Physics of Pre-Plasma & the Mechanics of Intense Electron Beam Generation by Relativistic Laser Radiation

Sergei Krasheninnikov (UCSD)

Farhat Beg (UCSD)

UCSD:
C. McGuffey
J. Peebles
A. Sorokovikova
C. Krauland
D. Wu
S. Suntar
B. Qiao

U. Texas, Austin:
C. Wagner
M. Martinez
G. Dyer

GA:
M-S. Wei

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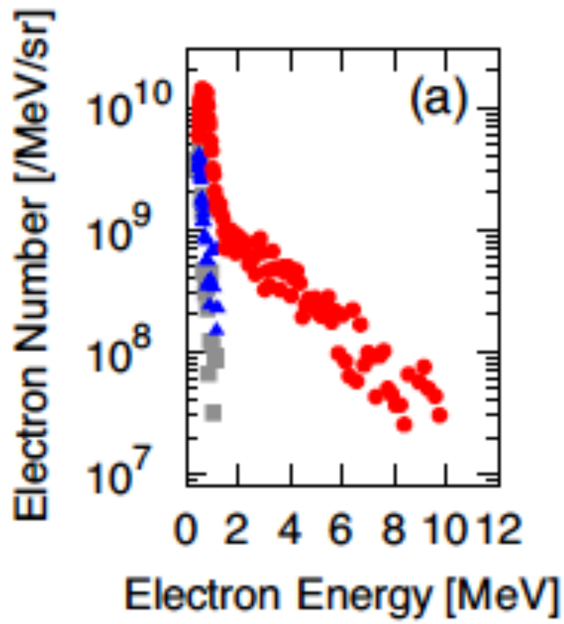
Outline

- Introduction & Motivations
- Theory/simulation
- Experimental studies
- Summary

Introduction & Motivations

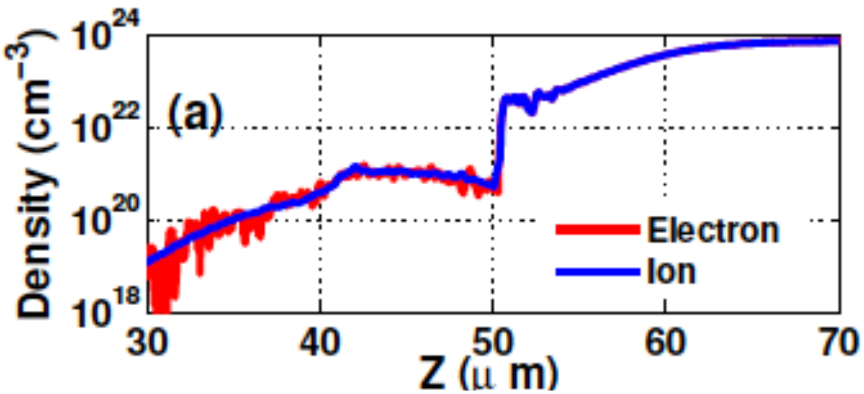
- Recent experiments have shown that the large-scale preplasma significantly affects the LPI dynamics and fast electron energy distribution
- The fast electron energies are found to be much higher than that predicted by ponderomotive scaling

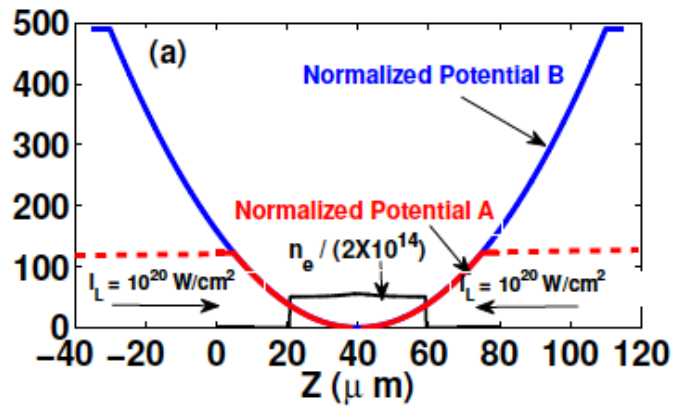


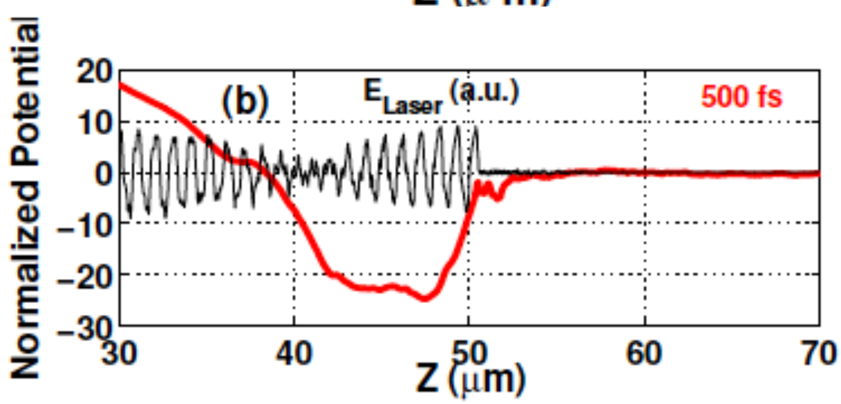
electron spectra with and w/o preplasma (Yabuuchi, 2010)

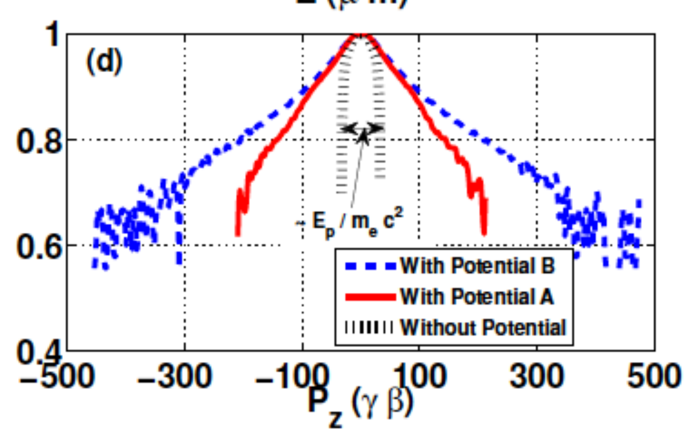
Introduction & Motivations (con-ed)

- Our theoretical models and numerical simulations have shown that the formation of deep electrostatic potential well in preplasma results in synergistic effect of electron interactions with both laser field and electrostatic potential, which provides a novel and very efficient mechanism for electron acceleration (Paradkar, 2011, 2012)



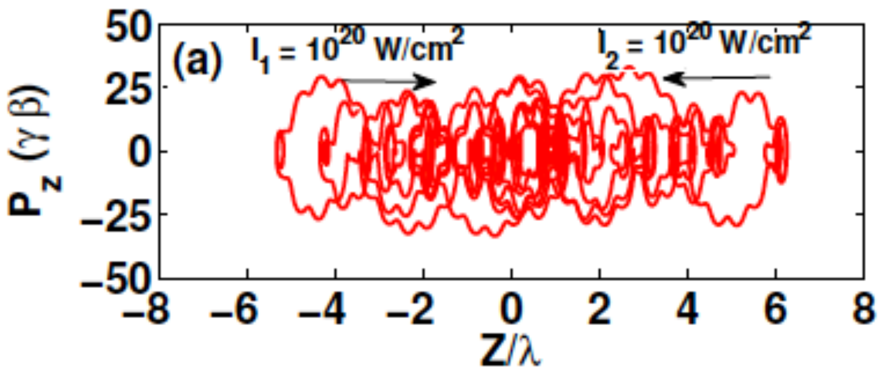


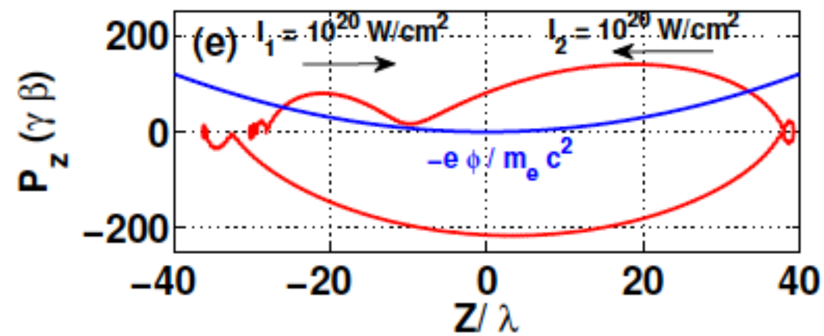


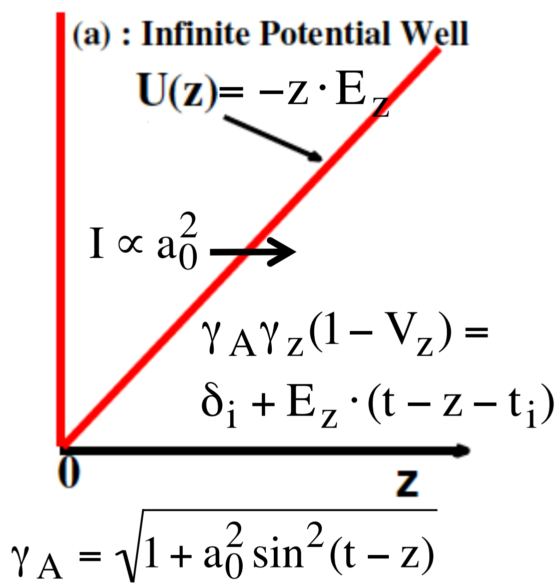


Introduction & Motivations (con-ed)

