DEVELOPMENT OF A QUANTUM ELECTRON BEAM DIAGNOSTIC APPARATUS

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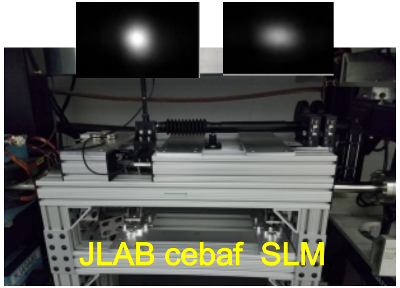
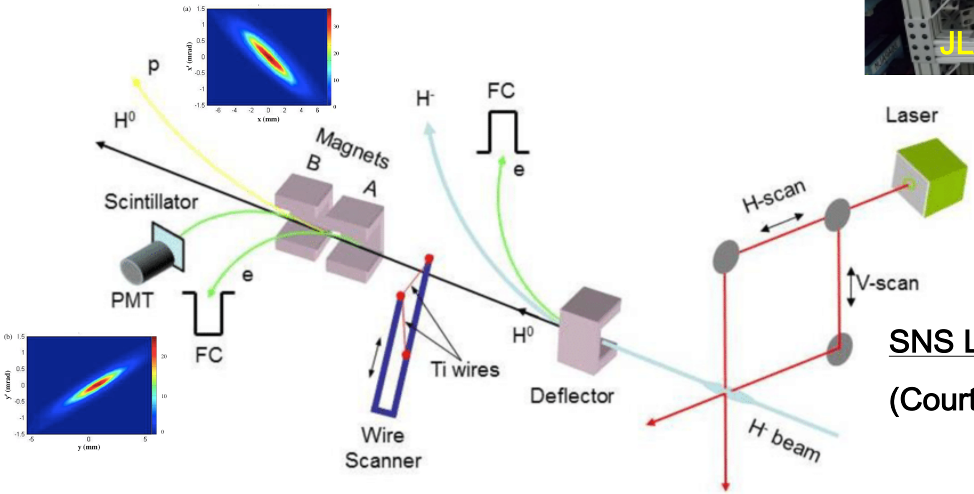
Outlines

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

Various Electron Beam Profile Diagnostics

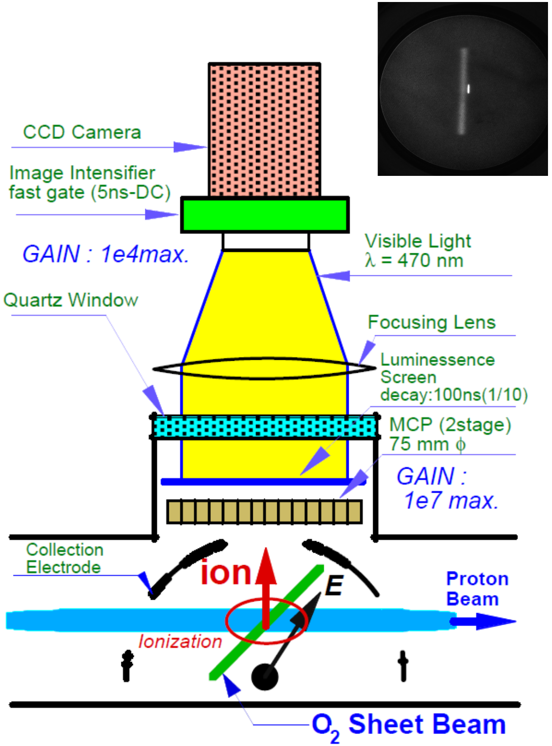
- Phosphor screen, OTR, Wire scanner, EO sampling, Laser scattering,
- Tomography, profile reconstruction,……





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

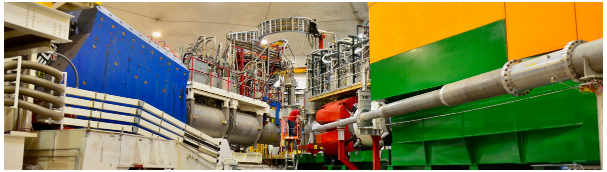
- Wire Chamber,
- Bubble Chamber,
- Hodoscope scintillator,
- Gem Chamber, …

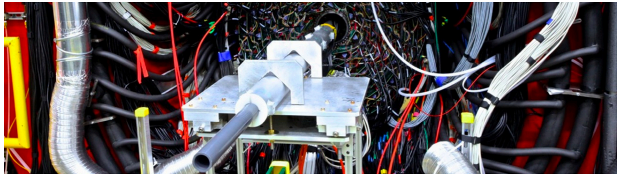
- Each one has limitations
- Common Features:

  Sophisticated, Gigantic

  Expensive, Time consuming

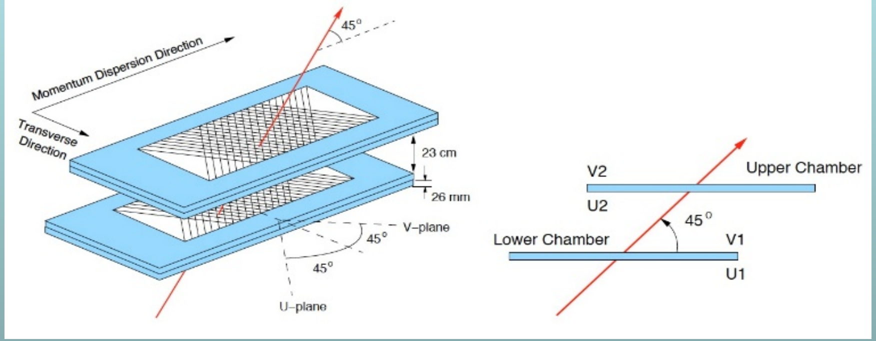
- Any improvement in *rate capability, cost or size* of the tracking device may greatly benefit current and future physics experiments.
- Quantum Tracker maybe a glimpse of hope?





