Development of a ^{3}He-based absolute calibration magnetometer for the muon g-2 experiment

- New Muon g−2 Experiment
- Magnetometers and the magnetic field standard
- Proposed ^{3}He probe: optical pumping, lasers, gas cells, polarimetry
- Towards a ^{3}He magnetometry standard for g−2

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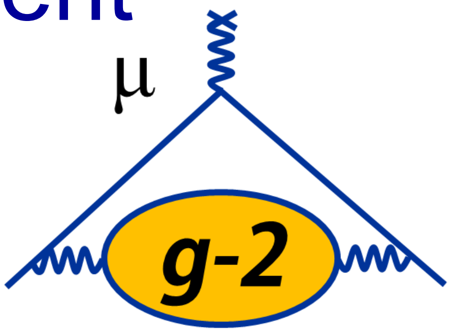
New Fermilab Muon g−2 Experiment



Muon anomalous magnetic dipole moment

$$a_\mu = \tfrac{1}{2}(g-2)$$

$$a_\mu = a_\mu^{QED} + a_\mu^{Hadronic} + a_\mu^{Weak} + \ldots New\ physics?$$

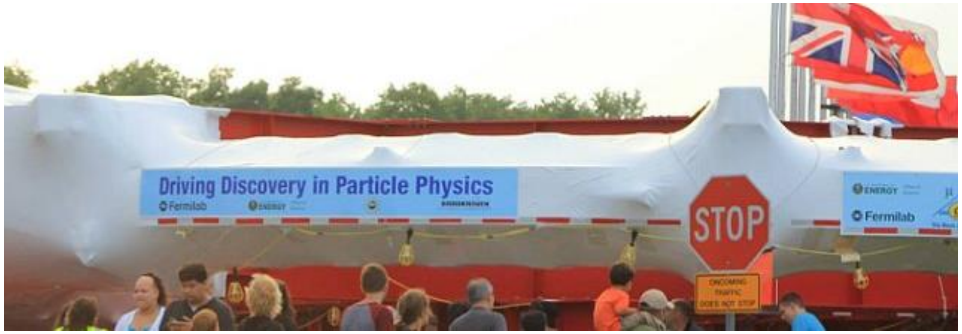
Standard Model: $a_\mu = 116\,591\,802 \pm 49 \times 10^{-11}$ (0.42 ppm)

BNL measurement: $a_\mu = 116\,592\,089 \pm 63 \times 10^{-11}$ (0.54 ppm)

Discrepancy ~3.6σ

New experiment to reach 140ppb

Probe for signs of SUSY and alternative theories



The g−2 magnetic field measurement

Shim 1.45T field to 1ppm

Measure the magnitude to 70ppb using NMR probes

Muon anomalous spin precession frequency – measured from oscillation frequency of positrons from muon decay

$$a_\mu = \frac{m_\mu \omega_a}{eB} = \frac{\omega_a / \omega_p}{\mu_{\mu^+} / \mu_p - \omega_a / \omega_p}$$

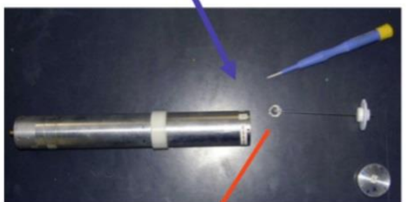
(Measured by E1054 muonium experiment)

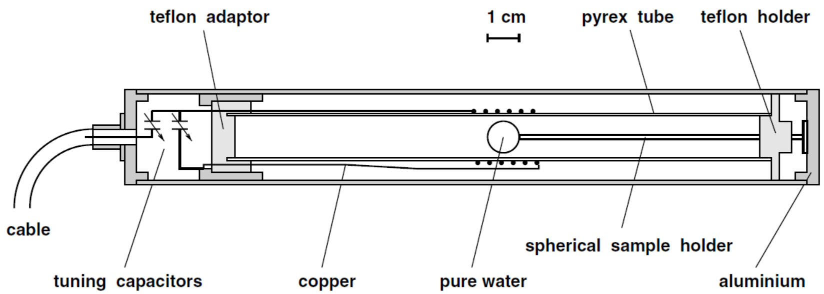
Proton precession frequency measured with NMR magnetometer probes

