Laser Channeling and Electron Acceleration from High Intensity Laser Interactions with an Underdense Plasma

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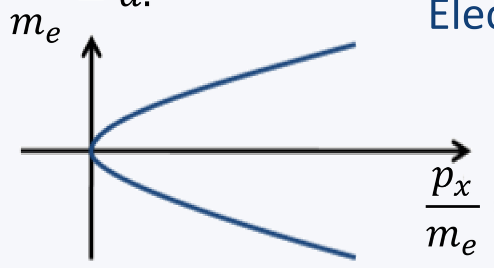
Energy transfer from laser to electrons

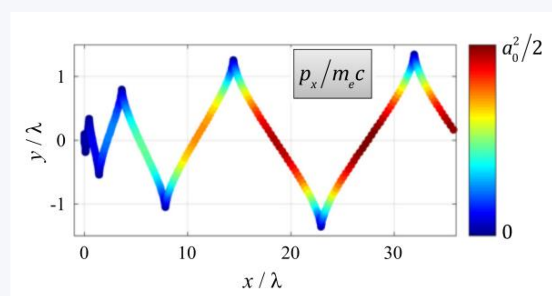
In a vacuum, an electron moves according to: $\frac{d\mathbf{P}}{dt} = -|e|\mathbf{E} - \frac{|e|}{\gamma m_e c}(\mathbf{P}\times\mathbf{B})$

We are considering the regime where $a = \frac{|e|E_0}{m_e \omega c} > 1$.

$\frac{p_y}{m_e} = a.$ $\frac{p_x}{m_e} = \frac{a^2}{2}.$

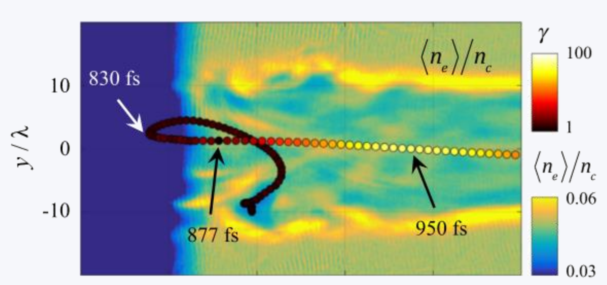
Electron motion

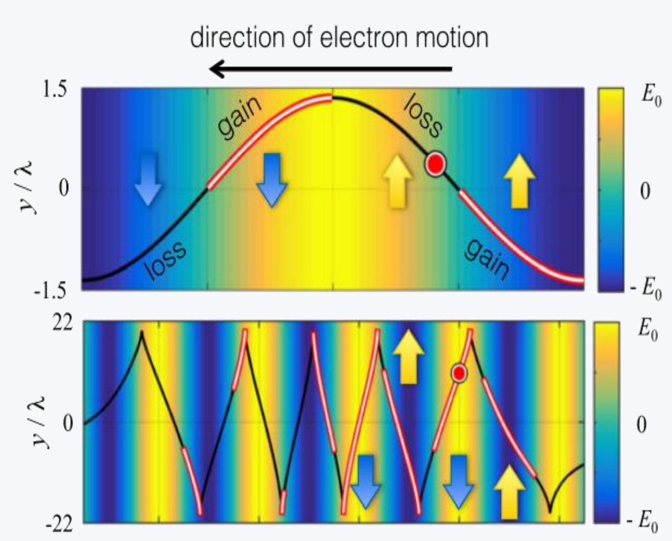




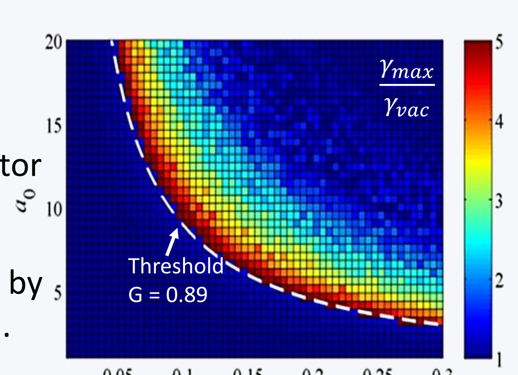
If the high-intensity laser pulse propagates into a plasma:

- Electrons are expelled radially by the ponderomotive force, producing an ion channel.
- Quasi-static transverse and longitudinal E fields are established, since the pulse duration exceeds electron response time.





