# Recent Progress on the Laser-driven High-energy Proton/Heavy Ion Acceleration

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# Outline

- ☐ Major acceleration schemes and recent progress of high-energy proton acceleration

- ☐ Progress of the laser-driven heavy ion acceleration

- ☐ laser ion acceleration in Peking University

# Laser pulses for ion acceleration

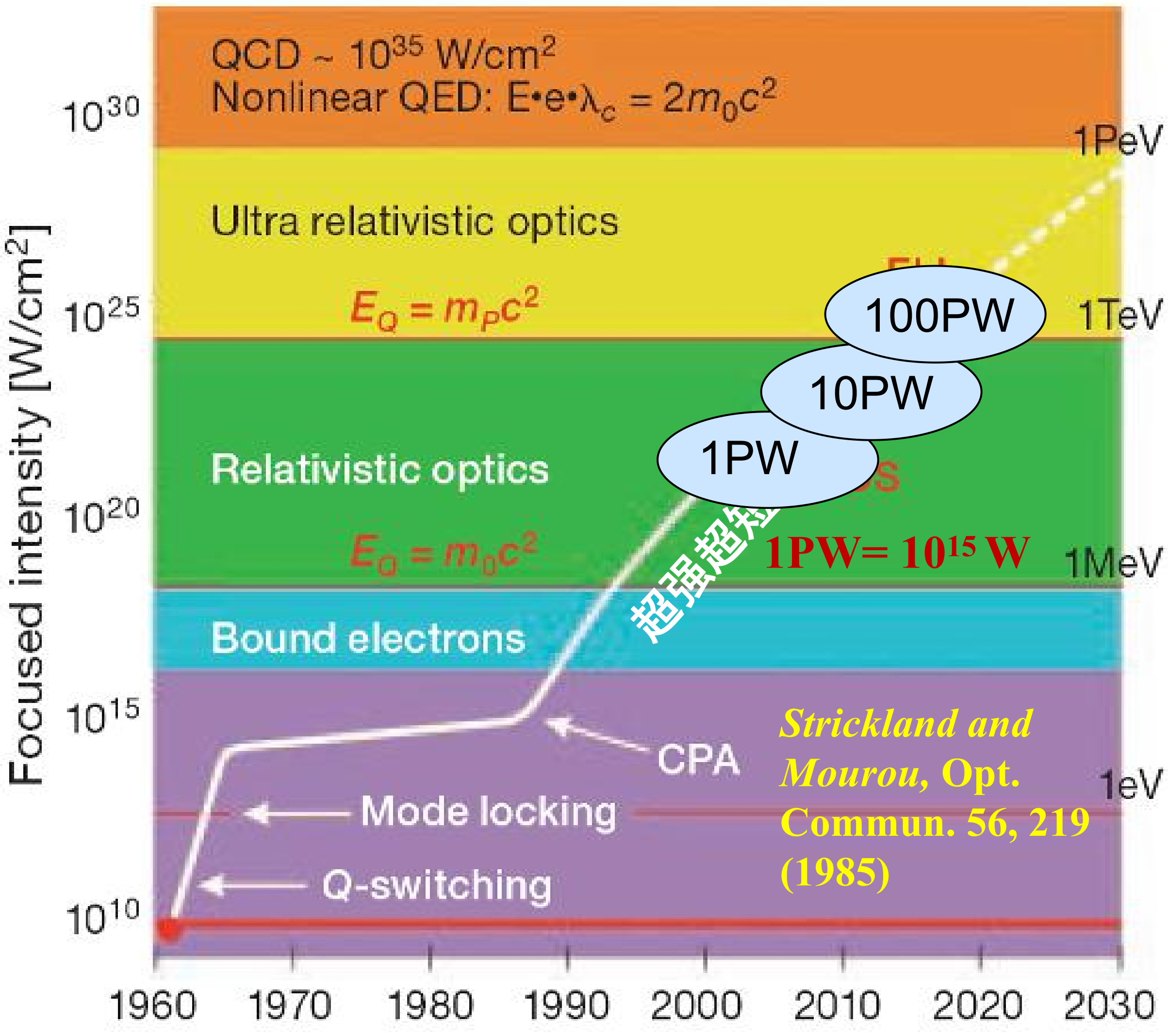
**For ion acceleration, we use:**

**tightly focused high-power pulses**

$$a_0 = \frac{eE_0}{m_e c\omega} = \sqrt{I_0/1.37\times10^{18}Wcm^{-2}(\mu m/\lambda)^2} > 5$$

Typically : $I_0 > 10^{19}$ W/cm²

Highest achieved: $I_0 \sim 10^{22}$ W/cm²



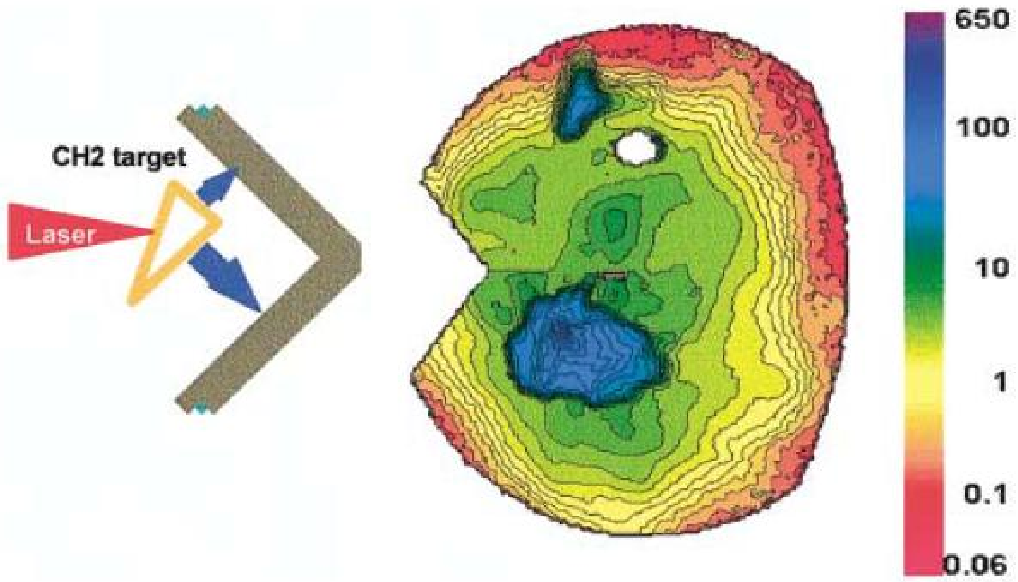
*Strickland and Mourou*, Opt. Commun. 56, 219 (1985)

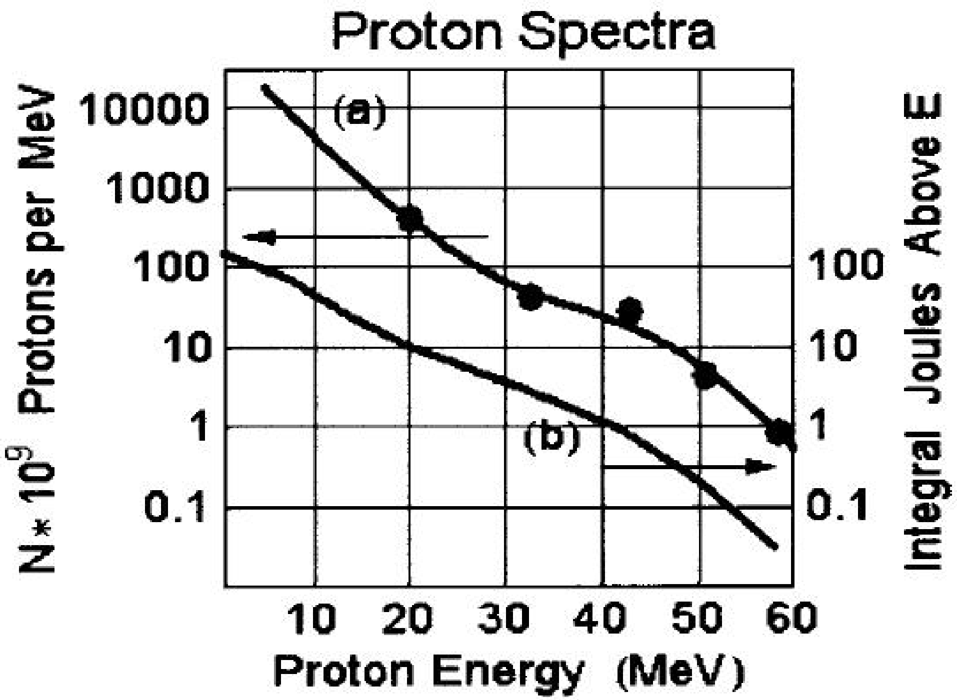
## ☐ 2 types of lasers:

- **Long pulse lasers (glass lasers):**
  **100s fs-ps, 10s-100sJ**
- **Short pulse lasers (Ti:Sapphire):**
  **20-50 fs, 1-10sJ**

# Early proton acceleration results

Parameters：
- 423 J, 500 fs laser pulse， 100 μm-thick plastic targets
- Cut-off proton energy: 60 MeV

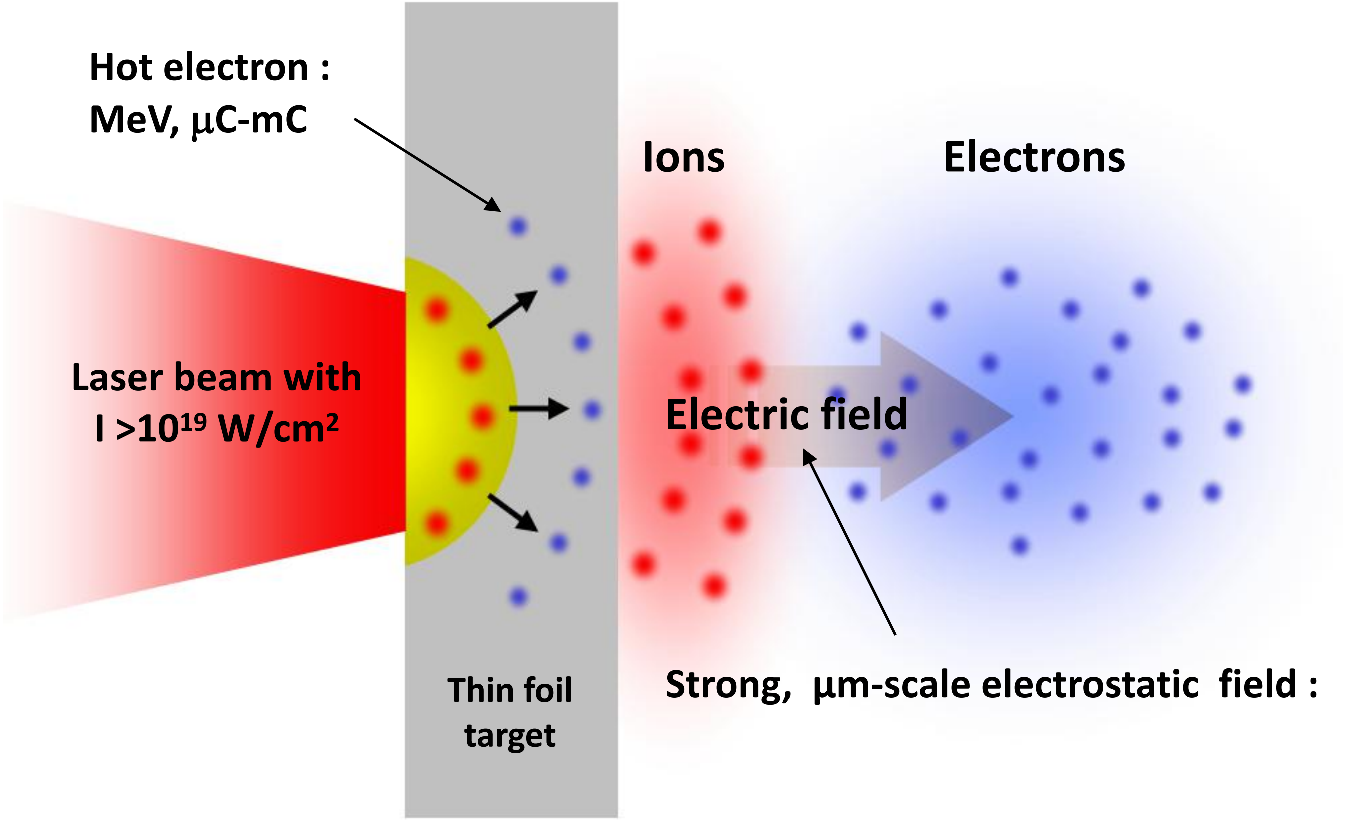




R. A. Snavely *et al.*, Phys Rev Lett **85**, 2945 (2000).

# Target Normal Sheath Acceleration （TNSA） regime

$T_e \approx m_e c^2(\sqrt{1+a_0^2}-1)$



Hot electron :
MeV, μC-mC

Ions

Electrons

Laser beam with
I >$10^{19}$ W/cm$^2$

Electric field

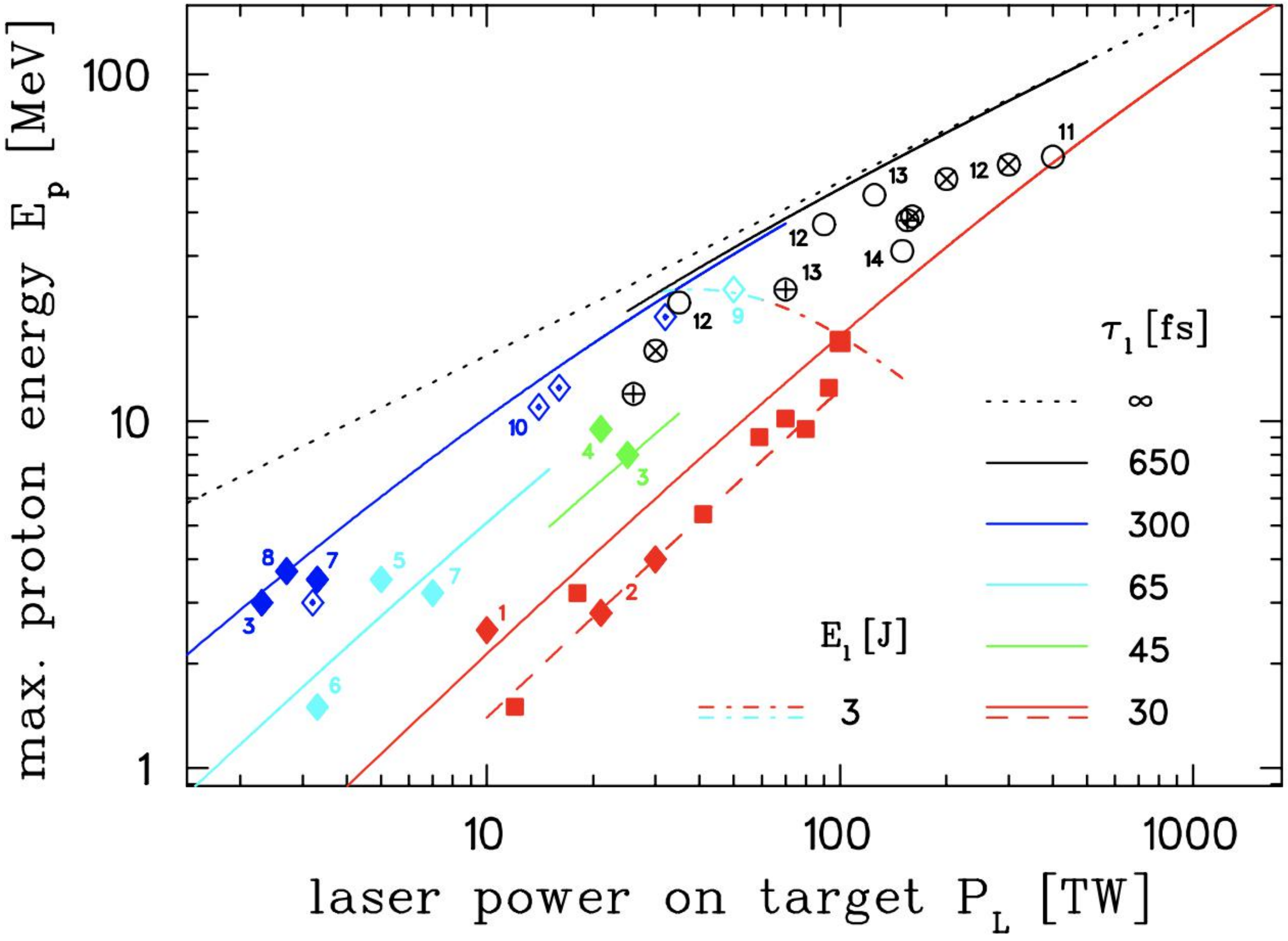
Thin foil
target

Strong, μm-scale electrostatic field :

Field strength: $E \approx \frac{k_B T_e}{e\lambda_D} = \sqrt{4\pi n_e k_B T_e} \approx MV/\mu m\ \ (TV/m)$

Daido, H., et al. (2012). "Review of laser-driven ion sources and their applications." Rep Prog Phys **75**(5): 056401.

