Hg and Xe Comagnetometry

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Purpose

Phase 1: Hg Comagnetometer

Calculate the **volume-and time-averaged** magnetic field **B_0** from Hg precession frequency

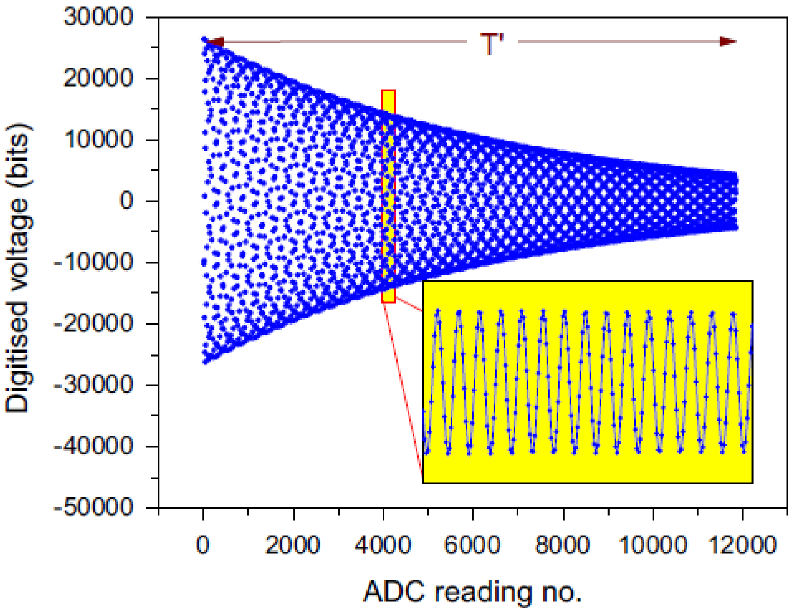
$$\frac{\nu_n}{\nu_{Hg}} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right| + \frac{(d_n + |\gamma_n/\gamma_{Hg}| d_{Hg})}{\nu_{Hg}} E = \left|\frac{\gamma_n}{\gamma_{Hg}}\right| + \frac{d_{meas}}{\nu_{Hg}} E.$$

Phase 2: Hg-Xe Dual

Calculate volume-and time-averaged magnetic field **and vertical gradient dB/dz (GPE)**

Implementation:

- Optical probe beam
- Record ~100s of Free Spin Precession
- Fit average precession frequency
- ILL & PSI: Fit a decaying sinusoid to the **first** and **last** 15s of the precession signal



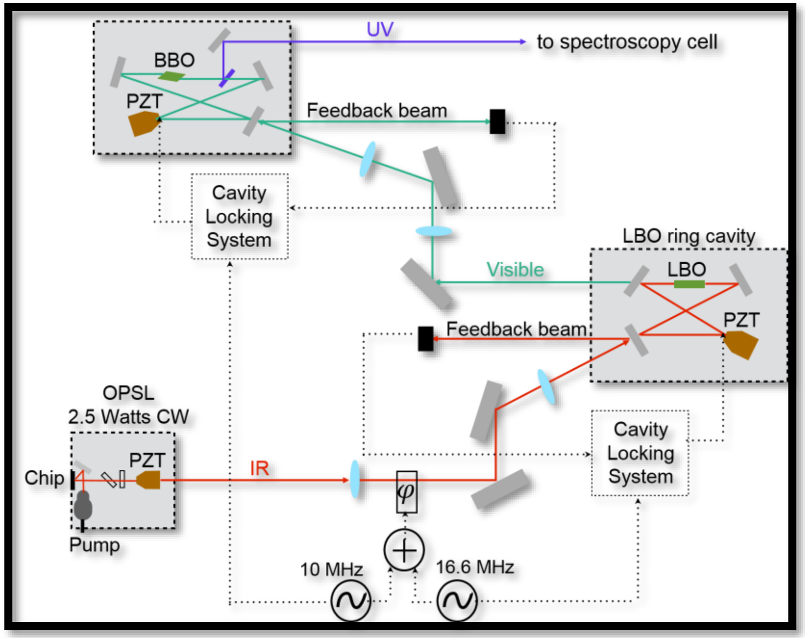
$$\sigma_f \approx \frac{1}{4T'} \frac{a_n}{a_s} \frac{1}{\sqrt{n}} (1 + e^{2T'/\tau})^{1/2}$$

