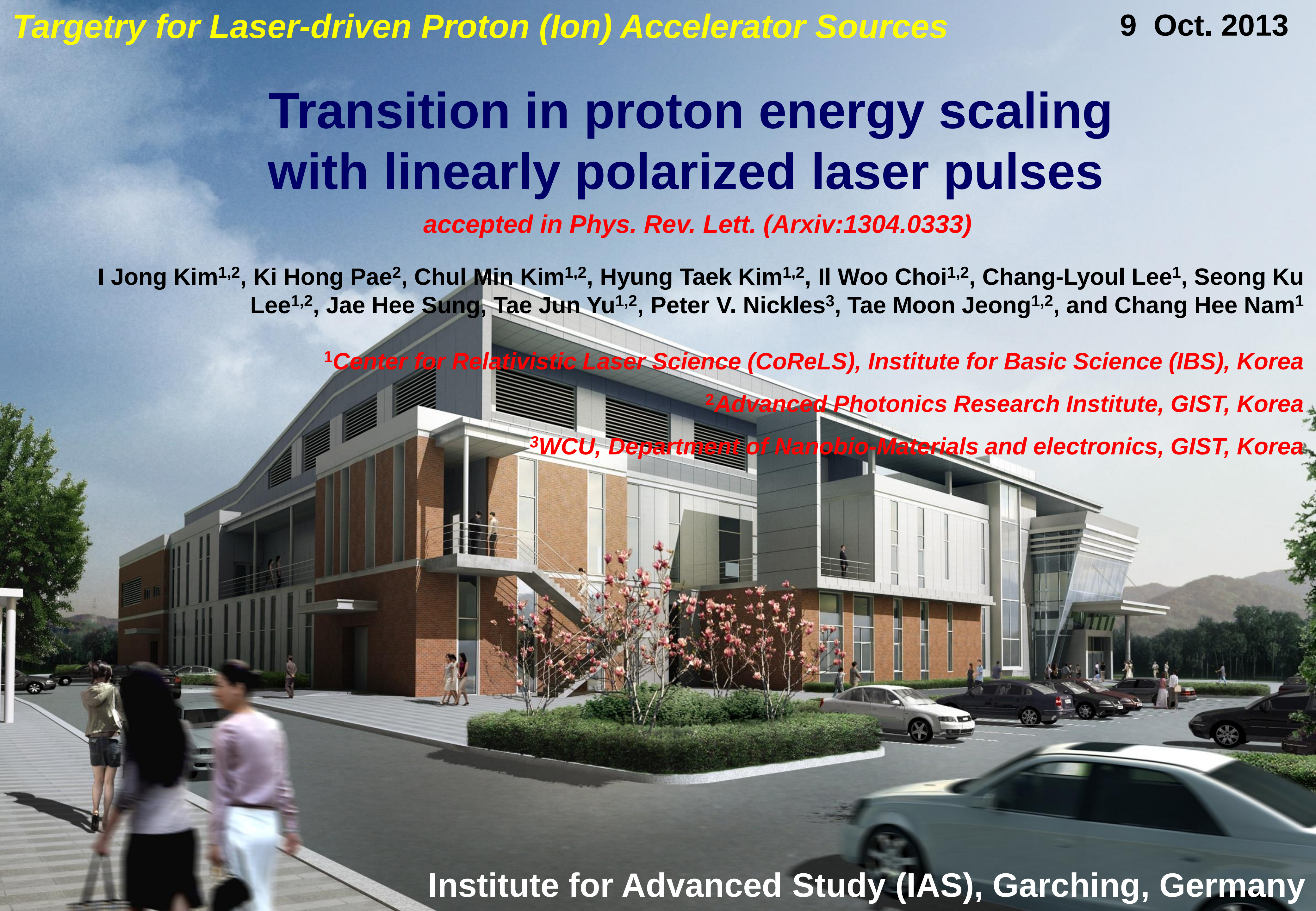

Transition in proton energy scaling with linearly polarized laser pulses

accepted in Phys. Rev. Lett. (Arxiv:1304.0333)

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[1]Center for Relativistic Laser Science (CoReLS), Institute for Basic Science (IBS), Korea

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Institute for Advanced Study (IAS), Garching, Germany

Contents

I. Proton/ion acceleration mechanism

- TNSA & thermal electrons
- RPA & collective electrons

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- Double plasma mirror
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- Diagnostics (Thomson parabola)

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- Transition of proton energy scaling from $I^{1/2}$ to I^{1}
- Quasi-monoenergetic peaks in the C^{6+} ion

IV. 3D PIC simulation

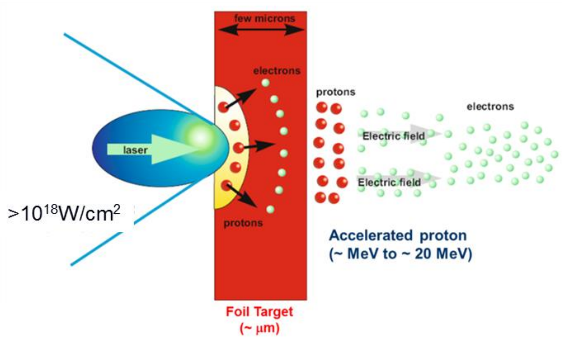
- Temporal evolutions of number density of electron and proton
- Phase space distribution
- Temporal evolution of the longitudinal electrostatic field

V. Conclusion

Mechanism of proton/ion acceleration

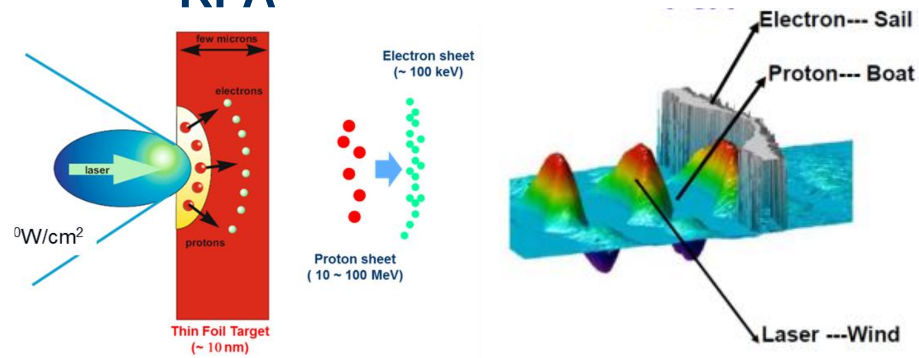
Mechanism of proton/ion acceleration

TNSA



Proton acceleration by electro-static field

RPA



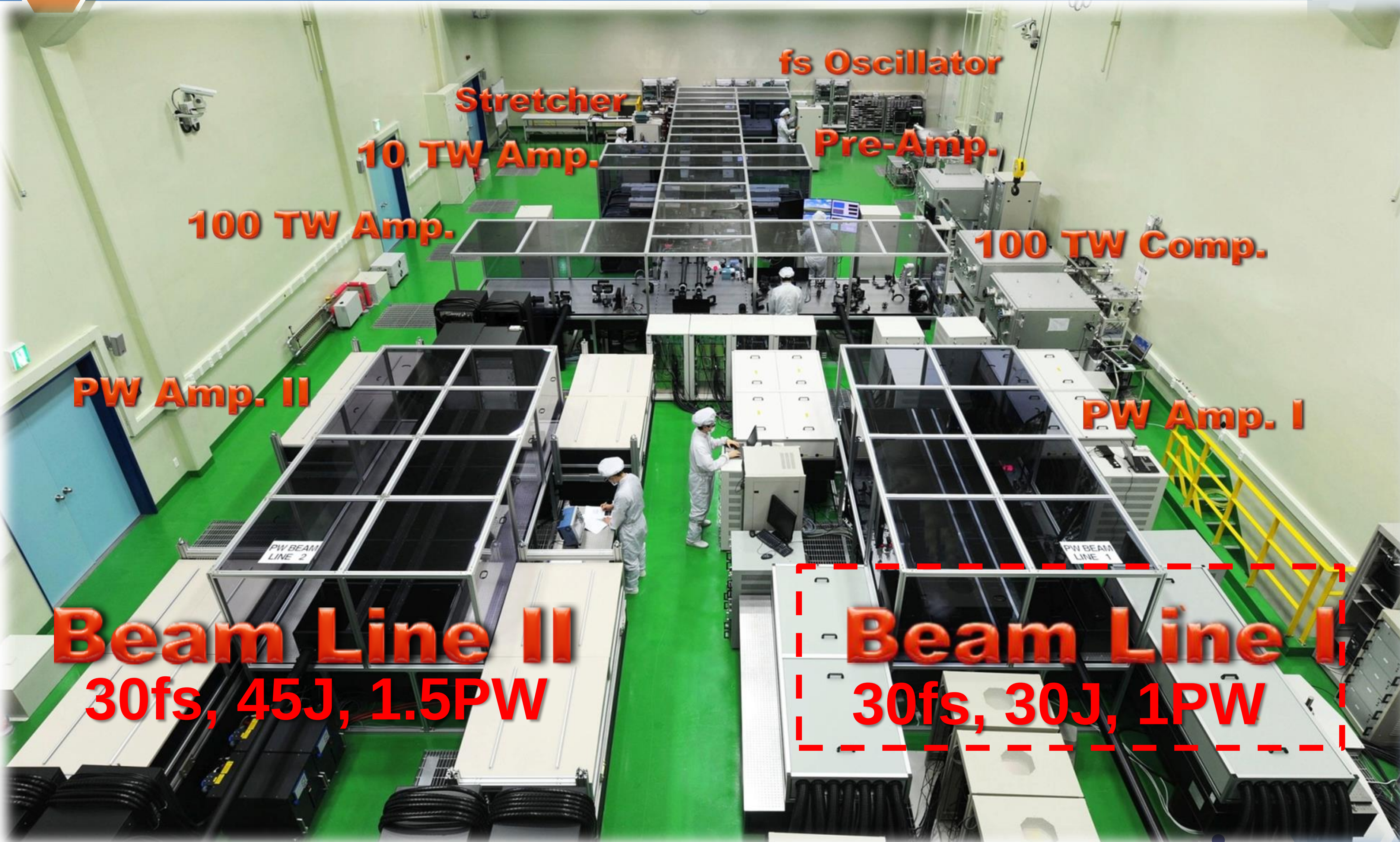
Balance between electro-static field and ponderomotive force

Acceleration mechanism	Laser	Target thickness	Characteristics of proton-ion spectrum	Electron energy distribution	Energy scaling
TNSA	I>10^{18}W/cm^2 Linear pol.	~ μm	**Continuous**	High-temperature, Broad **thermal electrons**	$E_{ion} \approx I^{1/2}$
RPA	I>10^{20} W/cm^2 Linear pol. Circular pol.	~ 10nm	**Quasi-monoenergetic**	Low-temperature, Narrow **collective electrons**	$E_{ion} \approx I^{1}$

Experimental realization !!!

Experimental set up

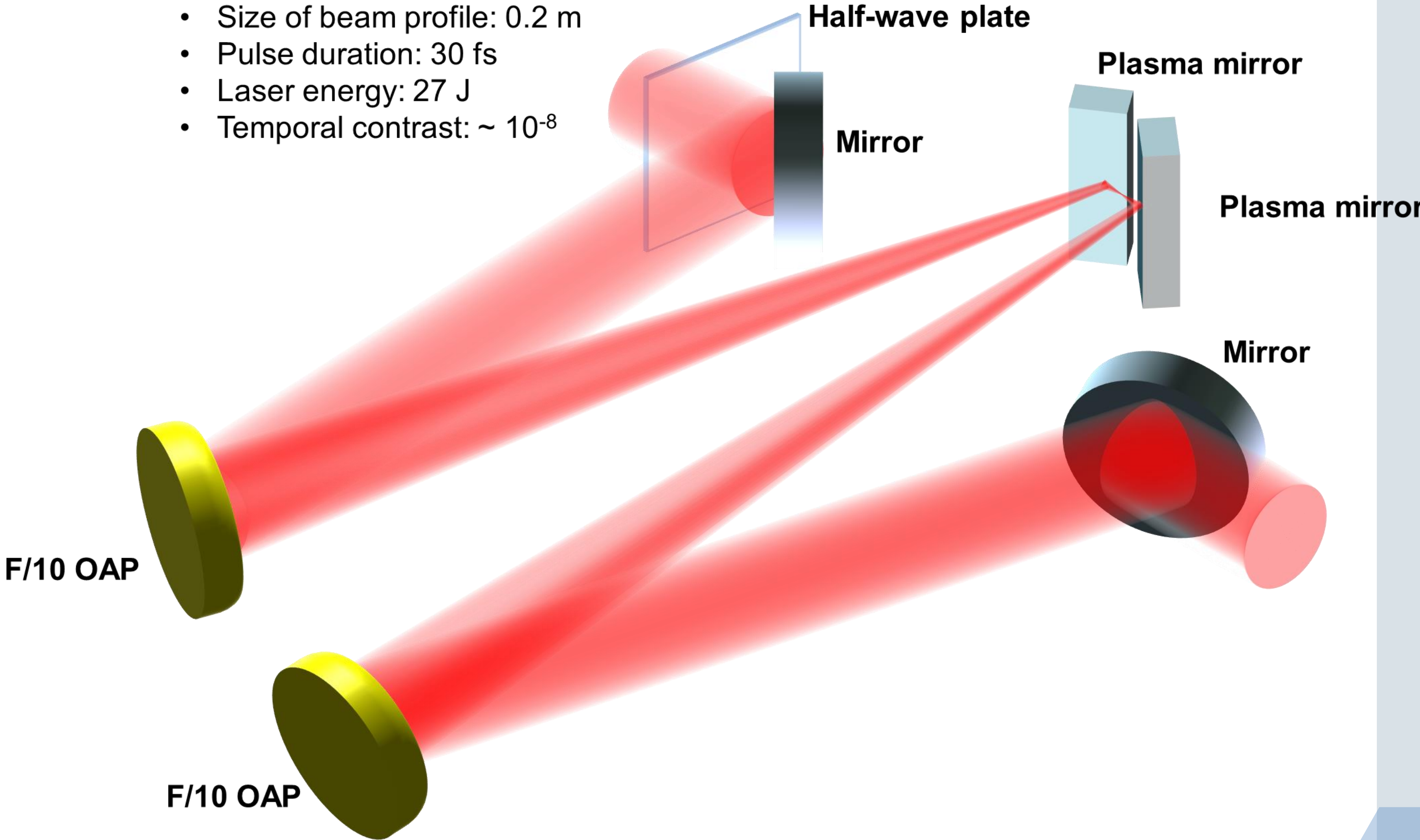
PW Ti:Sapphire Laser (PULSER)



