Multi-Stage Laser Ion Acceleration

S. Kawata[1], D. Sato[1], T. Izumiyama[1], T. Nagashima[1], D. Barada[1], Y. Y. Ma[1],
W. M. Wang[2], Q. Kong[3] P. X. Wang[3], Z. M. Sheng [2, 4],
J. Limpouch[5], O. Klimo[5]

[1]Graduate School of Engineering, Utsunomiya University,
7-1-2 Yohtoh, 321-8585 Utsunomiya, Japan
[2]Inst. of Physics, CAS, Beijing 100190, China
[3]Institute of Modern Physics, Fudan University, 200433 Shanghai, China
[4]Dept. of physics, Shanghai Jiao Tong University, Shanghai 200240, China
[5]Czech Technical University in Prague, CZ-115 19 Praha, Czech Republic

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Presentation Outline:

1. Purpose & Issues
2. Background – Previous studies in Laser foil interaction
3. Multi-stage laser ion acceleration
   in laser gas plasma interaction
1. Conclusions

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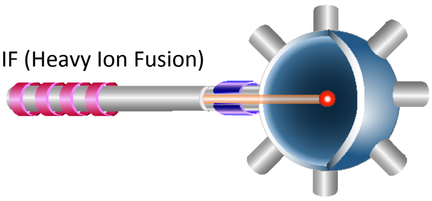
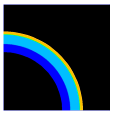
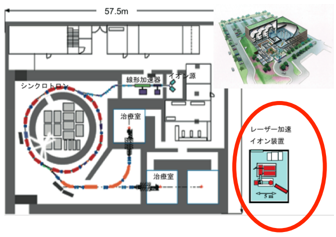
Ion Accelerator and Ion Beam

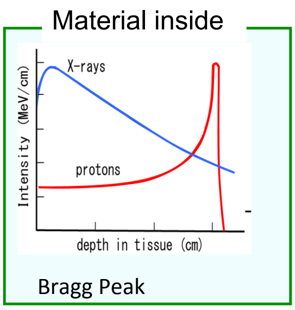
/ Ion fusion
/ Ion cancer therapy
/ material procession, …

HIF (Heavy Ion Fusion)









Issues of Laser Ion Accelerator

1. Ion beam quality
   --- transverse divergence
   --- energy & spectrum control
2. Low energy efficiency from laser to ion beam
   ~ a few % or less
3. Total number of ions accelerated
   ~ 10^{12} particles or so
4. Low laser efficiency

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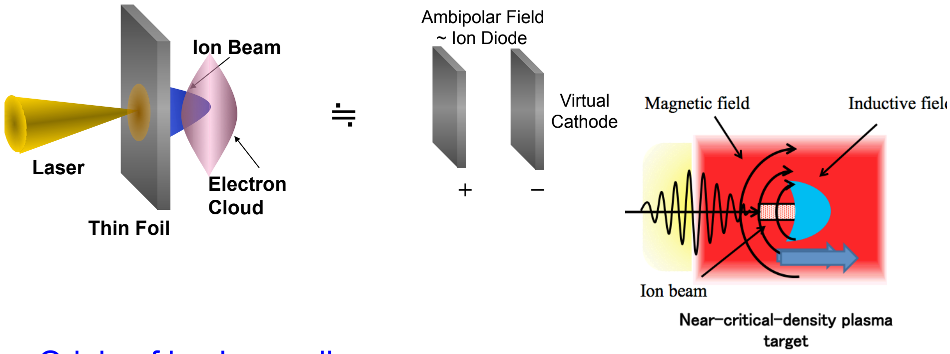
Background: Collimated Ion Beam



Origin of ion beam divergence:
/ Edge fields of ion source & electron clouds
/ Ion beam temperature

Suppression of transverse proton divergence
by shielding edge fields of electron cloud & ion source.

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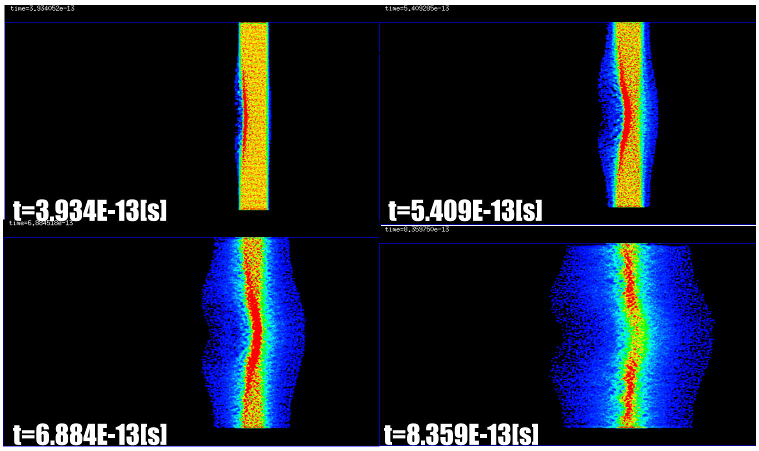
Simulation Results

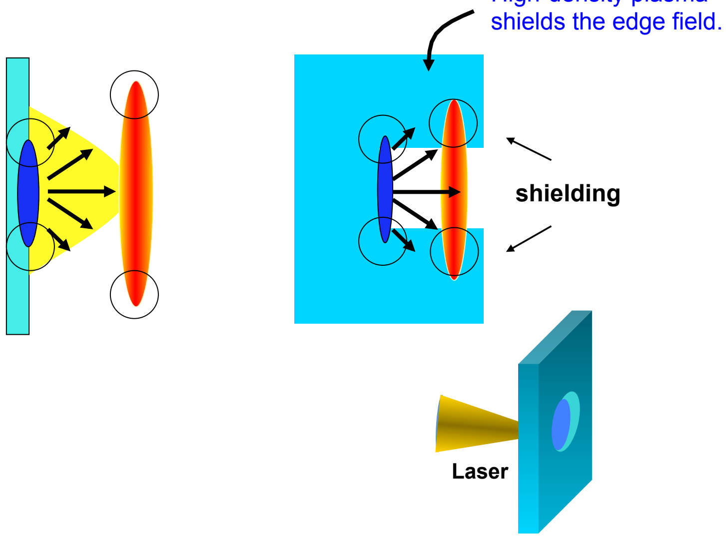
Target density $n_F = 2 \times n_c = 2.01 \times 10^{21} [cm^{-2}]$

