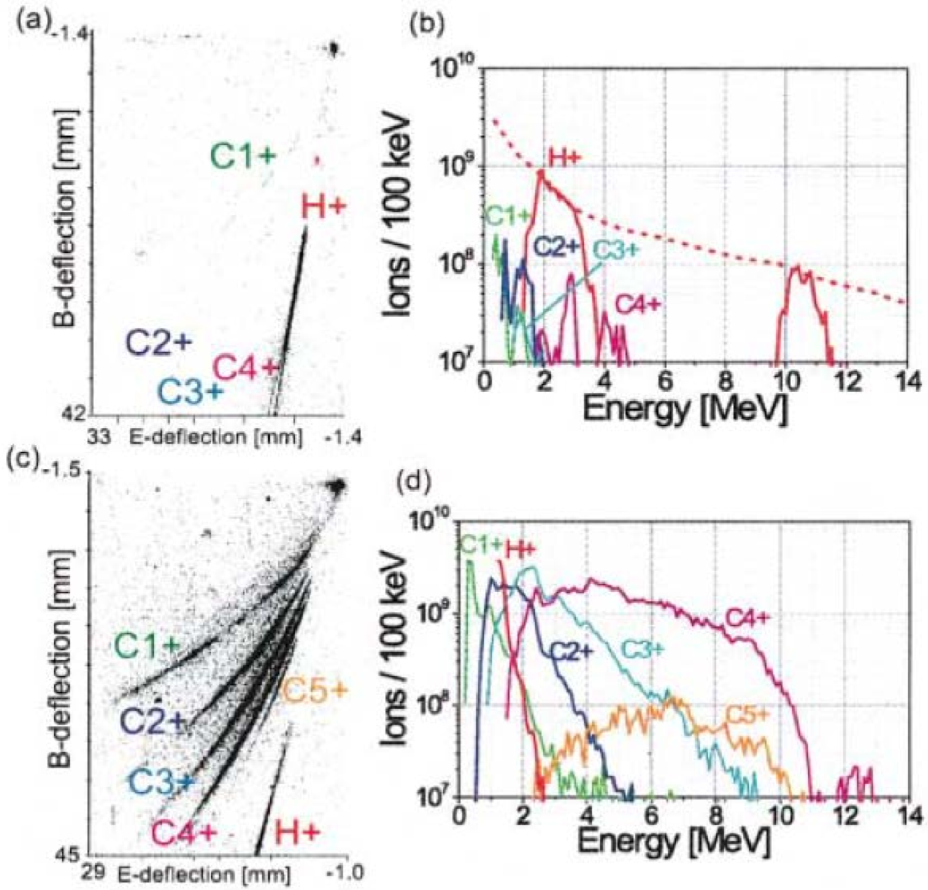
北京大學

Cascaded laser acceleration of carbon ions from double-layer nanotargets

Wenjun Ma

Peking University

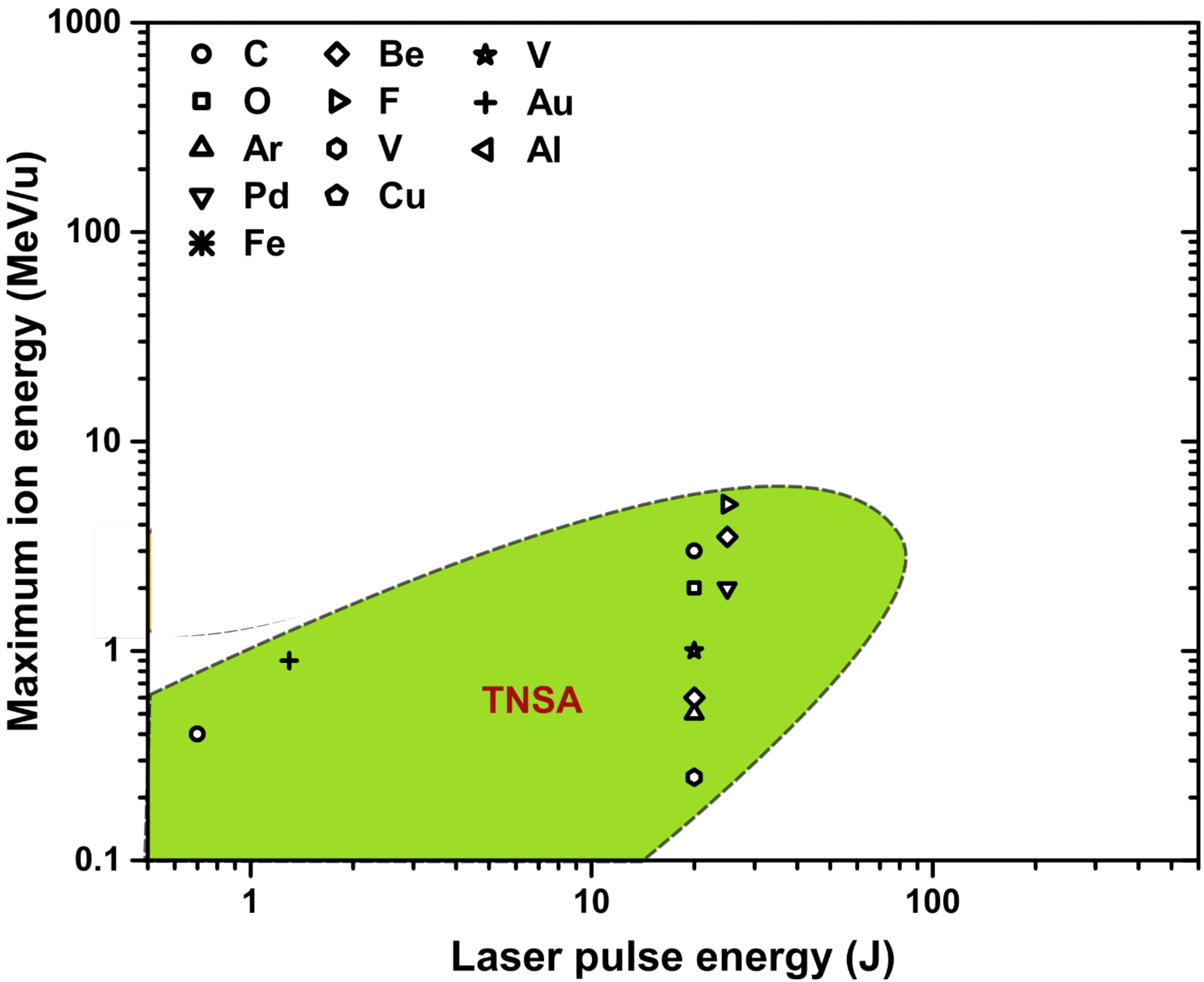
Acceleration of energetic heavy ions



- 5 MeV/u F^{7+} obtained by heating the targets

M. Hegelich, S. Karsch, G. Pretzler, D. Habs, K. Witte, W. Guenther, M. Allen, A. Blazevic, J. Fuchs, J.C. Gauthier, M. Geissel, P. Audebert, T. Cowan, M. Roth, MeV Ion Jets from Short-Pulse-Laser Interaction with Thin Foils, Phys Rev Lett, 2002, 89(8)：085002.

Status of heavy ion acceleration in TNSA



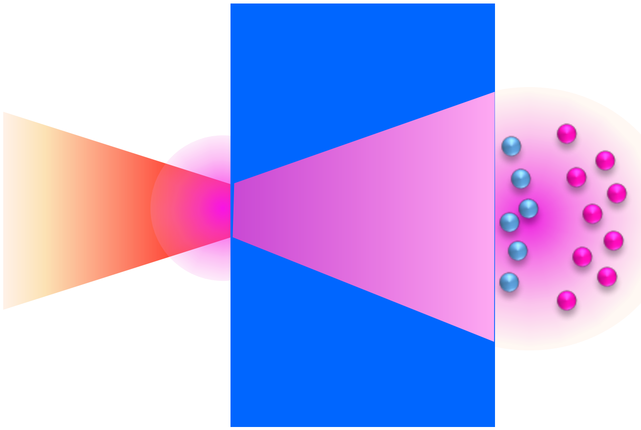
Why heavy ion acceleration is inefficient in TNSA

1. Contamination problem

- acceleration field built by dilute hot electrons (~ n_c)
- 1 nm*(10um)^2 contamination layer contains 10^9 protons, which can easily diminish the field

2. Ionization and injection problem

- sheath field/collisional ionization is evolving
- Ions with highest stage-of-charge are injected only after the peak of the intensity



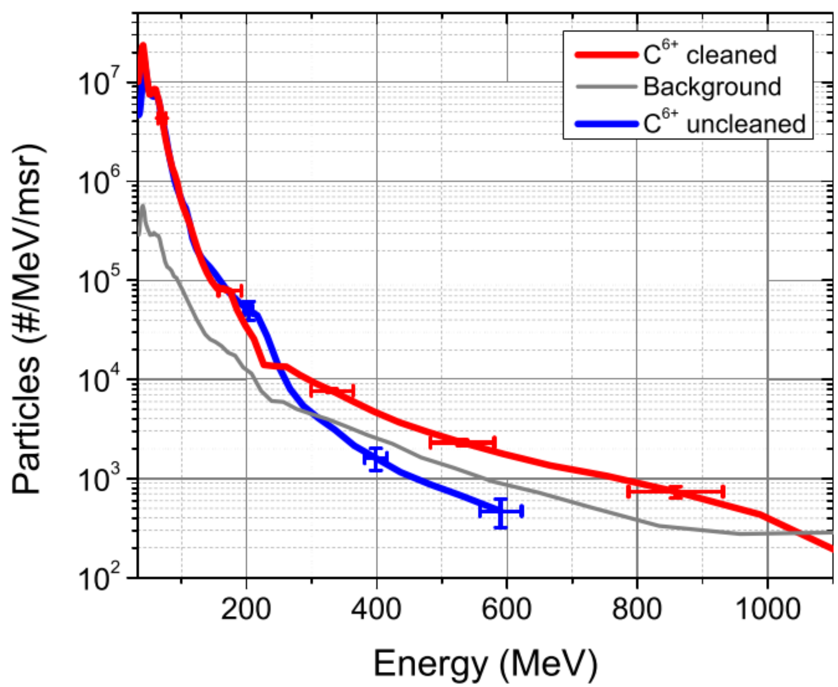
3. Acceleration time problem

- Heavy ions can not gain the full potential energy before the fade of the sheath field if the pulse duration is too short

$$N_e^{sep} \ll N_i^{all}$$

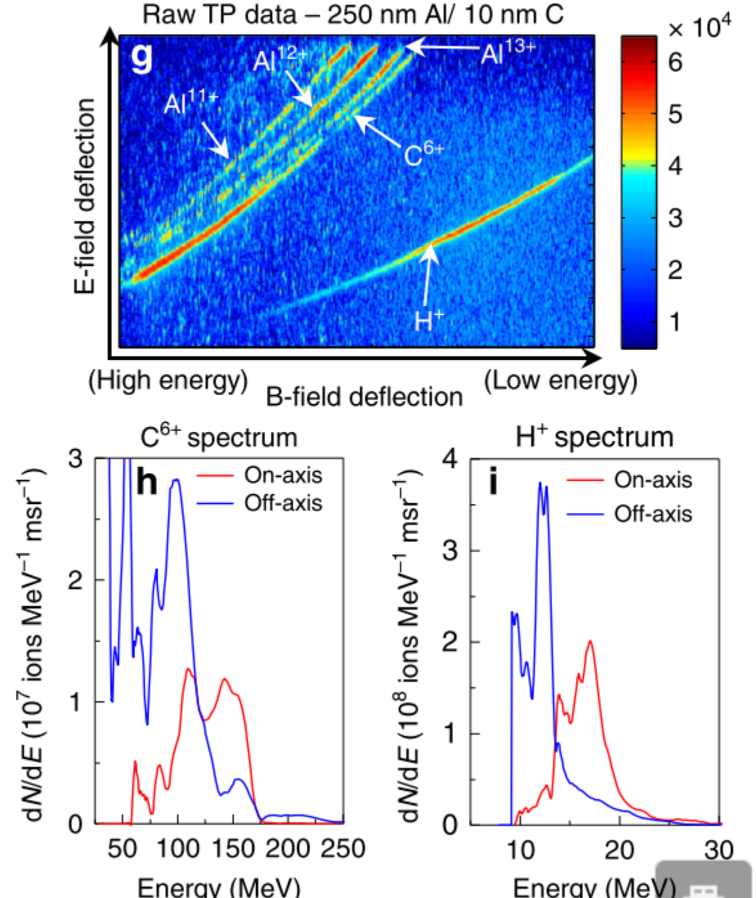
$$E_{sheath} \approx \sqrt{4\pi n_h k_B T_h}$$

BOA & Relativistic Transparency



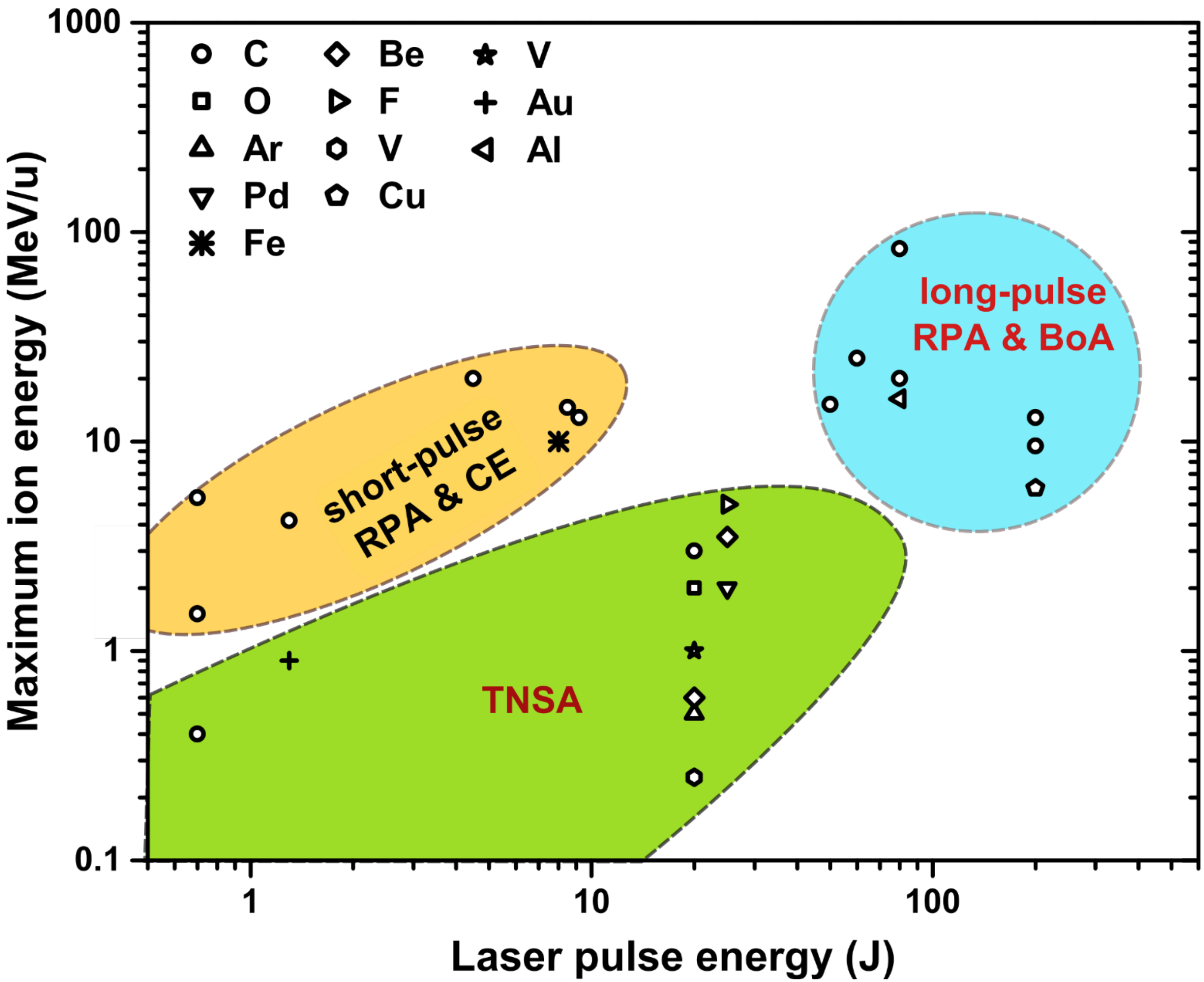
D. Jung *et al.*, Phys Plasmas **20**, 083103 (2013).

