NWP-2

Laser-ion acceleration boosted by multi-picosecond pulses

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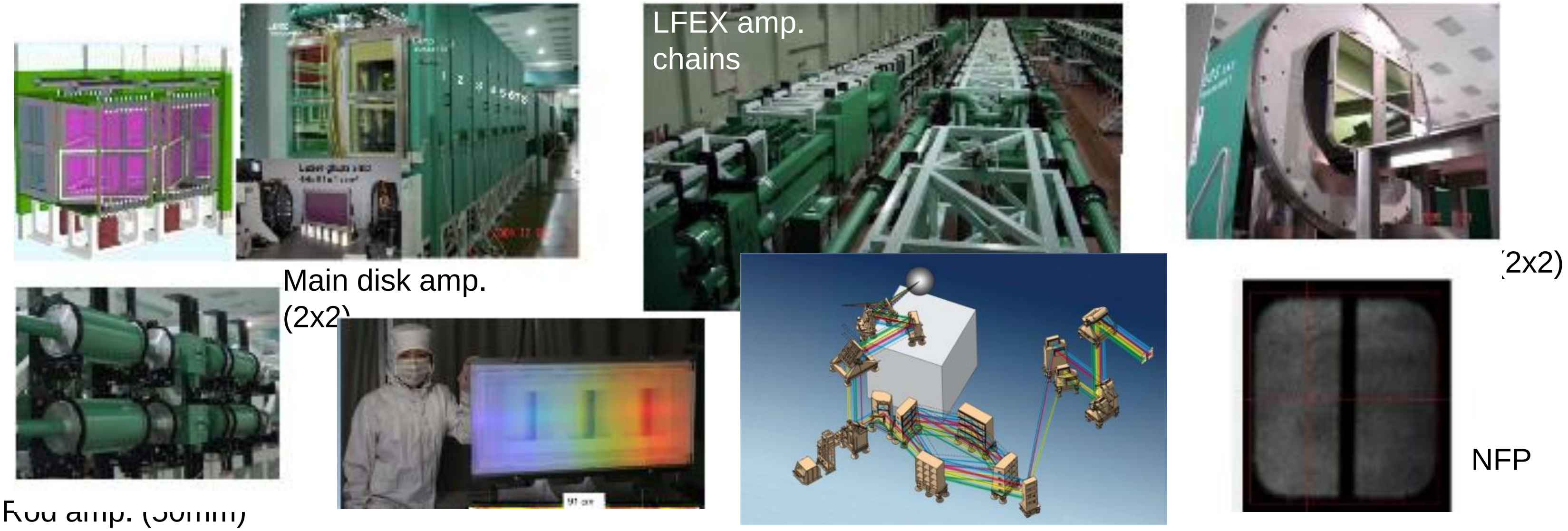
LFEX at ILE



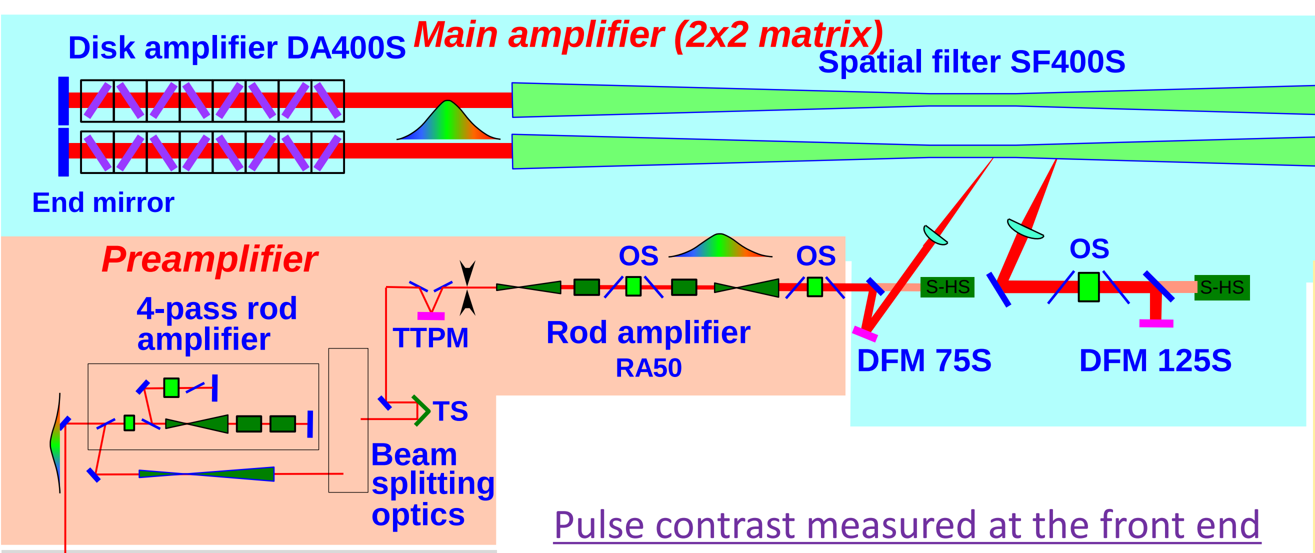
Using LFEX laser system, we demonstrate for the first time that high-contrast, multi-ps, relativistic-intensity laser pulses are advantageous for proton acceleration.

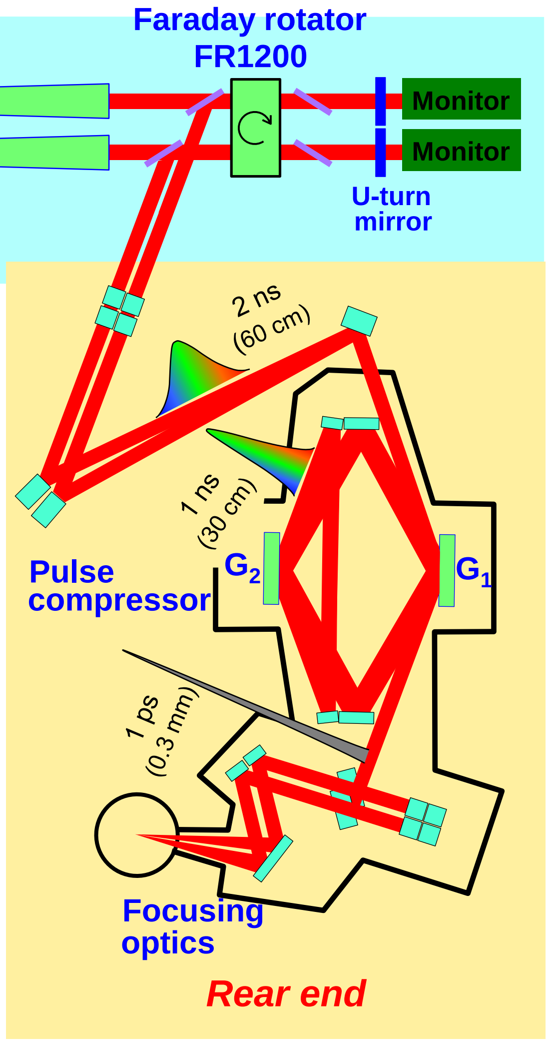
A. Yogo et al., Sci. Rep. 7, 42451 (2017).

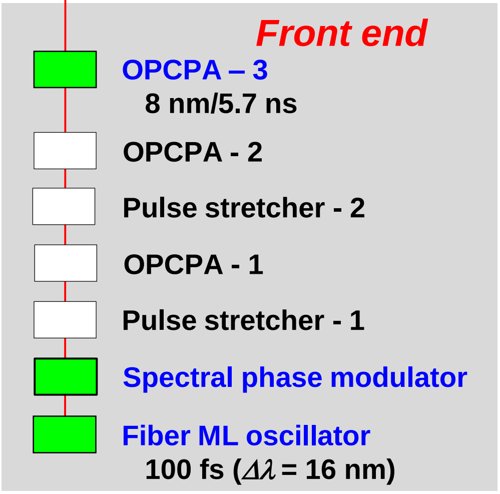
By extending the pulse duration from 1.5 to 6 ps, the maximum energy of protons is improved more than twice (from 13 to 33 MeV) although the laser intensity in fixed on 10^{18} Wcm^{-2}. The proton energy observed are discussed using a plasma expansion model newly developed by taking into account the enhancement of electron temperature depending on the pulse duration, when the laser pulse accelerates electrons beyond the ponderomotive energy.

Present Status of LFEX: 2PW operation

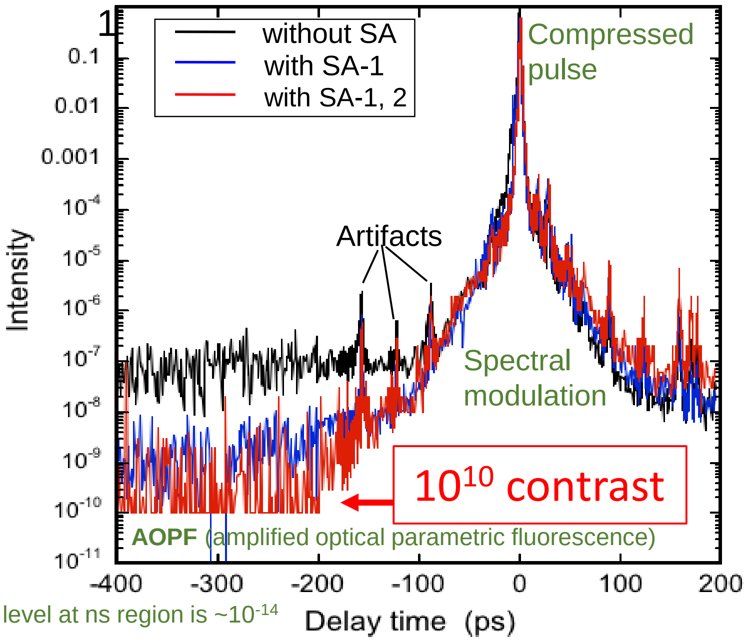
High-Contrast, kJ, ps pulses are delivered on targets.







