Magneto Optic Diagnostics for Laser Wakefield Accelerators

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Outline

- Introduction – Accelerators
- LWFA Background– 5 Slides
- Diagnostics
- Magneto Optic Effects (Faraday + Cotton Mouton Effects)
- Cotton Mouton Test Experiment
- Data
- Conclusion

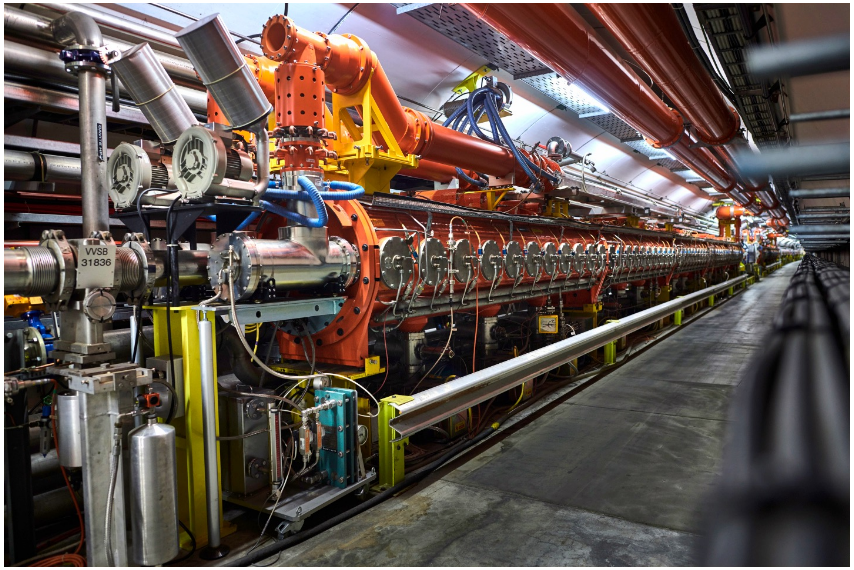
Accelerators

- Goal: Accelerate ions to high energies (MeV-TeV) for use in other applications
- CERN RF LINAC has metallic chambers to ‘fit’ an accelerating frequency mod EM field
- Works by injecting particles & accelerating them (450GeV -> 6.5 TeV)

Cons

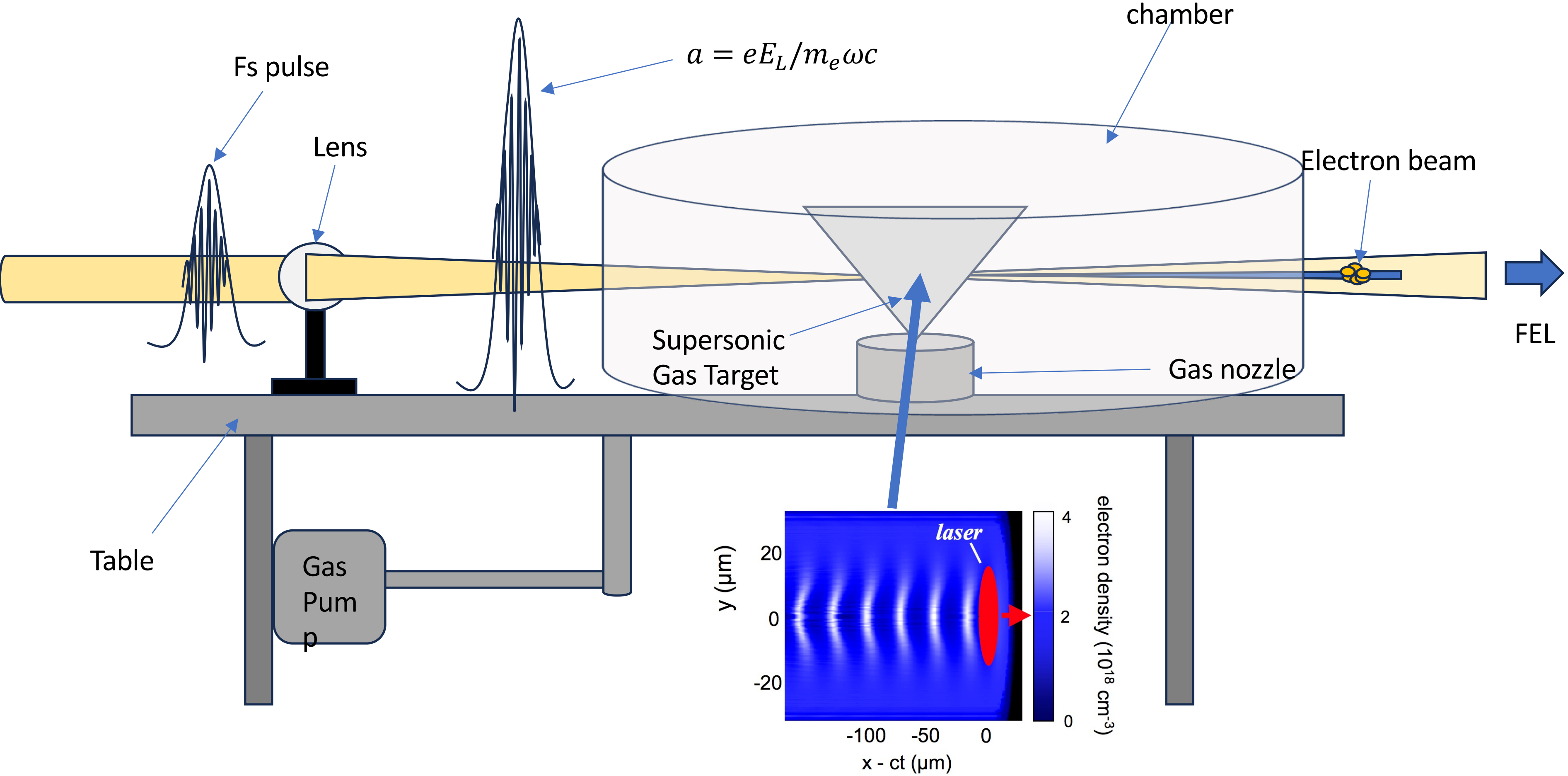
- Occupies a lot of space
- Lots of money to build and operate (order of billions)
- Takes 20 min to accelerate ions already at high energy to higher energy

