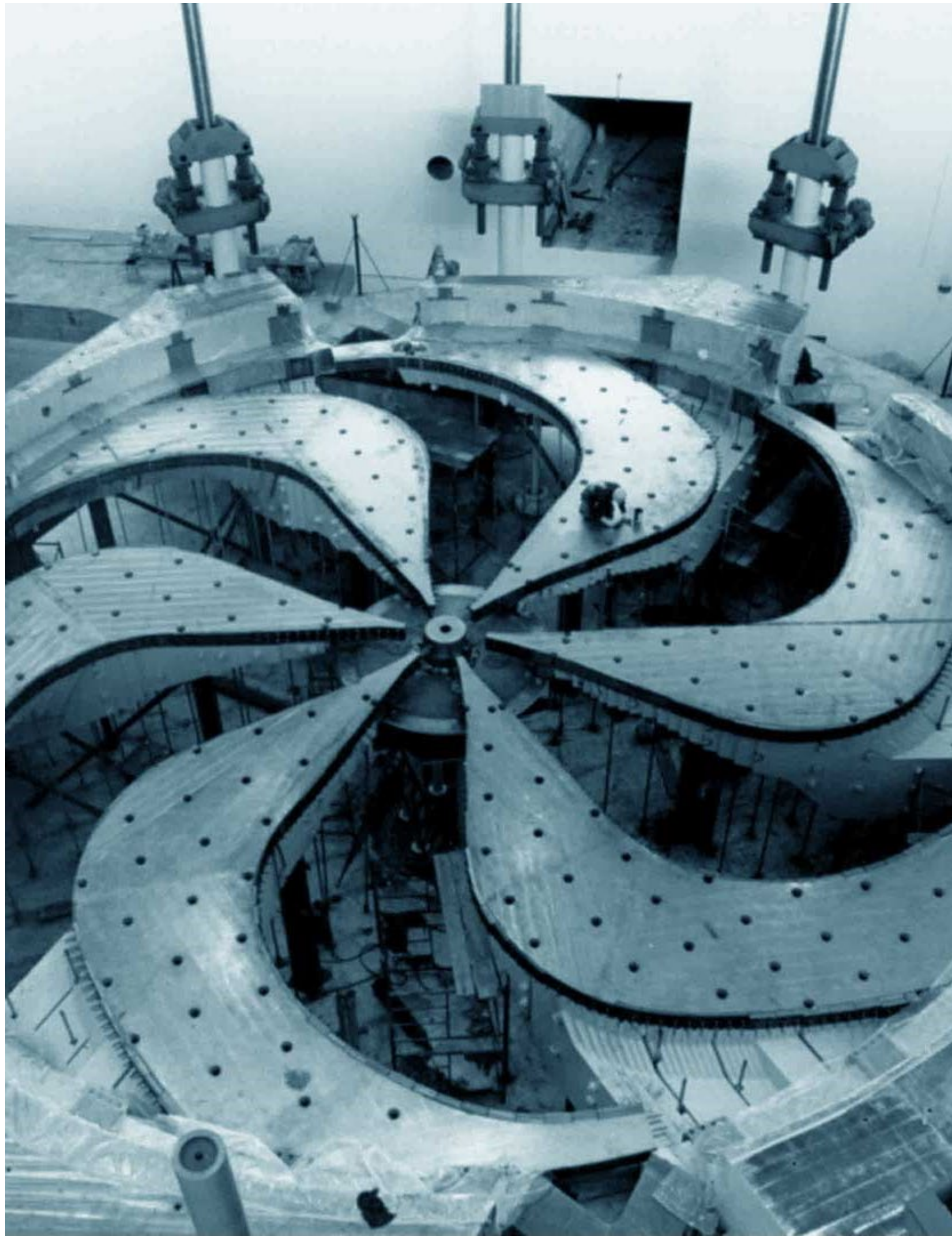
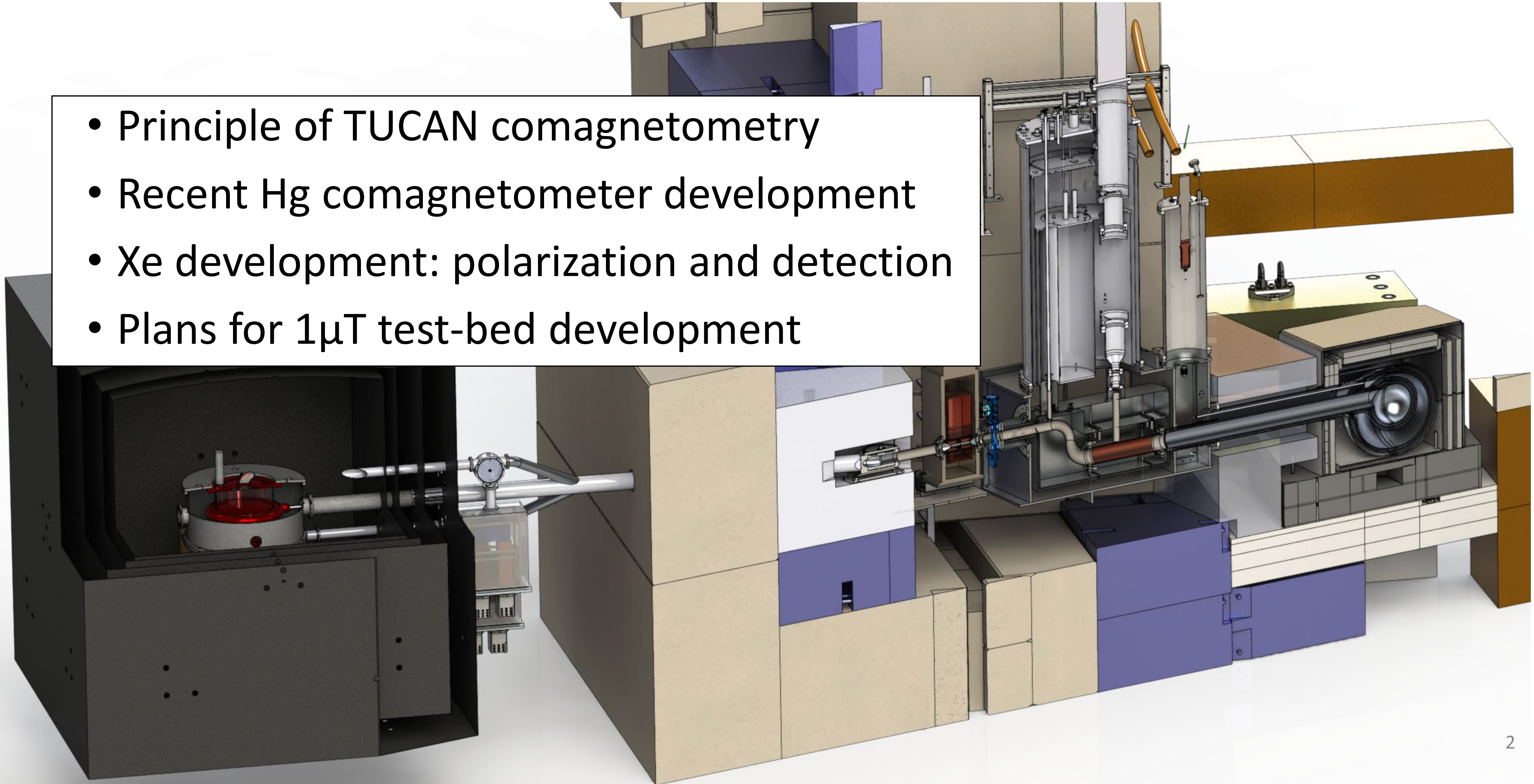
(laser-based) Co-magnetometry
for the TUCAN nEDM measurement