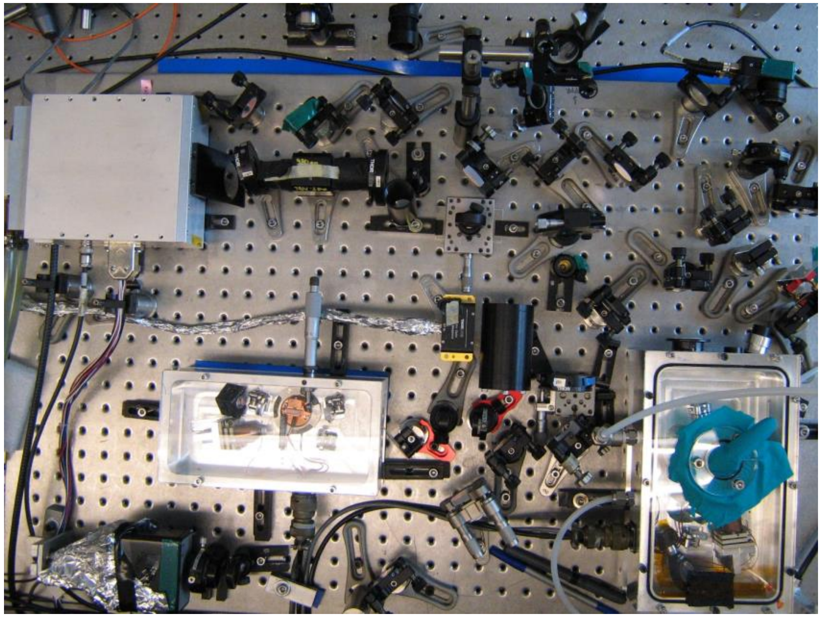
	B	$\sigma_B = \frac{2\pi}{\gamma} \sigma_f$
ILL, typical (Baker et. al, 2014)	1 µT	50 fT (50ppb)
Target (2015CDR)	1 µT	30 fT (30ppb)
Target (CFI 2017) *100s in 1mTorr*	1 µT	10 fT (10ppb)

Hg Comagnetometry

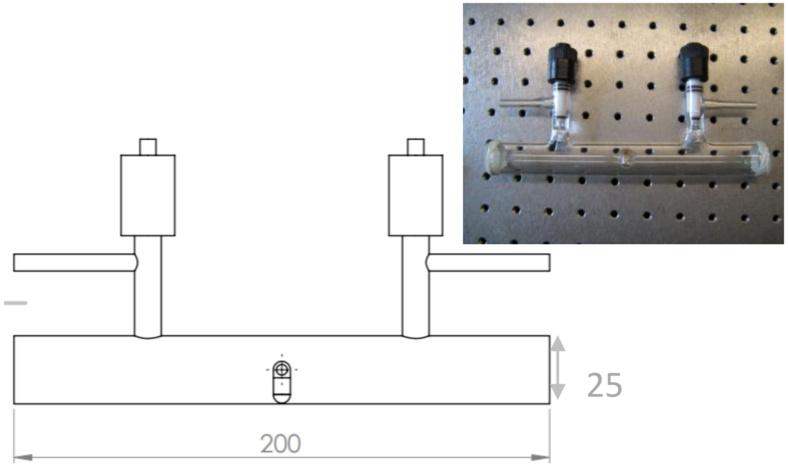
Laser

- 254 nm CW laser (OPSL +SHG)
  - Mode hop –free tuning range < 2 GHz
  - UV power > 10mW
    - Compare to lamp pumping: e.g PSI lamp 20μW (10^{13} photon/s) over all emission lines
  - 5-15 min stability of cavity locks
  - Wavelength stabilized by feedback signal from wavemeter

