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RF-μSR and Pulsed Techniques

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Outline

- Why use pulsed techniques?
- RF Resonance
  - how it works
  - science
- Other pulsed stimuli
- Other sample environments

Why pulsed?

- Science:
  - Direct effect of time-varying environment (eg. RF)
  - Observe slow formation of final muon states
  - Measure recovery time of sample after a pulse (eg. charge carrier recombination), or non-equilibrium state of the sample

- Practical:
  - At ISIS, muons are only in the sample for 0.1% of the time!
  - Higher intensity available (eg. RF fields, lasers or flash lamps)
  - Timing easier, know in advance when muons will arrive
  - Avoid sample heating (eg. RF, light, pulsed currents)
  - Avoid other problems with steady state conditions (eg. charge accumulation due to electric field)

Practical points

- The stimulus must be pulsed at the same frequency as the beam: 50Hz at ISIS, or a sub-multiple such as 25Hz.
- Time the pulse to:
  - Before the muons, to measure the sample in its excited state, or with varying delay to follow the relaxation time
  - Coincident or just after the muon arrival, to interact directly with the muon
- Usually measure in period mode, 2 sets of histograms
  - Red: stimulus applied
  - Green: control measurement without pulse

Rapid switching compensates for any drifts in temperature, field, beam current, etc.

RF resonance

- Just like NMR
  - but not limited by T_1
- Scan field (or frequency) to plot resonance lines
- Sit on resonance and measure amplitude as function of temperature, timing, etc.

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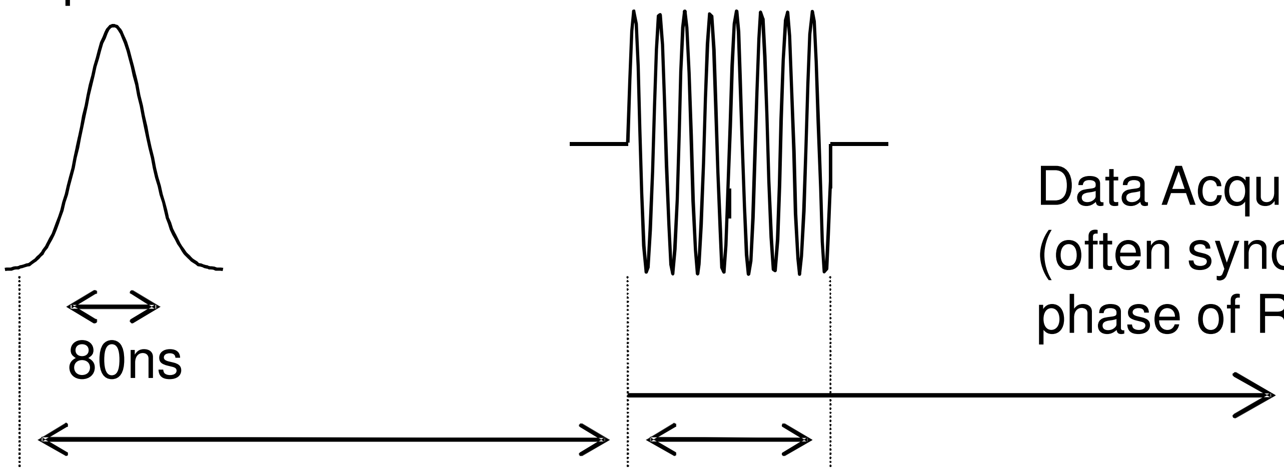
Pulsed RF

High intensity RF pulse
Very low duty factor (e.g. $5*10^{-5}$)

Muon
pulse



Data Acquisition
(often synchronised with
phase of RF burst)

Variable Δt
(100ns-10μs)

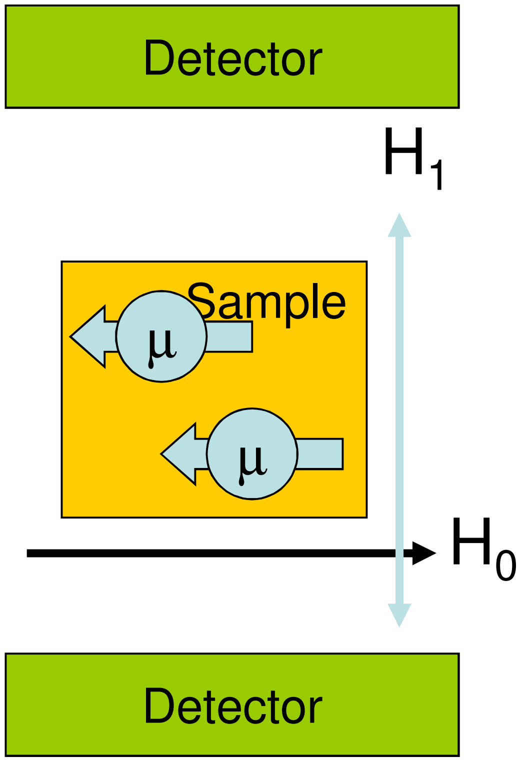
δt ($\approx 1\mu$s)

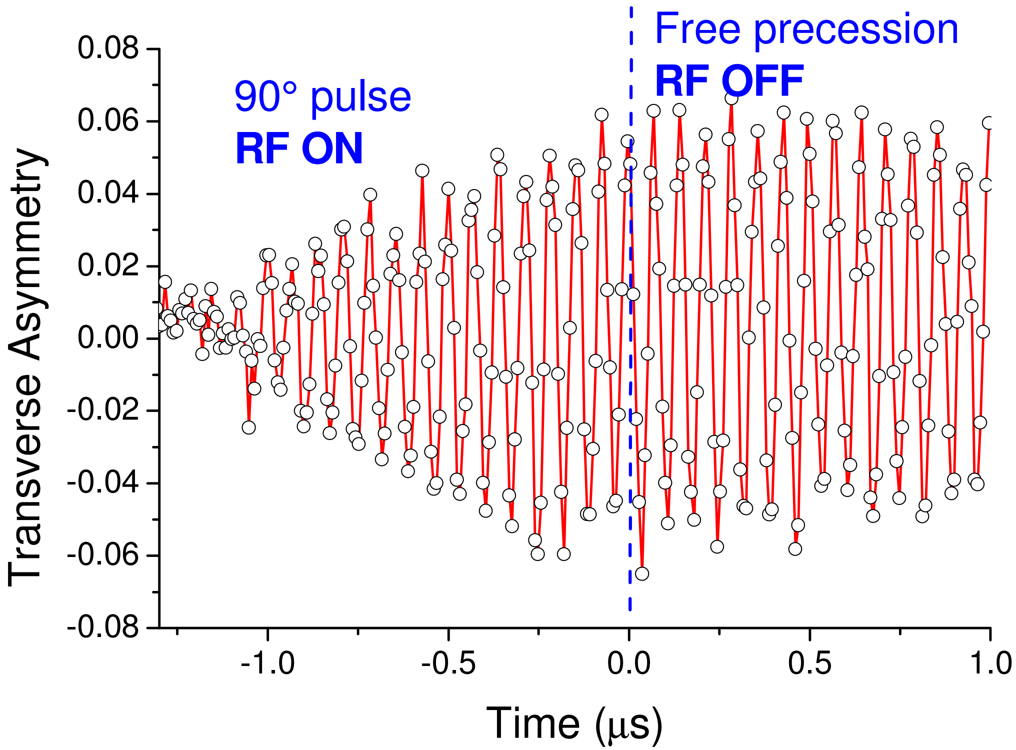
Allows muon state kinetics to
be studied

Determines rotation angle of
muon polarisation, e.g. $\pi/2$

Transverse RF

- Muons implanted parallel to static magnetic field
- Short RF pulse at the muon's Larmor frequency
- Similar to Free Induction Decay in NMR
  - but can measure during the pulse too!
- Measure local field and its distribution