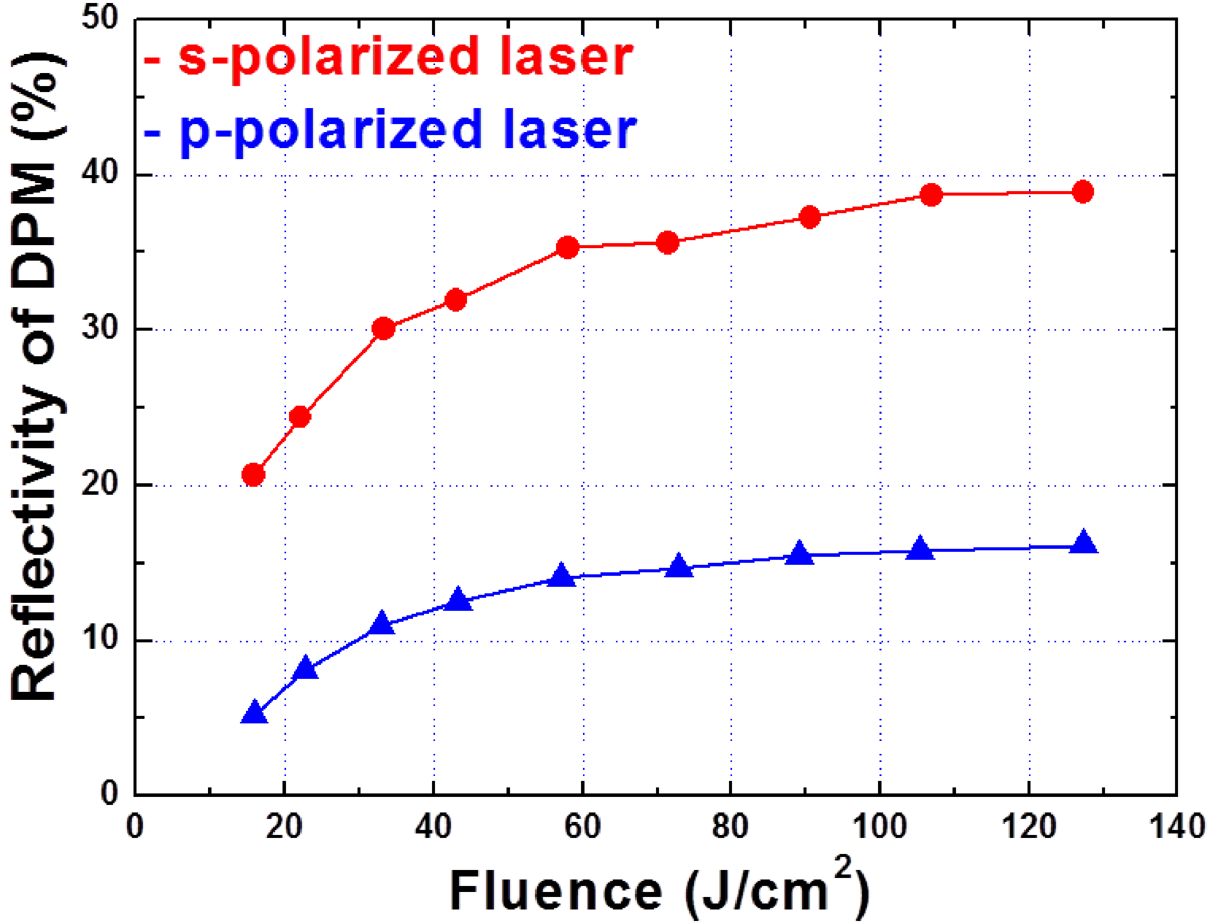
Configuration of PW double plasma mirror system

PW laser beam after pulse compressor

- Size of beam profile: 0.2 m
- Pulse duration: 30 fs
- Laser energy: 27 J
- Temporal contrast: ~ 10^{-8}



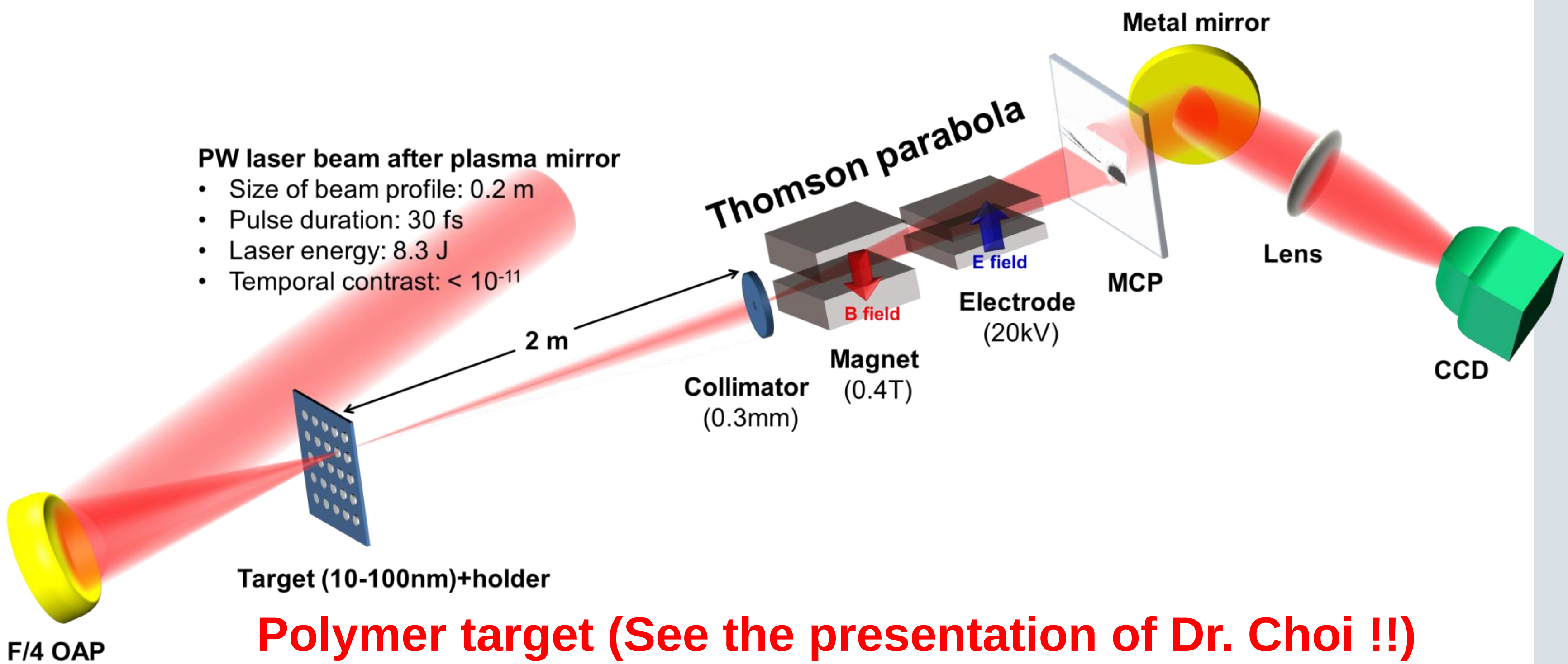
Reflectivity of double plasma mirror



T: Transmittance
HW: Half-wave plate
R: Reflectivity
DPM: Double plasma mirror

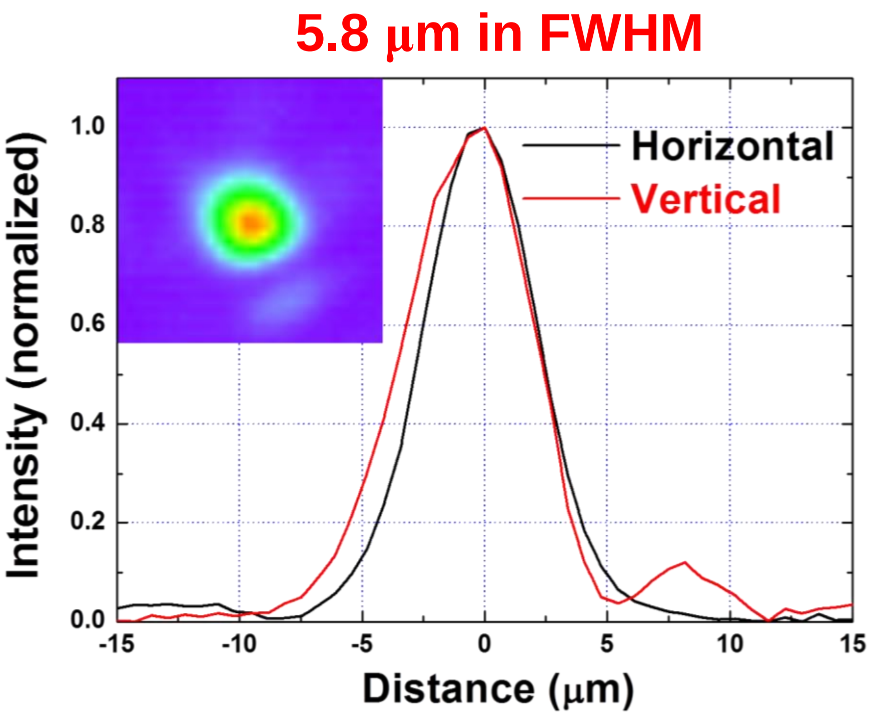
Total reflectivity of DPM system: 32 % (T of HW: 82 %, R of DPM: 39%)

Target and Thomson parabola

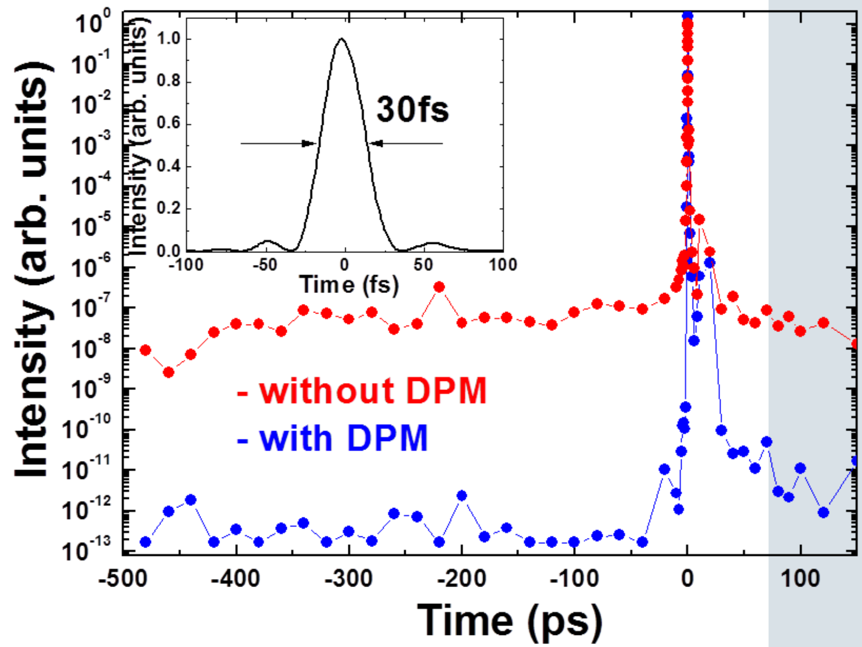


Polymer target (See the presentation of Dr. Choi !!)

Spatio-temporal profiles of laser beams



Spatial beam profiles of a focused laser after F/4 OAP. The inset shows the focused image of laser beam

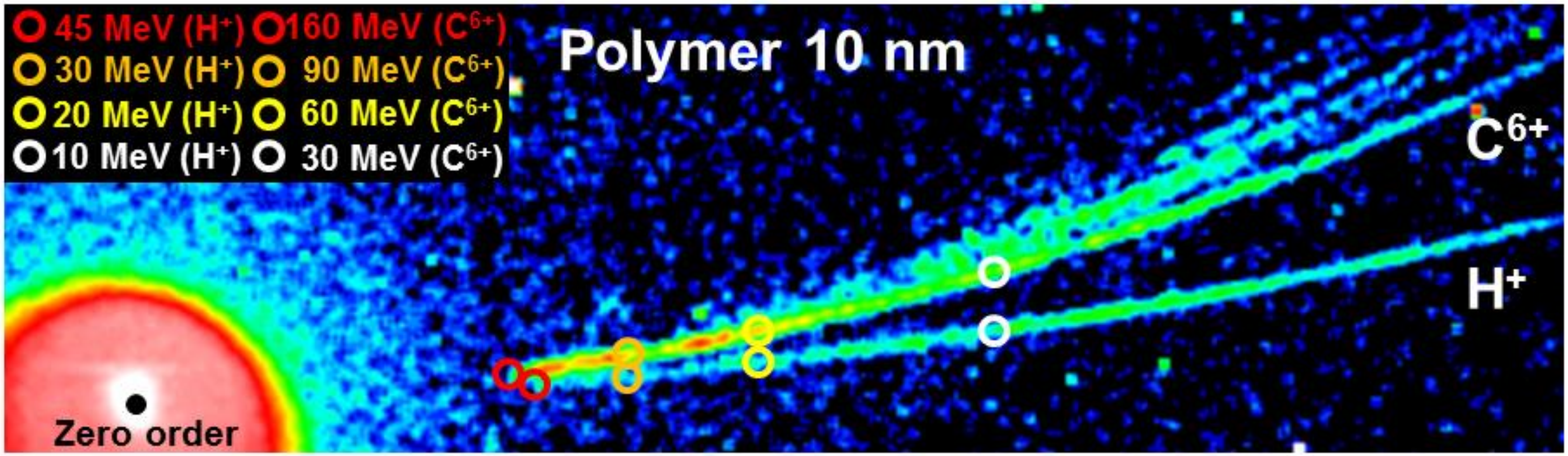


Temporal profiles of the laser beam between -500 ps and +150 ps is obtained by third-order cross correlator. The inset shows the temporal profiles measured with SPIDER.

Experimental result

Proton and C^{6+} energy measured from the Thomson parabola

Achieve 45 MeV proton energy using real time TP !

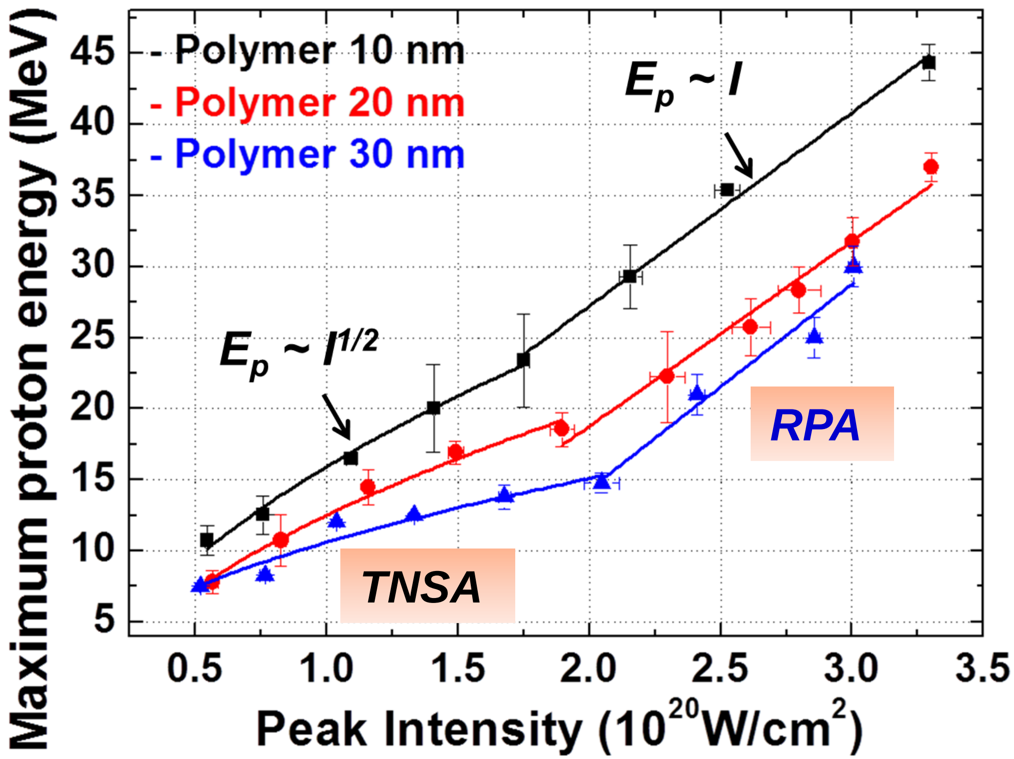


Energy spectra of the protons and carbon ions obtained from a **10-nm-thick polymer target** irradiated by a laser pulse with an intensity of **3.3×10^{20} W/cm^2**.