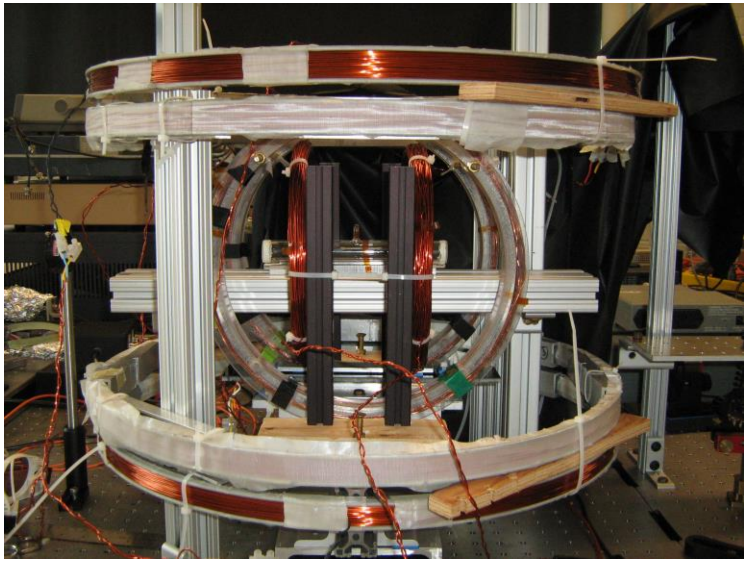




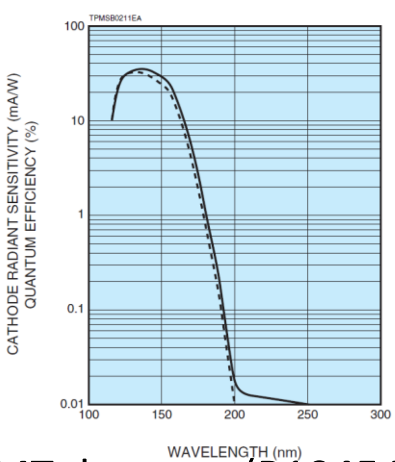
Equipment



Hg vapour cell w/ quartz windows



3-axis magnetic coil

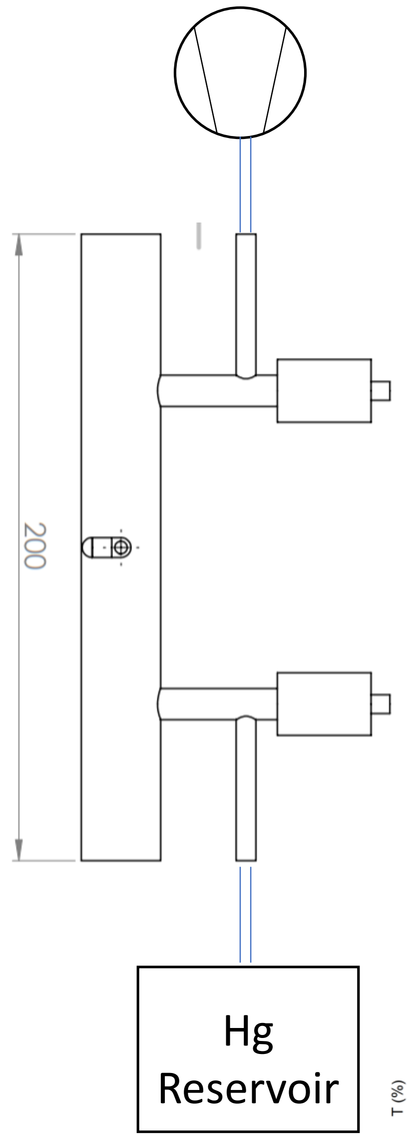


Solar blind PMT detector (R10454)

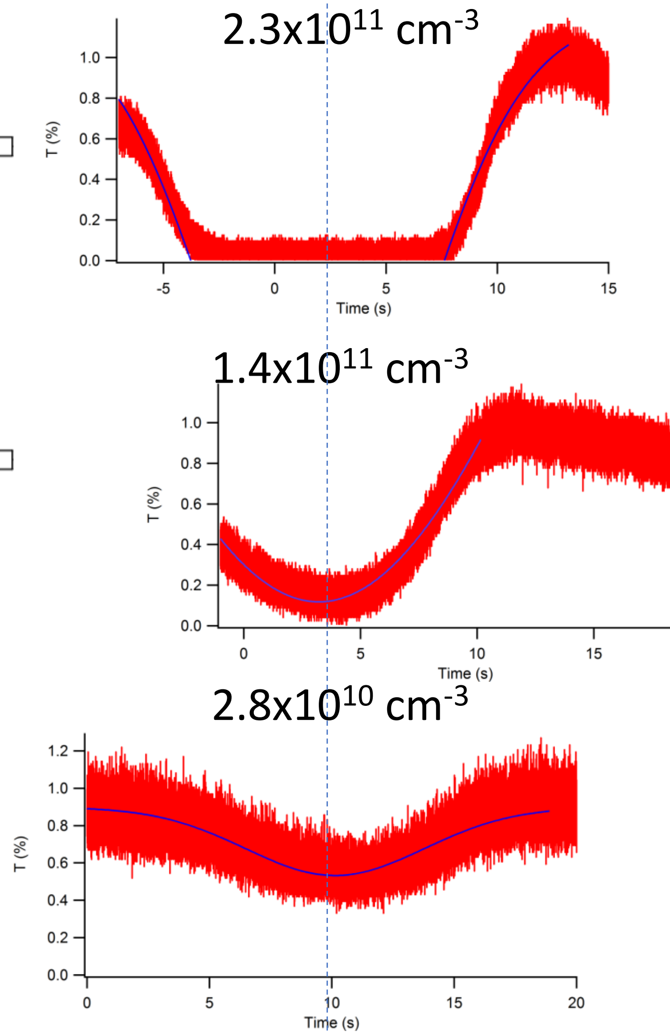
Bristol 671-NIR wavemeter

Hg Cell filling

- At room temperature, Hg is optically thick:
    - $\sigma_{Hg} = 8\times10^{-13}\ cm^2$
    - $n_{Hg} = 6.4\times10^{13}\ cm^{-3}$
- Hg fill procedure:
    - pump lines 30 min to < .001 Torr
    - open Hg for 30s
    - close reservoir
    - Leave pump valve open ~30s to pump below saturation vapour pressure
    - Trial and error!
- Need: controlled fill system
    - Heating HgO or cooling Hg



Estimated number density:

