Recent Progress of Laser Ion Acceleration at Peking University

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Awake Meeting at The Wigner Research Centre for Physics, May 5, 2017, Budapest

Outline

1. Introduction
2. Progress of Laser Ion Acceleration @ PKU
3. Compact Laser Plasma Accelerator (CLAPA)@ PKU
4. Summary

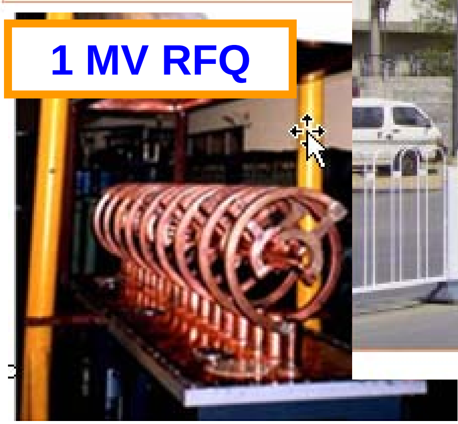
Institute of Heavy Ion Physics

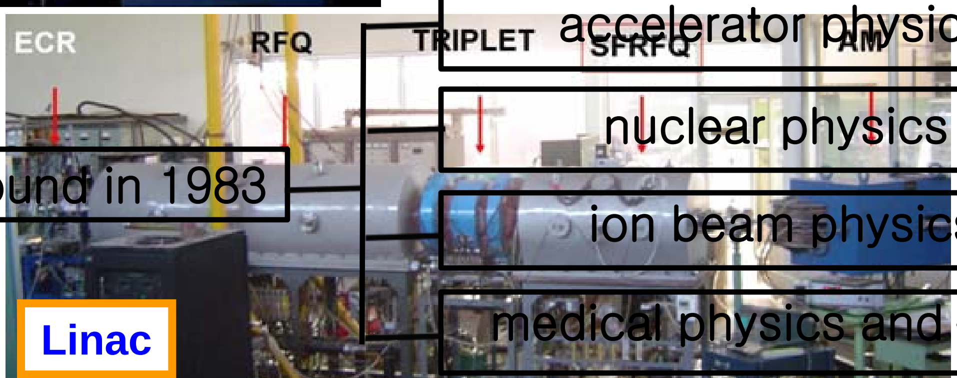
4.5 MV electrost

AMS facility

2*1.7MV tandem

1 MV RFQ





Linac

Found in 1983

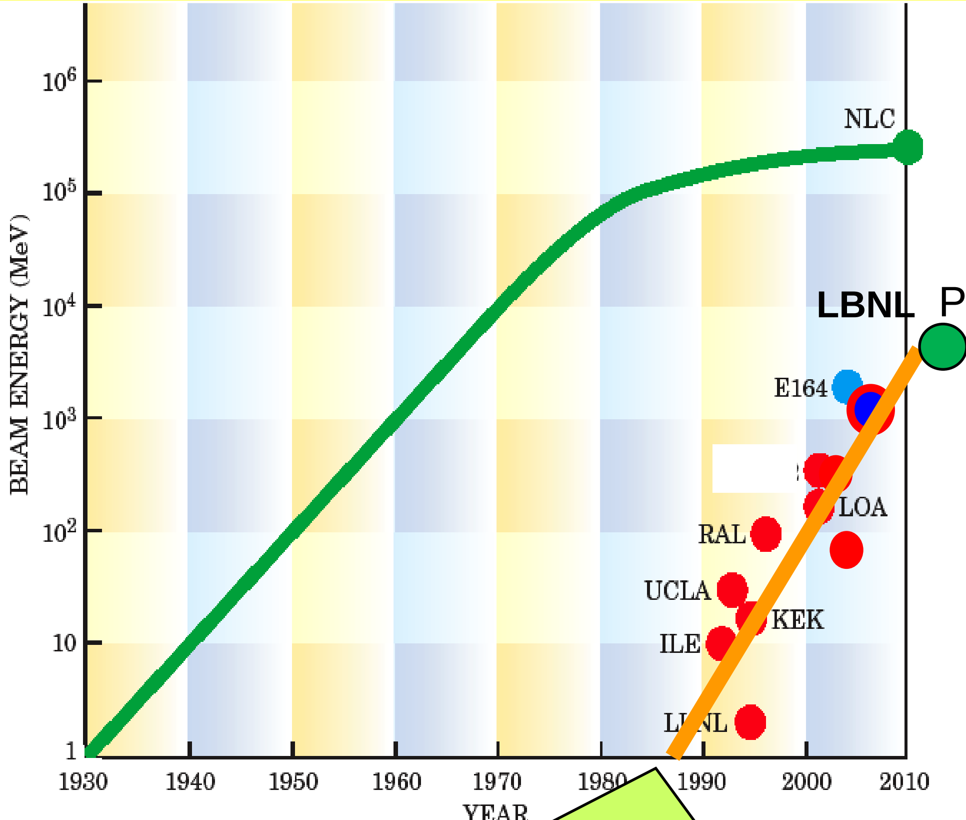
- accelerator physics
- nuclear physics
- ion beam physics
- medical physics and imaging

In 2007, upgraded to SKL of Nuclear Physics and Technology

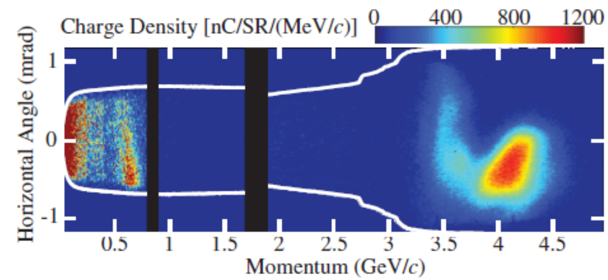
Laser proton accelerator

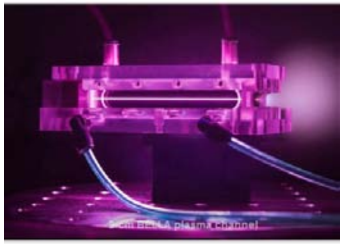
Why laser-driven ion beams?

The energy of conventional accelerator is close to saturation！
Laser plasma accelerator has rapid development ！



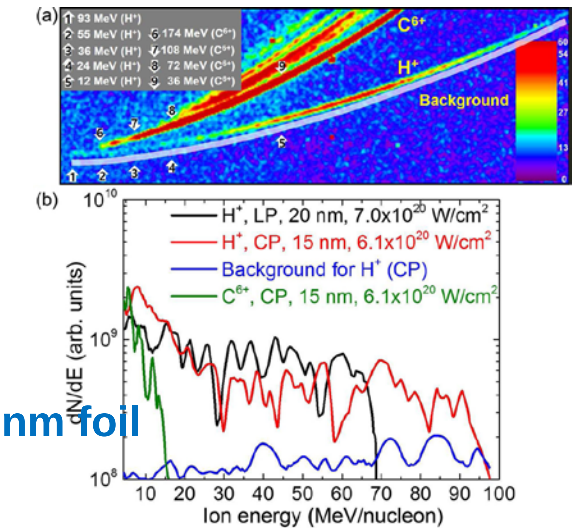
Acceleration gradient is three orders of magnitude higher





4.2 GeV e- by 9 cm Capillary in 2015

LBNL PRL 113, 245002 (2014)



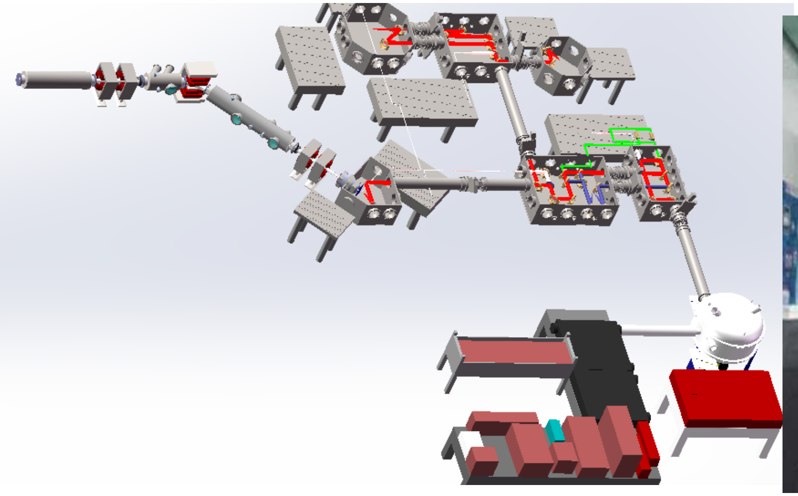
93 MeV P+ by nm foil in 2016

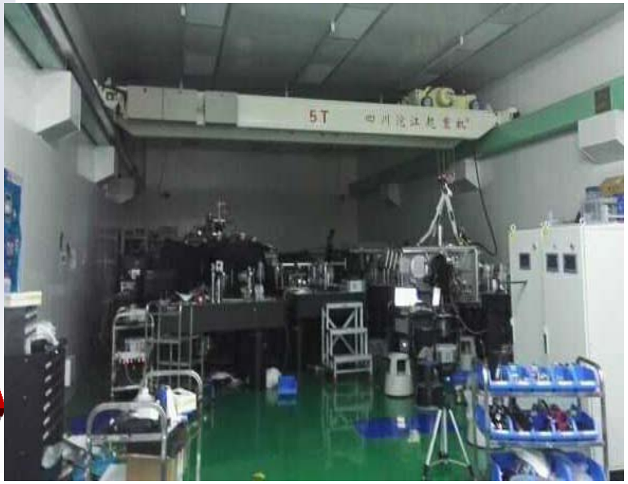
PHYSICS OF PLASMAS 23, 070701 (2016)

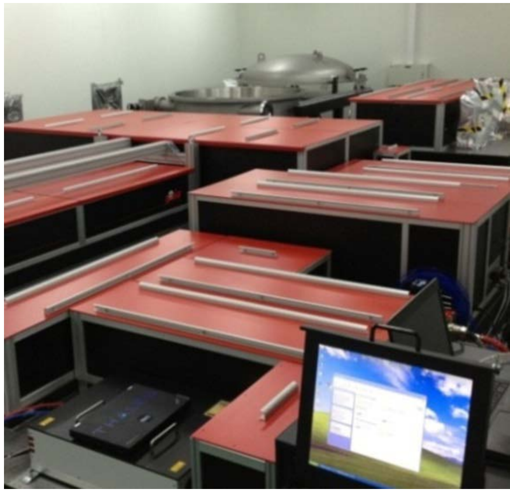
Compact laser plasma accelerator (CLAPA)

2013

2015







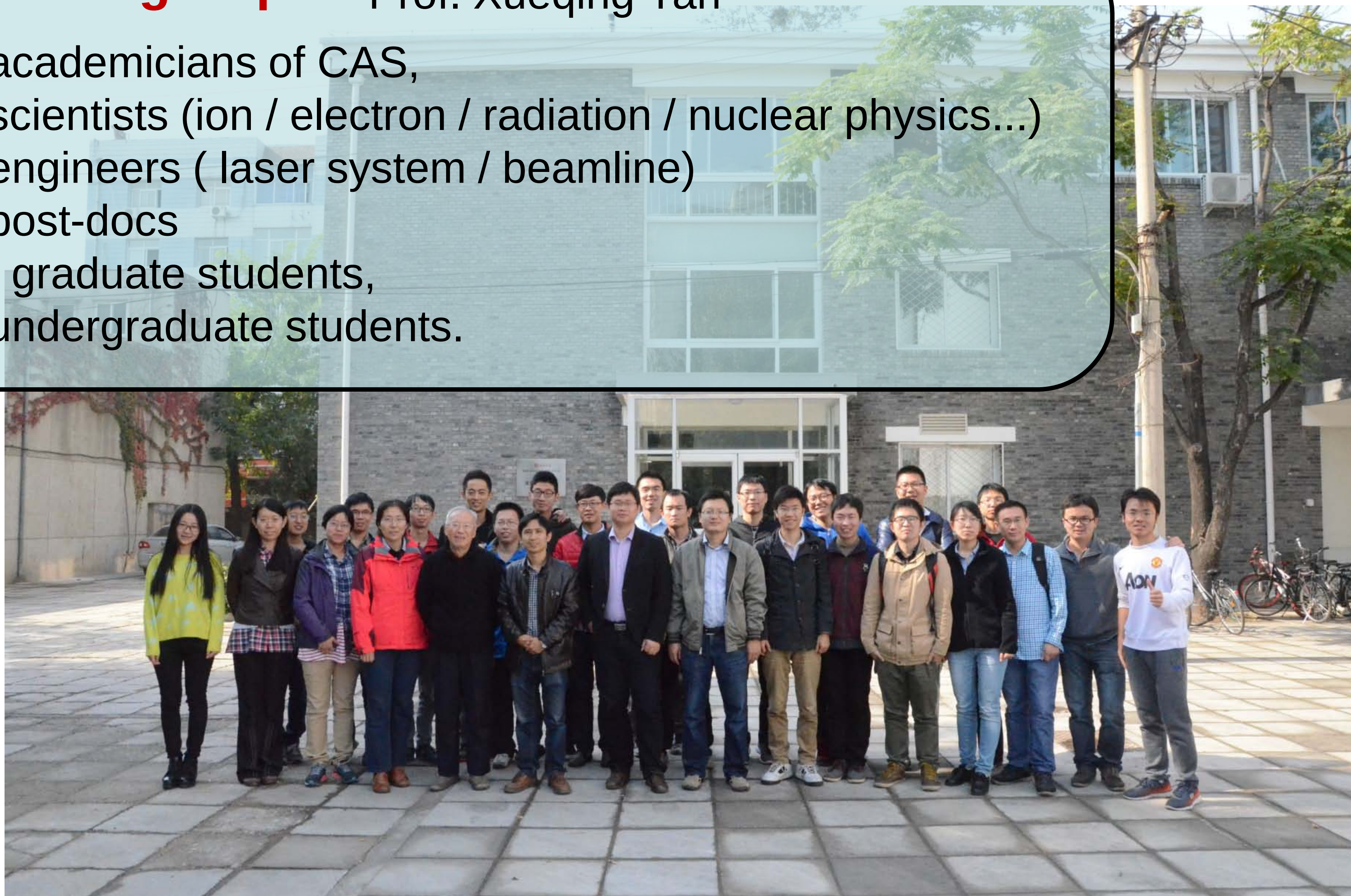
Funded by Ministry of Science and Technology of the People's Republic of China

HEDP Group

HEDP group

Prof. Xueqing Yan

2 academicians of CAS,
4 scientists (ion / electron / radiation / nuclear physics...)
2 engineers (laser system / beamline)
2 post-docs
21 graduate students,
5 undergraduate students.



