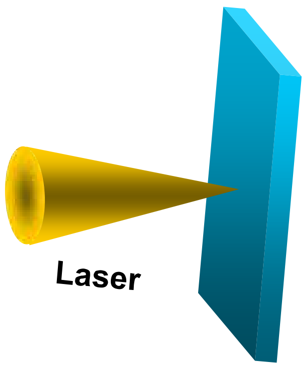
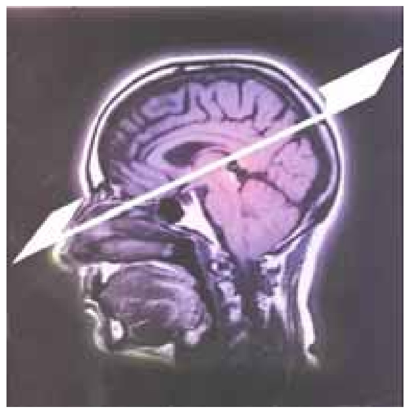
Efficient Laser Ion acceleration in an Intense-Short-Pulse-Laser Foil Interaction

- Ion Beam Radio Therapy
  => Compact Ion Accelerator

1) Collimated Ion Beam by a Multi-Hole Target
2) Possibility of Energy Spectrum Control

US-Japan Workshop September 7-8, 2009, San Francisco





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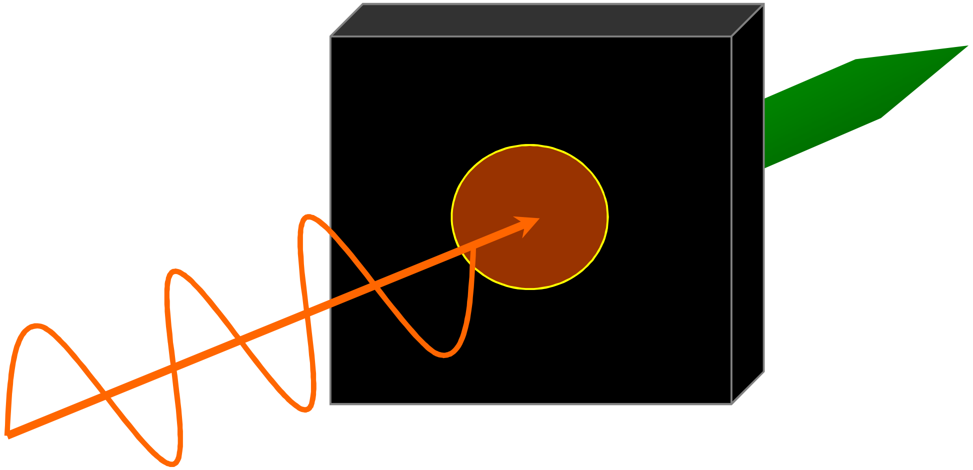
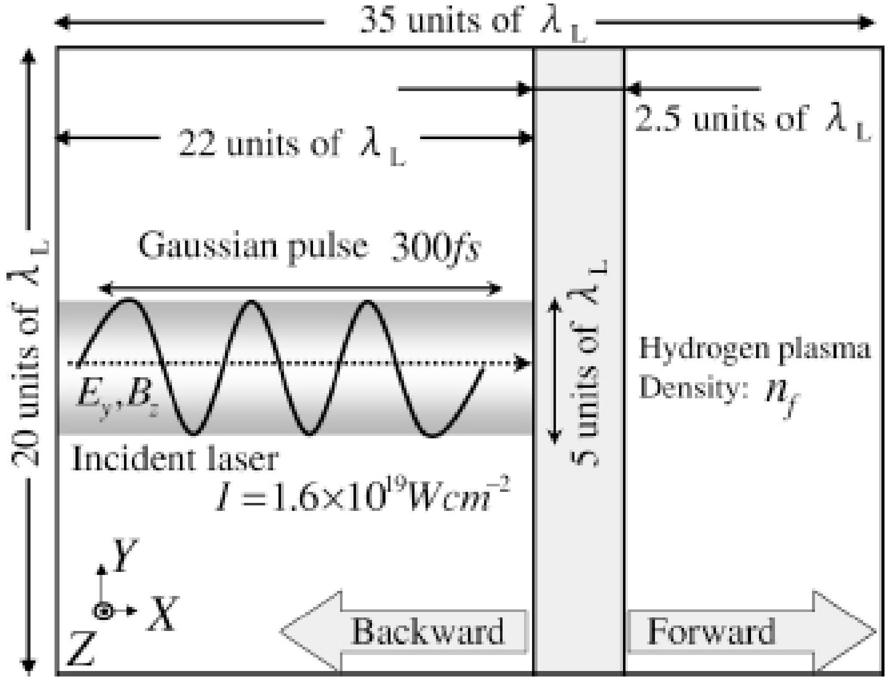
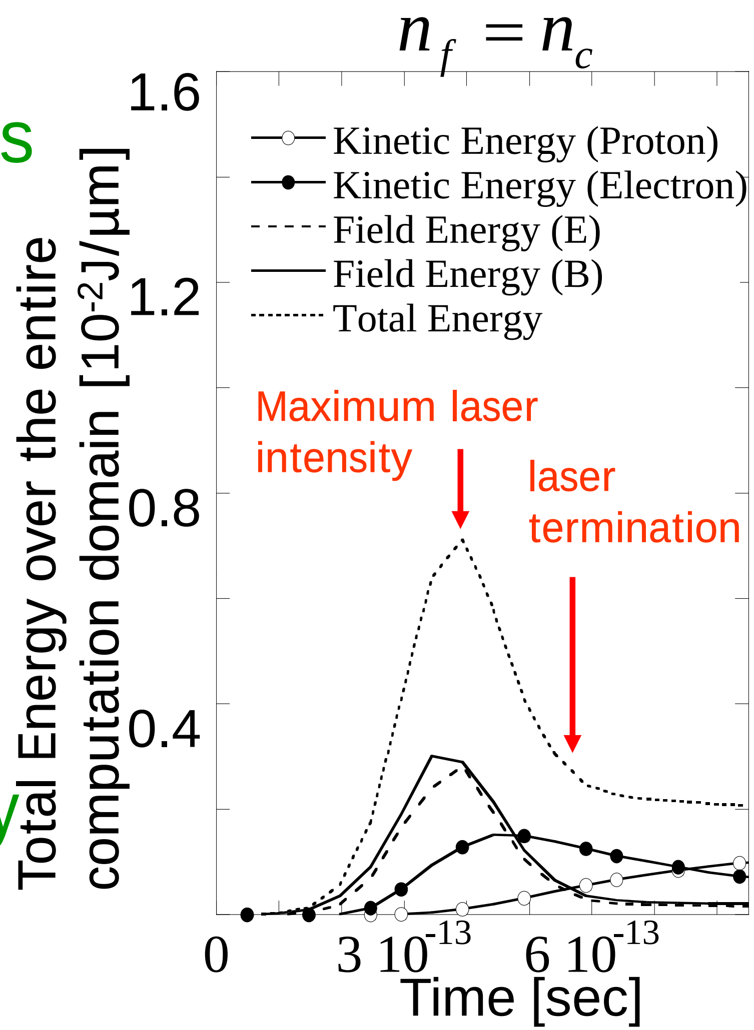
Laser Ion Accelerator





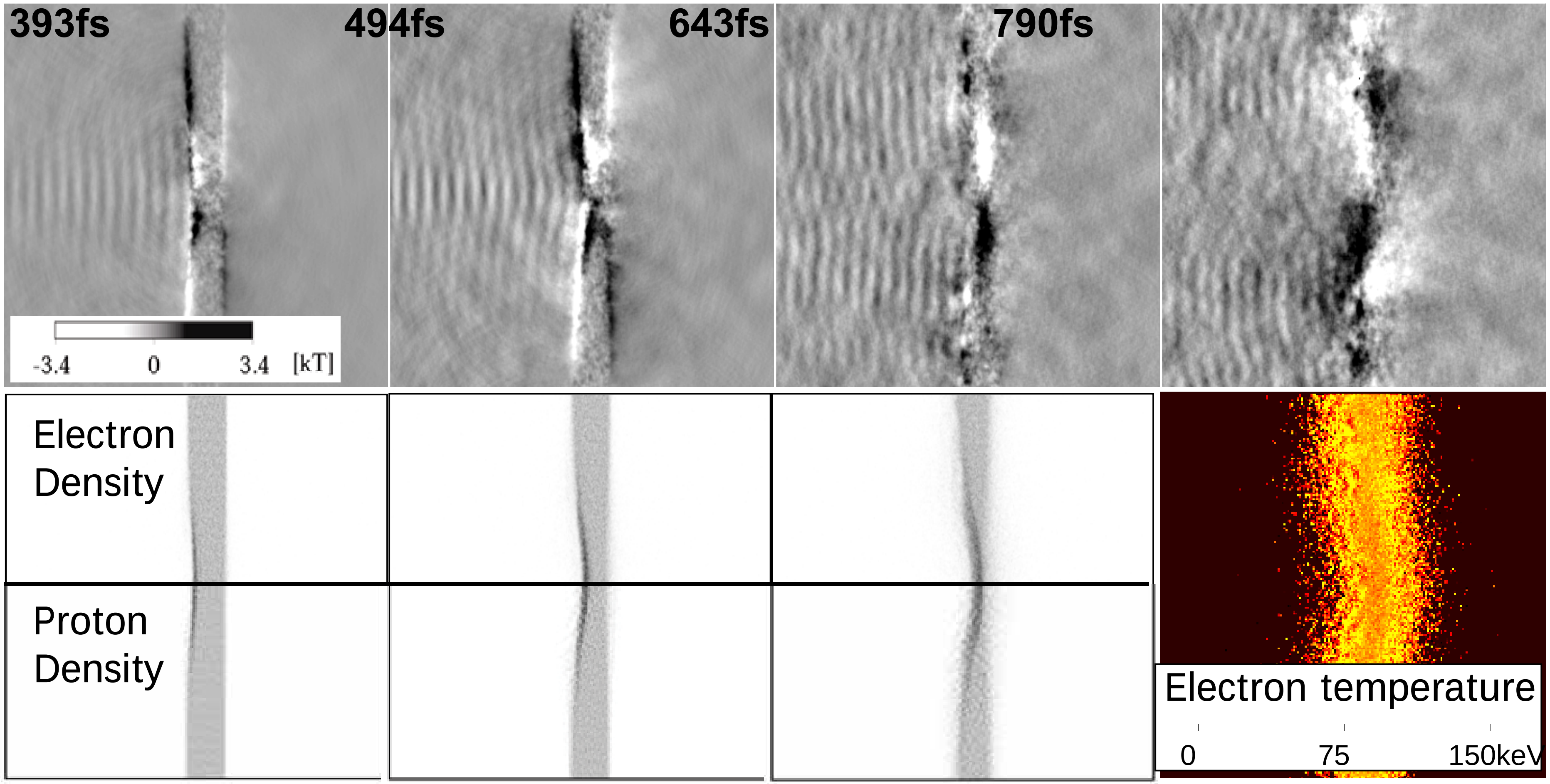
Continuous Increasing of the Electron Energy in Optimal Density

- Energy Storage as Excited Strong Electric and Magnetic Field.
- Continuous Energy Transfer to Electrons from the Stored Field Energy



Excited magnetic field ($n_f = 2n_c$)

Averaged magnetic field B_z^{avg} in one laser period.



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

Problems of Laser Ion Accelerator

1. Ion beam quality
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   --- energy spectrum control

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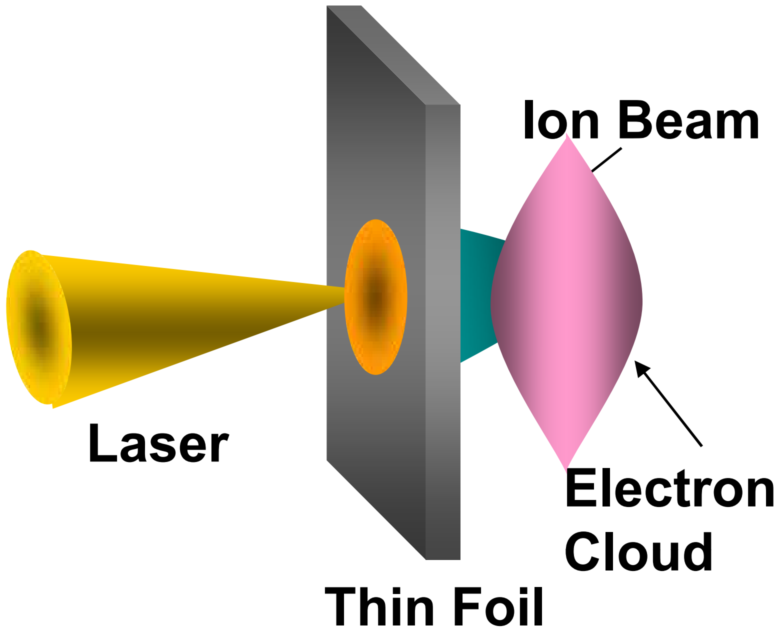
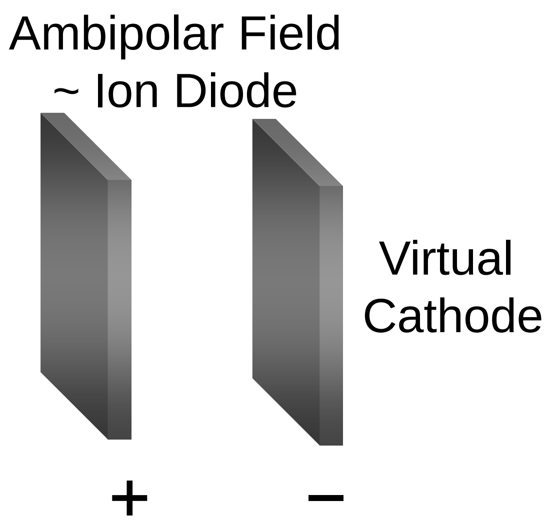
Collimated Ion Beam





