



Science & Technology Facilities Council

ISIS

# RF- $\mu$ SR and Pulsed Techniques

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ISIS



# 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)

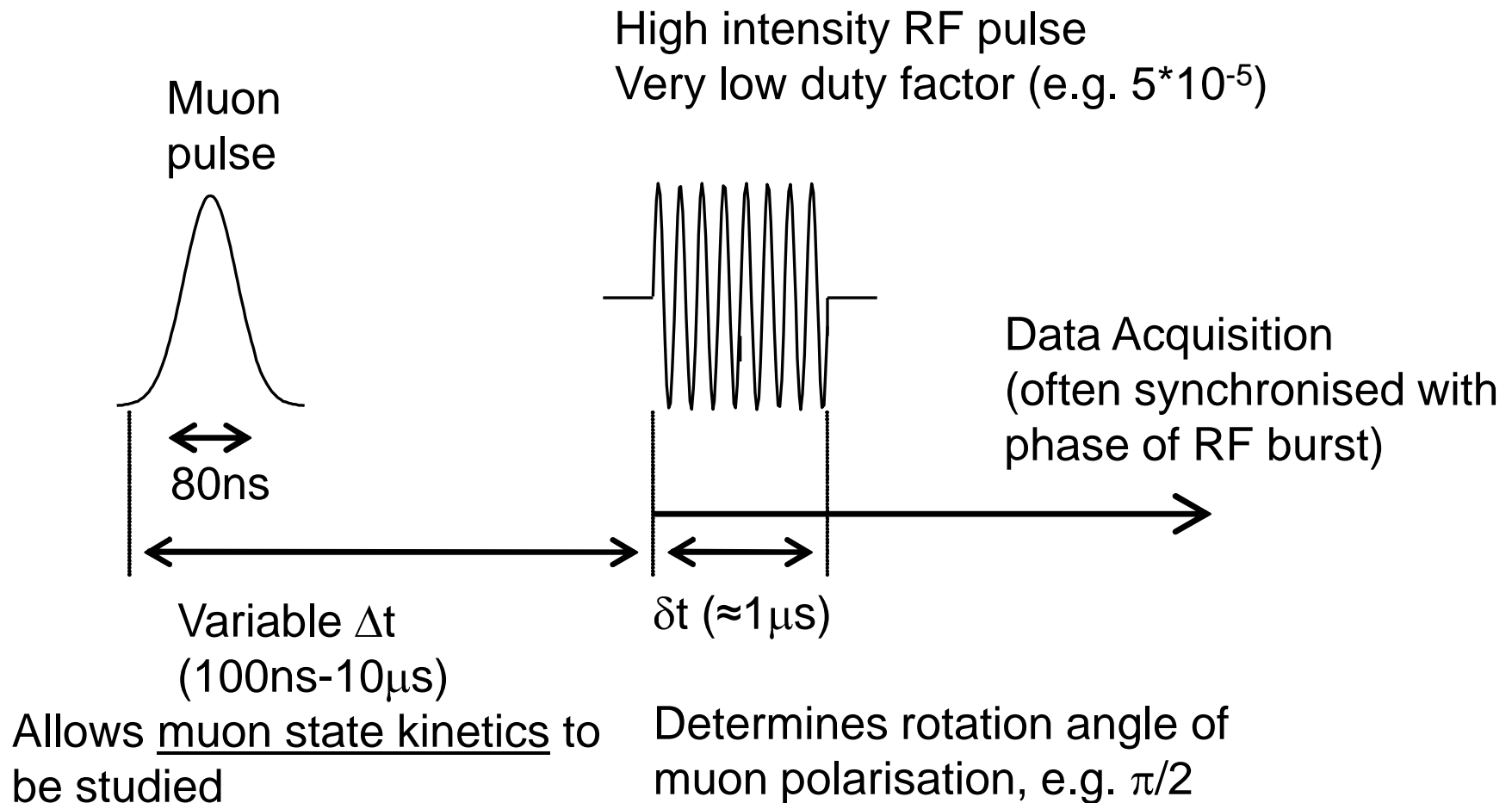


# Practical points

- The stimulus must be pulsed at the same frequency as the beam: 50Hz at ISIS, or a sub-multiple such as 10Hz.
- 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 “red-green” mode, 2 sets of histograms
  - Red: stimulus applied
  - Green: control measurement without pulse



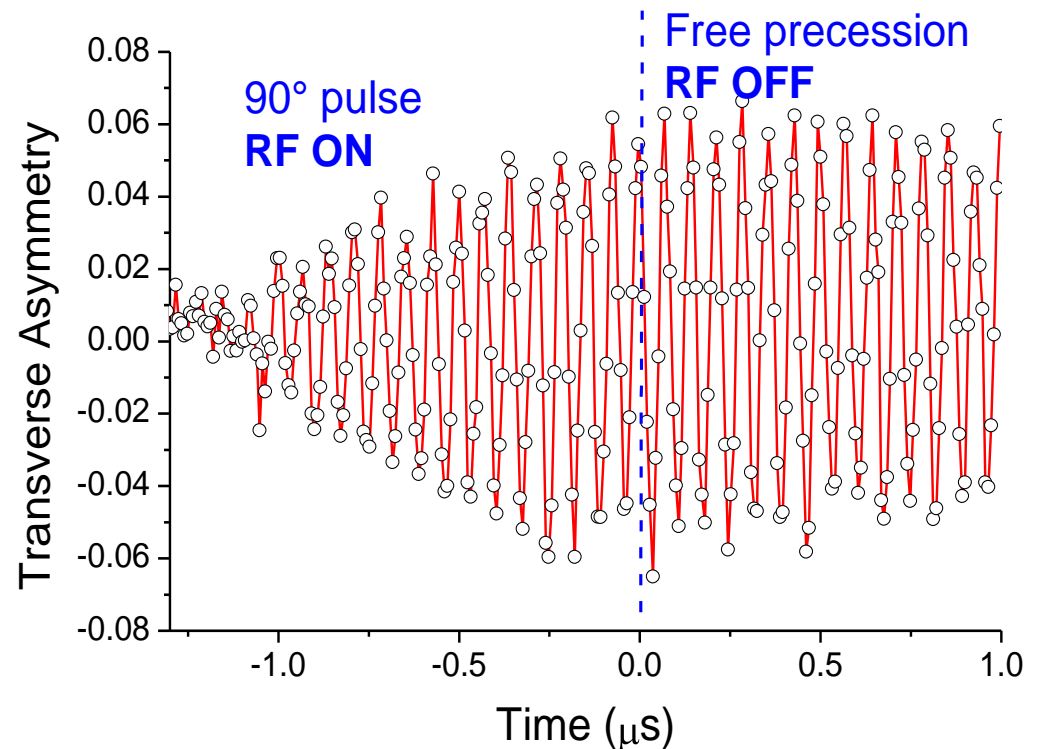
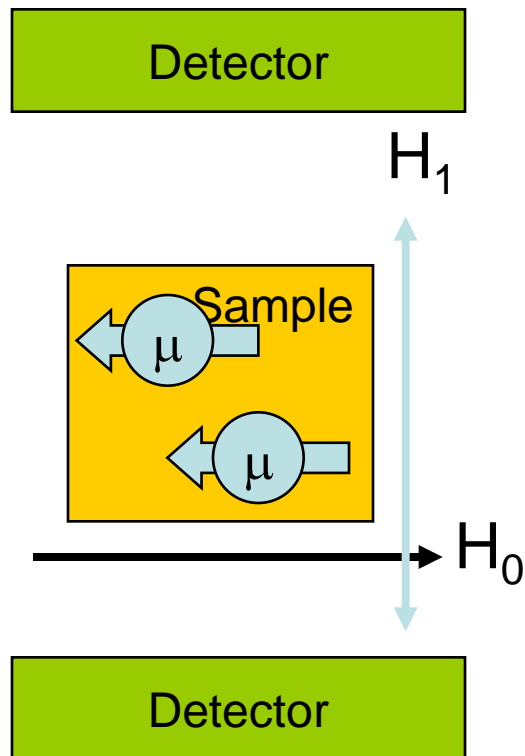
# Pulsed RF





