DEVELOPMENT OF A QUANTUM ELECTRON BEAM DIAGNOSTIC APPARATUS

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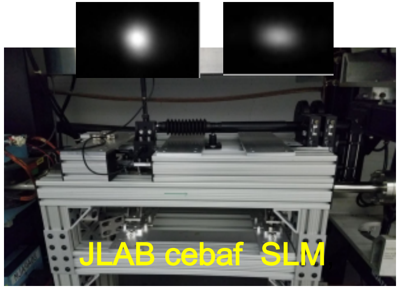
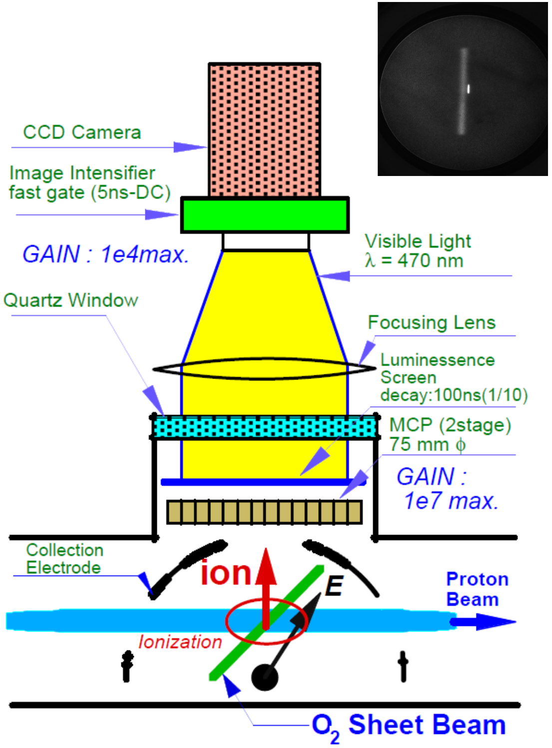
Outlines

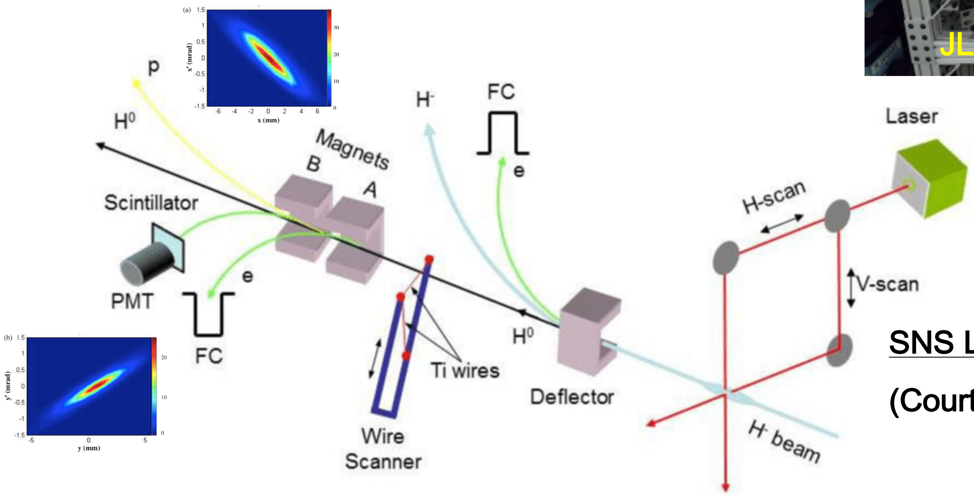
- Motivation
- Principles & Experimental Setup
- Results and Analysis
- Summary & Future Perspectives

Various Electron Beam Profile Diagnostics

- Phosphor screen, OTR, Wire scanner, EO sampling, Laser scattering,
- Tomography, profile reconstruction,……







SNS Laser Wire Scanner

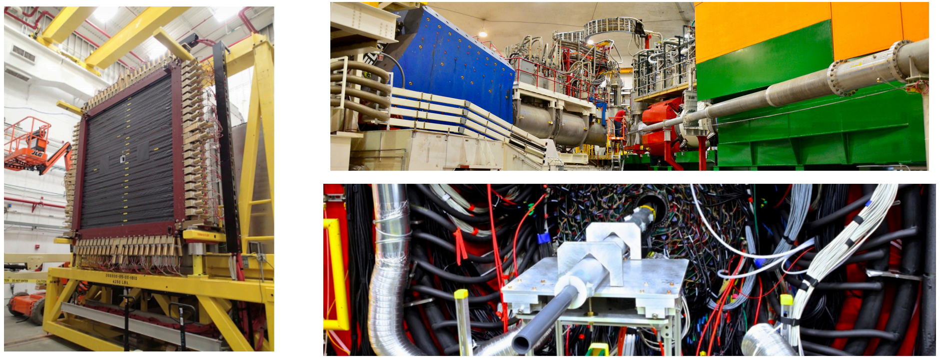
(Courtesy Y. Liu)

- **Is there a non-invasive beam apparatus measuring both longitudinal and transverse spatial profiles?**

- Refs:
  - GJBHM (Courtesy A. Jeff)
  - H. Zhang, MONPOPT045

Potential Application - Charged Particles Tracking for NP

- Wire Chamber,
- Bubble Chamber,
- Hodoscope scintillator,
- Gem Chamber, …



- Each one has limitations
- Common Features:

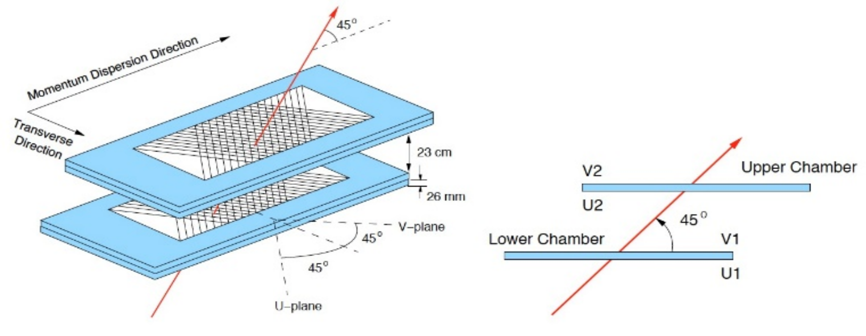
  Sophisticated, Gigantic

  Expensive, Time consuming

- Any improvement in *rate capability, cost or size* of the tracking device may greatly benefit current and future physics experiments.
- Quantum Tracker maybe a glimpse of hope?

