ICUIL

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"Hot Electron Production for High Energy Density Physics"

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ILE

RAL

GRE

Session 8 -1
Tongi, China

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One of the Extreme HEDS

One extreme condition created using large ultra-intense laser system could be fast ignition which provides an interesting high energy density physics.

Typically we talk,

1. Plasma density 10^{21}-10^{26}/c.c.
2. Plasma temperature 1-10 keV
3. Hot electron temperature 0.1-100 MeV

Outline of my talk

Hot electron generation from UIL matter interactions

1. Hot electron generation relevant to fast ignition condition.
2. Hot electron generation to tune the spectrum suitable for fast ignition.
3. Hot electron affected by its own field.

Hot electron generation relevant to fast ignition condition

Fast Ignition Condition

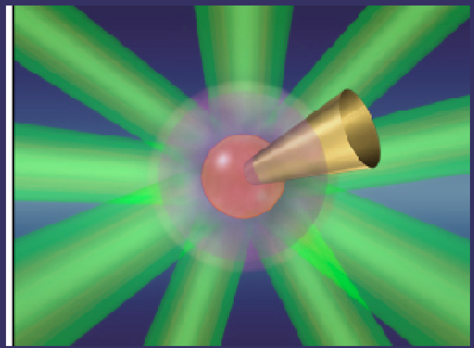
Fast ignition condition may be accessed by using up-coming ultra-intense laser systems at Osaka Univ. and Univ. of Rochester.

Fast heating laser system at Osaka

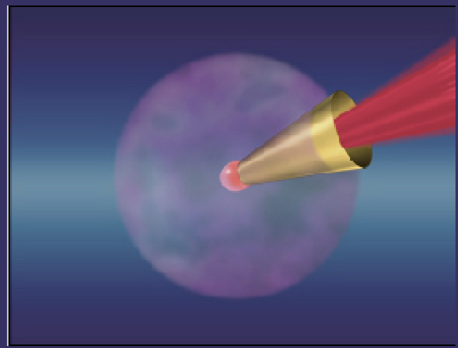
Energy: 10 kJ/Pulse: 10 psec/ Wavelength: 1053 nm

Compression and heating can be separated in fast ignition.

ILE Osaka



Compression by multiple laser beams



Heating by ultra-intense laser pulse

Ignition & Burn

Two large laser machines

Hot electron generation from UIL matter interactions relevant to fast ignition condition.

Experimental Conditions 1

Vulcan PW:

Contrast = $4x10^{-8}$

Pulse Width: 500 fsec – 5 psec

Energy: < 300J

Wavelength = 1054 nm

Focusing Optics: f/3 Parabola 7 μm spot

Experimental Conditions 2

GKKO XII PW:

Contrast = 1.5 x10^{-8}

Pulse Width: 600 – 700 fsec

Energy: < 100 J

Wavelength = 1053 nm

Focusing Optics: f/7.6 Parabola 15 μm spot

Figure 1

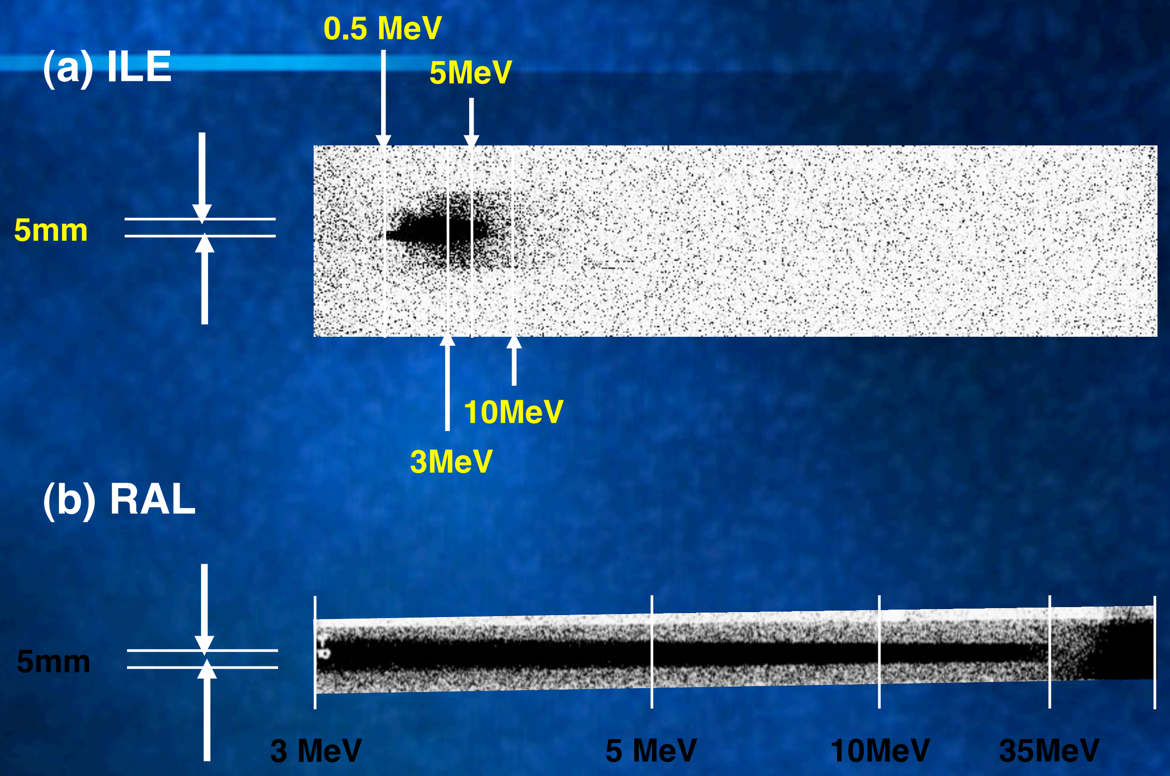


Figure 1. Figure 1 shows the ESM raw data. Figure (a) and (b) are the ILE case and the RAL case, respectively. These ESM are put on the laser axis. The collimator size becomes 5mm in each case. The figure horizontal direction is the electron energy. In the (a), the laser intensity is 6.43×10^{18} W/cm^2 . The target material and thickness are Al and 100μmt, respectively. In the (b), the laser intensity is 3.16×10^{20} W/cm^2 . The target material and thickness are Cu and 25μmt, respectively.