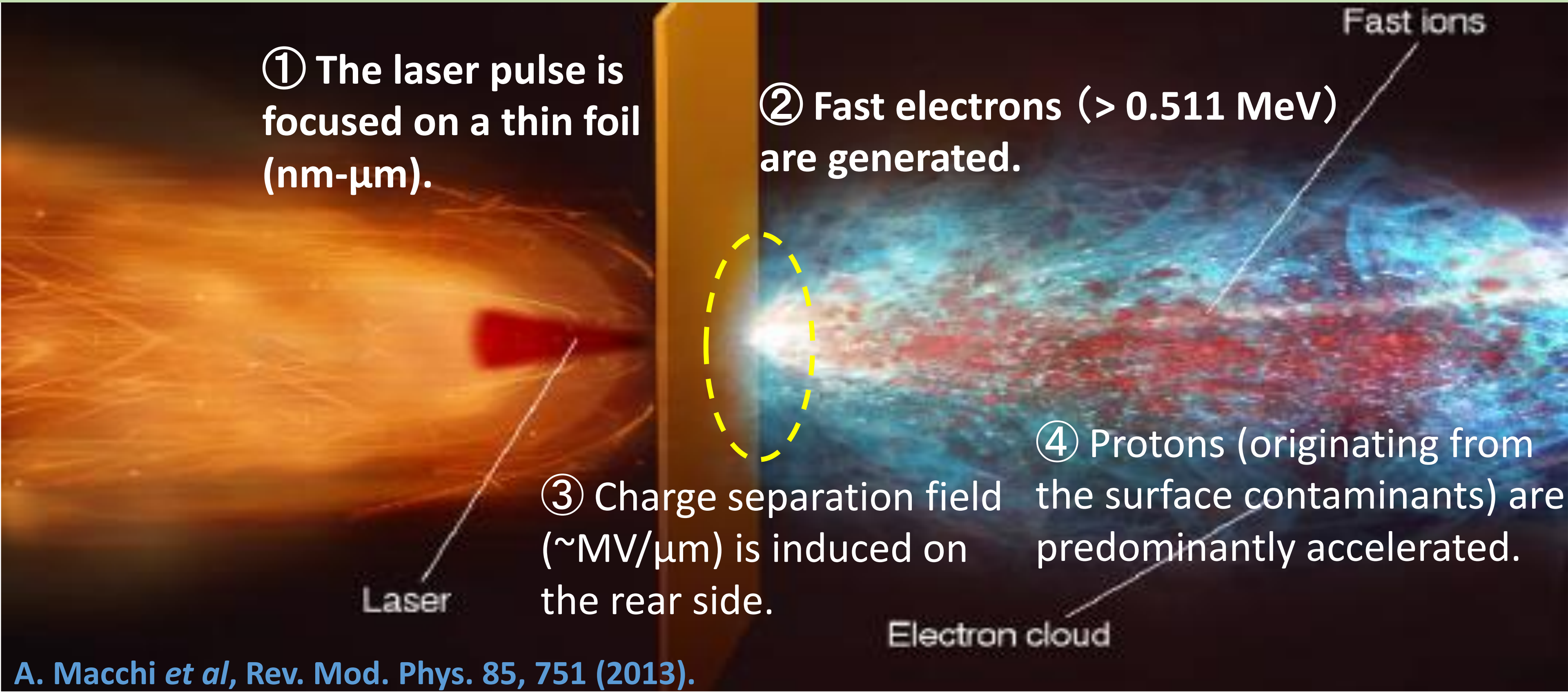
Pulse contrast measured at the front end



ASE level at ns region is ~10^{-14}

Ion acceleration with 10^{18}-10^{20} Wcm^{-2} laser intensity

TNSA model: ion acceleration from the target rear surface.



① The laser pulse is focused on a thin foil (nm-μm).

② Fast electrons（> 0.511 MeV） are generated.

③ Charge separation field (~MV/μm) is induced on the rear side.

④ Protons (originating from the surface contaminants) are predominantly accelerated.

A. Macchi *et al*, Rev. Mod. Phys. 85, 751 (2013).

Maximum ion energy predicted by 1 dimensional (1D) isothermal model

$$\boxed{\mathcal{E}_{max} = 2T_h\left[\ln\left(t_p + \sqrt{t_p^2+1}\right)\right]^2}$$

P. Mora Phys. Rev. Lett. **90**, 185002 (2003)

To explain experimental results, adiabatic cooling and 3D effect are often introduced in the 1D isothermal model.

Experimental conditions

Ion energy distributions are measured at the rear side of thin-foil targets.

LFEX: ps laser

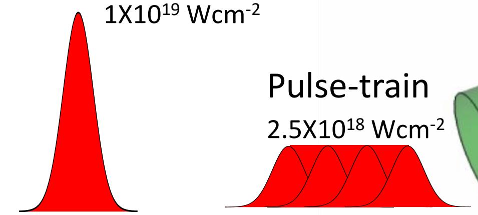
1.5 ps, 1 kJ on target

1.2×10^{19} Wcm^{-2}

60 μm spot (FWHM)

4 beams in total.

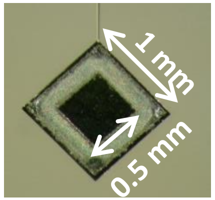
The arrival timing of 4 LFEX beams can be set independently of each other.



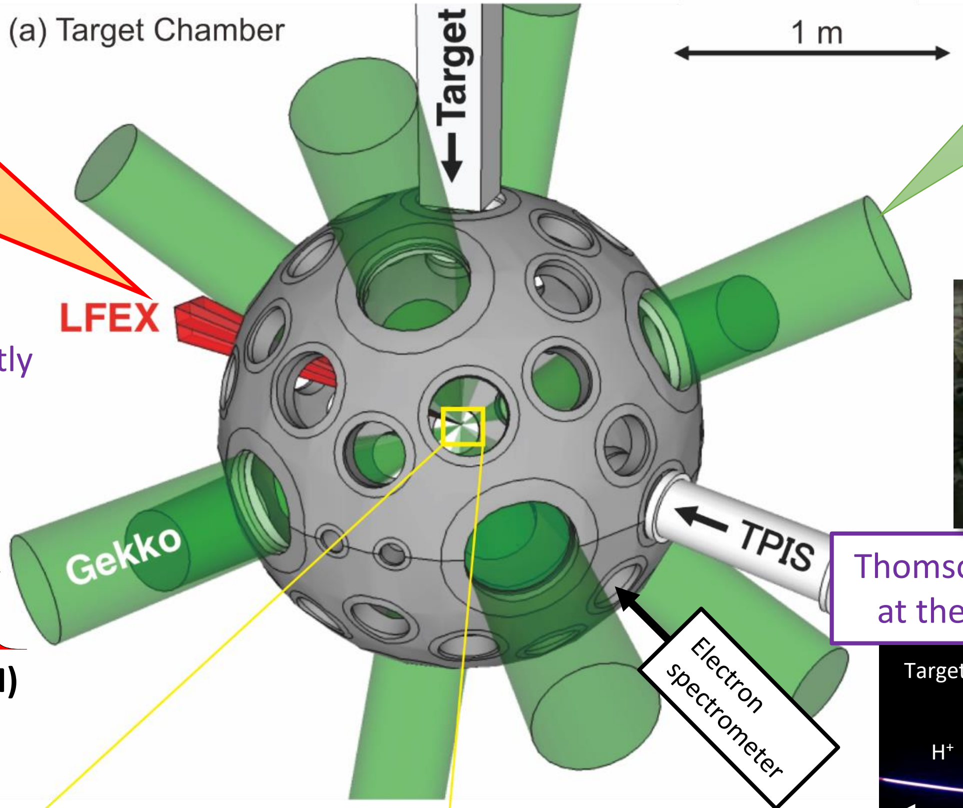
1.5 ps (FWHM) **6 ps (FWHM)**

Thin-foil target

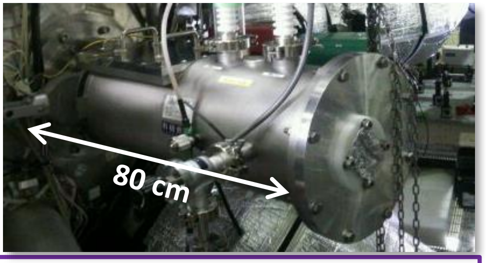
5 or 10-μm-thick AL



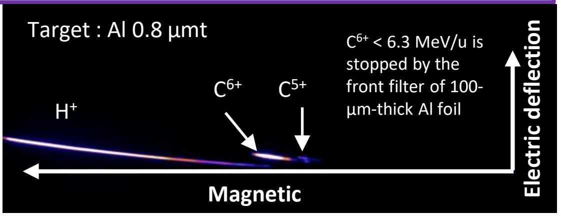
Spot size >> target thickness
(60 μm) (5-10 μm)



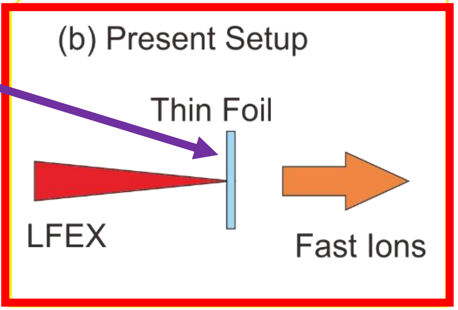
Gekko-XII: ns laser for fuel implosion 12 beams in total.