# A review on TNSA results



Zeil, K., et al. New Journal of Physics **12**.(2010).

- **Long pulses:**

$$E_{max} \propto \sqrt{\eta P_{laser}}$$

- **Short pulses :**

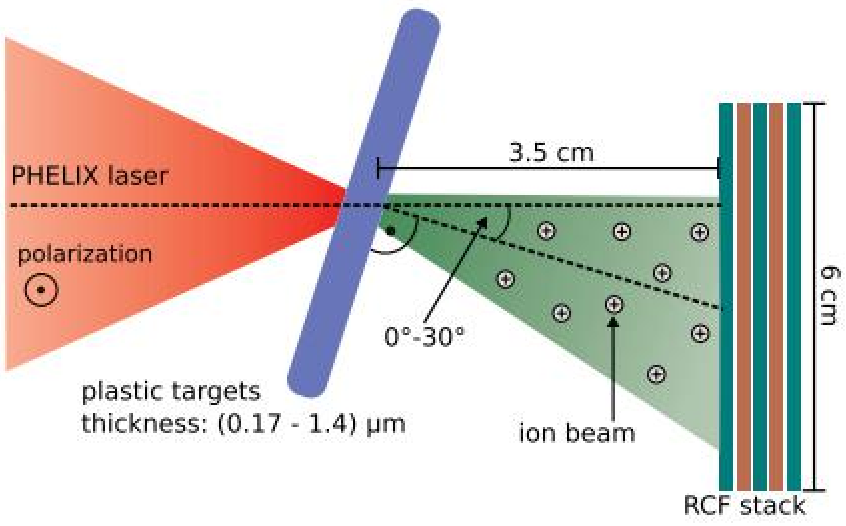
$$E_{max} \propto \eta P_{laser}$$

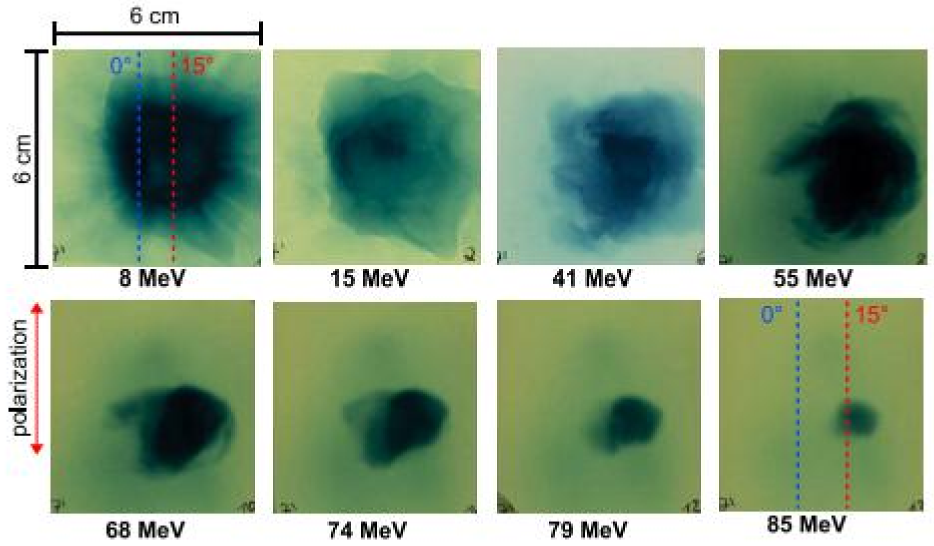
It’s difficult to exceed 60MeV in TNSA regime

# Record proton energy in TNSA regime

Parameters：

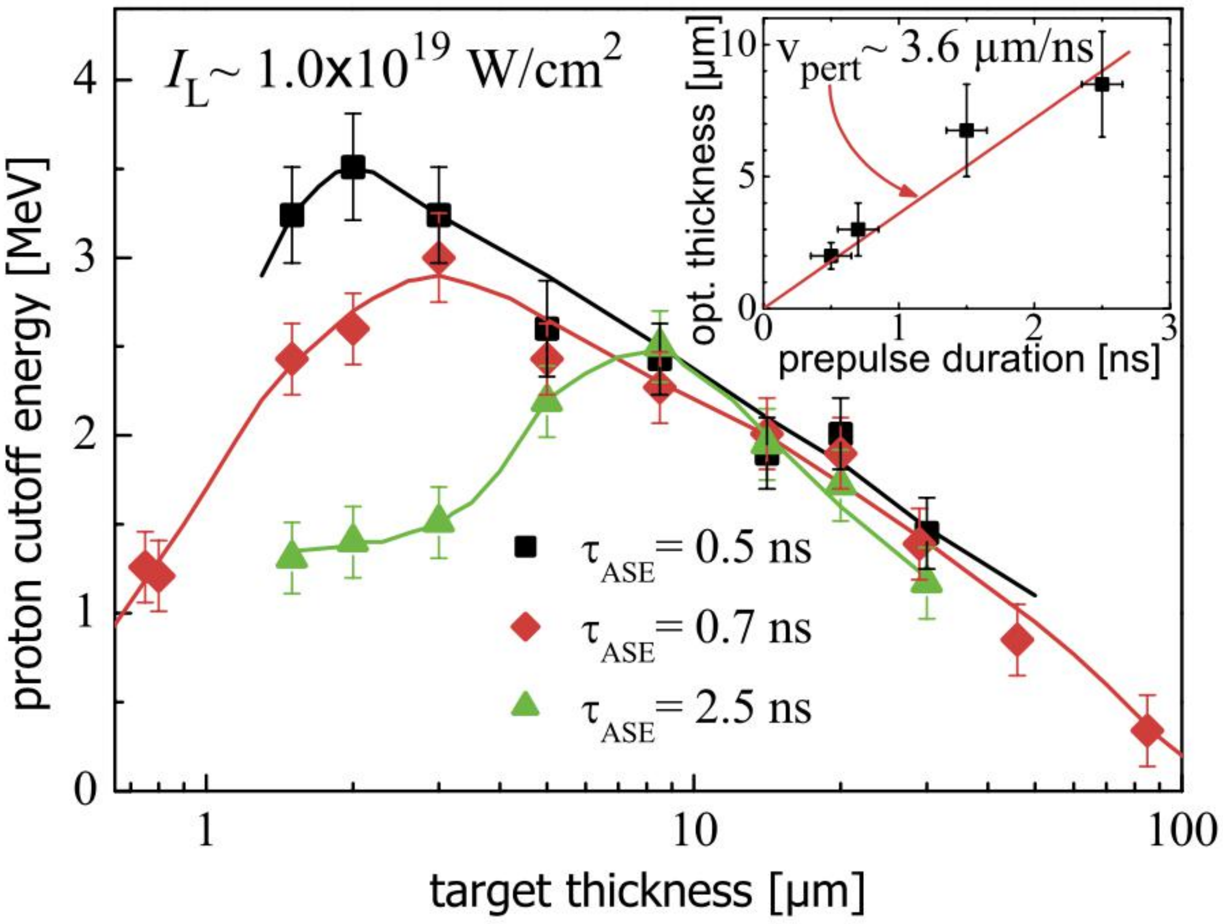
- 200 J, 500fs laser pulses, 900nm plastic targets
- $E_{max}$: 85MeV





F. Wagner, et al., Phys Rev Lett **116** (20), 205002 (2016).

# The influence of the target thickness in TNSA



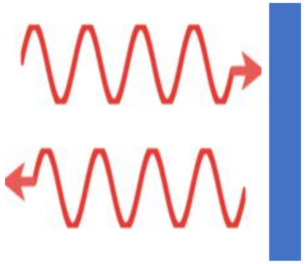
M. Kaluza, Phys Rev Lett **93** (4), 045003 (2004).

- ✓ the thinner, hot electrons are denser at target rear⟶stronger field
- ✓ the thinner, hot electrons circulated more times ⟶longer lifetime of the field
- ✓ The shock launched by the pre-pulses limits the thinnest targets that can be used for a given lasers system

# Accelerating an ultrathin foil by radiation pressure

What happens when a ultrathin foil is irradiated by a ultraintense laser pulse?

Radiation pressure for $I = 10^{20}\, W/cm^2$:

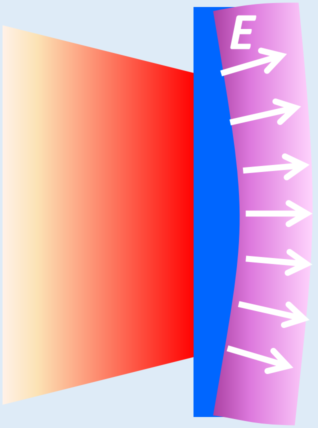


$$P_{rad} = \frac{2I_{rad}}{c} = \ 2I_{rad}/3 \times 10^3 W cm^{-2} \text{ (Pa)}$$
$$= 6 \times 10^{12} \text{atm}$$

Acceleration of a 10 nm target at $10^{20}\, W/cm^2$:

$$a = \frac{P_{rad}}{m} \approx 10^{22}\, m/s^2 = 0.06\ c/fs \approx 2MeV/fs$$

Acceleration field built by collective electrons



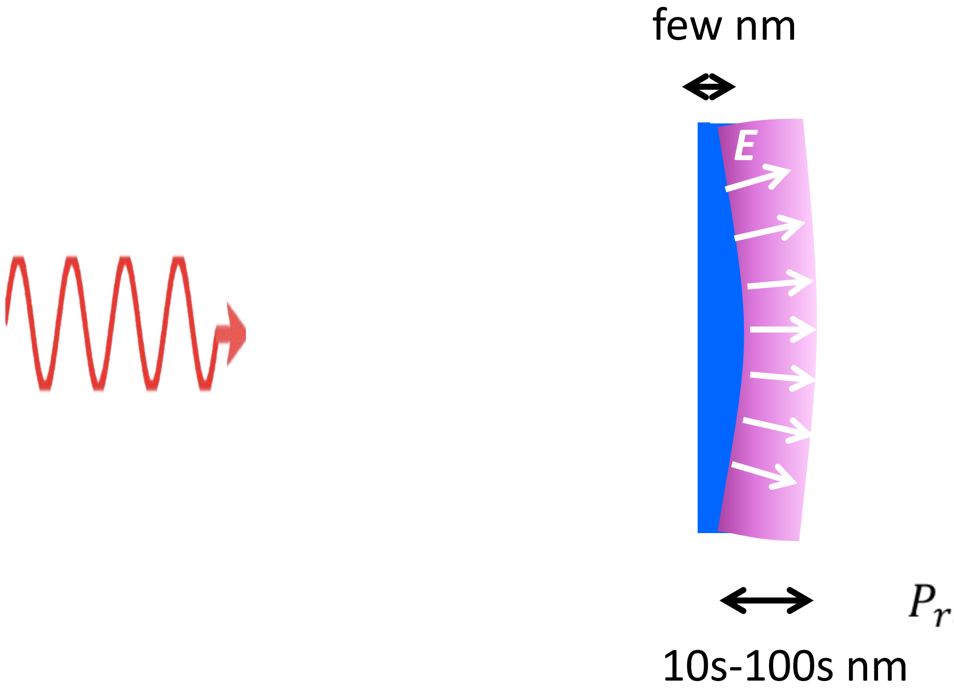
$$N_e^{sep} \sim N_i^{all}$$

# Light-sail radiation pressure acceleration (LS-RPA)

Radiation pressure

Electrostatic pressure

$$\frac{2I}{c} \approx 2\pi(en_e d)^2$$



$$P_{rad} \approx P_{es}$$

$$E_p \propto \begin{cases} I^2 \ (d < \sigma) \\ I \ \ (d \sim \sigma) \end{cases}$$

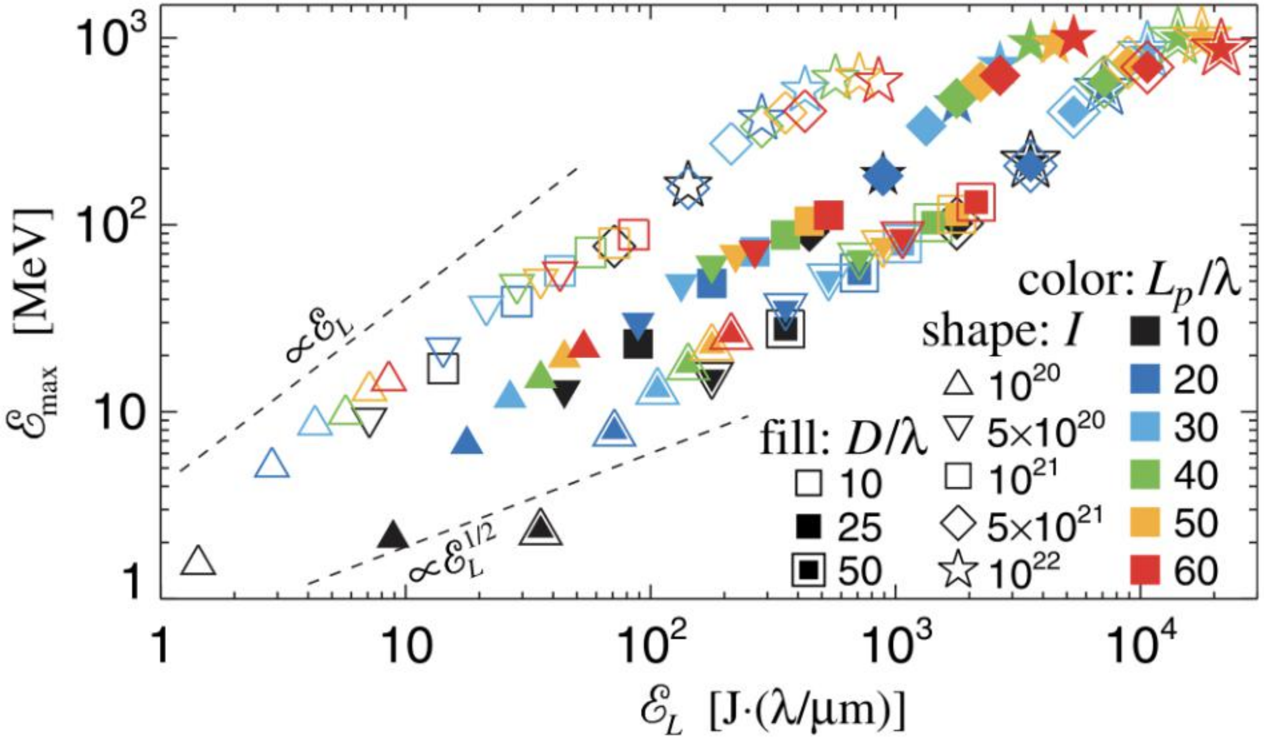
Esirkepov, et.al, Phys Rev Lett **92**,175003 (2004)