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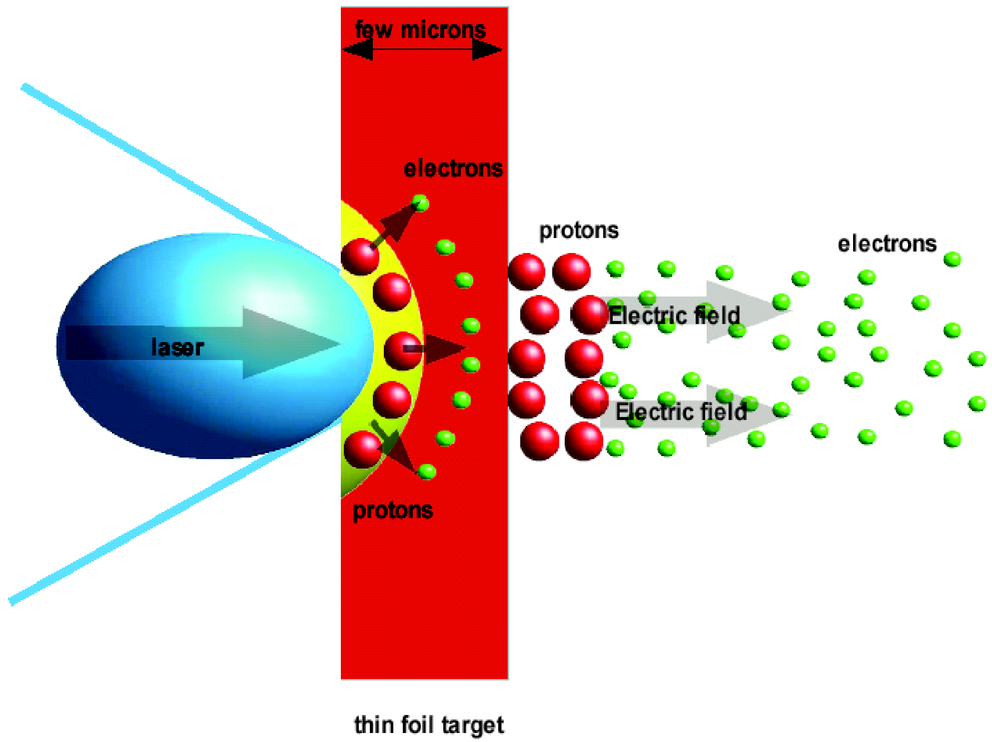
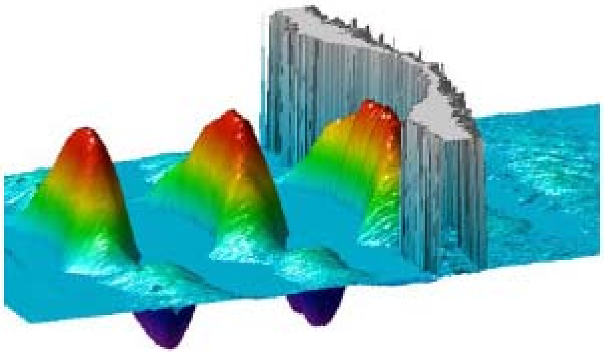
The TNSA Acceleration Mechanism



- Linear polarized laser irradiates on a micron-thickness target.
- Have achieved 67 MeV protons or 500 MeV Carbon ions.
- large energy spread and low energy transfer rate (~0.1%)

Nature 439, 441 (2006); Nature 439, 445 (2006); POP 18, 056710 (2011)

The RPA Acceleration



$$\pi \frac{n_e}{n_c} \frac{\ell}{\lambda} \equiv \zeta$$

Phase Stable Acceleration

Sailboat

Laser light pressure:

$$P_{rad} = \frac{I}{c} = \frac{3 \times 10^{-3}\ \mathrm{Pa}}{1W/cm^2}$$

$$= 3 \times 10^{12}\mathrm{atm} \quad \left(I = 10^{20}\,W/cm^2\right)$$

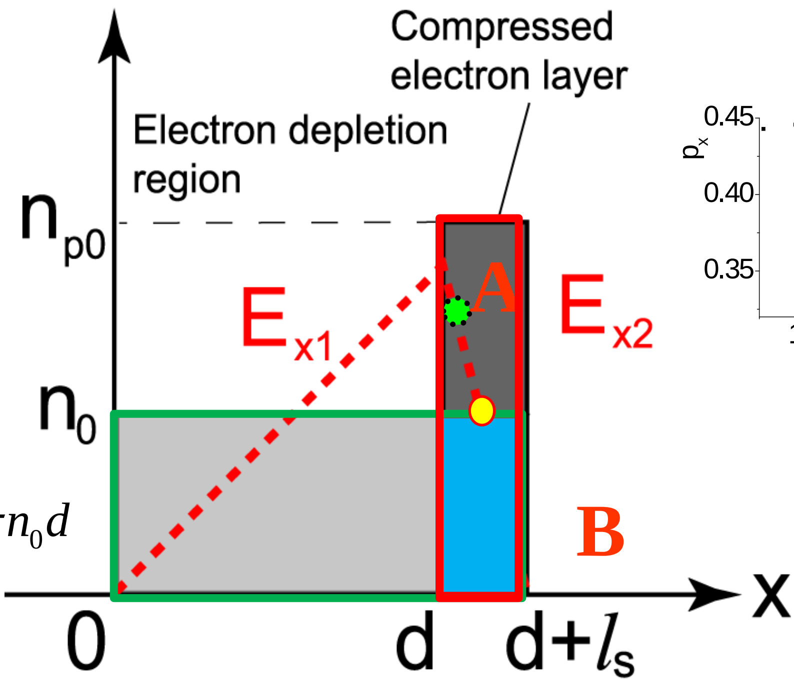
with 10 nm DLC foil~2 μg/cm²:

$$a = \frac{P_{rad}}{m} \approx 10^{22}\,m/s^2 = 0.03\ c/fs$$

$$\approx 1MeV/u/fs$$

Phase Stable Acceleration

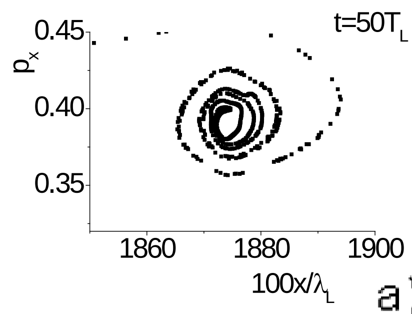
$$a=\pi\left({n_e}/{n_{cr}}\right)\left({d}/{\lambda}\right)=\zeta$$

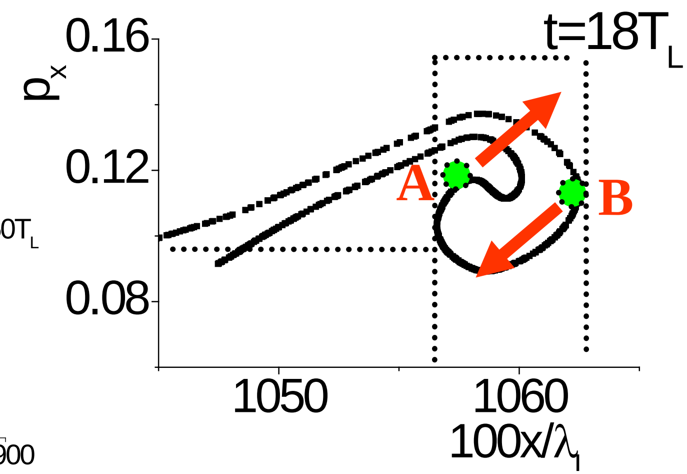


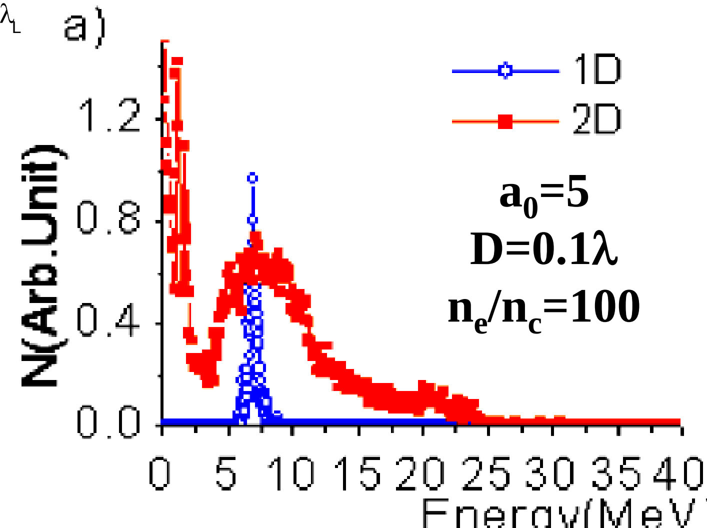
$$E_0=4\pi n_0 d$$

$$E_{x2}=E_0(1-(x-d))/l_s,(d<x<d+l_s)$$

Phase space (x~p$_x$)

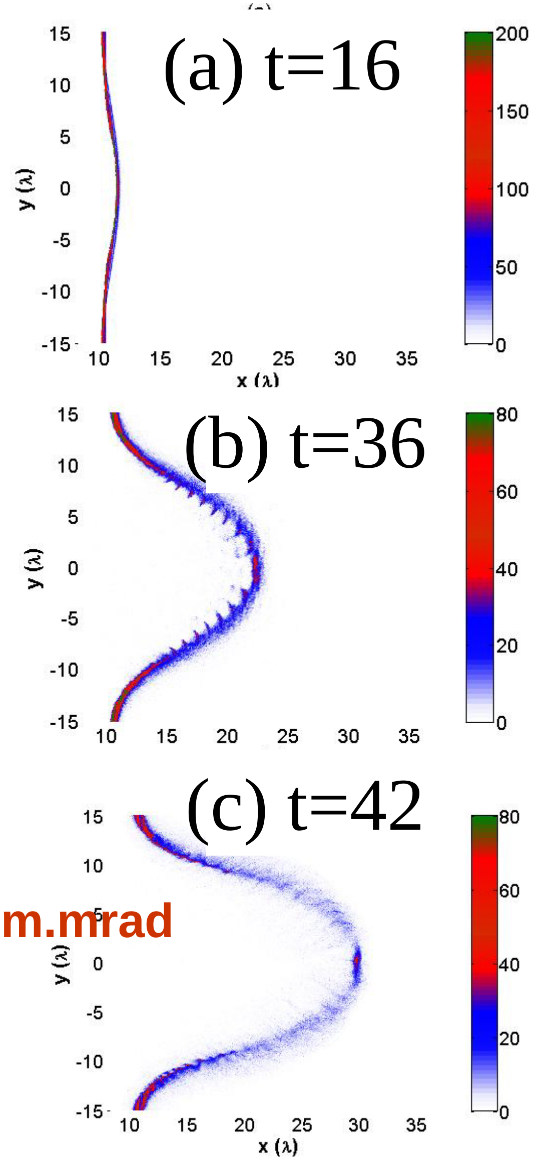






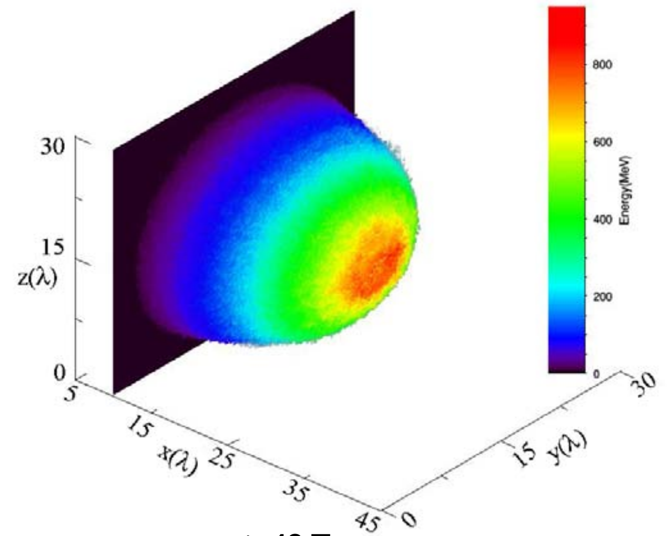
X.Q.Yan et al, PRL 100, 135003 (2008)

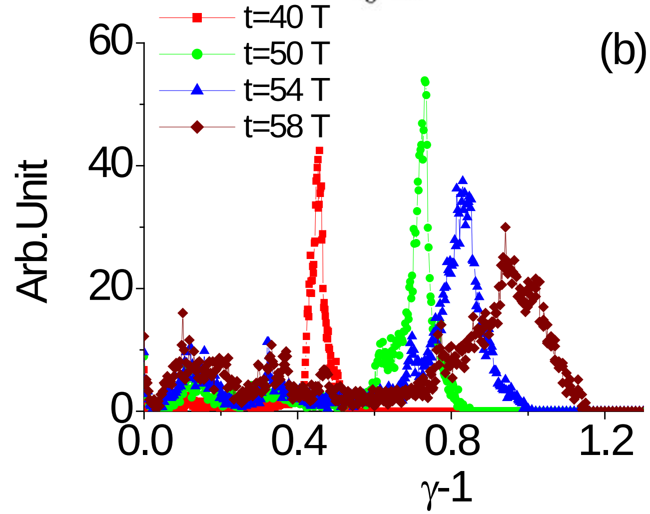
Self-organizing nc GeV proton by PSA



ε_r~0.5 mm.mrad

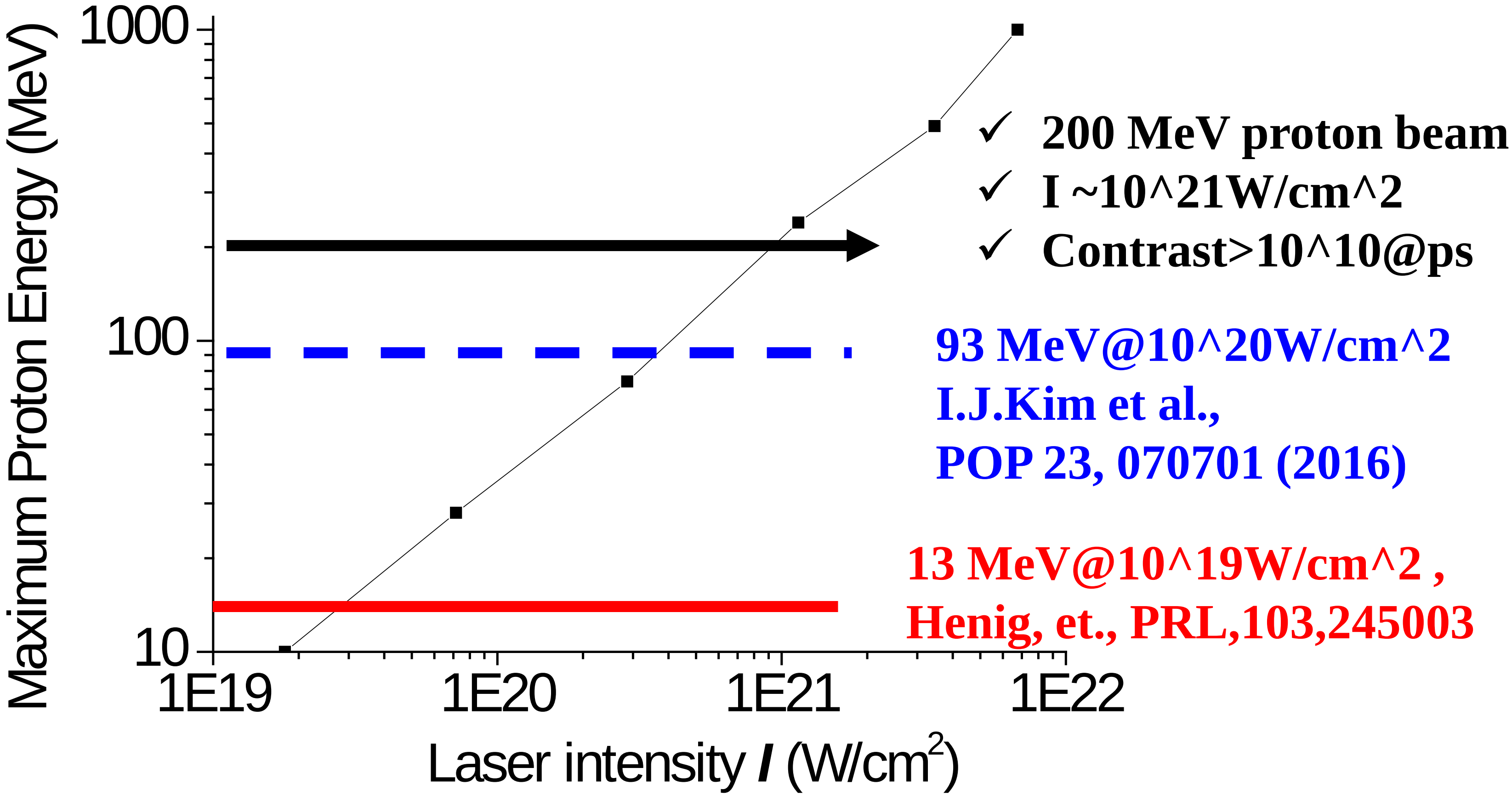
I~10^22W/cm2, CE>10%





X.Q.Yan, …, J.MtV, et al., PRL, 103, 135001, (2009)

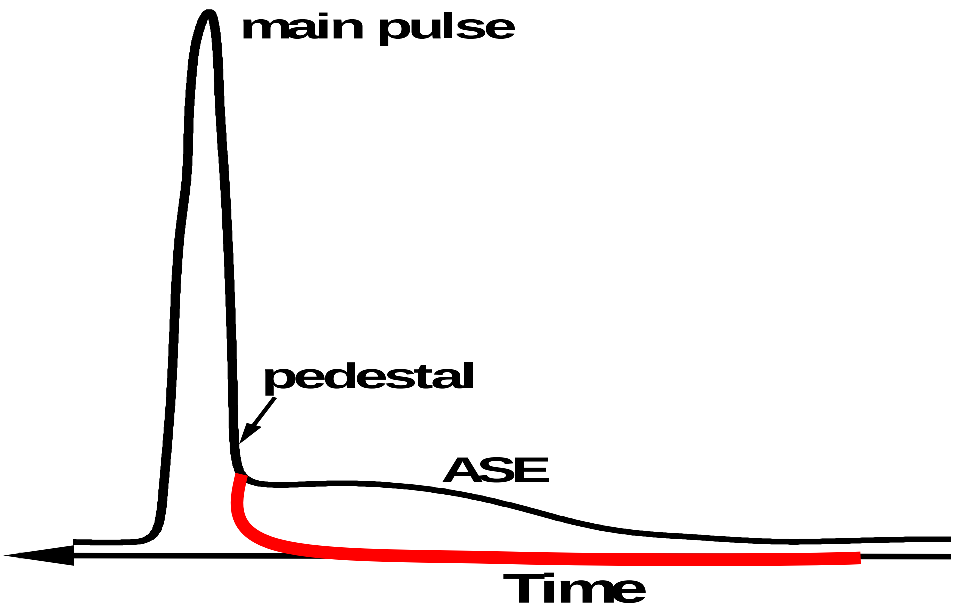
RPA Challenge (I): High Laser Intensity



T.Tajima, D.Habs, and X.Q.Yan. *Review of Accelerator Science and Technology*, 2(201-228),2009.

