Second Harmonic and Off-Axis Electron Generation in a High Intensity Laser Produced Plasma Cavitation*

A. Ting, D. Gordon, M. Helle[1], D. Kaganovich,[2] and B. Hafizi[2]

Plasma Physics Division
Naval Research Laboratory
Washington, DC 20375
USA

* Supported by US Dept. of Energy and Office of Naval Research

[1] Georgetown University, Washington, DC 20057

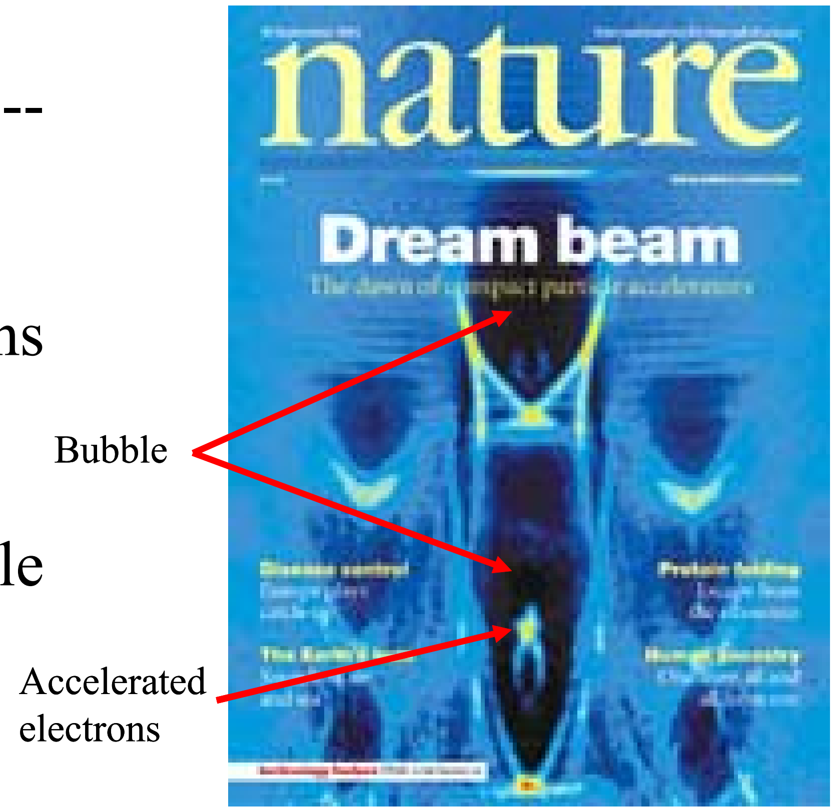
[2] Icarus Research, Bethesda, MD 20824

Introduction

- Intense laser pluses can drive plasma waves
- At high intensities blowout regime can be reached
- This is of great interest to advanced laser plasma based accelerators

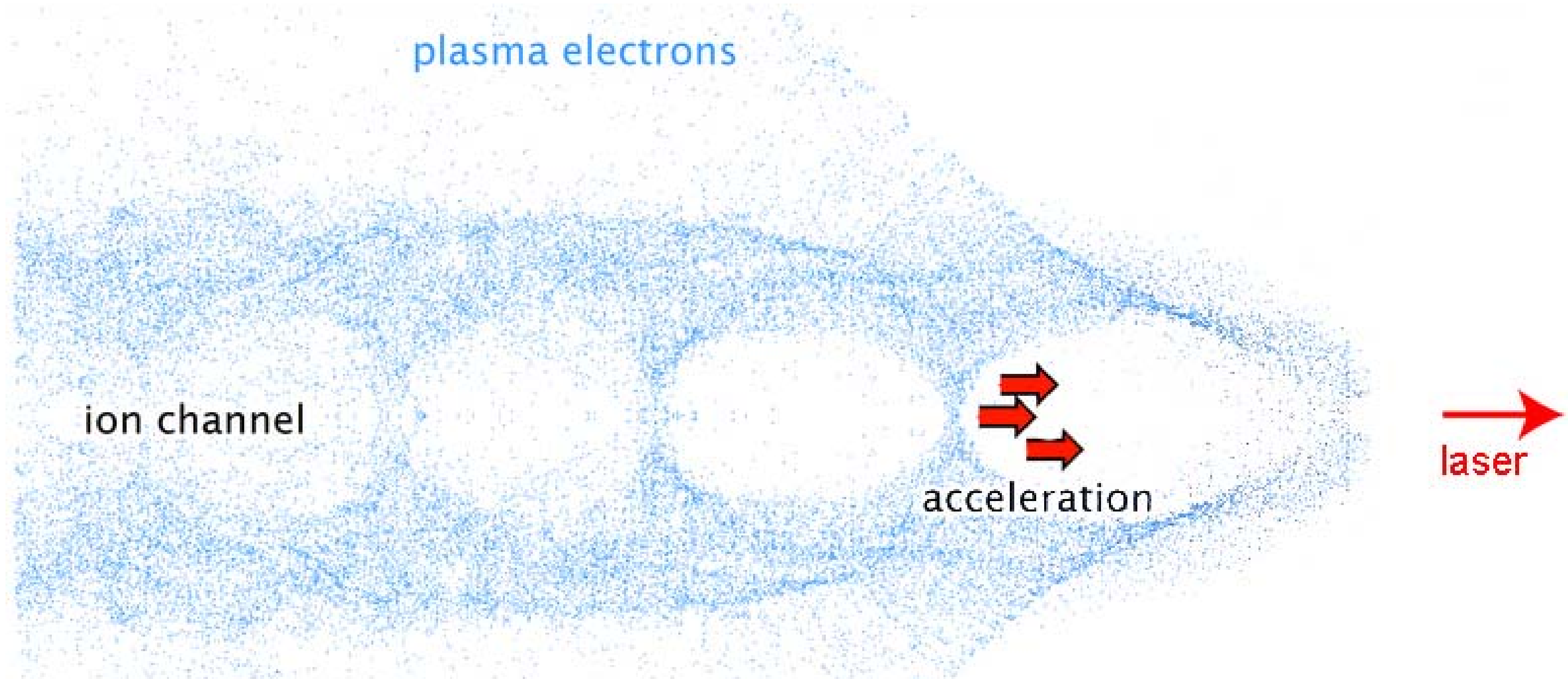
Motivation

- Optical signatures of plasma bubble -- ultra-fast harmonic generation
- To create quasi-monenergetic electrons using minimum laser power.
- Off-axis electrons are easier to couple into acceleration stages.



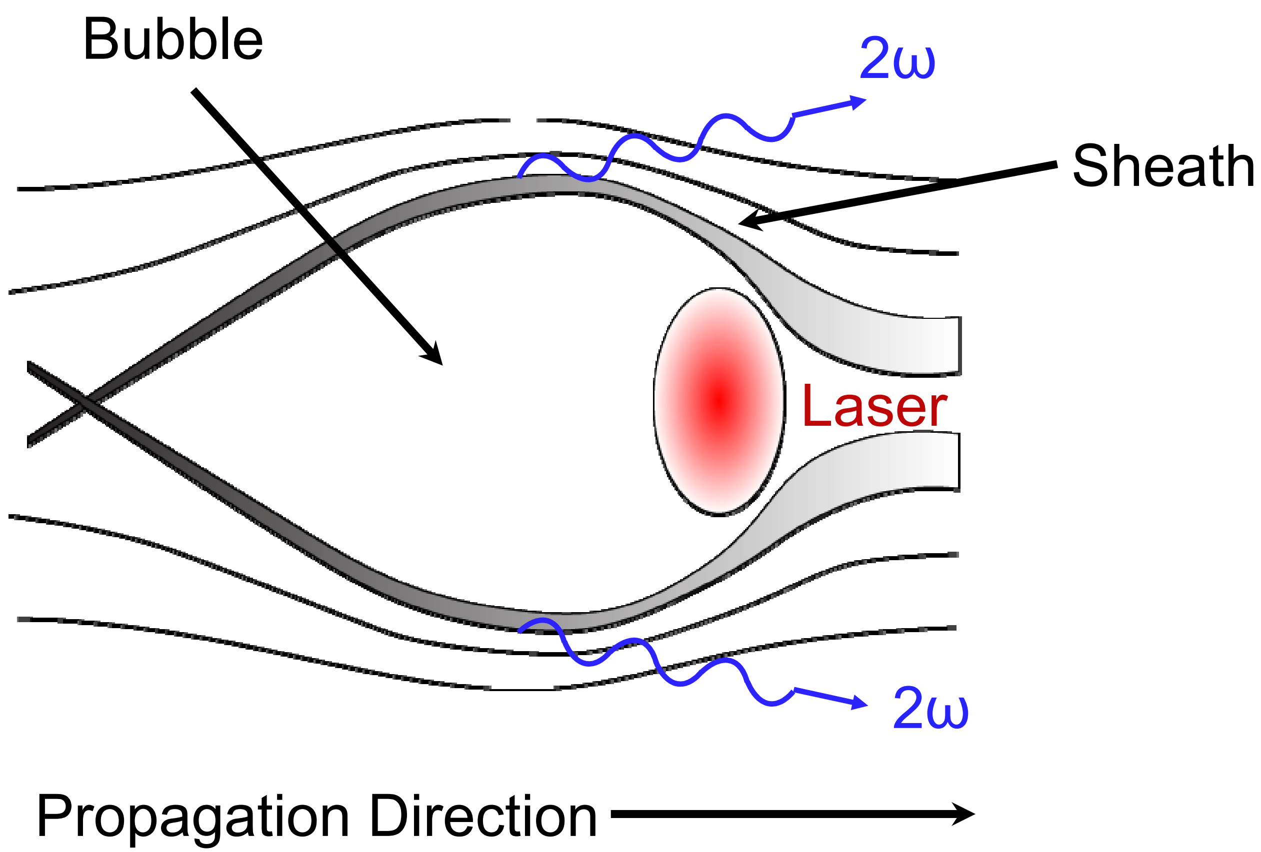
Nature 9/30/04 cover – 3 papers on LWFA experiments

