UNIVERSITY OF MARYLAND AT COLLEGE PARK
INSTITUTE FOR RESEARCH IN ELECTRONICS AND APPLIED PHYSICS

MeV electron acceleration at 1 kHz with mJ-scale laser pulses

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@ λ=0.8μm (1 kHz)

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@ λ=3.9μm (20 Hz) [1]***Tech. Univ. Wien***

EAAC2017

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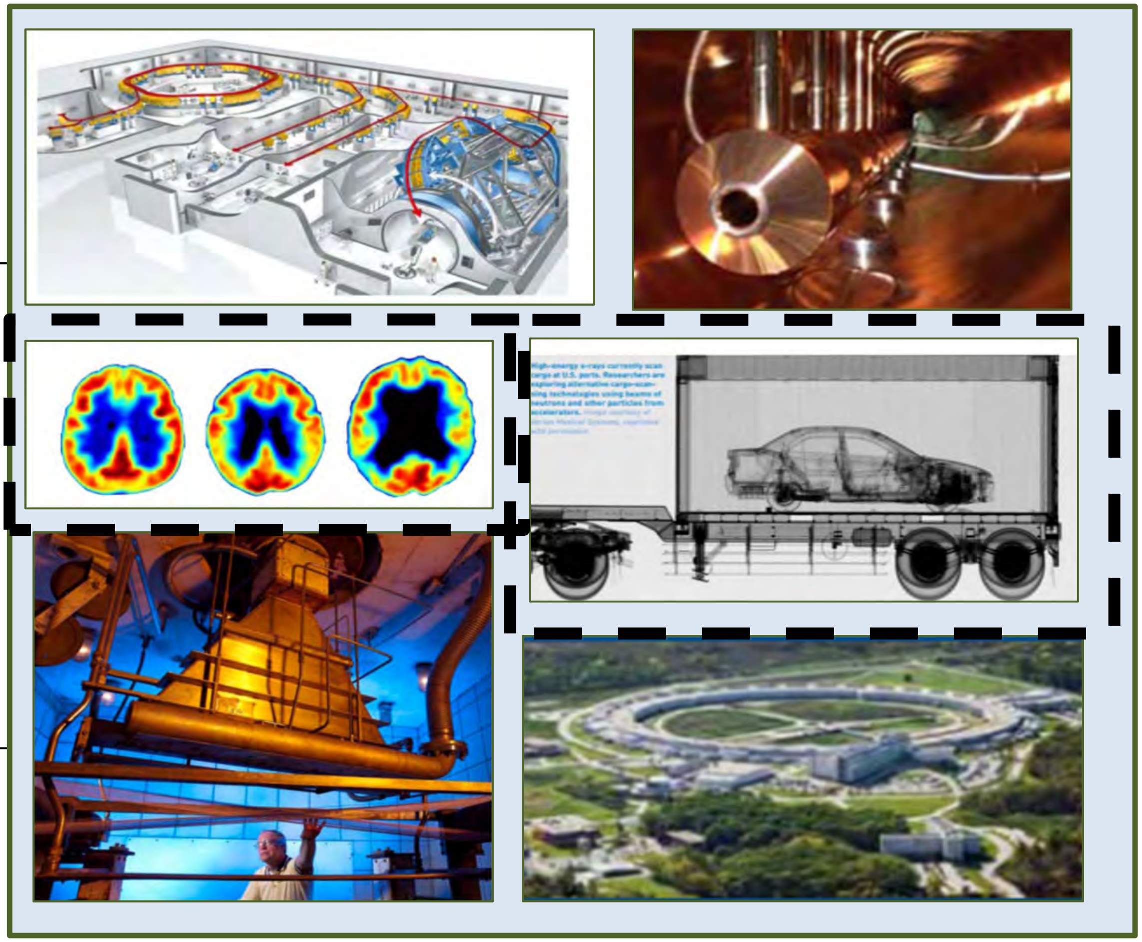
“There’s plenty of room at the bottom” –R. Feynmann

Accelerators for America’s Future

https://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf

protons

PET scans using ^{18}F $T_{1/2}$=100min ~10 MeV protons for radioisotope generation



electrons

Convert to ~10 MeV photons: Femtosecond radiography; scientific imaging; Photofission

What does it take to drive a LWFA?

- Scaling of single stage energy gain in a LWFA in the bubble regime, limited by pump depletion and dephasing:

$$\frac{\Delta W_{max}}{m_e c^2} \cong \left(\frac{P}{m^2 c^5/e^2}\right)^{\frac{1}{3}} \left(\frac{\lambda_p}{\lambda}\right)^{\frac{4}{3}} \propto N_e^{-4/3}$$

W. Lu et al., Phys. Rev. Spec. Top. - Accel. Beams **10**, 061301 (2007).

- Laser couples efficiently (resonantly) to the plasma wave when:

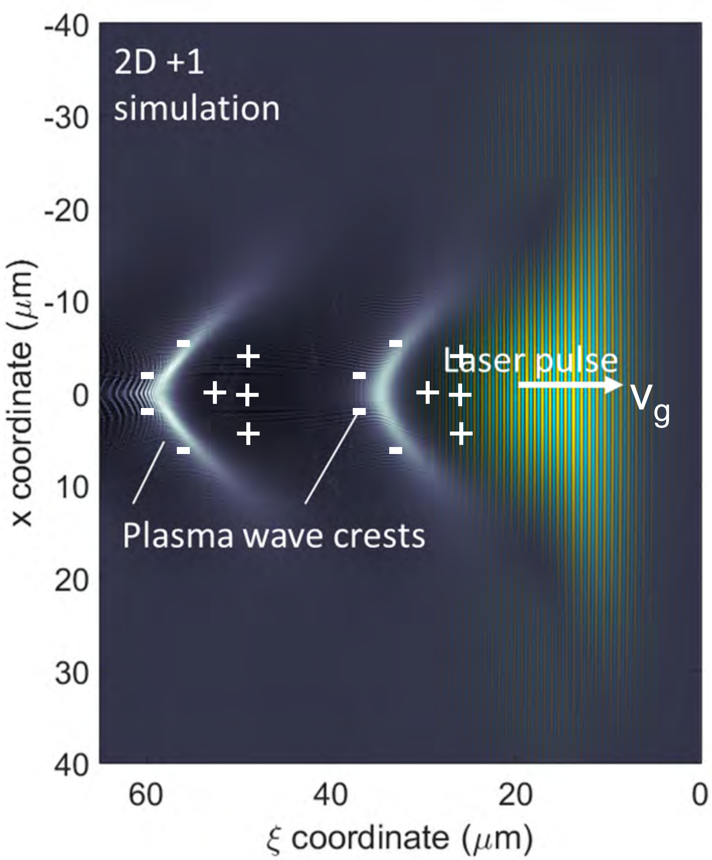
$$c\tau_L \approx \frac{\lambda_p}{2} \propto N_e^{-1/2}$$

- Lower plasma density →higher single stage energy gain→longer pulses & higher energies to maintain same peak power

- Current state of the art LWFA facilities are building multi-petawatt laser systems with low repetition rate (1 Hz or less)

Laser wakefield acceleration

Ponderomotive force $\boldsymbol{F}_p$ expels electrons out of high intensity region and sets up plasma wave



$$\boldsymbol{F}_p \propto -\nabla(a^2)$$

$$a = \frac{eA}{mc^2}$$

Use of TurboWave PIC code: Thanks to Dan Gordon (NRL)

How to get large *a*?

In vacuum or low density plasma

$$a \propto \frac{\lambda}{w_{spot}} \sqrt{\frac{\varepsilon_{laser}}{\tau_{pulse}}}$$

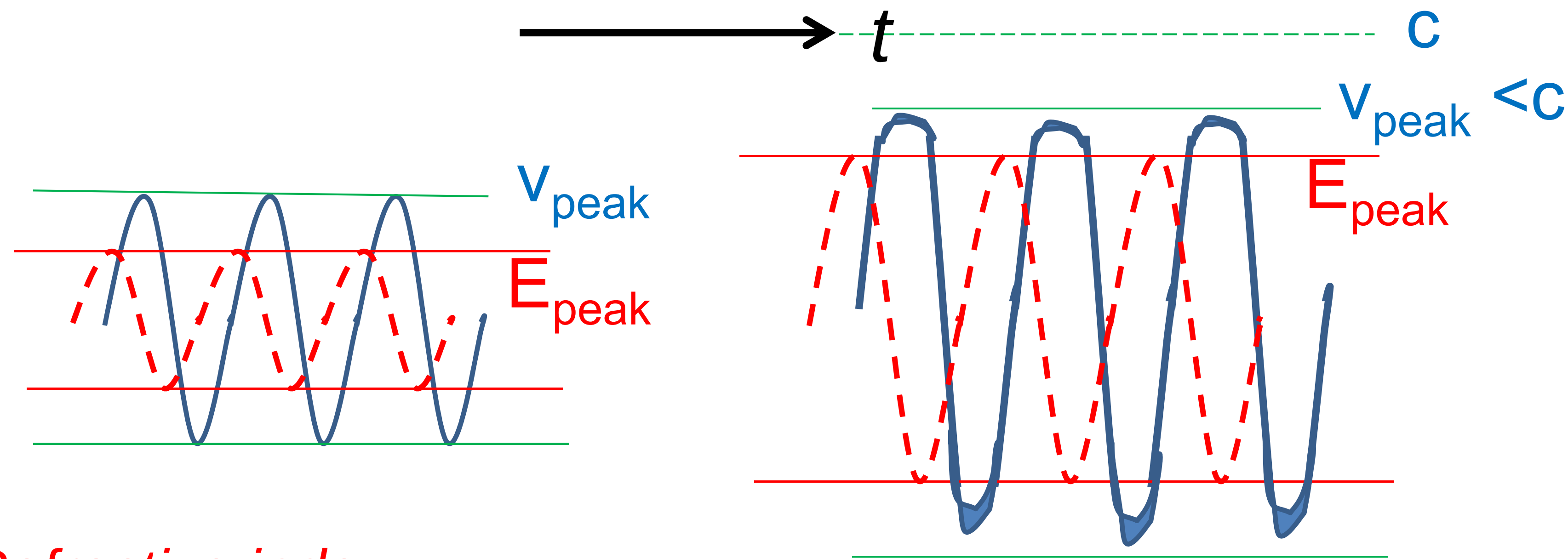
The usual suspects
$$

But in higher density plasma, one can reach

$$w_{spot} \sim \lambda_p \propto N_e^{-1/2}$$

How? Relativistic self-focusing

Lower field | higher field

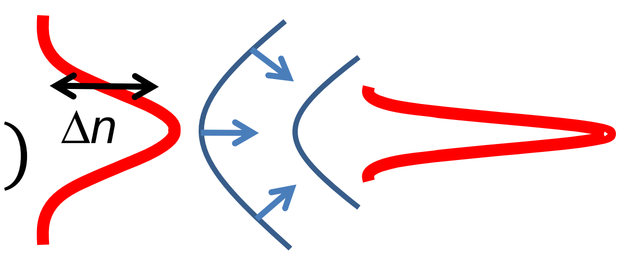


Refractive index

$$n = n_0 + n_{2,rel}|E|^2$$

$$\Delta n = n_{2,rel}|E|^2 \propto Ne\lambda^2 a^2 < Ne^2\lambda^2\,(\varepsilon/\,\tau)$$

Our interest



A < 1 TW wakefield accelerator ?

Another way of considering self-focusing is to compare the laser power to the relativistic SF critical power.