Wire Chamber

- Ionization of gas collected on nearby wires, High-rate capability
- Multiple planes for 3-D track, High density electronic readout



Quantum Idea for Charged Particle Monitoring/Tracking

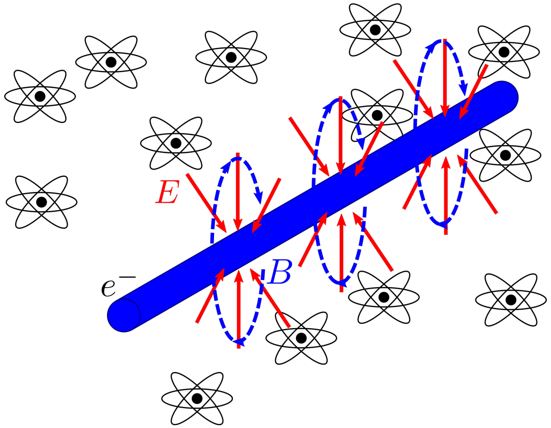
Charged particles produce electric/magnetic fields

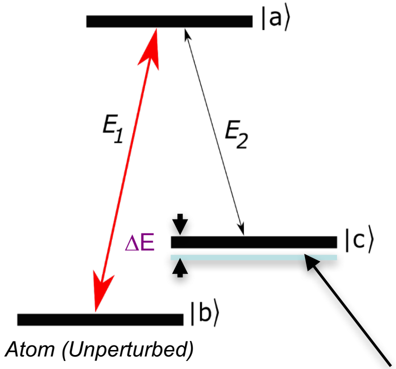
The energy levels of Rb atoms are shifted, changing the atomic quantum state

Particle track is recreated by detecting the altered optical properties of atoms via optical device

Quantum Enhanced Tracker (QET)

Use phase sensitive superposition of atomic levels to greatly increase optical sensitivity to energy shifts.

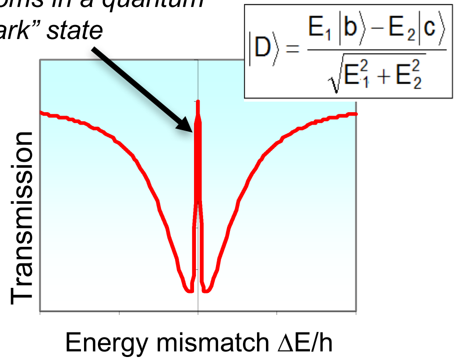




Atom (Unperturbed)

Energy shift due to passing charged particle

Atoms in a quantum "dark" state

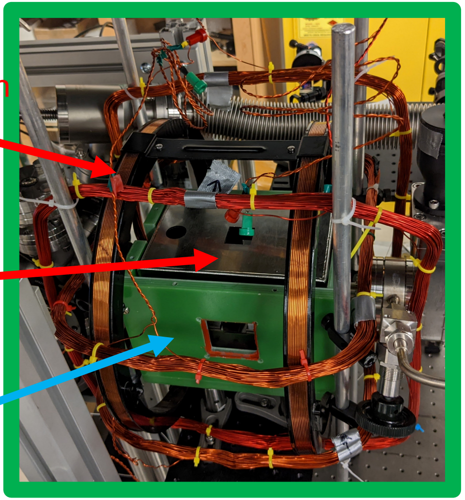


$$|D\rangle = \frac{E_1|b\rangle - E_2|c\rangle}{\sqrt{E_1^2 + E_2^2}}$$

- *Sensitive only to charged particles*
- *High Resolution, High Speed*
- *3D tracking in single volume*
- *Small number of channels, high rate capability*
- *Modern 3D "bubble chamber"*

An approach yet to be demonstrated!