Blowout Regime



- Plasma electrons are ejected from the laser path by the pondermotive force ($\propto \nabla I$)
- "Plasma bubble" is created when electrons are completely blown out of wake
- A thin electron sheath surrounds ionic core

Electro-optic shock second harmonic radiation



- Second harmonic light is generated within the electron sheath and emitted at a defined angle

D. Gordon, B. Hafizi, D. Kaganovich, A. Ting, PRL **101**, 045004(2008)

Electro-Optic Shock

Cylindrical electron sheath

$$n^{(0)} = n_0 \Delta\rho\, \delta(\rho - \rho_0) g(z - v_b t) h(z)$$

$\Delta\rho$ is the sheath thickness

2^{nd} order current perturbation on sheath by pump laser

$$\mathbf{j}_2 = \frac{e c^2 n^{(0)}}{8 i \omega_0} \frac{\partial a_1^2}{\partial \rho} (3\hat{\mathbf{x}} \cos\phi - \hat{\mathbf{y}} \sin\phi) + j_{2z}\hat{\mathbf{z}}$$

$k_0/|\partial_z g| \to \infty$ and $\omega_0/\omega_p \to \infty$

2^{nd} harmonic radiation (F.T.)

$$\hat{\mathbf{A}}_2 = -4\pi^2 i \mathbf{S}_0 J_1(k\rho_0 \sin\theta) \hat{g}(-\delta\omega/v_b) \hat{h}(K) \frac{e^{ikr}}{r/\rho_0}$$

where $\mathbf{S}_0 = -\frac{e c^2 n_0 \Delta\rho}{8 i \omega_0 c v_b} \frac{\partial a_1^2}{\partial \rho} (3\hat{\mathbf{x}} \cos\phi - \hat{\mathbf{y}} \sin\phi)$, $K = \frac{\delta\omega}{v_b} + 2k_0 - k\cos\theta$

Neglecting bubble evolution

$$\tilde{\theta}_c(\omega) = \cos^{-1}\left(\frac{c}{v_b} \frac{\delta\omega + 2k_0 v_b}{\sqrt{\omega^2 - \omega_p^2}}\right)$$

$$\theta_c \equiv \tilde{\theta}_c(2\omega_0) = \cos^{-1}\sqrt{\frac{\epsilon(\omega_0)}{\epsilon(2\omega_0)}}$$

Conical Emission Angle

- Conical emission is not due to phase matching
- It is determined by a Cherenkov type angle
- It is similar to an electro-optic shock in a crystal*

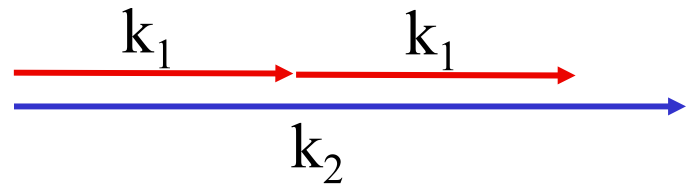
$$\cos\theta = \frac{v_\phi(2\omega_0)}{v_{\phi,s}} \approx \frac{v_\phi(2\omega_0)}{v_\phi(\omega_0)}$$

Agrees with high-res 2D run to within 4%

* D.A. Kleinman and D.H. Auston, IEEE J. Quant. Elect. QE-20, 964 (1984)

Angular Emission

In a plasma, $k_2 > 2\ k_1$



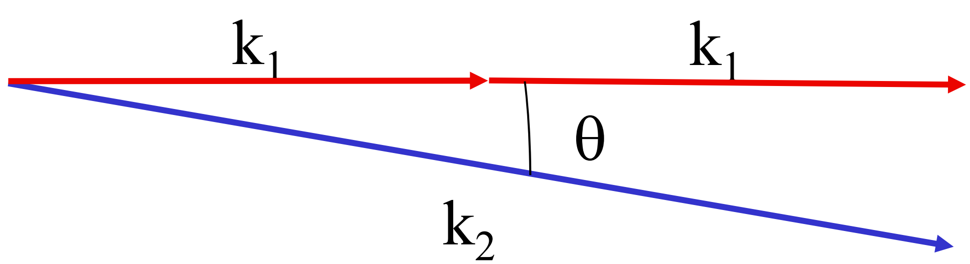
- From geometric considerations

$$\mathrm{Cos}\ \theta = 2\ k_1 / k_2$$

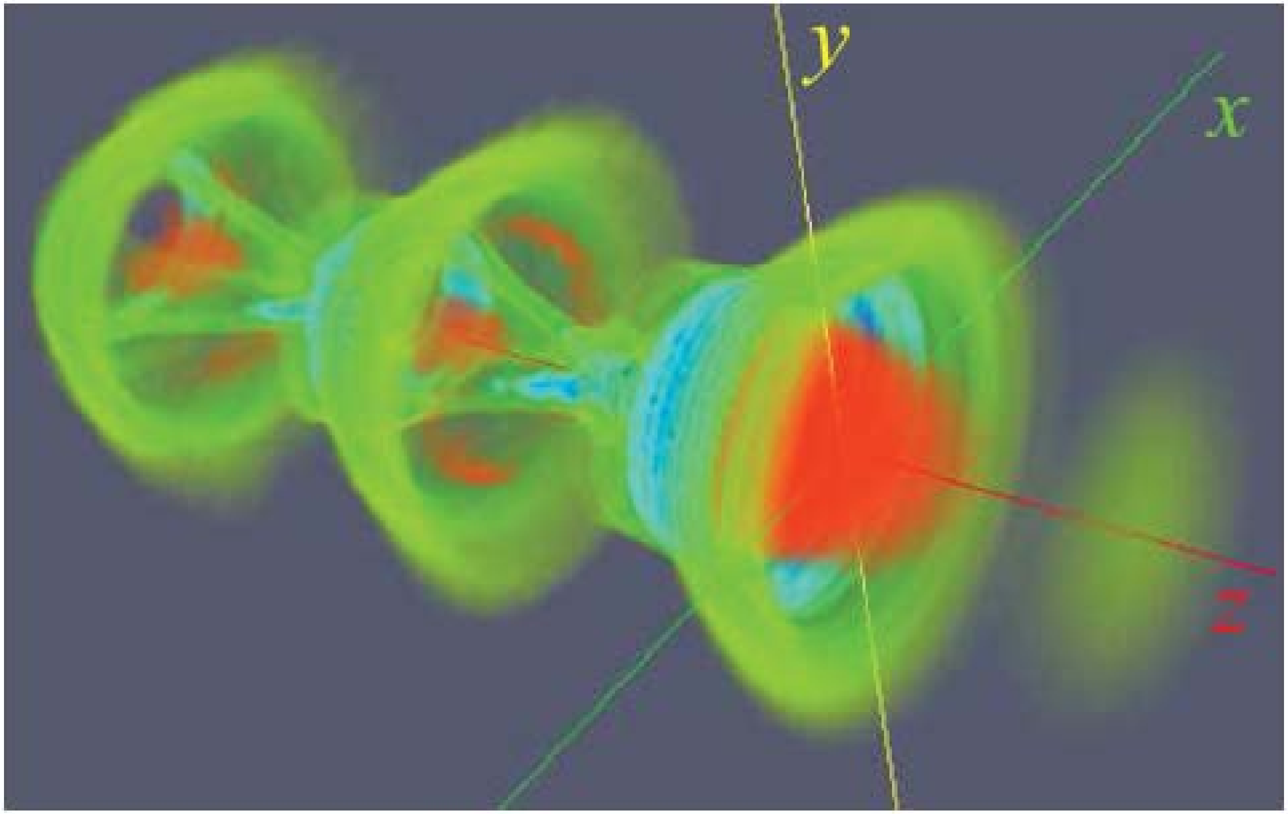
- Using the sum frequency condition $\omega_2 = \omega_o + \omega_o$

$$\mathrm{Cos}\ \theta = v_\phi(2\omega_o)/ v_\phi(\omega_o)$$

(Cherenkov Angle)