- What if we could accelerate particles to comparable energies or complement these accelerators using a more compact and quicker method?
- Enable wider usage of accelerators for fundamental physics and industrial needs



CERN

Laser Wakefield Accelerators



Target chamber

Fs pulse

Lens

$a = eE_L/m_e\omega c$

Electron beam

FEL

Supersonic Gas Target

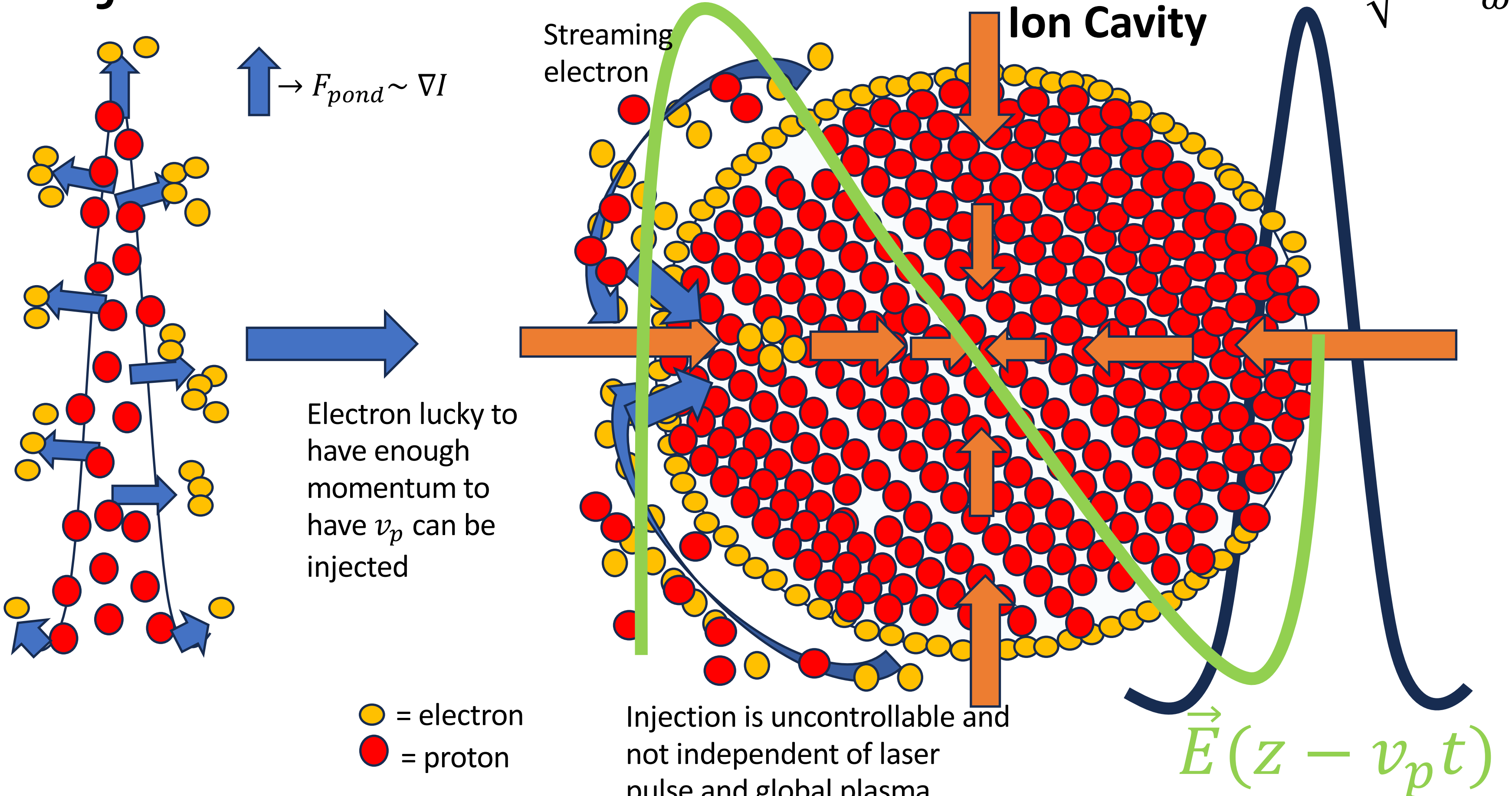
Gas nozzle

Table

Gas Pump

Injection and Acceleration

$$v_g = c\sqrt{1 - \frac{\omega_p^2}{\omega}}$$



$\rightarrow F_{pond} \sim \nabla I$

Streaming electron

Ion Cavity

Electron lucky to have enough momentum to have v_p can be injected

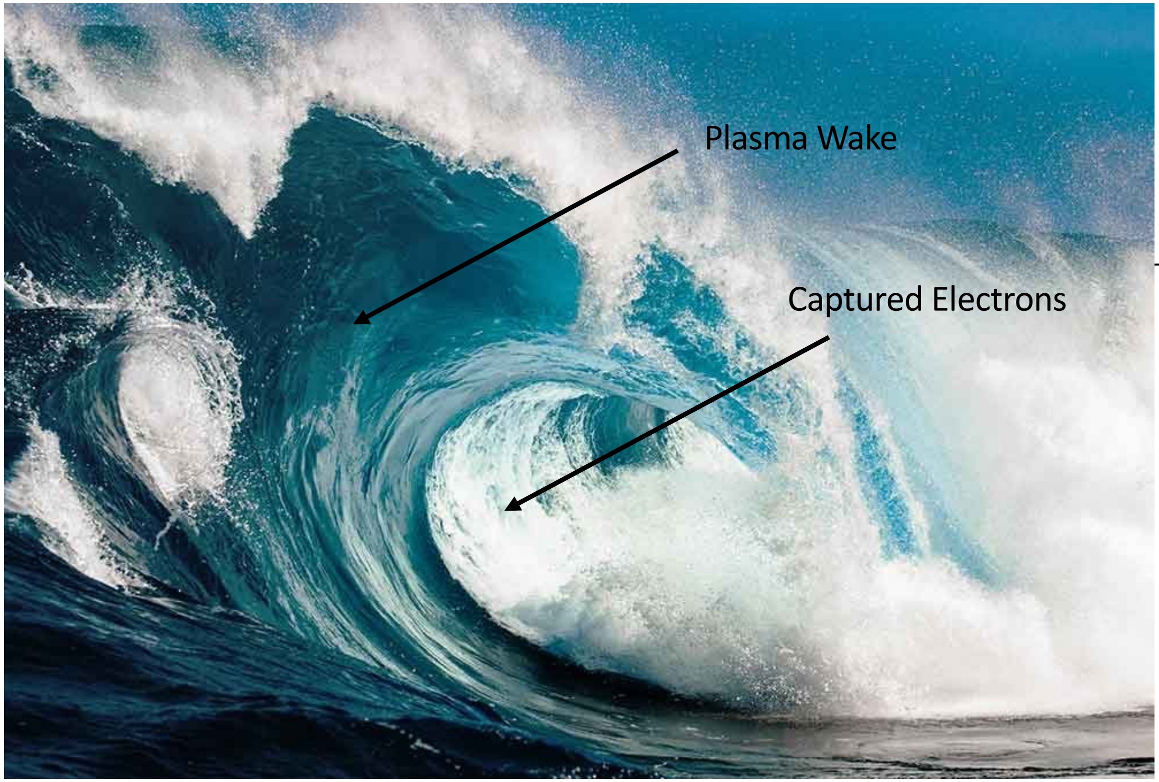
🟡 = electron

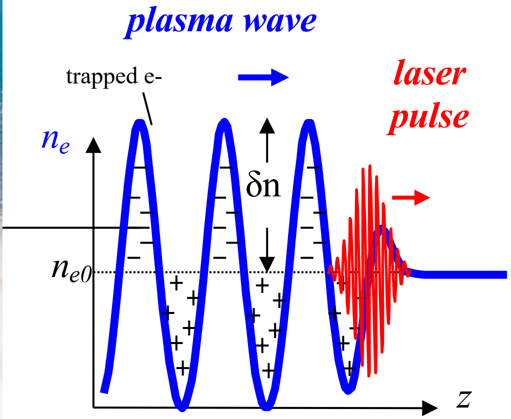
🔴 = proton

Injection is uncontrollable and not independent of laser pulse and global plasma density

$\vec{E}(z - v_p t)$

Cont.