- Maximum ~83 MeV/u C^{6+}
- ~80 J, 550fs



S. Palaniyappan, et al., Nat Commun **6**, 10170 (2015).

- Peak at 18.3 MeV/u C^{6+}
- ~80 J, 550fs



1000
100
10
1
0.1
Maximum ion energy (MeV/u)
1
10
100
Laser pulse energy (J)
C
O
Ar
Pd
Fe
Be
F
V
Cu
V
Au
Al
short-pulse
RPA & CE
long-pulse
RPA & BoA
TNSA

Heavy ion acceleration in RPA

1. Contamination problem

- Acceleration driven by bulk electrons instead of dilute thermal electrons

Superior to TNSA

2. Ionization and injection problem

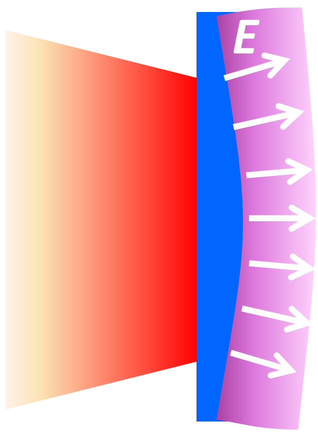
- Additional optical field ionization happens at the laser-plasma interface

Superior to TNSA

3. Acceleration time problem

- Hole-boring and plasma instability lead to early end of the acceleration process
- Fast fade of acceleration field after the reflection of laser pulses

Inferior to TNSA

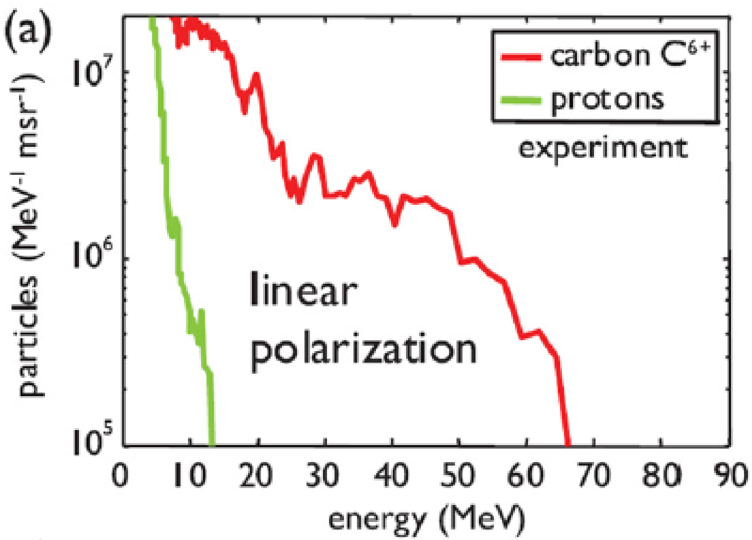


collective electrons

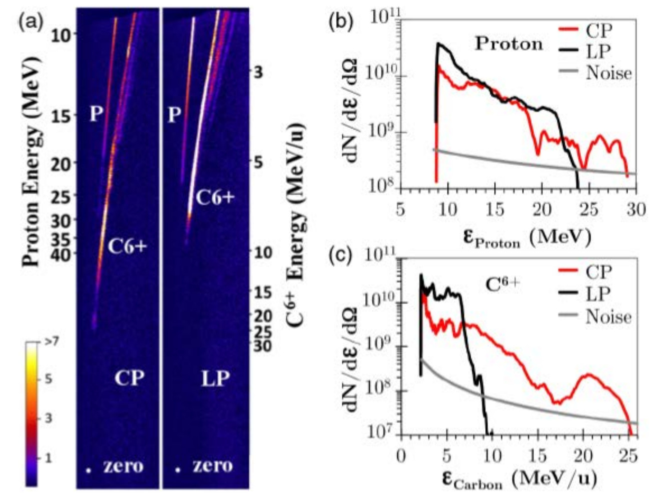
$$N_e^{sep} \sim N_i^{all}$$

$$E_{seperation} \approx 4\pi e n_e d$$

Heavy ion acceleration in RPA regime



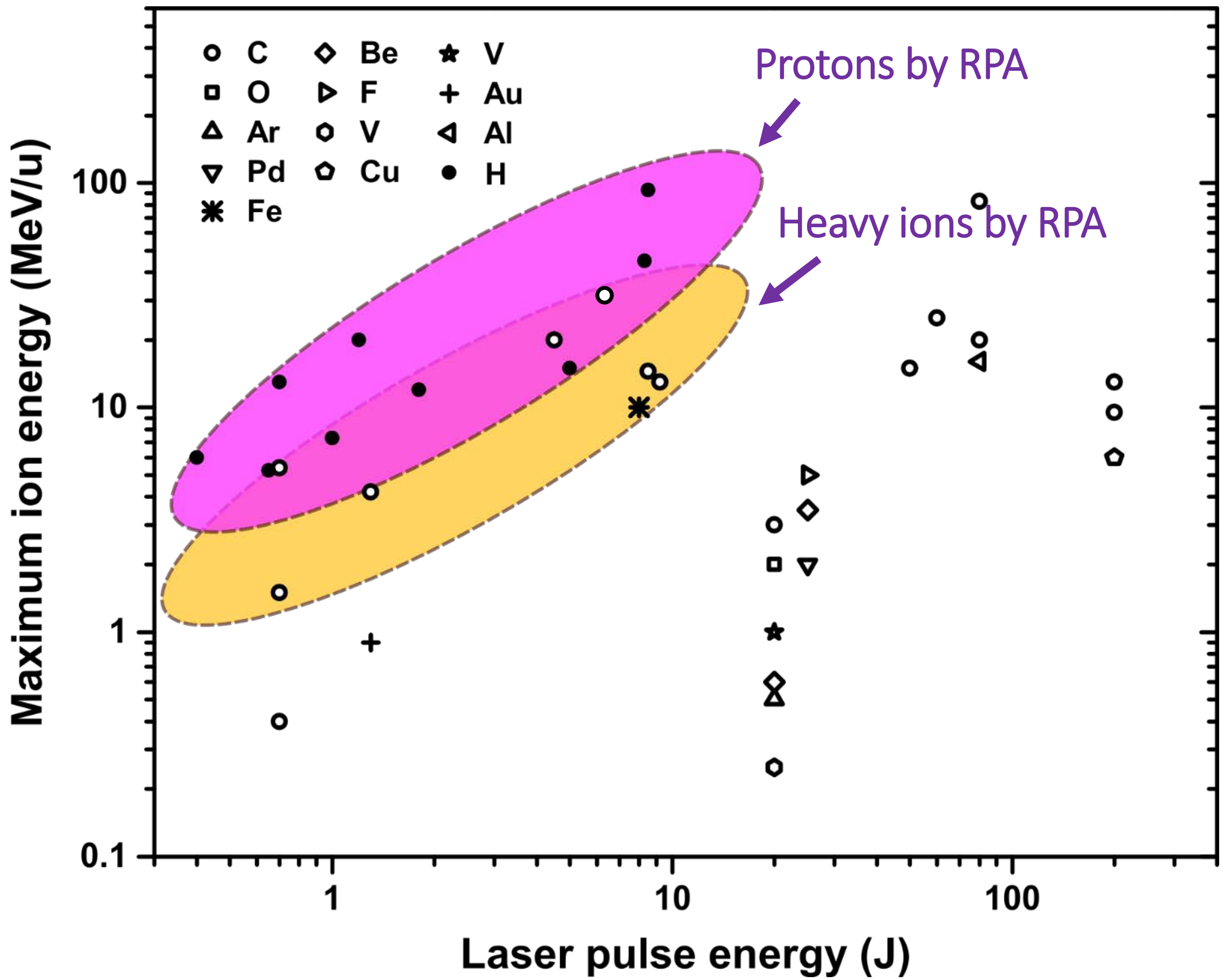
A. Henig *et al.*, Phys Rev Lett **103** (2009).



C. Scullion, PRL 119, 054801 (2017)

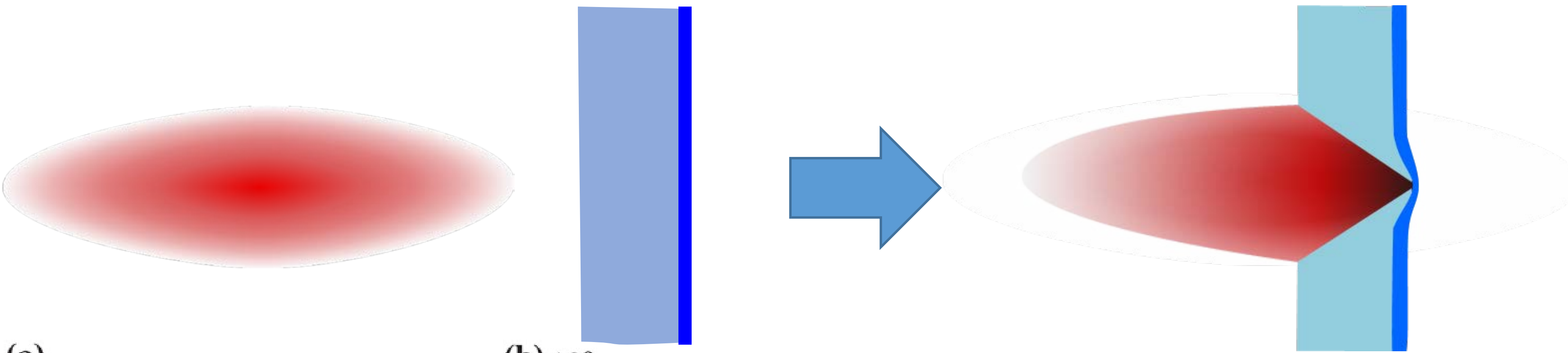
- Maximum ~5 MeV/u C^{6+}
- ~0.7 J,45 fs

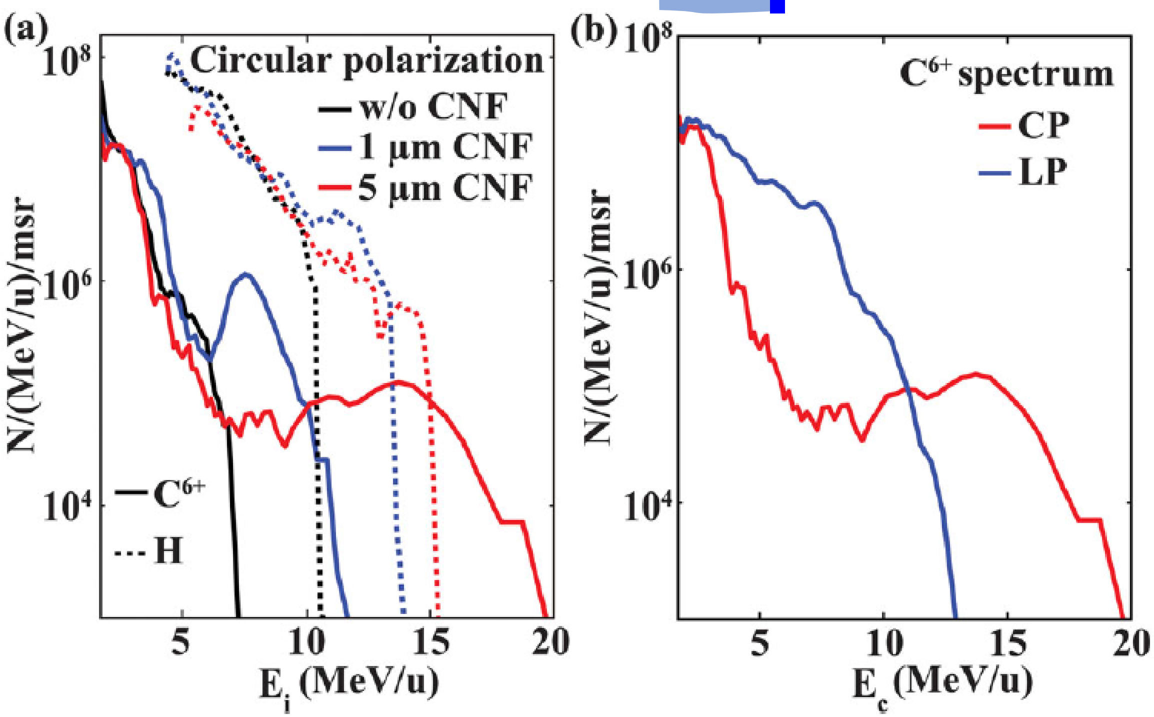
- Maximum ~25 MeV/u C^{6+}
- ~6 J, 50 fs



C
O
Ar
Pd
Fe
Be
F
V
Cu
V
Au
Al
H
Protons by RPA
Heavy ions by RPA
Maximum ion energy (MeV/u)
0.1
1
10
100
1
10
100
Laser pulse energy (J)

Plasma lens enhanced RPA



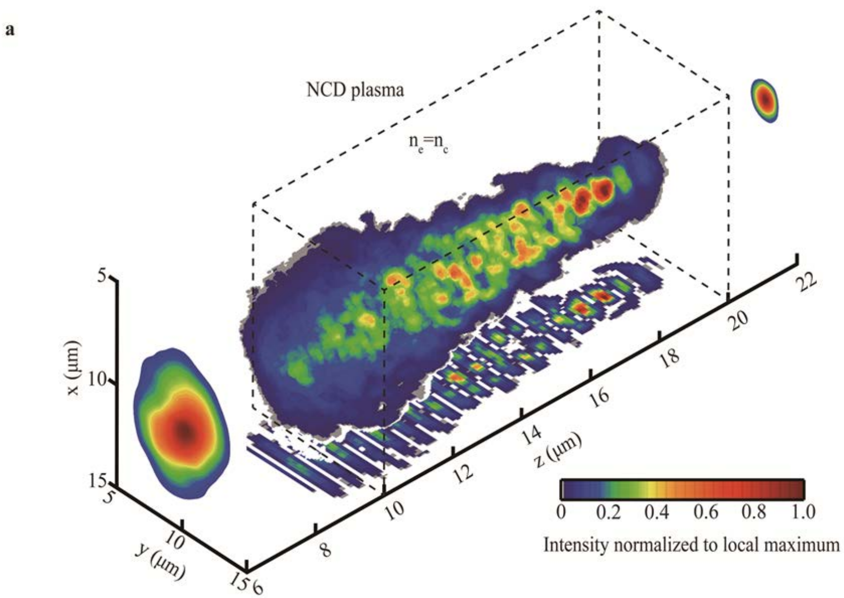


- ~5 J,50 fs
- ~20 MeV/nucleon quasi-monoenergetic C^{6+} generated
- 2 n_c near-critical density plasma lens

J.H.Bin*, W.J.Ma*, et. al. *Physical Review Letters 115, 064801 (2015).*

Near-critical-density(NCD) plasma lens

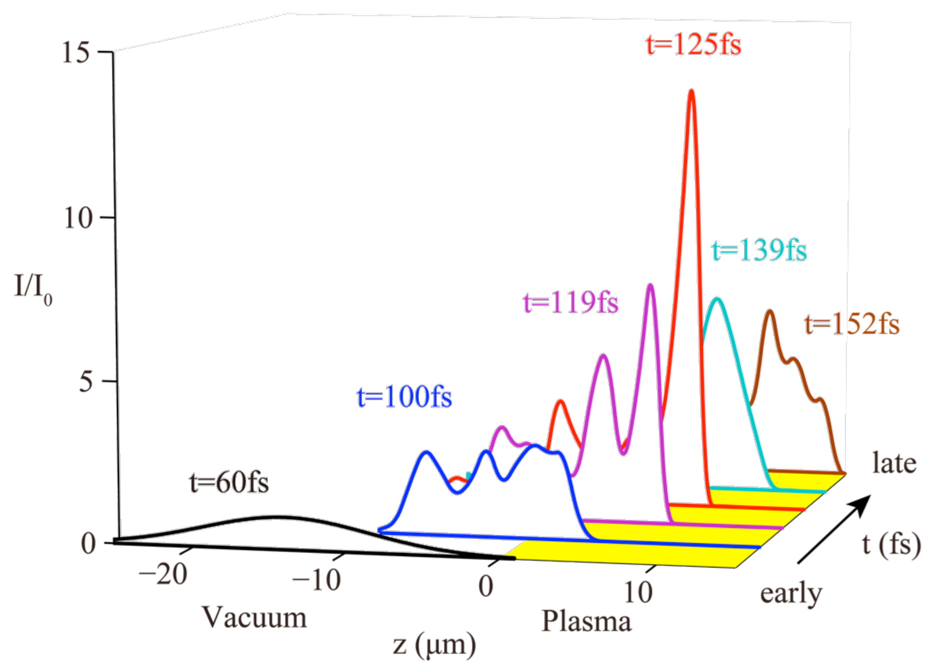
With the propagation of laser pulse within NCD plasma, it becomes shorter, front-steepened, and strongly self-focused. If we use such shaped laser pulse in ion acceleration, the acceleration field will increase because of the enhanced intensity, and the major acceleration process can be finished before the break of the plasma thin slab.



Intenisty increased by 10

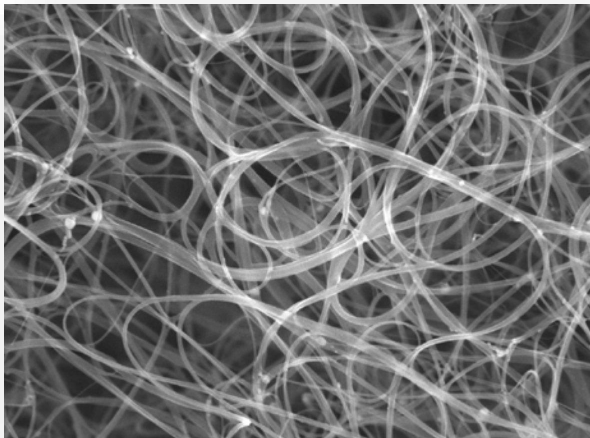
Pulse duration reduced by 50%.

