Comagnetometer Status

Eric Miller

Current Members:
UBC: T. Momose, E. Miller
(W. Klassen, starting PhD Sept)
U.Winnipeg: M. Lang

07/02/2020

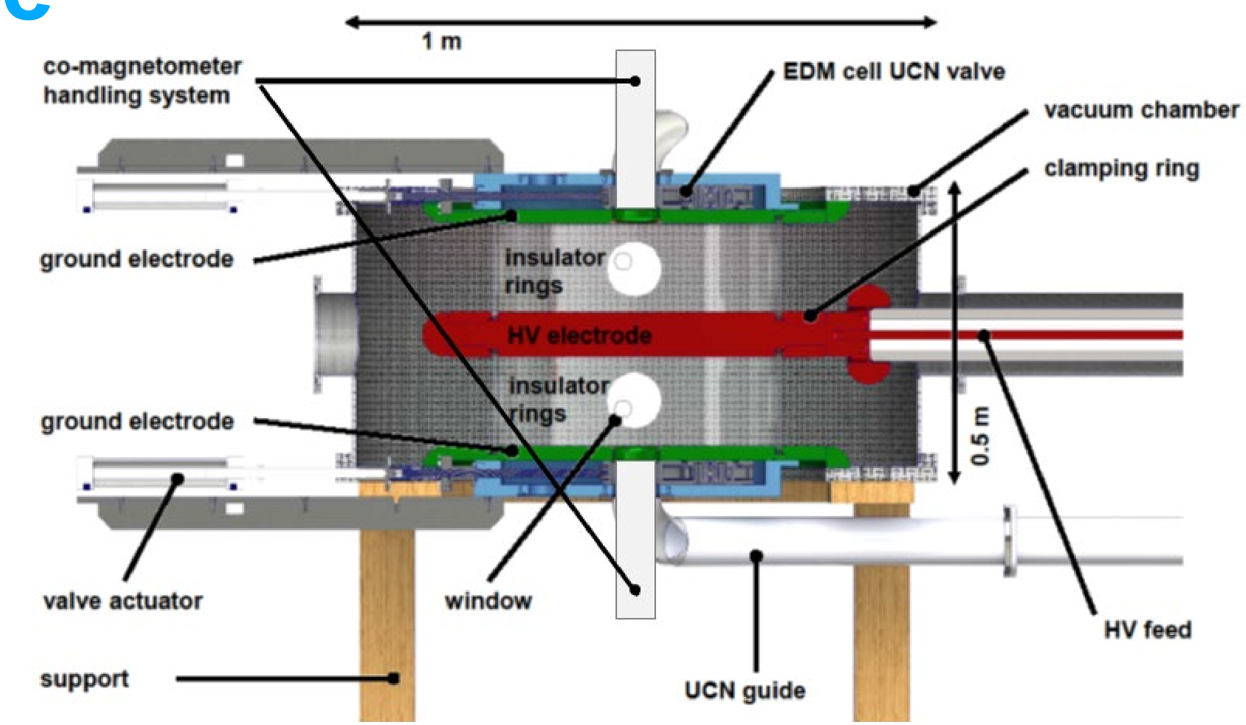
Discovery, accelerated

Goals/Requirements

Goal: Calculate the **volume-and time-averaged** magnetic field **B_0** from ^{199}Hg precession frequency to correct the neutron precession frequency for B-field drifts.

RS 3.-28	The Hg comagnetometer shall be capable of measuring a 1 μT magnetic field to a precision of **10 fT over 100s**
RS 3.-30	The comagnetometer systems shall not introduce total systematic uncertainty of more than **0.1×10^{-27} e·cm** into the nEDM measurement due to systematic uncertainty in the comagnetometer frequency.
RS 3.-33	Development of the comagnetometer shall be completed in the timeframe given by the Level 1 schedule shown in Document-154393. Critically this specifies **installation of all hardware by ~~2021~~ 2023 at TRIUMF.**

Technique



Phase I: following established technique

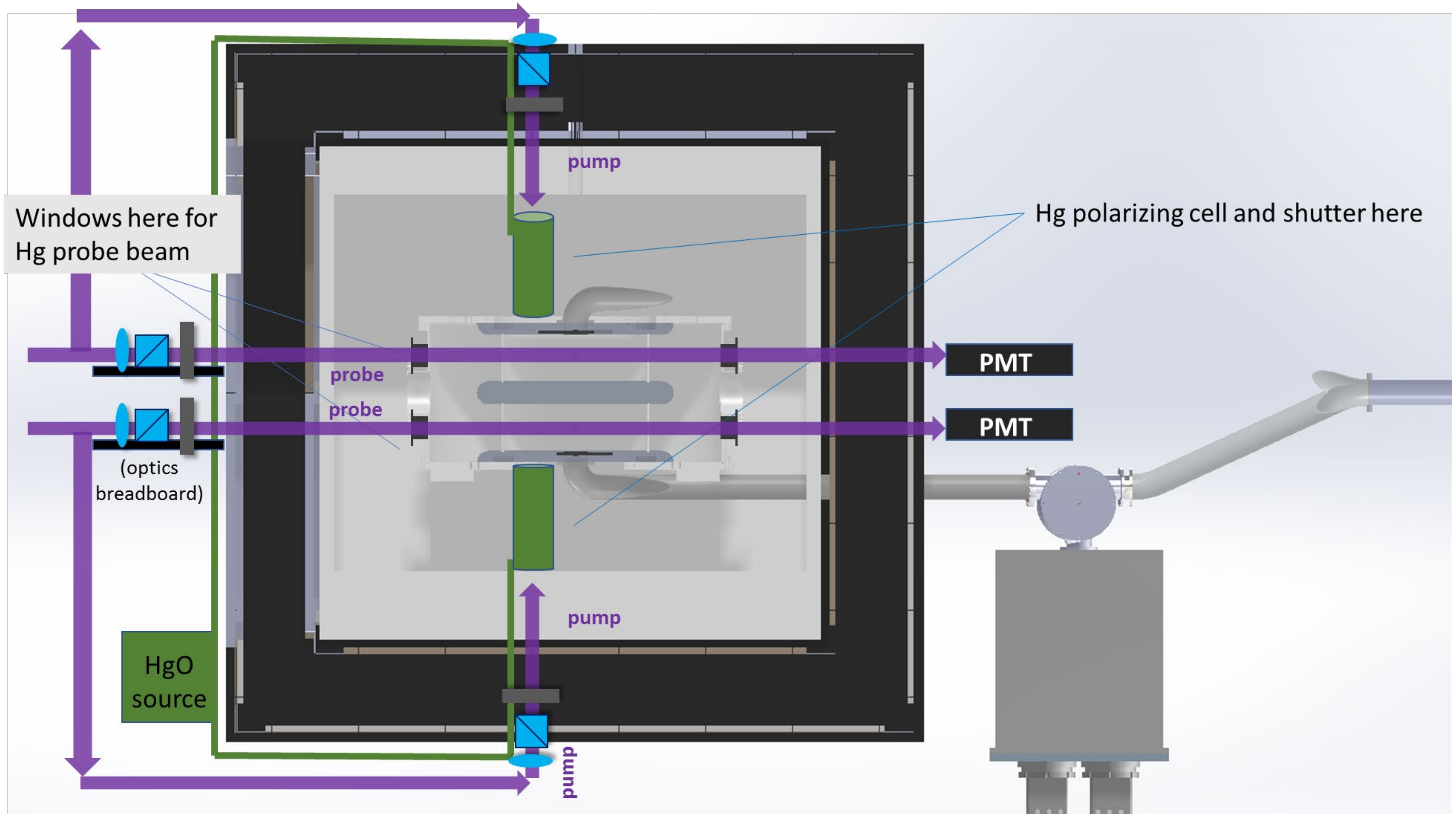
- ^{199}Hg comagnetometer + crossing-point analysis
- 2x Hg polarizing cells, 2x nEDM cells
- Baseline: lamp pump & laser probe; also testing the feasibility of laser-based pumping