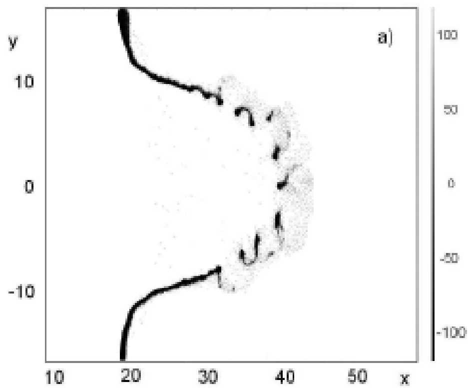
RPA Challenge(II) : Contrast of 10^{10}@ps

It is very difficult to satisfy a contrast >10^{10} @10ps,ns and an intensity of 10^{20}W/cm^2 ！

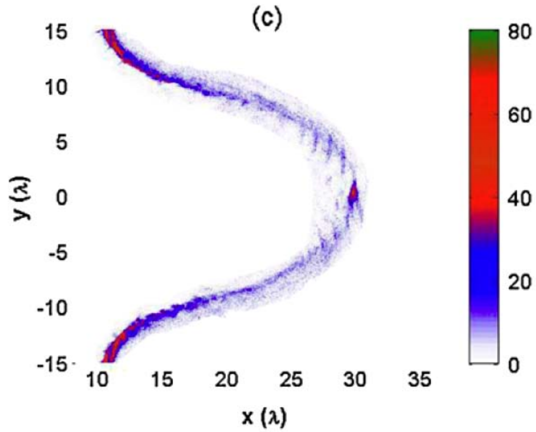


1. **Amplified Spontaneous Emission**
2. **Pedestal：100ps before the main pulse**
3. **Replica: a few ns**

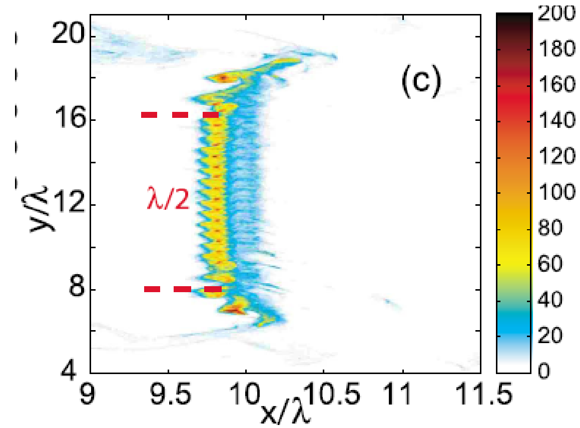
RPA Challenge (III): Instabilities



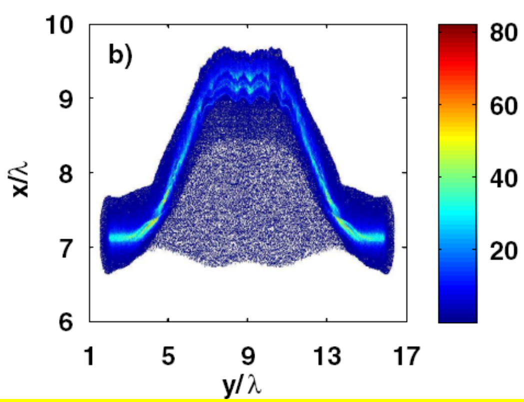
F. Pegoraro et al., **PRL** 99, 065002 (2007)



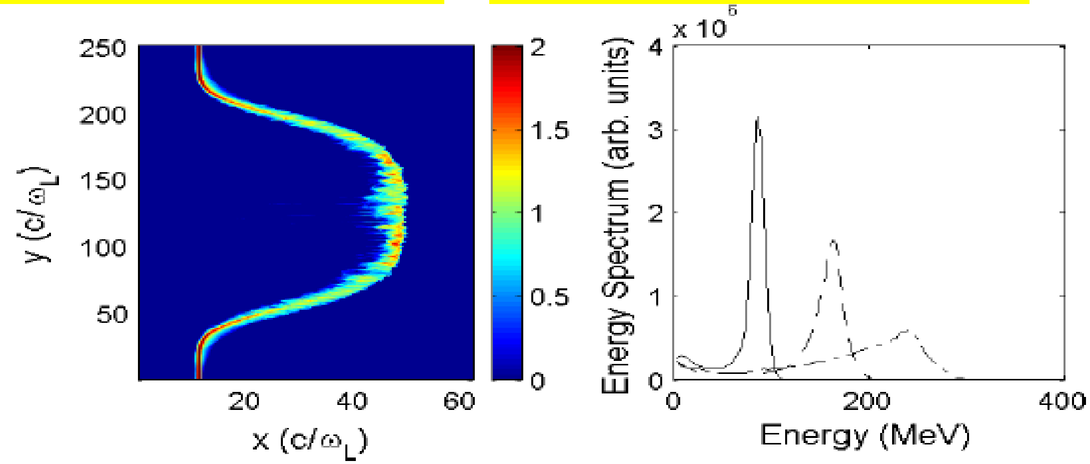
X. Q. Yan et al., PRL 103, 135001 (2009)



M.Chen et al., **POP**, 15, 113103, 2008

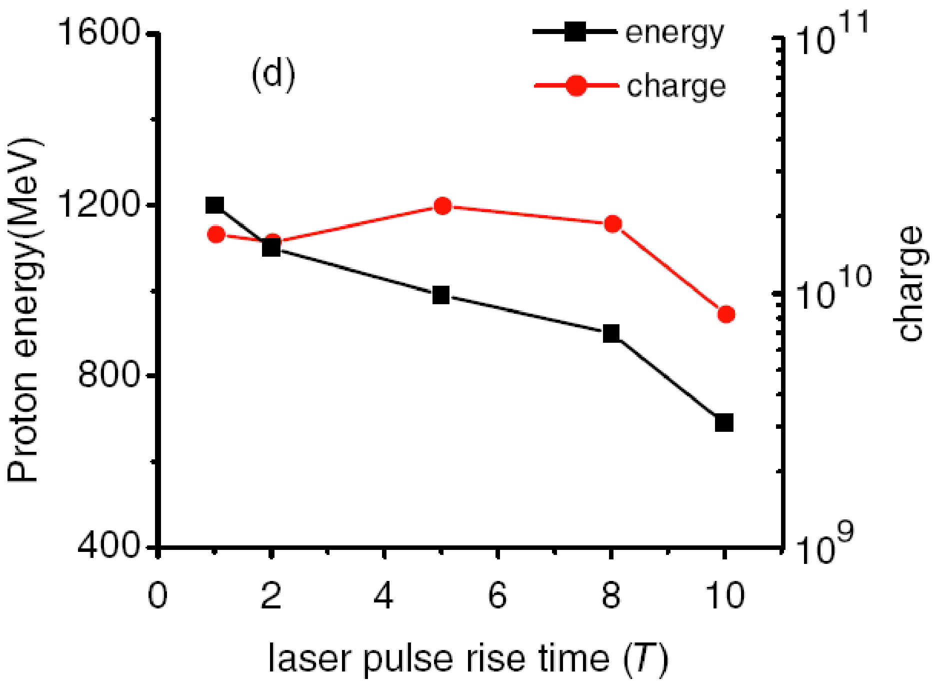


Klimo et al., **Phys. Rev. ST AB** 11, 031301 (2008)



A P L Robinson et al., **New J. Phys.** 10 013021 (2008)

Challenge(IV): Short Rise Time is Required

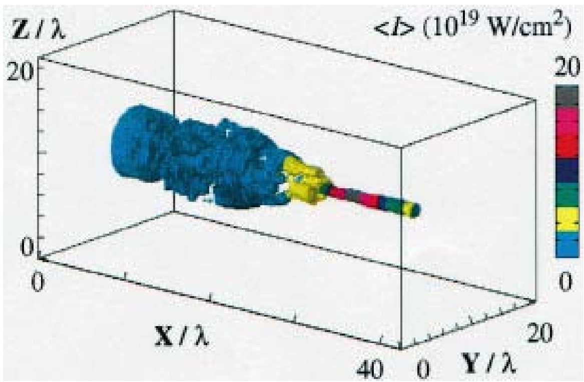


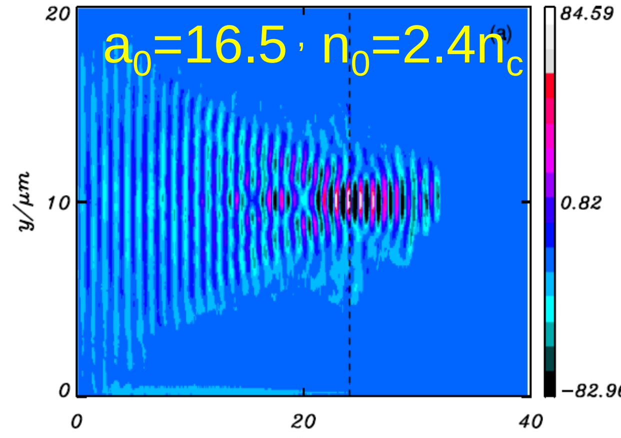
Step pulse with I>10^21W/cm2 for RPA!

X. Q. Yan et al., PRL 103, 135001 (2009)

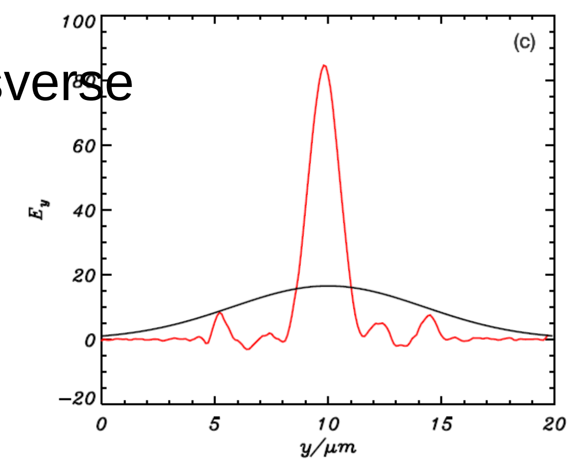
Laser Shaping by a Plasma Lens

Laser pulse propagating in near-critical plasma will synchronously experience Self-focusing, temporally steepen and prepulse clearing.