Threshold of the enhancement factor $G = \frac{a_0 \omega_{p0}}{\omega}$ can be decreased by electron injection.



Longitudinal E field: decrease the electron dephasing with the wave.
Transverse E field: leads the transverse electron oscillations anti-parallel to the laser electric field.

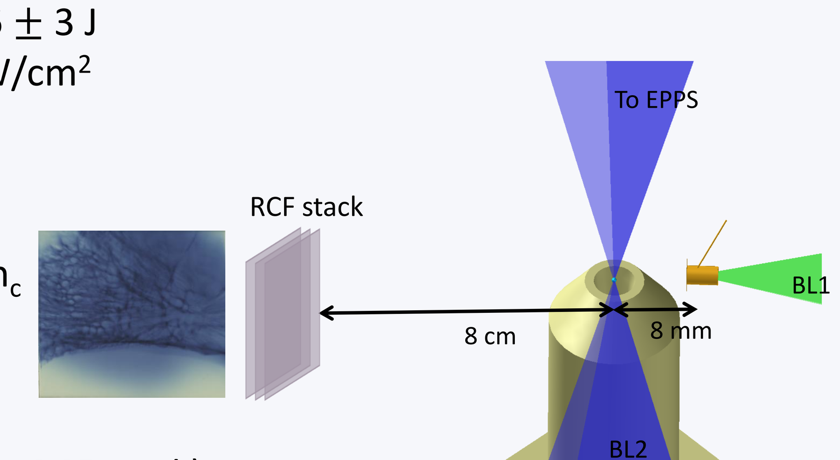
- The electrons injected into the channel are accelerated by the laser pulse, generating localized B field.
- The quasi-static electric and magnetic fields significantly enhance electron energy gain from the wave.

AV Arefiev, et. al. PoP 23, 056704 (2016)
AV Arefiev, et. al. PoP, 21, 033104 (2014)

Experiment performed on Omega EP

Main interaction

- BL2: accelerate electrons
  - Pulse duration: 1ps, 2ps
  - Energy: 111 ± 2 J, 244 ± 2 J, 496 ± 3 J
  - Intensity: 4.1 ×10^{19} ~ 1.6×10^{20}W/cm^2
- Gas jet target: Helium gas
  - Nozzle diameter: 4 mm, 2mm
  - Pressure: 35 ~ 720 PSI
  - Plasma density: 0.004n_c ~ 0.064n_c
  - n_c = 1.01×10^{21} cm^{-3}



Diagnostics

- Proton radiography (BL1, 50 µm Cu + RCF stack)
  - BL1 pulse duration: 1 ps
  - Energy: 150 ± 2 J, 300 J
- Electron-Proton-Positron-Spectrometer (EPPS)