Proton

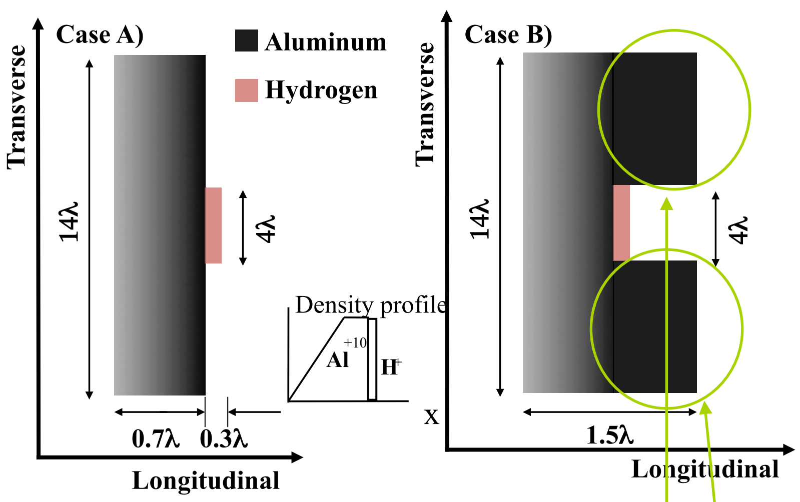


Maximum Kinetic Energy of Proton
Forward: 3.73 [MeV] Backward: 2.89MeV

Collimated Ion Beam



Initial Target Profile

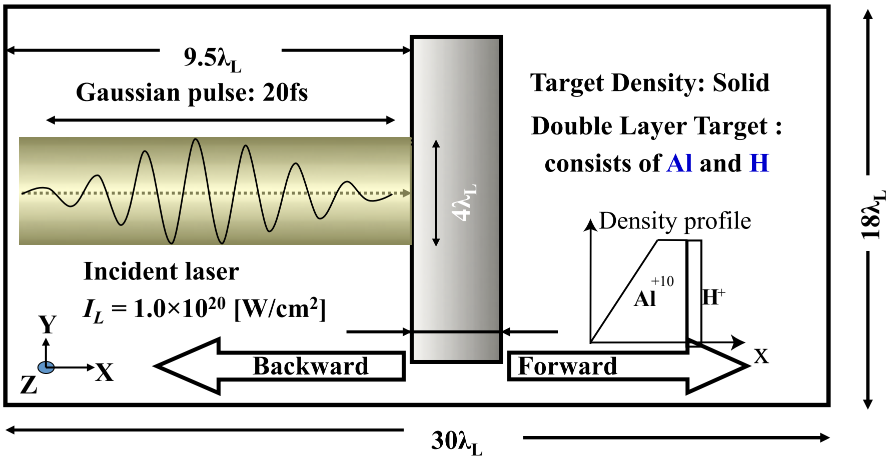


Target of Case A is the conventional slab foil plasma.

Target of Case B has a hole at the opposite side of the laser illumination.

Gradation part in figures mean density gradient.

Simulation Model of 2.5D PIC Simulations



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Initial Parameter Values

- **Intense laser pulse**

  Wave length: λ_L=1.053[μm]

  Gaussian laser duration: $t_L = 20$[fs]

  Laser intensity: $I_L = 1.0 \times 10^{20}$[W/cm^2]

  Laser spot diameter: $r_L = 4\lambda_L$ (FWHM)

- **Target**

  Double layer target consists of Al and H

  Initial density: solid

  Initial distribution: Partial balance-Maxwell

  distribution (temperature Te=1.0,Ti=1.0[KeV])

- **Calculation conditions**

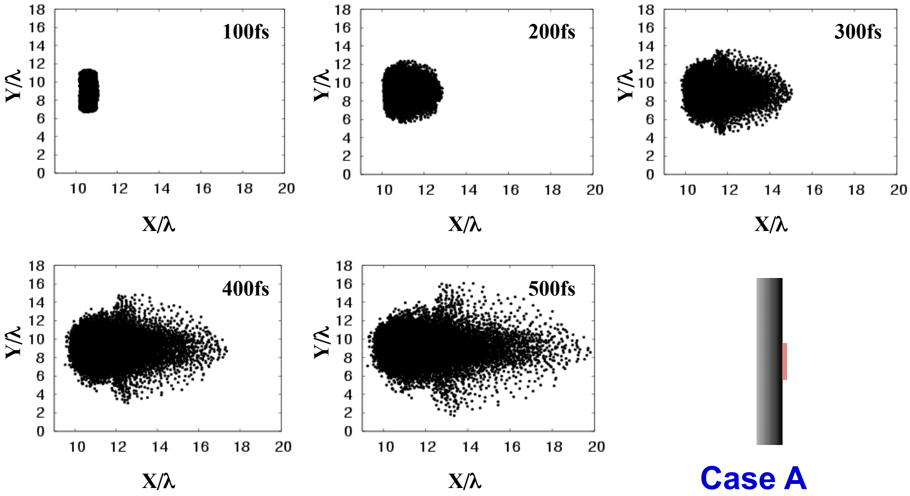
  The calculation mesh size Δx=Δy is 0.02λ

  The integration time step Δt is 0.04×Δx/c

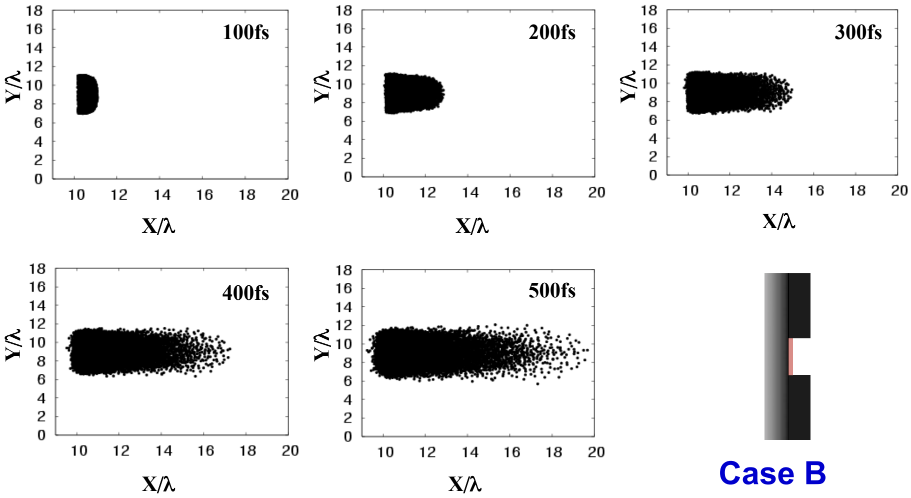
  We employ about 1.6-million super particles in our simulations

No.22

Proton Distribution in X-Y Space in Case A

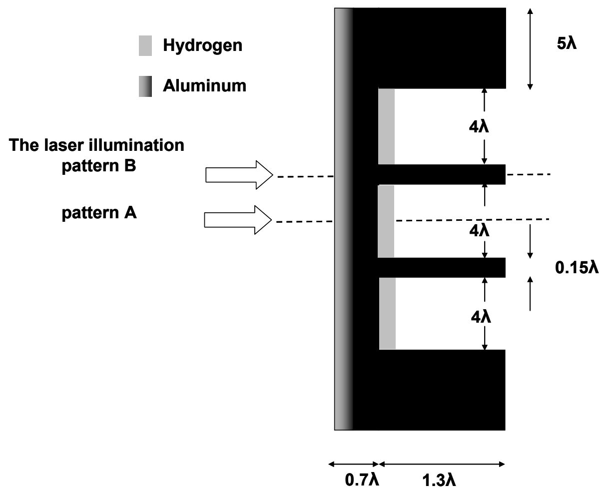


Proton Distribution in X-Y Space



The proton beam transverse divergence of CaseB is suppressed successfully by the shaped target and the electron cloud localization.

