PIC Simulation and Experimental Researches on Laser Particle Acceleration and Their Applications

ILE OSAKA

K.Mima

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ILE, Osaka Univ., On leave from Max Born Institute, Germany[a)], and University of Nevada, Reno, Nevada Terawatt Facility (NTF)[b)]

Outline

1. Introduction; Peta watt laser and high energy particle generation from solid target

2. Fast ignition research and generation of high energy particles

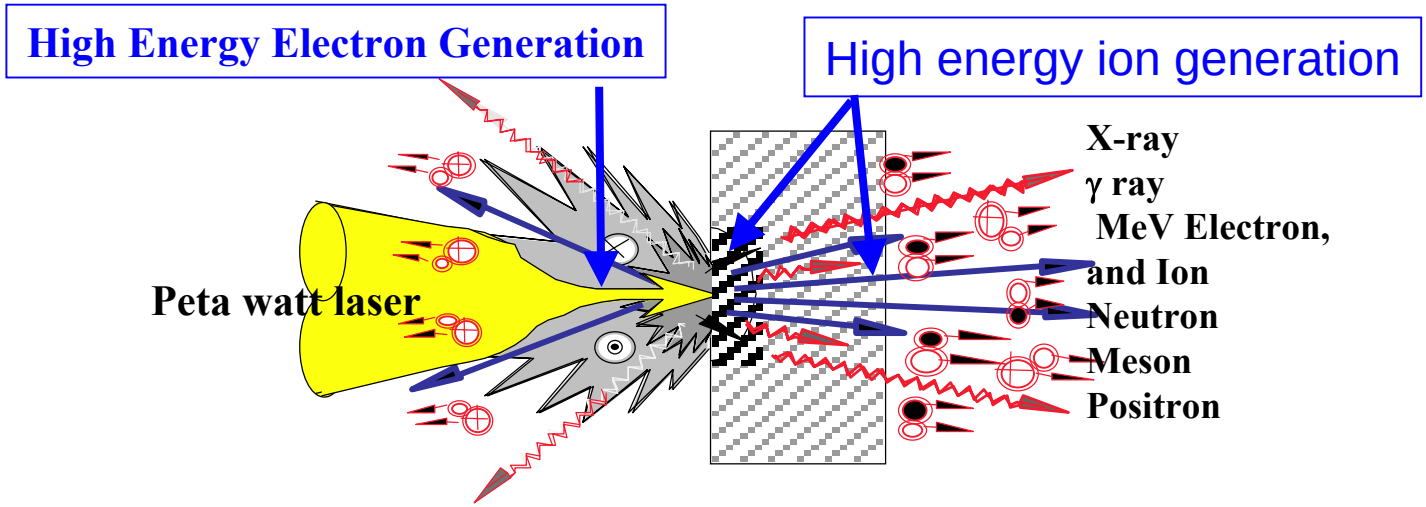
3. Ion energy enhancement with preformed plasma

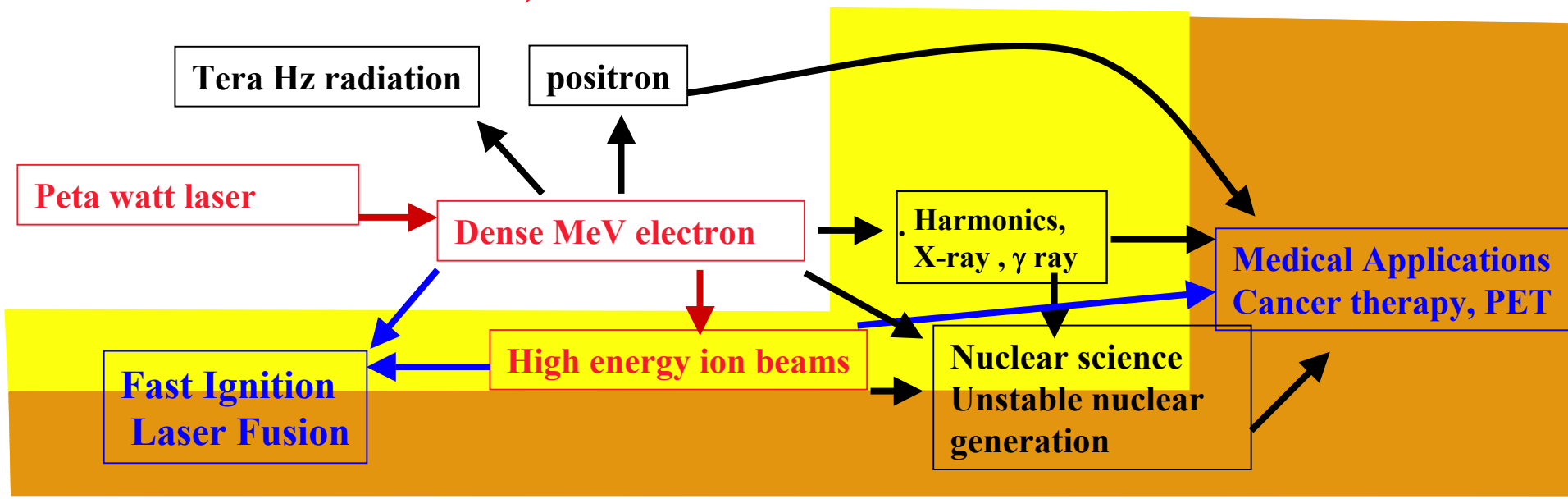
4. Researches on tailoring ion energy spectrum

5. Summary

Presented at the AAC Workshop'04, at BNL, N.Y.

Introduction
Generation of High Energy Particles and High Energy Density Plasmas with Peta Watt Laser





ILE, Osaka has unique capability to conduct dense plasma-peta watt laser interactions and Fast Ignition experiment, since 1998.

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GEKKOXII laser: 12 green laser beams since 1983
E= 10kJ, t = 1-2 nsec.
Uniform implosion for high density compression.

PW laser: 500J/0.5ps
At 1 micron.
PW laser pulse is synchronized with Gekko XII

FIREX(Fast Ignition Realization Experiment) project LFEX (Laser for Fast Ignition Experiment / 10Peta Watt; 10kJ/1 ps) . First light on 2004/Sept.

Application of high energy electron and ion heating to laser fusion

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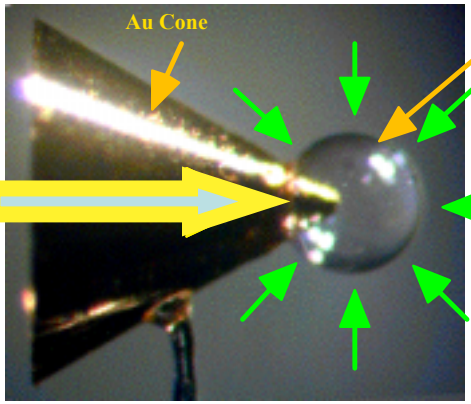
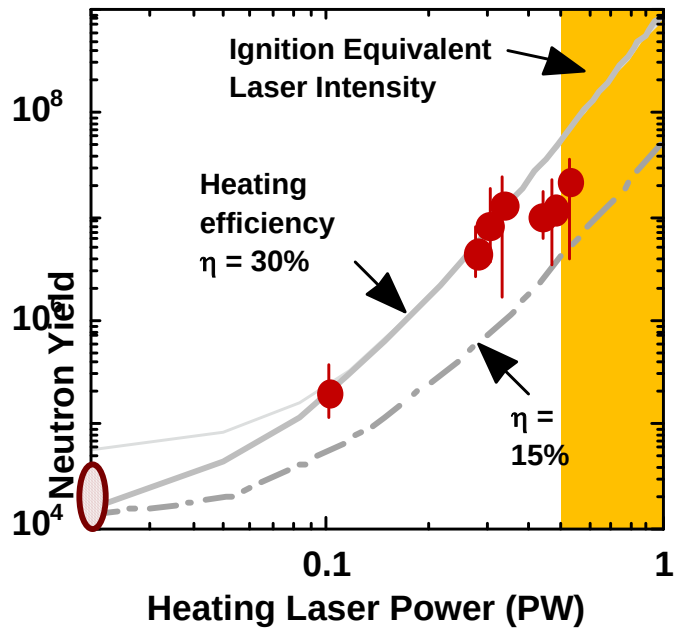
Cone shell target



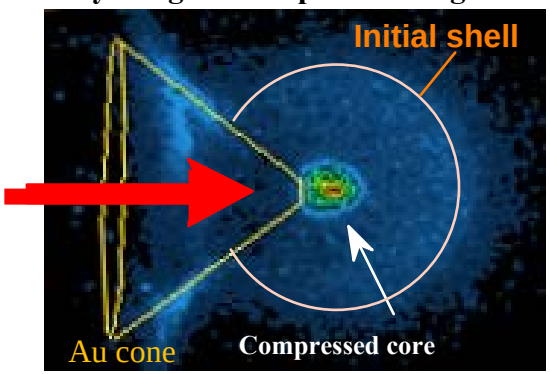
PW laser
for heating
1.053μm
300J/0.5ps

GEKKO XII
for implosion
9 beams
0.53μm
1.2 kJ / 1ns
2.5kJ/1.2 ns

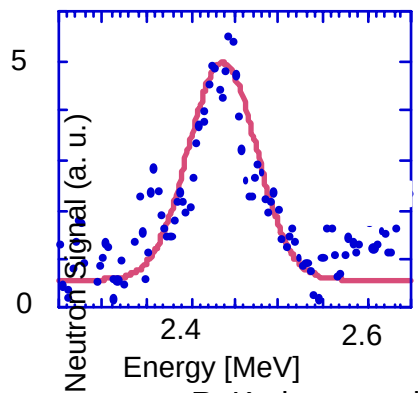
Au cone
Cone angle 30°
Cone wall thichness: 5μm



X-ray image of compressed target



Neutron spectrum by TOF
@Ti - 1 keV



R. Kodama et al. Nature 2002.

Heating Efficiency; η ~ 0.2

3-D PIC simulation of laser propagation and absorption in the cone target

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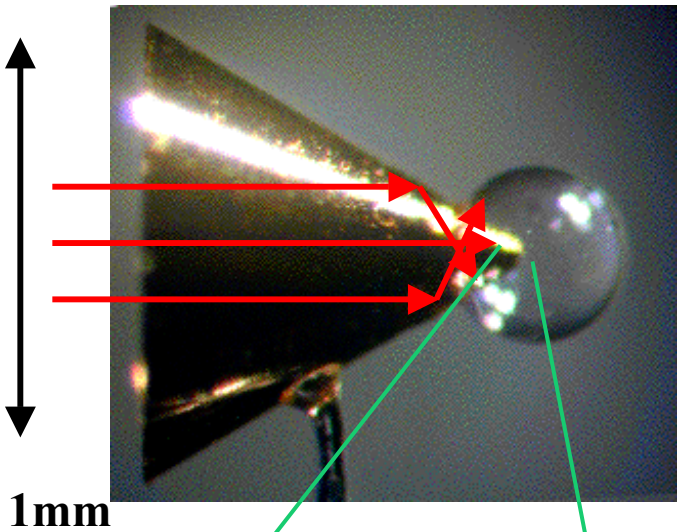
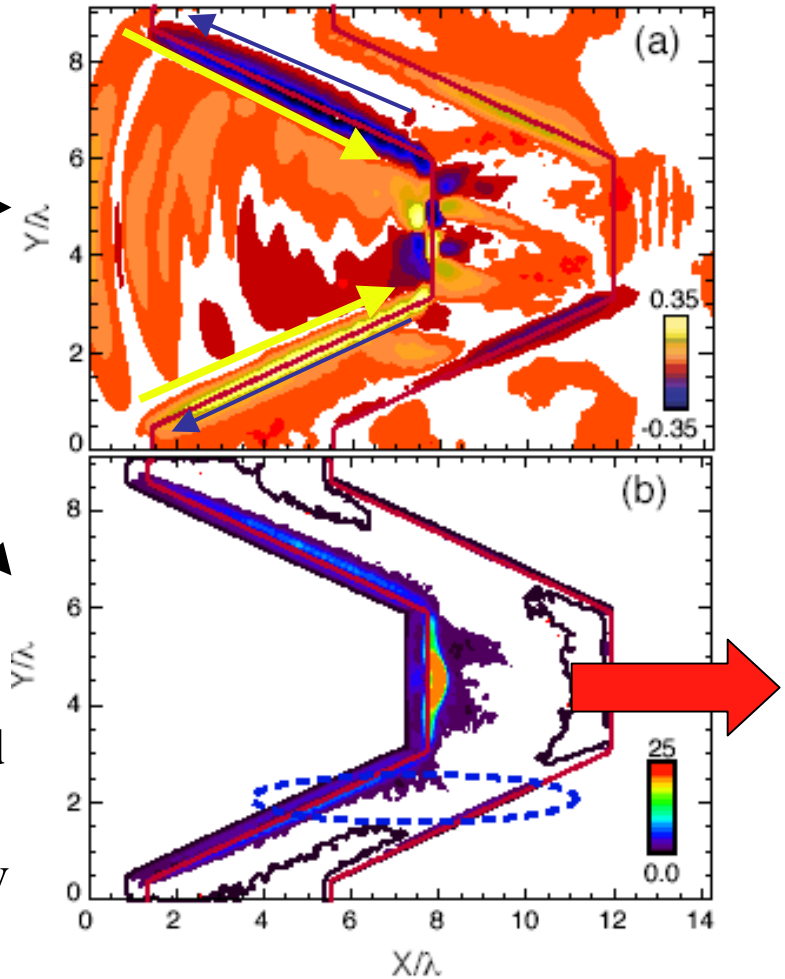