Eric Miller



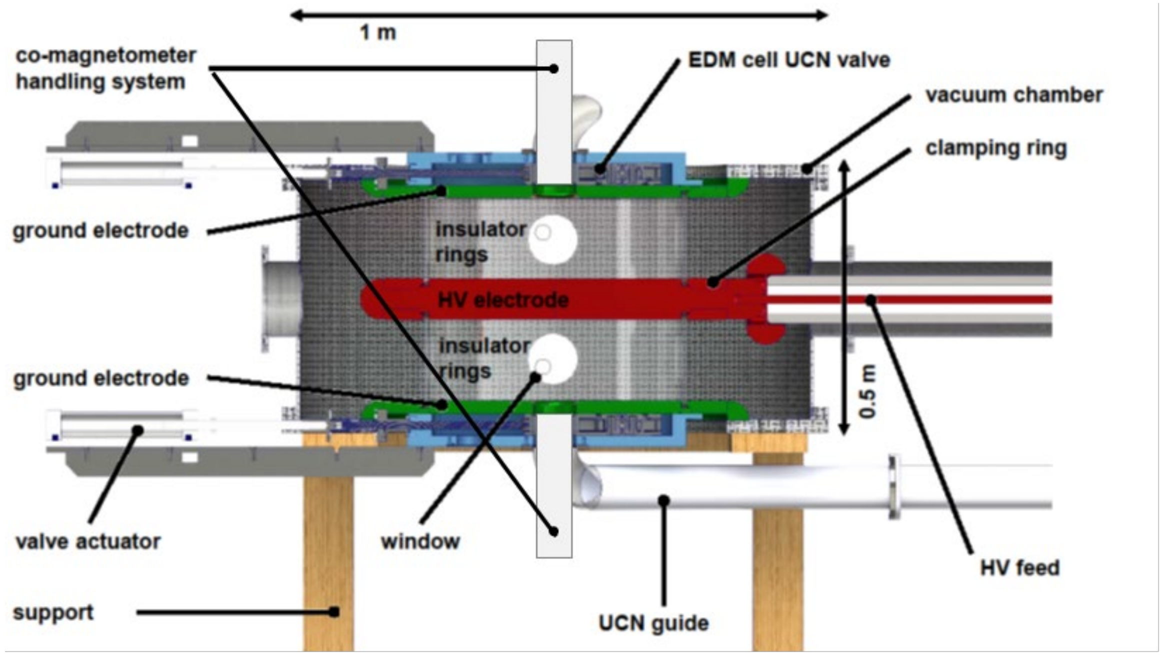
Overview

- Principle of TUCAN comagnetometry
- Recent Hg comagnetometer development
- Xe development: polarization and detection
- Plans for 1μT test-bed development



Principle

- **Phase I:** two vertically-stacked 12-16cm cells, both with ^{199}Hg comagnetometry & external Cs magnetometers
- Make use of all available gradient information, including:
  - external Cs magnetometers → **W. Klassen**
  - Hg gradiometer measurements at zero HV
  - *R* crossing-point analysis



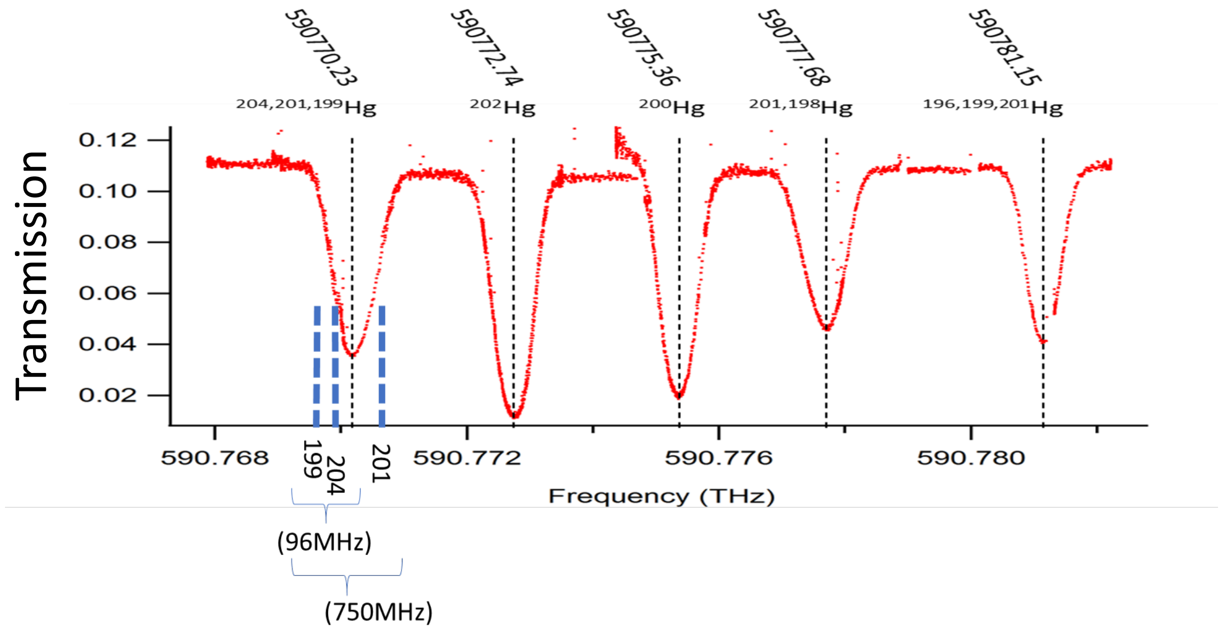
- **Phase II:** dual Hg/Xe comagnetometry
  - Utilize v×E → extract gradient

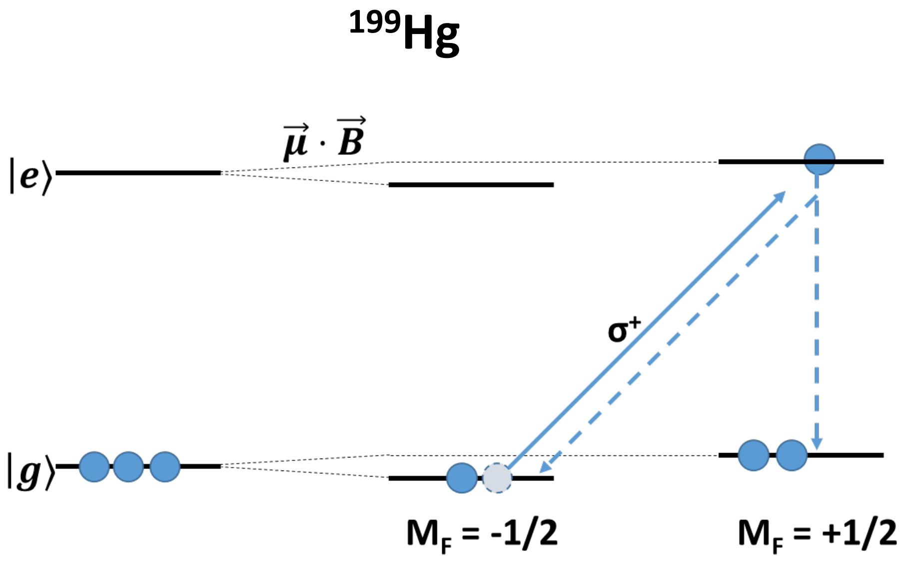
$$B_{0z} = \frac{\gamma_{\mathrm{Xe}}^2 \omega_{\mathrm{Hg}} - \gamma_{\mathrm{Hg}}^2 \omega_{\mathrm{Xe}}}{\gamma_{\mathrm{Xe}}\gamma_{\mathrm{Hg}}\left(\gamma_{\mathrm{Xe}} - \gamma_{\mathrm{Hg}}\right)\left(\frac{1}{2c^4}\gamma_{\mathrm{Xe}}\gamma_{\mathrm{Hg}} R^2 E^2 + 1\right)}$$

