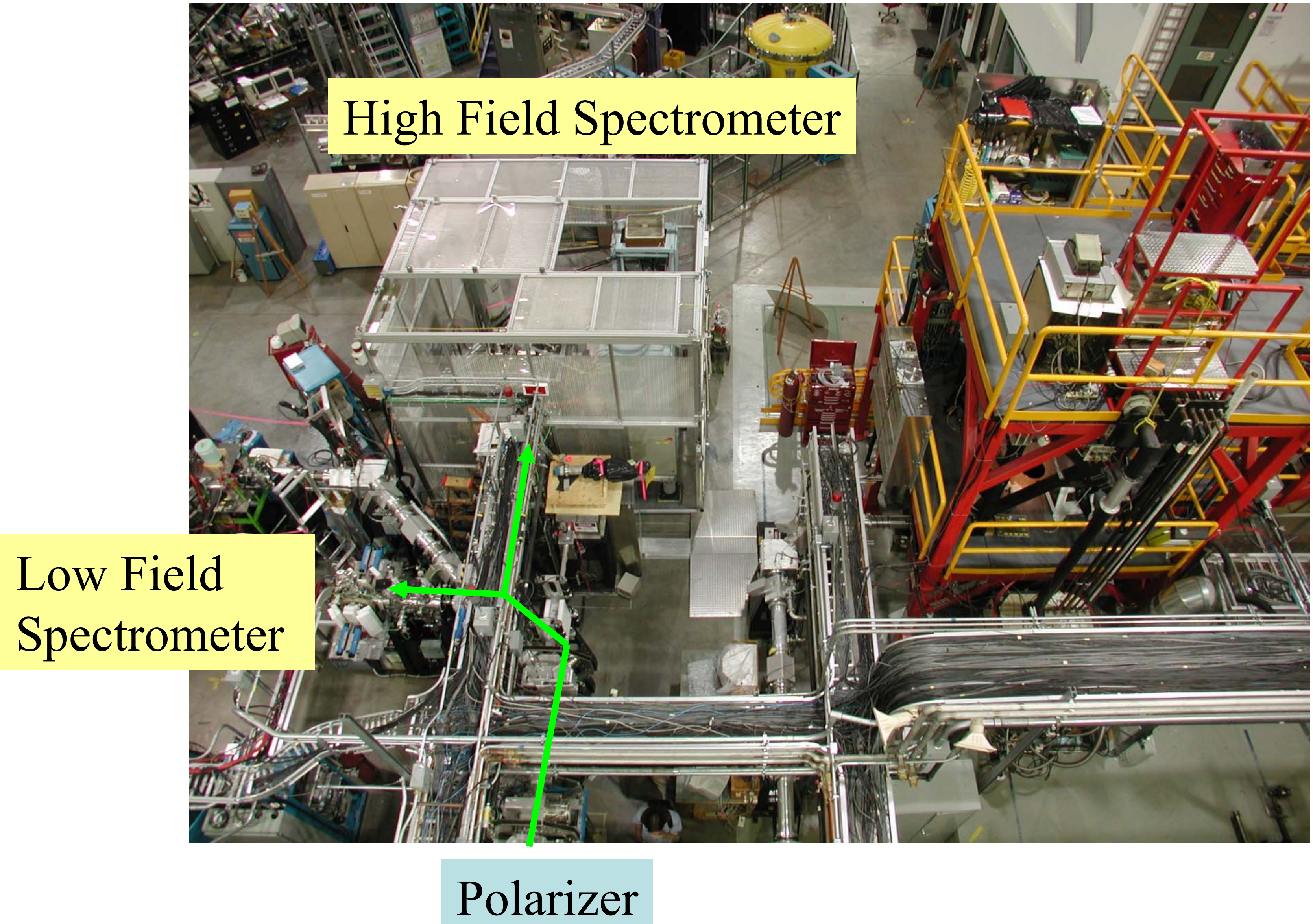
OPTICAL PUMPING SCHEME FOR ^{8}Li



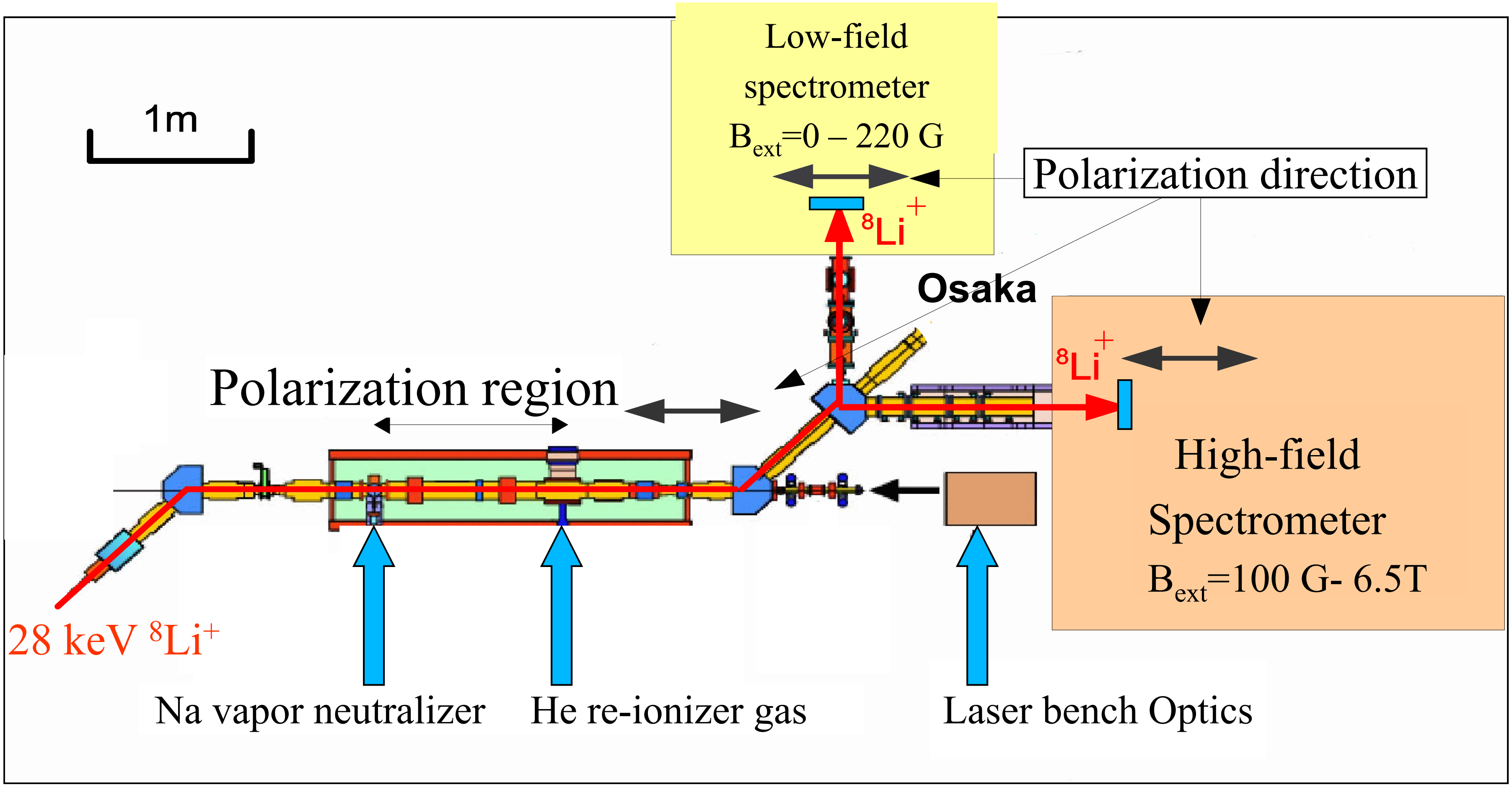
Optical Polarizer



