Pulsed NMR:

Relaxation times vs. viscosity and impurities

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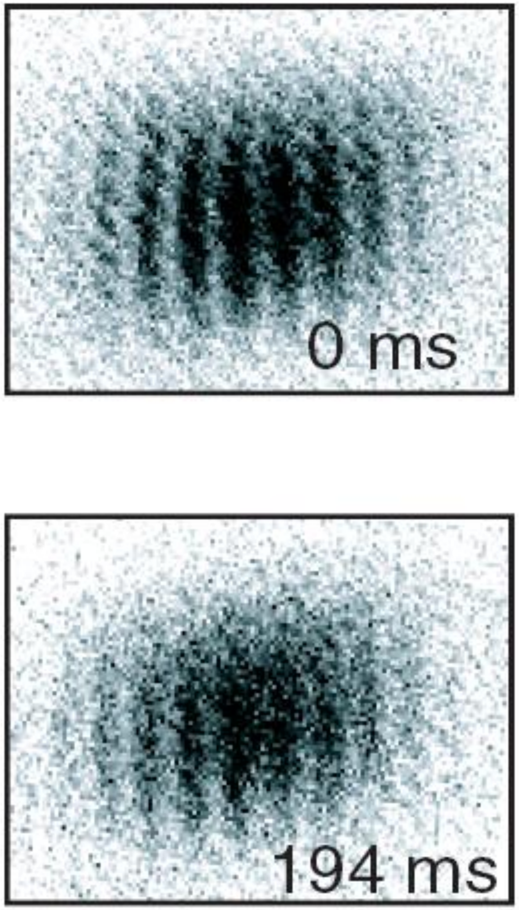
Topics to be discussed

1. Introduction
   1. Relaxation times (T_1, T_2)
   2. Theory of NMR
   3. Carr-Purcell sequence for T_2 measurement
2. Experimental setup
3. Analysis and results
   1. Processing of Carr-Purcell data
   2. Relaxation times as function of viscosity
   3. Relaxation times as function of impurities
4. Sources of error; possible improvements
5. Conclusions
   1. More microscopic interaction → faster relaxation
   2. Verify Bloembergen's inverse-law relationship.

Relaxation times in current research



- Modern applications of quantum mechanics (e.g. quantum computing) limited by relaxation times.

- Relaxation time is the timescale for which the system remains under coherent control by experimenter.

- Investigate dynamics of spin ensemble as prototype of the relaxation phenomenon.

Image source: G.-B. Jo, et al. Phys. Rev. Lett. 98, 030407 (2007)

Coherent manipulation of spin ensemble

- Standard NMR technique:
  - Strong **bias field B_0** = 1770 gauss;
  - Small, **oscillating field B_1** at w = w_L (Larmor freq.);
- "Macroscopic" Hamiltonian: $H = -\vec{\mu} \cdot \vec{B}$
  - Coherent dynamics in static field: Precession of magnetic moment
  - Can manipulate the spin vector via proper "pulsing" of B_1

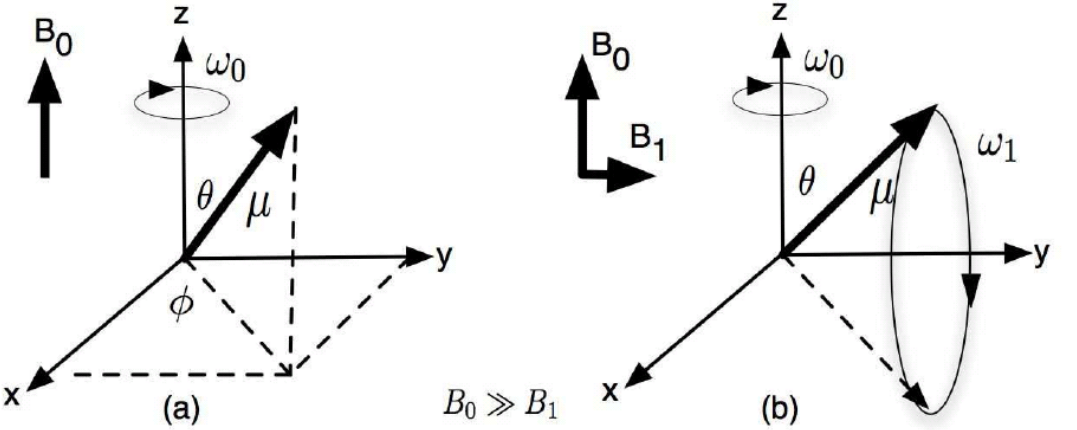


Image source: Q. Hu's 8.06 paper on NMR (2006)

T_2 measurement: General theory

- Reasons for loss of transverse magnetization (without collapse to axis):
  - Spin-spin interactions, $B_{dip} \sim \dfrac{\mu}{r^3}$
  - Bias field inhomogeneity;
  - Diffusion of spins through volume;
  - …

