HyperV Plasma Jet Optical Diagnostics: Status and Plans*

A Case, F. D. Witherspoon, S. Messer, R. Bomgardner
HyperV Technologies Corp., Chantilly, VA

The current optical diagnostic suite for the HyperV Technologies plasma jets includes Interferometry, Spectroscopy, and Fast Imaging. The Interferometer is a HeNe Quadrature Heterodyne system currently with only a single channel, but with the potential to expand to two channels in the future. Resolution is $\approx 5 * 10^{13} cm^{-3}$, and time response is better than 50 ns. The Spectrometer is a 1 meter f/8.7 Czerny-Turner configuration with a 2400 lines/mm grating and a PImax camera for recording the spectrum. The camera has a phosphor with extended response in the blue-UV, and is capable of time resolution down to 50 ns, though the full system time response is limitated by light collection. The third major optical diagnostic is a high speed PIMax II camera with time response down to 5 ns which is used for imaging the plasma in the visible. The camera has a multiple exposure feature that allows measurements of jet motion, and which has been used with a simple ballistic pendulum to make rough measurements of total jet momentum. Future plans include optical deflectometers based on an existing design developed by Sam Brockington and David Hwang at UC Davis to resolve plasma density gradients, improvements in spectroscopy collection optics, coupling to the spectrometer, and more sophisticated analysis routines, all intended to improve time resolution, and an additional channel of interferometry to allow for simultaneous measurements at two locations.

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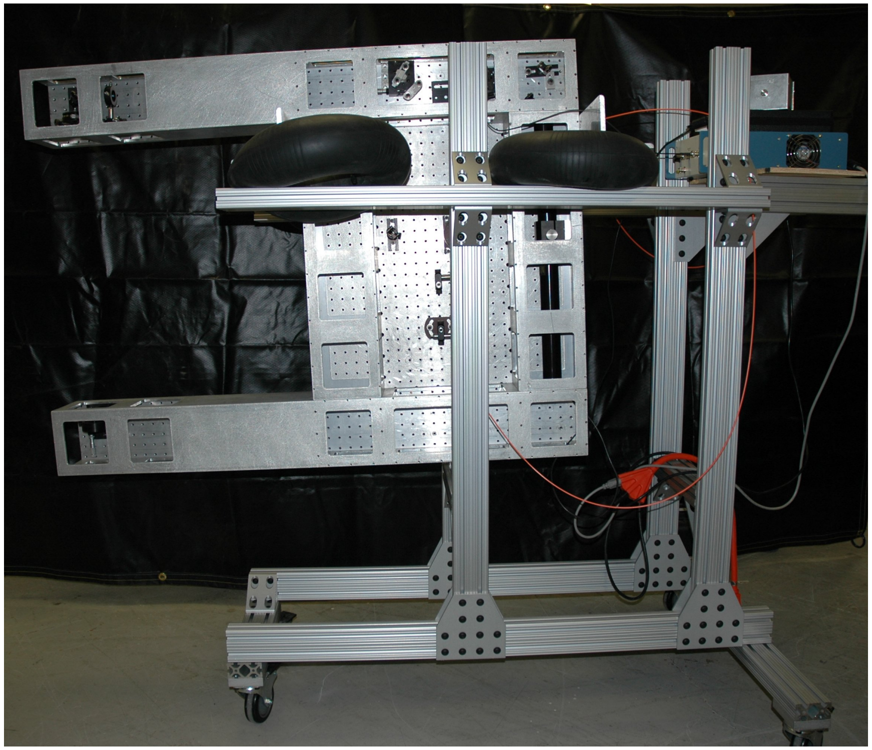
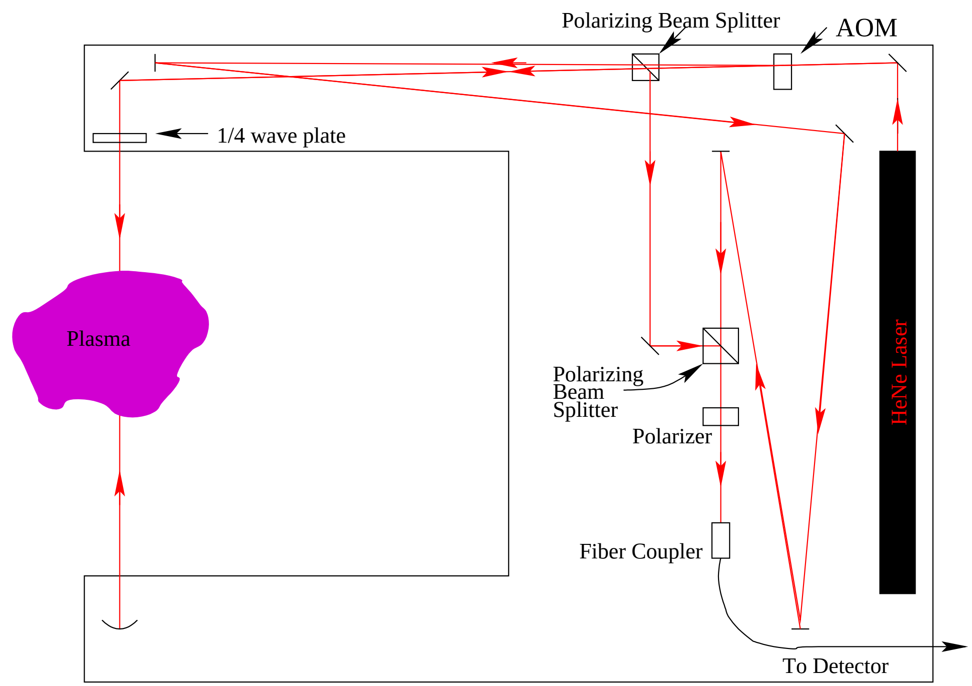
Interferometer System