A. Macchi, et al., Phys Rev Lett **94** 165003 (2005).

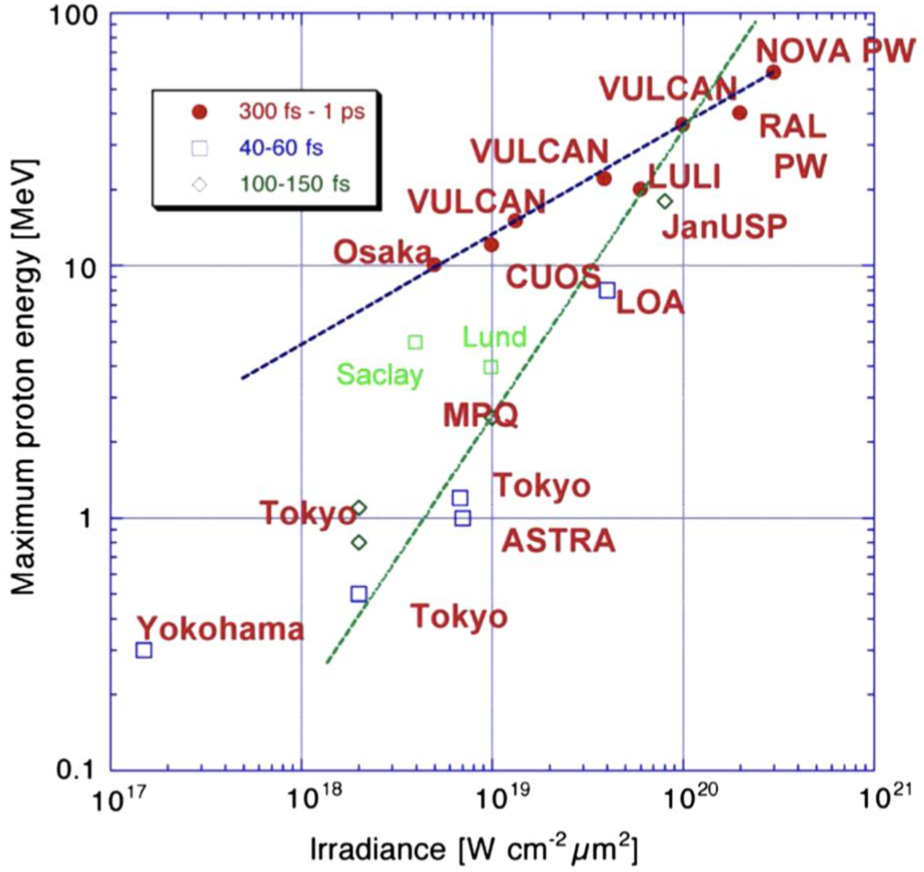
# Scaling law in RPA regime

☐ Theory & simulations

$E_{max} \propto E_L$



☐ Experimental results



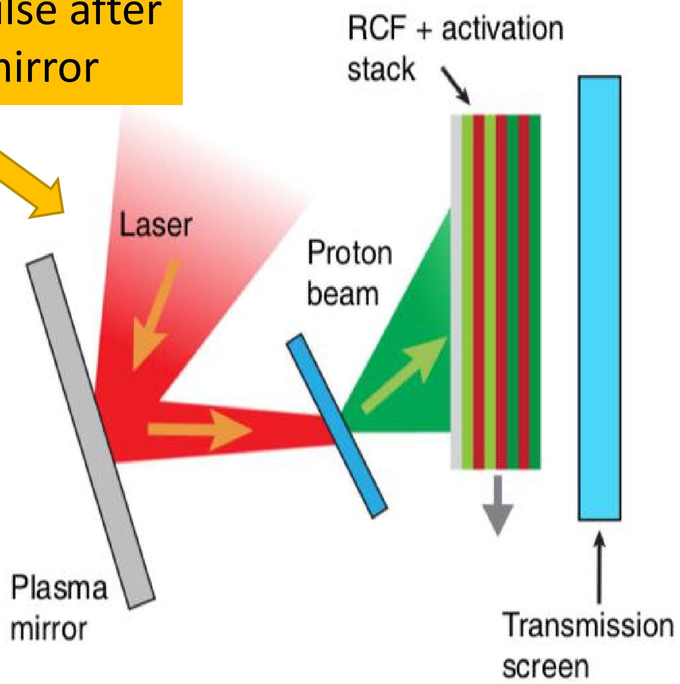
A. Macchi Rev Mod Phys **85** (2), 751-793 (2013).

# Recent experimental results in RPA regime

☐ long pulses

- 210 J, 1ps, 100nm plastic targets
  - $E_{max}$: 94MeV

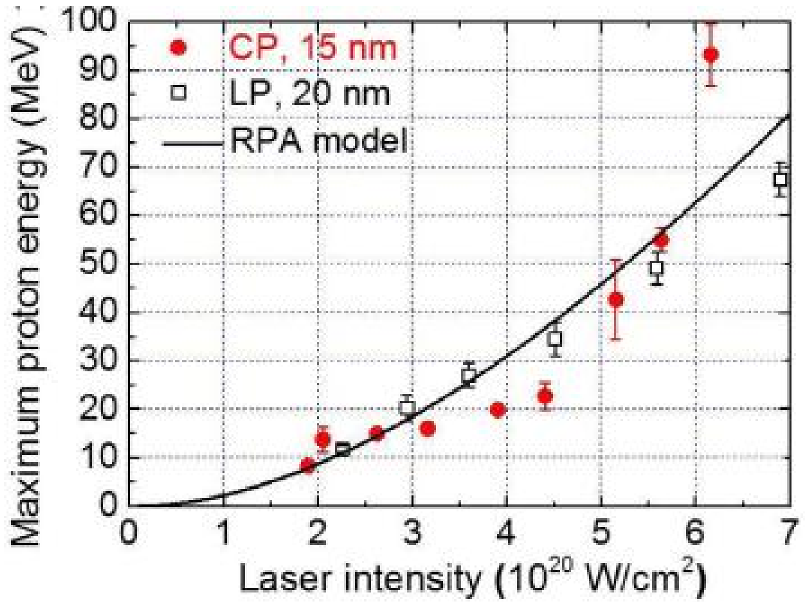
high-contrast pulse after the plasma mirror



A. Higginson et.al. Nature communication 9:724 (2018)

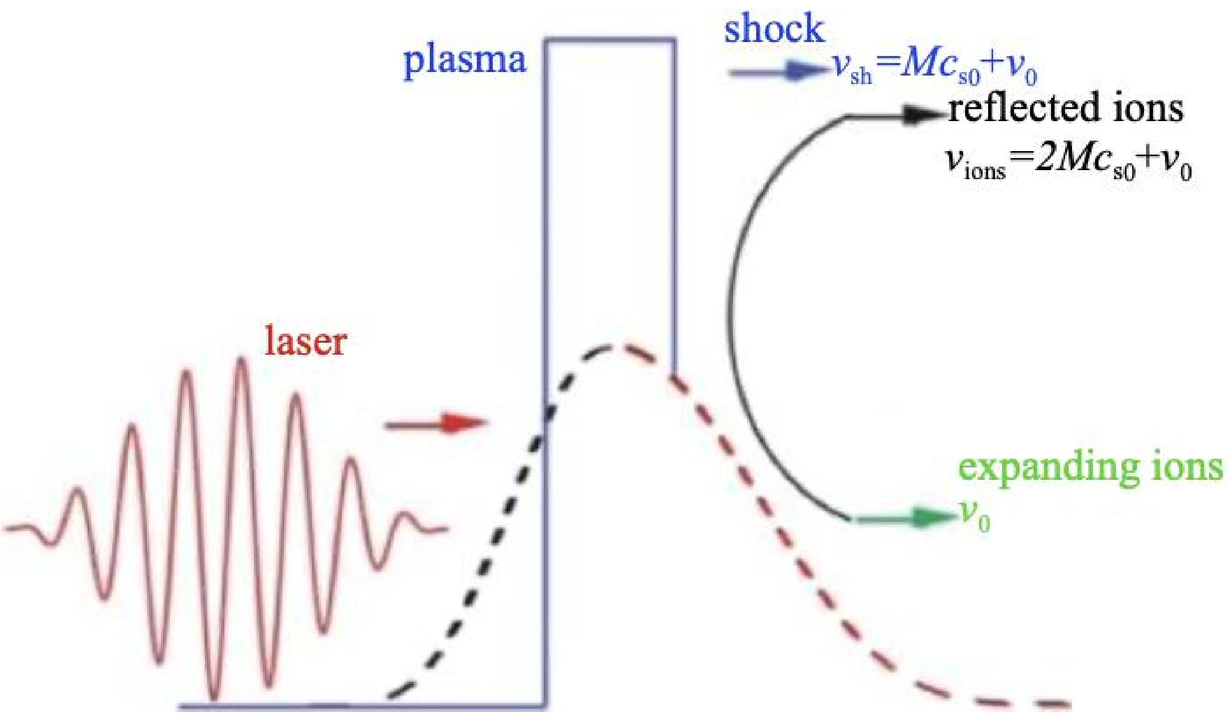
☐ short pulses

- 8.5 J, 30fs， 20nm plastic targets
  - $E_{max}$: 93MeV



Kim IJ, et al. Phys Plasmas. 23(7):6 (2016).

# Collisionless electrostatic shock acceleration (CES)



✓Laser plasma interaction leads to the pileup of the electrons, forming a shock with speed of $Mc_s$

✓Ions ahead of the shock are reflected in the electrostatic shock can gain a speed of $2Mc_s$

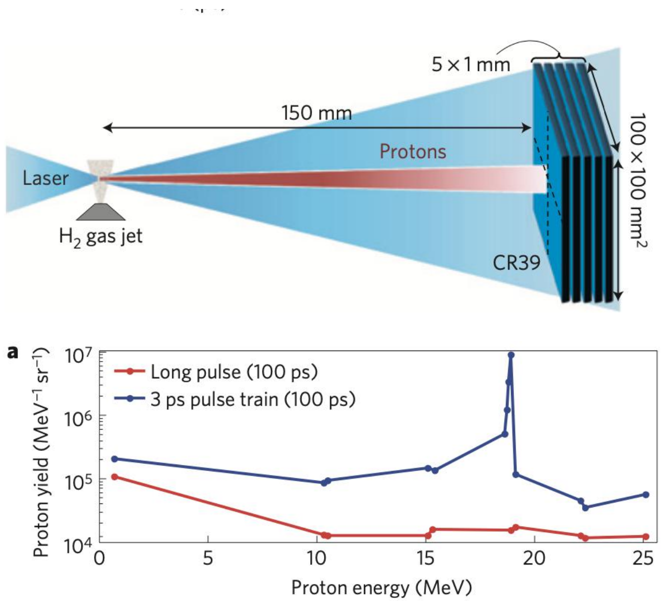
✓monoenergetic ions can be generated if the shock is stable

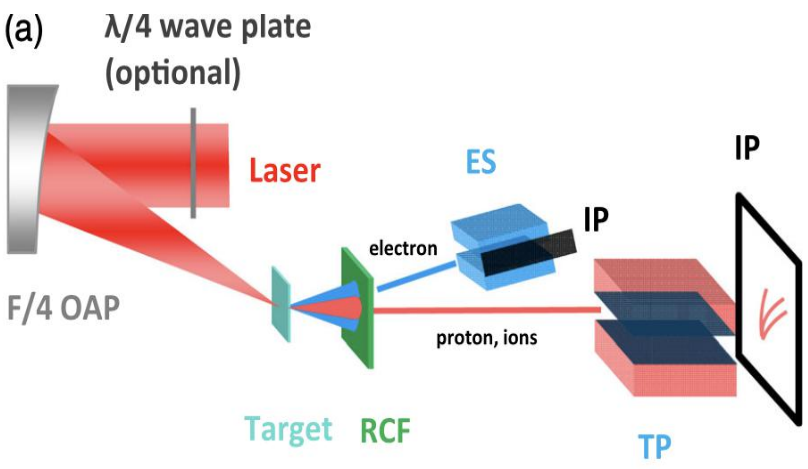
# Experimental results in CES regime

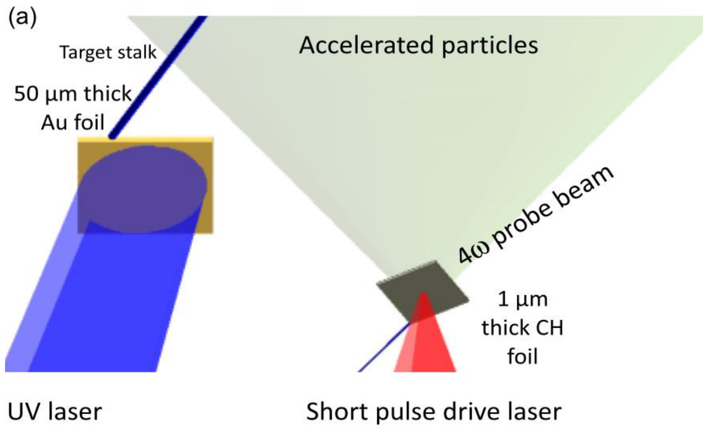
- 60 J, 3ps $CO_2$ laser, $H_2$ targets
- 22 MeV monoenergetic protons

- 13J, 55fs, expanded thin foils
- 9MeV monoenergetic protons

- 500J, 500fs, expanded thin foils
- 50MeV monoenergetic protons





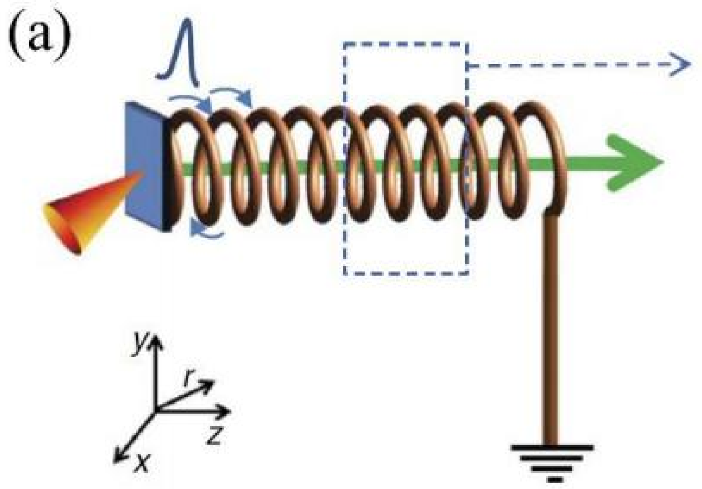


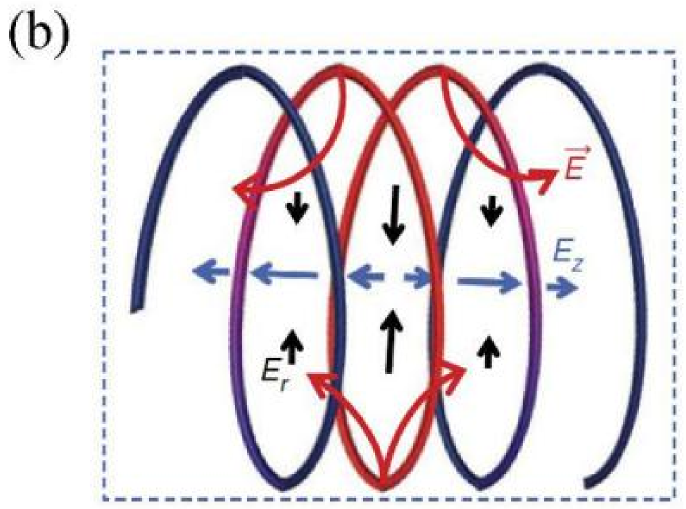
Nat Phys **8** (1), 95 (2012)