Experimental Setup

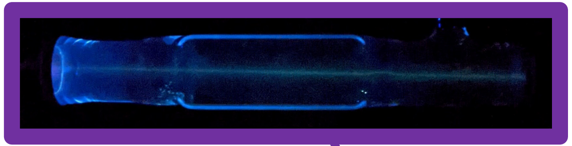


Magnetic compensation coils

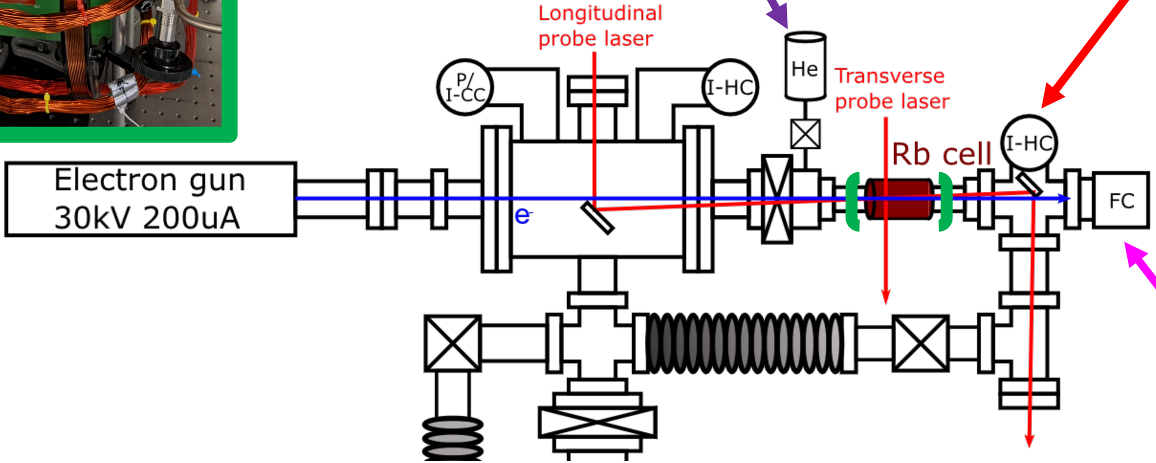
Magnetic Shielding

Built-in oven

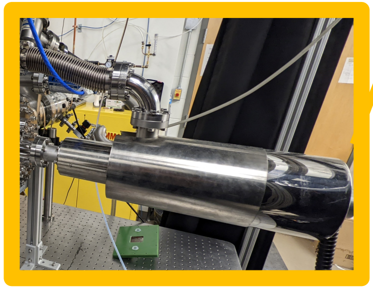
Electron fluorescence in He



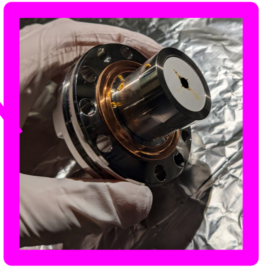
Laser fluorescence in Rb



Electron gun

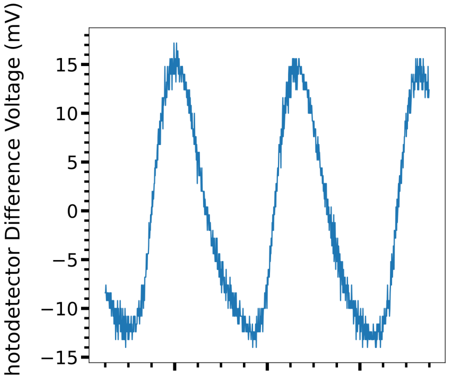


Faraday cup

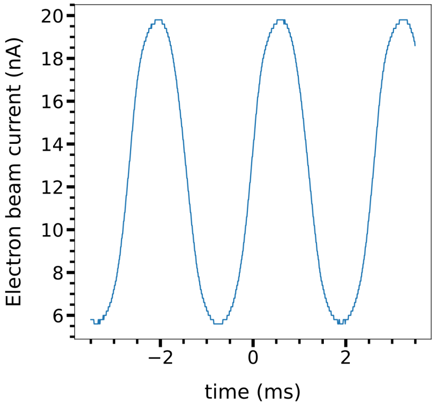


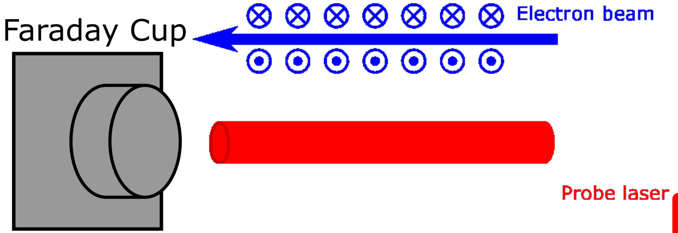
Longitudinal Detection

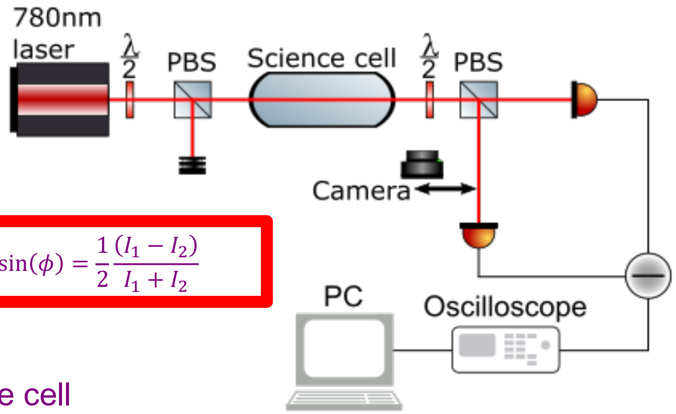
Longitudinal Polarization Rotation



Electron Current



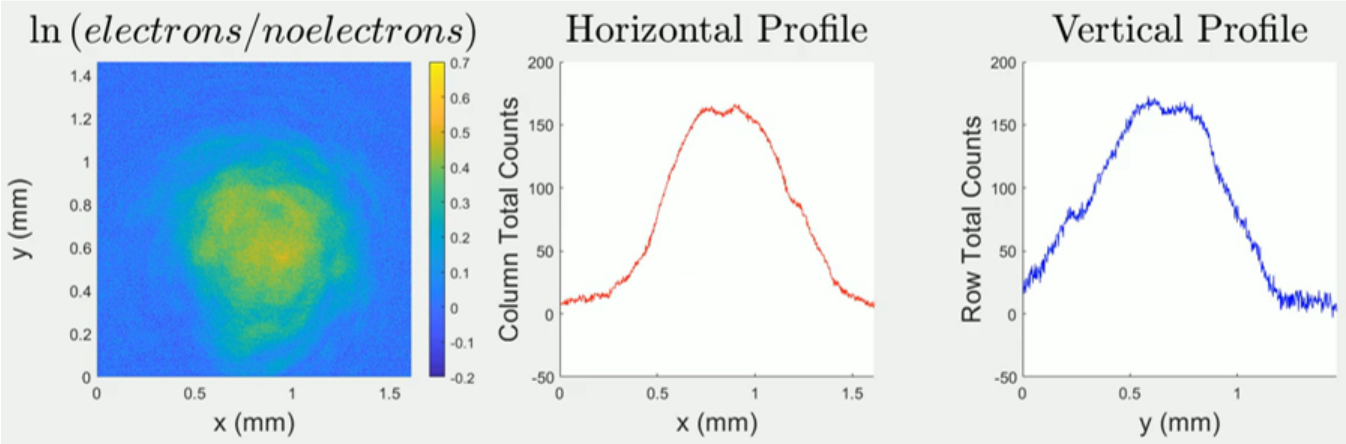