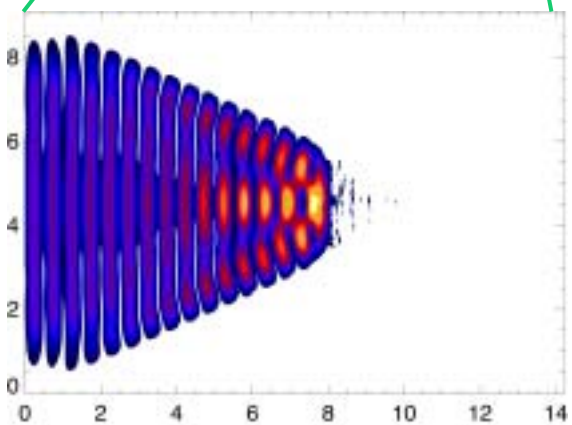
1mm

B field profile

Electron energy density distribution



The focused intensity reaches 20 times larger than I_0.



Magnetic field ;B/B_0 and energy density normalized by $n_c mc^2$

Short pulse laser driven REB is pinched to a tip of cone.

Hot electron spectra show clear laser intensity dependence. Au cone (30º) shows increased hot electrons in the forward. (After K.Tanaka)

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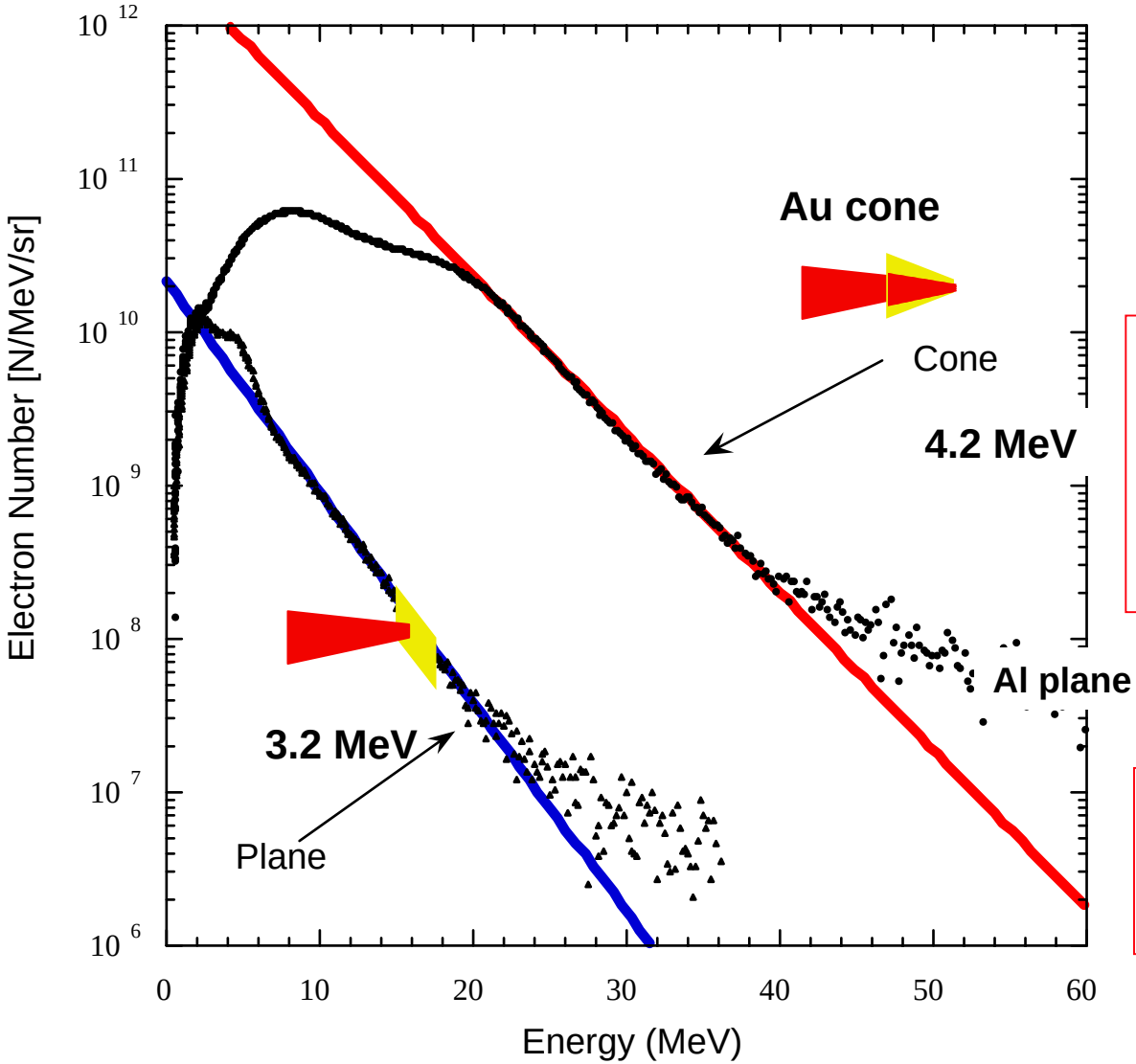


E=190 J
I=5x10^{18} W/cm^2

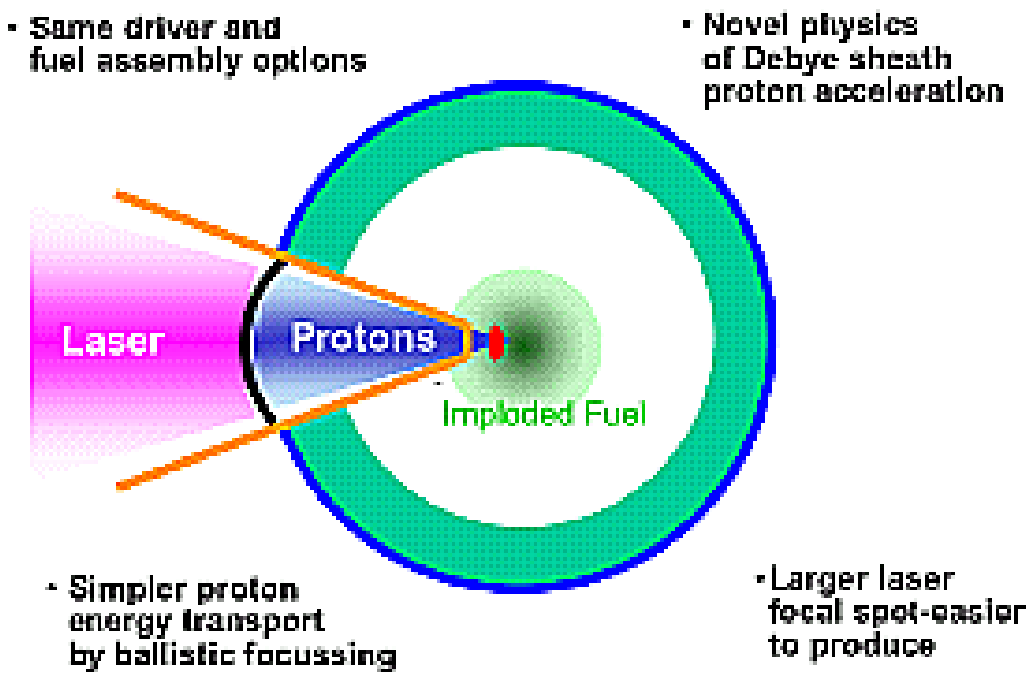
Stopping range of T_h =4.2 MeV is too long to deposit the energy into the imploded plasma.

Anomalous stopping and/or soft components of relativistic electron

Highly Collimated Proton Beam heating could contribute to Fast Ignition and HEDS

Proton-heating contributes dense plasma heating together with electron heating. The collimated proton beam is also useful to study the EOS of got dense matter with isochoric heating.

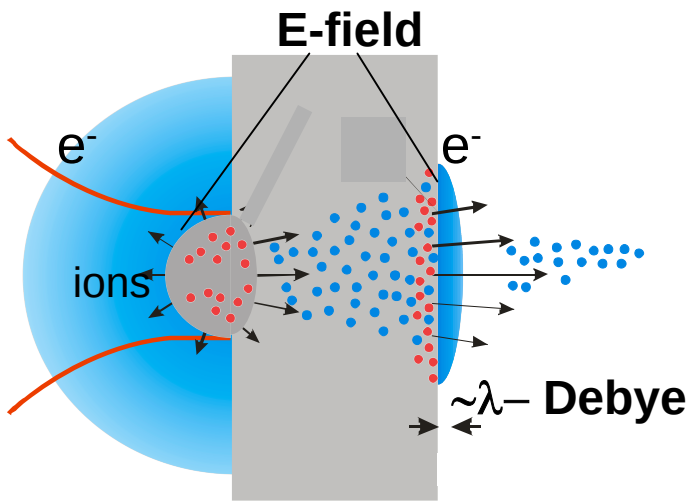
>10kJ/10ps ,15~25 MeV proton beam for ignition



Ions are Accelerated on Solid Target Surface both in Backward and Forward Directions

Quasi-static electric field (a few 10's MeV/μm) is created for $\tau \geq \tau_{laser}$ by driving the electrons out of the target.

→ Resulting space charge field accelerates ions in a short distance .



Debye sheath ~ μm

Electron temperature ~3~ 5MeV

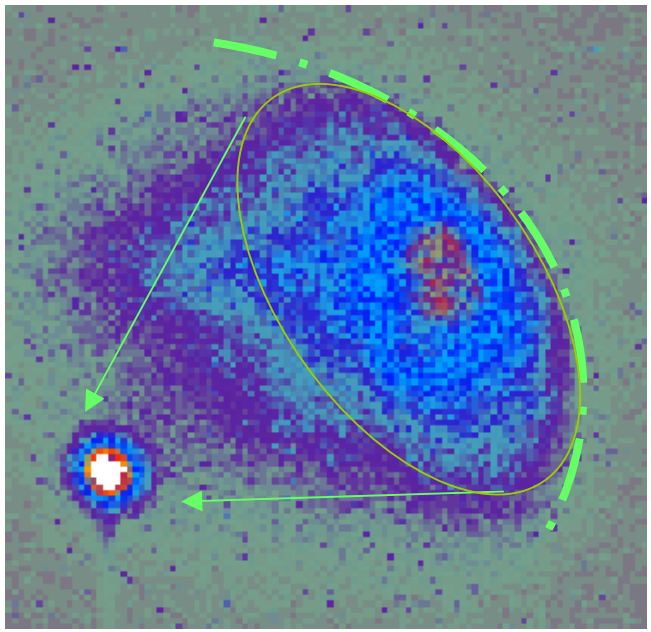
$E_{rear} = kT_e / e\lambda_{Debye}$

Issues are 1)ion energy, 2) ion beam emittance ,

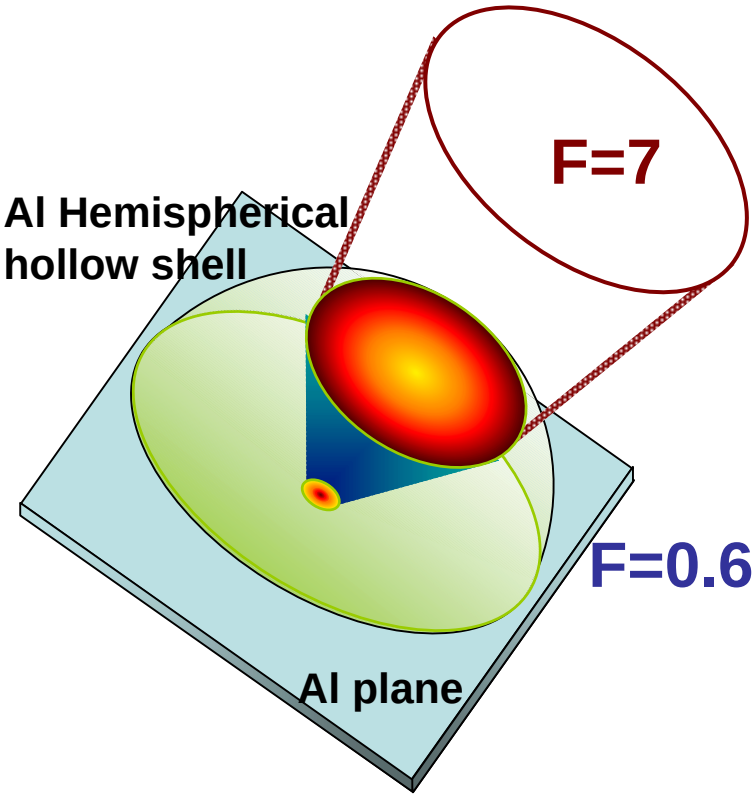
and conversion efficiency.