3D simulation showing the pulse shaping process in $2n_c$plasma

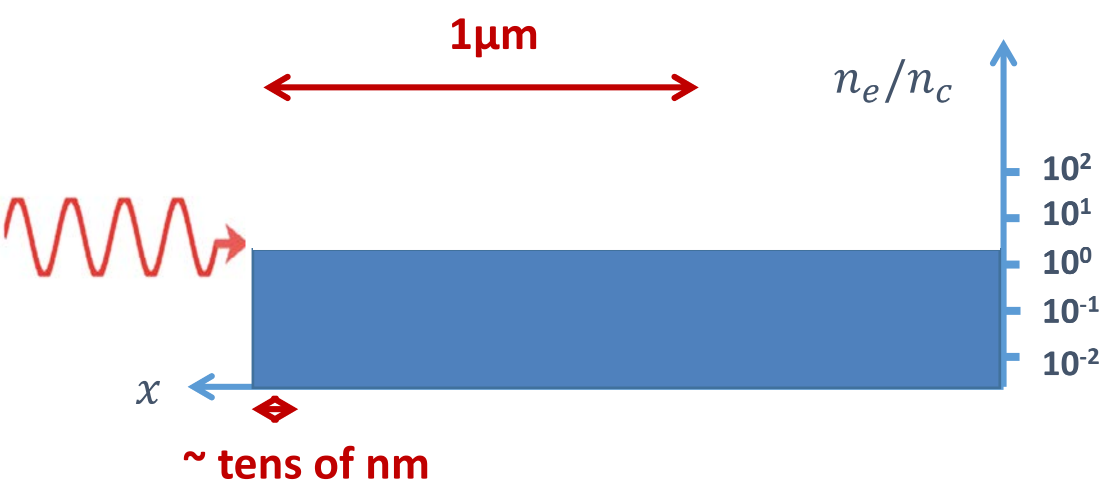


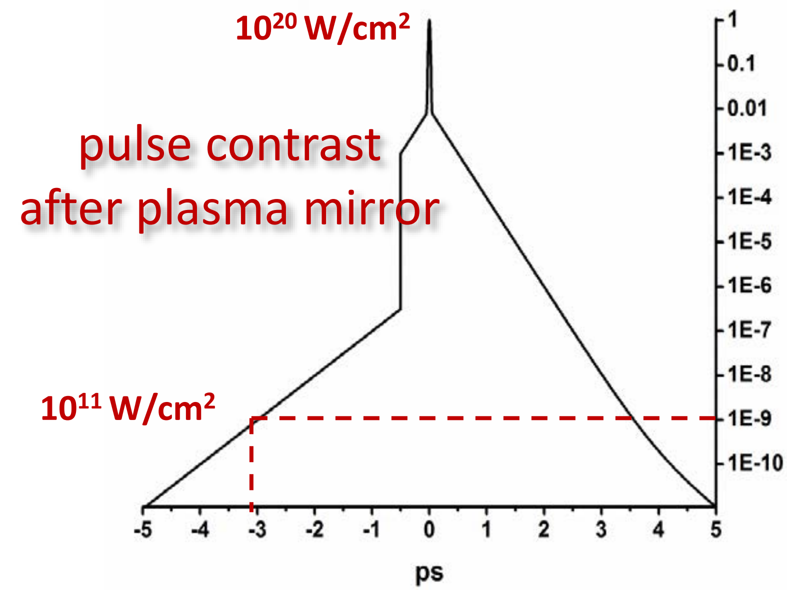
H.Y.Wang, X.Q.Yan et. al. *Physical Review Letters* 107(26) (2011)

Key targets： Carbon nanotube foams

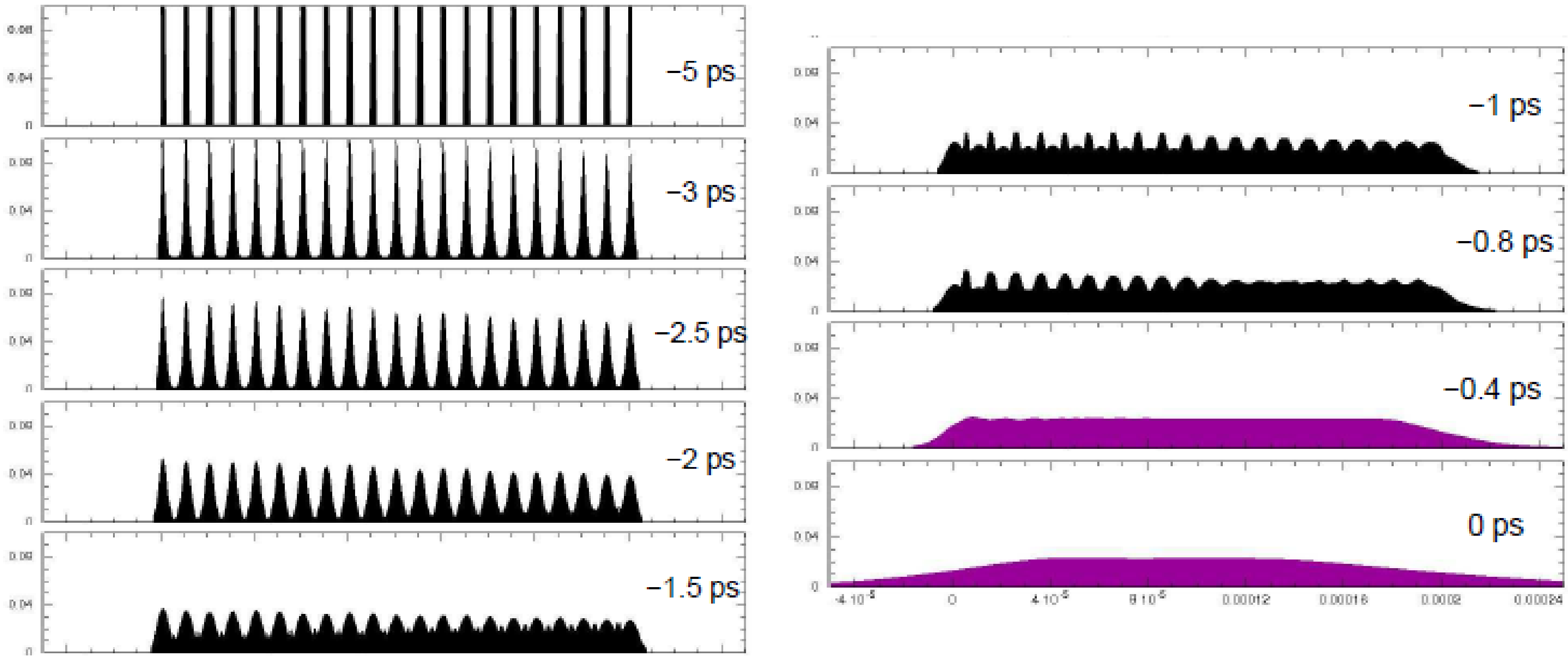


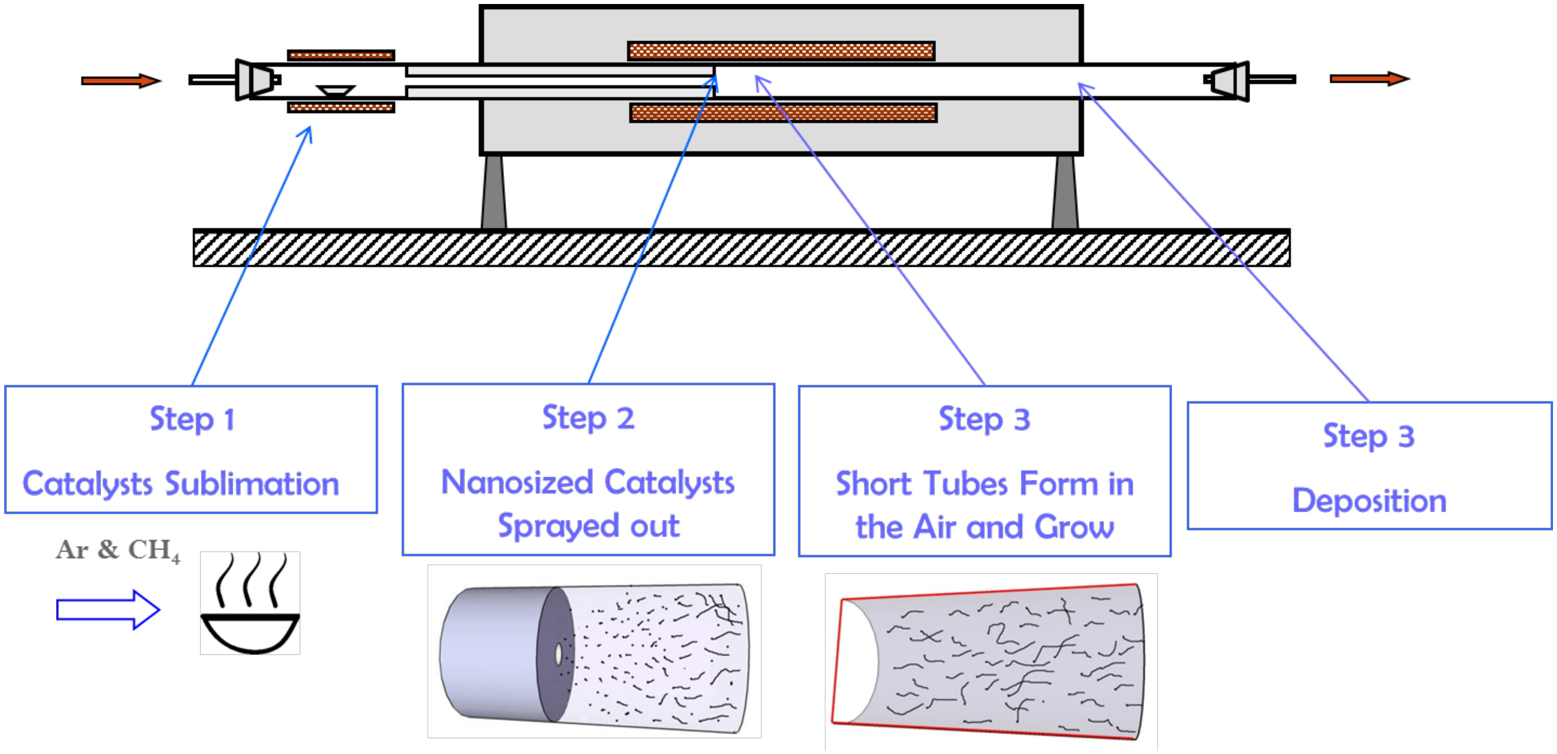
Carbon nanotube foam(CNF): ~1% solid density, highly homogenous at um scale, as thin as a few um, will become homogenous plasma with density around critical density, can be used as plasma optics