Acknowledgements

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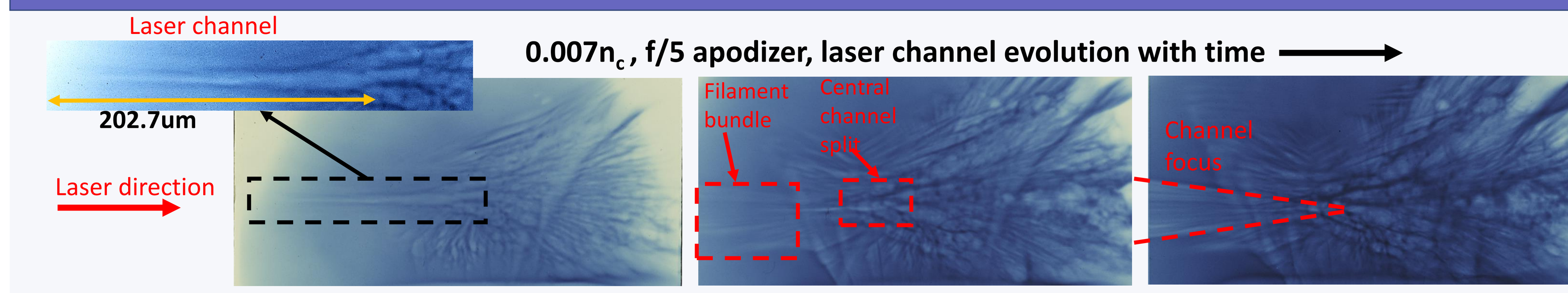
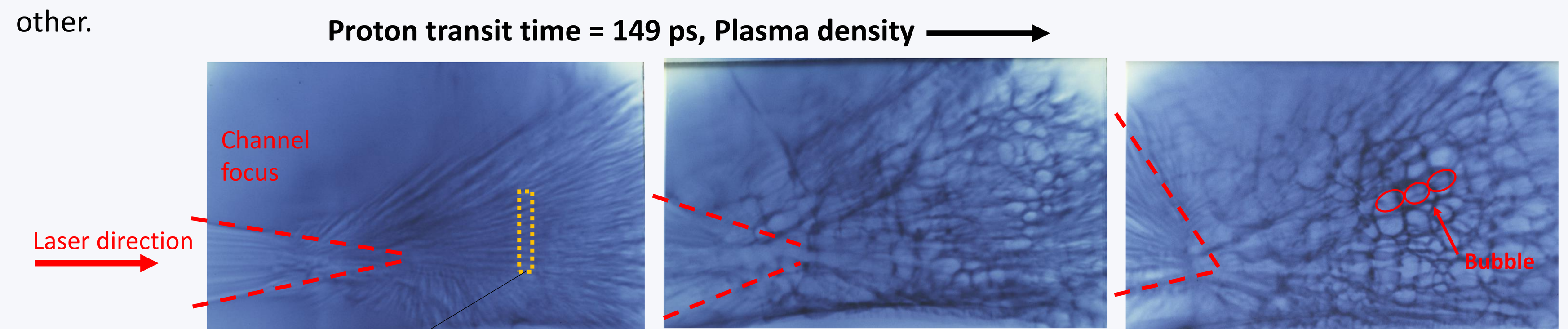
- We would like to acknowledge the OSIRIS Consortium, consisting of UCLA and IST (Lisbon, Portugal) for the use of OSIRIS 4.0 and the visXD framework.

