Update on Seeded SM-LWFA and Pseudo-Resonant LWFA Experiments – (STELLA-LW)

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  - Tom Katsouleas

- PASER Experiment (Technion - Israel Institute of Technology)
  - Samer Banna

STELLA-LW: Staged Electron Laser Acceleration – Laser Wakefield

- STELLA-LW is examining two new LWFA schemes
- 1st Method: Seeded self-modulated LWFA[1] (seeded SM-LWFA)
  - Use seed *e*-beam bunch to generate wakefield
  - Laser pulse immediately follows to amplify wakefield
  - Probe amplified wakefield using second witness *e*-beam bunch
- 2nd Method: Pseudo-resonant LWFA[2] (PR-LWFA)
  - Use nonlinear plasma interaction to steepen tail of laser pulse
  - Causes laser pulse to generate wakefield like shorter pulse
- Both may permit more controllable wakefield formation, which would be important for staging LWFA
- For more details on theory and modeling, see talk on Thursday in WG6

[1] N. E. Andreev, et al., Phys. Rev. ST Accel. Beams **9**, 031303 (2006).
[2] N. E. Andreev, et al., Phys. Rev. ST Accel. Beams **6**, 041301 (2003).

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Overview of Experimental Approach

- Seeded SM-LWFA and pseudo-resonant LWFA being pursued in parallel
  - Both require technology development and device upgrades
  - These developments and upgrades are pacing the program effort
- Both experiments use ATF CO_2 laser beam
  - Current laser performance adequate for seeded SM-LWFA
  - Additional upgrades needed for pseudo-resonant LWFA
- Both experiments use capillary discharge as plasma source
  - Both polypropylene and gas-filled capillaries operational
  - It appears experiments can use either type of capillary
- Preliminary PWFA measurements have been performed and results will be presented in this talk

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Summary Experiment Status

- Seeded SM-LWFA requires:
  - Ultrafast (~100 fs) *e*-beam seed followed by laser pulse (< 1 TW is OK) — Have two seed bunches
  - Witness *e*-beam bunch follows laser pulse to probe amplified wakefields — Demonstrated
  - Plasma density of ~10^{17} cm^{-3} — Demonstrated
- Pseudo-resonant LWFA requires:
  - High-power laser pulse (≥3 TW) — Achieved 1 TW
  - Witness *e*-beam bunch to probe wakefields — Available
  - Plasma density of ~10^{16} cm^{-3} — Demonstrated
- Use either polypropylene or gas-filled capillary discharge — Currently using polypropylene
- Located on Beamline #1 at ATF
  - Various diagnostics available

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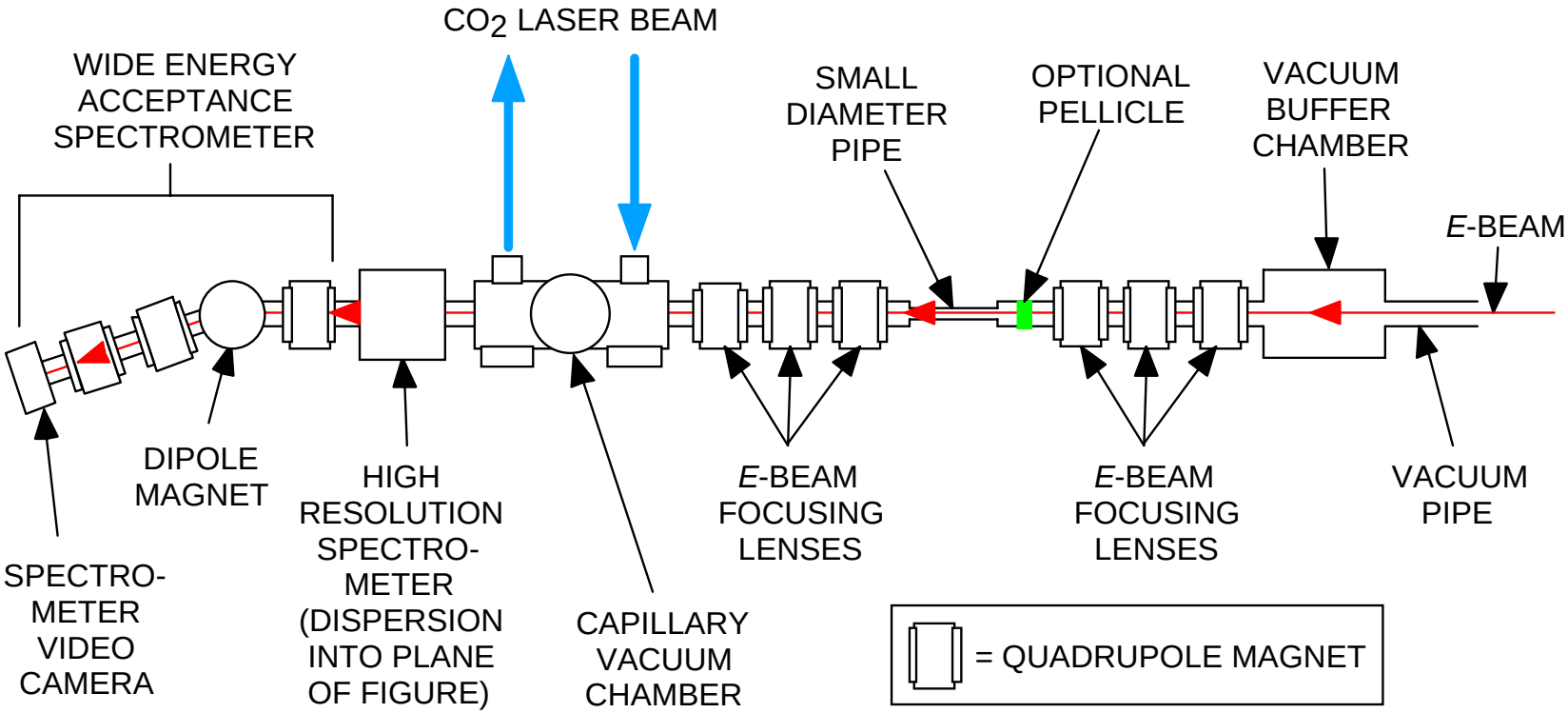
Schematic of STELLA-LW Experiment Layout on ATF Beamline #1