$$\sin(\phi) = \frac{1}{2}\frac{(I_1 - I_2)}{I_1 + I_2}$$

$20\ kV, 110\ \mu A, \sim 1\ mm\emptyset$ electron beam parameters

Minimum detection current $10\ \mu A$ room-temperature cell



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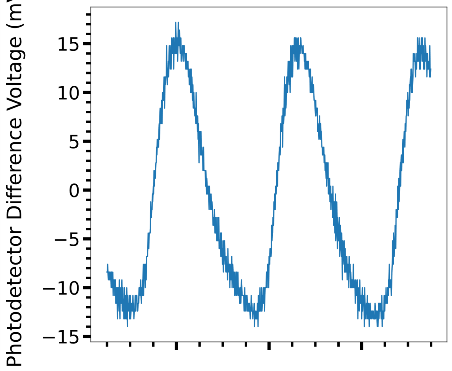
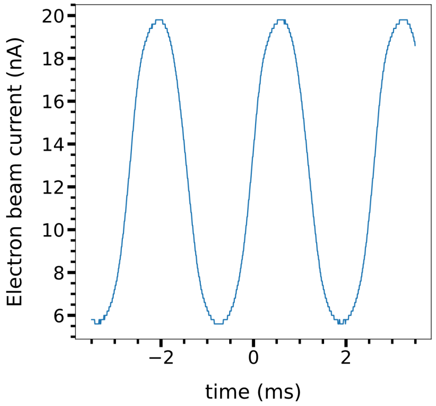
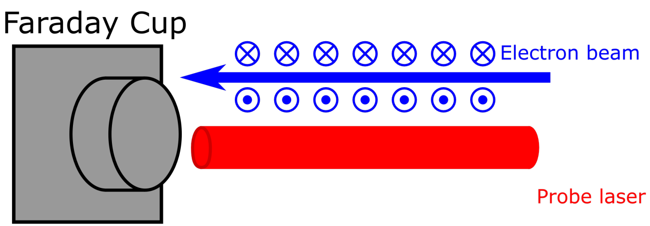
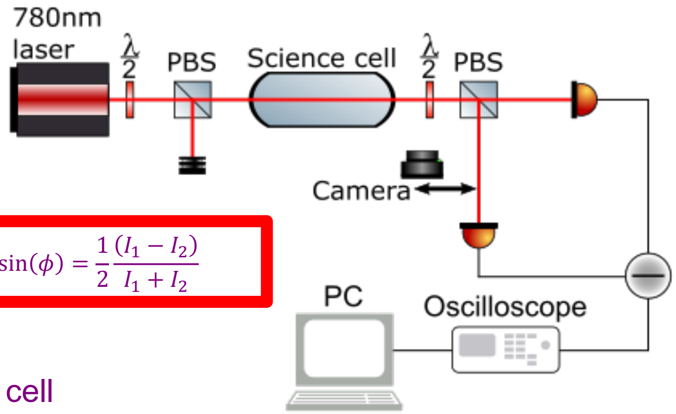


Electron Current







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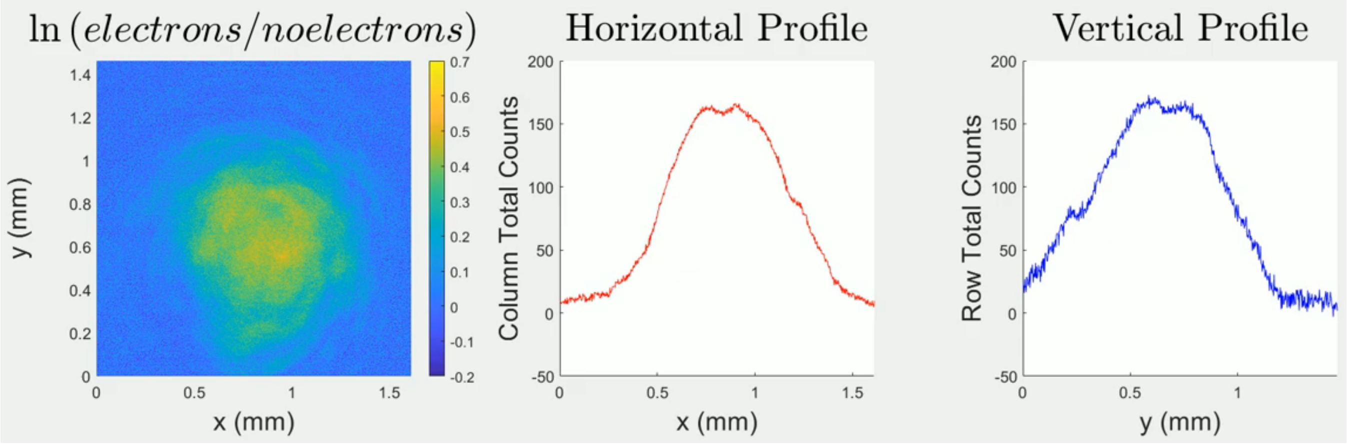
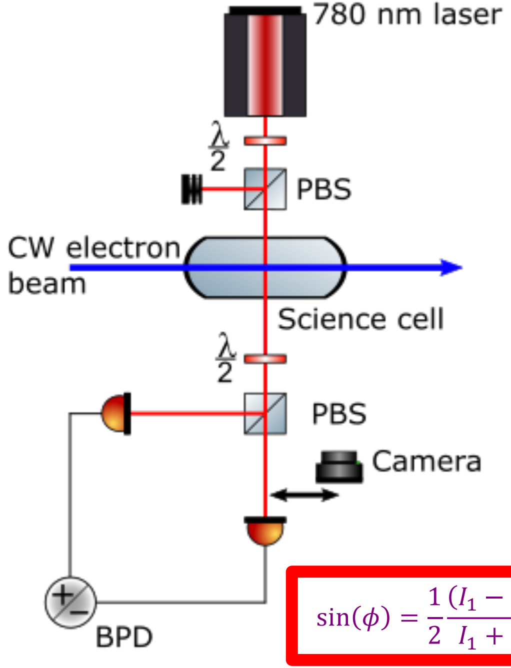
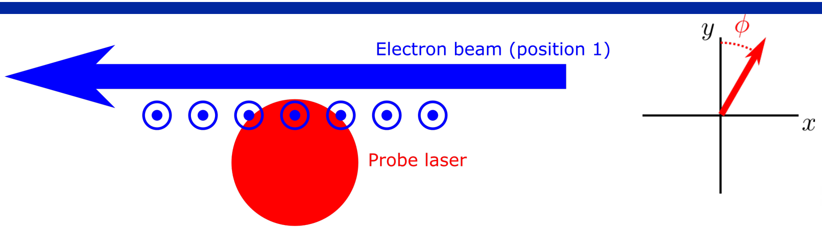