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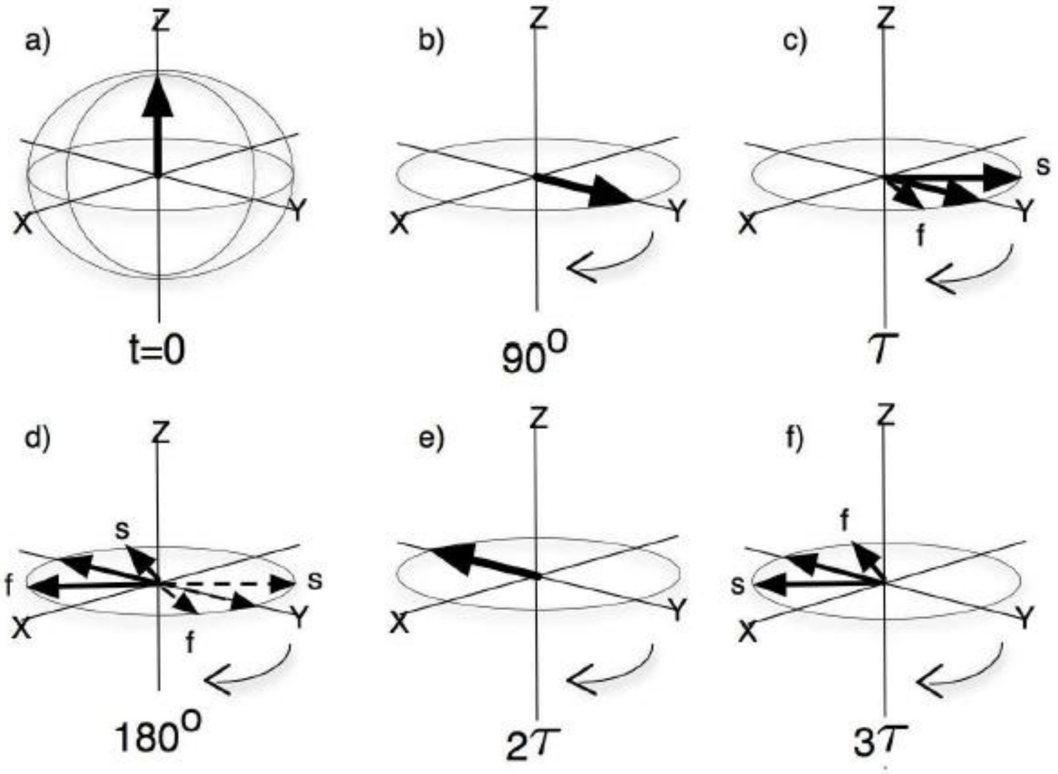
  - …

- Intuition: $H_{micro} \neq (H_{macro} = -\vec{\mu} \cdot \vec{B})$
  - More microscopic interactions (viscous, impurities) should lead to faster relaxation.

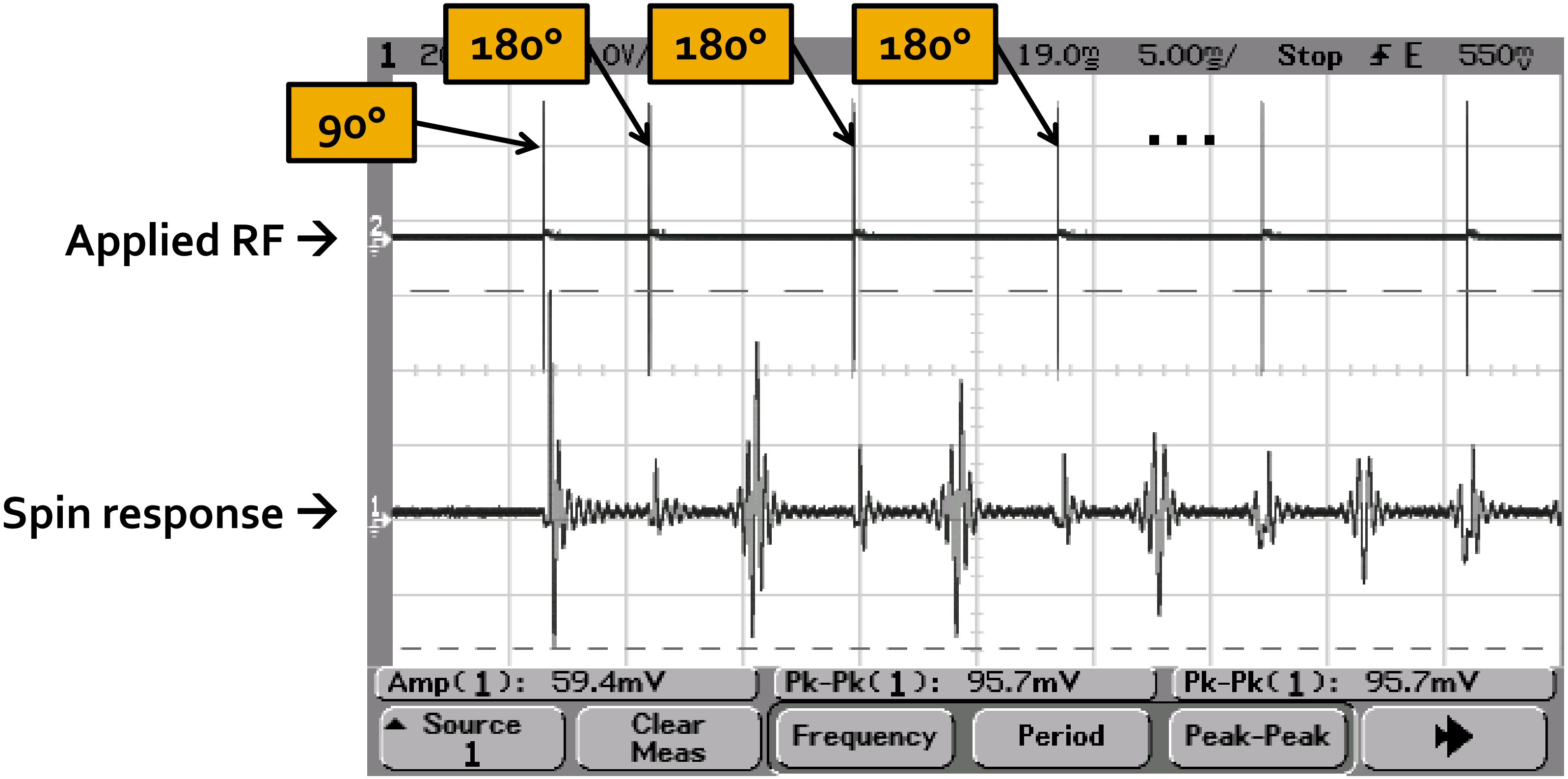
T_2 measurement: Spin echo technique



- Eliminate field inhomogeneity effect;
- Choose small τ → Overcome diffusion effects;