STELLA-LW Capillary Chamber Drawing

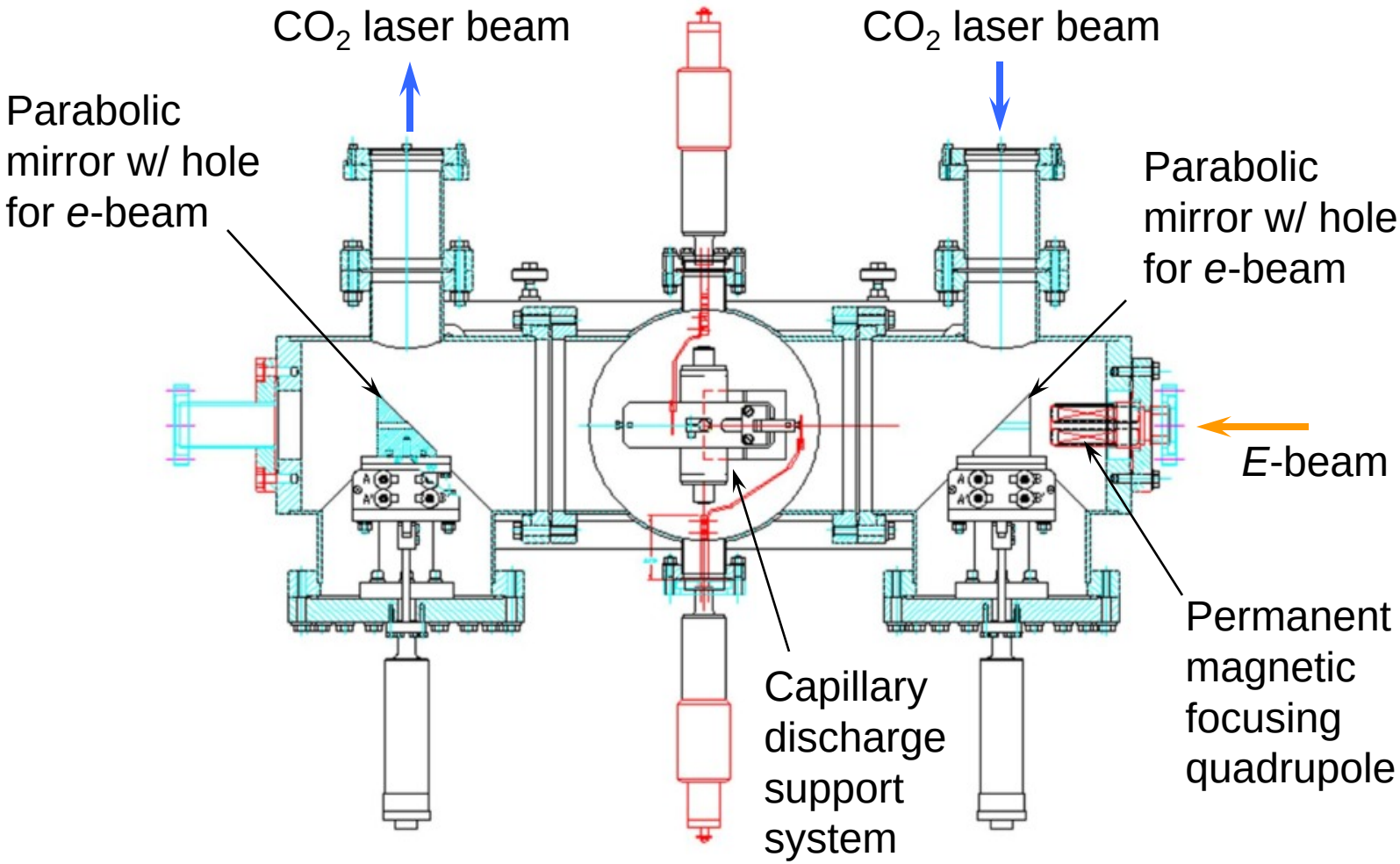


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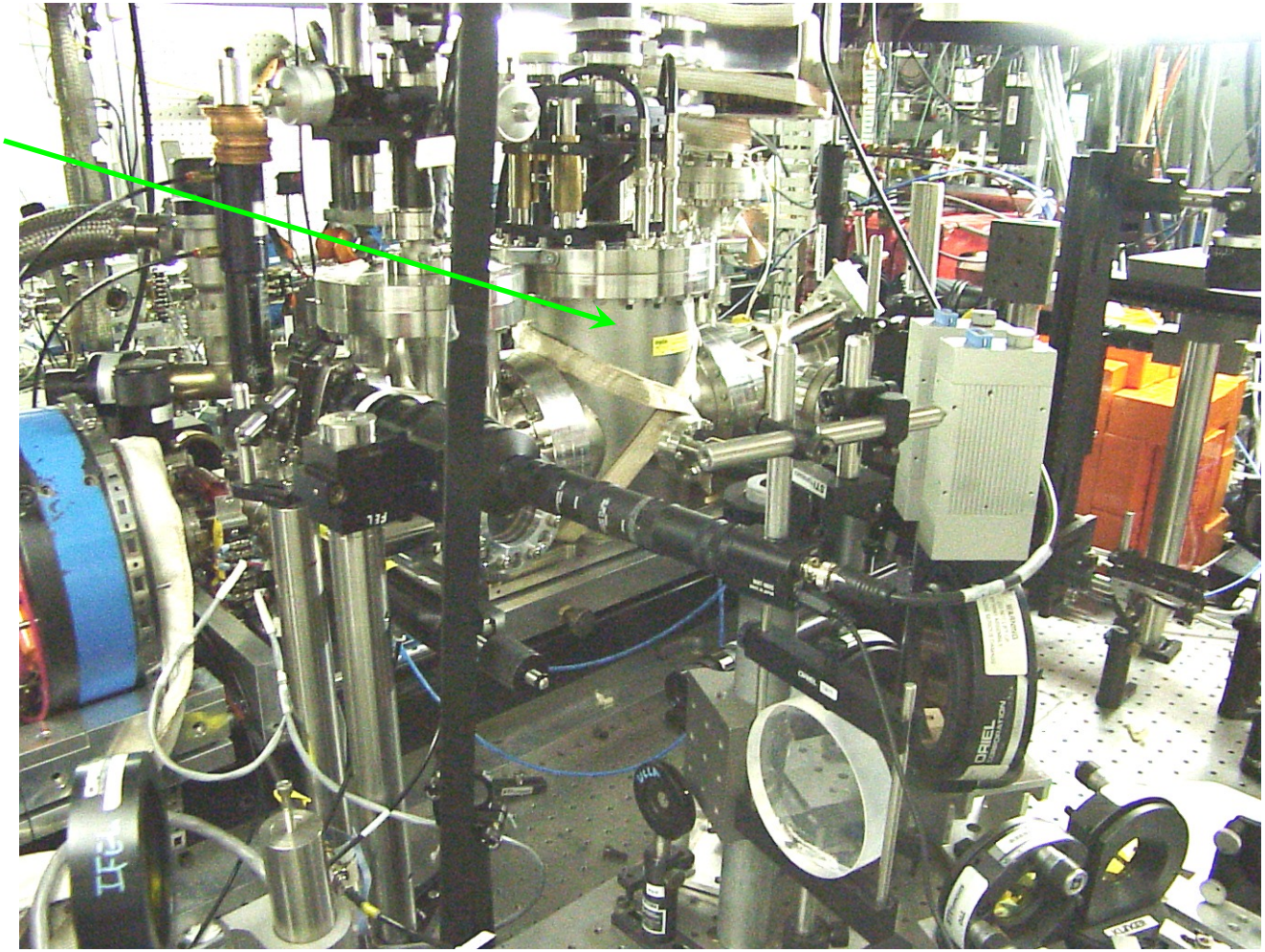
Photo of Capillary Vacuum Chamber

Vacuum Chamber