Low transverse emittance ;
Energetic Proton beam is focused to produce hot dense plasmas.

PW laser light was focused on a hemispherical target trough an F/7 off axis mirror. MeV protons are generated at the rear surface of the hemi sphere . The heated area observed with x-ray pinhole camera is a few 10 μm diameter, which is much smaller than the spot size of laser irradiation.

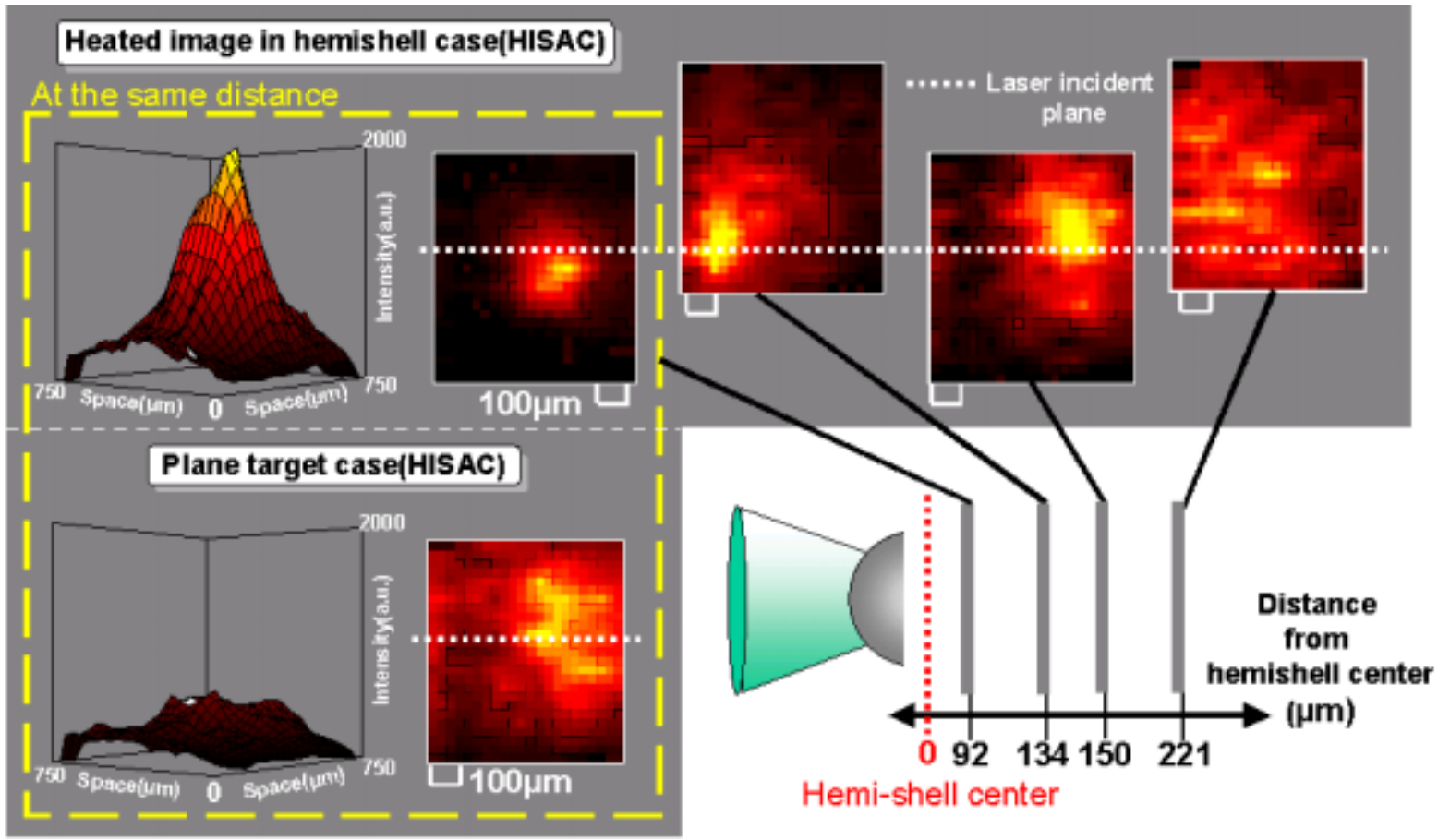


X-ray Pinhole Image from the front side



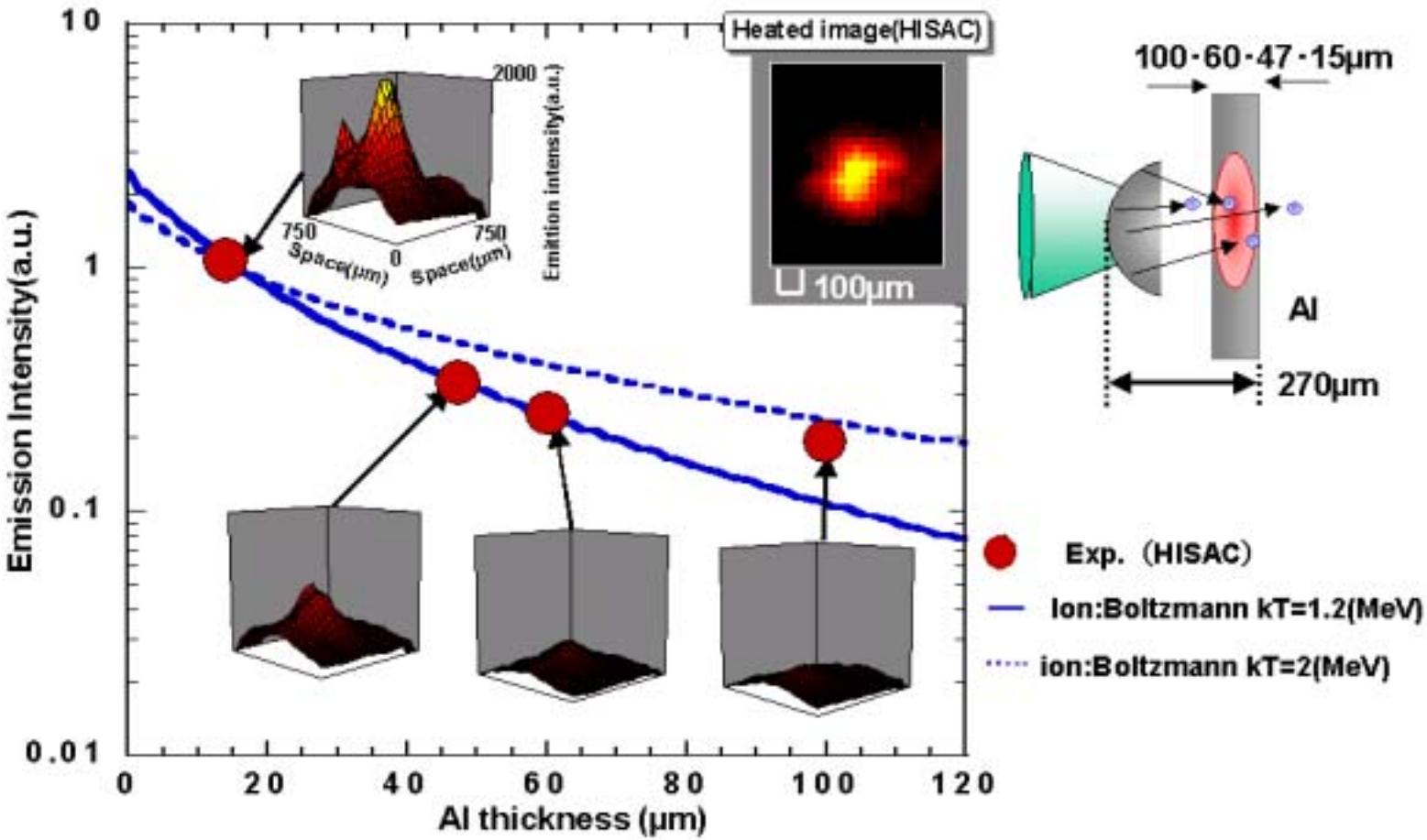
Heating Image and Relative Temperature of the Rear Side of the Witness Plate Measured with a High Speed Sample Camera

The heating size is smaller and the temperature is higher when the witness plate is set closer to the Hemi-shell center.



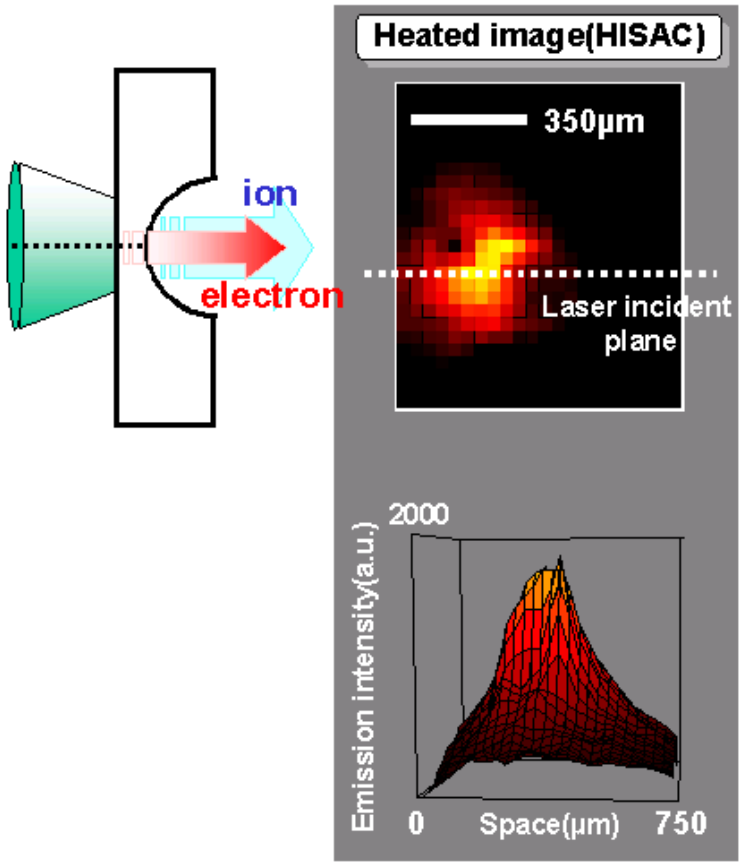
The Heating Property in Different Thick Samples to Investigate the Stopping

The heating property indicates that 1-2MeV protons heat the sample whereas clear discrepancy appears between the experiment and simple calculation in the thick sample.