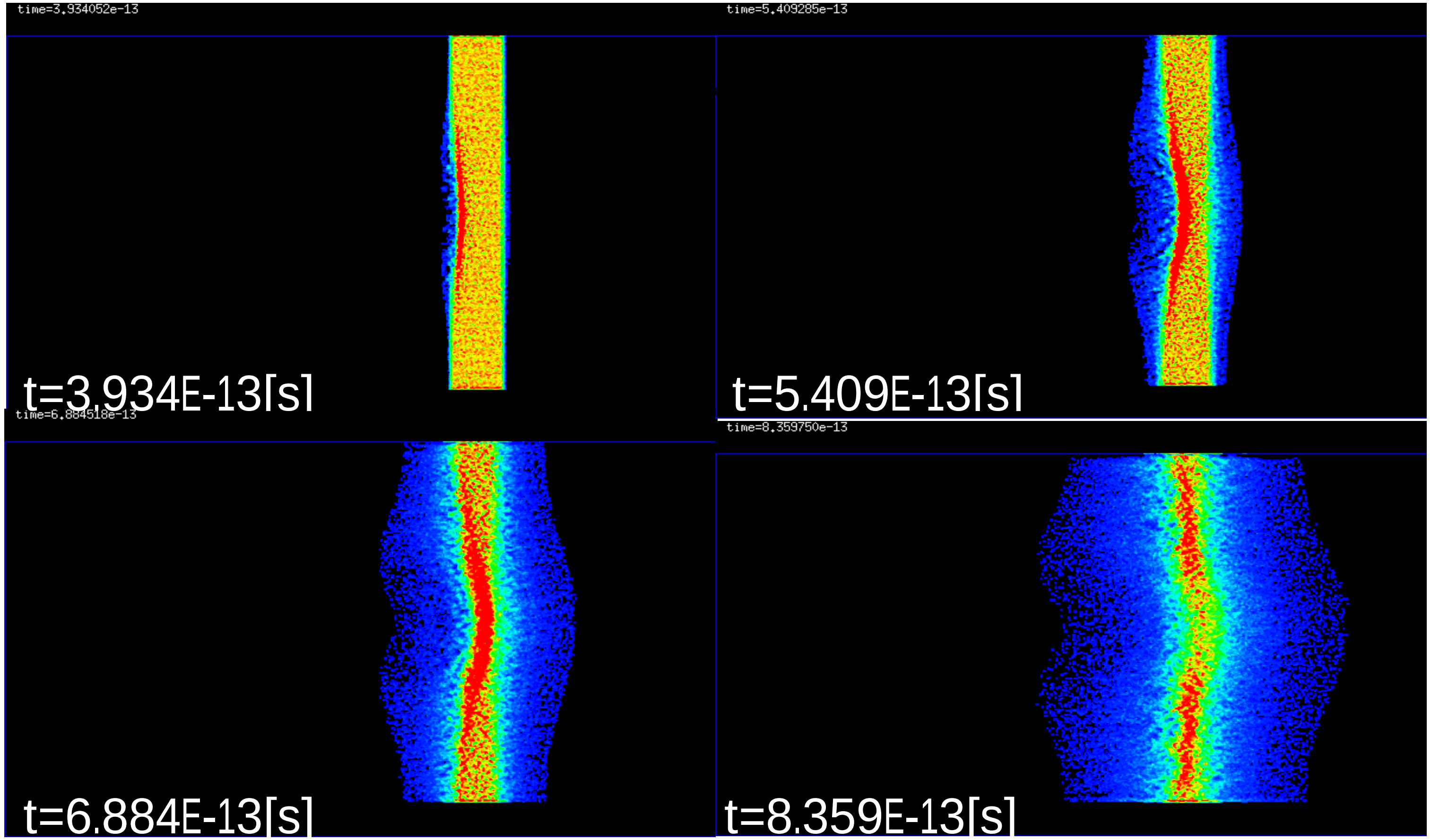
Origin of ion beam divergence:
/ Edge fields of ion source & electron clouds
/ Ion beam temperature

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

Simulation Results

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

Proton

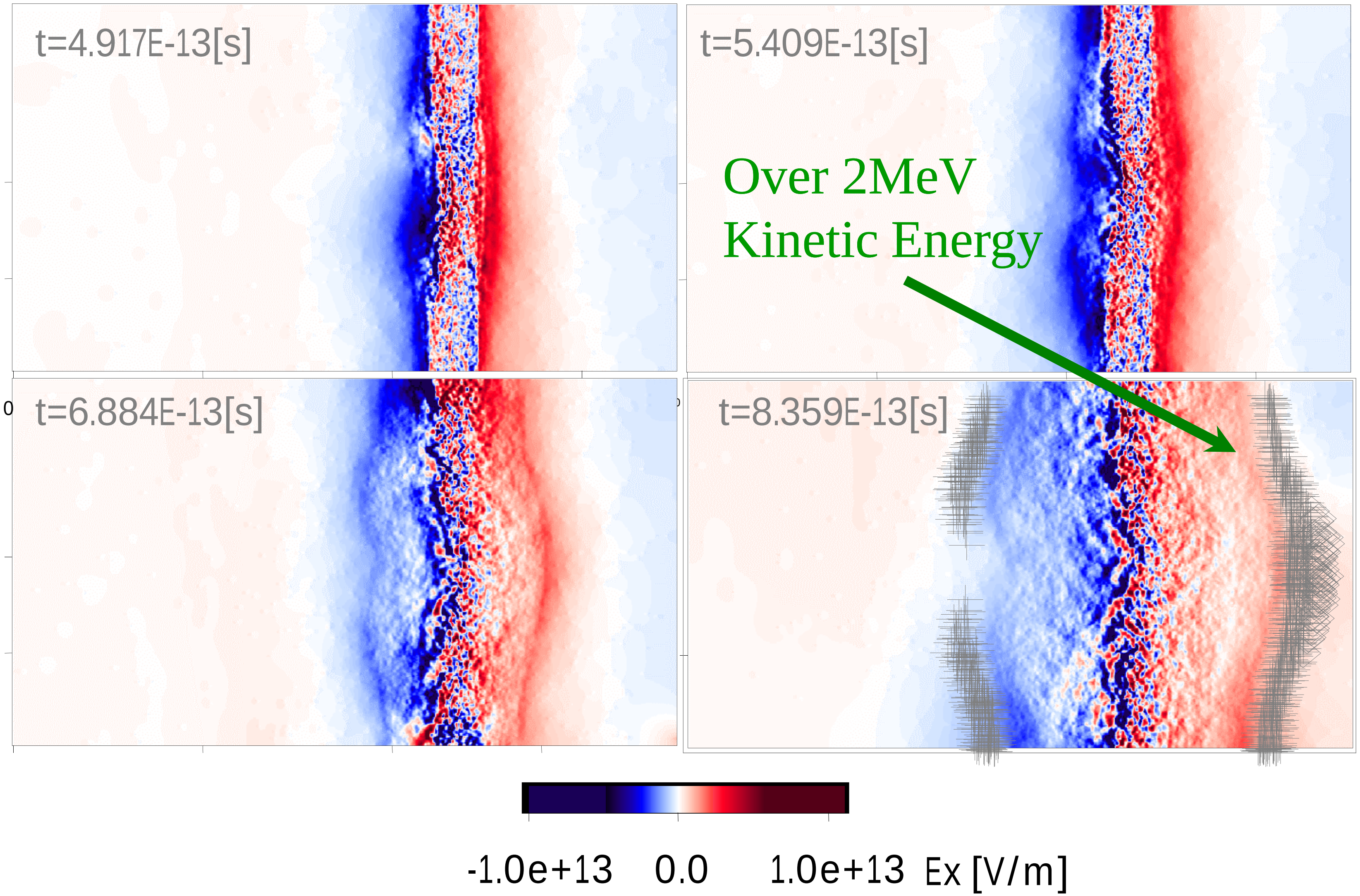


Maximum Kinetic Energy of Proton

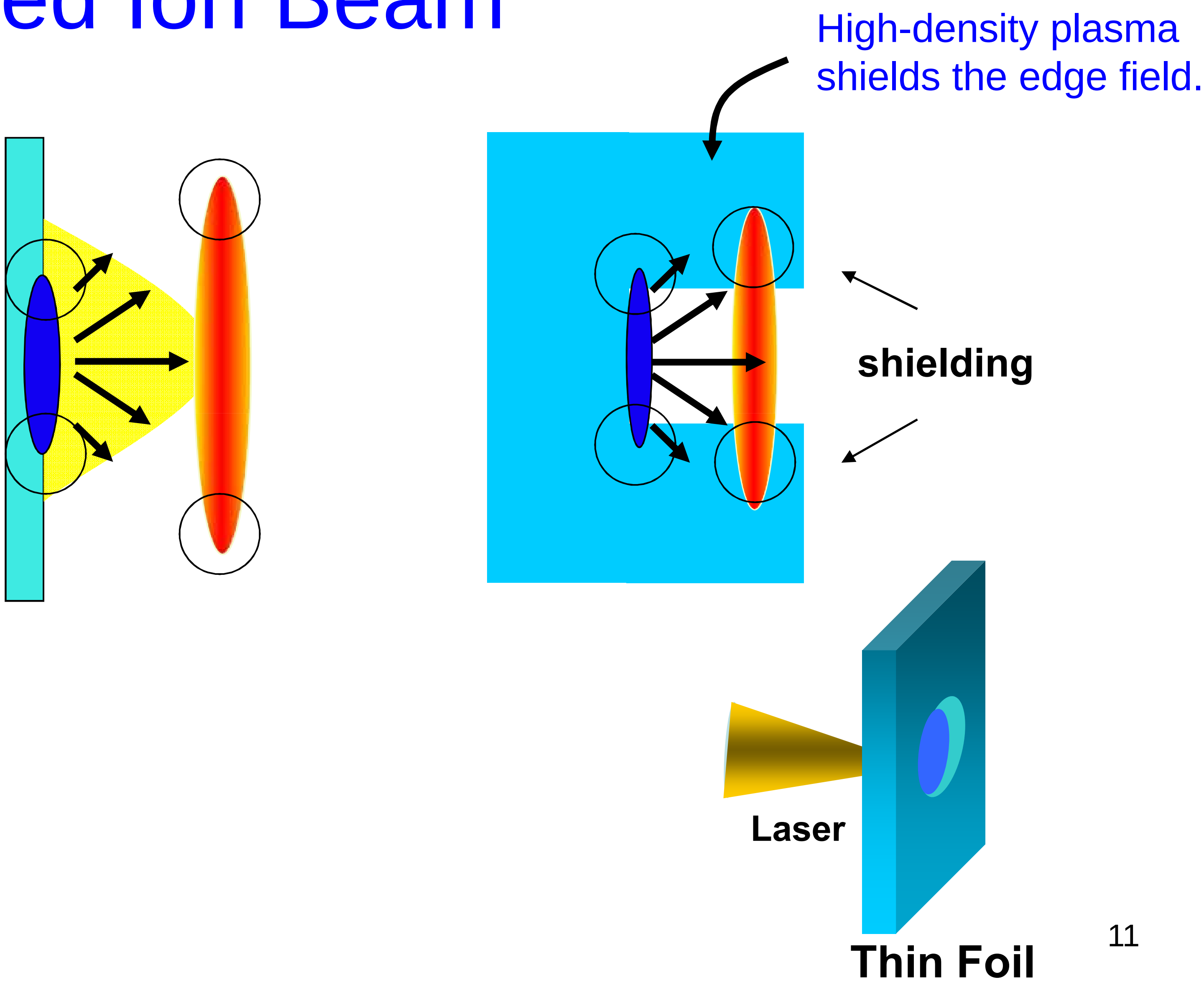
Forward: 3.73[MeV] Backward: 2.89MeV

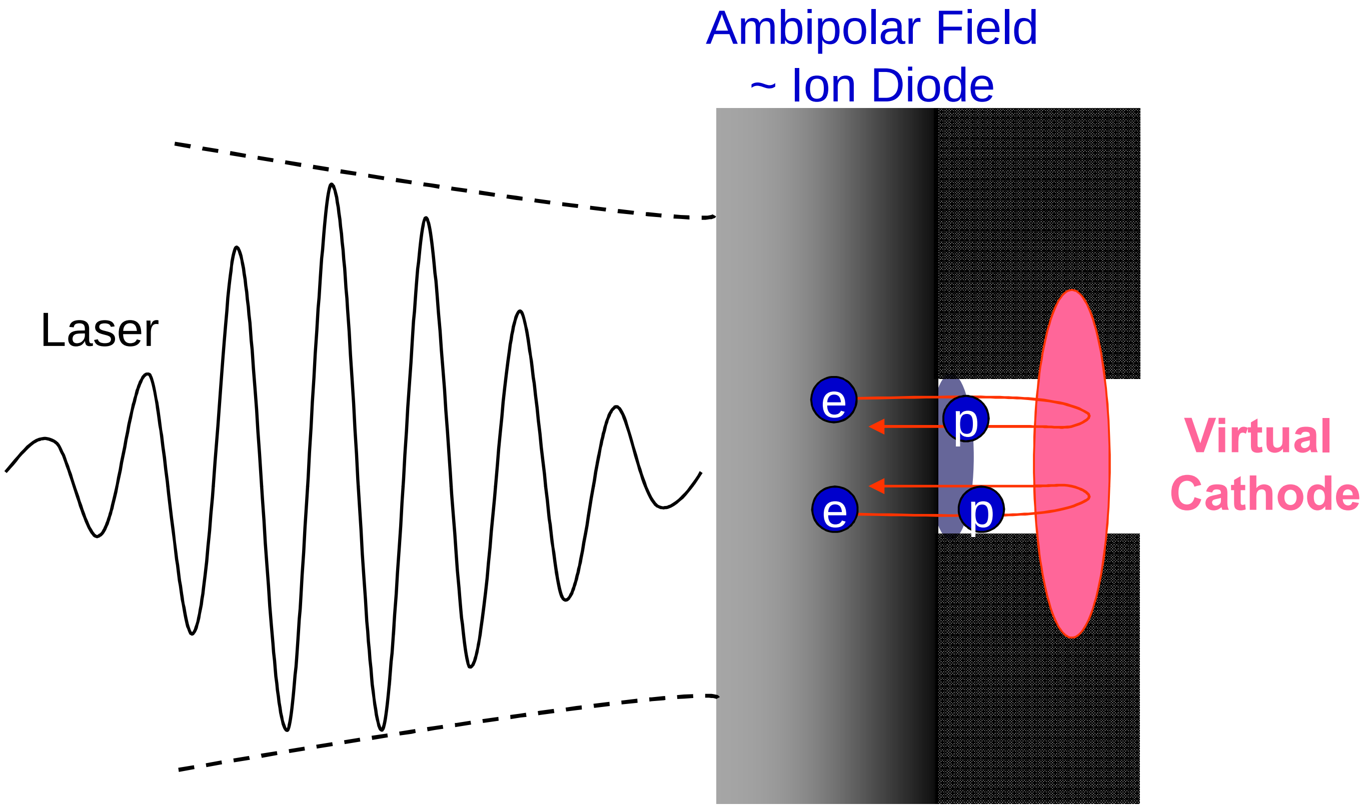
Simulation Results

Electrostatic Field (Time developmet of Ex)