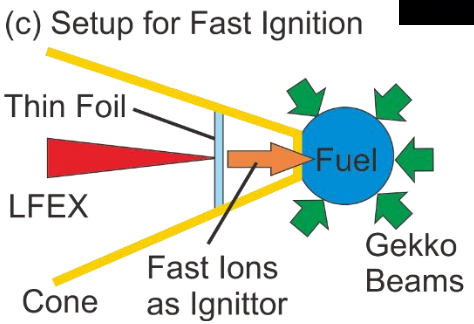


Thomson parabola Ion spectrometer at the laser propagation direction



C^{6+} < 6.3 MeV/u is stopped by the front filter of 100-μm-thick Al foil





Electron energy spectra are measured simultaneously with ions.

Experimental conditions

Ion en targets.

LFE

1.5 ps,

1.2X10

60 μm

4 bean

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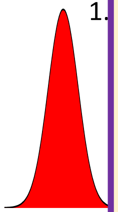

1.5 ps (FV

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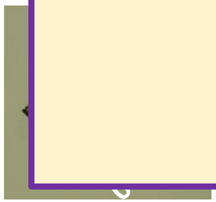
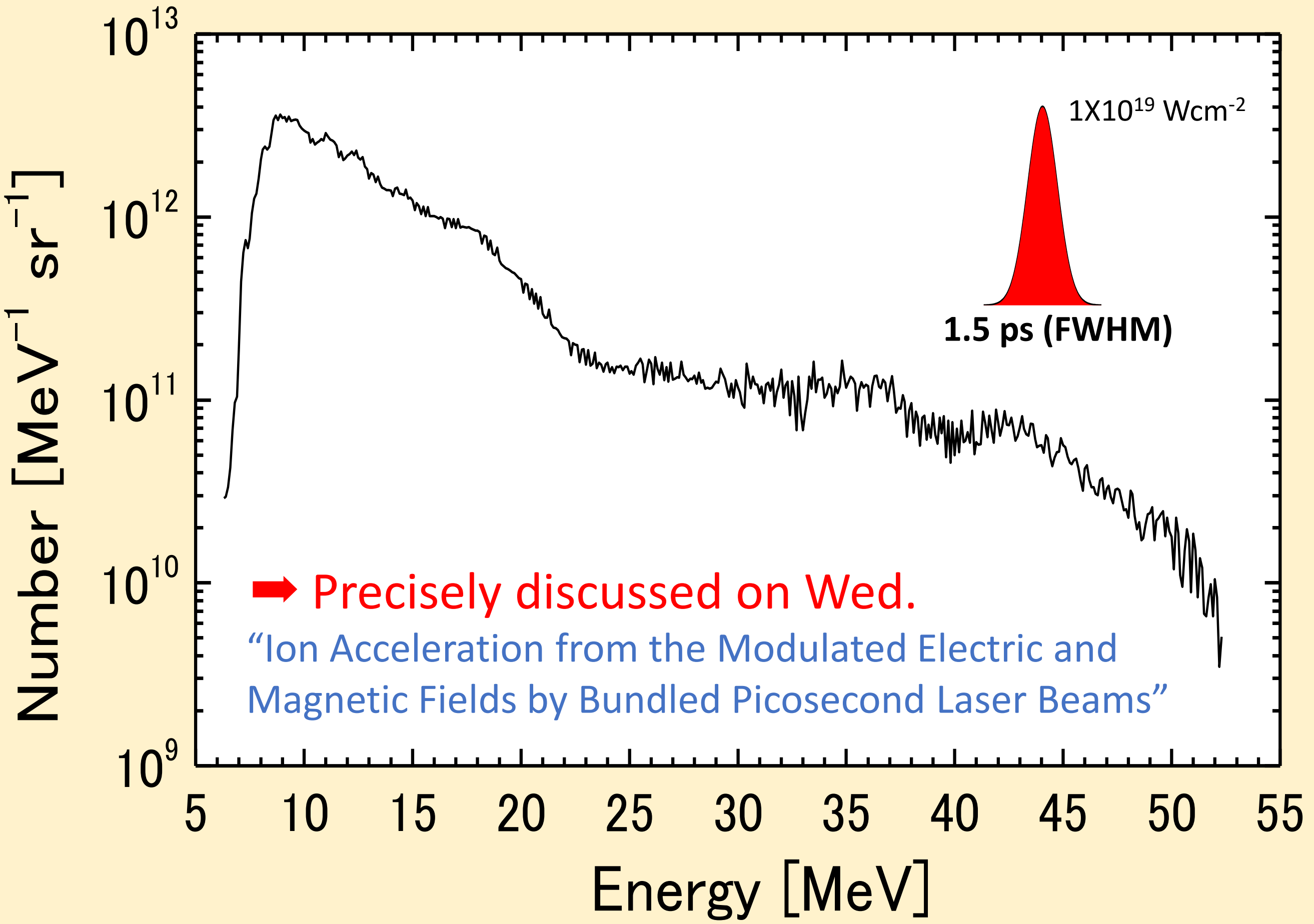


Spot size >> target thickness
(60 μm) (5-10 μm)

Maximum Proton Energy 52 MeV with 1.2X10^{19} Wcm^{-2}
Energy Conversion Efficiency into Protons (>6 MeV): 4 %



➡ Precisely discussed on Wed.

"Ion Acceleration from the Modulated Electric and Magnetic Fields by Bundled Picosecond Laser Beams"

laser
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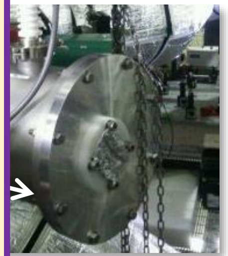
total.



pectrometer
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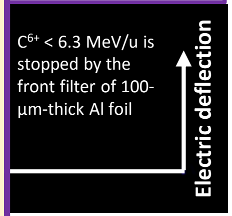

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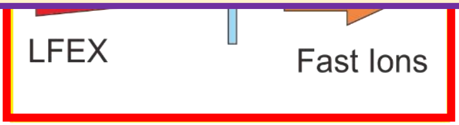
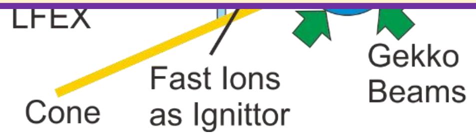




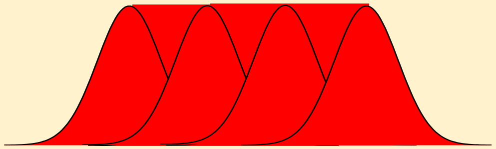
Experimental conditions

Ion ene

targets.

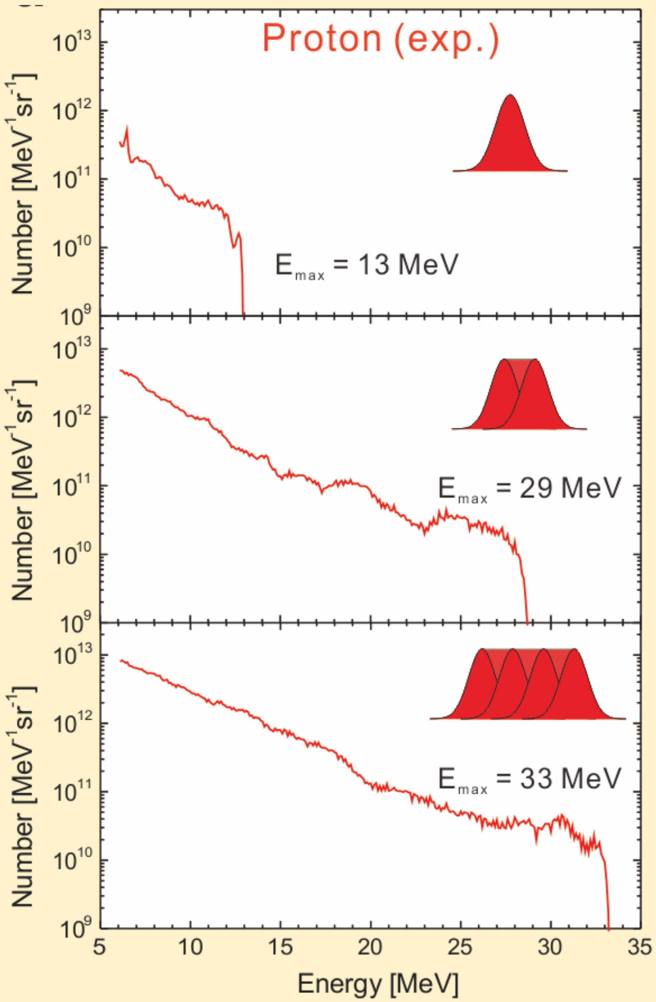
The main topic of this talk:
Laser pulse "train" boosts proton acceleration