$$\frac{\partial B_{0z}}{\partial z} = \frac{2c^2\left[\gamma_{\mathrm{Xe}}\left(\gamma_{\mathrm{Xe}}^2 R^2 E^2 - 2c^4\right)\omega_{\mathrm{Hg}} - \gamma_{\mathrm{Hg}}\left(\gamma_{\mathrm{Hg}}^2 R^2 E^2 - 2c^4\right)\omega_{\mathrm{Xe}}\right]}{\gamma_{\mathrm{Hg}}\gamma_{\mathrm{Xe}} R^2\left[\gamma_{\mathrm{Xe}}\left(\gamma_{\mathrm{Hg}}^2 R^2 E^2 - 2c^4\right) - \gamma_{\mathrm{Hg}}\left(\gamma_{\mathrm{Xe}}^2 R^2 E^2 - 2c^4\right)\right]}$$

Our approach so far…

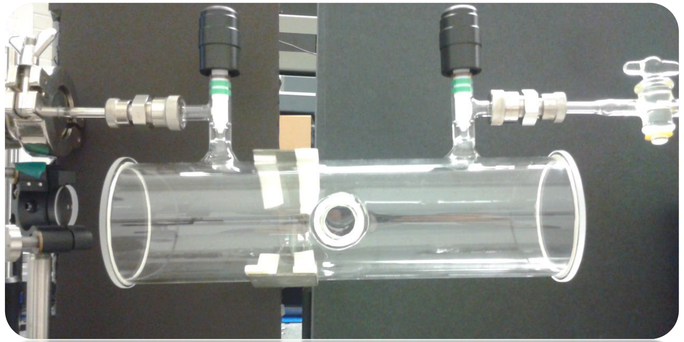
- We don't yet have an MSR or an EDM cell…
- Hg development started with spectroscopy, polarization and NMR in realistic-sized cells at high field (>200µT), using natural abundance Hg

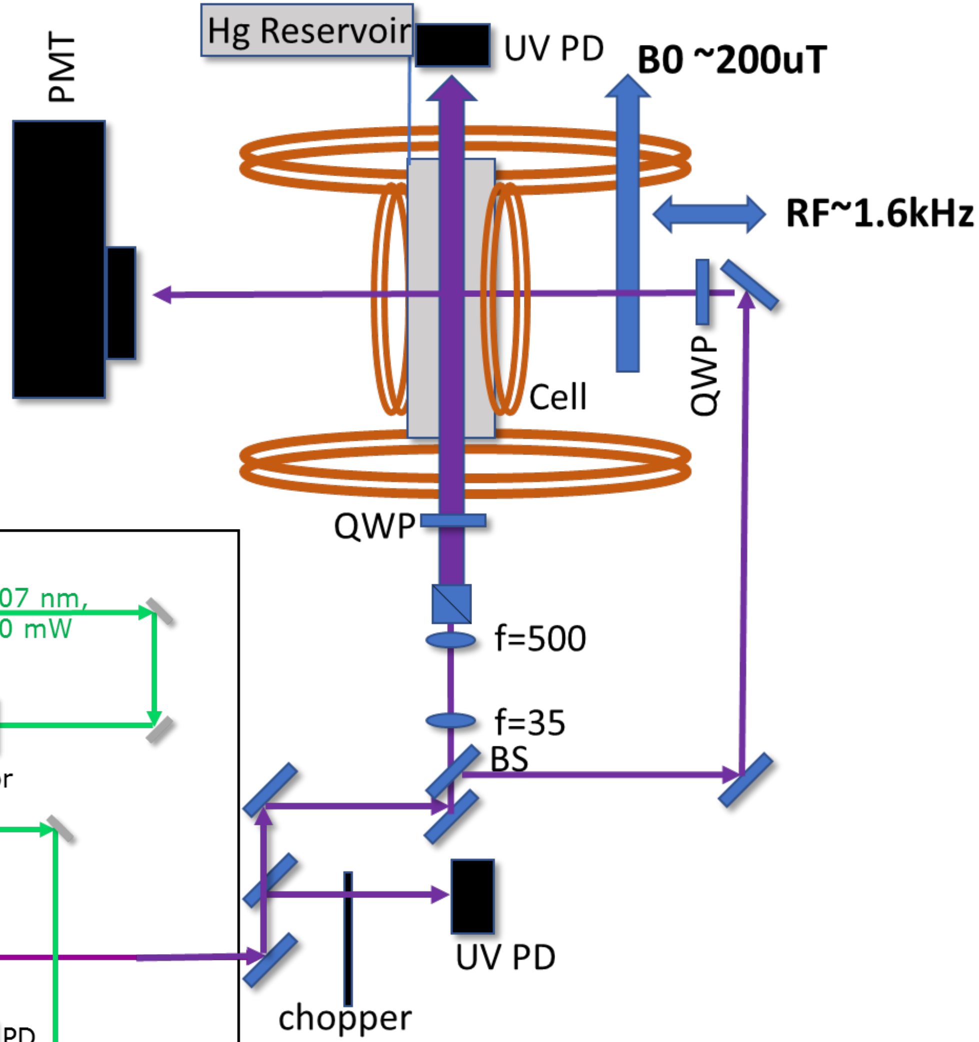


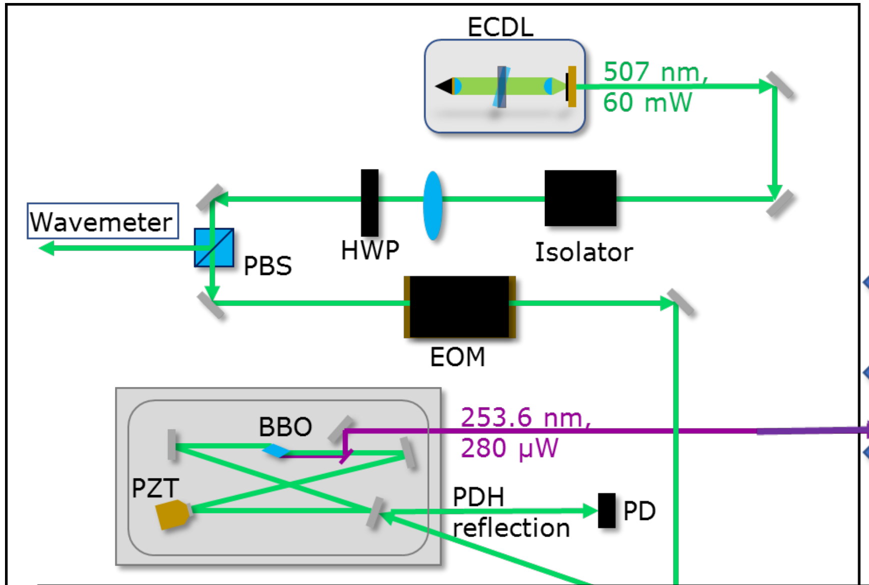


Hg Apparatus

- Prototype: ECDL laser + BBO doubling cavity @254nm provides pump and probe light (= 10-100µW UV), wavemeter stabilized < 2MHz
- Free-space B_0 coils (Helmholtz)
- Hg cell (70mm ID x 200mm) based on prepolarizer dimensions
- natural abundance Hg from a metal bead, controlled vapour to $n_{Hg} = 10^{11}$ cm^{-3}, for ~50% absorption