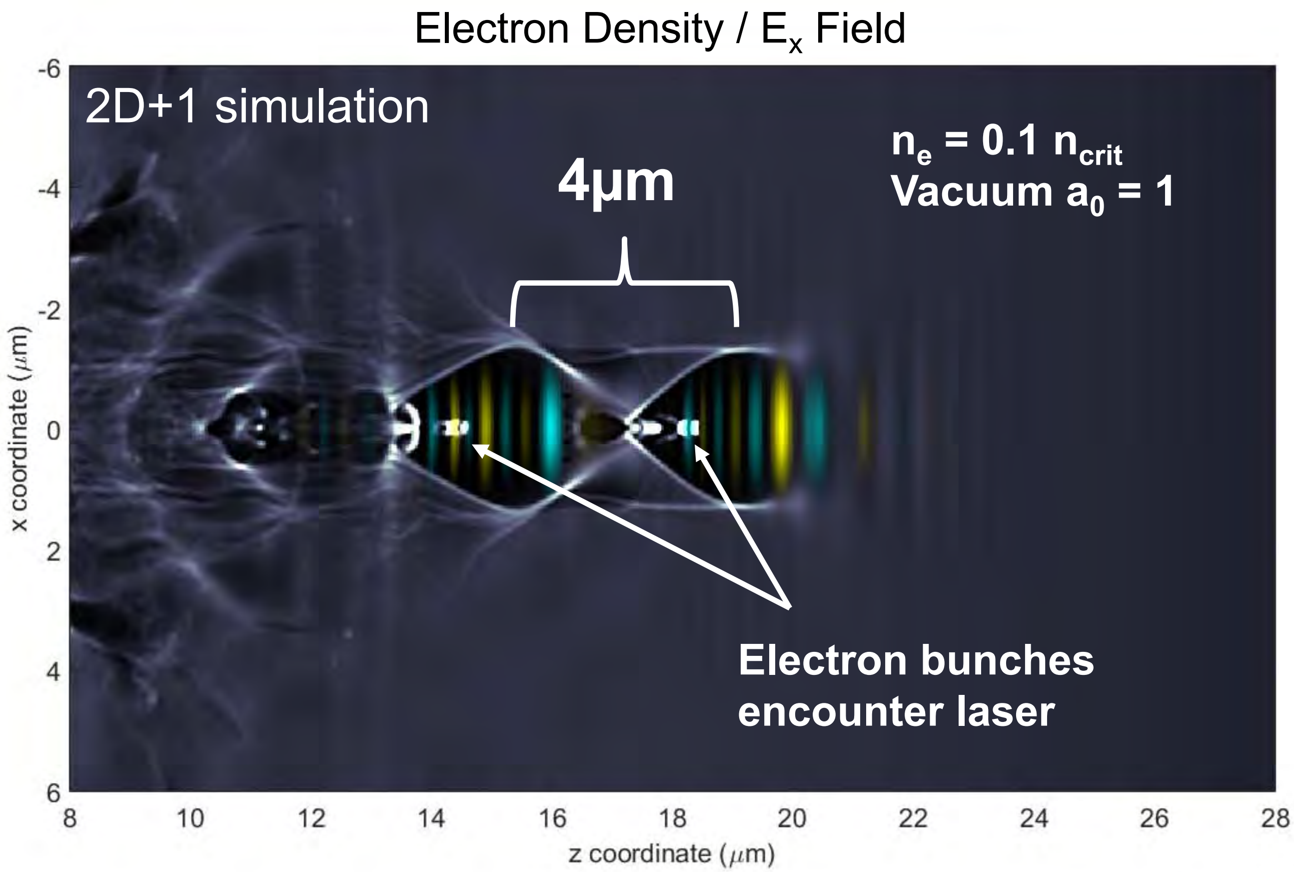
$$P_L > P_{cr}[GW] = 17.4\, {}^{N_{cr}}/_{N_e} \qquad l_{SF} = z_{Rayleigh}\left(\frac{P}{P_{cr}}\right)^{-1/2} < ljet$$

For a 1 TW laser pulse centered at λ=800 nm, $N_{cr} = 1.7 \times 10^{21} cm^{-3}$, so $P_L \gg P_{cr}$ when $N_e > 10^{20} cm^{-3}$.

At high densities the self-focusing laser pulse breaks up into a self-modulated (SM) pulse train resonantly driving a plasma wave

$$N_e \sim 10^{20} cm^{-3} \Longrightarrow 2\pi\omega_p^{-1} \sim 10\, fs < \tau_L \approx 40\, fs$$

Plasma Wave Generation in SM Regime



- Injected beams interact with laser and can lead to direct acceleration by the laser pulse through resonance of transverse (betatron) oscillations about the ion column

Goal of the research

Improve the state of the art in laser driven electron accelerators by enabling electron acceleration with lower energy lasers.

Why?

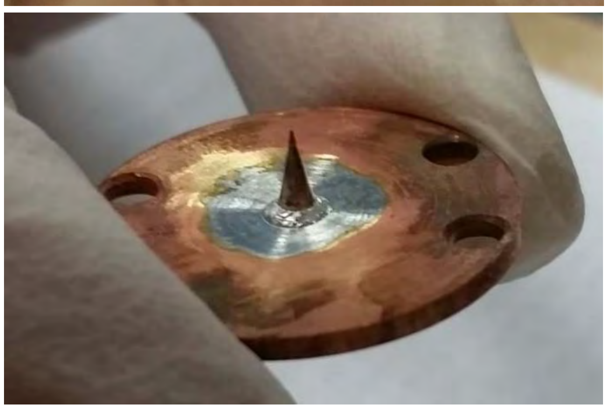
- Maintain a true “table top” accelerator
- Enable high repetition rate applications

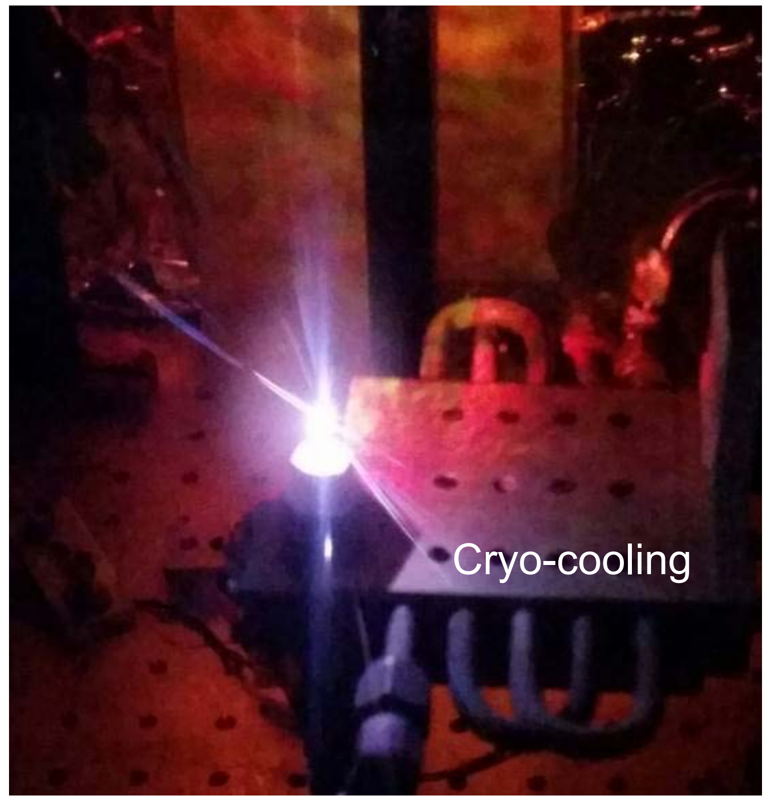
How?

- Leveraging scaling of nonlinear processes in plasma to drive a high amplitude wake with modest (< 1 TW) laser systems
- Exploring a “new” regime of laser-plasma acceleration (near-critical density)

High density wakefield accelerator

To take advantage of relativistic self focusing and self phase modulation we need to work at high plasma densities; dephasing requires thin gas jet targets





High density jet: pulsed and continuous

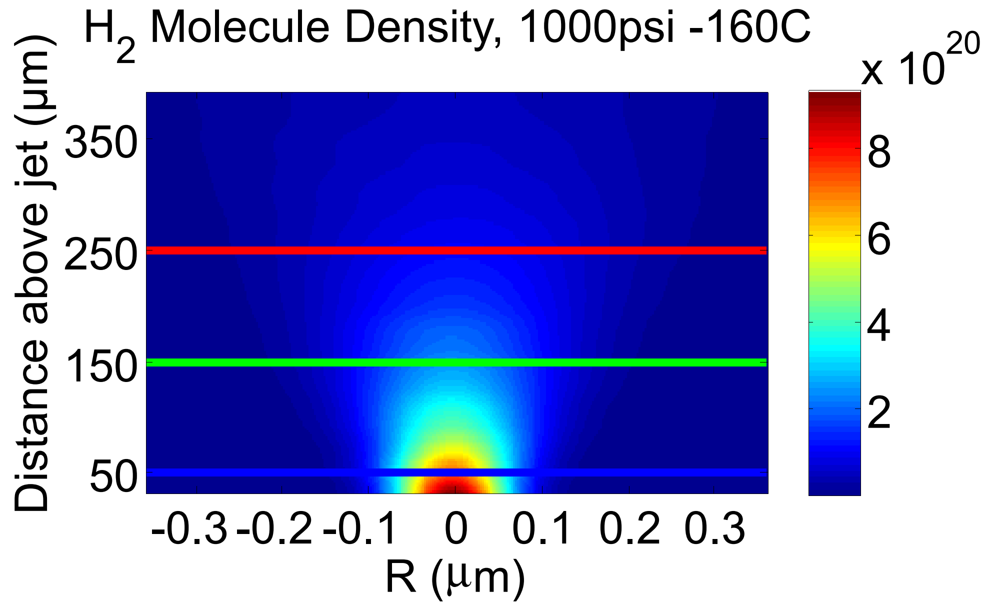
- Cryogenically cooled solenoid valve with 50-150μm nozzles

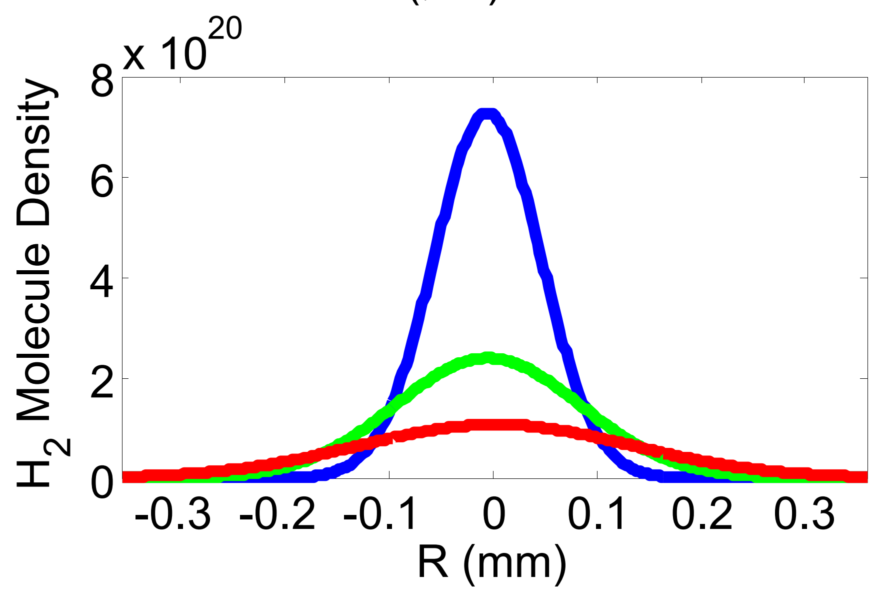
$$N = \frac{P}{kT}$$

- H_2 gas densities near the nozzle approach critical density for backing pressures of 1000psi