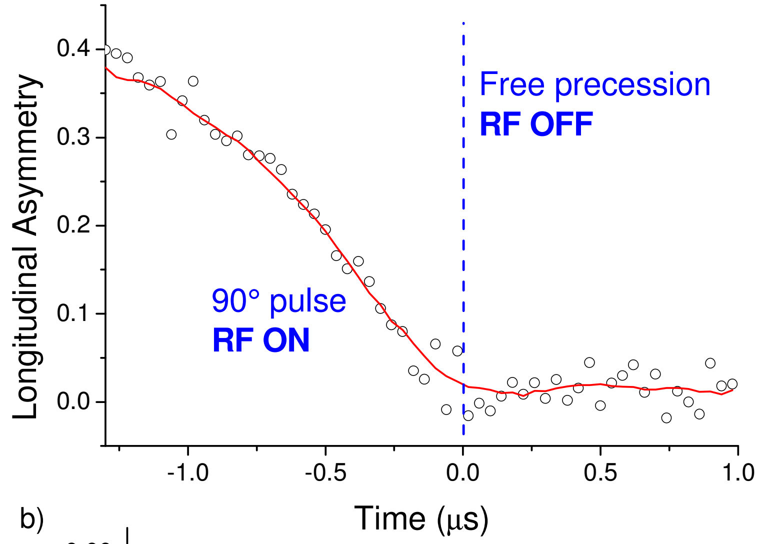


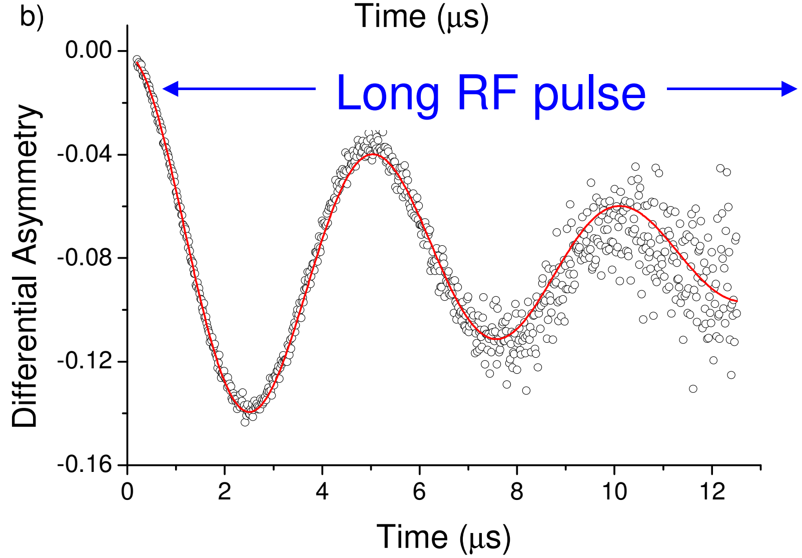


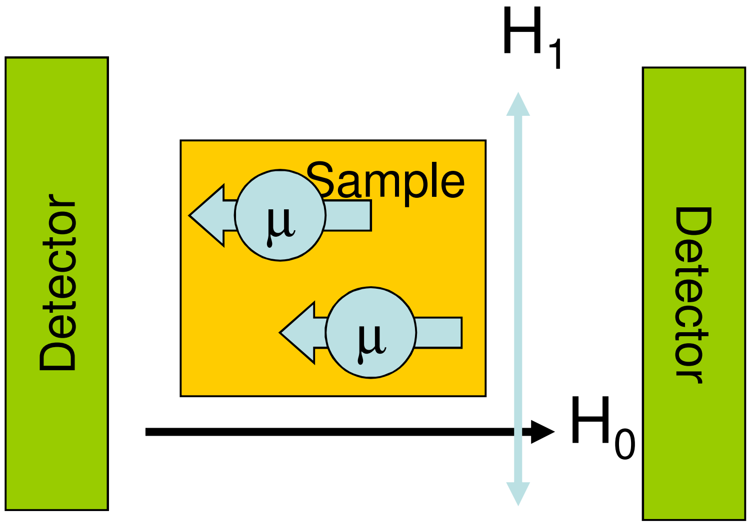
Data acquisition synchronised with RF waveform, not muon pulse

Longitudinal RF

- Can't measure longitudinal polarisation directly by NMR
- Precession in H_1 field
- Amplitude gives diamagnetic fraction at time RF applied
- Damping gives conversion between states



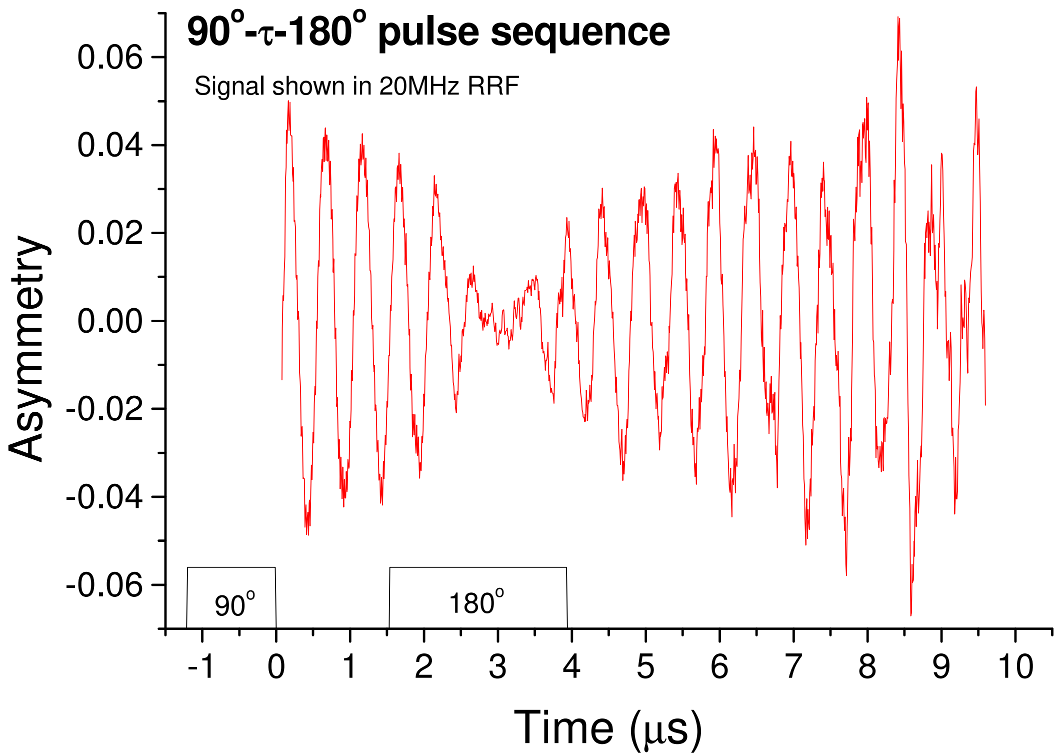




Spin echoes

- Precession damped by random nuclear fields
- Re-focus spins with 180° pulse at time τ
- Echo at 2τ, similar to NMR

Boron diamagnetic resonance in 1672G



S.R. Kreitzman / RF resonance techniques for continuous muon beams 1067

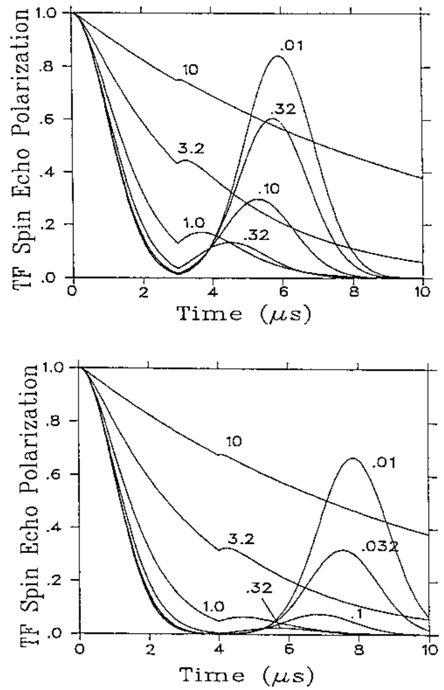


Fig. 6. Theoretical spin echo response for various hop rates. The value of Ω_2 is 1 μs and pulses are tacitly assumed to be *ideal*. The numerical captions denote hop rates in units of $1/t_\pi$, which for fig. (a) is 3 μs and for fig. (b) is 4 μs. Note that even for reasonably rapid hop rates, the echo position can be distinguished.