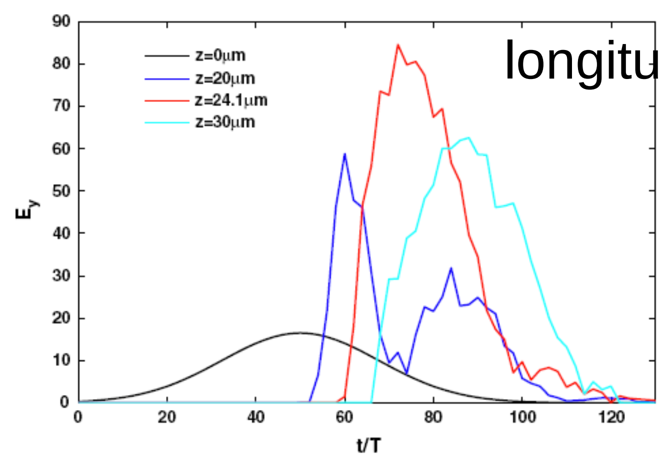




Transverse



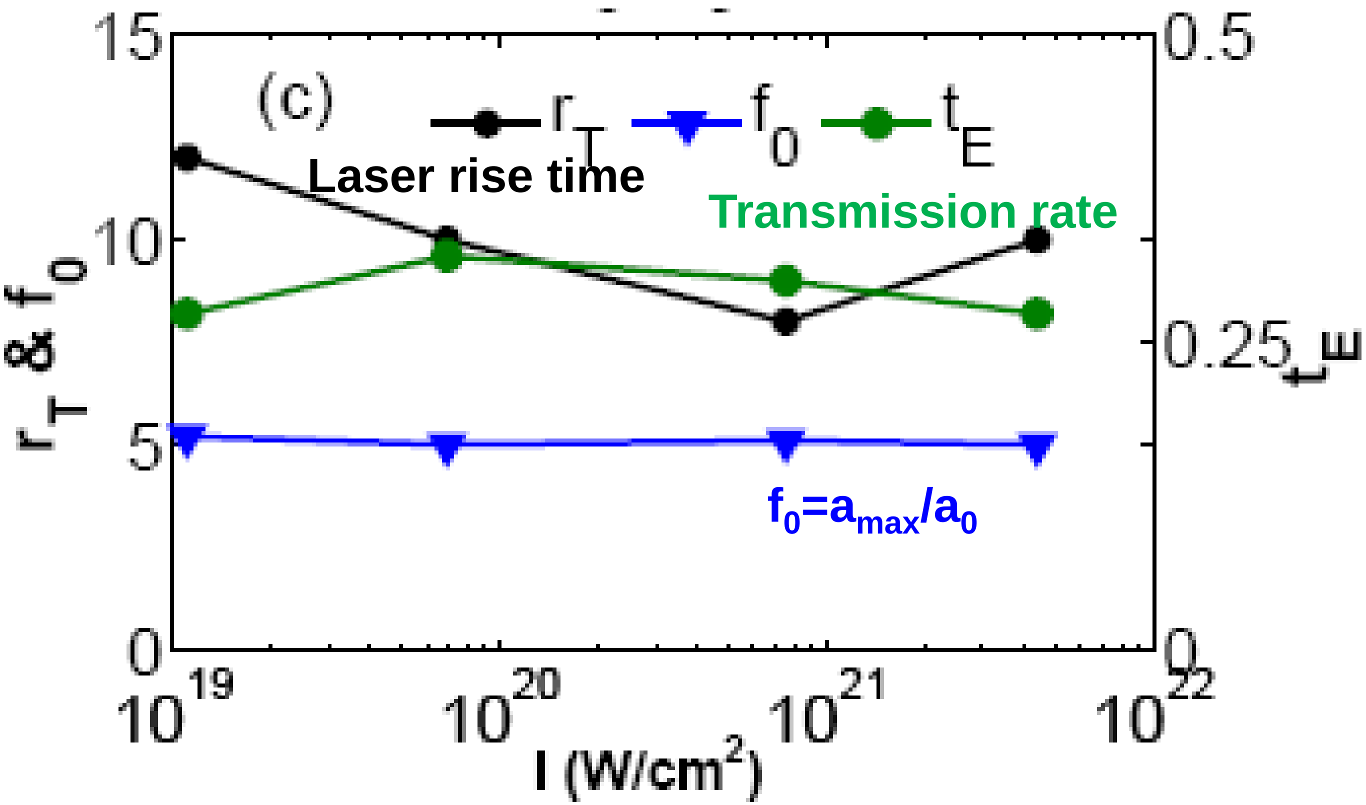
longitudinal



A. Pukhov et al., PRL 76 3975 (1996); H. Y. Wang et al., PRL 107, 265002 (2011)

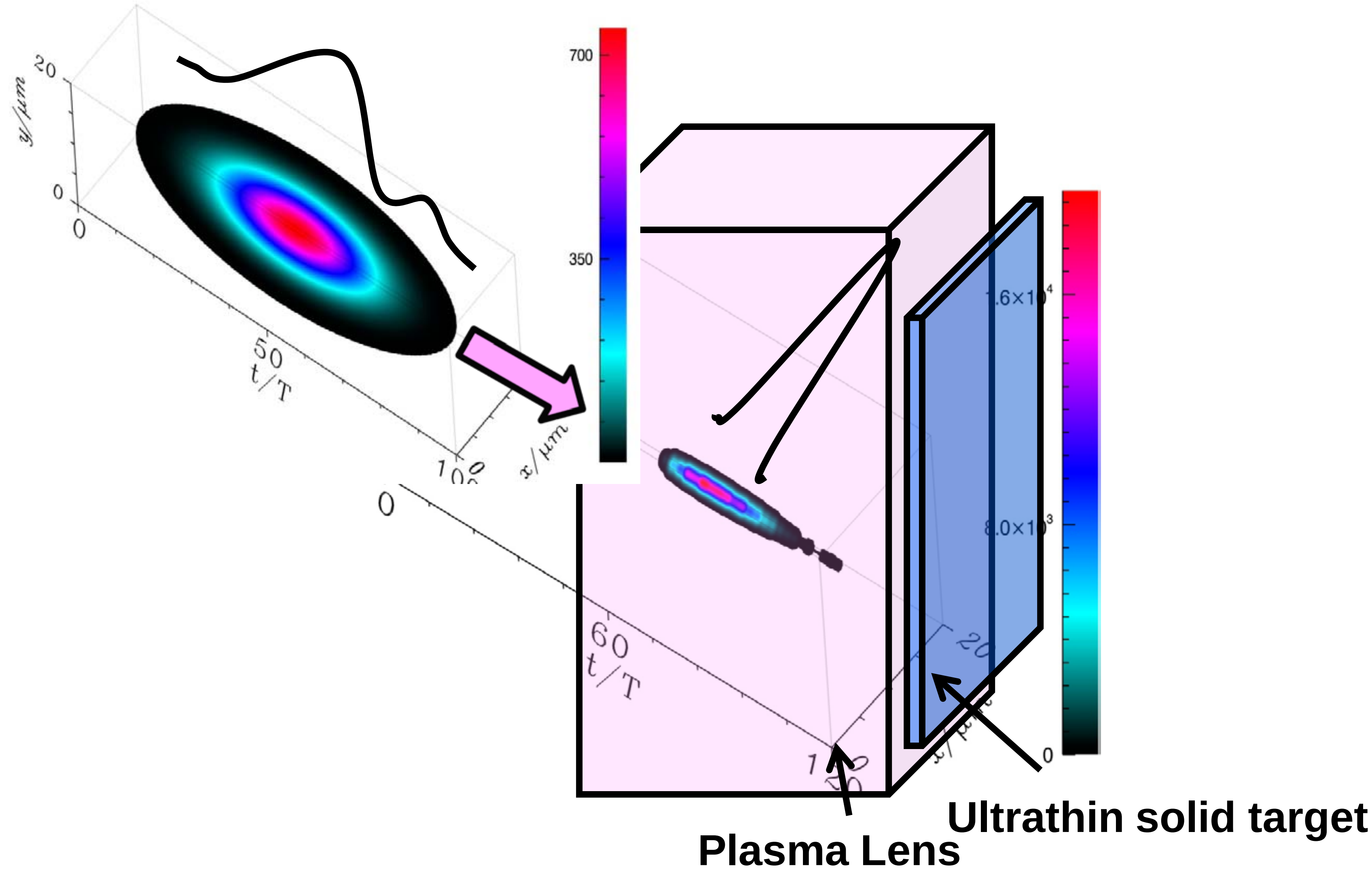
Universal of Plasma Lens

$l_s/\lambda=(an_c/n_e)^{0.5}\sim 2.6$



H. Y. Wang et al., PRL 107, 265002 (2011)

Plasma lens to generate high quality laser pulses



Laser ablated plasma lense

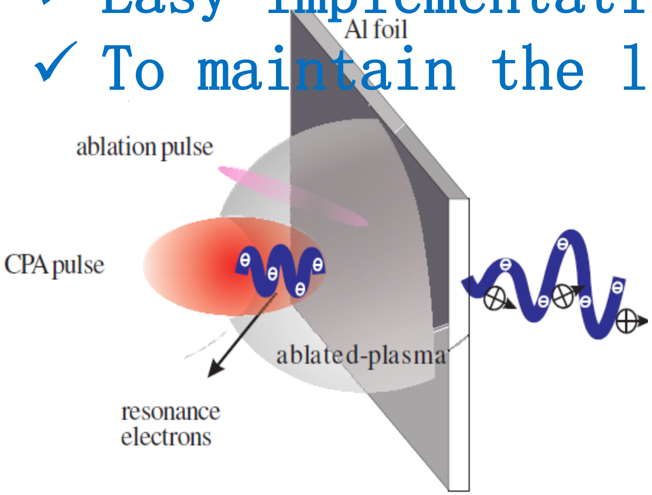
- ✓ Using additional ablation laser pulse to generate pre-expanded plsma lense with exponential density distribution.
- ✓ The laser direct accelerated electrons play important role.

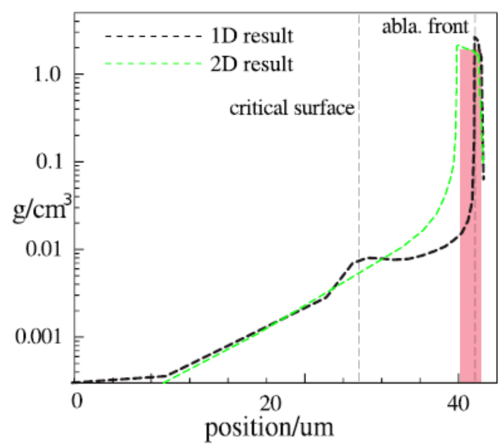
$$E_{sheath} \propto \left(\frac{8\pi}{e_n} n_e T_e\right)^{1/2}$$

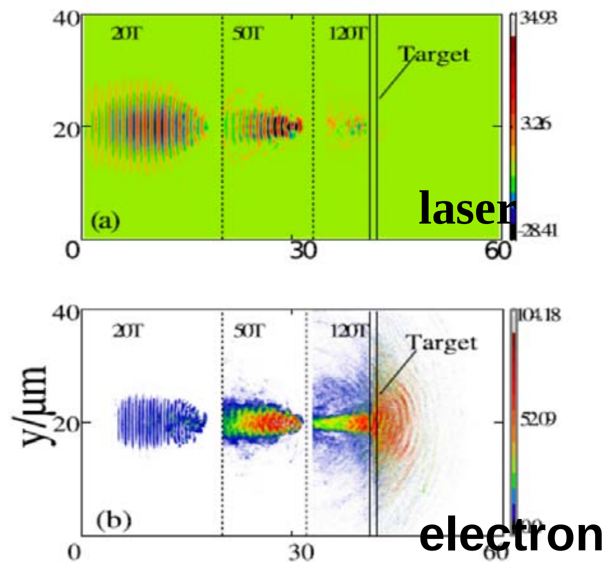
$$\sqrt{a n_c/n_e} = 2.6$$

- ✓ Easy implementation
- ✓ To maintain the laser in self focu

I~10^{12} W/cm^2, 200 ps





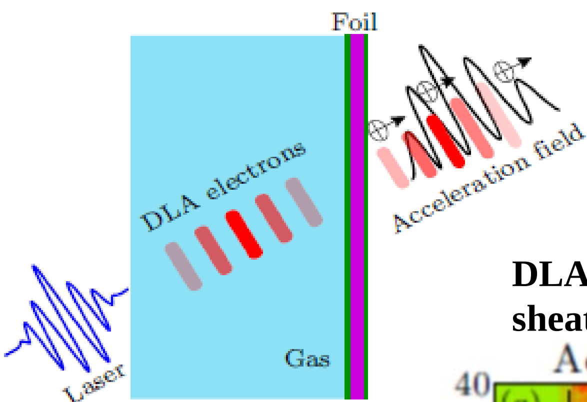


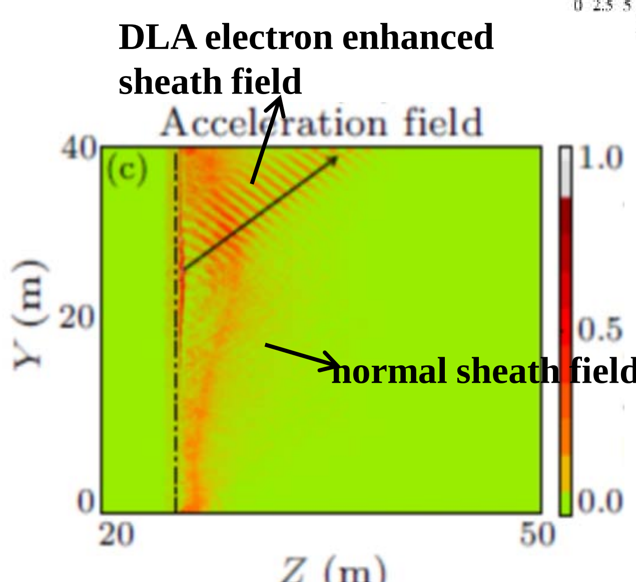
S. Zhao et al., Physics of Plasmas 22, 073106 (2015).

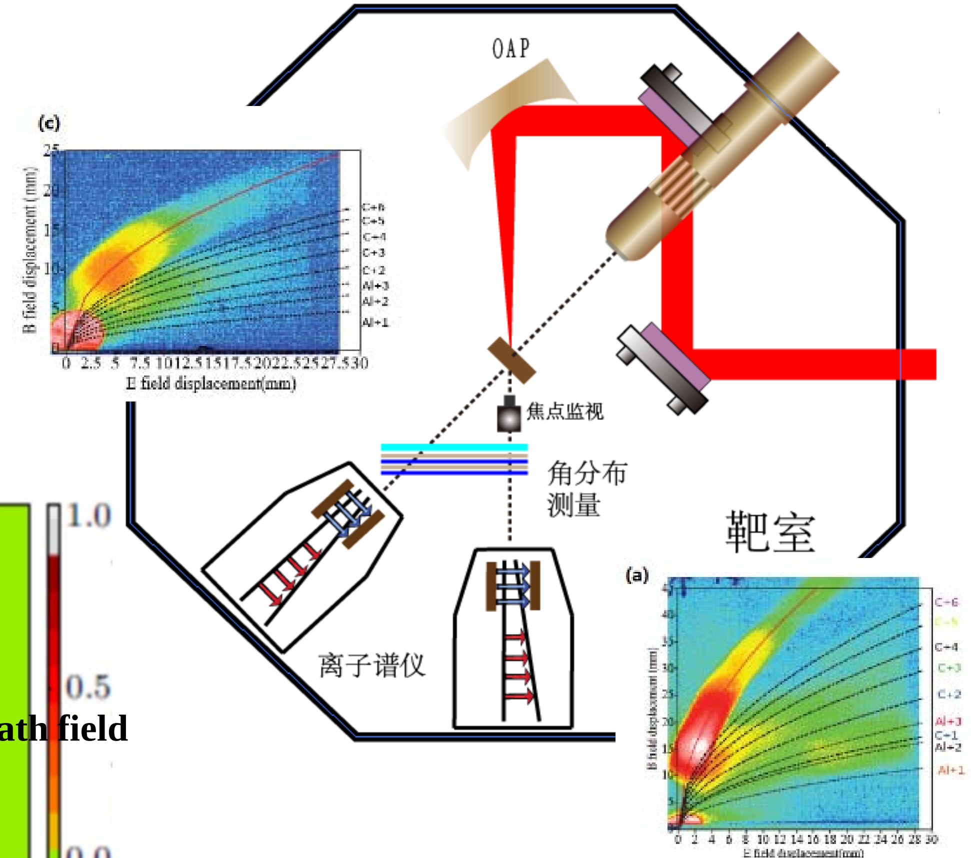
Ion acceleration with low contrast laser

Quasi-monoenergetic ion beams observed in the experiment.

Laser：2 J， 8 um (FWHM)，80fs,
I=2*10^{18} W/cm^2 , 10^-6@ 5 ns

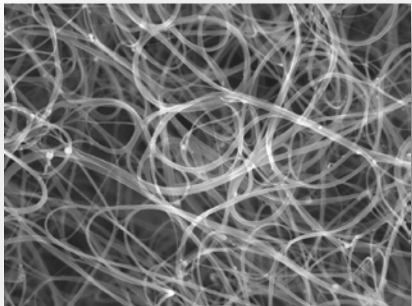


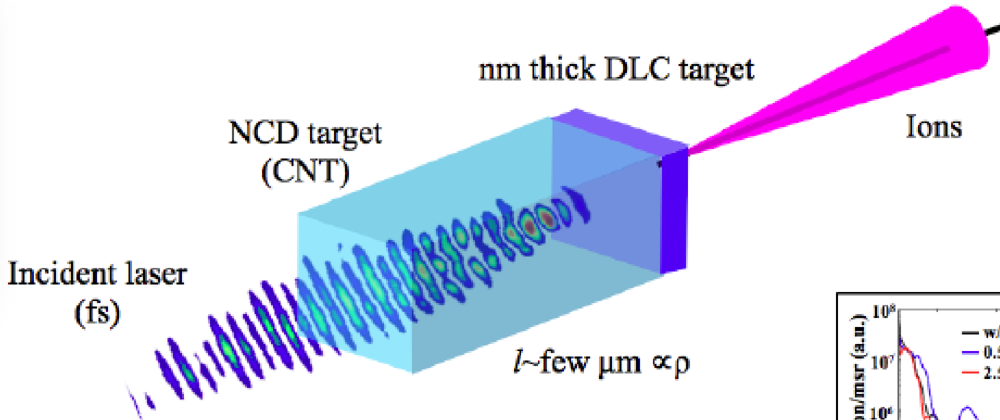


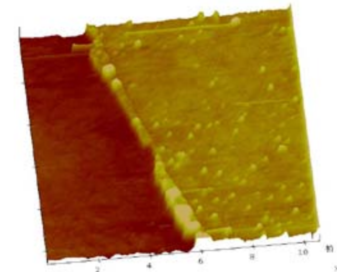


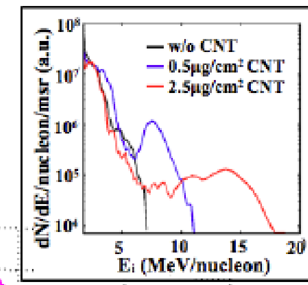
S. Zhao et al., CHIN. PHYS. LETT. Vol. 33, No. 3, 035202(2016)

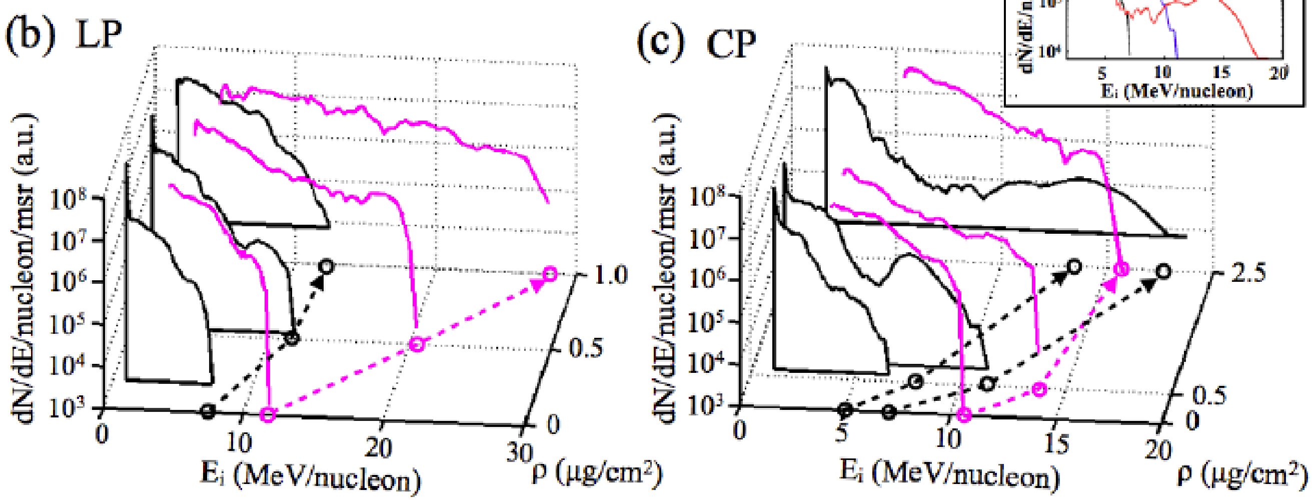
Carbon nanotubes as the Plasma lense











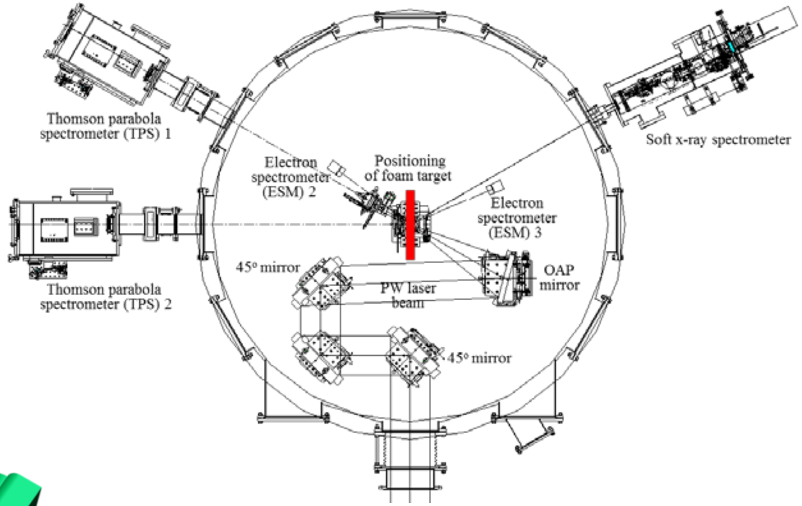
J.H.Bin*, **W.J.Ma*** et. al. "Ion Acceleration Using Relativistic Pulse Shaping in Near-Critical-Density Plasmas". *Physical Review Letters 115, 064801 (2015).*