# 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

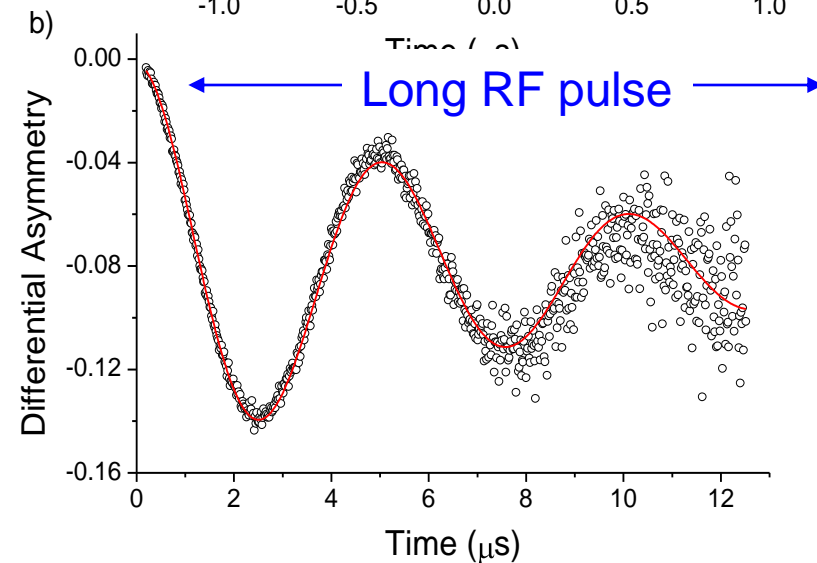
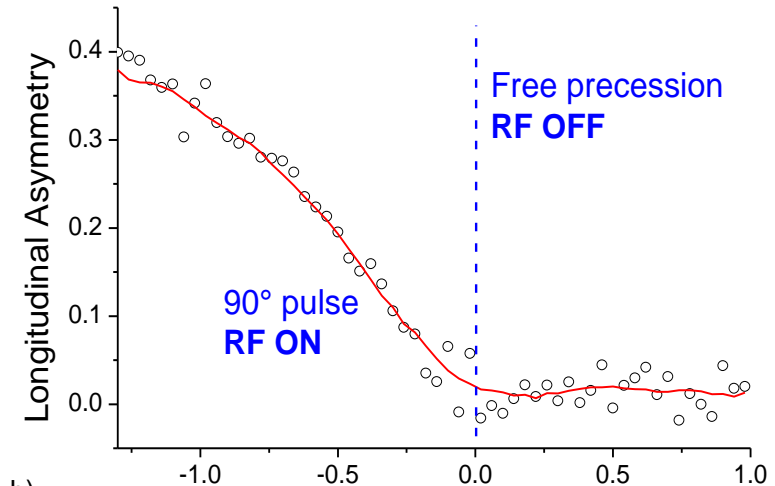
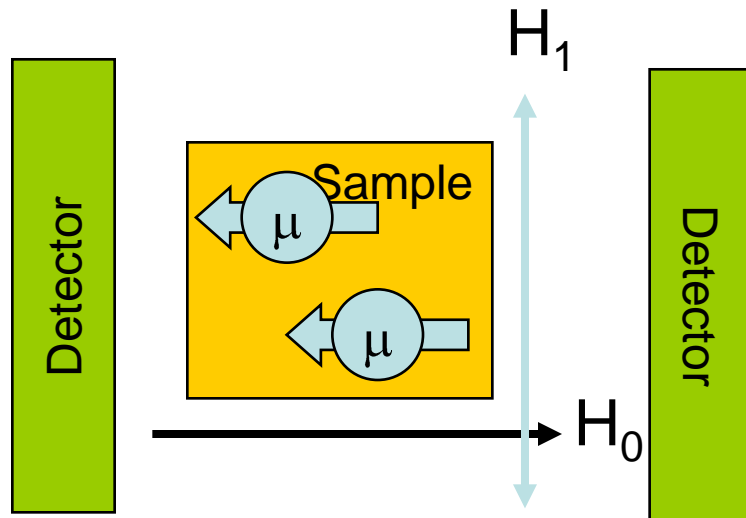


Data acquisition synchronised with RF waveform, not muon pulse



# 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

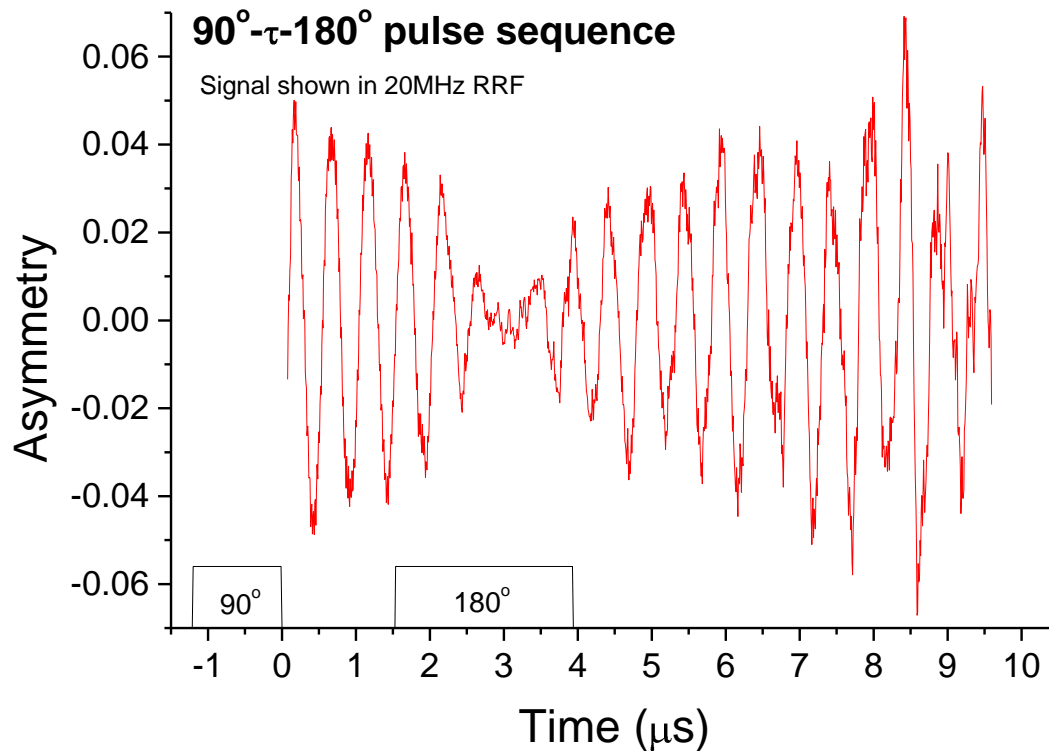




# Spin echoes

- Precession damped by random nuclear fields
- Re-focus spins with  $180^\circ$  pulse at time  $\tau$
- Echo at  $2\tau$ , similar to NMR