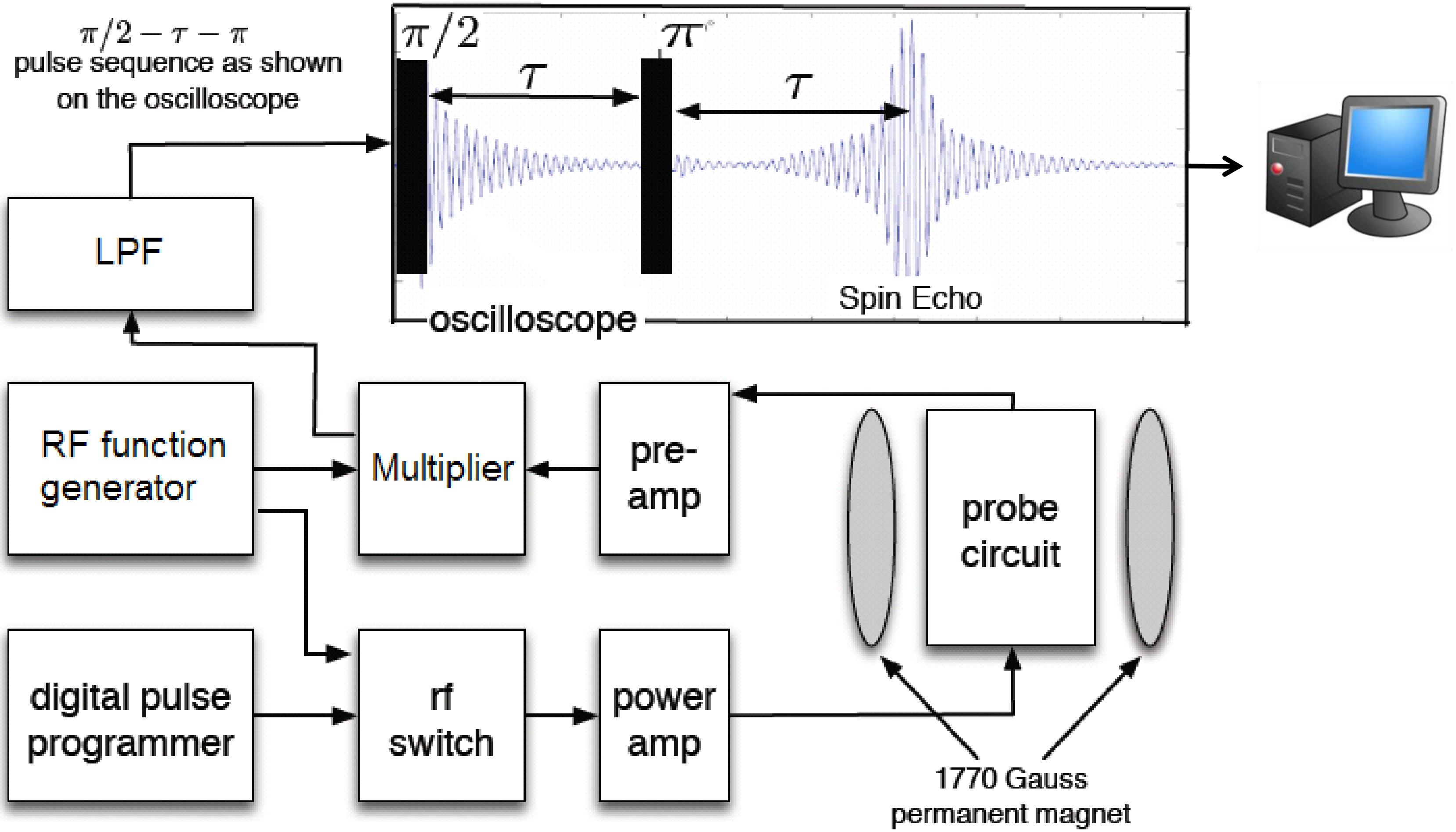
Image source: Q. Hu's 8.06 paper on NMR (2006)