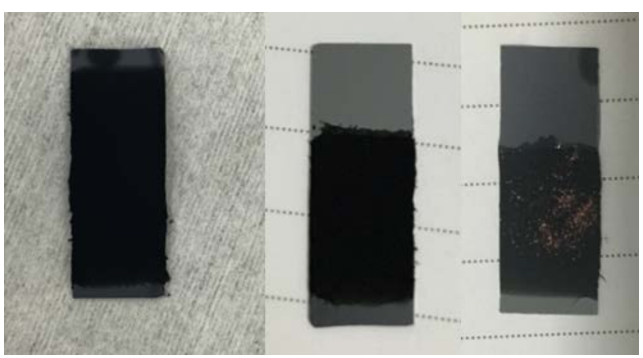


Hydrodynamic simulations on the expansion of CNTs





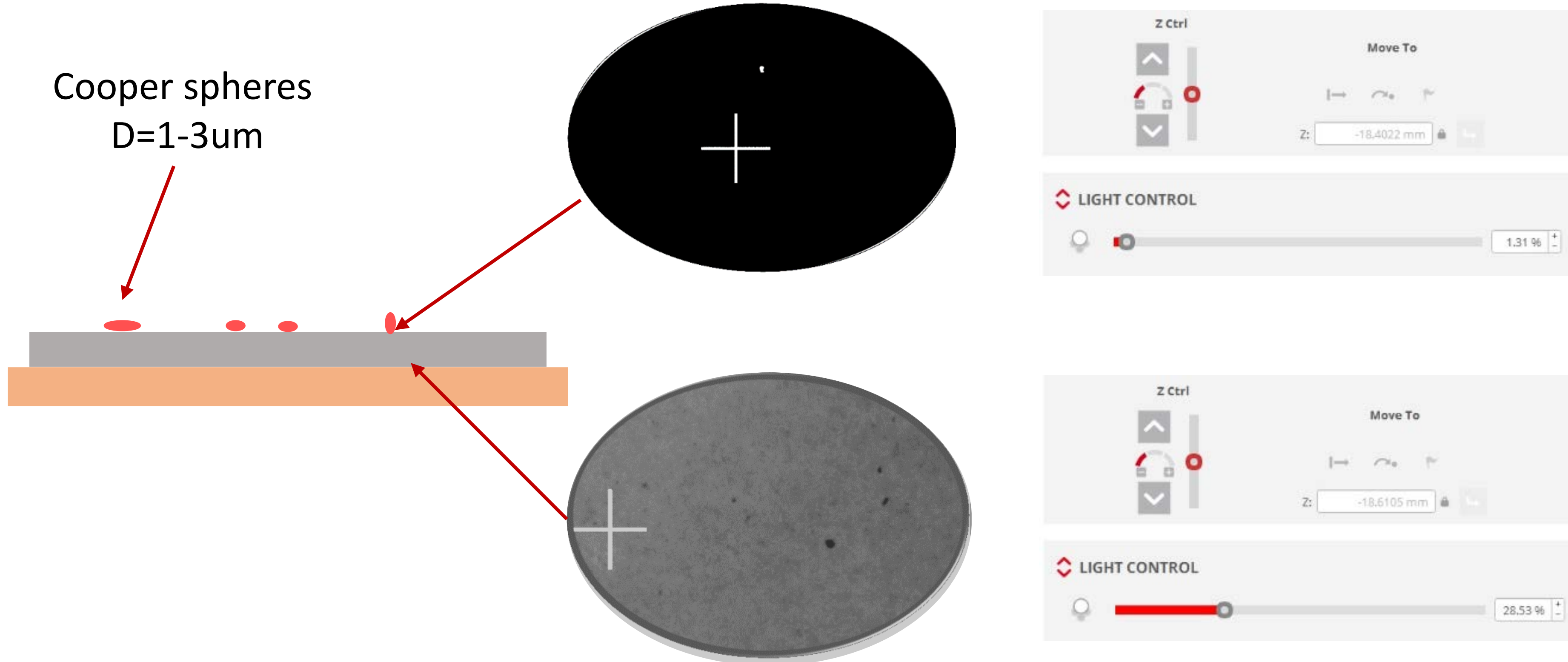
CNF sample on Si wafer



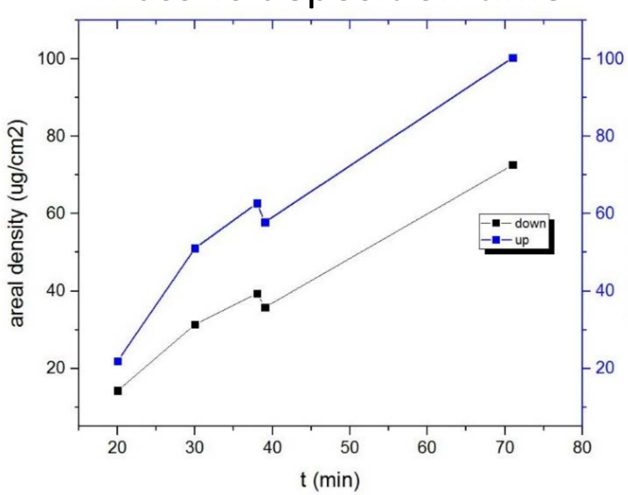
Microbalance

Optical profiler

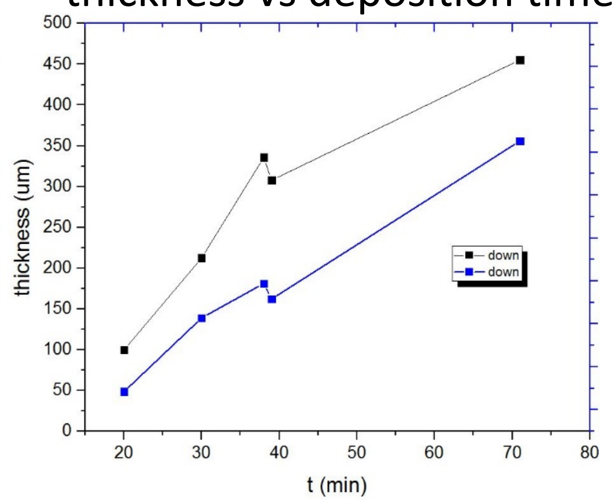
Height of the imaging plane



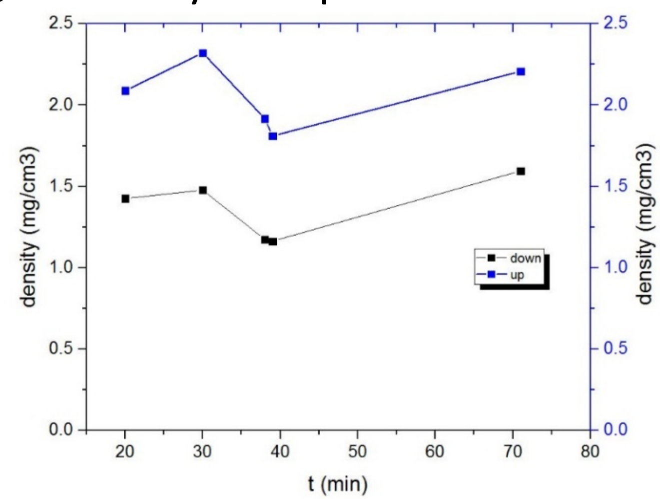
Mass vs deposition time



thickness vs deposition time

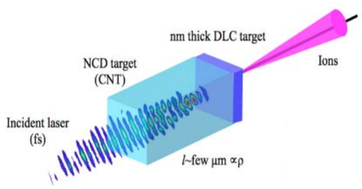


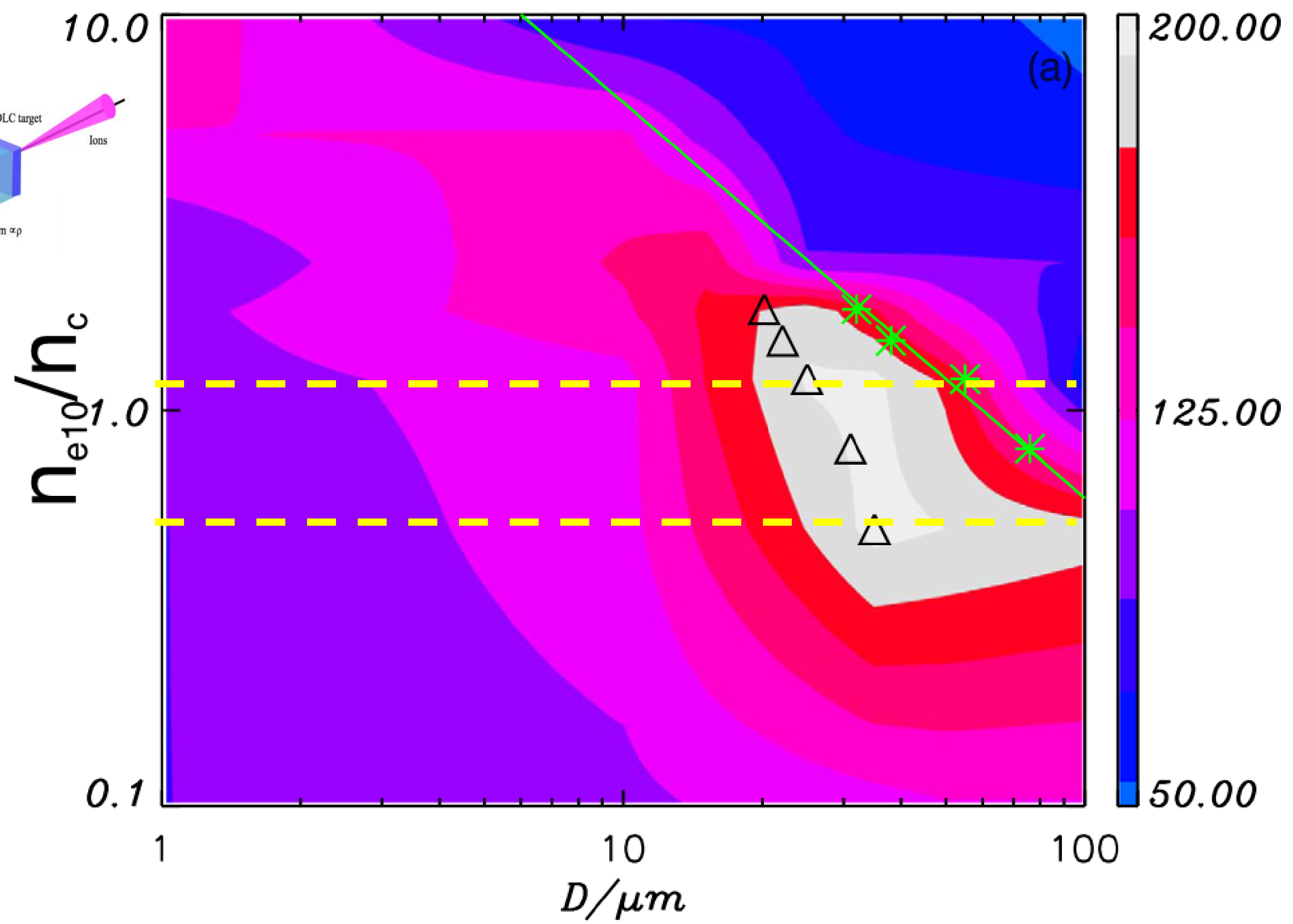
density vs deposition time



Parameters scan for double-layer targets

a=21,FWHM=45fs





H.Y.Wang, X.Q. Yan, W.J.Ma et al. (2013). Physics of Plasmas **20**: 13101.

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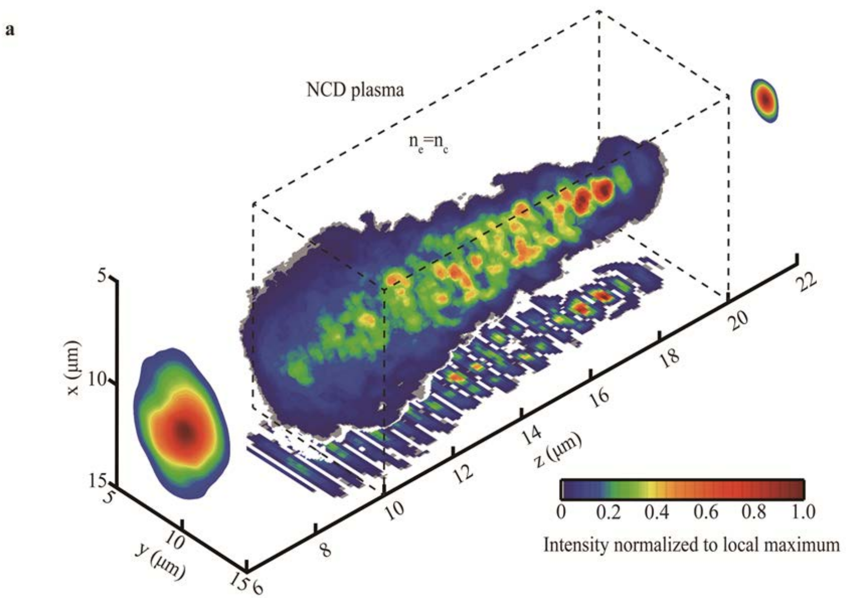
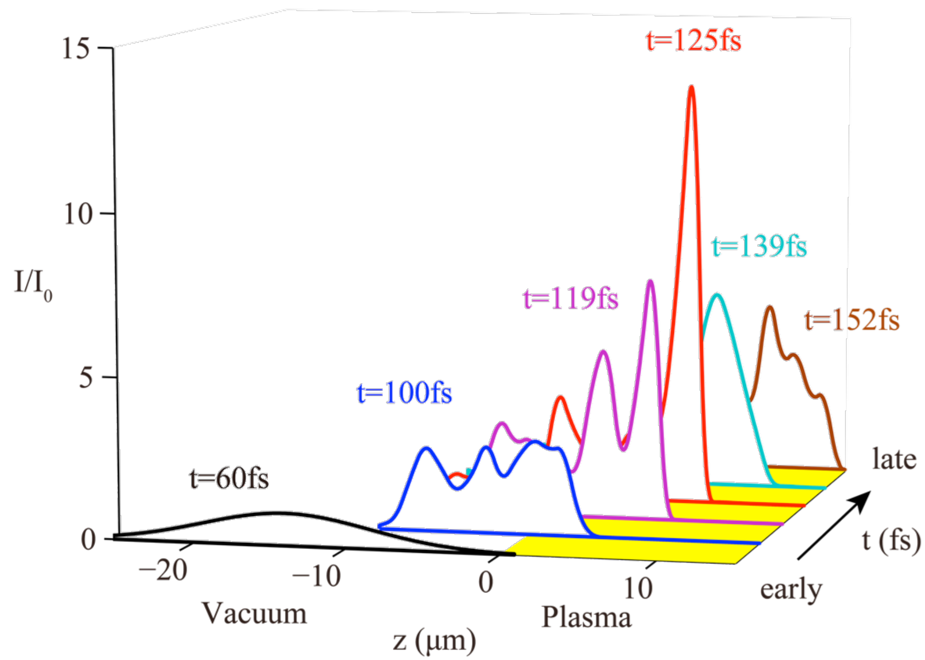
3D simulation showing the pulse shaping process in $2n_c$plasma



Intenisty increased by 10

Pulse duration reduced by 50%.



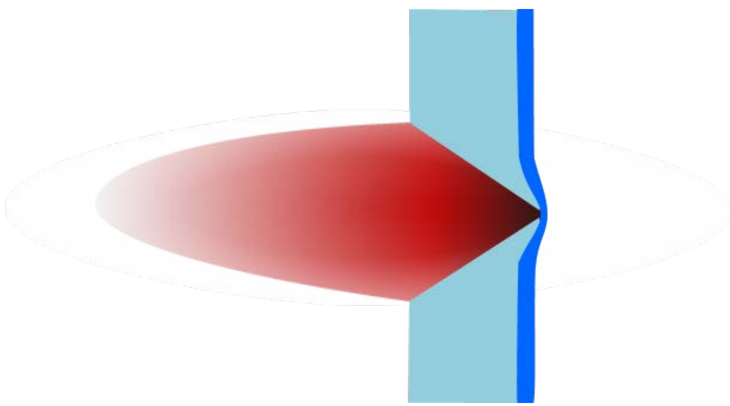
H.Y.Wang, X.Q.Yan et. al. *Physical Review Letters* 107(26) (2011)

Sub-classification of near-critical-density plasma

Zone I： relativistic transparent

$$1 < n_e < \gamma n_c$$

Strong pulse shaping



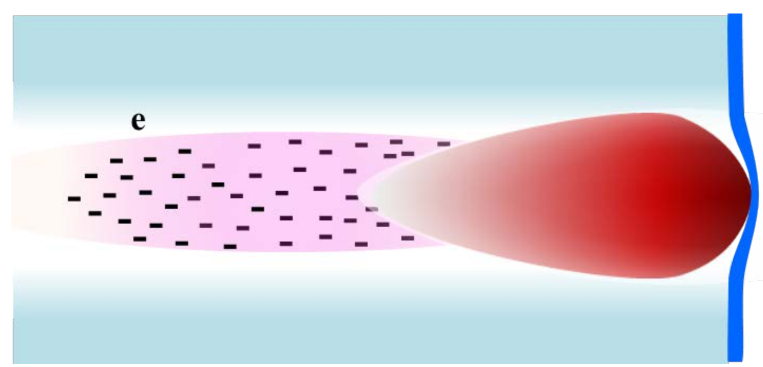
H. Y. Wang *et al.*, Phys Rev Lett **107** (2011).

H. Wang,et.al., Phys Plasmas **20**, 13101 (2013).

Zone II： slightly sub-critical

$$0.1 < n_e < 1$$

Moderate pulse shaping, high-energy electron generation



A. Pukhov, Z.-M. Sheng, and J. Meyer-ter-Vehn, Phys Plasmas **6**, 2847 (1999).

B. Liu, et.al. Phys Rev Lett **110** (2013).

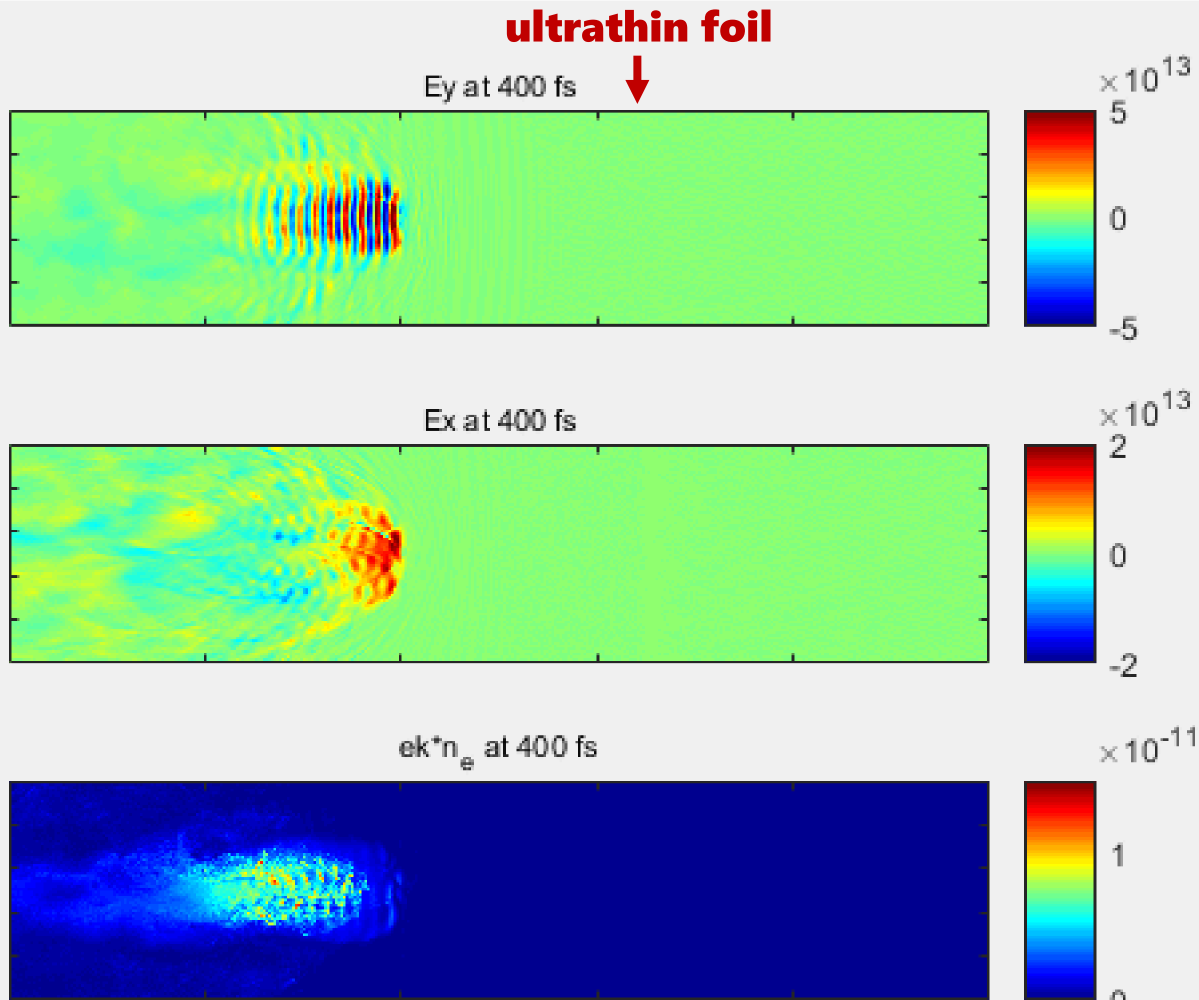
Simulation results

a=15, n_{e1}=0.2n_c,L_1=60 um

Laser field

Longitudinal E field

$(\gamma_e - 1)n_e$

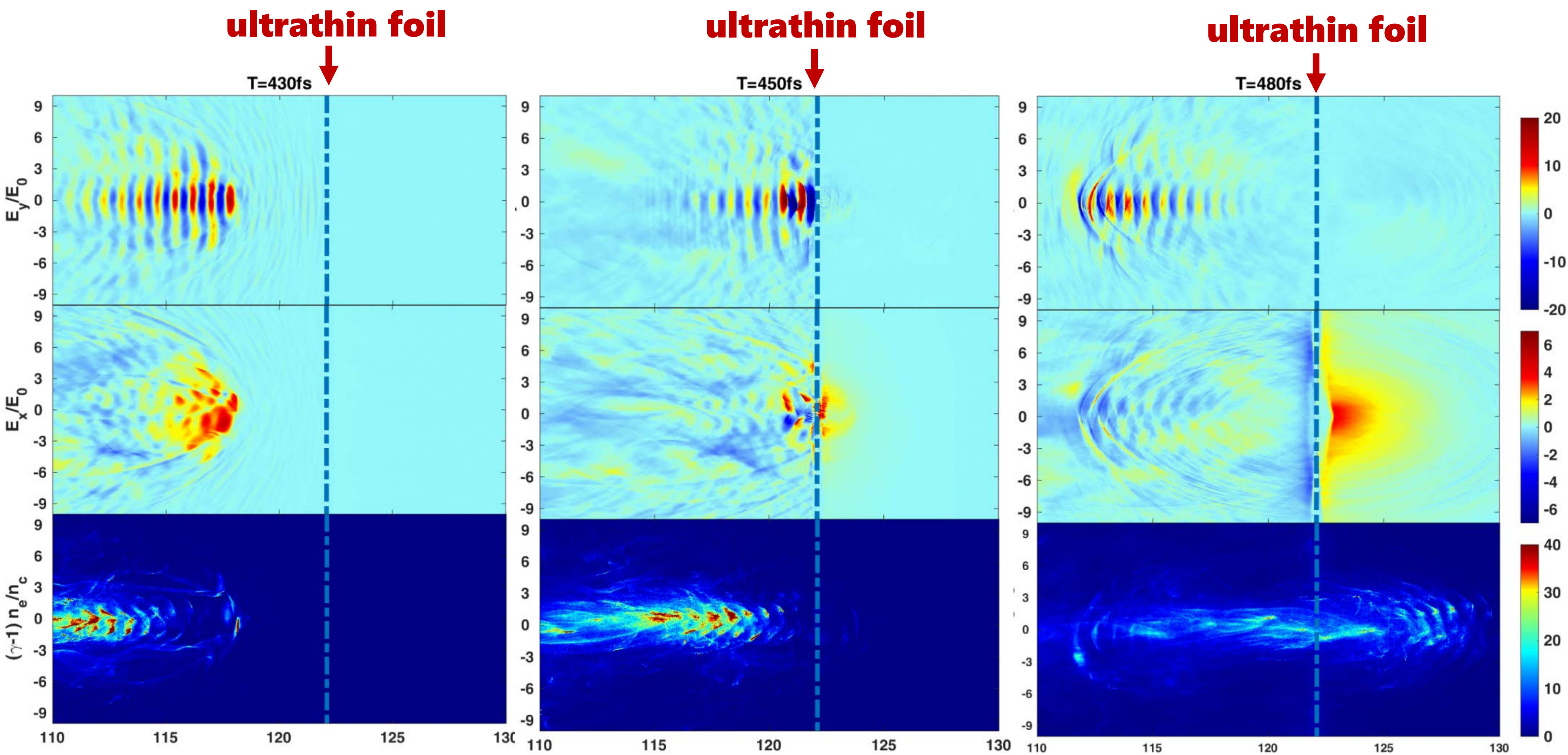


Cascaded acceleration

Laser shaping and electron flow generation

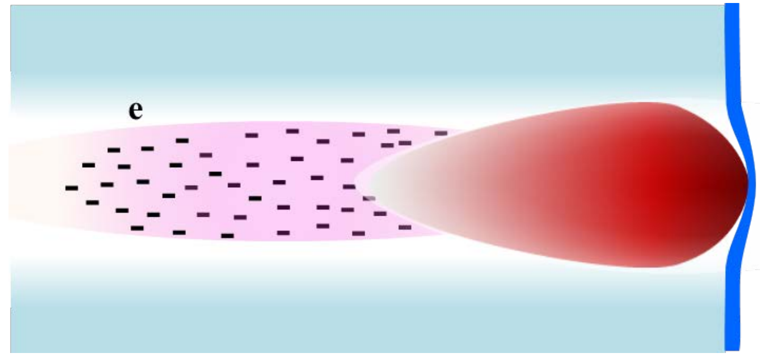
Stage 1 : Radiation pressure acceleration