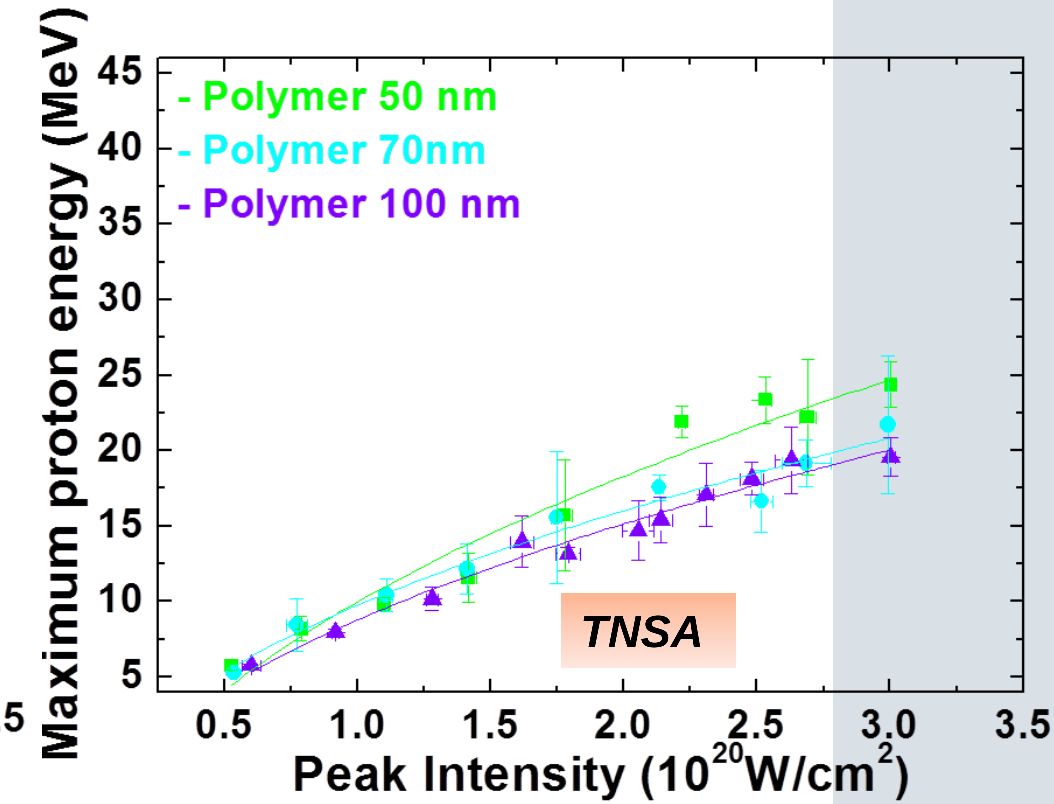
The proton energy is one of the highest value obtained with several tens of femtosecond high-power laser systems.

Maximum proton energy as a function of the laser intensity

Transition of proton energy scaling from $I^{1/2}$ to I^{1} !



Maximum proton energy for 10-, 20-, and 30-nm-thick polymer target



Maximum proton energy for 50-, 70-, and 100-nm-thick polymer target

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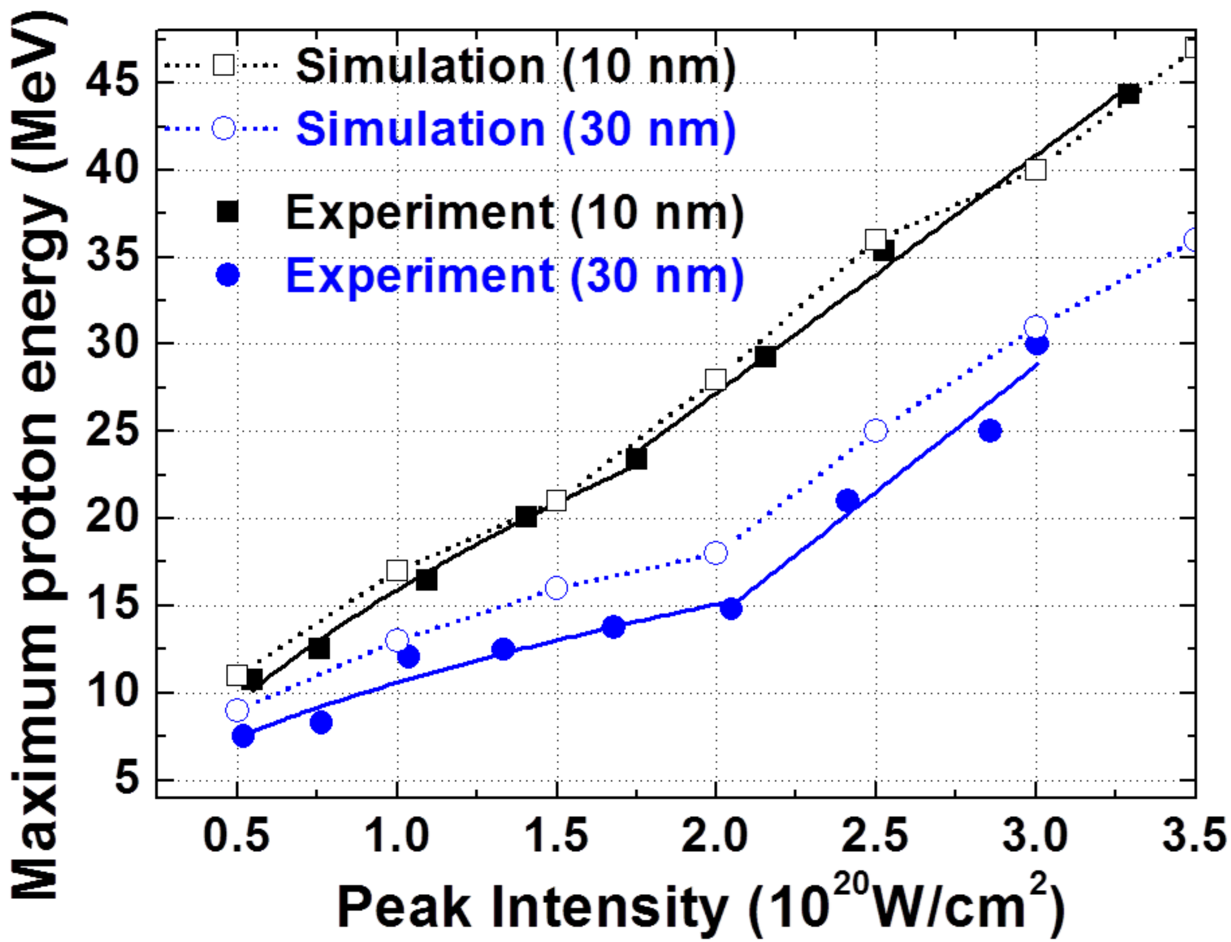
Comparison between the simulation and experimental results

The experimental energy scaling agrees well with the PIC simulation results !



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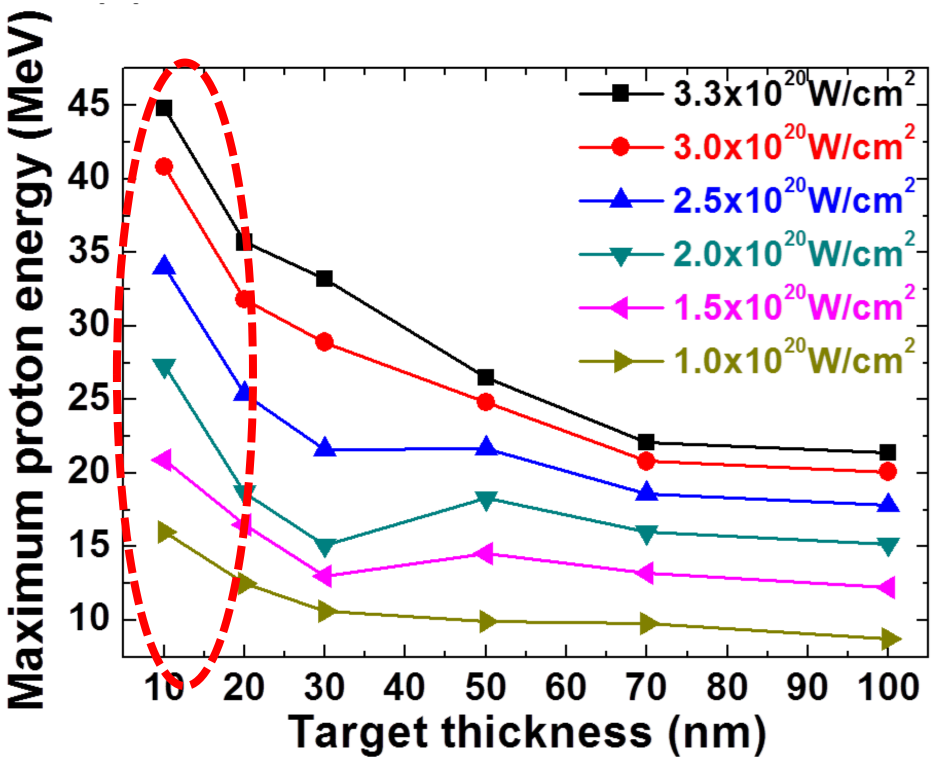
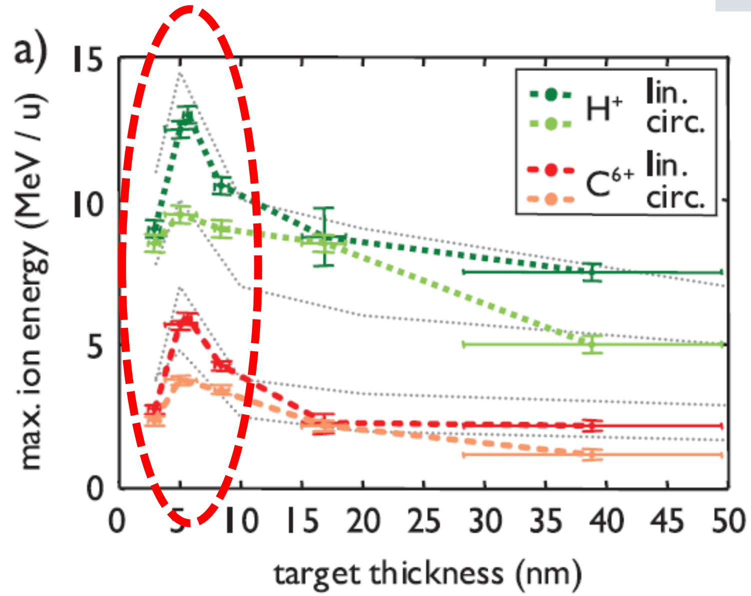
Thickness dependence on the maximum proton energy

The maximum proton energy generally increases as the target thickness decreases !



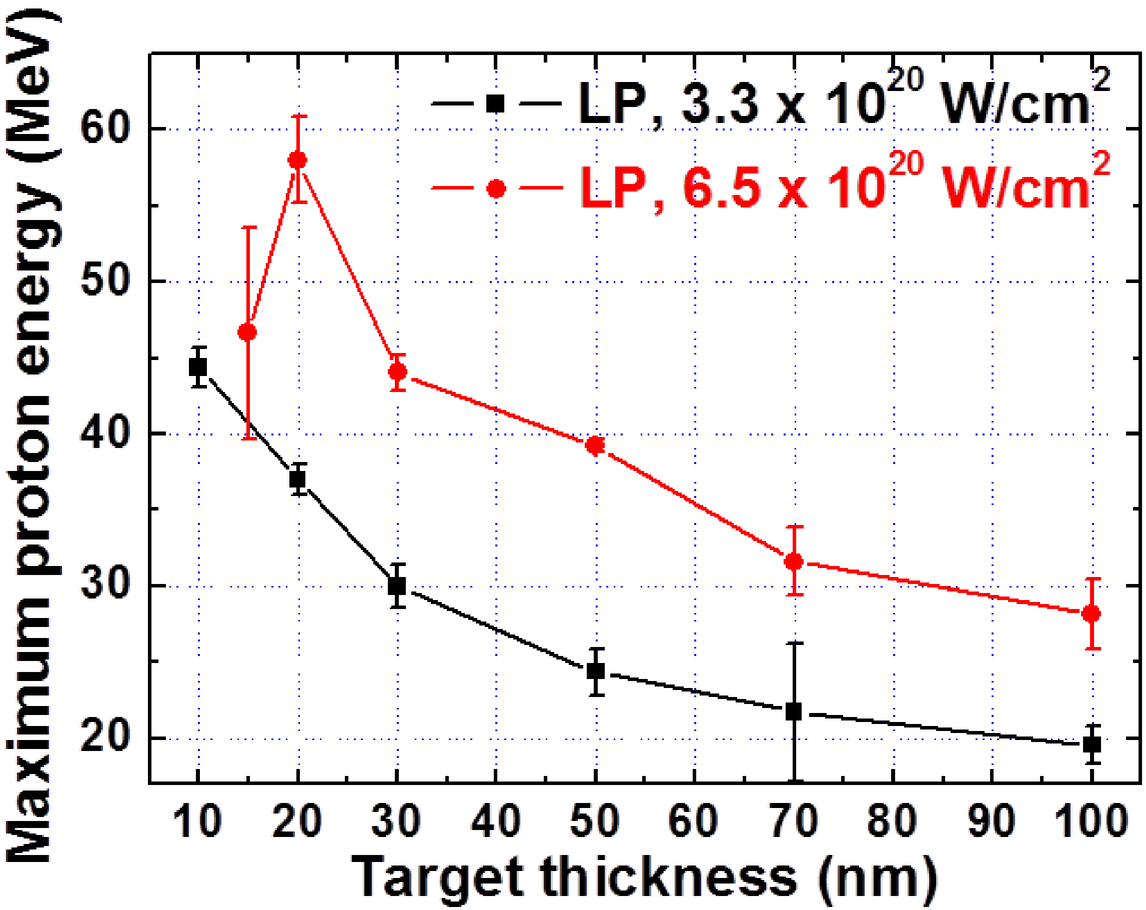
The calculated optimum target thickness for F8BT

-> 15.8 nm (from $a_0 \sim \pi\sigma = \pi \frac{d}{\lambda}\frac{n_e}{n_c}$)



A. Henig *et al.* PRL, 103, 245003 (2009)

Optimum target thickness



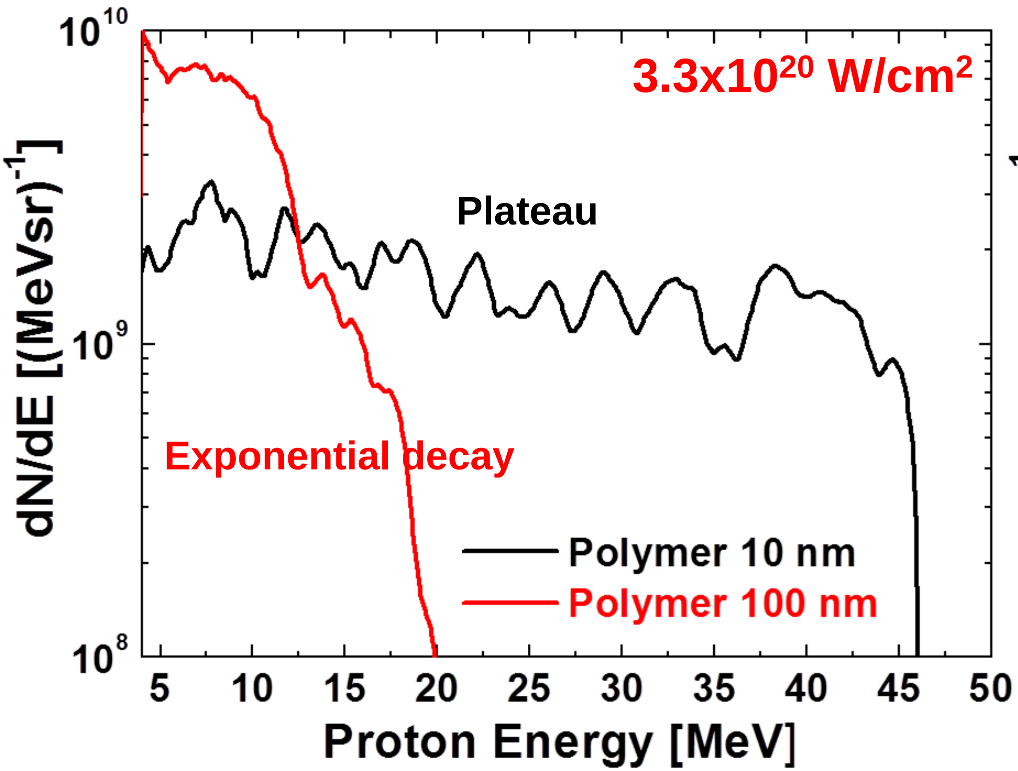
the maximum proton energy at I = 6.5×10^{20} W/cm^2