Electron Spectra at Osaka and Rutherford

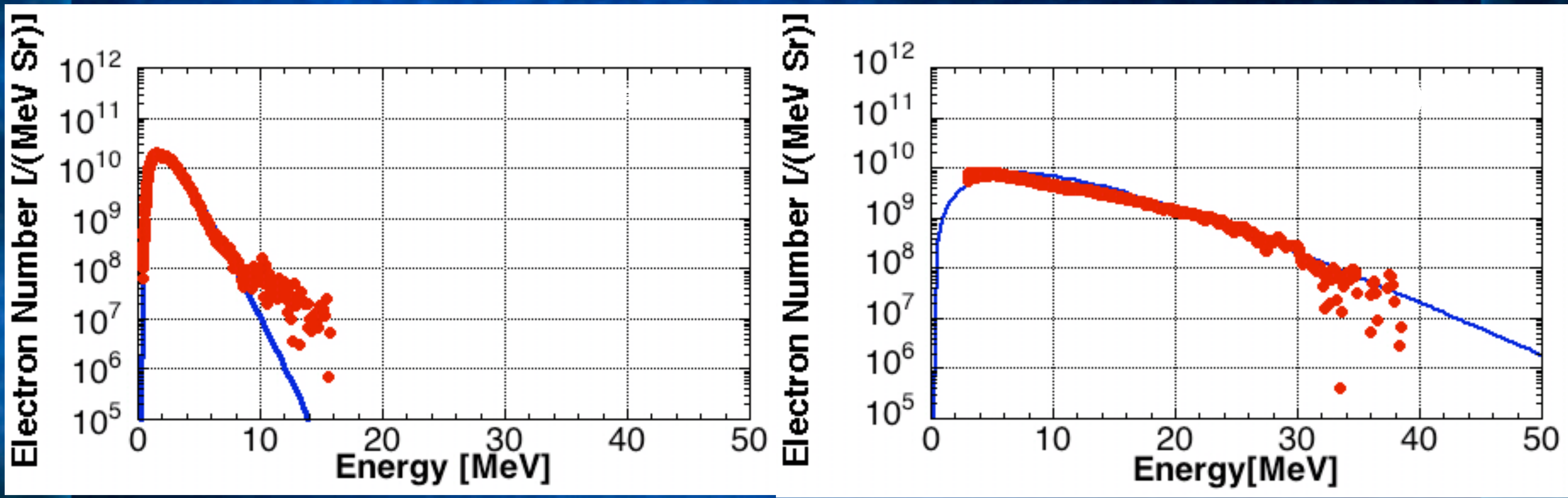
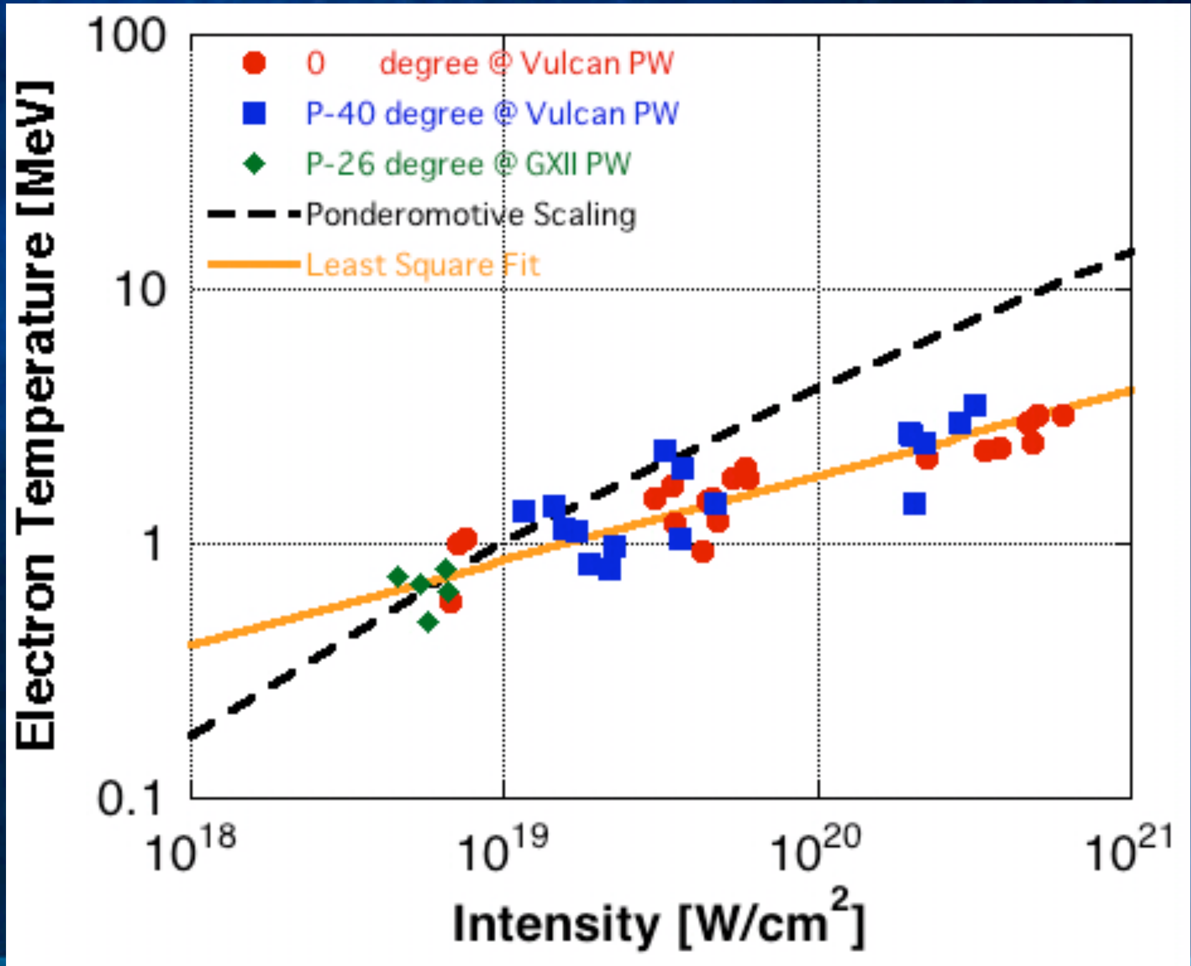


Figure (a) and (b) are the ILE case and the RAL case. In (a), the laser intensity is 6.43×10^{18} W/cm^2 . The target material and thickness are Al and 100μmt. In (b), the laser intensity is 3.16×10^{20} W/cm^2 . y The target material and thickness are Cu and 25μmt.

Temperature scaling with 0.5 – 5 psec laser pulse.



Target, laser condition and the electron temperature.