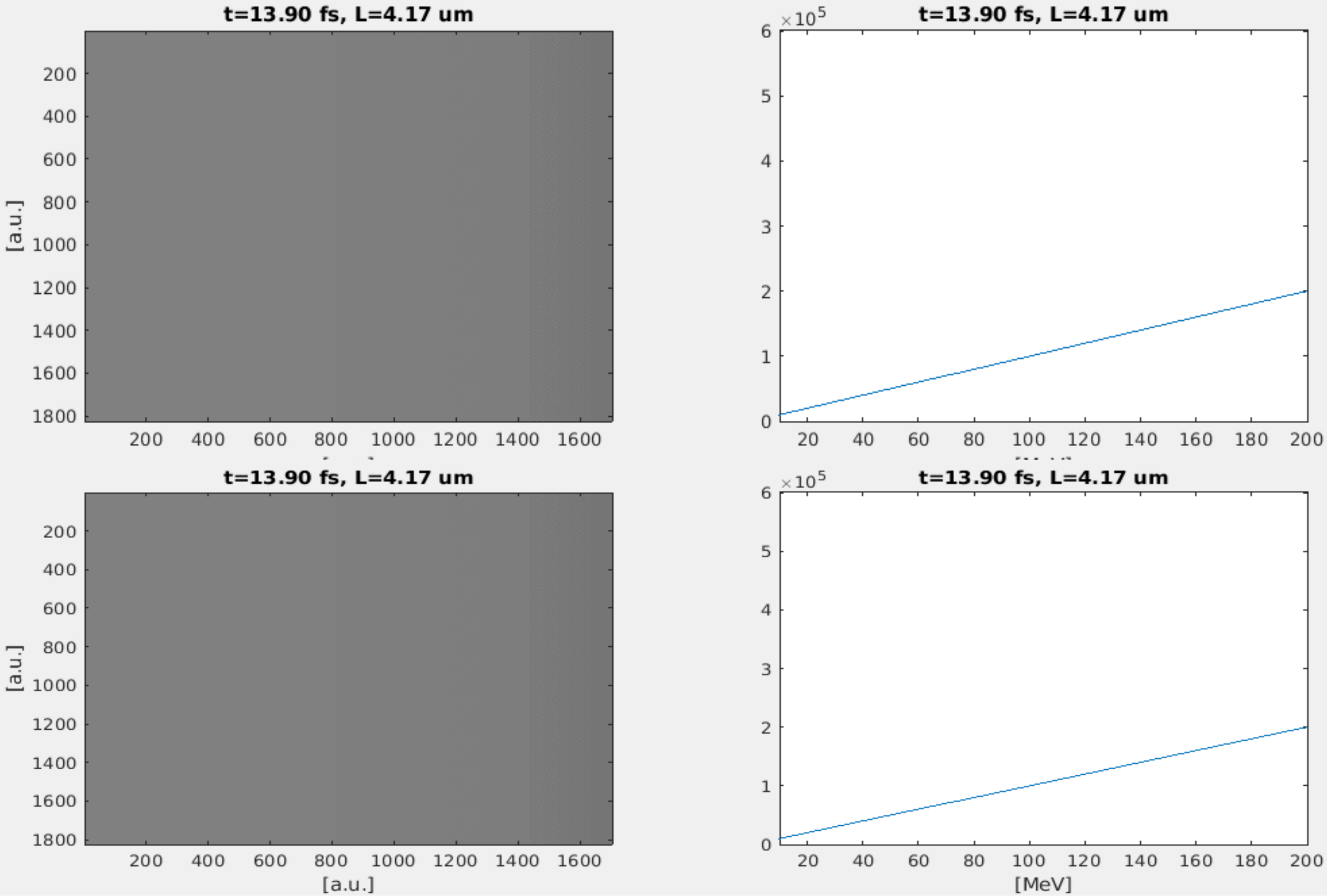
Accelerating Field:

$$E_z = \frac{mc\omega_p}{e} \approx (n_{e0}[cm^{-3}])^{1/2} \frac{V}{cm}$$

$2\text{x}10^9$ V/cm	$4\text{x}10^{18}$ cm^{-3}
$0.7\text{x}10^9$ V/cm	$5\text{x}10^{17}$ cm^{-3}
$\sim 10^5$ V/cm	(conventional accelerators)