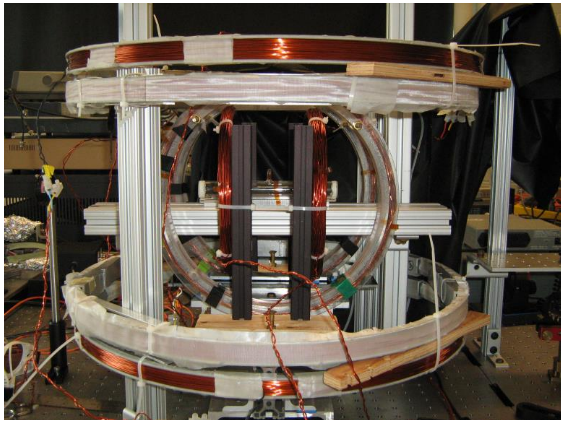


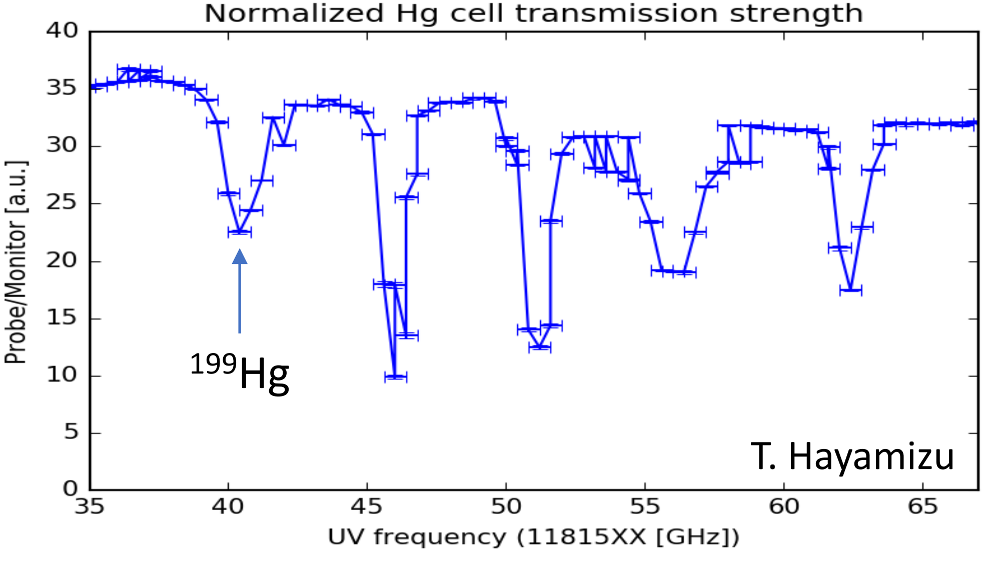
Progress towards Optical Pumping

1. Filled cell w/ 10^{12}~10^{13} Hg atoms
2. Applied 800 µT B_0 (nulled off-axis fields < 10 µT)
3. Confirmed ^{199}Hg resonance frequency via spectra: (peaks above but no below.
4. Pump beam: 10 µW & 2 cm diameter, circularly polarized

No OP signal yet!

We suspect wall collisions



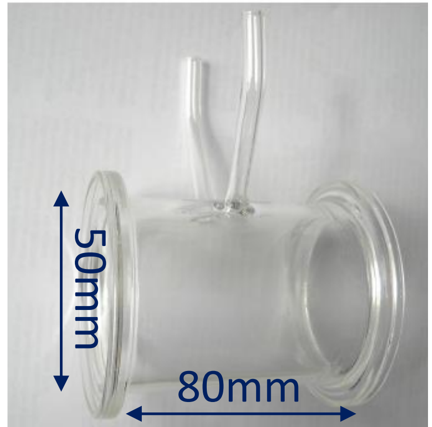


Hg $6s^2(^1S_0)$ - $6s6p(^3P_1)$ @ 253.7nm

Some approximate rates for optical pumping:

UV photon flux (10 µW)	10^{13} s^{-1}	
Integrated ^{199}Hg pumping rate	1.6×10^{12} s^{-1}	At n_{Hg}= 2.8×10^{10} cm^{-3}
Hg thermal velocity, 300K	160 m/s	
Wall collisions, uncoated? (est. Loss per bounce = 10^{-3})	1.4×10^{13} s^{-1} 1.4×10^{12} s^{-1}	For cell ID = 2cm For cell ID = 20cm
Wall collisions, coated (est. Loss per bounce = 10^{-5})	1.4×10^{11} s^{-1} 1.4×10^{10} s^{-1}	For cell ID = 2cm For cell ID = 20cm

Next steps



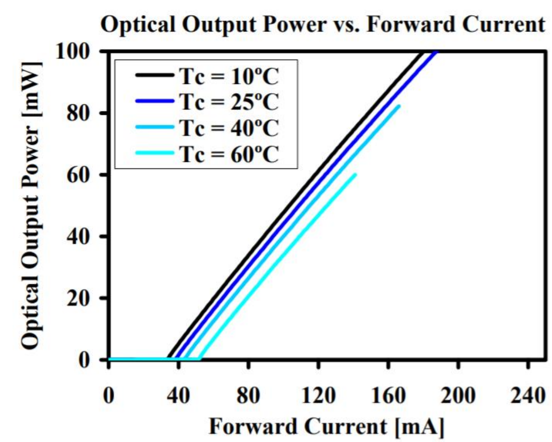
Chowdhuri, App. Phys. B, 2014

Table 1 Measured τ-times (first measurement τ_1, second τ_2) for studied coatings

Coating material and its chemical structure	τ_1 (s)	τ_2 (s)
Perfluorinated paraffin	40.5 (1.2)	34.6 (6)
$C_{20}F_{42}$(80 %) + $C_{16}F_{34}$ (10–20 %)		
Fomblin grease	34.7 (7)	30.6 (5)
$CF_3-[-O-CF_2-CF_2]_n-[O-CF_2]_m-O-CF_3$		
mixed with CF_2-CF_2		
SurfaSil	32.2 (4)	30.6 (7)
$Cl-[-(CH_3)_2-Si-O-]_n - (CH_3)_2-Si-Cl$		
Paraffin	26.3 (4)	28.0 (2)
$C_{32}H_{66}$		
Fomblin oil type "Y"	28.4 (5)	27.0 (6)
$CF_3-[-O-CF_2-CF_2]_n-[O-CF_2]_m-O-CF_3$		
n/m = 20…40		
AquaSil	23.0 (1.0)	26.0 (6)
$CH_3-(CH_2)_{15}-Si-(OH)_3$		
Black Teflon	<5	–
CF_2-CF_2 mixed with carbon		
Apiezon "J" oil	No signal	–
based on hydrocarbons		