- In the presence of electrostatic potential well and laser field the electron heating resembles the Fermi-acceleration mechanism (Paradkar, 2012)



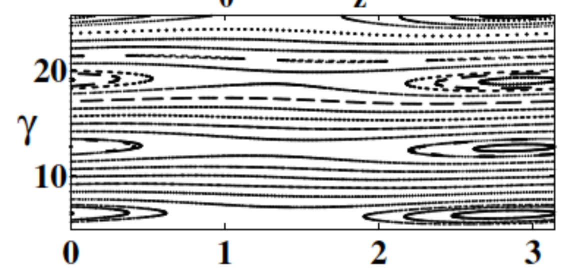




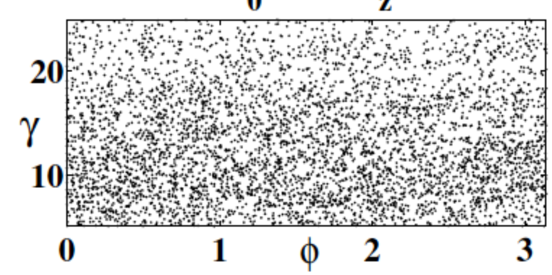
$$a_0^2 / |E_z| \gtrsim 1$$

Stochastic heating in electrostatic potential well!

(a) $a_0 = 1$; $E_z = 4$



(d) $a_0 = 1$; $E_z = 1$

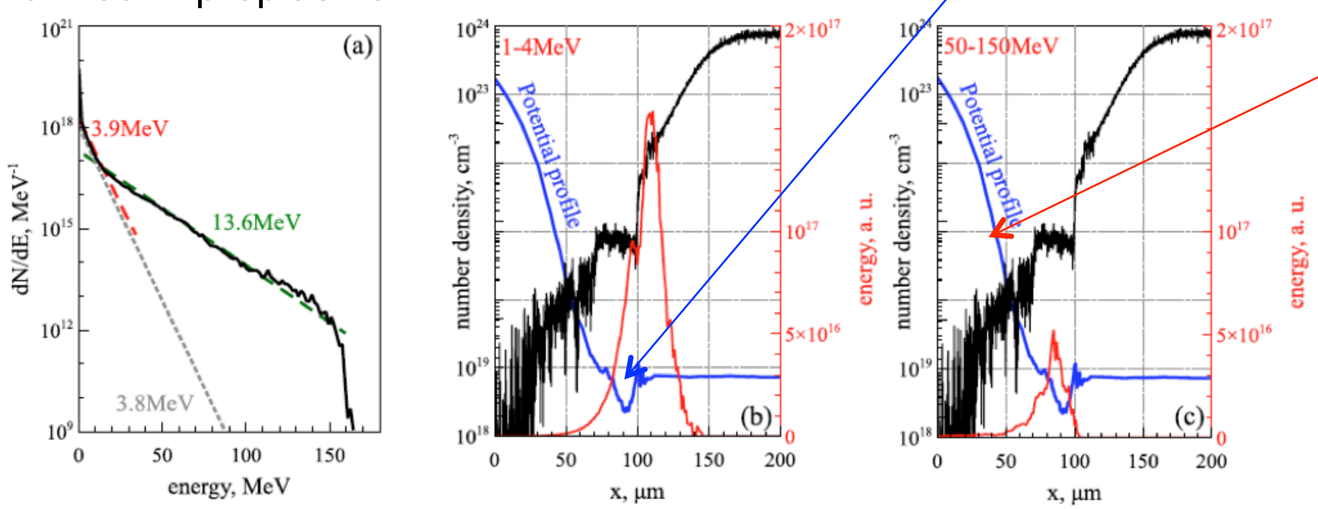


Introduction & Motivations (con-ed)

- Based on this short review of recent developments in the area of the interactions of intense laser radiation with solid targets, the overarching goals of our current studies are:
  - Detail theoretical/numerical assessment of the impact of preplasma on electron energy spectra, the role of magnetic field generation and filamentation
  - Experimental confirmation of the presence of the electrostatic potential well in preplasma and an impact of preplasma on electron energy spectra
  - Benchmarking of theoretical/numerical predictions against experimental measurements

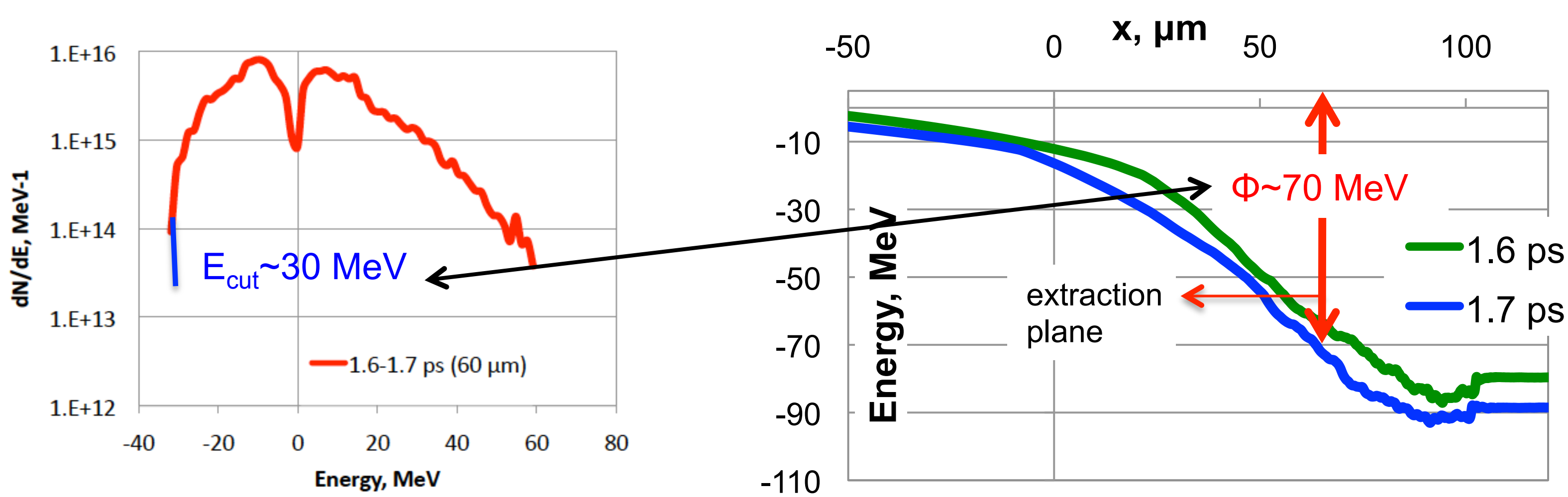
Theory/simulation

- We performed massive amount of 1D simulations for different initial scale-length of preplasma, L, $n_{prep}(x)=n_{crit}/\{1+\exp[(x-x_{crit})/L]\}$, laser intensities, and laser pulse lengths
- The main findings are:
  - The distribution function of electron beam has two distinct slopes
  - The low energy part of electron spectra is originated in the vicinity of critical plasma density and the energy of these electrons is compatible with ponderomotive scaling
  - The most energetic electrons, with the energies well above that predicted by ponderomotive scaling, are coming from potential well and ~100 MeV potential barrier formed in preplasma