Target Material (Thickness [μm])	On Target Energy [J]	Pulse Duration [ps]	On Target Intensity [W/cm2]	Electron Temperature [MeV]
Al (100)	62.82	0.7	4.57E+18	0.75
Al (100)	88.45	0.7	6.43E+18	0.80
Au (15)	267.24	0.5	2.86E+20	3.00
Au (5)	204.66	0.5	2.19E+20	2.52
Au (7) + Ti (25)	228.12	0.5	4.65E+20	3.00
CH (10) + Ti (25)	238.08	0.5	4.85E+20	2.50
Cu (10) +Ti (10)	182.28	0.5	1.95E+20	2.72
Cu (25)	295.20	0.5	3.16E+20	3.50
Cu (25)	348.54	5.0	3.73E+19	2.00
Ti (25)	29.40	0.5	5.99E+19	1.80
Ti (25)	298.20	0.5	6.07E+20	3.20
Ti (25)	32.88	5.0	6.70E+18	0.60
Ti (25)	168.54	5.0	3.43E+19	1.70

This table shows the target condition, the laser condition and the electron temperature. In this experiment, the single and the multi layer targets are used. The dependence of electron temperatures are not observed from target condition. The electron temperatures varied when the laser intensity is changed.

M. Haines explanation

$$I = \frac{1}{2} n_h m_e v_h^{\,3}$$

$$\gamma_h \simeq \gamma_h \frac{v_{osc}}{c} = \frac{e\tilde{E}_0}{\omega m_e c} \equiv a_0$$

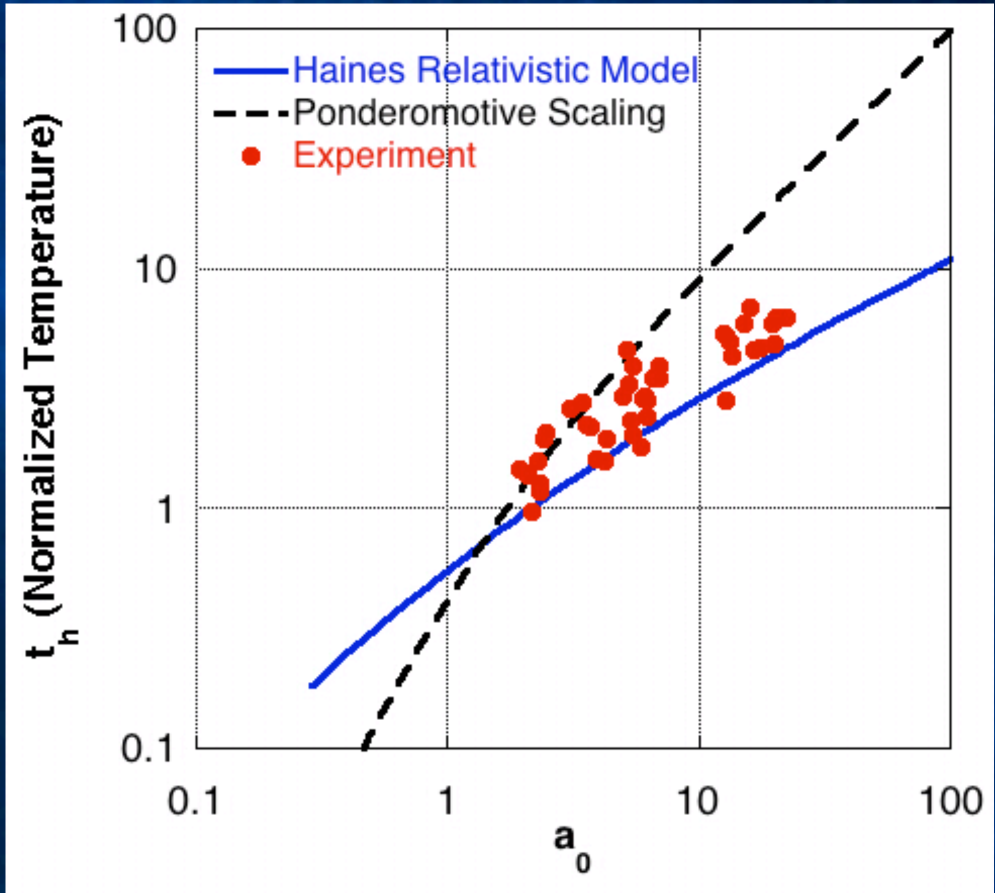
$$n_h = \gamma_h n_c = \gamma_h \frac{4\pi^2 m_e}{\mu_0 e^2 \lambda^2}$$

M Haines continued

$$I_L = \frac{2\pi^2 m_e^2 c^3 a_0^2}{\mu_0 e^2 \lambda^2} = I = \frac{1}{2}\left(\frac{4\pi^2 m_e a_0}{\mu_0 e^2 \lambda^2}\right) m_e \left(\frac{2eT_h}{m_e}\right)^{3/2}$$

$$T_h = \frac{m_e c^2}{2e} a_0^{2/3}$$

M Haines' model shows a good fit to the experiment than S Wilks's Ponderomotive scaling.