Hg work:

- Reduce wall collision loss rate
  - Increase cell size to reduce frequency of wall collisions
  - Coat cell with Surfasil or paraffin to reduce loss probability per bounce
- Increase pumping light intensity up to I_{sat}
- Build controlled Hg fill system
- We will begin testing a 507nm diode laser to replace the OPSL/LBO

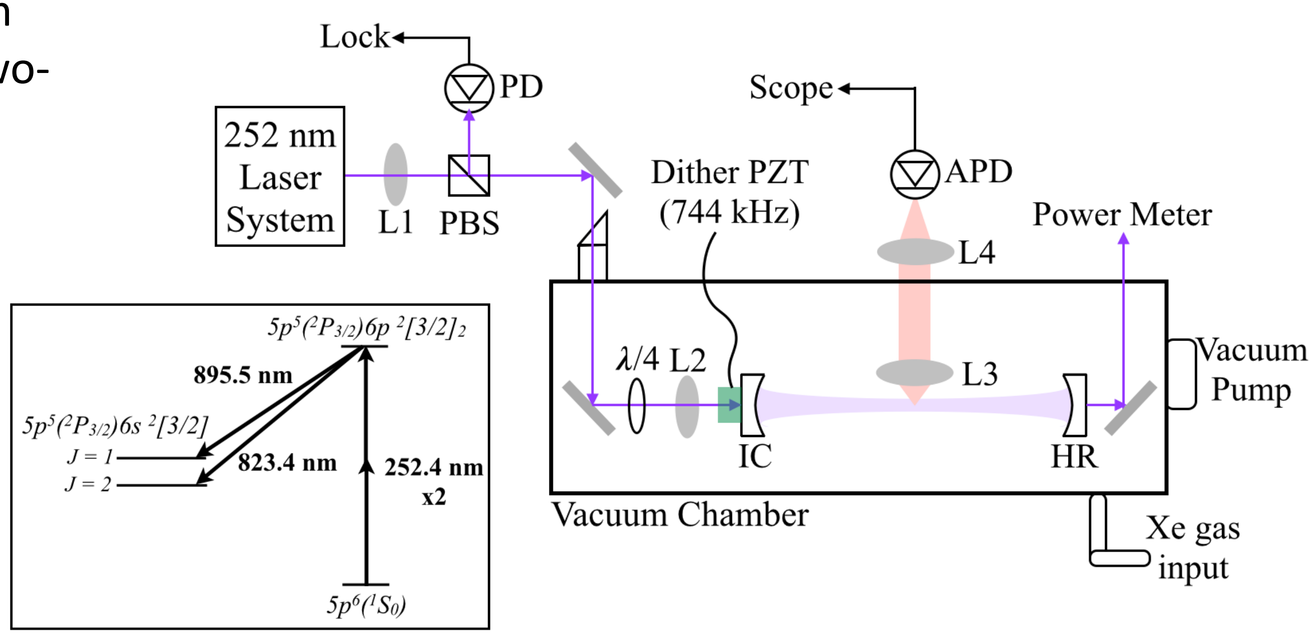


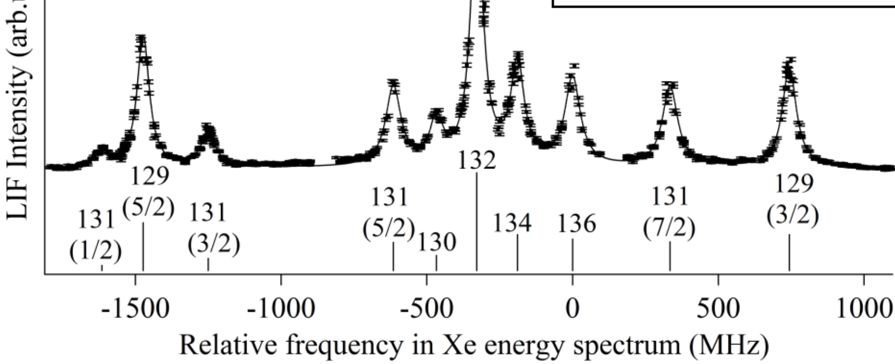
Nichia NDE4116E 507nm diode

Xe Comagnetometry

Xe Two-photon Spectroscopy

- Obtained LIF spectra from excitation of the 5p-6p two-photon transition
- Xe- O_2 mixture
- Lowest pressure 1.6 Torr
- Laser power 40mW
  (P_{circ} = 228mW)