T_2 measurement: Carr-Purcell sequence



- Initial 90°: Initiate precession
- Repeated 180°: Produce spin echoes

Experimental setup



$\pi/2 - \tau - \pi$

pulse sequence as shown on the oscilloscope

$\pi/2$

τ

π

τ

Spin Echo

oscilloscope

LPF

RF function generator

Multiplier

pre-amp

probe circuit

digital pulse programmer

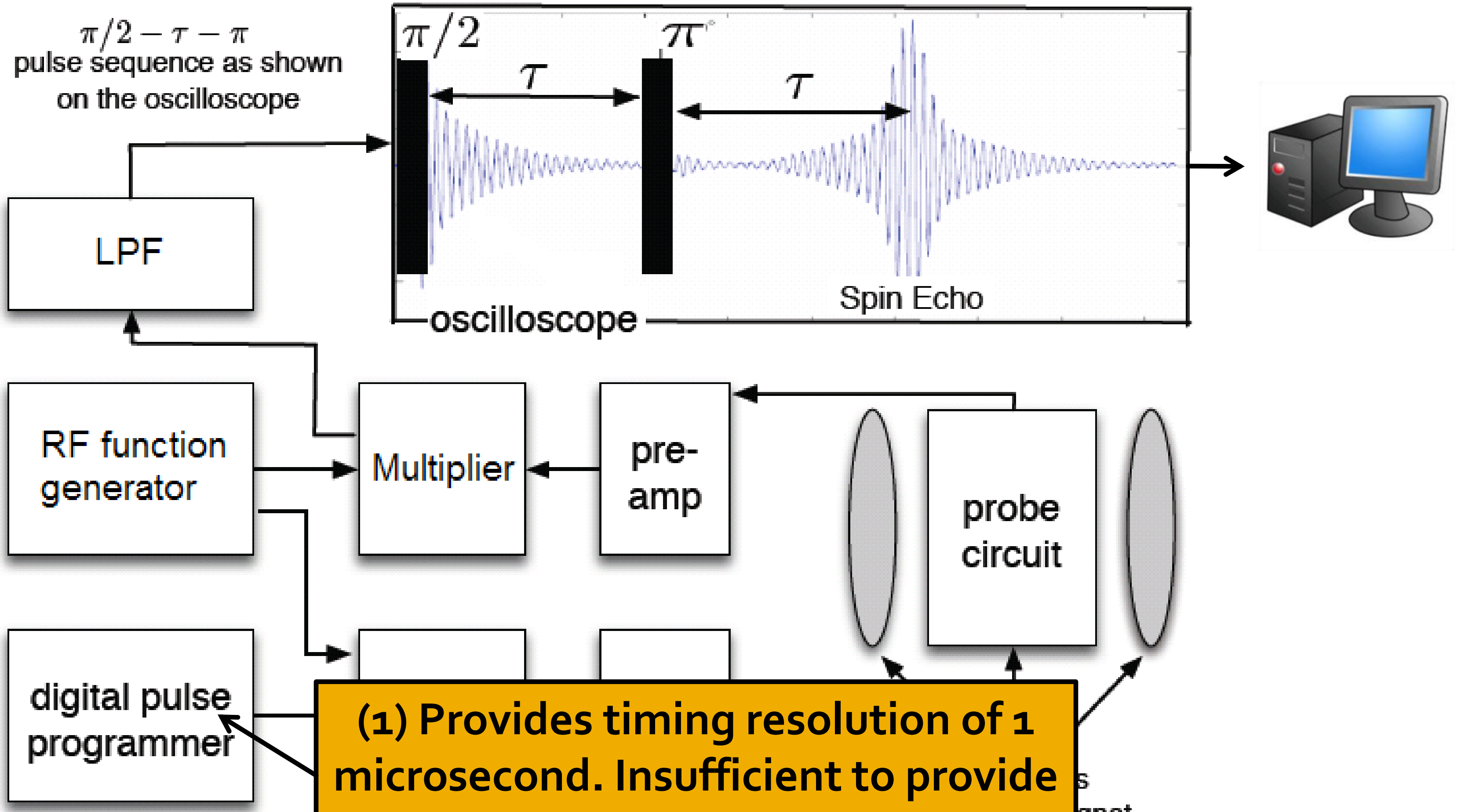
rf switch

power amp

1770 Gauss permanent magnet

Image source: S. Sewell. Pulsed NMR. (MIT Copy Tech, 2005)

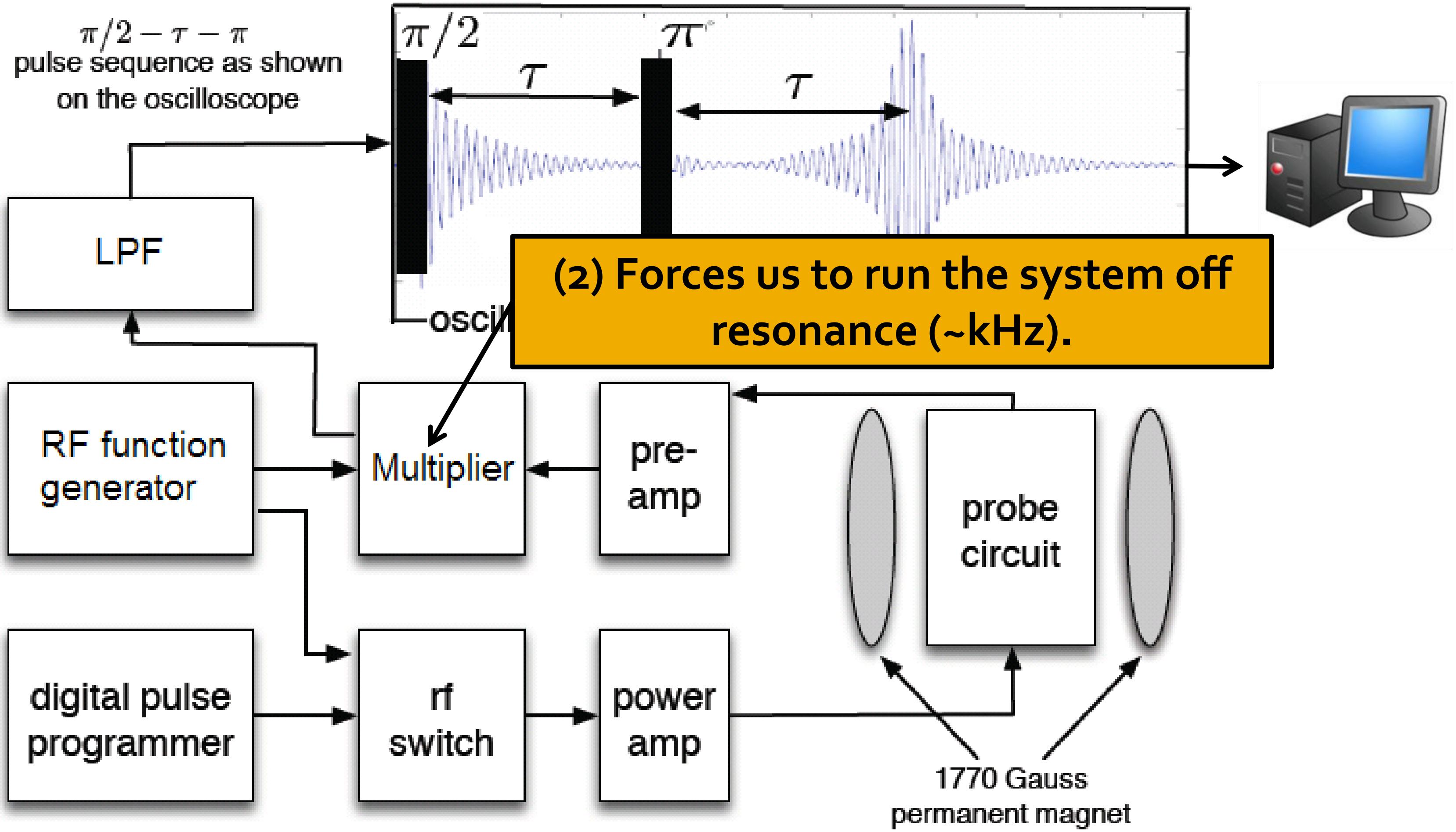
Experimental setup: Drawbacks



(1) Provides timing resolution of 1 microsecond. Insufficient to provide ideal 180° pulses.