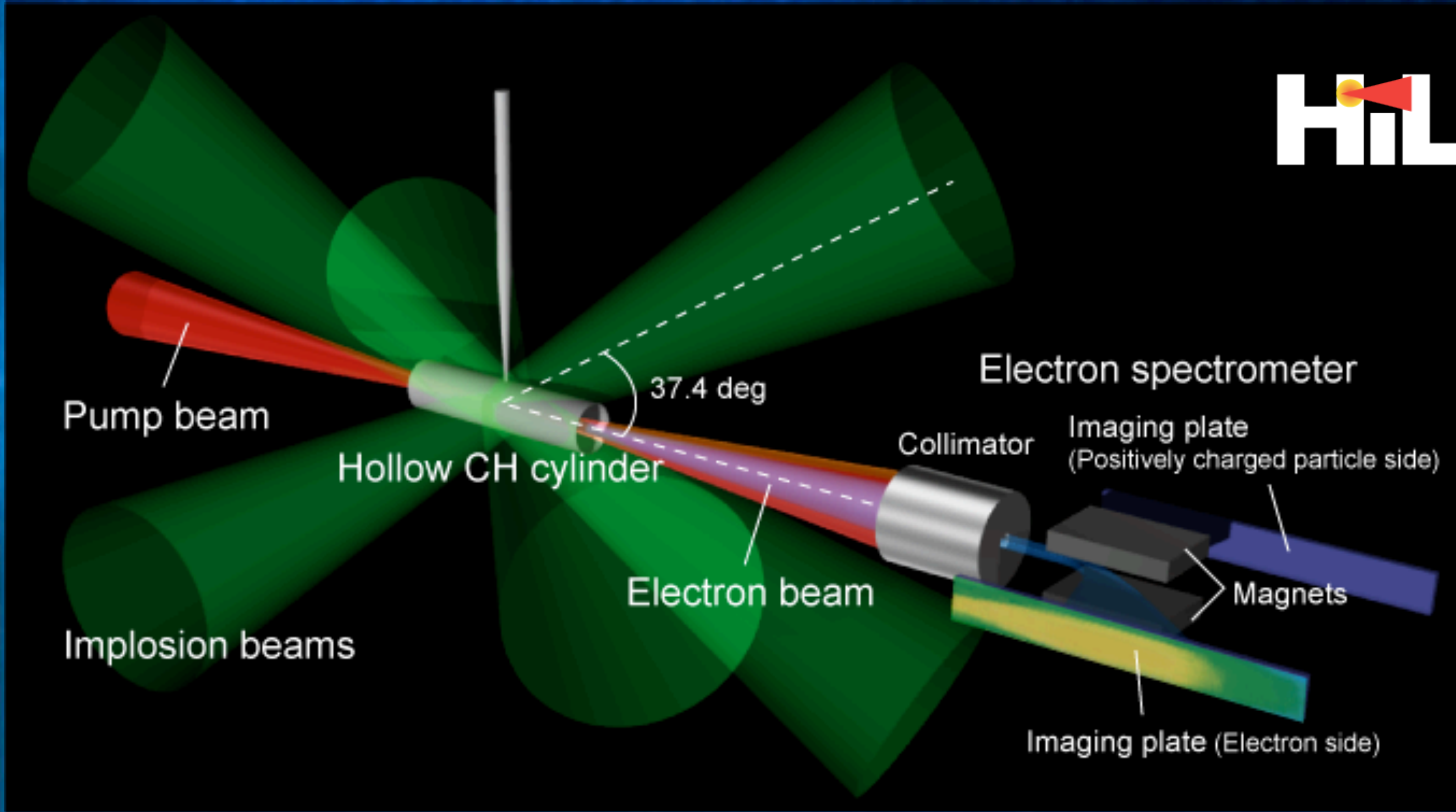


Hot electron generation to tune the spectrum suitable for fast ignition

N Nakanii, K Kondo, KA Tanaka et al., APL 93 081501(08)

Pump beam was injected to imploded cylinder

Energy spectrum of accelerated electrons has been measured with electron spectrometer(ESM), which was placed along the propagation axis of pump beam.



Implosion beams (6 beams)
- pulse width: 1 ns
- wavelength: 0.53 μm
- total energy: 1.9 kJ, 2.0 kJ, 2.3 kJ

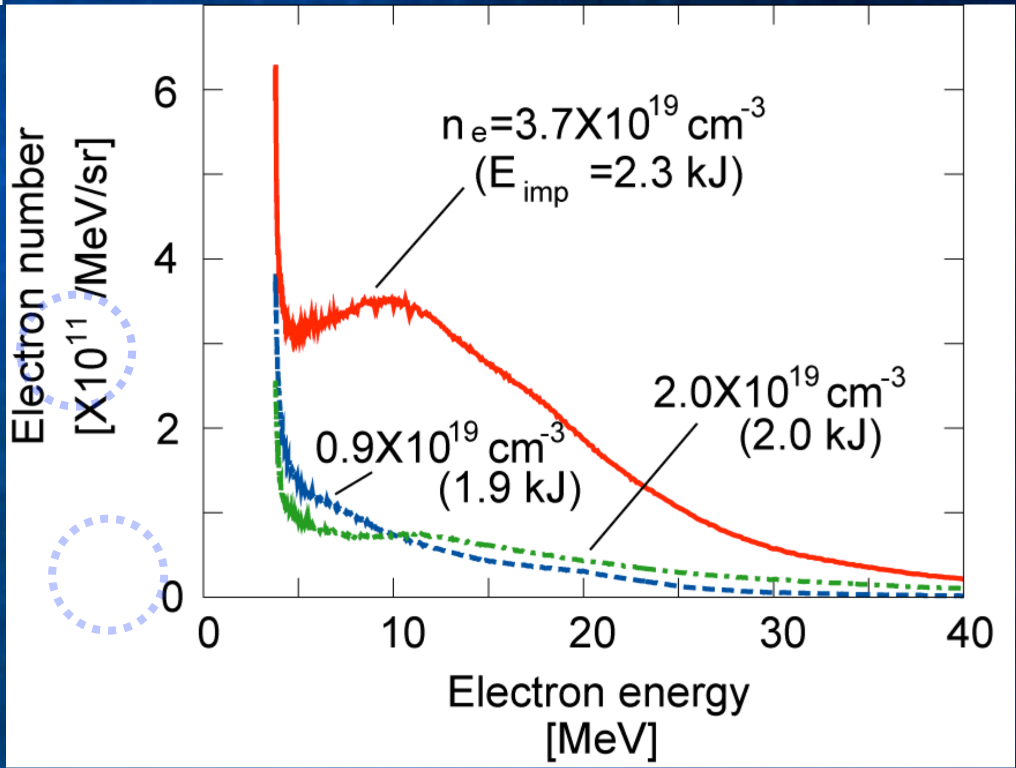
3.1 ns →

Pump beam
- pulse width: 700 fs
- wavelength: 1.053 μm
- energy: 100 J

Bump around 10 MeV was formed in the energy spectra of high density cases

- By changing the energy of implosion beams (E_{imp}=1.9, 2.0, 2.3 kJ), electron density was varied (n_e=0.9, 2.0, 3.7 X10^{19} cm^{-3}).

PW laser energy is 100 J.