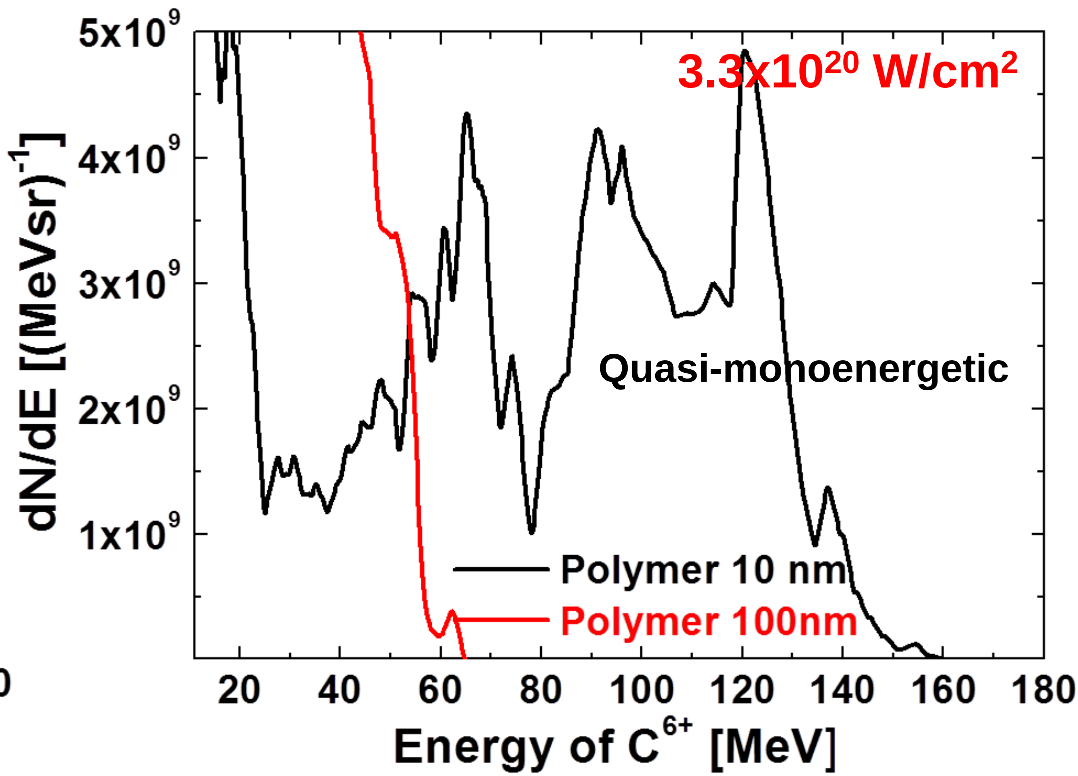
-> 58 MeV at a thickness of 20 nm

It is close to the optimal thickness of 22 nm obtained with the relation of $a_0 \sim \pi\sigma$.

Energy spectra of protons and C^{6+} ions

Quasimonoenergetic peaks in the C^{6+} ion spectrum !





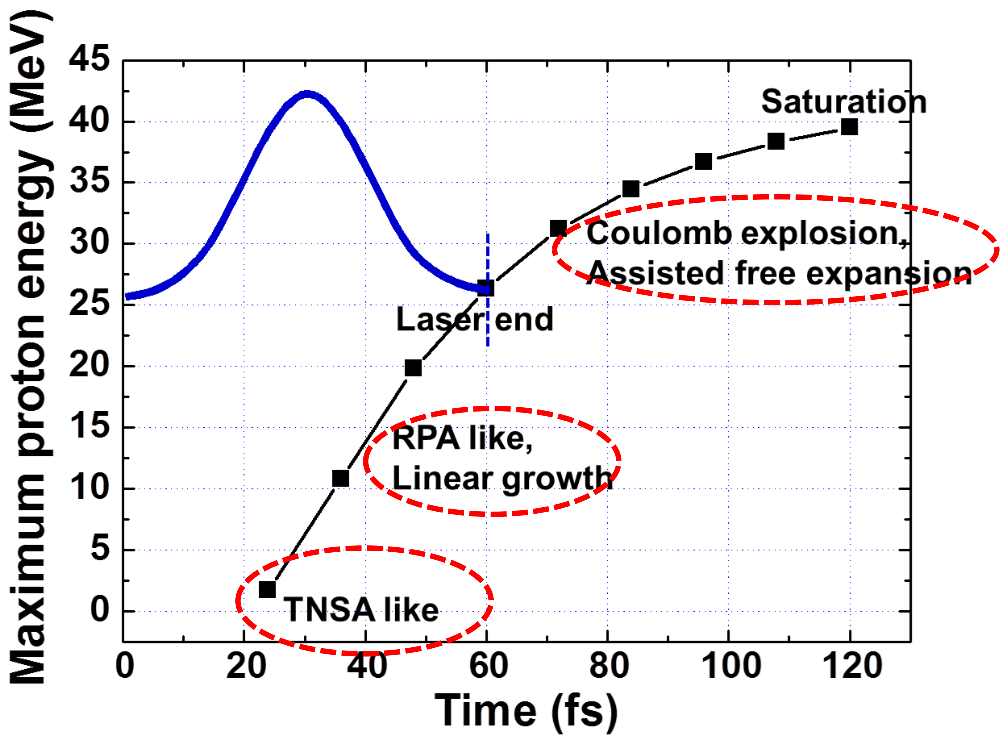
Proton energy spectrum obtained with an intensity of 3×10^{20} W/cm^2.

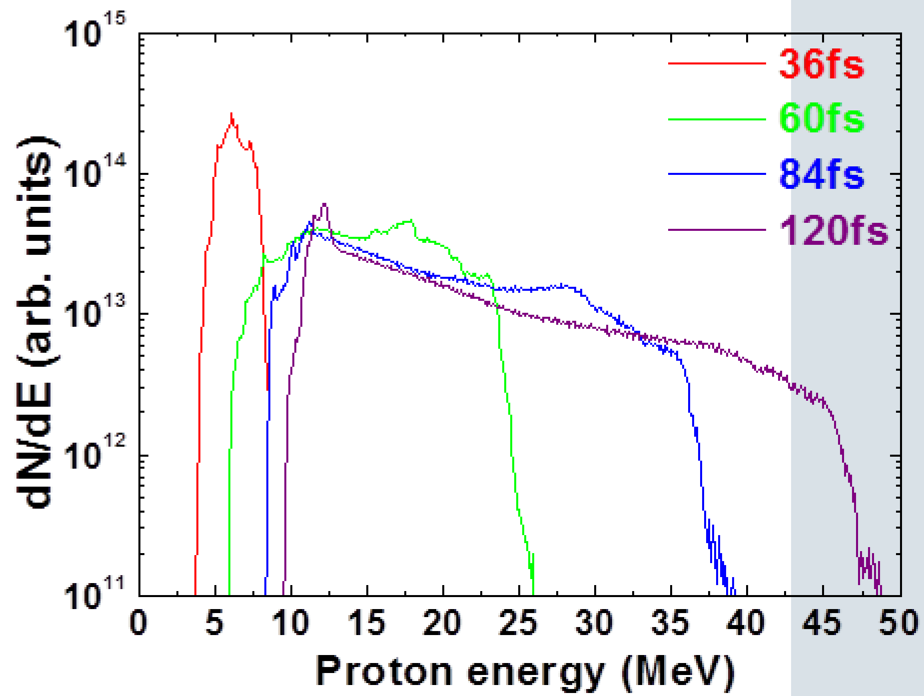
C^{6+} energy spectrum obtained with an intensity of 3×10^{20} W/cm^2.

3D PIC simulation

Temporal evolutions of maximum proton energy

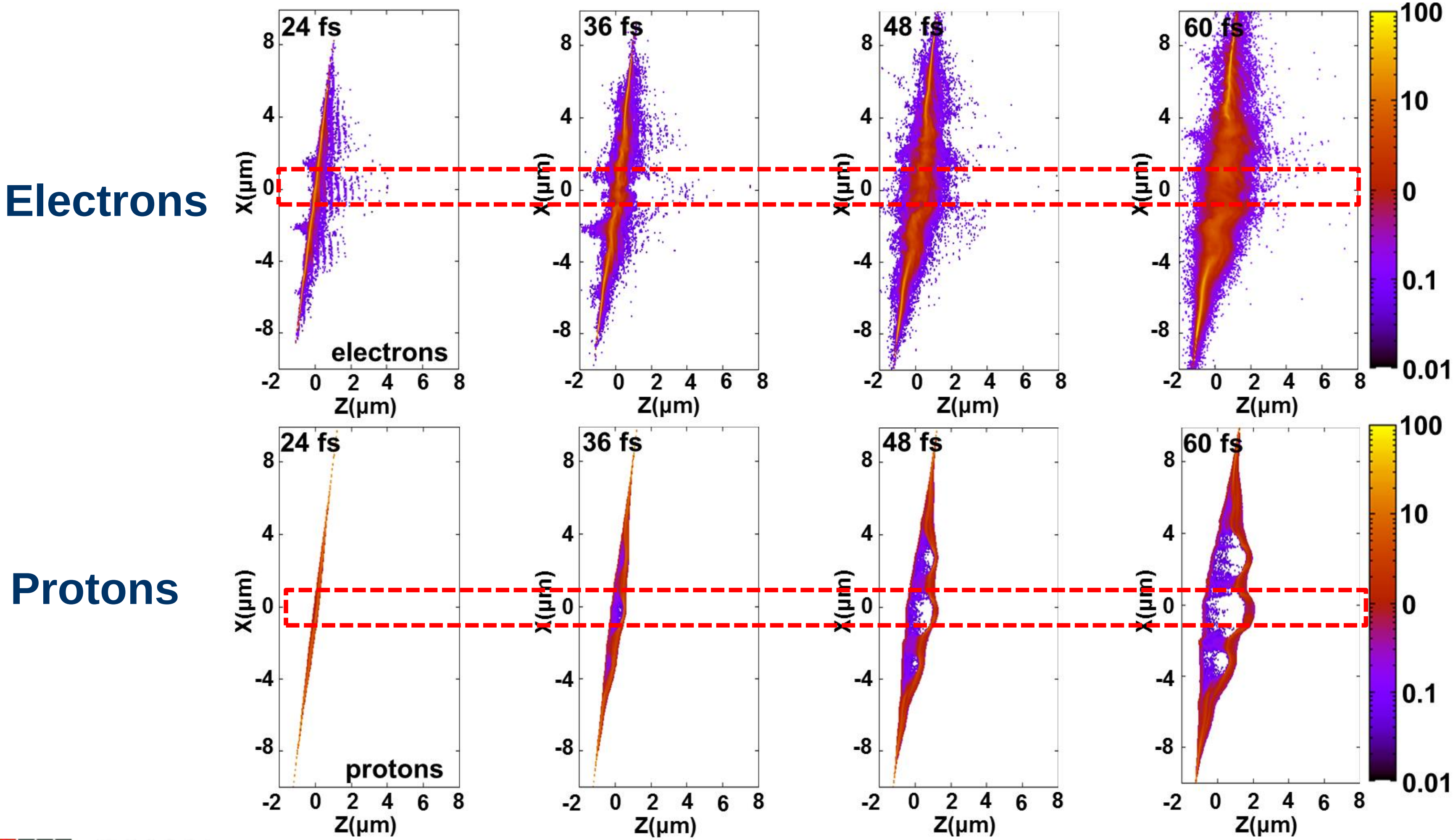
10-nm target, 3.0 x 10 ^{20} W/cm^{2}





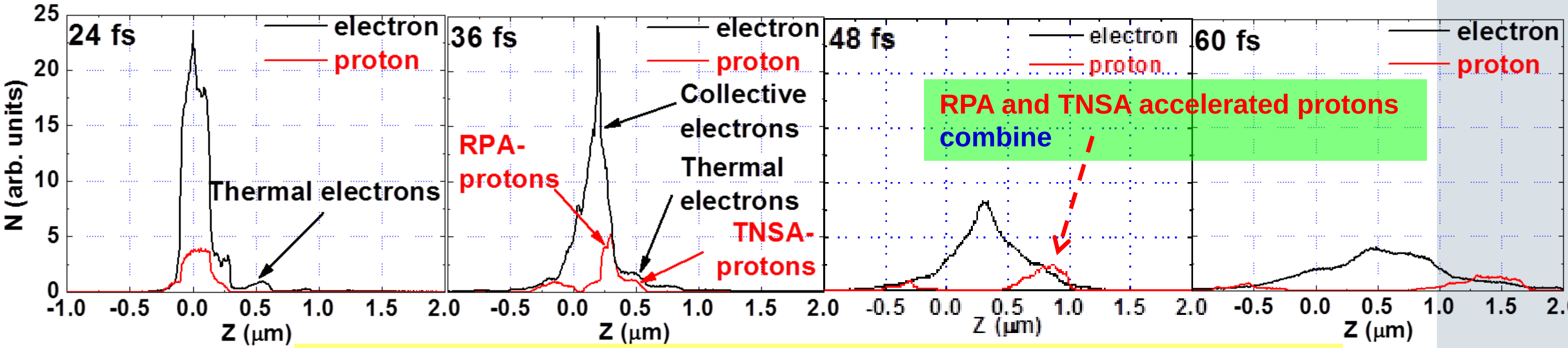
Temporal evolutions of number density (electrons and protons)

10-nm target, 3.0 x 10 ^{20} W/cm^{2}



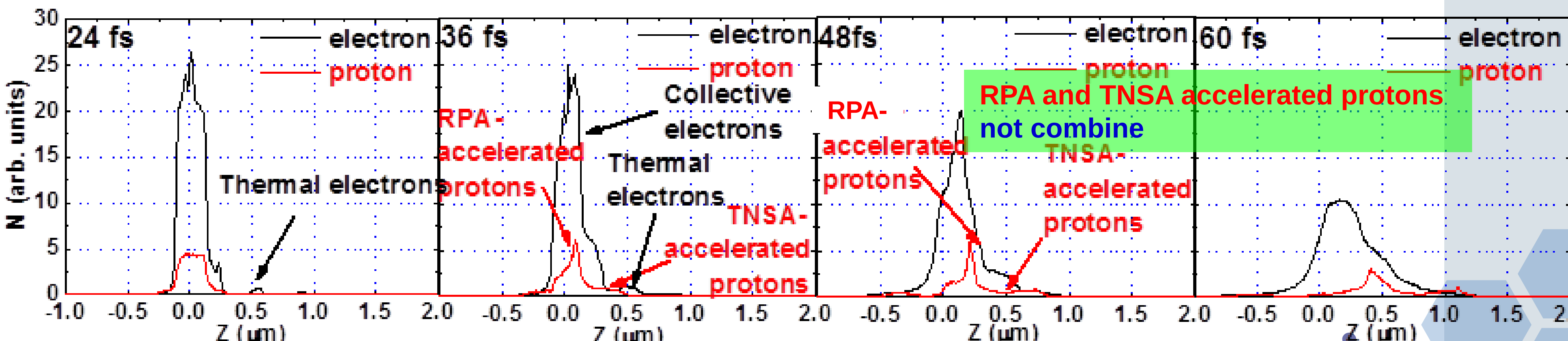
Temporal evolutions of number density line profile