Robust hole target against laser alignment



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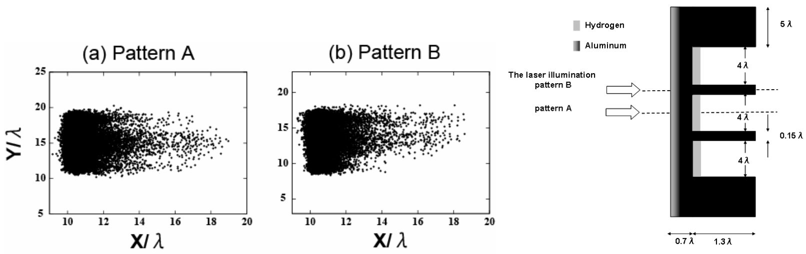
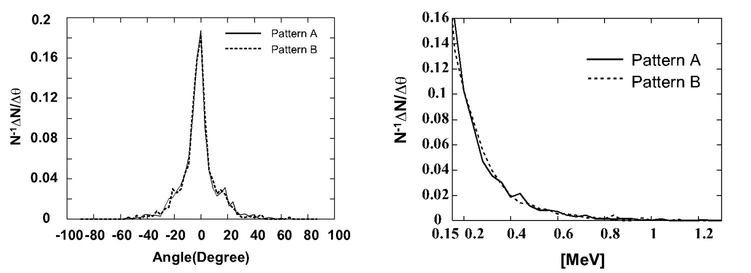
Robust hole target against laser alignment





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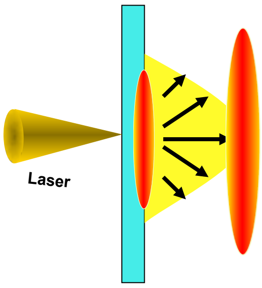
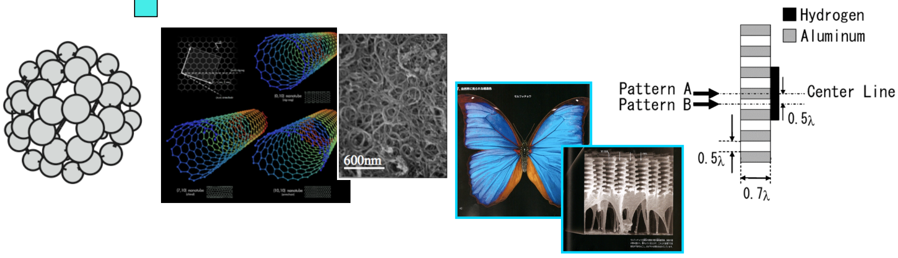
Energy Efficiency Enhancement
From Laser to Ion Beam



2. Low energy efficiency from laser to ion beam
   ~ a few % or less

⇔

/ jaggy or rough surface target
/ cluster, amorphous, many-holes. …
/ long life of electrons



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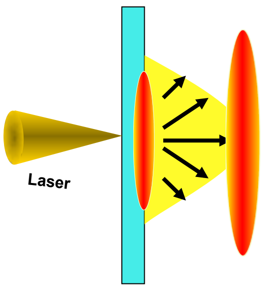
Energy Efficiency Enhancement
From Laser to Ion Beam

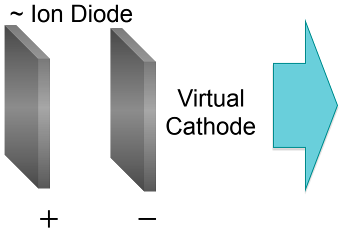


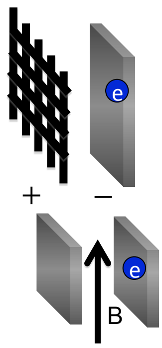
2. Low energy efficiency from laser to ion beam
   ~ a few % or less

⇔

/ long life of electrons
➔ long life of acceleration E-field

Ambipolar Field
~ Ion Diode





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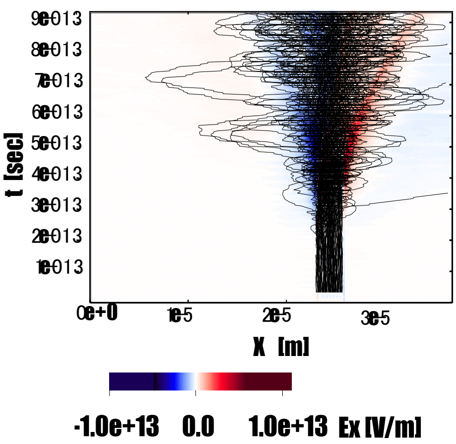
Ion Acceleration

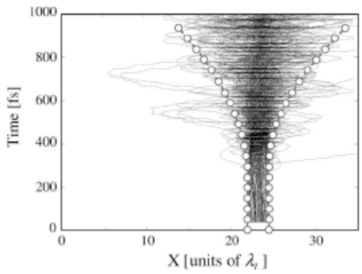
Target density $n_F = 2 \times n_c = 2.01 \times 10^{21} [cm^{-2}]$

Electron trajectory



Electrons oscillate in a potential well of the ESF with a high frequency

The number of the electrons to sustain the ESF wave depends on the energy of the electrons

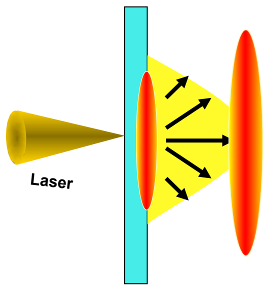


Energy Efficiency Enhancement From Laser to Ion Beam

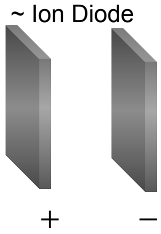
2. Low energy efficiency from laser to ion beam
   ~ a few % or less