Theory/simulation (con-ed)
Potential barrier

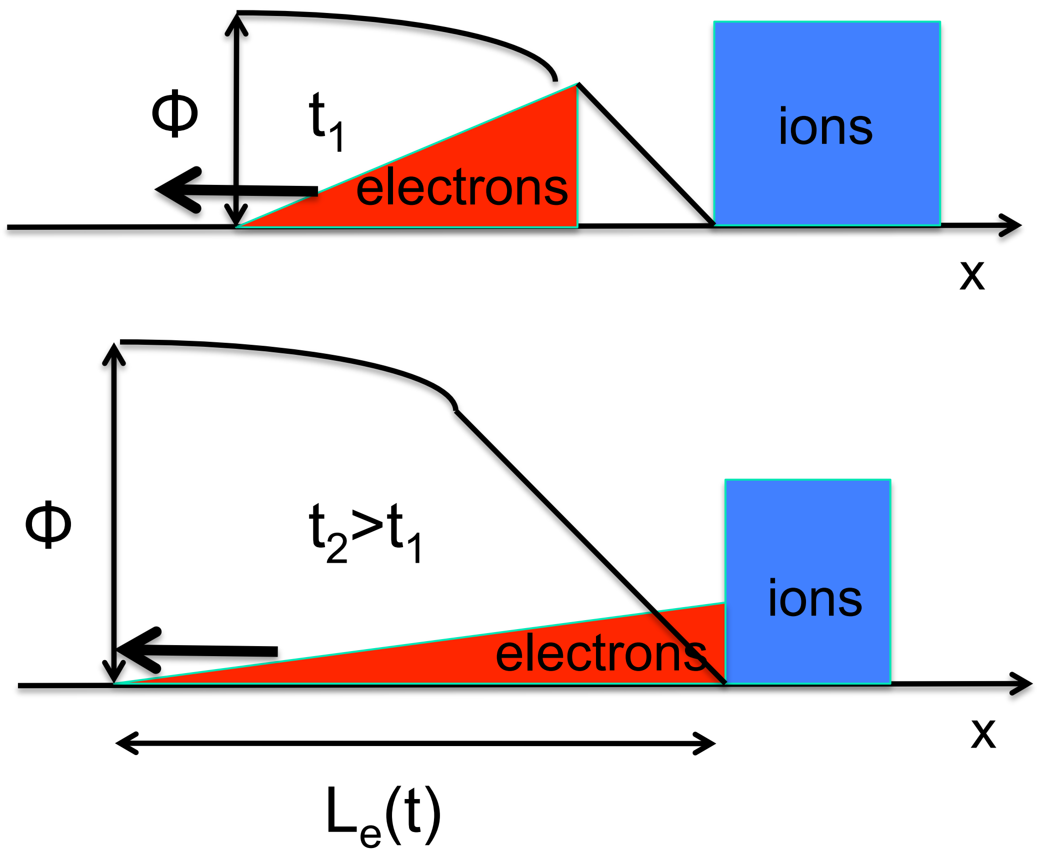
- We also found that the height of potential barrier, Φ, during the laser shot stays at least two times larger than the maximum energy, E_{cut}, of backward going electrons which suppose to maintain this barrier



- Of course, it is impossible to maintain the potential barrier higher than E_{cut} in a steady-state conditions
- However, in dynamic process, the height of potential barrier can be significantly larger than E_{cut}

Theory/simulation (con-ed)
Potential barrier

- As an illustration, consider a 1D problem where a bunch of electrons with initial kinetic energy E_k expand into vacuum leaving immobile ions behind



- Head electrons in the bunch will expand continuously, although their density drops as $n_e \sim 1/t^2$
- Recalling that $d^2\phi/dx^2 = 4\pi e n_e(x)$ and $L_e(t) \sim ct$, we find

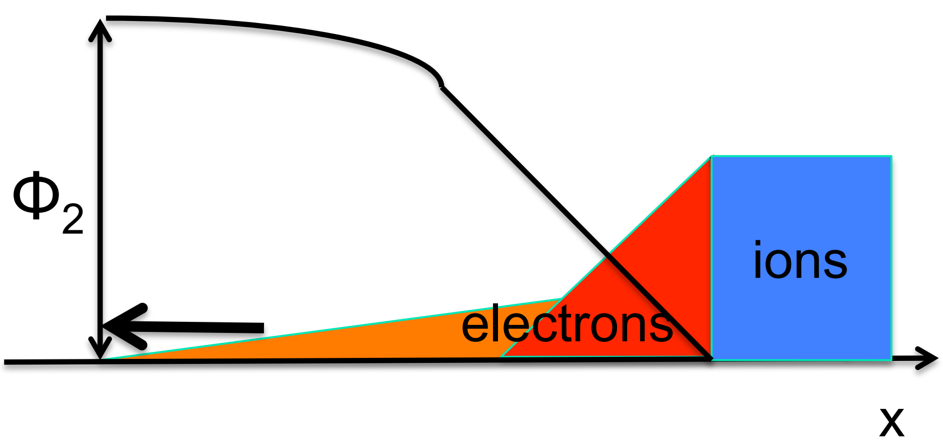
$$\Phi_1(t \to \infty) \to \text{const}.$$

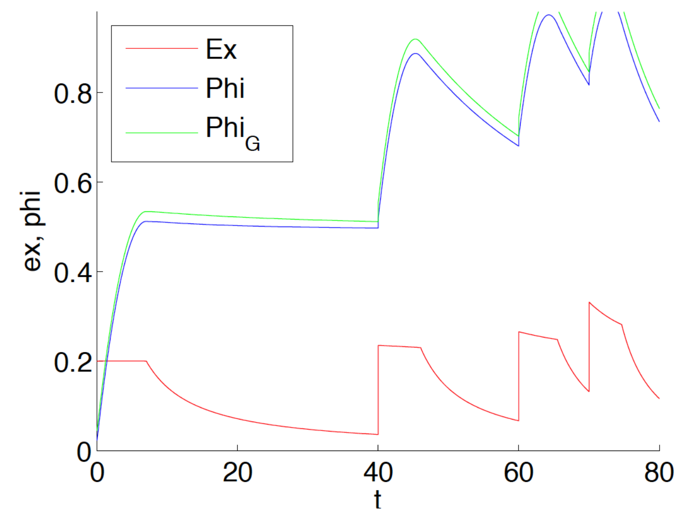
- Exact analytic calculations for relativistic case give

$$\Phi_1(t \to \infty) \to 2\ell n(2) E_k \approx 1.4 E_k$$

Theory/simulation (con-ed)
Electron acceleration in the barrier

- An expansion of a single electron bunch is fully reversible and electrons that coming back have the same kinetic energy E_k
- However, for the case of a few (N) separate electron bunches we find:
  - An increase of the height of the potential barrier: $\Phi_N \approx \Phi_1 \ell n(N)$
  - An increase of the energy of returned electrons of the first bunch: $E_{first} \approx N \times E_k$



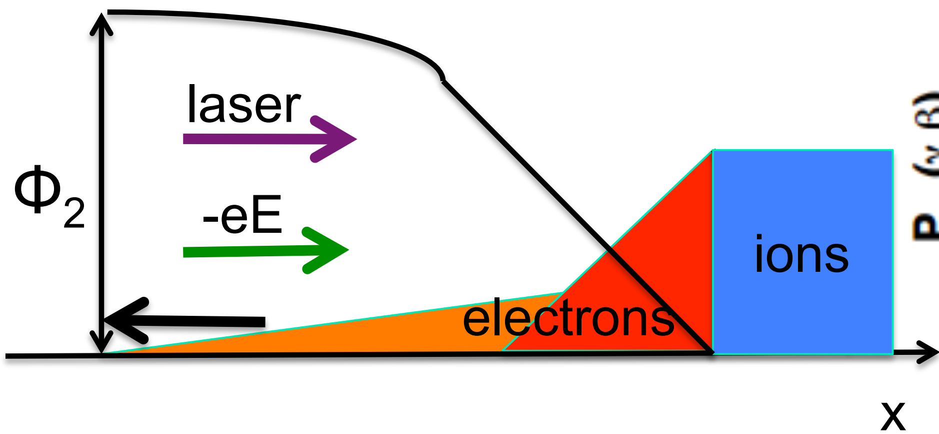


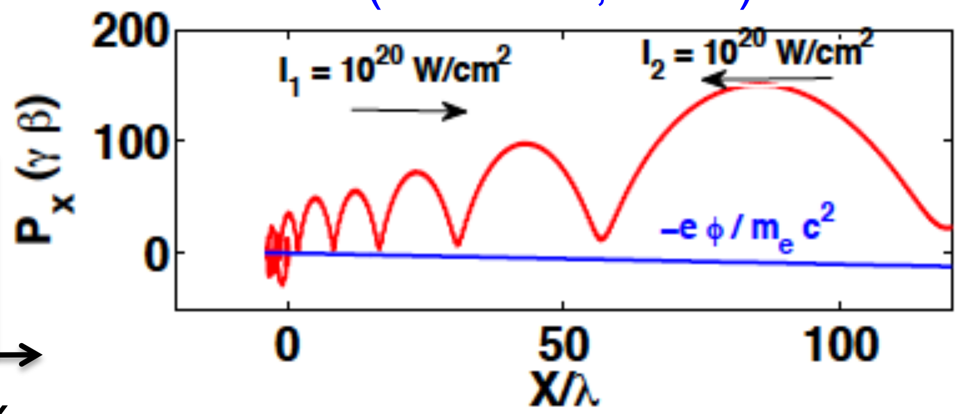
- Numerical simulations confirm our analytic results

Theory/simulation (con-ed)
Electron acceleration in the barrier

- Finally, backward going energetic electrons, being constantly accelerated by electric field, can effectively "ride" on the laser wave and additionally increase kinetic energy

(Paradkar, 2011)