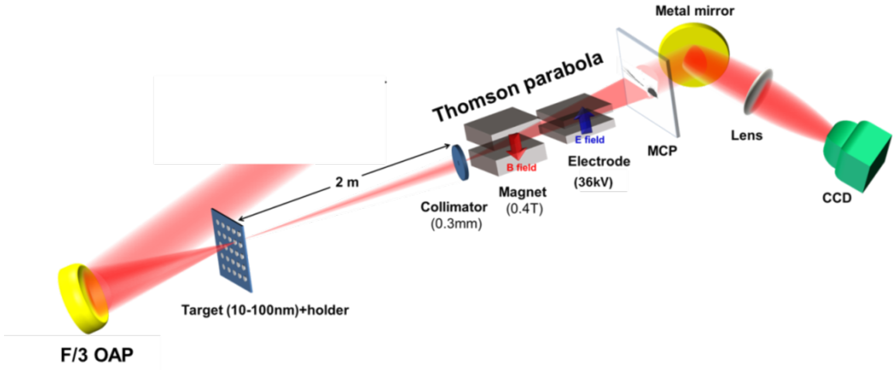
Experiments were performed CoReLS PW Laser

Laser： 10 J， 4.5um (FWHM)

CP： $4*10^{20}$ W/cm^2

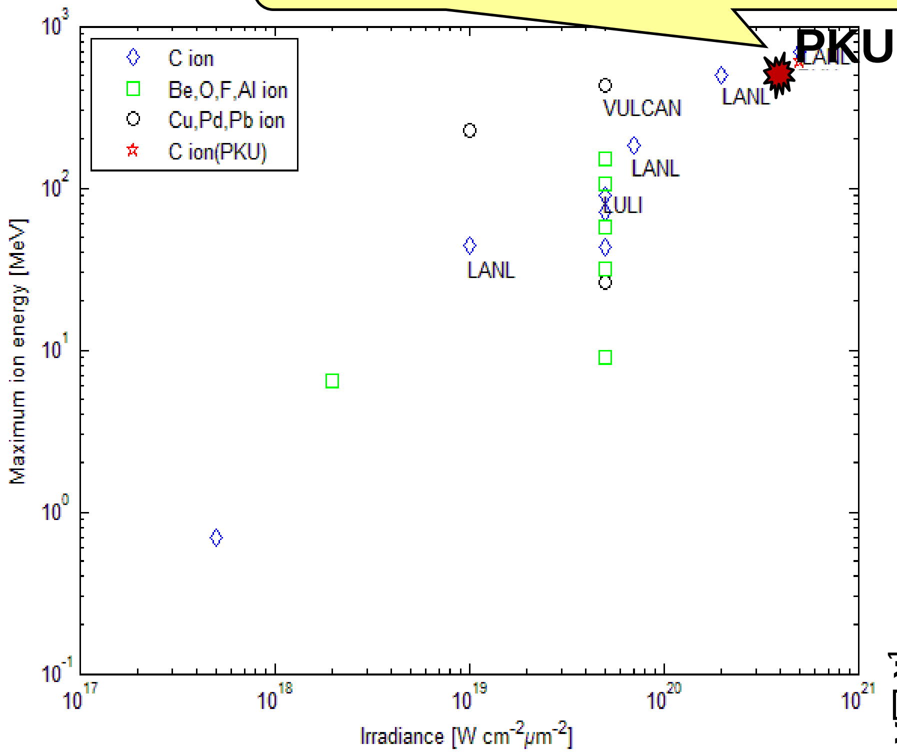
Target: Carbon nanotube+DLC

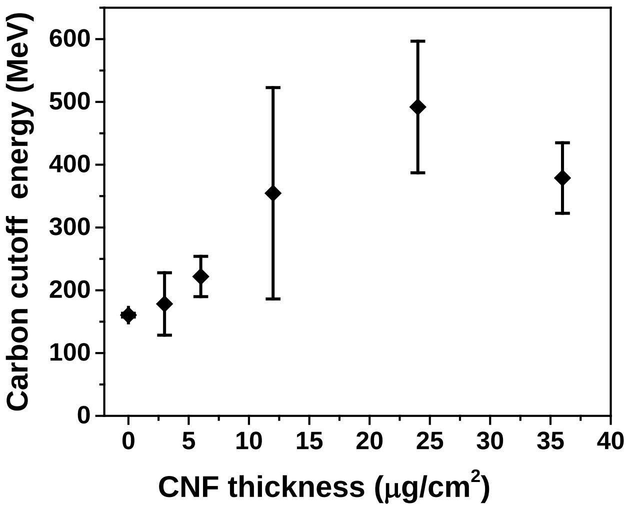


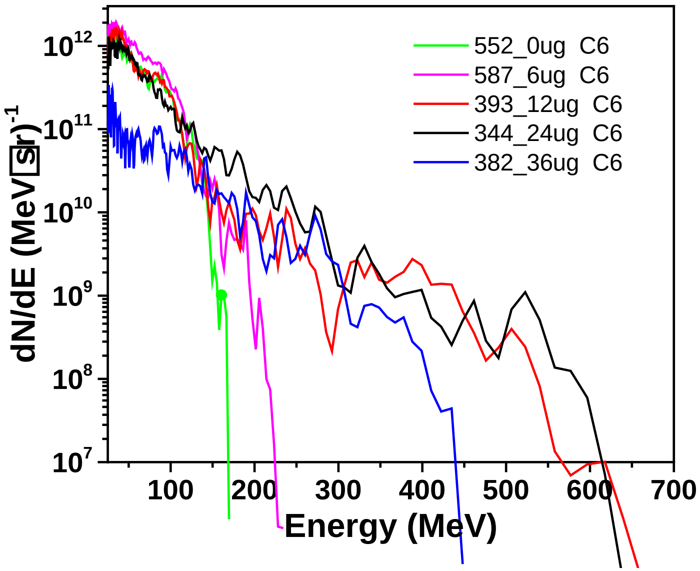


New energy record of fs laser driven ions

9 J/30 fs, 600MeV Carbon ions







By Yan ,Ma, Lin, Schreiber, Zepf, Kim &Nam et al., ready to submittion.

Ionization Dynamics is important

- **It may be accurate to model a pre-ionized system in proton acceleration since hydrogen is easy to be ionized.**

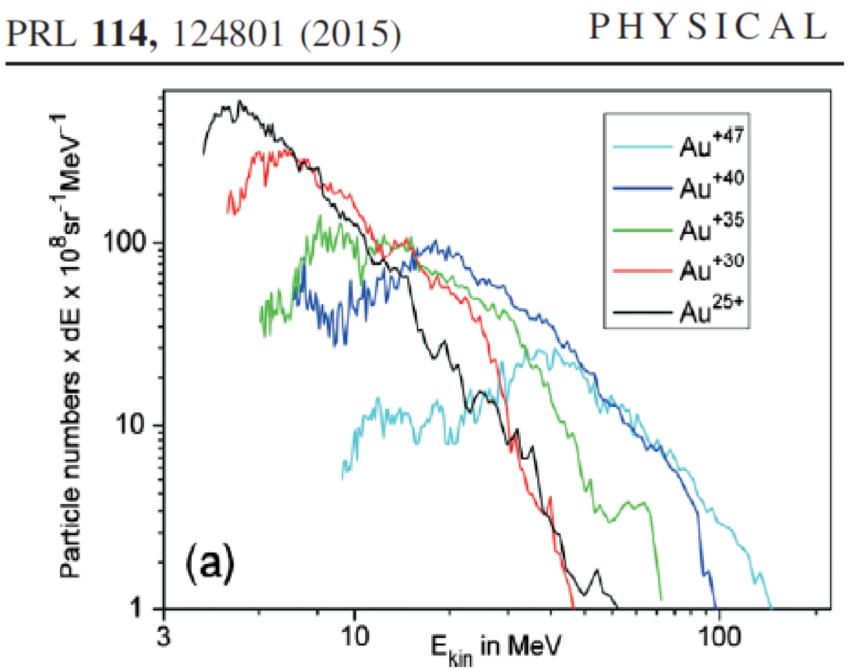
$$E_{\text{th}} = -\frac{U_{\text{H}}^2}{16 Z U_{\text{i}}^2(\text{eV})} E_{\text{as}}$$

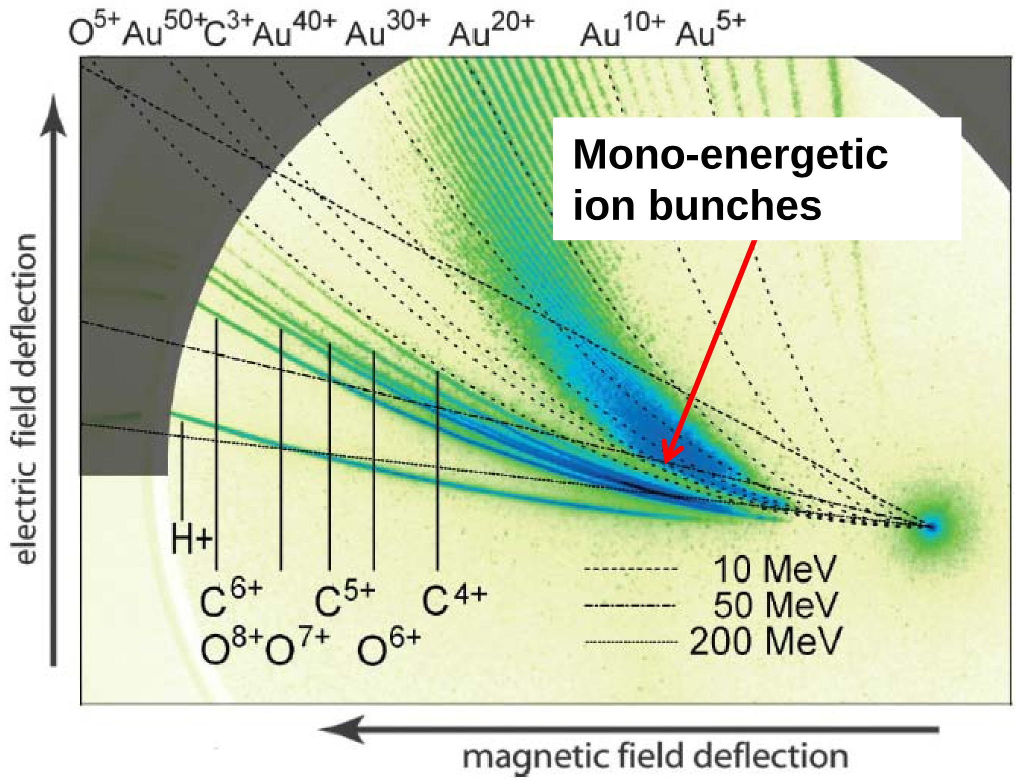
- **For heavy ions, whose ionization threshold field is much higher than hydrogen, ionization plays a critical role on plasma formation.**

E_{as} = 5. 1×10ˆ11 V/m is the atomic field strength,
U_H = 13. 6 eV is the hydrogen ionization potential,
Ui is the reference ionization potential
Z is the ion charge after ionization.

Ion type	Threshold field (V/m)
H^{1+}	$3.19 \cdot 10^{10}$
C^{4+}	$1.8 \cdot 10^{11}$
C^{6+}	$6.9 \cdot 10^{12}$
O^{6+}	$2.1 \cdot 10^{12}$
O^{8+}	$1.6 \cdot 10^{13}$
Al^{13+}	$7.0 \cdot 10^{13}$
Si^{14+}	$8.8 \cdot 10^{13}$

Mono-energetic ions produced in the normal TNSA experiment

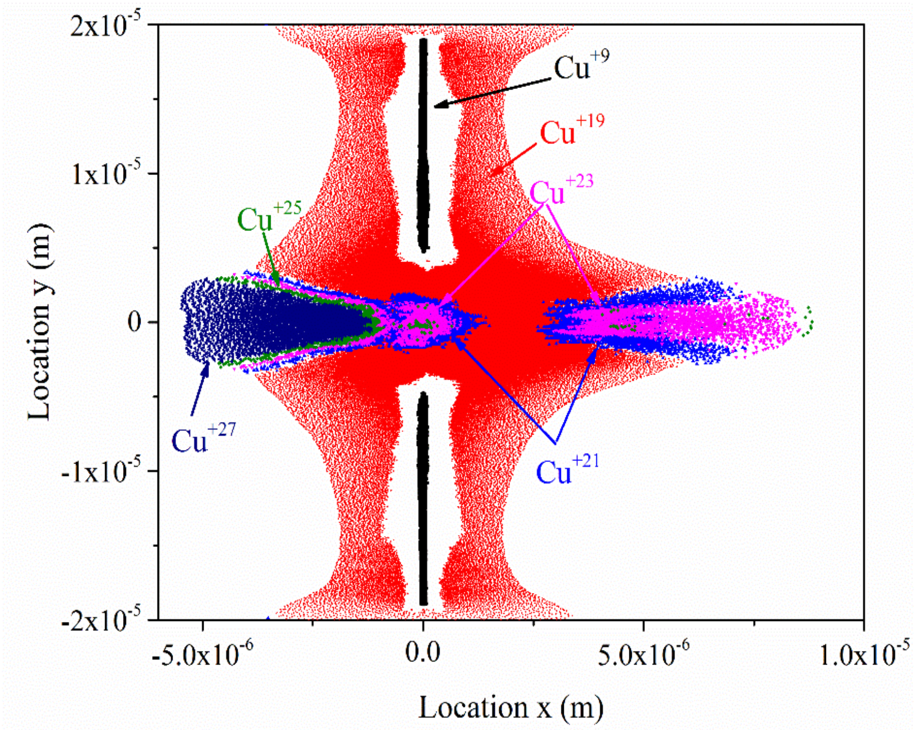


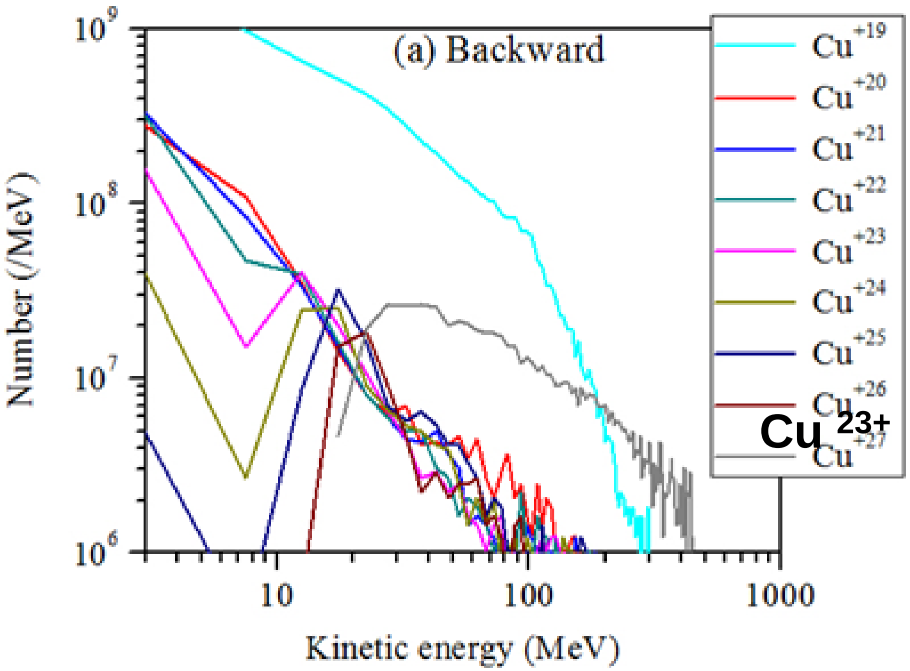


Including ionization in the simulation, we may reproduces the mono-energetic bunches!