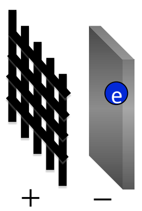
⇔

/ long life of electrons

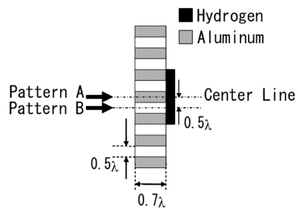


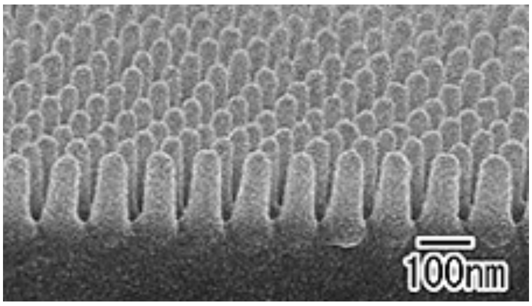
Ambipolar Field
~ Ion Diode

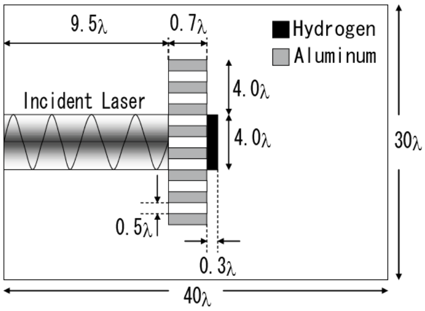


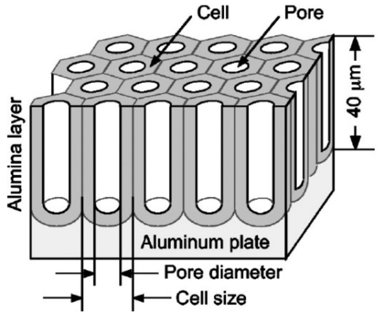


Virtual Cathode









Laser absorption and ion acceleration in micro-structured targets 10

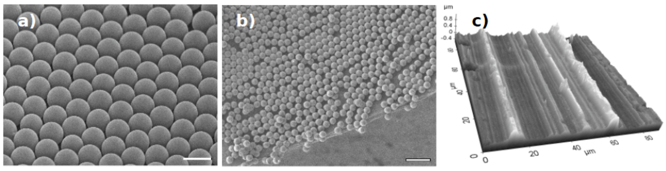
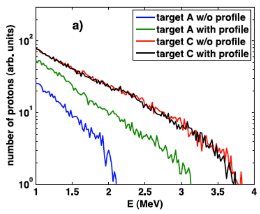


Figure 5. a) Scanning electron microscope (SEM) image of the target surface covered by monolayer of polystyrene spheres with the diameter of about 0.9 μm. b) SEM image of a thin mylar foil (100 nm) covered by polystyrene spheres (0.26 μm). Image is taken at the border of the foil, where the spheres are not regularly arranged due to the cutting process. c) Atomic force microscope image of the surface of a common commercially available (supplied by Goodfellow SARL) thin Aluminum foil (2 μm thick).



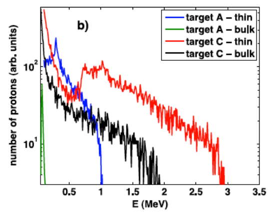


Figure 11. The energy distribution of protons accelerated from the rear side of targets A and C (from table 2) and the targets with density profiles plotted in figure 10. The distributions are compared 0.2 ps after the laser target interaction. (b) The energy distributions of protons accelerated out of the target from its front side. The distributions for thin and bulk targets are compared 130 fs after the laser target interaction.

New J. of Phys. 13 **(2011) 053028,** O. Klimo, J. Psikal, J. Limpouch, et al.

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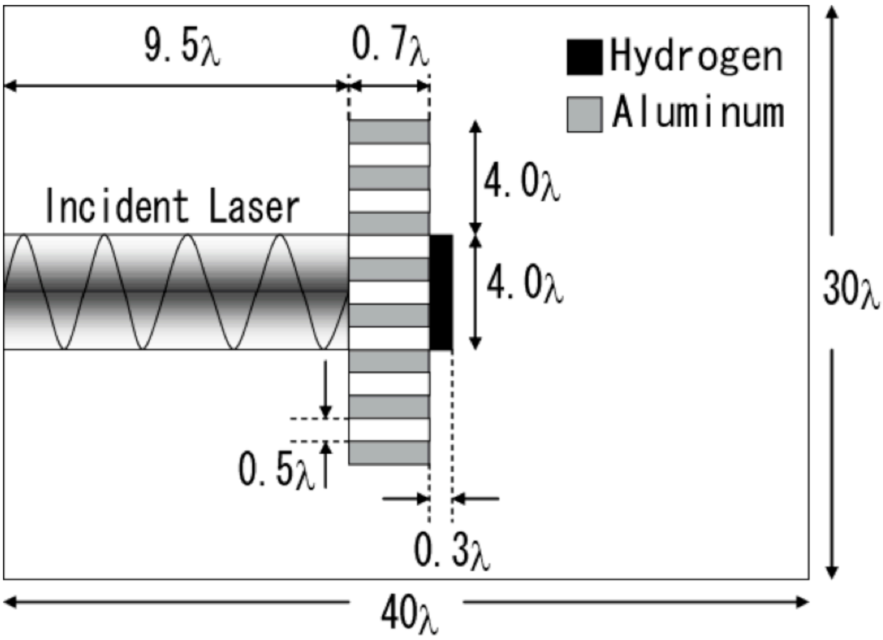

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- Intense laser pulse

  Wave length: $\lambda_L = 1.053[\mu m]$

  Gaussian laser duration: t_L = 100[fs]

  Laser intensity: $I_L = 5.0\times10^{20}[W/cm^2]$

  Laser spot diameter: $r_L = 4\lambda_L$ (FWHM)

- Target

  Double layer target consists of Al and H

  Initial density: solid

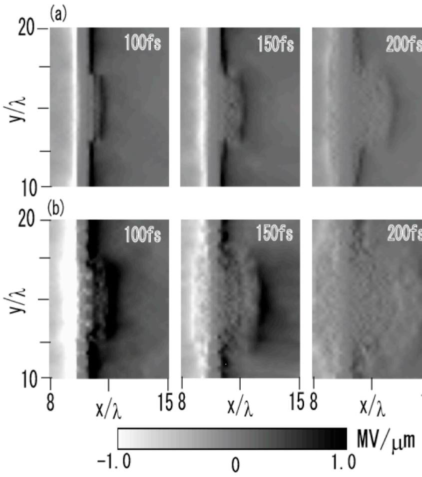
  Initial distribution: Maxwell distribution (temperature Te=1.0,Ti=1.0[KeV])