10-nm target, 3.0 x 10 ^{20} W/cm^{2}



Thermal electrons -> Broad momentum distribution of protons (TNSA)
Collective electron -> Narrow momentum distribution of protons (RPA)

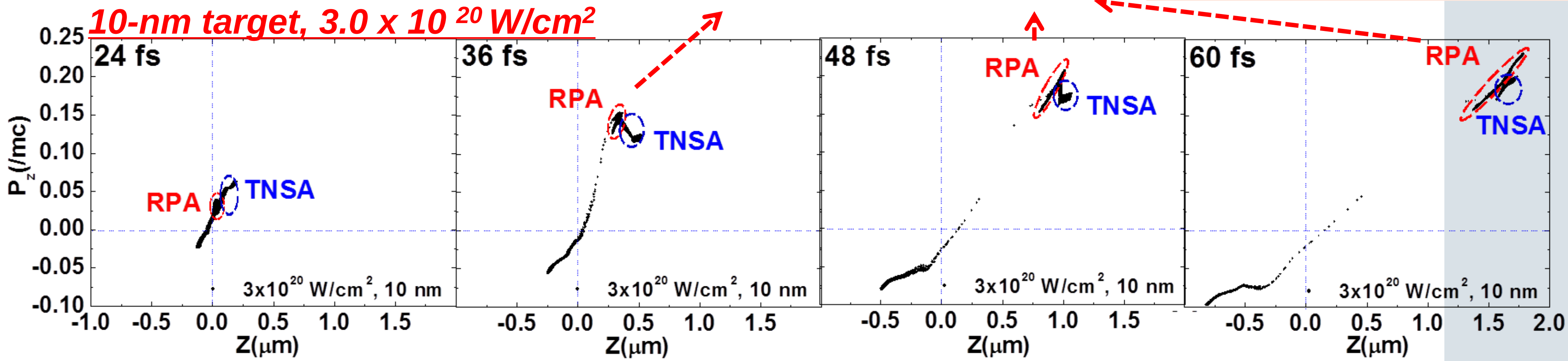
30-nm target, 1.0 x 10 ^{20} W/cm^{2}



Proton phase space distribution (in momentum space)

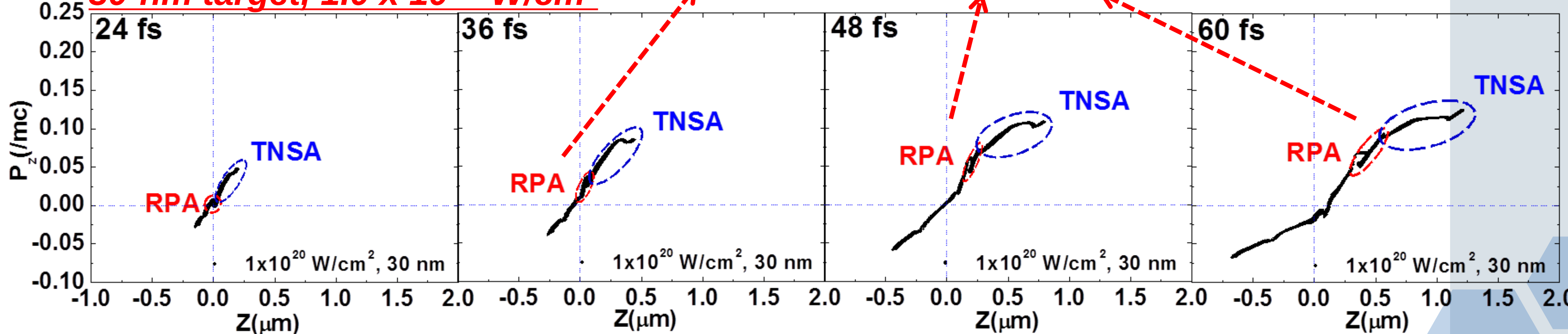
Protons accelerated by RPA are faster than those accelerated by TNSA → *Maximum proton energy is determined by RPA mechanism*

10-nm target, 3.0 x 10 ^{20} W/cm^2



Protons accelerated by RPA are lower than those accelerated by TNSA → *Maximum proton energy is determined by TNSA mechanism*

30-nm target, 1.0 x 10 ^{20} W/cm^2



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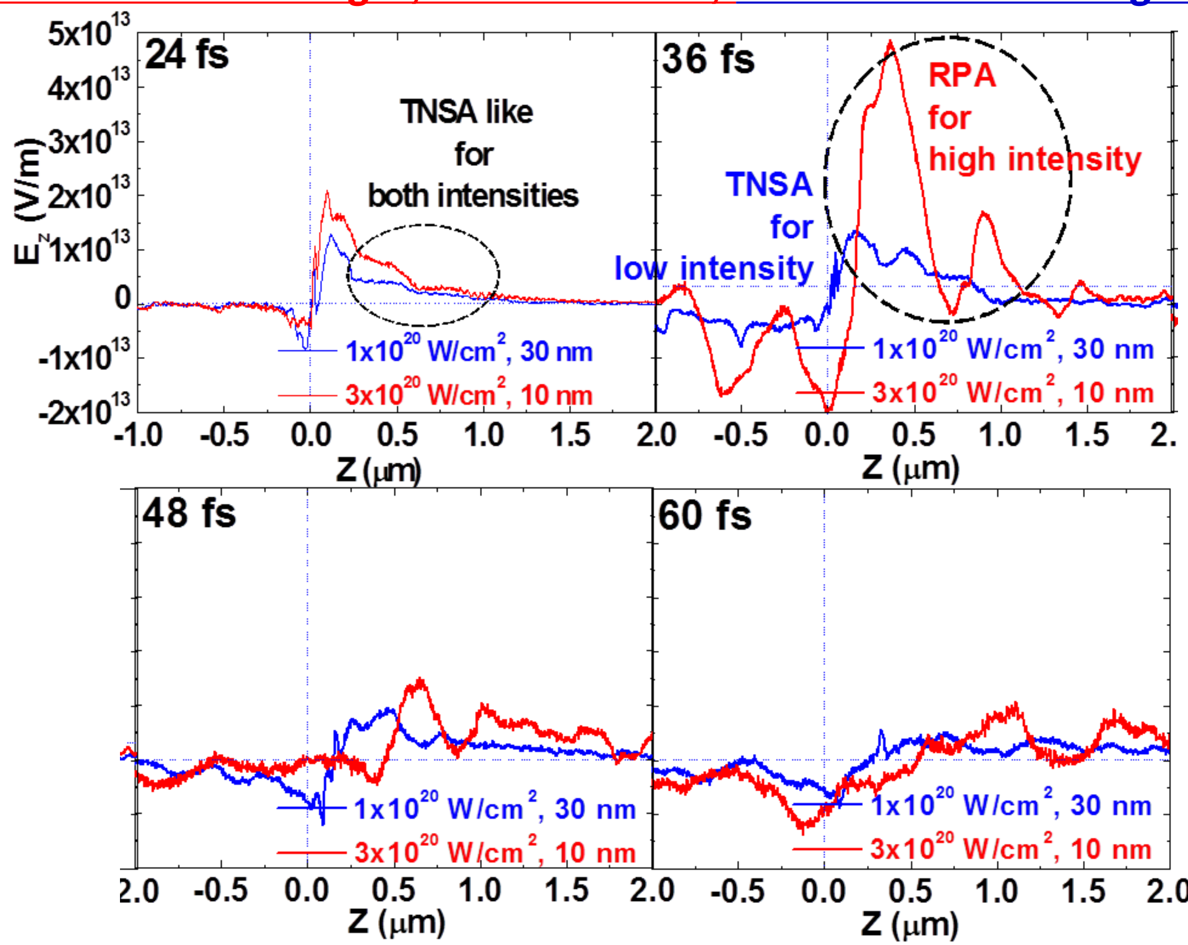
Temporal evolutions of longitudinal electrostatic field

Strong longitudinal electrostatic field for high intensity !

Red line: 10 nm target, $3x10^{20}$ W/cm^2 , Blue line: 30 nm target, $1x10^{20}$ W/cm^2



Thermal electrons:

1. Generation-> early stage of interaction

2. Effect -> whole interaction process

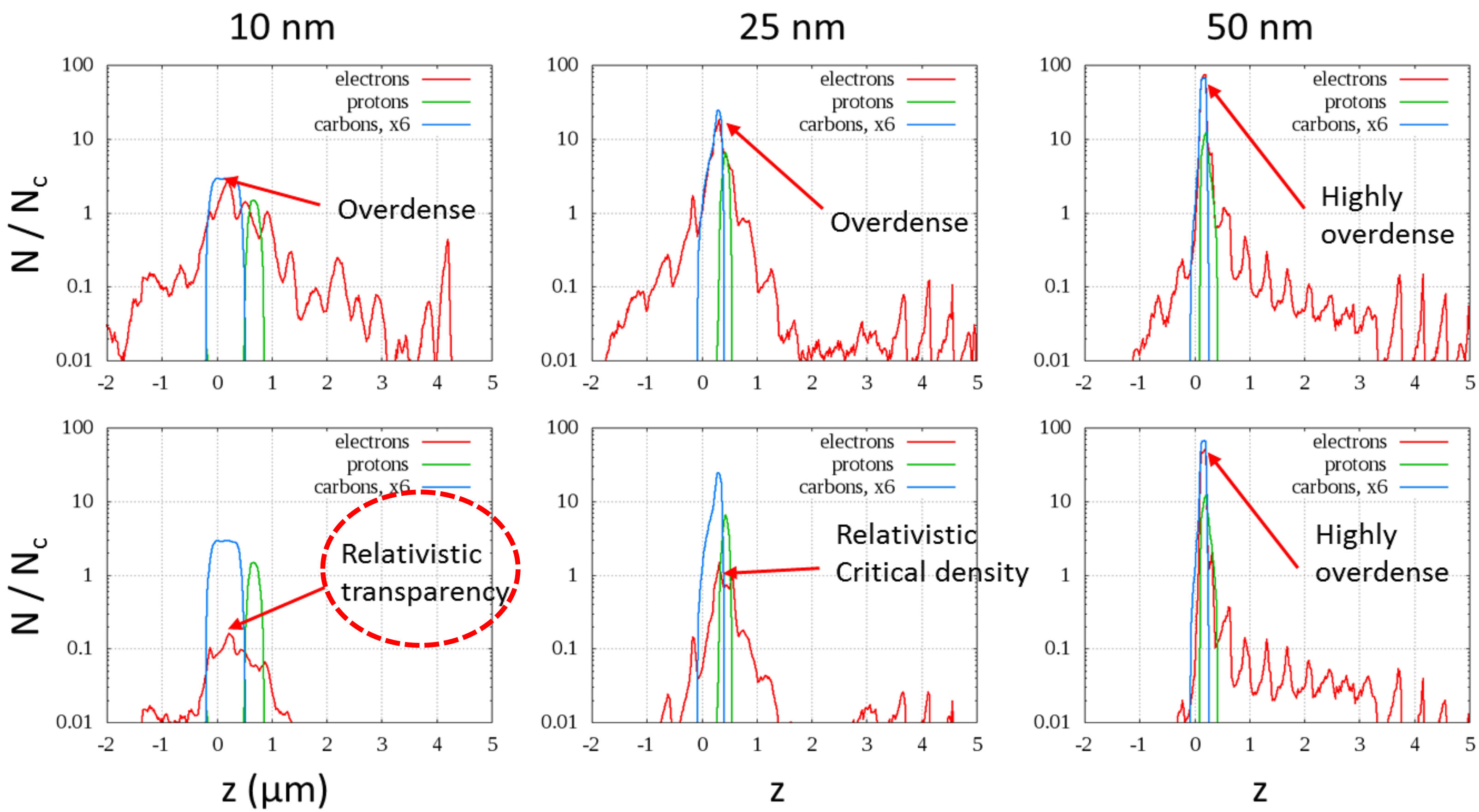
Collective electrons:

1. Generation -> high intensity part of laser pulse

2. Effect -> specific time period

Particle density distribution along the laser propagation direction

Upper part denotes nonrelativistic effect while lower part denotes relativistic effect



after the interaction of 40 fs at 2×10^{20} W/cm^2

Conclusion

1. The experiments performed with LP 30-fs, 1-PW laser pulses have produced maximum proton and C^{6+} ion energies of 45 MeV and 164 MeV, respectively, at a laser intensity of 3.3×10^{20} W/cm^2.

2. The change in the energy scaling obtained from a target with a thickness below 30 nm indicated a transition of the dominant acceleration mechanism (i.e., from TNSA to RPA) and a further acceleration by Coulomb explosion-assisted free expansion (in the post acceleration stage) was responsible for the maximum proton energy.

3. The 3D-PIC simulations gave a detailed understanding of the acceleration dynamics, and reproduced the spectra and the energy scaling that agreed well with the experimental results.

4. Assuming the validity of the measured linear scaling for the ultrathin polymer target, a proton energy of 190 MeV should be possible at an intensity of 1.5×10^{21} W/cm^2.

Thank you very much for your attention

This work was supported by the Ministry of Knowledge and Economy of Korea through the Ultrashort Quantum Beam Facility Program. And this work was supported by the Institute for Basic Science (IBS) in Korea. This work was also supported by Applications of Femto-Science to Nano/bio-Technology Utilizing Ultrashort Quantum Beam Facility through a grant provided by GIST. PVN acknowledges support of the World Class University program (R31-2008-000-10026-0) grant provided by National Research Foundation (NRF) of Korea.