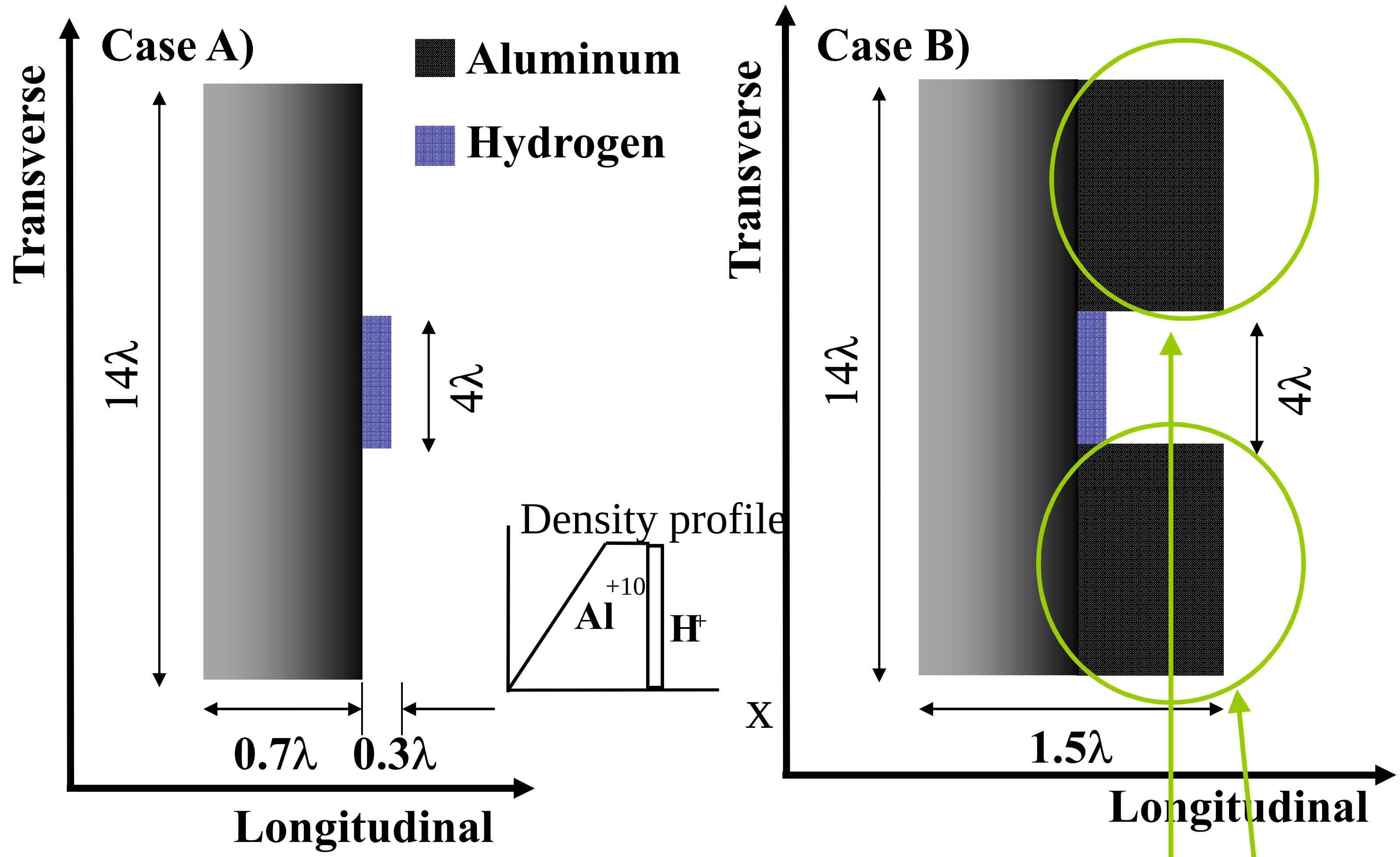


Collimated Ion Beam




Ambipolar Field
~ Ion Diode
Laser
e
p
e
p
Virtual
Cathode

Initial Target Profile

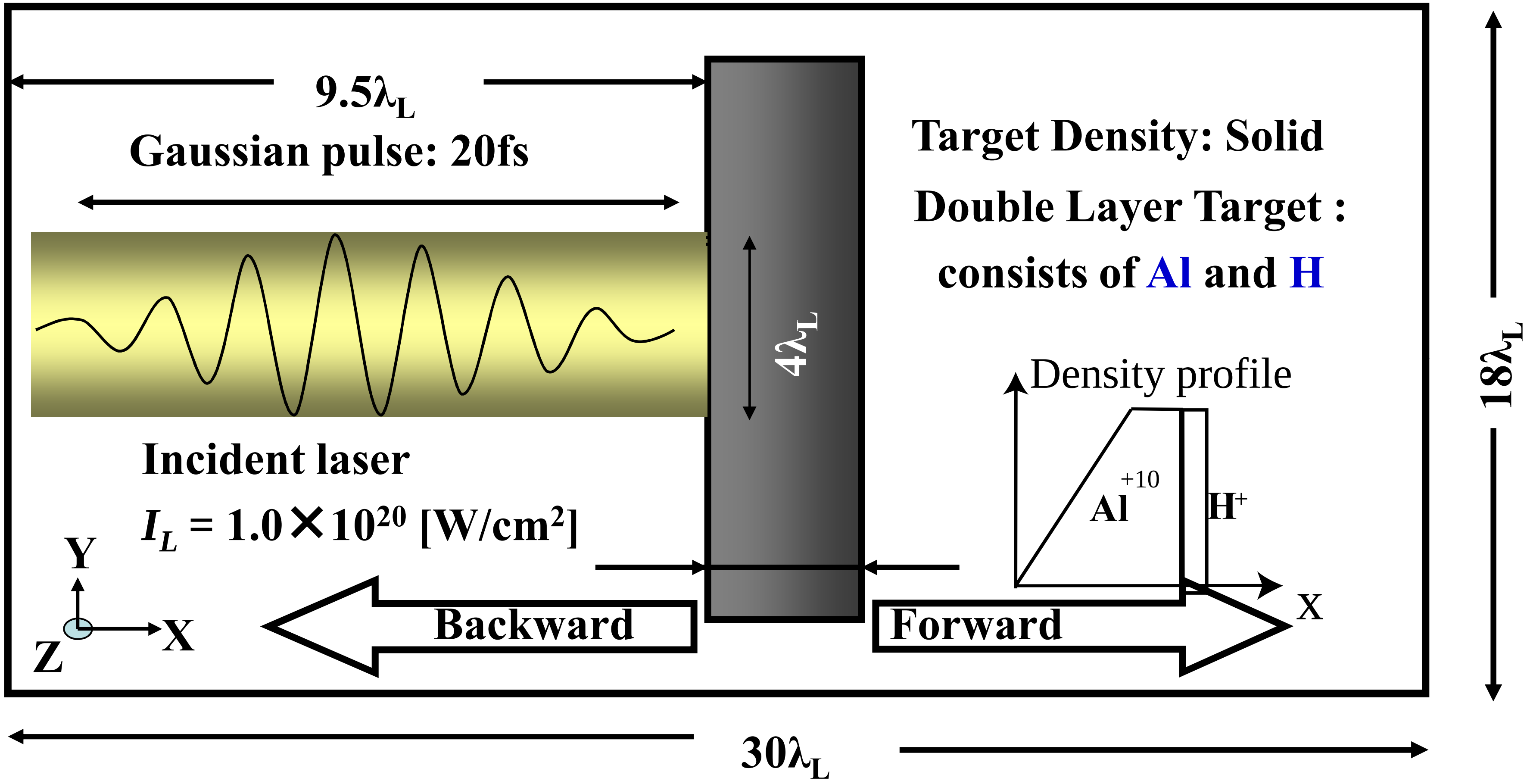


Target of Case A is the conventional slab foil plasma.

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



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 × 10^{20}[W/cm^2]

  Laser spot diameter: r_L = 4λ_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])

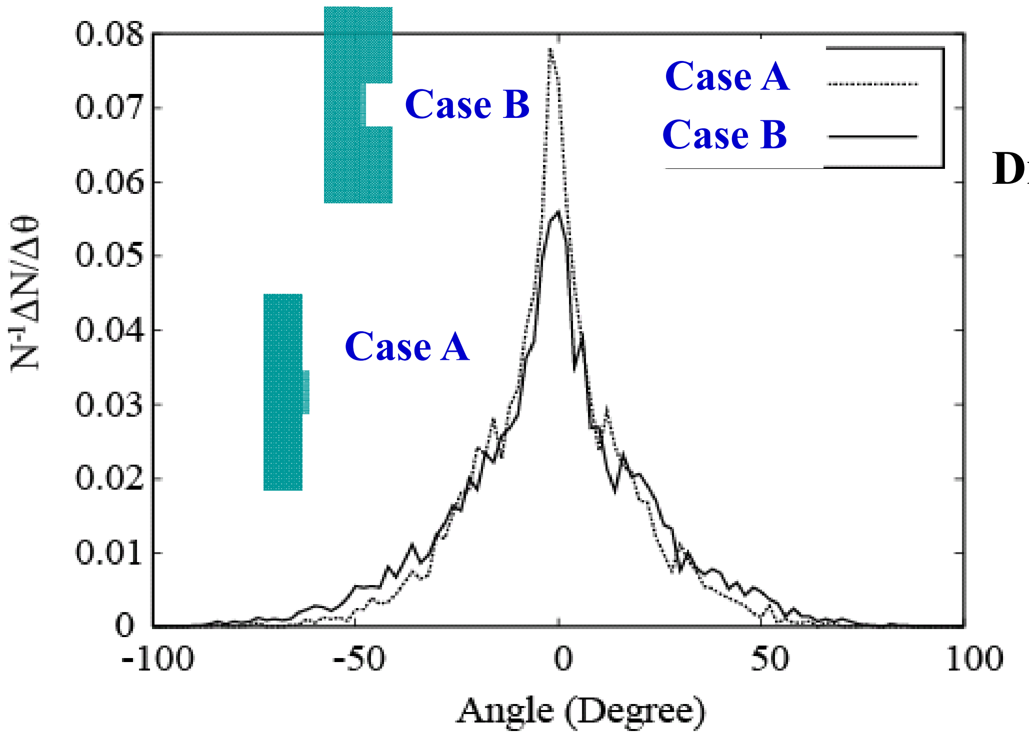
- **Calculation conditions**

  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

Estimation of Divergence Angle



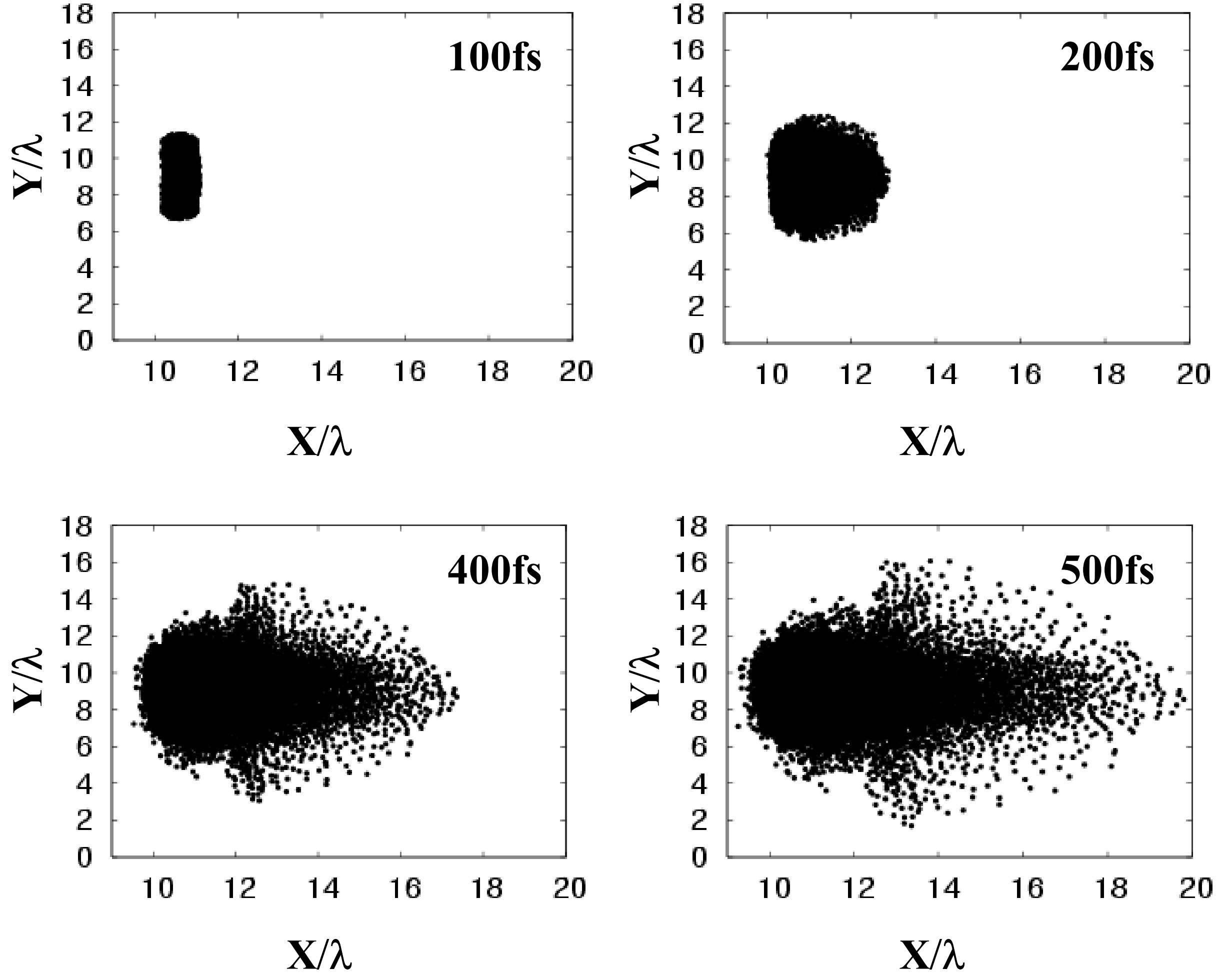
Divergence Angle: $\dfrac{\sqrt{\sum_{i=1}^{N}(\Delta\theta)^2}}{N}$

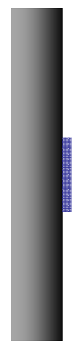
Case A : 2.805 **Case B 2.399**

N: total particle number of the proton beam.
$\Delta\theta = \mathit{arctan}(v_y/v_x)$.

These values also mean that the proton beam divergence in case of the target with the hole is suppressed compare with that the case of the conventional slab target. The proton beam quality in Case2 is controlled by the electron cloud localization, which is realized by the configuration of the plasma target (Case2).