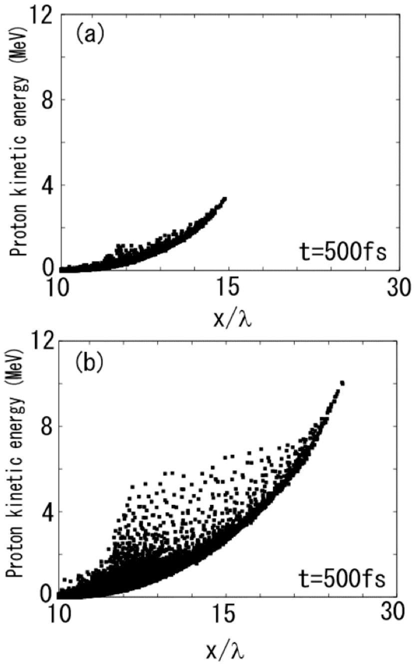
- Calculation conditions

  The calculation mesh size $\Delta x=\Delta y$ is $0.02\lambda_L$

  The integration time step Δt is $0.04\times\Delta x/c$

  We employ about 1.6-million super particles in our simulations





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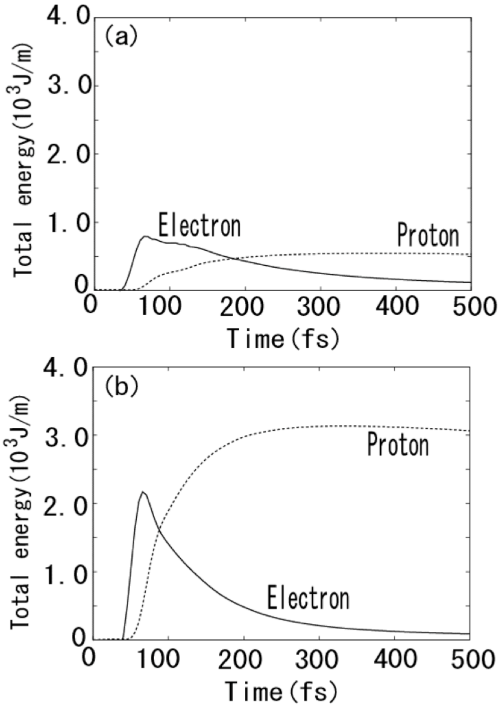

Laser -> protons

1.5%

Laser -> protons

9.3%

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Problems of Laser Ion Accelerator

1. Ion beam quality
   --- transverse divergence
   --- energy & spectrum control <=

2. Low energy efficiency from laser to ion beam
   ~ a few % or less

3. Total number of ions accelerated
   ~ 10^{12} particles or so

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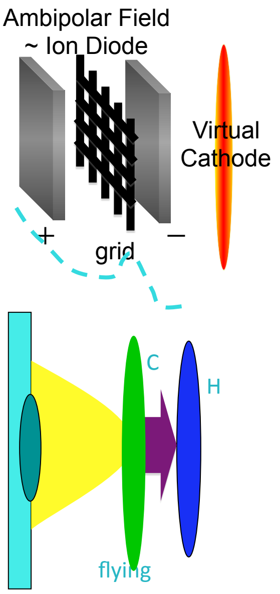
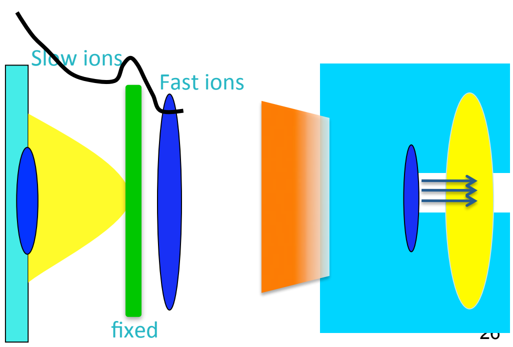
Energy Spectrum Control



1. Ion beam quality
   --- energy spectrum control
   ⇔
   / very thin ion source < skin depth
   / double layer – flying or fixed



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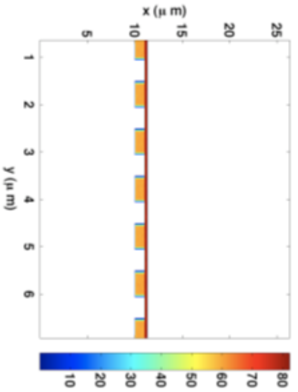

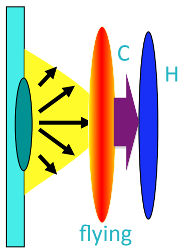

Laser: intensity 10^{20} W/cm^2
wavelength 1 µm
duration 15 fs
pulse shape $\sin^2$
polarization P
spot size 3 µm
incidence angle 0◦

Foil: thickness 300 nm
density 0.4 g/cm^3
composition CH_2
ion charge state C^{6+}, H^+ initial temperature 1 eV
profile step-like boundary conditions
thermalization of fast electrons

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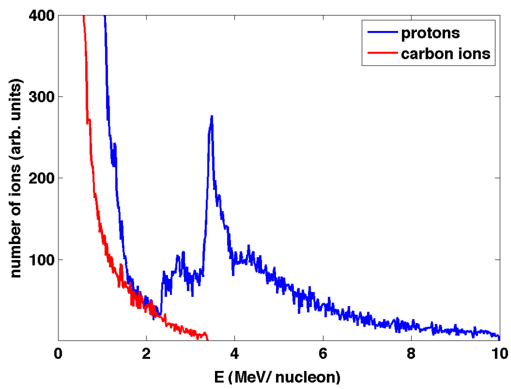

case 3 periodic array with structure composed of boxes of 60 nm × µm separated by 0.25 µm, material composition C^{6}+, density 0.35 g/cm^3

=> Flat target: 2.8% (Laser -> ions)
Structured target: 26%(Laser -> ions) case 3(20% C, 6%Protons)

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Problems of Laser Ion Accelerator

1. Ion beam quality
   --- transverse divergence
   --- energy & spectrum control <=

2. Low energy efficiency from laser to ion beam <=
   ~ a few % or less

3. Total number of ions accelerated
   ~ 10^{12} particles or so

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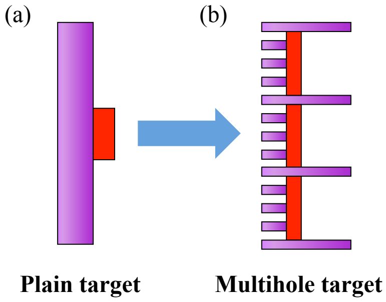
Multi-stage laser ion acceleration

Control of ion energy & enhancement of energy efficiency

↓

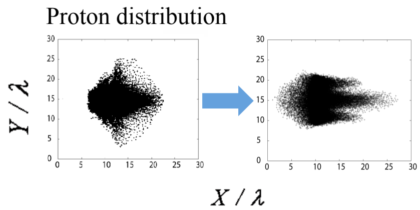
Near-critical-density Plasma target for multi-stage acceleration

従来の研究成果



レーザーからプロトンへのエネルギー変換効率

Plain target 6.32% → Multihole target 16.7%



これまでの研究において，薄膜ターゲットに多数の穴を設けたマルチホールターゲットを考案し，レーザーからプロトンへのエネルギー変換効率を飛躍的に上昇させることに成功した．また，ターゲット後方にウォールを設けることでプロトンの発散を抑制できることができる[1,2].