We have performed a simple numerical calculation in order to explain the spectra

Simple sinusoidal wakefield

$$E_{lwf} = E_{wb} sin\left(k_p z - \omega_p t - \phi\right)$$

Wave breaking limit

$$E_{wb} = 30\sqrt{\frac{n_e}{10^{17}}}[GV/m]$$

Wave number of plasma wave

$$k_p = \frac{\omega_p}{v_{ph}}$$

Phase velocity

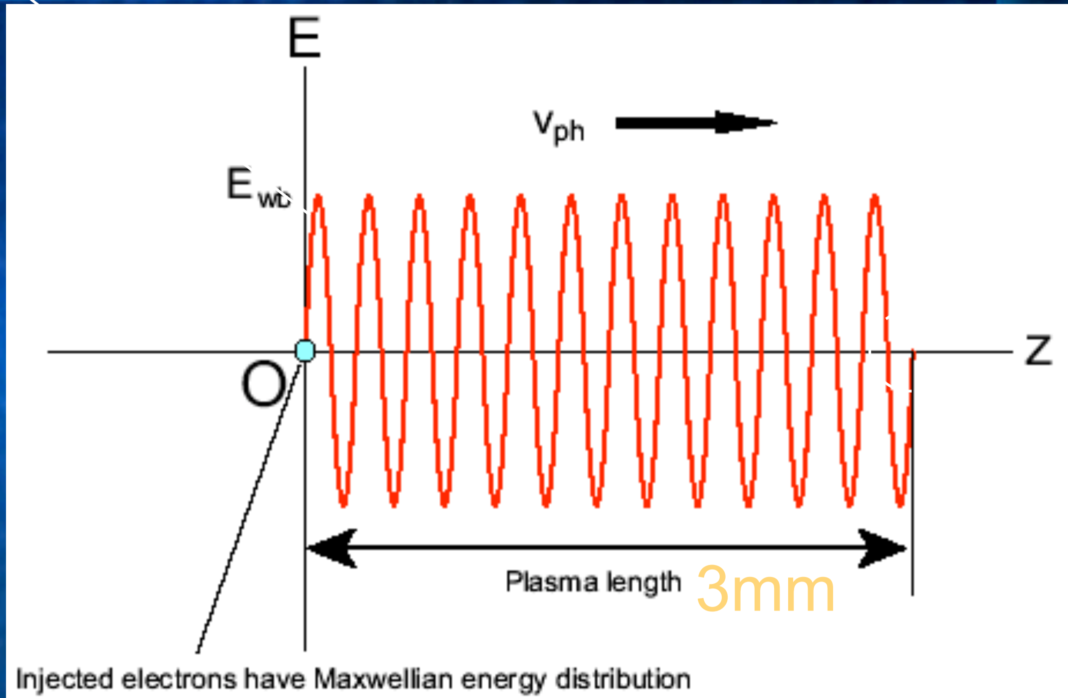
$$v_{ph} = c\sqrt{1 - \frac{\omega_p^2}{\omega_0^2}}$$