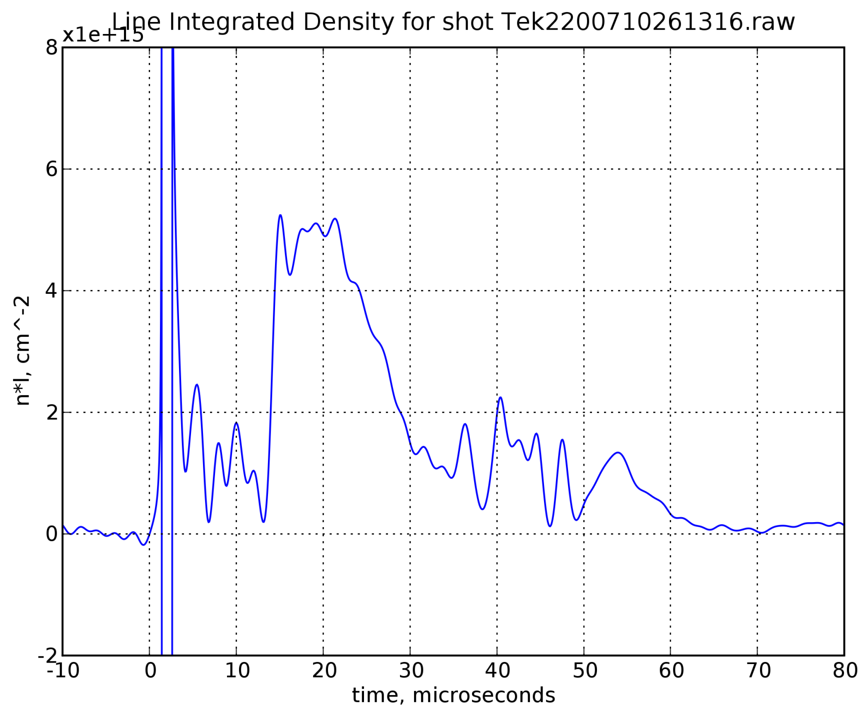




The interferometer system is a double-pass Helium-Neon (632 nm) interferometer using polarizing beamsplitters to separate and recombine the reference and scene beams. The optical components are mounted on a rigid aluminum frame with extension arms which permit the scene beam to pass through the plasma without requiring a separate vibration isolated retroreflector mount. Phase detection is via a quadrature heterodyne circuit, using the acousto-optic modulator to create a beat frequency of 110 MHz in the interference pattern, which serves as the carrier for the phase information. Time resolution is approximately $0.1\mu s$and the line integrated density resolution is $\approx 5 \times 10^{13}\text{cm}^{-3}$. The design is based on existing systems constructed at Swarthmore College (for the Swarthmore Sustained Spheromak Experiment, SSPX) and the University of California, Davis (for the Compact Toroid Injection Experiment, CTIX).