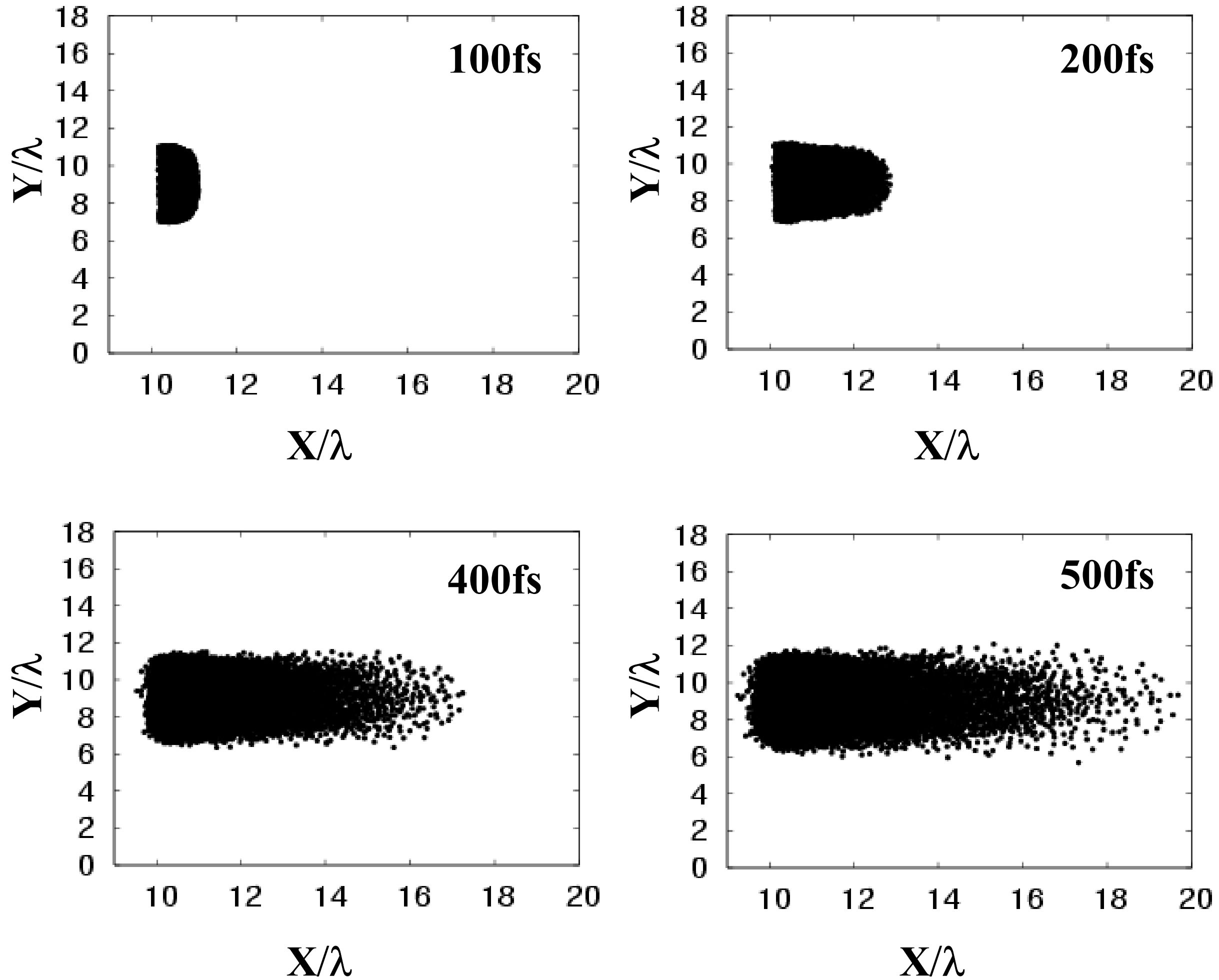
Proton Distribution in X-Y Space in Case A

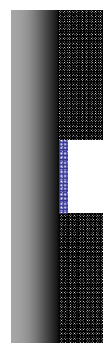




Case A

Proton Distribution in X-Y Space

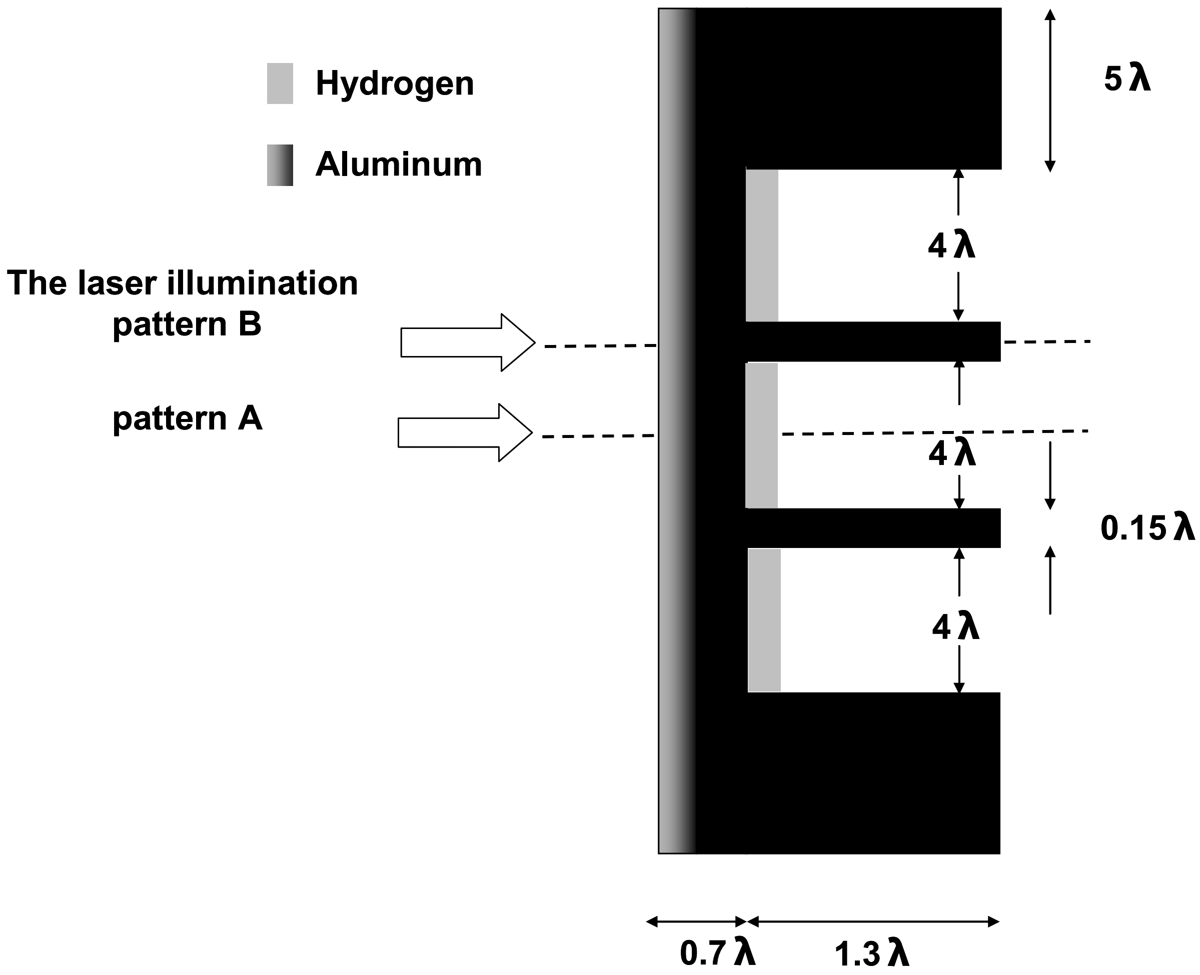




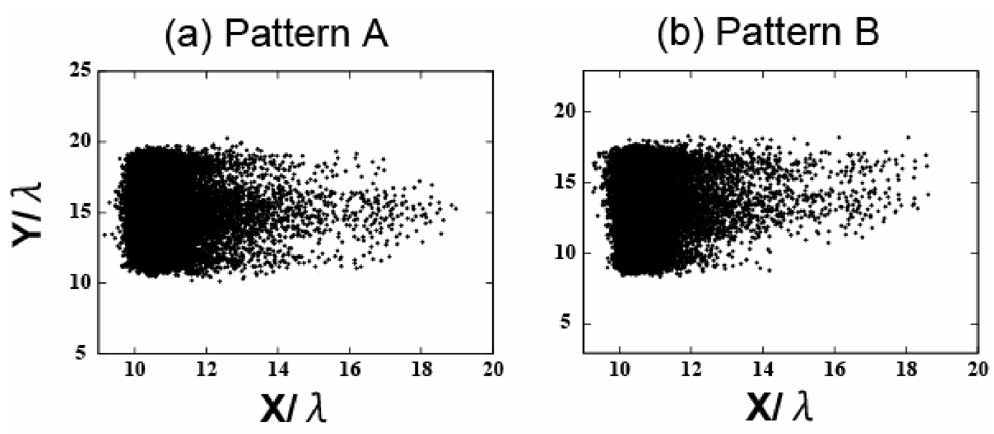
Case B

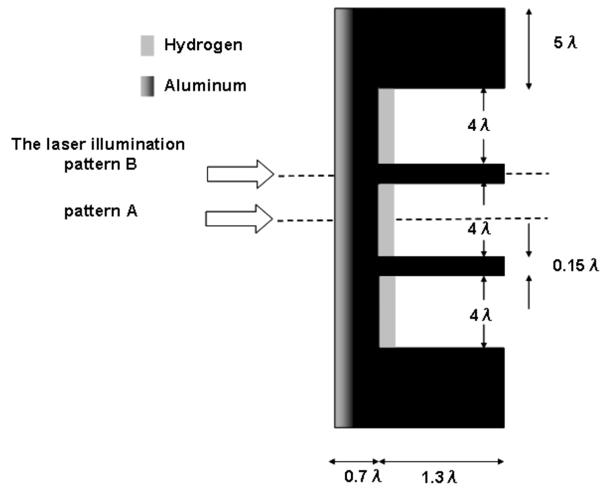
The proton beam transverse divergence of CaseB is suppressed successfully by the shaped target and the electron cloud localization.

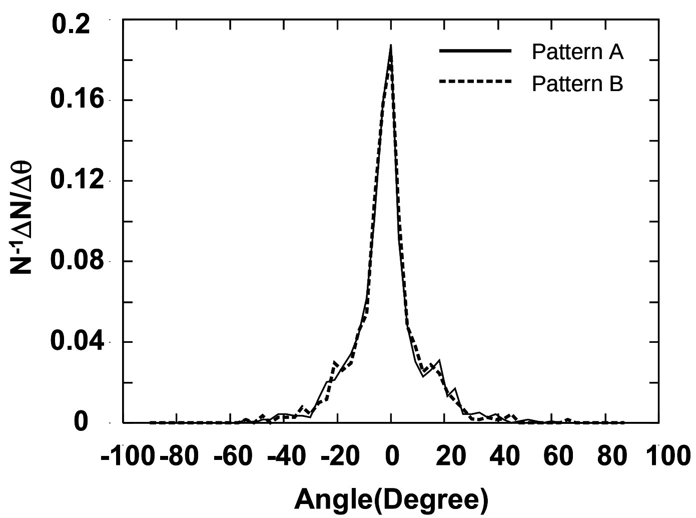
Robust hole target against laser alignment