Initial phase

$$0 \le \phi < 2\pi$$

Relativistic equation of motion

$$\frac{d\mathbf{p}}{dt} = eE_{lwf} \qquad \mathbf{p} = \gamma m_e v$$

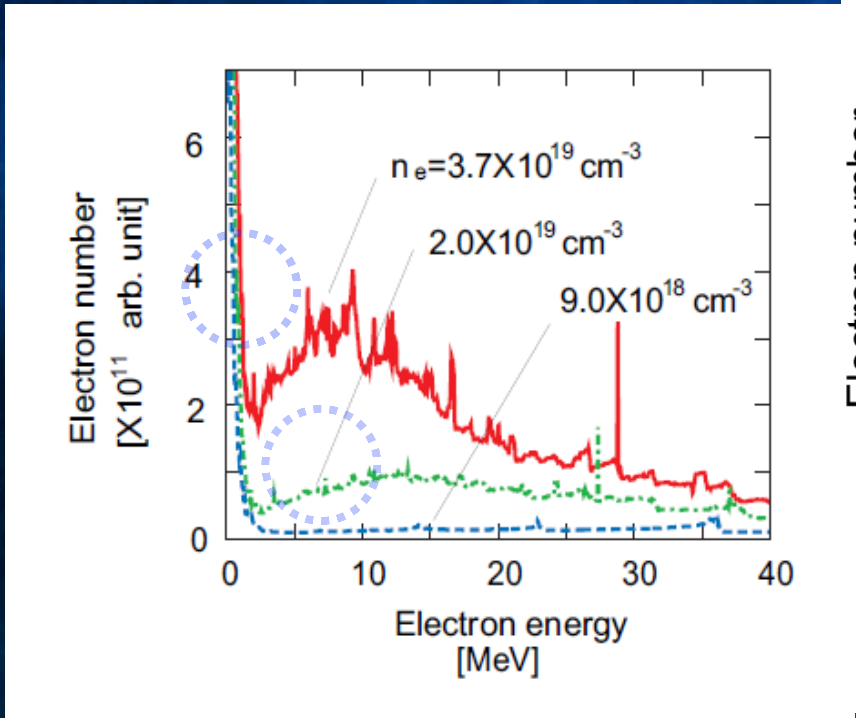


$$f(\varepsilon) \propto \exp(-\varepsilon / k_B T_e)$$

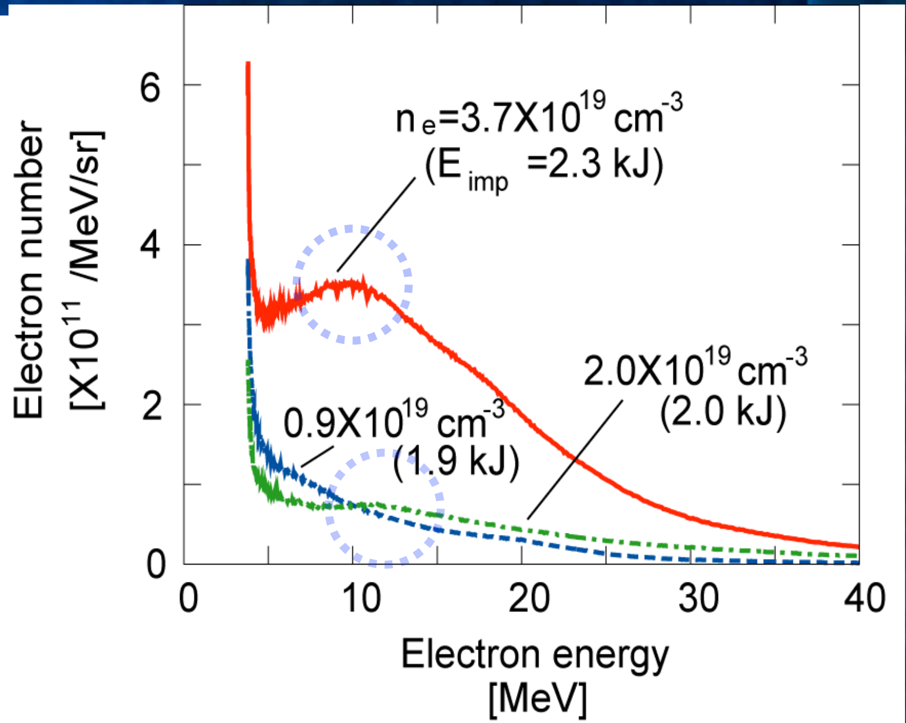
Temperature: 300 keV

Calculated spectra also have a bump around 10 MeV like experimental spectra

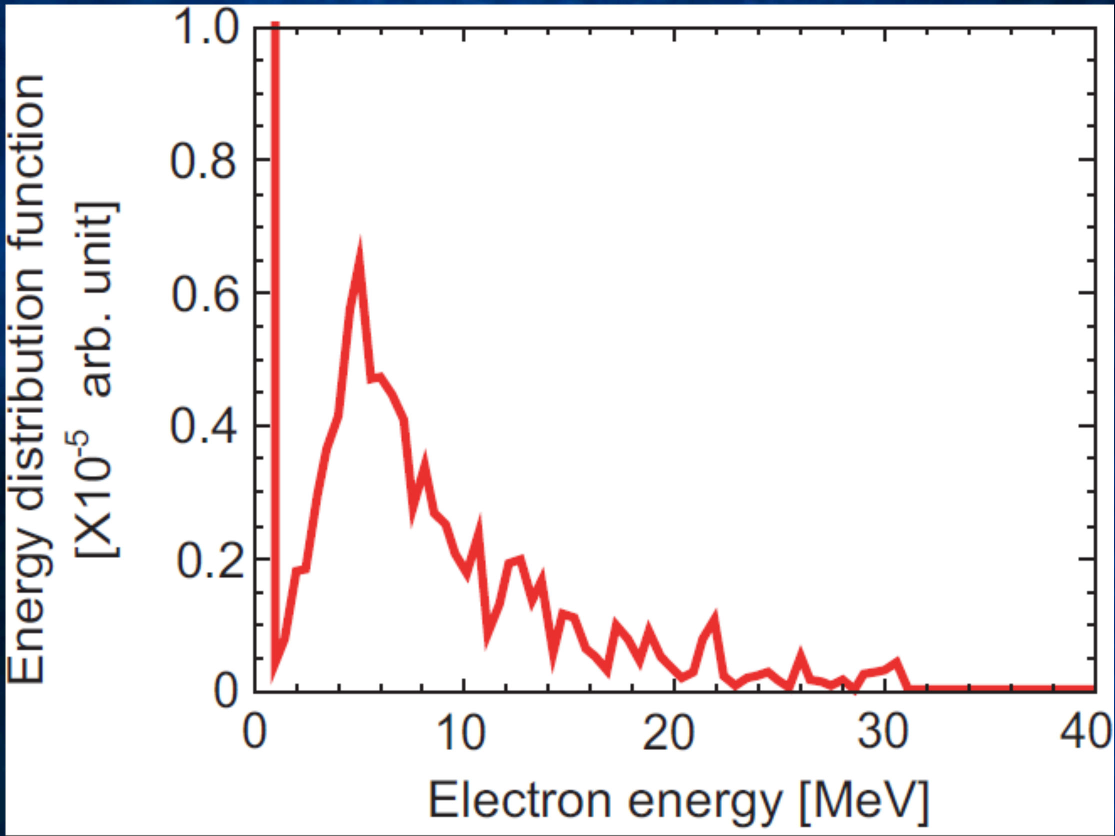
Calculations



Experiments



2D PIC confirms the multi-dephasing process.



$Ne = 3.7 \times 10^{19}$ /c.c

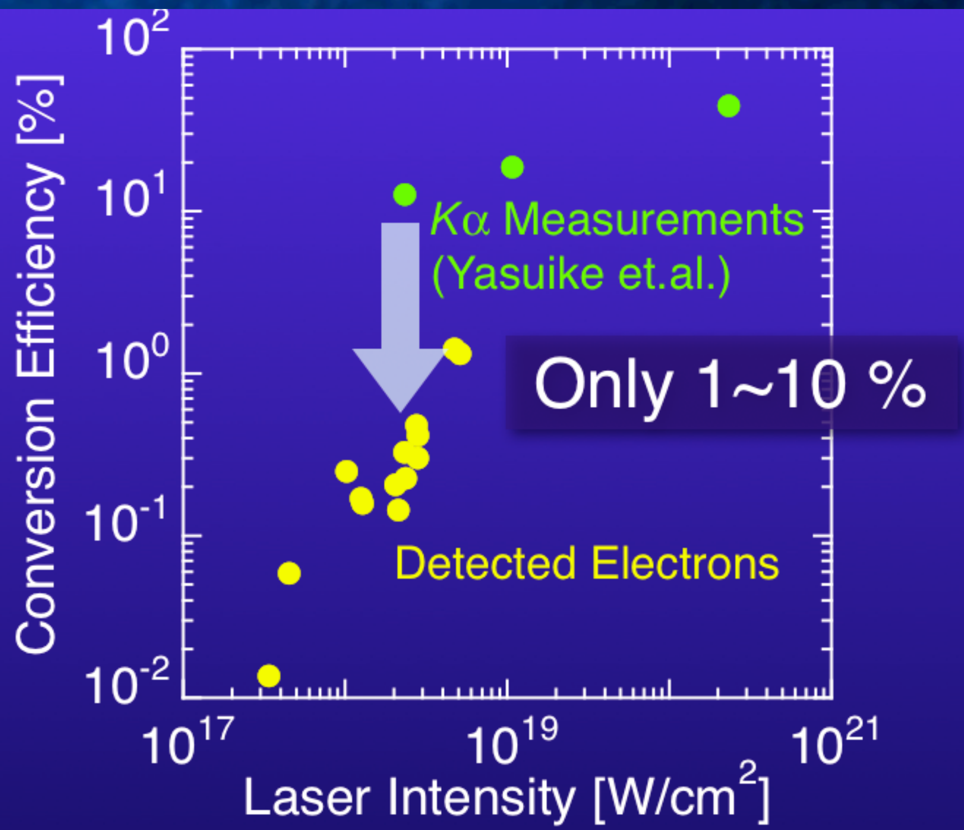
Spot = 20 μm

τ = 150 fsec.