Our New Interferometer is now Operational

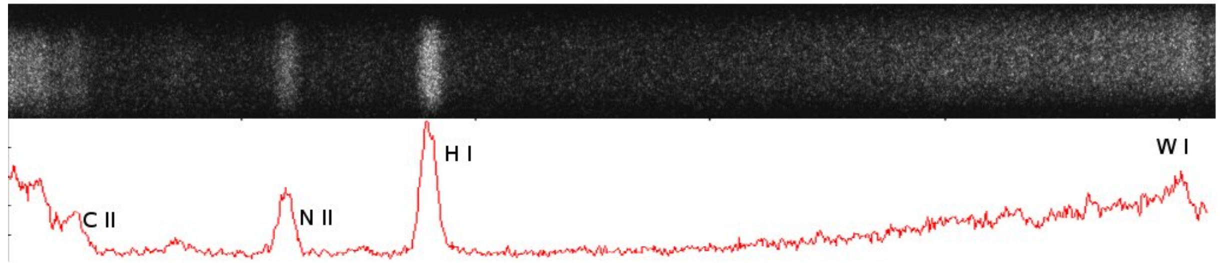
- Measurements show typical densities of $\approx 5 \times 10^{14}\text{cm}^{-3}$ based on a plasma diameter of 10 cm.
- Sharp rise in measured density corresponds to the arrival of the plasma front as measured using fast imaging.
- Plasma pulse duration is consistent with imaging and pressure probe data.
- The brief burst of noise due to switch firing is much shorter than the delay between trigger and plasma arrival

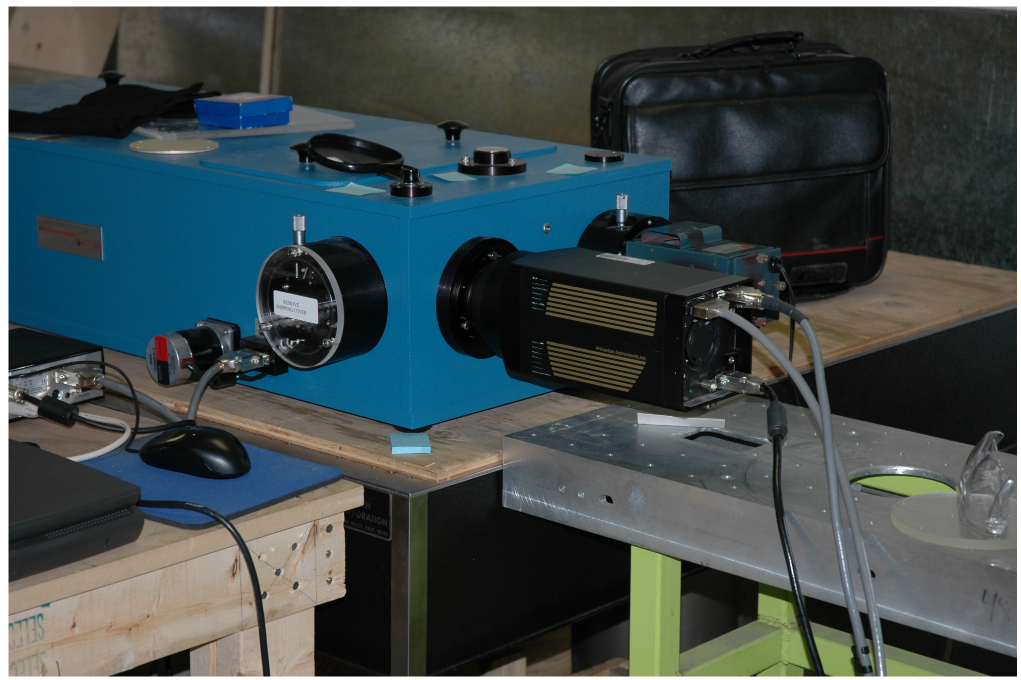


Smoothed interferometer data from a shot taken at 35 kV capillary voltage, 17 kV accelerator voltage, with 1 μs delay between capillary trigger and gun trigger. Observation volume is 20 cm from gun exit. Sharp rise in density is at 13 μs after capillary trigger.

Spectrometer

- We have clearly identified $H\alpha, \beta, \gamma$ lines, Carbon II, and possibly Cu I, W I, Zn I, and N II.
- Observed temperature is 1.5-2.0 eV in the plume, based on ionization ratios of carbon.
- A new camera has been selected and ordered from Princeton Instruments/Acton, with a high performance Blue/UV phosphor to improve time resolution of Stark measurements as well as temperature and velocity measurements.
- Improved collection optics have been designed and are under construction. When fully operational this will further improve the time resolution of spectrometer measurements.