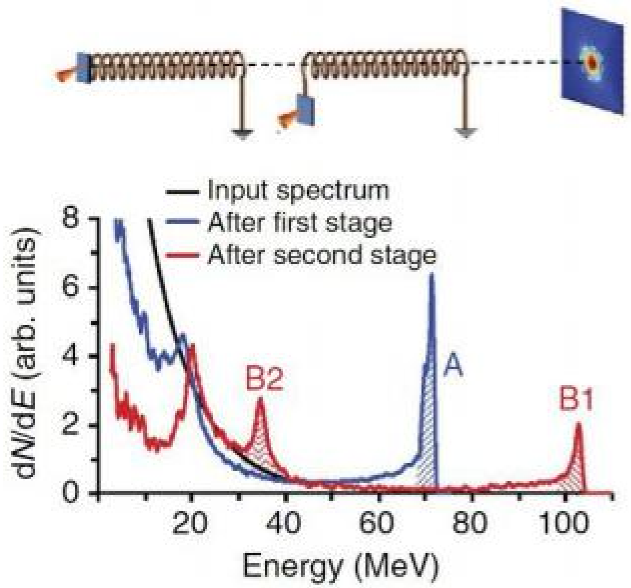
Phys Rev Lett **119** (16) (2017)

Phys Plasmas. **27** 083102 (2020)

# Post acceleration with helical coils







- ✓ laser-excited electromagnetic pulses directed along a helical coil behind the target work as a miniature linear accelerating module to post accelerate the protons
- ✓ The acceleration gradient is 0.5 GeV/m, beyond conventional accelerators
- ✓ Cascaded acceleration is possible by using multiple coils

S. Kar, et al. Nature Communications **7**, 7 (2016).

# Outline

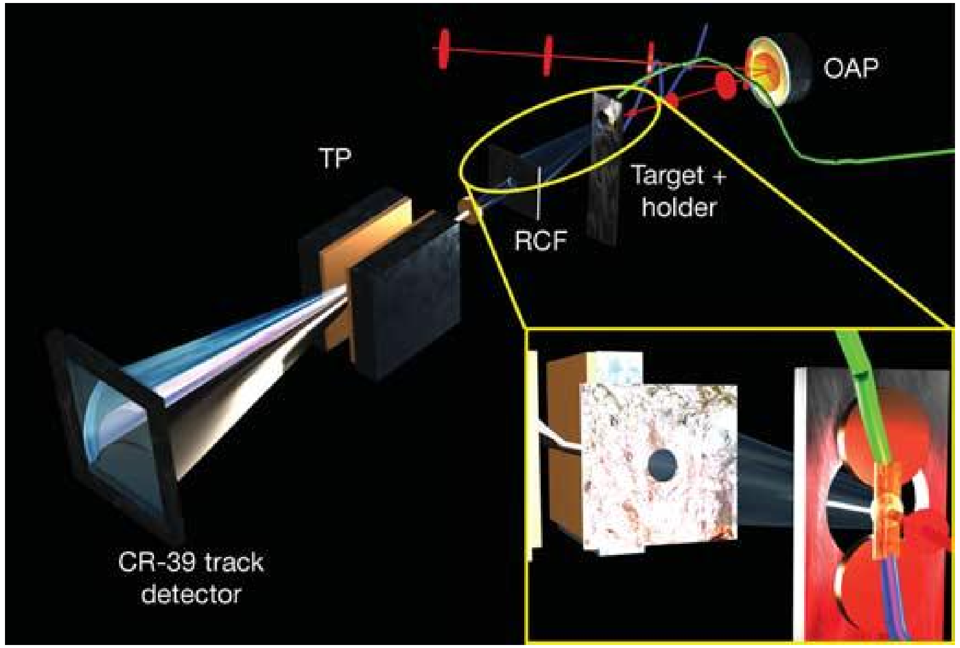
- ☐ Major acceleration schemes and recent progress of high-energy proton acceleration

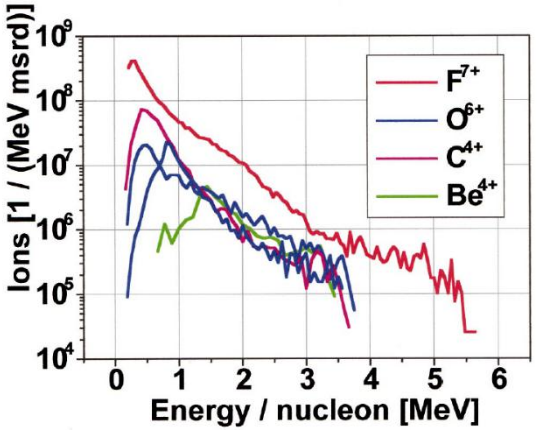
- ☐ Progress of the laser-driven heavy ion acceleration

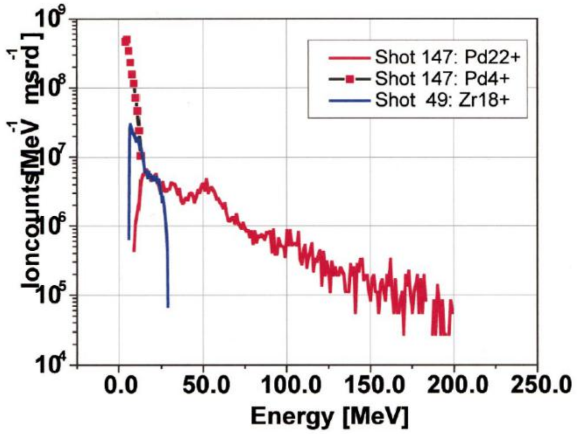
- ☐ laser ion acceleration in Peking University

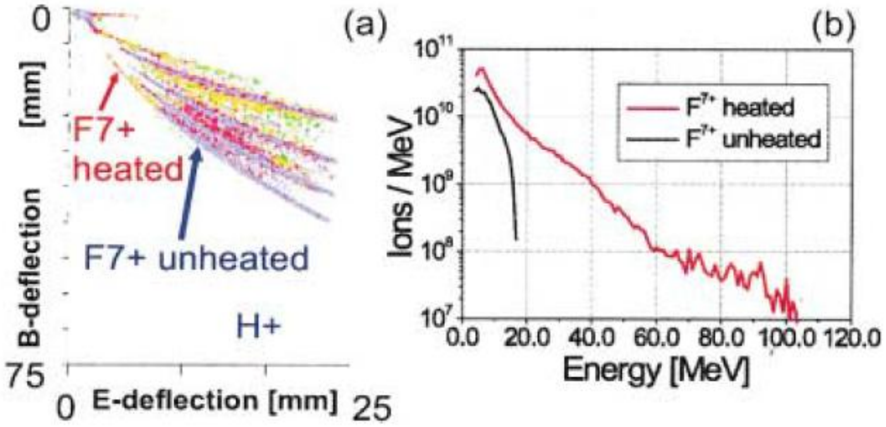
# Early heavy ion acceleration results

- **TNSA acceleration by removing the protons**
  - >1 MeV/u Be, C, O, F, Pd
  - 5 MeV/u F



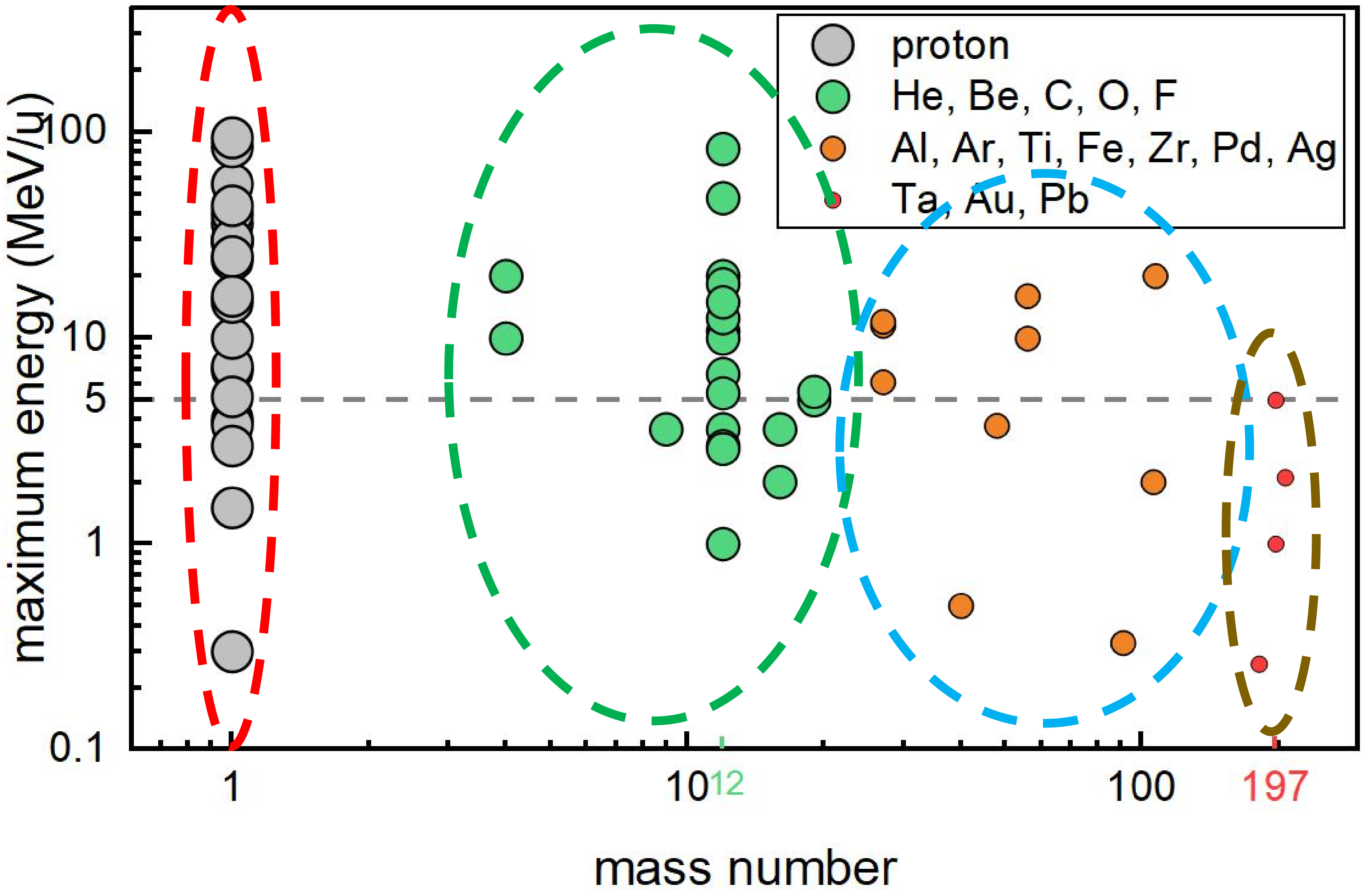






Hegelich et al,. Physical review letters 89 : 085002 (2002)
Hegelich et al,. POP 12, 056314 (2005)
Hegelich et al. Nature 439: 441(2006)
Schreiber et al. Physical Review Letters 97: 045005 (2006).

# A review on heavy ion acceleration (2020)

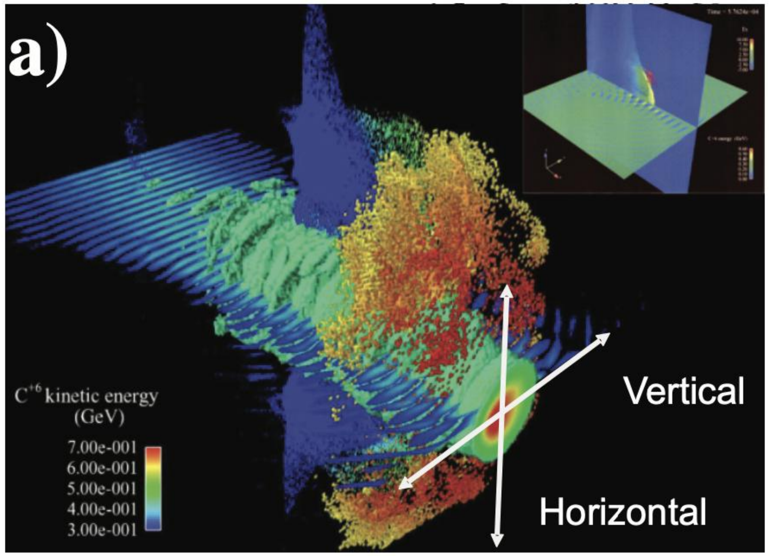


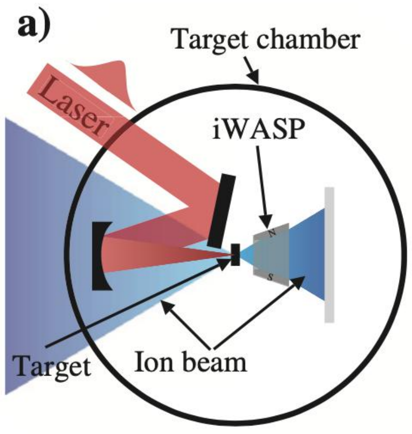
**Difficulties for HIA:**

- ✓ Low charge to mass ratio
- ✓ Hard to ionize to high charge states
- ✓ Mismatch between the injection and acceleration
- ✓ Longer acceleration time needed
- ✓ Suppression from accelerated protons