Wire Chamber

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

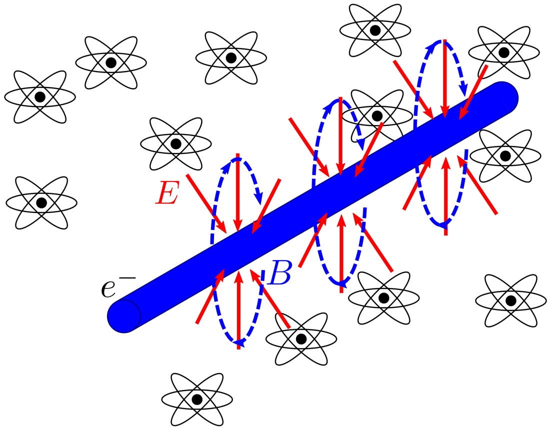


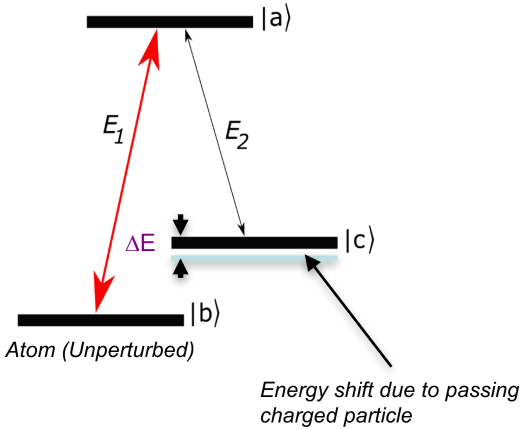
Quantum Idea for Charged Particle Monitoring/Tracking

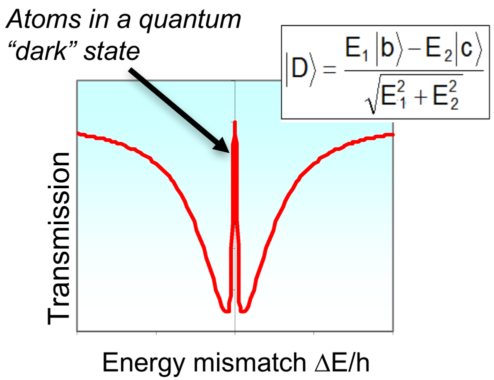
Charged particles produce electric/magnetic fields → **The energy levels of Rb atoms are shifted, changing the atomic quantum state** → **Particle track is recreated by detecting the altered optical properties of atoms via optical device**

Quantum Enhanced Tracker (QET)