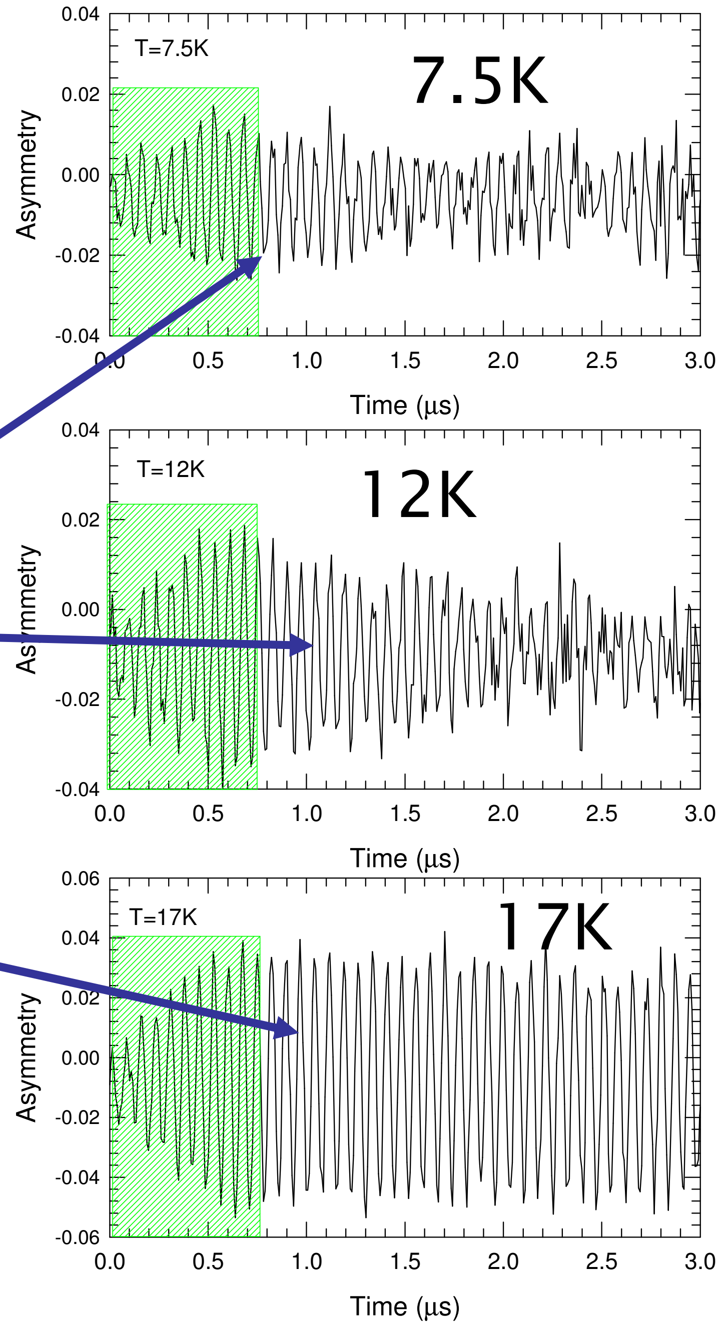
Superconductors

- YNi_2B_2C
- Type II
- T_C=15K
- λ=103nm
- ξ_0=8nm

- Field 1034G
- 13.6MHz – above usual ISIS frequency range

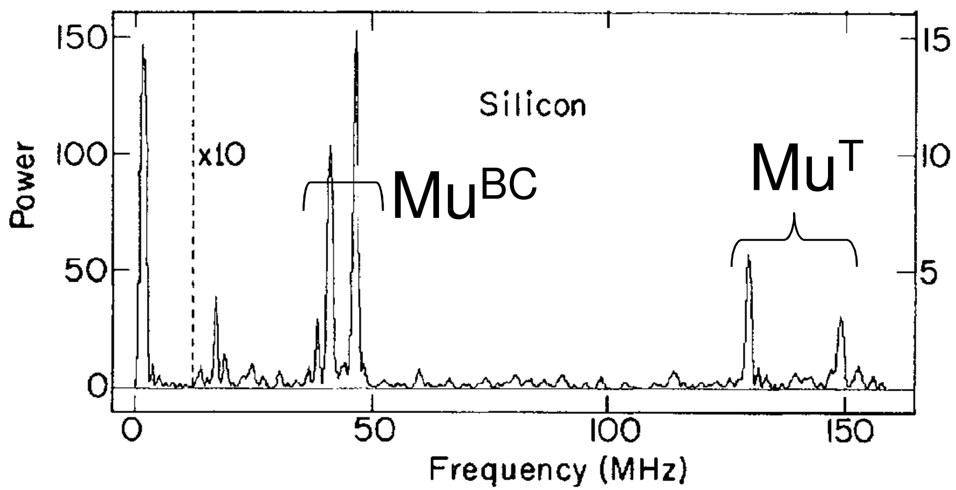
Superconducting (mixed) state

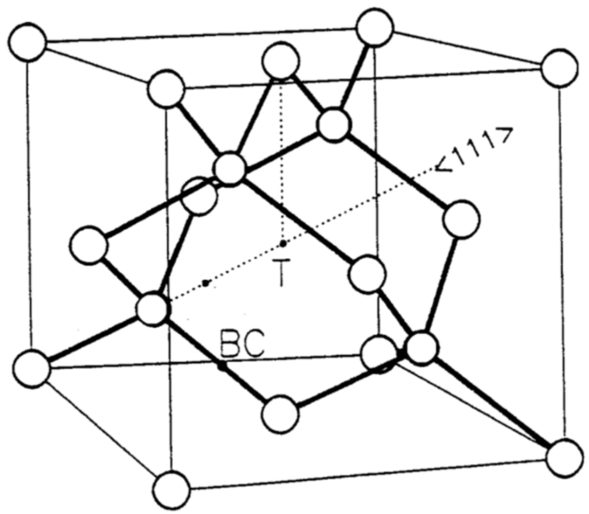
Normal state



Charge state dynamics in semiconductors

- In silicon, muonium found in 2 sites, seen by TF-muSR at low temperature:
  - Cage centred (T) or normal muonium
  - Bond centred (BC) or anomalous muonium





- Above 120K the Mu^{BC} signal disappears

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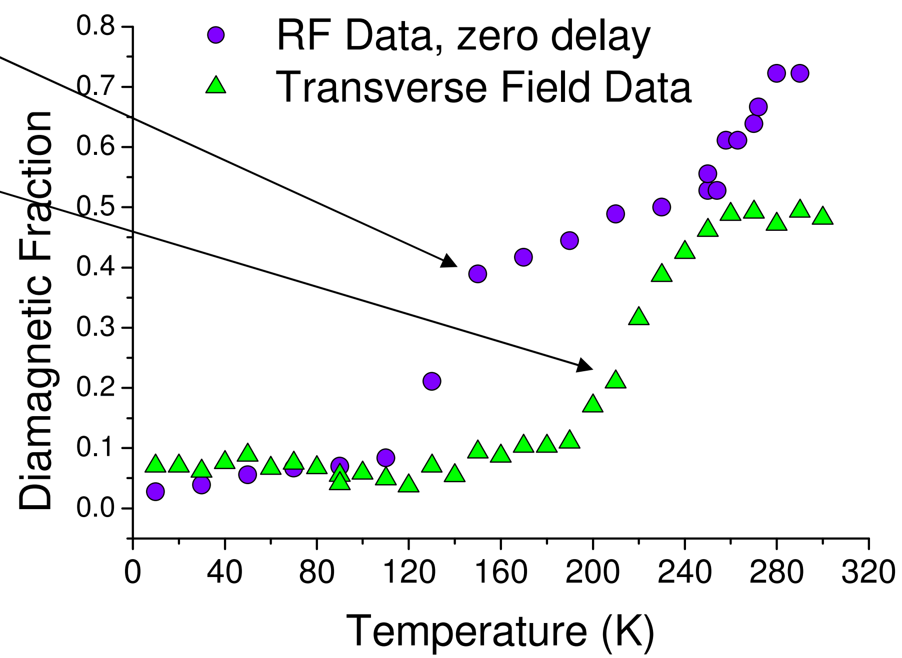
Dynamics

- RF shows appearance of diamagnetic species when TF Mu^{BC} signal disappears
- No diamagnetic signal in low TF until much higher temperature
- In TF muons spend a short time as muonium, and dephase
- In the RF experiment the muon spins are locked along high LF before the pulse



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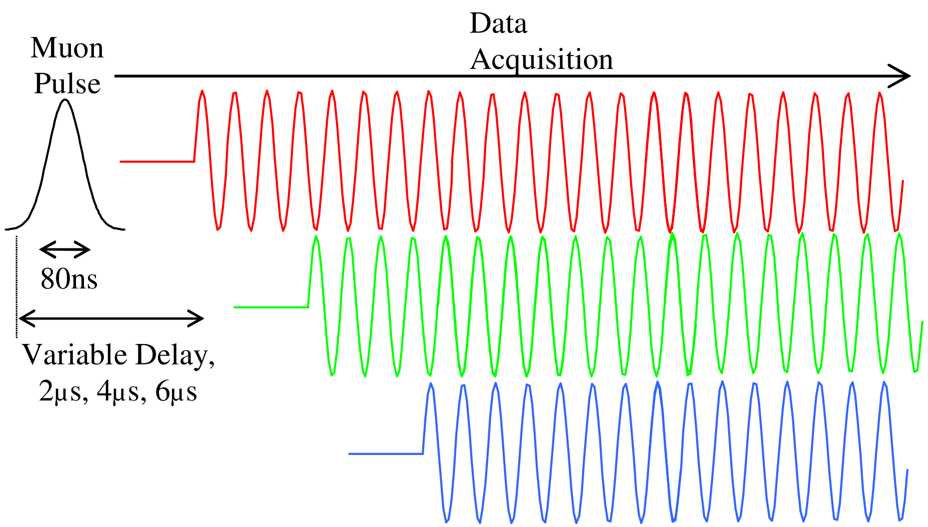
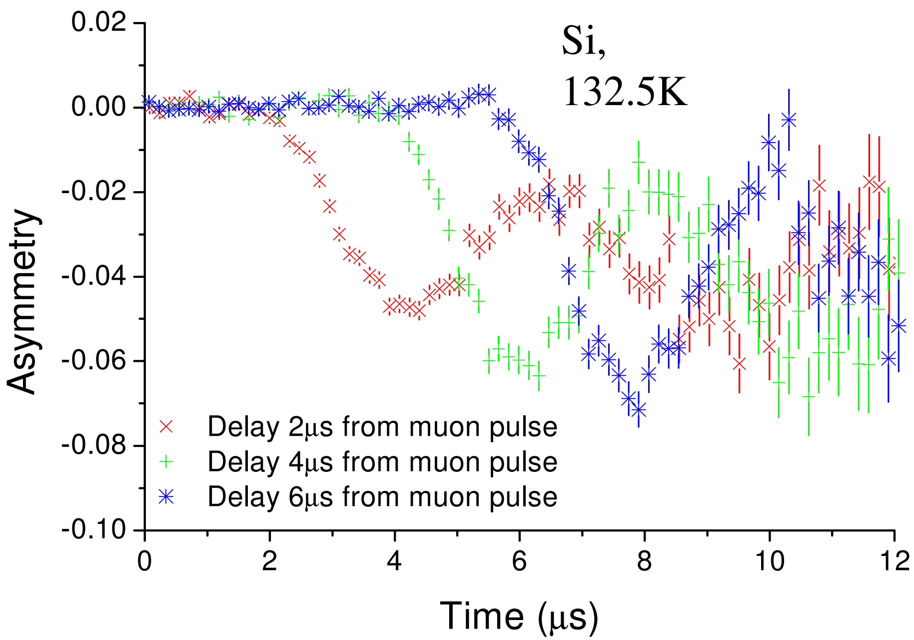
Dynamics