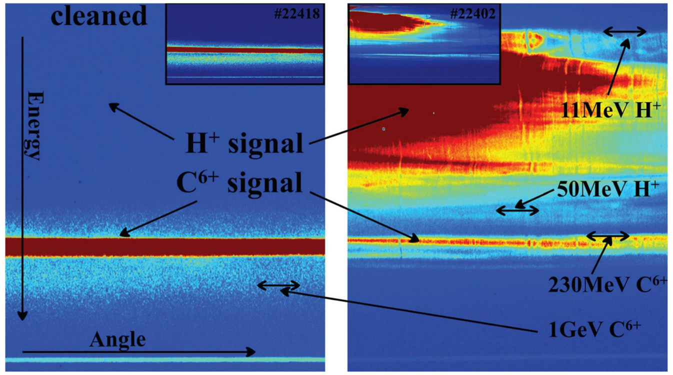
# Carbon acceleration with long pulses

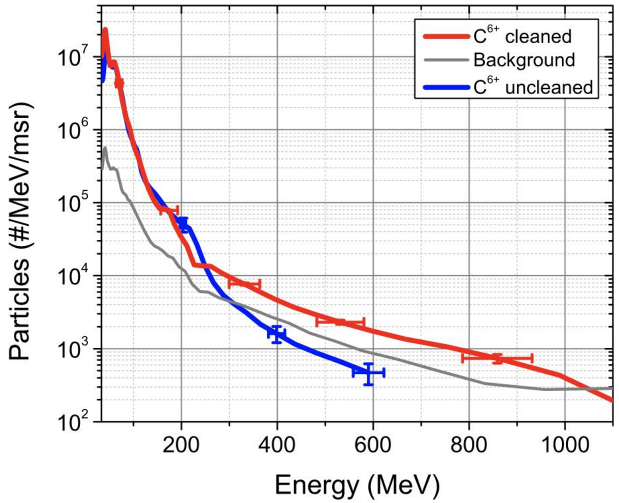
- Breakout Afterburner (BOA) regime





D. Jung et al. New Journal of Physics 15.(2013).



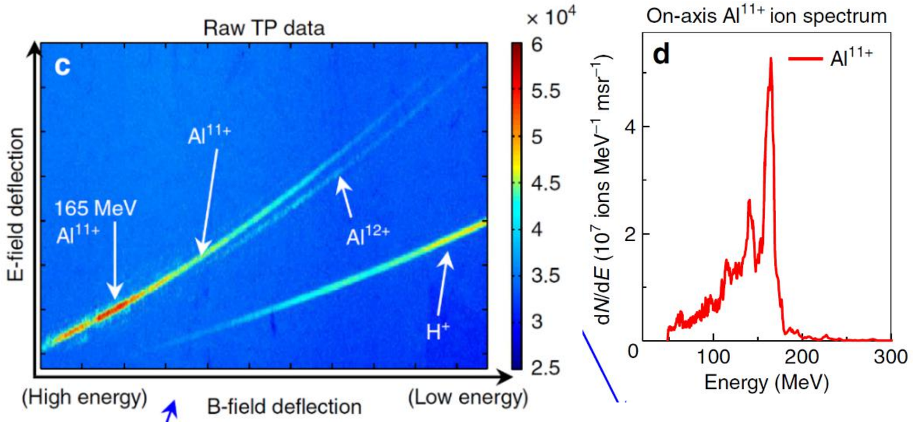


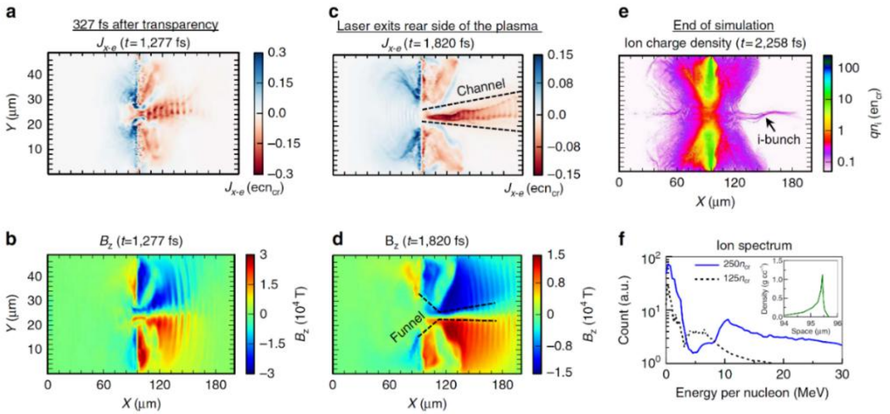
◆ 1 GeV carbon

D. Jung et al. Physics of Plasmas 20(8): 083103.(2013).

# Mid-Z ions acceleration (Al, Fe, Ag...)

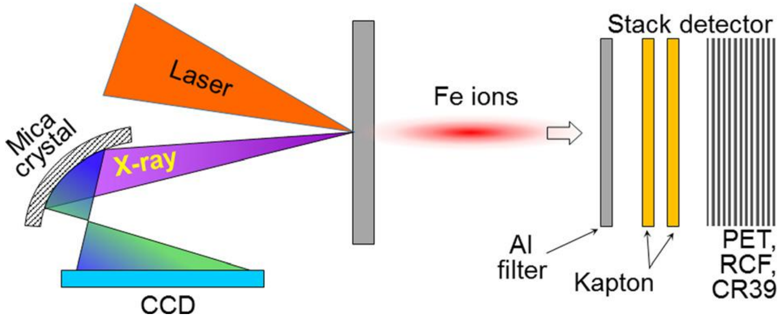
- Relativistic transparency regime

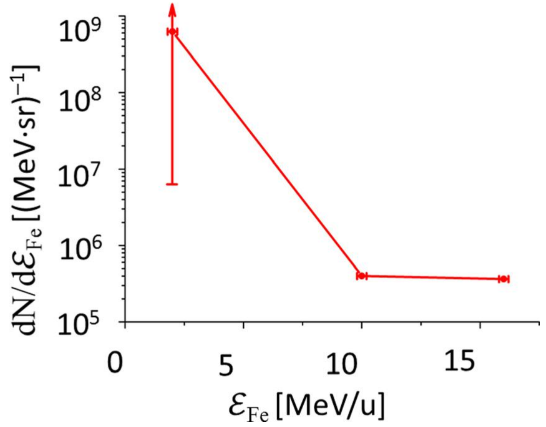




◆ 80J,650fs， 11.5 MeV/u Al

Palaniyappan, et al. Nature communications 6 (2015): 10170.

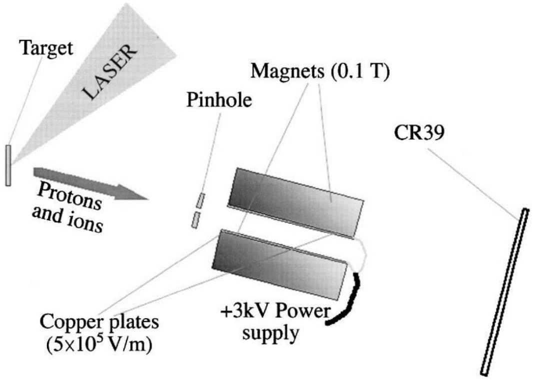


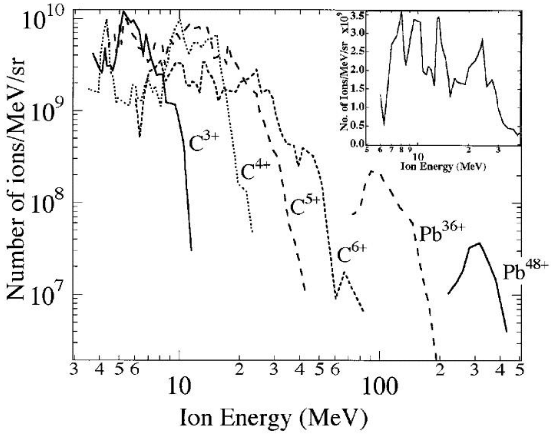


◆ 30 fs, 16 MeV/u Fe

Nishiuchi, M., et al. Phys. Plasmas 22, 033107 (2015)

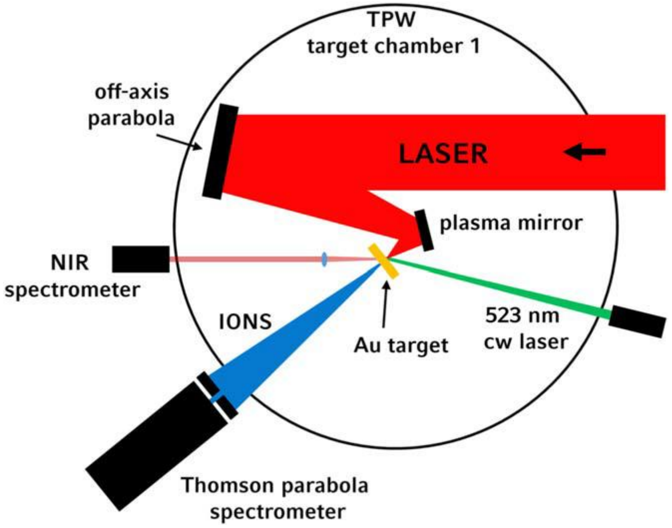
# Supper-heavy ion acceleration with long pulses

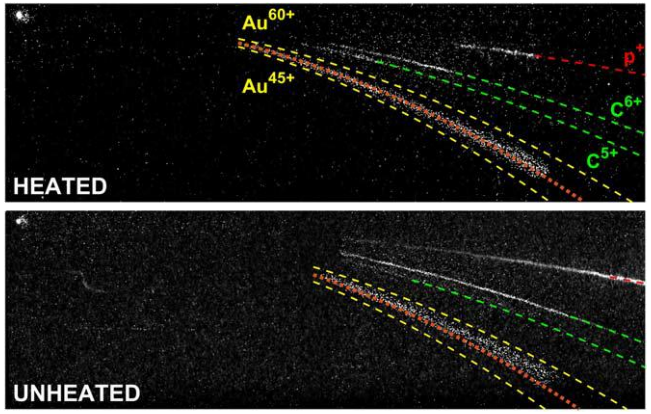


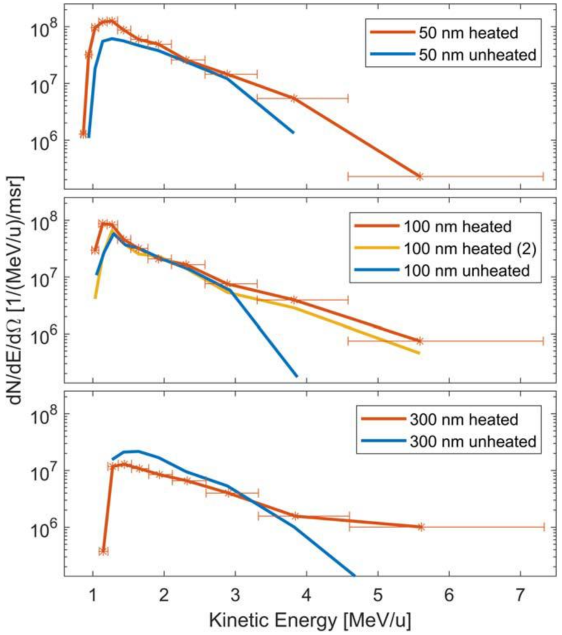


- 900 fs, 50 J
- 2 MeV/u Pb

Clark, et al. Physical Review Letters 85.8 (2000)



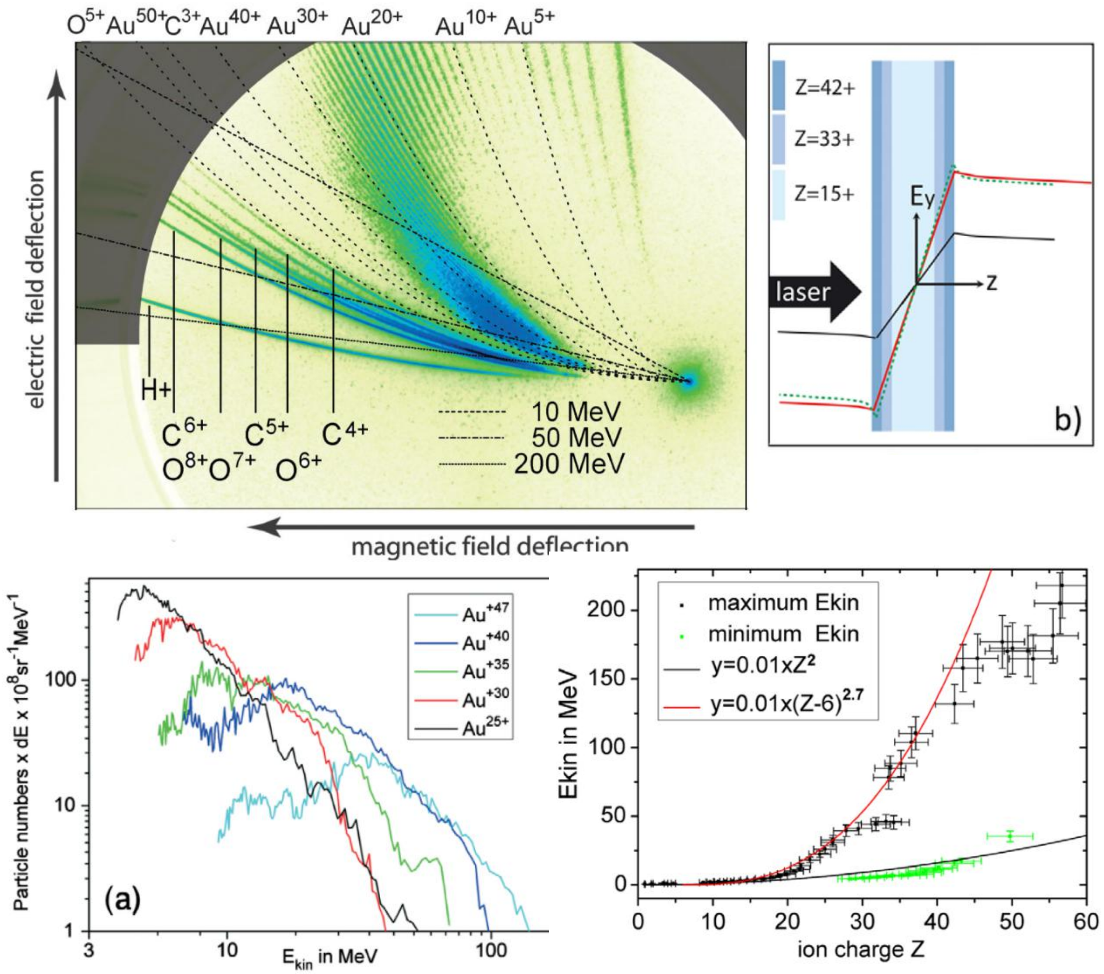




- 140 fs; 110 J
- 5 MeV/u Au

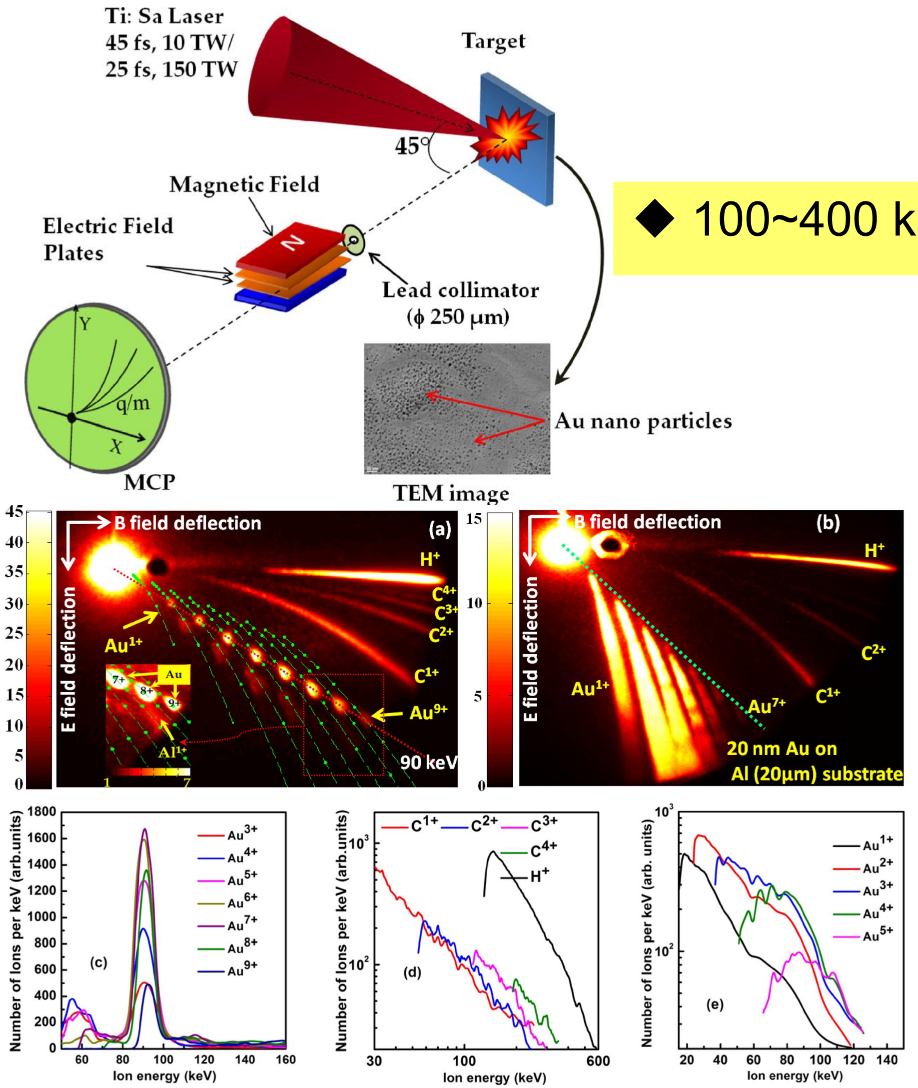
Lindner, et al. Plasma Phys. Control. Fusion 61 055002 (2019)