PIC Simulation

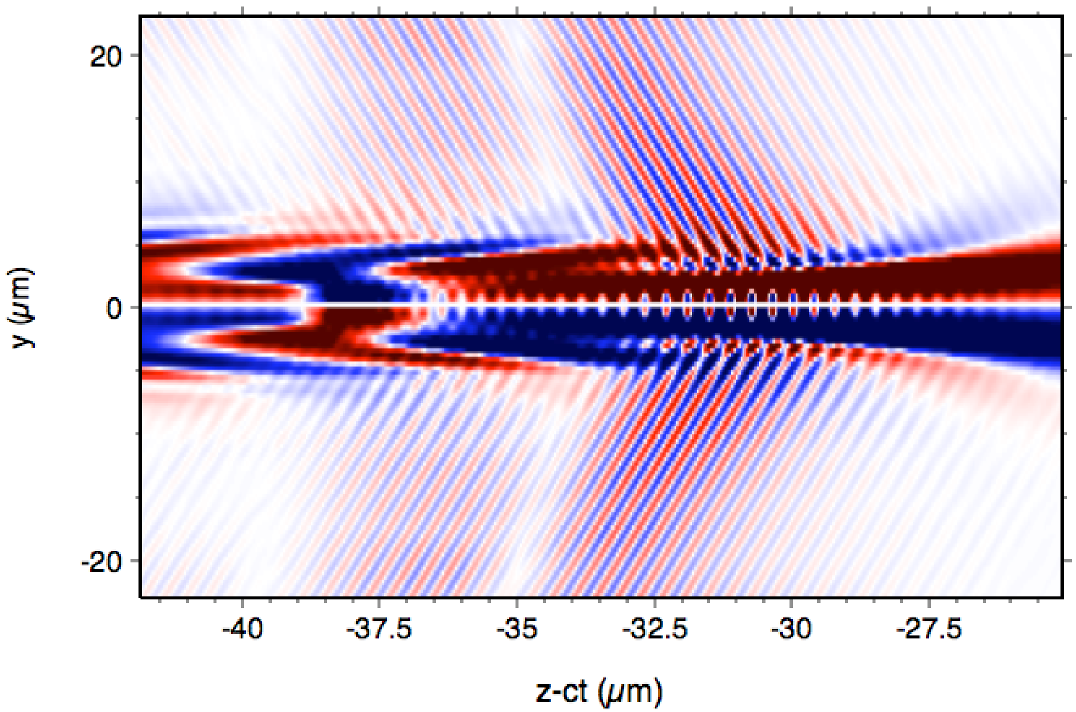


$r_L = 5\ \mu m$
$\rho_0 = 2.9\ \mu m$
$\Delta\rho = 0.25\ \mu m$

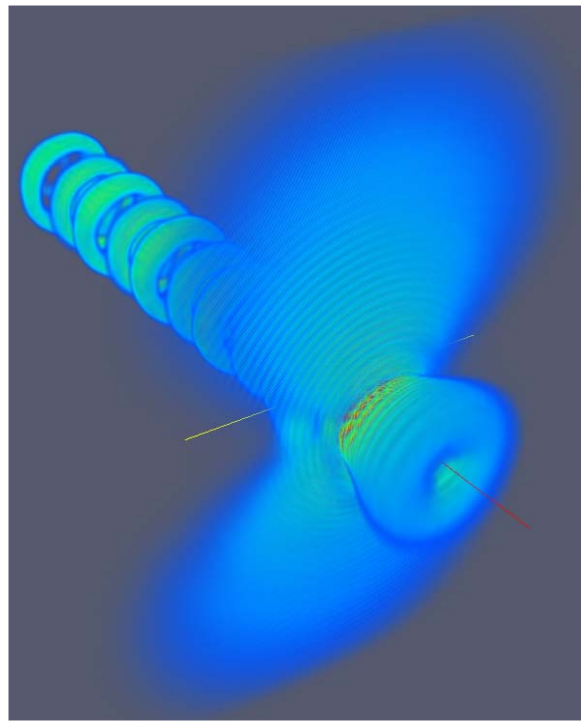
FIG. 2 (color). 3D ray tracing image of the charge density in the $2 \times 10^{19}\ cm^{-3}$ case. The laser pulse propagates to the right and slightly down. Red corresponds to $n_e = 0$, while blue corresponds to $n_e \approx 10^{20}\ cm^{-3}$. The blue area furthest to the right is the electron sheath which emits the electro-optic shock.

Second Harmonic and Wake

Conical Wavefronts of 2[nd] harmonic

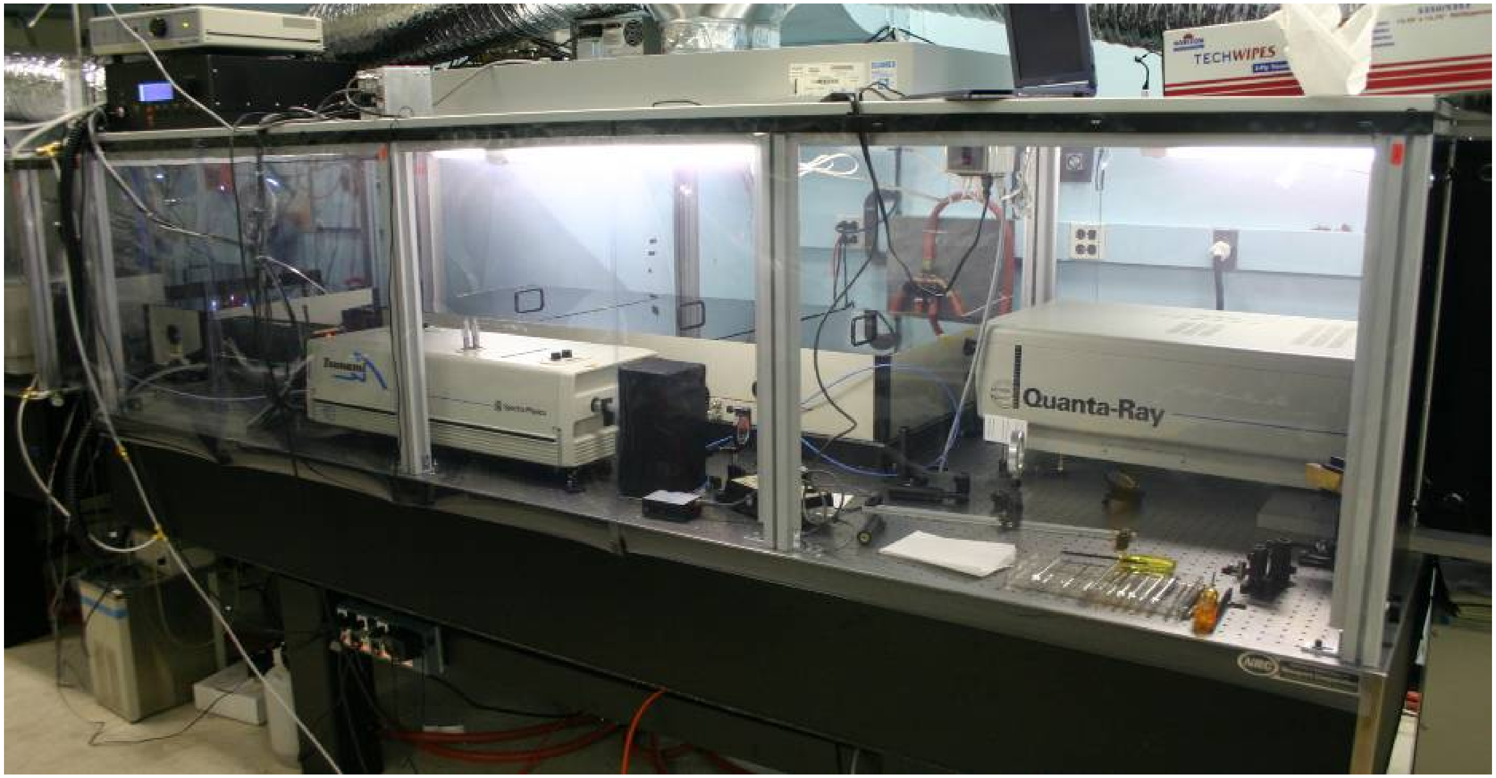


$E_\perp^2$ (ω_0 is filtered out)



Laser polarization is out of the plane (in x-direction)

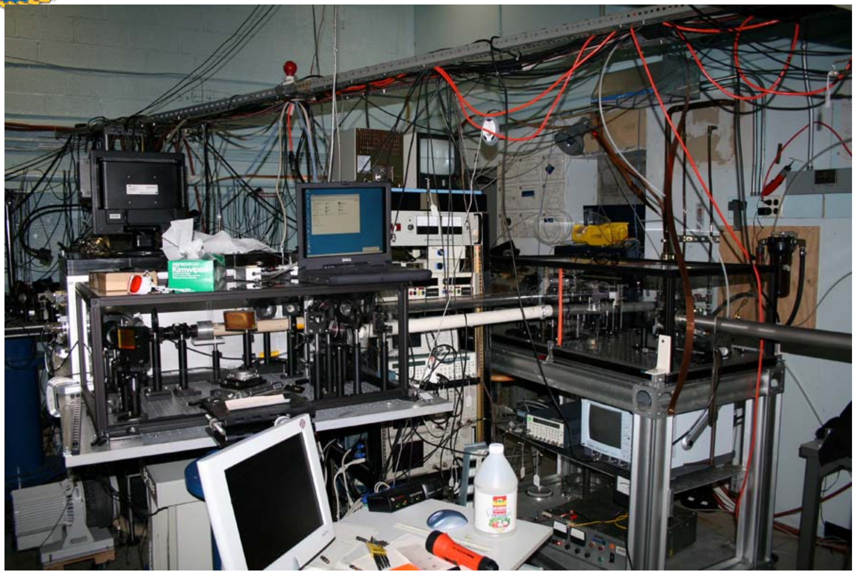
Setup: TFL Laser System



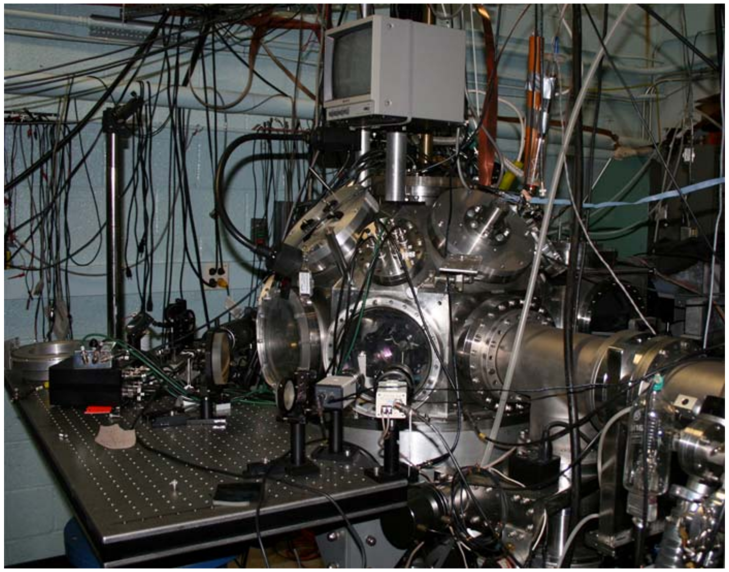
Ti:Sapphire Femtosecond Laser Parameters:

Wavelength:	800 nm
Pulse length:	50 fs compressed
Rep. Rate:	10 Hz
Energy $\leq$	600 mJ/pulse

Setup: Experimental Chamber

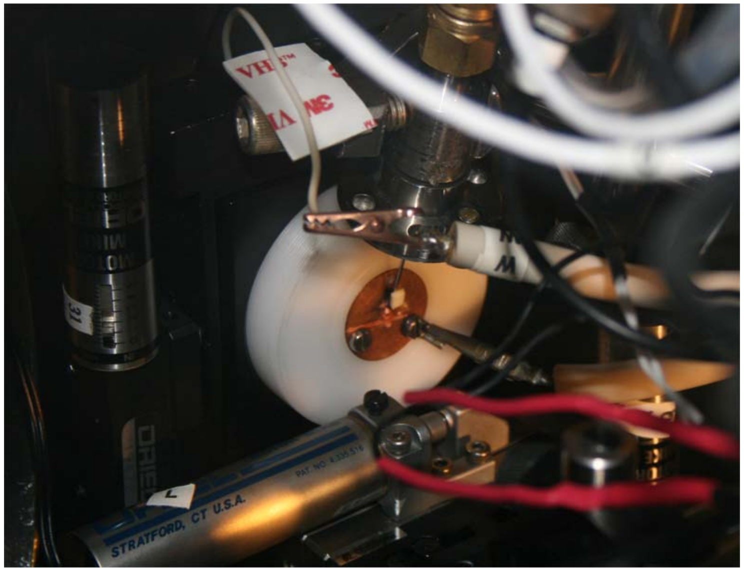


- Laser train switch yard



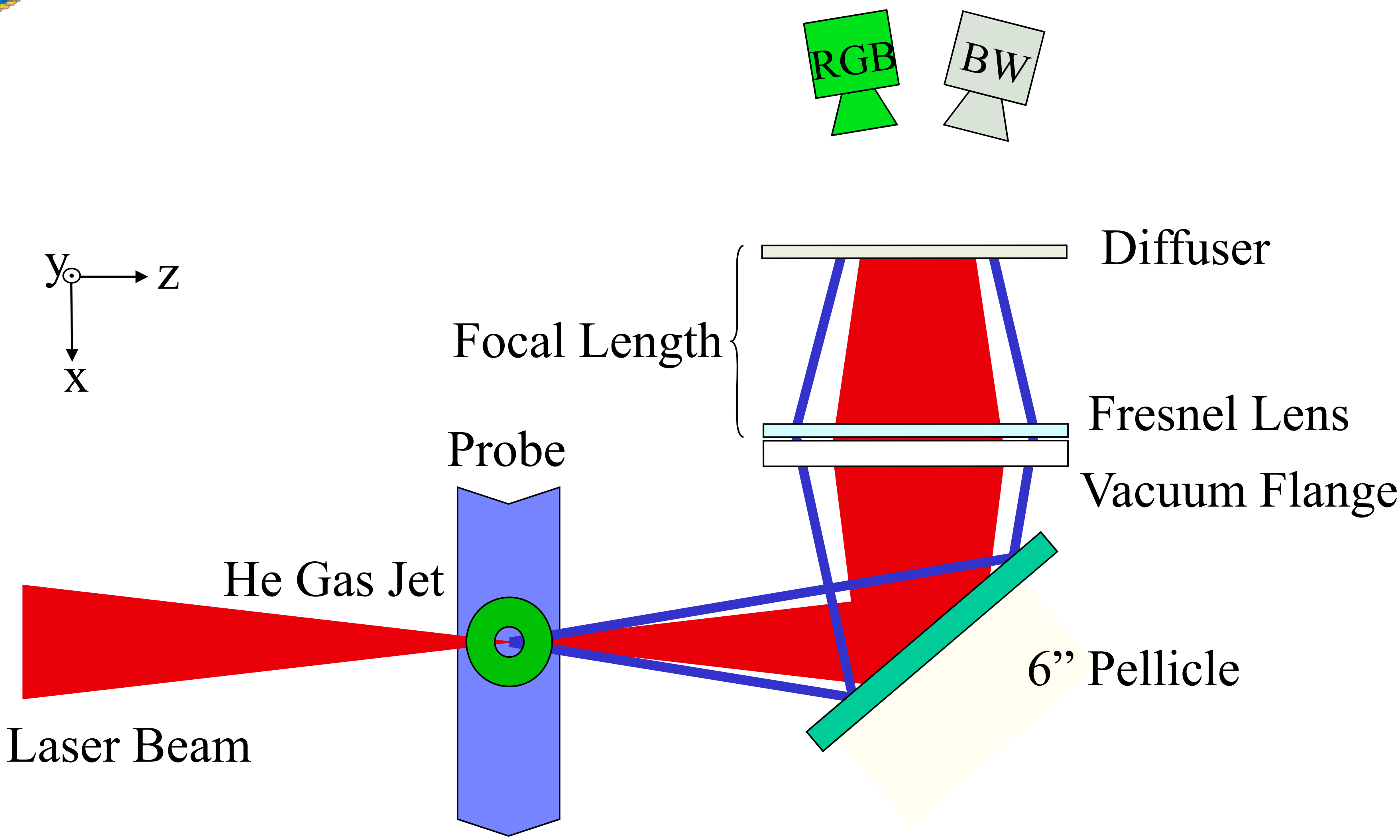
- Interaction chamber

- Radiation shielding surrounding electron detector



- Gas jet and plasma capillary (removed)