[1] W.-M Wang, et al., Phys.Plasmas 15 030702(2008)
[2]K. Takahashi, et al., Phys. Plasmas 10, 0931102(2010)

2011/5/27

Laser particle acceleration mechanisms

TNSA
(Target Normal Sheath Acceleration)

Inductive field acceleration

$$Laser \rightarrow electron\ current \rightarrow B_\theta \rightarrow -\frac{\partial B_\theta}{\partial t} \rightarrow E_{//}$$

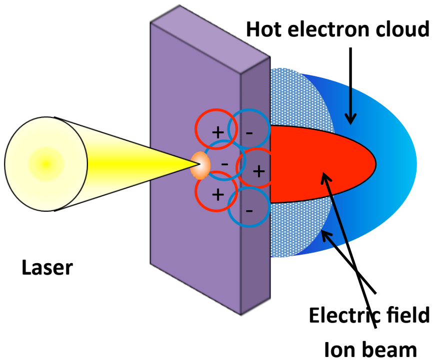
RPA
(Radiation Pressure Acceleration)

Laser photon pressure accelerates a very thin foil

Coulomb explosion

….., etc

TNSA



Inductive laser ion acceleration

Laser accelerates electrons

↓

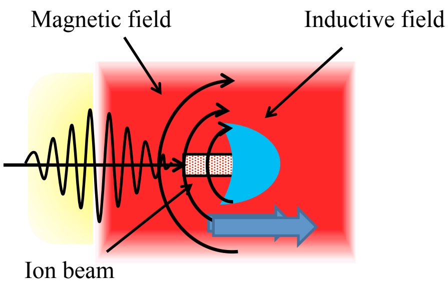
Strong electron current generates a strong magnetic field.

↓

At the increase phase of the magnetic field, ions are accelerated.

↓

The acceleration field moves forward. Ions could be accelerated for a longer time.



Near-critical-density plasma target

Synchronization of ion beam with acceleration electric field motion enhances controllability of ion energy & spectrum

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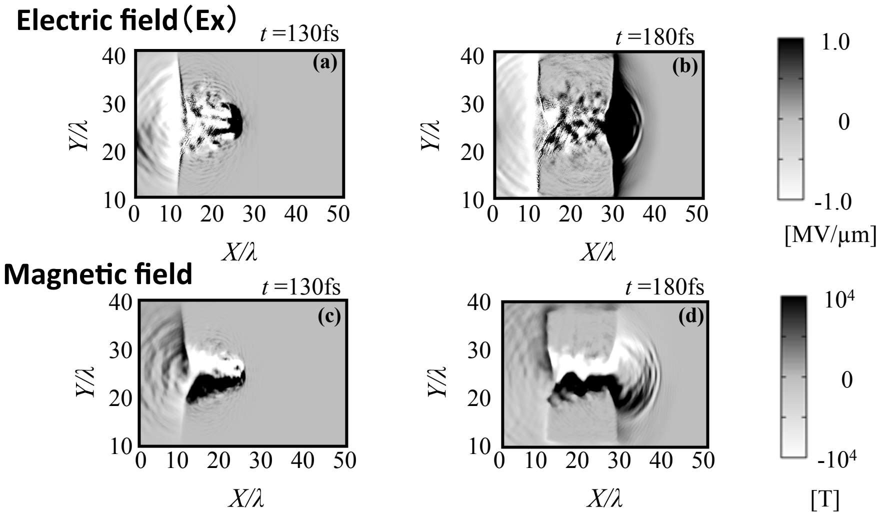
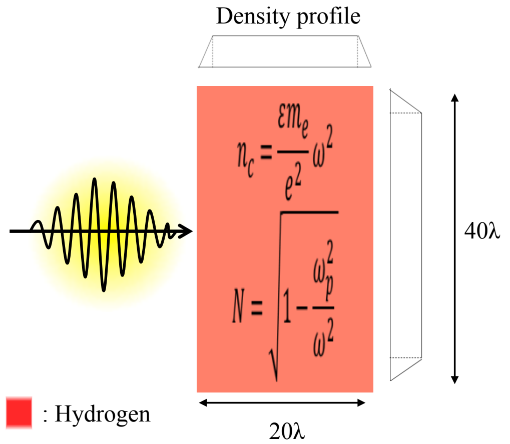
Laser plasma Interaction



1st & 2nd stages: TNSA + little inductive acceleration
3rd & 4th stages: Inductive acceleration + little TNSA