ε is the normalized electric field

$a(\tau) = a_0 \sin(\tau)$ is the normalized vector potential

$\tau = x - ct$

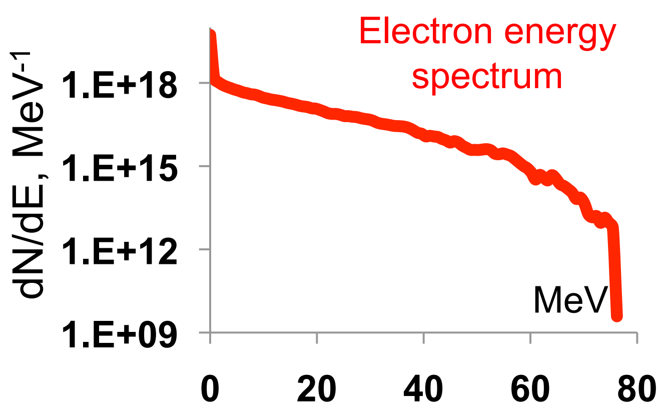
$\delta_0 \sim 1/\gamma_0 << 1$

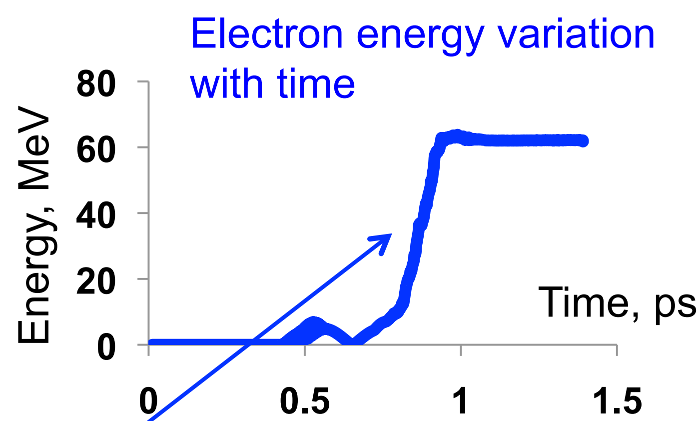
$$\Delta E_{L+E}(\tau) = \frac{1}{2}\int_0^{\tau} \frac{\partial a^2(\tau')/\partial\tau'}{\delta_0 - \varepsilon\tau'} d\tau'$$

For $\delta_0/\varepsilon \tilde{<} \pi/4$ electron is continuously accelerated in the laser field!

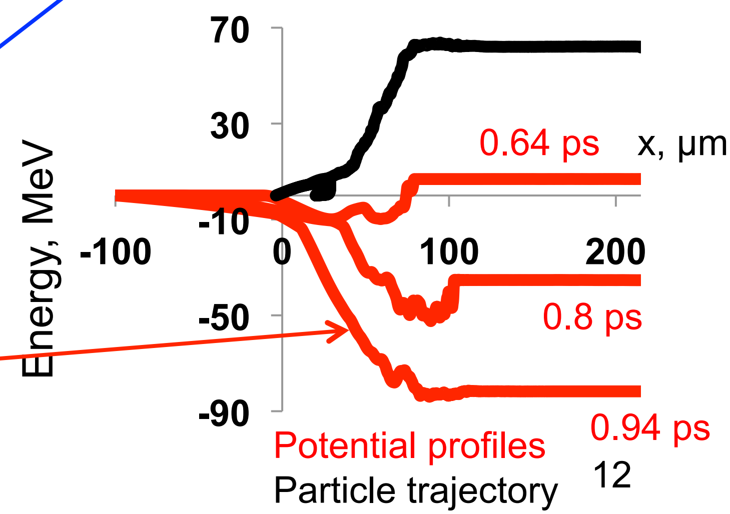
Theory/simulation (con-ed)
Electron acceleration in the barrier

- 1D numerical simulation support our conclusion that the most energetic electrons are due to the effects associated with potential barrier



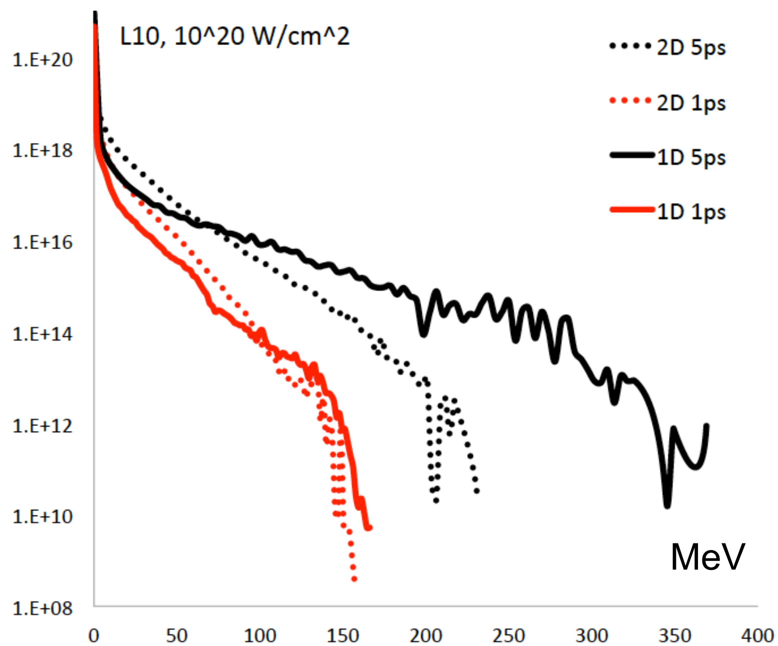


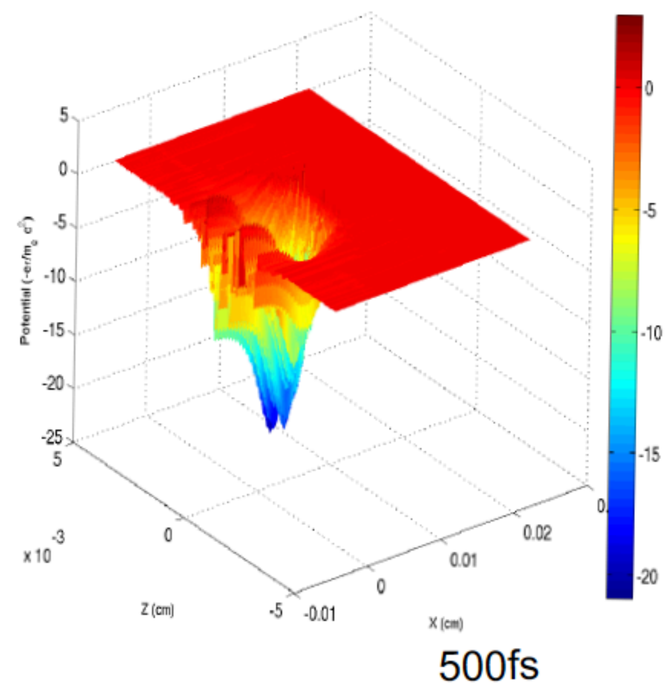
- From single particle trajectory it is seen that the electron gains maximum energy after ~0.8 ps when laser pulse is already over but potential barrier is still exist



Theory/simulation (con-ed)
2D effects

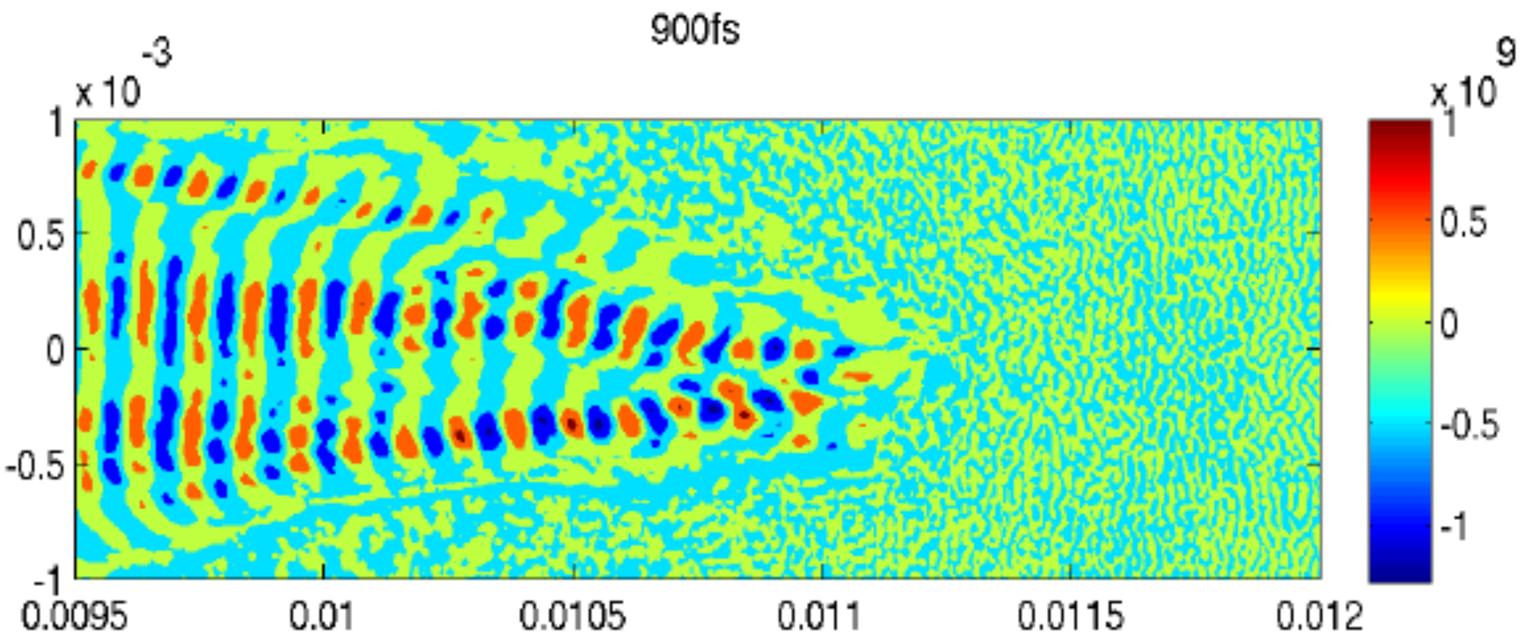
- To compare the validity of our conclusions based on 1D model we performed a set of 2D simulations which, in a ball park agree with the results of 1D simulations
- In particular:
  - Integrated electron energy spectra are rather similar
  - In 2D simulations we do observe the formation of deep potential well in preplasma similar to that we have in 1D casc