Phase II: ^{199}Hg + ^{129}Xe dual comagnetometry

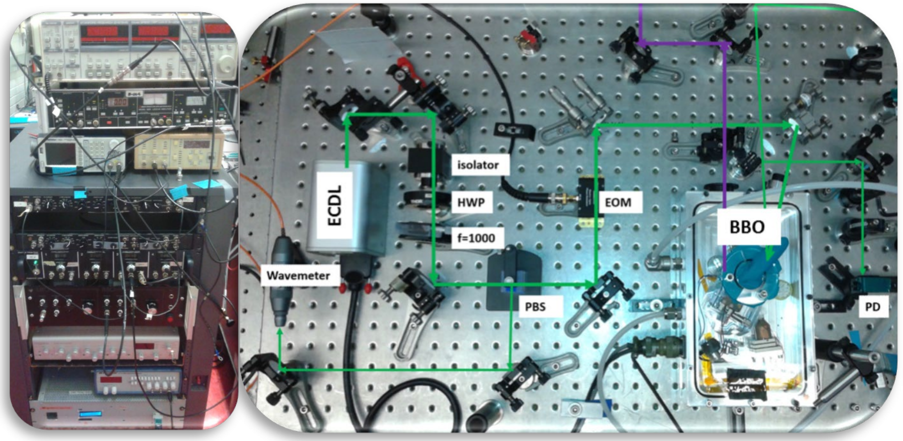
- Direct determination of $\frac{\partial B_z}{\partial z}$
- Subject to R&D readiness & budget

Potential layout

Starting to specify interfaces: MSR holes, vacuum connections, etc



Hg Laser Development

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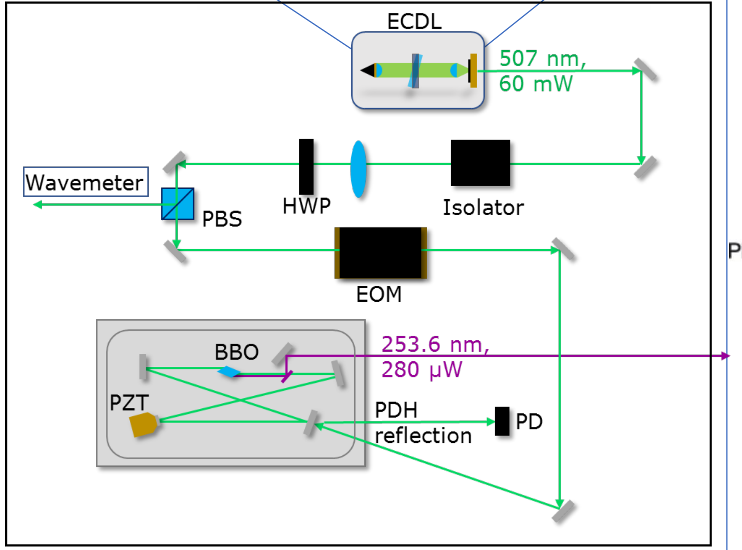
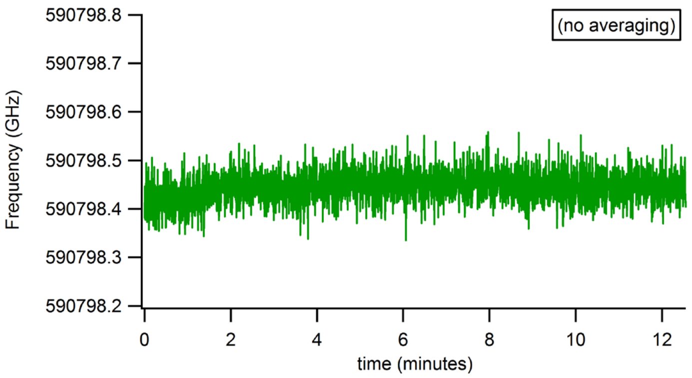
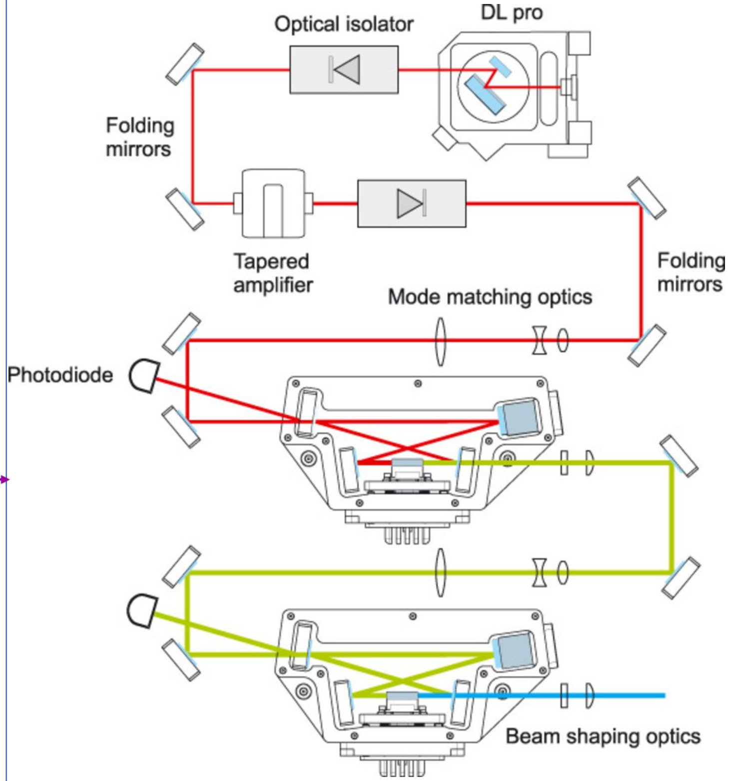