Micro-structured target via ionization dynamics

Laser	Intensity (W/cm^2)	Duration/simulation time(fs)	Spot size(μm)	Target	Simulation box
1.3J	$1 \cdot 10^{20}$	35/300	4	20nm Copper	60• m*10• m



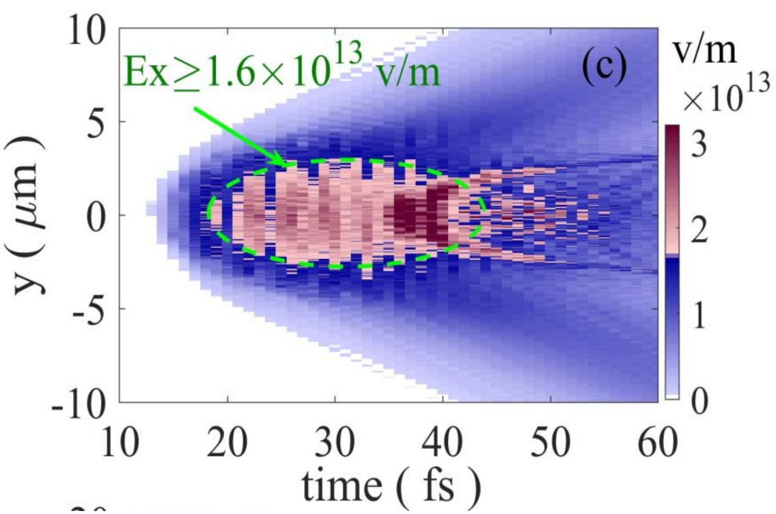


Target parameters

material	density	thickness	width
DLC	3.57 g/cm^3	20 nm	40μm

Laser parameters

	GIST
E (J)	9.6J
I (10^{20} W/cm^2)	4.7



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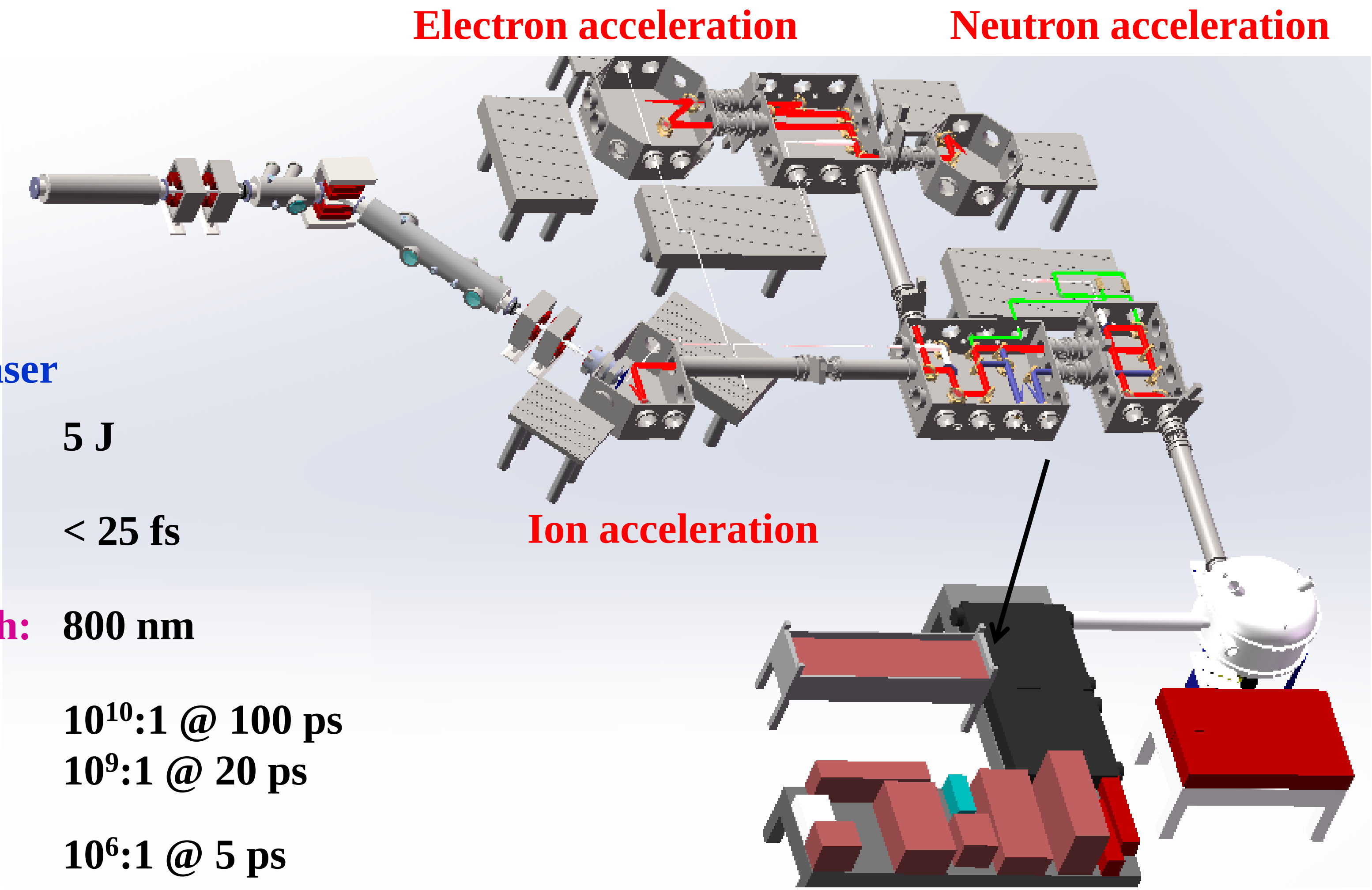
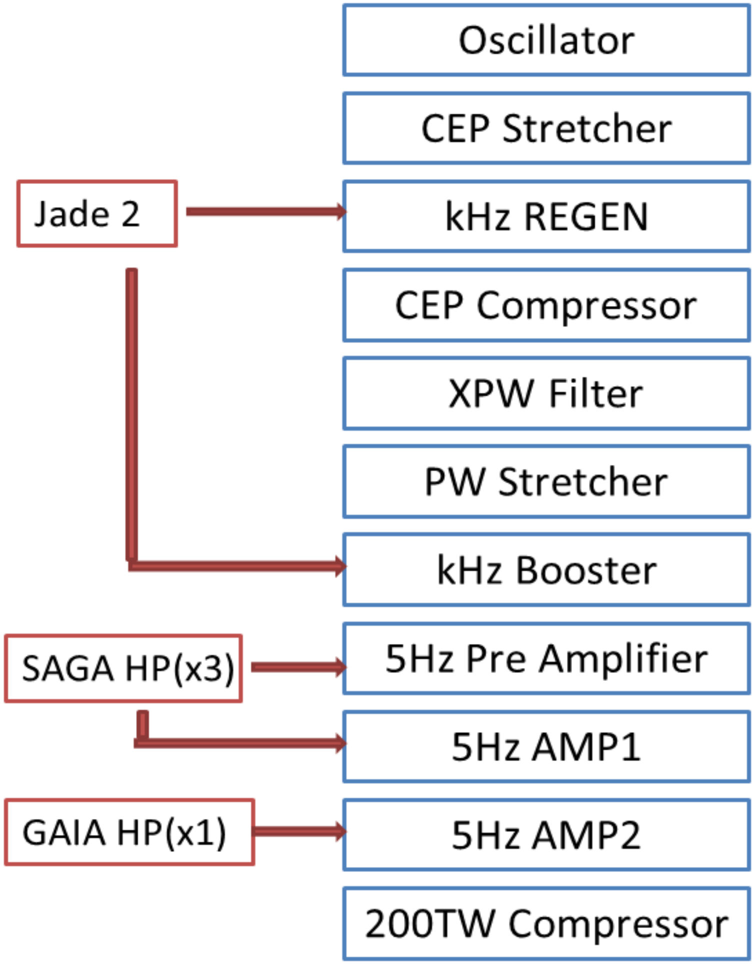
CLAPA at PEK



CLAPA Laser

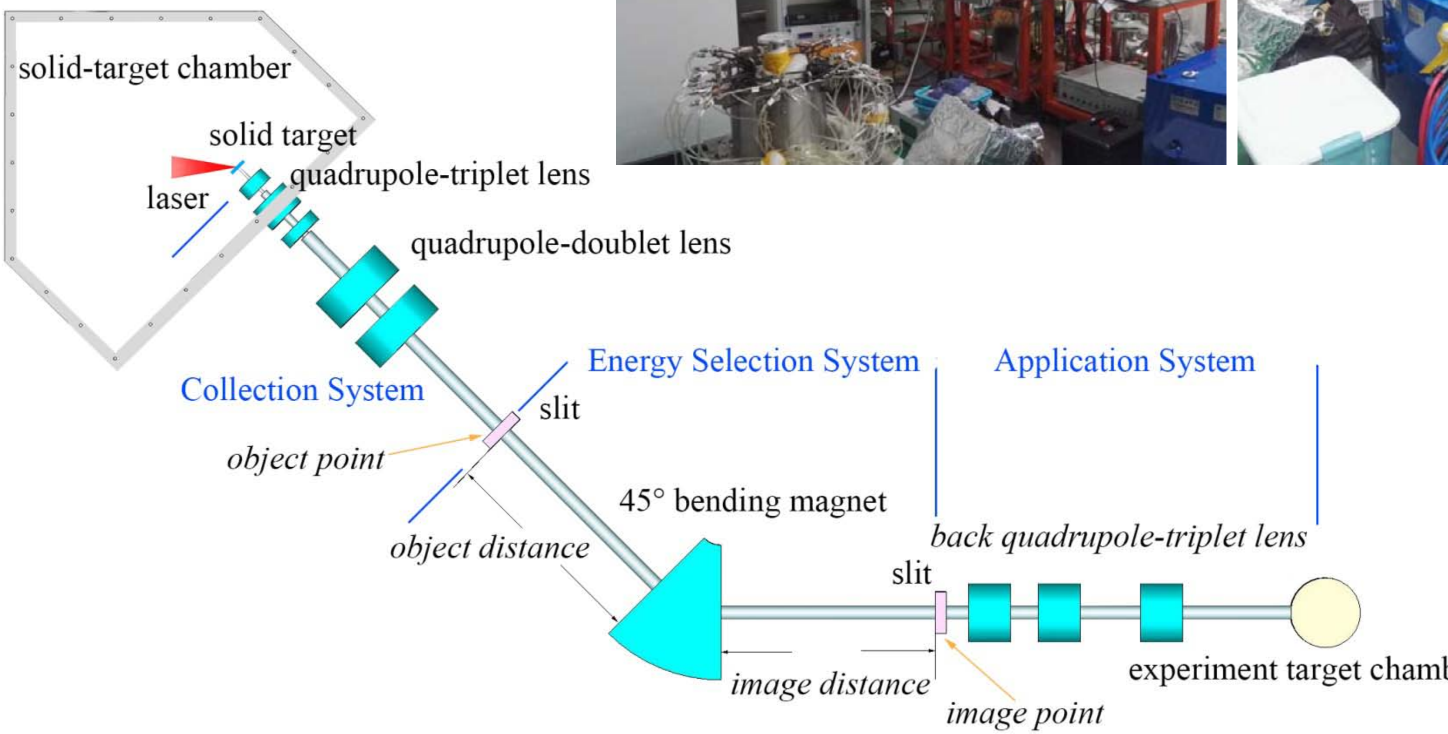
Energy:	**5 J**
Duration:	**< 25 fs**
Wavelength:	**800 nm**
Contrast :	**10^{10}:1 @ 100 ps** **10^{9}:1 @ 20 ps** **10^{6}:1 @ 5 ps**

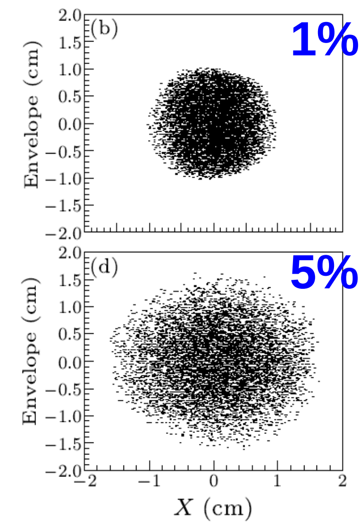
200TW Laser System



Current situation

Beamline system





Energy :1- 44 MeV energy spread: 0~• 5%，10^6-10^8 particles per bunch.

The beam line will be accomplished in October.