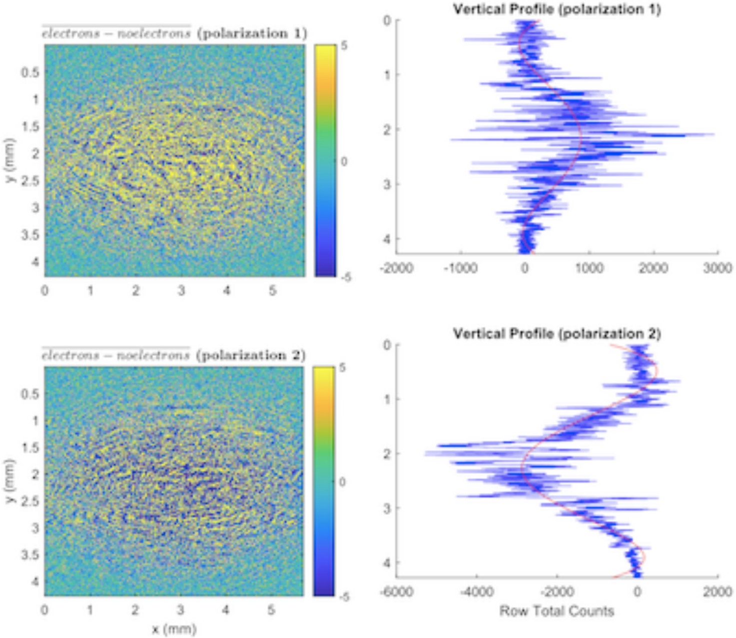
Transverse Detection

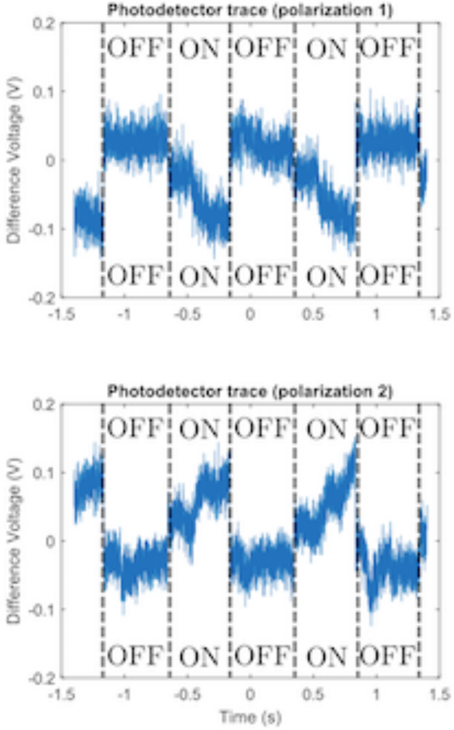


$$\sin(\phi) = \frac{1}{2}\frac{(I_1 - I_2)}{I_1 + I_2}$$

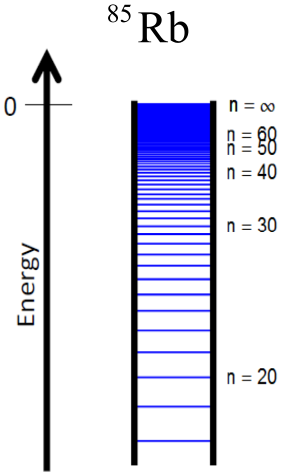
- E-Source: $20\ kV, 200\ \mu A, \sim 1\ mm\emptyset$
- Optimal laser power in: $3\ mW$
- Minimum detection current $1\ \mu A$ $70°C$ cell







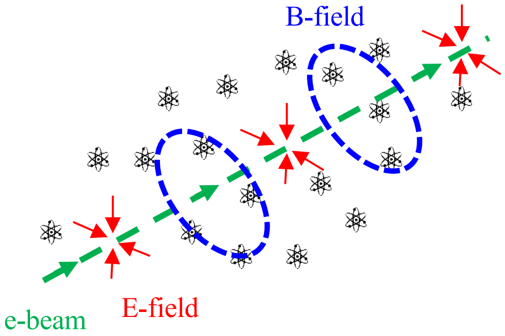
Another Approach - Detection with Rydberg Atoms

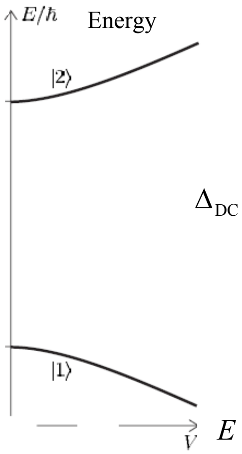


charged particles produce electric and magnetic → E-field shifts energy state of atoms (Stark effect) → particles are detected by monitoring Rydberg atom

$\alpha_p \propto n^7$

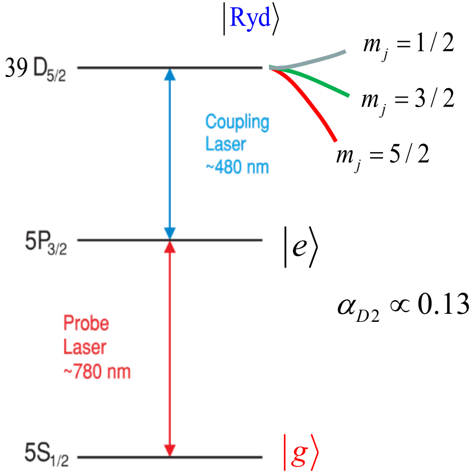
$\sim 40\ (\mathrm{MHz/(V/cm)^2})$





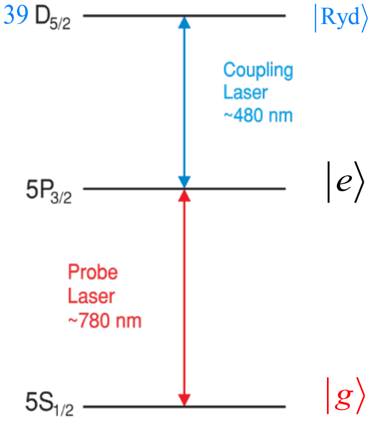
$$\Delta_{\mathrm{DC}} = \frac{1}{2}\alpha_p |E|^2$$