- Gas profiles have 250μm FWHM at distance ~200μm above the nozzle

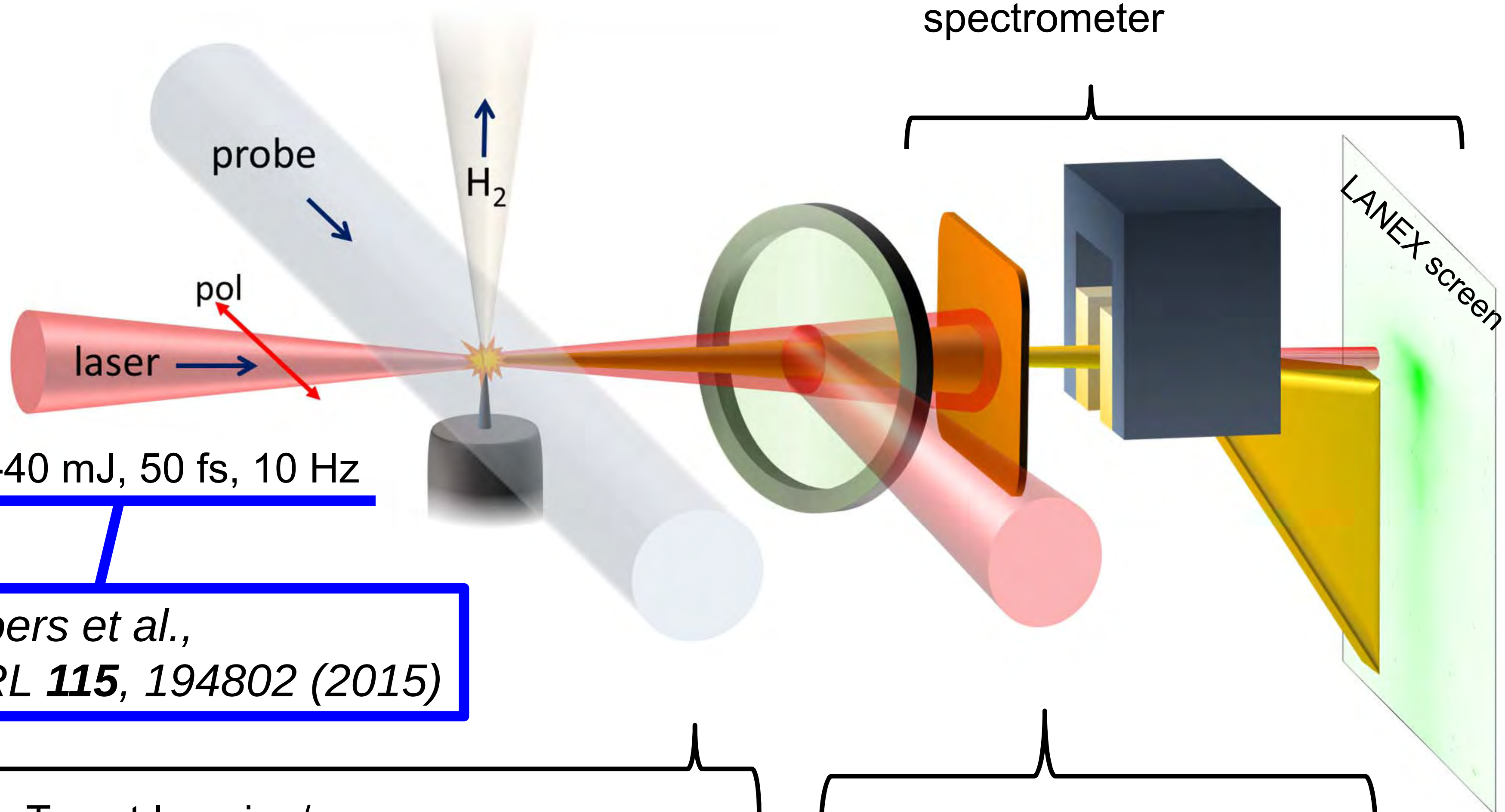
- Gaussian profile due to sonic flow properties





Experimental Setup (10 Hz, N_e<0.25N_{cr})

Permanent magnet electron spectrometer



10-40 mJ, 50 fs, 10 Hz

Goers et al.,
PRL ***115****, 194802 (2015)*

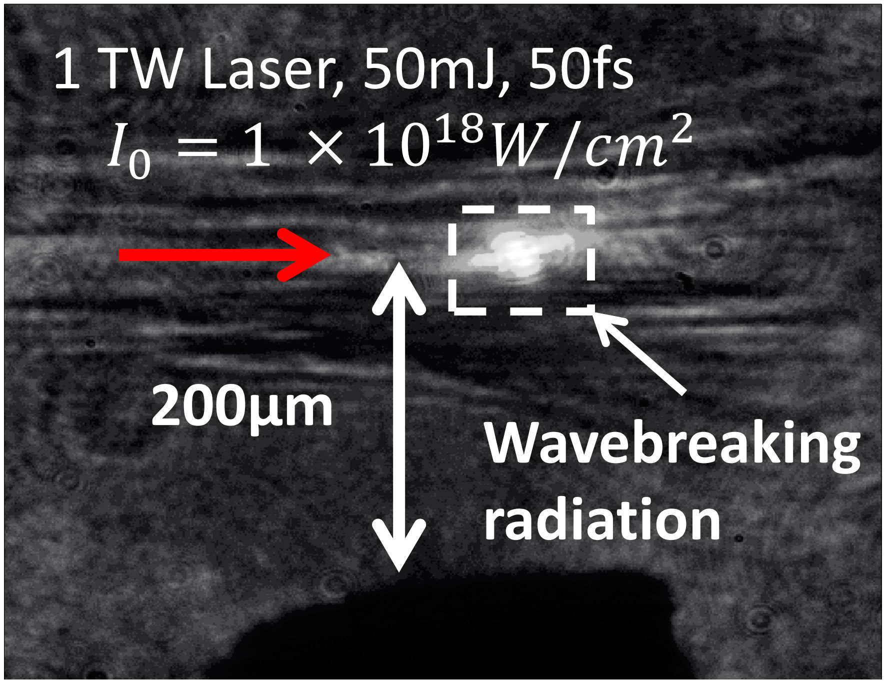
Target Imaging/
Transverse Interferometry/
Flash radiation spectral analysis

Laser Mode Imaging/
Drive laser spectral analysis

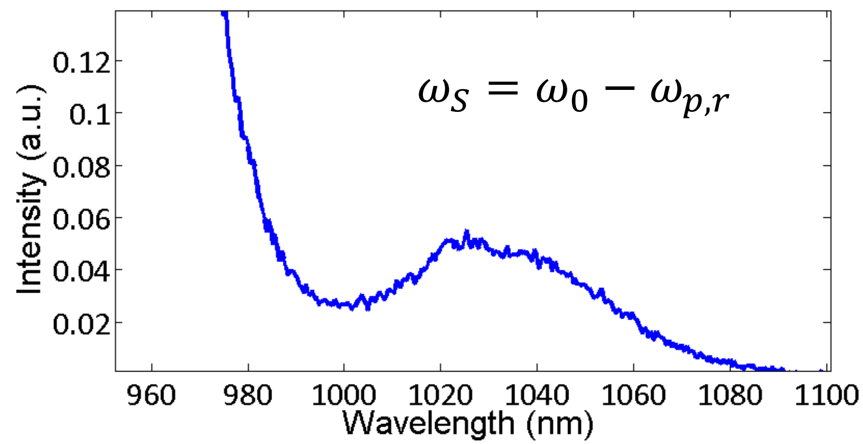
Plasma wave generation in high density jet

$250\mu m$ FWHM with $N_{e,\max} = 2 \times 10^{20}\ cm^{-3}$

A. J. Goers, *et al.*, PRL (2015)

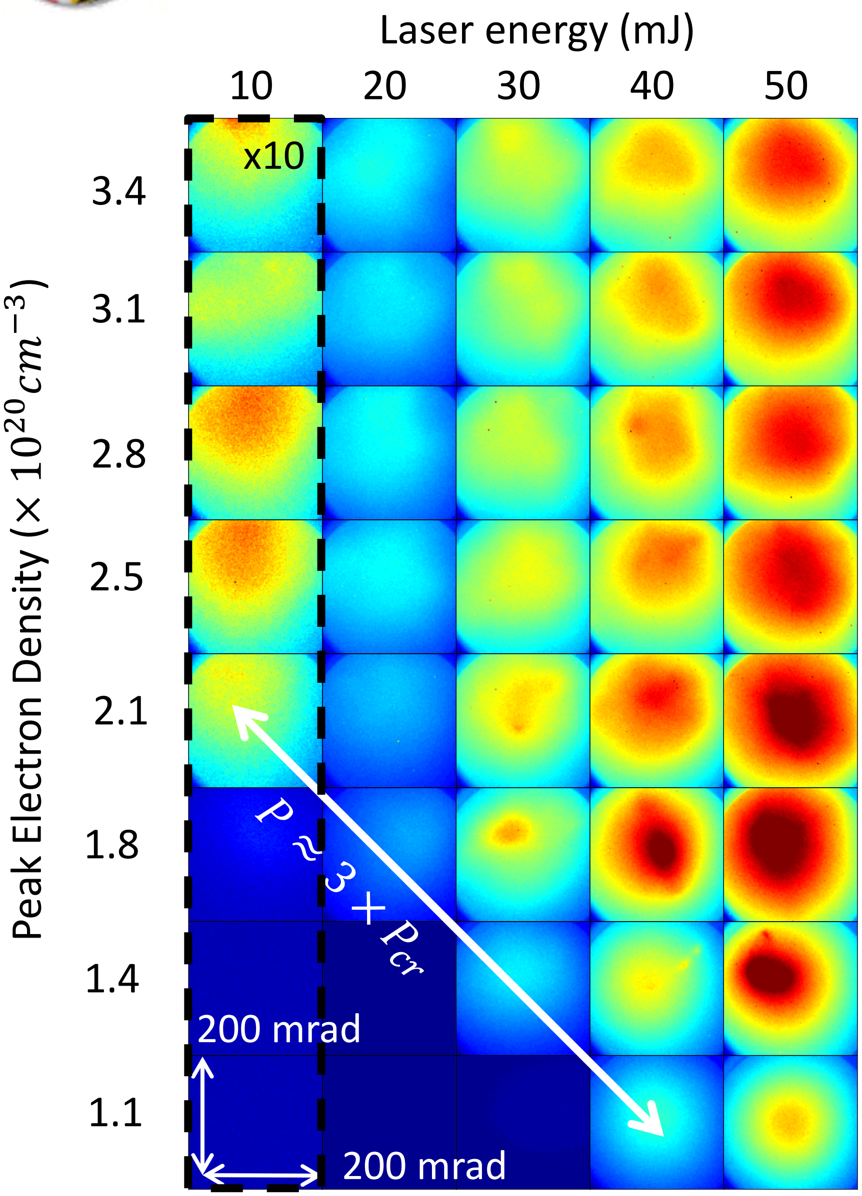


Stokes peak in forward optical spectrum implies peak $a_{SF} \sim 2.7$

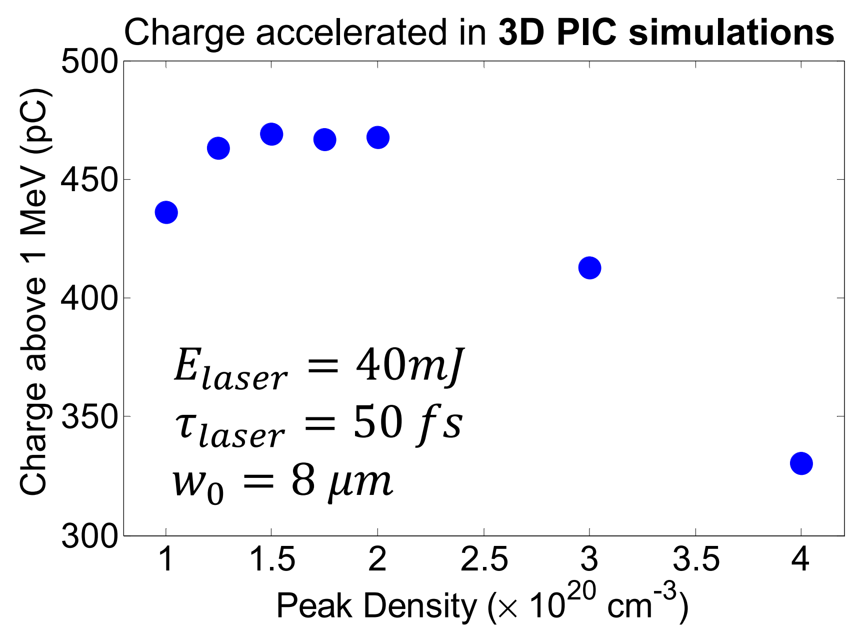


- Laser parameters:
  - Initial $a_0 = 0.68$, self-focused $a_{SF} = 2.7$
  - $50\ fs$ FWHM pulse
  - $f/9.5$ OAP focuses to $8\mu m$ FWHM spot size