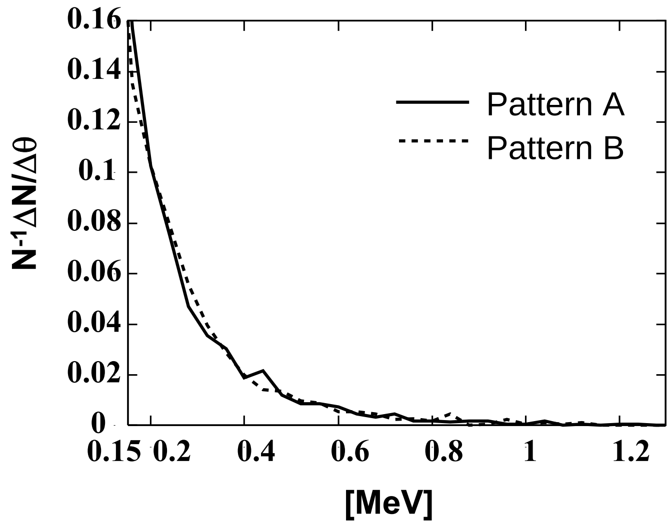


Robust hole target against laser alignment





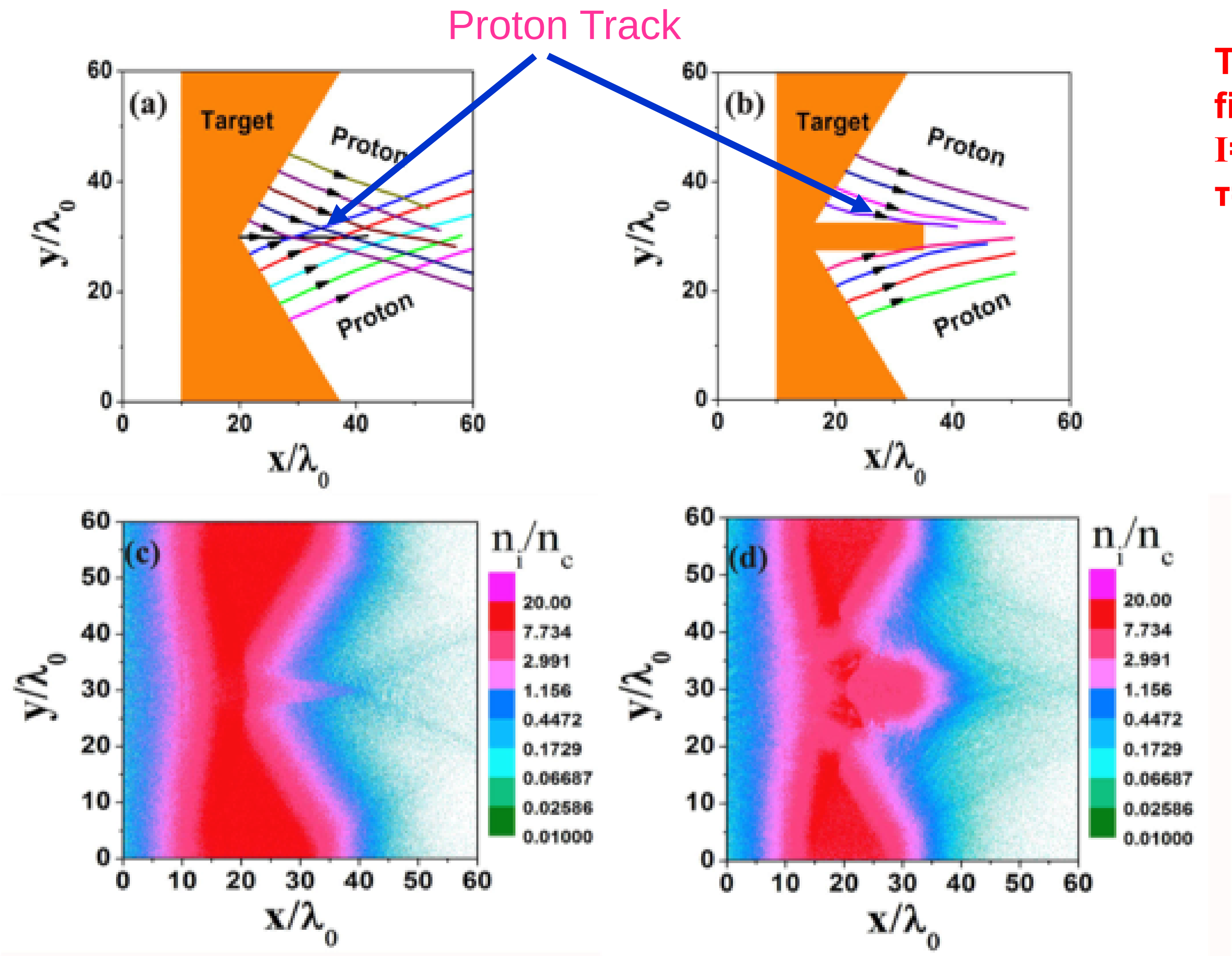




Collimated proton beam from umbrella-like target

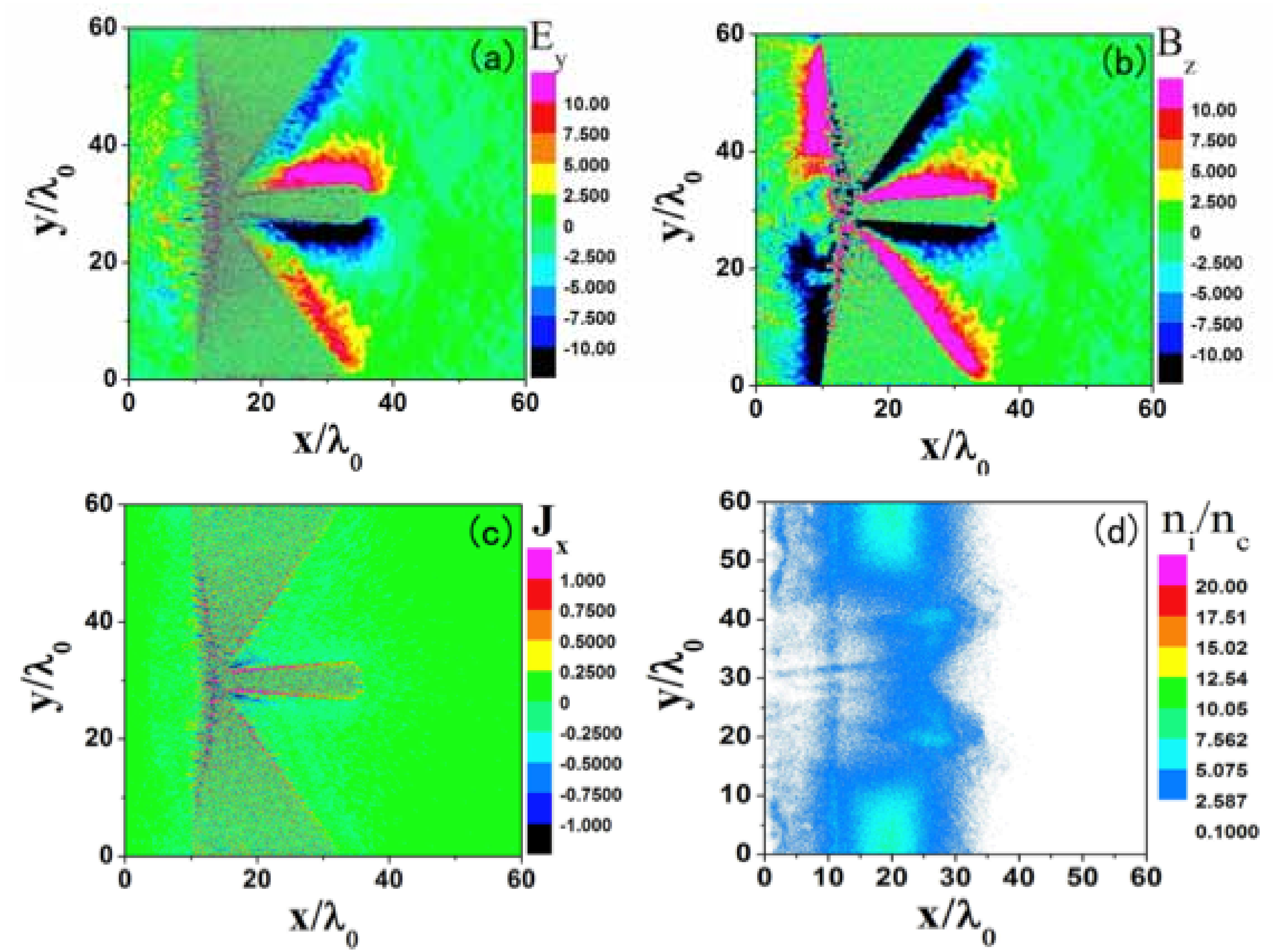
***Y.Y. Ma, et al.*, Physics of Plasmas, 16(3), 034502, 2009.**

Conic cavity target vs umbrella-like target



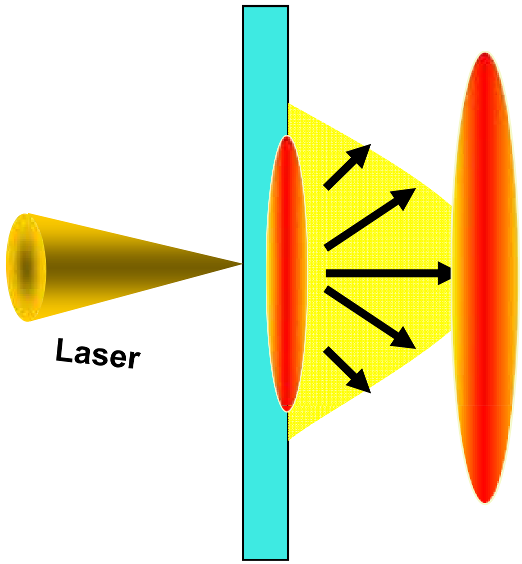
The wall：$8n_c$
filament：$12n_c$
$I=10^{20}W/cm^2$
$\tau=10T$

Umbrella-like target



208*T*

Energy Efficiency Enhancement
From Laser to Ion Beam

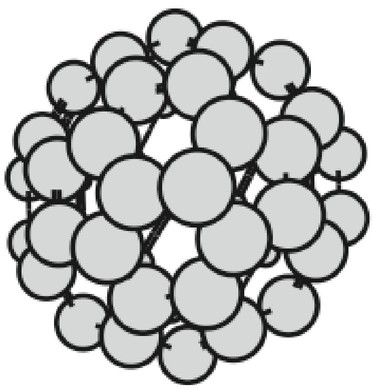


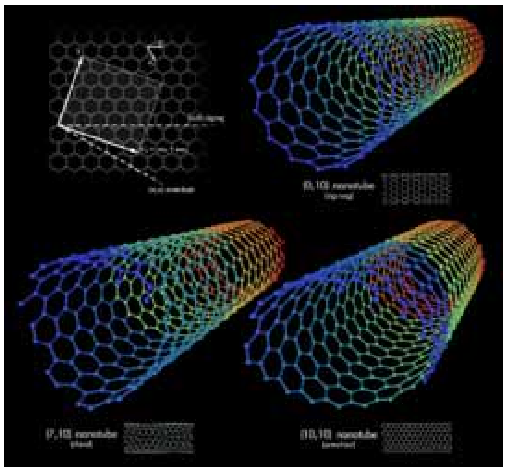
2. Low energy efficiency from laser to ion beam

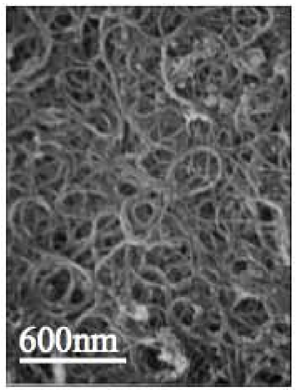
~ a few % or less

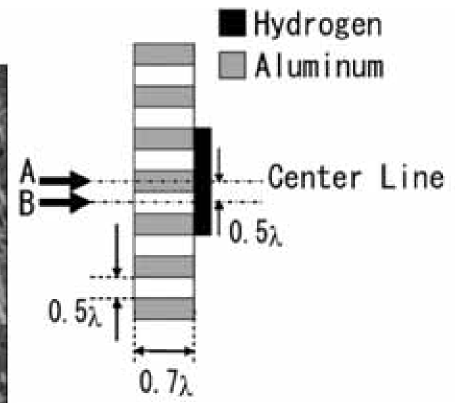
⇔

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









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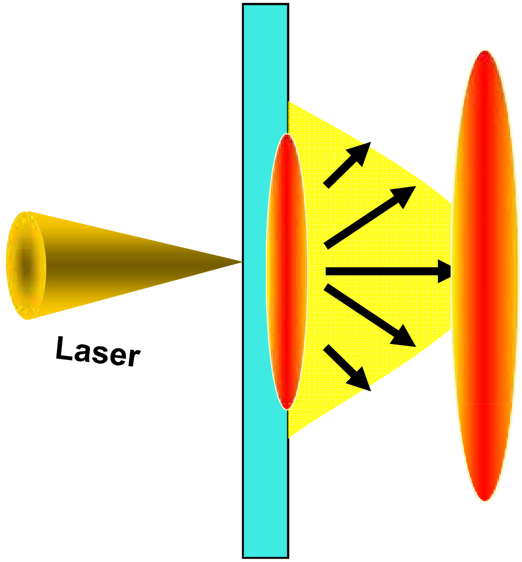
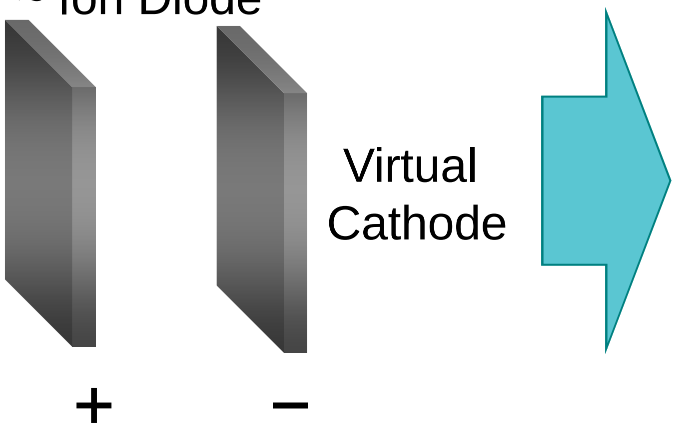


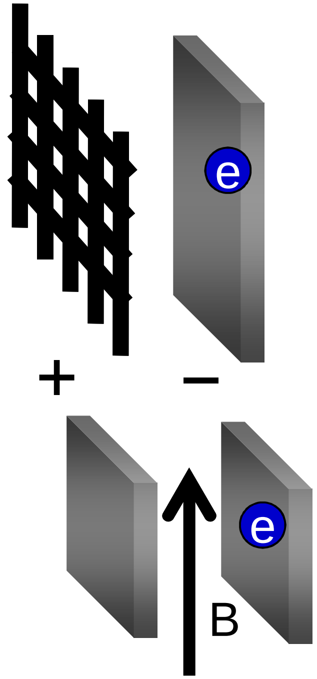
2. Low energy efficiency from laser to ion beam
   ~ a few % or less

⇔

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

Ambipolar Field
~ Ion Diode

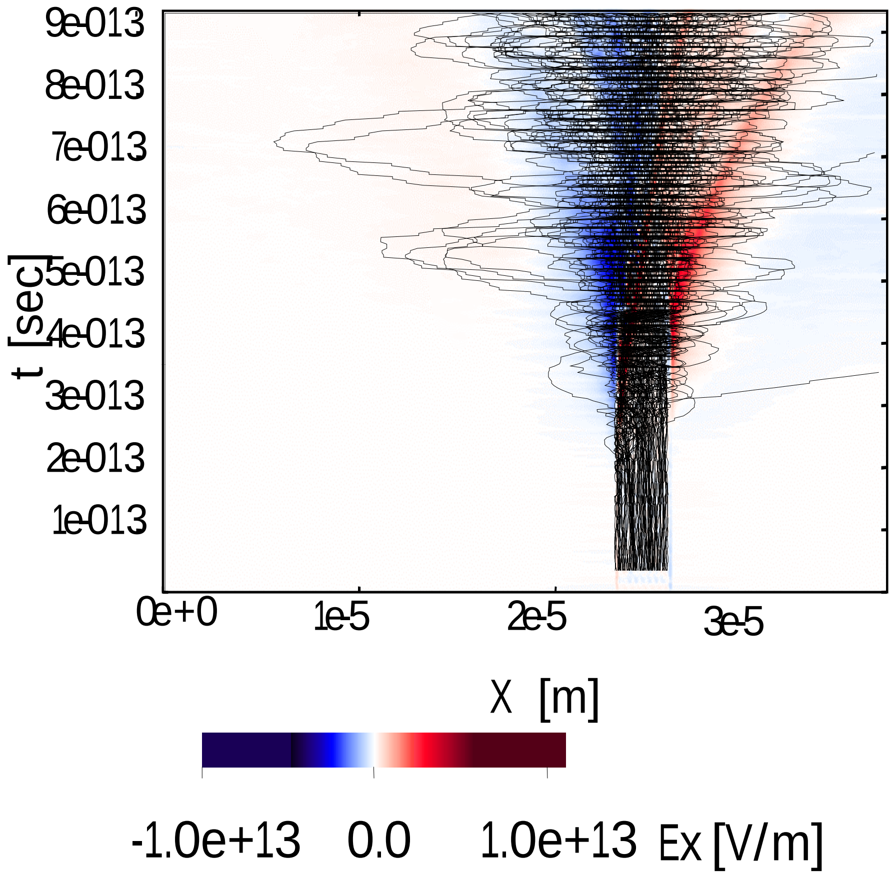




Ion Acceleration

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

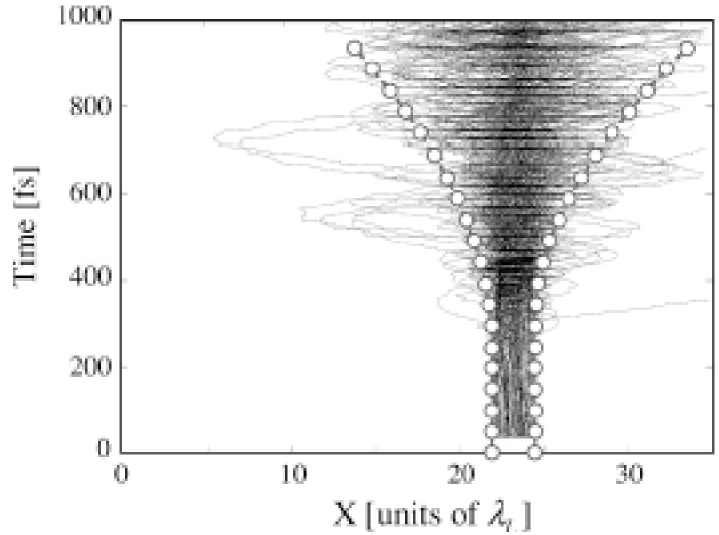
Electron trajectory



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



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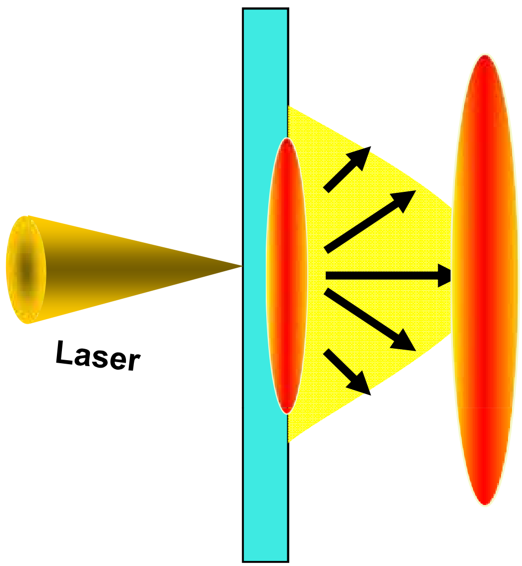