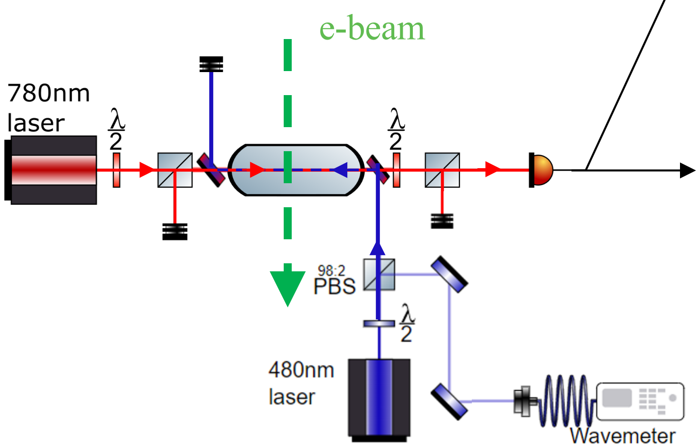
Presence of E-field

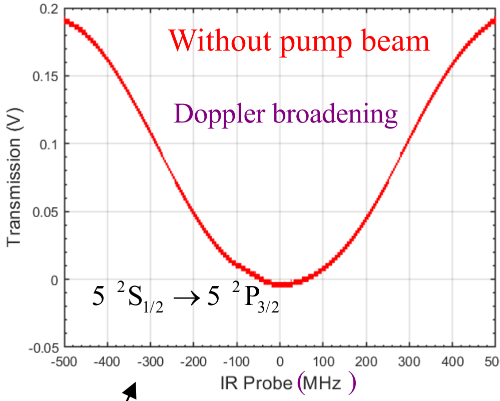


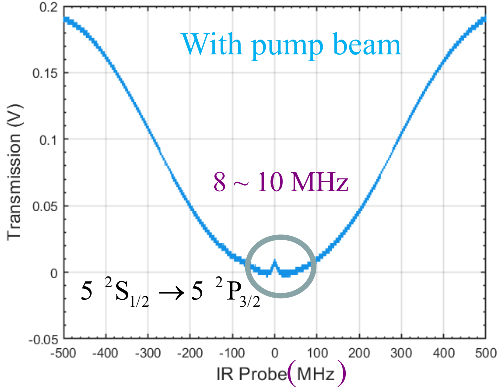
$\alpha_{D2} \propto 0.13\ \mathrm{Hz/(V/cm)^2}$

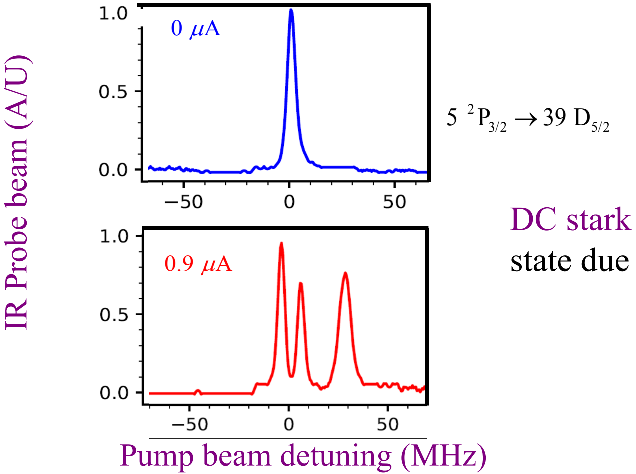
Rydberg EIT for e-Beam Sensor







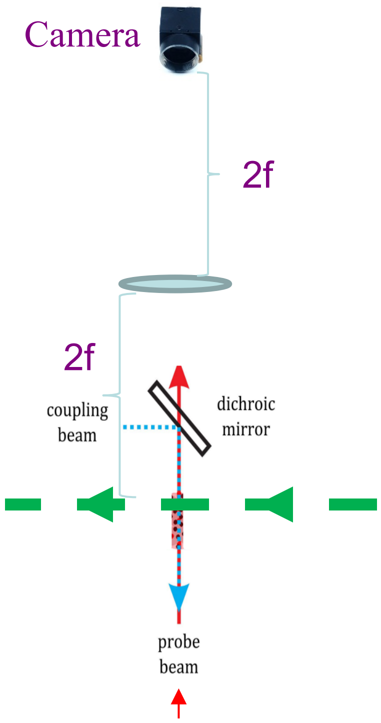


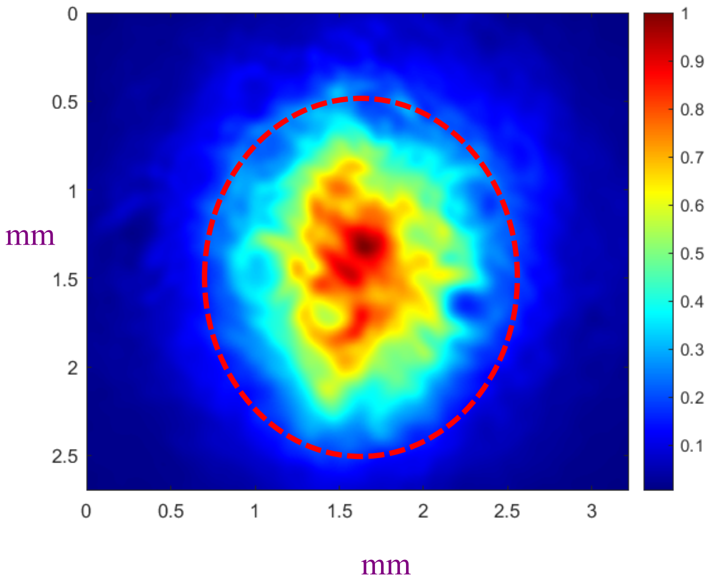


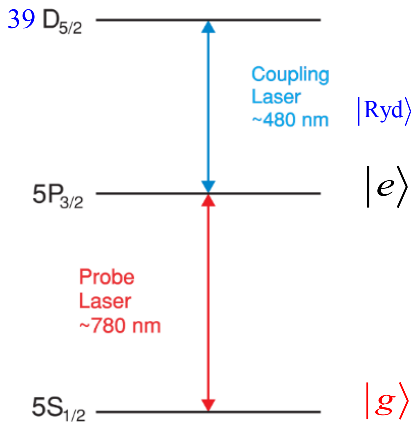
DC stark shift on Rydberg state due to e-beam