β-NMR Spectrometers at ISAC

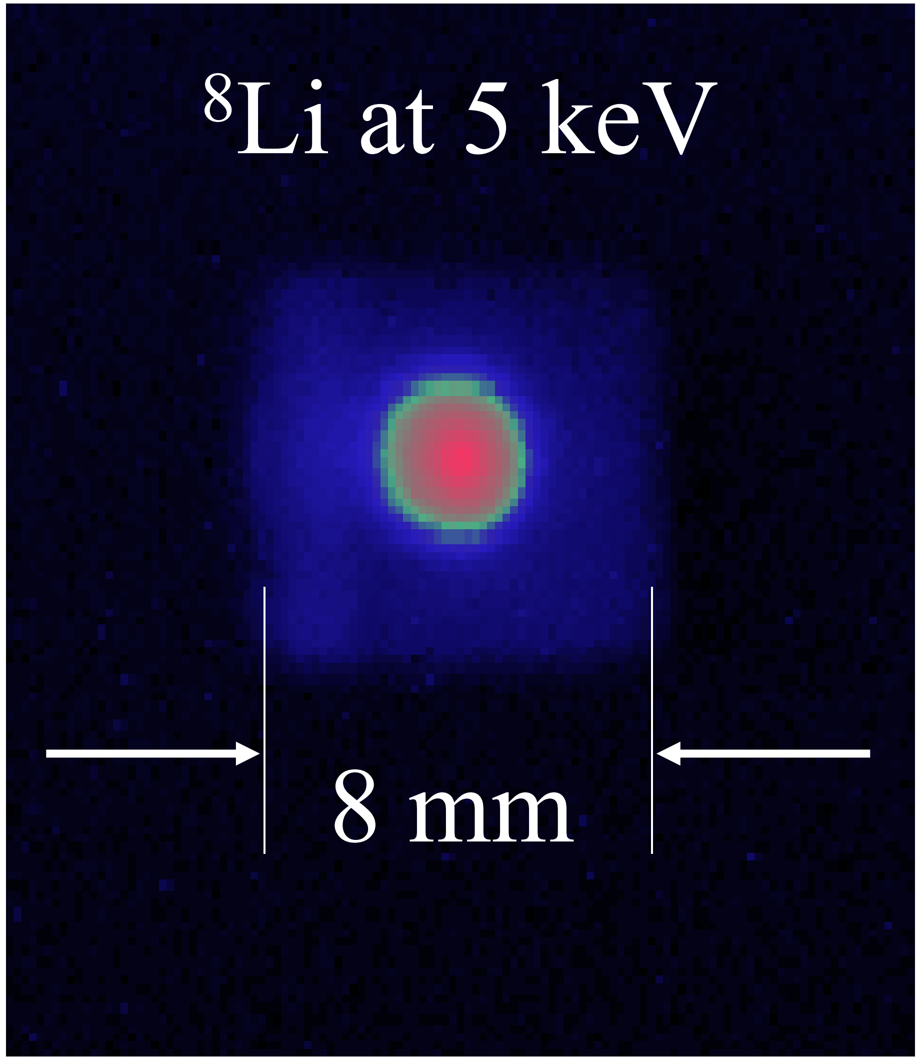


β-NMR setup at ISAC

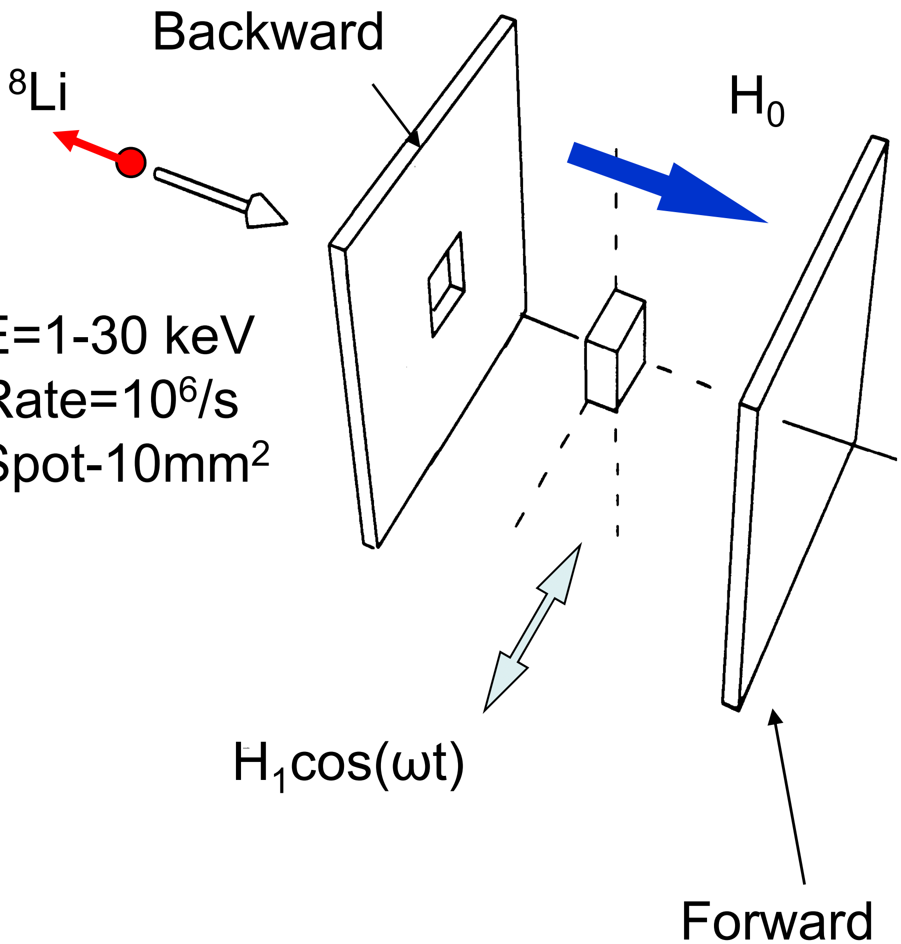


- Optical pumping with a tuned laser is used to achieve ~70% of spin polarization.
- Electrostatic deceleration is used to control the depth of the implanted ions (2-500nm)