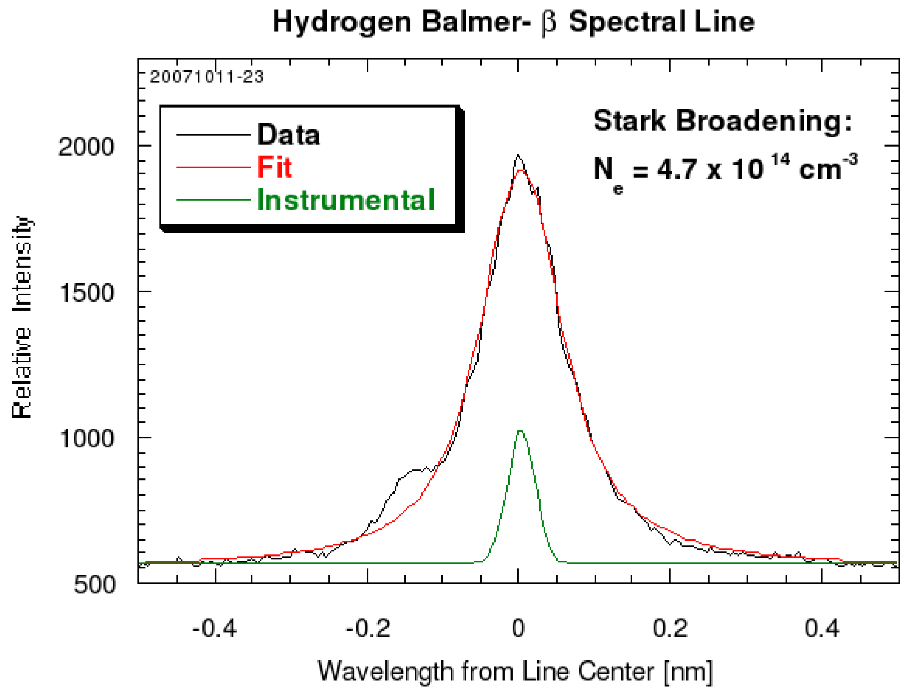




The 1.0 meter focal length f/8 high resolution monochrometer. The camera shown is the one used to take the data above. The new camera is also a PImax, with an improved Blue/UV phosphor.

Spectrometer Measurements of Density

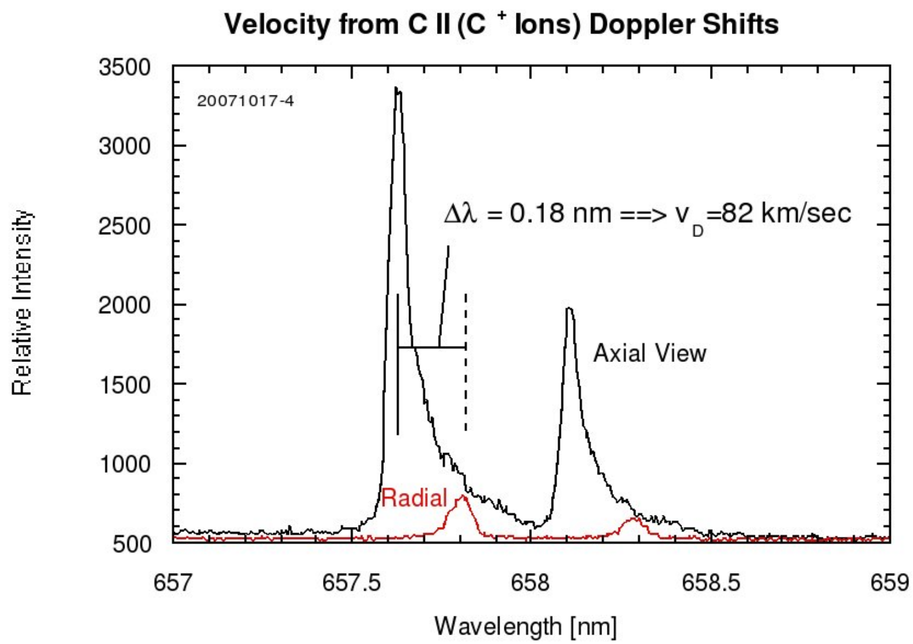
- Electron density increases as capillary ballast resistance decreases.
- H-β and H-γ stark broadening measurements are in close agreement, showing $N_e \approx 6 \times 10^{14}$ cm^{-3}with a capillary ballast resistance of zero.
- Stark broadening measurements tend to overestimate the density slightly, due to radial expansion of the plasma.



Hydrogen Balmer-β spectrum with best fit, taken with a capillary ballast resistance of 4 Ω. The delay from discharge initiation is 8 μs and the gate width is 8 μs.