Hot electron affected by its own field

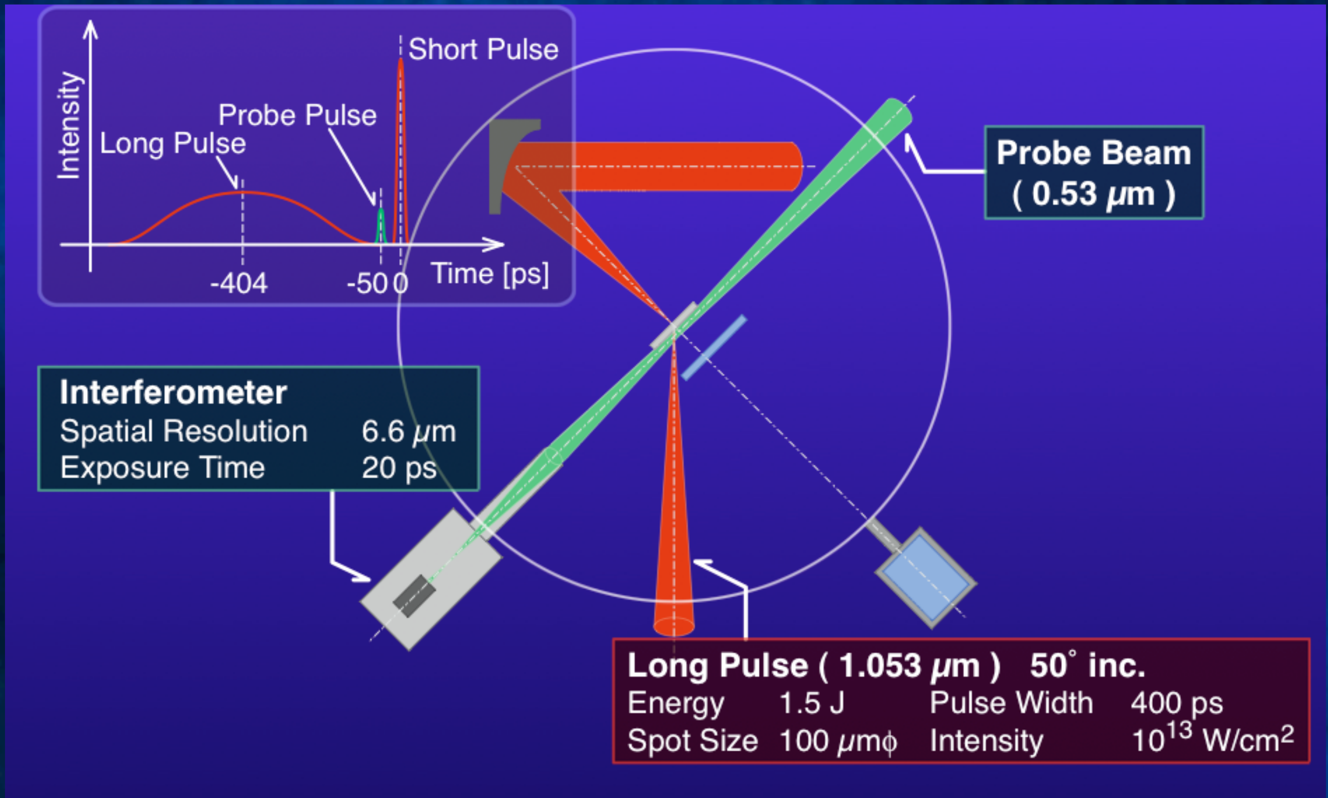
T Yabuuchi, KA Tanaka et al., Phys. Plasma 14, 040706 (07)

Measured electron number is always less than produced.

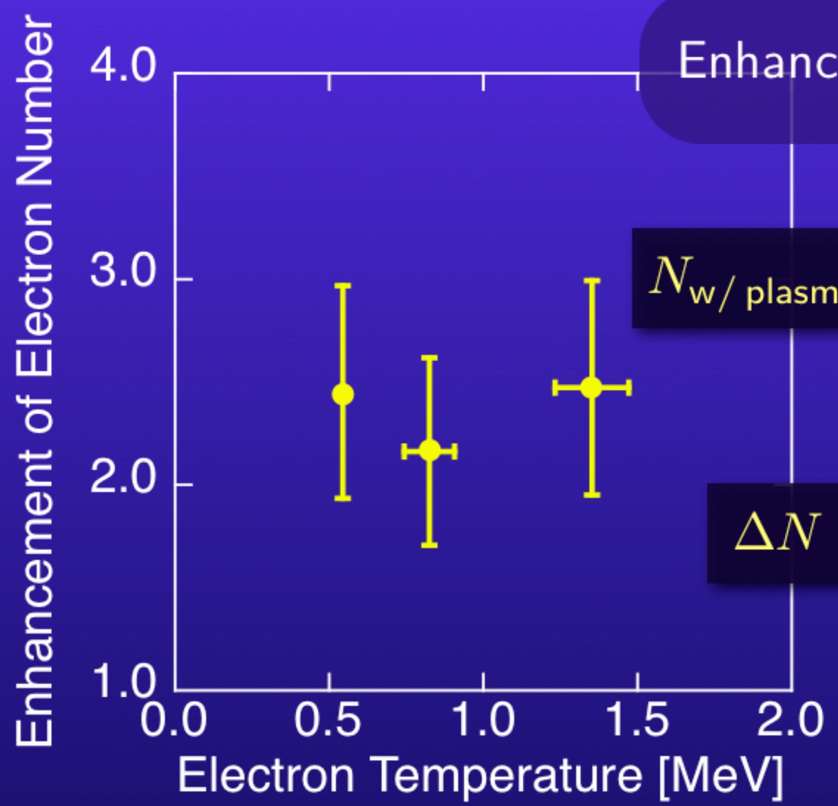


Ref : K.Yasuike et. al. RSI (2001)

Target rear plasma is created using another laser beam to control the rear sheath potential.