Stage 2 : Sheath field acceleration



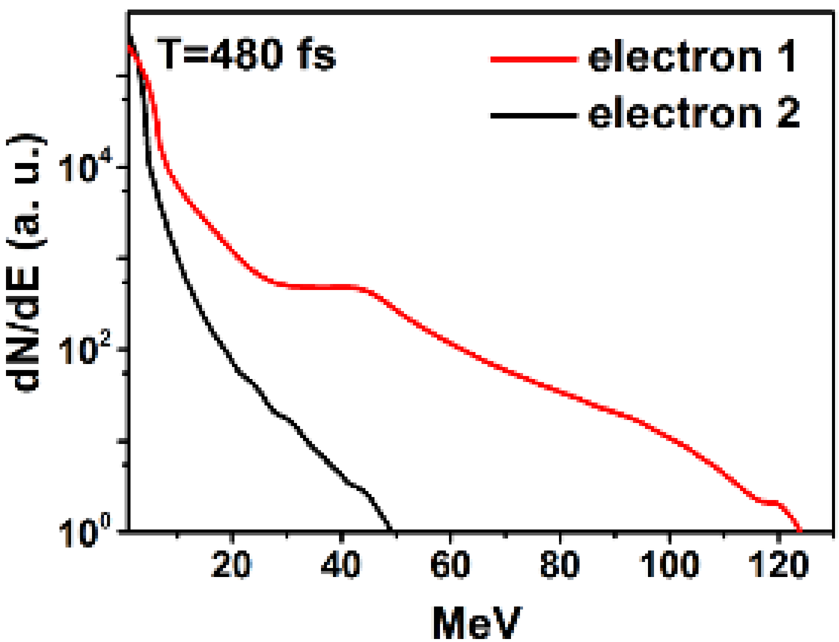
Energy spectra of electrons and ions

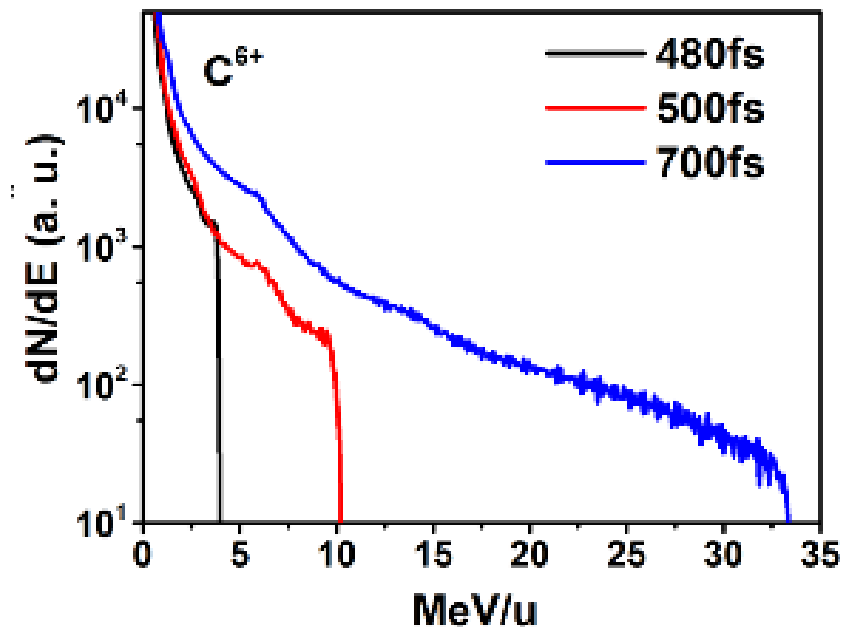
$a=15$, $n_{e1}=0.2n_c$, $L_1=60$ um



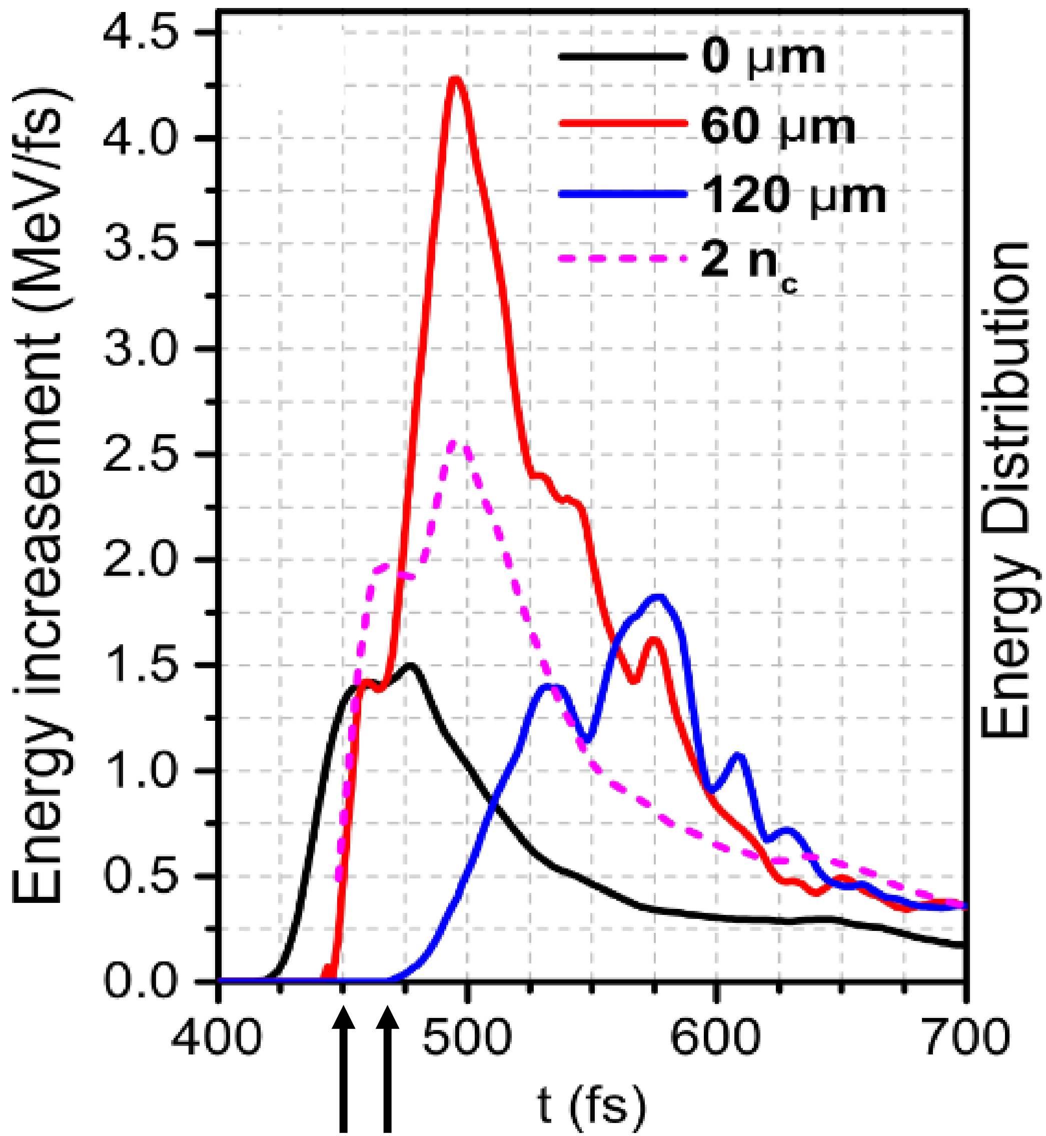
Energy spectra of electrons after the RPA stage