Image source: S. Sewell. Pulsed NMR. (MIT Copy Tech, 2005)

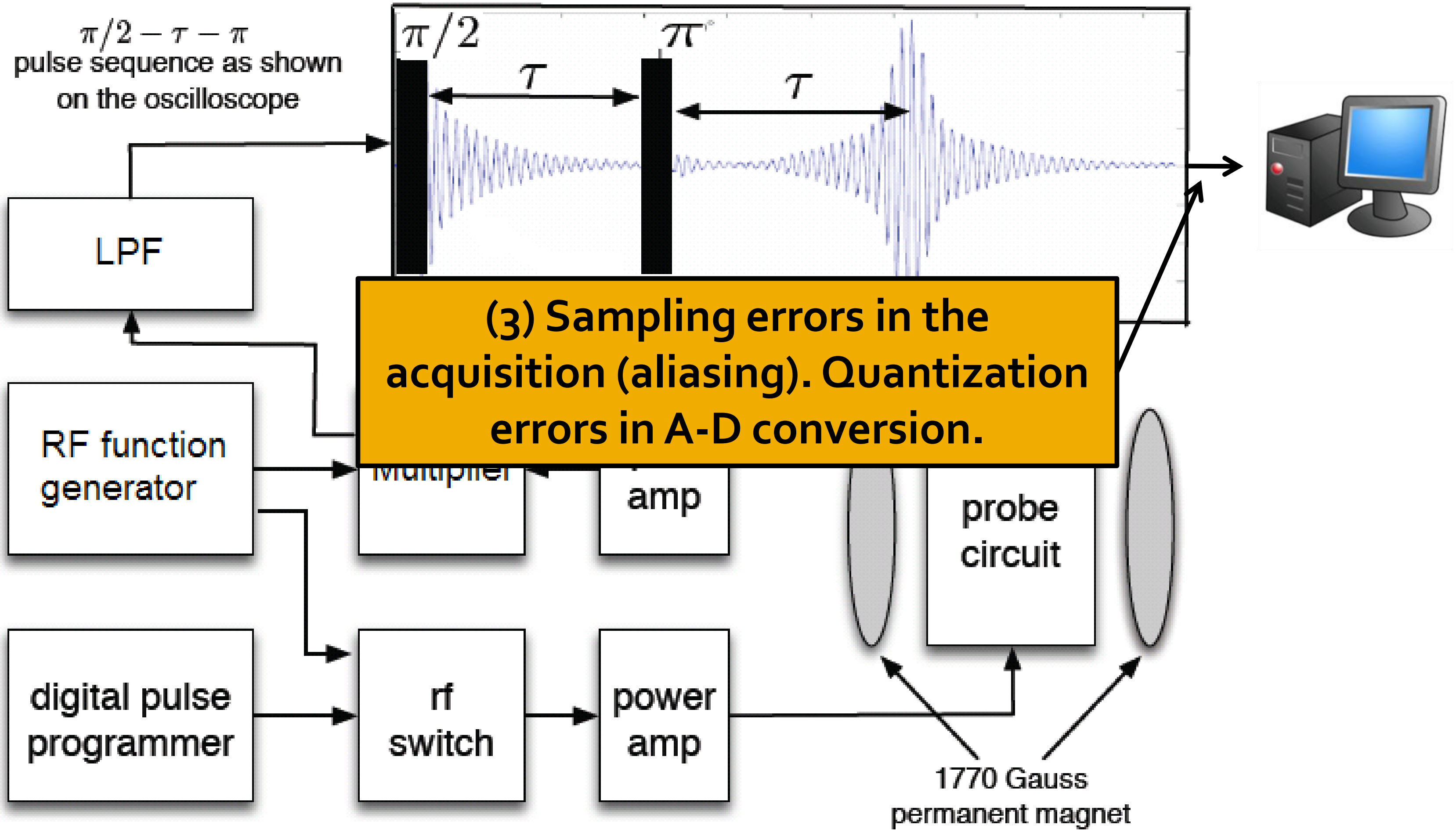
Experimental setup: Drawbacks



(2) Forces us to run the system off resonance (~kHz).

Image source: S. Sewell. Pulsed NMR. (MIT Copy Tech, 2005)