# Supper-heavy ion acceleration with short pulses



◆ 1 MeV/u Au, ~1.3J, 30 fs

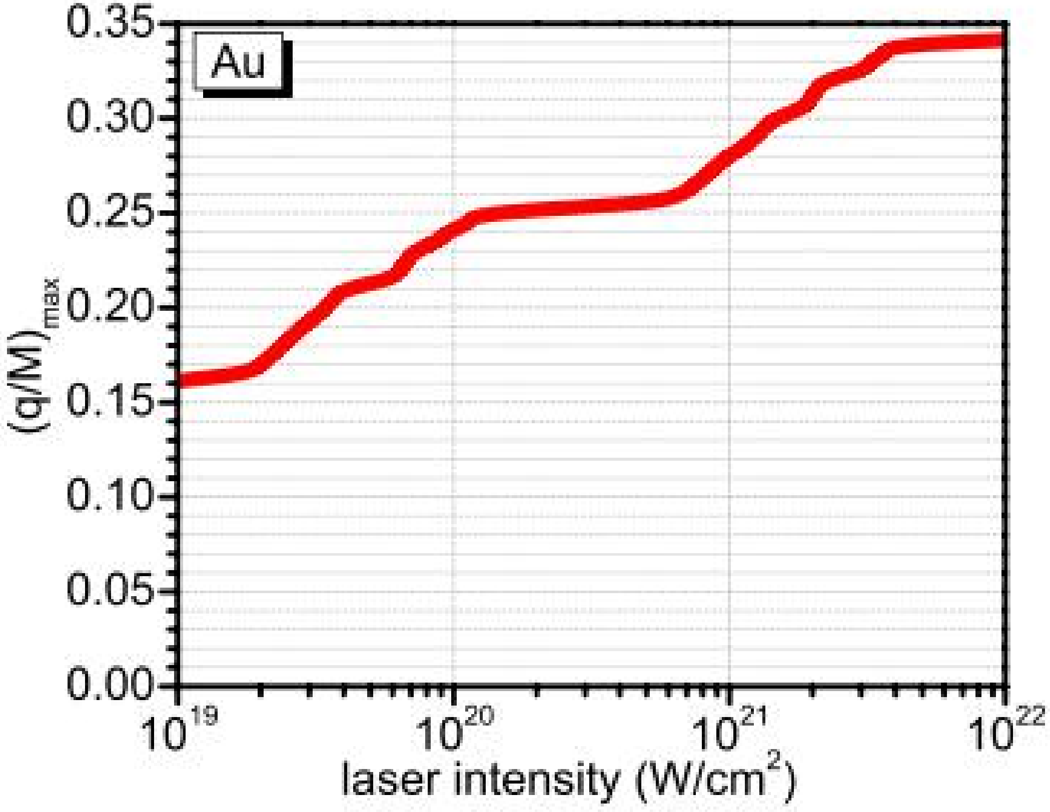
Braenzel,et al. Physical Review Letters 114, 124801 (2015)



◆ 100~400 keV Au

Tayyab, et al. Physics of Plasmas 25, 123102 (2018)

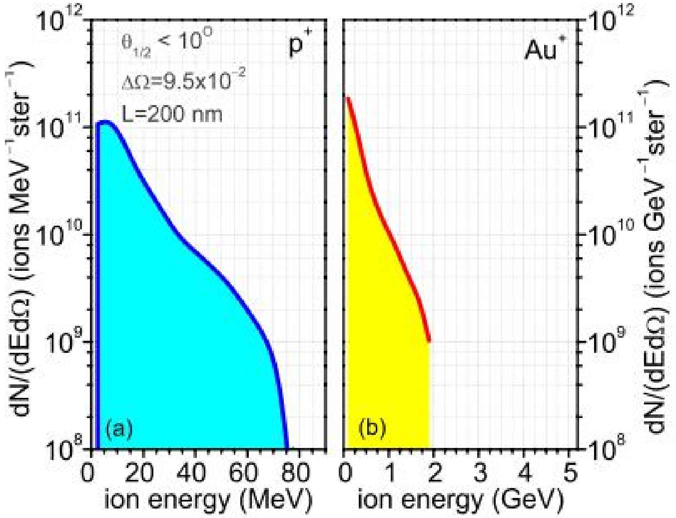
# Supper-heavy ion acceleration at ultrahigh intensity



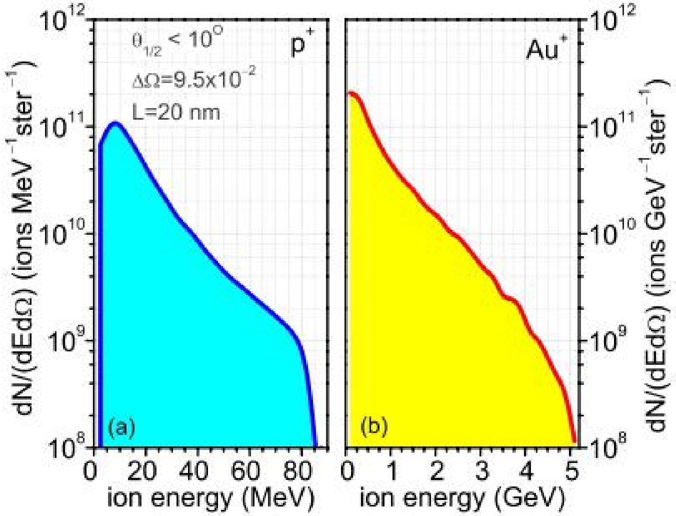
G. M. Petrov et al., Phys Plasmas **23** (6) (2016).

Simulation results at $I=3\times10^{21}W/cm^2$

- TNSA scheme
  200 nm Au,
  2GeV



- RPA scheme
  20 nm Au
  5GeV



# Outline

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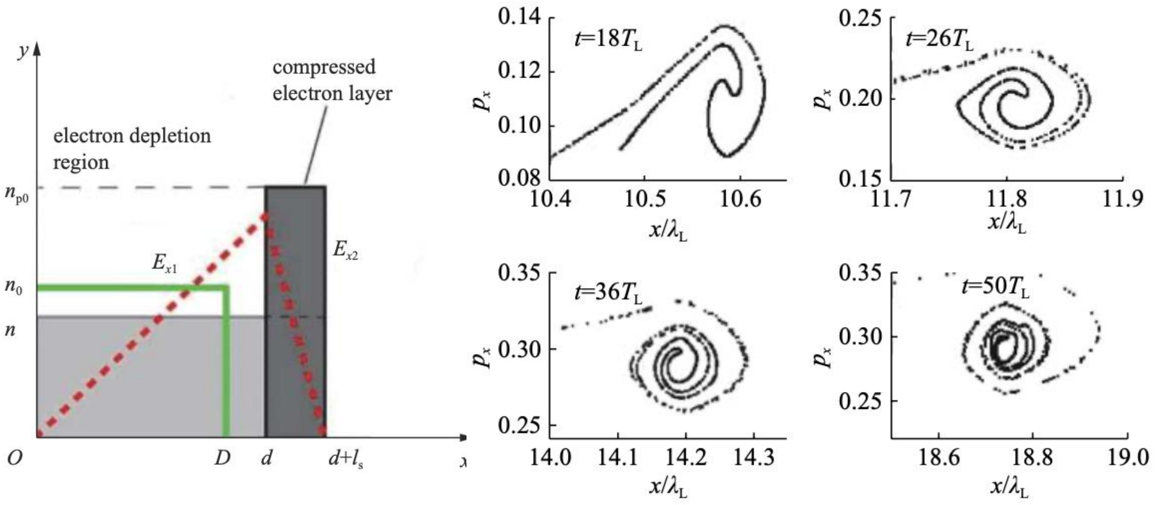
- ☐ laser ion acceleration in Peking University

# Lab of compact laser particle accelerator (CLAPA)

- directed by Prof. Xueqing Yan, currently 4 PIs, 6 postdoc, 8 staffs, >30 students

# Theoretical works on laser acceleration (Prof. Yan)

☐ Phase-stable radiation pressure acceleration



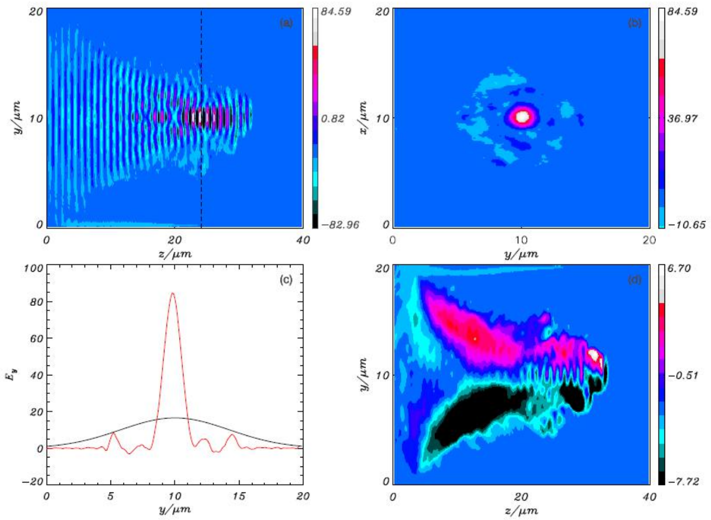
Phys Rev Lett **100,** 135003 (2008)

Phys Rev Lett **103** , 135001(2009).

Appl Phys B-Lasers O **98** (4), 711 (2010).

Phys Rev Lett **103** , 245003 (2009)

☐ Plasma lens enhanced ion acceleration



Phys Rev Lett **107**, 265002 (2011)

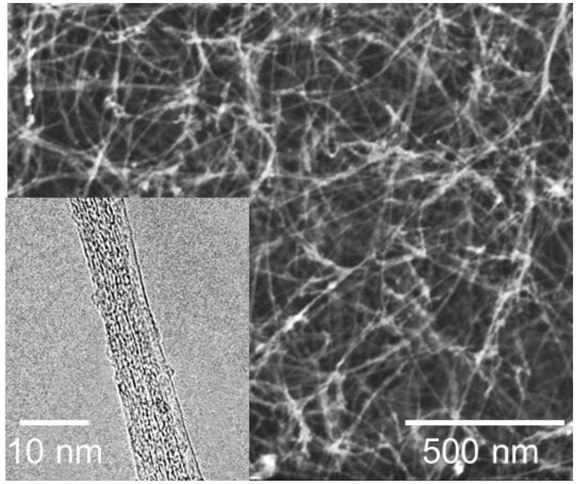
Phys Plasmas **20**, 13101 (2013)

Phys Plasmas **22** , 073106 (2015)

Phys Plasmas **23,** 083109 (2016)

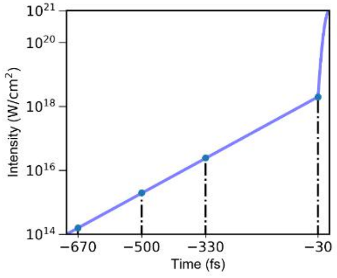
Scientific Reports **8**, 2536 (2018)

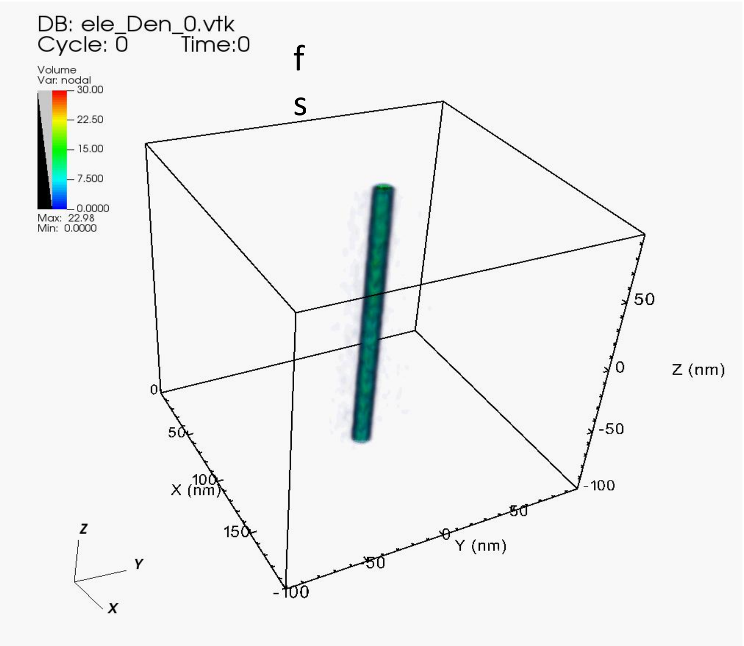
# Carbon nanotube foams：ideal near-critical-density targets