Energy spectra of carbon ions



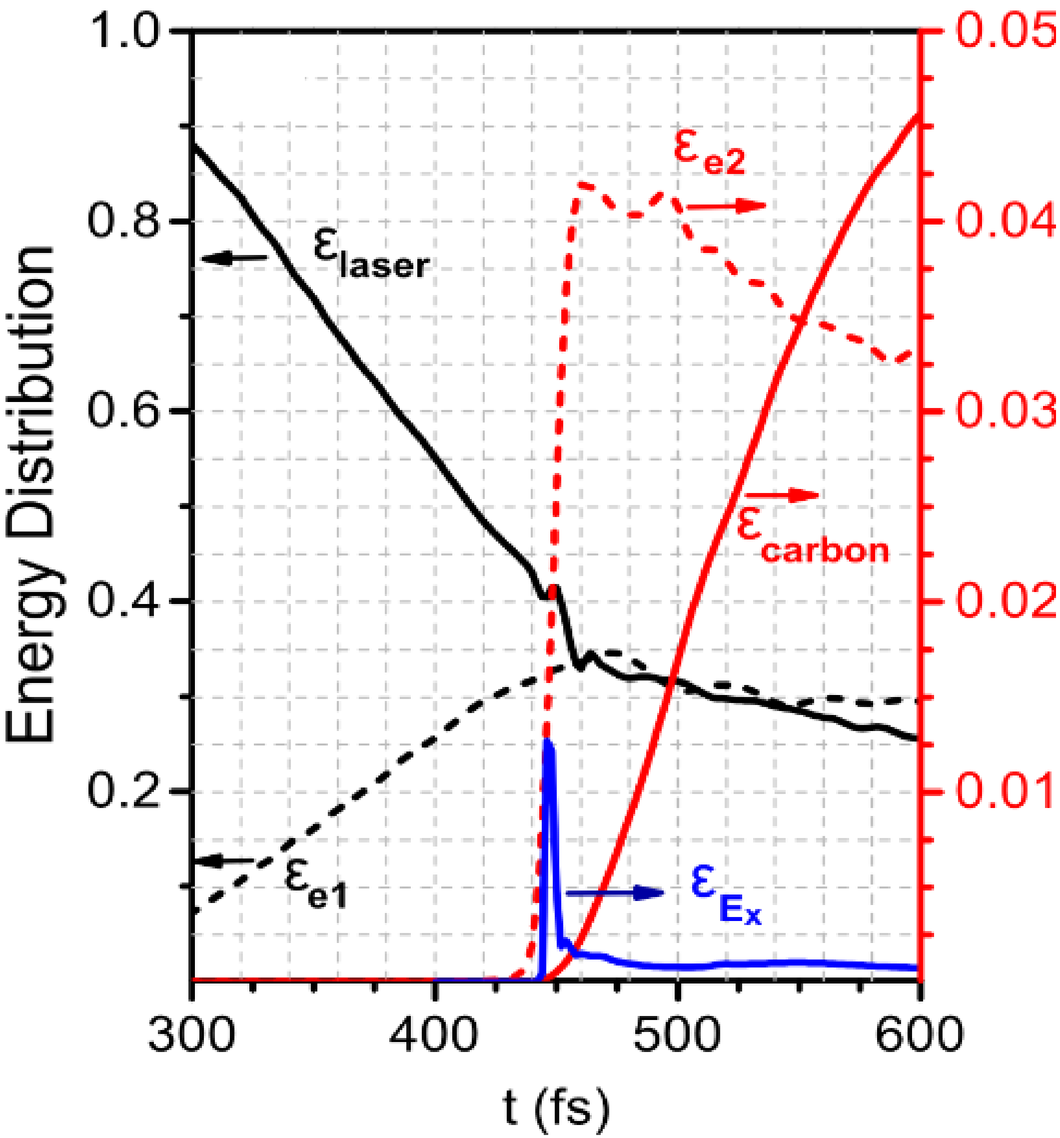


Instant energy increment for tracked carbon ions



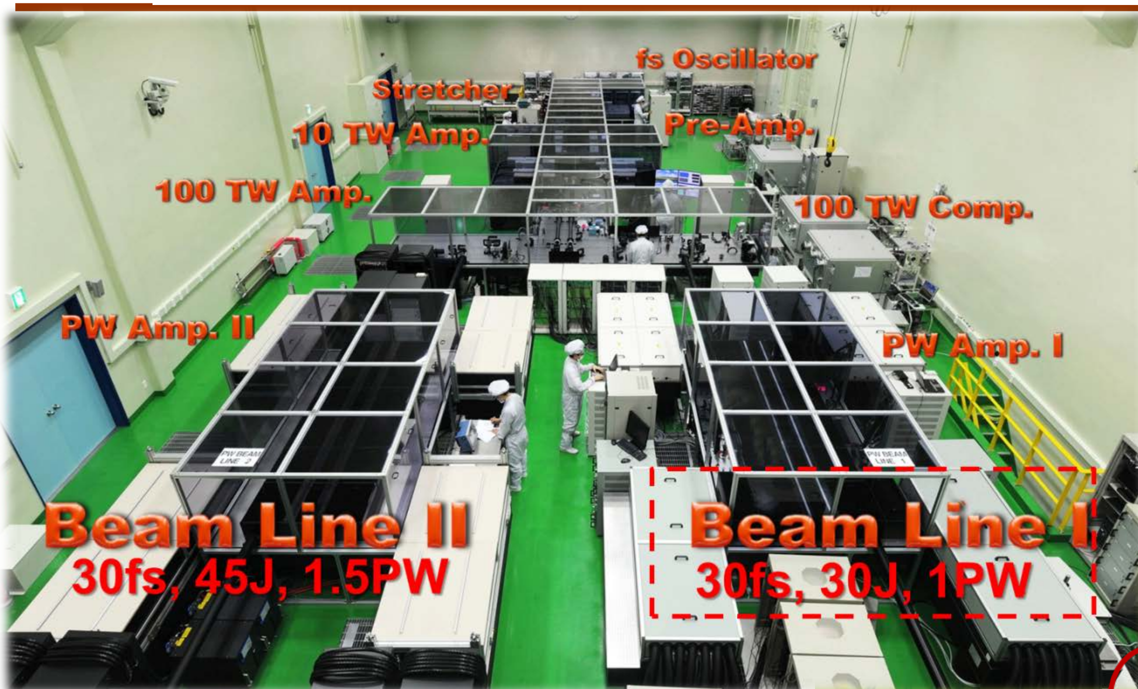
laser arrive laser reflected

Energy distribution among laser, particles and fields



70% energy of carbon ions comes from sheath acceleration stage

Experimental results



1.5 PW laser (PULSE) in Center for Relativistic Laser Science(IBS), Korea

PI： X. Q. Yan   C.H. Nam

25fs-30fs,
Double plasma mirror,
9.2J on targets for LP,

$I = 5.45 \times 10^{20}$ W/cm^2 ,a_0=16

CNF density fixed to $0.3 \pm 0.1 n_c$

Raw data from Thomson parabola spectrometer

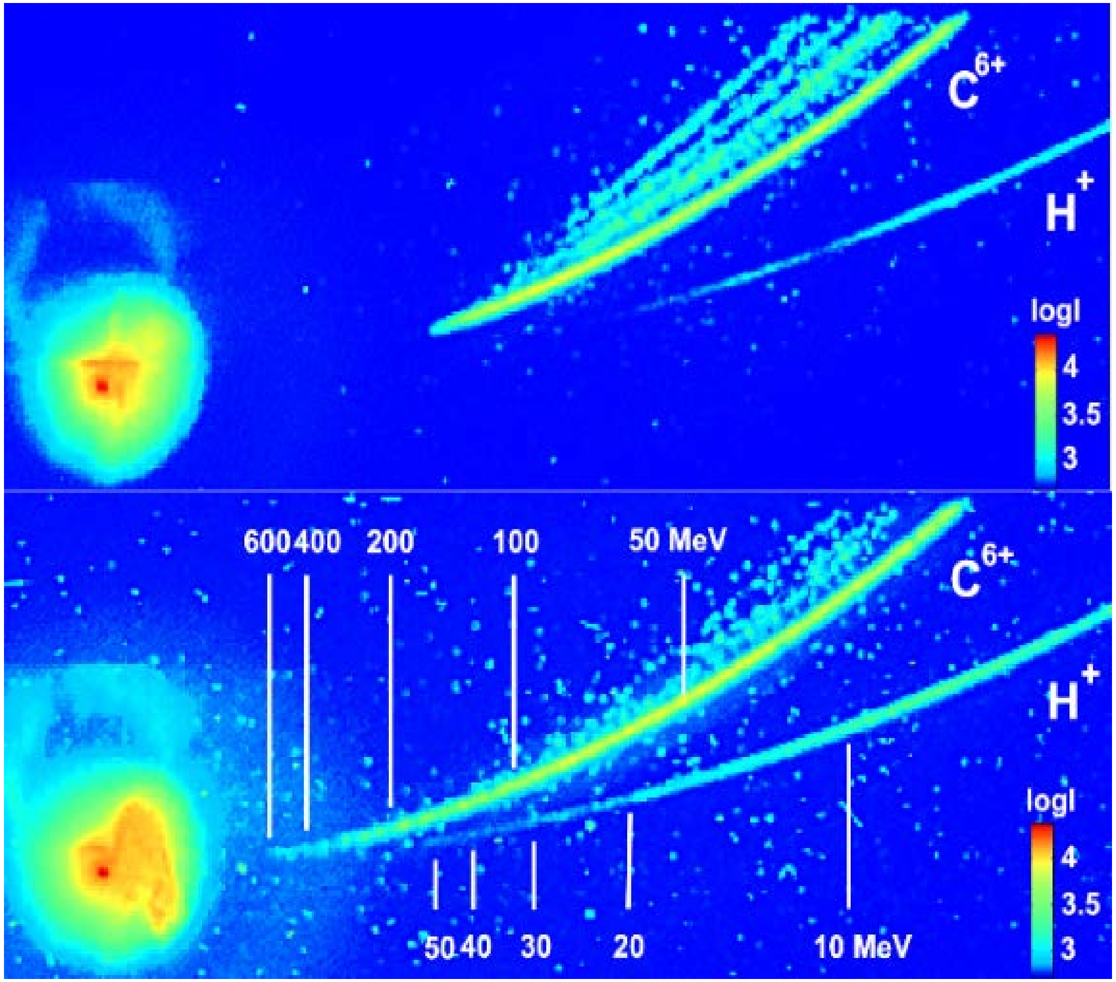
Single layer target

20 nm DLC

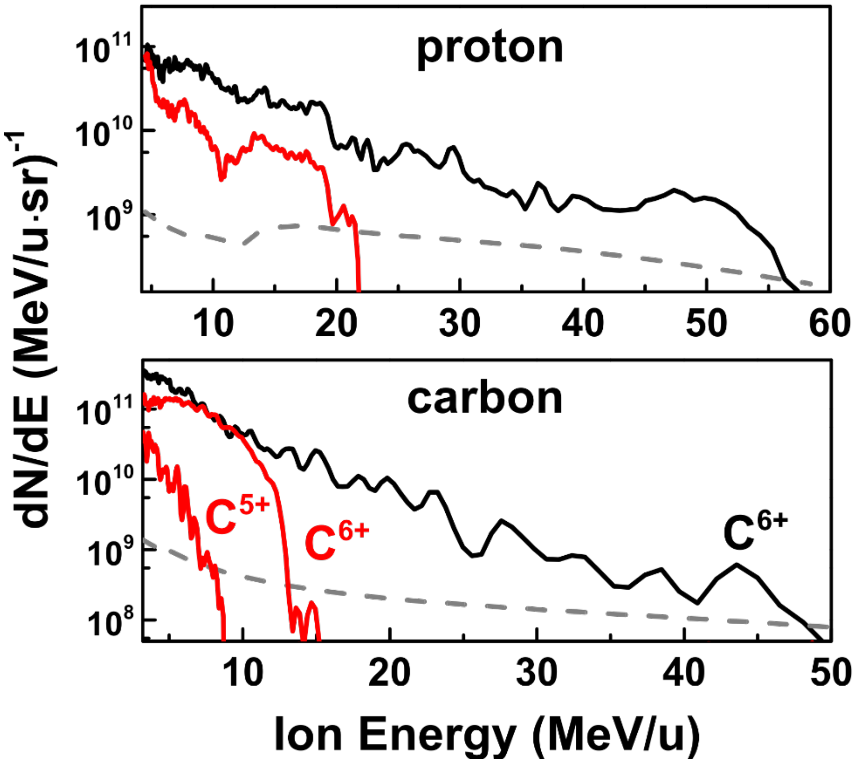
Double-layer target

20 nm DLC+80 um CNF

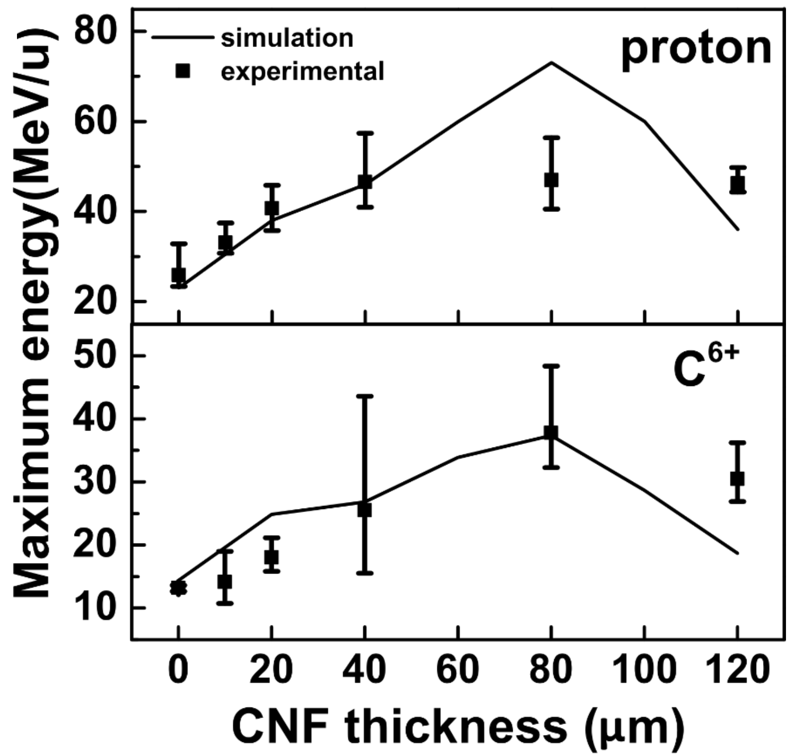
(optimal parameters)

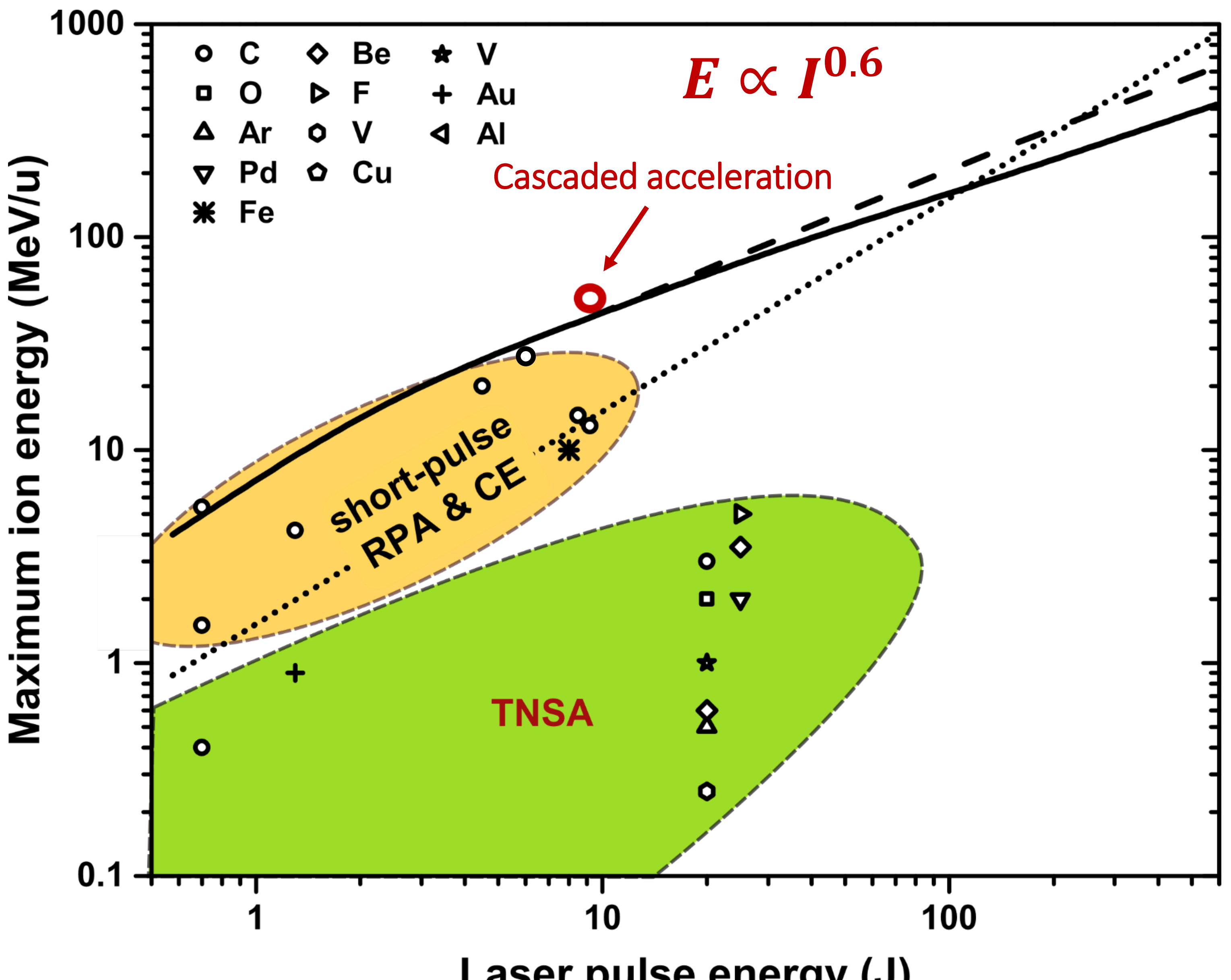


Energy spectra of the best shot

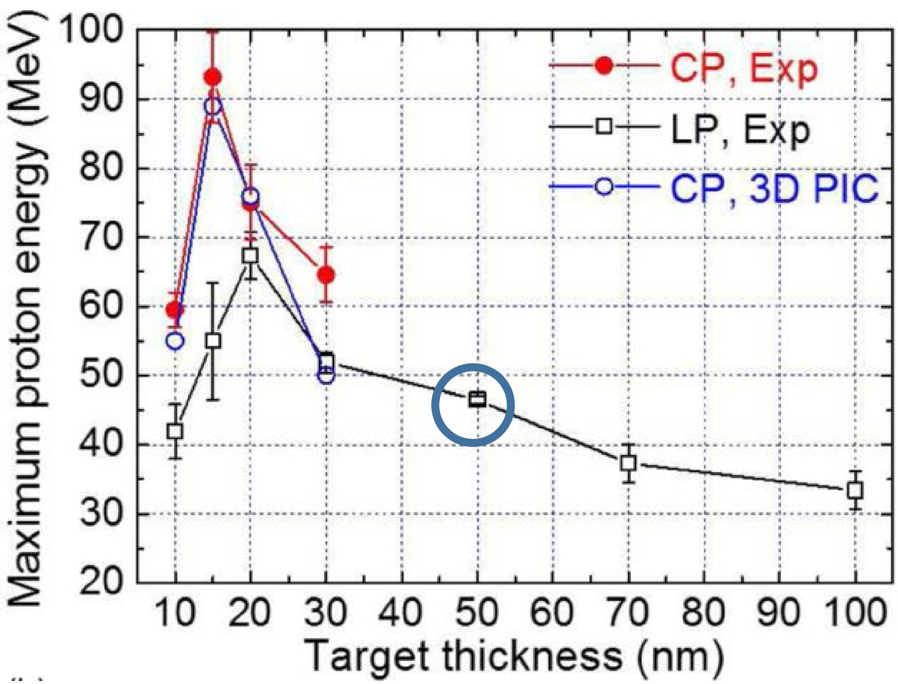


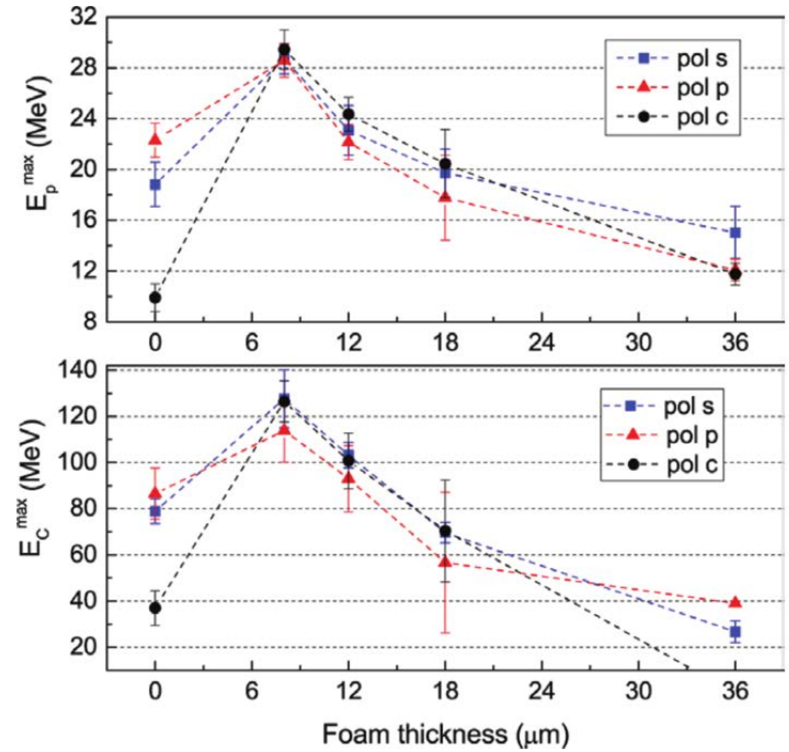
CNF thickness scan





1000
100
10
1
0.1
Maximum ion energy (MeV/u)
1
10
100
Laser pulse energy (J)
C
O
Ar
Pd
Fe
Be
F
V
Cu
V
Au
Al
$E \propto I^{0.6}$
Cascaded acceleration
short-pulse
RPA & CE
TNSA