378 fixed probes, plus mobile trolley probes must be calibrated against standard probe

Absolute Water Calibration Probe

Absolute Calibration Probe:
a Spherical Water Sample





(a) Absolute calibration probe

- 50ppb accuracy for Brookhaven experiment
- Target 35ppb for Fermilab

$$B_p = (1-\delta_t)B \qquad \delta_t = \sigma_{H_2O} + \delta_b + \delta_p + \delta_s$$

Shifts due to bulk shielding (δ_b), paramagnetic impurities in sample (δ_p) and probe structure (δ_s)

Protons in spherical water sample

$$\sigma_{H_2O} = \left(1 - \frac{\mu'_p}{\mu_p}\right) = 25{,}702(14)\times 10^{-6}$$

Free protons

Philips et al. *Metrologia 1977, 13, 179-195*

Proposed ^{3}He Absolute Calibration Probe

Advantages of ^{3}He:

- Lower uncertainty on diamagnetic shielding,
- Temperature coefficient 100 times smaller,
- Negligible susceptibility – no sample shape dependence

$$\sigma_{H_2O} = \left[25.702(14) + 0.01036(30) \times (T - 34.7°C)\right] \times 10^{-6}$$

$$\sigma_{^3He} = 59.967\,43(10) \times 10^{-6}$$

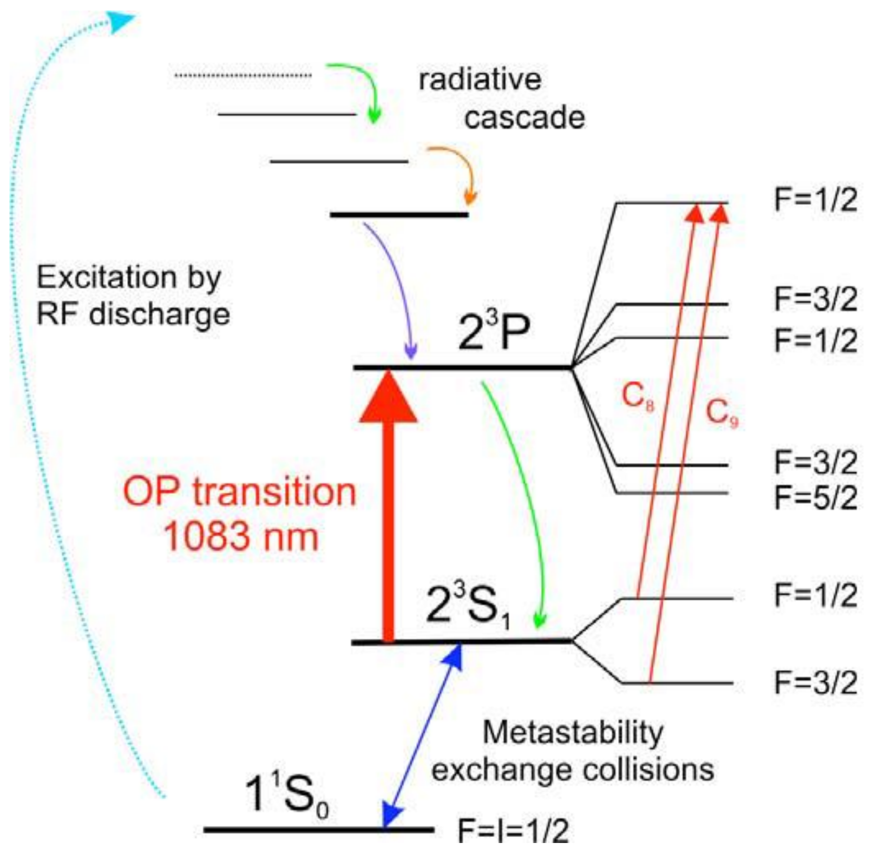
- Need to polarise sufficient amount of ^{3}He to get useful NMR signal

	Water probe	^{3}He probe
NMR detection and measurement	15	2
Field homogeneity	10	10
Materials outside probe	15	15
Sample holder shape	15	negligible
Probe materials	10	10
Diamagnetic shielding	14	negligible
Temperature effect	10	negligible
Total	34ppb	21ppb