Theory/simulation (con-ed)
2D effects

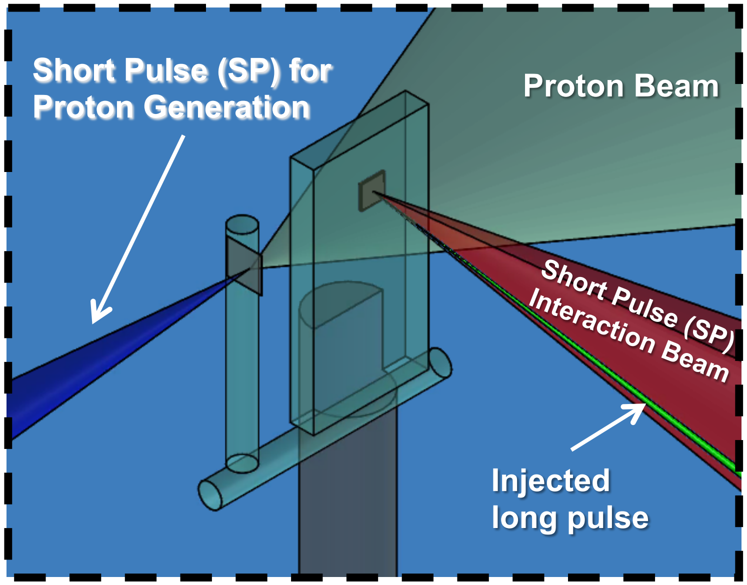
- In addition, we also observe the filamentation of the laser radiation and magnetic field generation at rather large pulse length
- However, observed magnetic field is not too strong to alter dynamics of energetic electrons and filamentation of the laser radiation does not produce laser field intensities, which, based on ponderomotive scaling, could be responsible for the observed large

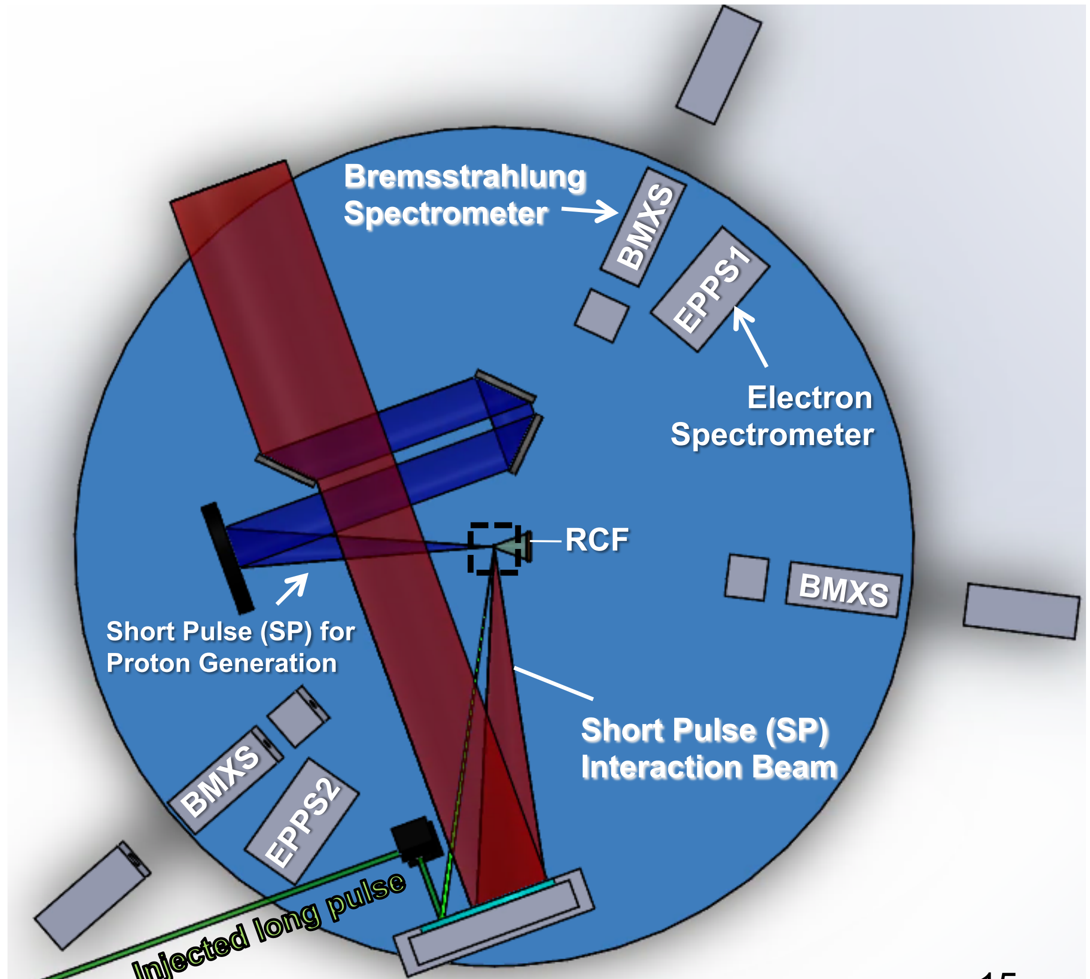


Experimental studies (con-ed)

Experiments on the Texas Petawatt laser facility

Schematic view of Texas Petawatt (TPW) experimental setup



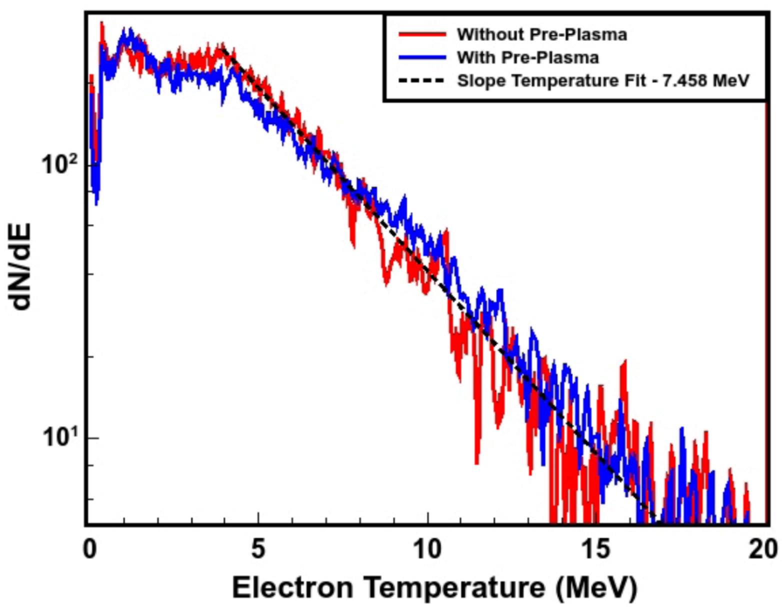


- The targets consisted of Al foils with a layer of Cu and a plastic “get lost” layer at the back to avoid refluxing of electrons
- Proton radiography was fielded with a separate Ti foil (proton source) roughly 5 mm from target and radiochromic film (RCF)