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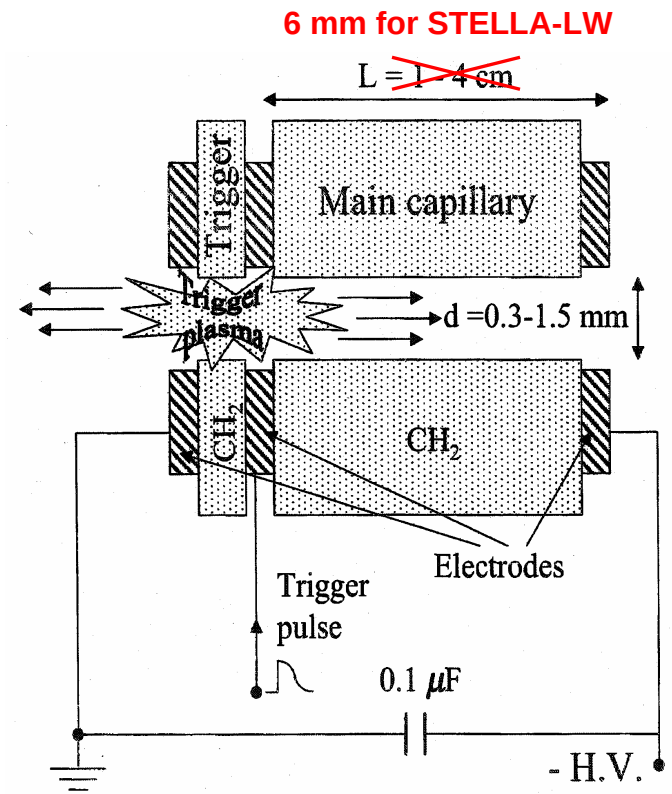
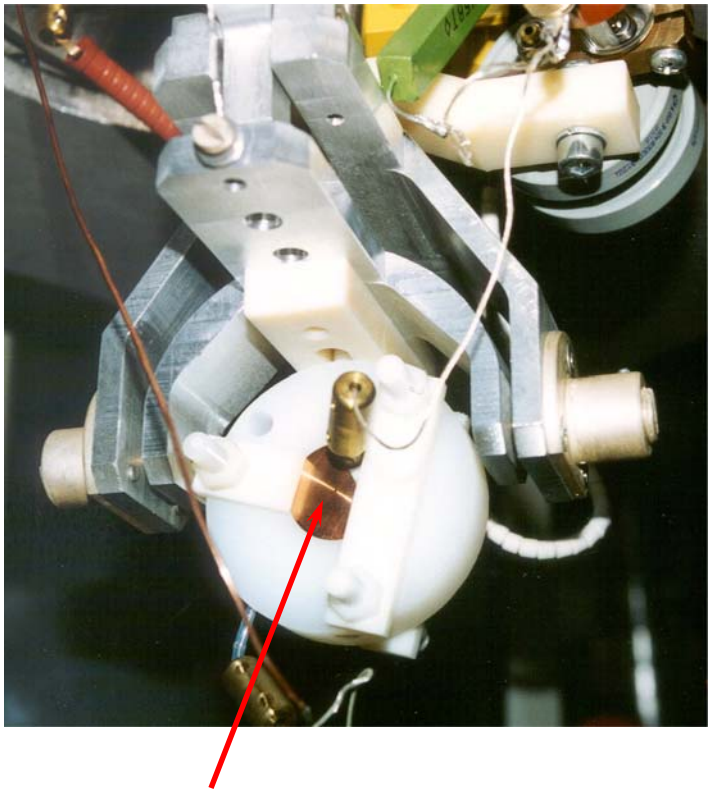
Polypropylene Capillary Discharge



Basic Zigler design [3]



Entrance to capillary

[3] D. Kaganovich, *et al*., Appl. Phys. Lett. **71**, 2925 (1997).