- R&D laser: **Generate UV light to pump/probe ^{199}Hg**
  - External cavity diode laser (ECDL, 60mW, 507nm) and second-harmonic generation (SHG)
  - Stability: <200MHz (free-running)
  - Lock time > 15 min
  - **>280 μW UV** produced:

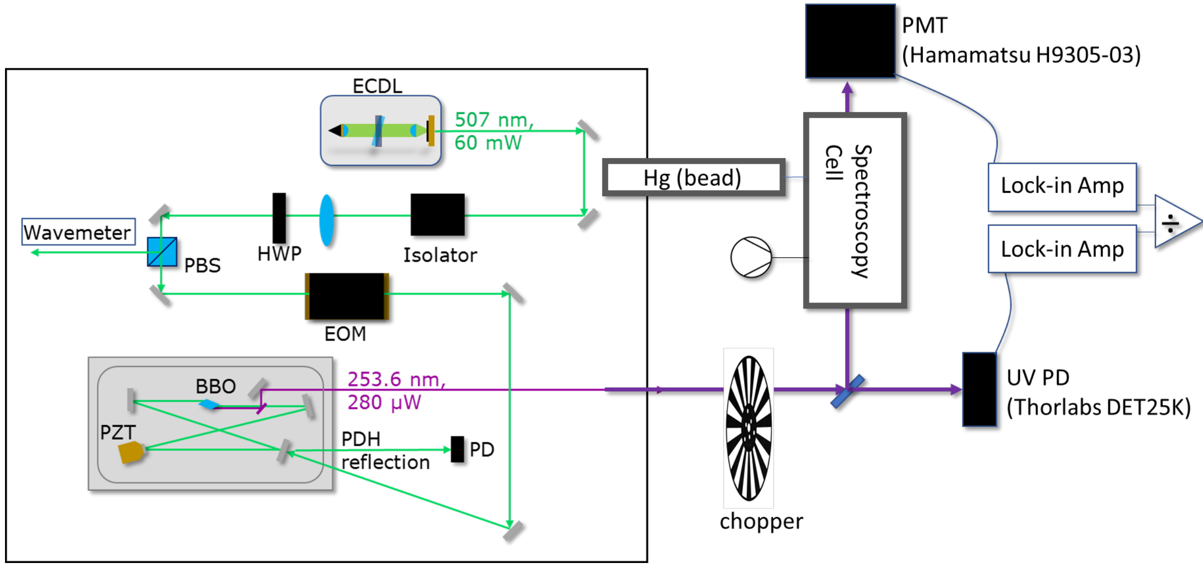
    (5-20μW required per cell for Hg optical pumping)
- **Pursue initial tests** (pumping/precession) with this laser
- Budget includes a commercial system (frequency-quadrupled Toptica TA-FHG) for **turn-key operation**