## Boron diamagnetic resonance in 1672G



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

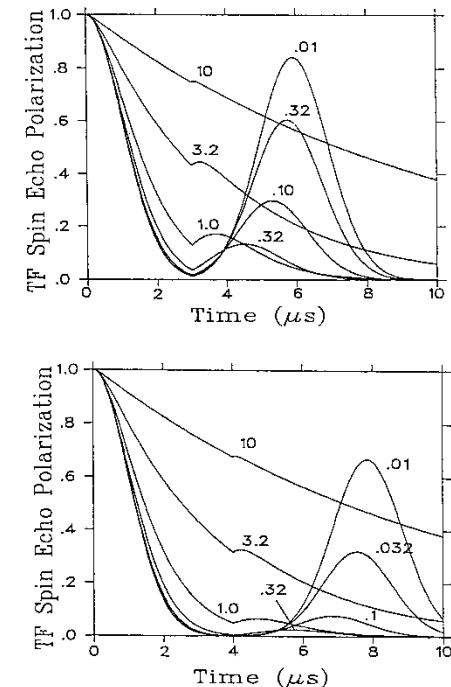


Fig. 6. Theoretical spin echo response for various hop rates. The value of  $\Omega_2$  is  $1 \mu$ s and pulses are tacitly assumed to be ideal. The numerical captions denote hop rates in units of  $1/t_p$ , which for fig. (a) is  $3 \mu$ s and for fig. (b) is  $4 \mu$ s. Note that even for reasonably rapid hop rates, the echo position can be distinguished.





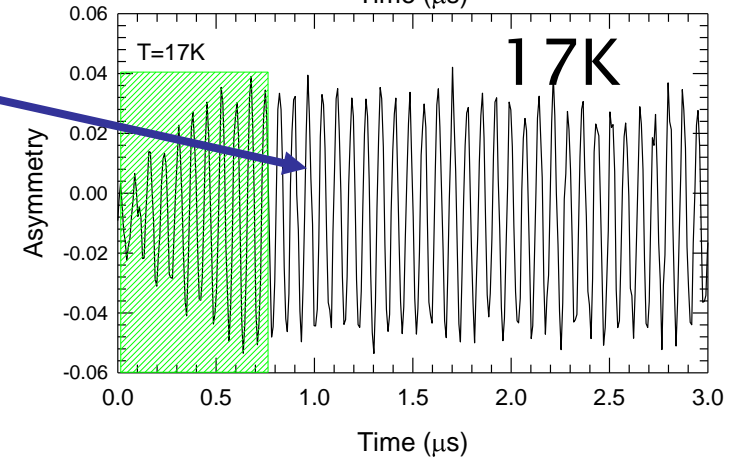
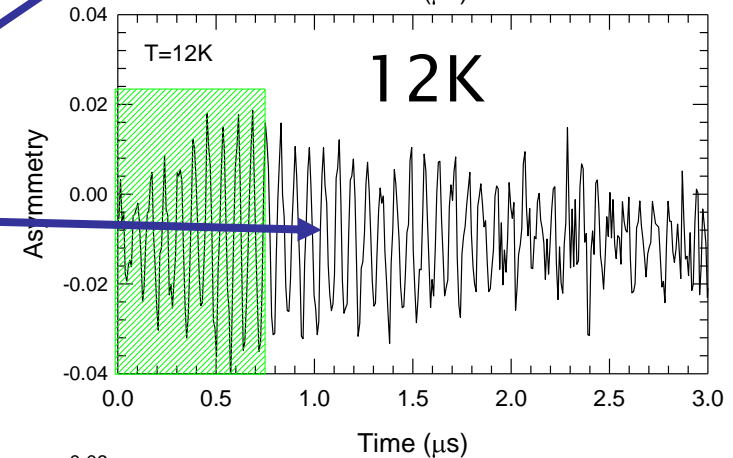
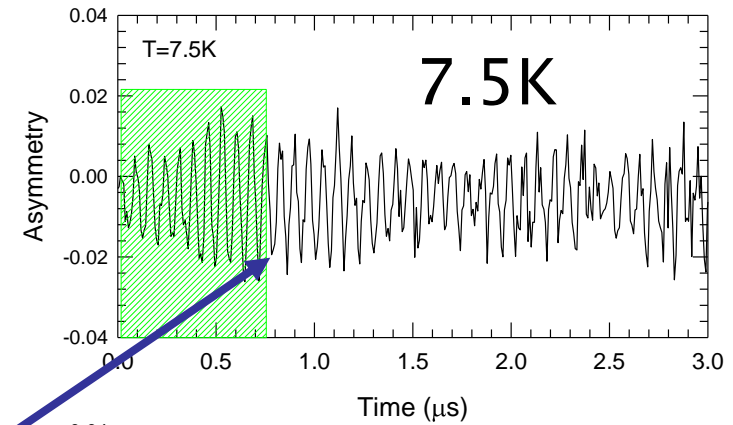
# Superconductors

- $\text{YNi}_2\text{B}_2\text{C}$
- Type II
- $T_C = 15\text{K}$
- $\lambda = 103\text{nm}$
- $\xi_0 = 8\text{nm}$