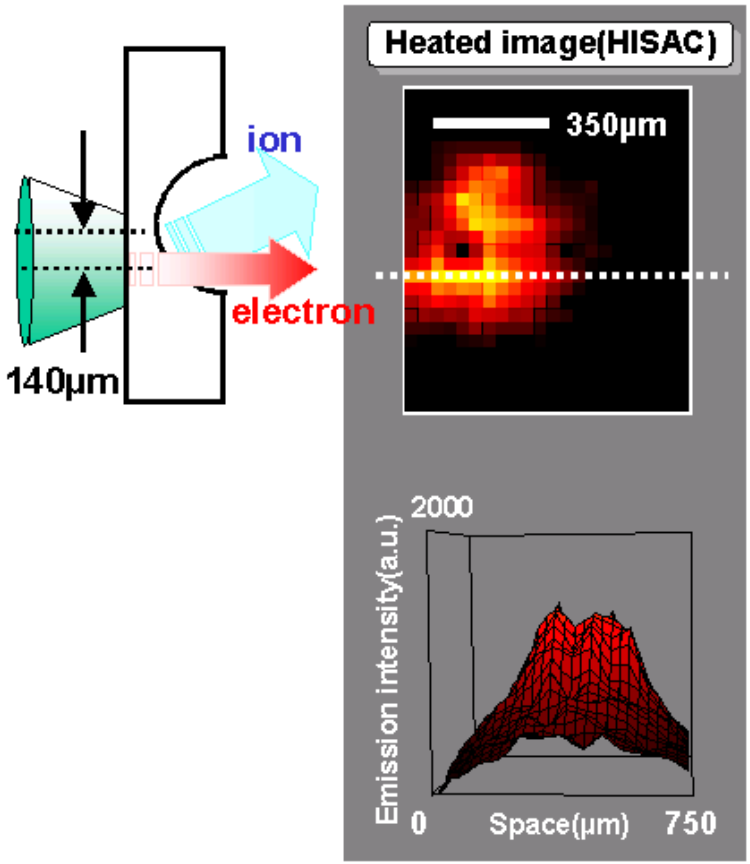


The heating Image indicates that Both proton and electron heat the witness plate.

Coaxial geometry between the laser normal (JXB) and the rear normal (potential direction)

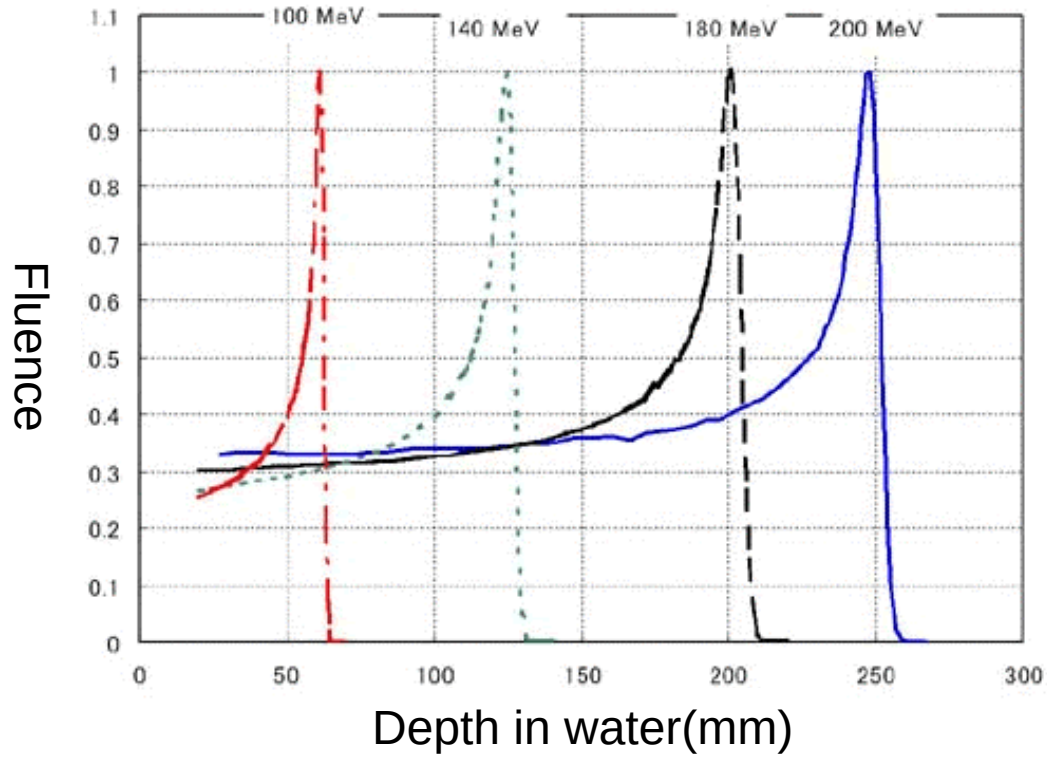


Offset geometry between the laser normal and the rear normal



Laser driven Ion beam is bright enough to heat dense plasmas for fast ignition and create hot dense plasna EOS research.

Another Interesting Application of laser ion beam; PET and/or Cancer Therapy
Bragg Peak of Ion Energy Deposition in Water



..Range in body.a few mm.30cm.fluence.2.5Gy/min

..*These conditions are met for ion beam*

..Proton energy.a few 10.235MeV.proton current.20.100nA

This requires about 1W of ion beam or

average laser power of 100W---- 10 J / 0.1ps / 10 Herz

Issues of laser ion acceleration R&D

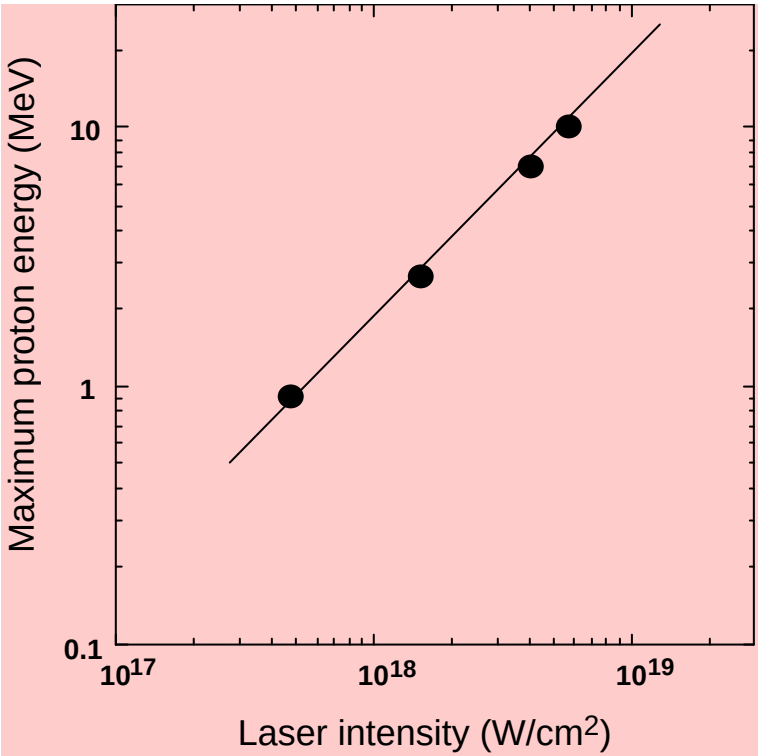
- **Ion energy scaling with respect to laser power**

- **Tailoring ion energy spectrum;**
  quasi-monochromatic ion beam

- **Higher conversion efficiency from laser to ion**

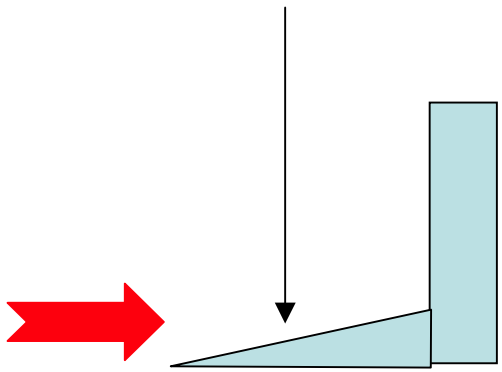
- **For an example;**
  Laser ion accelerator construction cost for 300MeV/ 100nA proton beam should be less than 50 M$

CUOS Experiments Shows Maximum Proton Energy is Enhanced and Proportional to the Laser Intensity [3]



(1 ~10) TW Laser with intensity contrast ratio; $5 \cdot 10^{-5}$

Estimated preplasma scale is $\leq$ 10 microns.



For prepulse level is 10^{-7} proton energy was much less.

[3] K. Nemoto, A. Maksimchuk, S. Banerjee *et al*., Appl. Phys. Lett. **78,** 595 (2001).

2D PIC results (a=1)

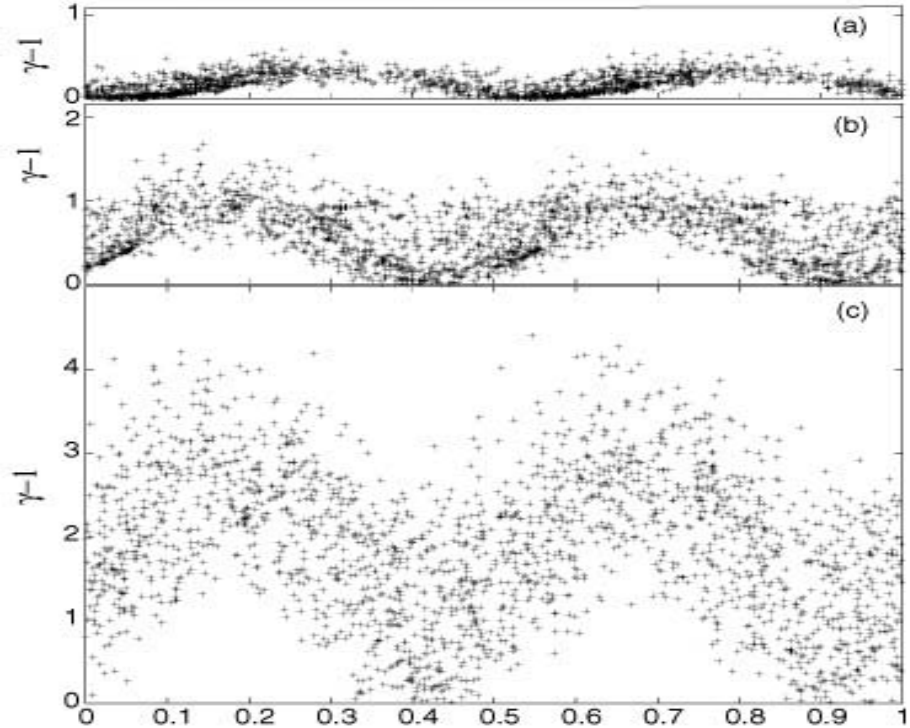
(a) Laser intensity at 106 fs.
(b) Quasistatic magnetic fields at 185 fs.
(c) Longitudinal E-fields, Ex, at 185 fs.
(d) Slice plot of Ex at 185 fs (center)

Ex has two peak at the target rear side, and the maximum is about 40% of the laser E-field, which corresponds to 1.5 MeV/μm.

The second peak of Ex appears at the deuteron front.