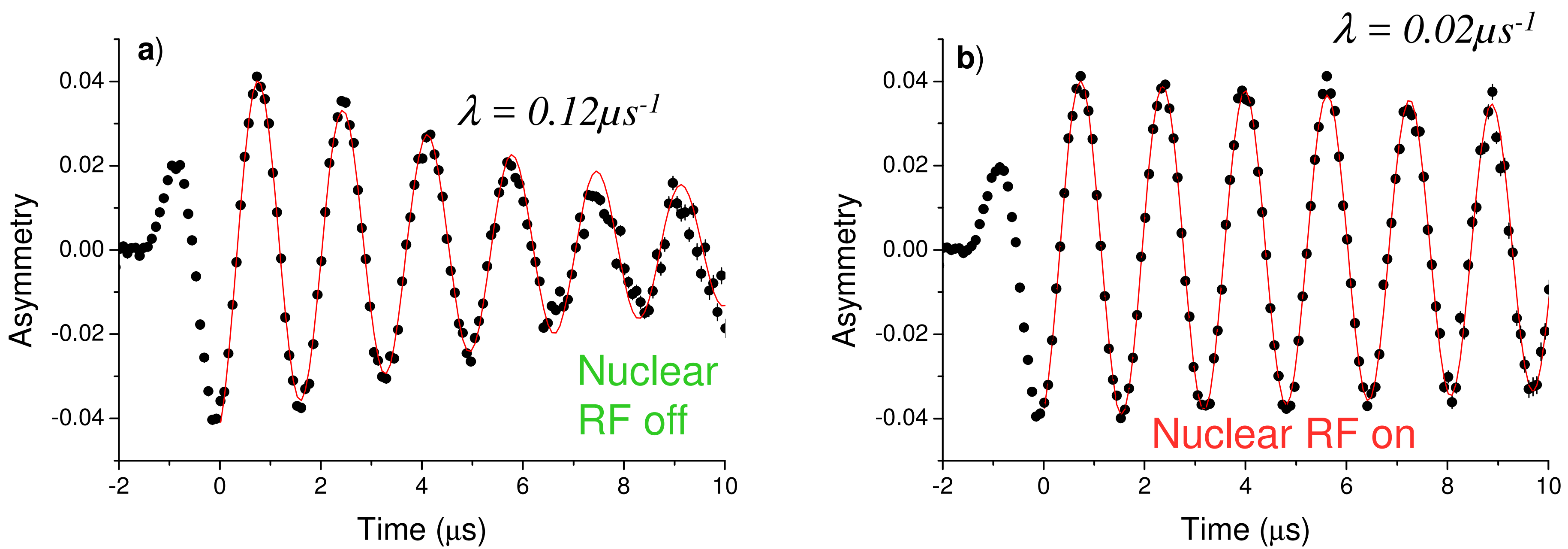
- For favourable reaction rates (μs^{-1}) we can follow the conversion by delaying the RF pulse





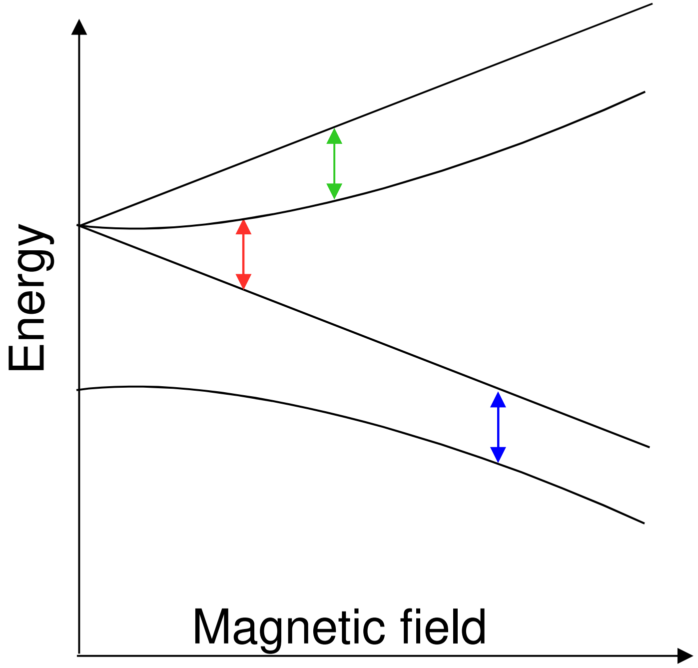
RF Decoupling

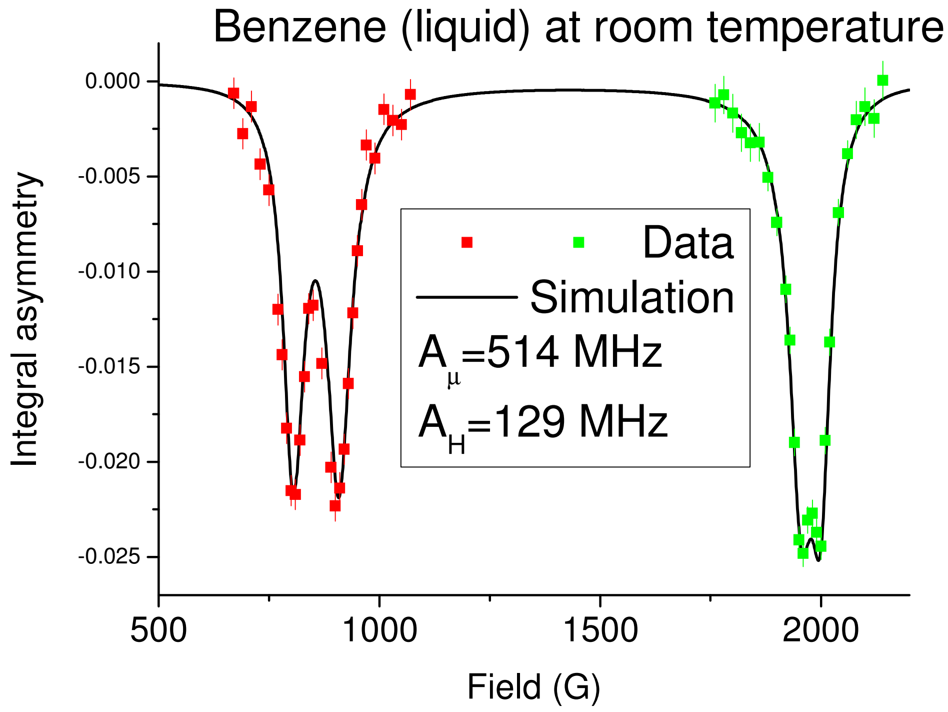
- Two RF signals simultaneously
  - 90 degree pulse to set the muons precessing
  - Continuous RF at the nuclear Larmor frequency to “stir” the nuclear spins and average out the dipolar coupling
- Observe reduced relaxation of muon signal
- Identify which nuclei are coupled to muon