E =
800mJ
Dur =
30fs
W =
10um

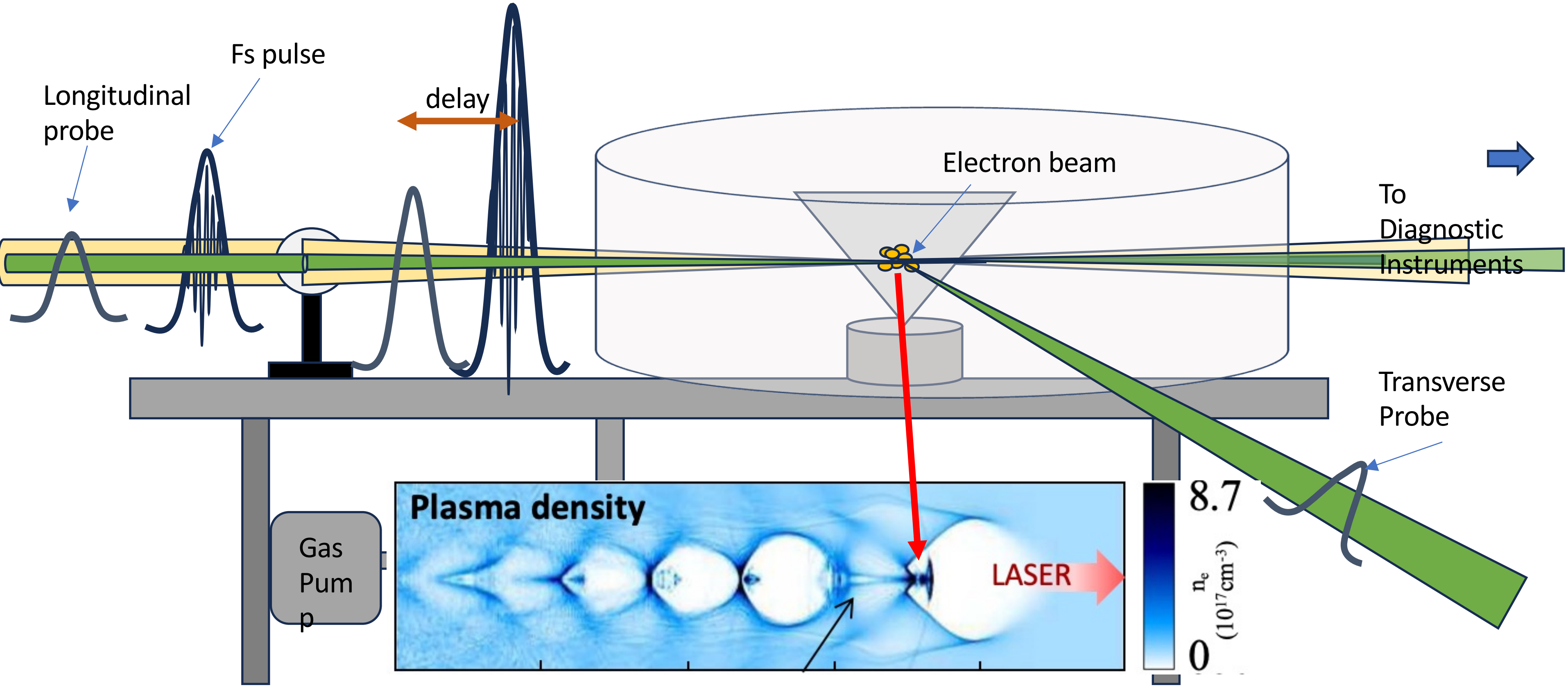
E =
800mJ
Dur =
10fs
W =
10um



Diagnostic Challenge

- Diagnostics allows us to judge performance of accelerator
  - Electron beam Duration
  - Transverse emittance
  - Beam Charge
  - Energy Spread
- Diagnostics for conventional rf accelerators are not effective for bunches produced by LWFA
  - Bunches have duration ($\frac{\sigma_z}{c} \sim 1-10fs$) and transverse beam size ($.1 < \sigma_r < 1\mu m$) make them smaller than beams from km scale accelerators
  - Bunches from LWFA evolve and transient unlike conventional stationary accelerator structures
  - Accelerator performance depends on details of plasma structure and dynamics which depends on evolution of laser drive. Bubble structure governs self injection of electrons
- Diagnostics for characterizing e-beam & Plasma wakes
  - Synchrotron
    - TR, bremsstrahlung, Betatron
  - Frequency Domain Interferometry, Holography, Tomography (requires optical probe)
  - Magnetic spectrometers
  - Magneto Optics Methods (Polarimetry)

Laser Wakefield Accelerators



Longitudinal probe

Fs pulse

delay

Electron beam

To Diagnostic Instruments

Transverse Probe