Superconducting  
(mixed) state

Normal  
state

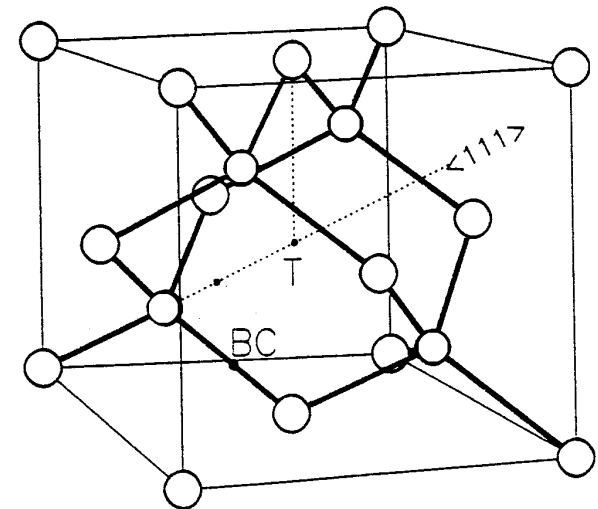
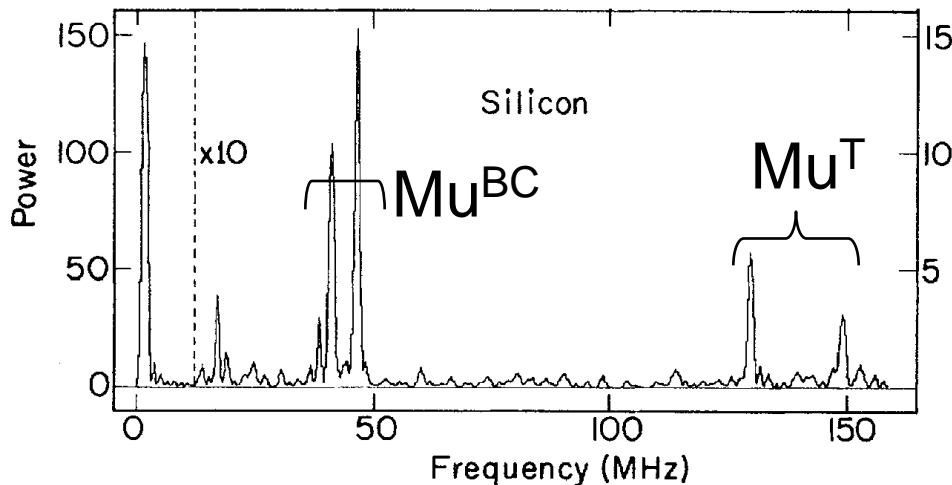
- Field 1034G
- 13.6MHz – above usual  
ISIS frequency range





# 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

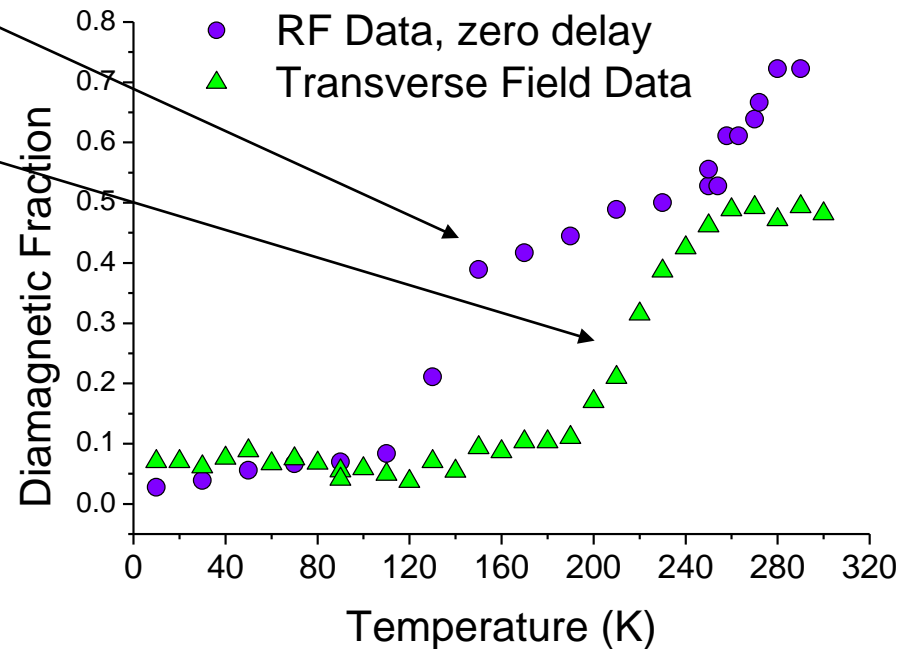


- Above 120K the  $Mu^{BC}$  signal disappears



# Dynamics

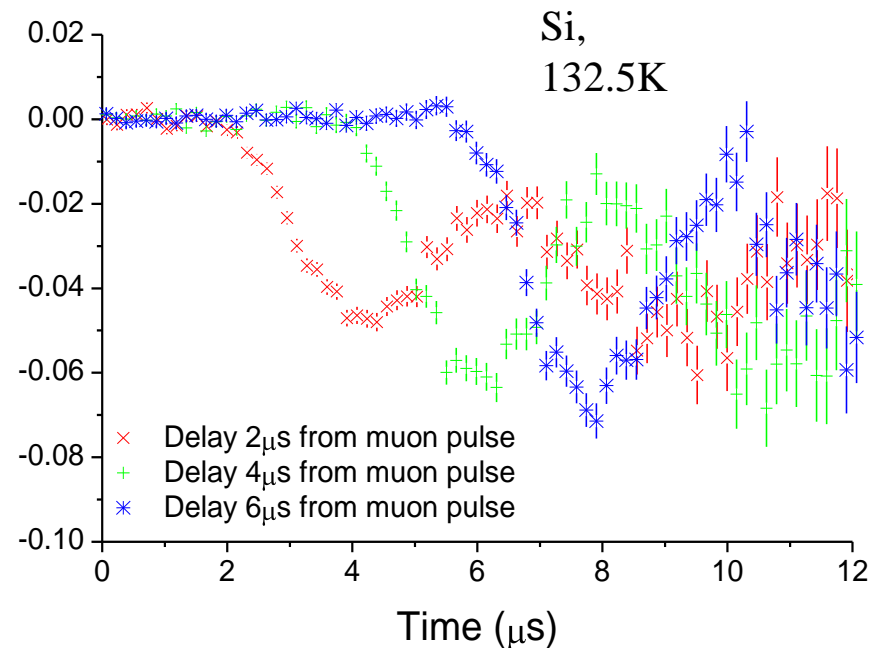
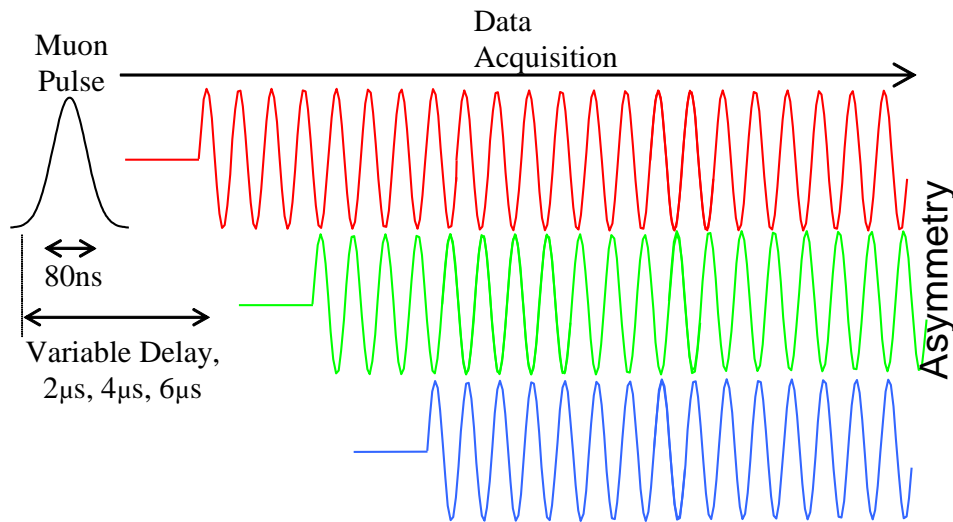
- RF shows appearance of diamagnetic species when TF  $\text{Mu}^{\text{BC}}$  signal disappears
- No diamagnetic signal in low TF until much higher temperature
- In TF muons spend a short time as muonium, and dephase
- In the RF experiment the muon spins are locked along high LF before the pulse