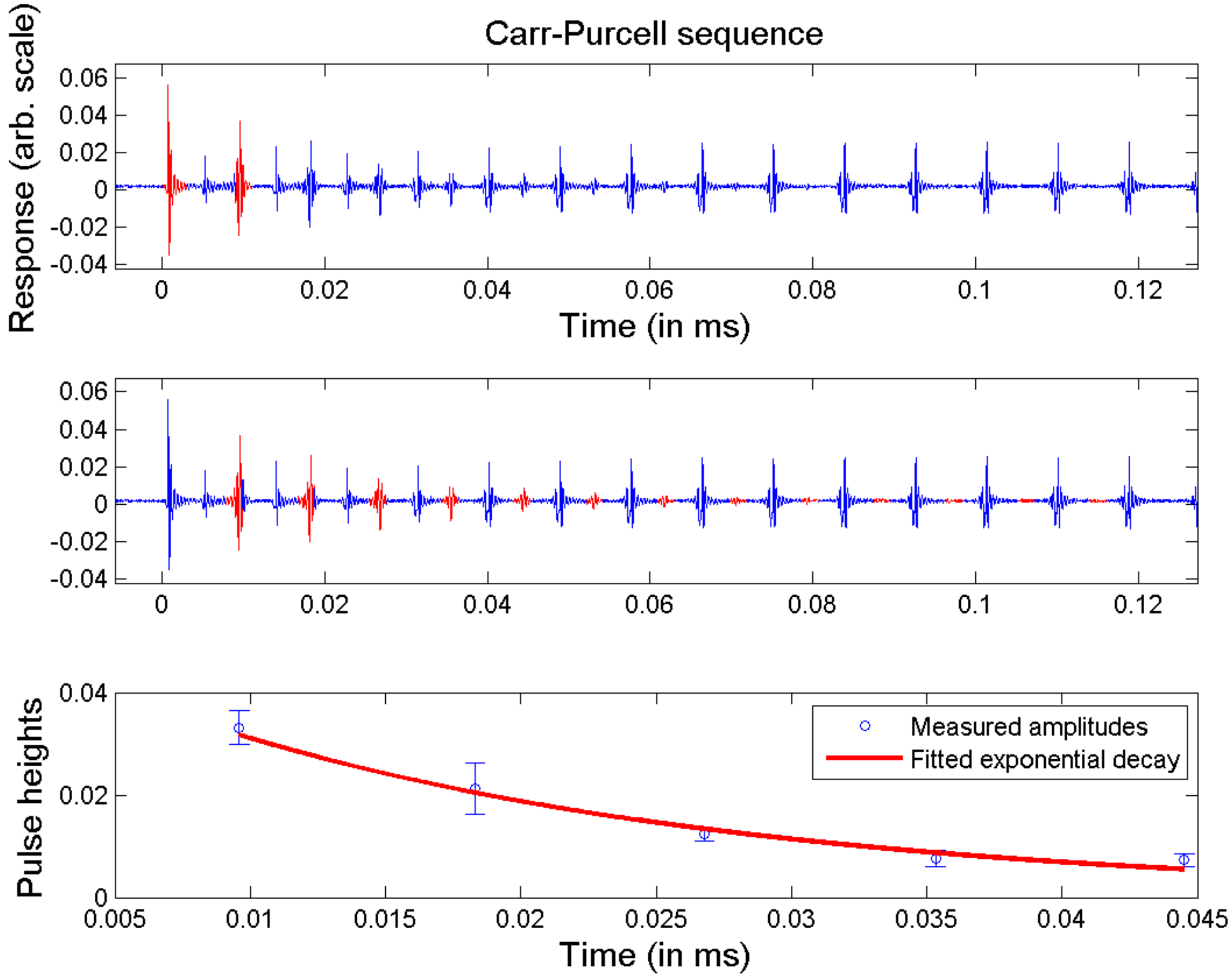
Experimental setup: Drawbacks



(3) Sampling errors in the acquisition (aliasing). Quantization errors in A-D conversion.

Image source: S. Sewell. Pulsed NMR. (MIT Copy Tech, 2005)

Typical Carr-Purcell data (98% glycerine)