Gas Pump

Magneto Optic Methods

- Purpose: To understand the structure of $\vec{B}$ (or provide a complementary measurement of n_e) in magnetized plasma in which plasma wakes are formed
- Two sources of $\vec{B}$: E-beam $\vec{j}(\vec{r},t)$ and $\frac{\varepsilon_0 \partial \vec{E}(\vec{r},t)}{\partial t}$ form azimuthal field according to Maxwell Eq $\nabla\, x\, \vec{B}(\vec{r},t) = \mu_0(\vec{j}(\vec{r},t) + \frac{\varepsilon_0 \partial \vec{E}(\vec{r},t)}{\partial t})$
- Can understand internal $\vec{B}$ through change in polarization that it induces on optical probe through two magnetic optic effects: Faraday and Cotton Mouton Effects
  - Measure polarization through measurement of intensity of probe through different projections of polarizer to obtain Stokes Parameters
  - Can also measure through observed modulations in intensity from changes in polarization of probe

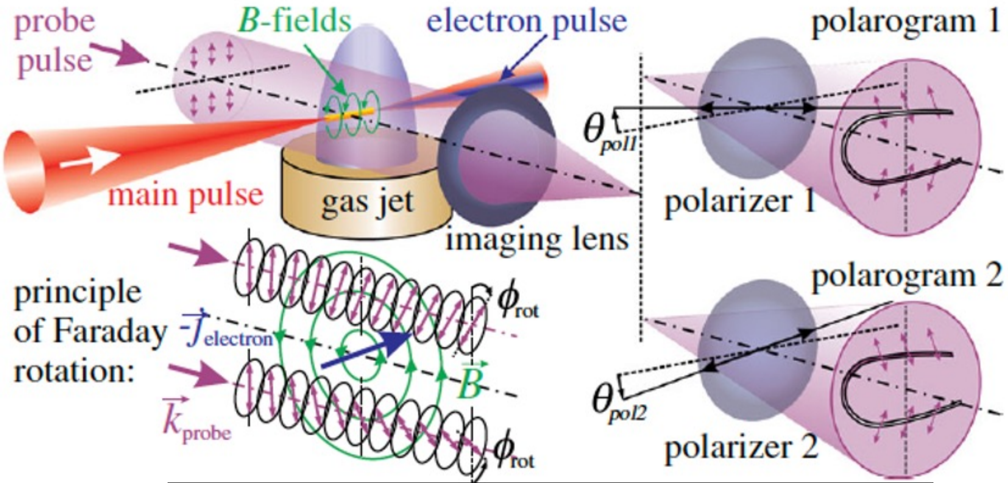
Magneto Optic Effects

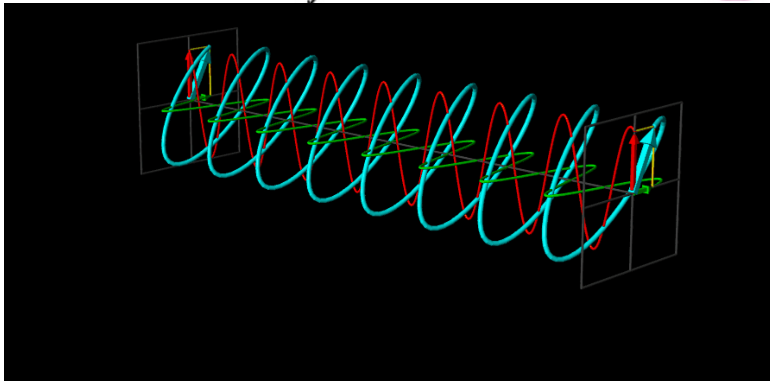
- Faraday Effect ($\vec{k}_{probe}||\vec{B}$)
  - Induces a local rotation of the linear polarized probe $\Delta\theta \propto \lambda^2 \int n_e B \cdot dl$
  - Independently measured with transverse probe