# Dynamics

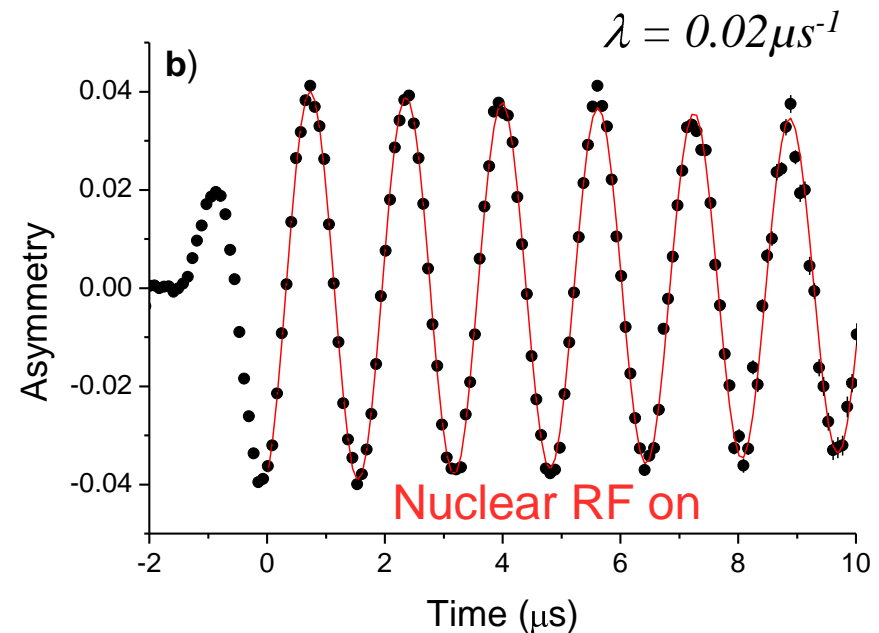
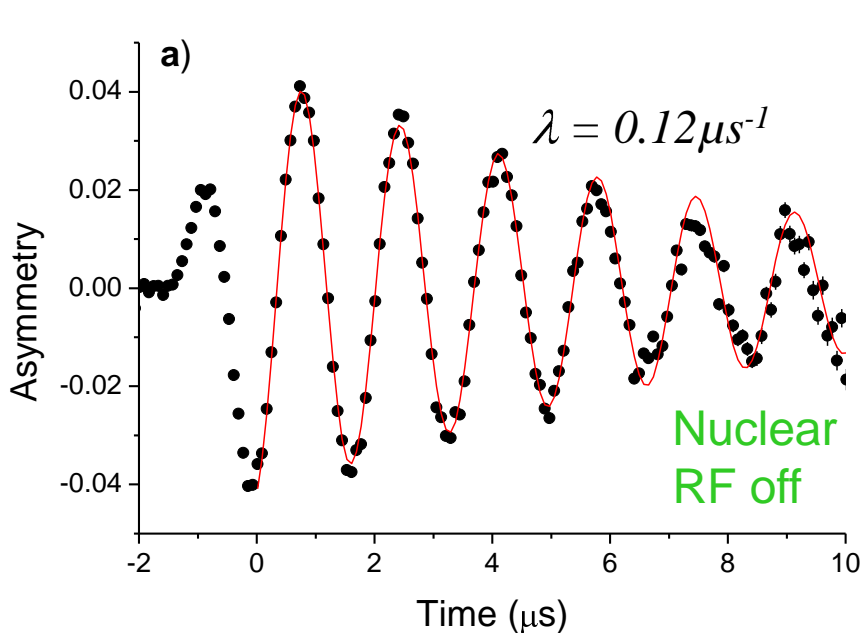
- For favourable reaction rates ( $\mu\text{s}^{-1}$ ) we can follow the conversion by delaying the RF pulse





# RF Decoupling

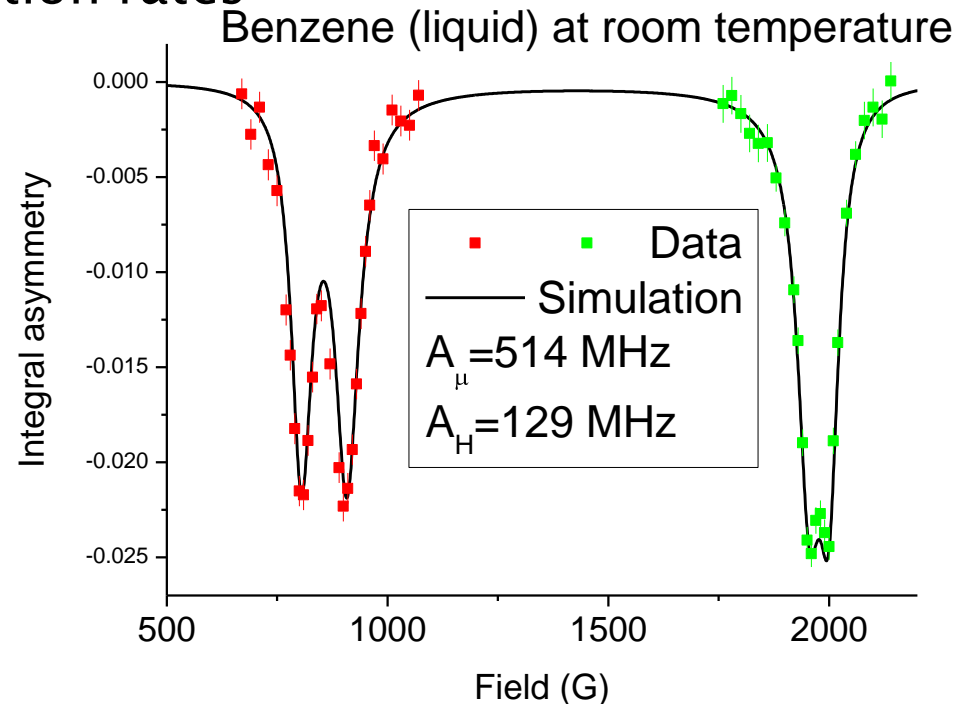
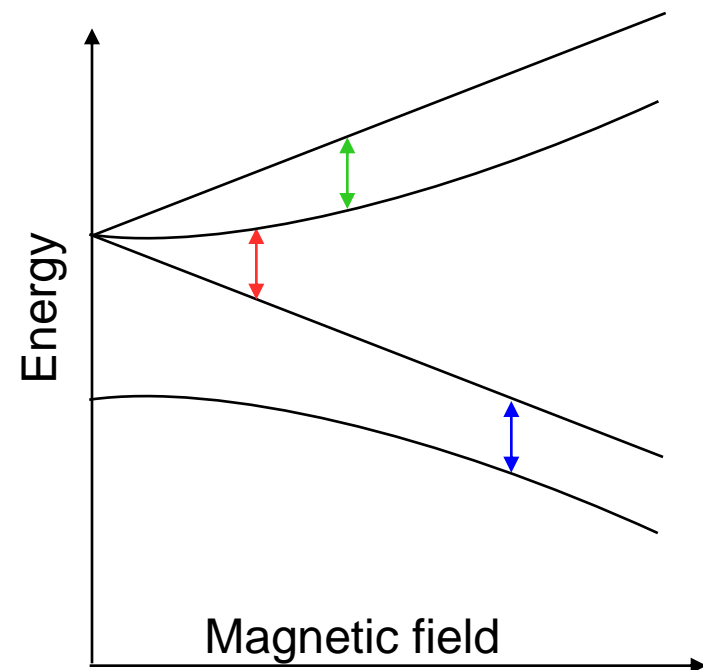
- Two RF signals simultaneously
  - 90 degree pulse to set the muons precessing
  - Continuous RF at the nuclear Larmor frequency to “stir” the nuclear spins and average out the dipolar coupling
- Observe reduced relaxation of muon signal
- Identify which nuclei are coupled to muon