Polarisation of ^{3}He for NMR

Metastability Exchange Optical Pumping (MEOP)

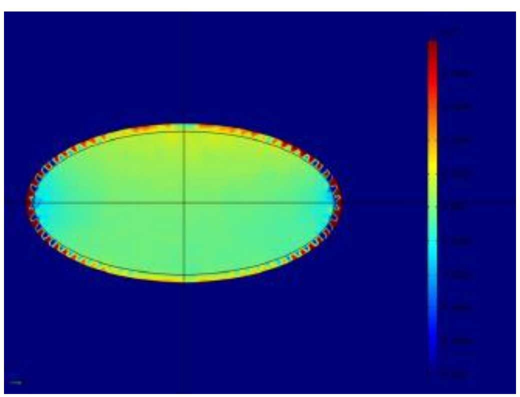
- RF discharge excites ^{3}He atoms to the metastable $^3S_1$ state.
- Circularly polarised 1083nm laser light applied to cell to optically pump excited atoms
- Electronic polarization transferred to the nucleus by hyperfine interaction.
- Metastable state polarization transferred to ground state through collisions

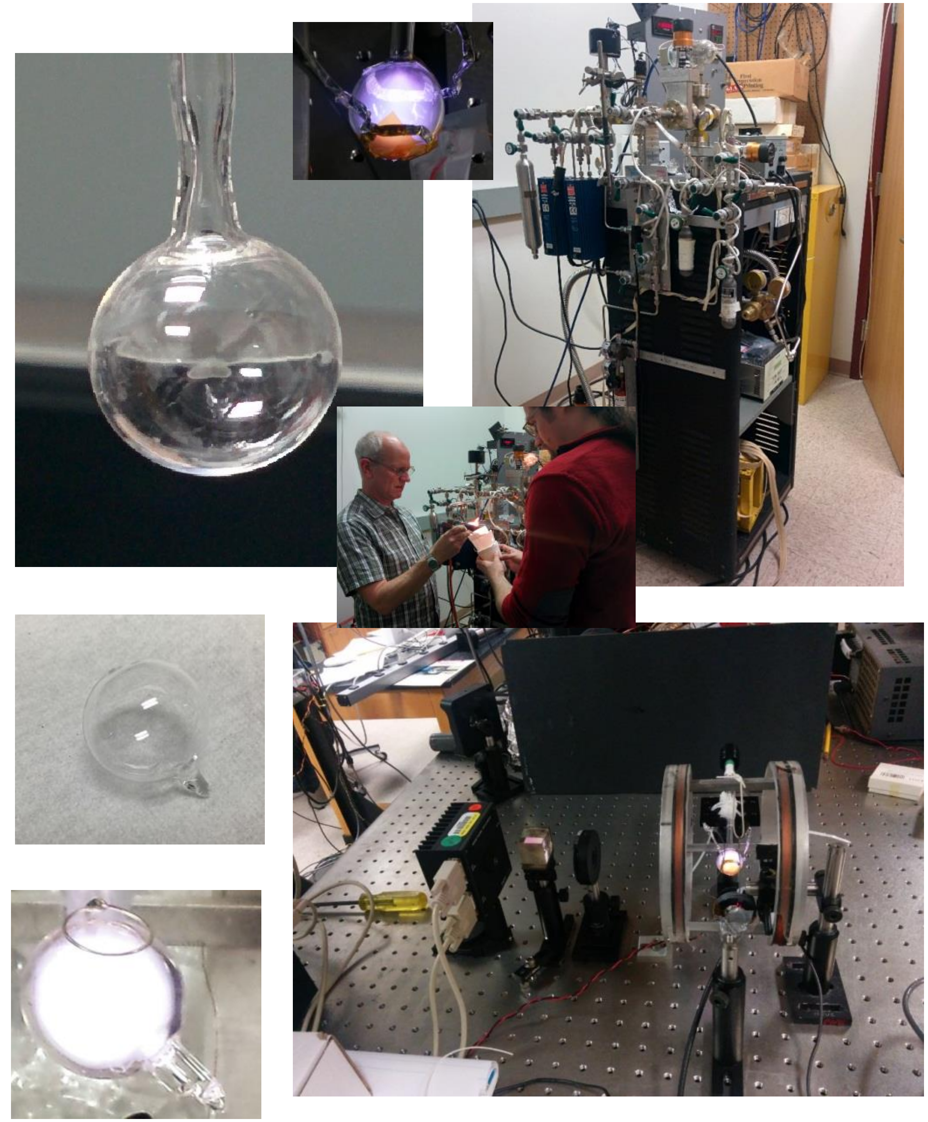


→ Require 1083nm laser 100mW

^{3}He cells

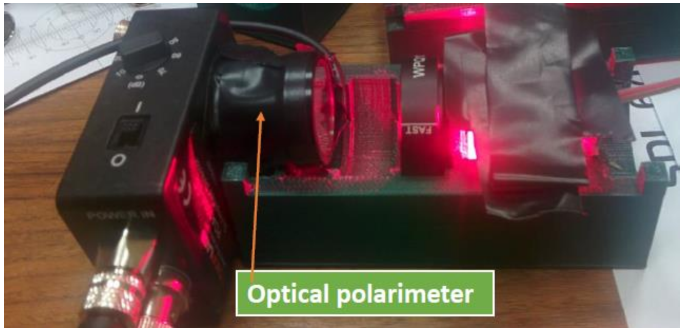
- Supplied by Tim Chupp, University of Michigan
- Custom glassware
- Aggressive cleaning procedure
- Fill with ^{3}He from dedicated gas handling system.
- Spherical cell reduced inhomogeneities due to cell walls