Factor 2-3 increase with rear plasma



$$\text{Enhancement} = \frac{N_{\text{w/ plasma}}}{N_{\text{w/o plasma}}}$$

$$N_{\text{w/ plasma}} = 2 \sim 3 \times N_{\text{w/o plasma}}$$

$$\Delta N \simeq 10^{11} \quad \text{[electrons]}$$

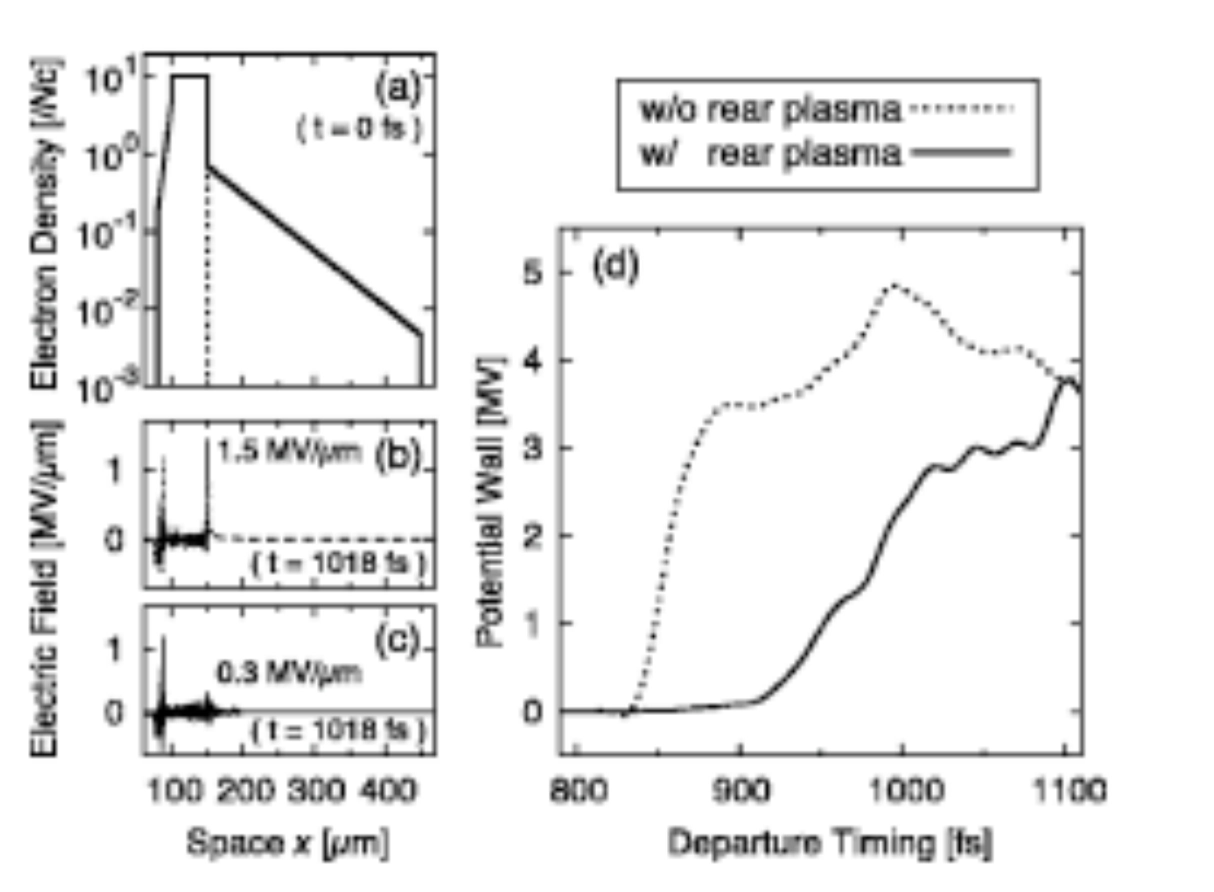
Retardation time is determined with rear plasma capacity.

$n_{plasma} = \ell\, N_{max}$ [μm/cm^3] :Total Number Electr.

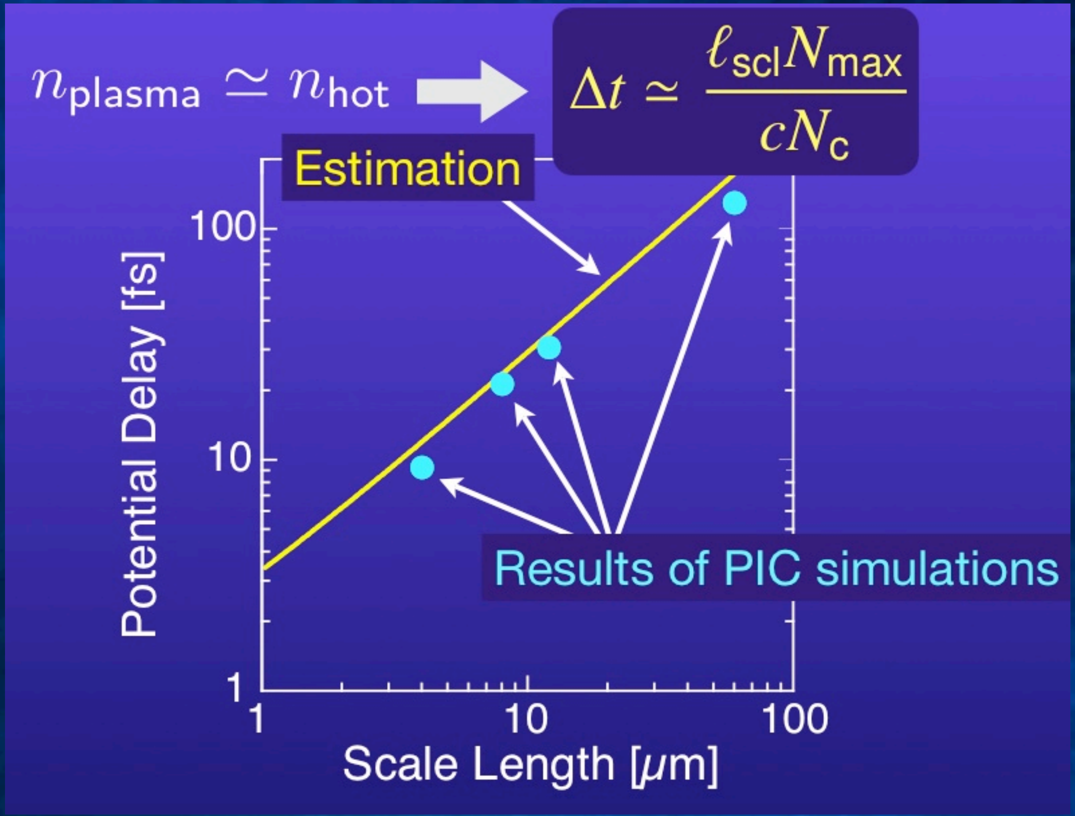
$n_{hot} = c\, N_{cmax}$ [μm/cm^{3}s]: Hot Electr. Flux

$$T_{retard.} = \frac{\text{Total No. Electr.}}{\text{Hot Electr. Flux.}}$$

PIC simulation set up



Analytical line fits well with PIC results.



Net electron increase of factor 2-3 consistent with Alfven limit.

Alfvén Limit $I^{\text{Alfven}} = 17000\beta\gamma$ [A]

Maximum number of electrons within a pulse duration, Δt.

$$N_{\Delta t}^{\text{Alfven}} = 1 \times 10^{8}\beta\gamma\Delta t \quad \text{[electrons]}$$

In our experiments, the electron temperature is 0.5-1.5 MeV.

↓

Average energy is 1.5-4.5 MeV (γ =4-10).

$$N_{\Delta t=\text{delay}}^{\text{Alfven}} \simeq 5 \times 10^{10} \sim 1 \times 10^{11} \quad \text{[electrons]}$$

This electron number is consistent with the enhanced number observed in the experiments.

Hot electron Summary I

- Hot electron spectrum was measured using two PW laser systems at RAL and Osaka.
- There is now clear pulse width difference on Te.
- The Te dependence on laser intensity is close to 1/3 slower than the S Wilks ponderometive force scaling.

Hot electron Summary I I

- Hot electron spectrum was modified to have a bump on 10 MeV.
- The plasma guide utilizing a cylinder tube implosion to have a proper plasma density.
- Multi-dephasing mechanism is proposed to explain this spectrum.
- Energy efficiency was 4.7 %.

Summary III

- Electro-static potential formation is studied to understand hot electrons leaving from a target.
- T. Yabu-uchi, K.A. Tanaka et al.,
  Phys. Plasmas 14, 040706 (2007)

Electrons are generated more with rear plasma