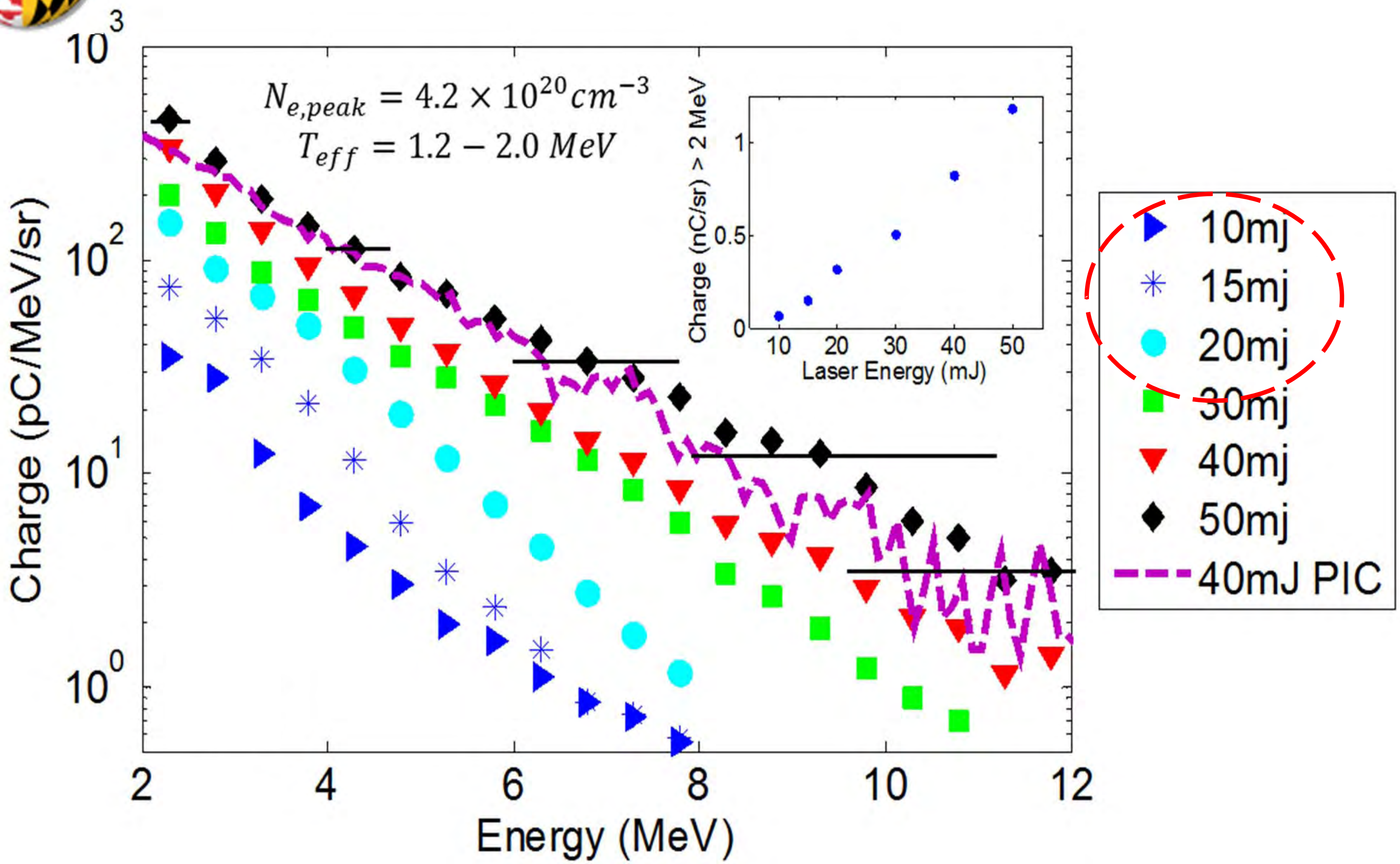
Onset of Self Injection



- Forward directed electron beams appear at $P \approx 3 \times P_{cr}$
- Beam FWHM divergence angles range from 175-225 mrad
- 3D PIC simulations suggest acceleration of 450pC bunches of MeV electrons using 1 TW drive laser.



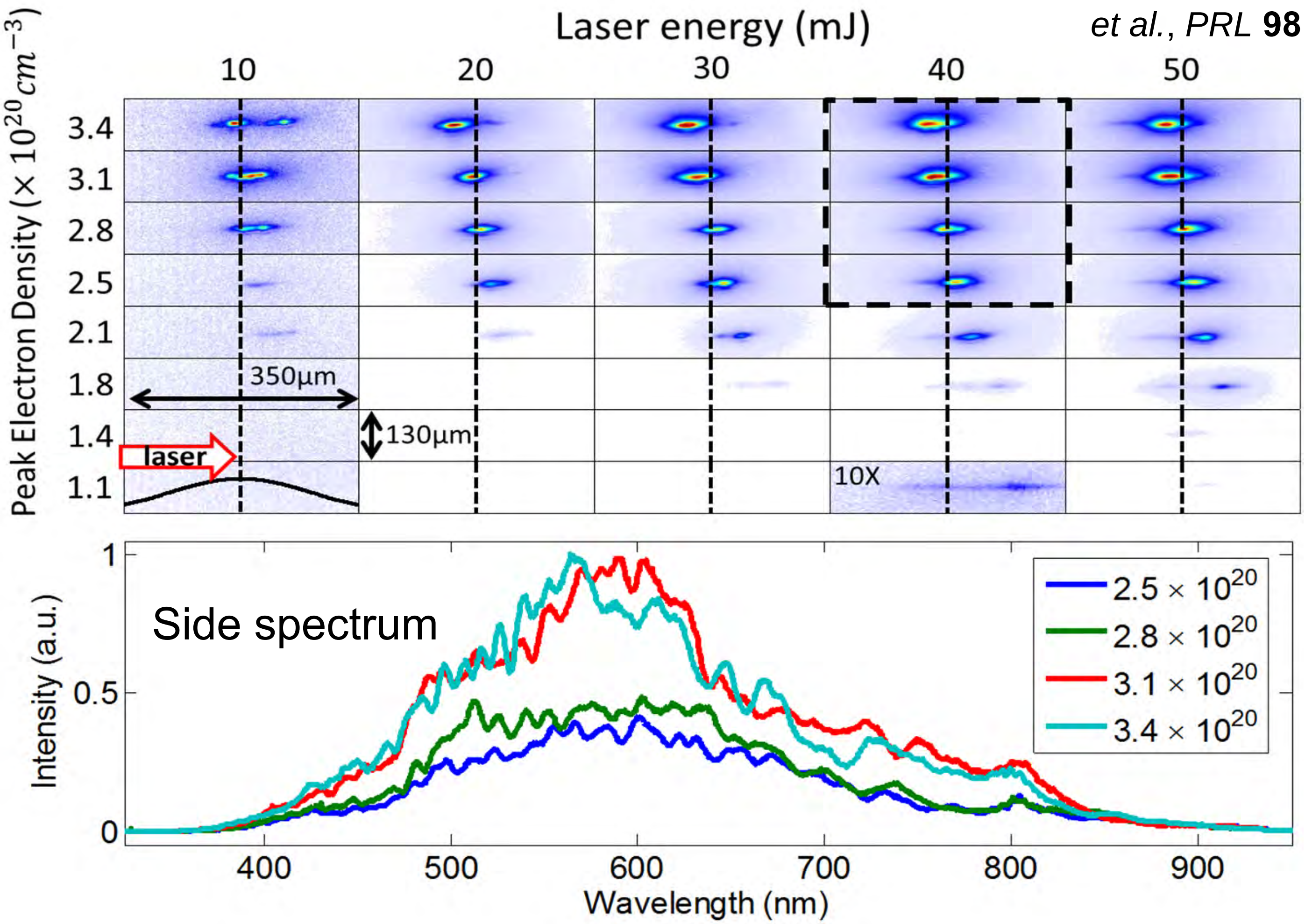
electron energy spectrum



- Spectra in good agreement with simulation
- Thermal spectrum characteristic of SM-LWFA

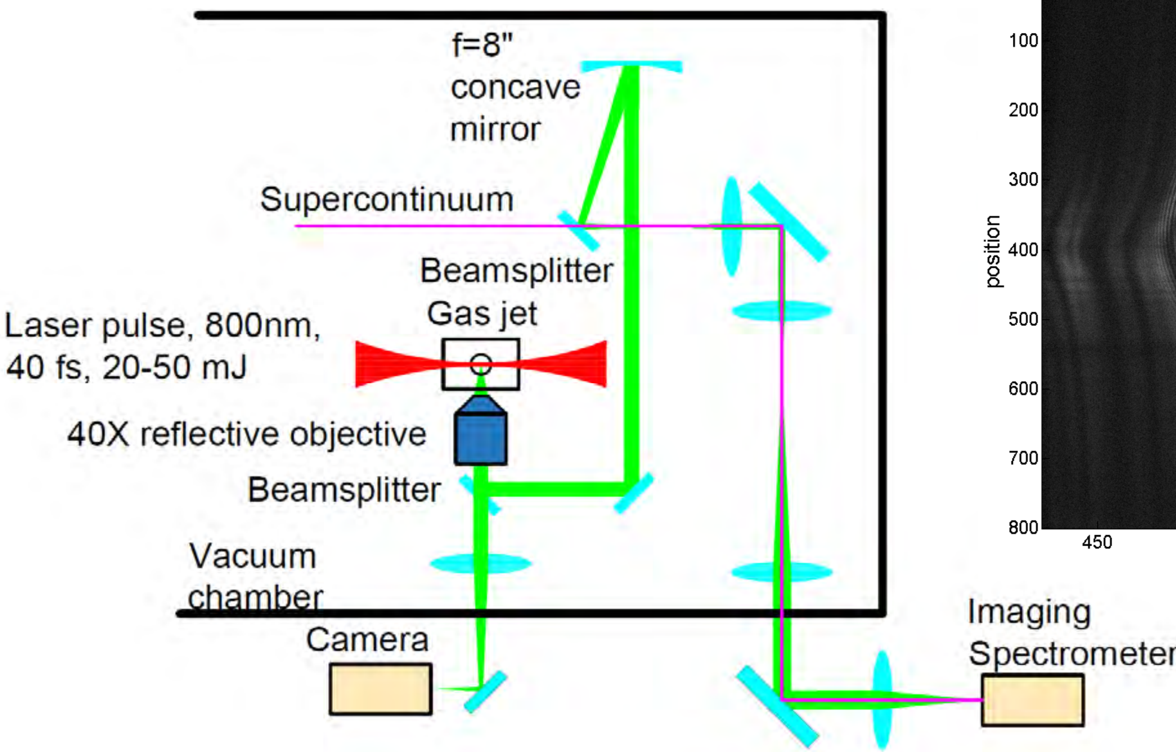
Wave-breaking flash radiation at high density

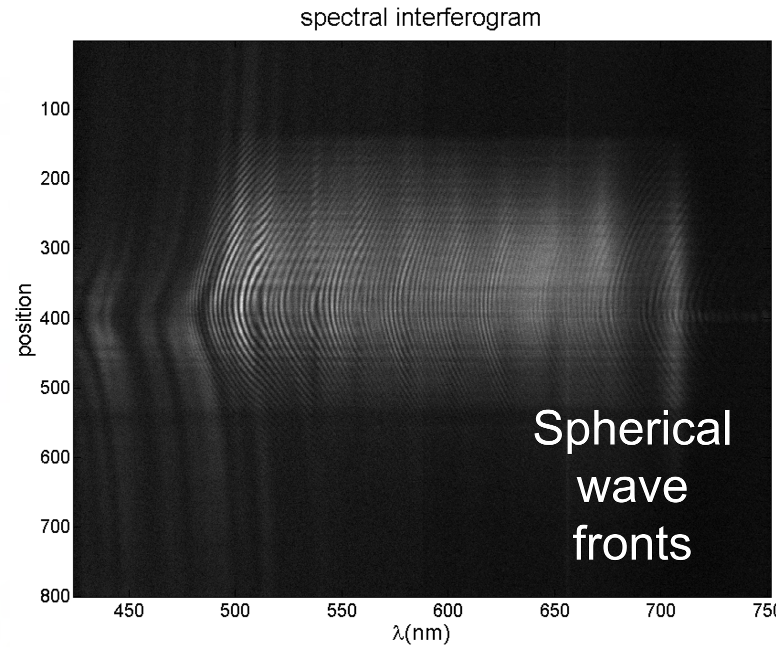
Seen at lower density: Thomas *et al.*, *PRL* **98** 054802 (2007)



Flash energy measured to be $\sim 15\ \mu J$ into $f/2.6$ collection optics implies radiation of ~3% of total laser energy into 4π. Maps out self-injection location in jet. Flash bandwidth corresponds to a transform limit of ~1 fs!