Spectrometer Measurements of Velocity

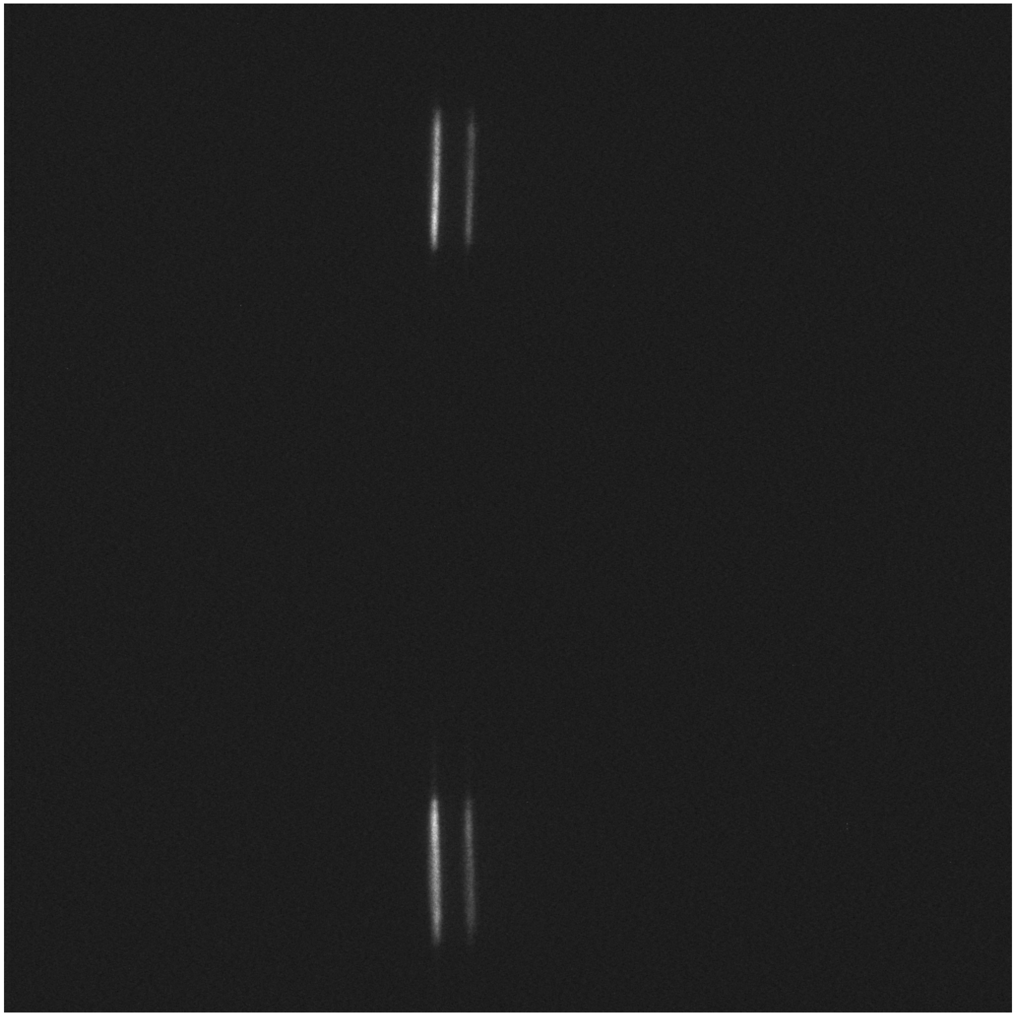
- H-α measurements show Doppler shifts consistent with a velocity of 75 km/s, and possibly a slow component at 12 km/s.
- Carbon II shifts corresponds to 82 km/s (see spectrum at right).
- Carbon III has a major component at 71 km/s, with a significant zero velocity component.
- Carbon IV shows a 63 km/s shift, with no detectable zero-velocity component.



Carbon II spectra from axial (black) and radial (red) collection optics. Measurements are taken simultaneously using two fibers and collimating collection optics. The delay from discharge initiation is 8 μs and the gate width is 8 μs.