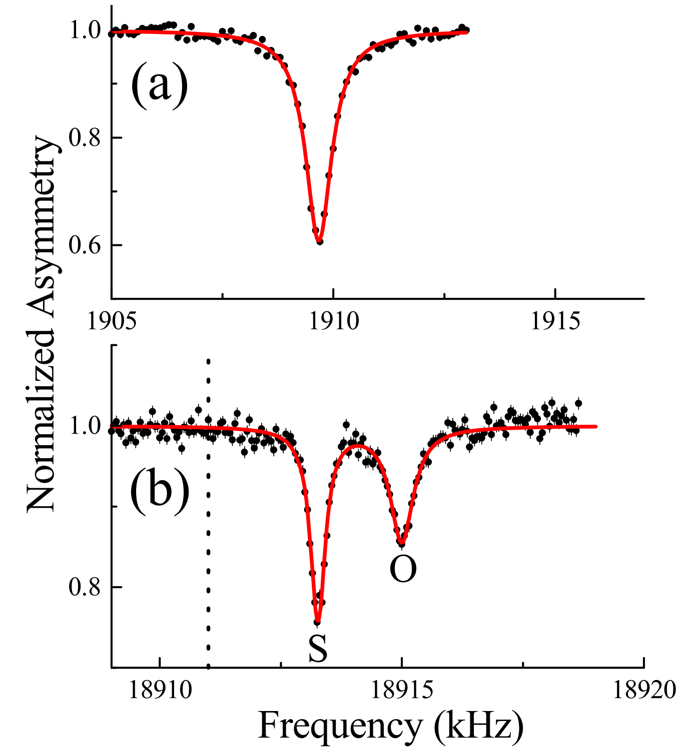
Beamspot

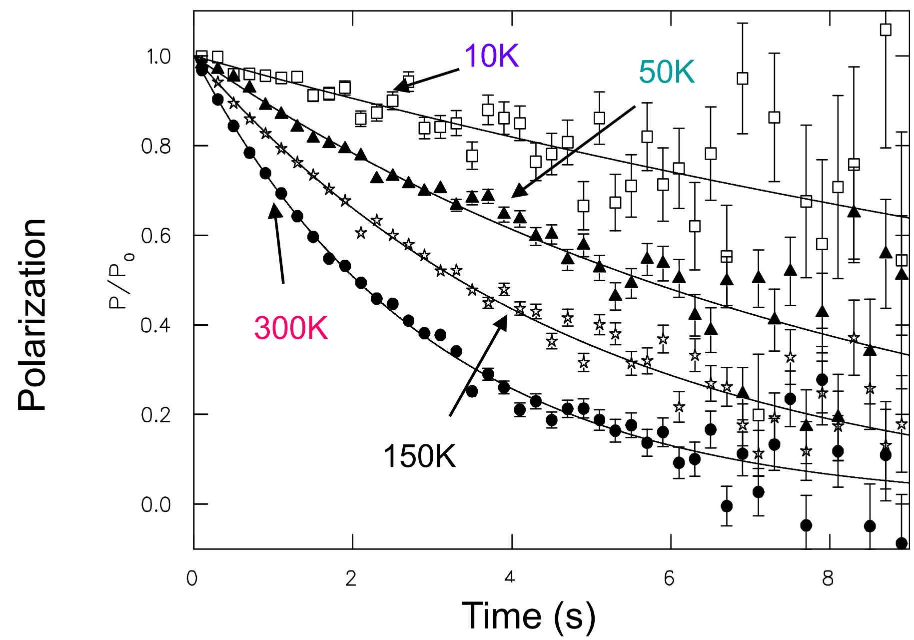


Schematic of a β-NMR Experiment

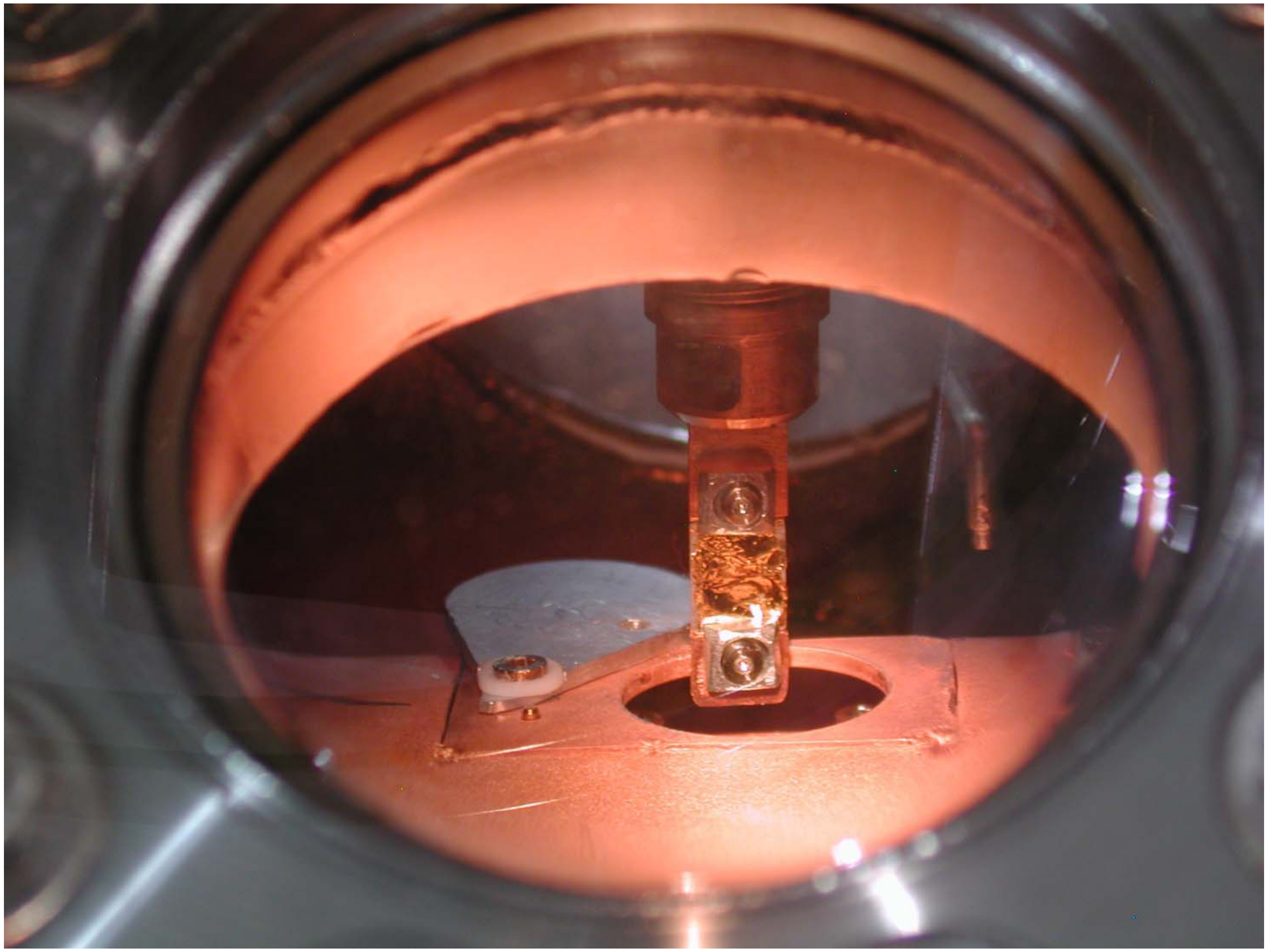


E=1-30 keV
Rate=10^6/s
Spot-10mm^2



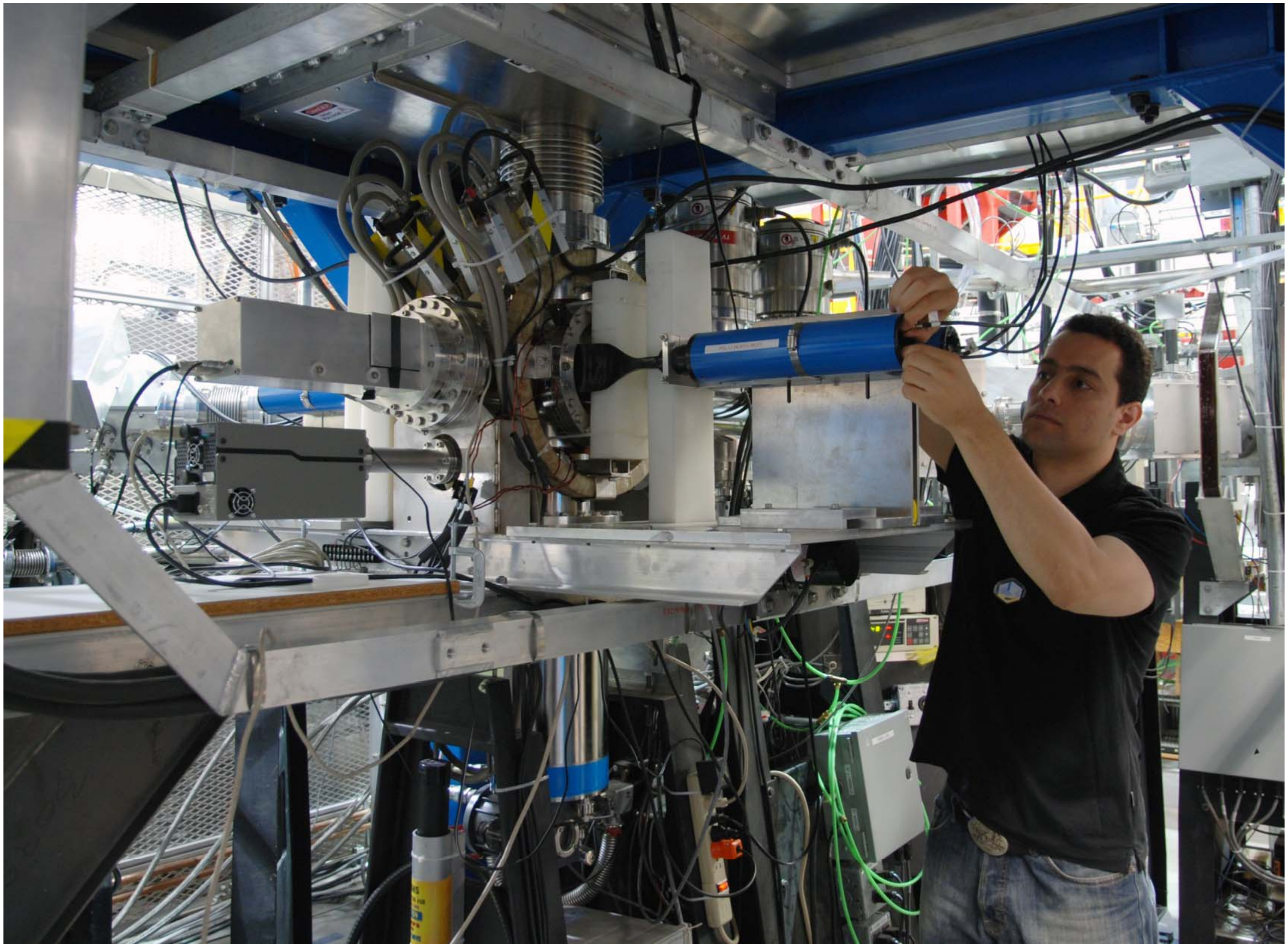


Loading a sample into the high-field βNMR spectrometer



Hapke/TRIUMF

βNQR Spectrometer



Hassan Saadaoui

β-NMR spectrometers at ISAC

	Low Field	High Field
Magnetic field range	0-20 mT	1-7T
T range	4-300K *300mK-1000K*	4K-300K
Energy (depth) range	1-30 keV (2-200 nm)	1-30 keV (2-200nm)
Beam spot	10 mm^2	10 mm^2

Summary

- Low energy β-NMR and LE-μSR provide unique way to probe depth dependent magnetic properties on nm length scale. The much different lifetimes of the muon and 8Li means that they are sensitive to much different timescales and are thus very complementary.

- Tomorrow we will see some specific examples.