Single shot characterization of ultrashort pulse wave breaking radiation

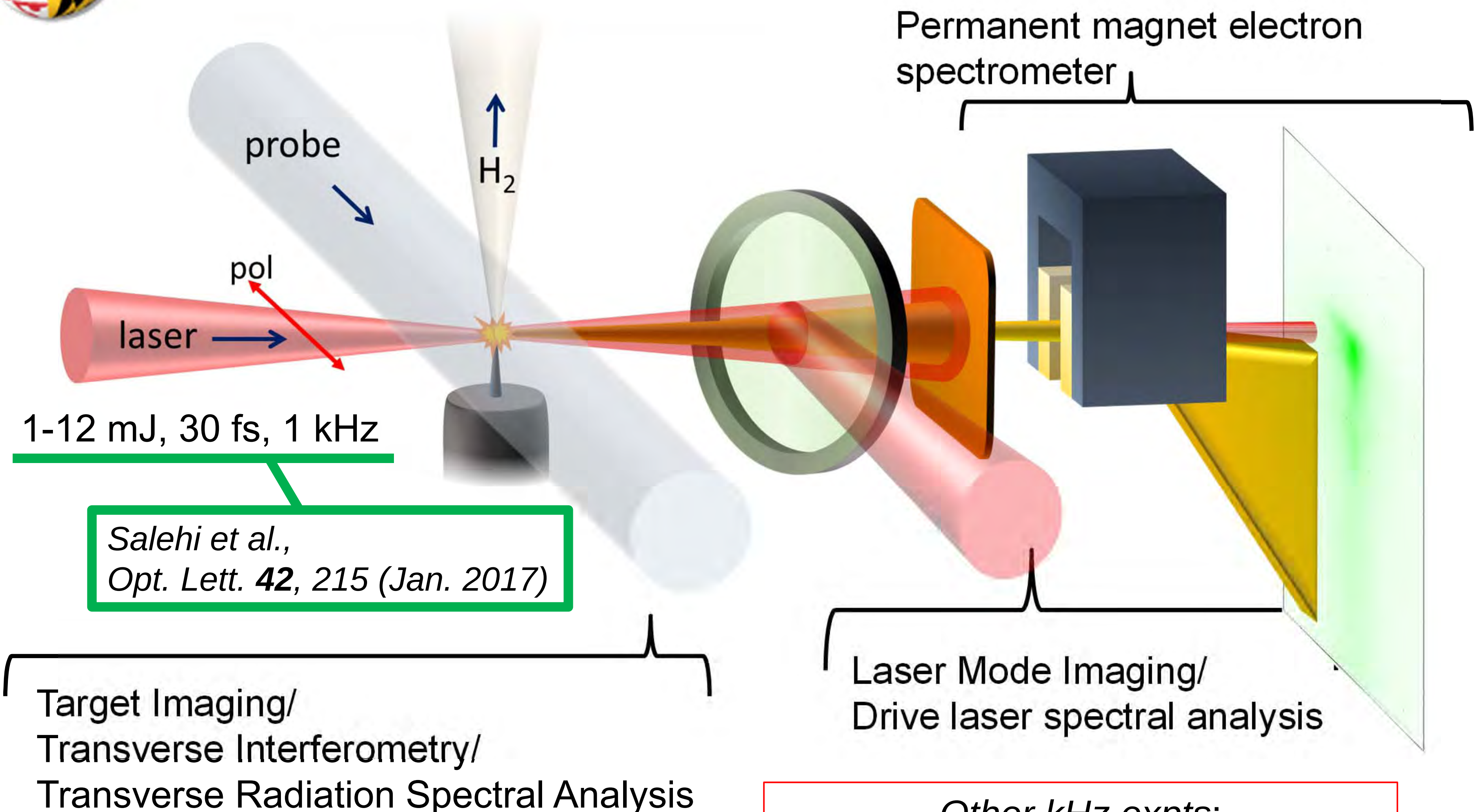




B. Miao et al., to be published

- Supercontinuum pulse is generated by filamentation in a Xe gas cell, then compressed with a grism compressor and used as a probe
- Spectral interferometry between the flash and a supercontinuum pulse show that the flash is coherent and ultrashort

Experimental setup (1 kHz, N_e<0.7N_{cr})



Other kHz expts:

- He *et al*. NJP (May 2013) <150keV
- Guenot *et al*., Nat. Phot. (May 2017)

3 MeV, Δ*E/E*>50%

Warning! Radiation safety

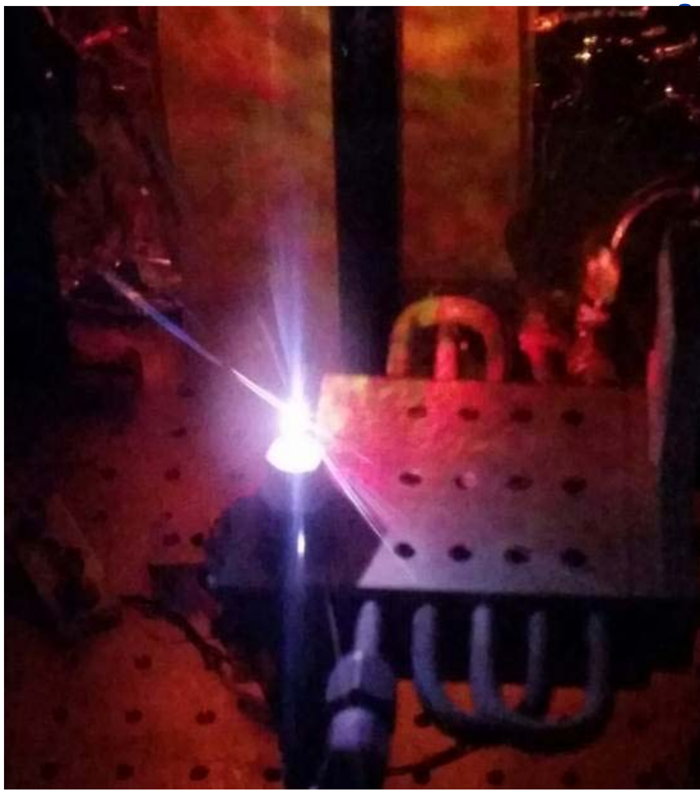
We use a solenoid valve in the gas line to reduce accumulated ionizing radiation dose.

The gas jet was typically operated at 10-50ms open time with 0.5 Hz repetition rate.

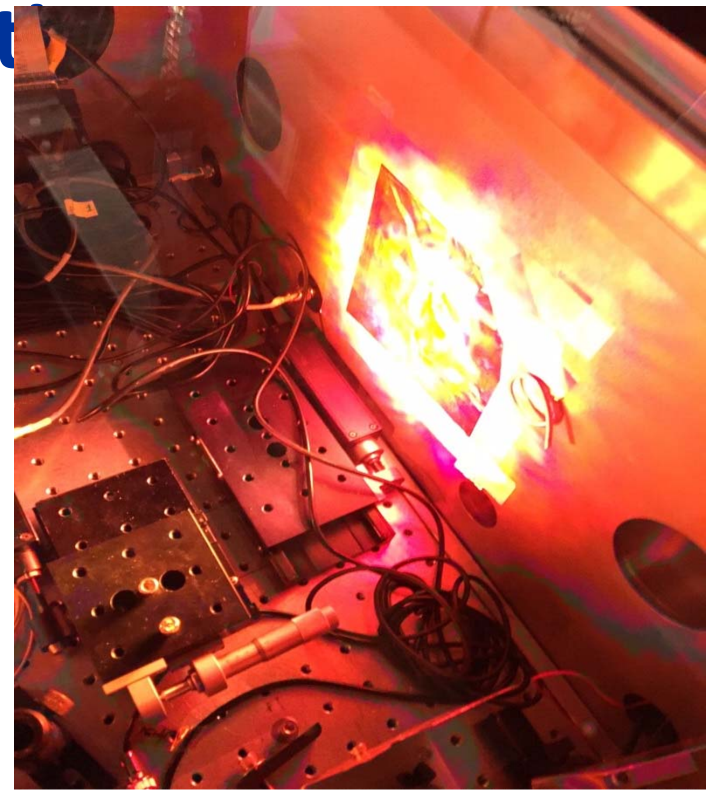
50 shot bursts proves the set up can work with continuous flow.

With continuous flow one would pass the annual occupational dose limit in ~50 hours standing next to experimental chamber.

Electron acceleration at 1kHz



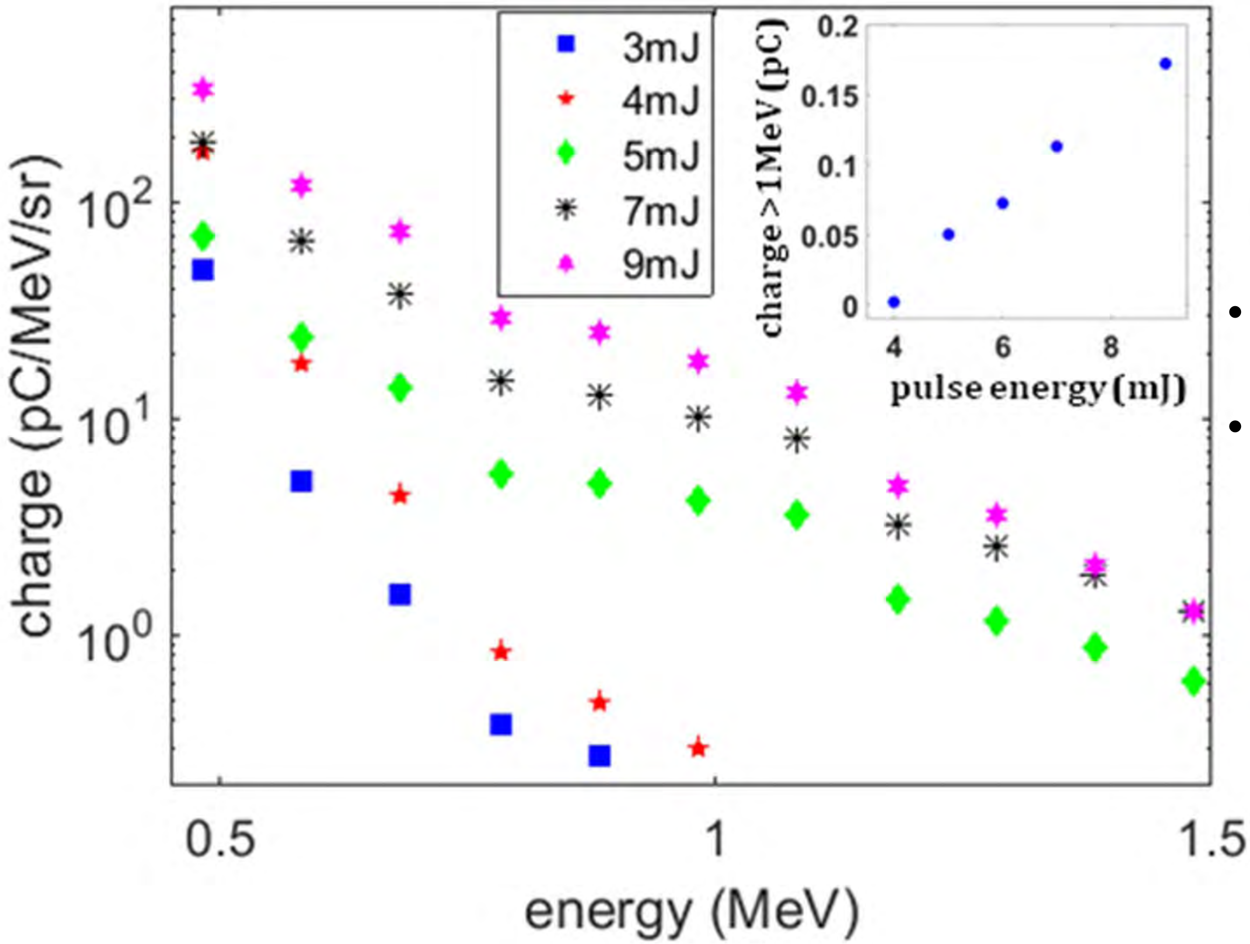
Cooling assembly and gas jet



Bright supercontinuum from laser interaction with gas jet.

Using $< 10mJ$ laser pulses requires even higher plasma densities $(N_e < 0.7N_{cr})$ to achieve electron acceleration.