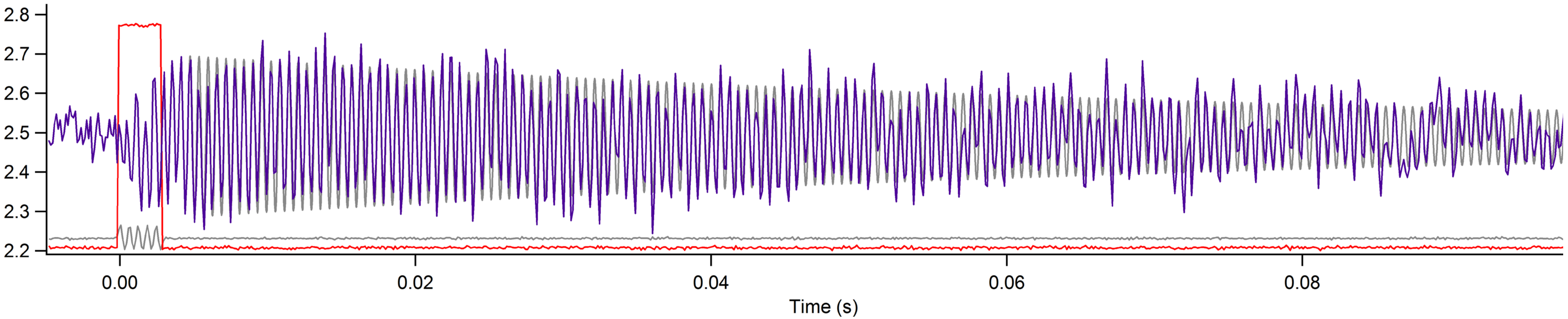




- Crossed pump & probe beam configuration allows optical pumping, T_1 & T_2 tests, Rabi flopping, AFP

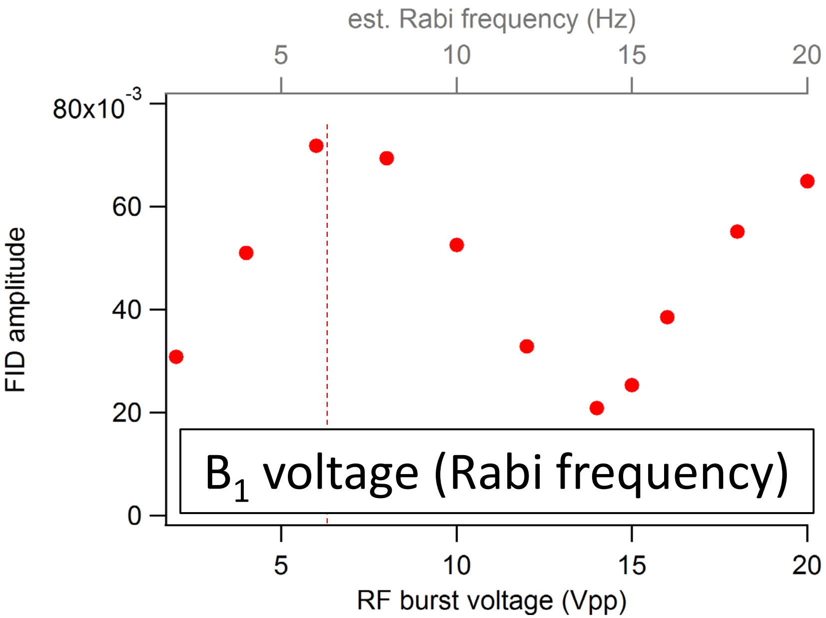
→ Soon to be replaced by TOPTICA FHG to improve UV power stability