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



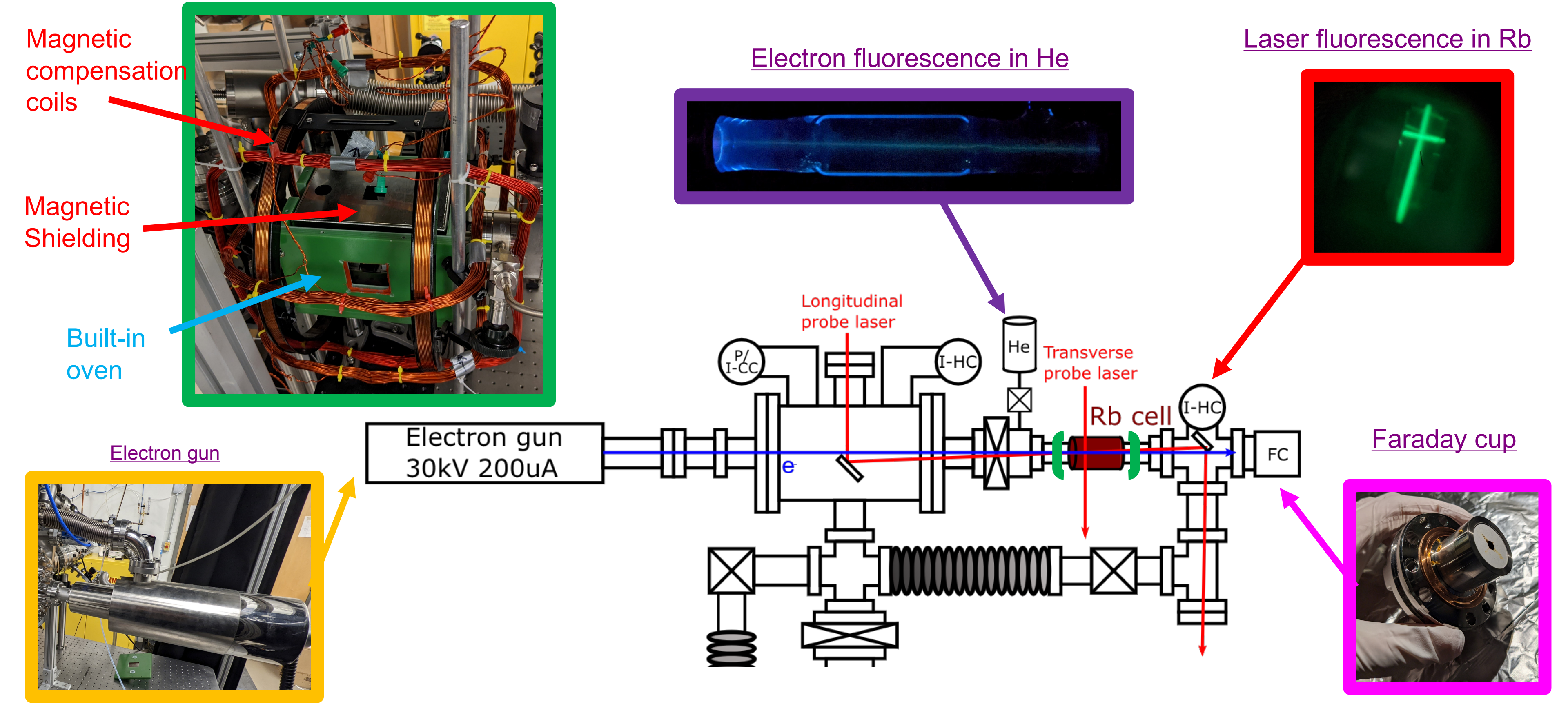




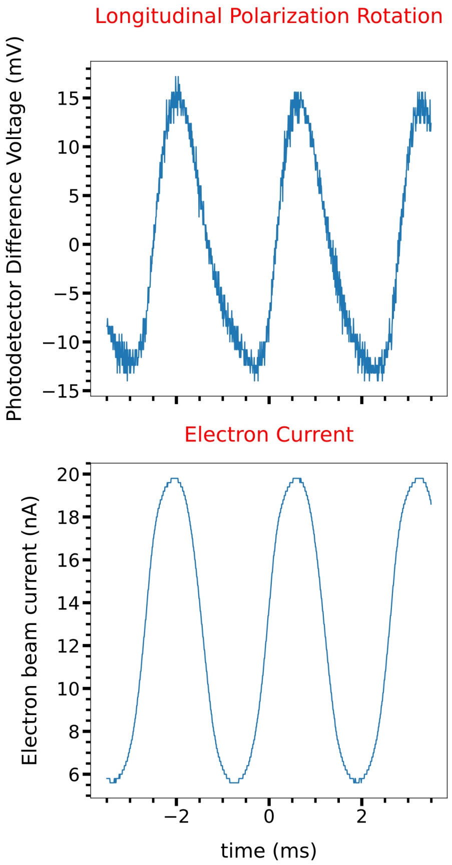
- *Sensitive only to charged particles*
- *High Resolution, High Speed*
- *3D tracking in single volume*
- *Small number of channels, high rate capability*
- *Modern 3D "bubble chamber"*

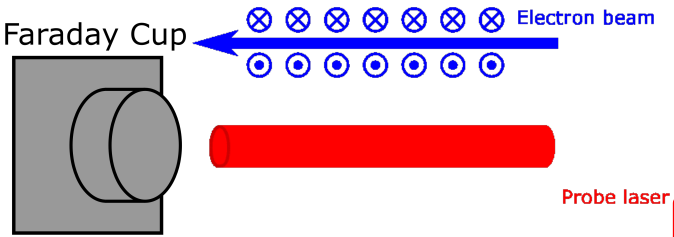
An approach yet to be demonstrated!

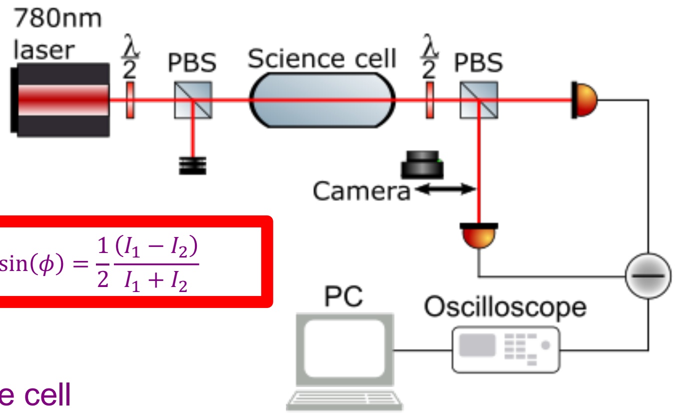
Experimental Setup



Longitudinal Detection



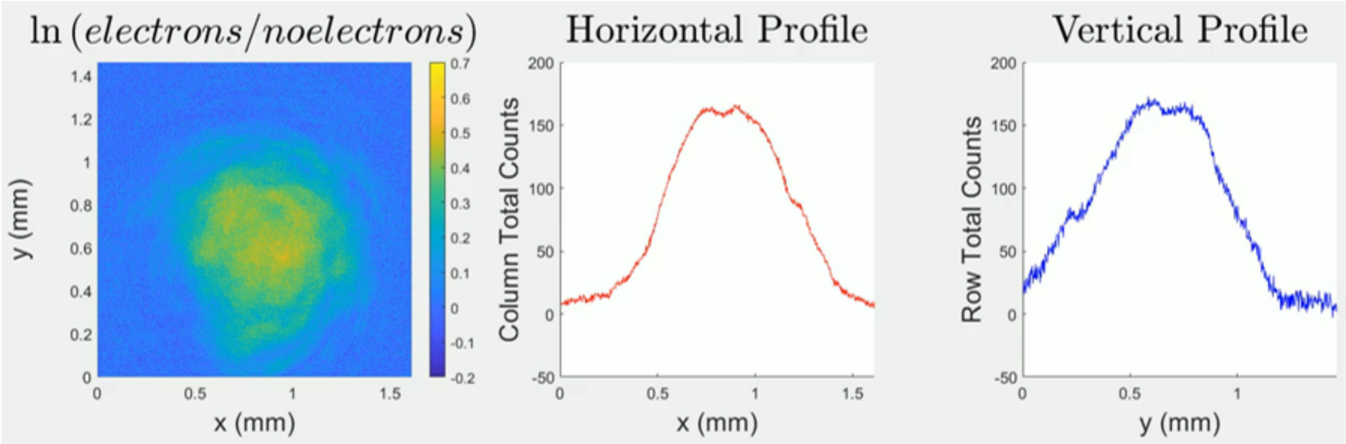




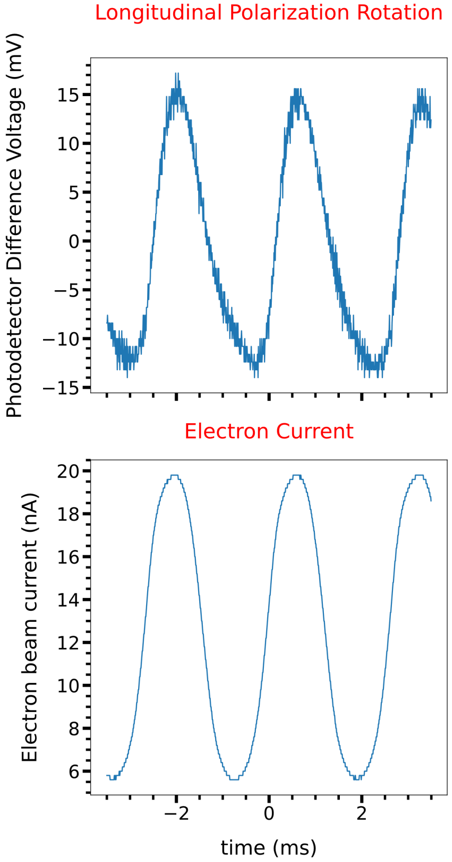
$$\sin(\phi) = \frac{1}{2}\frac{(I_1 - I_2)}{I_1 + I_2}$$