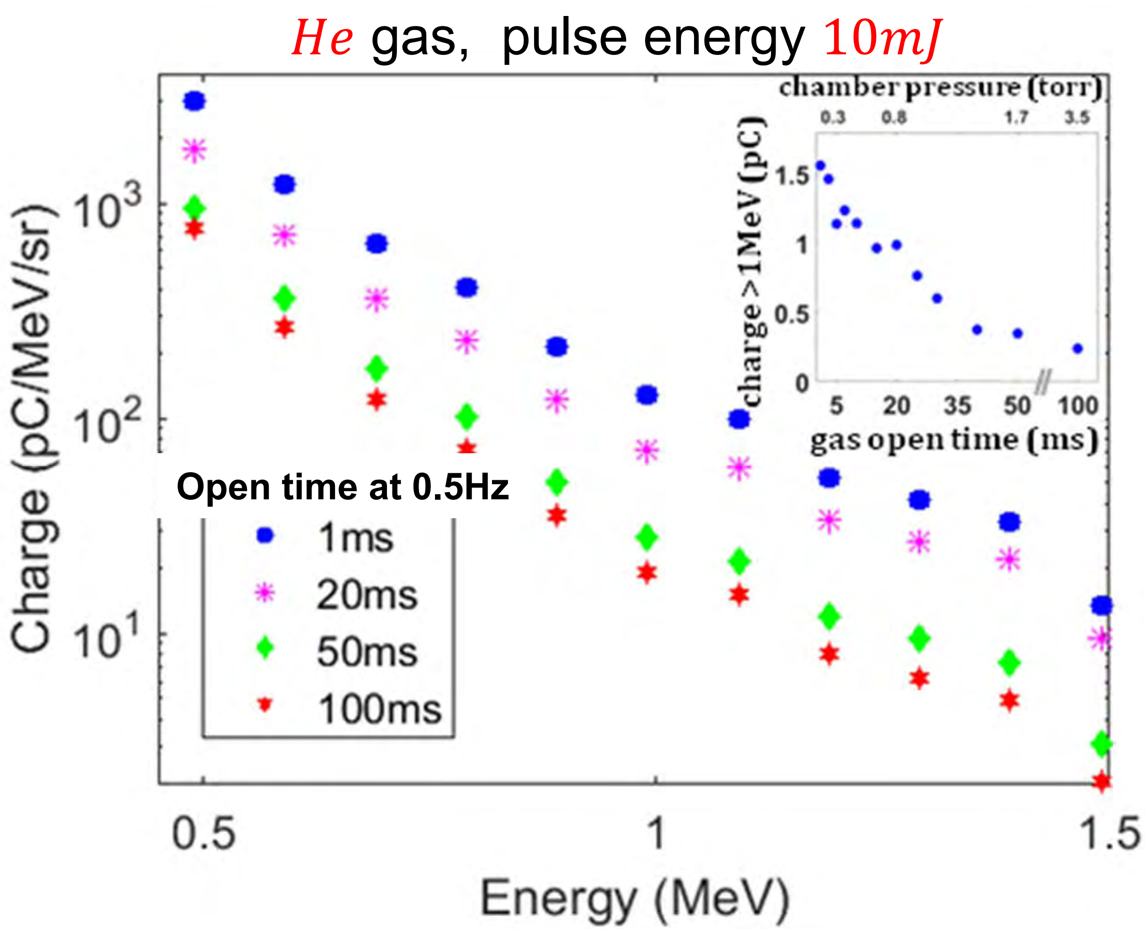
Wakefield acceleration at 1 kHz



- $10ms$ valve open time
- $N_{e,max}$ ranges from $0.2 - 0.7N_{cr}$

Using H_2 gas, laser pulses with as low as $1.3mJ$ energy accelerate electron bunches with $\sim 10fC$ charge up to $0.5MeV$.

Background pressure effect



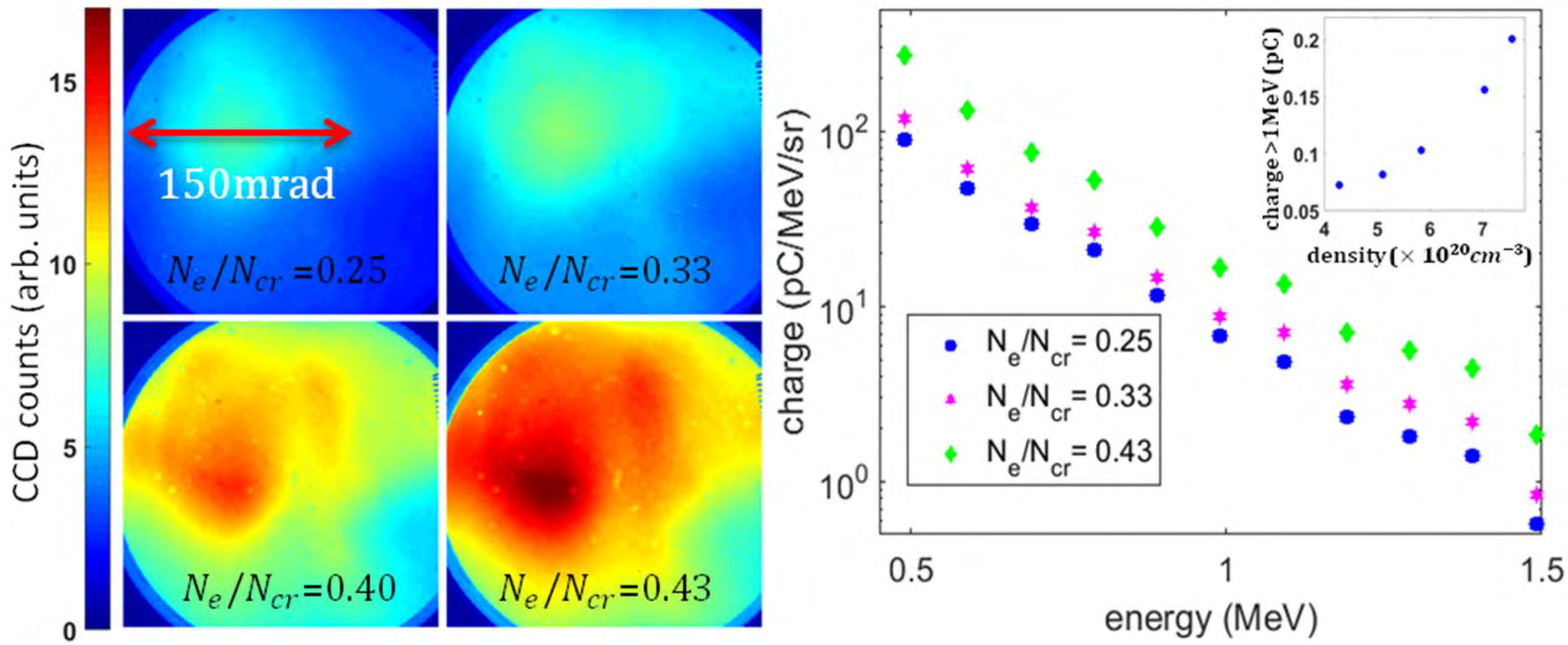
- 10 mJ laser pulse
- Valve operated with 1 second open time at 0.5 Hz
- Steady chamber background pressure ~20 torr

Scanning a 50 shot burst over the 1 second valve open time shows electron acceleration surviving at all delays even with high background pressure.

Higher gas density leads to higher charge

Total charge increases significantly with increase in gas density.

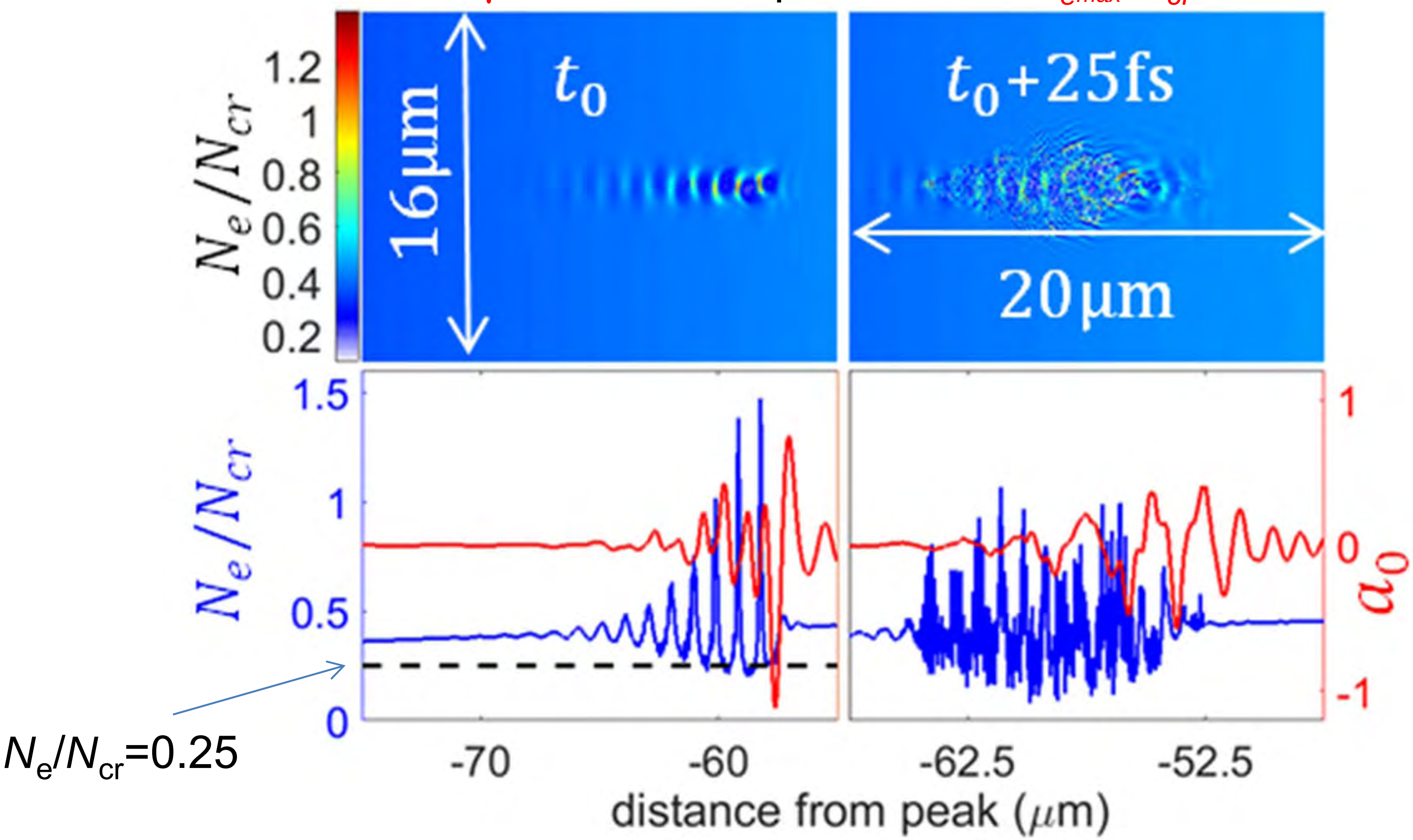
He gas with $20ms$ valve open time, and $9.5mJ$ pulse energy



With He gas no accelerated electrons detected and any density for laser pulses below $5mJ$ due to ionization-induced refraction

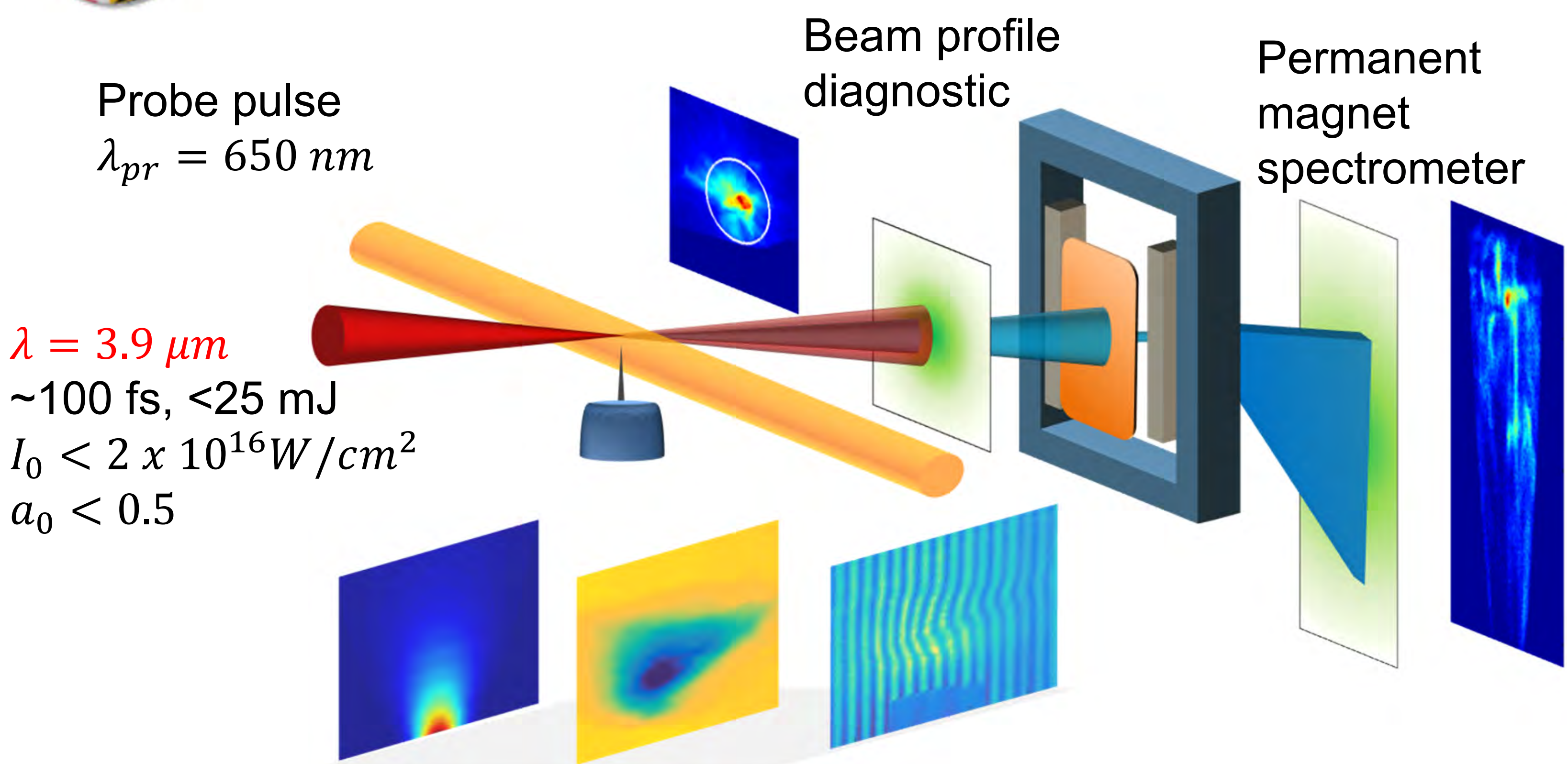
Acceleration at greater than quarter-critical density