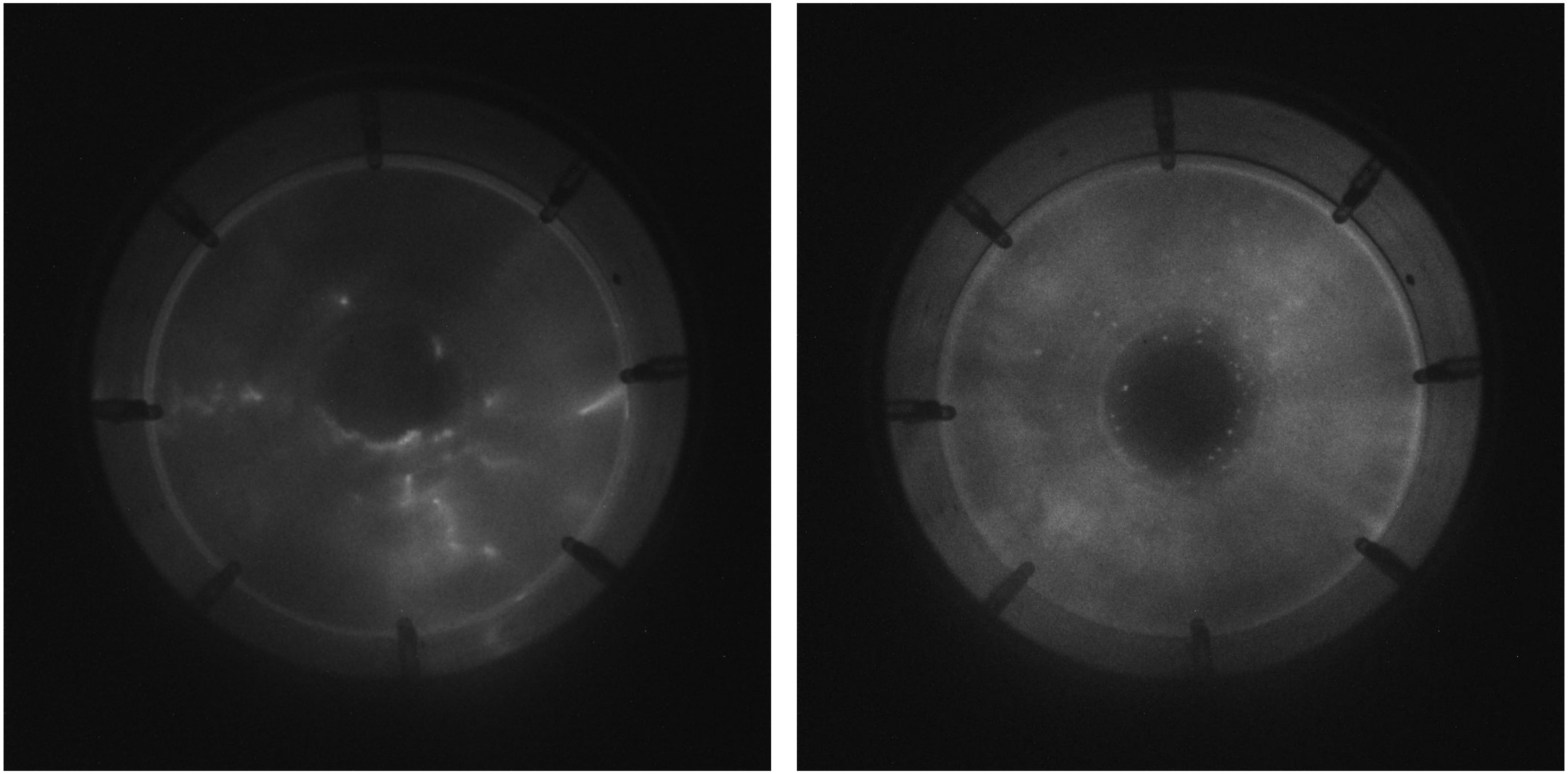
Spectrometer Upgrades

- New dedicated PIMax II camera with improved Blue-UV response will increase resolution of H_β
- Custom fiber coupler using seven fibers per leg (two legs) in spot-to-line configuration will increase light throughput
- Software to correct for line distortion is under development
- All the above will result in improved signal/noise ratio, which can be traded off against time resolution



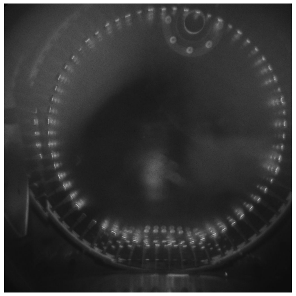
Calibration image of H_α and D_α lines using two fibers

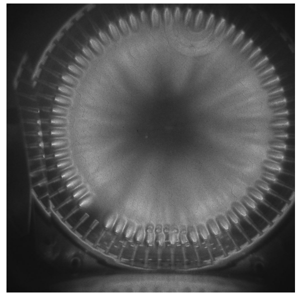
PIMax Imaging along gun axis

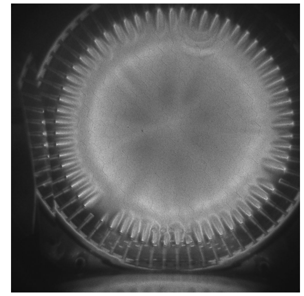


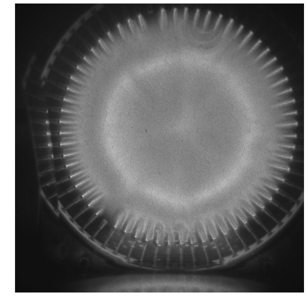
Images taken looking into the breech of the gun. Center electrode is positive in left hand image, negative in right hand image. Both images are taken at the peak accelerator current. Varying shutter delay allows imaging of all phases of plasma acceleration, from armature injection to current termination.