# Muonium RF

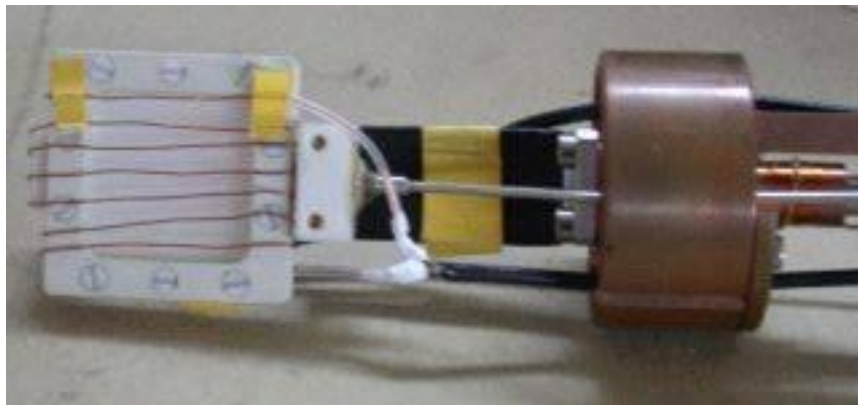
- RF causes spin-flips of the combined muon and electron system.
- Many resonance fields or frequencies
  - Hyperfine coupling
  - Coupling to other nuclei
  - Dynamics and reaction rates





# RF equipment

- Usually tuned coils for higher  $H_1$  at same power
  - Work at fixed frequency and sweep field where required (muonium)
- Coil with widely spaced wires, or thin foil, to let muons into sample



Liquid cell  
with RF coil



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



# 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)



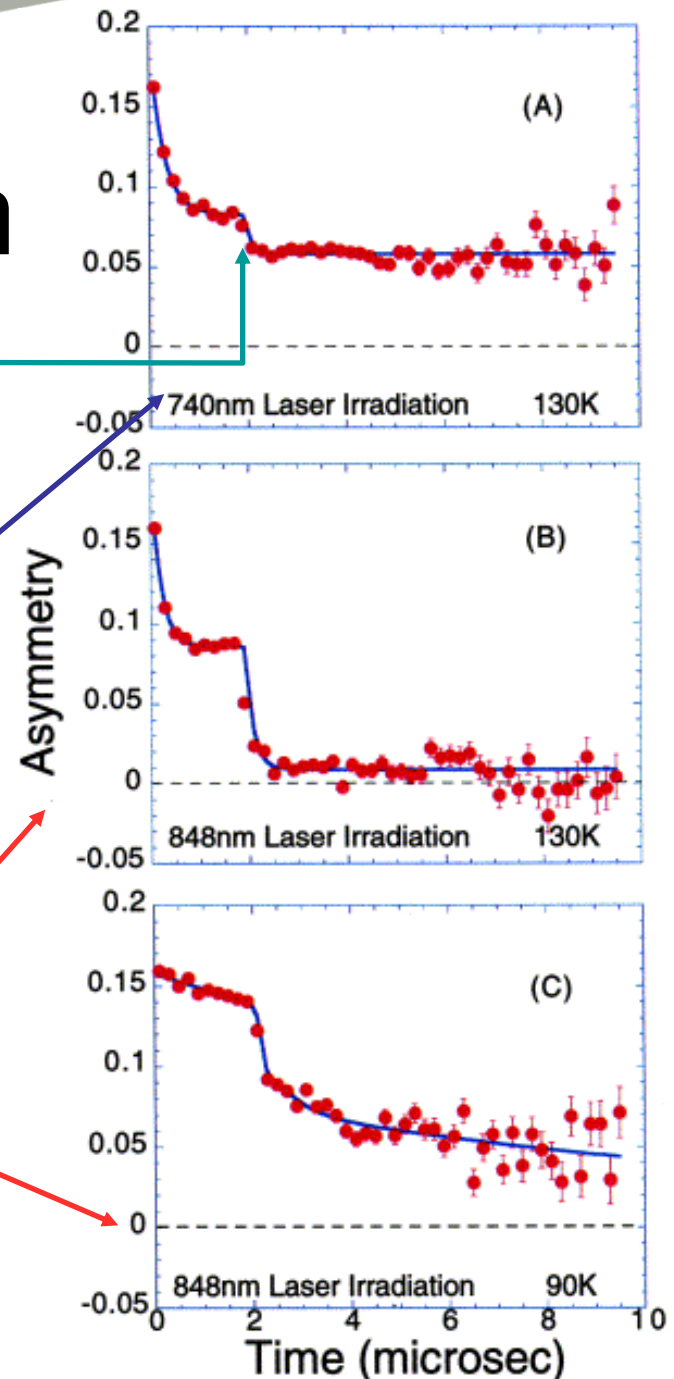


# Illumination

In this example a laser pulse is applied at  $t=2\mu\text{s}$  (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