Pulse Train



Multi-ps duration
1.5 X 4 = 6 ps (FWHM)

Flat-top-like intensity peak
2.5×10^{18} Wcm^{-2}



LFEX

1.5 ps, 1
1.2X10^{19}
60 µm s
4 beams

The arrival
beams can
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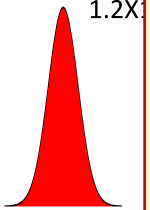
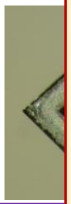


1.5 ps (FWH

Thin-
5 or 10-



Spot size >> target thickness
(60 µm) (5-10 µm)

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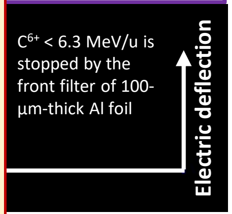
spectrometer
on direction



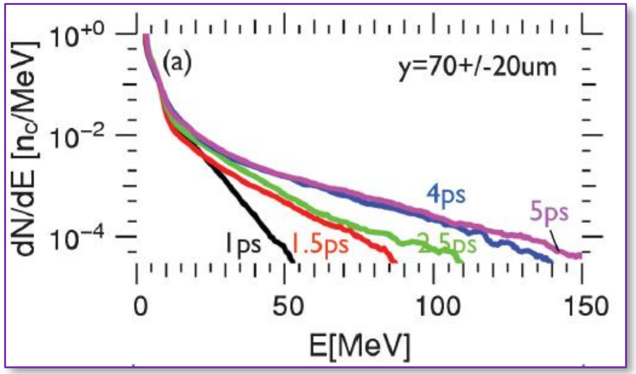
C^{6+} < 6.3 MeV/u is stopped by the front filter of 100-µm-thick Al foil

Cone

Fast ions
as Ignittor

Beams

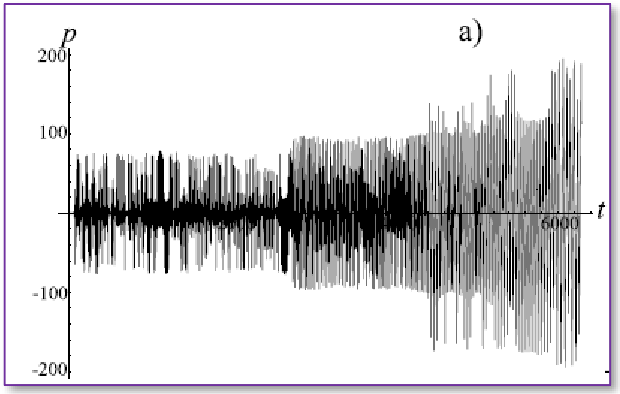
Recent theoretical studies predict electron heating depending on time.



Picosecond pulse + semi-infinite solid target

A. J. Kemp and L. Divol PRL 109, 195005 (2012)

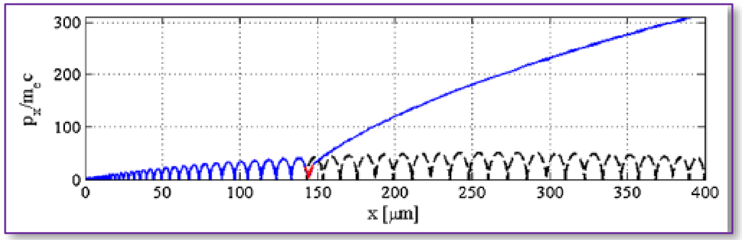
Electron temperature are heated depending on time up to several times of the ponderomotive potential.



Femtosecond pulse + thin foil target

S.V. Bulanov et al., Physics of Plasmas 22, 063108 (2015)

Electrons are stochastically heated during the chaotic motion around the thin foil target.



Femtosecond pulse + near-critical gas target

A.P.L. Robinson, A. V. Arefiev and D. Neely, PRL 22, 065002 (2013)

Super-ponderomotive electrons are generated due to non-wake field (= stochastic) mechanism.

We investigate time-dependent electron heating in multi-ps range and its effect on ion acceleration.

Proton energy increases with the pulse duration.

Our experimental results clearly exceed the prediction of TNSA model.

【Pulse duration】

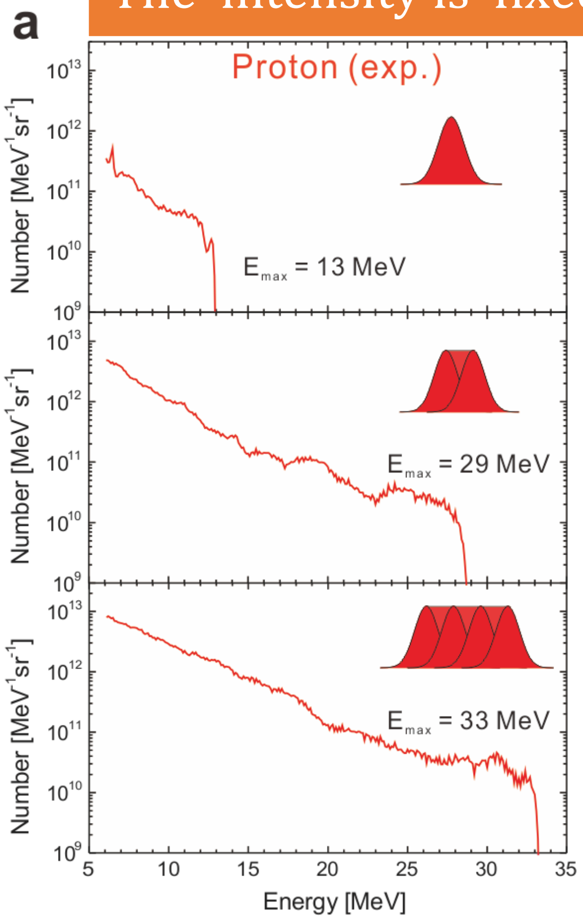
1.5 ps ⇒ **3 ps** ⇒ **6ps**

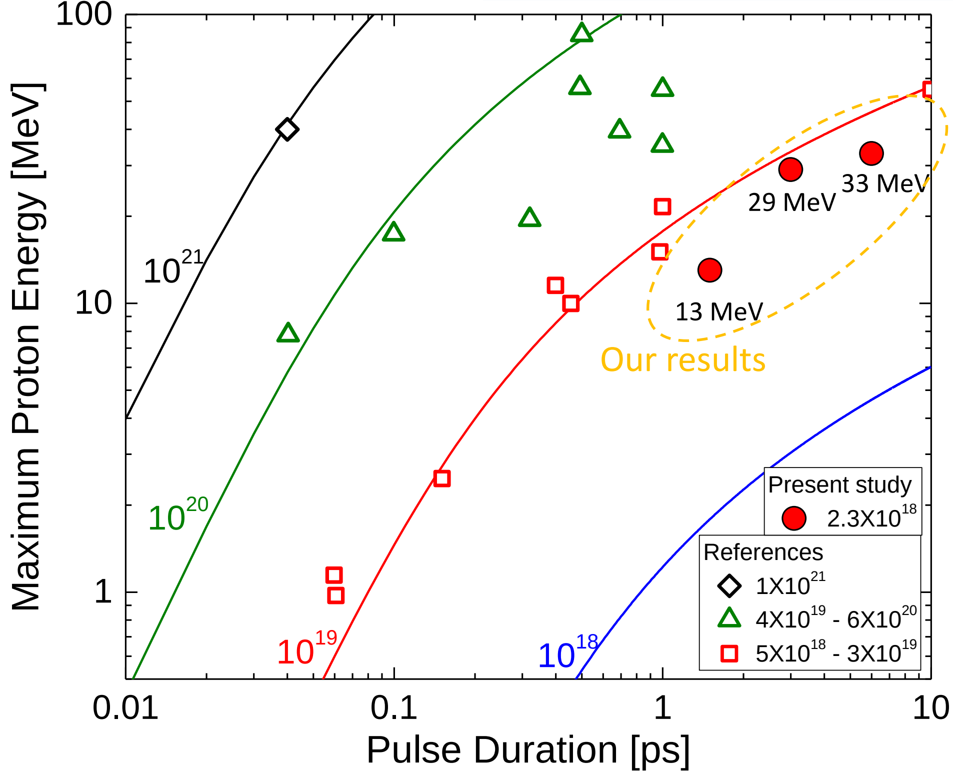
1 pulse 2-pulse train 4-pulse train

The intensity is fixed on $2.3 \times 10^{18}\ Wcm^{-2}$

⇔

Our proton energy is close to 10^{19} $\mathrm{Wcm^{-2}}$ line by TNSA.





Fuchs, J. *et al.* Laser-driven proton scaling laws and new paths towards energy increase. *Nat. Phys.* **2**, 48-54 (2006).

Electron temperature increases with pulse duration.