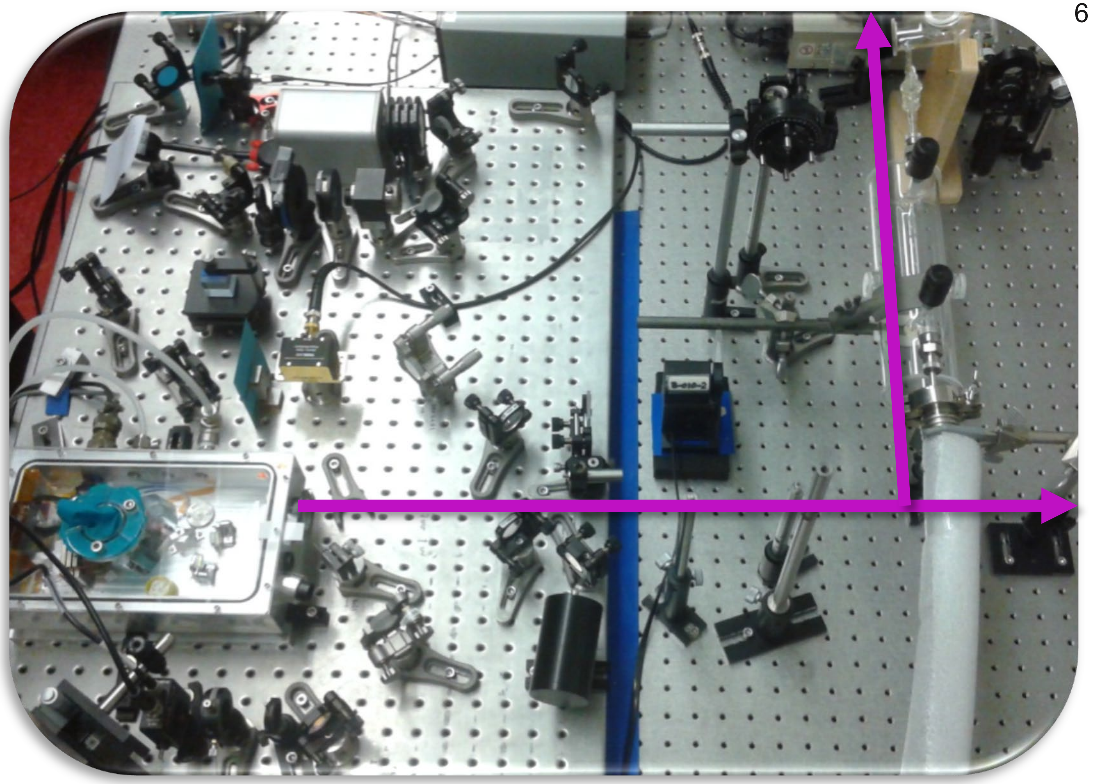


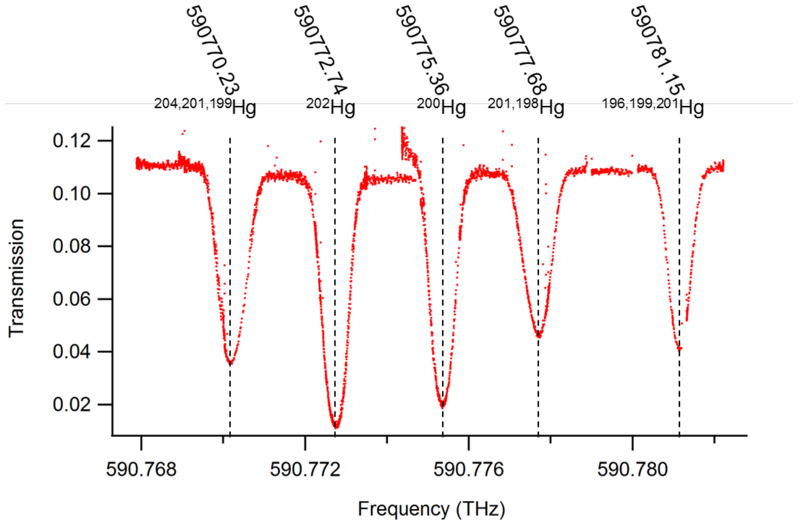
Commercial FHG



Hg Spectroscopy



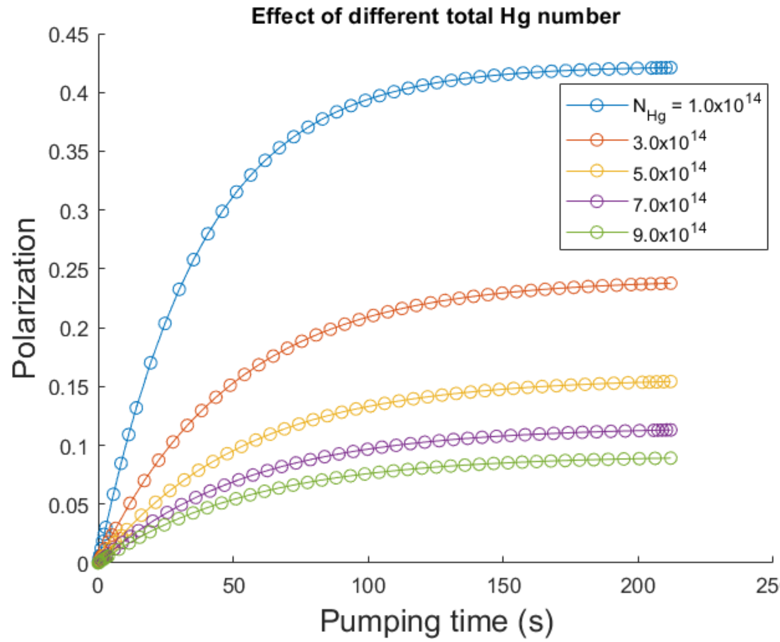




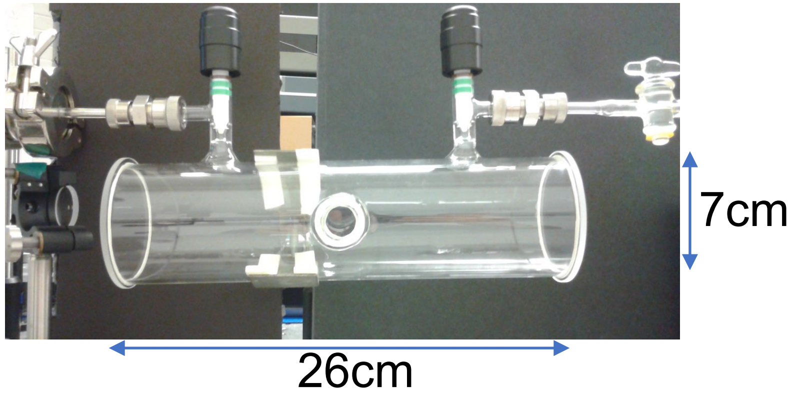
- Detection setup for transmission spectroscopy
- PMT transmission signal normalized to PD using optical chopper & lock-in detection
- Natural abundance, n=5x10^{11}cm^{-3}
  - comparable with ~$n_{199Hg,prepol.}$ in polarizing cell
  - cf. $n_{199Hg,precess.}$ ~3x10^{10}cm^{-3} in nEDM cell
- Doppler-broadened peaks FWHM ~1 GHz means different isotopes overlap

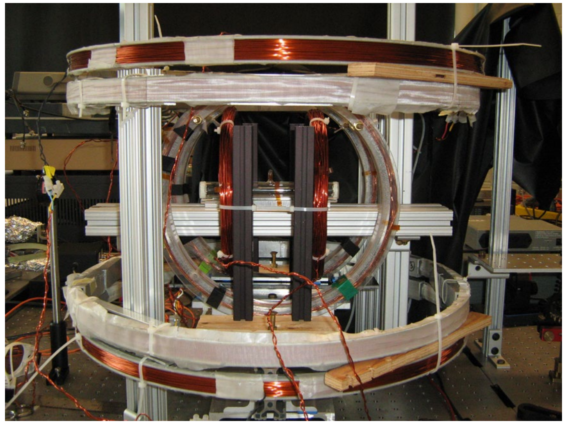
Hg: Optical Pumping

- Polarization P_{Hg} ~ 40% predicted from simulation (eqn. from ETH thesis, M. Fertl)
    - Pump source: laser, >5uW
    - 1.2 L polarization test cell (26cm L x 7cm ID)
    - We will test the performance (relaxation) of Surfasil coating polarization cell
- Initial tests will be with Hg pump & probe in same cell.
- Design work started on Hg shutter **(S. Lan)**
- Hg source: we are currently using a metal bead; plan to switch to HgO to control vapour pressure.



$$\frac{dP(t)}{dt} = \frac{2}{3}\Phi\frac{1}{N}\left(\frac{1-P(t)}{1+\beta+P(t)}\right)\left(1-e^{-N\sigma(1+\beta-P(t))l_{pol}/V}\right) - \frac{P(t)}{N(t)}\frac{dN}{dt} - \Gamma_R P(t)$$