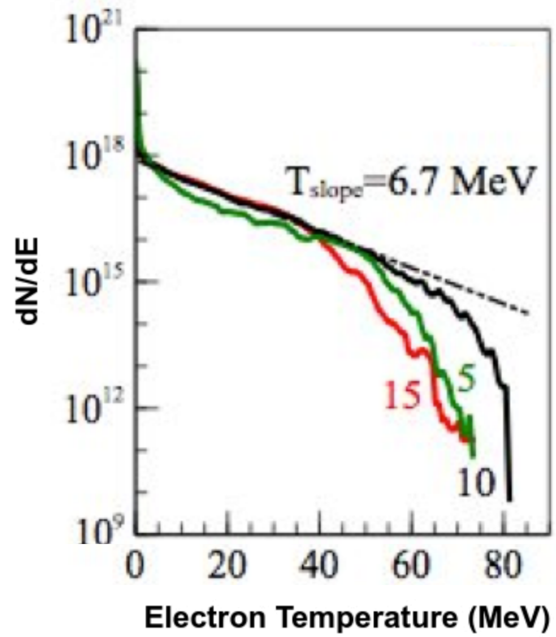
Experimental studies (con-ed)

Experimental data and simulations shows that preplasma does not affect electron spectrum for 150 fs laser pulses

TPW data (150 fs)



LSP output (180 fs)

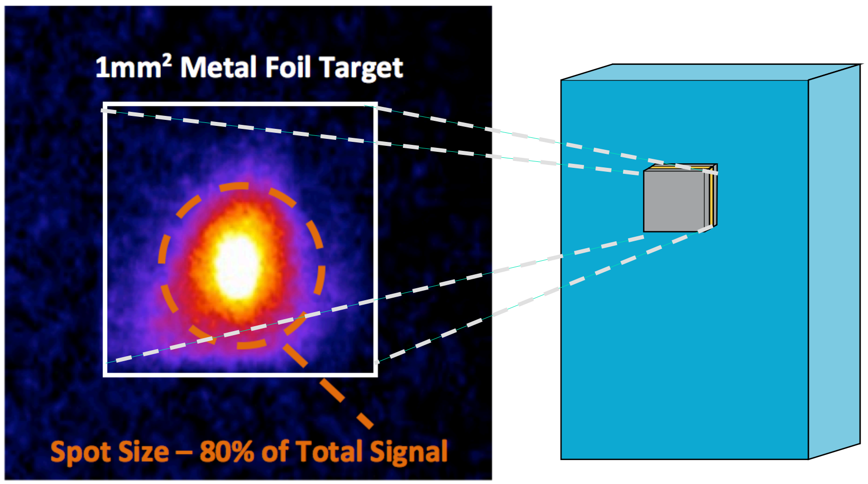


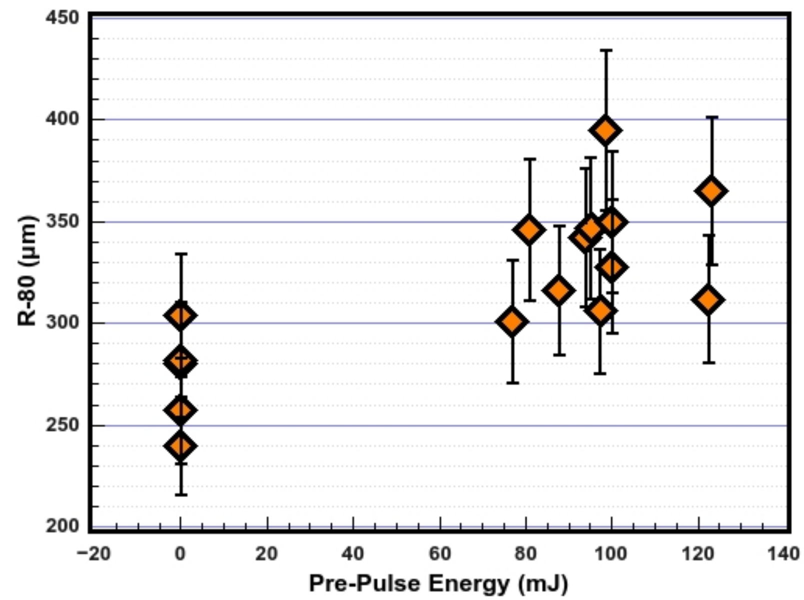
- Longer plasma density scale length does not have impact on electron temperature at such low pulse length
- Interestingly, the slope temperatures observed in experiment (left) and simulations (right) agree rather well and stay close to the ponderomotive scaling

Experimental studies (con-ed)

Cu Kα spot size increases with the extent of preplasma

Spherical crystal imager shows Cu Kα fluorescence from buried layer in target

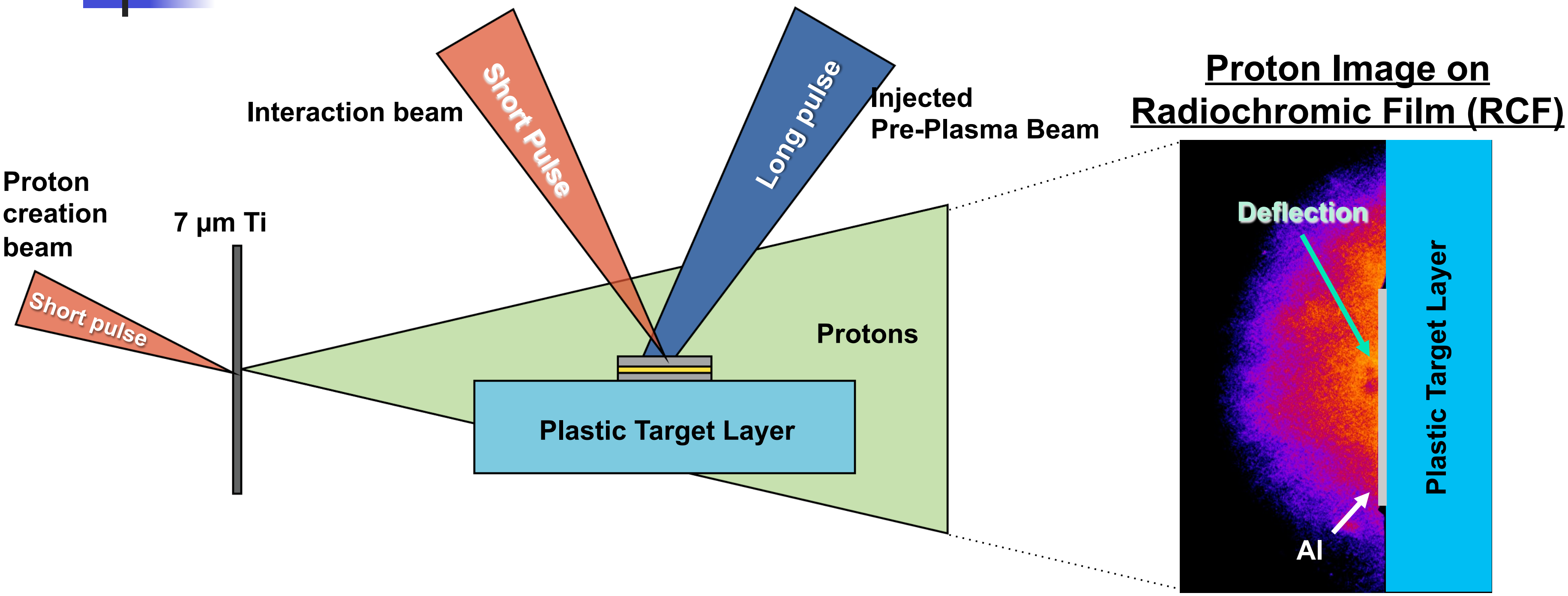




- Main interaction beam interacts with critical density (n_{crit}), creating electrons
- Increasing Kα spot size corresponds to displacement of n_{crit} , which agrees with longer pre-plasma scale lengths

Experimental studies (con-ed)

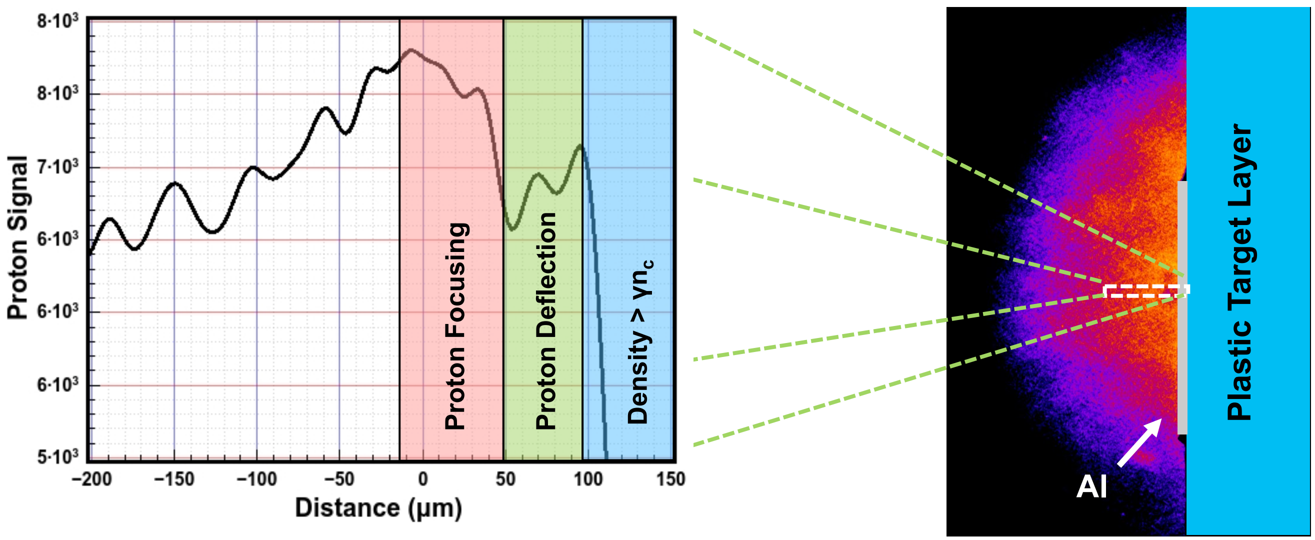
Proton radiography was used to measure the deflection of protons due to both magnetic and electric fields on the front of the target