- Cotton Mouton Effect ($\vec{k}_{probe} \perp \vec{B}$)
  - Probe sees a birefringent plasma in which $\Delta\phi \propto \lambda^3 \int n_e B_\perp^2 \cdot dl$
  - Results in local induced ellipticity of the probe

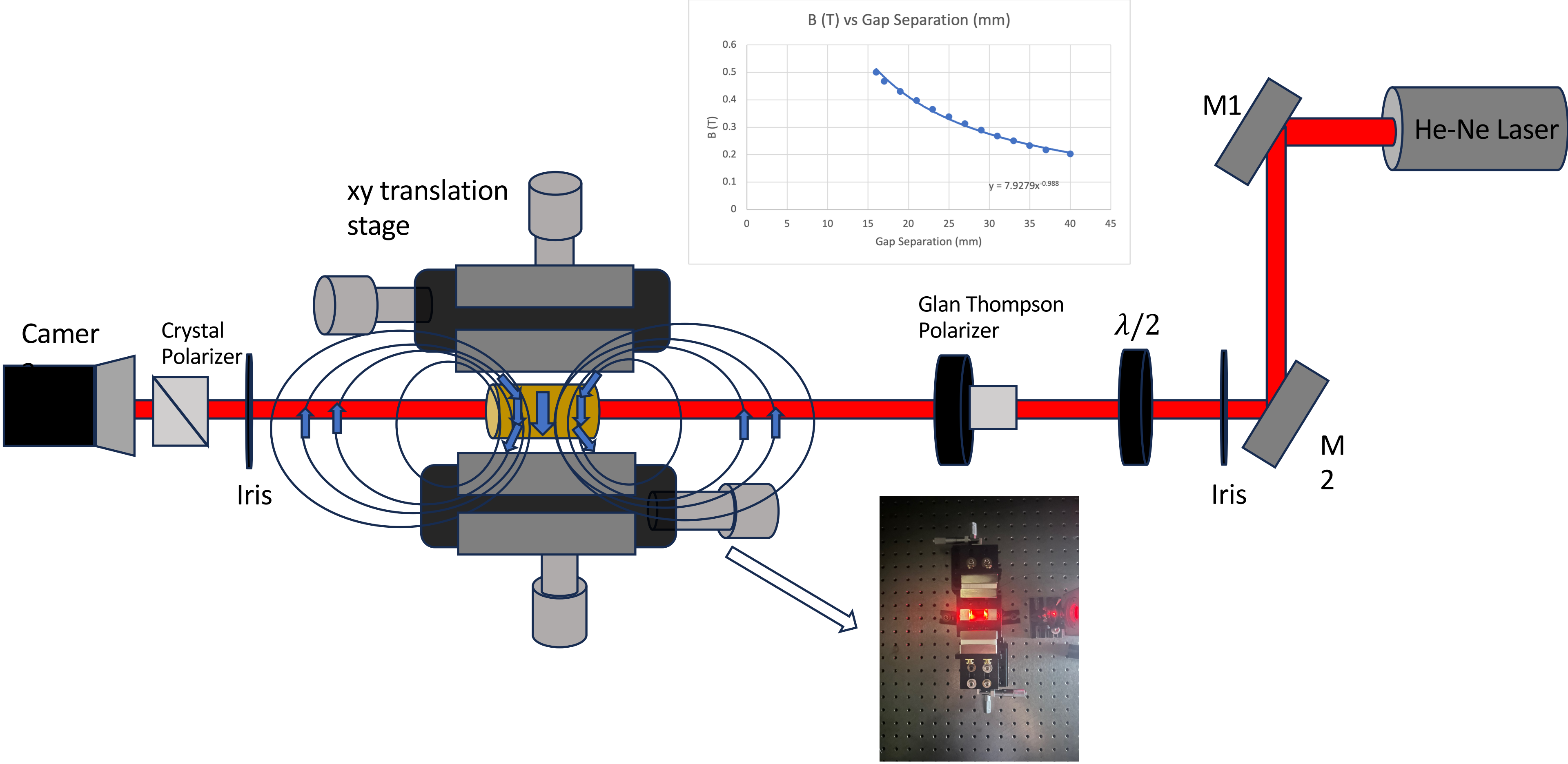
- Complicated evolution of polarization for any probing geometry in between two above cases

- CM Test Experiment: To develop polarimetric and experimental techniques and analysis methods for a MO system (Terbium Gallium Garnet crystal) that has similar MO features to a plasma