Dynamics of the electromagnetic fields

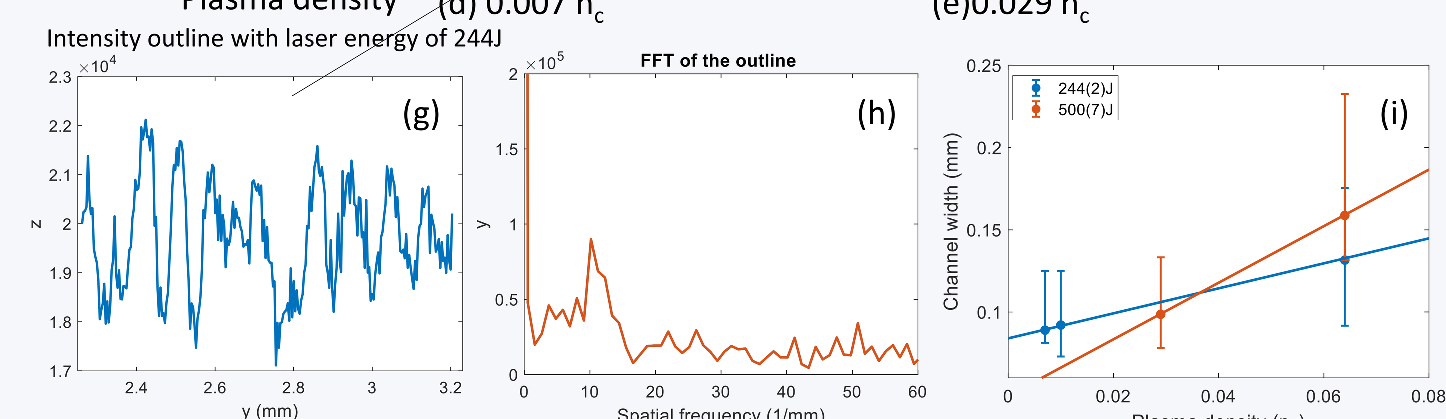


Proton transit time from source (a) t = 117 ps (b) t = 136 ps (c) t = 149 ps

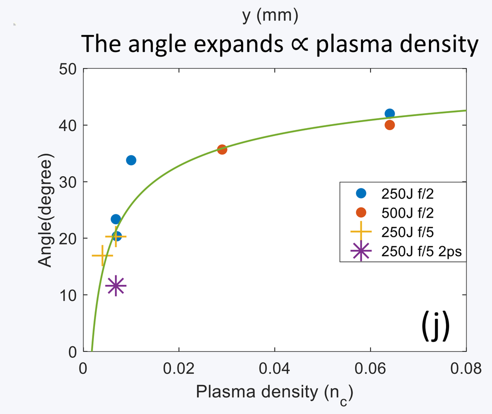
The RCF stack recorded the laser channel formation and filamentation development. The pictures above are raw data from a single shot with density n_e = 0.007 n_c, laser energy of 111 J. (a) The channel keeps an averaged radius of 4.5um, a length of 202.7um, before expanding and breaking up into several branches and filaments. (b) Filament bundle form around the central channel. Filamentation grows from where central channel splits. (c) The pre-focus filament bundle shows explicit boundaries (red dash lines) and focus. At right half part, the filaments intercross each other.



Plasma density (d) 0.007 n_c (e)0.029 n_c (f)0.064 n_c



The channel width increase with plasma density/laser energy. High density: high deviation

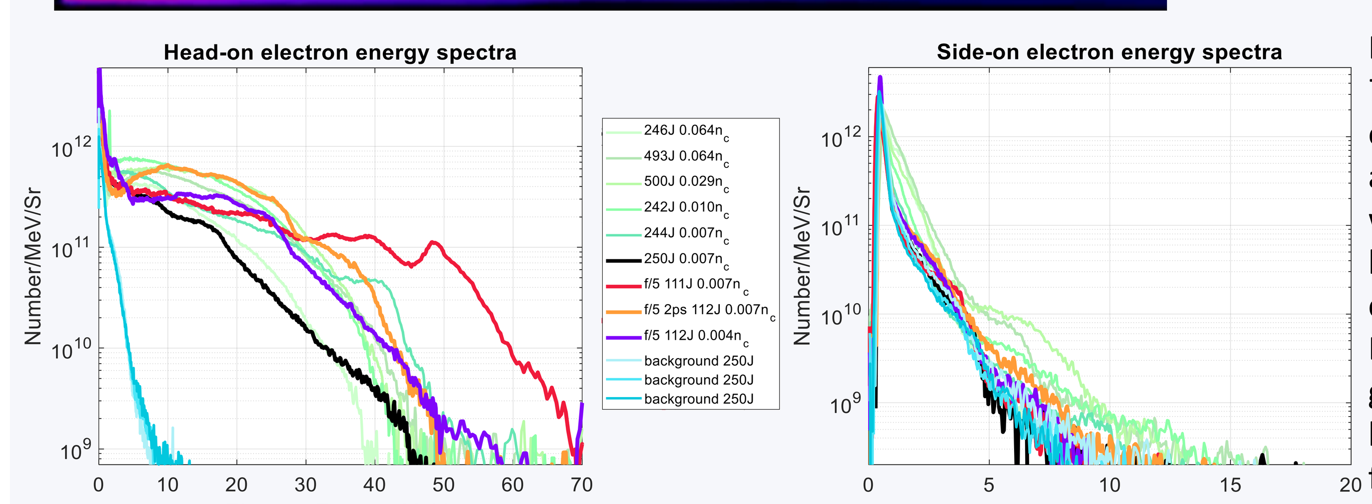


▲ Fig.(d-f) show the proton radiograph at same time (t=149ps) from different shots. (g): The averaged intensity outline across the orange rectangle in (d). (h): Fourier transform of (g) gives averaged channel width~90um. (i): A summation of shots with two different laser energies (242±2J and 500±7 J) implies the channel width increase linearly with plasma density. At low density, filaments have a relatively uniform distributed along transverse direction. At higher density, the filaments are messed up by bubbles.