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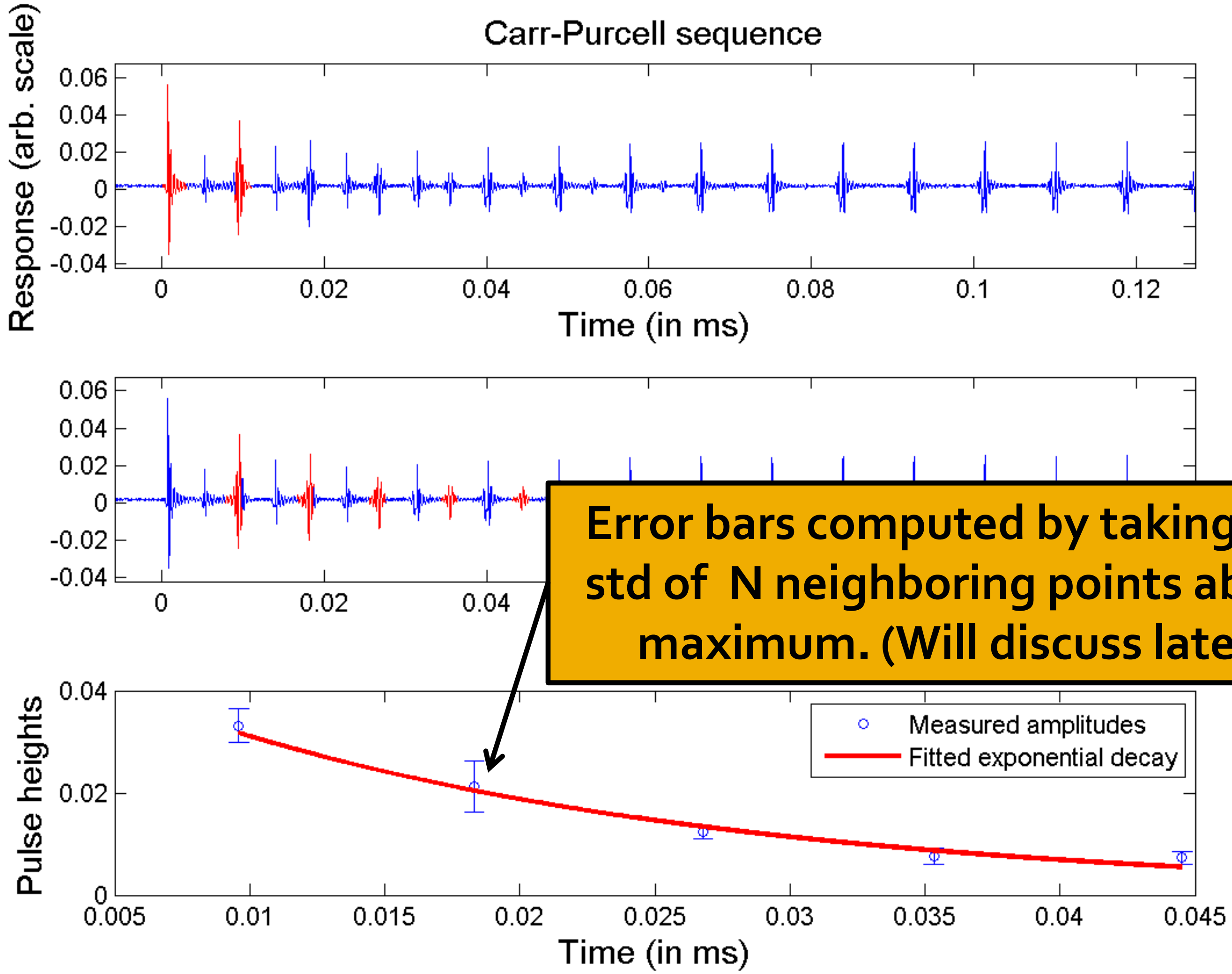
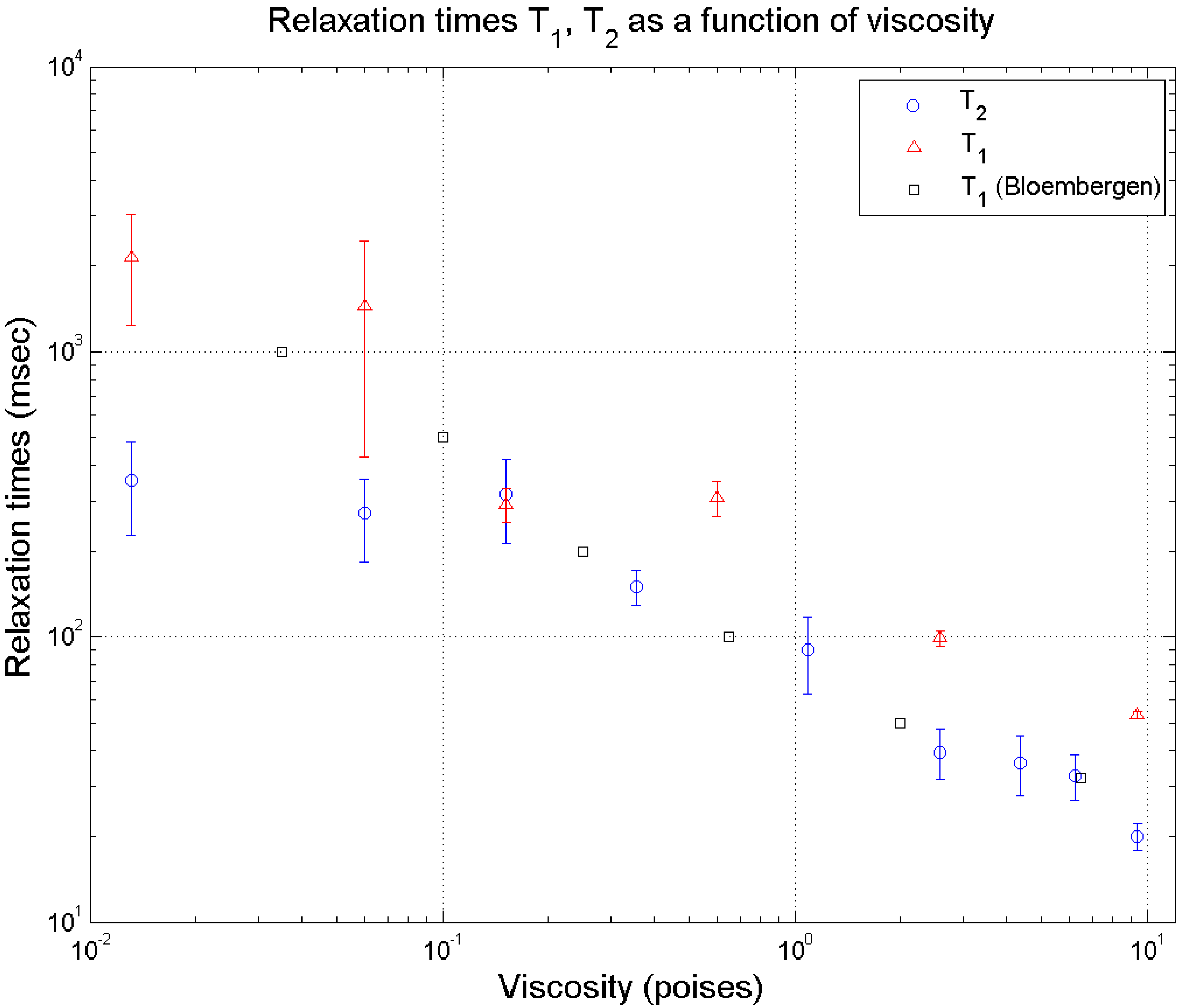
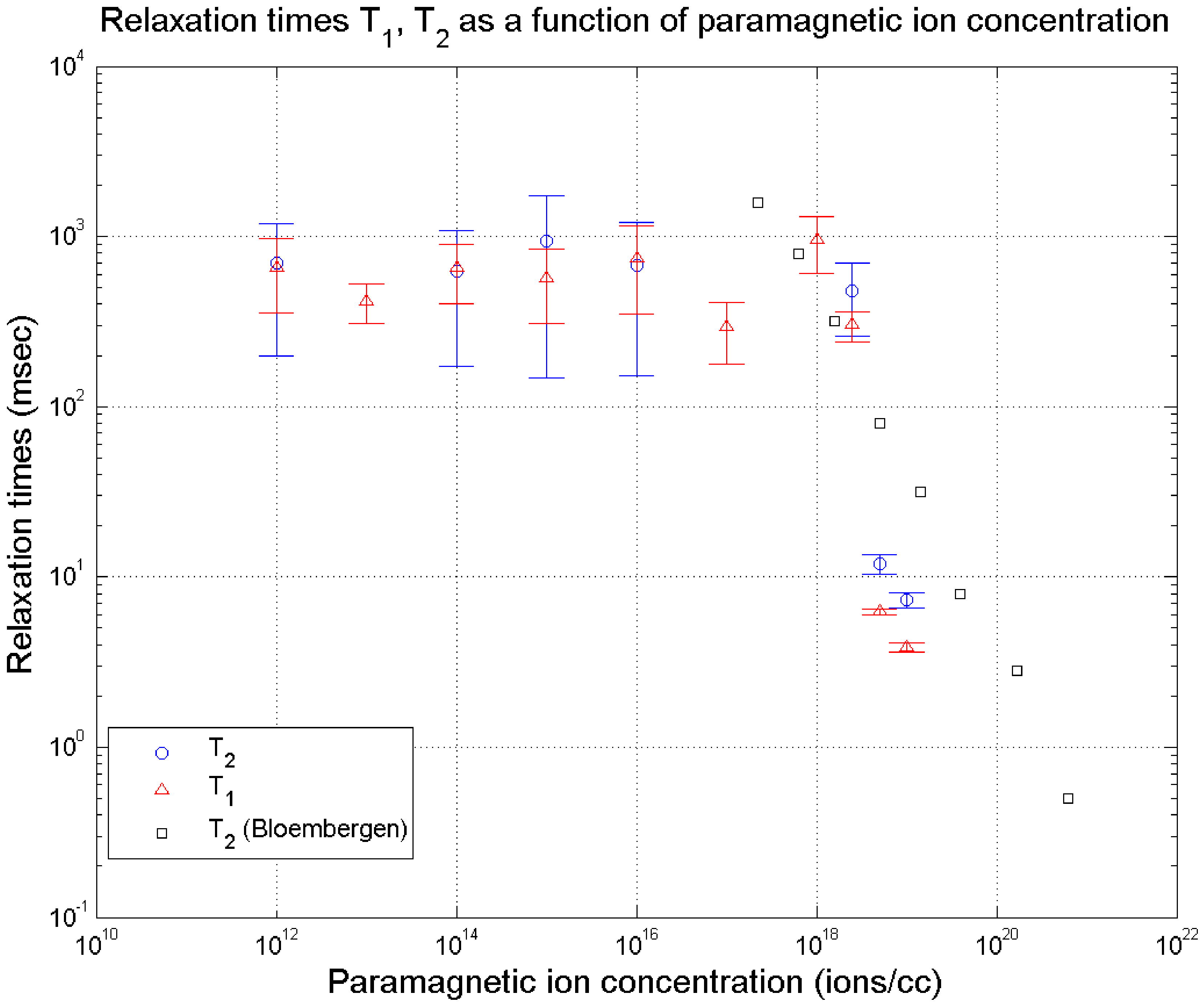