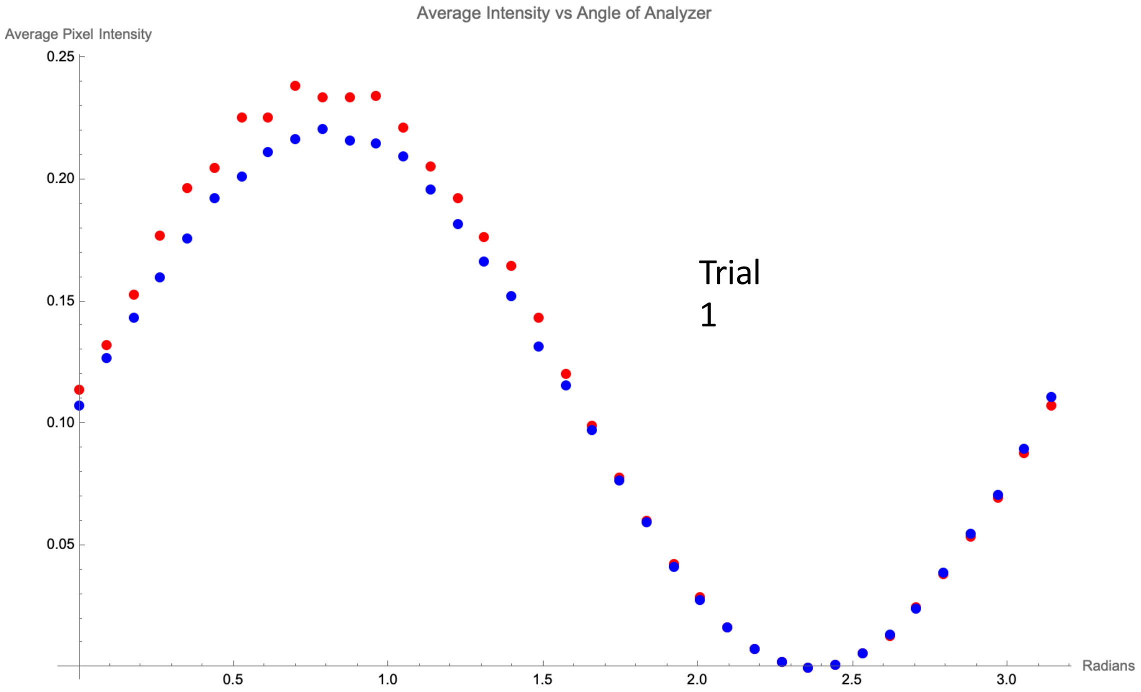


Cotton Mouton Test Experiment



Method I: Measure Intensity vs Angle of Analyzer

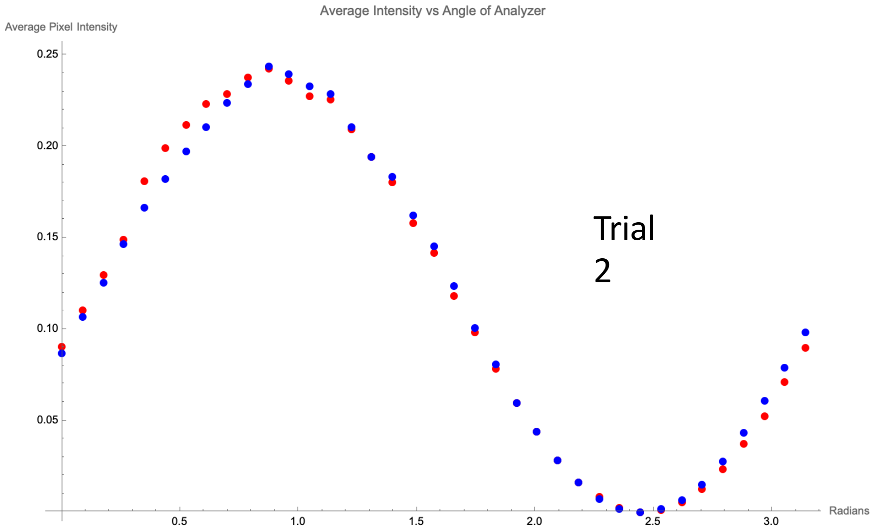
- Procedure: Rotate analyzer through π for both no B and with B
- Average Intensity computed over beam profile at different moments in time
- Idea: To detect modulation at max and min locations @ $\theta = \frac{\pi}{4}$ & $\theta = \frac{3\pi}{4}$ of analyzer, respectively
- Observed asymmetry between max and min positions
- $\Delta I \approx .015$ @ max position

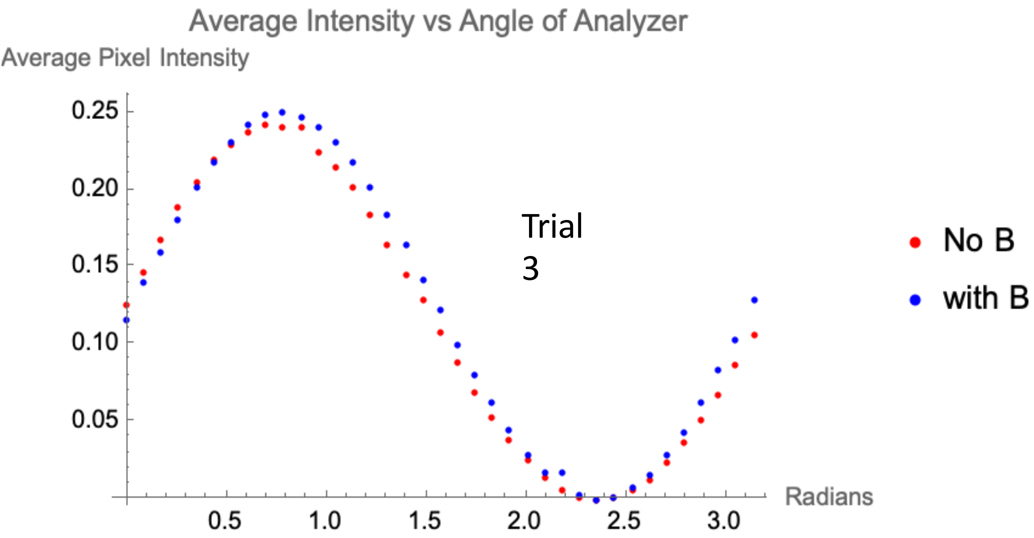


Blue: With B field, Orange: Without B field
B = .3T

Trial
1

(cont.)