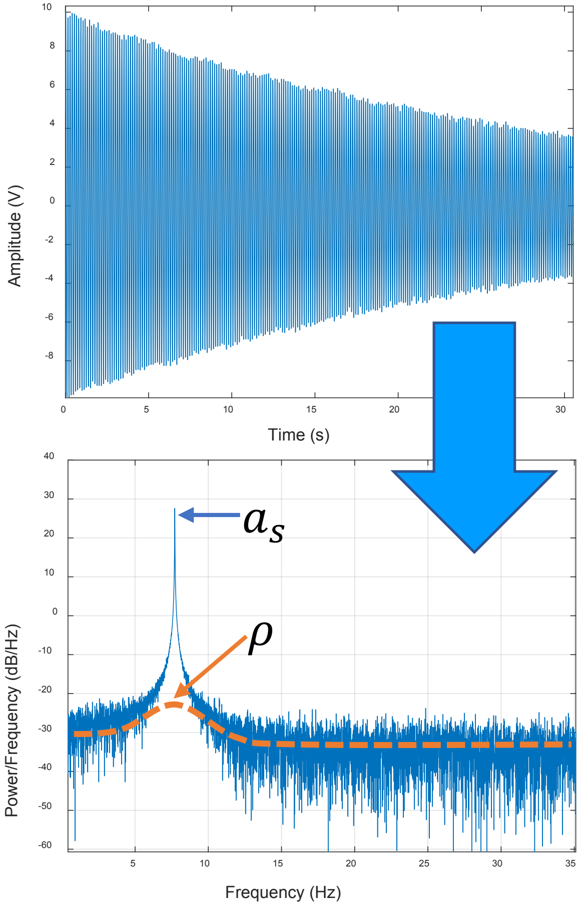
Sensitivity and Systematic Uncertainty

- 10 fT requirement depends on Hg signal to noise density ratio $\frac{a_s}{\rho}$ (SNDR) and depolarization lifetime τ: (Ban et al., NIMA 896 (2018) 129–138)

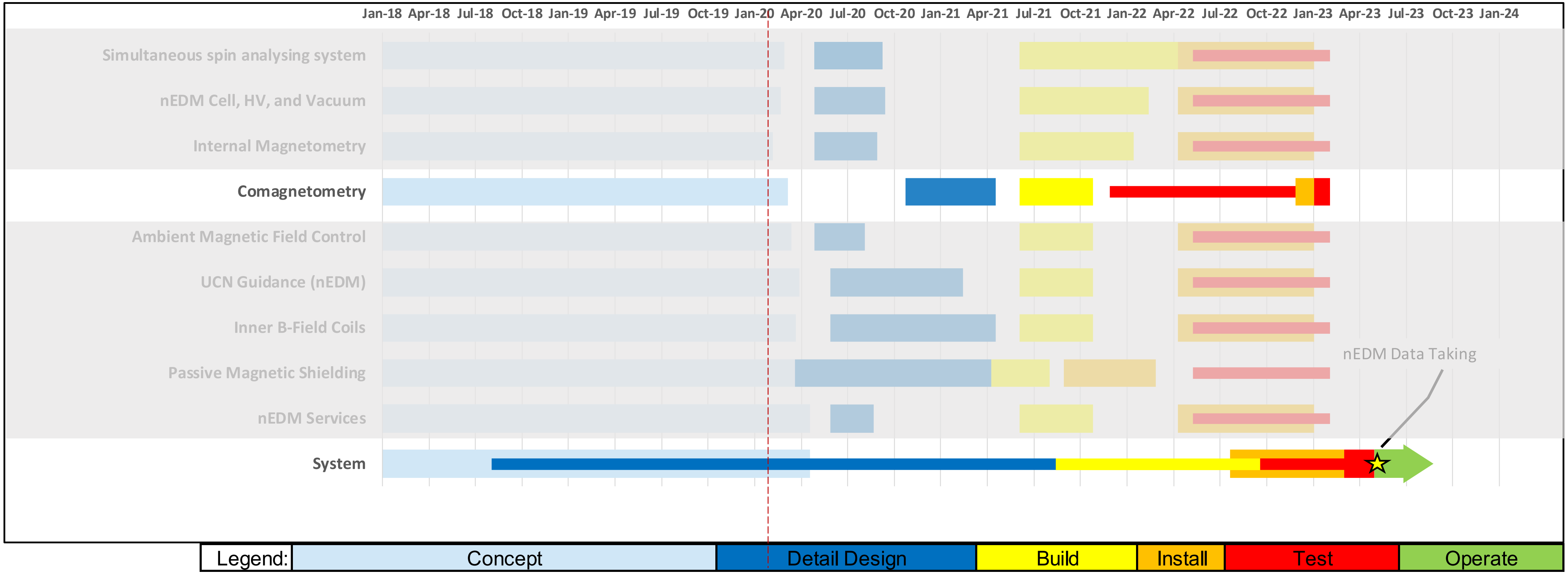
$$\delta B \geq \frac{\sqrt{12}}{\gamma_{\mathrm{Hg}} \frac{a_s}{\rho} T^{3/2}} \sqrt{C(r = T/\tau)}$$

δB target	T_{Ramsey}	$\tau_{\mathrm{depol,Hg}}$	SNDR $\frac{a_s}{\rho}$
10 fT	132 s	100 s	> 9300 V/V√Hz
10 fT	200 s	120 s	> 6400 V/V√Hz

- We’re starting to consider systematics in light of target 0.1×10^{-27} e·cm
  - (such that all systems total < 10^{-27} e·cm)
- ν_{Hg} light shift can be mitigated by laser stabilization
  - We will lock laser to a Fizeau-type wavemeter (HighFinesse WS8) with <<10MHz stability
- Will perform crossing-point analysis to limit GPE/motional false EDM effects
  - Cs magnetometers provide useful measurement of $\frac{\partial B_z}{\partial z}$



Hg Schedule



Milestones and estimated dates:

- ✓ Hg transmission spectra: **achieved Dec 2019**
- Lock laser (<10MHz) to wavemeter: **Feb 2020**
- Optical pumping tests with laser: **Apr 2020**
- HgO oven preliminary design with natural abundance HgO: **Aug 2020**

Also:

- Source & test ^{204}Hg lamp for baseline design.
- Free-spin precession (FSP) tests in high field (e.g. 1mT)
- Free-spin precession in 1μT field with model shield

Xenon Status

Phase II:

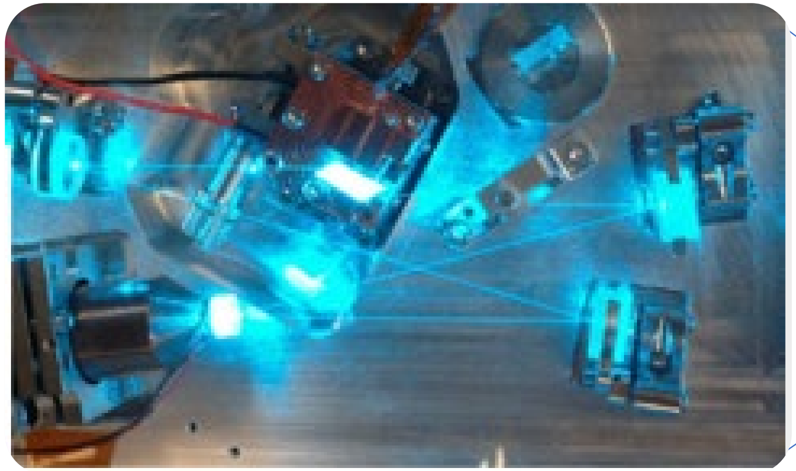
- There is a strong case for dual species comagnetometry using ^{199}Hg and ^{129}Xe
- Possible to measure magnetic field gradient $\frac{\partial B_z}{\partial z}$ directly without crossing technique

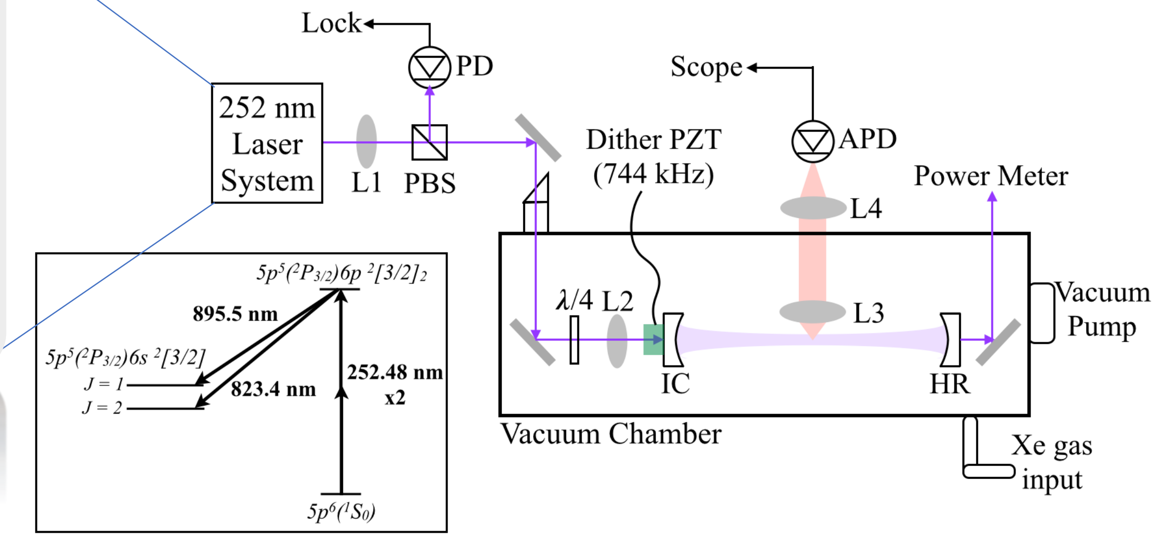
$$B_{0\mathrm{z}} = \frac{\gamma_{\mathrm{Xe}}^2 \omega_{\mathrm{Hg}} - \gamma_{\mathrm{Hg}}^2 \omega_{\mathrm{Xe}}}{\gamma_{\mathrm{Xe}} \gamma_{\mathrm{Hg}} \left(\gamma_{\mathrm{Xe}} - \gamma_{\mathrm{Hg}}\right) \left(\frac{1}{2c^4} \gamma_{\mathrm{Xe}} \gamma_{\mathrm{Hg}} R^2 E^2 + 1\right)}$$

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

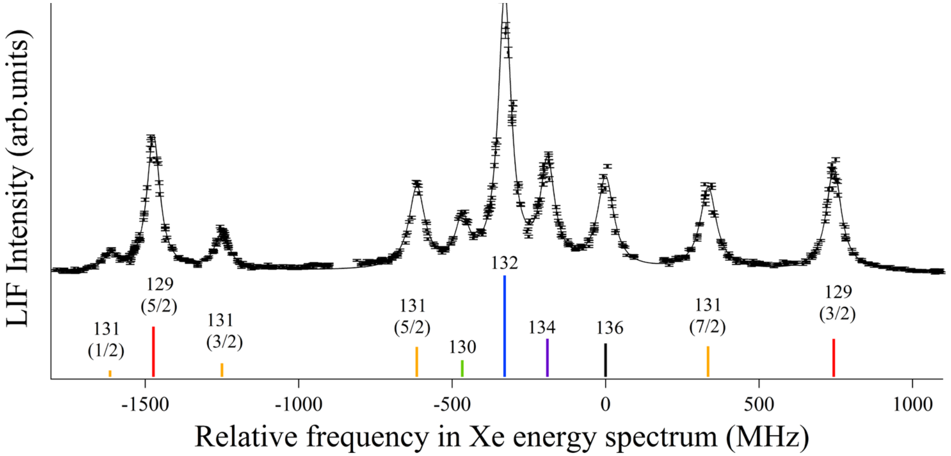
- Important progress has been made in optical pumping, freezeout & detection
- Schedule: 2023 and beyond…

Xenon: Detection





- Detect Xe via two-photon excitation & spontaneous fluorescence detection
- OPSL-based frequency-quadrupled laser system
  - Optically pumped semiconductor laser
  - Up to 400mW UV, 174kHz linewidth
- Doppler-free *5p^{5}6p* ← *5p^6* LIF spectra obtained in a retroreflective setup
  - Signal obtained from as low as 15mTorr Xe
  - Goal for comag use: ~1-10mTorr, depending on HV breakdown



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

Current @ UBC: T. Momose, E. Miller

Xenon: Polarization

- Polarization by spin exchange optical pumping (SEOP)
- $P_{Xe} \approx 25\%$ achieved with U.Winnipeg prototype; commercial systems >90% available
- Automated freezeout and recovery of polarized ^{129}Xe from SEOP gas
  - 100-700s accumulation time
  - Efficiency up to 80%