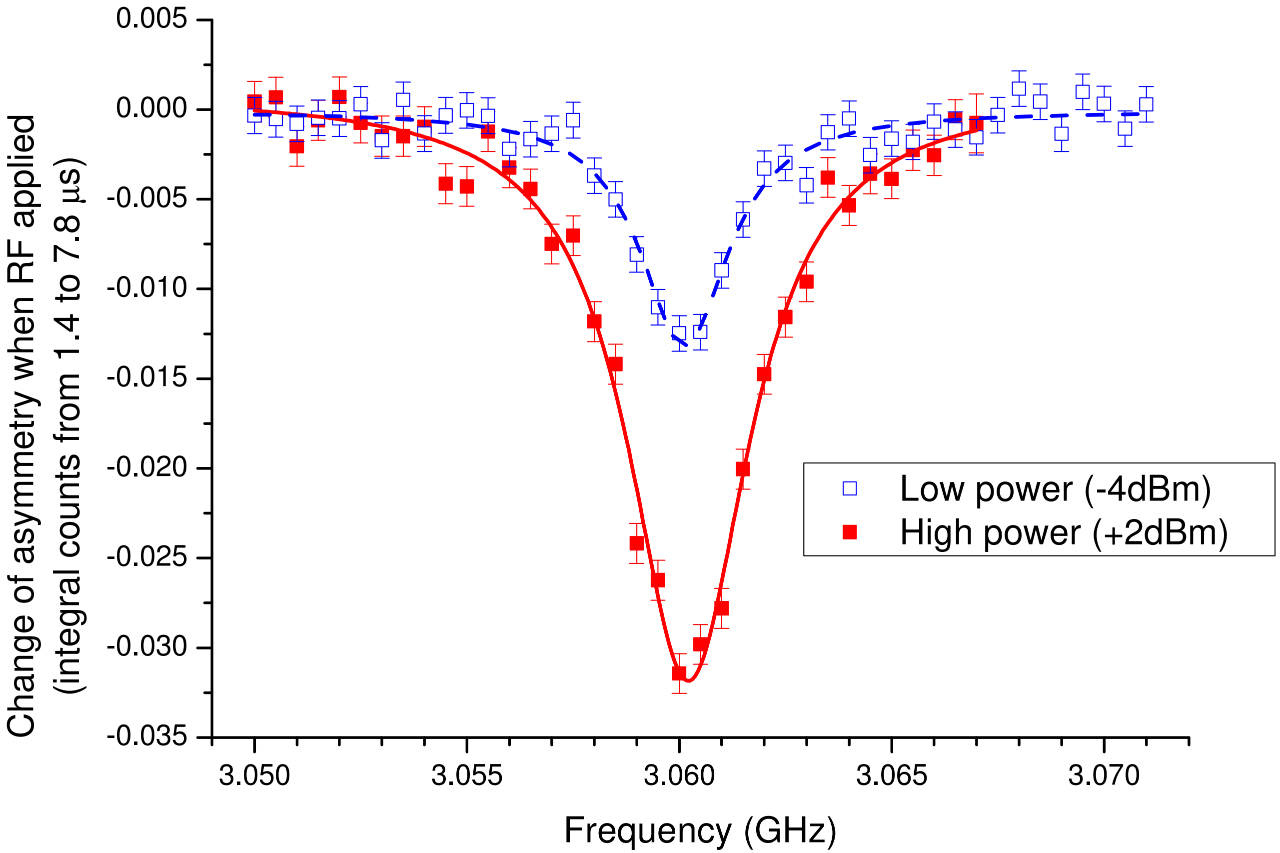
Muonium RF

- RF causes spin-flips of the combined muon and electron system.
- Many resonance fields or frequencies
  - Hyperfine coupling
  - Coupling to other nuclei
  - Dynamics and reaction rates





High frequencies (microwaves)



High frequency excitation (3GHz)

Low frequency detection (integral)

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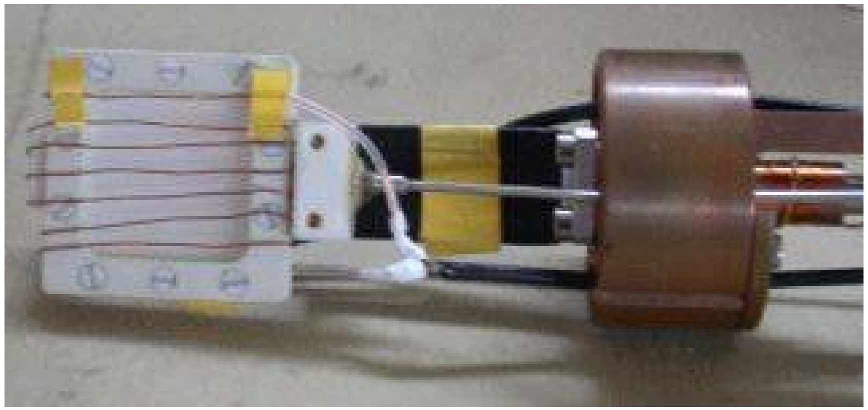
RF equipment

- Coil of widely spaced wires or thin foil to let muons into sample
- RF field B_1 of 10s of Gauss for diamagnetic muons or in high static fields
- Lower B_1 for low field muonium resonance

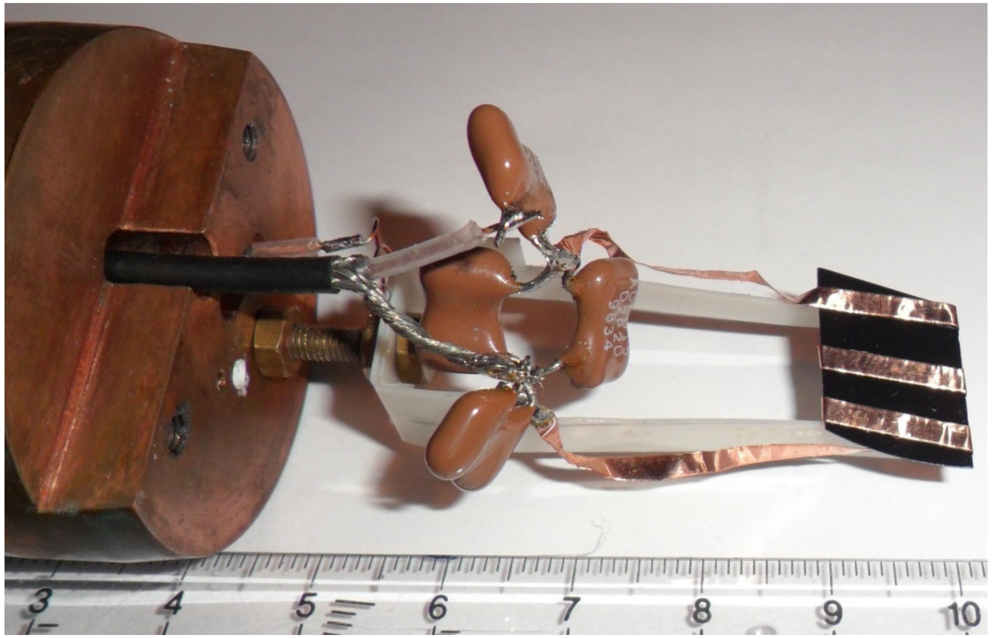


Liquid cell with RF coil

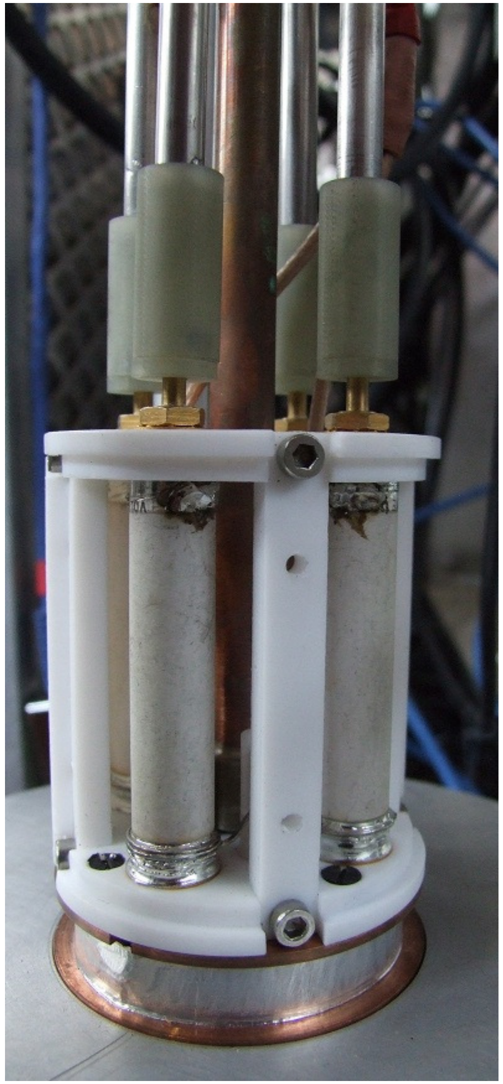
Copper foil coil wrapped round small sample (fly-past)

Tuned coils

for higher RF field strength



Fly-past sample and copper foil coil
Fixed frequency 400 MHz (3T for μ^{+})