PIC simulation: 200μm FWHM H plasma with N_{emax}/N_{cr} = 0.5, 4mJ pulse



- Modulations form at $N_e > 0.25\ N_{cr}$, with anti-Stokes line appearing
- Apparently 2-plasmon instability suppressed by strong steepening of waves

NEXT UP: Experimental setup (λ=3.9μm, 20 Hz)



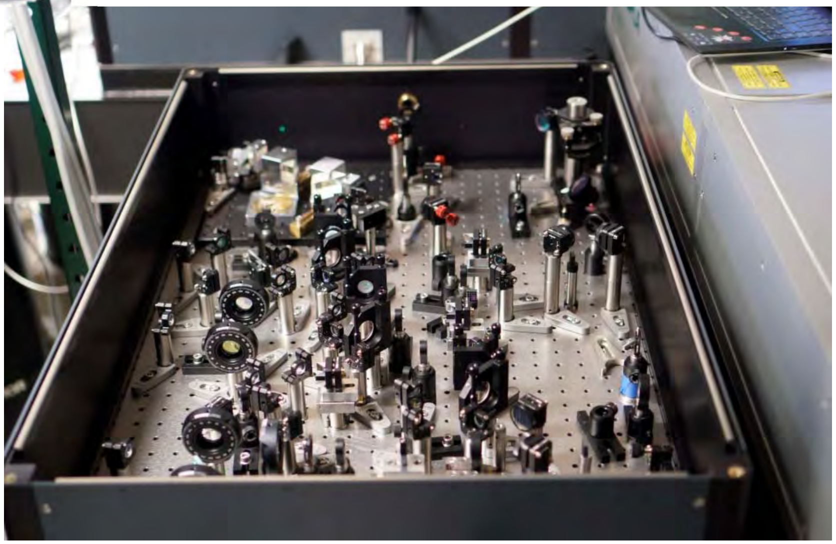
- **High density jet reaches $N_e > N_{cr}$ in the mid-IR even at room temperature**
- **Experiments performed up to $> 2\ N_{cr}$**

Based on previous work at 800 nm:

- *A. J. Goers et al., Phys. Rev. Lett. 115, 194802 (2015)*
- *F. Salehi et al., Opt. Lett. 42, 215 (2017)*

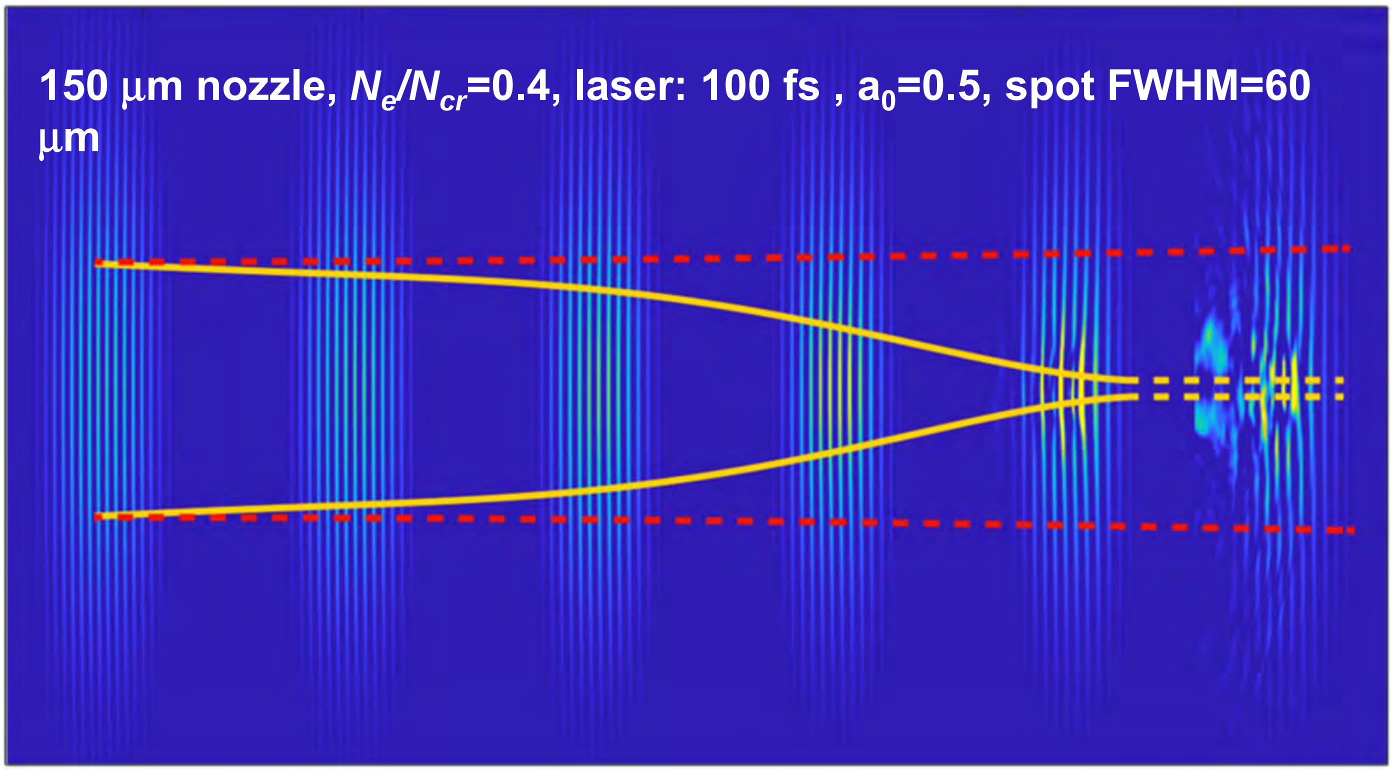
Mid-infrared OPCPA laser (λ_{idler} = 3.9μm)

Laser in our lab at Maryland; expts. described here were done earlier in Austria



Simulation of relativistic self focusing

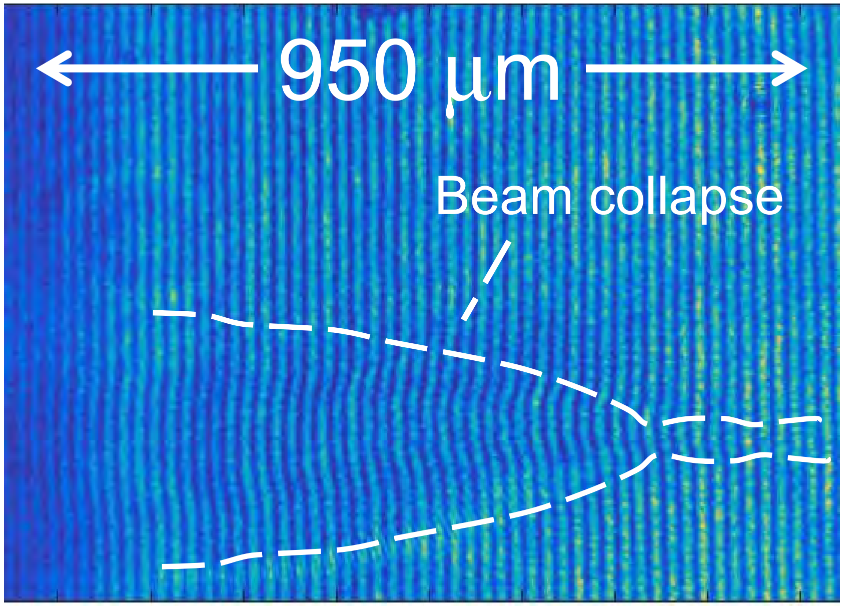
- **Snapshot of the 20 mJ, λ=3.9μm laser pulse every 50μm as it travels up a density ramp**
- **Overlay linear propagation beam FWHM for comparison**



Interferometric imaging of relativistic self-focusing collapse of λ=3.9μm pulses

$$\frac{N_e}{N_{cr}} \sim 0.25, \qquad \frac{P}{P_{cr}} \sim 2.5, \qquad \frac{d_{jet}}{l_{\mathrm{sf}}} \sim 1.5$$

- Plasma shows marked narrowing, tracking beam collapse
- For λ=3.9μm, $z_{\mathrm{rayleigh}} >> l_{\mathrm{jet}}$ allowing clear observation of collapse
- Interference fringes are not broken, due to lower N_e compared with all previous experiments using laser λ< ~1μm, allowing full extraction of densities



Scaling of relativistic e-beam generation with laser critical power and jet width

Relativistic e-beams are generated for laser powers P above the critical self focusing power P_{cr} , but only if the axial plasma scale length l_{plasma} is longer than the self-focusing length l_{SF}

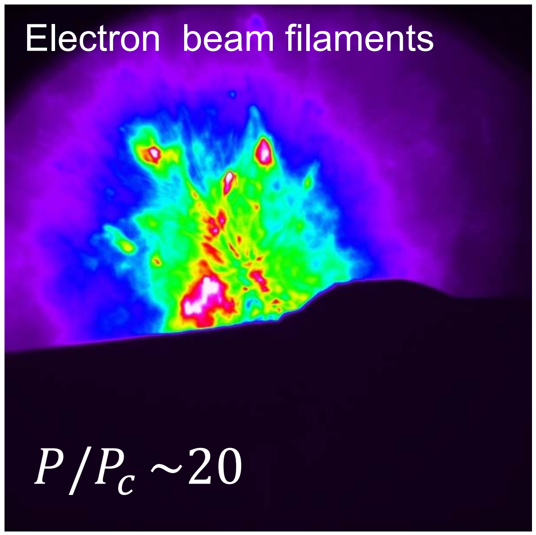
$$P_L > P_{cr}[GW] = 17.4\, {}^{N_{cr}}\!/_{N_e}$$

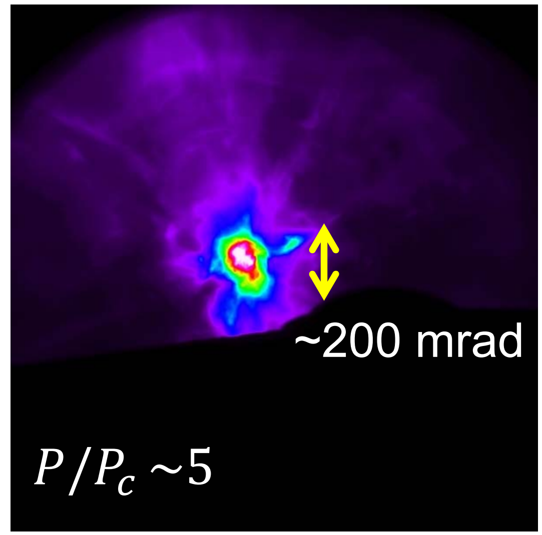
$$l_{plasma} > l_{SF}$$

$$= z_{Rayleigh}\left(\frac{P}{P_{cr}}\right)^{-1/2}$$

Relativistic multi-filaments in the λ=3.9 μm beam lead to relativistic electron multi-filaments