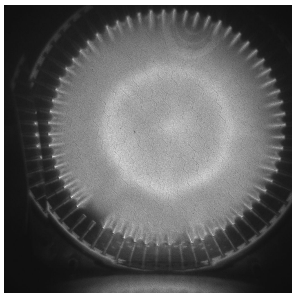
64 Jet Firing Sequence

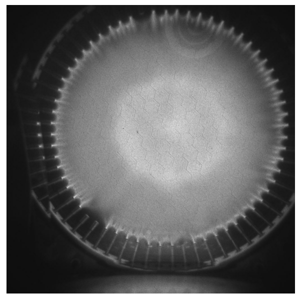

(a) 0.5 μs

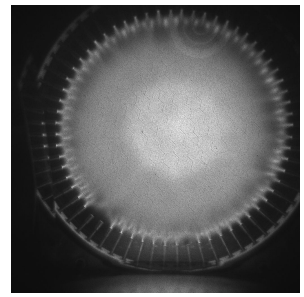

(b) 1.0 μs

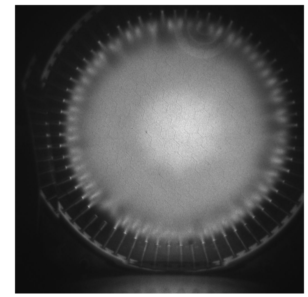

(c) 1.5 μs

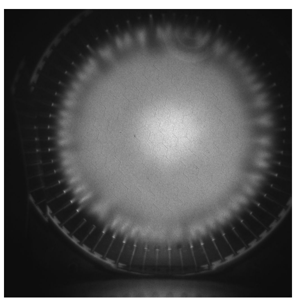

(d) 2.0 μs

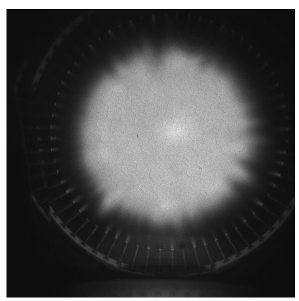

(e) 2.5 μs

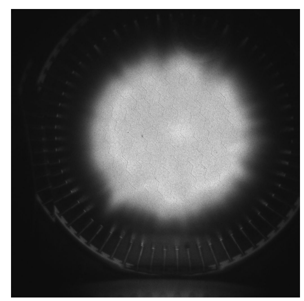

(f) 3.0 μs

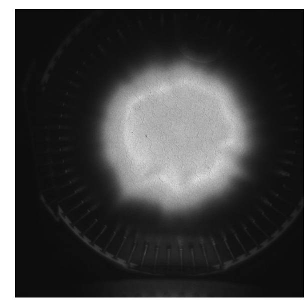

(g) 3.5 μs


(h) 4.0 μs


(i) 4.5 μs

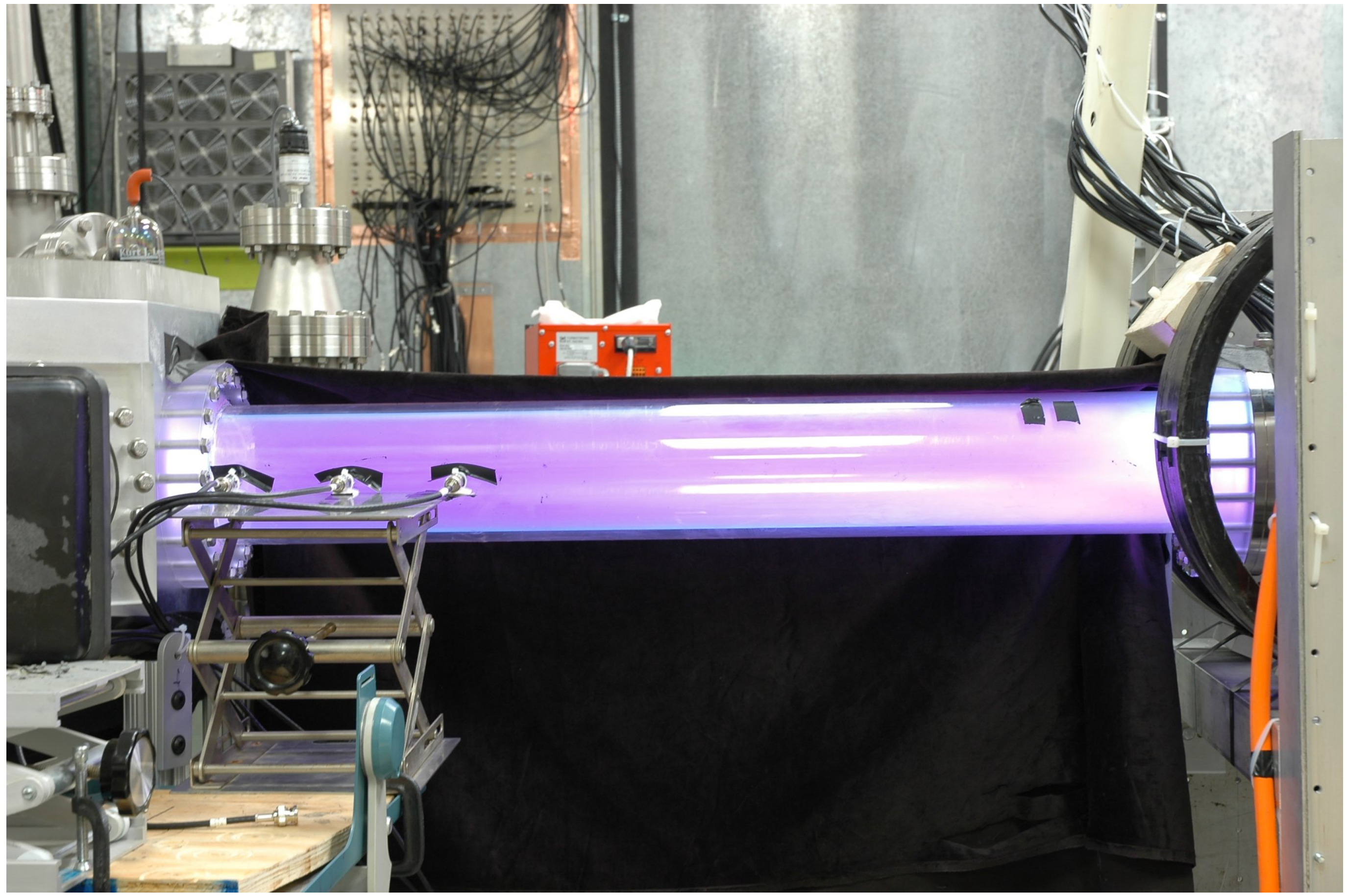

(j) 5.0 μs


(k) 5.5 μs


(l) 6.0 μs

Photodiode Measurements Provide a Cross Check on Velocities

- Simple photodiode setup without biasing provides a cross check on other measurements of velocity.
- Photodiodes are noise sensitive and subject to uncertainties due to reflected light, but nonetheless provide a repeatable measurement showing time delays between photodiode signals that are consistent with plasmoid velocities measured by spectroscopy.
- Photodiodes indicate velocities in excess of 100 km/s at gun exit.
- New amplified fast photodiodes (150 MHz bandwidth) have been purchased and are undergoing testing.



SUMMARY

The HeNe Quadrature Heterodyne Interferometer is functioning as a turnkey diagnostic. Future improvements will include an additional channel for space resolved measurements.