I. J. Kim *et al.*, Phys Plasmas **23**, 6, 070701 (2016).

I. Prencipe *et al.*, Plasma Phys Contr F **58**, 034019 (2016).

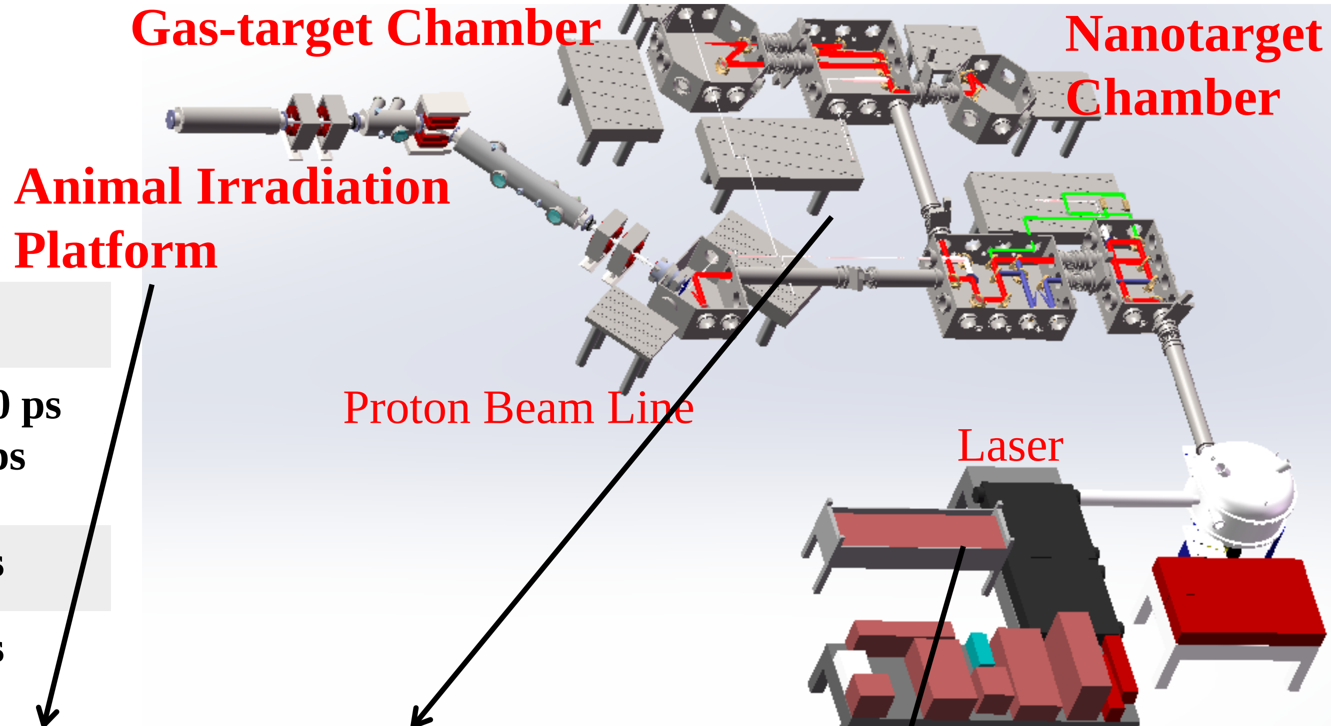
- ~8.5 J, 30fs
- ~7.4 J, 30fs

Laser accelerator team at Peking university

CLAPA layout

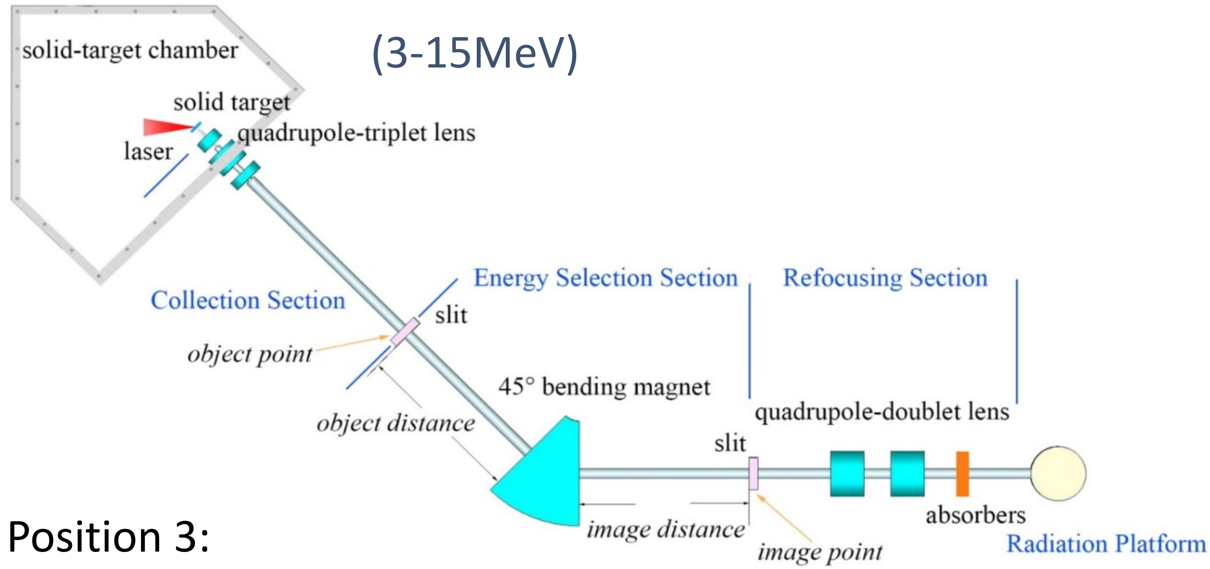
CLAPA Laser Parameters

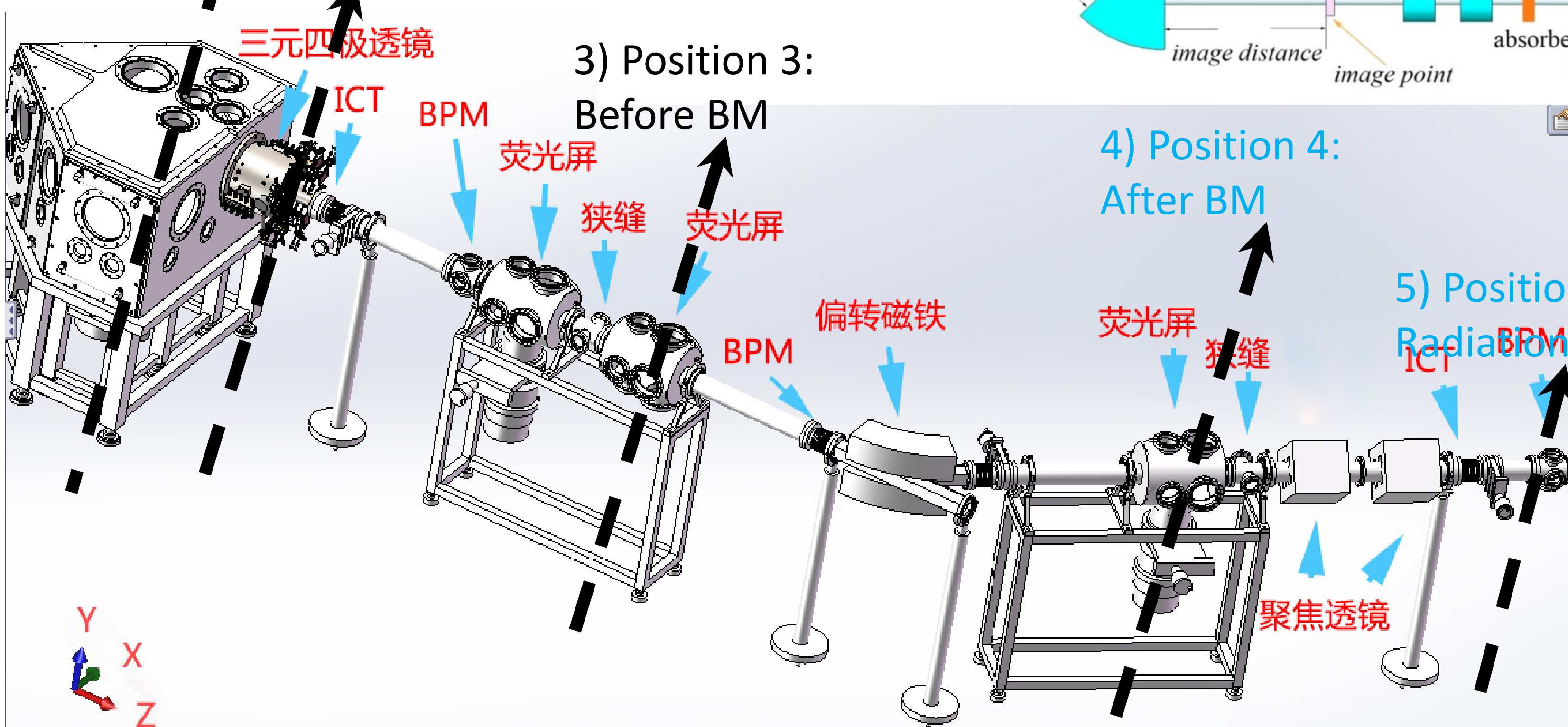
Pulse Energy:	5 J /5Hz
Pulse Duration:	< 25 fs
Wavelength:	800 nm
Contrast Ratio:	10^{10}:1 @ 100 ps 10^{9}:1 @ 20 ps
	10^{6}:1 @ 5 ps
	10^{3}:1 @ 1 ps



The first proton Beam test

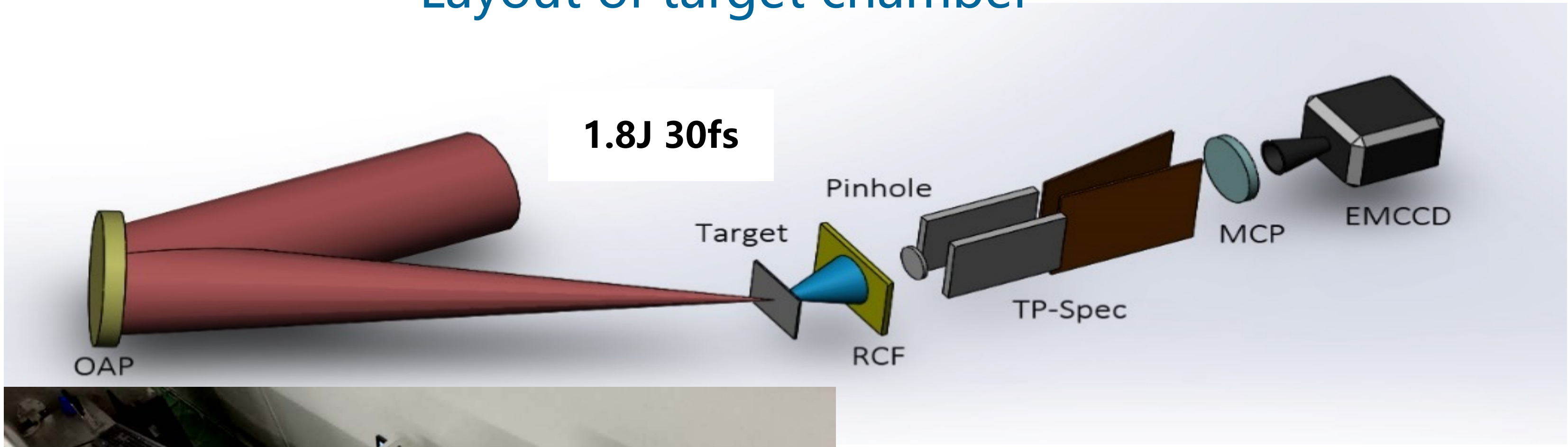
(3-15MeV)

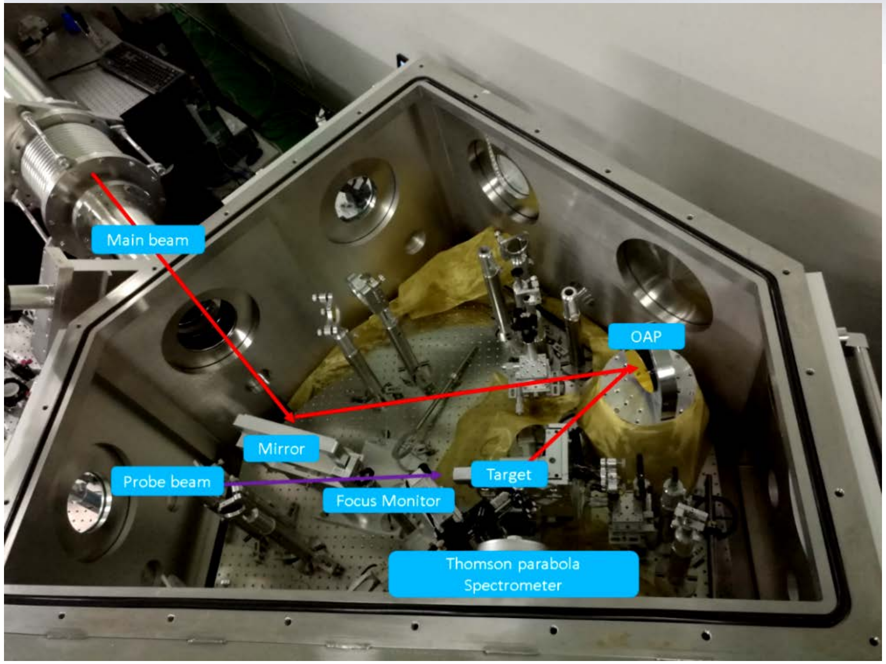




Proton Beam before beam-line

Layout of target chamber





Laser parameters:

Energy 1.8J

Duration 30fs

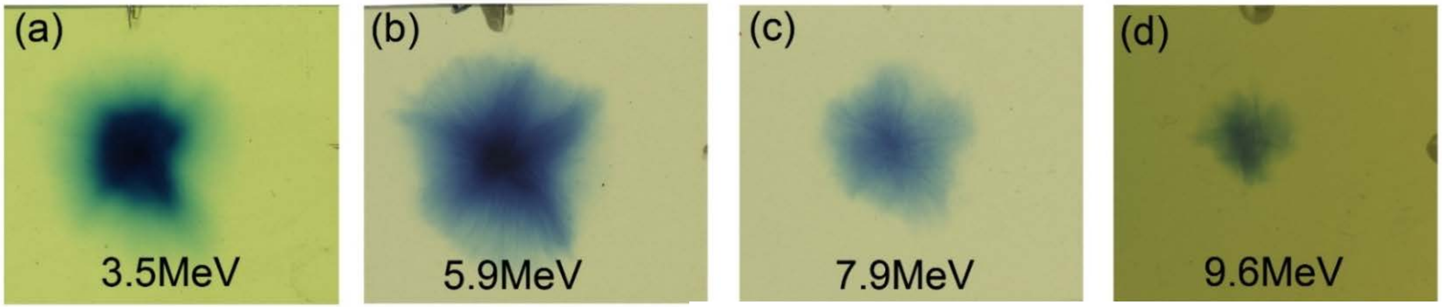
intensity 8.3×10^{19}W/cm^2

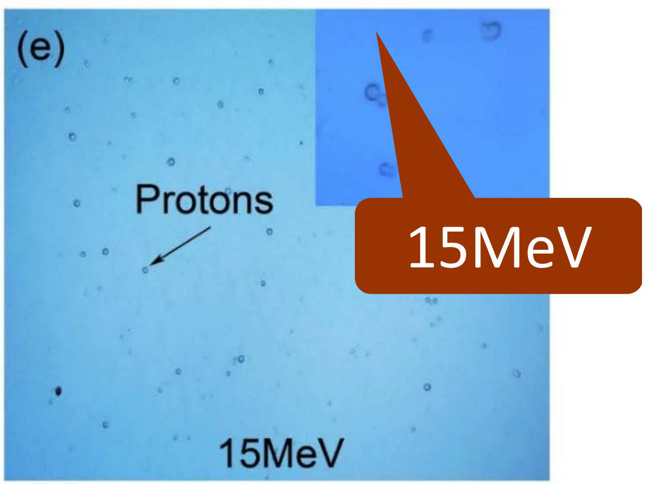
angle : 30 degree

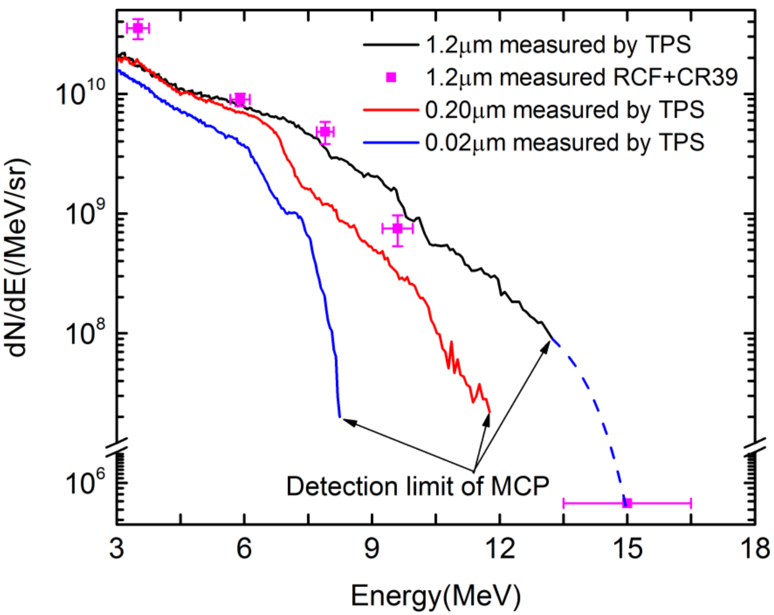
spot : 4.5μm×5.3μm

Proton Beam before beam-line

Shooting nanometer foils, without using plasma mirror, very good contrast can be confirmed!