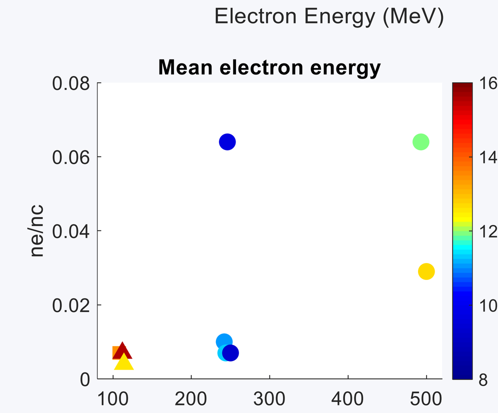
◄ Fig(j): The angle of the focusing laser channel is mostly effected by the plasma density.

MeV electrons generation

Electron-Proton-Positron-Spectrometer raw image



Electrons with energy up to 70MeV were generated. The energies of most electrons are below 50MeV. Compared with side-on spectra, all the high energy electrons are collected by the head-on EPPS. The highest energy was generated with 111J, 1ps laser, which is focused by a f/5 apodizer onto plasma with density of 0.007n_c.



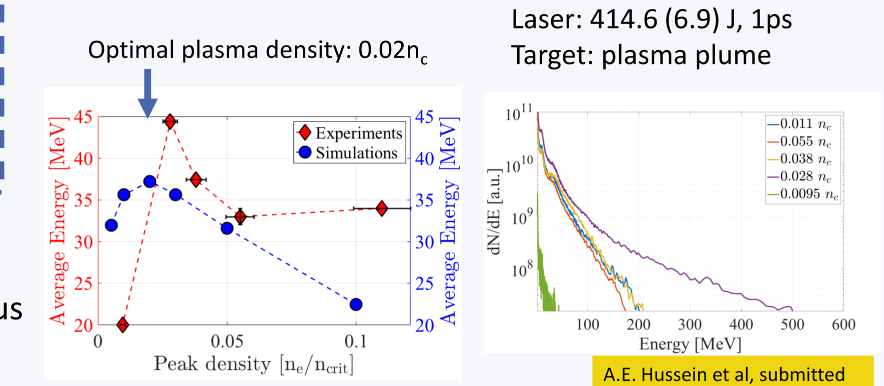
◄ Conditions for hot electron generation: Low laser energy; Low plasma density; Large f number.

Circular dots: square apodizer, ~f/2
Triangle: f/5
Square: f/5, 2ps

Previous work

► Higher-energy electrons were obtained in previous experiments using CH foil.

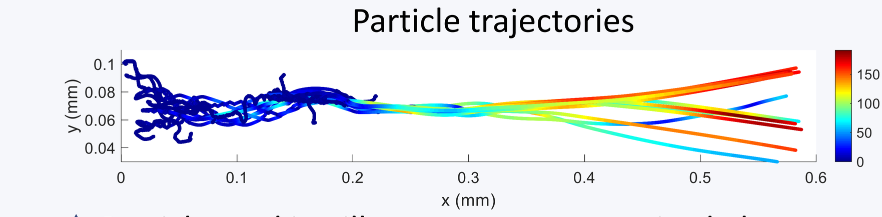
OMEPA EP laser experiment:
Laser: 414.6 (6.9) J, 1ps
Target: plasma plume