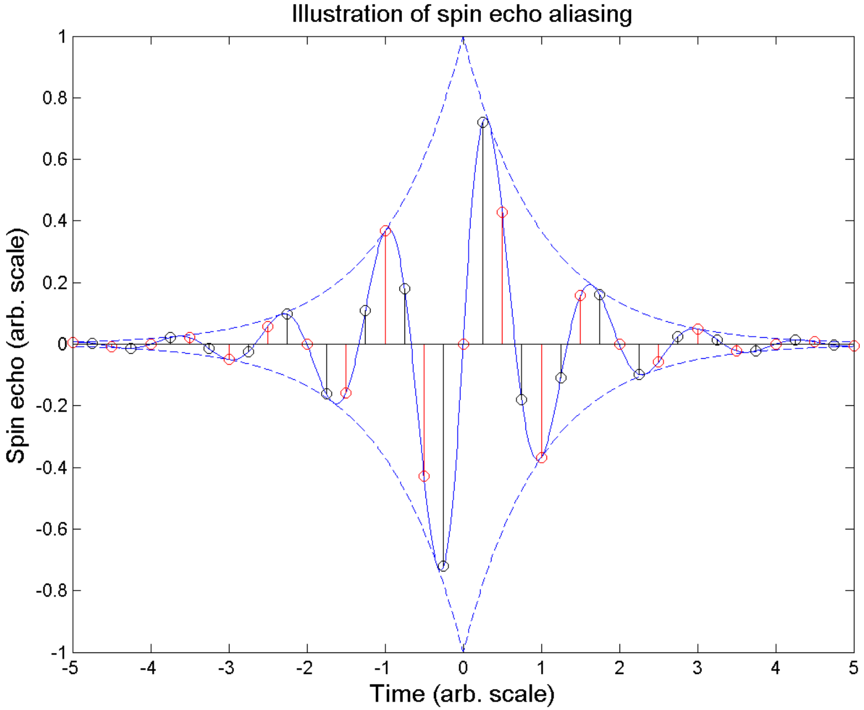
Error bars computed by taking the std of N neighboring points about maximum. (Will discuss later)


Relaxation times T_1, T_2 as a function of viscosity
10^4
10^3
10^2
10^1
Relaxation times (msec)
10^{-2}
10^{-1}
10^0
10^1
Viscosity (poises)
T_2
T_1
T_1 (Bloembergen)


Relaxation times T_1, T_2 as a function of paramagnetic ion concentration
Relaxation times (msec)
Paramagnetic ion concentration (ions/cc)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
○ T_2
△ T_1
□ T_2 (Bloembergen)

Sources of error; possible improvements

- Several instrumental drawbacks already discussed.
- T_2 echo height estimation is susceptible to aliasing.
  - T_1 analysis technique is sensitive to phase;
  - Two methods have shown up to ~100ms discrepancy.



Accommodated the aliasing error by using neighborhood of the point for error estimation.

Such errors ~ 0.005; c.f. quantization error = 0.0006;

Conclusions

- Investigated relaxation times as a function of:
  - Sample viscosity:
    - Verified the inverse-law relationship observed by Bloembergen.
  - Paramagnetic ion concentration:
    - Unclear results; need more samples in the range 10^{17}-10^{21} ions/cc.
    - Possible threshold effect ~ 10^{17}.

- In general: More interactions → Increased relaxation rates.