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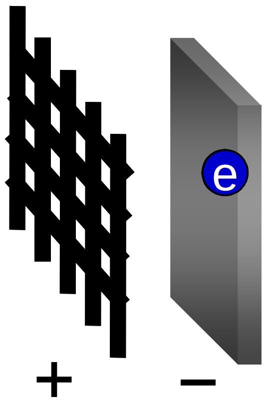
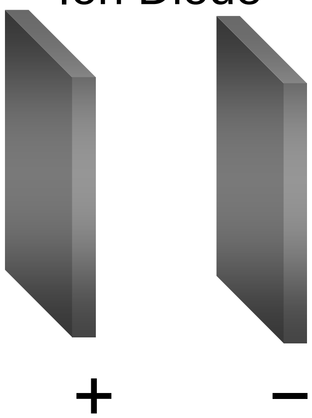
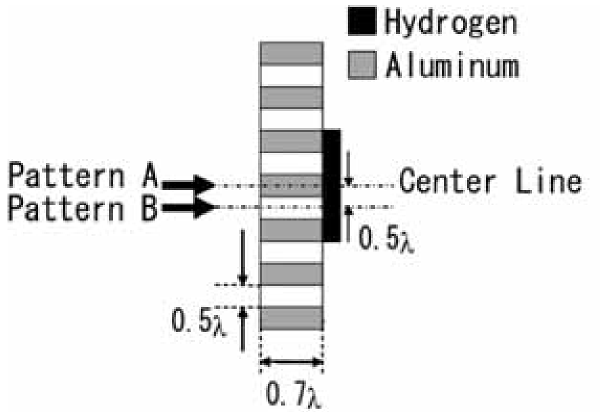
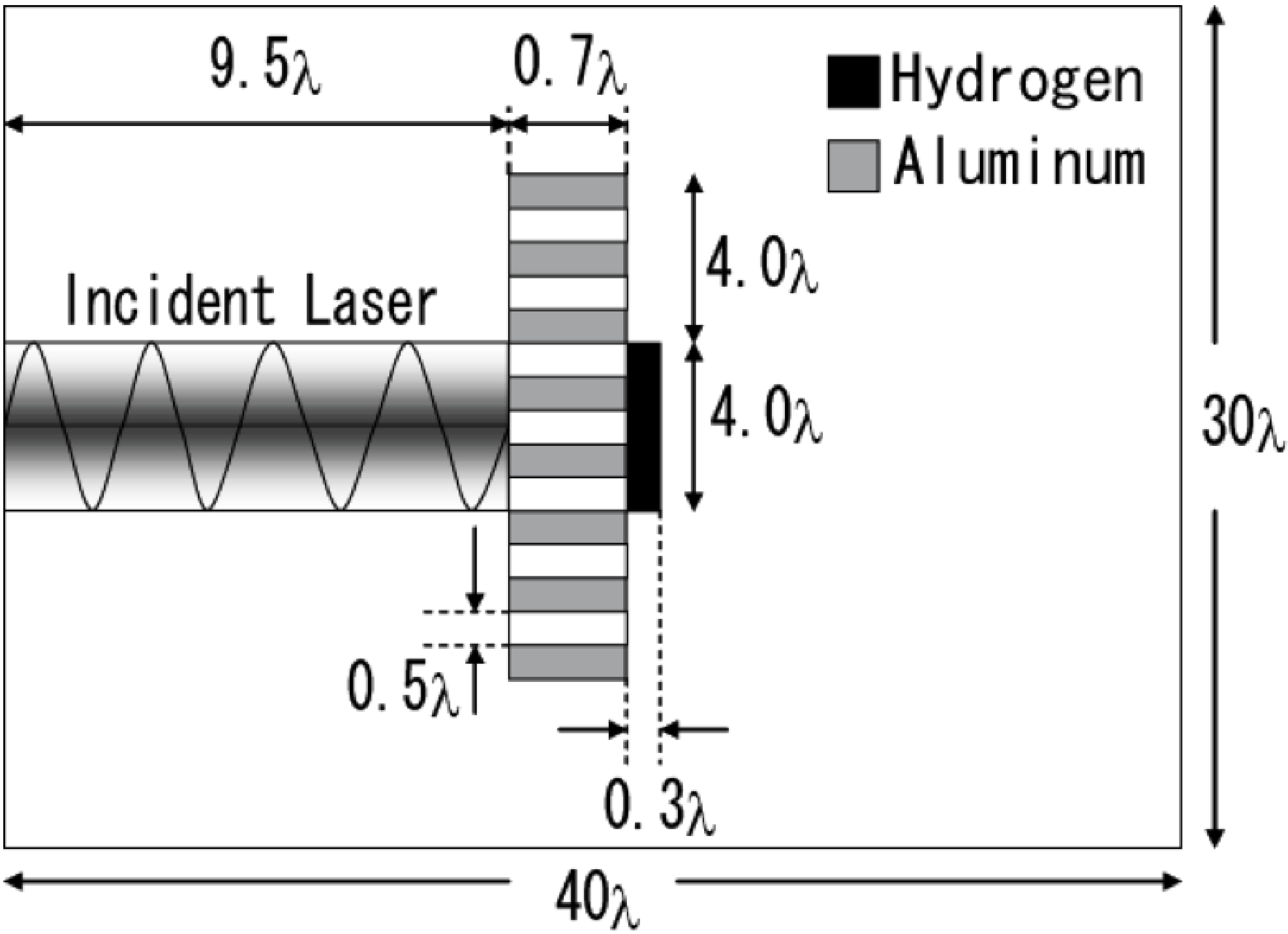


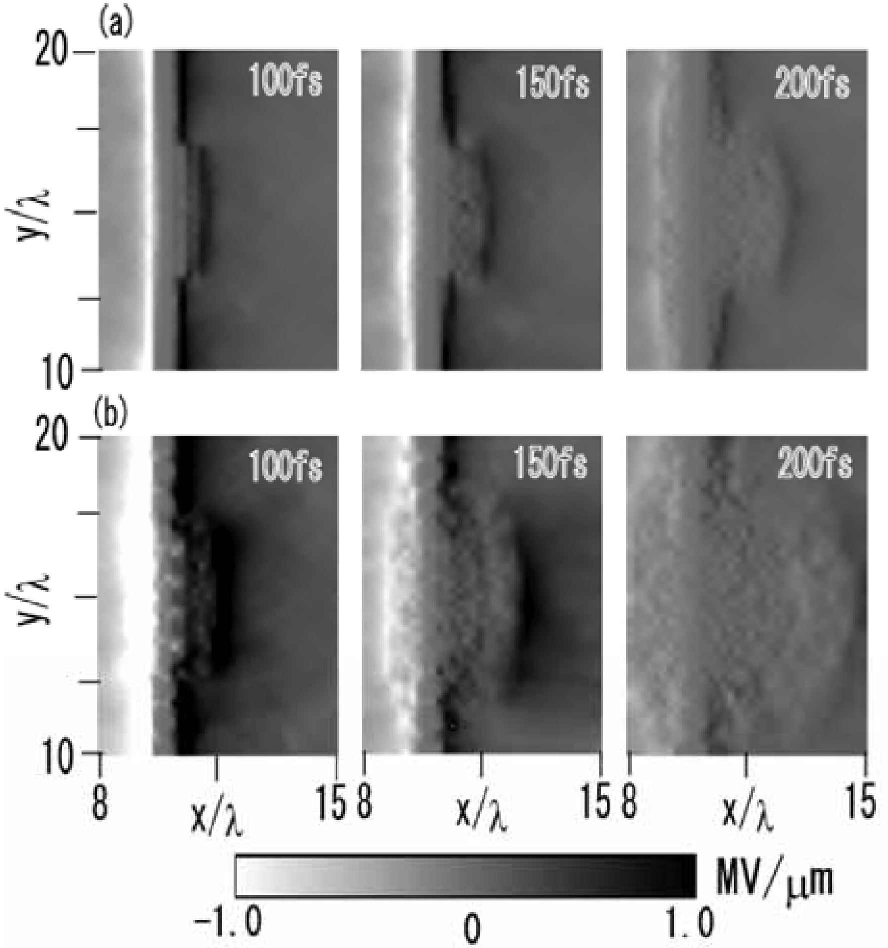
Ambipolar Field
~ Ion Diode

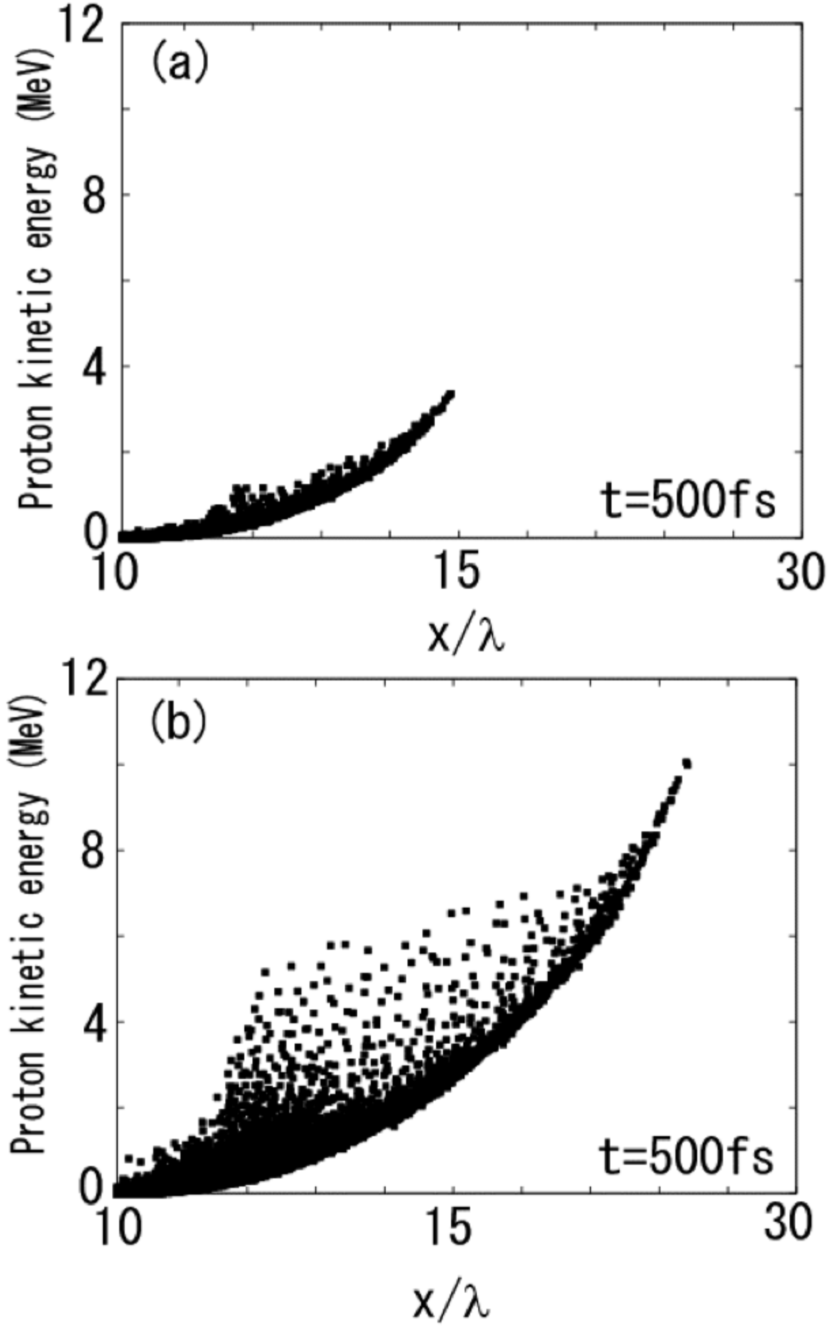


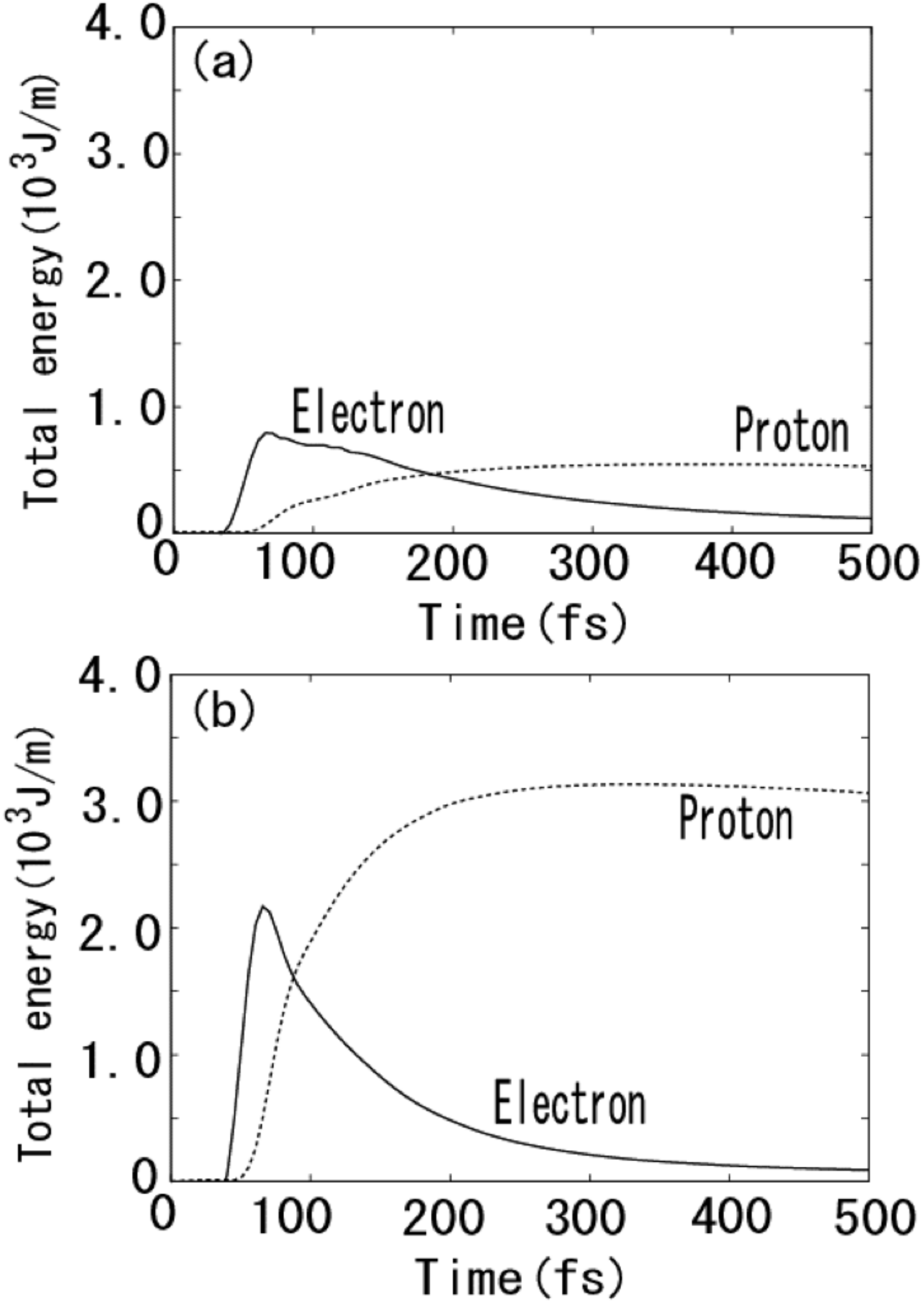
Virtual
Cathode




9.5λ
0.7λ
Hydrogen
Aluminum
4.0λ
Incident Laser
4.0λ
30λ
0.5λ
0.3λ
40λ


(a)
20
10
y/λ
100fs
150fs
200fs
(b)
8
x/λ
15
MV/μm
-1.0
0
1.0


(a)
12
8
4
0
Proton kinetic energy (MeV)
t=500fs
10
15
30
x/λ
(b)