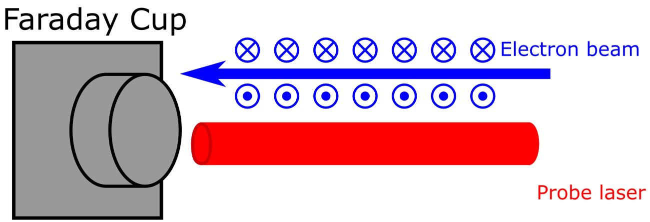
$20\ kV, 110\ \mu A, \sim 1\ mm\emptyset$ electron beam parameters

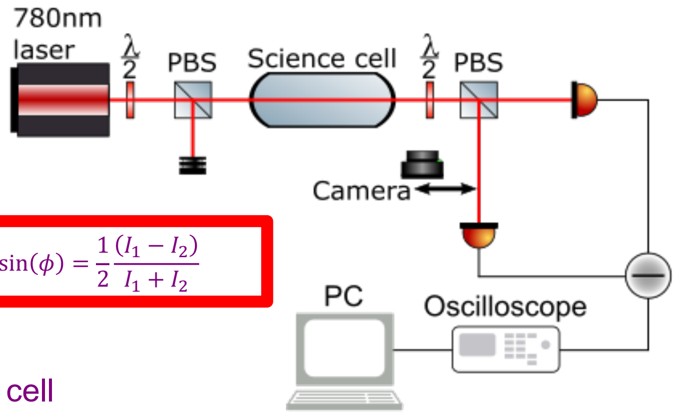
Minimum detection current $10\ \mu A$ room-temperature cell



Longitudinal Detection







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

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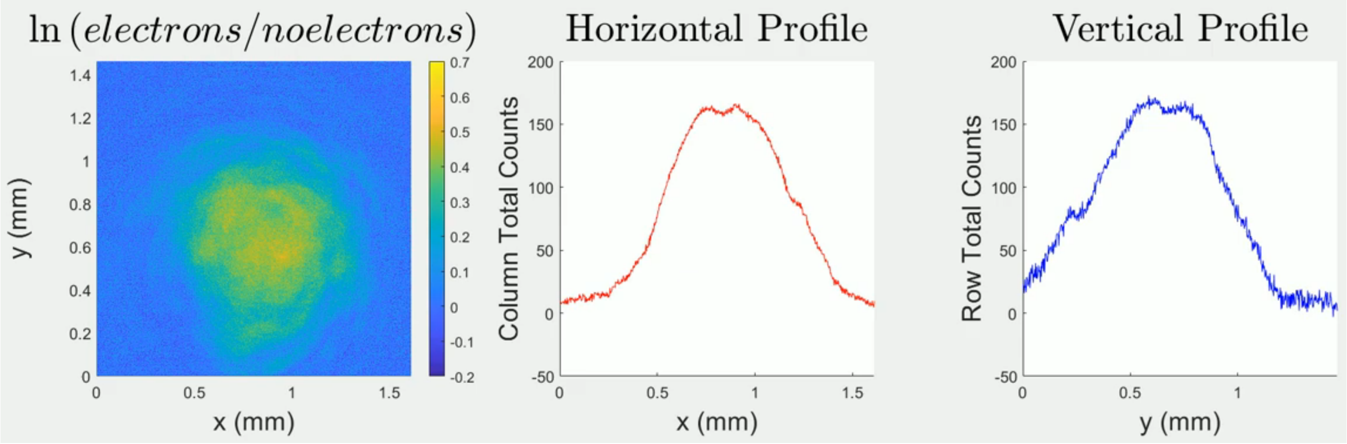
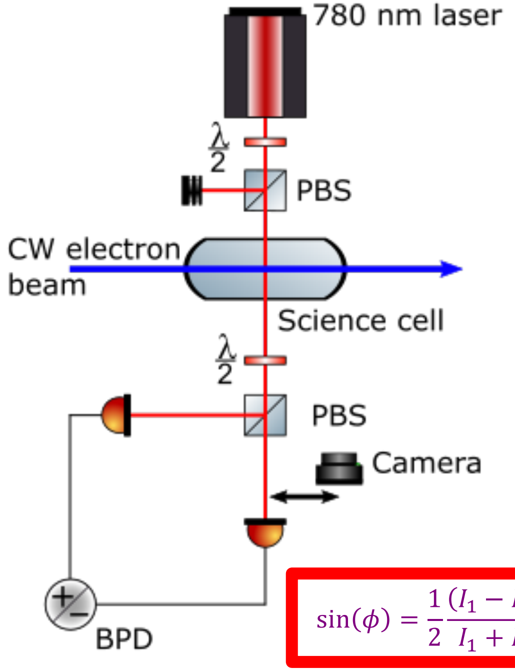
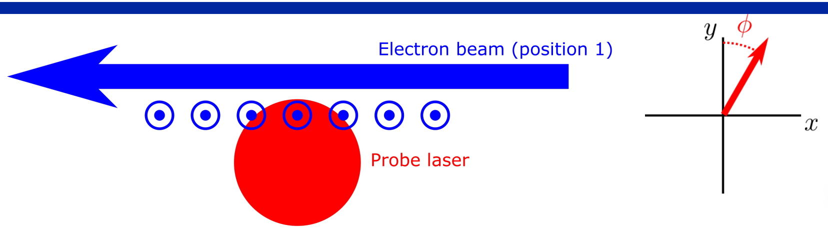