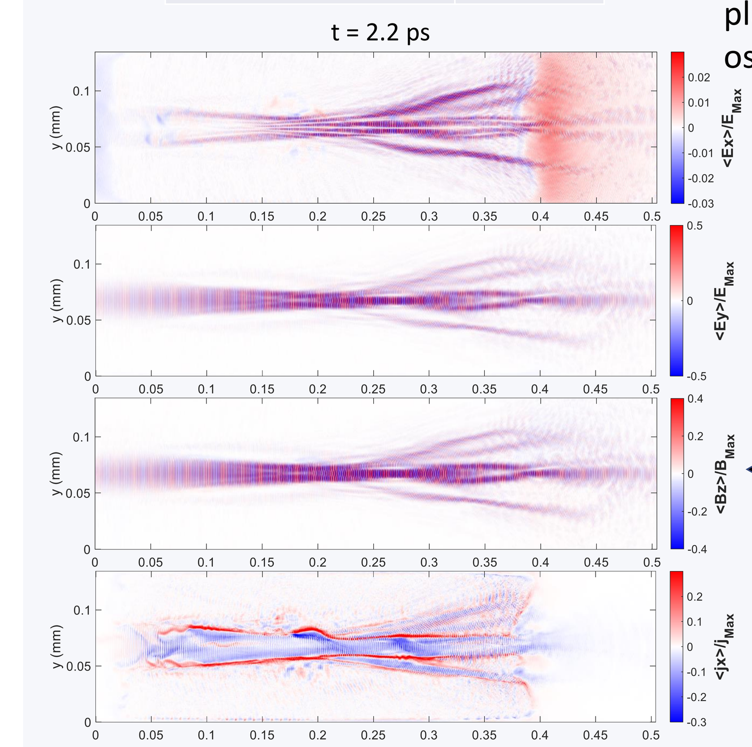
A.E. Hussein et al, submitted to New J Physics, (2020)

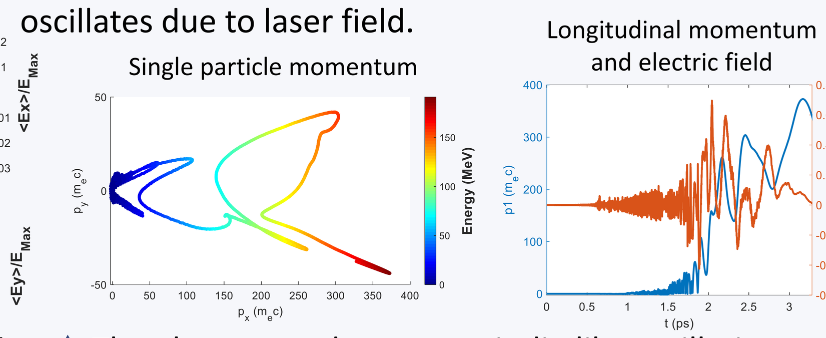
2D PIC simulation: electron motion

Simulation parameters	
a_0	8.05
λ [µm]	1
T [fs]	1000
FWHM [µm]	16
n_e [n_c]	0.03
Plasma length [µm]	380



▲ Particle tracking illustrates most energized electrons are injected from the opening of the channel, while the other small portion of electrons come from background plasma, travel through the channel boundaries and oscillates due to laser field.