Sample stick with
low temperature
tuning capacitors

Sample excitation

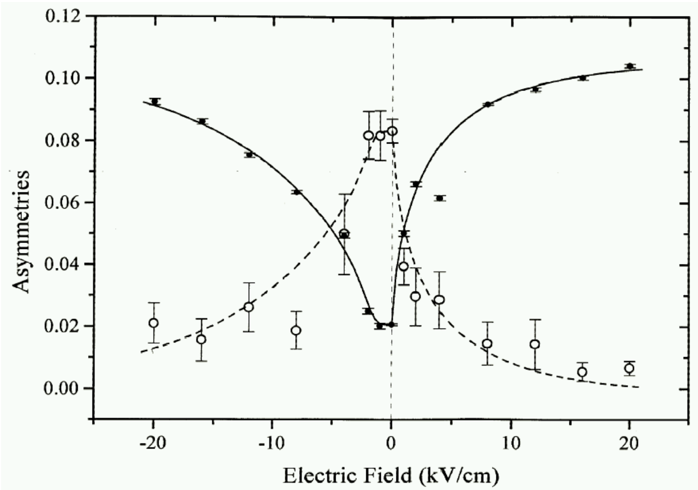
- Most muon experiments vary the temperature and magnetic field

- We can also consider applying:
  - Electric fields
  - Currents through the sample
  - Light (ionisation, excitation)
  - Pressure
  - Gases (reactions/absorption)
  - Strain (static, sound waves)

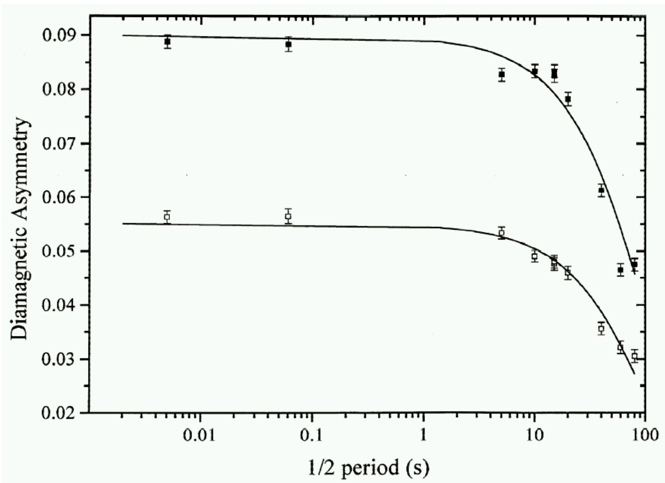
Koji Yokoyama's talk to follow

Electric fields

Electrons are produced as the muon stops in the sample. They may be swept away from the muon by the E-field, reducing muonium formation. Sample: GaAs, T=50K (Eshchenko et al)



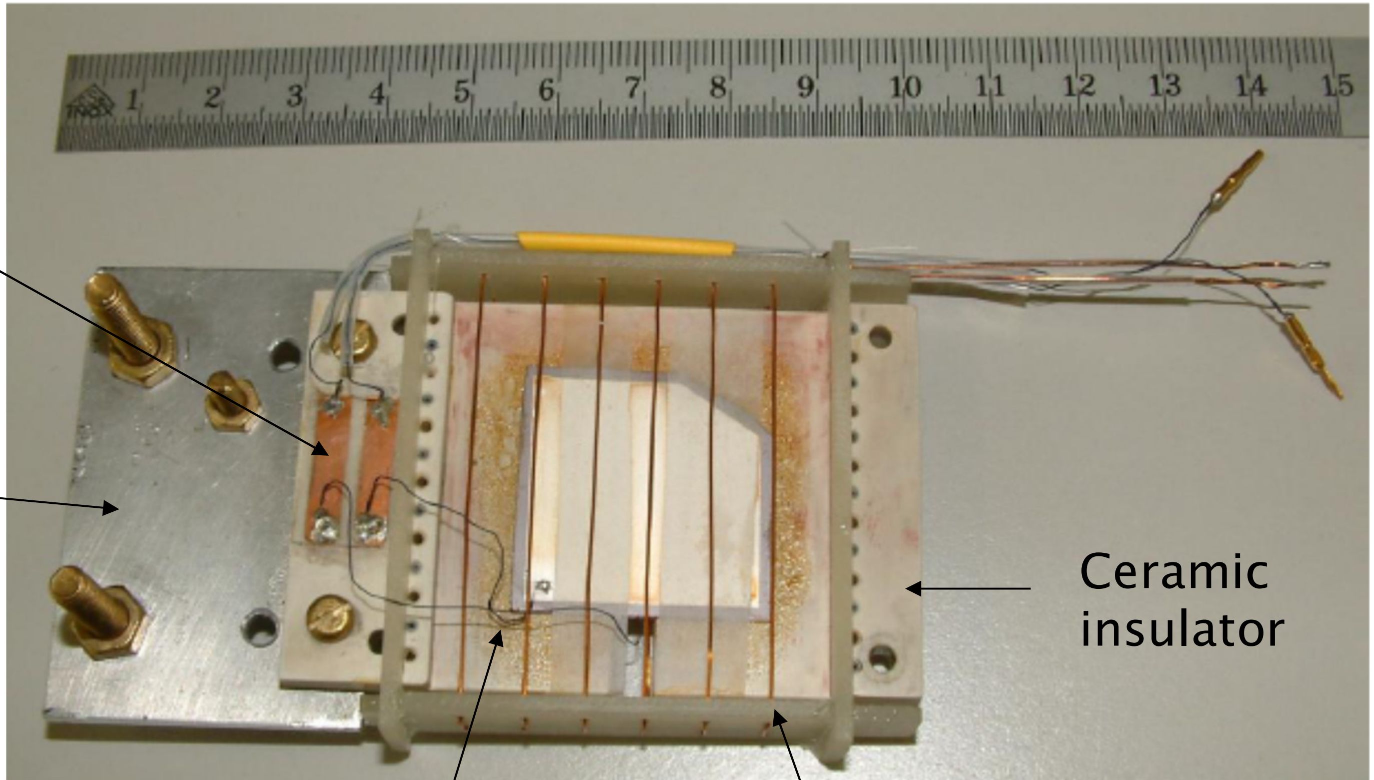
Muonium (open) and diamagnetic fractions (filled circles) as a function of electric field



Variation of the diamagnetic fraction with switching rate due to charge build-up.
(±8kV/cm applied at electrodes)

Electric fields

- Sample set up for simultaneous E-field and RF experiment (Eshchenko et al)



Thermal anchoring

Fixed onto CCR cold finger

From RF and HV sources

Ceramic insulator

E-field connections to silvered sample surfaces

RF coil and former

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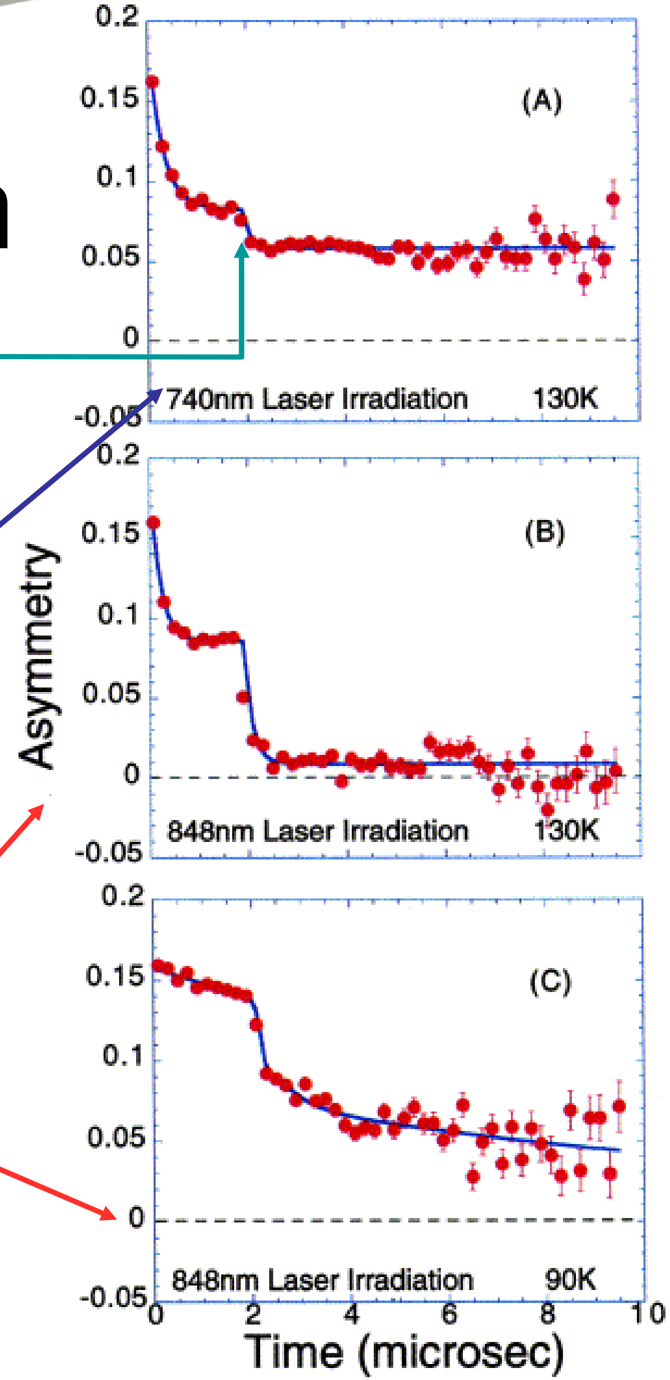
Illumination

In this example a laser pulse is applied at t=2μs (GaAs, Shimomura et al)

Photons with energy above the band gap generate electron-hole pairs, which may interact with the muon, changing its charge state and causing relaxation.