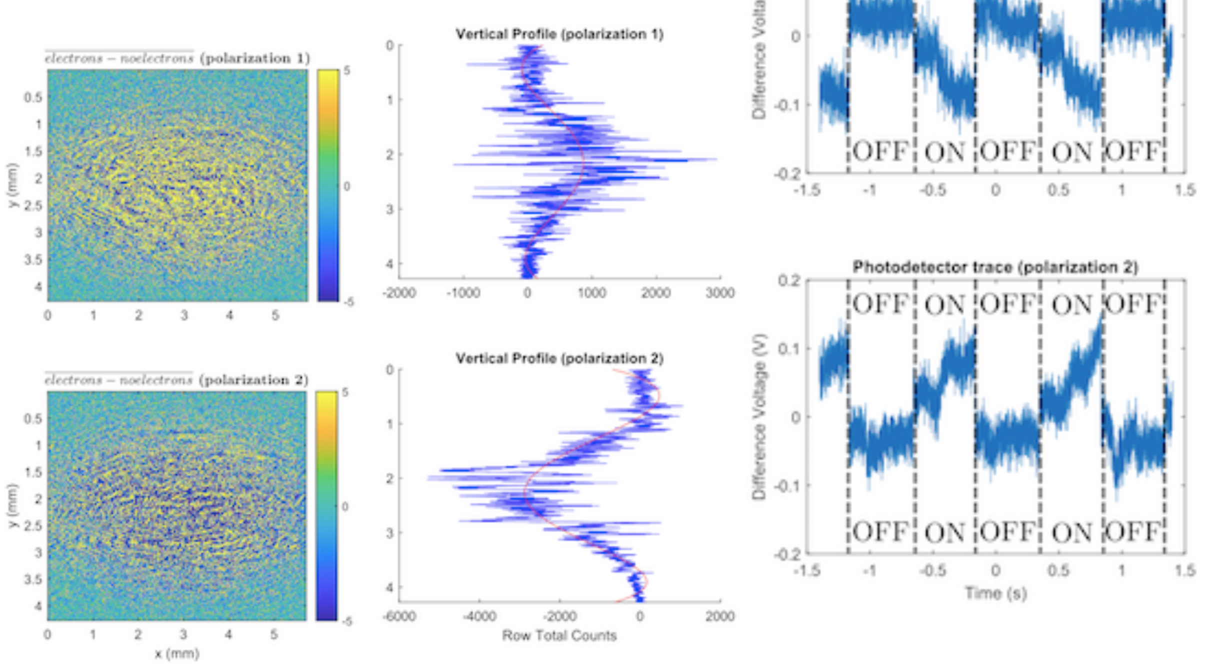
Transverse Detection



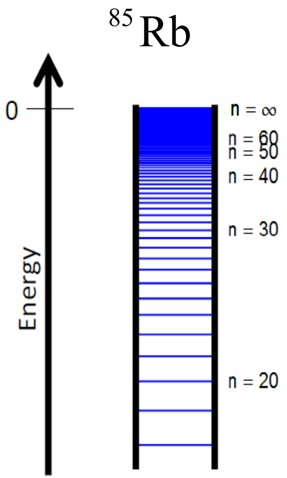
$$\sin(\phi) = \frac{1}{2}\frac{(I_1 - I_2)}{I_1 + I_2}$$

- 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



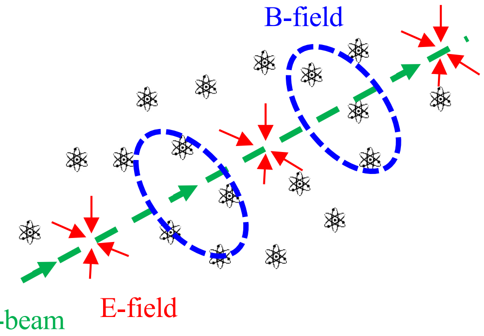
charged particles produce electric and magnetic

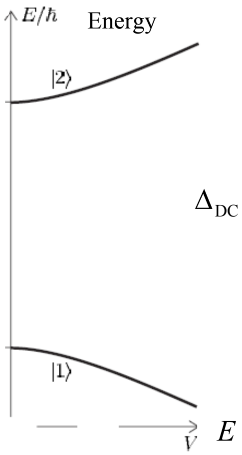
E-field shifts energy state of atoms (Stark effect)

particles are detected by monitoring Rydberg atom

$\alpha_p \propto n^7$

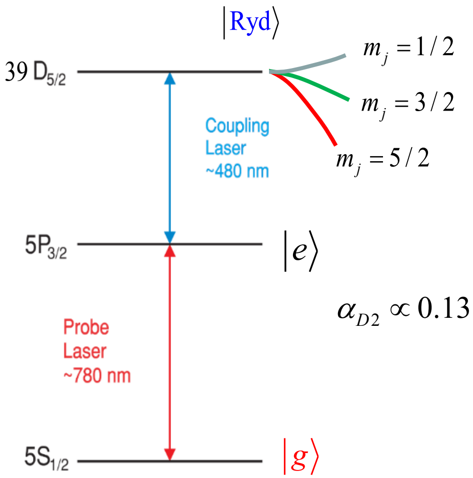
$\sim 40\ (\mathrm{MHz}/(\mathrm{V/cm})^2)$