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Update on Polypropylene Capillary

- Use short capillary for seeded SM-LWFA
  - Trigger section = 2.3 mm, main discharge = 3.8 mm, ID = 1 mm
- To avoid disrupting *e*-beam transport through capillary, delay arrival of *e*-beam until 1 μs after start of discharge current
  - Plasma density decays during 1 μs delay
  - Convenient method for achieving low plasma density
- Measure plasma density using time-resolved Stark broadening diagnostic (developed as part of Resonant PWFA Experiment)
  - Width of hydrogen lines depends on electron density
  - Indicates low densities achievable (~10^{15} – 10^{16} cm^{-3})
- Plan to improve basic capillary design by installing optical fiber to view inside of capillary for Stark broadening diagnostic
  - Present Stark broadening diagnostic collects light emitted from end of polypropylene capillary

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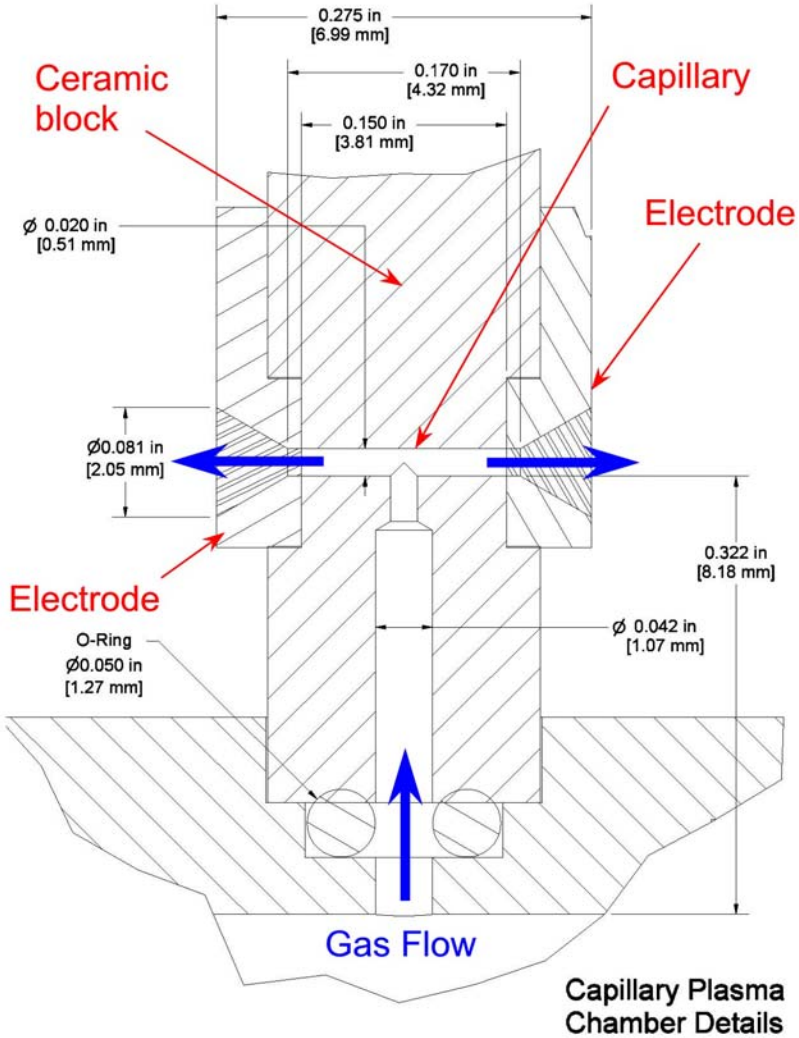
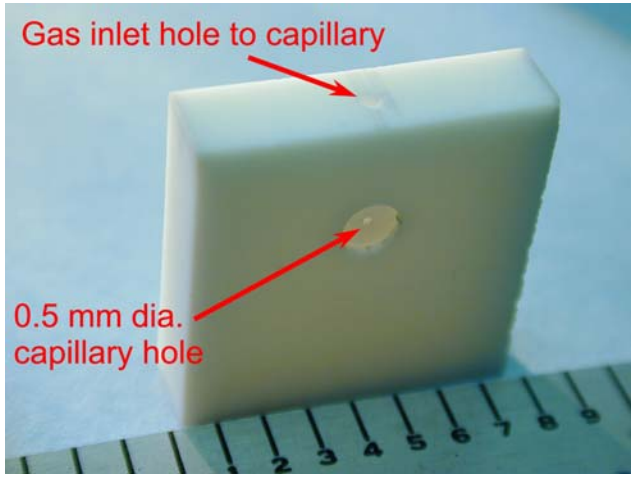
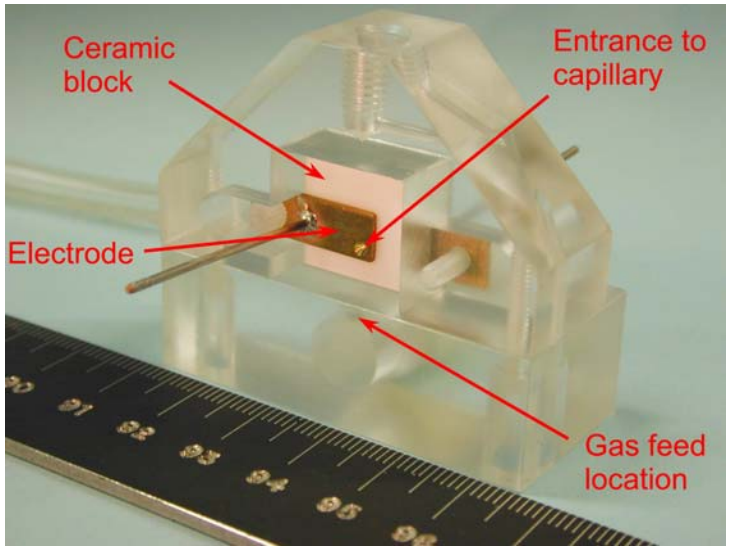
Gas-filled Capillary Discharge