(a)
Electron
Proton
Total energy (10^{3}J/m)
4.0
3.0
2.0
1.0
0
0
100
200
300
400
500
Time (fs)
(b)
Proton
Electron
Total energy (10^{3}J/m)
4.0
3.0
2.0
1.0
0
0
100
200
300
400
500
Time (fs)

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1. Ion beam quality
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   --- energy spectrum control <=

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

3. Total number of ions accelerated
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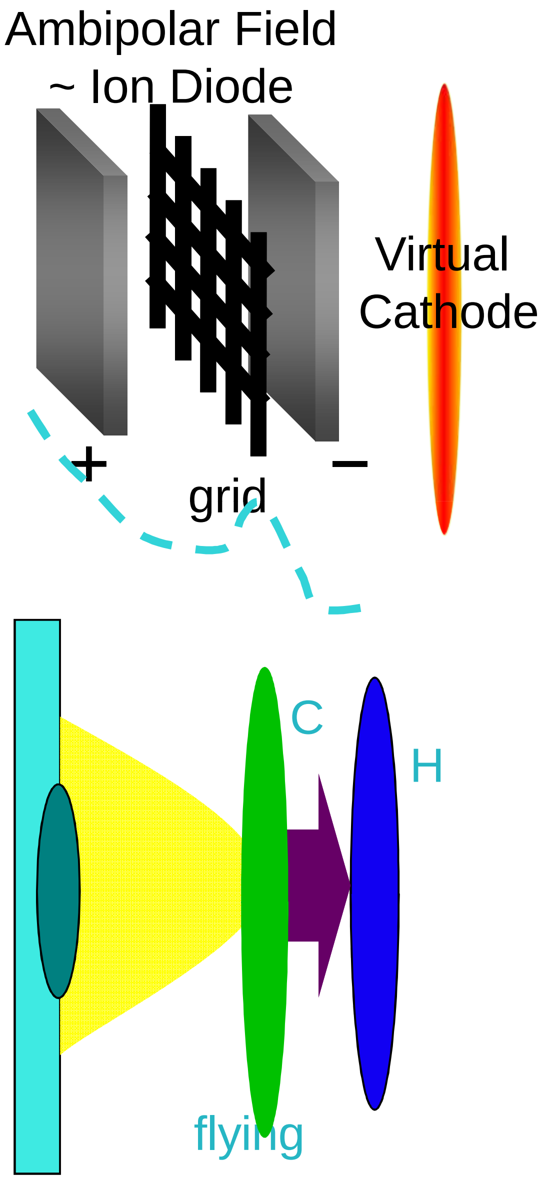
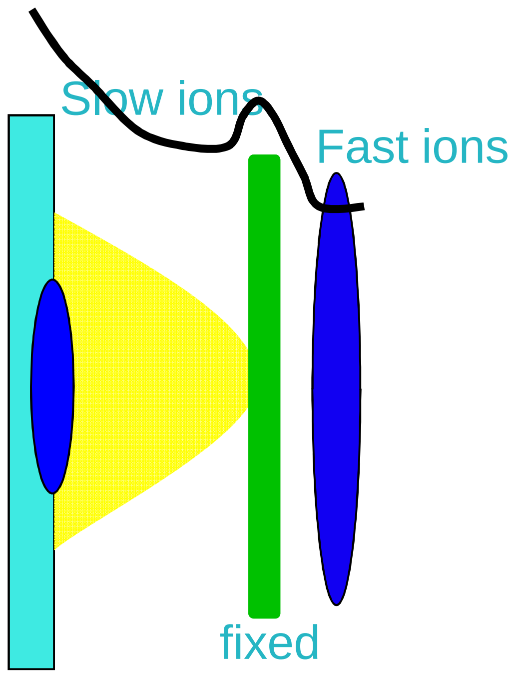
Energy Spectrum Control

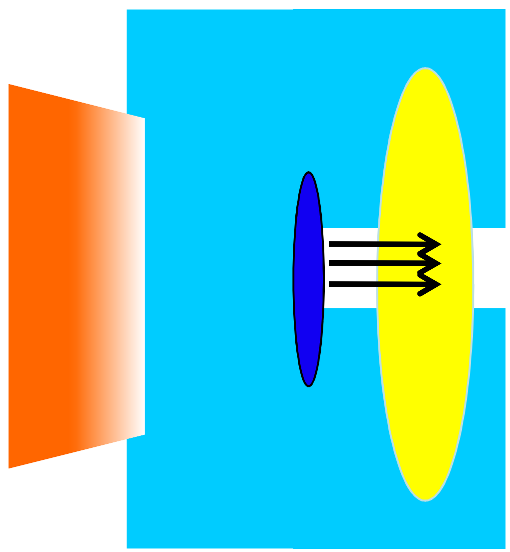


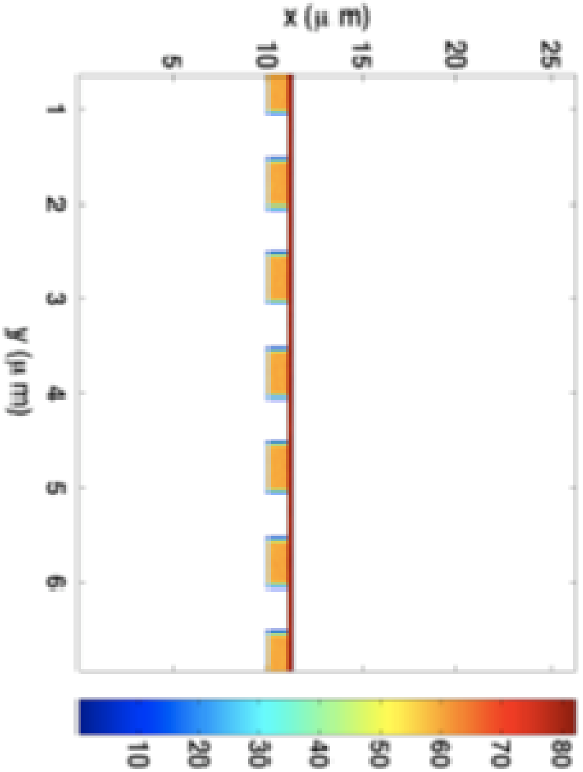
1. Ion beam quality
   --- energy spectrum control

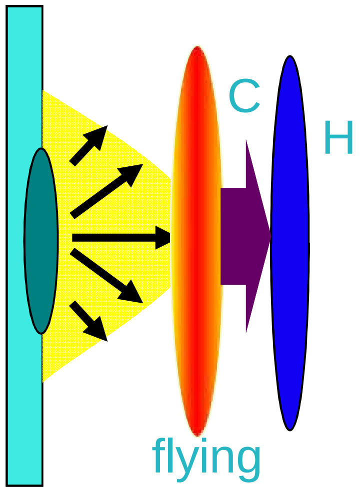
⇔

/ very thin ion source < skin depth
/ double layer – flying or fixed



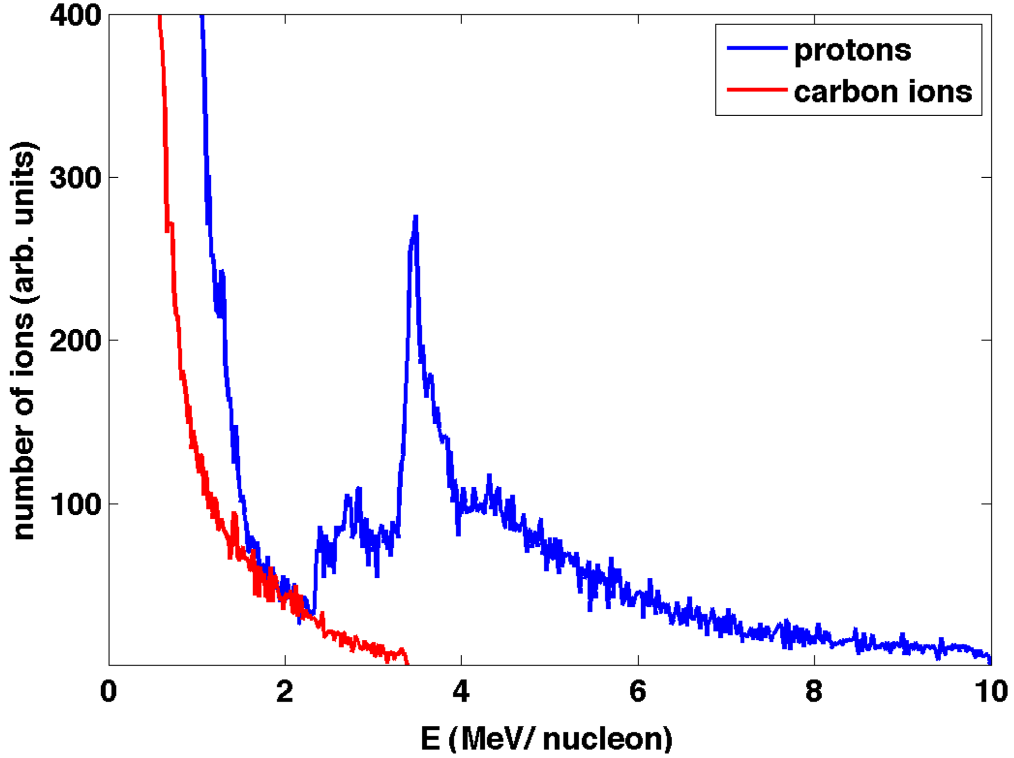






Laser: intensity 10^{20} W/cm^2
wavelength 1 μm
duration 15 fs
pulse shape $\sin^2$
polarization P
spot size 3 μm
incidence angle 0°

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



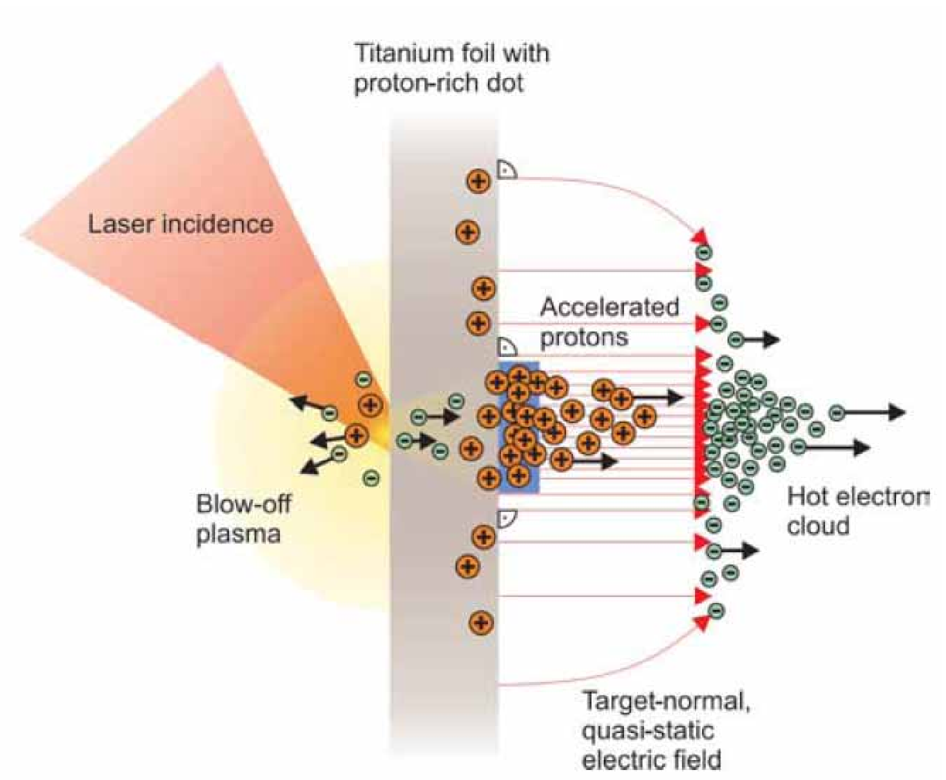
case 3 periodic array with structure composed of boxes of 60 nm × µm separated by 0.25 µm, material composition C^{6}+, density 0.35 g/cm^3