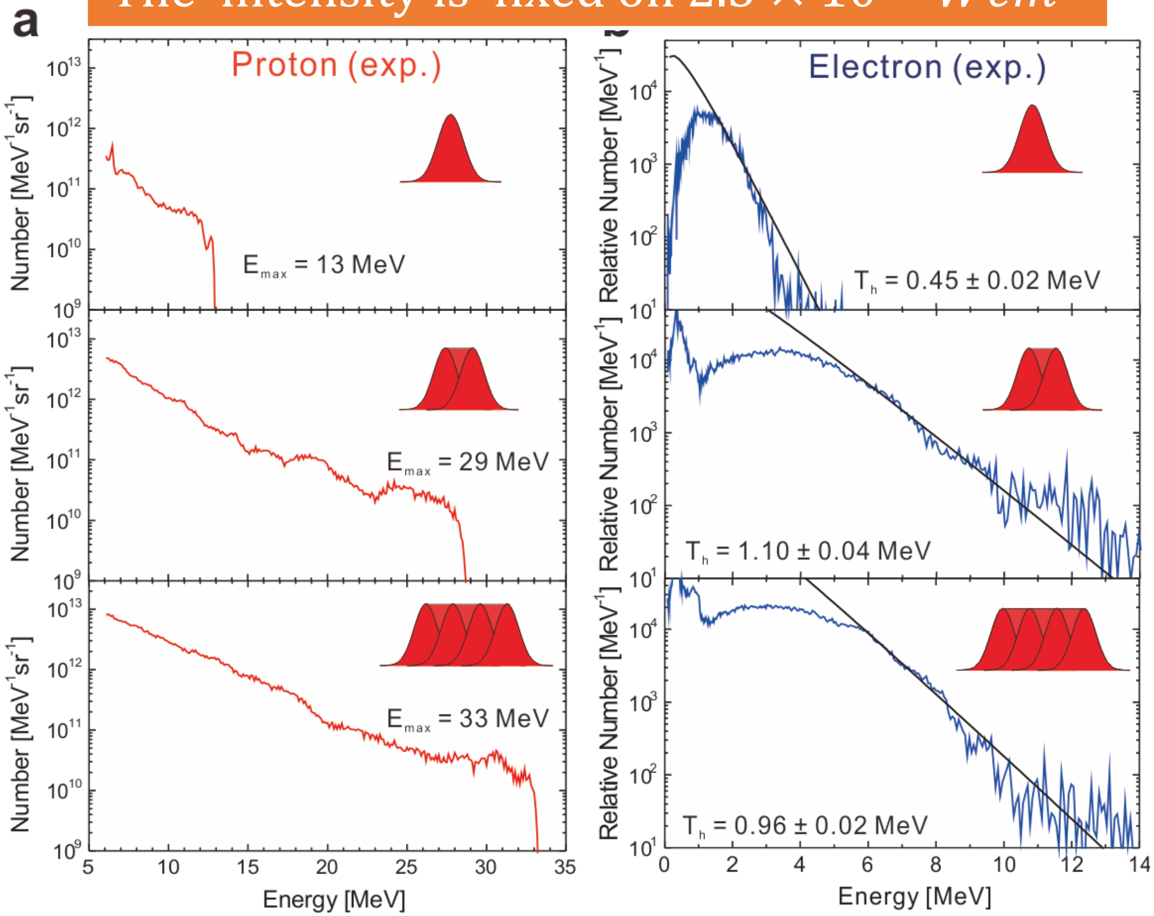
The temperature exceed a usual scaling low.

【Pulse duration】

1.5 ps ⇒ **3 ps** ⇒ **6ps**

1 pulse 2-pulse train 4-pulse train

The intensity is fixed on $2.3 \times 10^{18}\ Wcm^{-2}$



Ponderomotive energy

$$\boxed{T_0 = m_e c^2(\gamma - 1)}$$

Wilks et al., PRL 96, 13831992

$$\gamma = \sqrt{1 + a_0^2/2}$$

$$a_0 = 0.85\sqrt{I[Wcm^{-2}]\lambda^2[\mu m]/10^{18}}$$

$$T_0 = 0.2\ \text{MeV}$$

for $I = 2.3 \times 10^{18}\ \text{Wcm}^{-2}$

However, in our experiment,

0.45 ⇒1.10 ⇒ 0.96 MeV

Never explained by the ponderomotive scaling

The focal spot (60 μm) leads to quasi-1D plasma expansion.

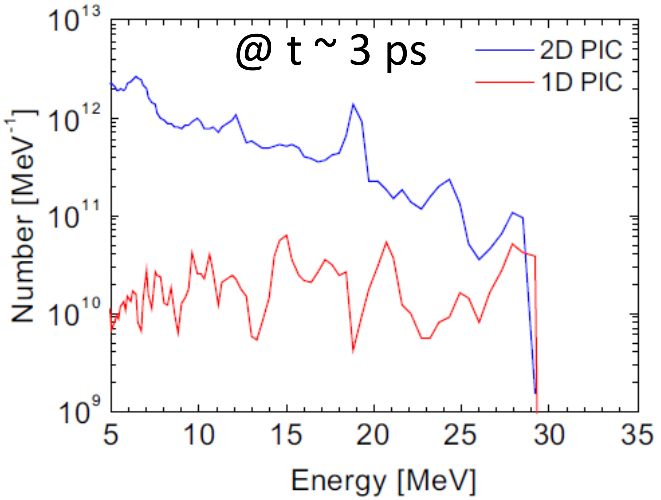
We try to explain the experimental results using 1D PIC simulation.

We have to evaluate the electron heating in the region up to 10 ps for the 4-pulse train case.

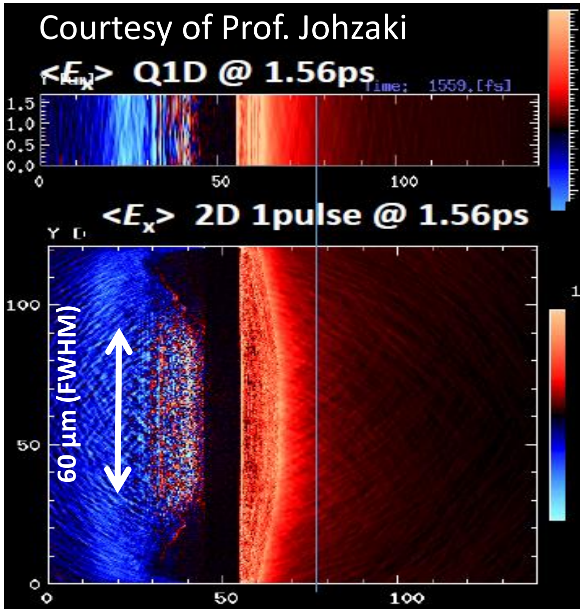
2D PIC simulation in the multi-ps time scale is time consuming, almost impossible.

We find that when the focal spot is set to be 60 μm, the 2D PIC results are well in agreement with the results obtained in 1D simulation, in the case of 1.5 ps pulse duration.

We evaluate the electron heating in multi-ps region by using 1D PIC simulation that probably reproduces the condition of actual experiment.

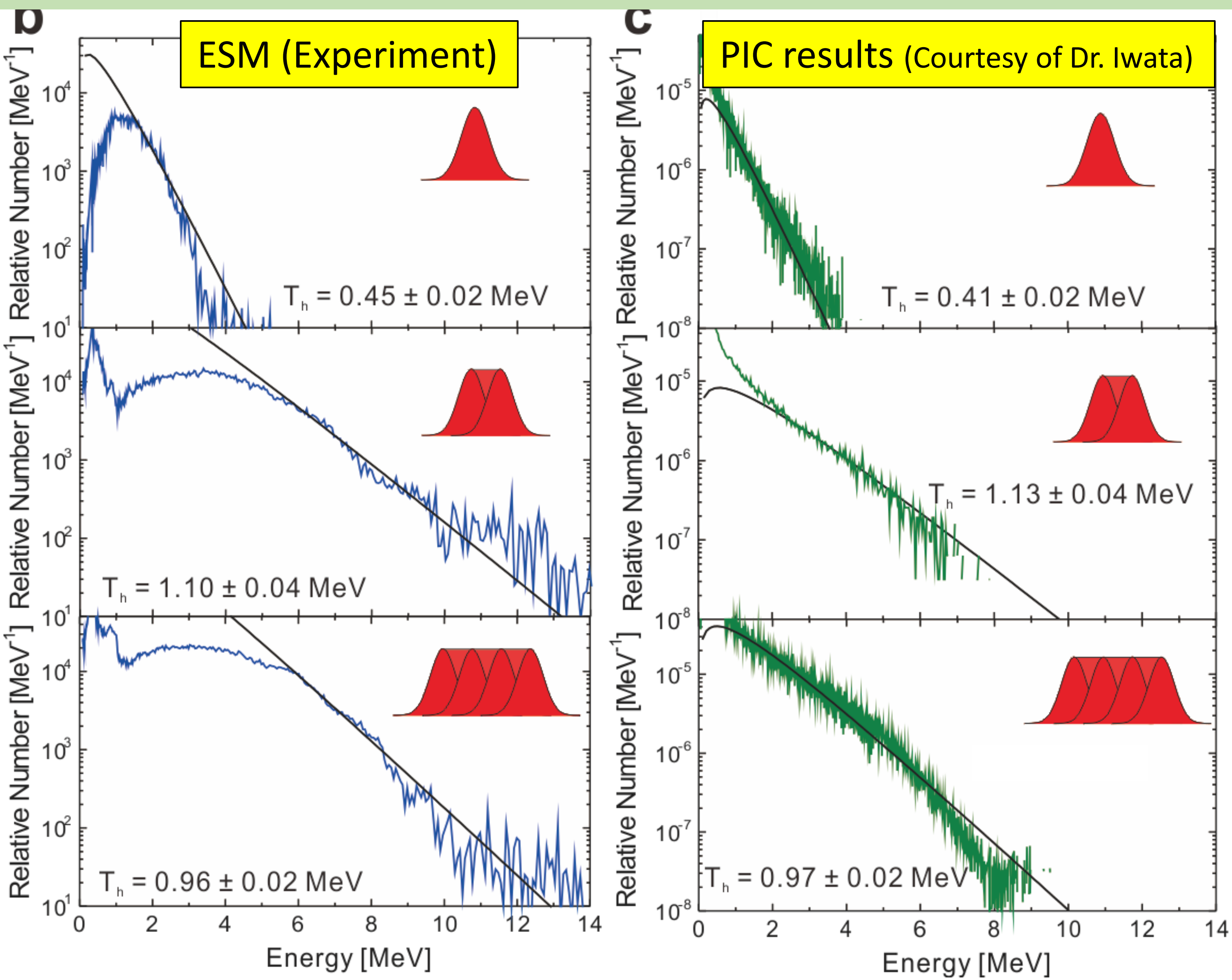


Proton energy spectra obtained with 2D PIC simulation assuming a 60 μm focal spot (blue) and 1D PIC (red). The laser pulse has 1.5 ps duration and 1X10^{19} Wcm^{-2} intensity.