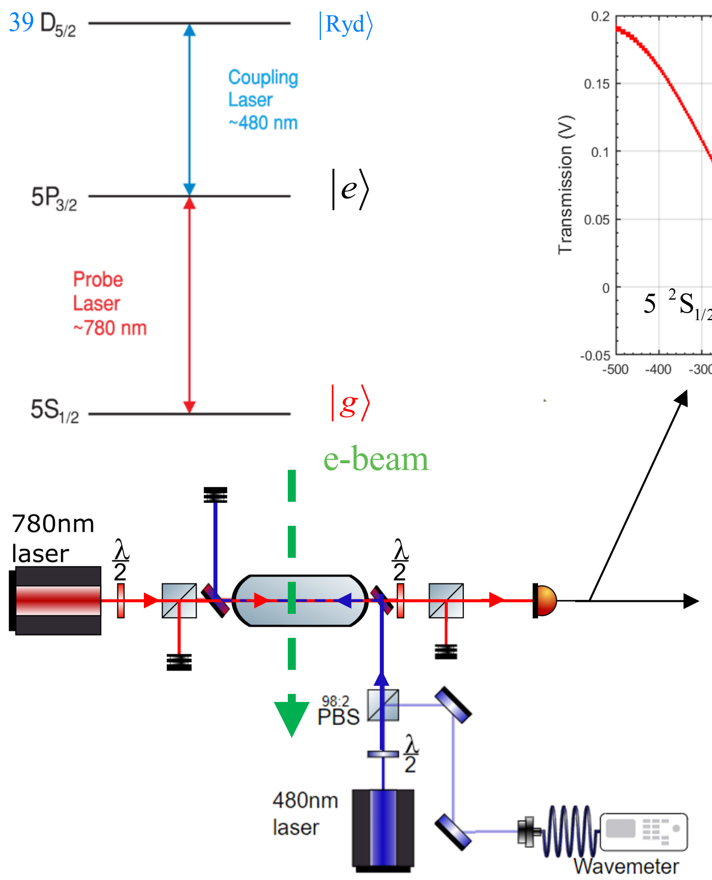
$$\Delta_{DC} = \frac{1}{2}\alpha_p |E|^2$$

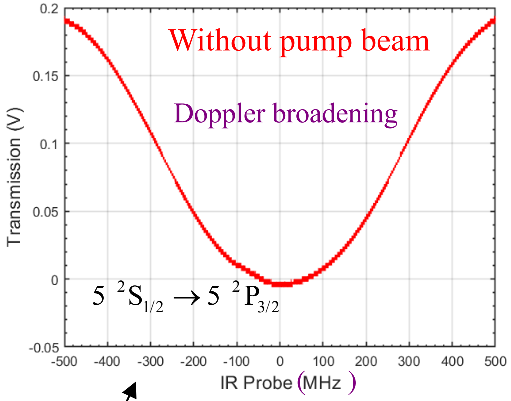
Presence of E-field

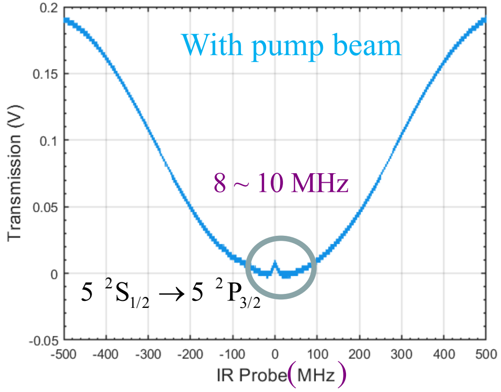


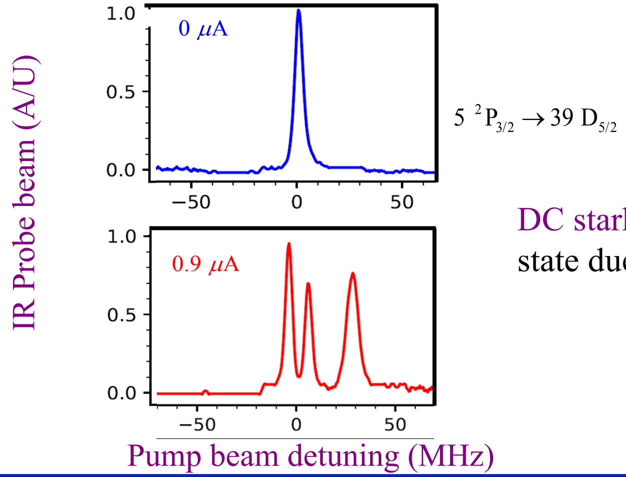
$\alpha_{D2} \propto 0.13\ \mathrm{Hz}/(\mathrm{V/cm})^2$