Current @ U. Winnipeg: M. Lang

THE UNIVERSITY OF
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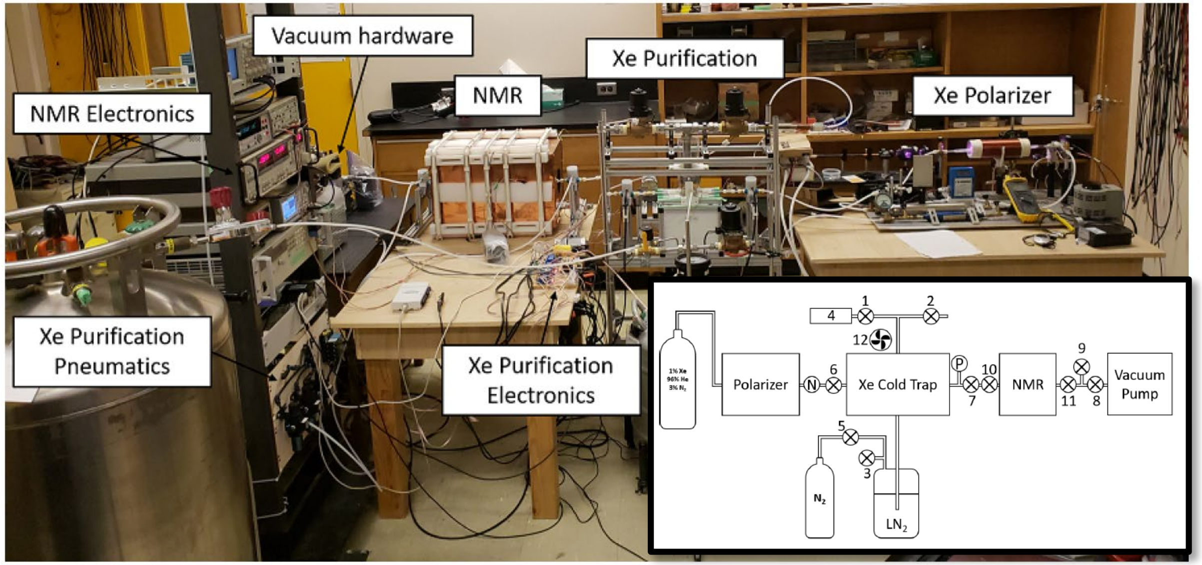
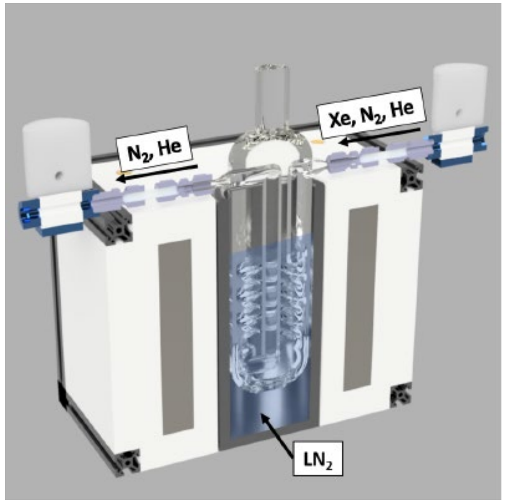
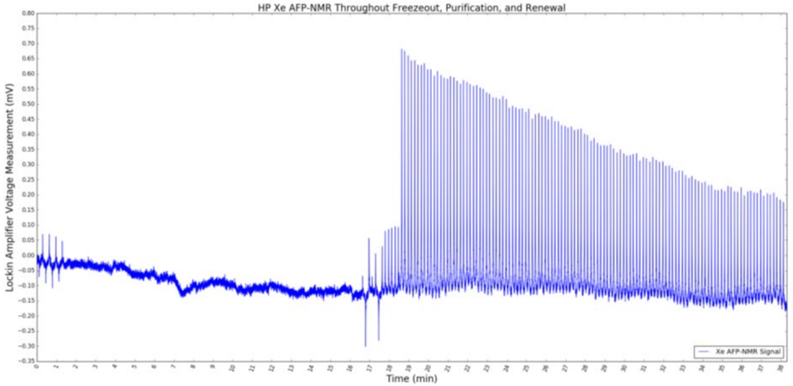


M. Lang, thesis (in progress)





Summary:

- Our current efforts are focused on developing the Hg comagnetometer for initial nEDM tests at TRIUMF
- Ready to start optical pumping ^{199}Hg in a 1.2L cell using the ECDL+SHG laser system; also working on laser stability & signal analysis.
- Learning and applying the lessons from previous-gen experiments.

Thank you!

07/02/2020

Systematic Uncertainty

- We're starting to consider systematics in light of target 0.1×10^{-27} e·cm
    - (such that all systems total < 10^{-27} e·cm)
- ν_{Hg} light shift can be mitigated by laser stabilization
    - We will lock laser to a Fizeau-type wavemeter (HighFinesse WS8) with <<10MHz stability
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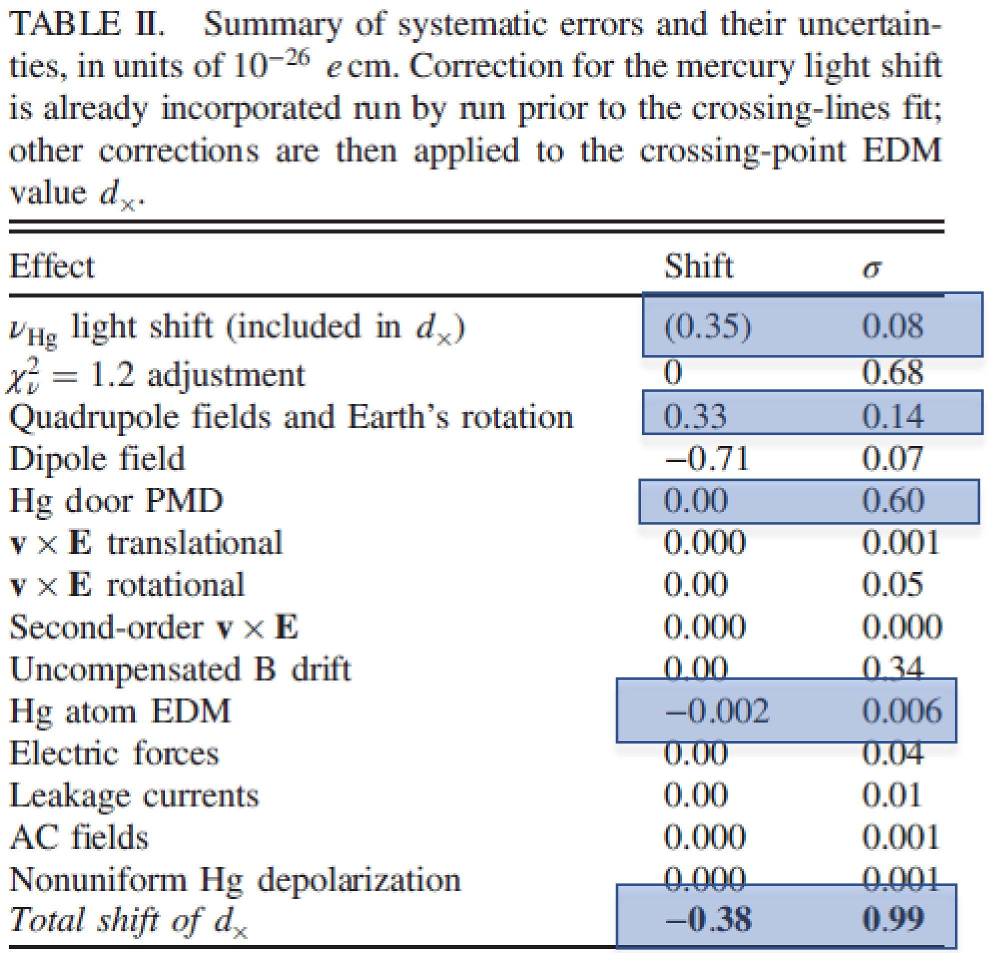