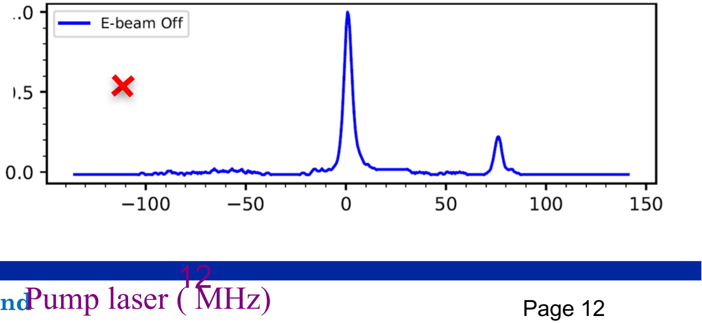
Beam Imaging by EIT

EIT = Probe [With Pump] - Probe [Without Pump]





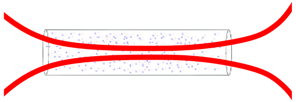




Monitoring e-Beam Profile

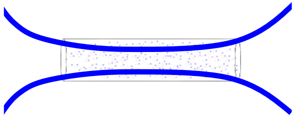
E-beam setup/focus 1

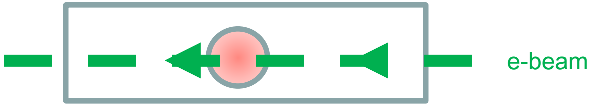
FWHM ~ 1 mm



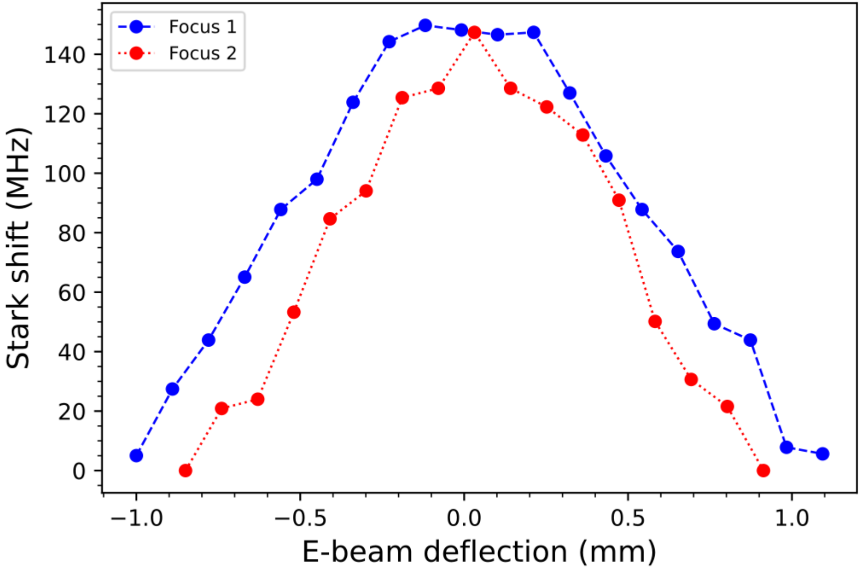
E-beam setup/focus 2

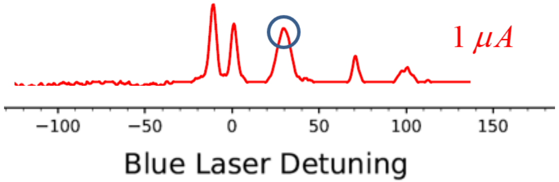
FWHM ~ 1.4 mm





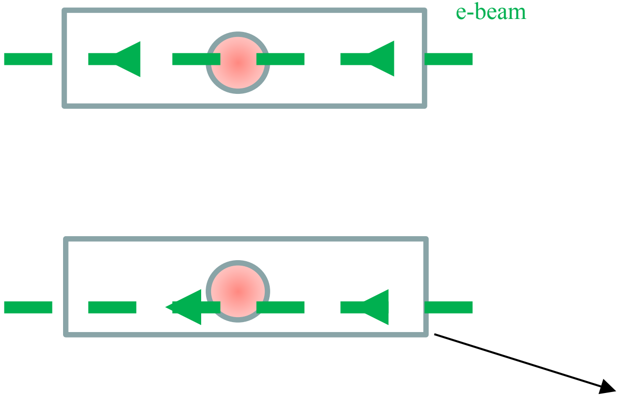
Extract e-beam width through DC Stark shift