Electron energy is proportional to a^2 at relativistic intensities

Model problem ⇒



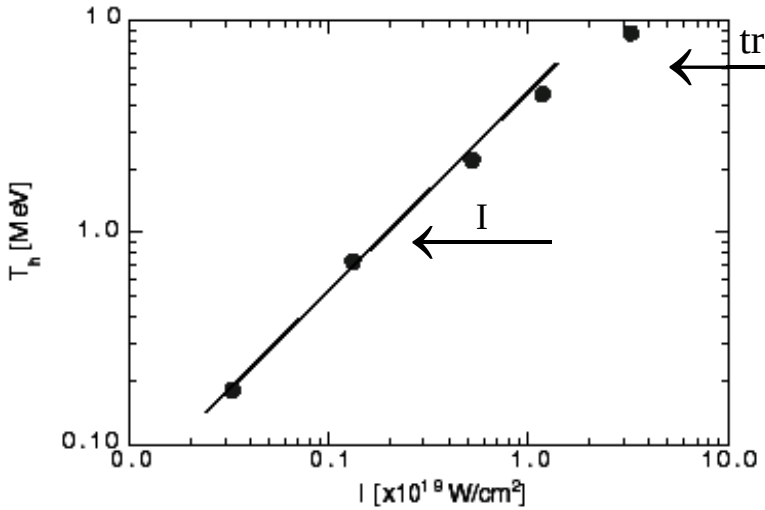
a=0.5

a=1.0

a=2.0

Reflection coefficient
$r = 0.75$

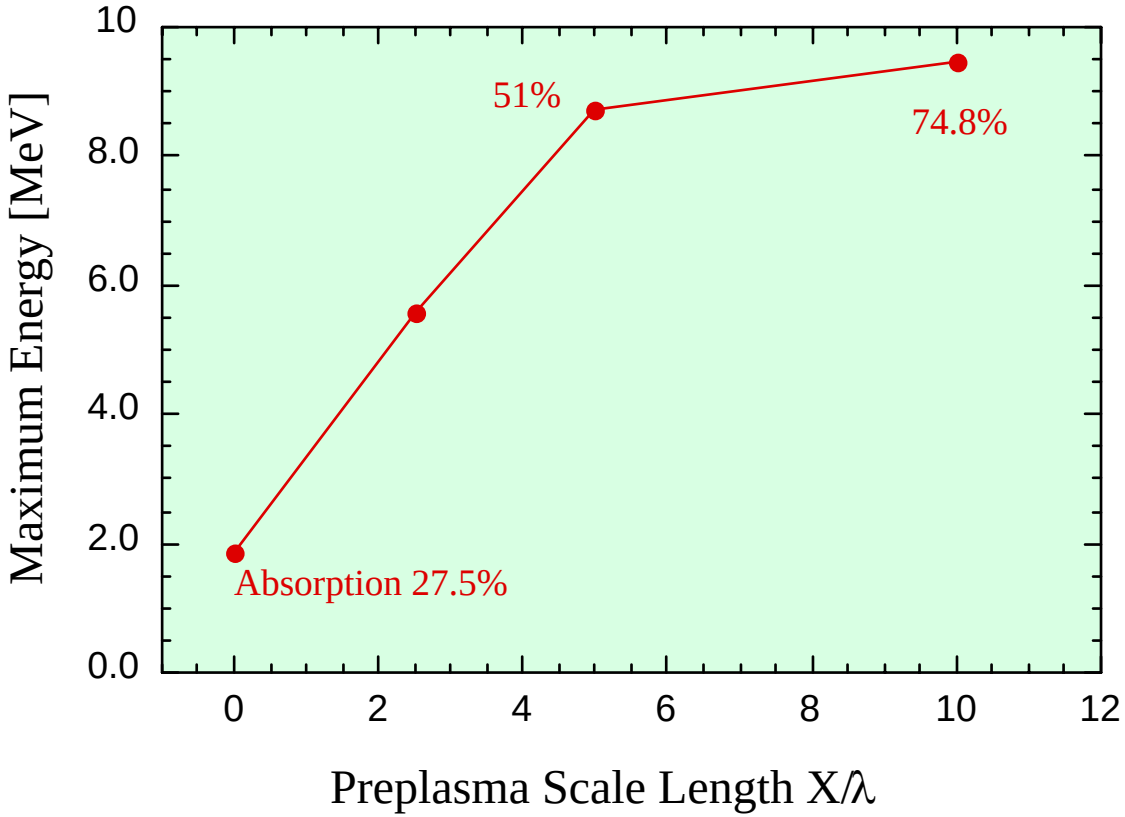
PIC simulation ⇒



transition to $\sqrt{I}$

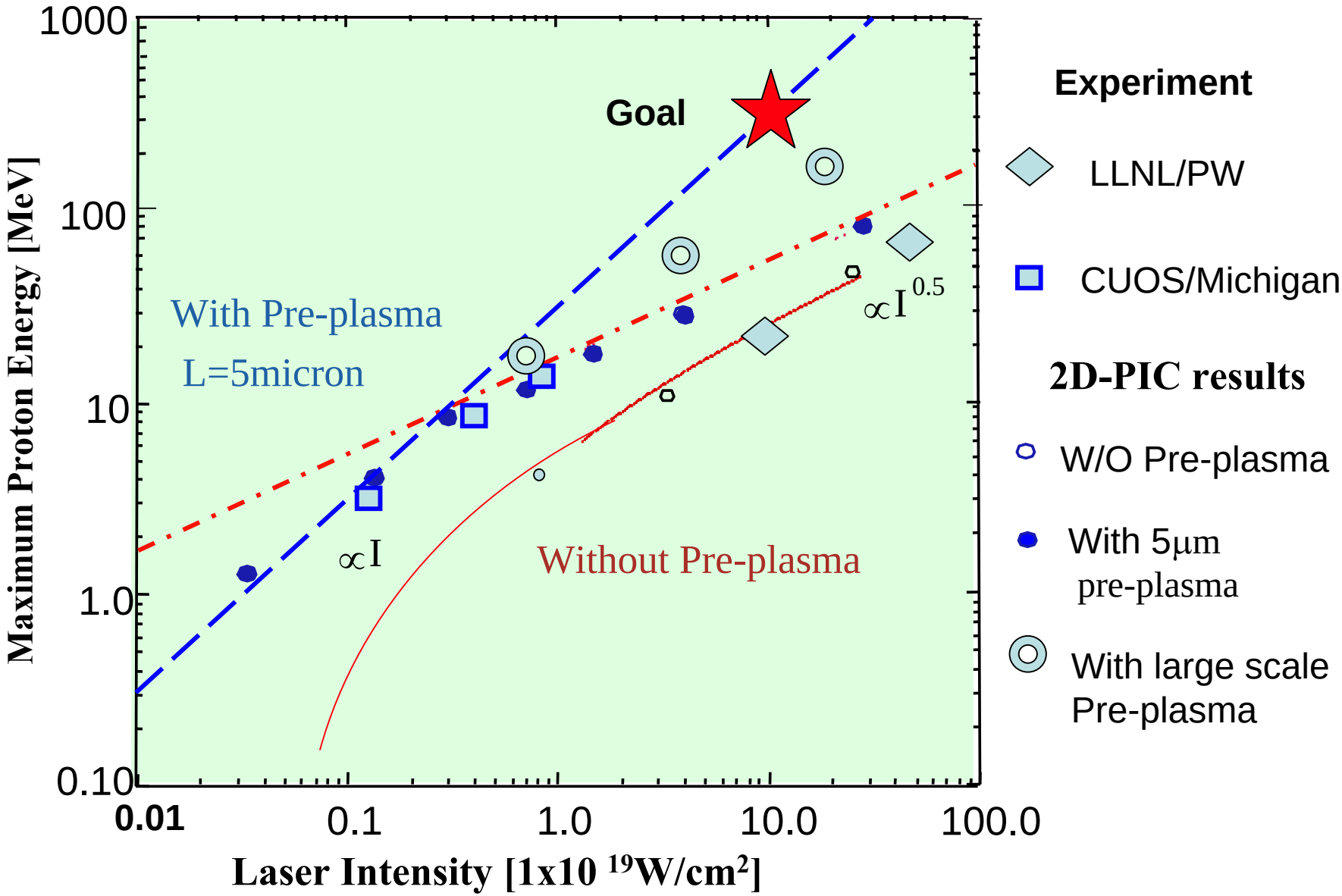
Maximum proton energy increases with the preplasma scale length

2D results (a=2)



•Ion energy increases with preplasma scale length and saturates. Absorption coefficient has similar behavior
• The ideal intensity contrast ratio is not optimal for efficient ion acceleration
•The "plateau" regime is restricted by the length where laser energy dissipates and scatters

With preformed plasma, the maximum proton energy is scaled as I



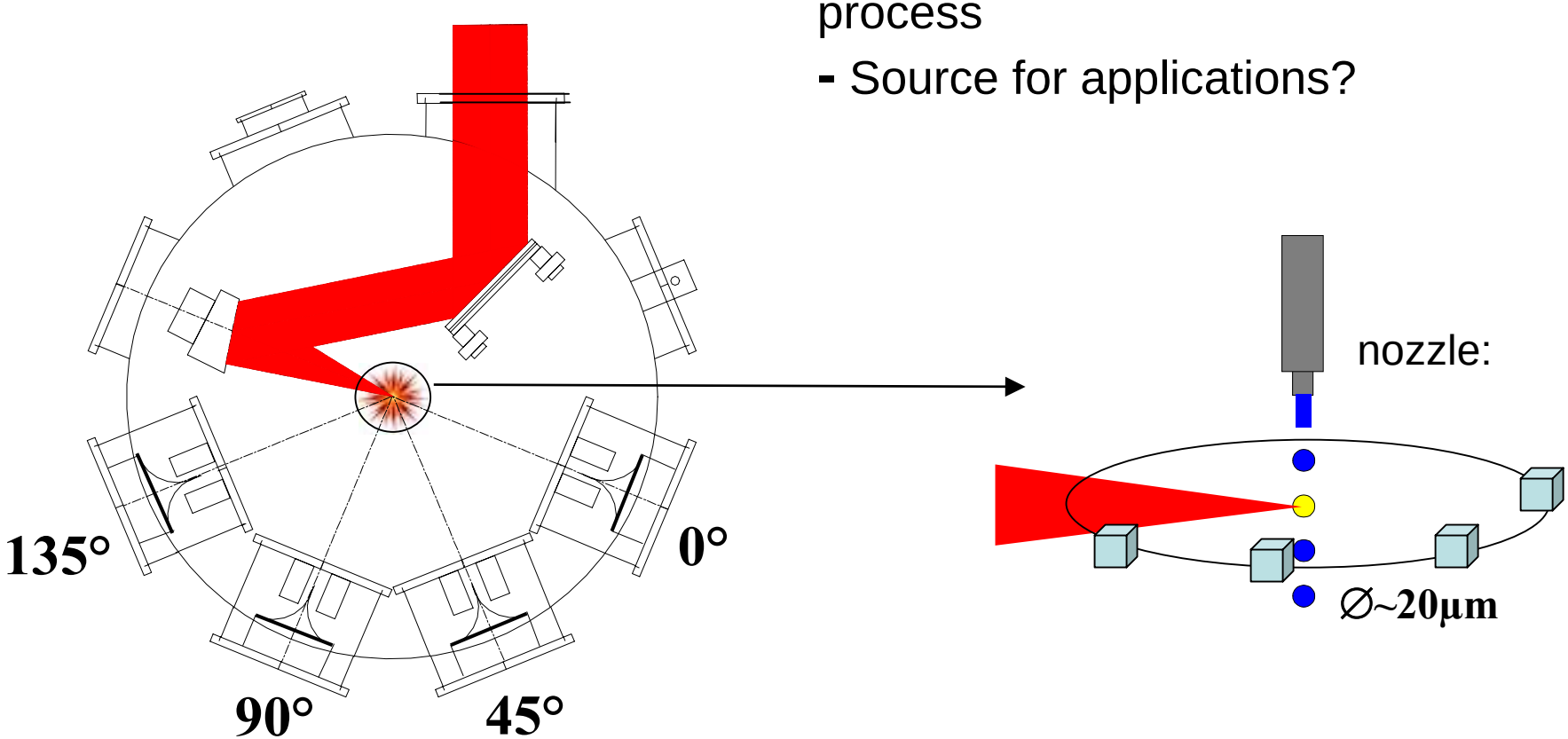
Monochromatic ion; H_2O / D_2O- microdroplet jet-target ; ion/proton emission set up at Max Born Inst. (P.Nickles)

Ti:Sa Laser: 35fs, 0.75J, I_L~10^{19}W/cm^2

Ion detection with 4 Thomson + CR-39 or MCP (single shot!)

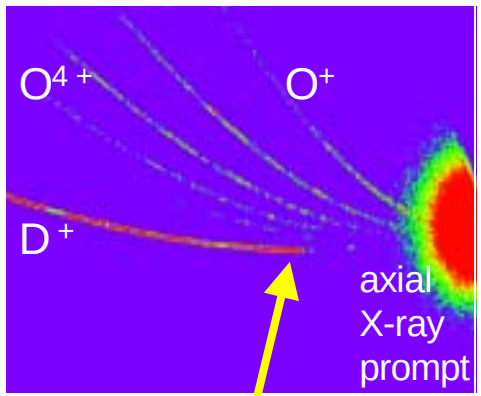
Why ion acceleration from isolated water droplets ?

- Understanding of proton / multicharged ion accelerat ion process
- Source for applications?