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Gas-Filled Capillary Update

- Optical fiber installed to view inside capillary for Stark broadening diagnostic
  - Indicates plasma density is ~3x higher than measurements taken collecting light from end of capillary
  - Also indicates 100% ionization may not be occurring at low gas densities
- Gas from capillary exhausted into beamline vacuum is an issue
  - Use fast, pulsed valve, but significant gas loading still occurs
  - To protect linac vacuum, have special 1-μm thick Ti foil pellicle, which can be inserted into beamline between capillary vacuum chamber and linac
- Resonant PWFA Experiment is interested in using gas-filled capillary at very high plasma densities (~10^{19} cm^{-3})
  - Achieving high plasma density requires higher drive current from high voltage capillary driver
  - STI Optronics loaning thyratron system to upgrade discharge circuit

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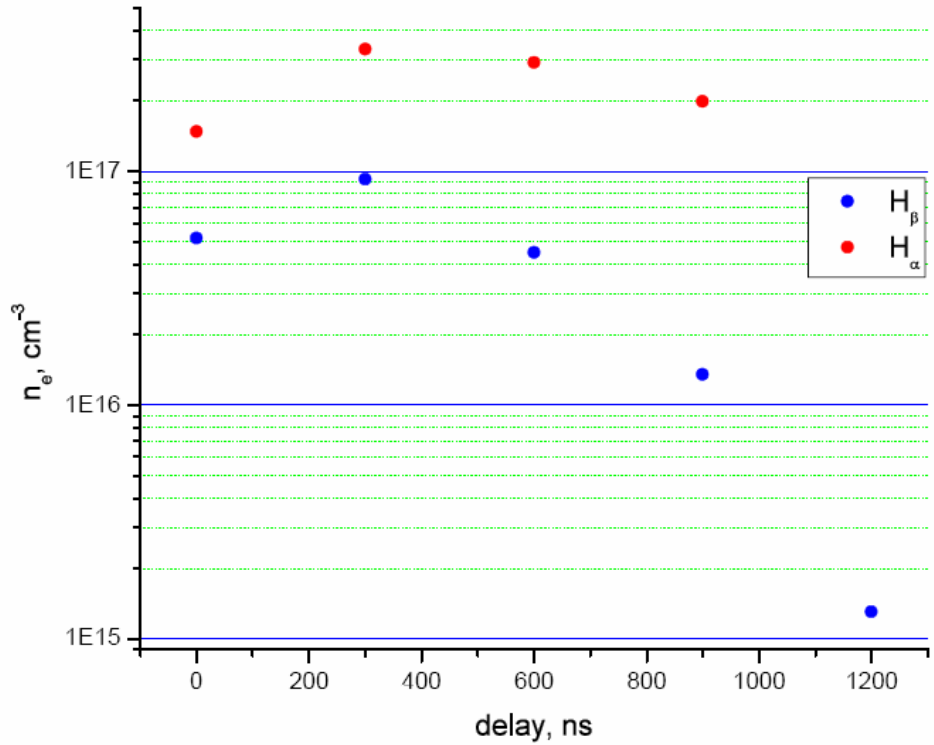
Example of Measured Plasma Density in Polypropylene Capillary

- Observe Stark broadening of hydrogen lines by sending light from discharge through optical fiber to spectrometer and high-speed, gated camera
  - Broadening of Hβ line (486 nm) tends to be better indicator than Hα line (656 nm) because Hβ broadening less sensitive to electron temperature
  - Therefore, rely primarily on broadening of Hβ line
  - Actual density is ~3X higher



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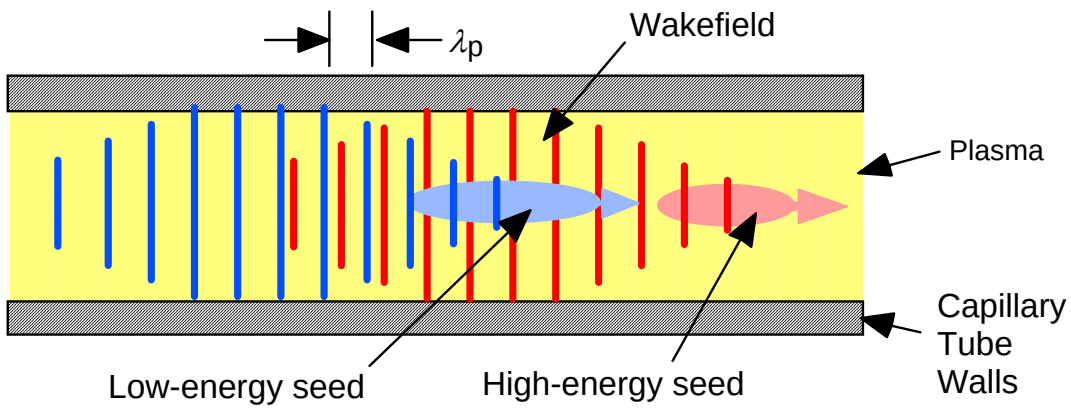
ATF Linac Produces Two Seed Bunches

- ATF uses chicane to compress *e*-beam bunch
- Discovered that chicane/dog-leg system causes *e*-beam to break up into two compressed bunches
  - Bunches separated in time (~0.5-1 ps) and energy (~1.8 MeV)
  - Refer to bunches as “high-energy seed” and “low-energy seed”
  - Bunch lengths are comparable to each other (~100-200 fs) with high-energy seed preceding low-energy seed
  - See talk in WG4 on Thursday for more details of double-bunch beam
- Can still generate wakefields from double-bunch seed
  - But, interference of wakefields now possible