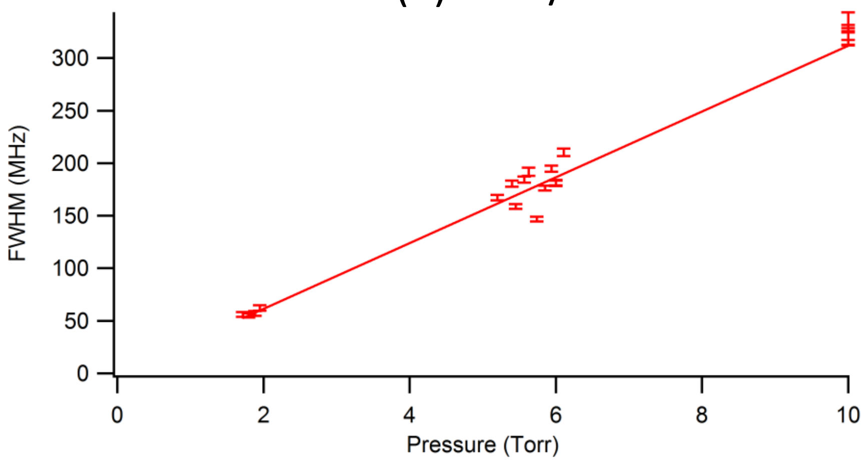




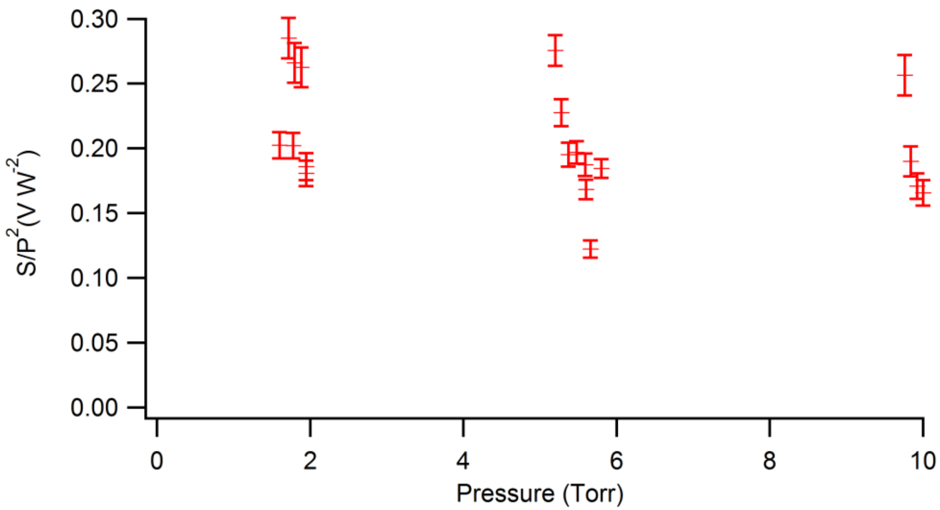
https://doi.org/10.1103/PhysRevA.97.012507

Pressure dependence

Pressure broadening
m = 31.3(3) MHz/Torr



Signal normalized to UV Power^2



- Some evidence for a pressure-independent signal over 1-10 Torr
- Similar behavior is expected down to 130mTorr
- Current work:
  - Measure pressure broadening over 20 mTorr - 1 Torr
  - Extrapolate to zero pressure to get the natural linewidth of the $5p^5(^2P_{3/2})6p\ ^2[3/2]_2$ state (natural linewidth = 4MHz expected)

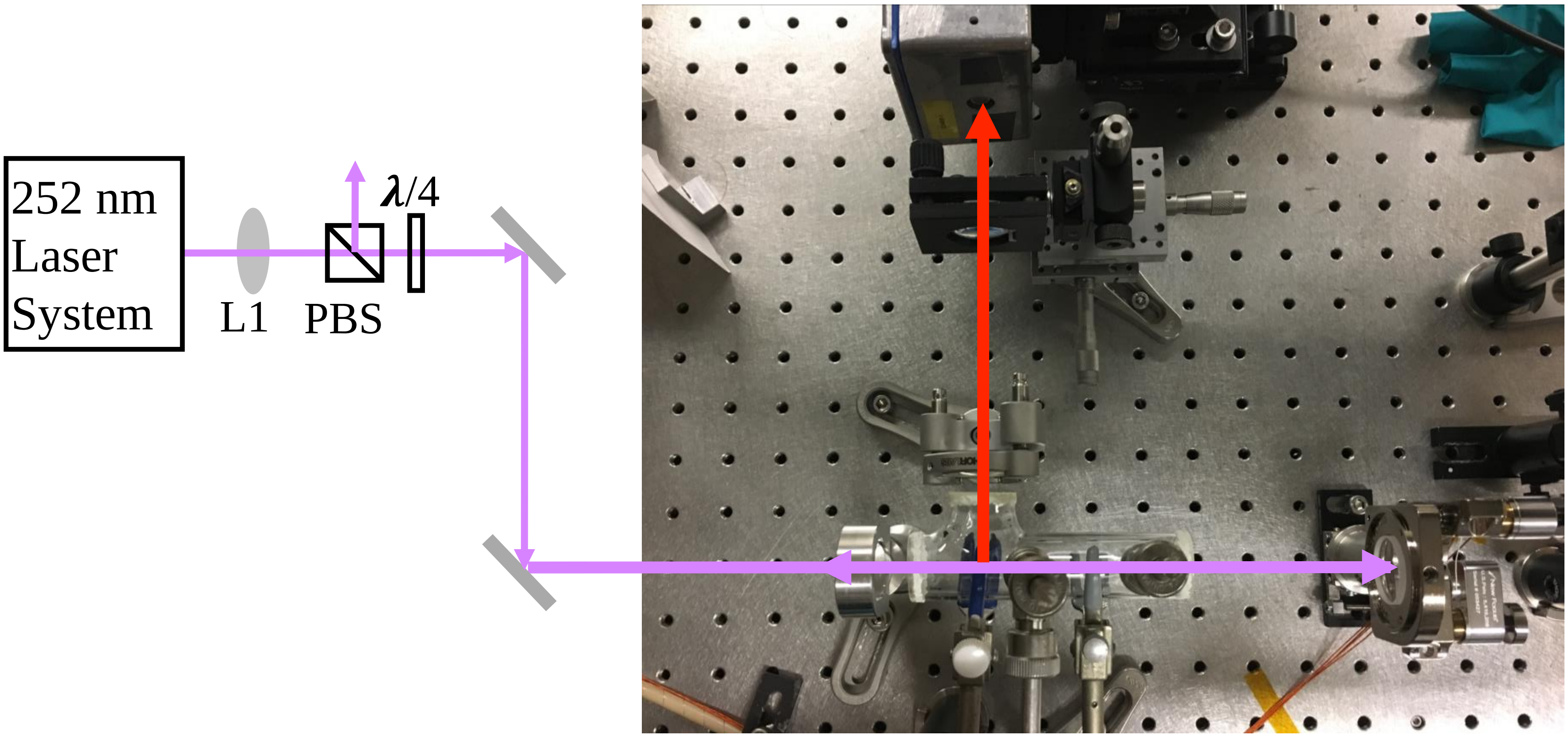
Extrapolation of measurement uncertainty