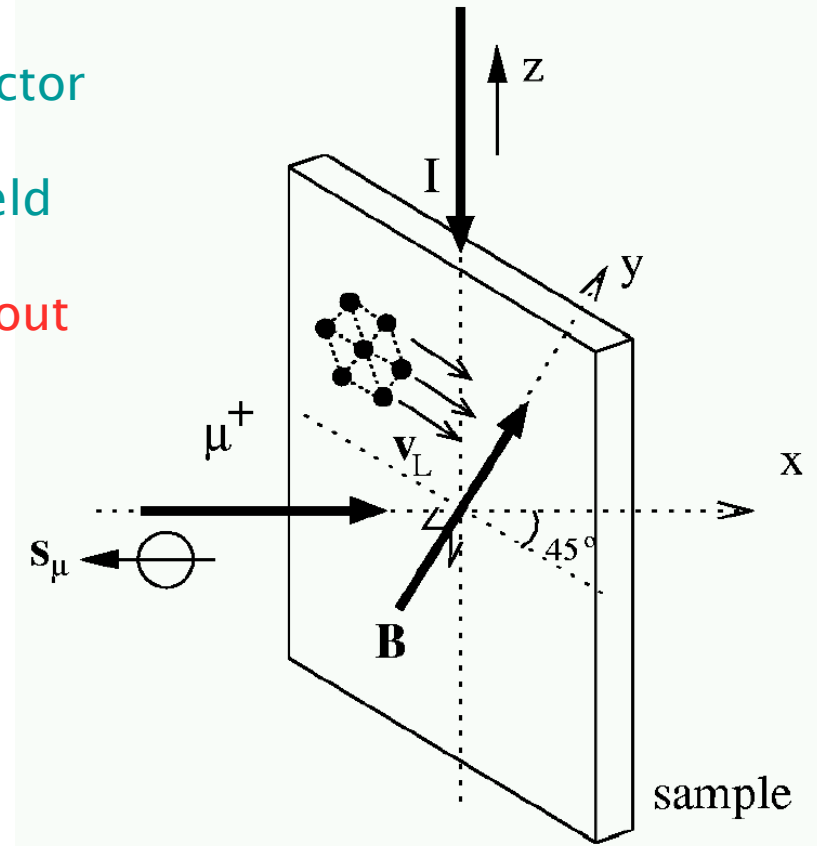
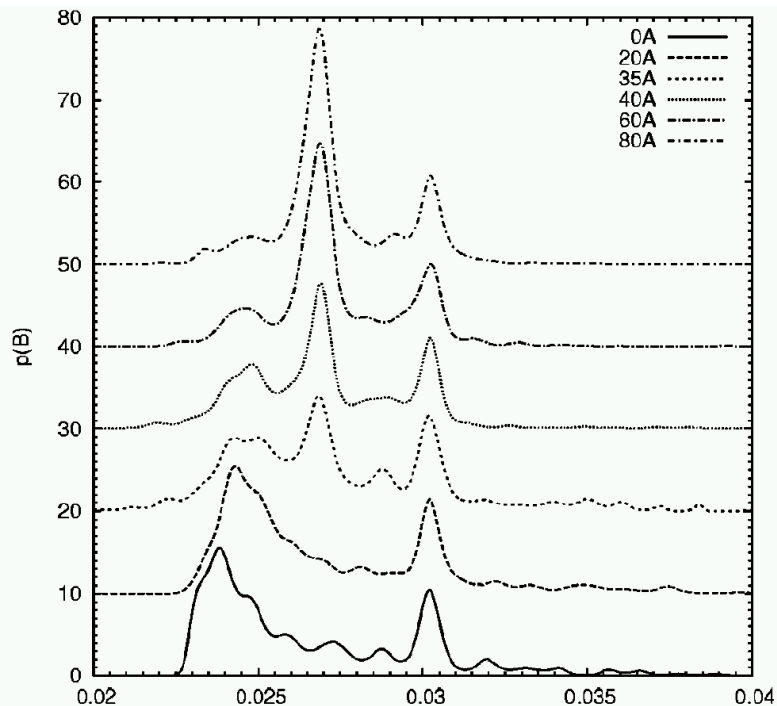




# Current

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



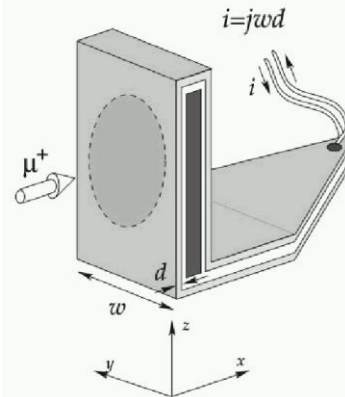
Internal field distribution  
(Maximum Entropy) for various  
currents  
(Pb-In sample, Charalambous et al)



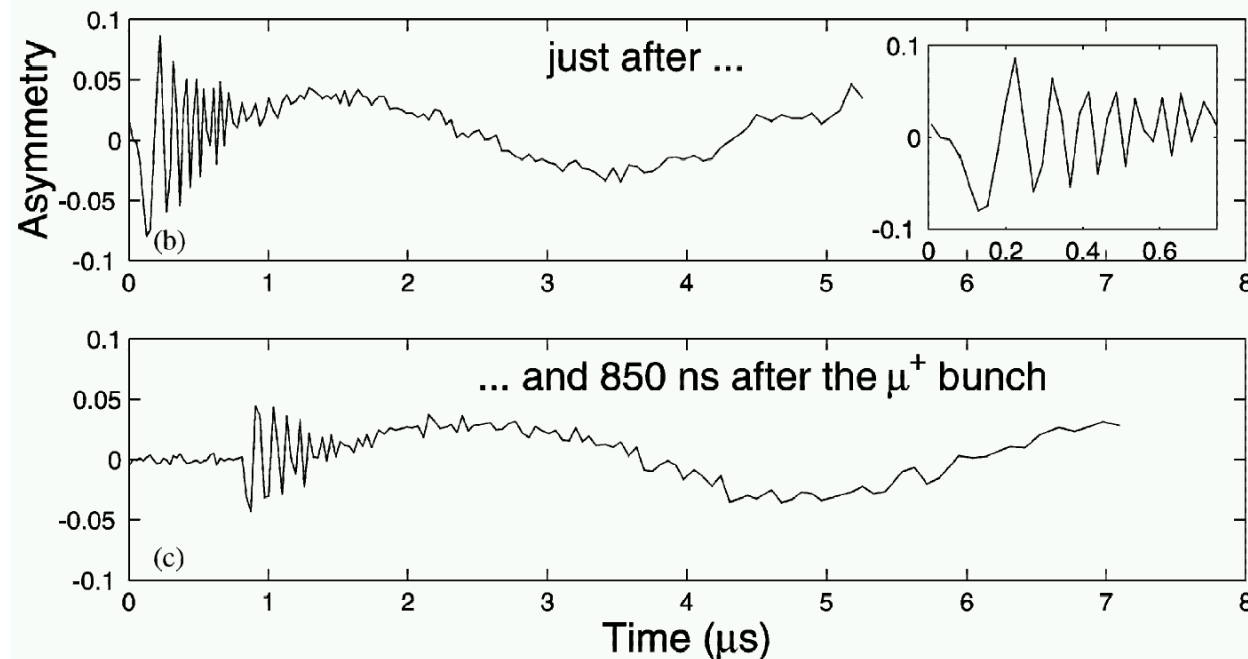
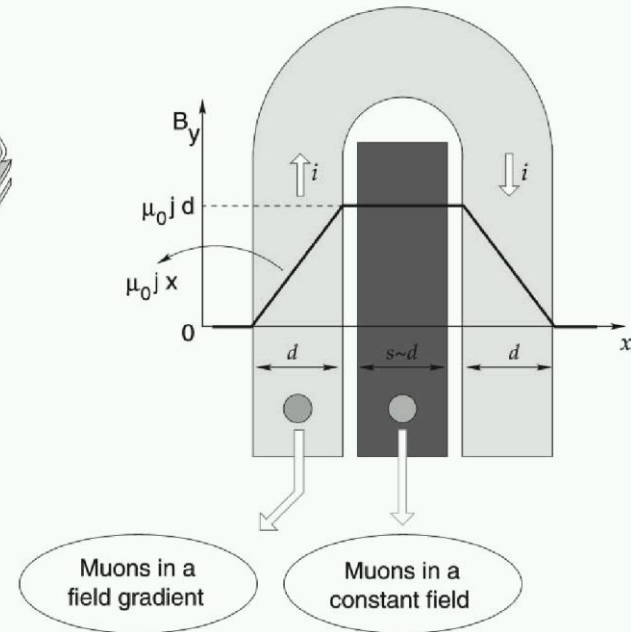
# Pulsed transverse fields