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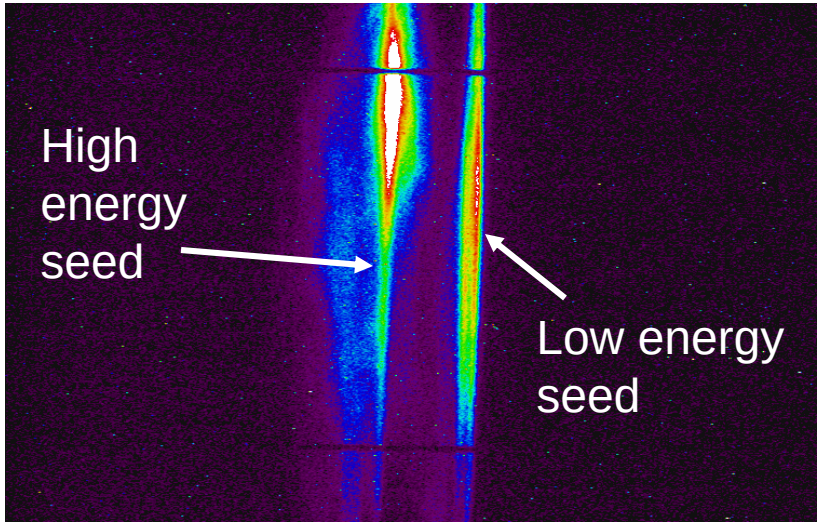
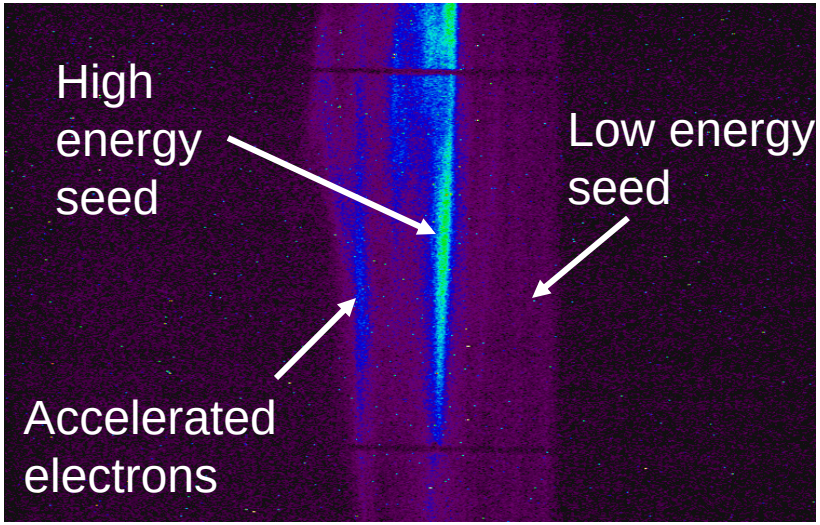
Example of PWFA Energy Spectrometer Raw Data

No Discharge



Energy dispersion

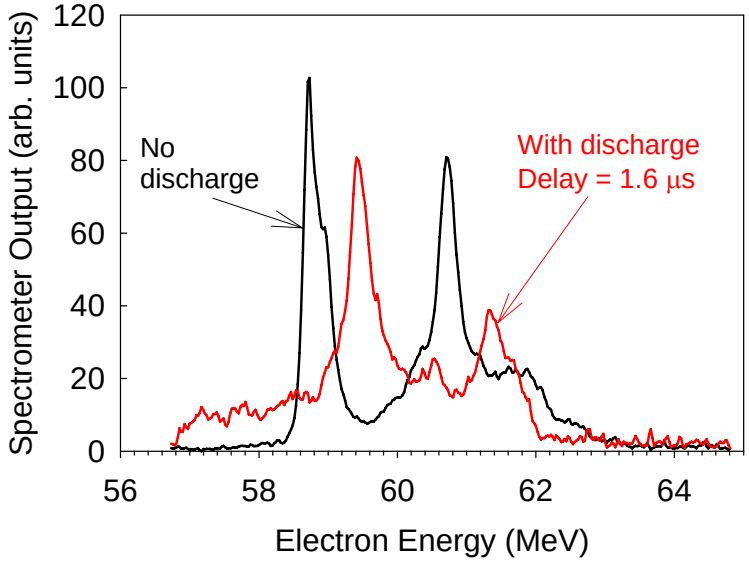
With Discharge
At Delay Time = 1.6 μs



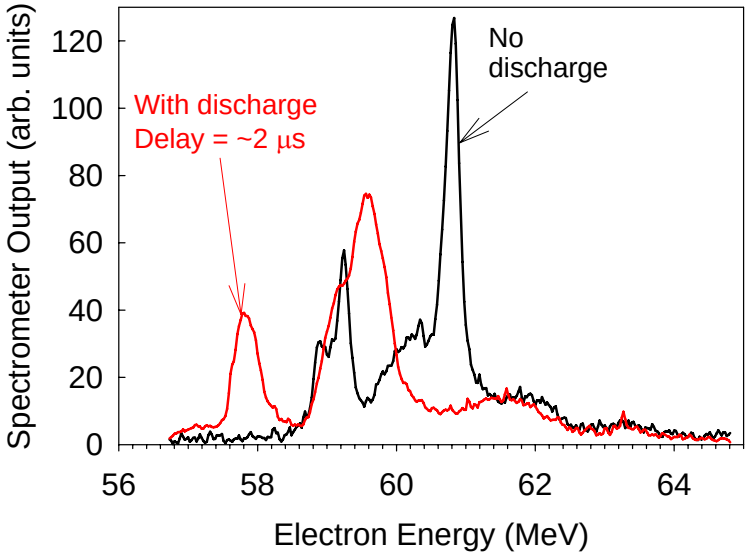
Energy dispersion

Energy Spectrums Sometime Show Gain; Sometime Show Loss

Case #1: Showing energy gain with seeds having comparable charge



Case #2: Showing energy loss of both seeds with charge in low-energy seed less than high-energy seed