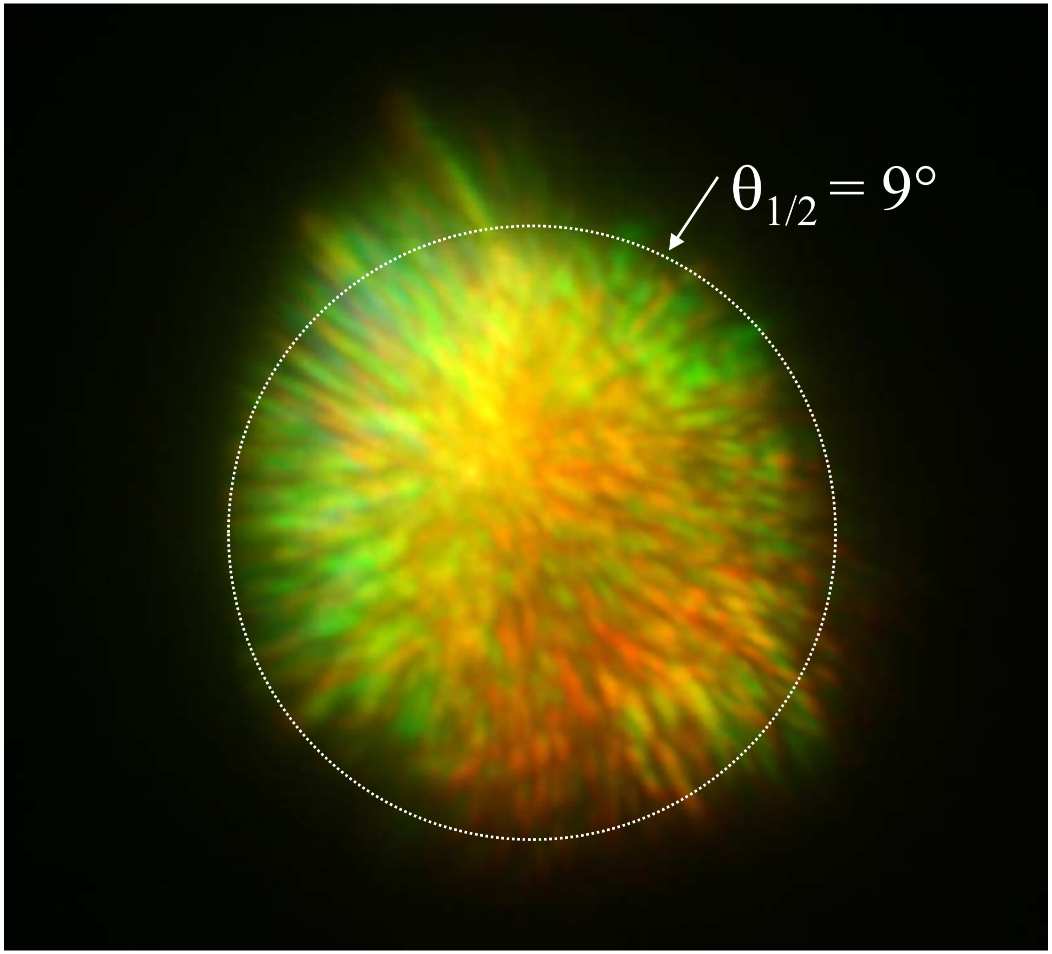
Experimental Setup



Schlieren & Interferometry Diagnostics

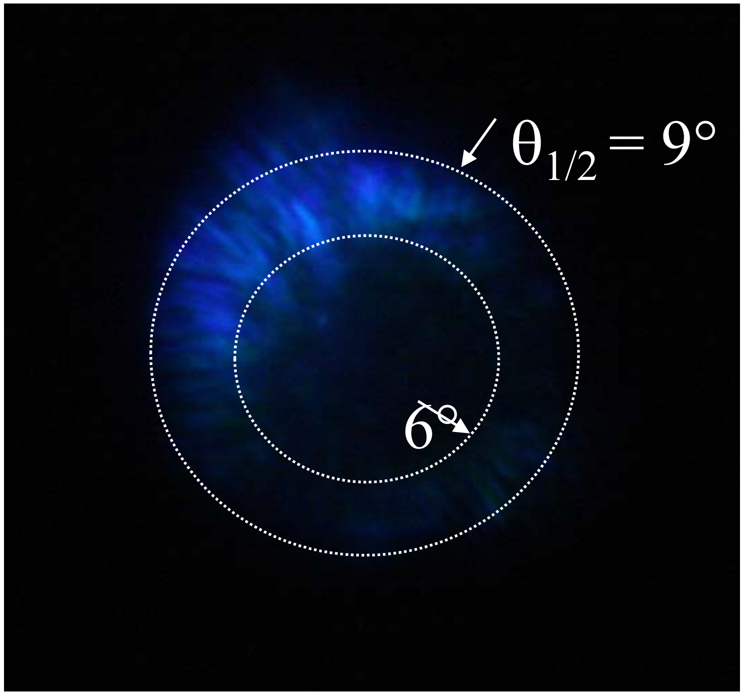
Limiting angle $\theta_{1/2} = 11°$ due to Pellicle

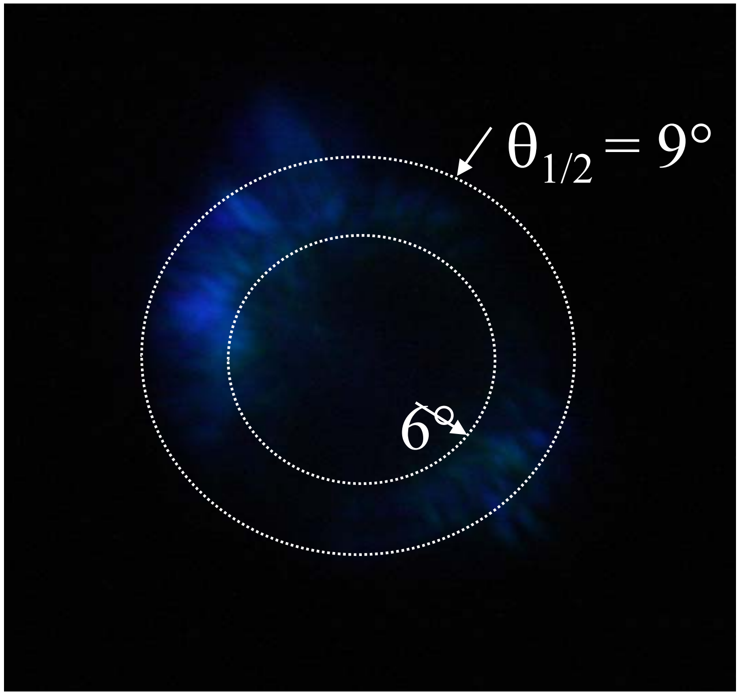
Forward Scattered Radiation (fundamental removed)



P = 2 TW n_e=3*10^{19} cm^{-3}

Forward Scattered Second Harmonic





P = 2 TW n_e=3*10^{19} cm^{-3}

Corresponding Density

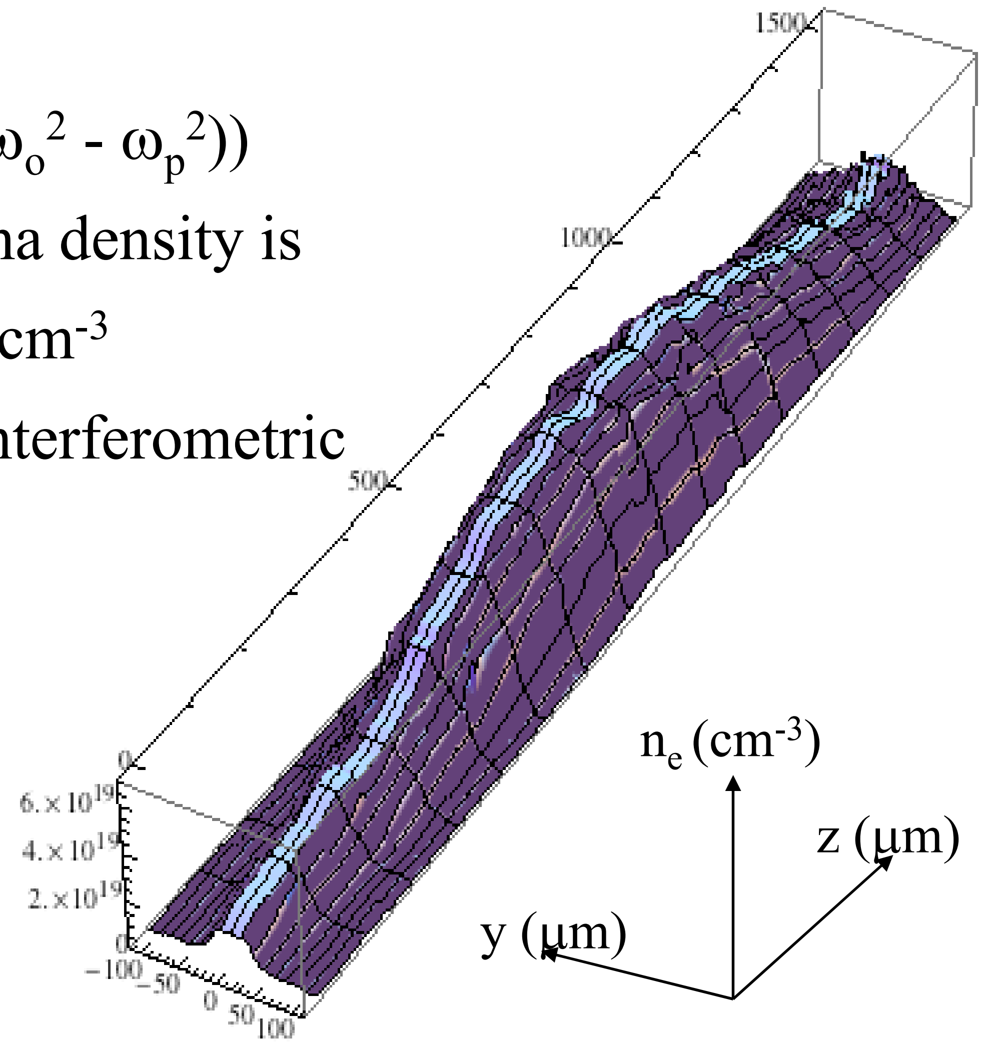
- Combining dispersion relation with Cherenkov condition

  $$\theta = \mathrm{Cos}^{-1}(\sqrt{4(\omega_o^2 - \omega_p^2)/(4\omega_o^2 - \omega_p^2)})$$

- For range of $6° \leq \theta \leq 9°$, plasma density is

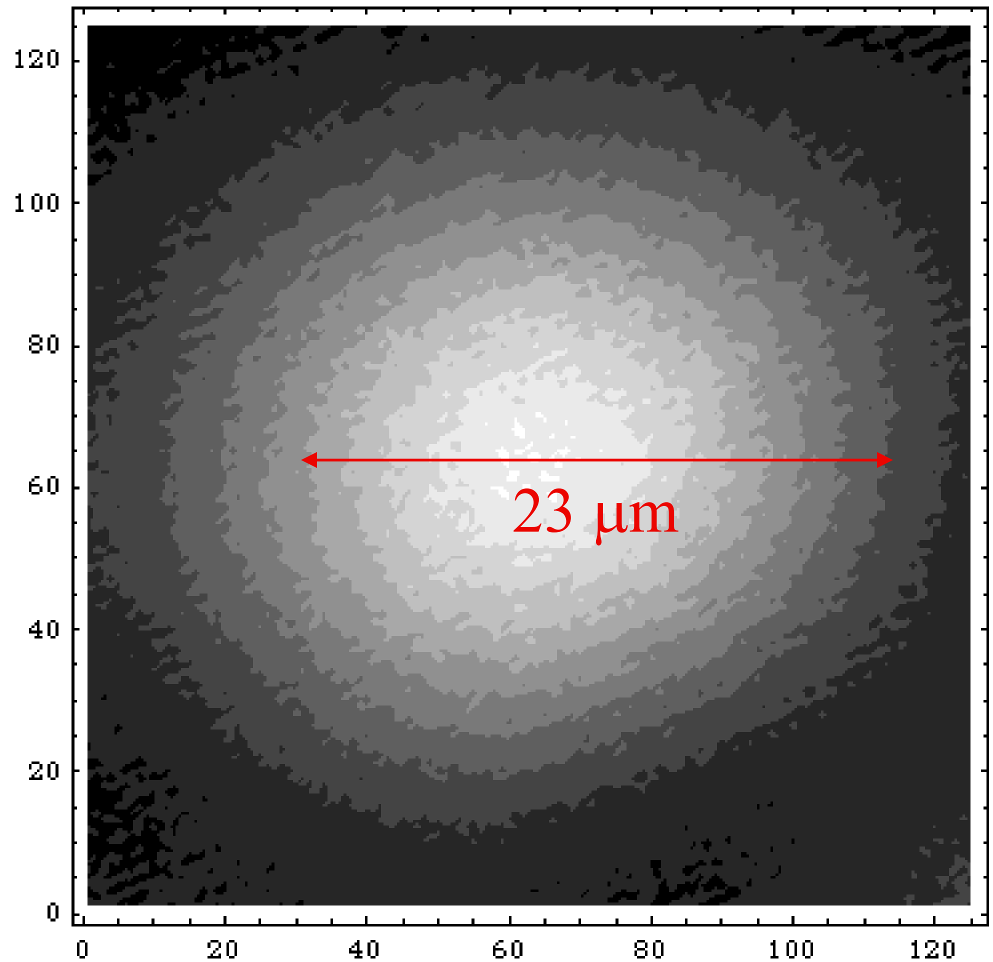
  $$2*10^{19}\ \mathrm{cm}^{-3} \leq n_e \leq 6*10^{19}\ \mathrm{cm}^{-3}$$