CHIN. PHYS.LETT. 34(2017) 054101

Advanced Target Lab



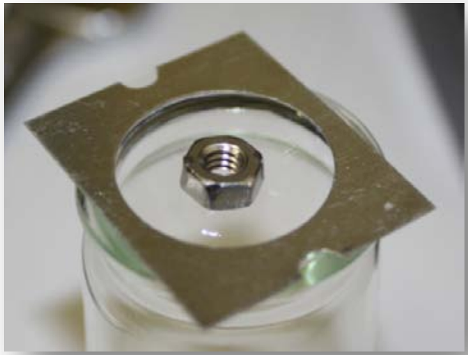




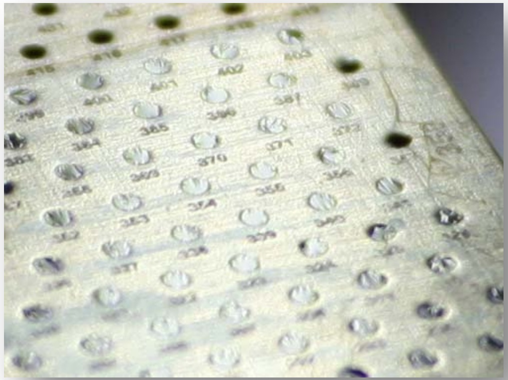

Multiple Targets manufacture ability

50nm-10μm,Metal foils

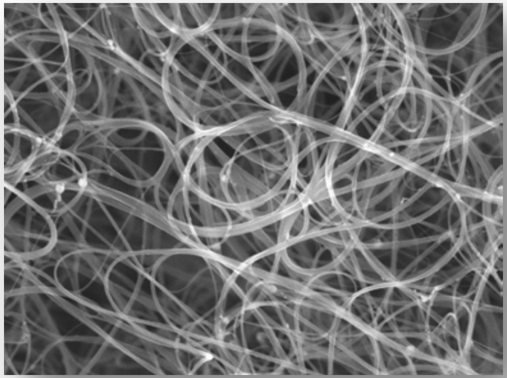
10nm-3 μm plastic foils

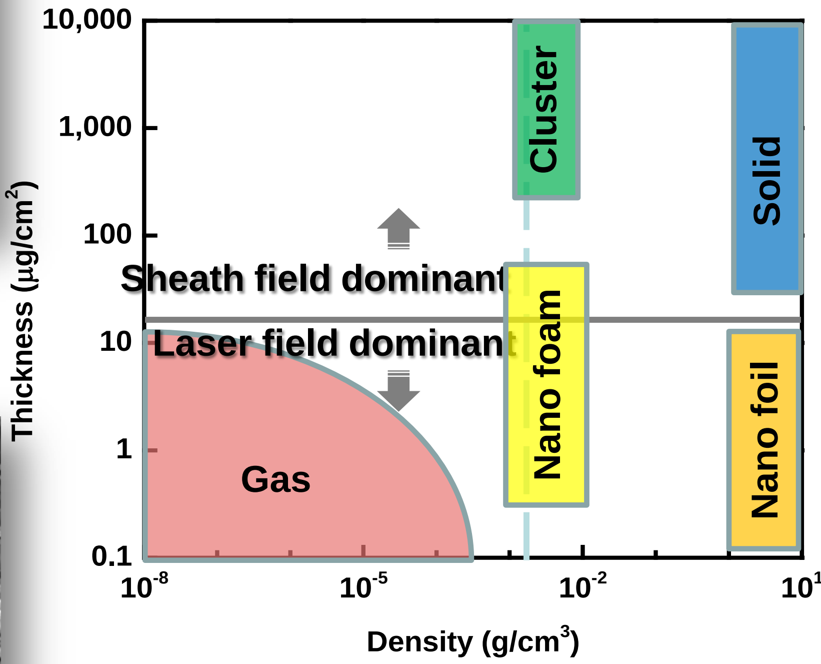


5nm -40nm DLC foil

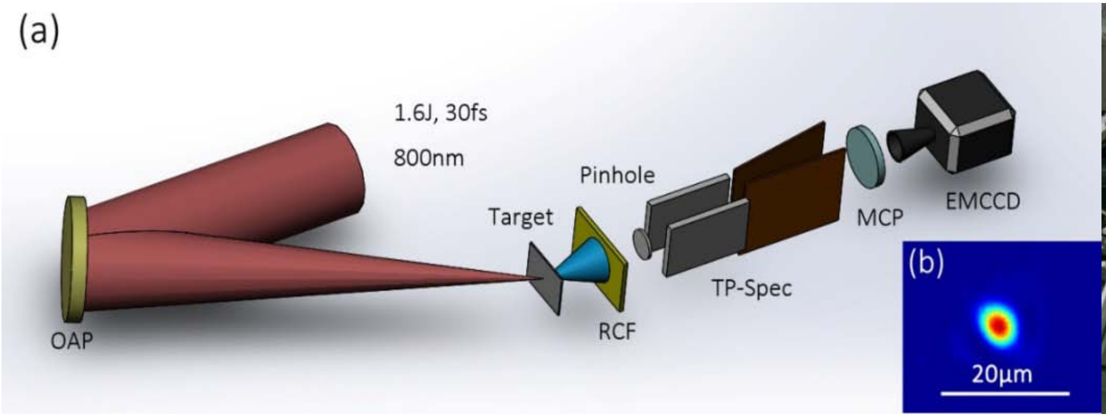


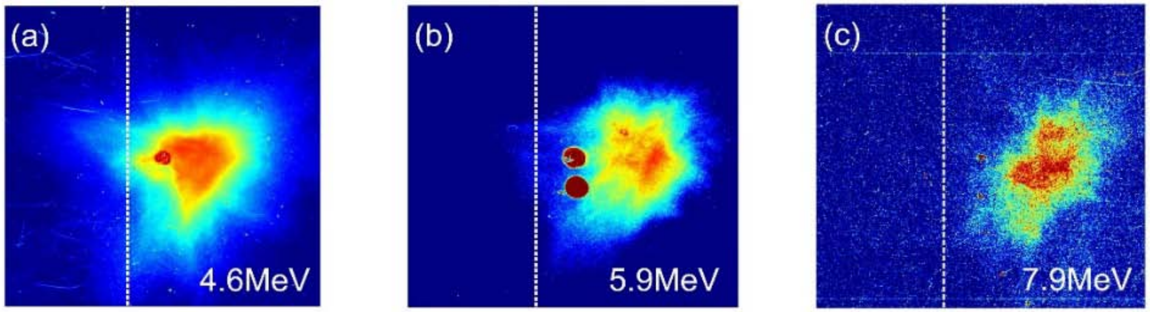
carbon nanotube





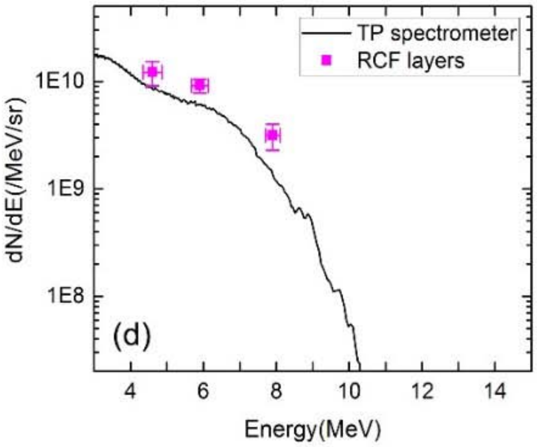
Experiment with metal target

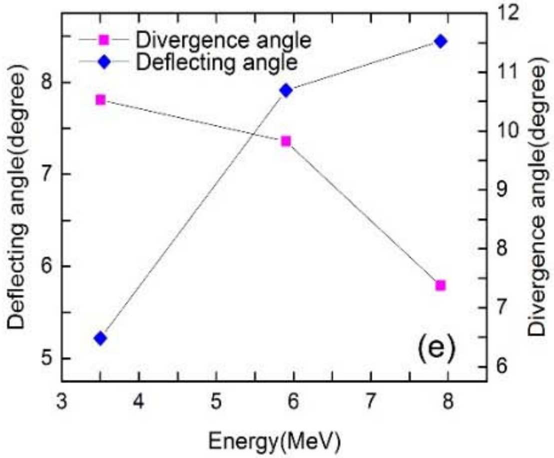




Laser: 60TW (on target)
1.8J, 30fs
I=8*10^19W/cm^2

Target: 2.5um Al

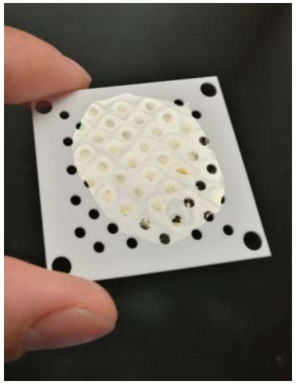


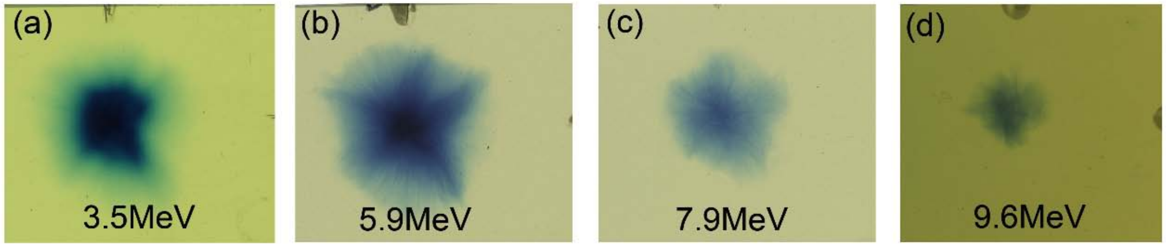


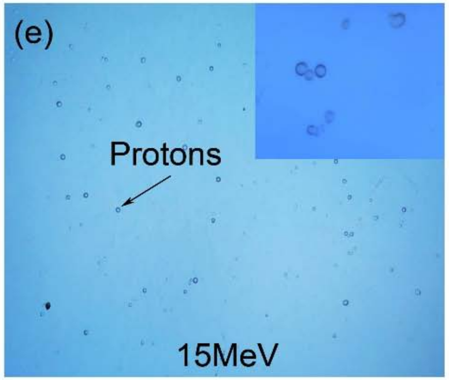
Paper submitted to CPL

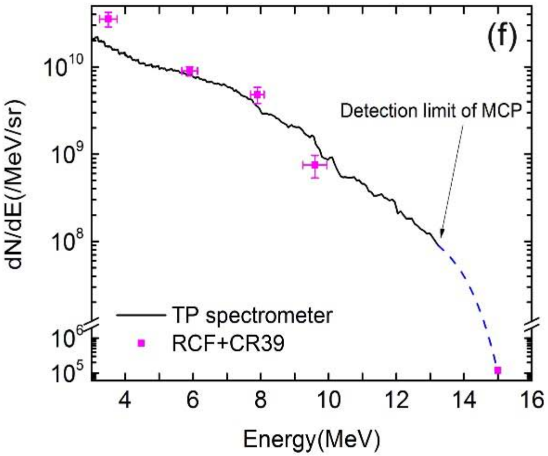
Experiment with plastic target

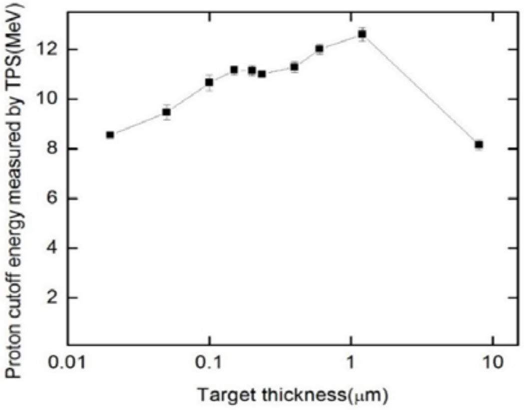
C5H8O2

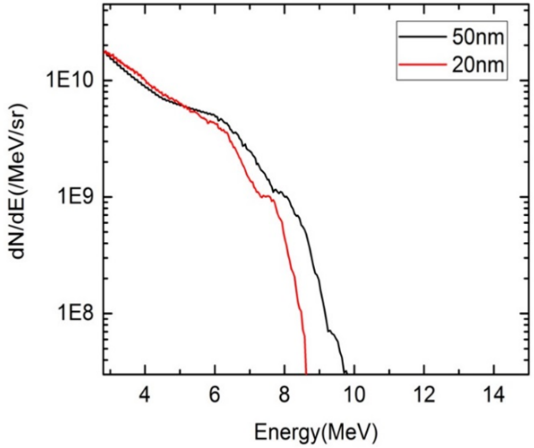






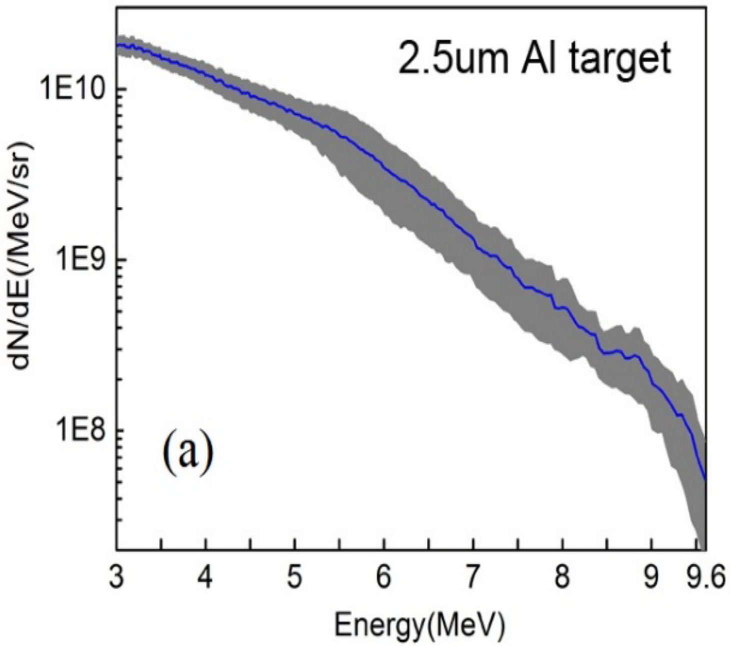


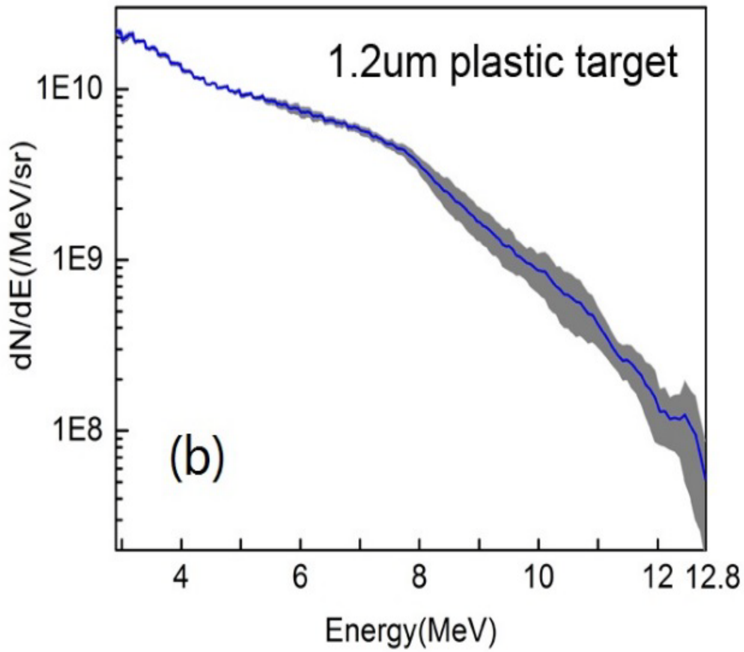




Acceleration based on nm target without plasma mirror!

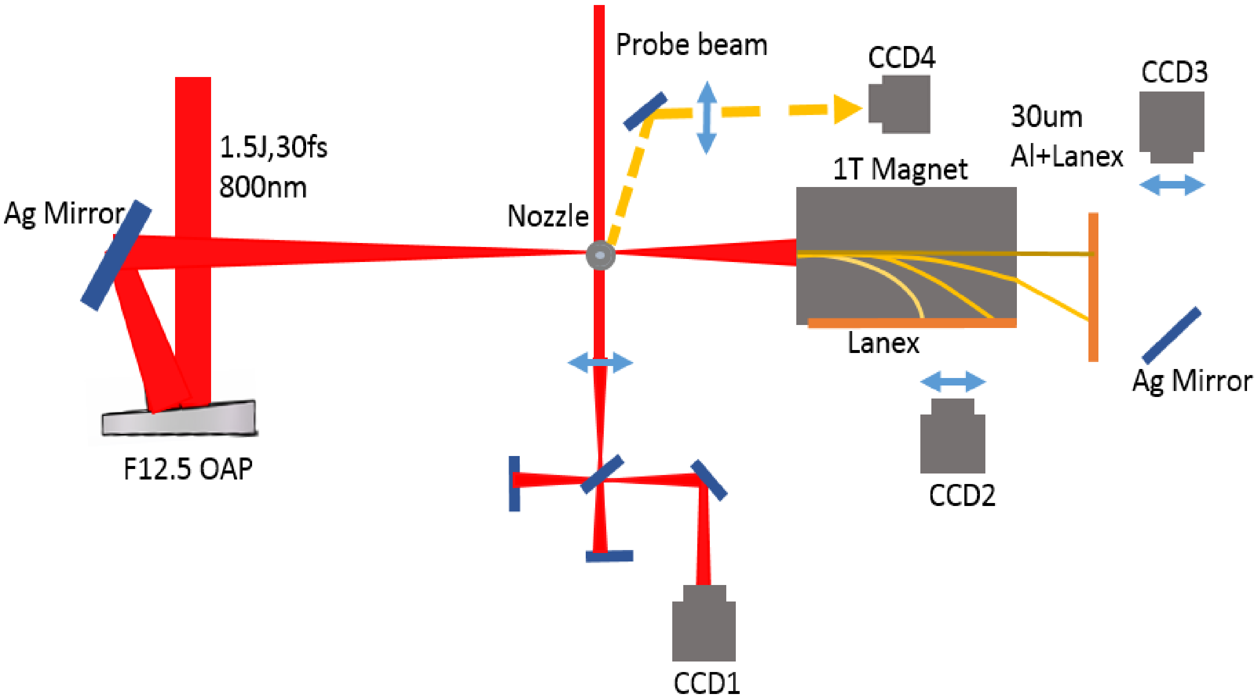
Proton beam with good stability

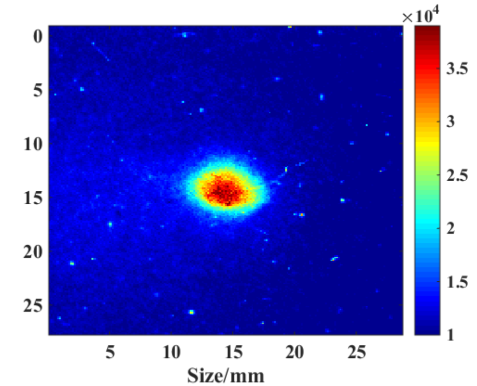


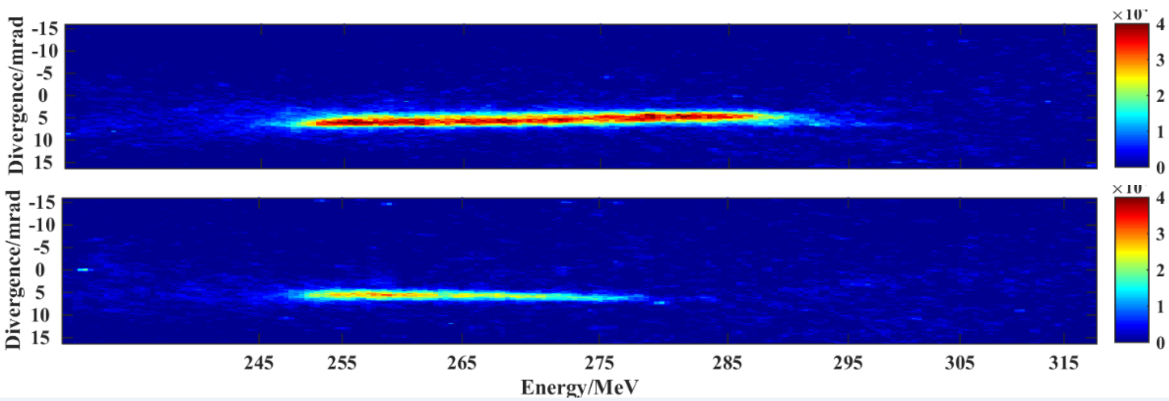


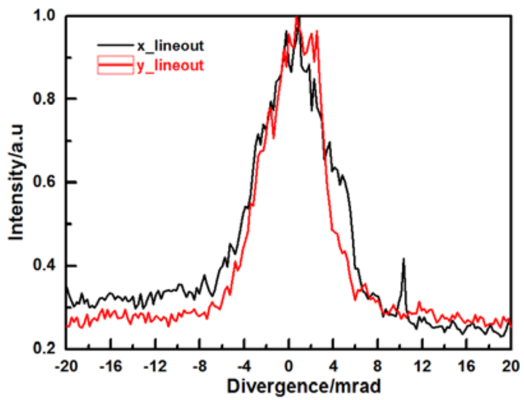
Paper submitted to APL

Electron acceleration is also in progress



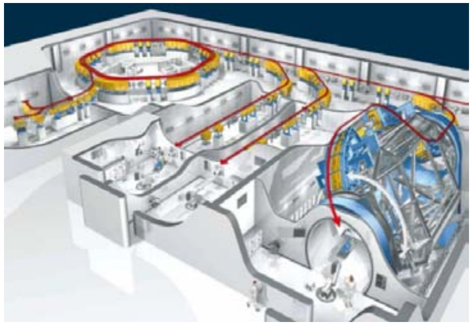


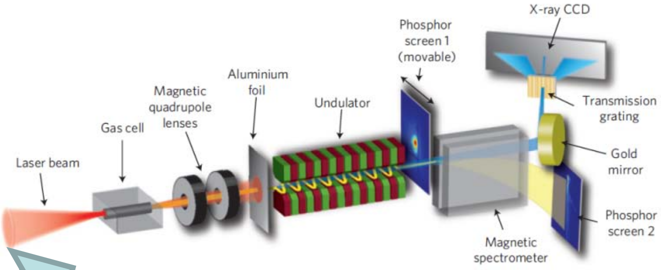


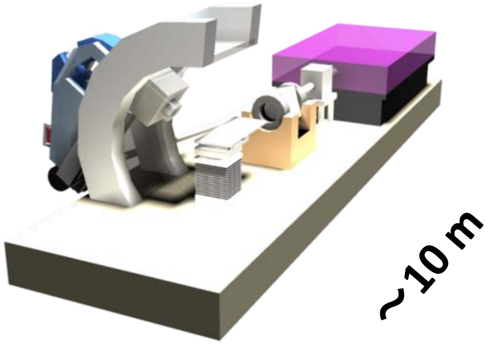


Future Plans

Tabletop light source and caner therpy machine!