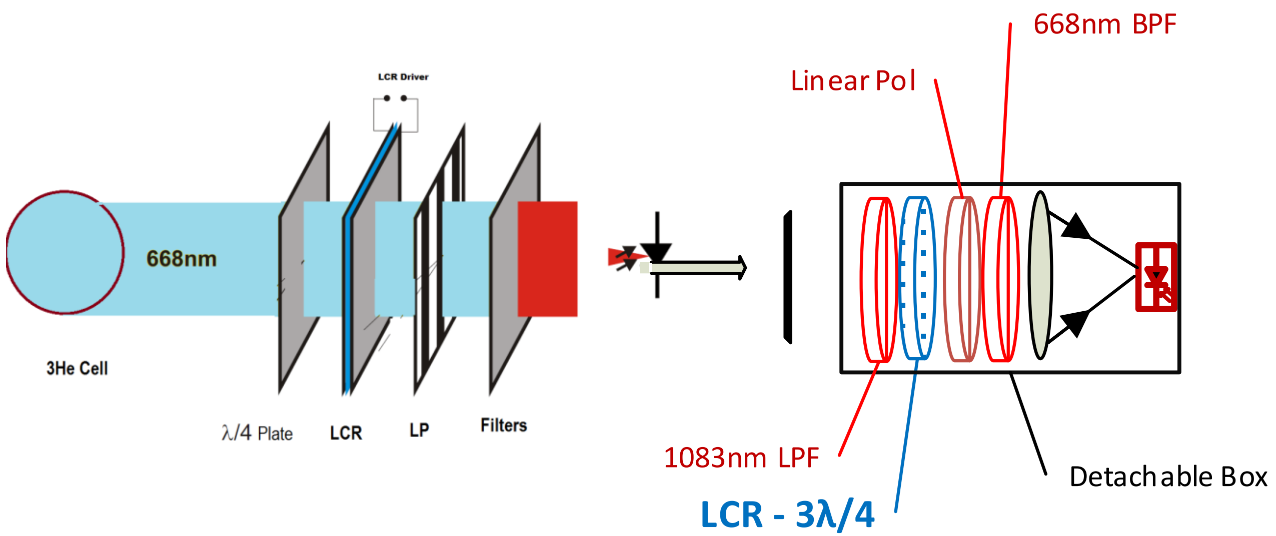




Monitoring the ^{3}He Polarimetry

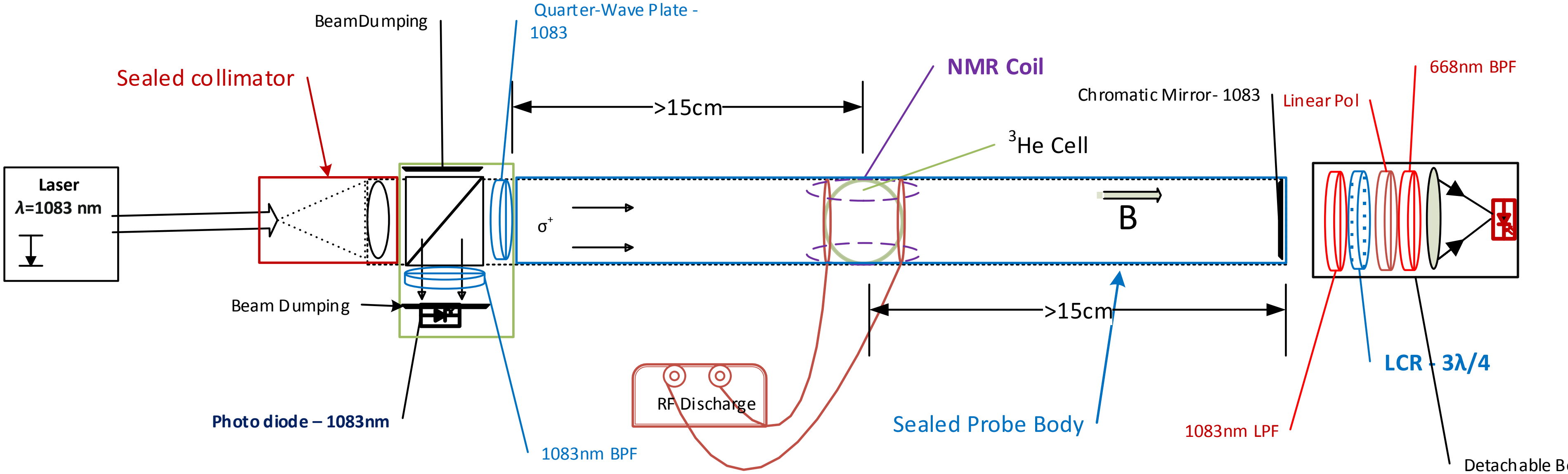
- Essential to tune laser wavelength to optical pumping transitions
- Measure circular polarization of 668nm light emitted by the 3^1D_2 to 2^1P_1 transitions.