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

Pulsed Magnetic Field Device



Section of the device

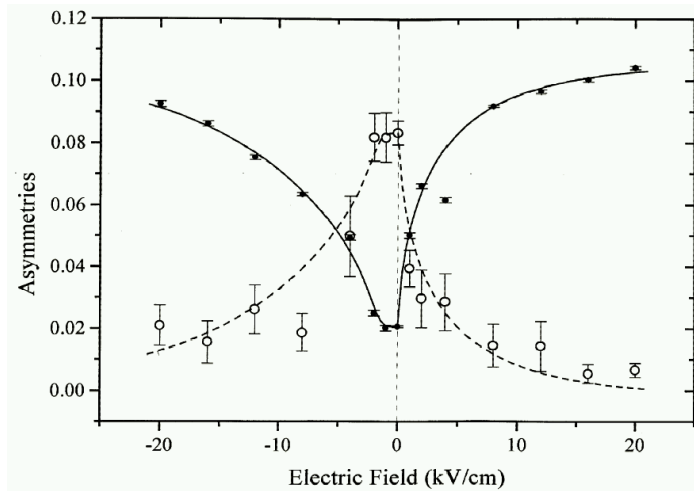


This technique removes the restriction of the muon pulse width and allows study of final states

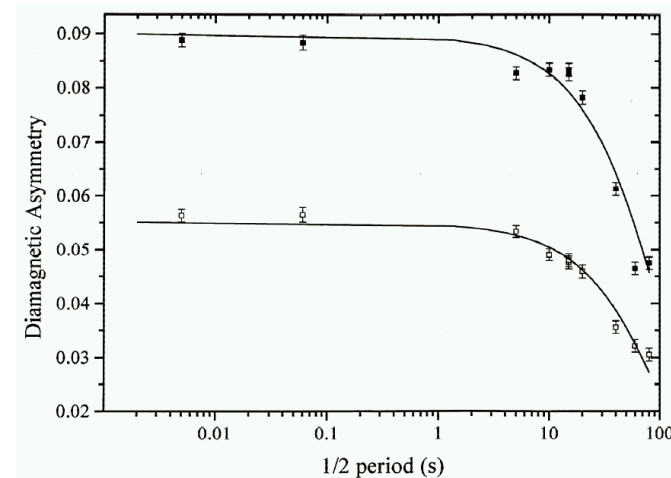


# Electric fields

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,  $T=50\text{K}$  (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.  
( $\pm 8\text{kV/cm}$  applied at electrodes)



# Electric fields

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

Thermal anchoring

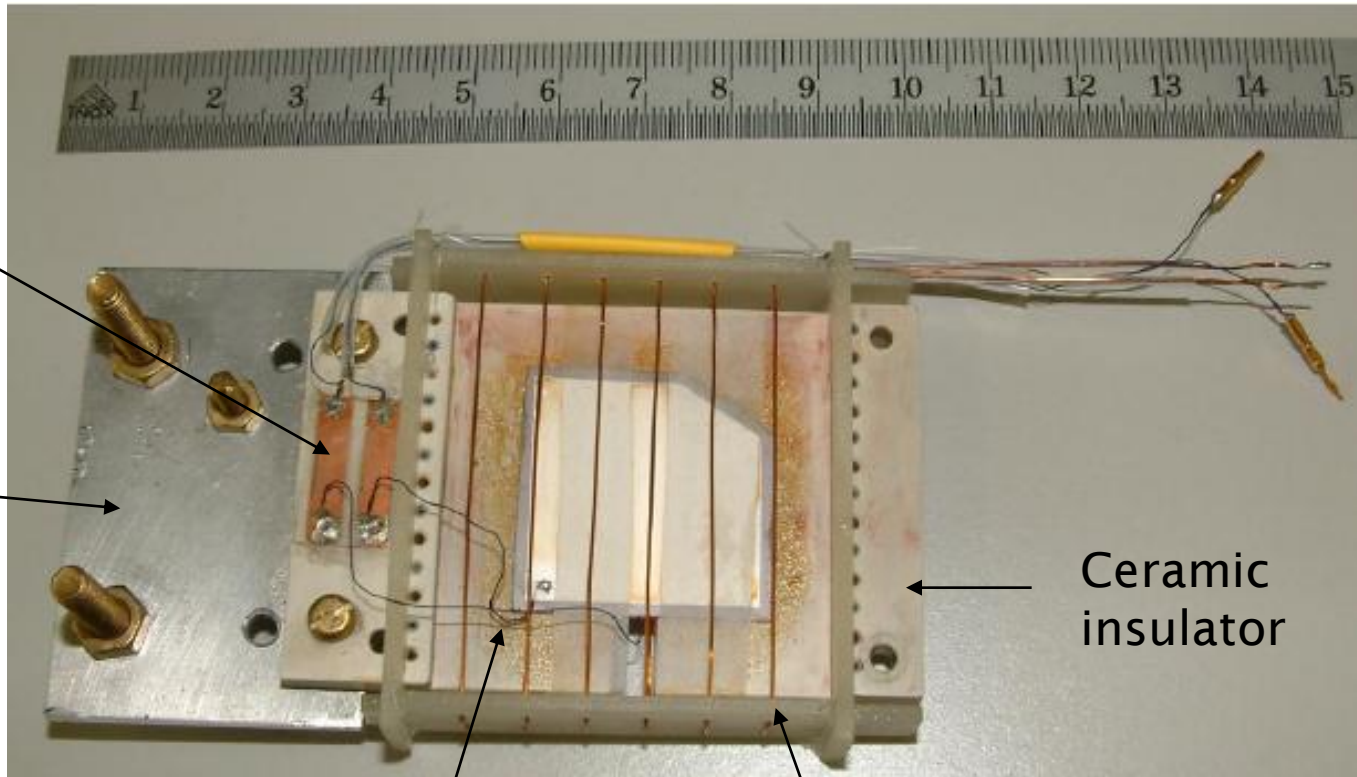
Fixed onto CCR cold finger

From RF and HV sources

Ceramic insulator

E-field connections to silvered sample surfaces

RF coil and former





# Pressure

- Muons can only penetrate a limited thickness of material (cell window)
- Thick windows are needed on a high pressure sample cell
- For “Surface” muons we can build cells up to 50 bar, eg. for gas experiments
  - Collision and reaction rates are pressure-dependent
  - Stopping range of muons in the gas depends on pressure



- “Decay” muons can penetrate cells up to a few kbar
  - Pressure dependence of solids eg. magnetic moments





# Where?

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