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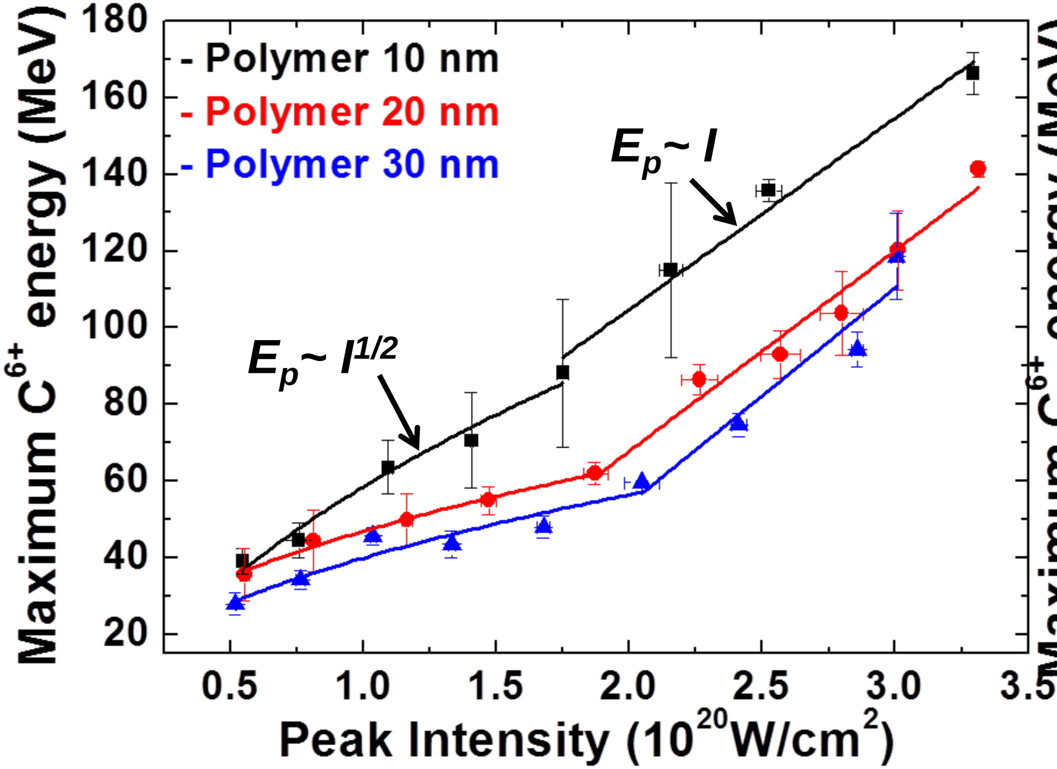
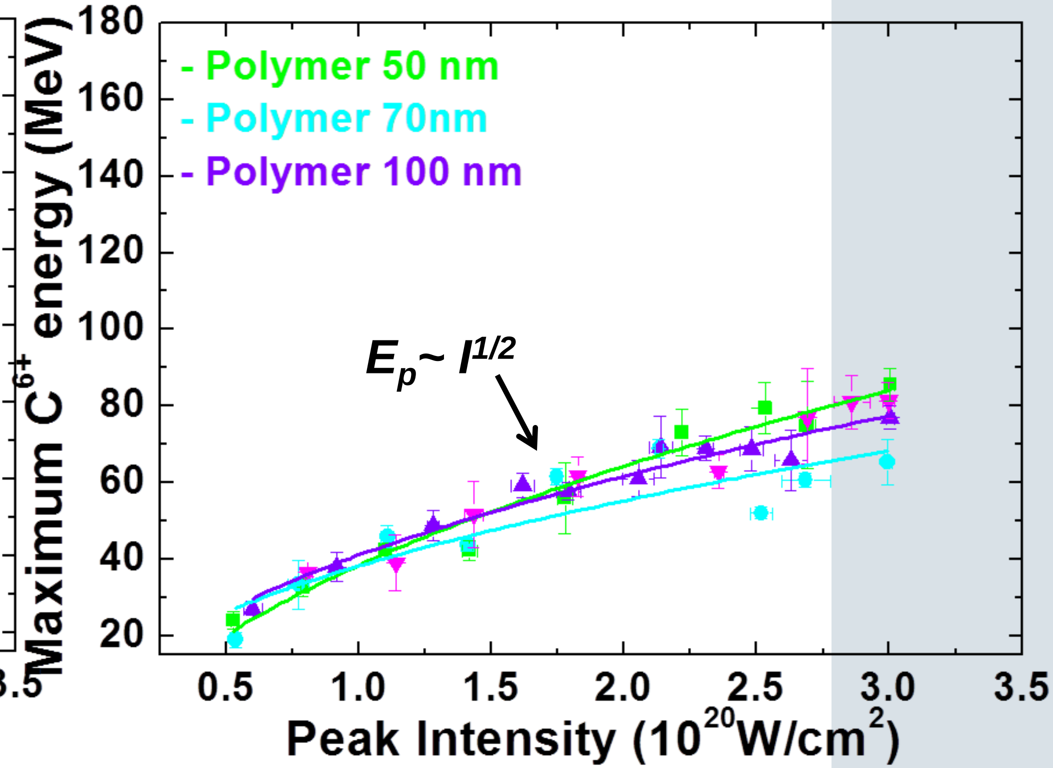
Maximum C^{6+} energy as a function of the laser intensity

Transition of proton energy scaling from $I^{1/2}$ to I^1 !



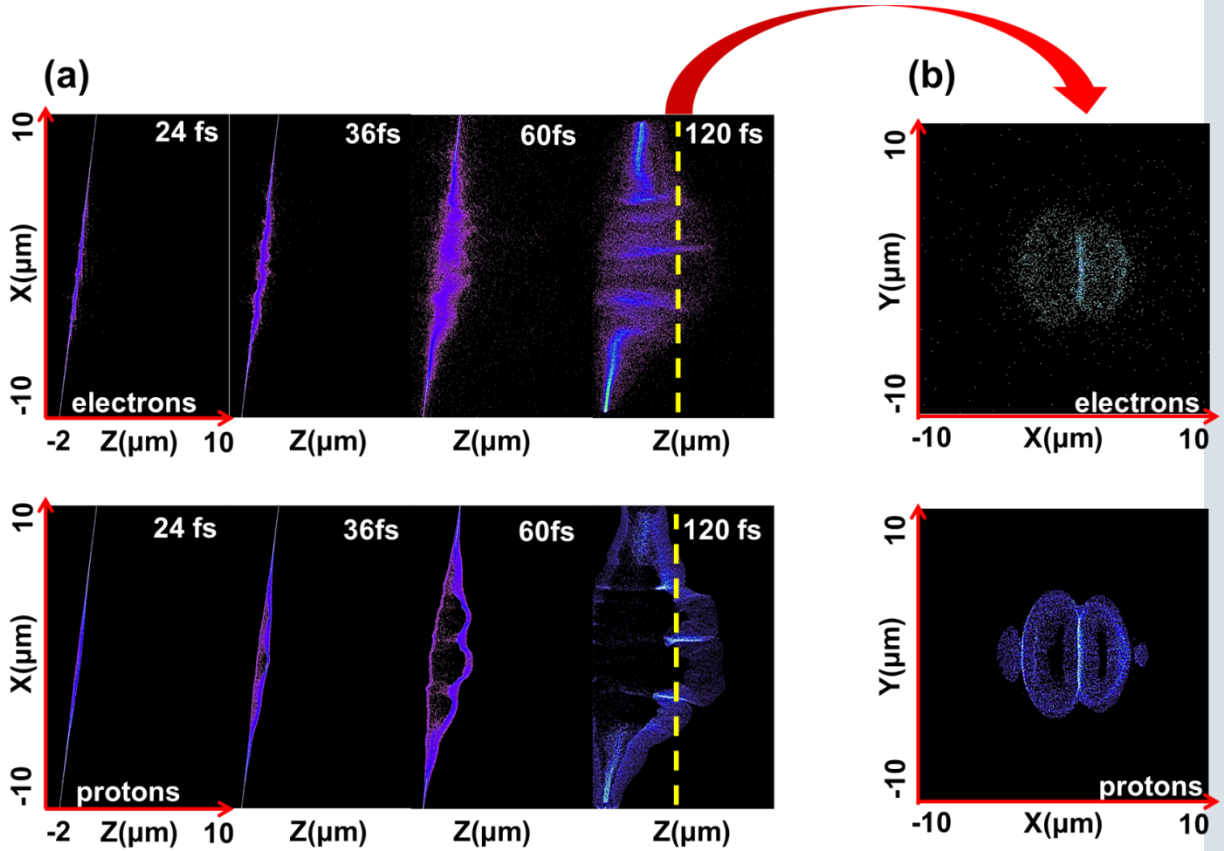
Maximum proton energy for 10-, 20-, and 30-nm-thick polymer target



Maximum proton energy for 50-, 70-, and 100-nm-thick polymer target

Temporal evolutions of number density of electrons & protons

A rough estimation on the instability growth rate, $\Gamma \approx (ka)^{0.5}$, gaves us $\Gamma\tau_L \approx 1$, which means the instability grows as $\sim e^1$ during the whole interaction and it is imprinted in the final proton distribution.

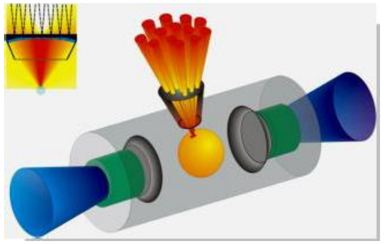


(a) Temporal evolution of number density of electrons and protons obtained from 3D PIC simulations. Results are shown for t = 24, 36, 60 and 120 fs after the interaction. (b) Cross section taken along the yellow dotted line (Z=4μm) at 120 fs.

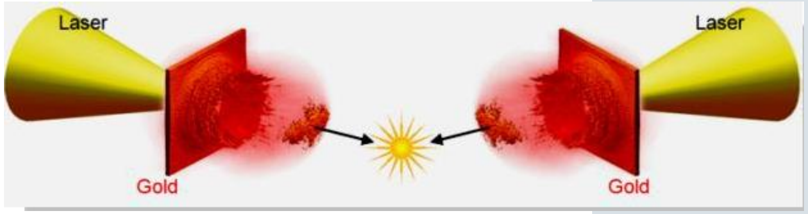
Why laser-driven proton/ion beams ?

Power	Applications
100TW	- Radiography(density measurement) (~ a few MeV) - Deflectometry (field measurement) (~a few MeV) - Isochoric heating of matter (~ a few MeV) - Material study (irradiation) (~ a few MeV) - Injection into conventional accelerators
1 PW	- Cancer therapy (200 MeV) - Production of isotopes for PET - Fusion energy (Fast ignition)
10 PW	- Nuclear/particle physics applications (> GeV)

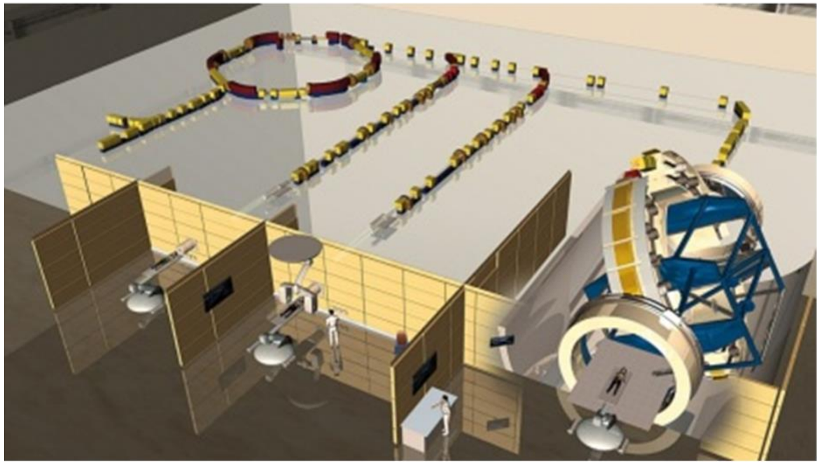
Reference from IZEST 2012

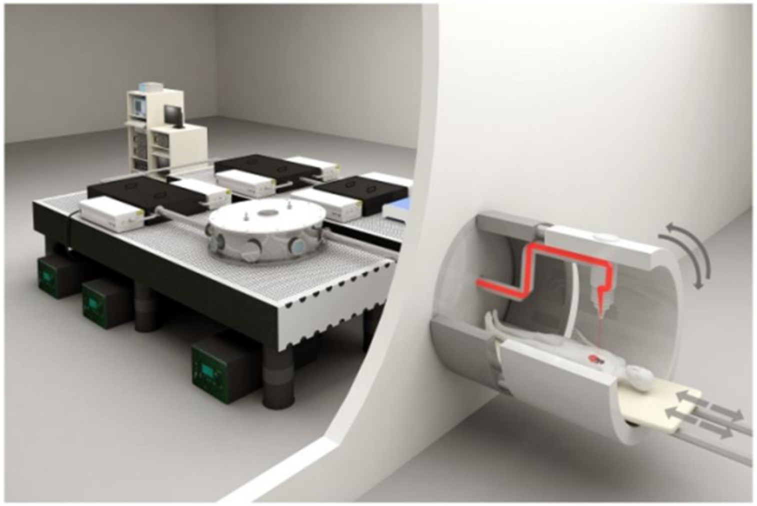


Fast ignition of thermonuclear targets with laser accelerated ions



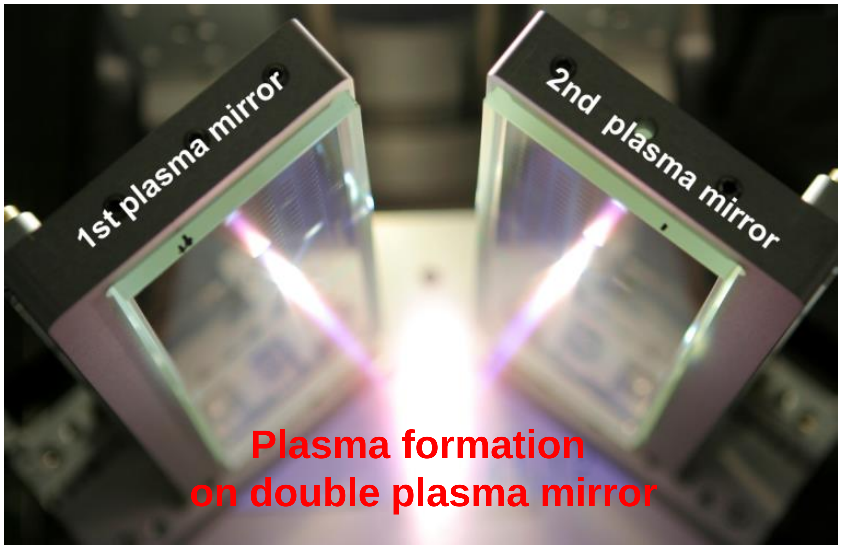
Compact heavy RPDA collider

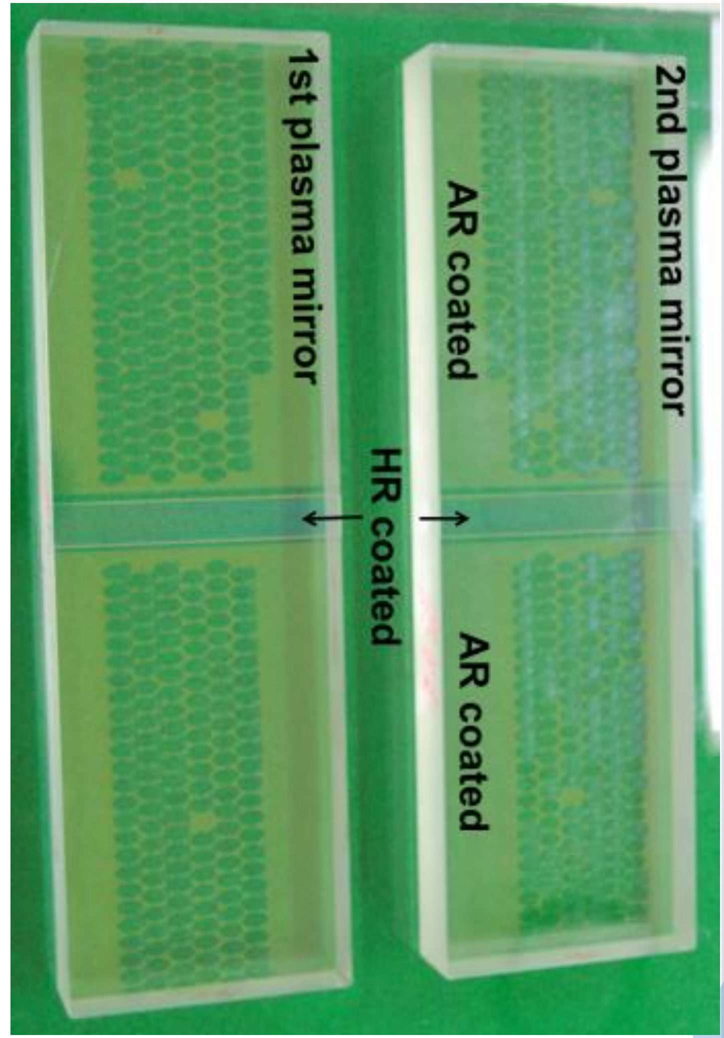




The feasibility of proton & heavy ion therapy using table top laser facility !!