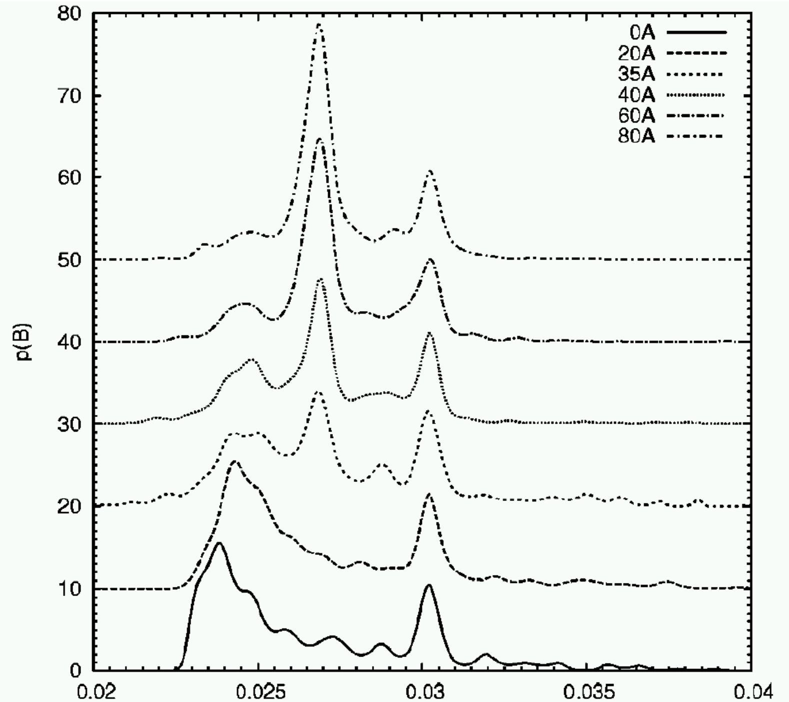
Below the band gap, the photons may directly ionise some muonium centres

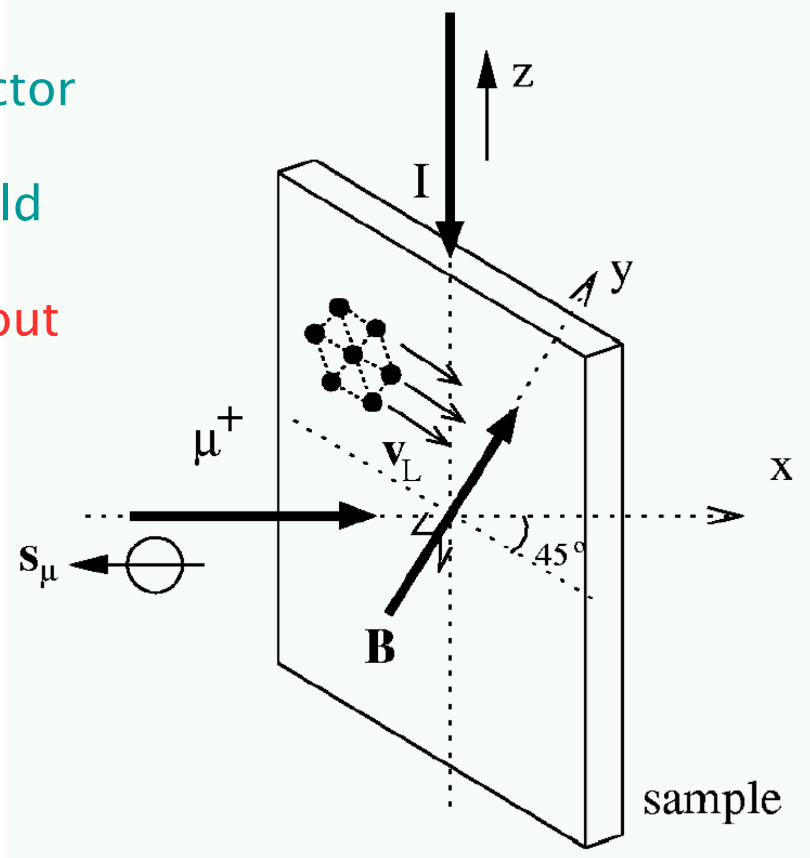


Current

Current flow in a type II superconductor is often accompanied by flux line motion. This “averages” the usual field distribution for a flux line lattice

Pulsed to allow higher currents without excessive sample heating

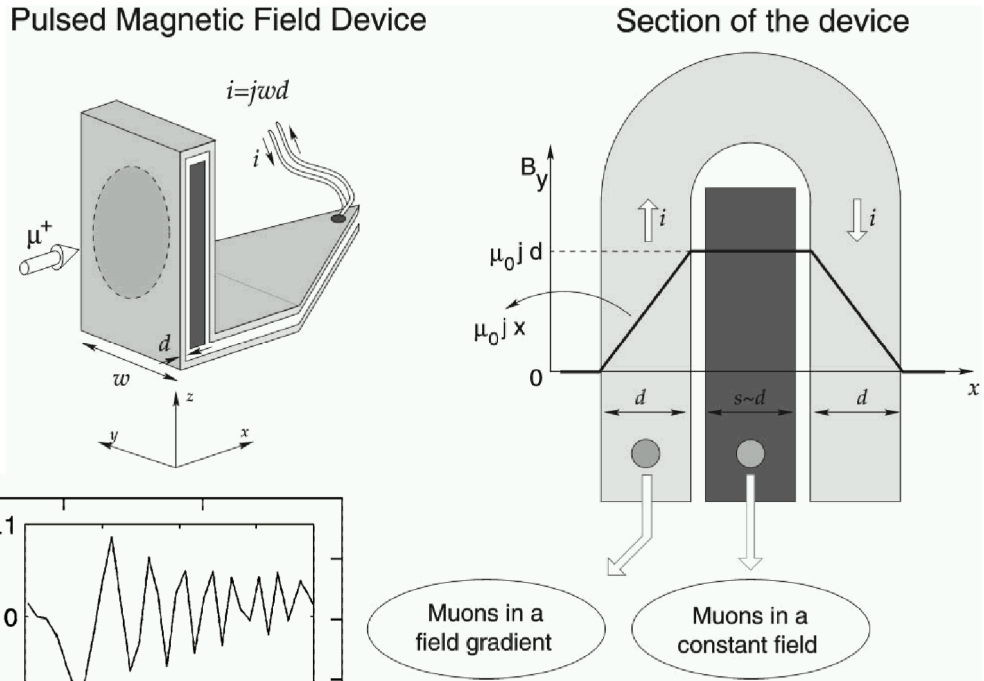


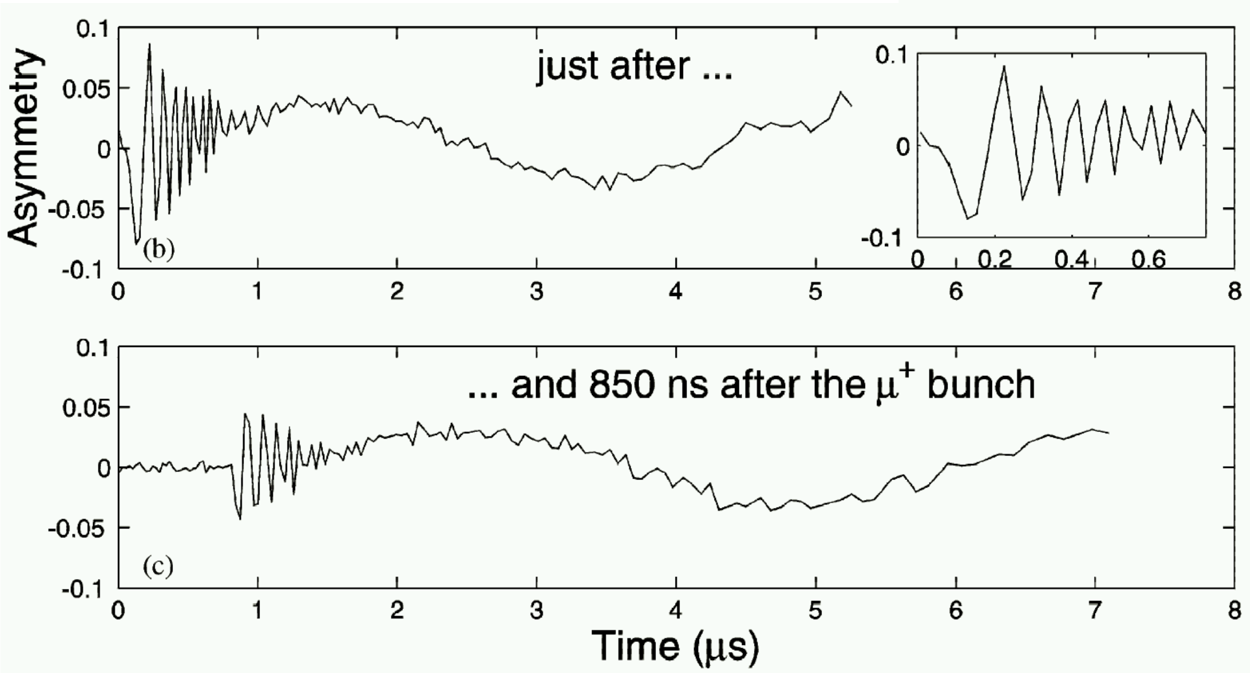


Internal field distribution (Maximum Entropy) for various currents
(Pb-In sample, Charalambous et al)

Pulsed transverse fields

Muons initially implanted in a small longitudinal field, then the pulsed transverse field is turned on rapidly compared to the precession frequency.