- This range is consistent with interferometric density measurements



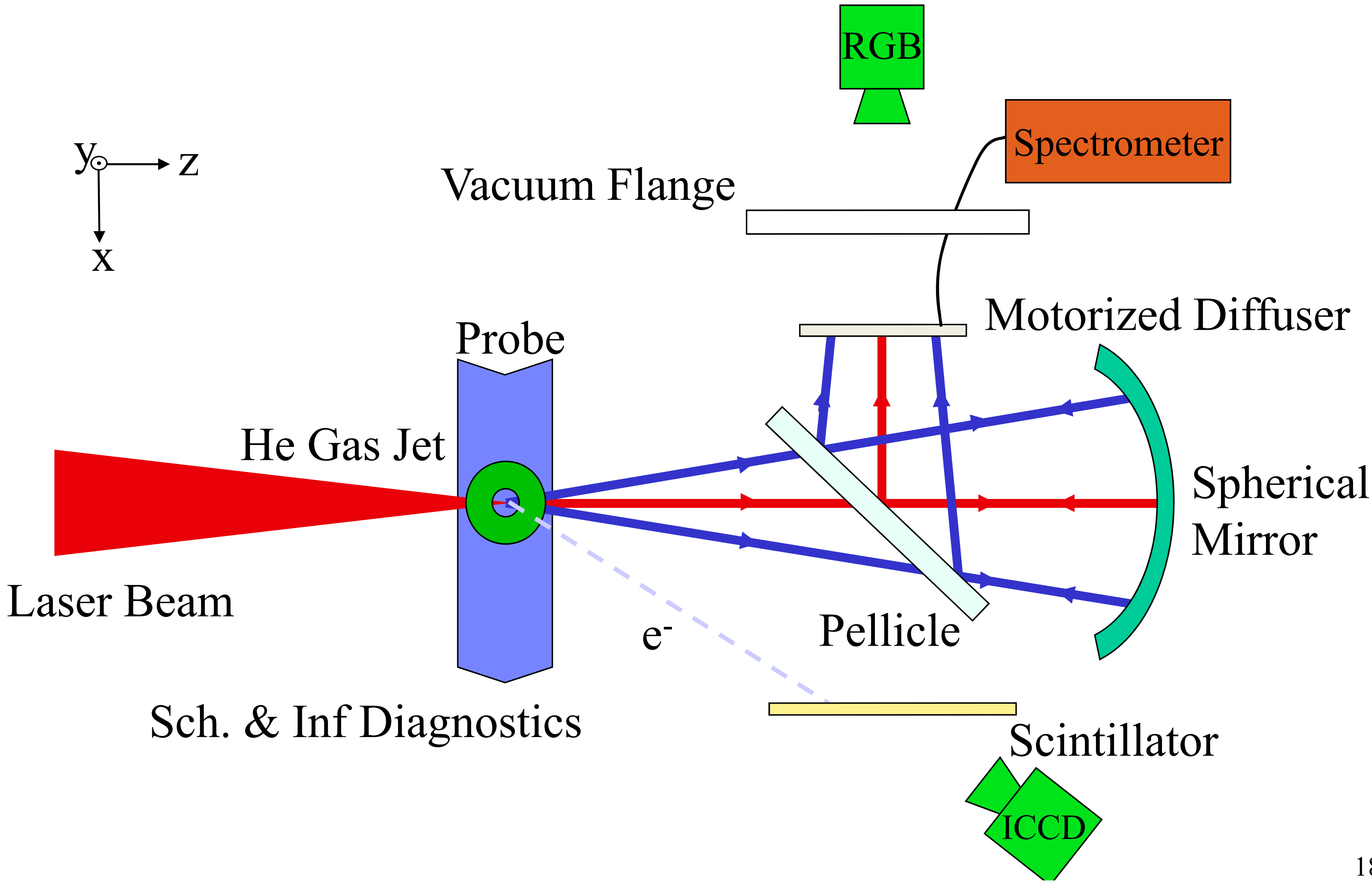
Focal Spot Asymmetry

- Azimuthal distribution not in agreement with theoretical prediction
- Possibly caused by asymmetry in focal spot
- Can be corrected by realigning off-axis parabolic focusing element