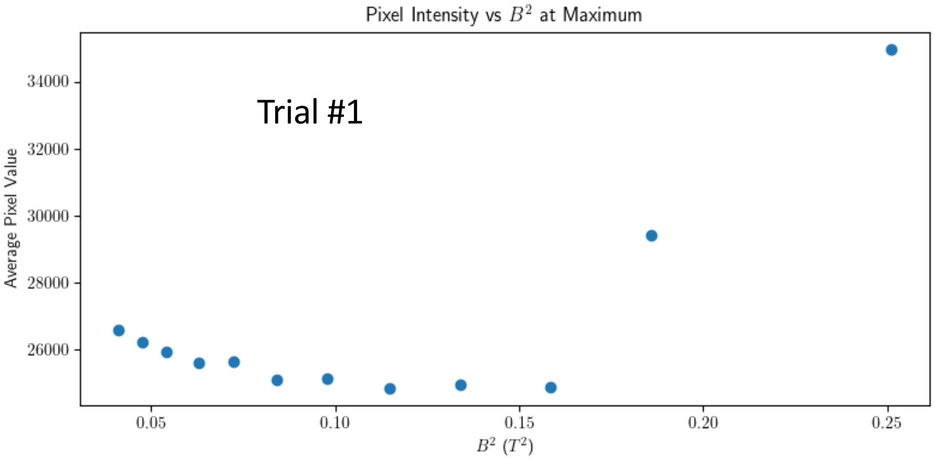


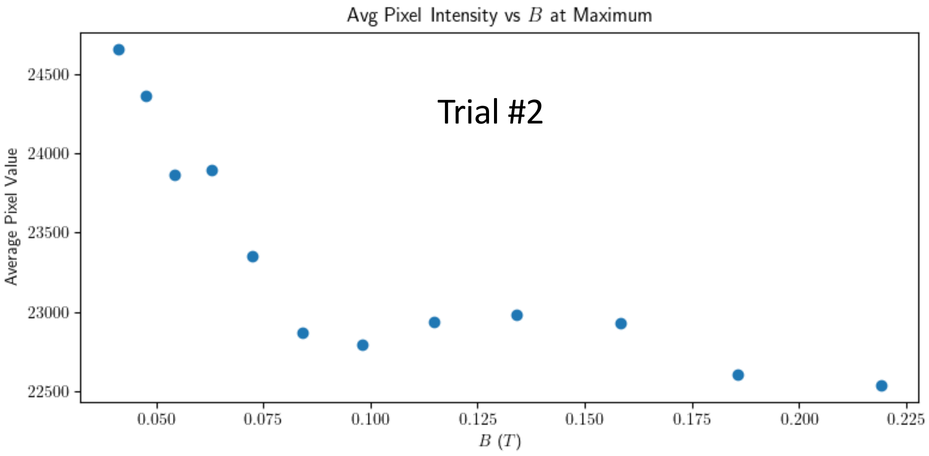
Sources of Noise:

- Human Error (Not going to exact same tick mark each time) (Random Error)
- Fluctuations in the Power output of He-Ne Laser ~ 2% (Noise within trial and between trials)
- Imperfections or Dust on Polarizer surface. (Could be systematic?)
- Beam profile would change between No B and with B (Crystal would move within holder due to a magnet field attraction)
  - I fixed this recently by adding mounting putty to bottom of holder

Method II: Intensity with Varying B Field

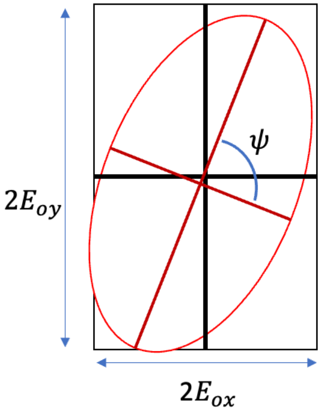
- Identify MO effect by its dependence of Intensity with B field at minimum or maximum
  - Faraday Effect: $\mathrm{I} = \mathrm{I}_0 \cos^2(\Delta\theta)$ (At Maximum), $\mathrm{I} = \mathrm{I}_0 \sin^2(\Delta\theta)$ (At Minimum)
  - Taylor Expanding ($\Delta\theta \ll 1$): $I = I_0(1 - V^2B^2L^2)$ (Max), $I = I_0(1 + V^2B^2L^2)$ $(At\ Min)$
  - Cotton Mouton Effect: $I = I_0(1 - k^2C^2B^4L^4)$ (Max) , $I = I_0(1 + k^2C^2B^4L^4)$ (Min)
  - For $|B_{max}|$ = .5 T & $|B_{min}|$ = .2 T , I expect $\Delta I_{CM} = .0029 = .29\%$ change





Conclusion

- Possible changes with setup and procedure
  - Need to try to isolate the possible errors in my experiment.
  - Can try measuring exclusively at minimum intensity since laser intensity fluctuations are uncorrelated between B and no B situations (ie errors can add)
  - Change crystal mount to allow for more ways to vary position of magnets
  - See if there is any residual birefringence produced by crystal or other optics from stress points on crystal



- Consider alternative methods for measuring state of polarization (ie measuring Stokes Parameters)
  - Rotate Polarizer to 4 angles to get measurements {S0, S1, S2} = $\{P_x + P_y, P_x - P_y, P_{45} - P_{-45}\}$ and then use QWP with polarizer for S3 measurement where S3 $= P_R - P_L$ which together determine state of polarization of beam.
  - Ellipse Parameters can be extracted $\psi = \frac{1}{2} tan^{-1}\left(\frac{S_2}{S_1}\right), E_{0x} = \sqrt{0.5(S_0 + S_1)}, E_{oy} = \sqrt{0.5(S_0 - S_1)}$