Target model



Laser parameter

Intensity $I_L = 1.0\times10^{20}$ W/cm^2

Pulse duration t_L= 40 fs

Spot diameter r_L= 10.0λ

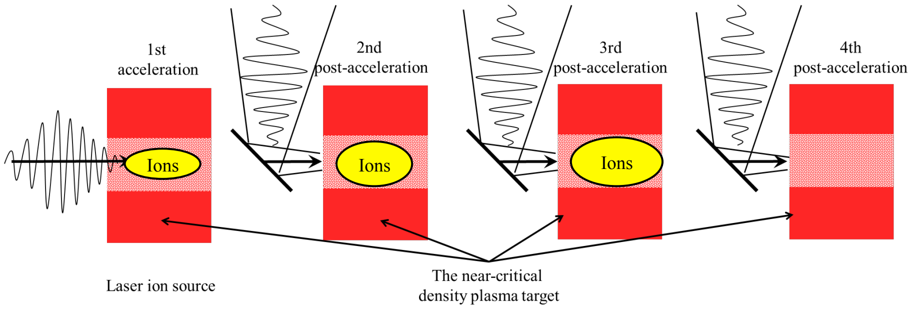
Wave length λ_L = 1.053 µm

Plasma Target density : 0.7n_c

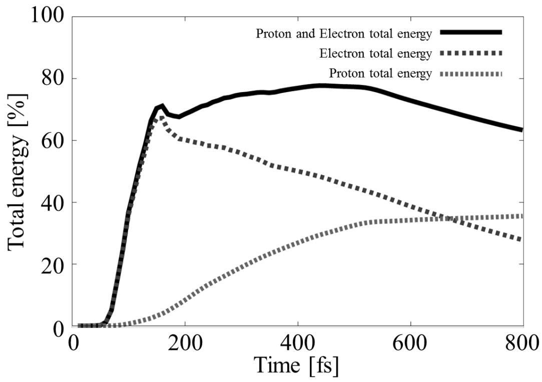
n_c : **Critical density**

N : refraction index

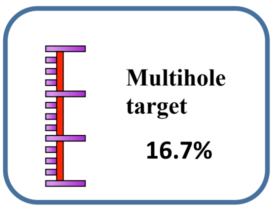
Multi-stage laser ion acceleration



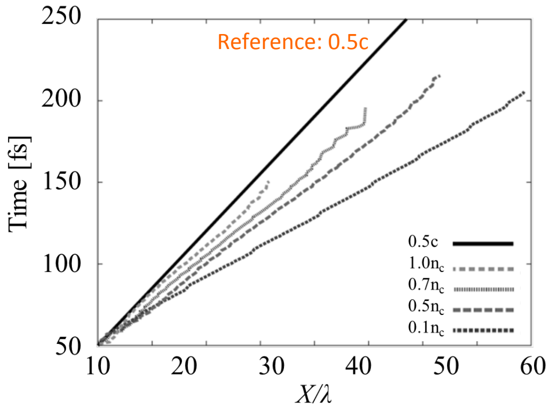
Energy efficiency from laser to ions



	800fsにおけるエネルギー変換効率[%]
Proton	35.5
Electron	27.8
Proton and Electron	63.3



Speed of inductive acceleration field

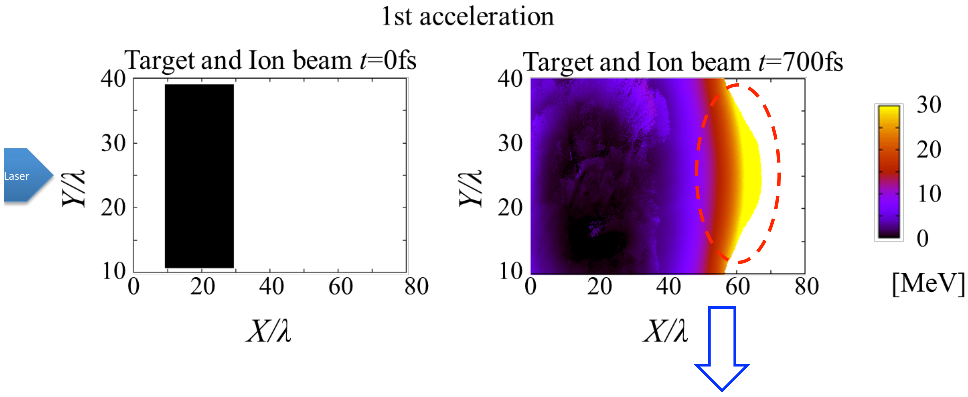


Target density [nc]	Speed of inductive field [m/s]	Speed of inductive field	Group speed Vg
1.0	1.504×10⁸	0.501c	---
0.7	1.872×10⁸	0.624c	0.548c
0.5	2.212×10⁸	0.740c	0.707c
0.1	2.874×10⁸	0.957c	0.949c

$$v_g = c\sqrt{1-\omega_{pe}^2/\omega^2}$$

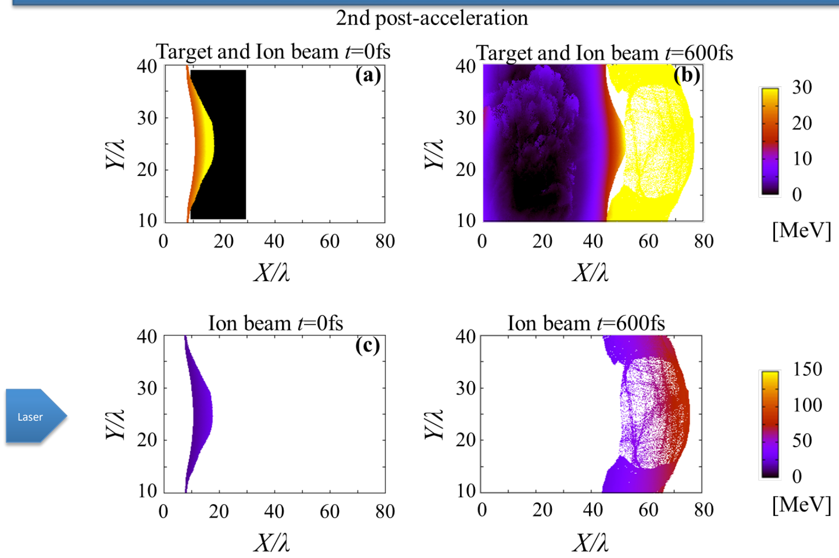
Synchronization of ions with the inductive E field speed enahances ion energy & controllability of ion energy & spectrum

Proton distribution in space 1st acceleration

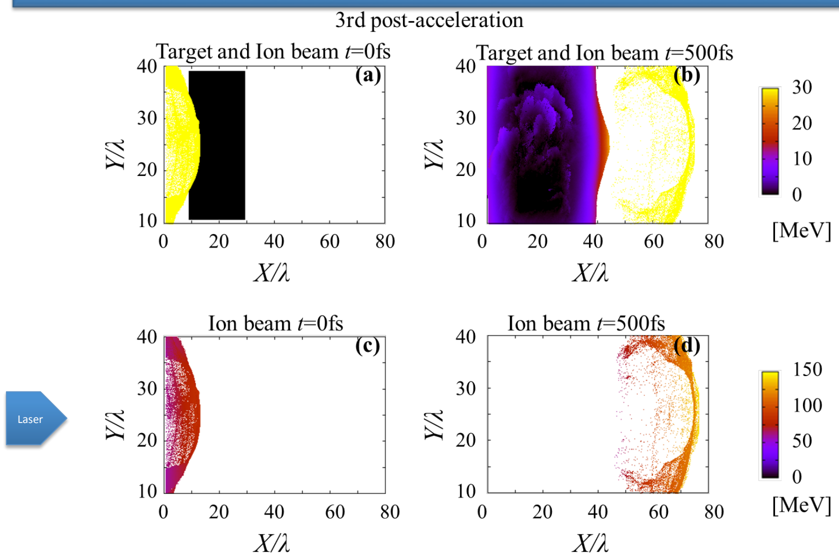


Ion beam accelerated is transferred to the second stage.