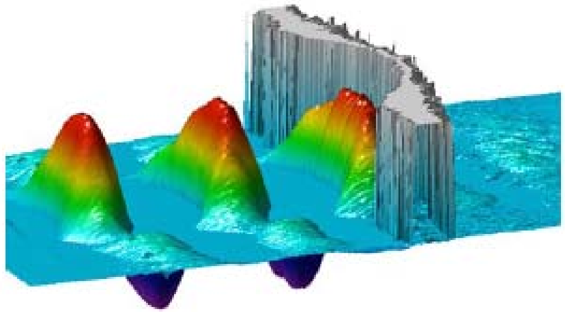




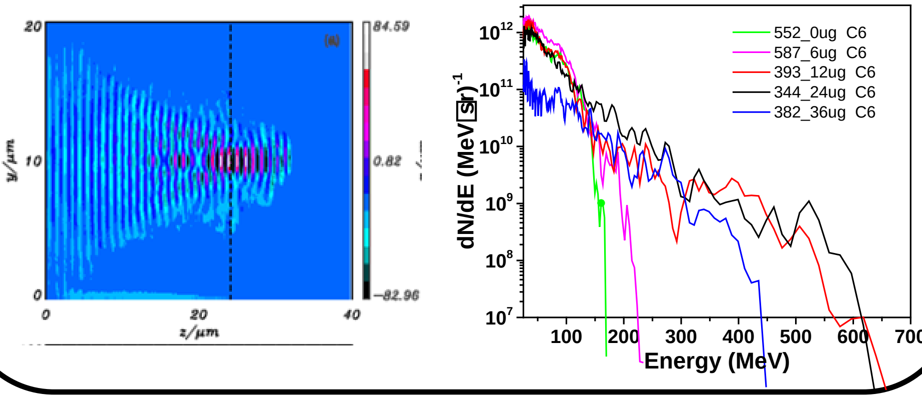


Summary

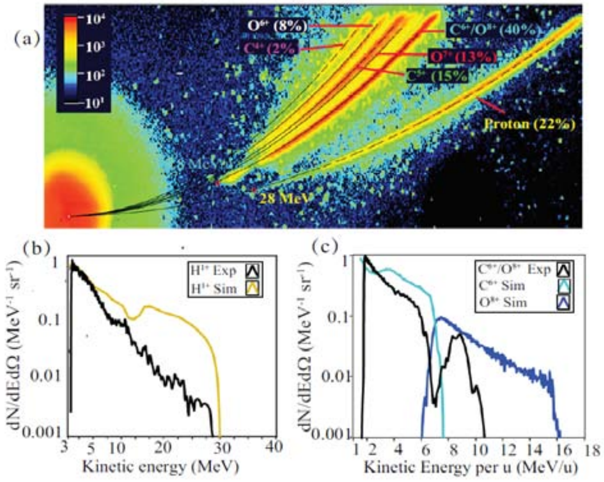
Phase-stable acceleration



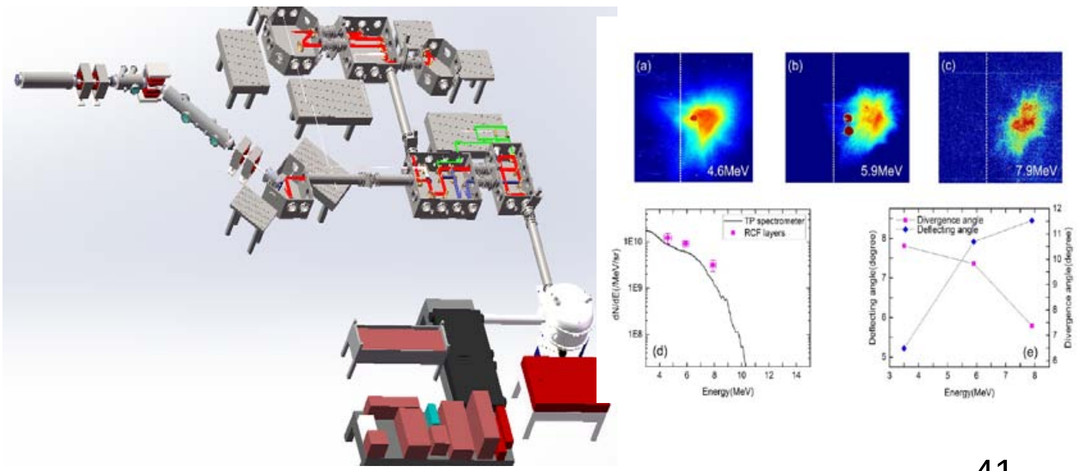
Near critical density plasma lens



Ionization dynamics



CLAPA system at PEK



Thanks for your attention!

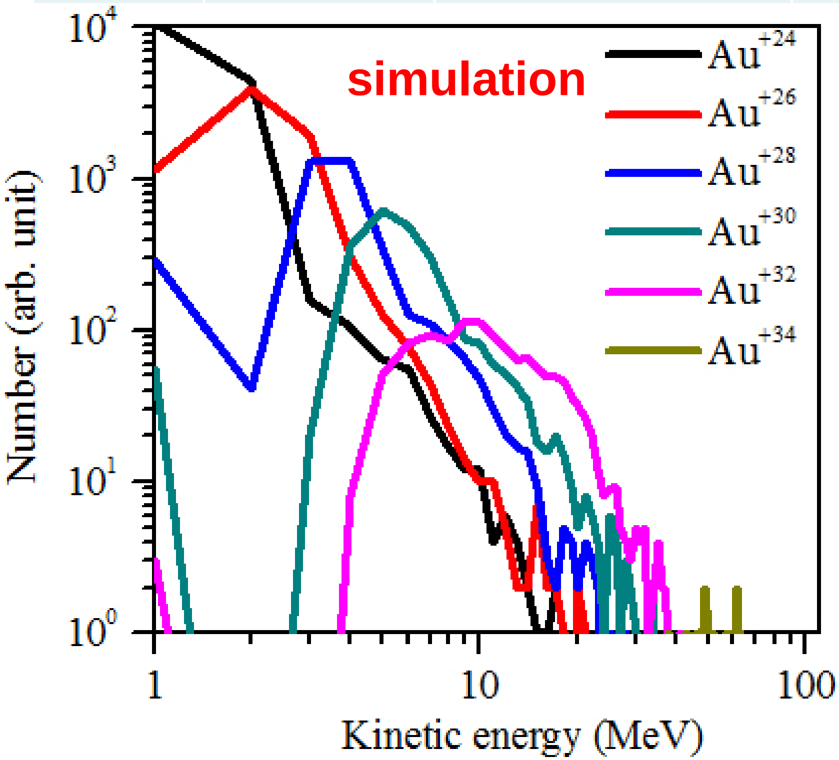
Welcome to visit CLAPA!

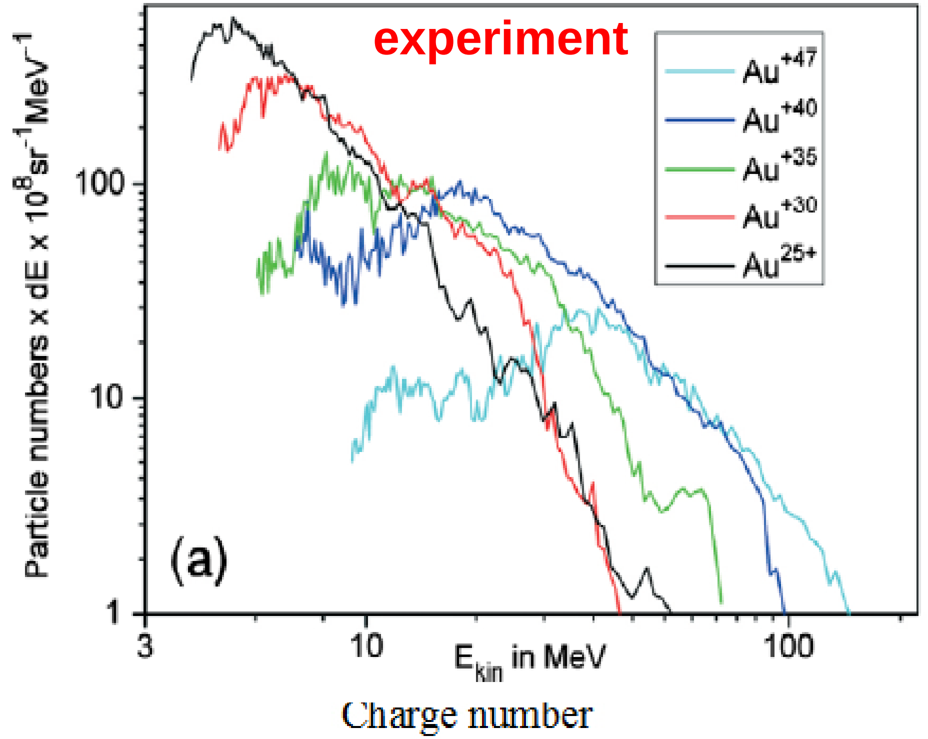
Micro-structured target via ionization dynamics

Simulation Result 1

Two-dimensional PIC code EPOCH

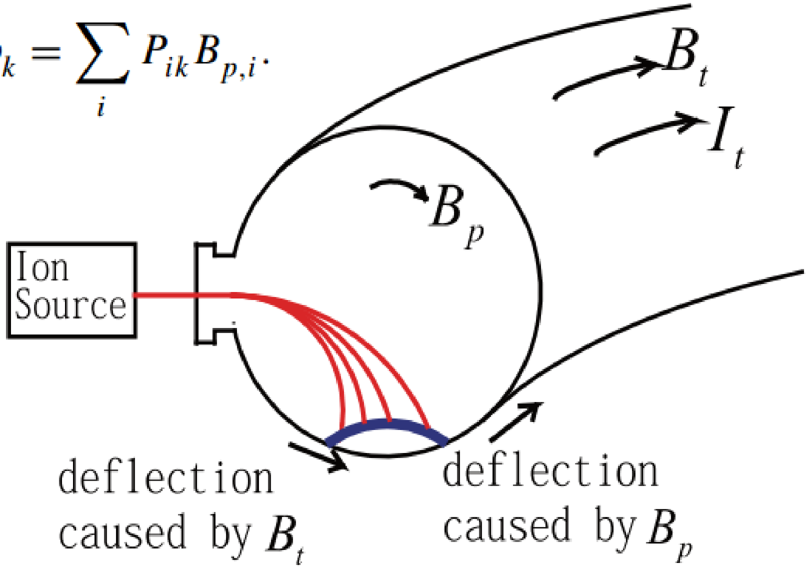
Laser	Intensity (W/cm^2)	Duration/simulation time(fs)	Spot size(μm)	Target	Simulation box
1.3J	1.92• 10^{20}	35/300	4	Au+C(2%)+O(2%)	60• m*10• m





Mono-energetic ion bunches were observed in the simulation!

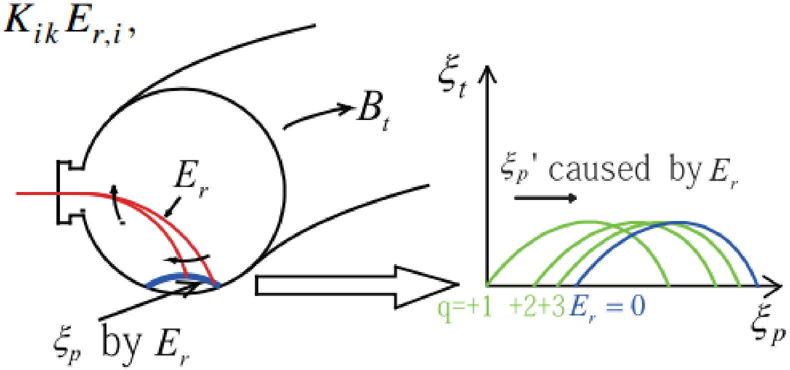
$$\varphi_k = \sum_i P_{ik} B_{p,i}.$$



toroidal displacement——
poloidal magnetic field

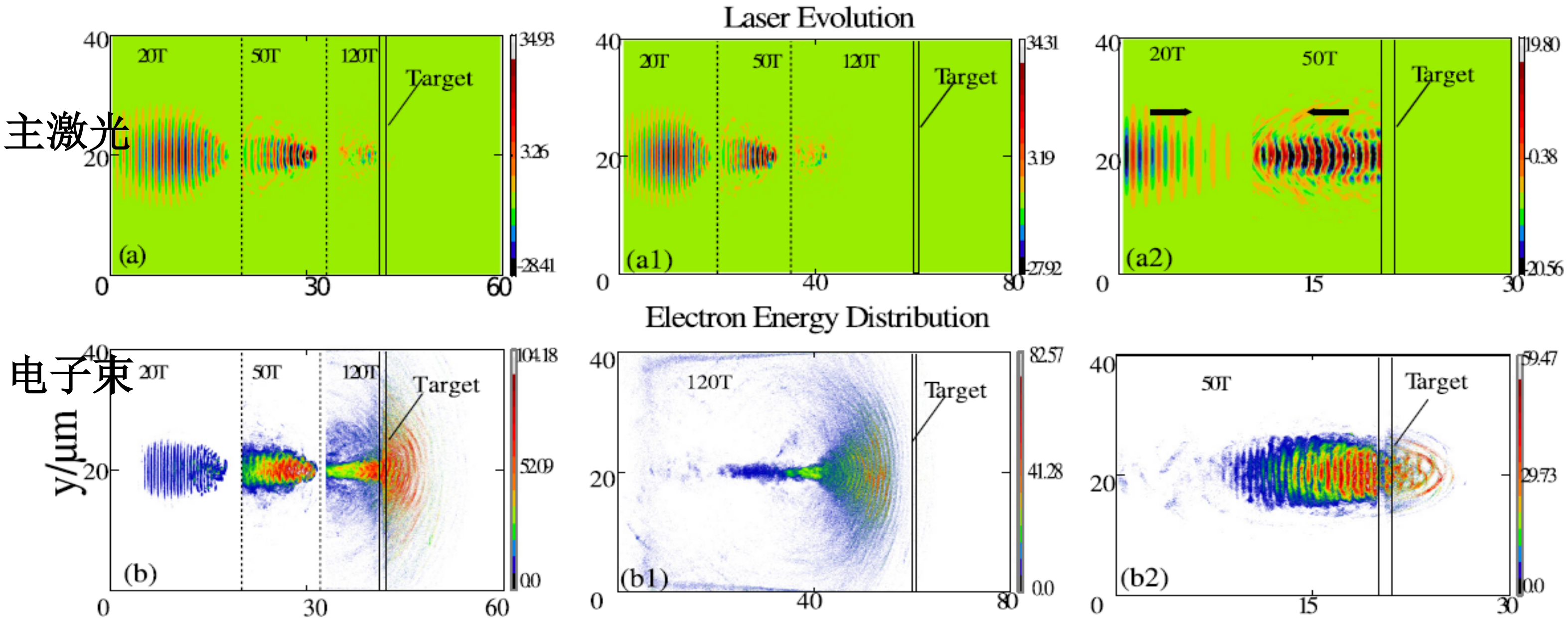
$$\xi'_{p,k} = \sum K_{ik} E_{r,i},$$

toroidal displacement——
poloidal magnetic field



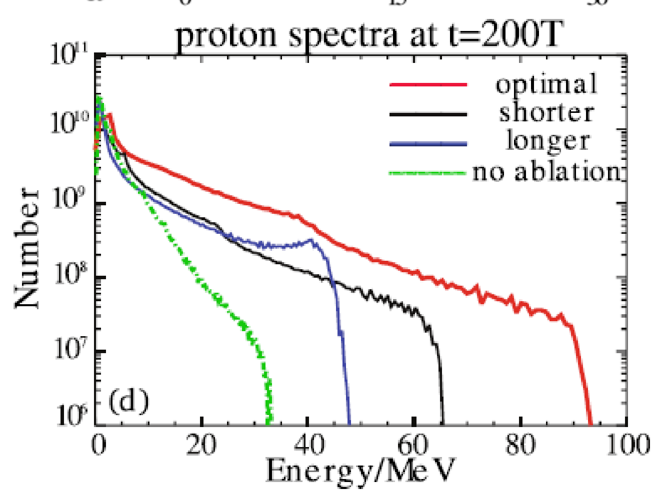
Matching of the ablated laser pulse

best matching **too long** **too short**



$$E_{sheath} \propto \left(\frac{8\pi}{e_n} n_e T_e\right)^{1/2}$$

$$a_{abl}^{2/3}\tau_{abl} \propto a_{cpa}\tau_{cpa}$$



200 TW laser, 90 MeV proton!
Experiments are underway.

S. Zhao, Physics of Plasmas 22, 073106 (2015).

Results from experiment