$$\sigma_f \approx \frac{1}{4T'}\frac{a_n}{a_s}\frac{1}{\sqrt{n}}(1+e^{2T'/\tau})^{1/2}$$

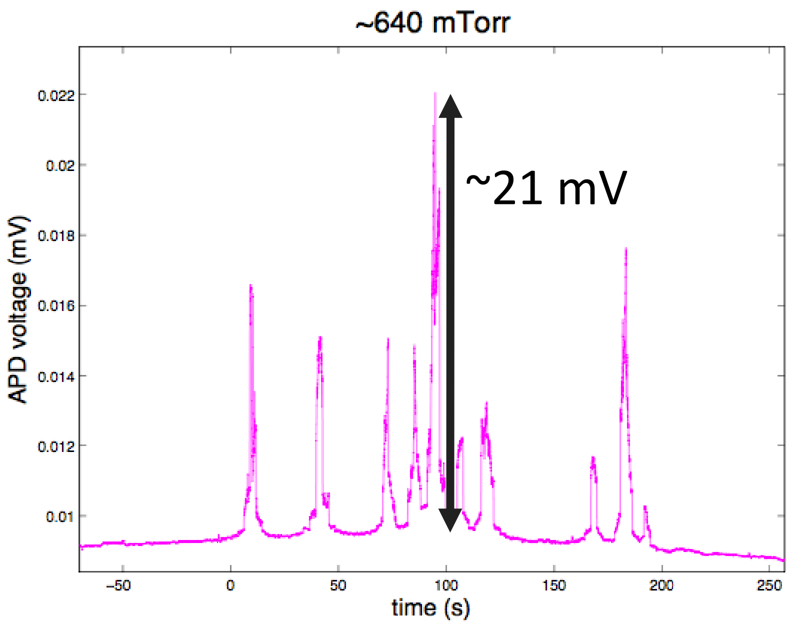
Conditions	Assumed P_{Xe}	Laser Power (W)	SNR	σ_B (fT)
1.6 Torr nat. abund. Xe/O_2	50%	.228	2.5	4000
1.6 Torr isopure ^{129}Xe	50%	.228	19.5	500
130 mTorr isopure ^{129}Xe	50%	.228	19.5	500
10mTorr isopure ^{129}Xe	50%	.228	1.5	6700

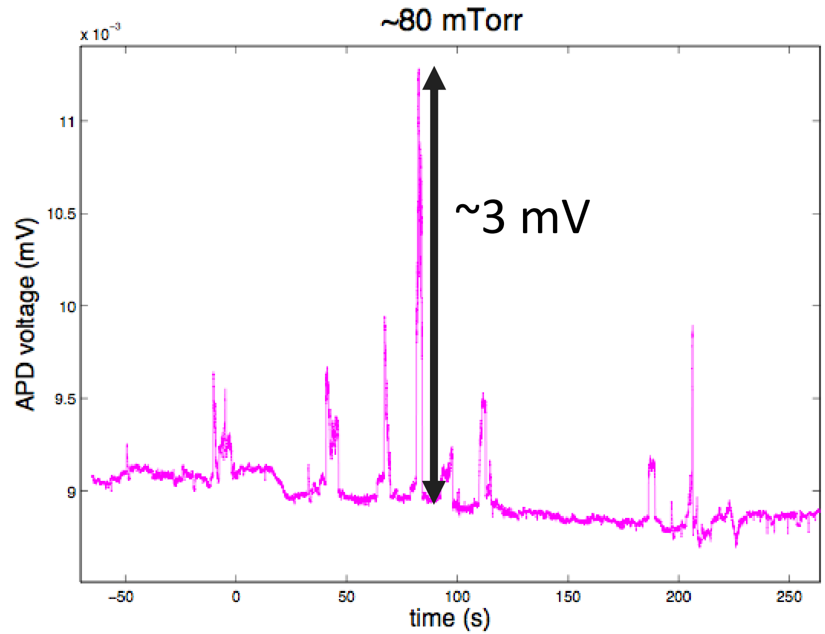
- The first row represents **achieved** pressure and laser conditions
- Following rows consider the change in number density and pressure broadening
- Assuming 100% isopure ^{129}Xe
- We should increase SNR using a cooled PMT.