Rydberg EIT for e-Beam Sensor





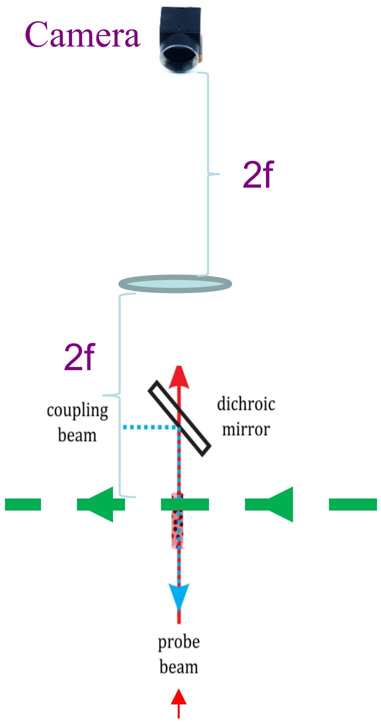


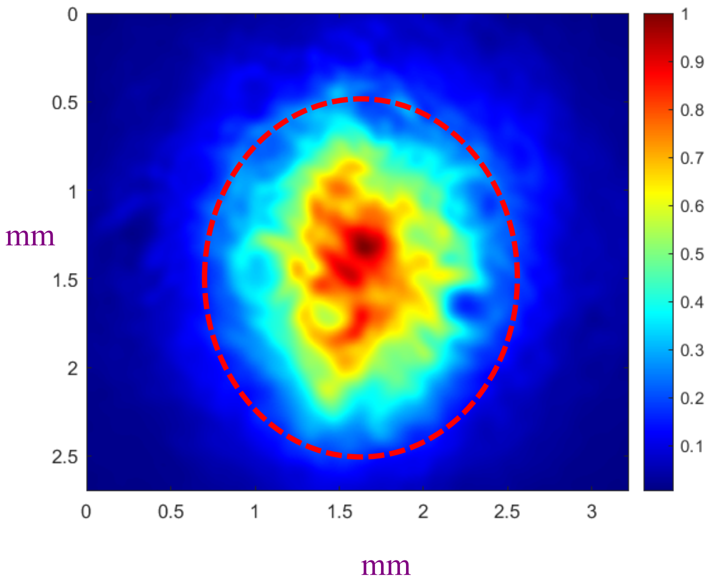


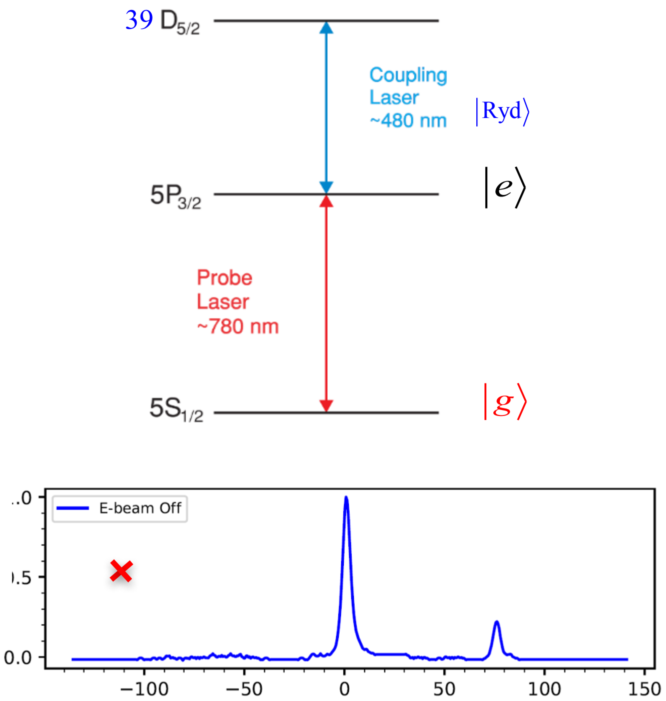
DC stark shift on Rydberg state due to e-beam