- Optical polarimeter using a nematic liquid crystal retarder and a photodiode



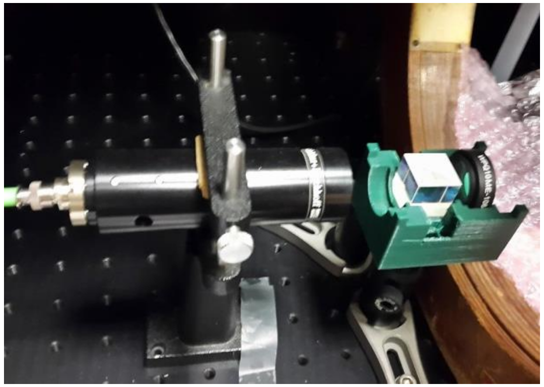


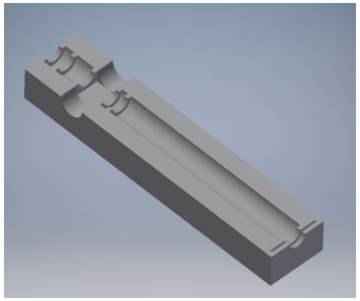
Liquid Crystal polarimetry for metastability exchange optical pumping of ^{3}He, JD Maxwell, CS Epstein and RG Miller, Nucl. Instrum. Meth. A 764 (2014) 215.