Courtesy of Prof. Johzaki

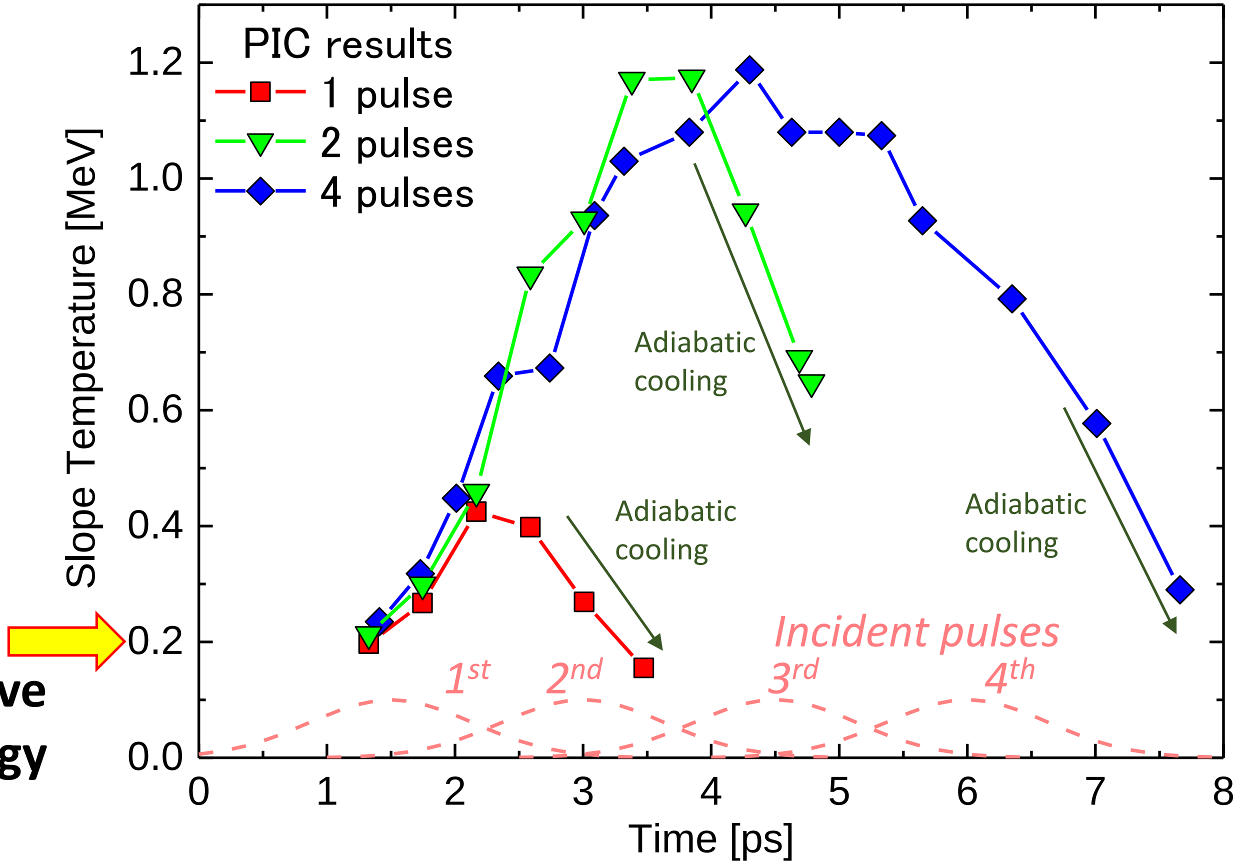
Comparison btw experiment and simulation

Note ESM used here has no time resolution, we show the PIC results integrated over all the time domain.



1D PIC results quantitatively agree with the experiments

Time evolution of the electron temperature by 1D PIC



Ponderomotive energy

The electron temperature for 3 ps (2 pulse train) is clearly exceeding the conventional scaling low (0.2 MeV).

Mechanism underlying the electron heating

PIC simulation shows that electrons are heated during recirculating the target.

2-pulse train (3 ps FWHM)

N. Iwata et al.,
PoP 24, 073111 (2017)

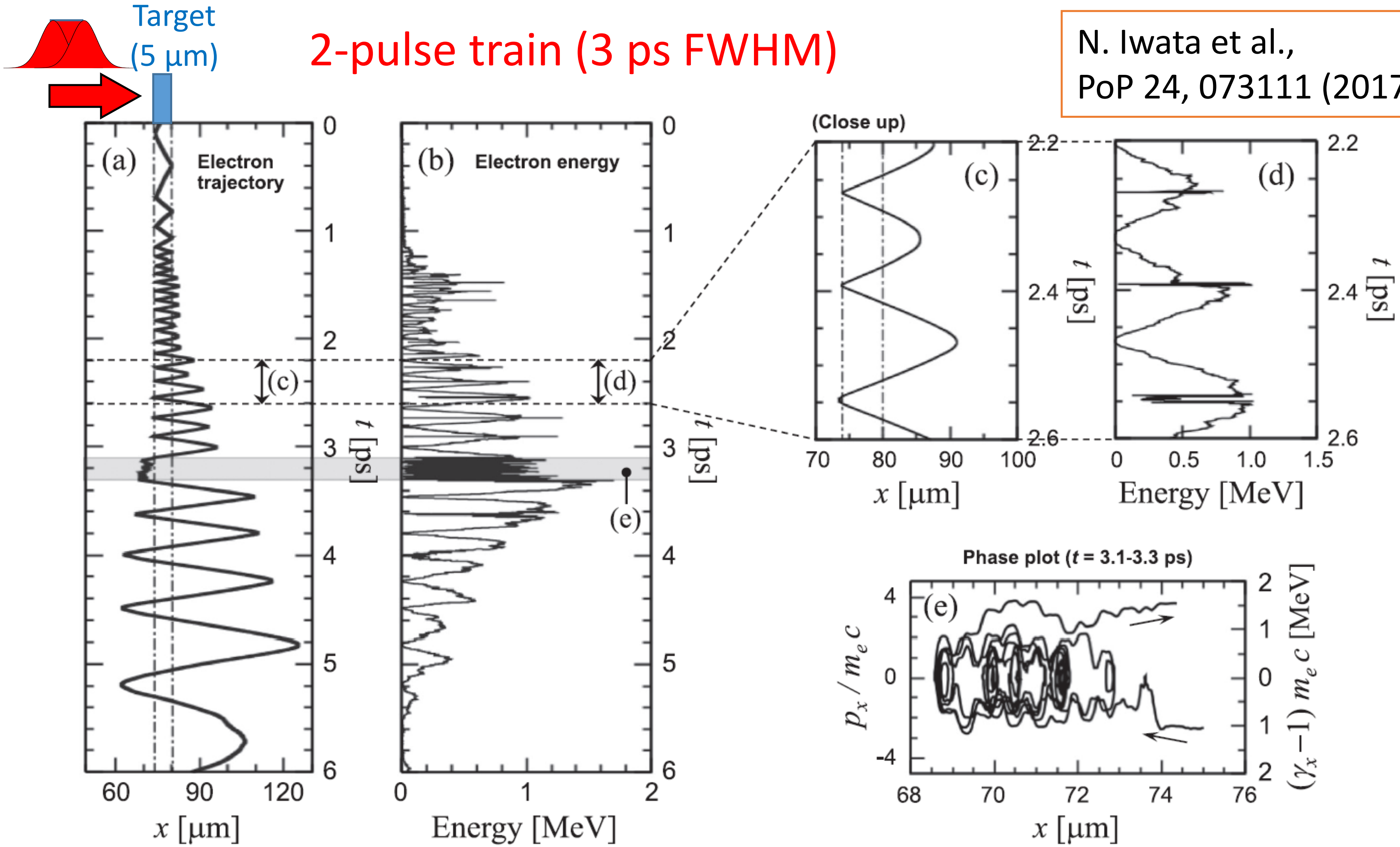


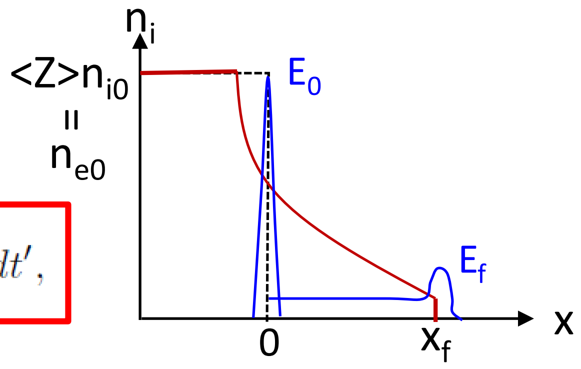
FIG. 4. PIC results for the 2 pulse case. (a) Trajectory of the same selected electron shown in Fig. 3(f). The thin dashed-dotted lines at $x = 74$ μm and 80 μm represent the initial positions of front and rear surfaces. (b) Energy of the same electron in (a). Trajectory in (a) and energy in (b) for time $t = 2.2$ ps–2.6 ps are closed up in (c) and (d), respectively. (e) Phase plot of the same electron in (a) for time $t = 3.1$ ps–3.3 ps.