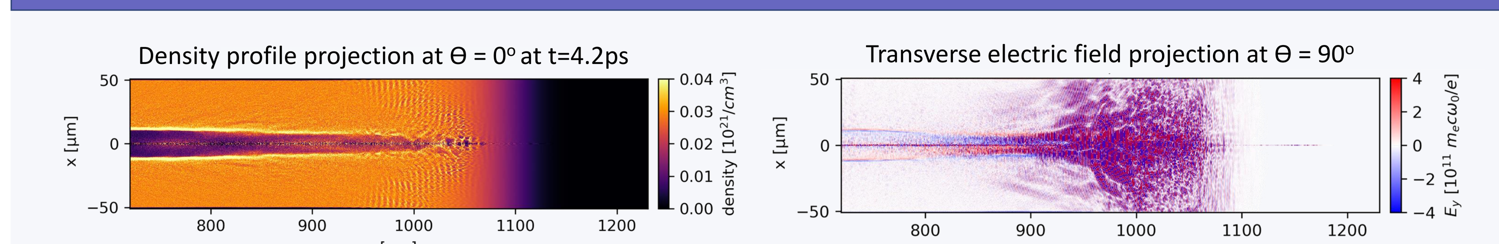




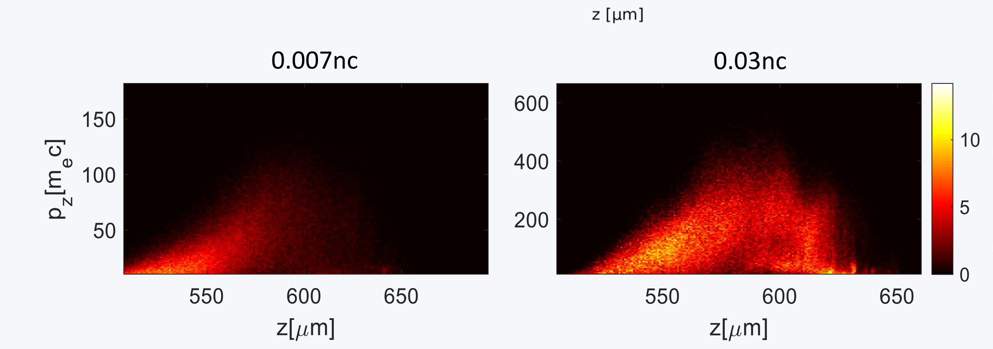
▲ The electron undergoes periodic-like oscillations and gain energy with each cycle.

◄ The 2D Osiris simulation gives overall pictures of the longitudinal electric field Ex, transverse electric field Ey, transverse magnetic field Bz and current flux jx. Both electric and magnetic fields show filamentation-like structures. The electrons move along the channel inside the channel and return currents flow back along the channel walls.

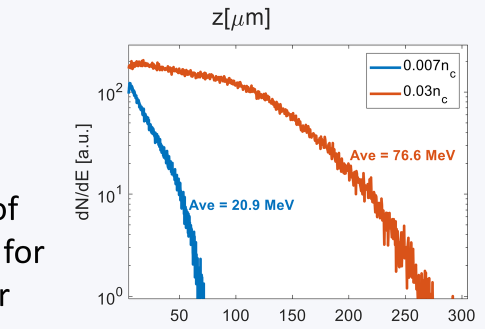
Preliminary quasi-3D simulation



Simulation parameters		
a_0	8.16	8.16
T [fs]	500	500
FWHM [um]	**16**	**8**
n_e [n_c]	**0.007**	**0.03**
Plasma length [um]	600	600



Preliminary quasi-3D simulation with two different plasma densities, 0.007n_c and 0.03n_c, are performed to investigate the optimal electron acceleration conditions. The electrons move behind of the laser tail. The mean energy and the total number of the accelerated electrons, with energy > 5MeV, are much higher for 0.03n_c, which is not consistent with the experiment data. Further convergence test will be performed for the quasi-3D simulation.



Conclusions and Future Work

Conclusions:

- The electromagnetic fields generated in the interaction of intense laser and an underdense plasma were highly dependent on both the plasma density and laser energy. With comparatively lower plasma density, a uniform laser channel was created and expanded, followed by filamentation growing up. As plasma density increase, the channel was merged in fiber bundles and the width of the filaments become less uniform and bubble-like structures are observed.
- Electrons with energy up to 70 MeV were produced. Highest mean energy was generated by low plasma density and low laser energy.
- The simulation demonstrate the electron oscillation and energy gain due to the laser field and plasma field. The energy is much higher than the experiment data.

Future work:

- Increase the simulation modes, spatial resolution and particle number per cell in the simulation and do the convergency test.
- Study the effect of the magnetic field generated by the electron currents and the ion movement.
- Optimize the experiment conditions to acquire electrons with higher energies.