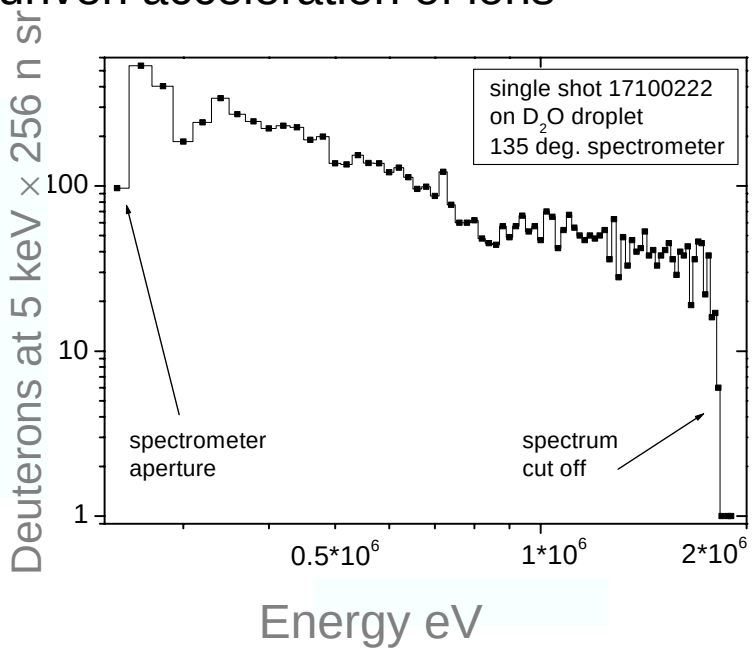


Acceleration of ions up to MeV-energies due to charge build-up

Ion / Deuteron spectra low contrast ratio: <10^7 :1

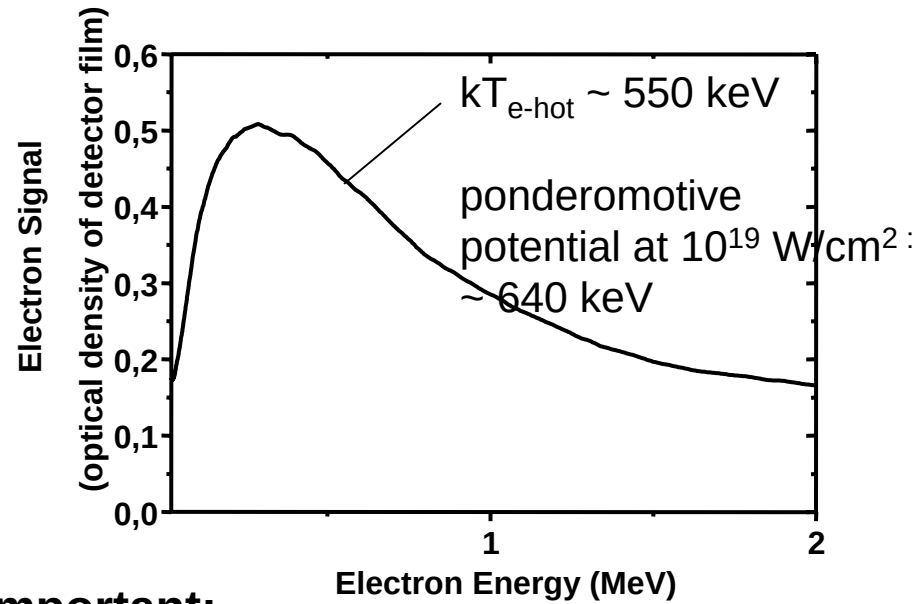


Sharp cut-off indicates a e-s-field-driven acceleration of ions



Electron spectrum

Lower energetic electrons are „embedded“ inside of „charged sphere“



Important:

Electron spectrum shows signature of a potential „trap“ which is responsible for MeV ion accelerationen at fs-laser pulses

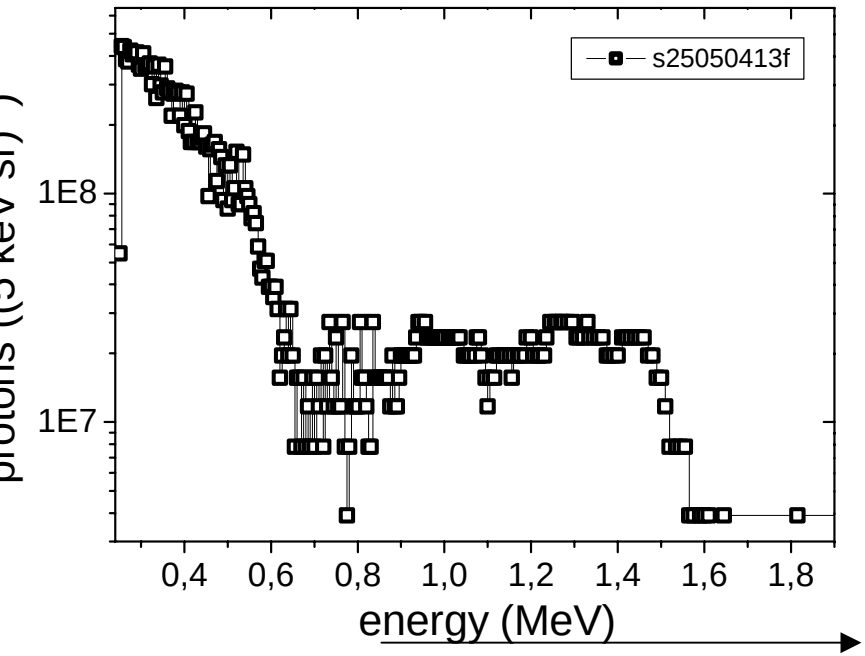
Proton and Deyteron spectra from plane target (forward direction)

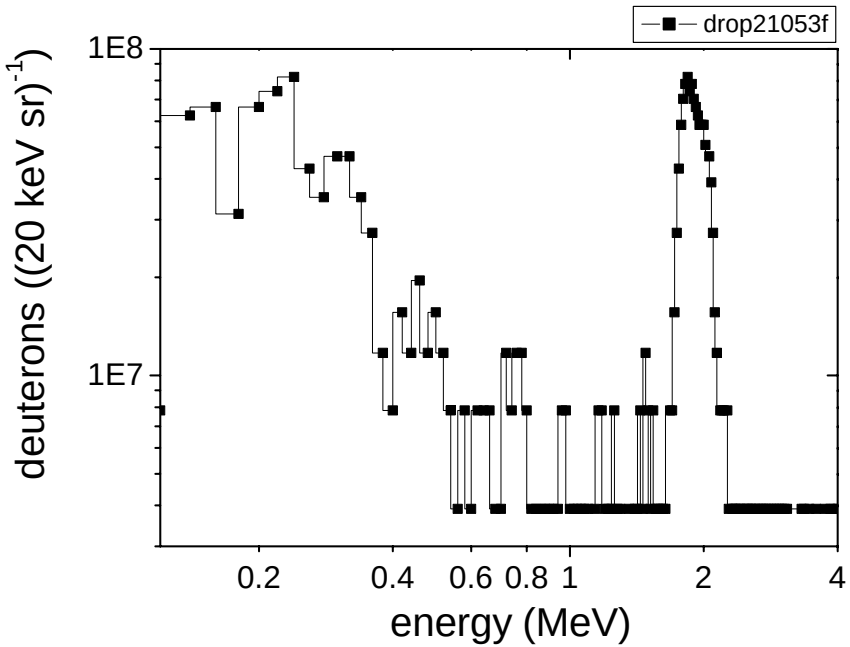
10^{19}W/cm^2, 40 fs ,

high contrast: 3×10^{-8} for $\tau \geq 10$ps

Also deep modulation:

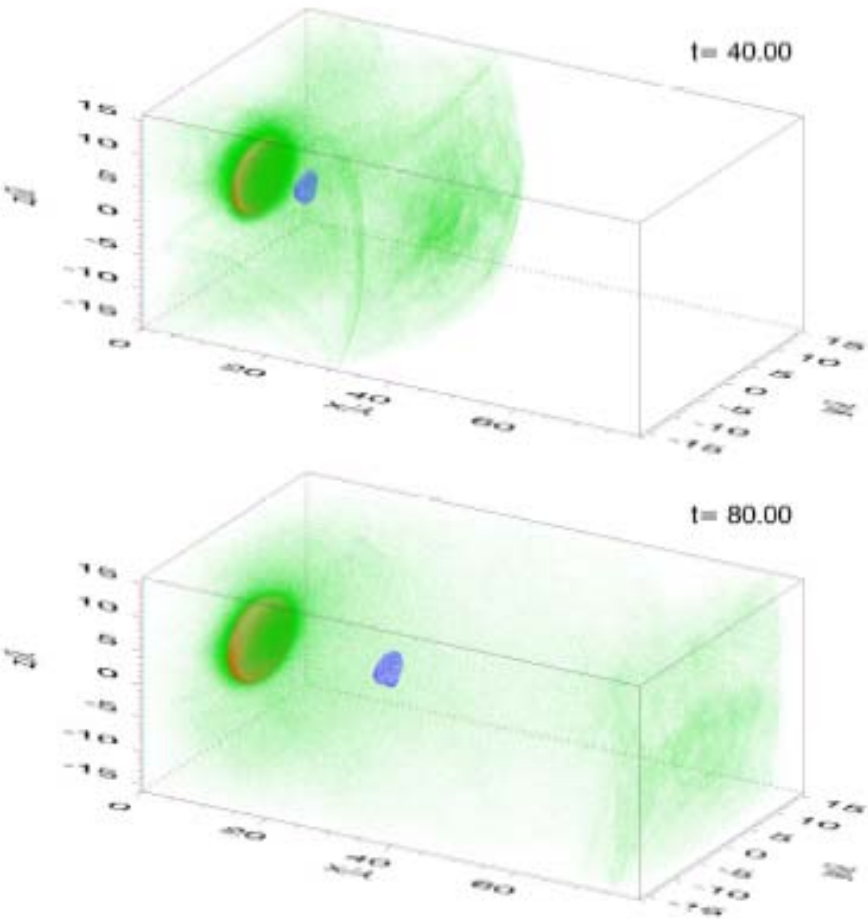
Modulation not caused by target geometry but due to plasma dynamics of multi-species and -temperature plasma at high contrast, ultrashort and intense pulse irradiation





Monochromatic Ion Beam from Double Layer Target

(by Esirkepov etal, PRL '02)



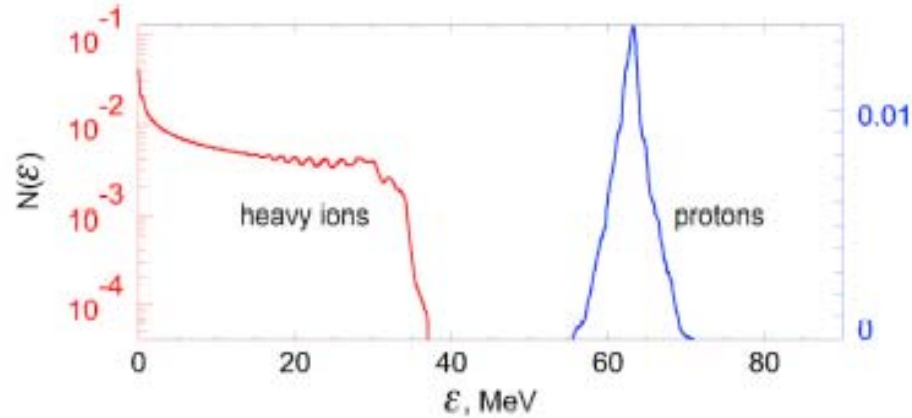


FIG. 3: The proton (blue) and heavy ion (red) energy spectra at $t = 80 \cdot 2\pi/\omega$.