We introduce the time-dependent temperature into 1D plasma expansion model, based on self-similar solutions.

$$n_e = n_{e0}\exp\left(e\phi/T(t)\right),$$
$$\epsilon_0\partial_x^2\phi = e(n_e - Zn_i),$$
$$\partial_t n_i + \partial_x(n_i v_i) = 0,$$
$$\partial_t v_i + v_i\partial_x v_i = -Ze\partial_x\phi/m_i,$$

We newly introduce time dependency onto the self-similar variable

$$\boxed{\xi = \frac{x}{R(t)}, \quad R(t) = \int_0^t c_s(t')dt',}$$



Ion acoustic velocity depending on time

Self-similar solution of the electric field

$$e\phi = -T(t)(\xi+1)$$
$$E_{ss} = -\partial_x\phi = T(t)/eR(t).$$

Electric field on the ion front Assumed by Mora

$$\boxed{E_f(t) \simeq 2E_{ss} = \frac{2T(t)}{eR(t)}.}$$

Ponderomotive energy

Norimarization $\tau = \omega_{pi0}t/\sqrt{2e_N}, \quad \bar{c_s}^2(\tau) = T(\tau)/T_0.$

Ion velocity at the front $v = 2c_{s0}\int \frac{\bar{c_s}^2(\tau)}{\sqrt{1+R^2(\tau)}}d\tau,$ $\quad c_{s0} = \sqrt{ZT_0/m_i}$

Ion kinetic energy

$$\boxed{\mathcal{E} \simeq \frac{1}{2}m_i v^2 = 2T_0\left[\int \frac{\bar{c_s}^2(\tau)}{\sqrt{1+R^2(\tau)}}d\tau\right]^2}$$

1D plasma expansion model for time-dependent temperature

Evaluating time dependency of temperature

Case 1. $T(\tau) = T_0 = const.$

Mora's isothermal model

$$\overline{C_s} = 1, \quad \frac{dR}{d\tau} = 1, \quad R = \tau \quad \Rightarrow \quad v = 2C_{s0}\ln\left(\tau + \sqrt{1+\tau^2}\right)$$

P. Mora Phys. Rev. Lett. **90**, 185002 (2003)

Case 2 (our case) $T(\tau)$ depends on time.

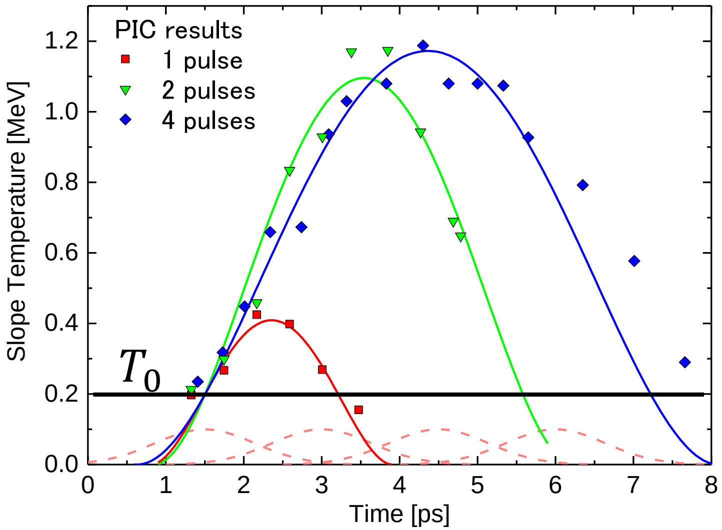
We derive the time dependency from the 1D PIC results, by assuming the following formula on `normalized acoustic velocity'.

$$\overline{C_s}^2 = \frac{T(\tau)}{T_0} = \left[1 + \alpha - \alpha(1 - \tau/\tau_0)^2\right]^2$$

α: degree of heating, $\alpha = 0 \rightarrow T(\tau) = T_0$

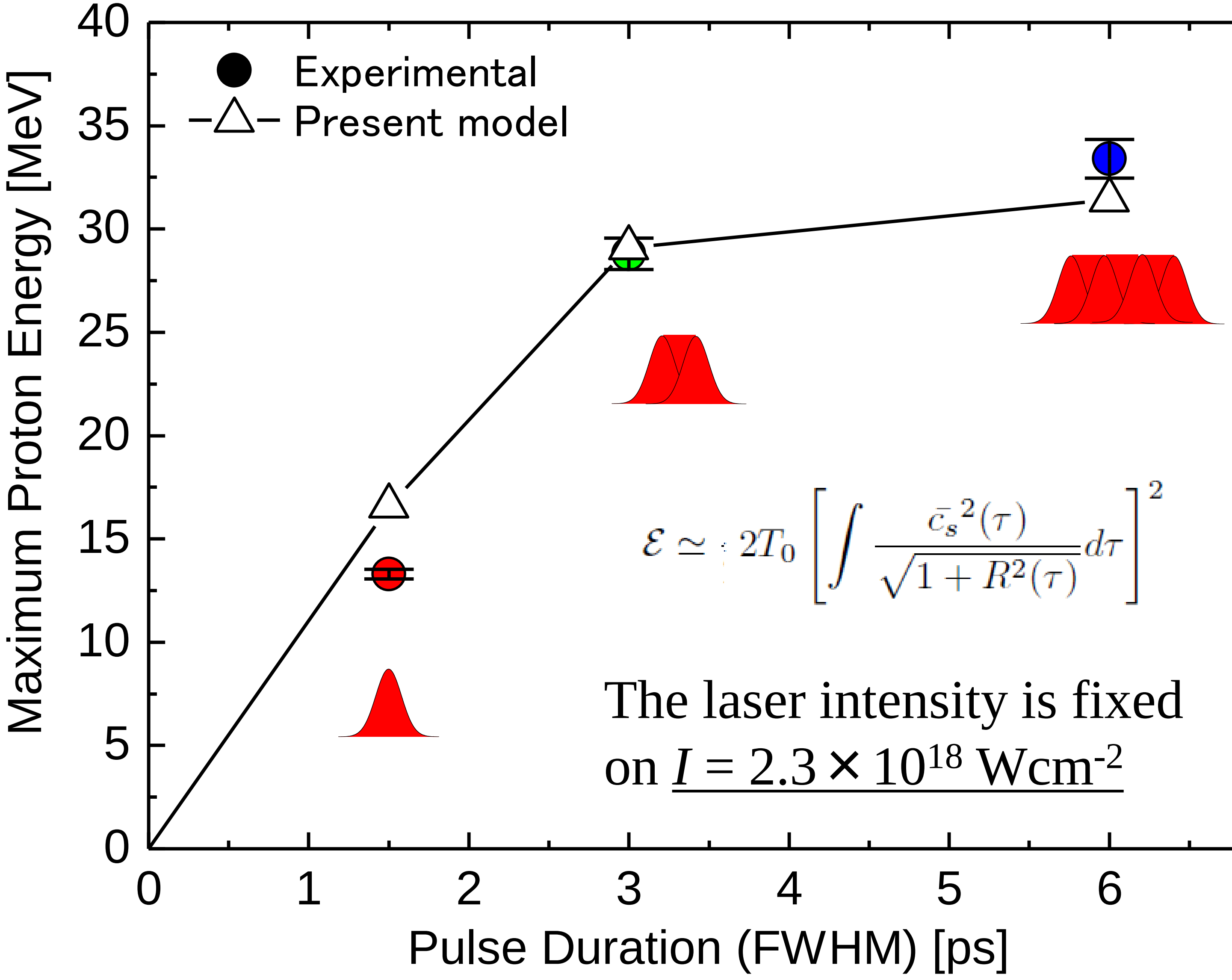
τ_0: characteristic time that cooling starts.

We determine α and τ_0 by fitting the PIC results.



Maximum proton is analytically reproduced.

We find a fairly well agreement with the experiments.