Structure in beam profiles correlates with laser power and self focusing length



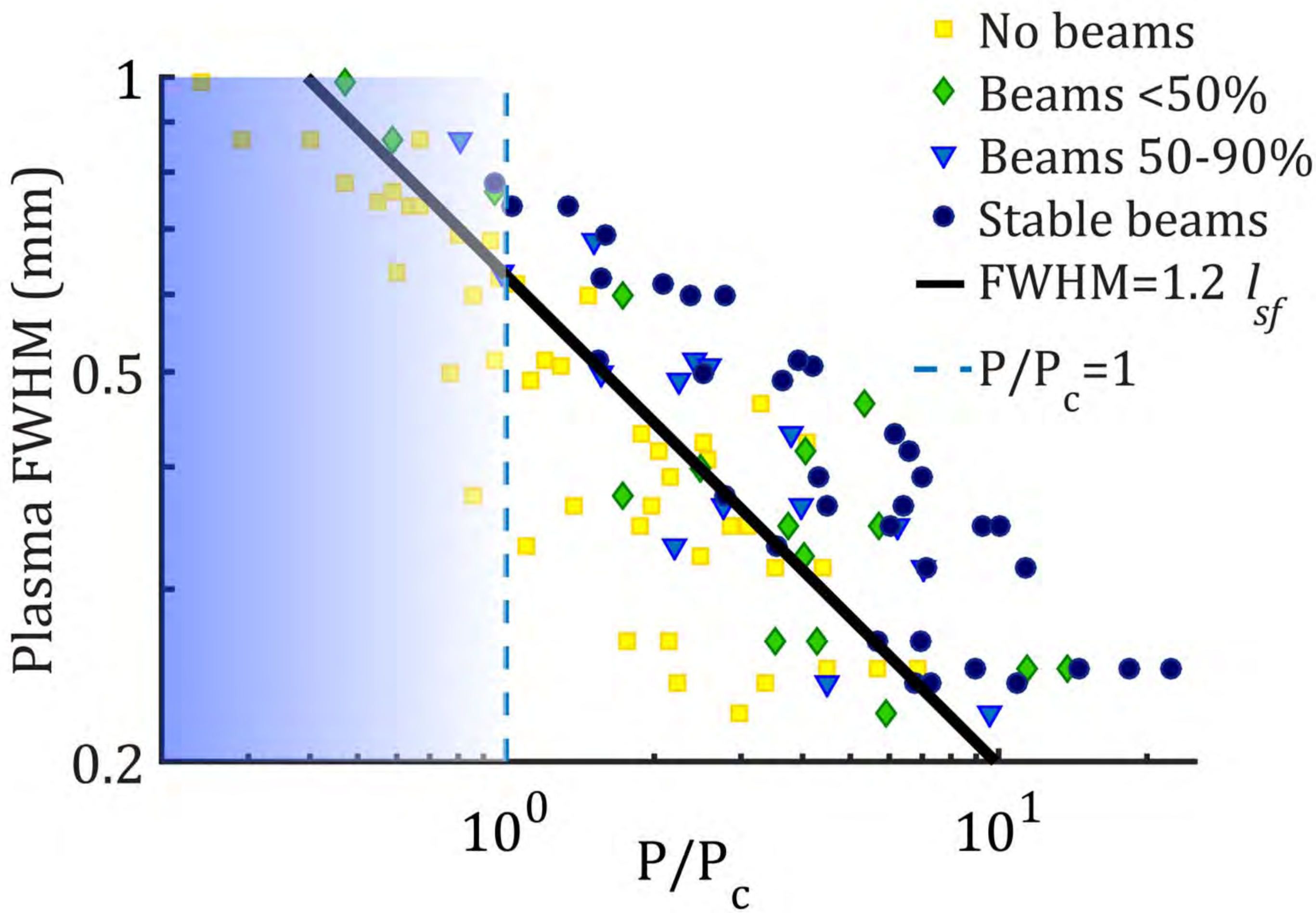


$N_{e,\,peak} > 2N_{cr}$ (100 μm from nozzle) e-beamlets from relativistic multi-filaments seen

$N_{e,\,peak} < N_{cr}$ (400 μm from nozzle), cleaner, less-divergent e-beam from single relativistic filament

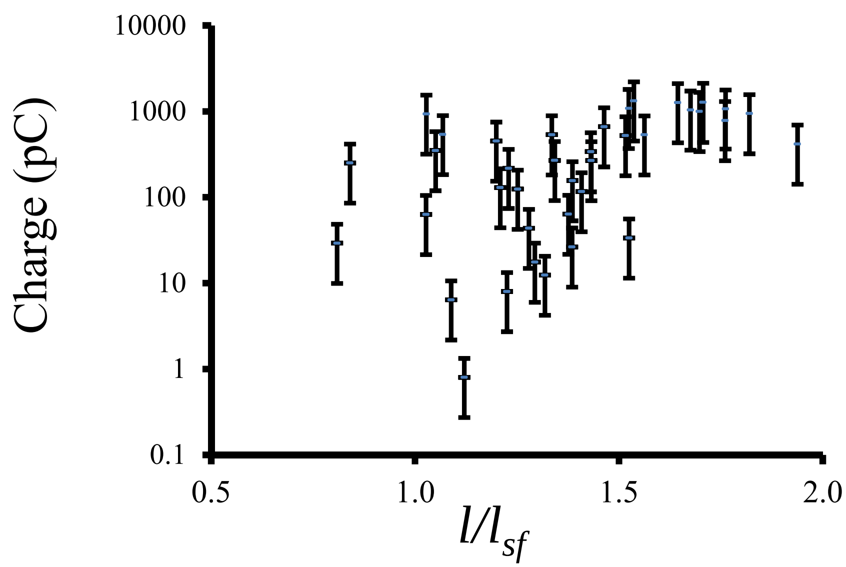
Self-focusing and acceleration thresholds

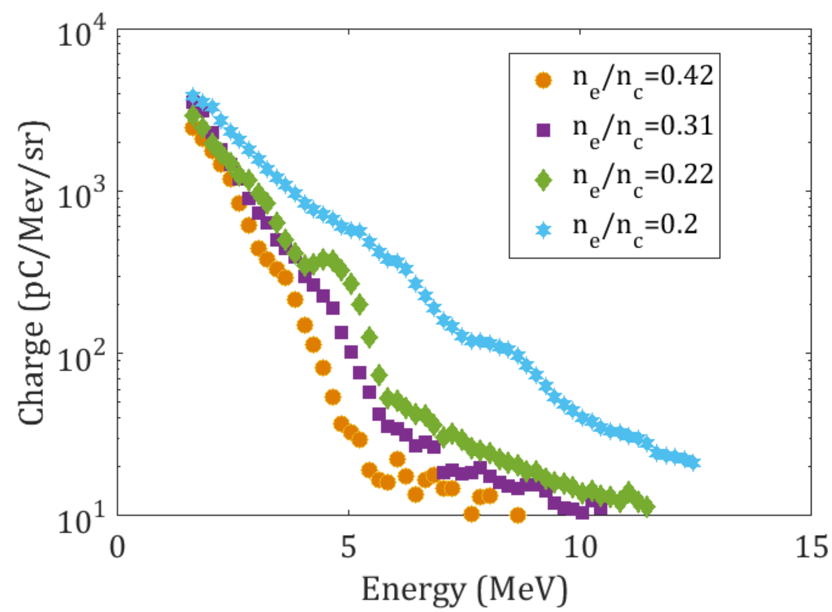
$$l_{SF} = z_{Rayleigh}\left(\frac{P}{P_{cr}}\right)^{-1/2}$$



Charge and energy of accelerated beams (@20 mJ 3.9μm laser)

- **Maxwellian distributions extend above 12 MeV (limit of our spectrometer)**
- **Charge estimates from full beam profiles give total charge at > 1 MeV of ~1 nC**
- **Amount of charge and energy spectra follow self-focusing length onset threshold**



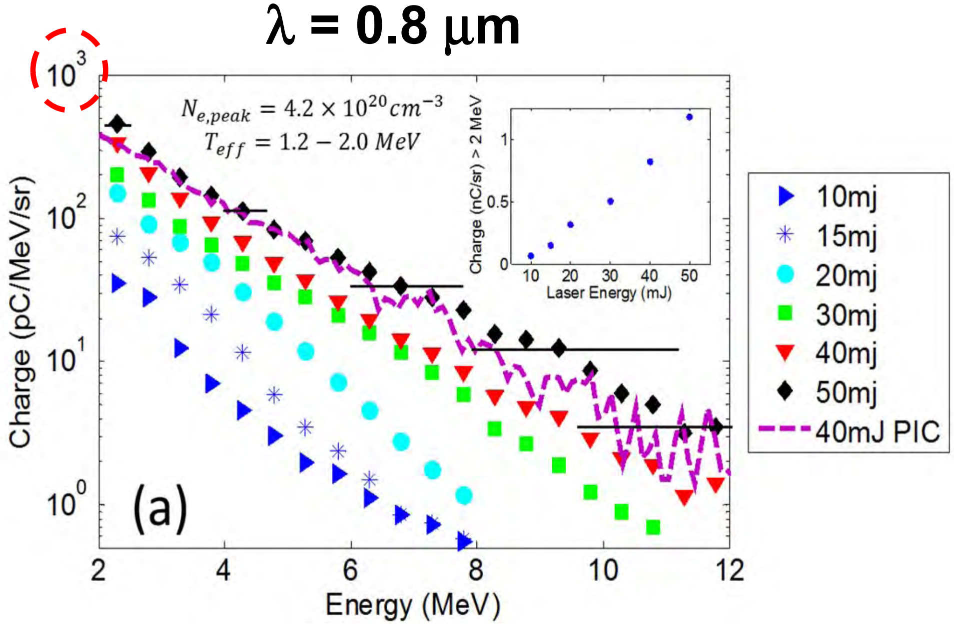


Charge and energy scaling with laser wavelength (compare λ=0.8 and 3.9μm)

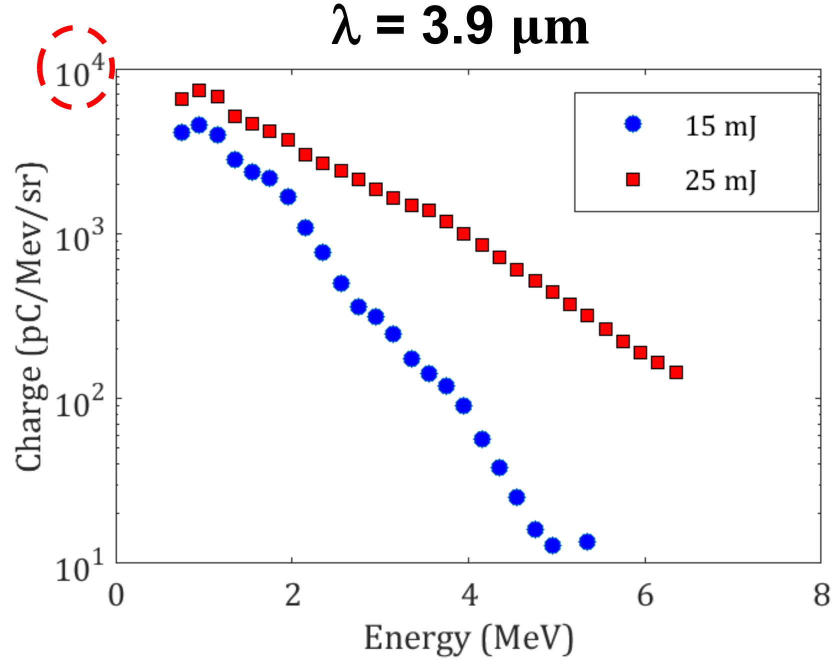
- Results show higher charge for longer wavelengths
- Possible combination of lower density and larger wake bucket

N_e/N_{cr} =0.25 and similar L_{jet}/z_0 for both cases

λ = 0.8 μm



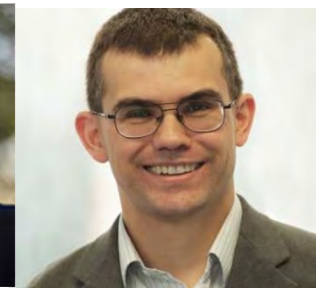
λ = 3.9 μm

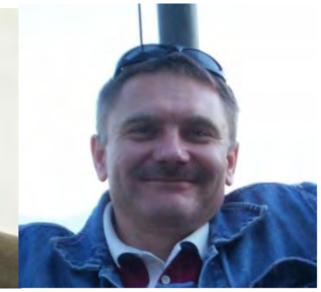


Conclusions

- Use of a high density gas target lowers the required pulse energy for relativistic self-focusing, enabling the use of high repetition rate lasers for wakefield acceleration. High density is determined by the driver wavelength.
- Using mJ-scale drivers, we have demonstrated kHz repetition rate acceleration of $\sim pC$ electron bunches to ~ 1-10 MeV energies at λ=0.8μm. At 20 Hz and λ=3.9μm, we have generated higher charge ~nC bunches at <12 MeV.
- High repetition rate, high charge, short duration electron bunches make our setup an ideal portable source for applications such as ultrafast radiography for science and medical applications.

Thank you!





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