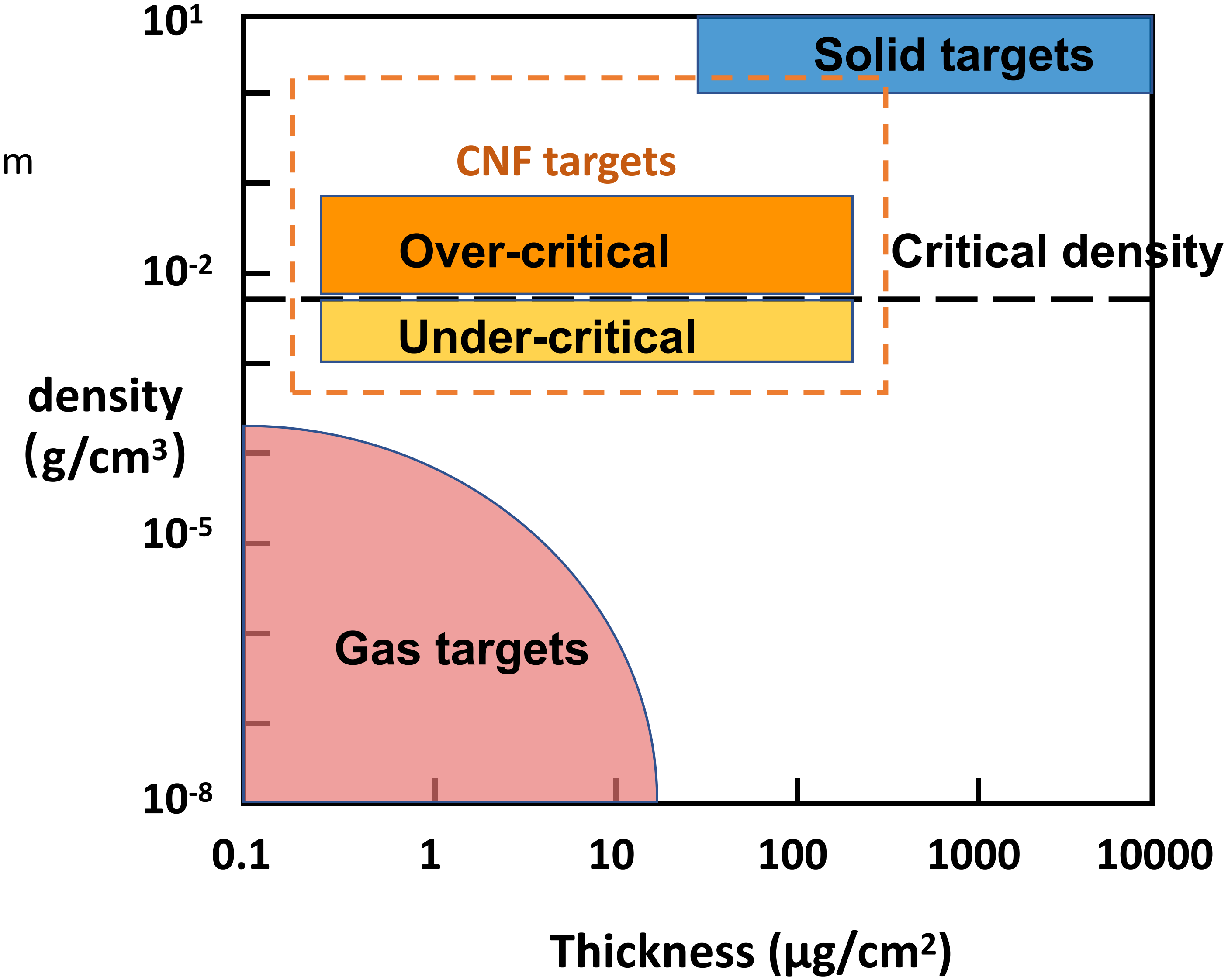


- ✓ diameter: ~10nm
- ✓ interspacing: 50-100nm

W.J. Ma *et. al.*Nano Letters 2007, 7 (8), 2307



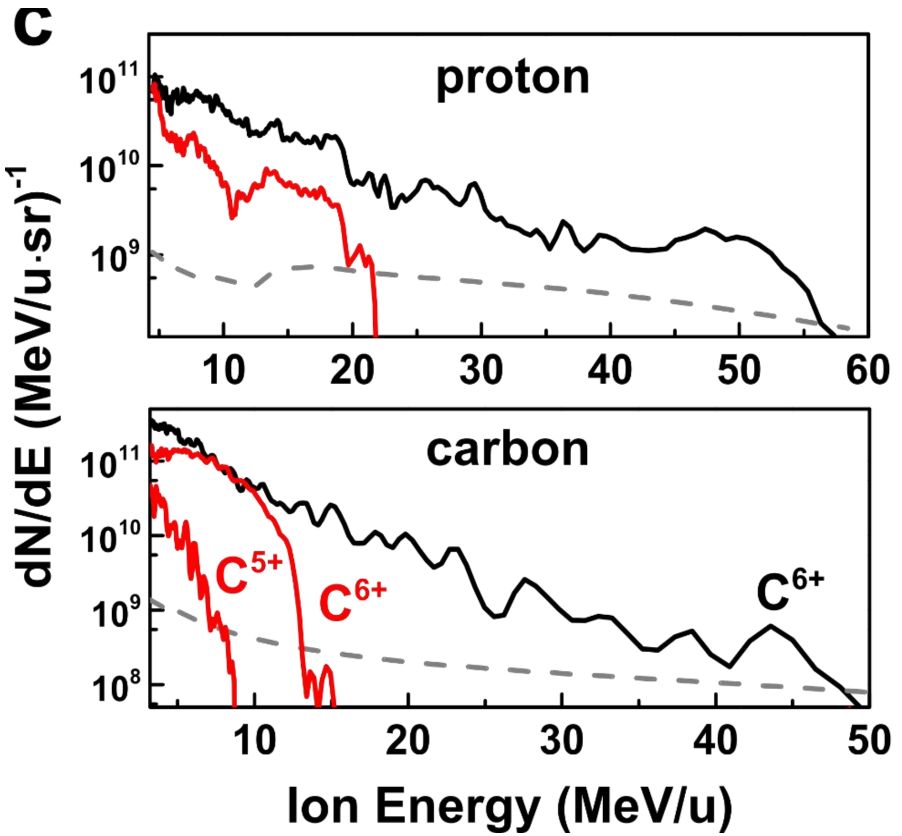




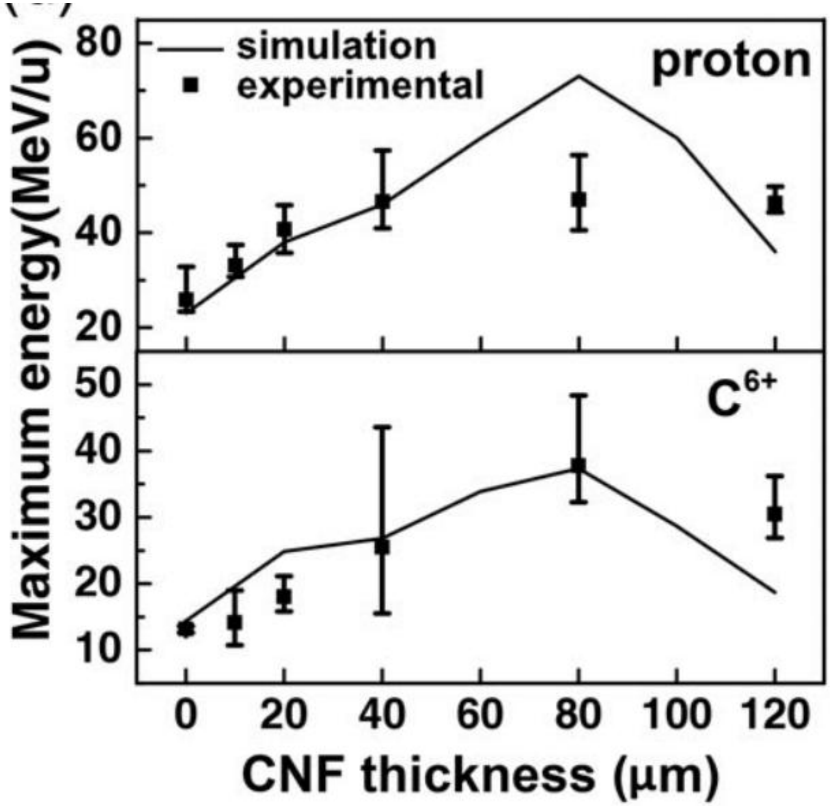
# Enhanced ion acceleration utilizing CNF targets

We generated 580 MeV (48 MeV/u) carbon ions (2.5 times of previous record ) by using CNF double-layer targets at intensity of 5×$10^{20}$ W/$cm^2$

- Ion spectra



- Parameter scan

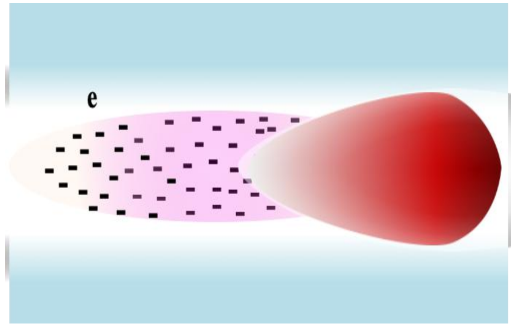


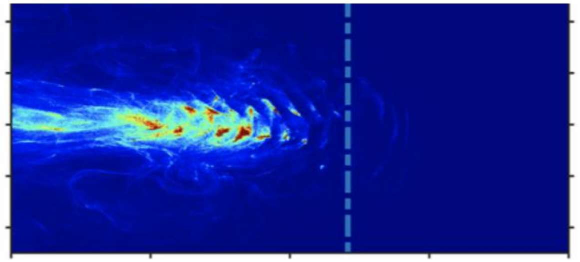
Ma, W. J., et al. *Physical Review Letters* **122**: 014803. (2019)

# Cascaded ion acceleration in CNF double-layer targets

**Stage I :**

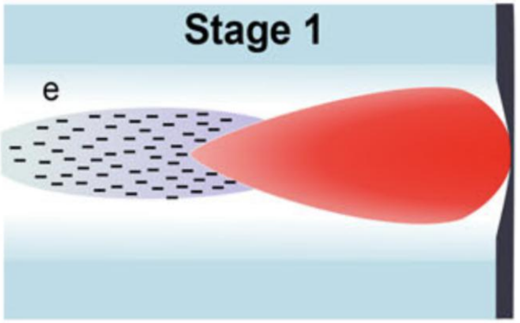
Supperponderonmotive electrons generation in CNF plasma

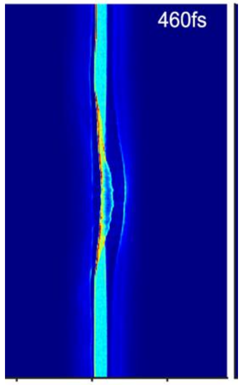




**Stage II :**

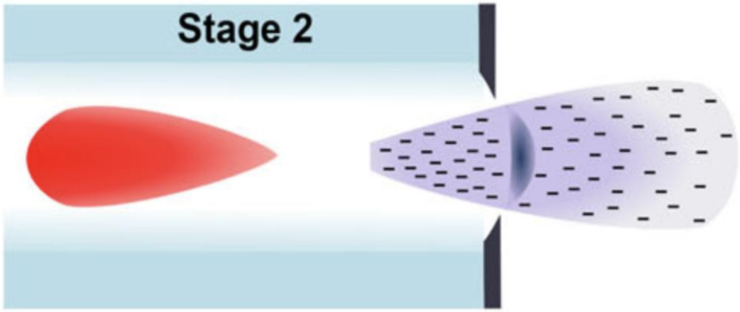
(hole-boring) radiation pressure acceleration

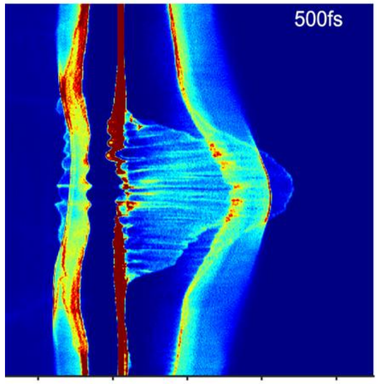




**Stage III :**

Enhanced TNSA acceleration

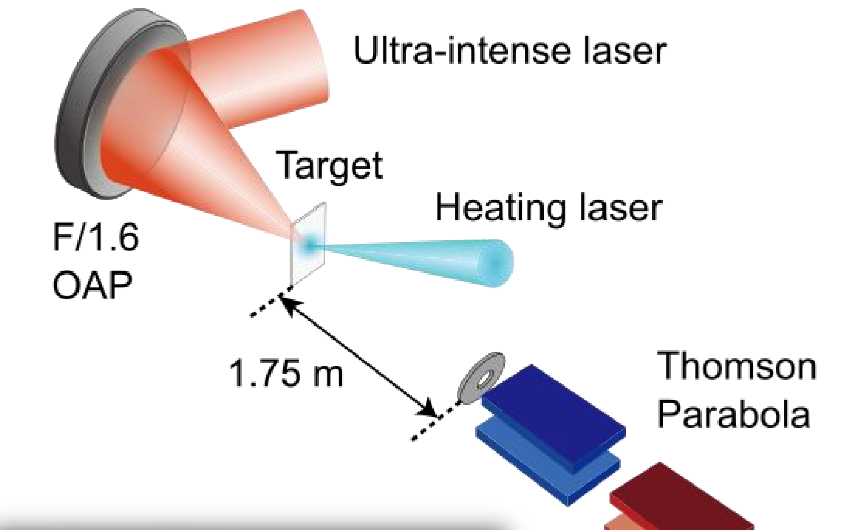


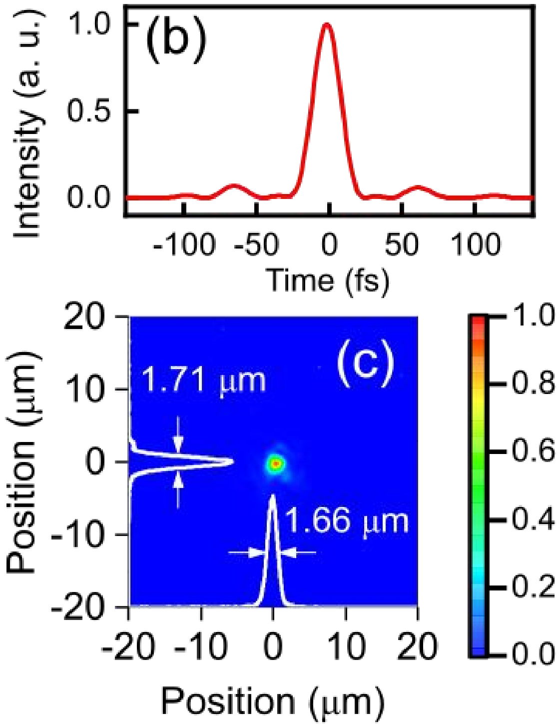


Ma, W. J., et al. *Physical Review Letters* **122**: 014803. (2019)

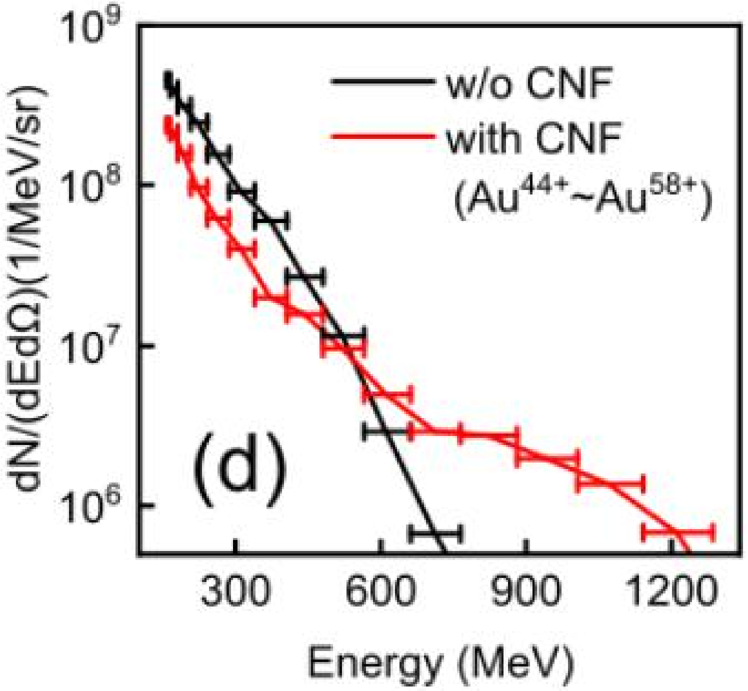
# Generation of 1.2 GeV Au ions at highest intensity

In collaboration with GIST, we generated record 1.2 GeV Au ions with femtosecond laser pulses at intensity of $10^{22}$ W/cm$^2$ by using CNF double-layer targets