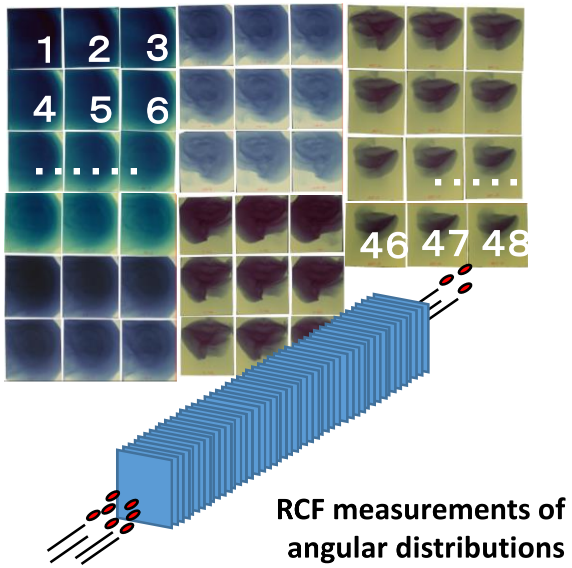
$$\mathcal{E} \simeq 2T_0 \left[\int \frac{\bar{c_s}^2(\tau)}{\sqrt{1+R^2(\tau)}} d\tau \right]^2$$

The laser intensity is fixed on $I = 2.3 \times 10^{18}$ Wcm^{-2}

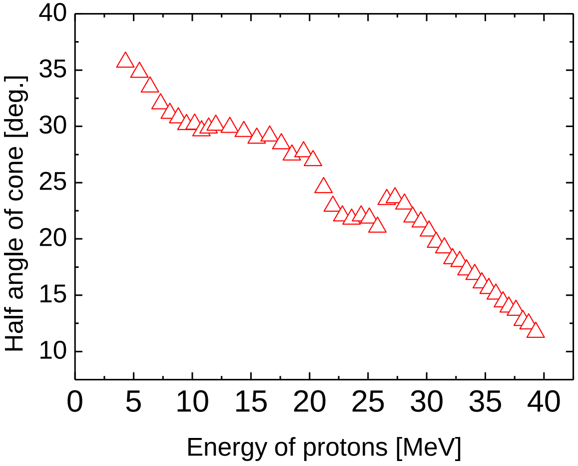
ILE OSAKA

Energy conversion efficiency into protons

5% efficiency is achieved with 10^{18} Wcm^{-2} intensity.

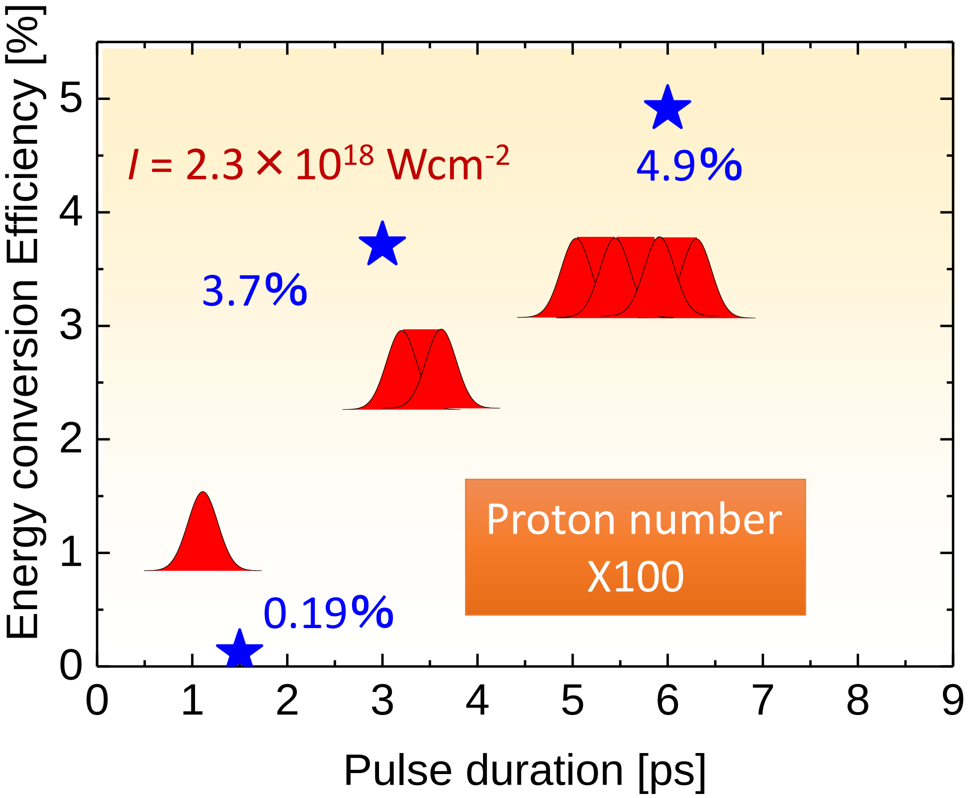


RCF measurements of angular distributions



Courtesy of Dr. Morace

ILE OSAKA



Longer pulse also improve the conversion efficiency.

- Fusion Fast Ignition driven by laser
- Laser-driven neutron generation
- Hadron therapy by laser

Conclusion

The high-contrast kilo-Joule picosecond laser allows to generate 1D (planner) expanding plasma experimentally.

We have clarified "time-dependent electron heating" that accelerates electrons beyond the ponderomotive energy depending on time.

We have found an optimum pulse duration for proton acceleration around 3-6 ps for $2.3 \mathrm{X} 10^{18}$ Wcm^{-2} intensity, when the Max energy and the Conv. Eff. increase up to 30 MeV and 5%, respectively.

The experimental results on the electron temperature and proton energy are quantitatively in agreement with our 1D analytical model.

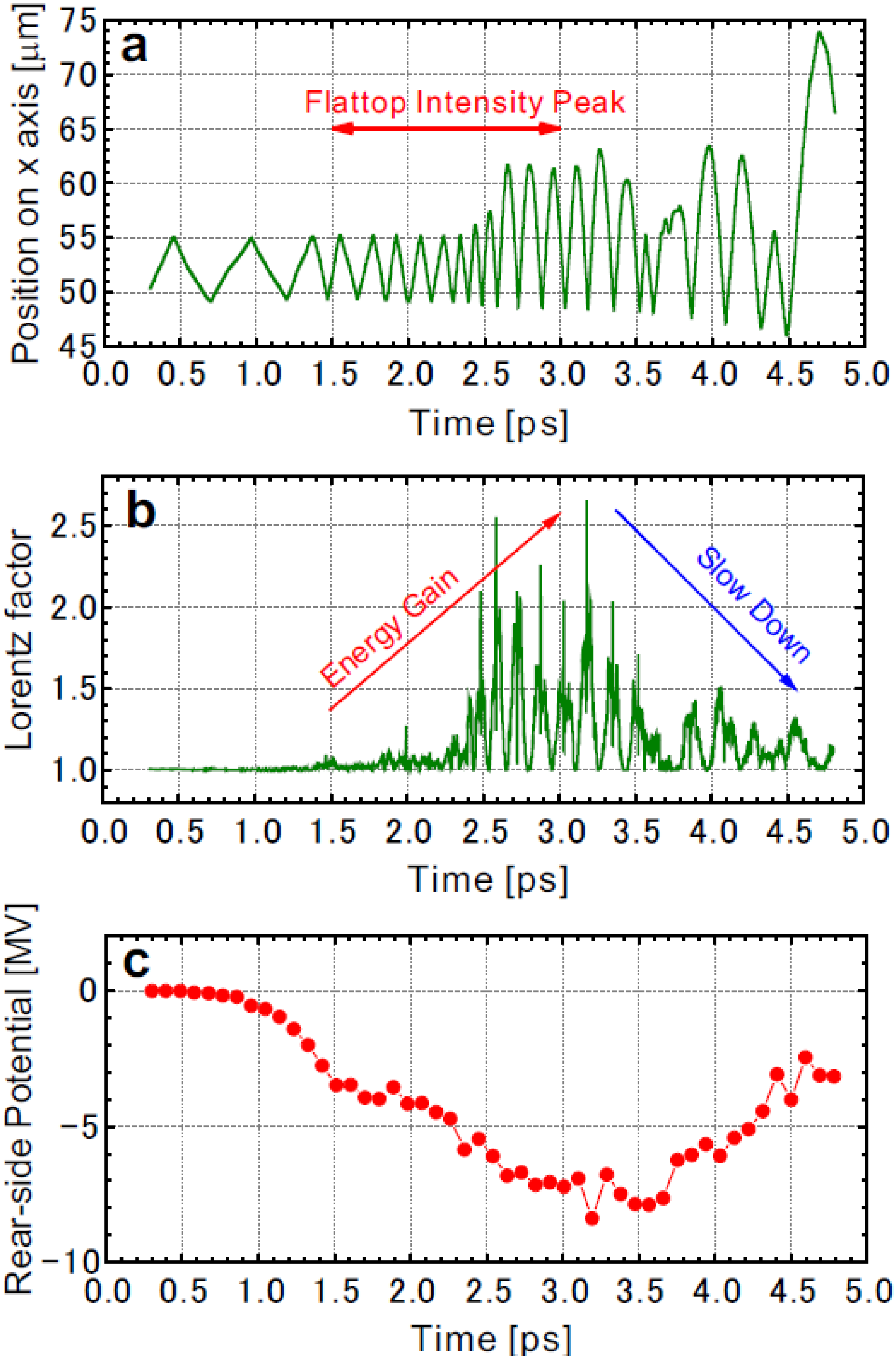


FIG. 3. (a) Trace of typical electron trajectory in the 1D PIC simulation. The target foil is initially at the position $x = 50$-$55\ \mu\text{m}$ and the laser (2-pulse train) is incident on the surface at $x = 50\ \mu\text{m}$. (b) Time evolution of the Lorentz factor of the electron shown in (a).