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

Quasi-monoenergetic proton beam from target with holed backside

T. P. Yu, Y.Y. Ma, et al., Physics of Plasmas, **16(3), 033112, 2009.**

The production of quasi-monoenergetic protons from microstructured targets



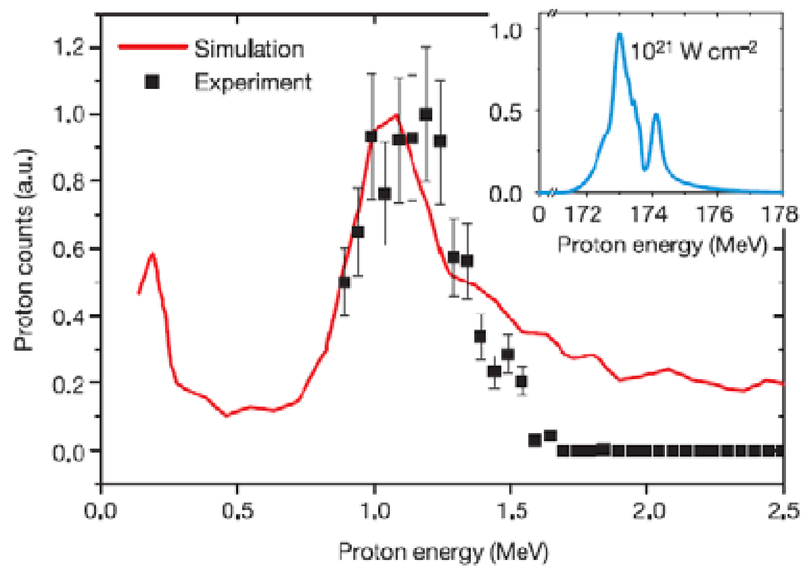


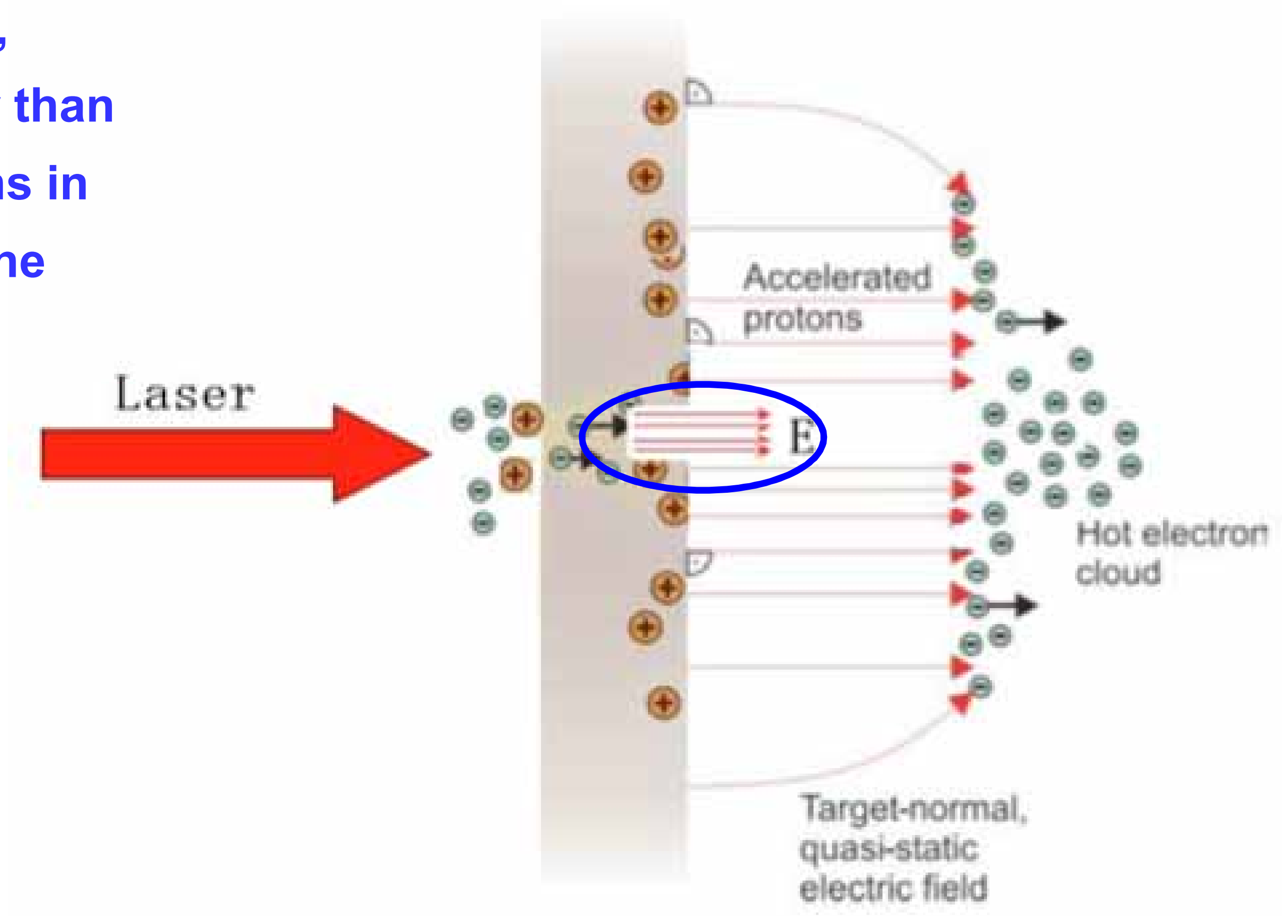
Figure 4 | Results from simulations and scalability of the technique. Comparison of experimental data (black squares) to the proton spectrum obtained from two-dimensional-PIC simulation (red line) for following conditions: laser intensity $I_L = 3 \times 10^{19}$ W cm^{-2}, and target dimensions 5 μm Ti foil + 0.5 μm PMMA dot (20×20) μm^2. Experimental data points comprise the observable energy range on the MCP detector. The statistical uncertainty for the measured data has a value of 20% s.d. as shown by the error bars. In the inset a simulation for a petawatt-laser system demonstrating the scalability of proton acceleration from microstructured targets is shown. The parameters for the simulation are $I_L = 1.2 \times 10^{21}$ W cm^{-2}, 5 μm Ti foil + 0.1 μm PMMA dot (2.5 μm diameter). The proton spectrum exhibits a narrow peak with relative energy width of $\Delta E/E \approx 1\%$ at a peak energy of 173 MeV.

H. Schwoerer, Nature 439, 445(2006)

German

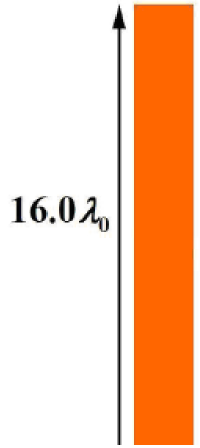
The Physical model for moicro-hole target

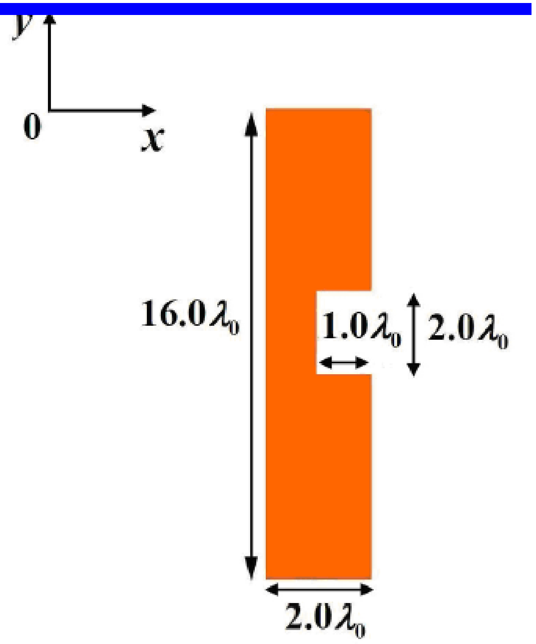
A micro-hole is made, whose size is smaller than the laser spot. Protons in the hole almost feel the unique electric field.



PIC simulation parameters

FIG 1. Scheme of the simulation geometry. The target is located from x=5.0λ_0 to x=7.0λ_0.





(b) case 2

FIG. 1: (Color online.) (a) Case 1: simple flat target. The target has a thickness of 1.0λ_0 and is located between $x = 5.0\lambda_0$ and 6.0λ_0. (b) Case 2: holed-backside target. The target has a thickness of 2.0λ_0 and is located between $x = 5.0\lambda_0$ and 7.0λ_0. The simulation box is 30.0λ_0 long and 16.0λ_0 wide. The laser impinges on the target from the left.

Laser parameters：I= $1.0\times10^{21} W/cm^2$ $\lambda_0 = 1.06\mu m$ **R=10** μm

$\tau = 10.0T_0 (\approx 33.3 fs)$ $a = a_0 \sin^2(\pi t/\tau_L)\exp(-y^2/2R^2)$

Plasm parameters： $n_0 = 20n_c$ $t_e = 1000eV, t_i = 333eV$ $h = 2.0\lambda_0, d = 1.0\lambda_0$

T. P. Yu, Y.Y. Ma, et al., Physics of Plasmas, **16(3), 033112, 2009.**

compare

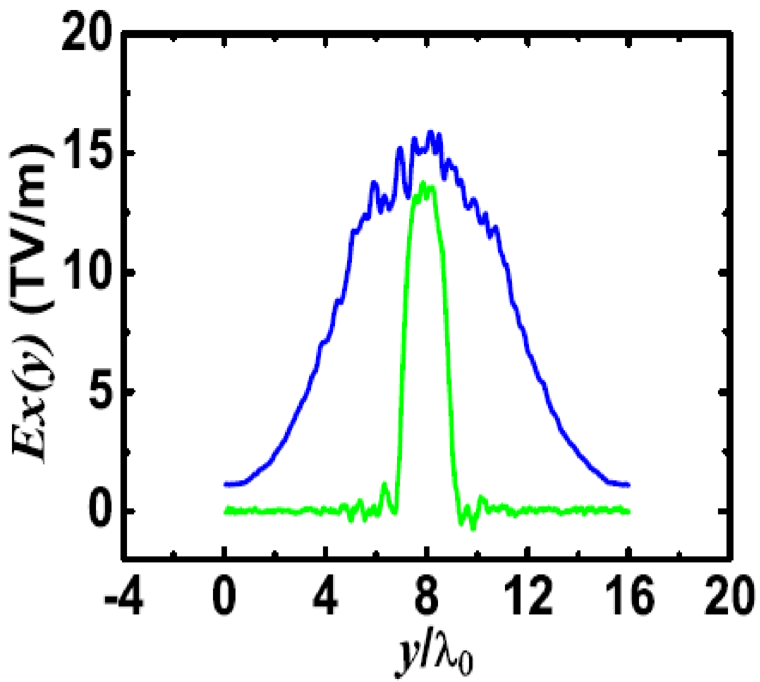


FIG. 2: (Color online.) Transverse distribution of the longitudinal sheath electric field E_x at $t = 16.08T$. Laser focal radius is $R = 2.0\lambda_0$ for Case 1 (blue/dark) and Case 2 (green/bright).

Energy spectra

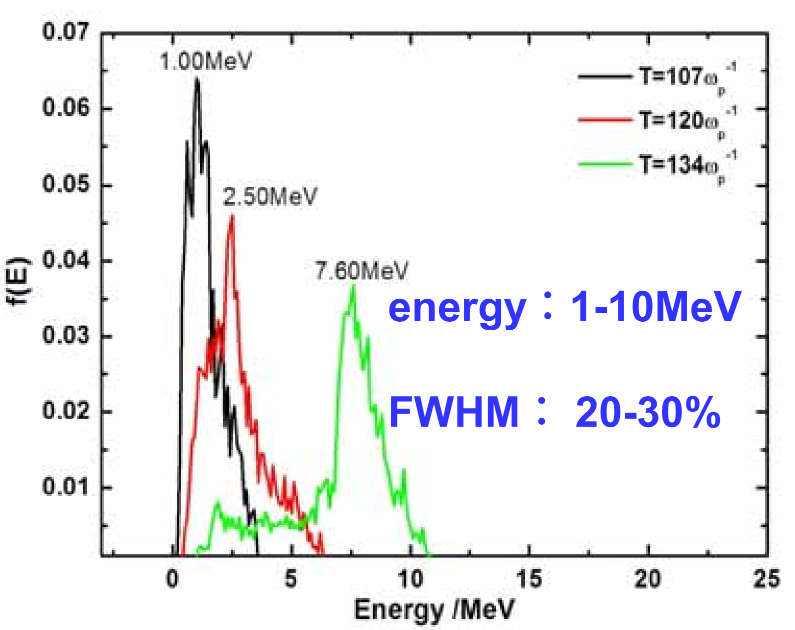
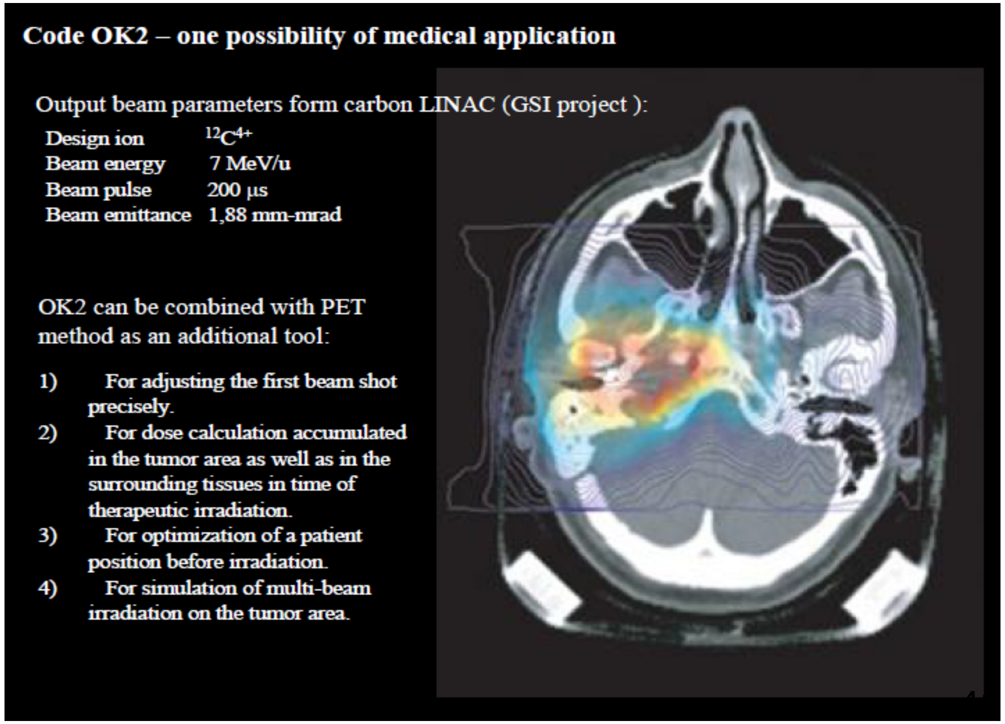


FIG 7. Proton energy spectra obtained from the concave at t=107ω_p^{-1} (black), t=120ω_p^{-1} (red) and t=134ω_p^{-1} (green)

T. P. Yu, Y.Y. Ma, et al., Physics of Plasmas, 16(3), 033112, 2009.

Future application to Ion Therapy

1. Doctor & Patient – friendly system for individual patient
2. Optimization of Curing Plan – Which direction, how much particle energy, how many times,
3. Ion illumination & deposition code OK2 + parallelization
4. Integrated PSE System
5. Compact ion accelerator – Laser ion accelerator



Thank you!

Location

From Narita (Tokyo) International Airport
-> 3hours by Bus or Train

From Tokyo
1hour by Train
(Shinkan-sen)

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