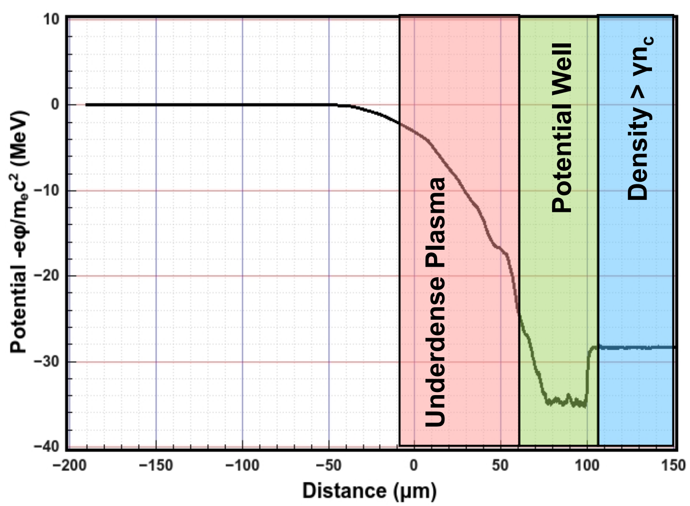


- Protons generated range from 1 to tens of MeV. The difference in flight time allows for multiple frames of proton images taken at different times.
- Deflection of protons confirms interaction between laser and pre-plasma tens to hundreds of microns off the target surface.

Experimental studies (con-ed)

Comparing proton results to LSP simulations



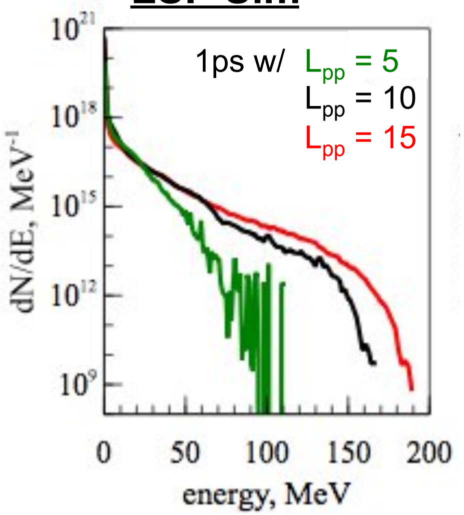


- RCF shows similar feature seen on multiple shots:
  - 0-50μm in front of the target surface: a region of proton deflection (dip in signal).
  - 50-100μm in front of the target surface: bright spot of focused protons.
- Deflection region is consistent with where a potential well would be generated

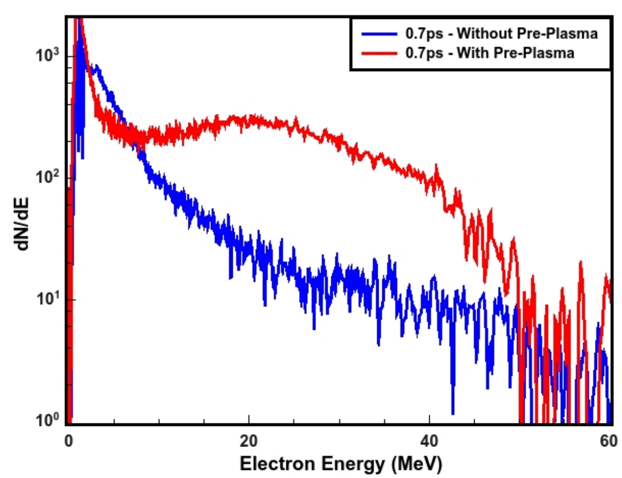
Experimental studies (con-ed)
Experiments on the Titan laser

- Further experiments on the Titan laser (LLNL) performed with similar set-up and diagnostic configurations but varying laser
  - 3ns pre-pulse beam with up to 150 J; 0.7ps, 3ps, 5ps interaction beam
- Preliminary results suggest good agreement with pre-pulse effects shown in LSP simulations for pulse lengths from 750 fs to 3 ps. The hot electron tail is clearly seen on diagnostics