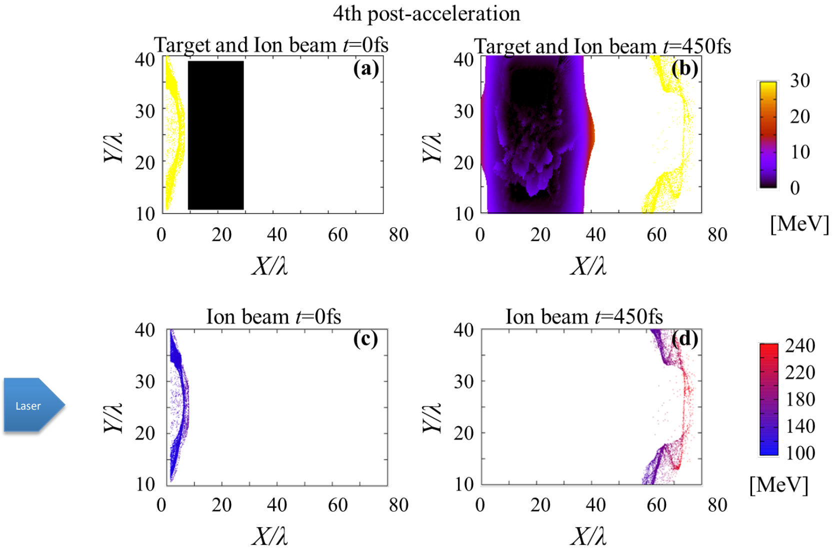
Proton distribution in space 2nd post-acceleration



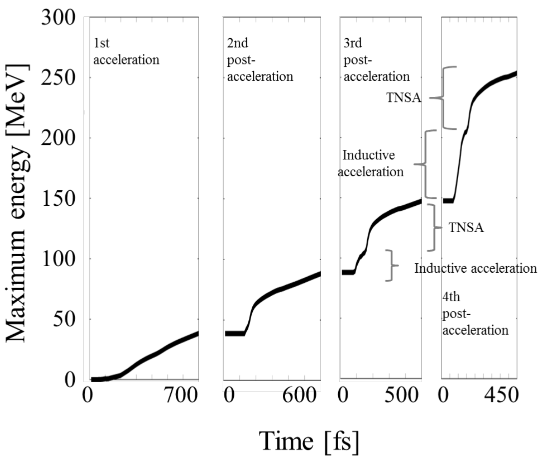
Proton distribution in space 3rd post-acceleration



Proton distribution in space 4th post-acceleration

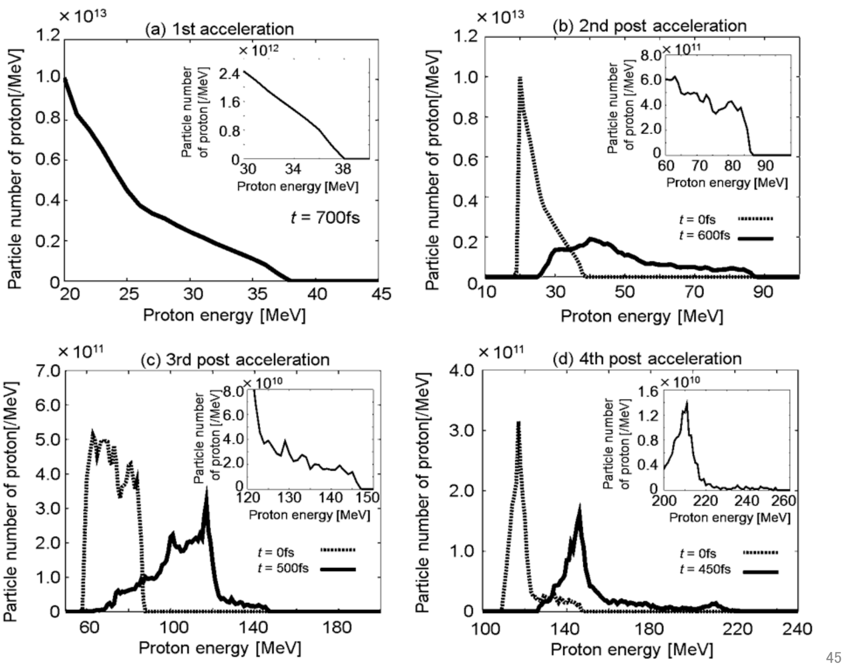


Maximal proton energy history

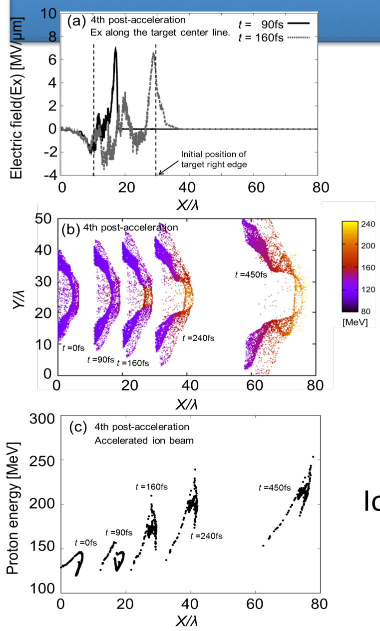


	Proton max energy [MeV]
1st	38.9
2nd	89.9
3rd	149
4th	254

1st & 2nd: TNSA
3nd & 4th: Inductive acceleration + TNSA



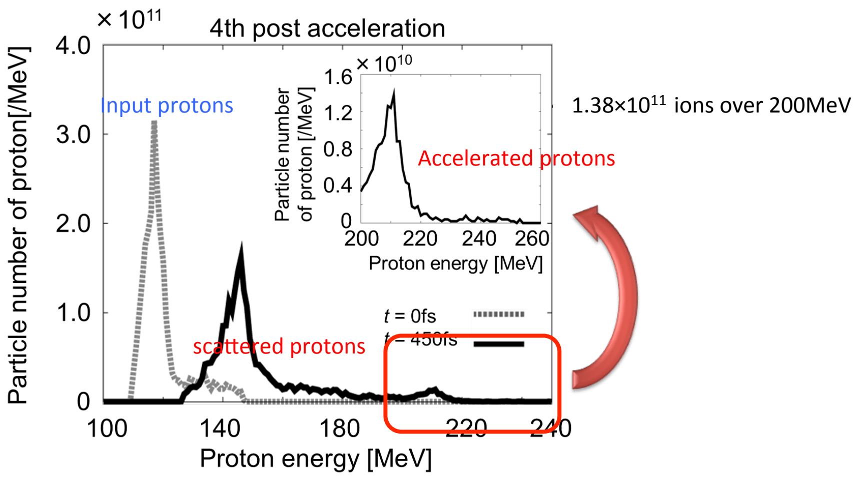
4th stage: Acceleration E field on the axis & ions



90fs<t<160fs: inductive acceleration
160fs<t: TNSA

Ions between 20λ < x < 30λ

Proton energy spectrum (4th post-acceleration)



Conclusions

Efficient controllable laser ion acceleration

1. Ion beam quality
   --- transverse divergence
   => Collimator (larger (>λ) hole structure)
   --- energy & spectrum control
   => Synchronization / multi stage acceleration / post acceleration, …
2. Low energy efficiency from laser to ion beam
   ~ a few % or less
   => sub λ fine structure / synchronization for a longer acceleration period
3. Total number of ions accelerated
   ~ 10^{12} particles or so
   => larger spot size, larger laser energy, …