Retro-reflection Setup

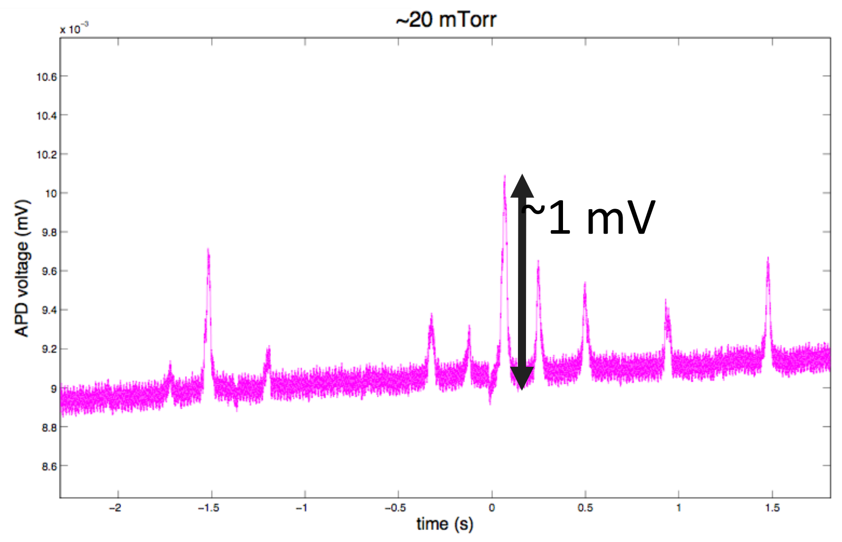


Retro-reflection TPA LIF Signal

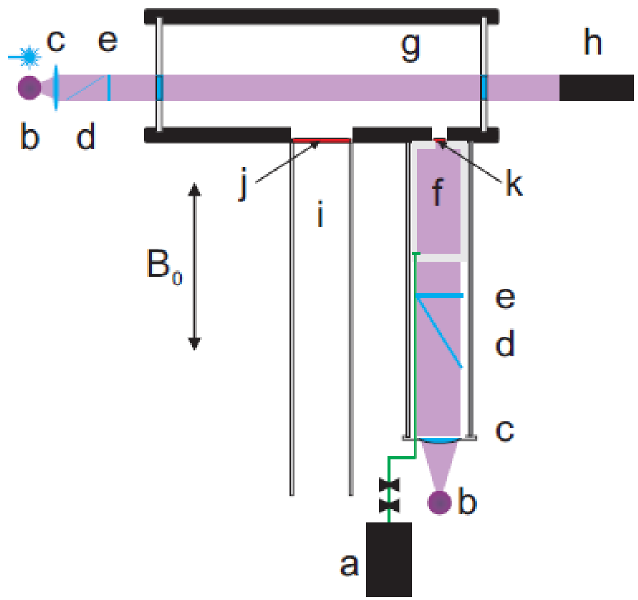


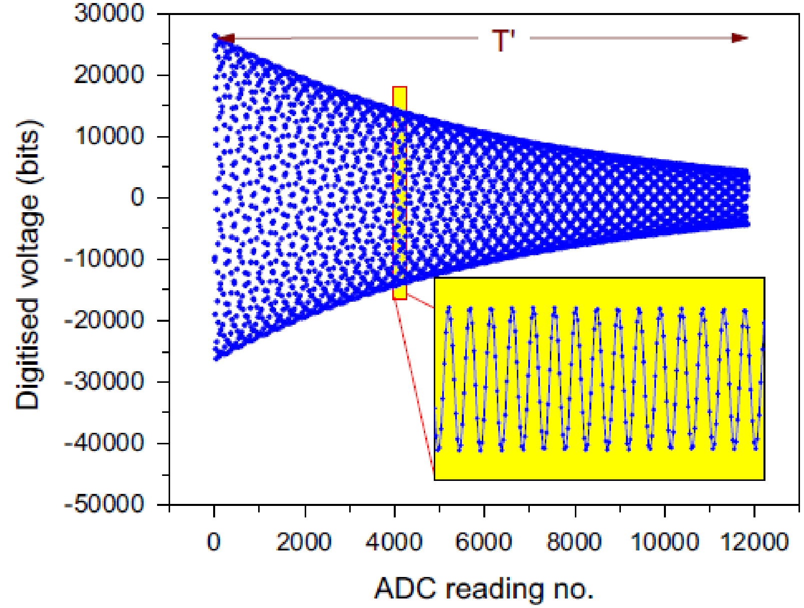


UV input power ~ 70mW



Next steps: requirements?





- what is needed for implementation?
  - UV laser windows
  - Gas inlet valve
  - Prepolarizing cell
  - Photodetector & electronics
- e.g. will there be two HgOP cells for the dual EDM cells?

Thank You!