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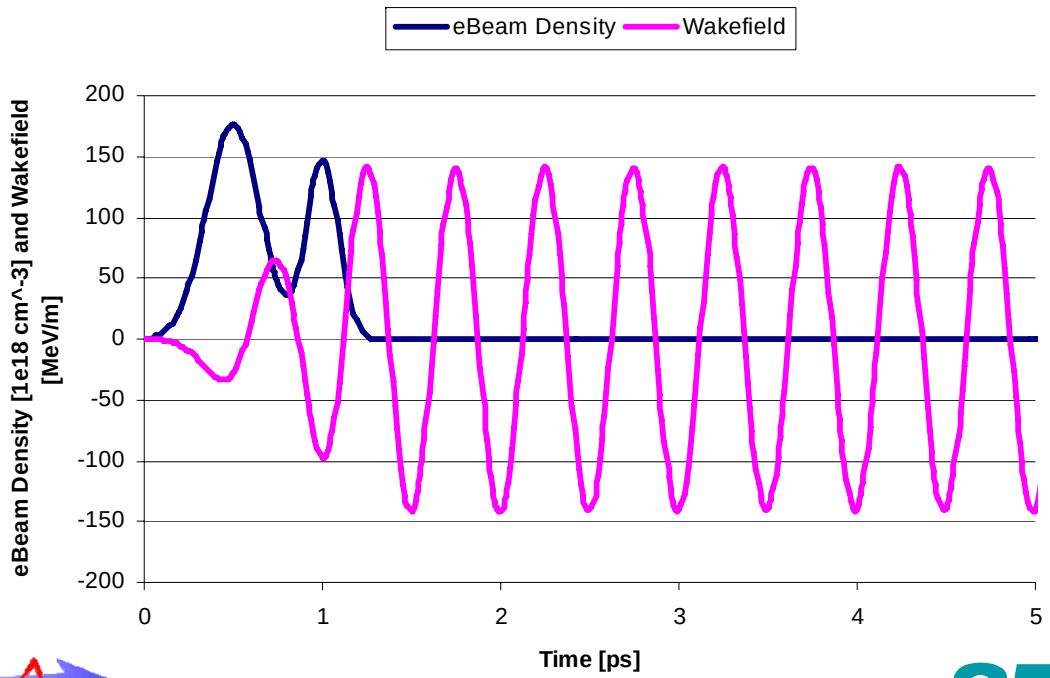
PIC Model[4] Used to Help Understand Double-Bunch PWFA Results

- Parameters assumed in model:
  - High-energy seed: σ_z = 150 fs, σ_r = 100 μm, charge = 200 pC
  - Low-energy seed: σ_z = 90 fs, σ_r = 100 μm, charge = 100 pC
  - Separation between bunches = 500 fs, n_e = 5 x 10^{16} cm^{-3}



[4] Courtesy E. Kallos

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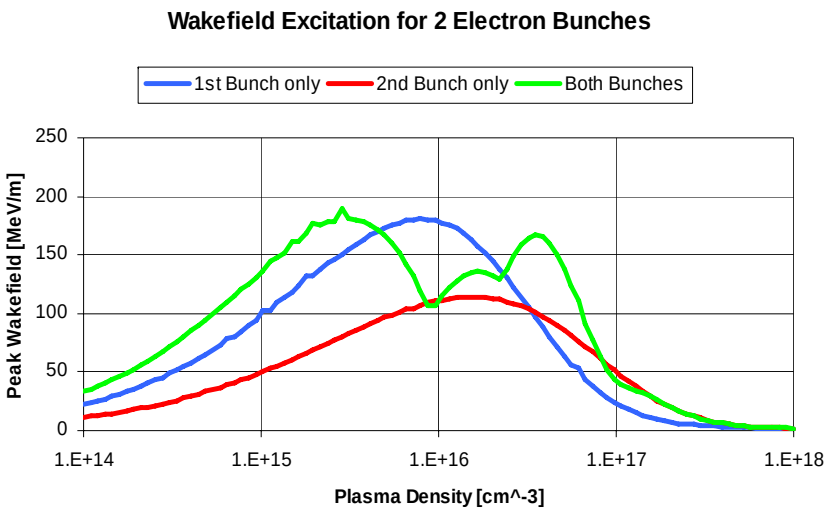
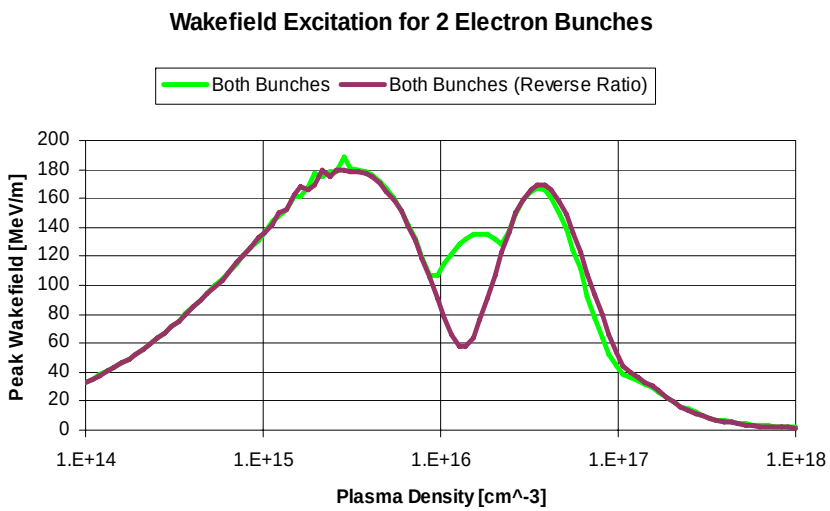
Model Predicts Wakefield Interference