☐ Energy spectra of Au ions

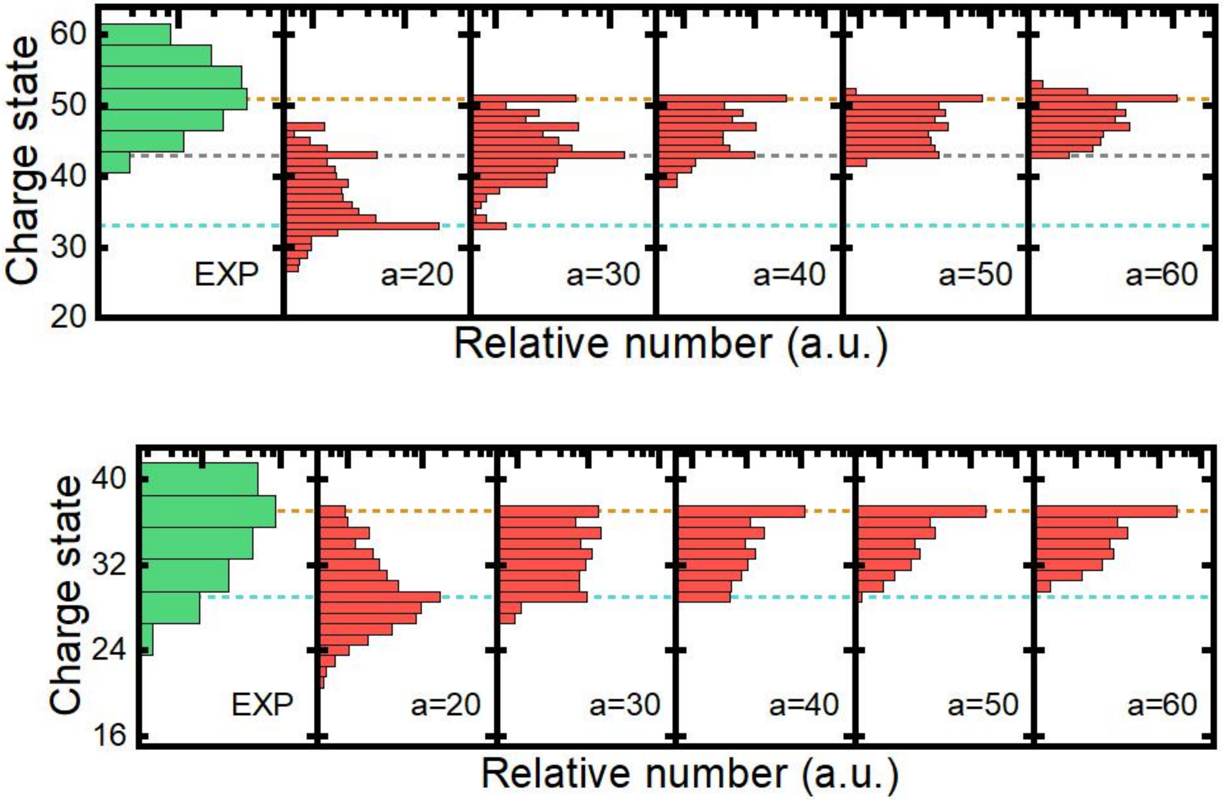


arXiV:2008.09358

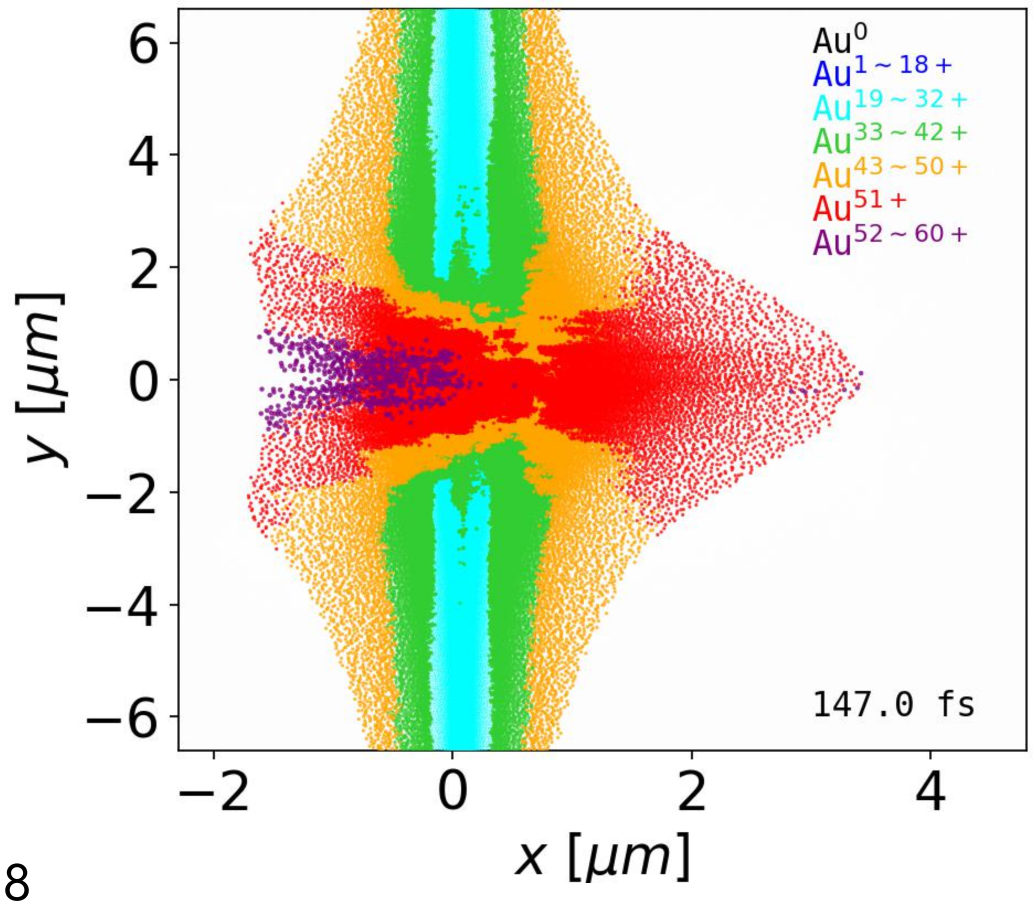
# ionization dynamics in supper-heavy ion acceleration

The measured charge state distribution reveals the ionization dynamics in supper-heavy ion acceleration

☐ Charge state distribution



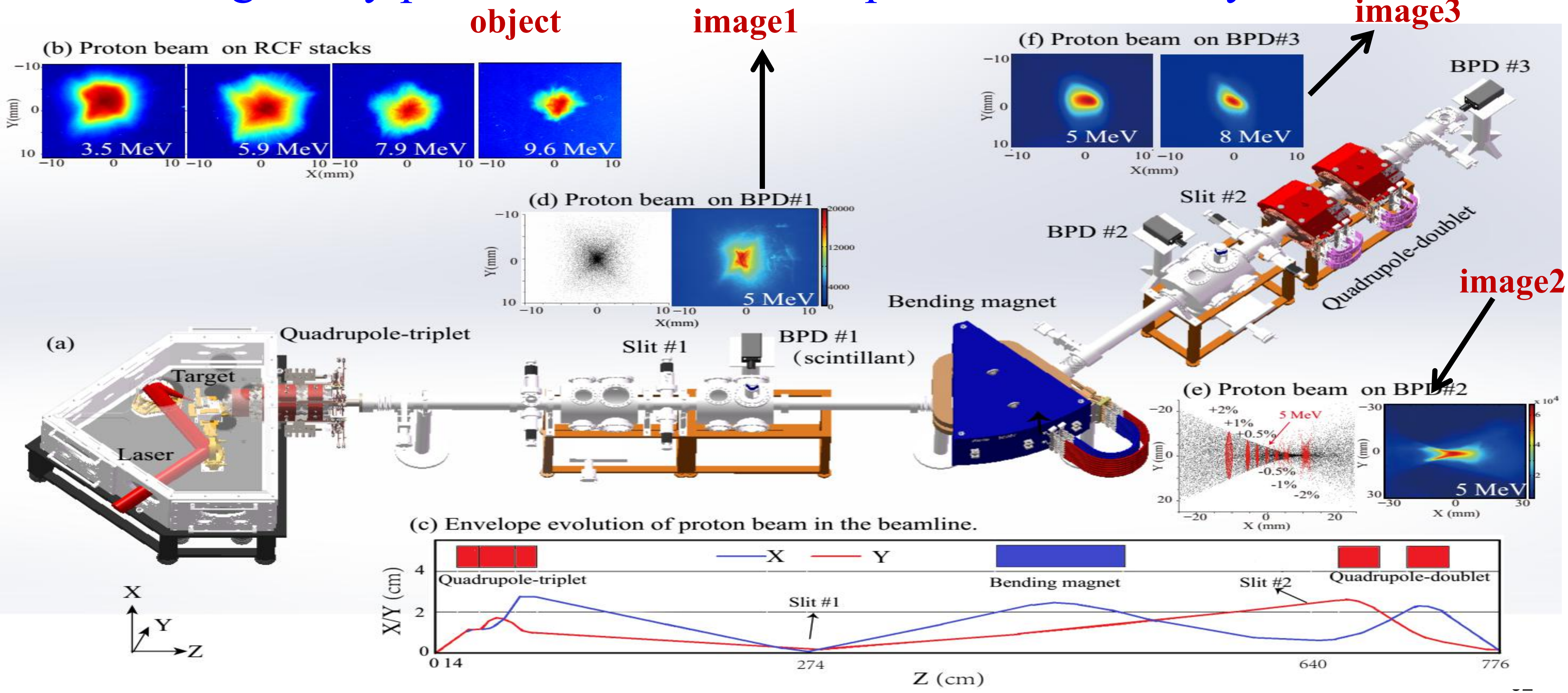
☐ 2D PIC simulation



arXiV:2008.09358

# A compact laser proton accelerator

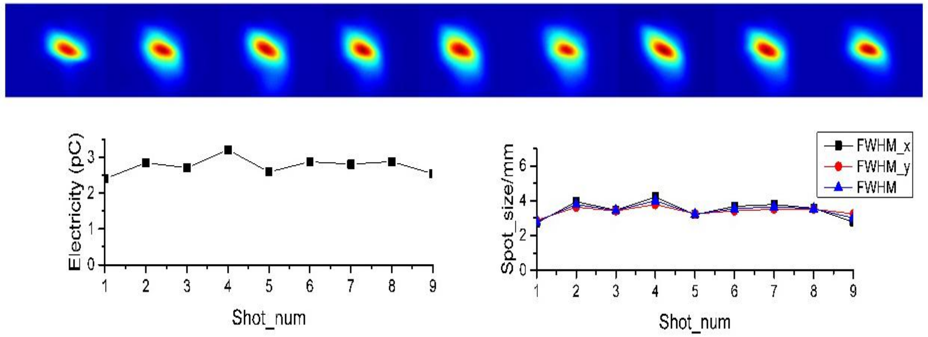
Image relay proton beamline： transportation efficiency ~90%



J.G.Zhu,…, C.Lin*,X.Q.Yan*, PRAB, **22** (6) (2019).

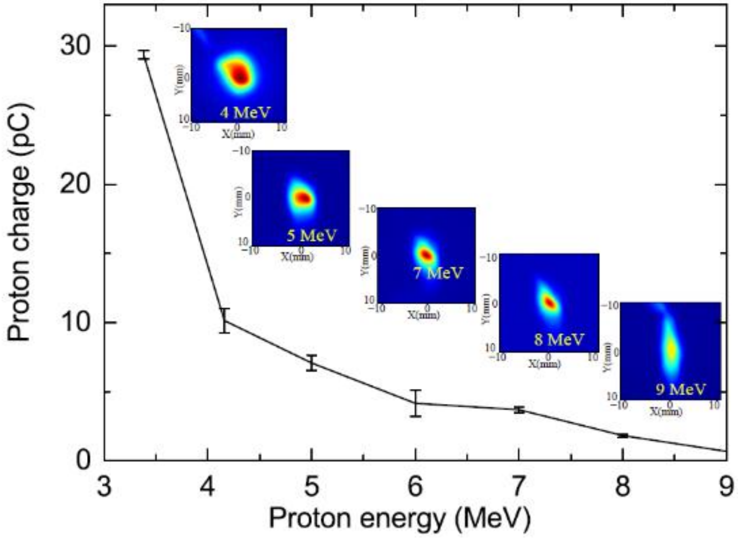
# Stability and controllability of the LPA

- Charge & beam spot stability



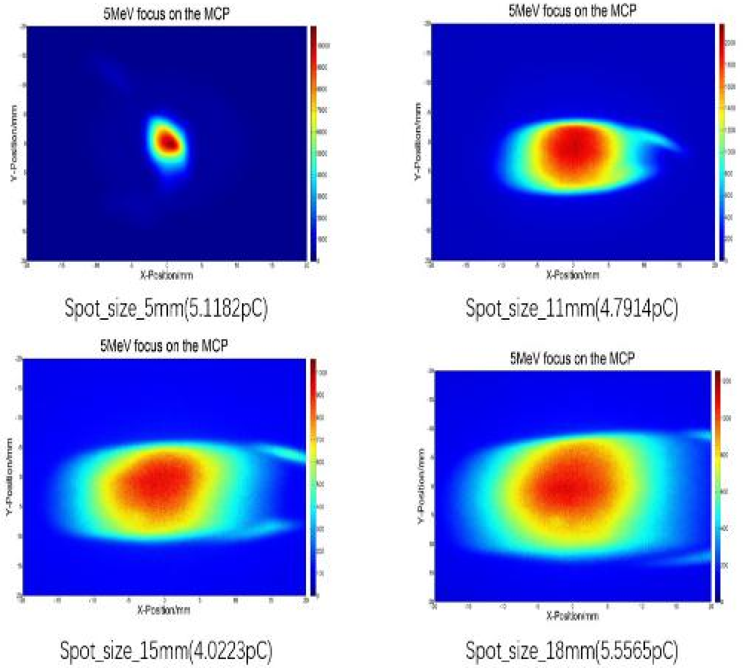
RMS fluctuation <3%

- Energy control



<1 % energy spread

- Beam profile control



Spot_size_5mm(5.1182pC)

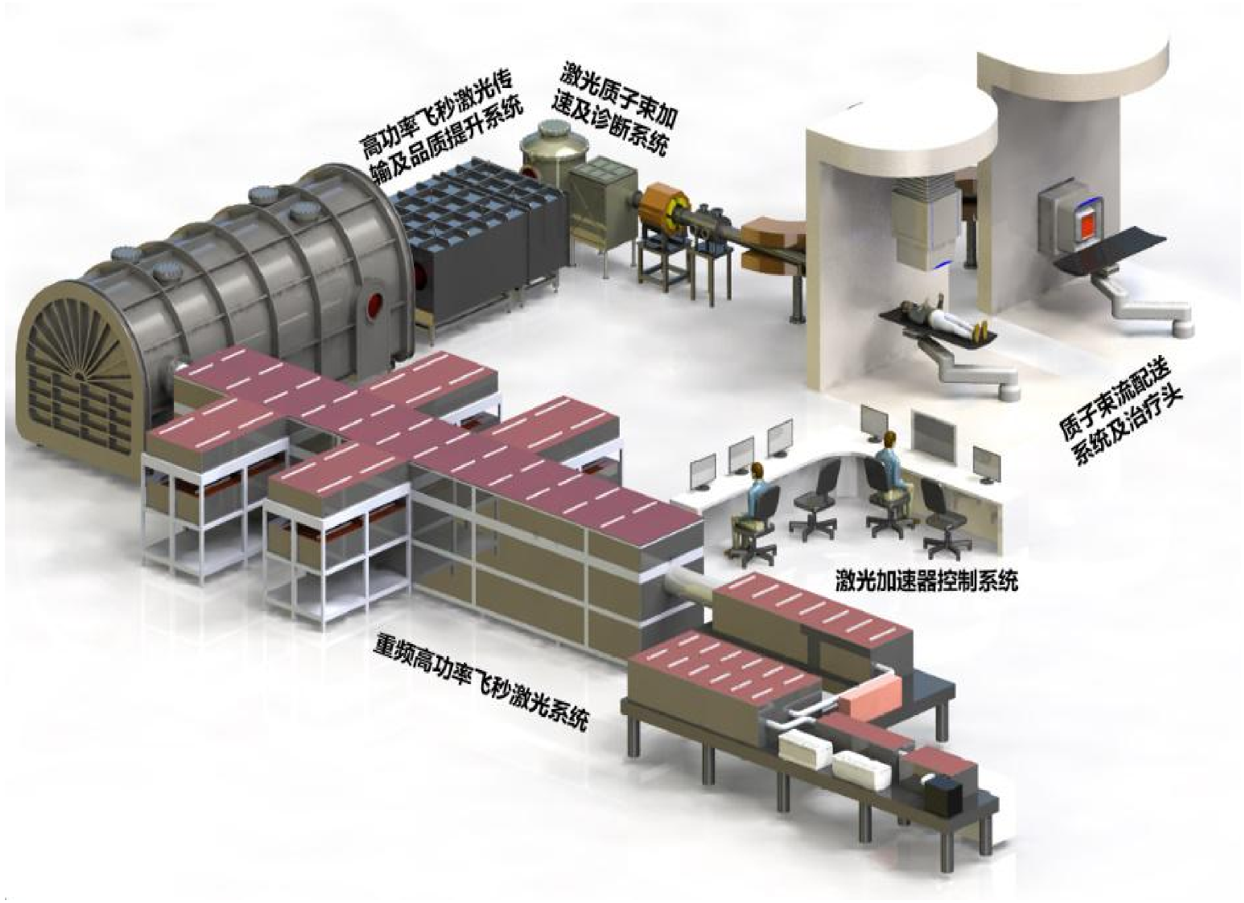
Spot_size_11mm(4.7914pC)

Spot_size_15mm(4.0223pC)

Spot_size_18mm(5.5565pC)

J.G.Zhu,…, C.Lin*,X.Q.Yan*, PRAB, **22** (6) (2019).

# The ongoing project for a laser-proton tumor therapy system



- ☐ Laser : 60 J, 30 fs
- ☐ Experimental hall : 4000 m$^2$

**Phase I（2019-2024）**

Demo system

- ✓ $E_{max} > 100\ MeV$
- ✓ Animal tumor therapy

**Phase II（2024-2026）**

Engineering machine

- ✓ $E_{max} > 150\ MeV$
- ✓ Superficial tumor therapy

**Phase III（2027-2030）**

Commercial system

- ✓ $E_{max} > 200\ MeV$
- ✓ deep tumor therapy

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M. Yeung, B. Dromey,

**Helmholtz institute of Jena (GE):**
M. Zepf, P. Hilz, B. Liu, et al.

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J. Meyer-ter-vehn

# Thank you