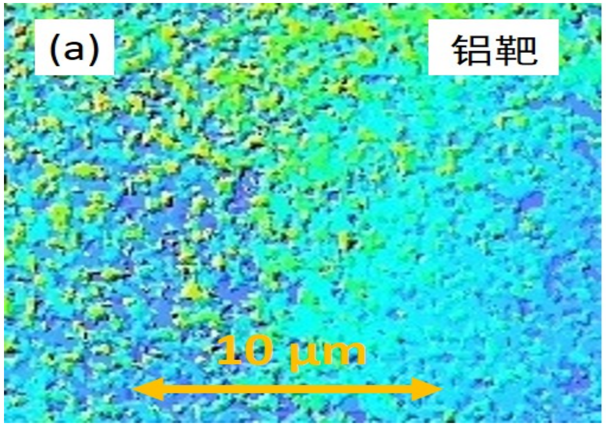


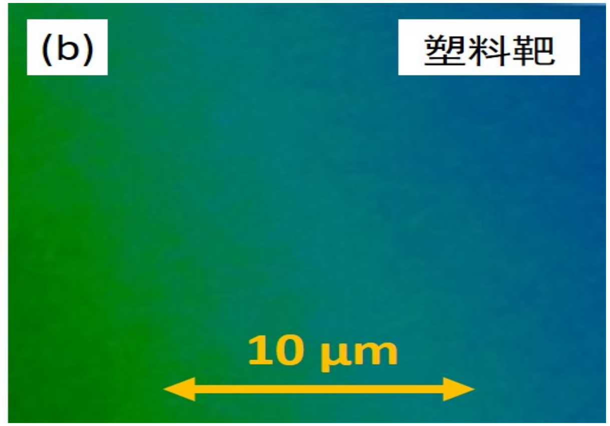


- **15MeV**
- 0.02-1.2μm plastic foil

Y. X. Geng et al Submitted 2017

Proton energy stability <3%

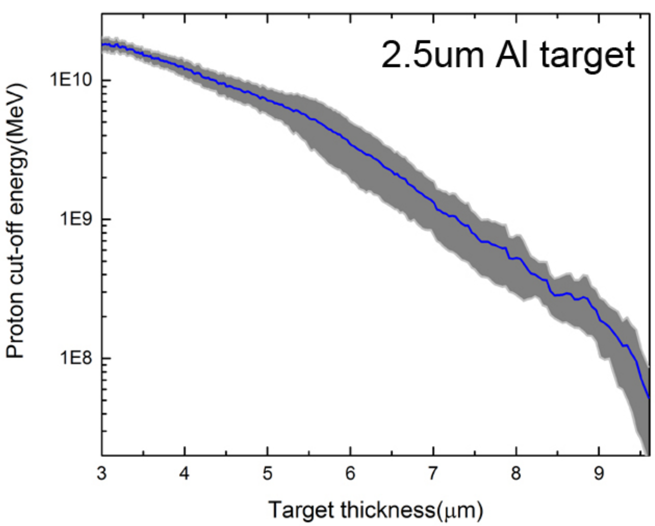


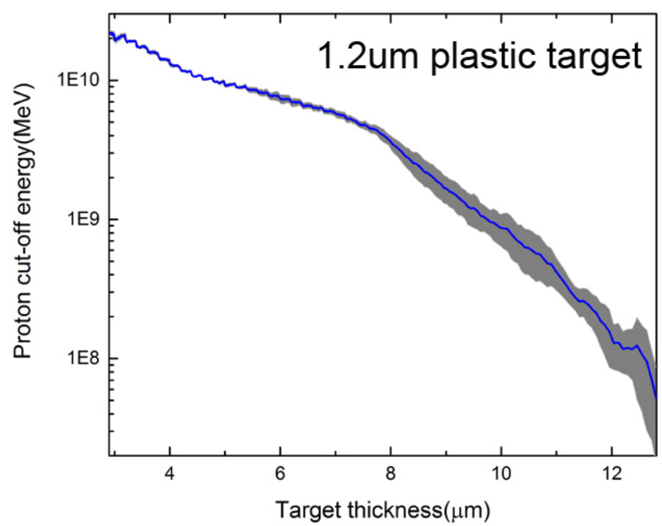


Thanks to:

- Target flatness
- Laser (2%)
- Beam target coupling (3μm)

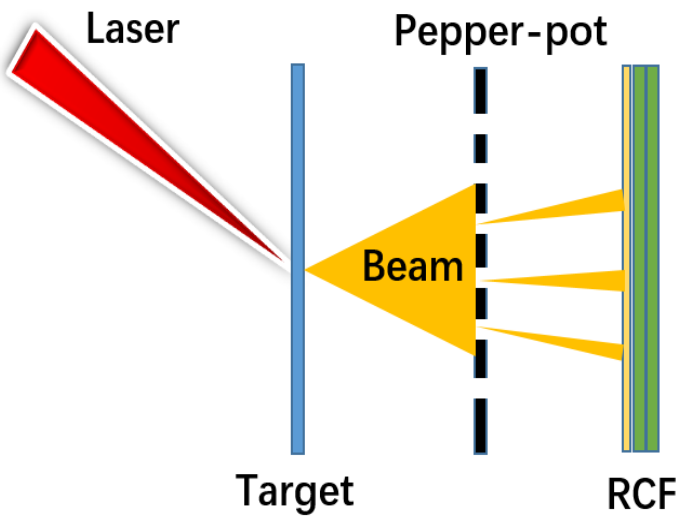
Ultra Stable acceleration

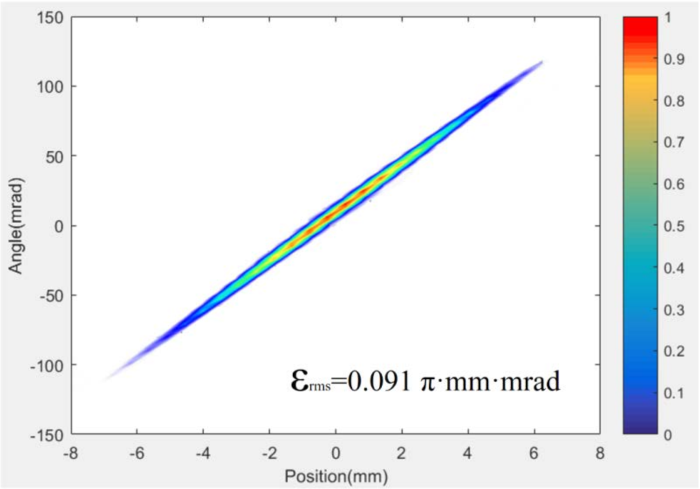


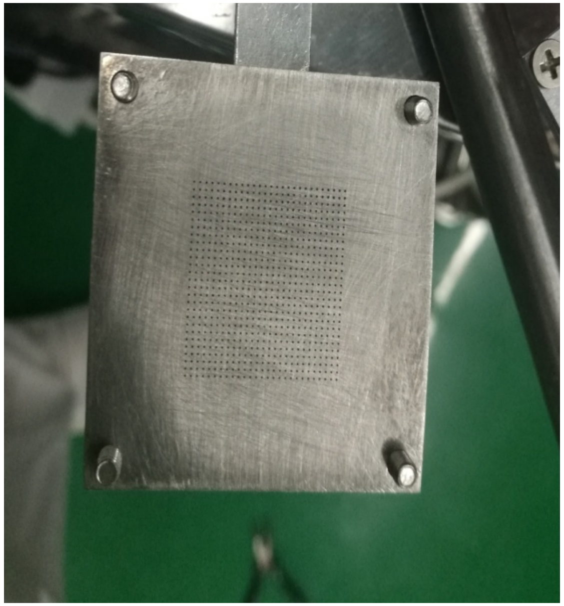


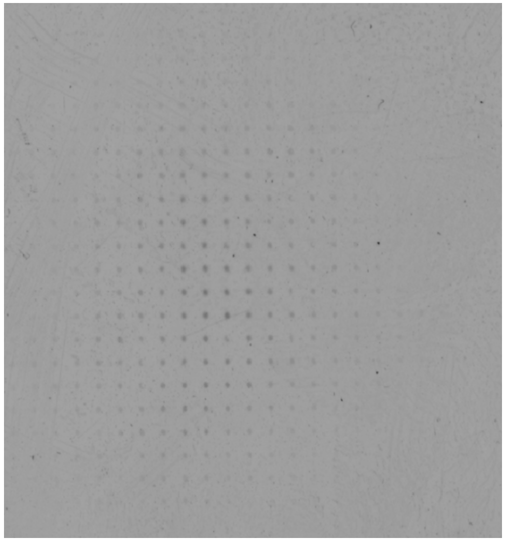
Proton energy stability<3% in ~10shots, 1.8J/30fs on target

Proton Emittance is measured by Pepper pot









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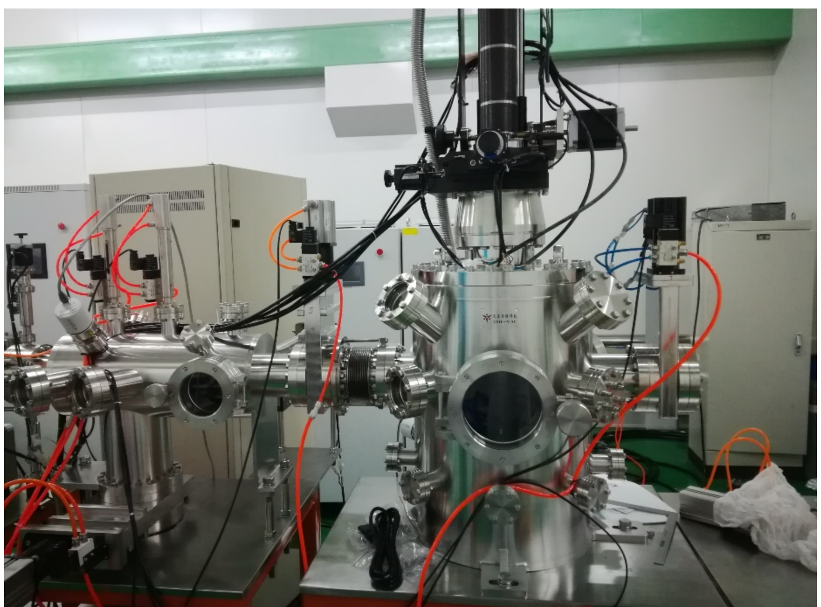
Components of the beam-line

overview

Dipole magnet

Biomedical Irradiation platform

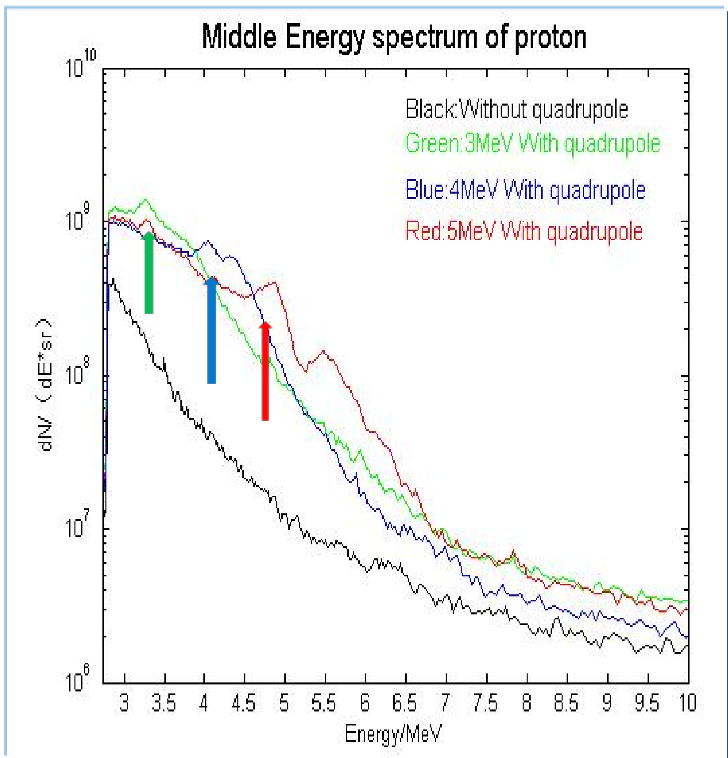


On-cite fluorescence microscope

Proton Beam at Position 2: Quadrupole

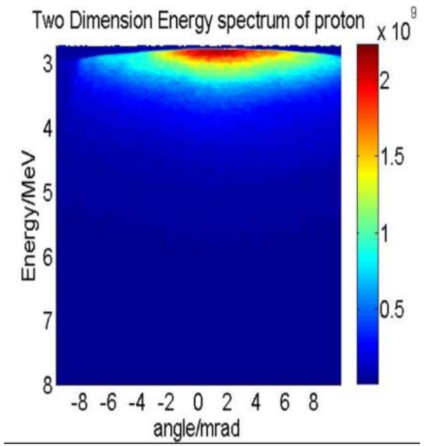
The proton charge on **MCP** was Significantly enhanced:

3.5 MeV ×7
4.5 MeV ×20
5.5 MeV ×20

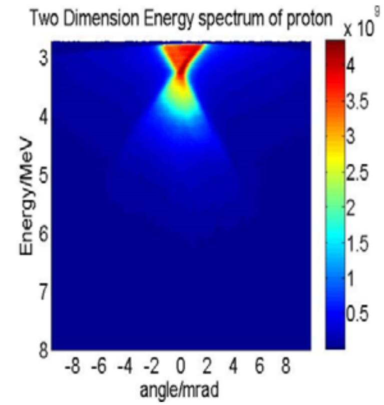


energy spectrum with Angular resolution

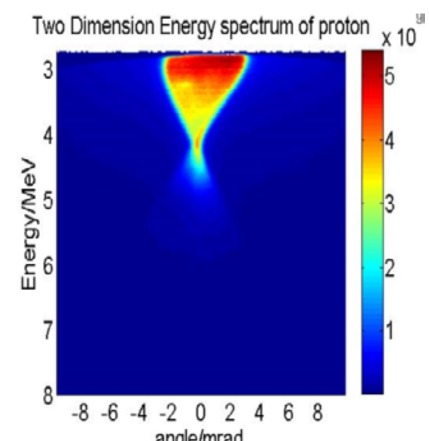
B=0



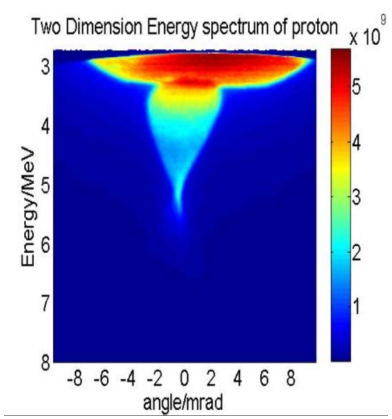
Focusing 3 MeV



Focusing 4 MeV



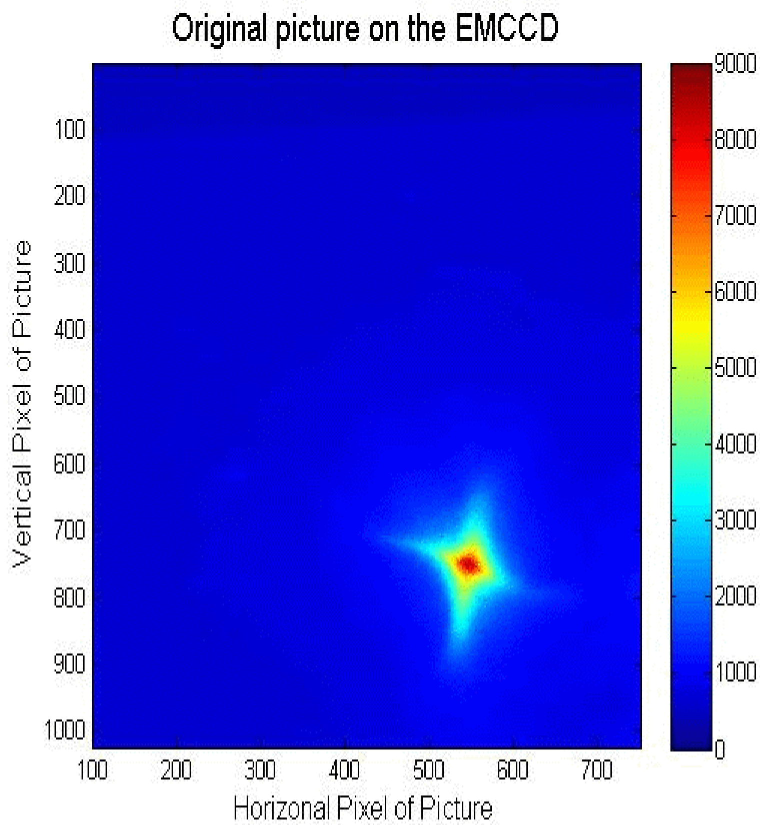
Focusing 5 MeV

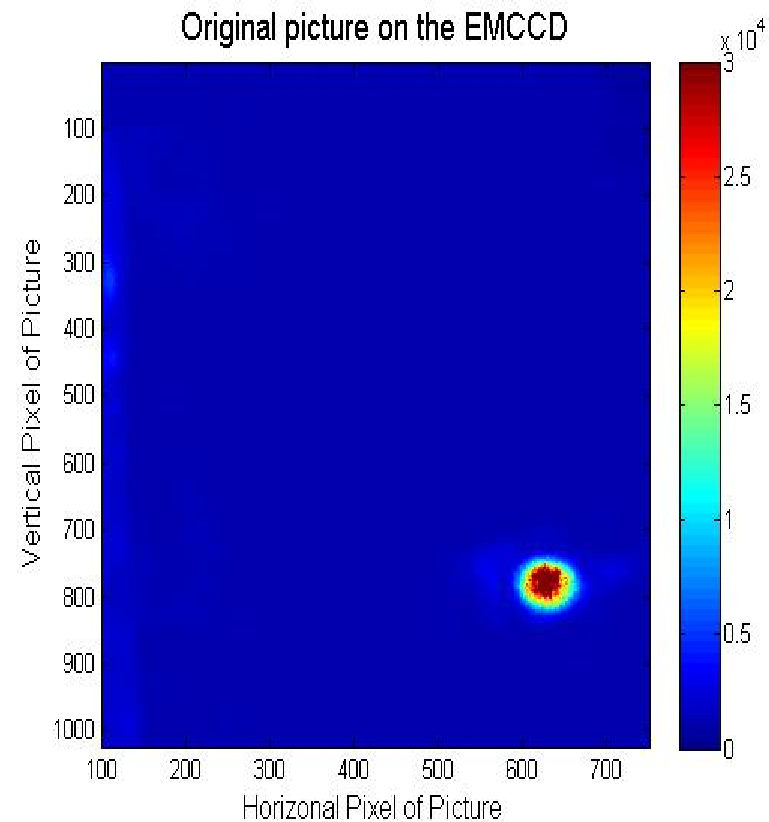


Beam at Position 3: before Bending Magnet

9月16日

Very good proton beam pointing





70（2.75MeV）	70（2.75MeV）
70（2.75MeV）	140（4.3MeV）

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