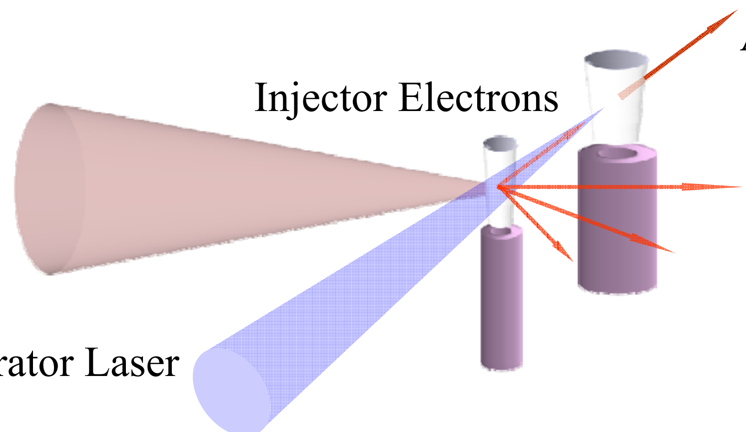


Focal spot of drive laser

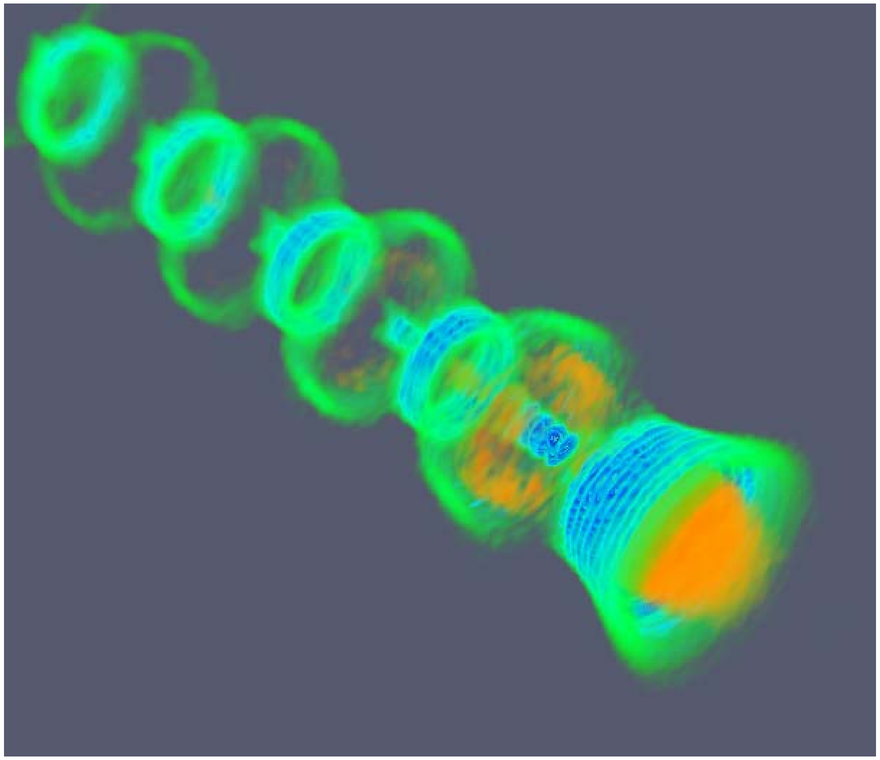
New Experimental Setup



Optical Injection and Acceleration

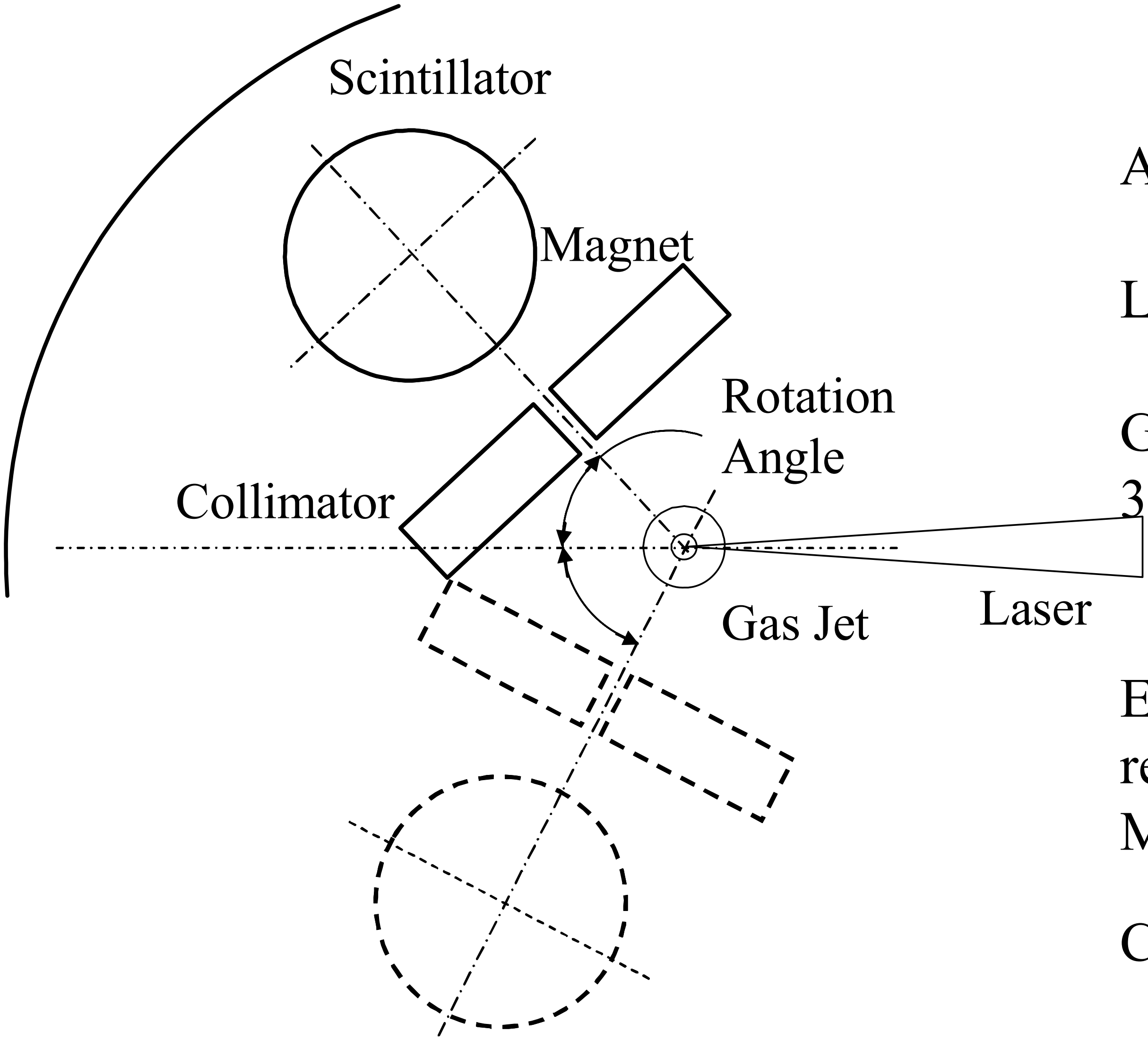


3D PIC Simulation



Volumetric rendering of charge density behind the laser pulse as computed by turboWAVE. Orange is positive and blue-green is negative. The propagation direction is down and to the right. The orange "bubble" in the lower right is the ion-rich cavitation region, and the blue-green sheath surrounding it is a dense shell of electrons.

Experimental Setup



Angle scan: 0-50 degree

Laser power: 1-10 TW

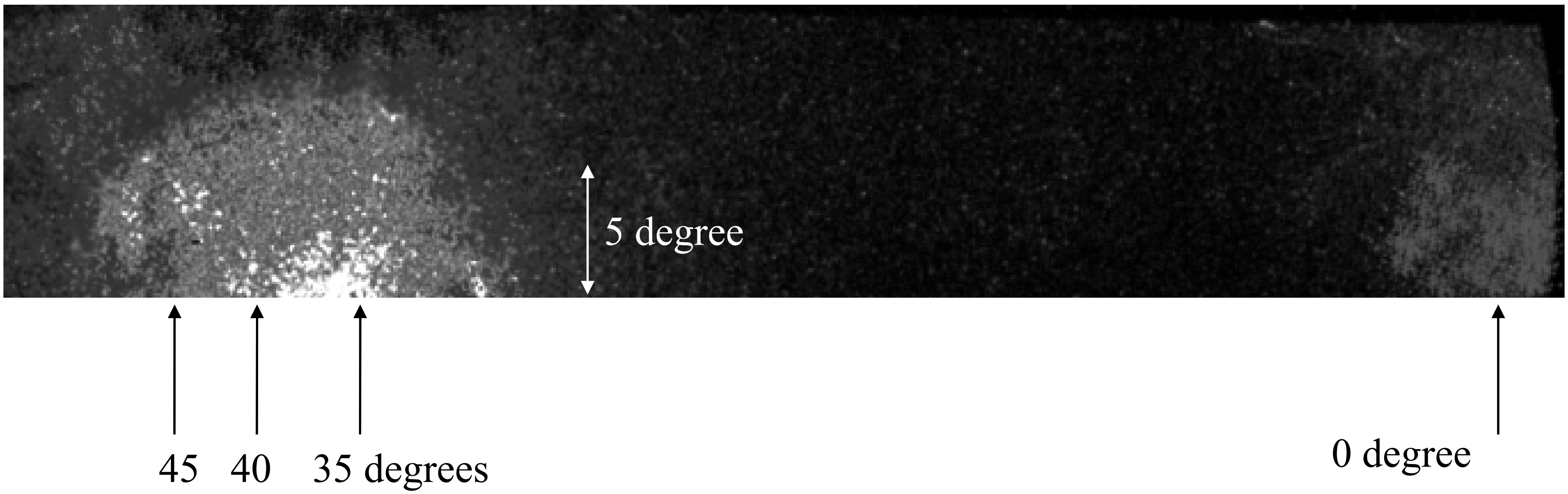
Gas density: $2x10^{18}$ – $3x10^{19}$ cm^{-3} (N_2 or He)

Electron spectrometer resolution 10% for 2 MeV electrons at 40^0

Collimator $F^{\#}30$

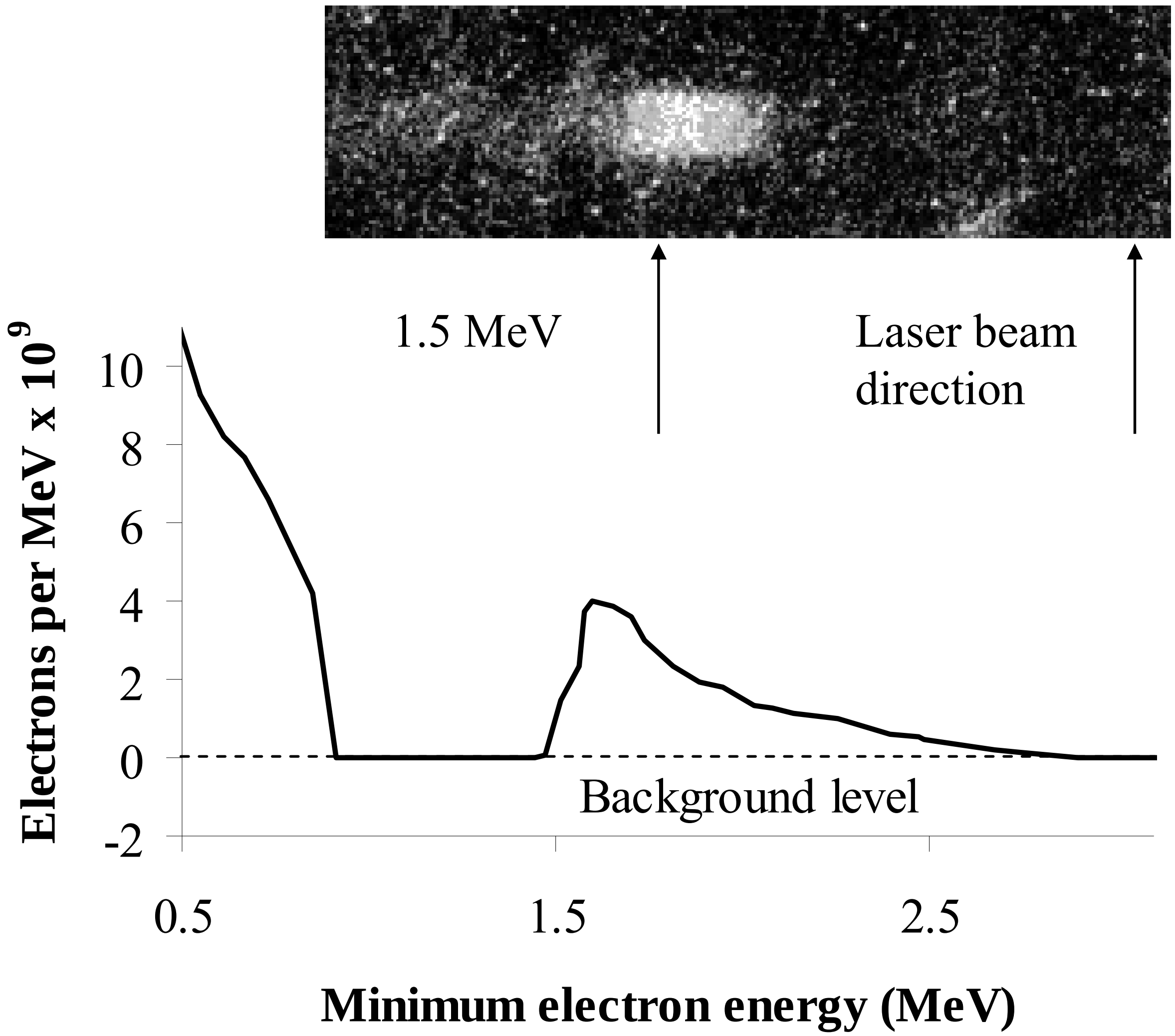
D. Kaganovich, D. Gordon, A. Ting, PRL **100**, 215002 (2008)