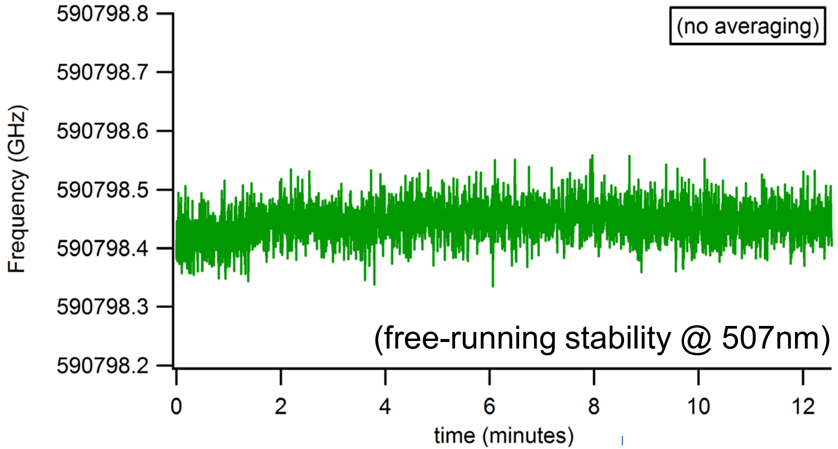
TABLE II. Summary of systematic errors and their uncertainties, in units of 10^{-26} e cm. Correction for the mercury light shift is already incorporated run by run prior to the crossing-lines fit; other corrections are then applied to the crossing-point EDM value $d_\times$.

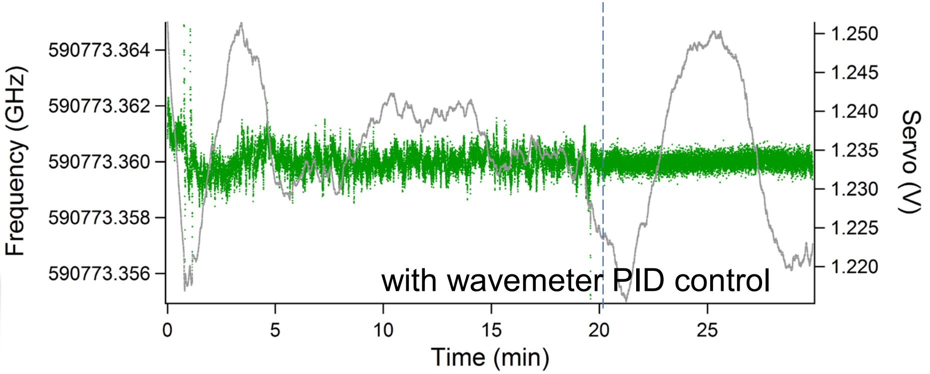
Effect	Shift	σ
ν_{Hg} light shift (included in $d_\times$)	(0.35)	0.08
$\chi^2_\nu = 1.2$ adjustment	0	0.68
Quadrupole fields and Earth's rotation	0.33	0.14
Dipole field	−0.71	0.07
Hg door PMD	0.00	0.60
$\mathbf{v} \times \mathbf{E}$ translational	0.000	0.001
$\mathbf{v} \times \mathbf{E}$ rotational	0.00	0.05
Second-order $\mathbf{v} \times \mathbf{E}$	0.000	0.000
Uncompensated B drift	0.00	0.34
Hg atom EDM	−0.002	0.006
Electric forces	0.00	0.04
Leakage currents	0.00	0.01
AC fields	0.000	0.001
Nonuniform Hg depolarization	0.000	0.001
Total shift of $d_\times$	**−0.38**	**0.99**

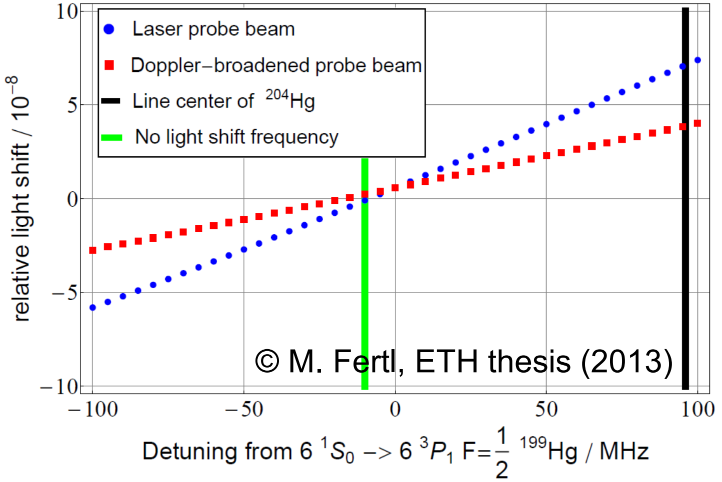
Pendlebury et. al. Phys. Rev. D 92, 092003 (2015)

Hg: Frequency Stability

- UV stability <200 MHz free-running
- We will lock to a Fizeau-type wavemeter (HighFinesse WS8)
  - absolute accuracy ±10 MHz
  - stability << 10MHz
- Light shift
  - < 10ppb (10fT) shift in precession from 10MHz uncertainty in laser stability
  - Detune laser to “no light shift frequency” to minimize direct and indirect (GPE) light shift effects







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