This technique removes the restriction of the muon pulse width and allows study of final states

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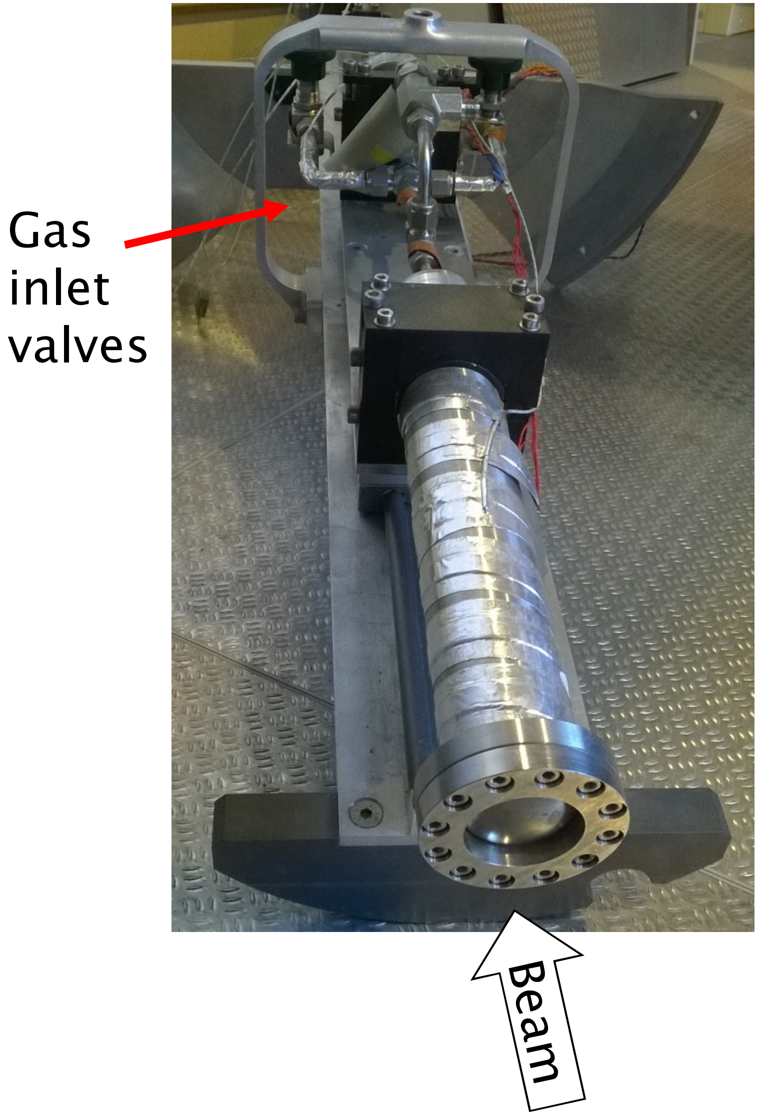
Pressure

- Muons can only penetrate a limited thickness of material (cell window)
- For "Surface" muons we can build cells up to 50 bar, eg. for gas experiments
  - Stopping range of muons in the gas depends on pressure
  - Range at 1 bar larger than instrument!
  - Collision and reaction rates are pressure-dependent



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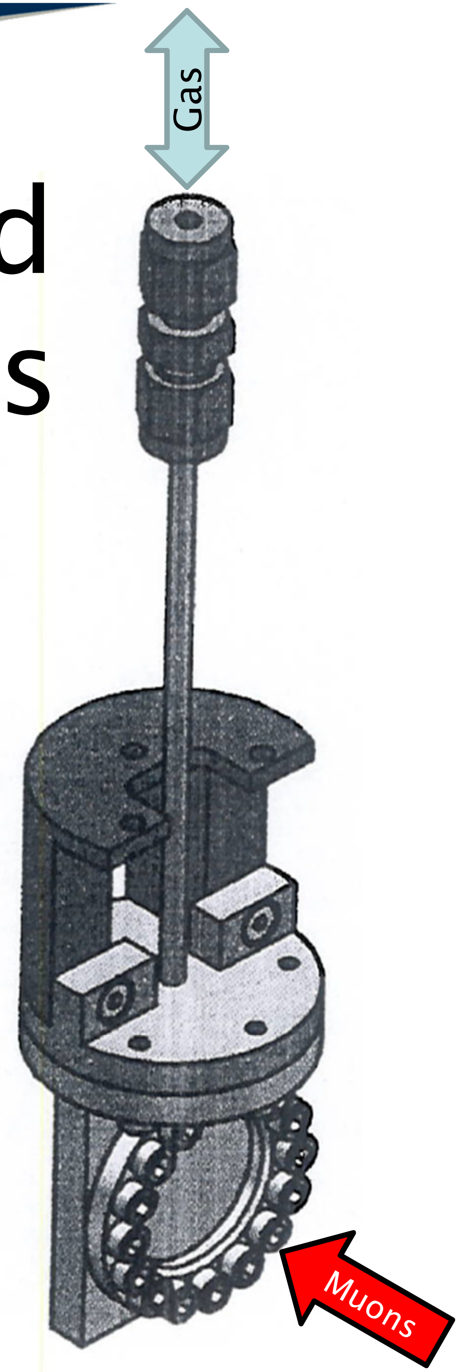
Condensed and absorbed gases

- Gas cell in cryostat
  - Can be filled with powder sample
- Capillary to gas handling rig

- Condense gas and measure in liquid or solid state
- Add gas to solid sample – reaction, adsorption or intercalation
- Evolve gas on heating
  - Safely collected and measured



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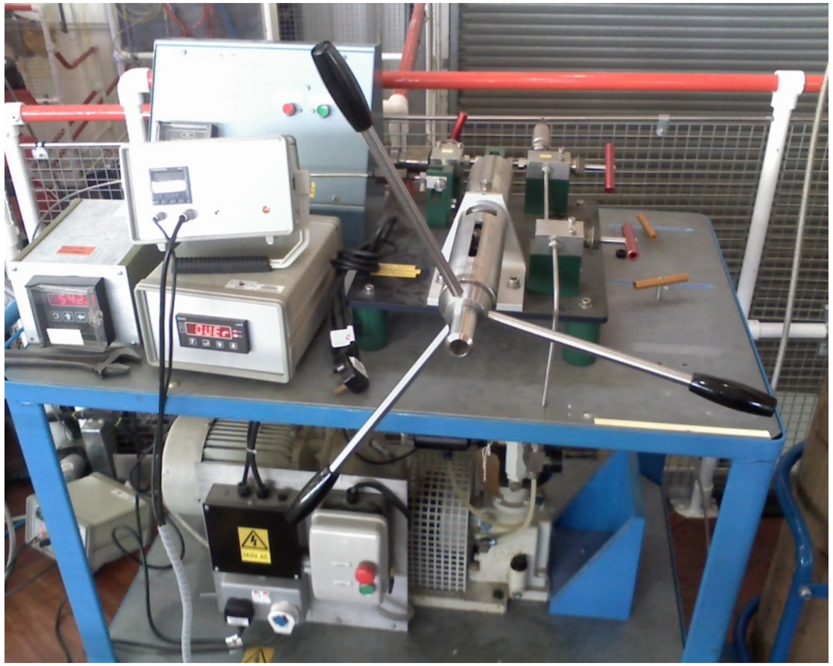
Pressure

- "Decay" muons can penetrate thick windows on a high pressure sample cell – 10 kbar possible
- Non-magnetic Be-Cu cell
- Helium gas as pressure medium (vary P in-situ)
  - Pressure dependence of magnetism, superconductivity, ...



Where?

- Much early RF development on DEVA (now replaced by HiFi)
- RF available on all ISIS muon instruments, 1.5 to 1500K
- ARGUS and HiFi have dedicated laser cabins
- Other pulsed experiments possible on most ISIS instruments (ask instrument scientists!)
- High pressure needs high momentum beam (ARGUS, CHRONUS or GPD)