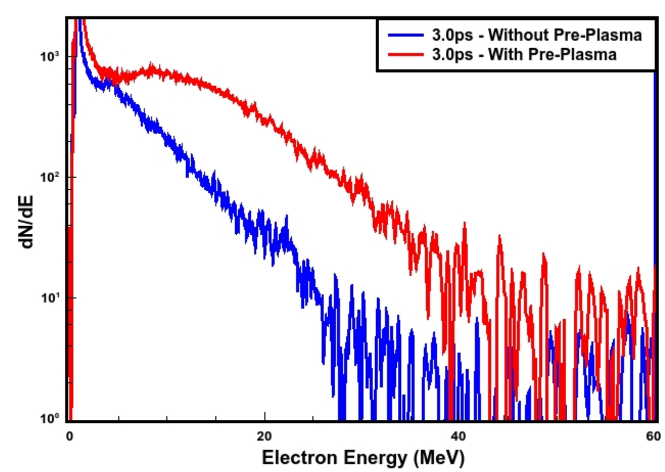
LSP Sim



EPPS1 Data, 0.7ps

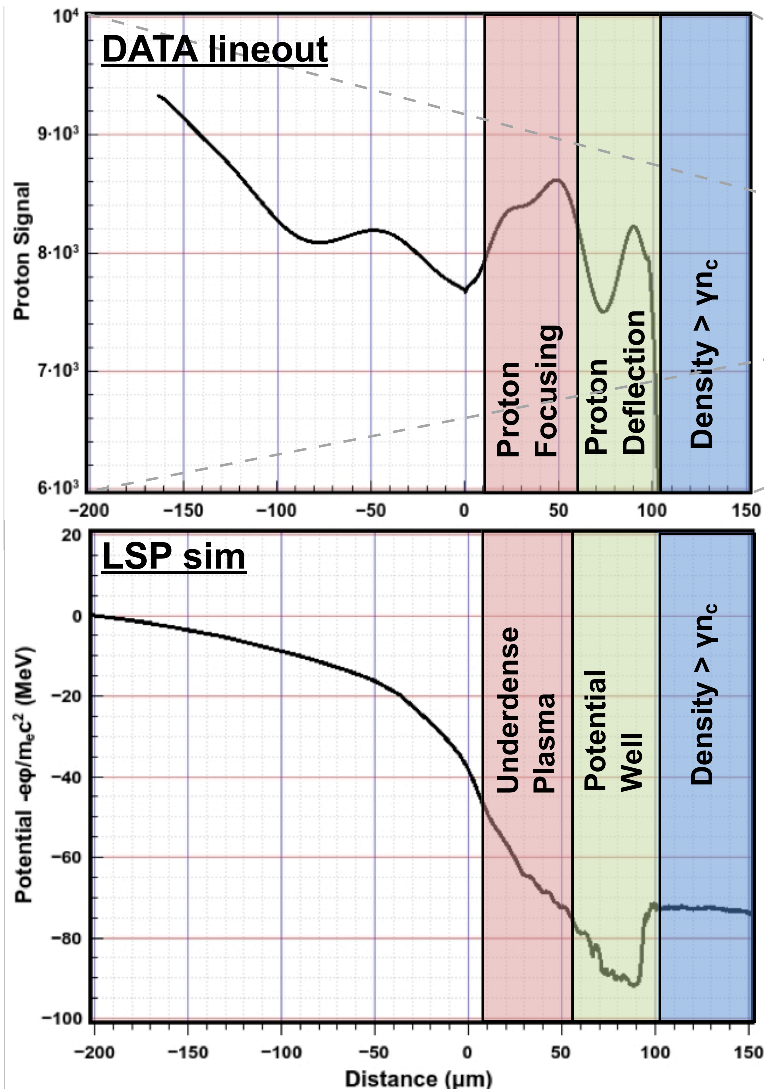


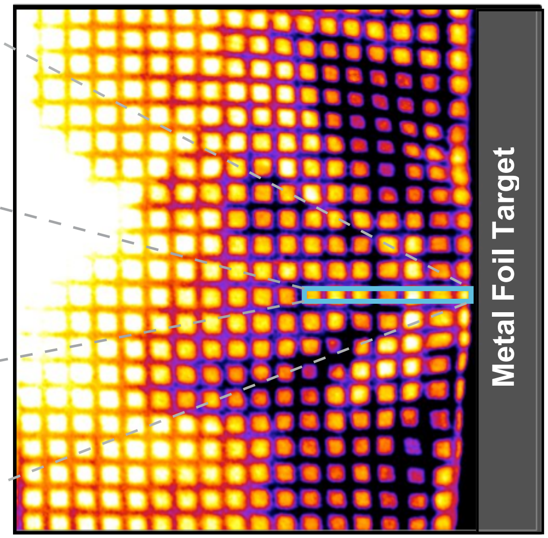
EPPS1 Data, 3.0ps

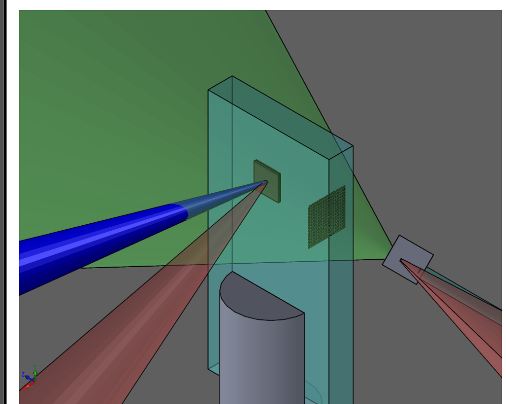


Experimental studies (con-ed)

Experiments on the Titan laser (data analysis)





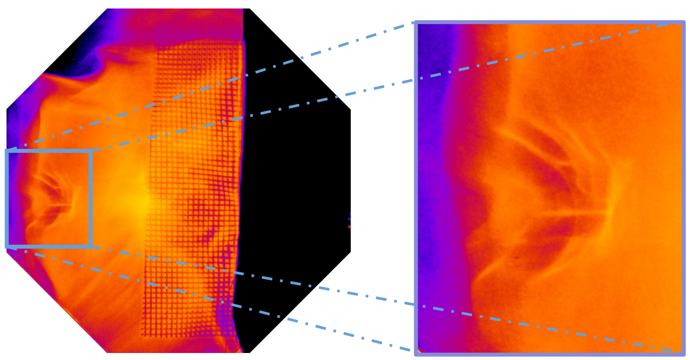


- The post-processing of Titan experimental results is in progress
  - ~0-50μm in front of the target, a region of less protons is seen in combination with the mesh spreading out, suggesting a region of deflection.
  - ~50-100μm in front of the target, more protons are seen with a pinched mesh suggesting proton focusing
  - Corresponding sections in simulation suggest agreement

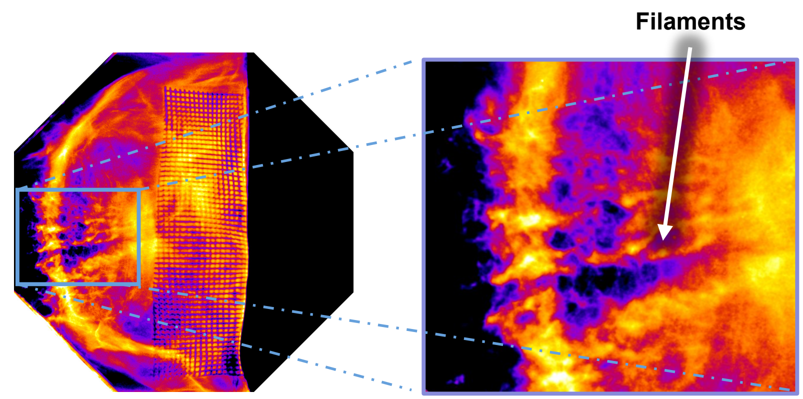
Experimental studies (con-ed)

Experiments on the Titan laser (data analysis)

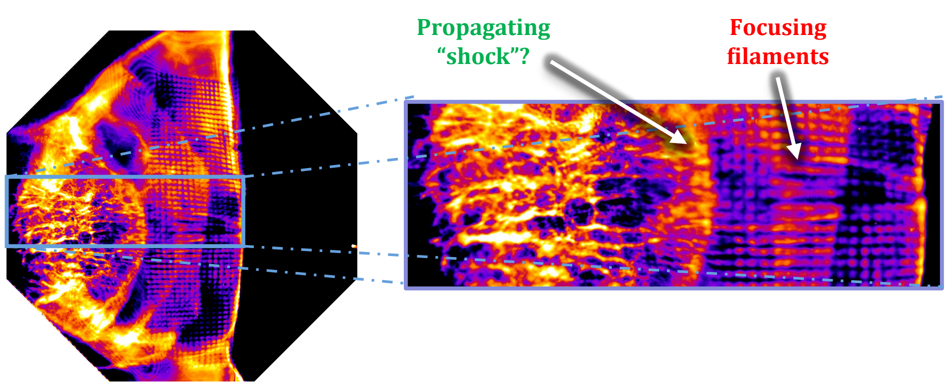
Interesting features are witnessed in time resolved proton images



RCF frame at Δt = 0ps (beginning of laser plasma interaction)



RCF frame at Δt = 15.1ps



RCF frame at Δt = 35.5ps

- The post-processing of Titan experimental results is in progress
- Can see short pulse laser propagation and filamentation in pre-plasma
- Large conical or parabolic structures due to shocks or field effects?
    - Only seen in shots with 15-25 J in the long pulse, and 3 ps short pulse duration

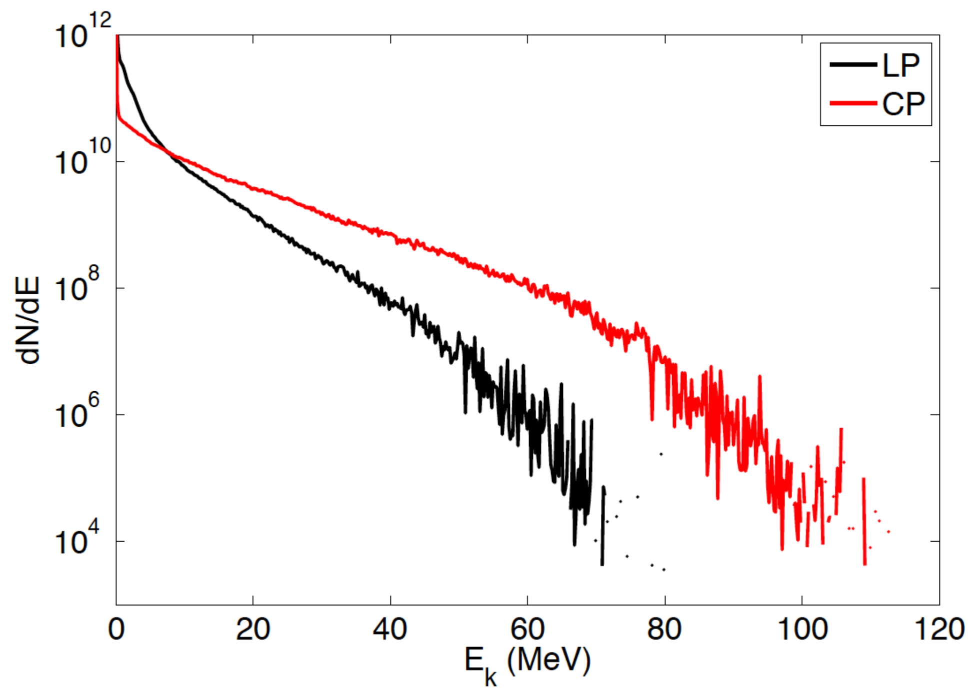
Summary

- Our comprehensive 1D simulations confirm our preliminary assessment of a crucial role of synergistic effects in electron interactions with electrostatic potential well, potential barrier and laser radiation, occurring in preplasma, in the generation of extremely energetic electrons
- Our 2D simulation results agree with 1D simulations
- Experimental data is consistent with simulations and show
  - Electron spectra is not altered with preplasma with 150 fs laser pulses
  - Electron spectra changes in the presence of preplasma for three pulse lengths, i.e., 0.75, 3 and 5 ps.

Outlook

Our theoretical predictions and numerical simulations show that the interaction of circular polarized laser radiation with preplasma can generate significantly more energetic electrons!

Let us try!



Extra slides

Additional experiments were performed on the OMEGA-EP laser, with longer duration, high intenstiy interaction beams

- May 6th and August 26th, 2014 on the OMEGA EP Laser at the Laboratory for Laser Energetics
    - 1ns pre-pulse beam with up to 20 J; 10ps interaction beam
- Data for longer 10ps interaction pulses indicate addition of pre-plasma actually lowers observed electron temperatures.