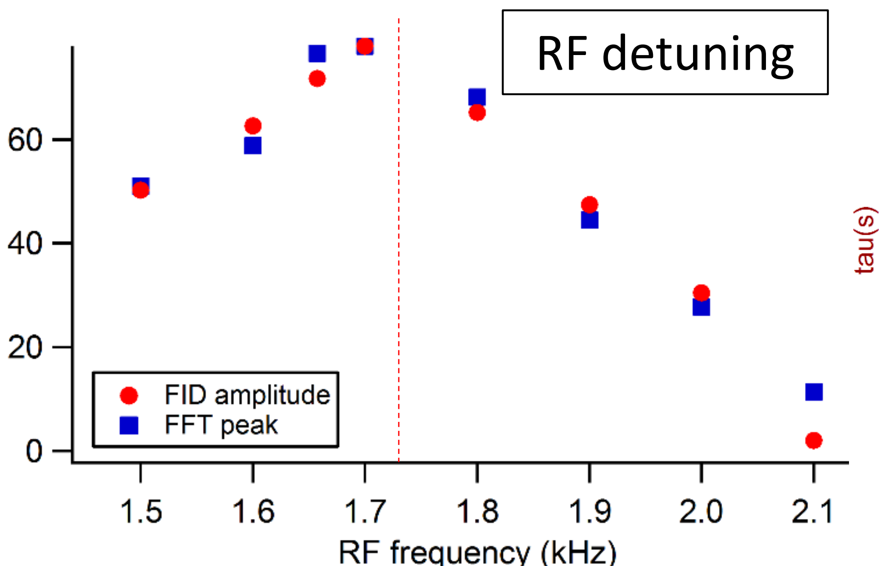
^{199}Hg precession: T_2, $\pi/2$

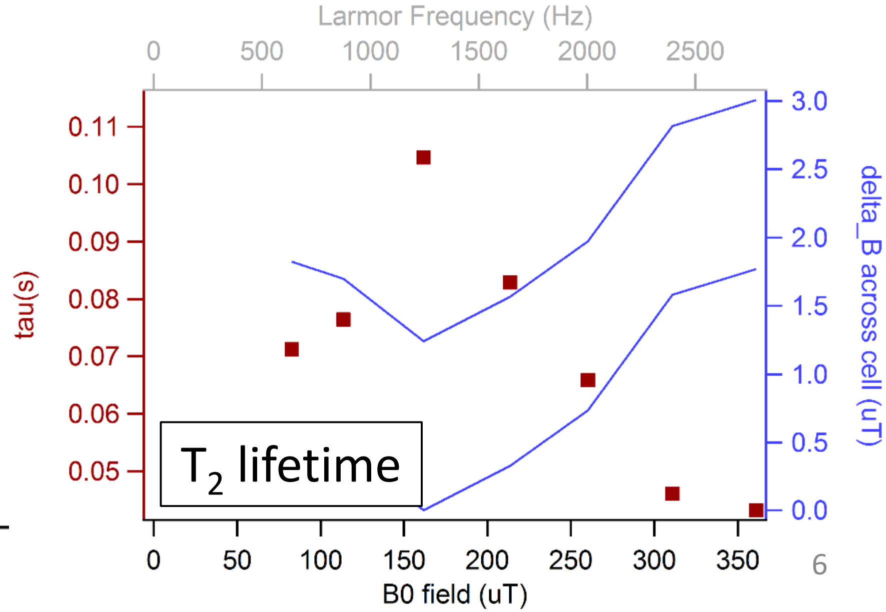


Obtained ^{199}Hg FID signal at ~200µT with n=100 averages

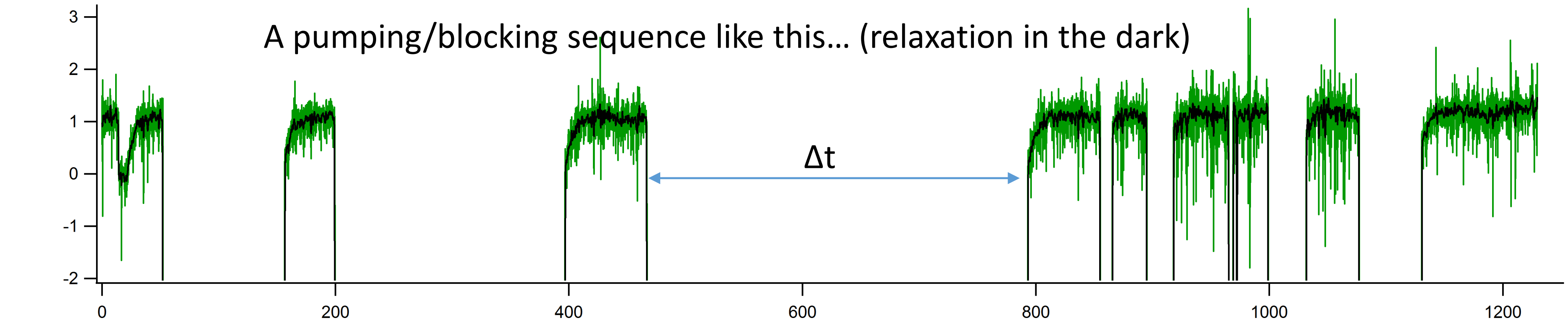
Study the dependence on $\pi/2$ pulse parameters and on inhomogeneous B_0 field:

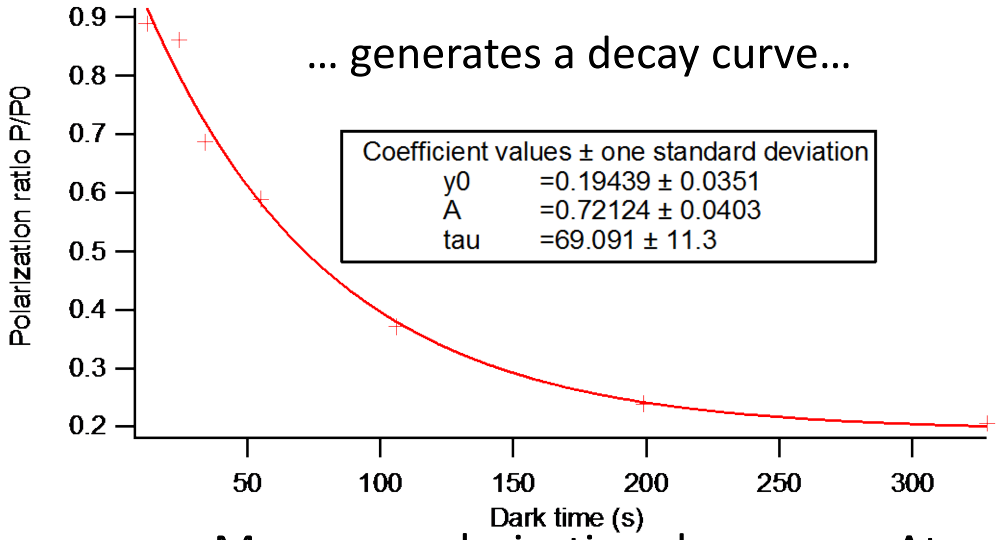


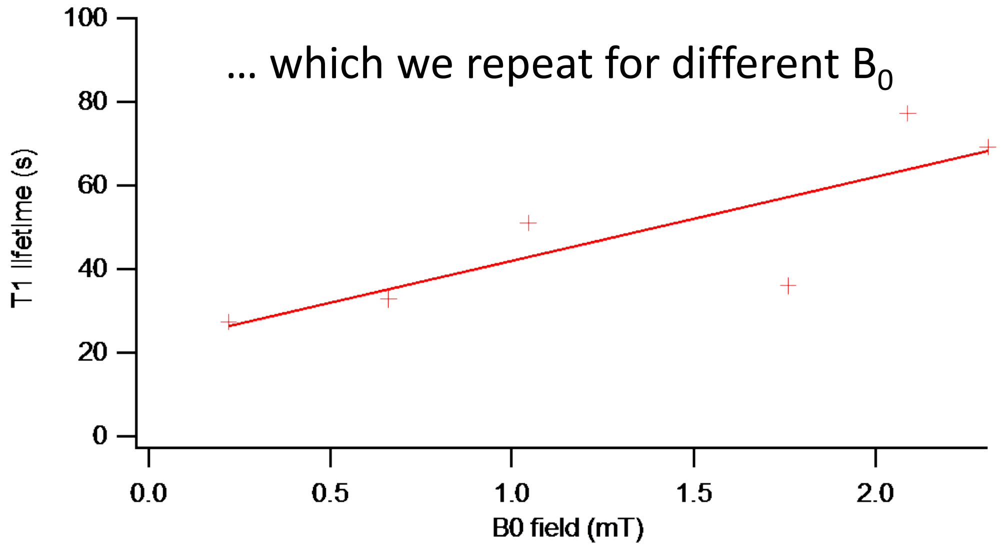




T_1 lifetime vs B_0 field

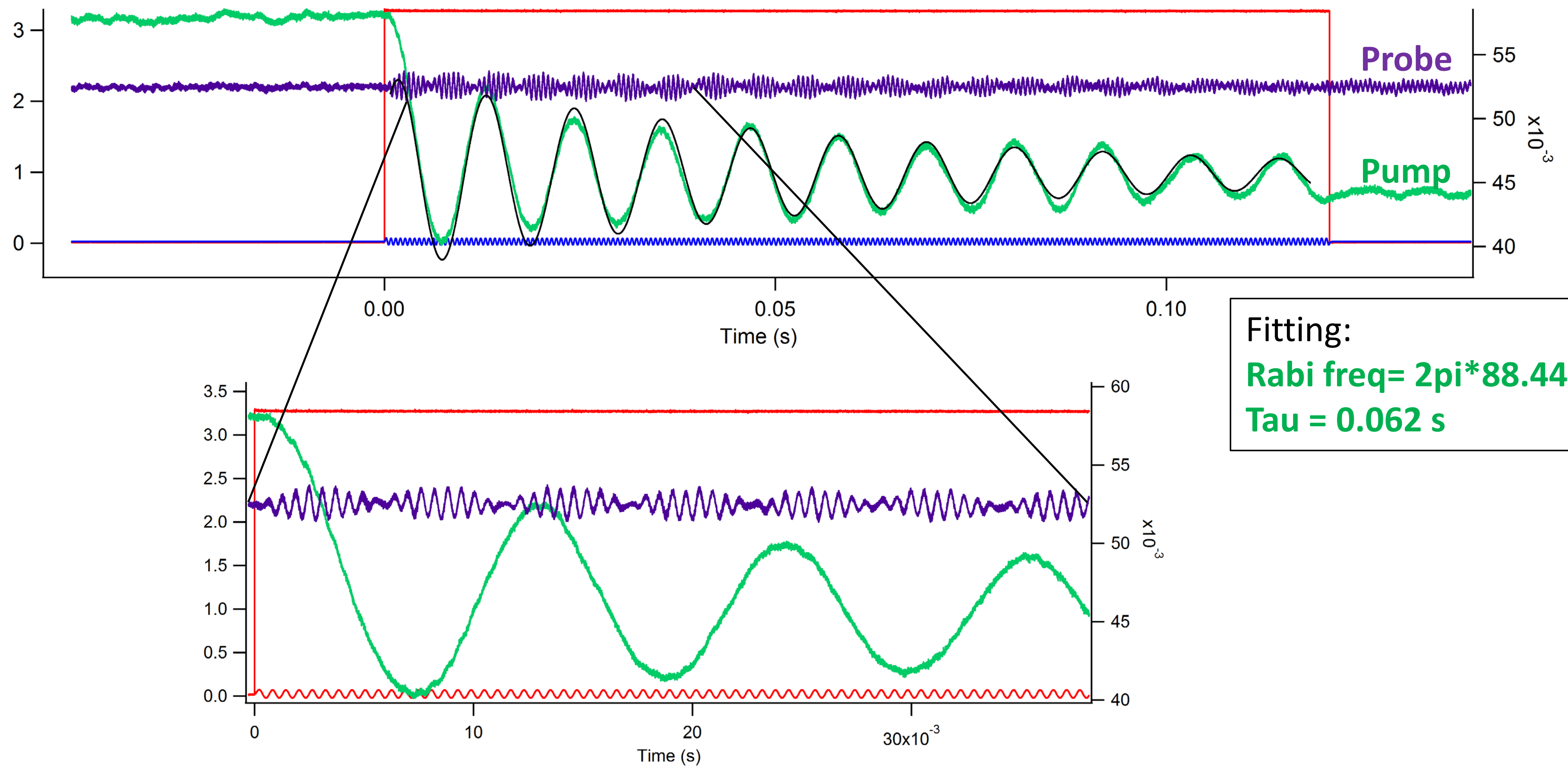






- Measure polarization decay over Δt
- T_1 = 25~80s at 200µT - 2mT in an <u>uncoated</u> cell
  - Goal : test wall coatings at low field (e.g. T_1=58s estimated at 1µT for Surfasil)

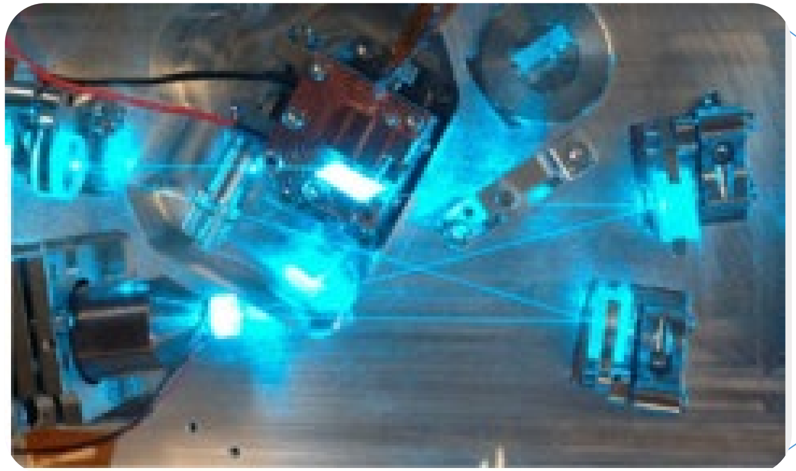
Rabi Flopping

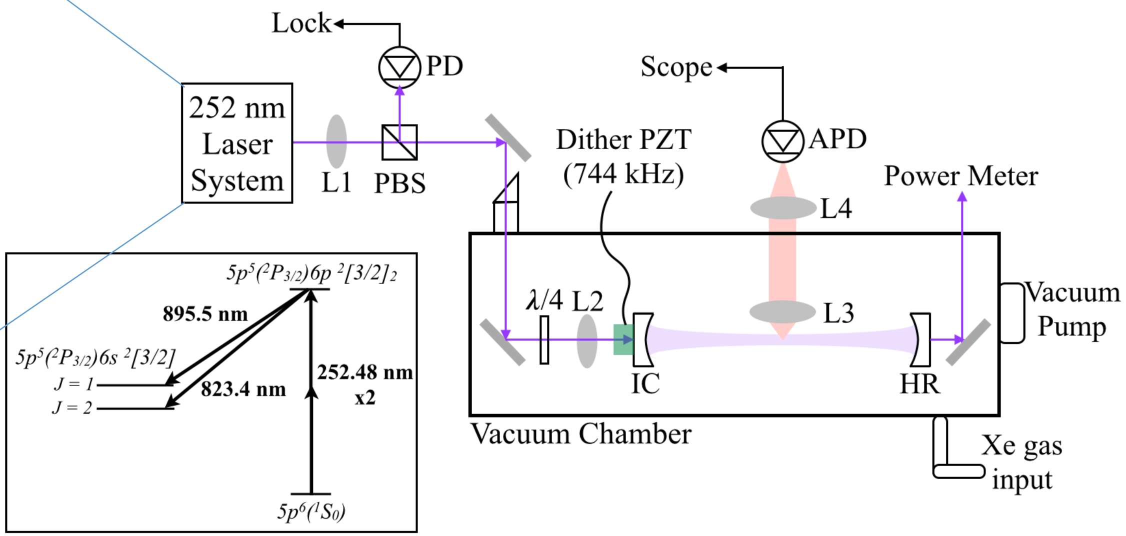


Fitting:
Rabi freq= 2pi*88.44 Hz
Tau = 0.062 s

- Another method of determining Rabi frequency & exact π/2 pulse
- 200-cycle RF burst, (100 averages)

Xenon: Detection



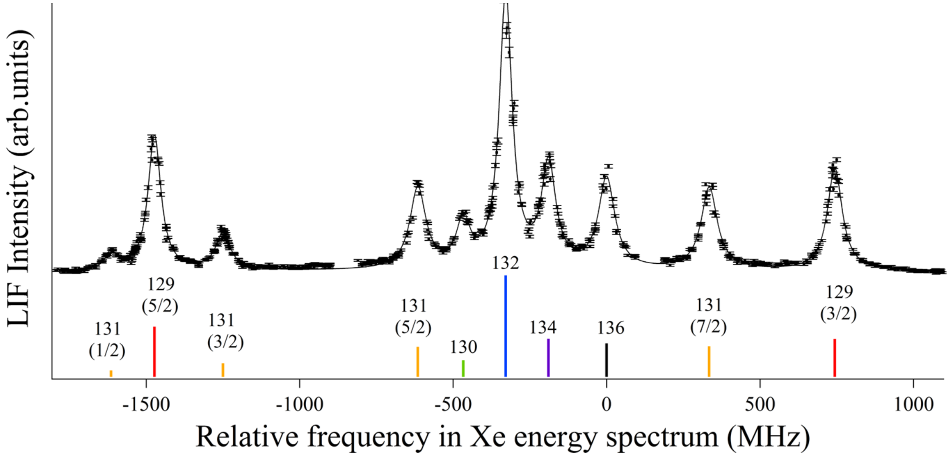


We have achieved optical detection of ^{129}Xe:

(**E. Altiere thesis, 2019; E. Miller thesis, 2018**)

- using 252nm two-photon excitation and 823nm fluorescence
- in natural abundance Xe, down to 15mTorr
- Frequency-quadrupled, optically pumped semiconductor laser, up to 400mW narrow-linewidth UV
- Goal for comag use: ~1-10mTorr (isopure)

Ongoing work to determine the Xe HV breakdown voltage limit in this pressure range: promising first results from initial data taking



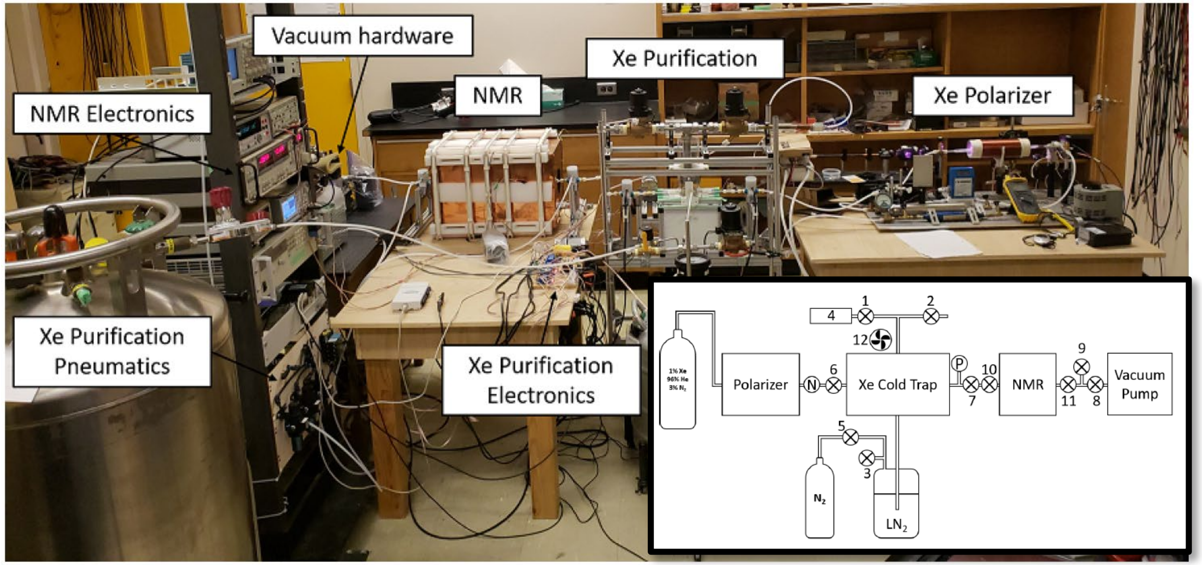
E. Altiere, E. Miller, T. Hayamizu, D. Jones, K. Madison, T. Momose, Phys. Rev. A. 97, 012507 (2018)

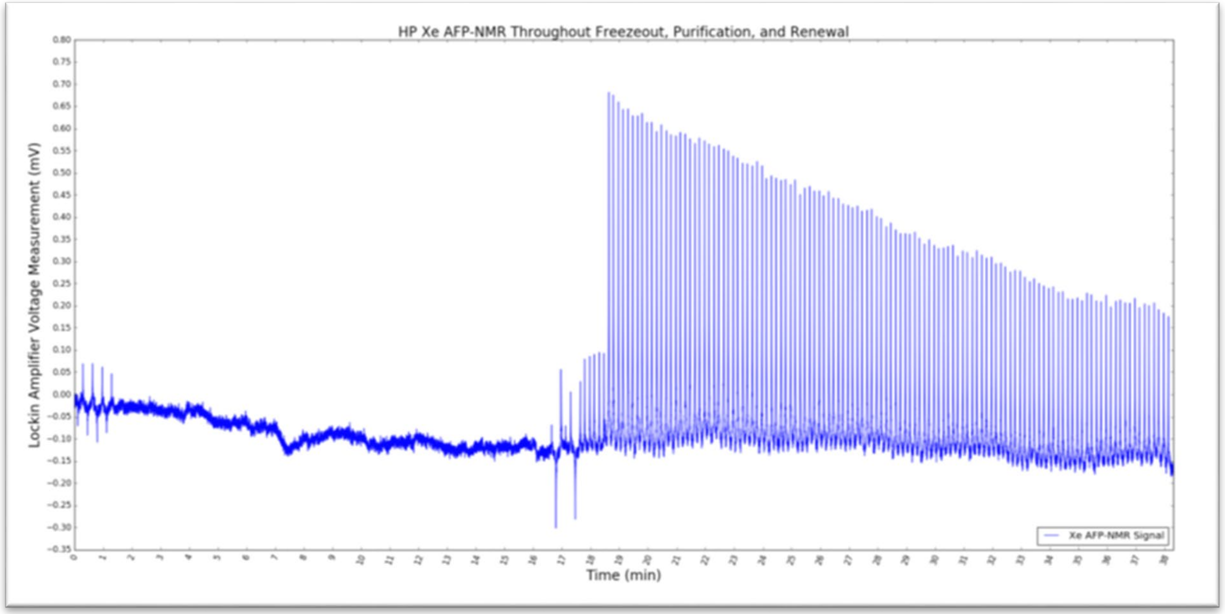
Xenon: Polarization

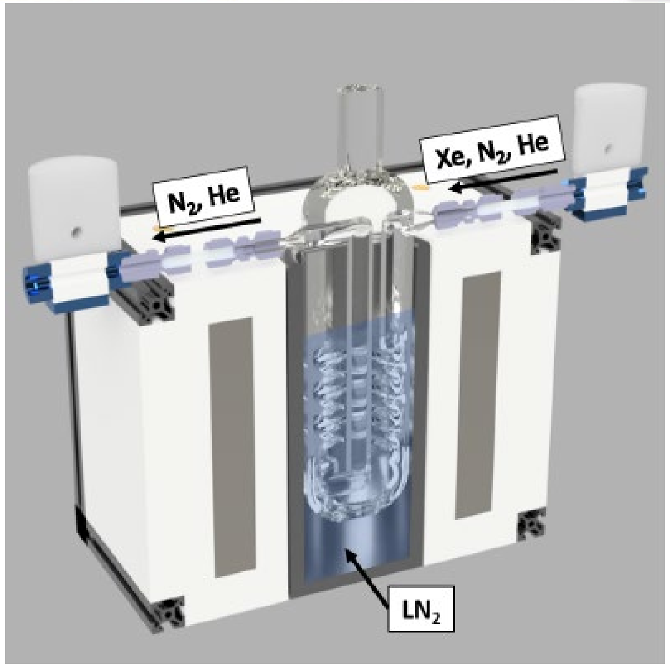
We have developed an automated ^{129}Xe polarizer and freezeout system

(**M. Lang thesis, 2019**)

- $P_{Xe} \approx 25\%$ polarization in spin exchange optical pumping (SEOP) prototype
- Up to 80% efficient freezeout and recovery of polarized ^{129}Xe from SEOP gas