- Amount of interference affected by relative amount of charge in each seed
  - Reverse ratio means low-E seed has less charge than high-E seed
  - Helps explain why data sometimes saw energy gain and sometimes saw energy loss of both seeds





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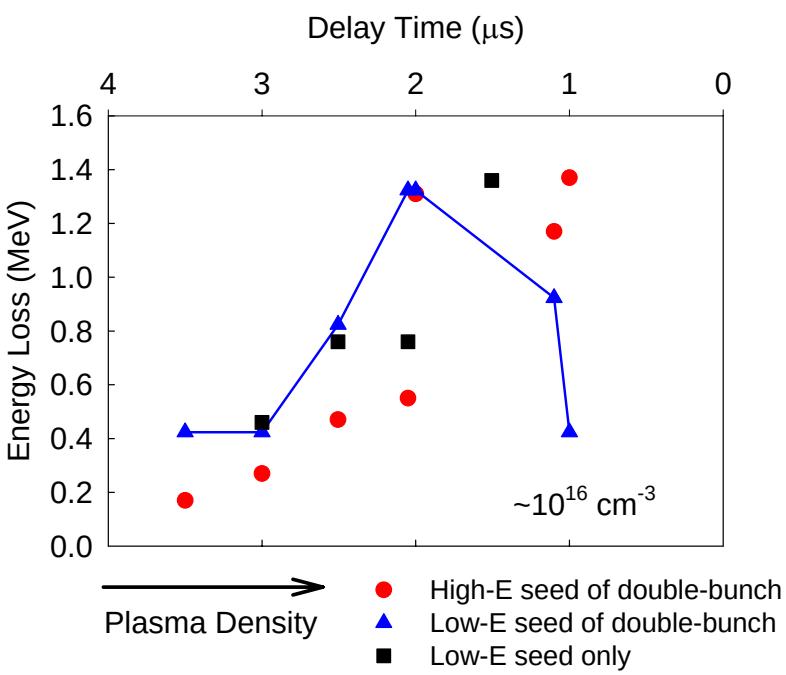
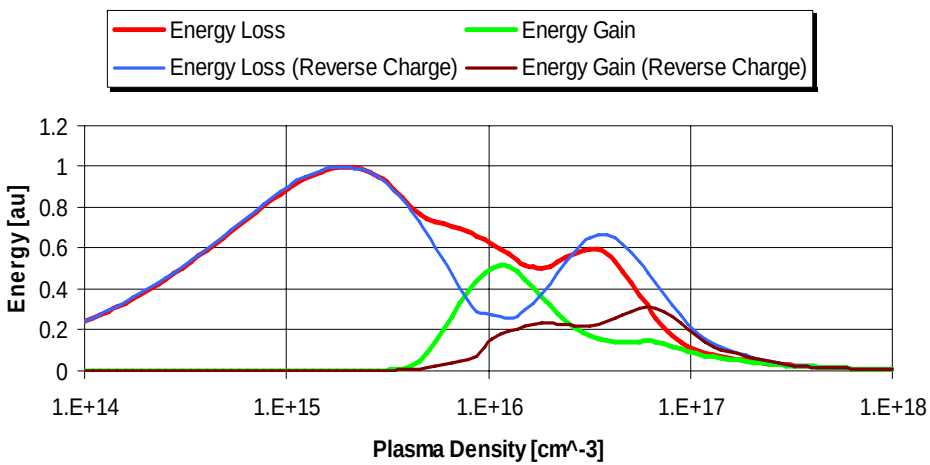
Model Predicts Energy Loss Dependence on Plasma Density Seen in Data

- Used only simple method for estimating energy gain or loss.
  - Consistent with energy loss behavior of low-energy seed
  - Also explains energy loss dependence on charge ratio between seeds



Model prediction for double-bunch



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ATF CO_2 Laser System Being Upgraded to Achieve 3 TW

- Recent upgrade has achieved 5 J/pulse in 5-ps pulse length (1 TW)
  - Achieved by increasing slicing speed of Kerr cell
  - Risetime of Nd:YAG slicing pulse now limiting minimum CO_2 pulse length
  - ATF in process of upgrading Nd:YAG system to enable faster slicing
- Preliminary tests with sending 1 TW laser pulse into capillary reveal need to control backscattered light
  - High-gain of CO_2 amplifiers can amplify backscattered light
  - Parasitic lasing must also be controlled
  - ATF implementing various schemes to isolate optical train and suppress parasitic lasing

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Near-Term Plans

- Perform PWFA experiment using double-bunch seed and witness bunch
  - Challenge is focusing three different bunches with three different energies into capillary
  - PIC model critical for understanding complex energy spectrum
- Modify polypropylene capillary to permit direct viewing of discharge with optical fiber
  - Provide more accurate measurement of plasma density
  - Will allow monitoring plasma density when laser beam is sent through capillary
- Send 1-TW laser beam into capillary discharge
  - Use Stark broadening diagnostic to detect any change in plasma density due to presence of laser beam
  - Next perform seeded SM-LWFA experiment

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Conclusions

- Double-bunch seed unexpected complication to seeded SM-LWFA experiment
  - As we have improved our understanding of this new phenomenon, it appears it may be still suitable as a wakefield seed
  - Double-bunch formation process may have other useful applications
- Pseudo-resonant LWFA in principle is simpler experiment, but further modeling analysis shows we must have 3 TW laser peak power
  - May require another 12 months for completion of laser upgrade
  - In meantime, will concentrate on seeded SM-LWFA
- Have begun thinking about next goals after completion of these proof-of-principle experiments
  - Demonstrating LWFA buncher
  - Staging of LWFA devices

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