Beam Imaging by EIT

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





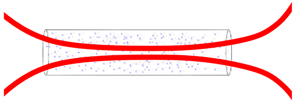


Monitoring e-Beam Profile

Extract e-beam width through DC Stark shift

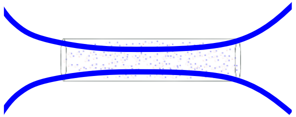
E-beam setup/focus 1

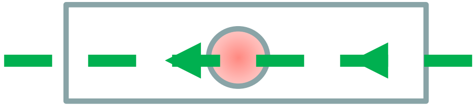
FWHM ~ 1 mm

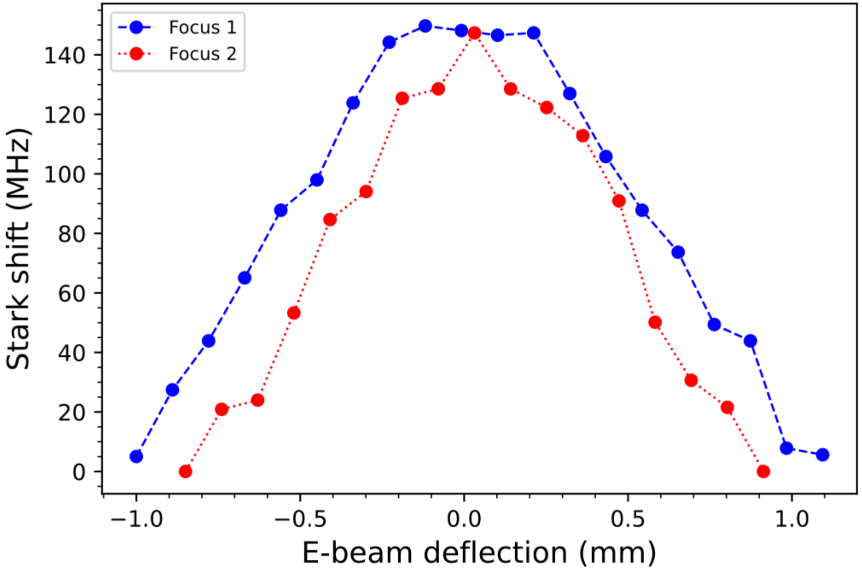


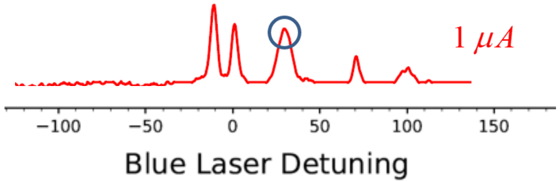
E-beam setup/focus 2

FWHM ~ 1.4 mm

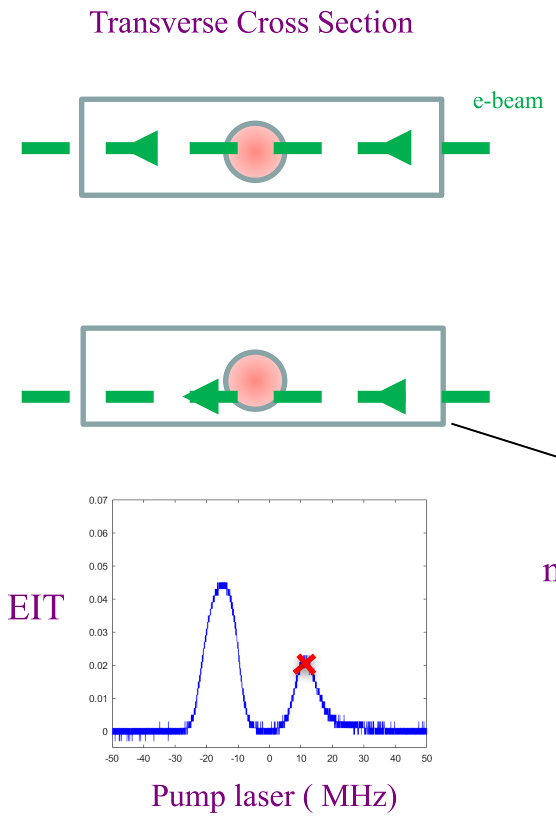


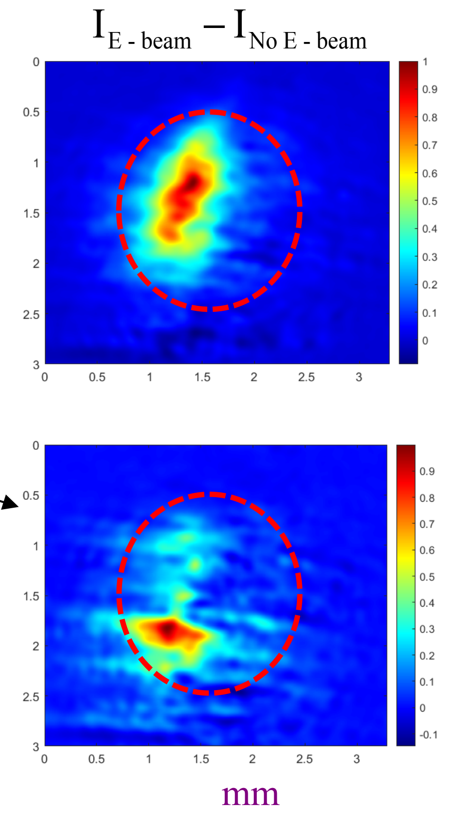


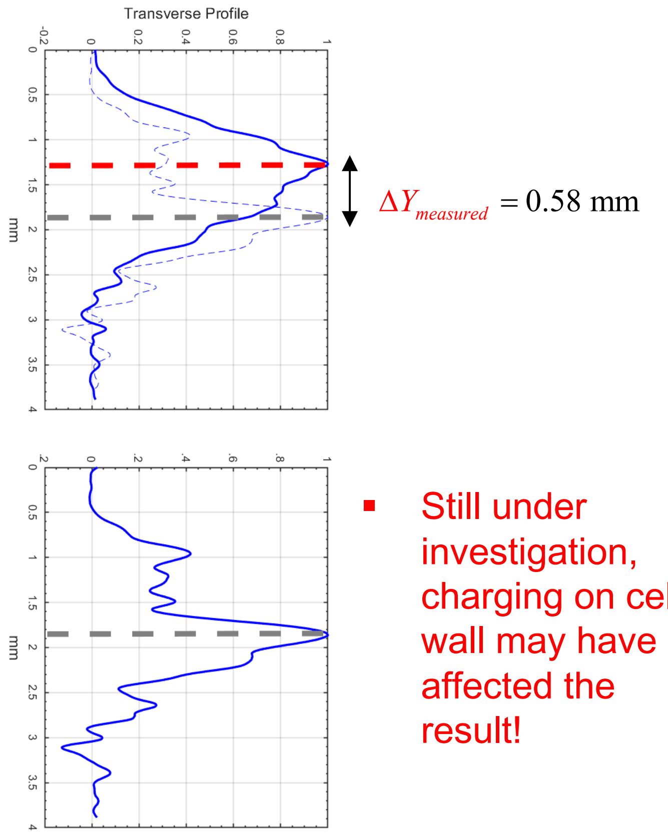




Imaging electron beam





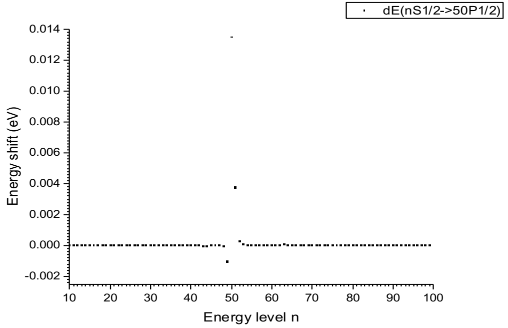


- Still under investigation, charging on cell wall may have affected the result!

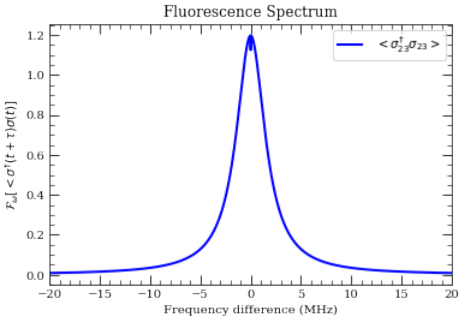
Semi-classical Theory Study

Demonstration of the effect of relativistic charged particles on EIT measurements

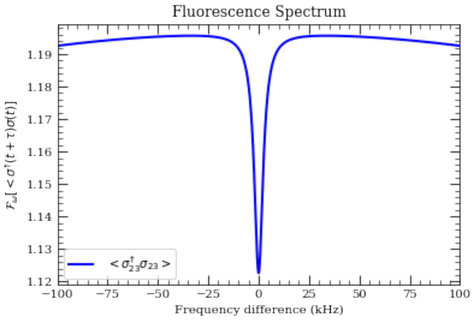
- **AC Stark shifts due to fields from relativistic charged particles calculated using semiclassical formalism with the minimal coupling Schrodinger equation.**
- **Effects of interest include phase shift to EIT wavefunction and the scattering spectrum including coherent and incoherent fluorescent effects.**



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, $\Delta_1 = \Delta_2 = 0$



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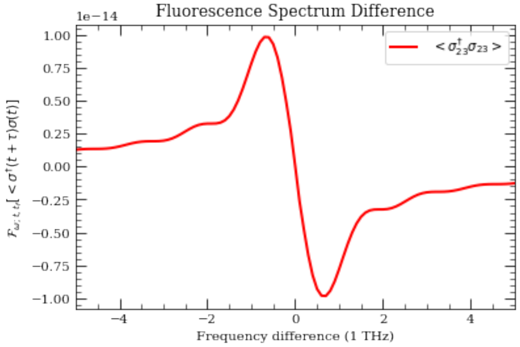

$\Omega_P = 0.1$ MHz, $\Omega_S = 10$ MHz, $\Delta_1 = \Delta_2 = 0$. Introduced gaussian DC Pulse with duration $\tau = 10$ fs causing effective AC Stark shift 20.0 MHz for the Rydberg level, 100 kHz for other levels, .

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*

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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