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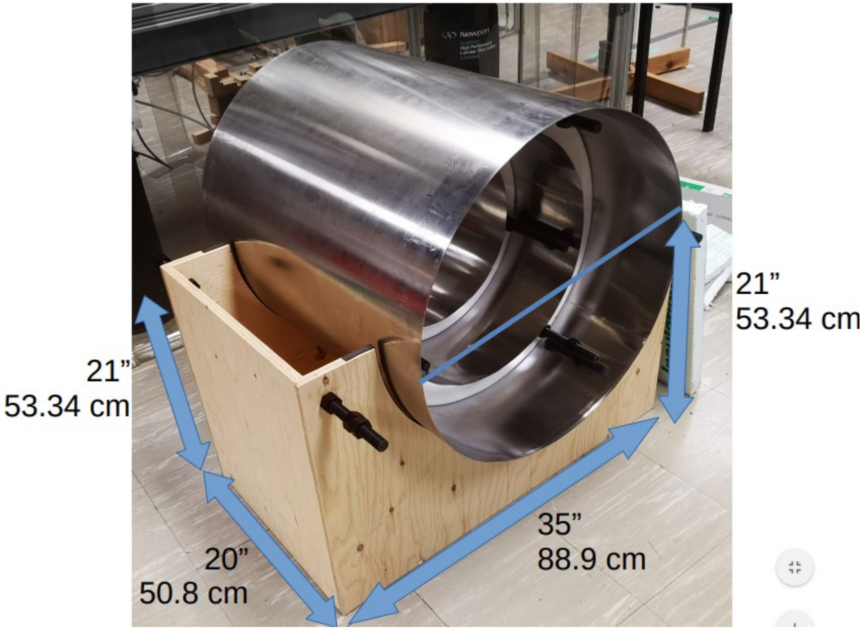
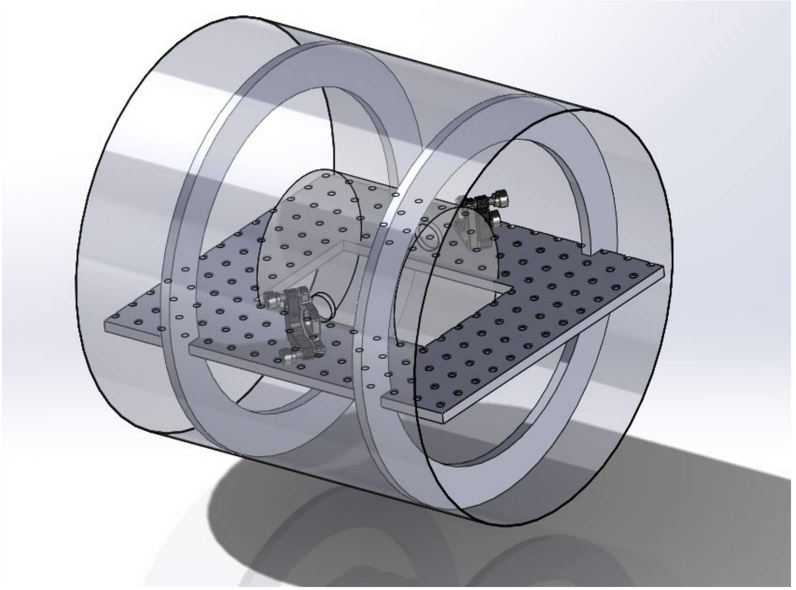
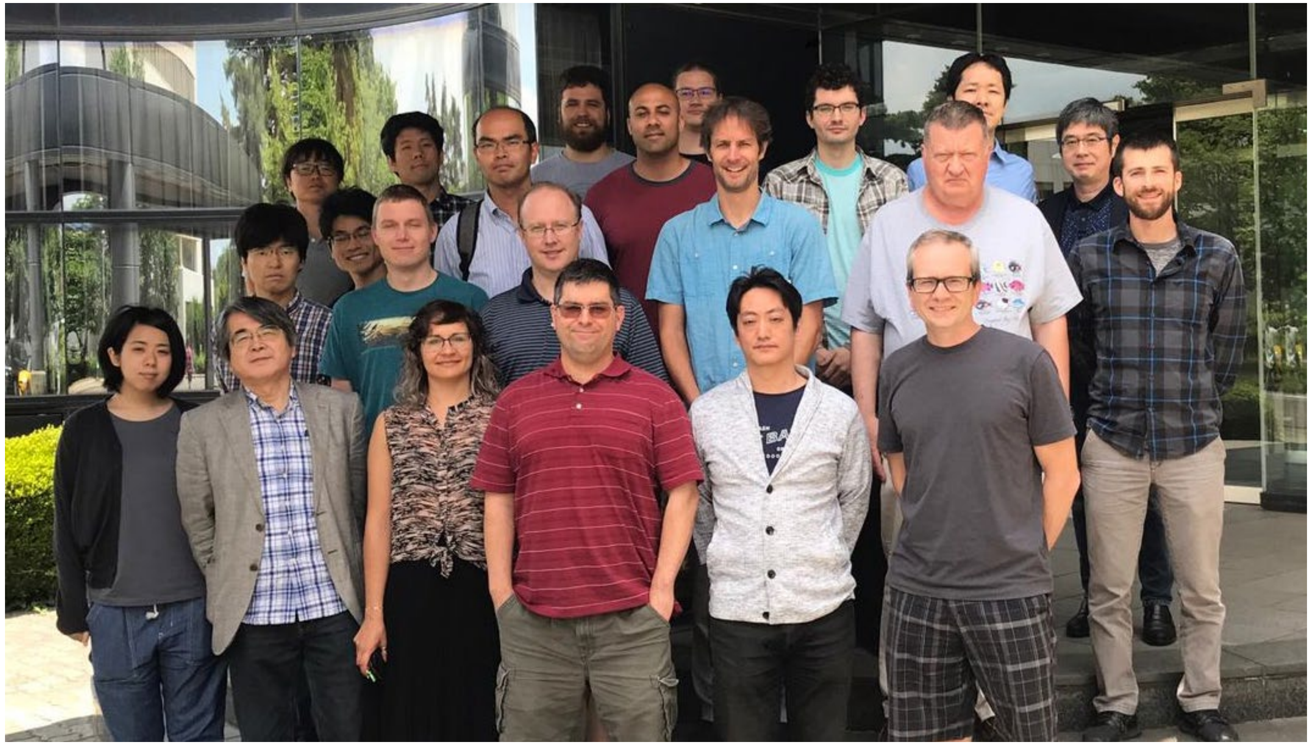
Next: 1μT tests in Magnetic Shield

- Plan: single cell inside repurposed cylindrical shield
  - **(S. Ahmed thesis 2019)**
  - SF = 10^6 for 4-layer, we will use 3-layers for $>10^4$
  - Quantify the effects of wall collisions & gradients using different cell sizes. (prepol. cell or slightly larger)
- 1μT operation using a solenoidal-wound coil
  - https://doi.org/10.1016/j.nima.2019.162837
  - Field uniformity = 1% (est.) e.g. 10 nT/30 cm
- Develop a ^{199}HgO-based vapour source





What's to be studied/demonstrated:
  Uniform B_0 at 1μT
  Long FID times
  Wall coating effect on relaxation (Surfasil)
What's not: (i.e, later…)
  Hg transfer between prepolarizer & EDM cell
  Hg valve operation



Questions?