Electron Angular Distribution

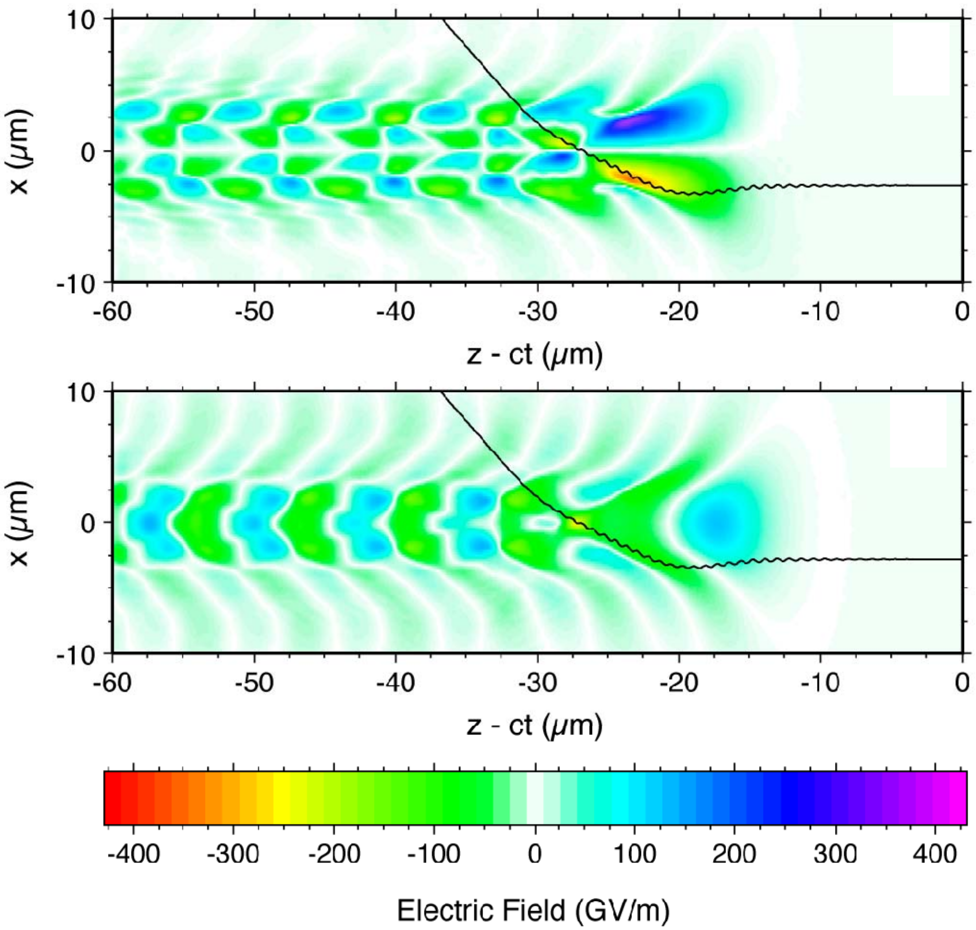


Total electron charge around 40 degrees > 1.5 nC
He gas density 4-6x10^{18} cm^{-3}
Laser power 2.5 – 3 TW
No off-axis effects for N_2 gas, other gas densities, or higher laser power.

Electron Energy Distribution at 40^0



Test Particle Trajectory



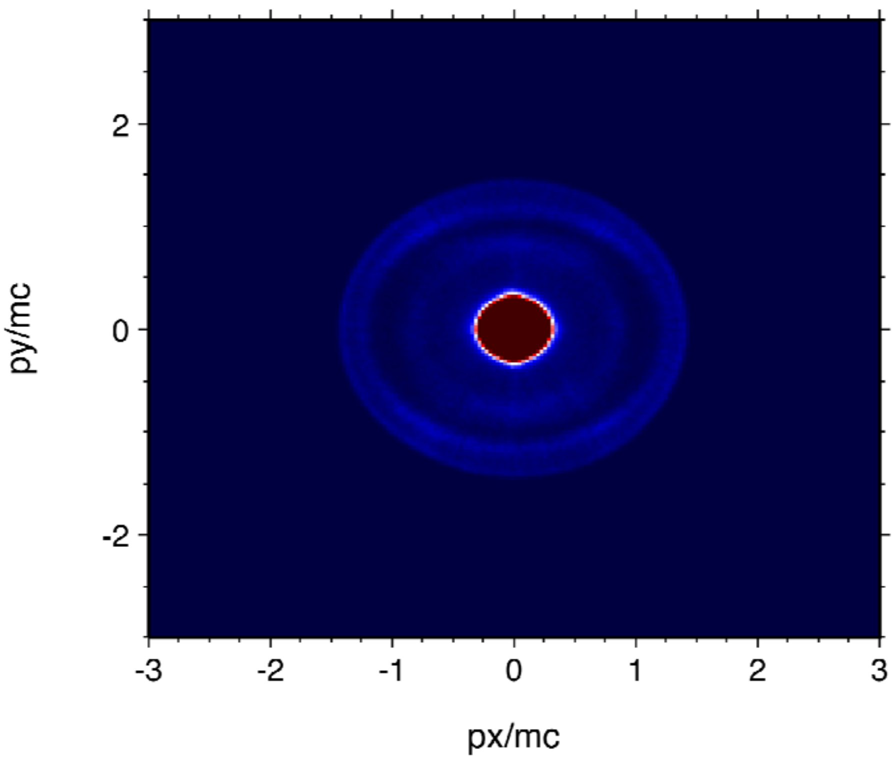
Trajectory through transverse wakefields

Trajectory through longitudinal wakefields

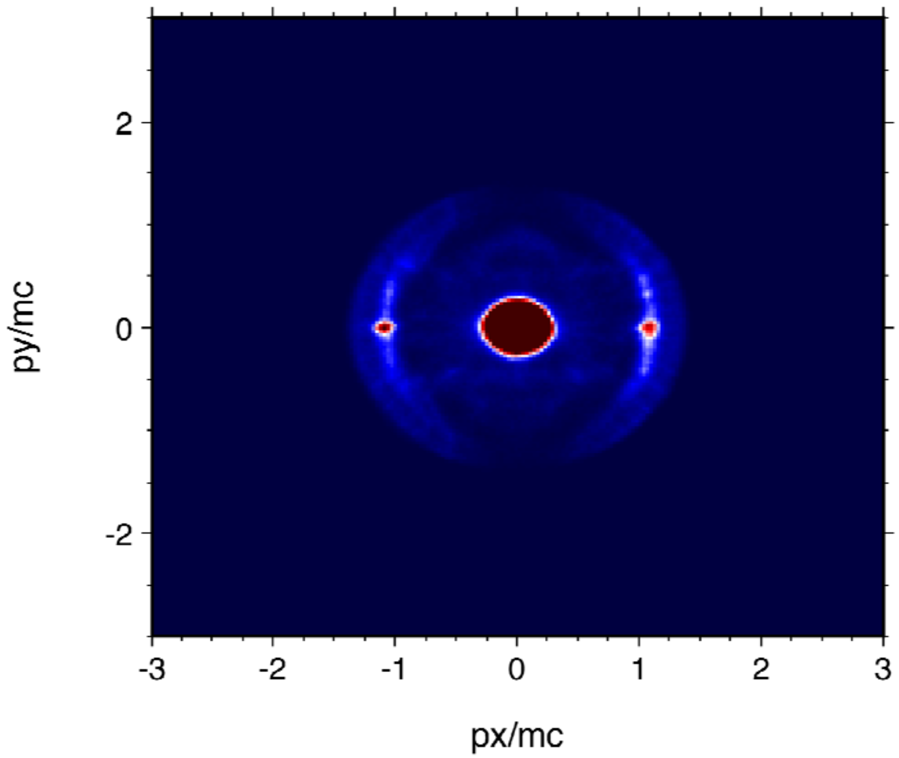
Trajectory of a test electron superimposed on the wakefields produced in the 2×10^{19} cm^{-3} plasma: The laser fields have been suppressed using a Fourier filter, though their effect is visible on the particle trajectory.

Pre-Ionized vs. non-Pre-Ionized

Electrons transverse phase space for pre-ionized plasma. No polarization dependence



Transverse phase space for the 2nd He electron, ionization included. Laser is horizontally polarized



Conclusions

- Simulations show conical emission of second harmonic in a plasma bubble which is similar to electro-optic shocks in crystals and is much shorter in time than the fundamental
- Conical emission of second harmonic radiation into a Cherenkov angle was observed and the plasma density extracted from angular spread is in agreement with density measured by interferometric means
- New experiment is underway to extract spectral data, further examine azimuthal intensity distribution, polarization state, and correlation to off-axis electron generation
- Quasi-monenergetic electrons emerging from a laser wakefield accelerator at a large angle to the propagation axis have been observed experimentally and in PIC simulations.
- Interplay between the bubble wakefield and the ponderomotive forces seems to be responsible for electrons generation.
- The angle between the laser beam and ejected electrons makes it practical to couple the injection and acceleration stages.