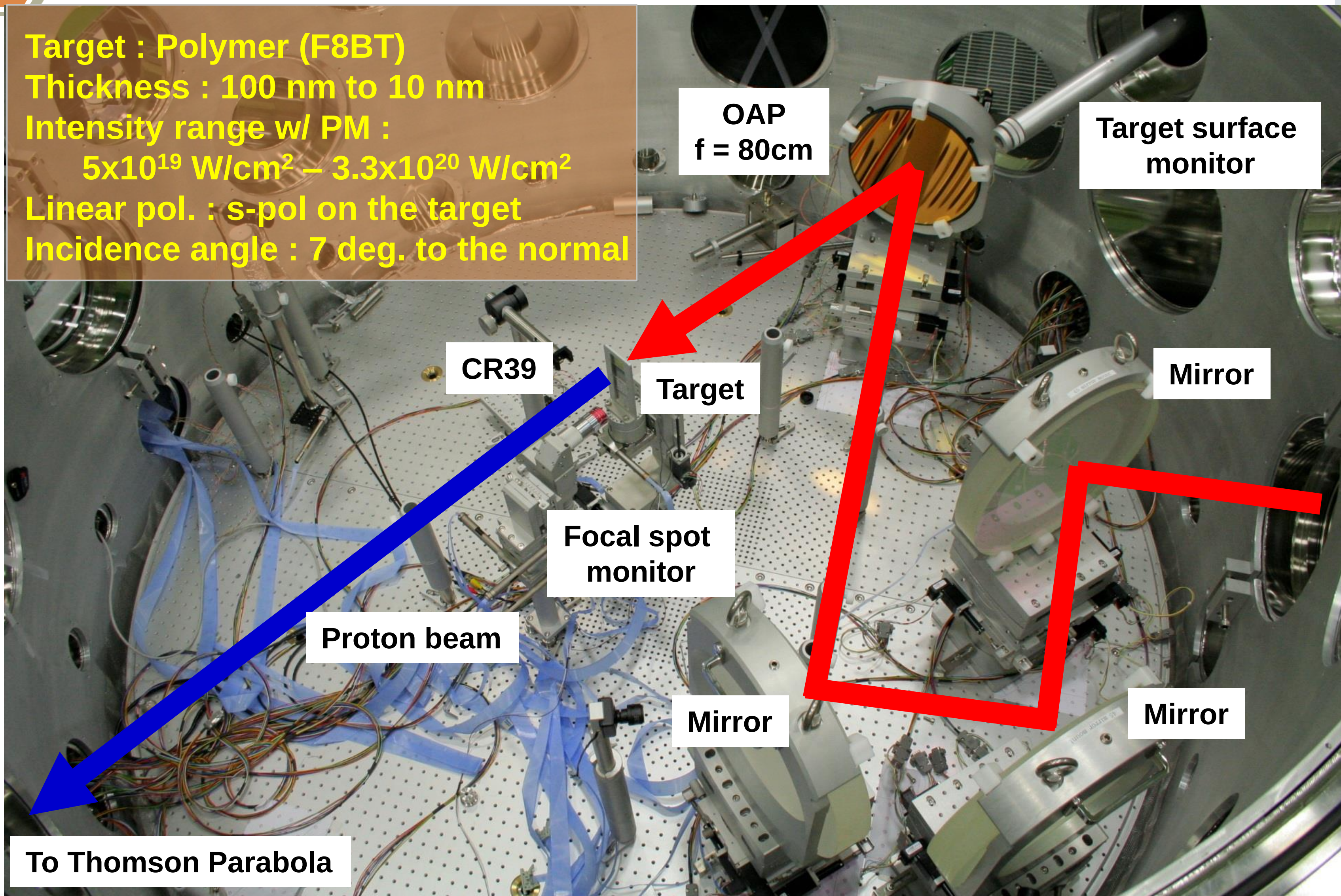
Characteristics of double plasma mirror





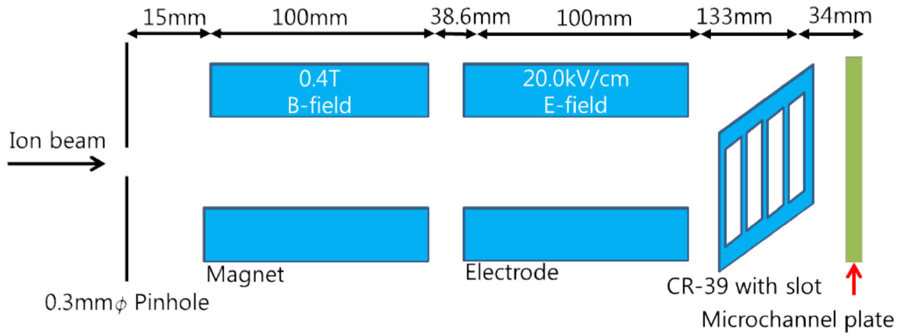
Configuration of PW target chamber

Target : Polymer (F8BT)
Thickness : 100 nm to 10 nm
Intensity range w/ PM :
5×10^{19} W/cm^2 – 3.3×10^{20} W/cm^2
Linear pol. : s-pol on the target
Incidence angle : 7 deg. to the normal



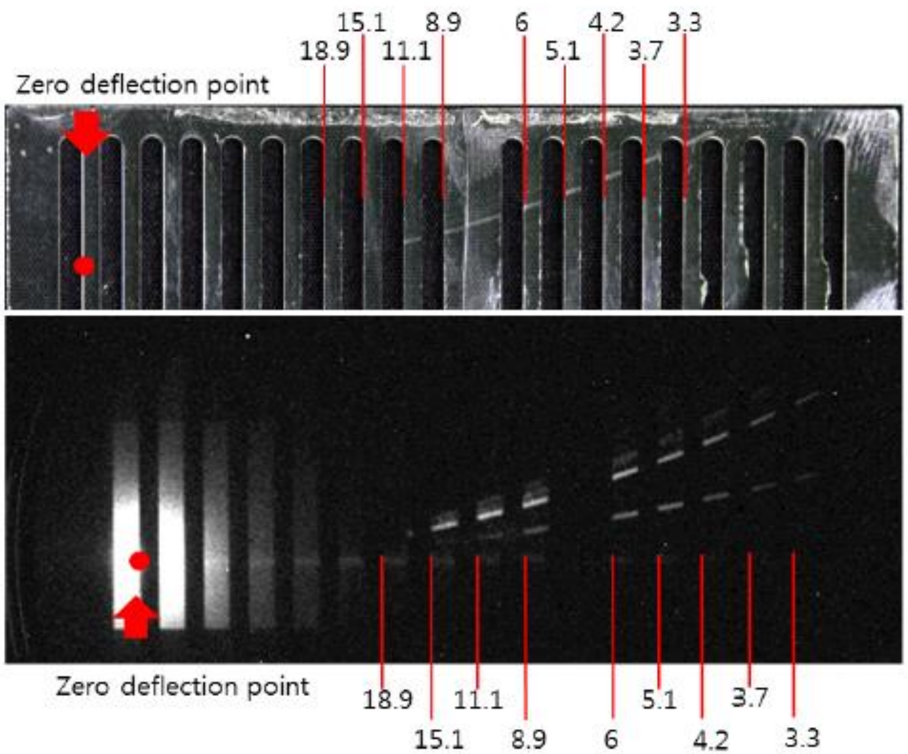
Absolute calibration of proton energy spectra

The absolute calibration for the proton energy spectra was done by installing striped CR-39 track detectors in front of the MCP devices.



CR-39

MCP



The numbers on the left image represents proton energies at the position in MeV unit.

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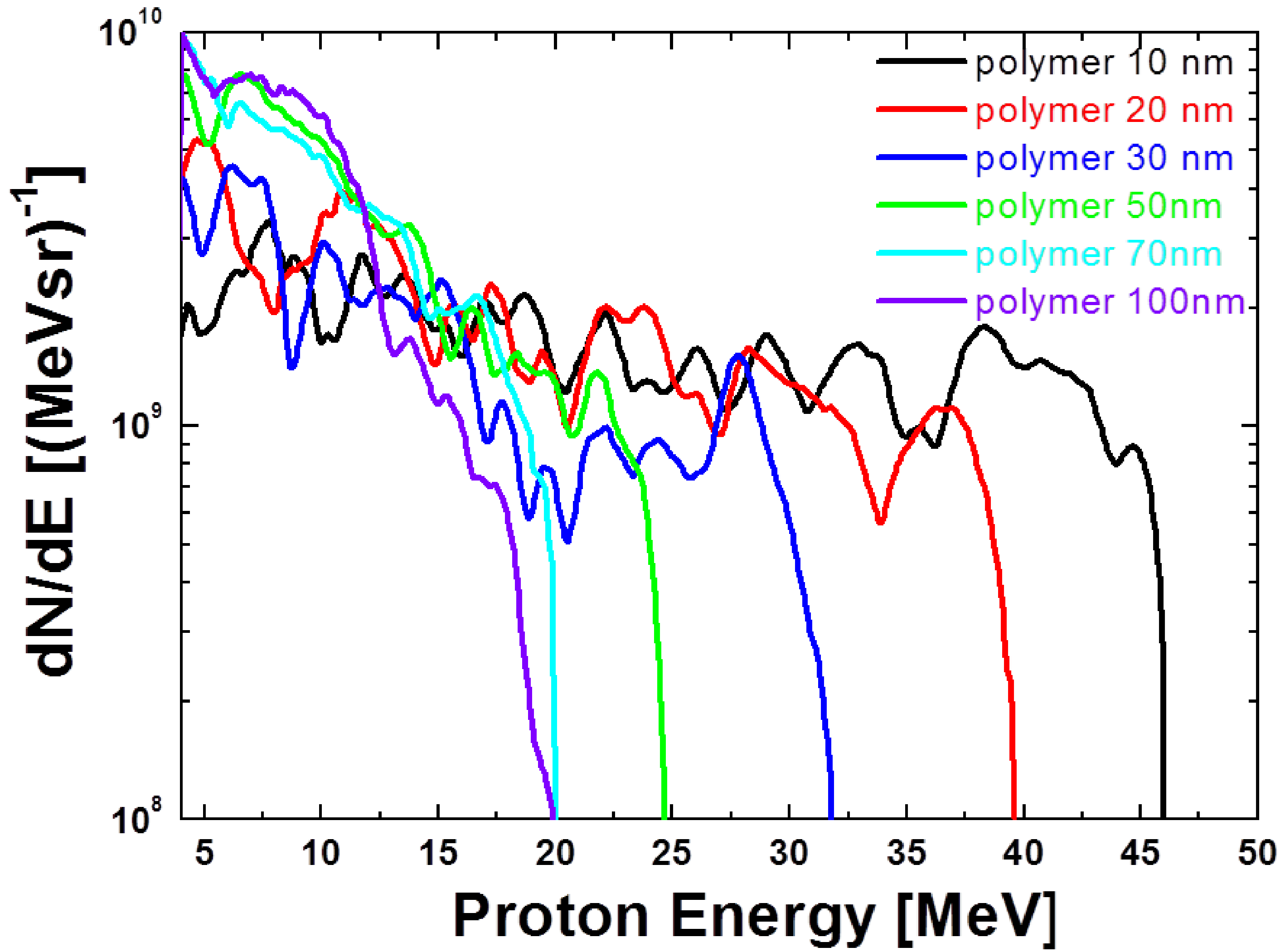
Energy spectra of protons



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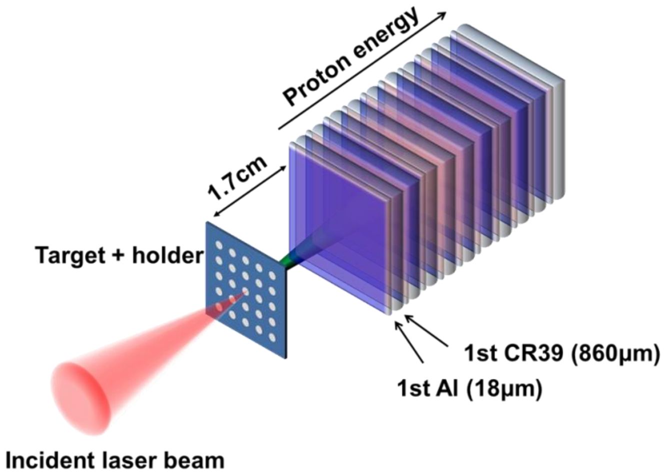
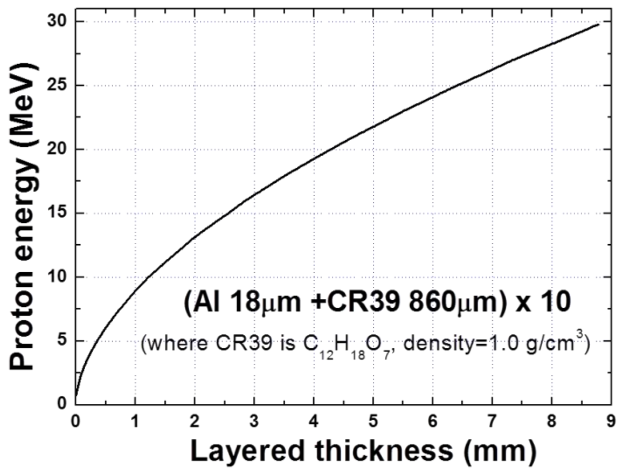
CR39 stack data (consistent with Thomson parabola)

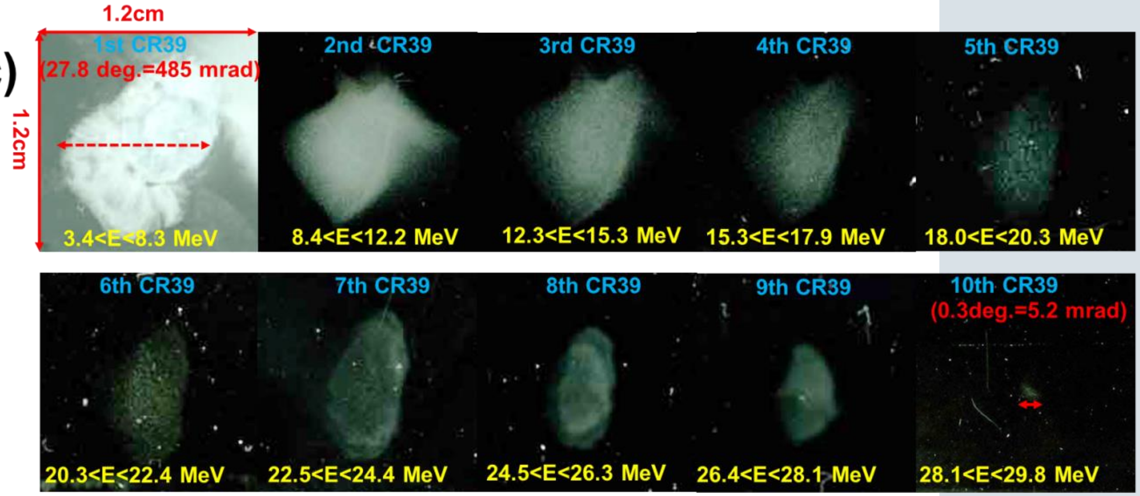
(a)



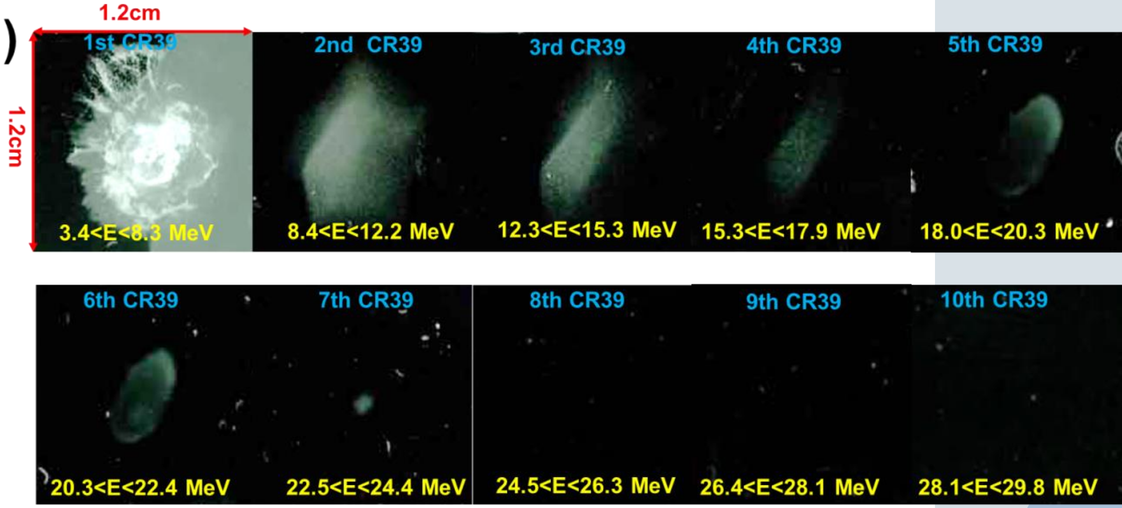
(b)