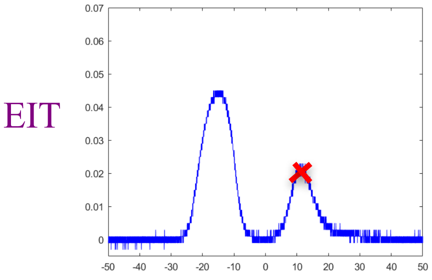


Imaging electron beam

Transverse Cross Section

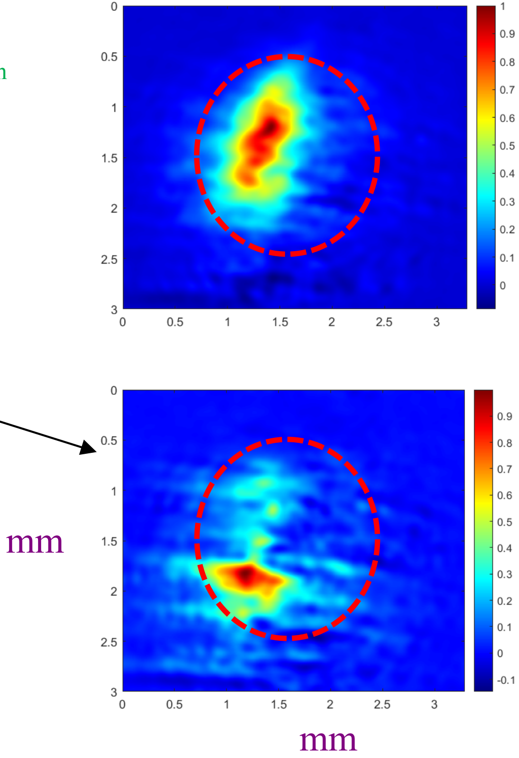


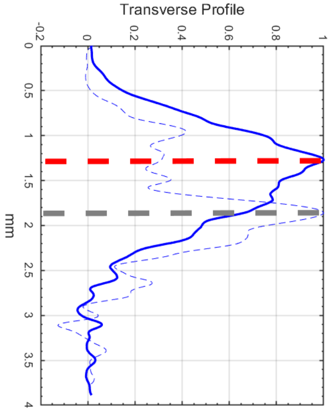
EIT



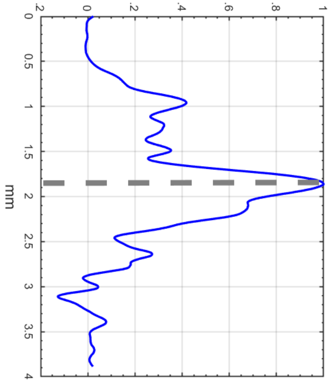
Pump laser (MHz)

$I_{E\text{ - beam}} - I_{No\ E\text{ - beam}}$





$\Delta Y_{measured} = 0.58\ \text{mm}$

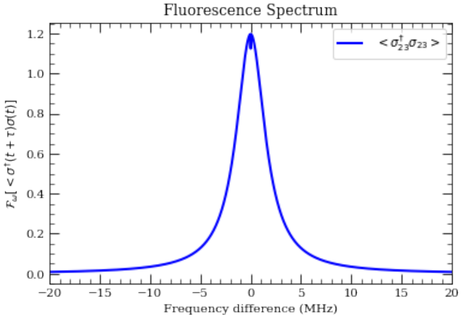


- Still under investigation, charging on cell wall may have affected the result!

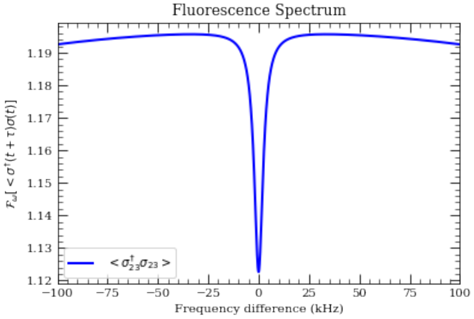
Semi-classical Theory Study

Demonstration of the effect of relativistic charged particles on EIT measurements

- **AC Stark shifts due to fields from relativistic charged particles calculated using semiclassical formalism with the minimal coupling Schrodinger equation.**
- **Effects of interest include phase shift to EIT wavefunction and the scattering spectrum including coherent and incoherent fluorescent effects.**



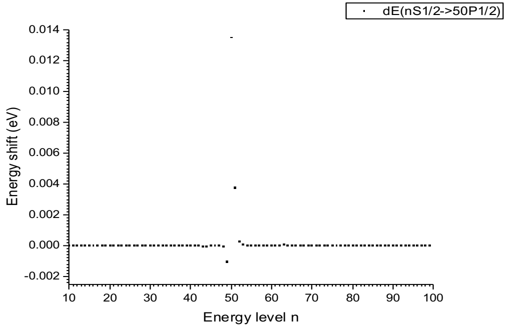
$\Omega_P = 0.1$ MHz, $\Omega_S = 10$ MHz, $\Delta_1 = \Delta_2 = 0$



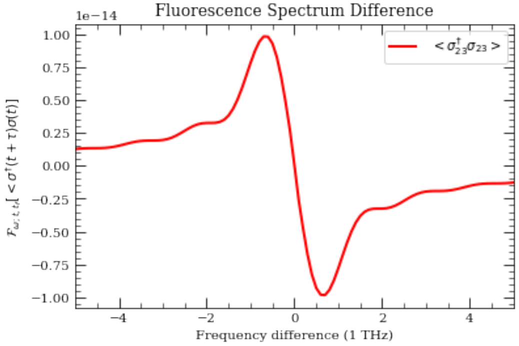
$\Omega_P = 0.1$ MHz, $\Omega_S = 10$ MHz, $\Delta_1 = \Delta_2 = 0$

The EIT steady state fluorescence spectrum from a driven single atom is proportional to the spectral transform of the two-time correlation function for the atomic dipole operator $g_\lambda^{(1)}(\vec{r}',t';\vec{r},t) = \left\langle \left(\sum_i \sigma_i^\dagger\left(\vec{r}',t'-\frac{|\vec{r}'-\vec{r}_a|}{c}\right)\right)\left(\sum_j \sigma_j\left(\vec{r},t-\frac{|\vec{r}-\vec{r}_a|}{c}\right)\right)\right\rangle$.

External perturbations will introduce Stark shifts and change the spectrum for the duration where the perturbation is active. A short-term Fourier transform of $g_\lambda^{(1)}(\vec{r}',t';\vec{r},t)$ *is used to evaluate the perturbed spectrum*



Lowest order perturbations for the energy of the n=50 Rydberg P1/2 state from S-state virtual transitions due to Coulomb field of relativistic charged particle with $\beta = 0.999$ *at 1 μm distance perpendicular to motional axis. No dipole approximation and inhomogeneity of field is considered.*



$\Omega_P = 0.1$ MHz, $\Omega_S = 10$ MHz, $\Delta_1 = \Delta_2 = 0$. Introduced gaussian DC Pulse with duration $\tau = 10$ fs causing effective AC Stark shift 20.0 MHz for the Rydberg level, 100 kHz for other levels, .

Summary & Future Perspectives

Studied e-beam detection by two approaches

- *NL magneto-optical rotation* to measure magnetic fields
  - Beam sensed in both longitudinal and transverse configurations
  - Beam image captured on camera via polarization rotation
  - Minimum detection of $1\ \mu A$ particle beam
- Rydberg atoms attempted for high sensitivity detection, under further study

Theoretical demonstration of the effect of relativistic charged particles on EIT measurements

In Future:

- **Study** across wider energies range, including *relativistic electron* source
- **Demonstrate *3D-imaging* capability**
- **Improve/Optimize system/explore *beam halo* & *Single-particle detection***

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