The 1m f/8 Czerny-Turner Spectrometer is functioning as a turnkey diagnostic. The camera has been upgraded to improve response in the Blue/UV. Further improvements in collection optics and analysis software are underway which will result in better time resolution.

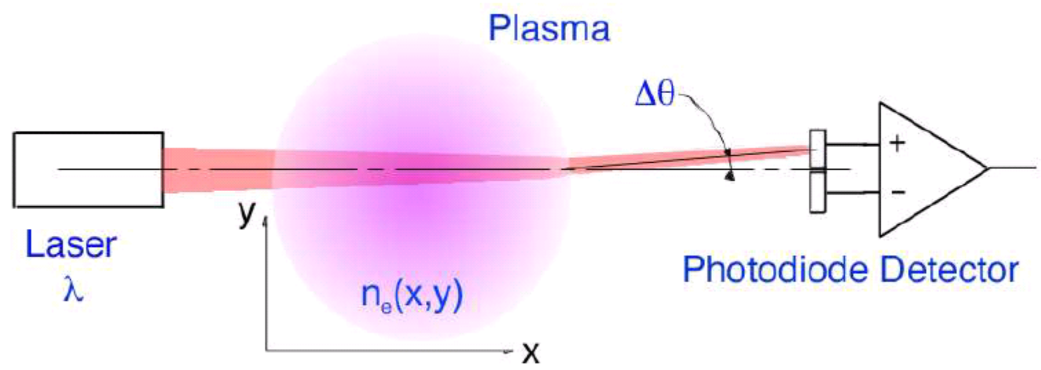
The PIMax II fast imaging camera is in regular use both for imaging the plasma and as an element in a simple ballistic pendulum diagnostic.

A new set of fast photodiodes has been purchased and is being tested. The bandwidth of these photodiodes is 150 MHz, which should allow more accurate measurements of plasmoid velocity.

Laser deflectometers based on those used by CTIX have been designed and are under construction. Coupled with interferometry this will permit measurements of plasma density gradients and provide insight into plasmoid structure.

Deflectometry

- Density gradients cause lateral shift of laser beam.
- Four segment PIN diode shows small AC signal due to deflection.
- AC signal is amplified and compared with DC signals to obtain angular shift.
- Angular shift is used to back out line integrated density gradients.



Schematic picture of deflectometer setup from Sam Brockington's PhD Dissertation (UC Davis, 2007)