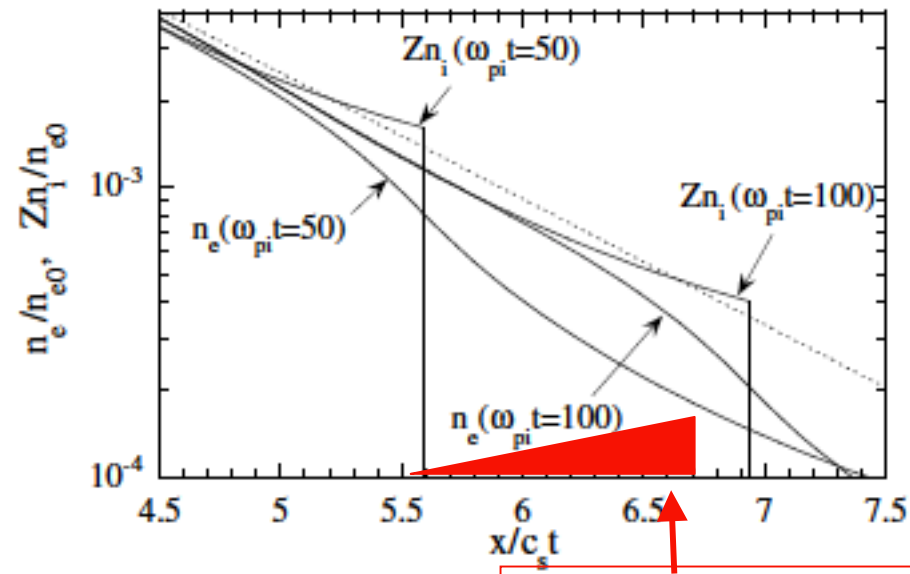
Sheath Field at the Iso-thermal Expansion Front

P.Mora(PRL,03) and Y.Kishimoto etal (Phy.Fluids,1983)

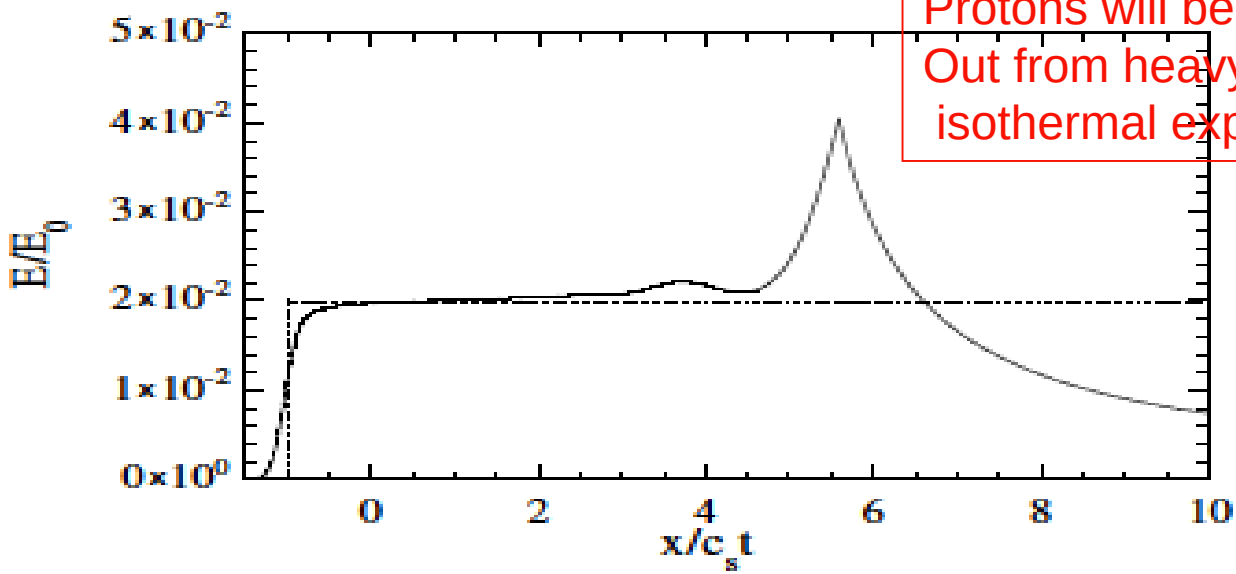
Interpretation with Wickens–fluid model (Wickens Allen, PRL 1979)

Ion emission from LPP with 2 T_e (c, h)

Ion energy distribution with fast and slow components with a pronounced dip in the distribution

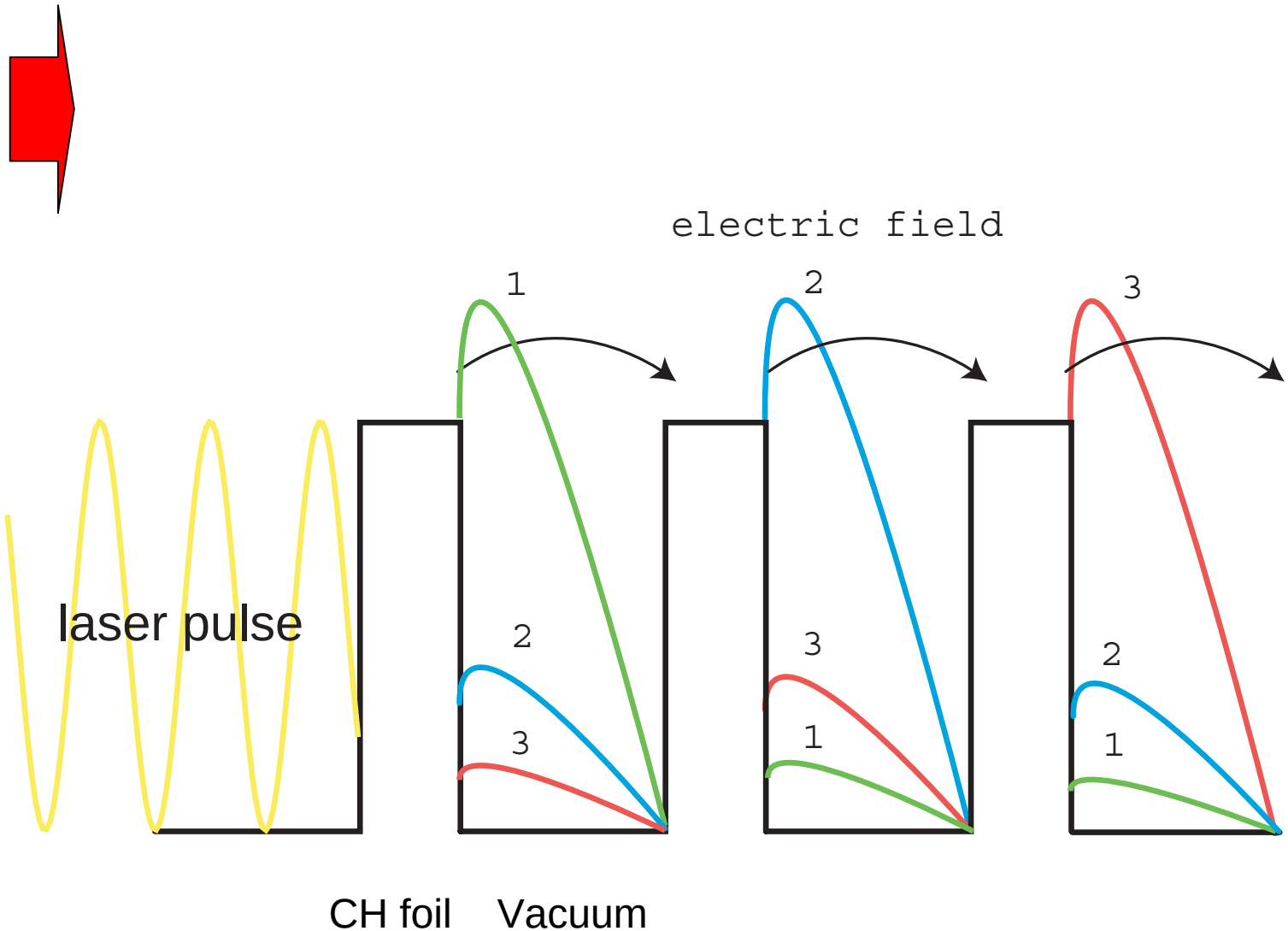


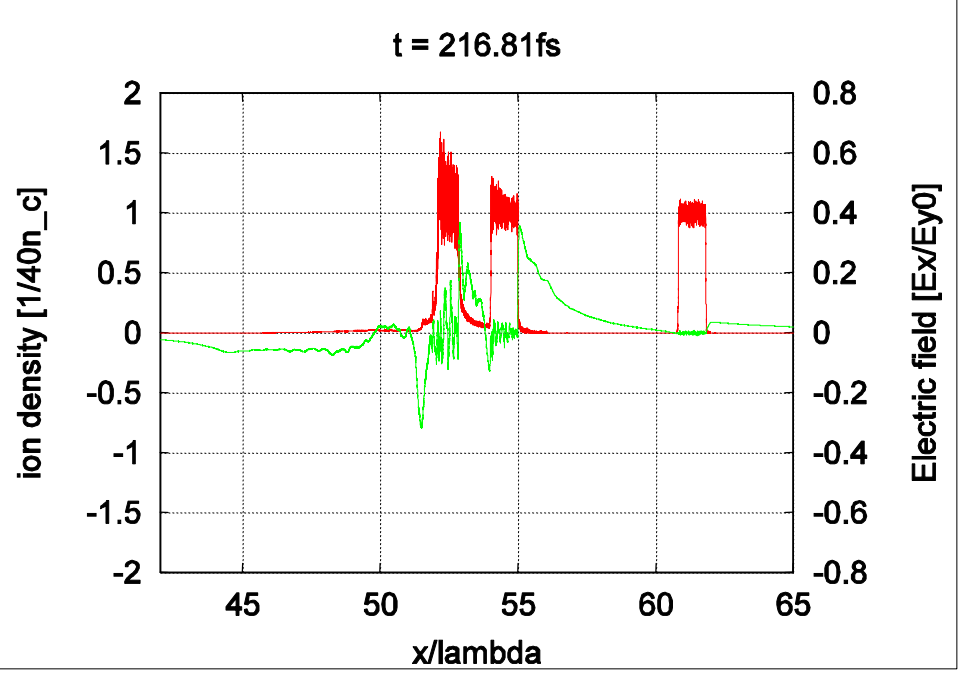
Protons will be pulled Out from heavy ion isothermal expansion

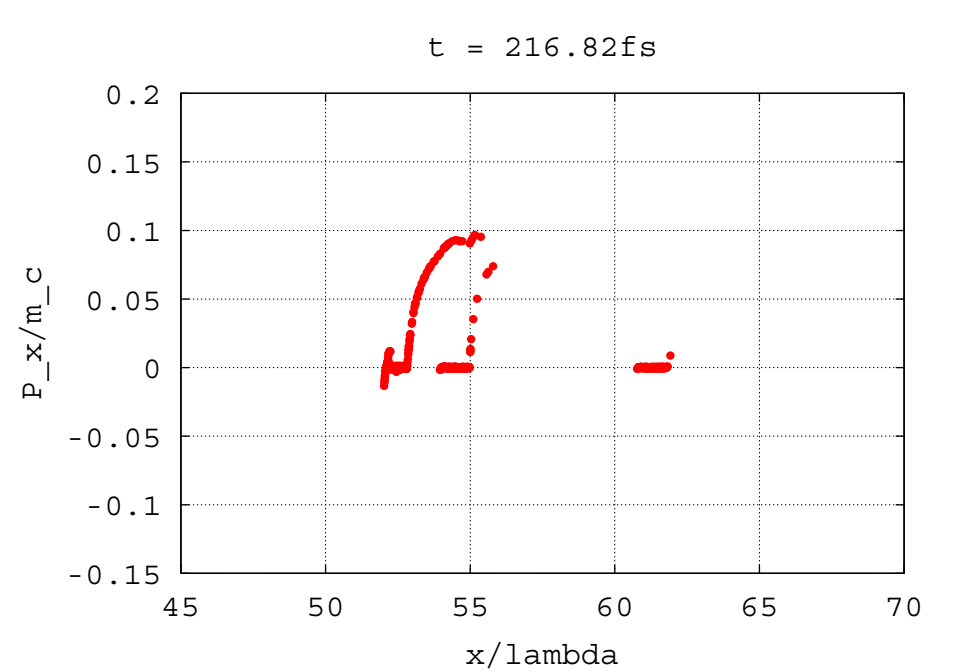


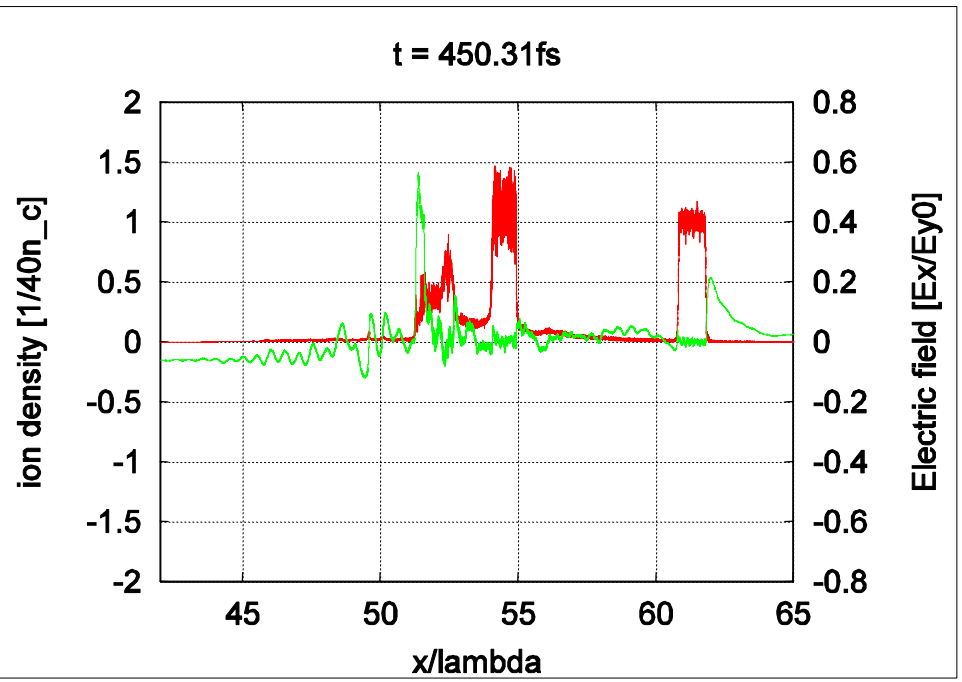
Multi-stage foil acceleration ;To be submitted by K.Mima etal