Proposed Design for ^{3}He probe

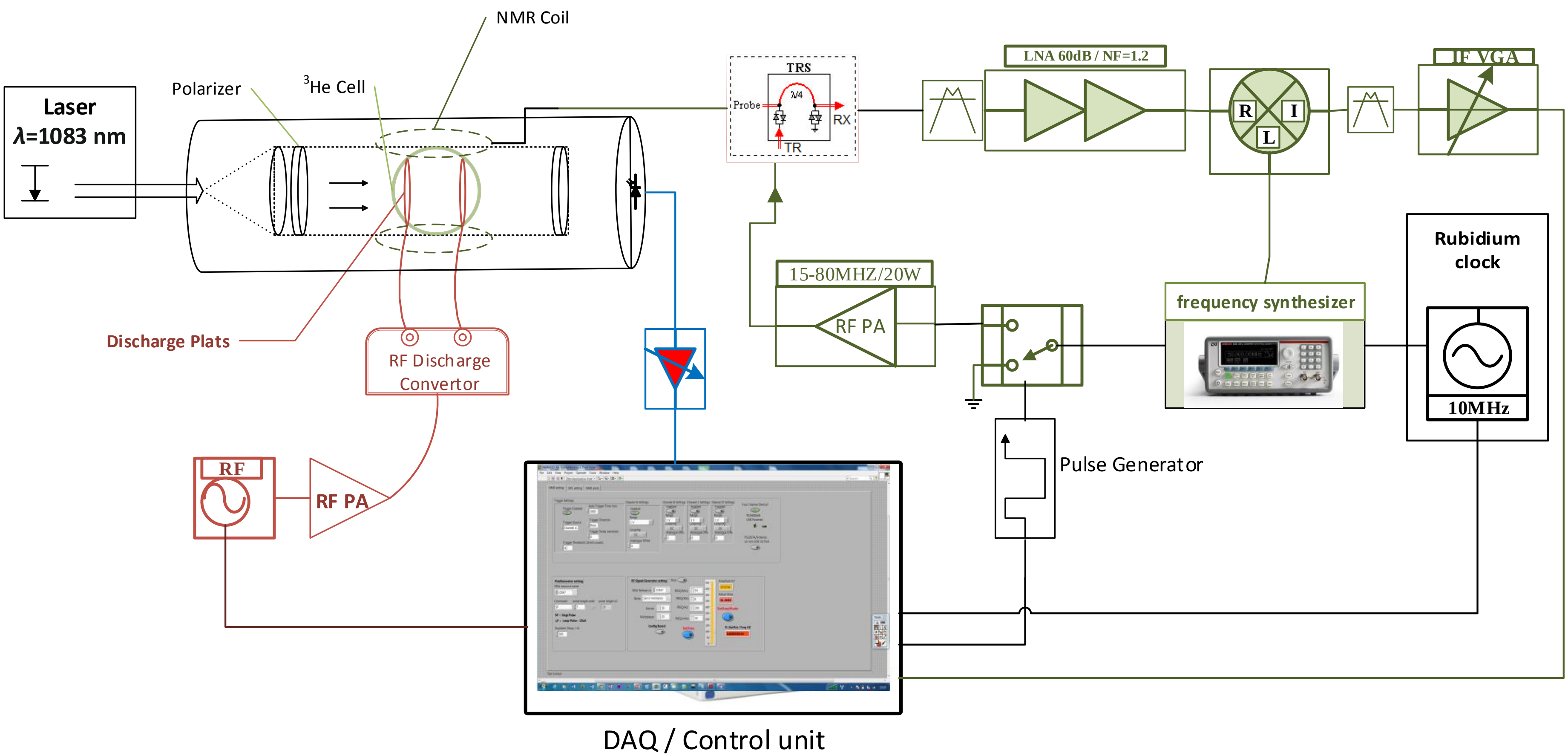


Design v.013





Proposed Design for NMR Electronics



- 47 MHz Free Induction Decay signal
- Synthesiser locked to rubidium clock

Towards a ^{3}He magnetometry calibration for g−2

- A ^{3}He absolute calibration probe will provide
  - Important cross-check of the magnetic field calibration for Brookhaven and Fermilab g−2 experiments
  - Further improve uncertainty on calibration below 30ppb
- R&D programme at Oxford a step towards the construction of g−2 calibration magnetometer
- Cross calibration and characterization to be done in test magnet at Argonne National Laboratory
- Long term future – Could ^{3}He replace the proton as a magnetometer standard for g−2?