(c)

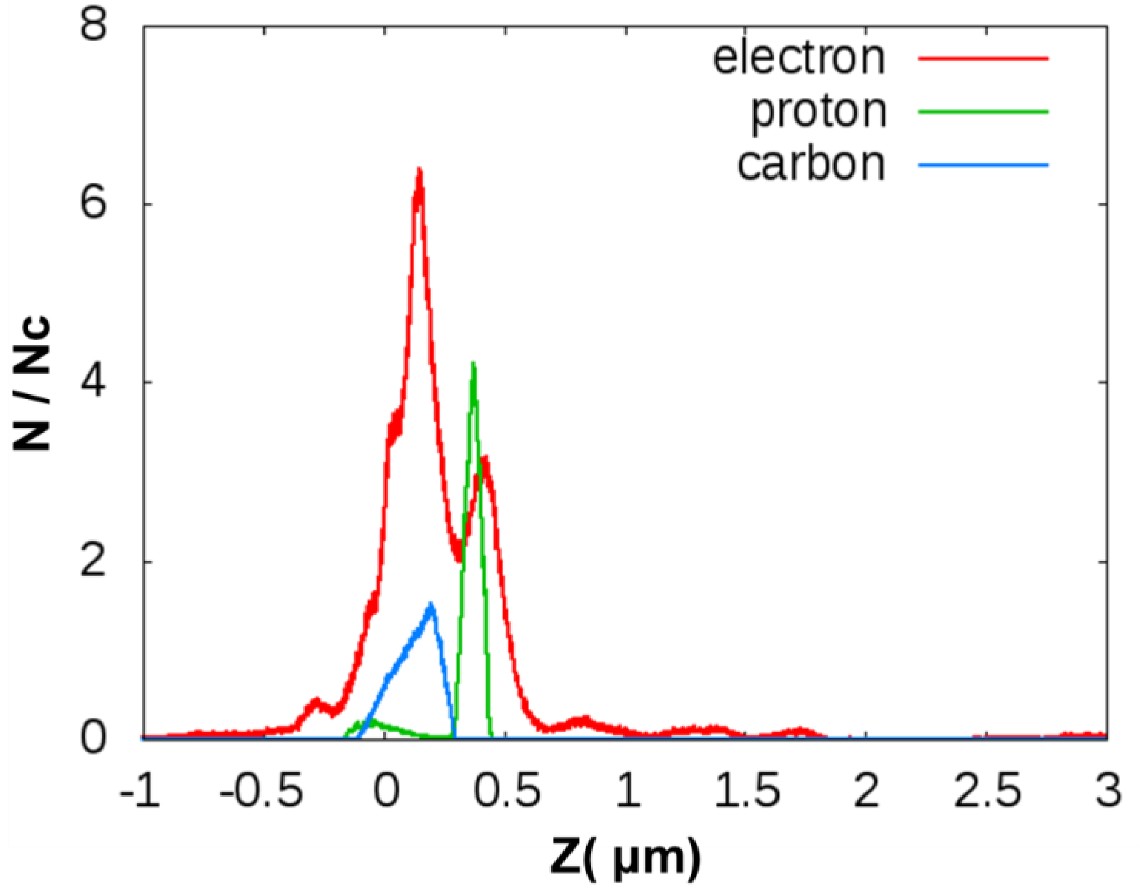


(d)



(c) 30nm thick polymer target
(d) 70nm thick polymer target

Double peak structure of electron density after the interaction of 30 fs



at the intensity of 3×10^{20} W/cm^2 and 10nm target obtained from 3D simulation

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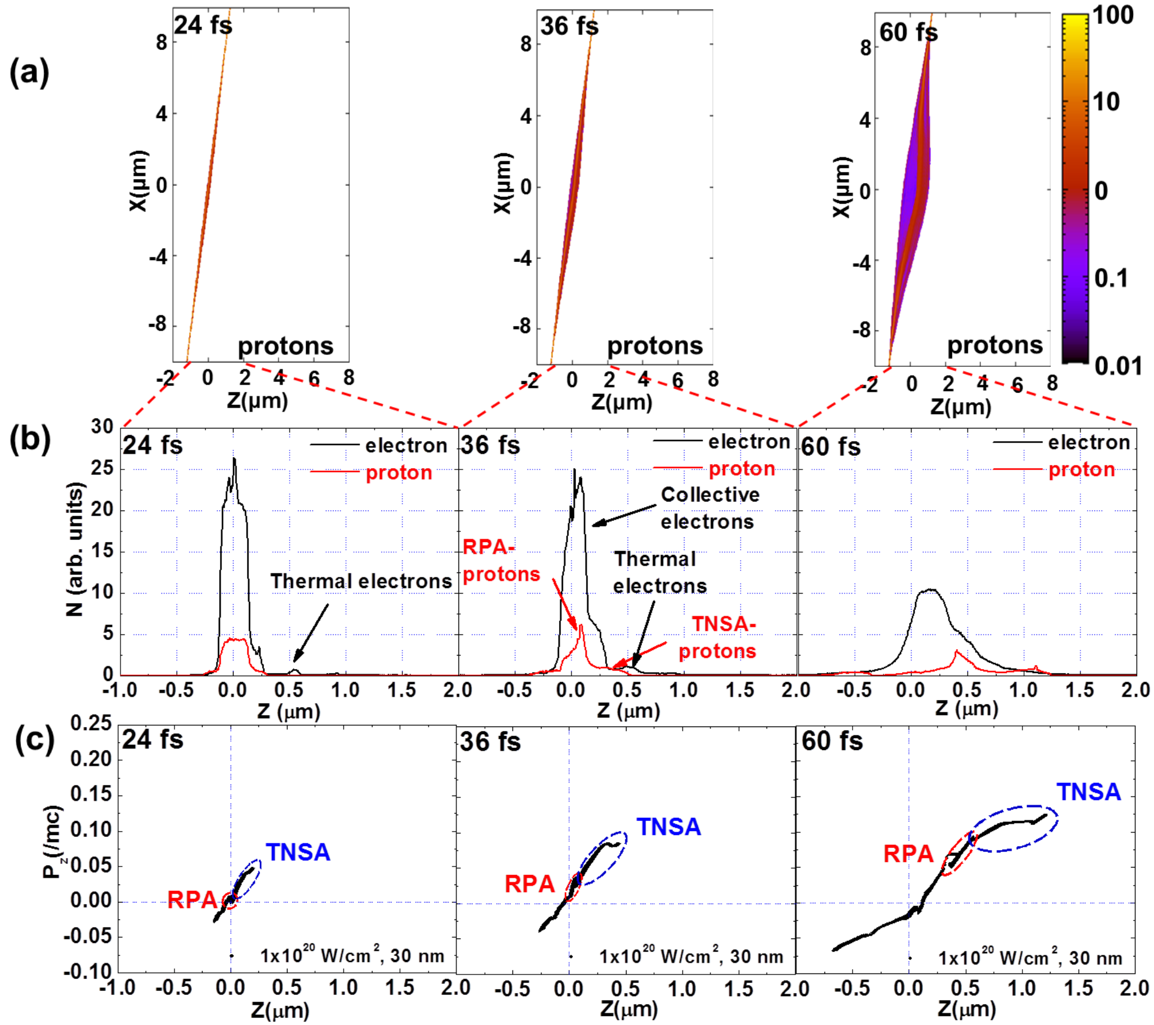
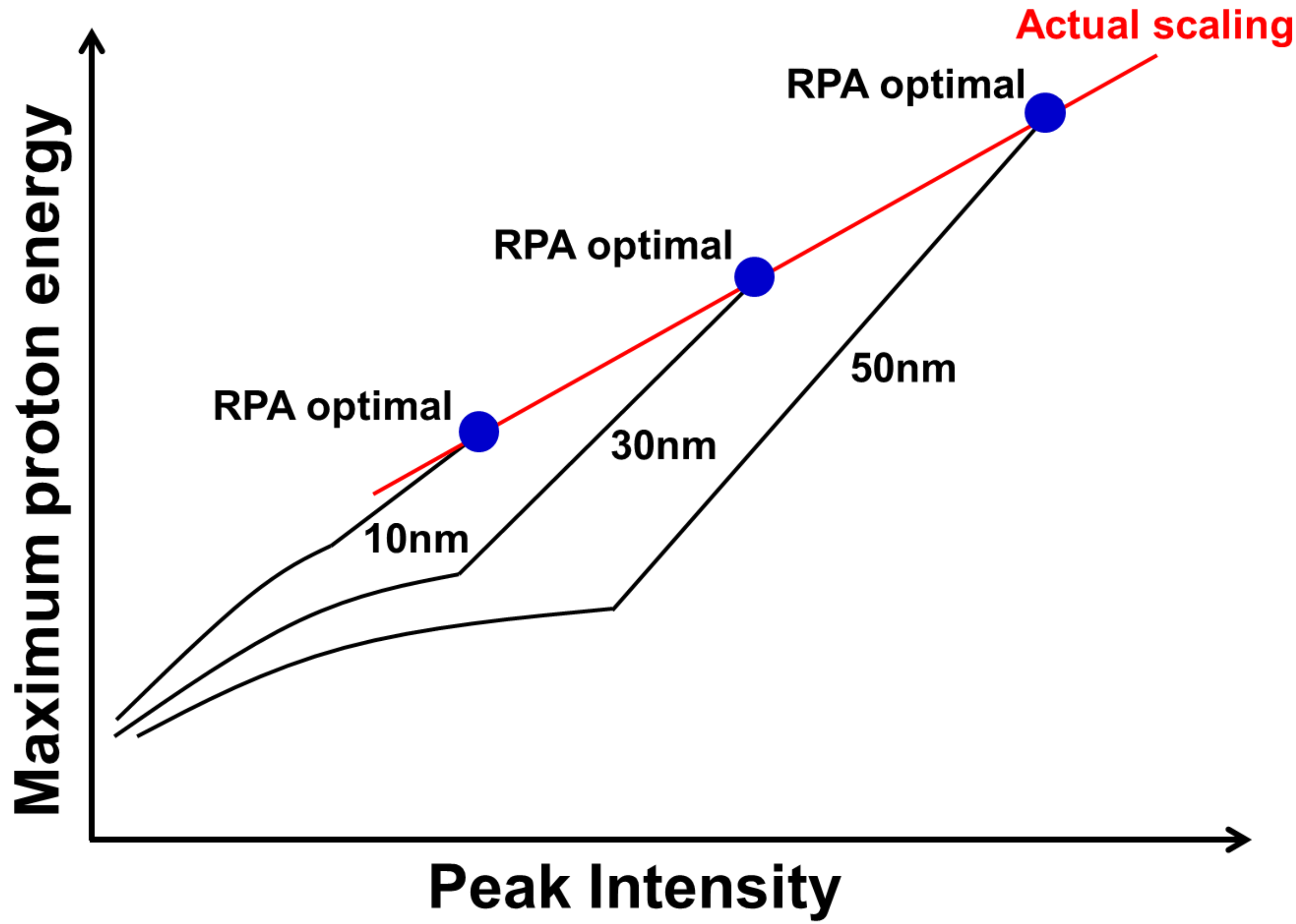
Temporal evolutions of number density of electrons and protons

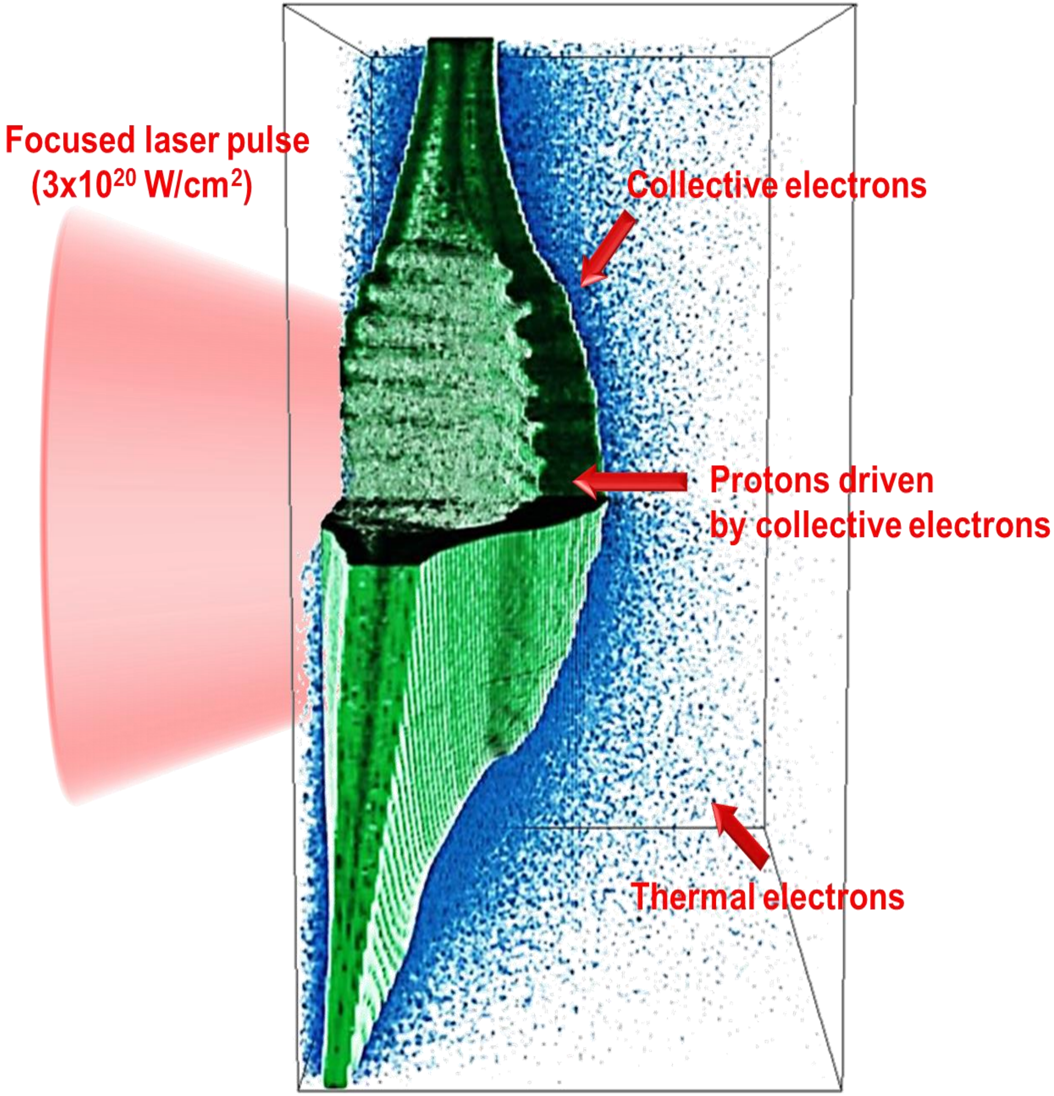
30-nm target, 1.0 x 10 ^{20} W/cm^{2}



Actual scaling for LP??



Proton acceleration scenario (3D PIC simulation)



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