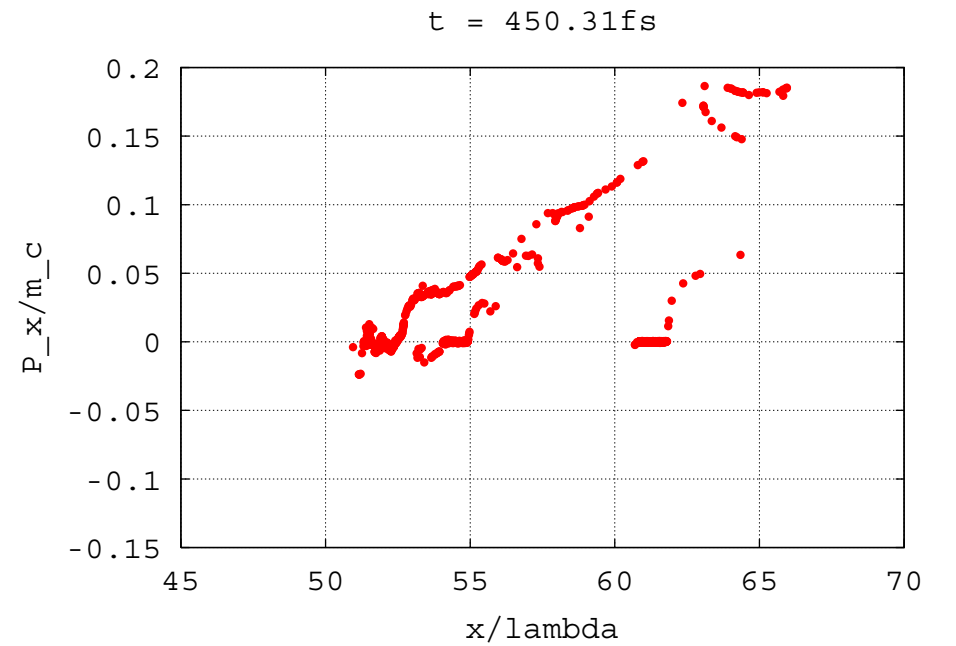
Propagation of sheath fields can be synchronized with ion propagation

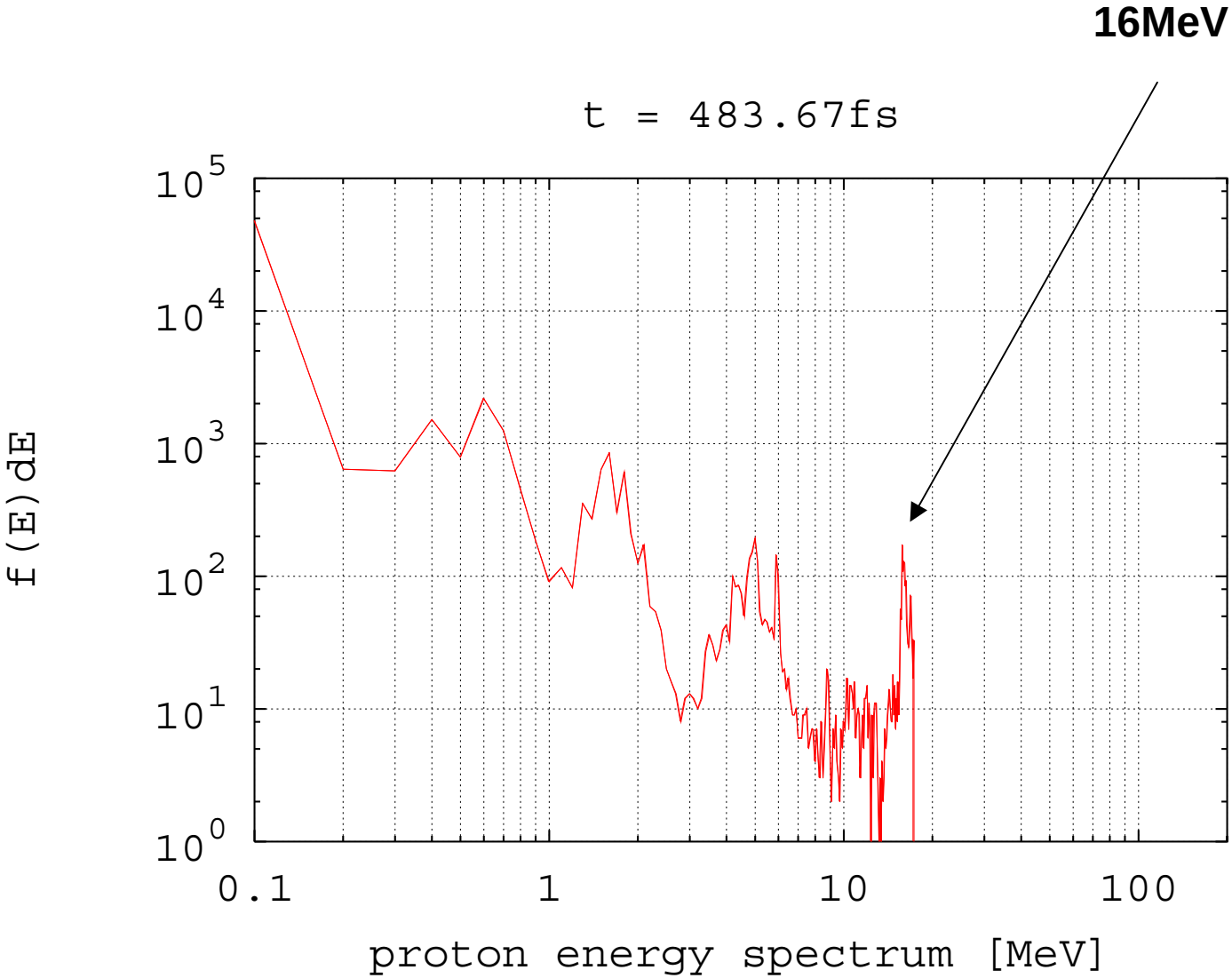



t = 216.81fs
ion density [1/40n_c]
Electric field [Ex/Ey0]
x/lambda
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
45
50
55
60
65


t = 216.82fs
P_x/m_c
x/lambda
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
45
50
55
60
65
70


t = 450.31fs
ion density [1/40n_c]
Electric field [Ex/Ey0]
x/lambda
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
45
50
55
60
65

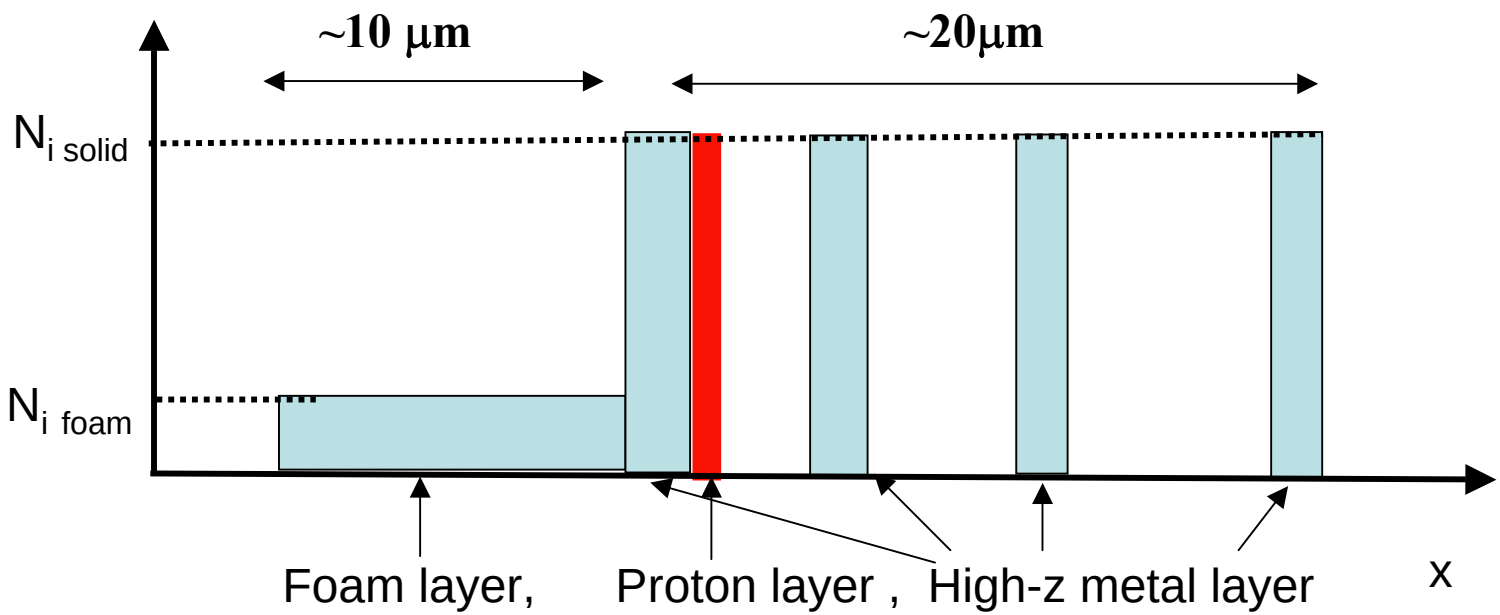

t = 450.31fs
P_x/m_c
x/lambda
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
45
50
55
60
65
70


16MeV
t = 483.67fs
f(E)dE
10^5
10^4
10^3
10^2
10^1
10^0
0.1
1
10
100
proton energy spectrum [MeV]

Summary

- **Multi-stage foil concept is investigated by 1-D PIC**
- **Quasi-mono-energy ion contains 1% of total laser energy.**
- **Laser intensity of 10^{20}[W/cm^2] will be necessary for 100[MeV] ion generation which is required for medical application.**

[Concluding Remark]
Target for high energy and monochromatic proton acceleration



$Zn_{i\ foam} < \gamma n_c$, $T_h \sim a^2 mc^2 /2$ ⟶ $I_L > 10^{21}$ W/cm^2
For 300 MeV proton

Summary

1. **Demonstrarion of dense plasma heating with focused laser produced ion.**
2. **Energy spectrum modulation:**

- **Deep modulations in proton spectra due to interaction with other ions and/or multi- foil and/or layer structure.**
- **High contrast laser pulse and target configuration allows for tailoring of proton spectra already in the MeV range at ~ 10^{19}W/cm^2**
- **Steps on the way to „monoenergetize“ proton beam self- organized multi stage , double layer (plane) and droplets**

3. **Higher ion energy:**

- **Preplasma or low density foam layer enhance ion energy which is proportional to laser intensity in stead of $I^{0.5}$.**

4. **Conversion efficiency:**

- **Efficient ions generation: 9% (~10^{11}/shot) of laser energy into protons or deuterons with energy between 120 - $1 \cdot 10^3$ keV in droplet (isolated) target.**