Laser-driven Proton Acceleration @ SIOM: Past and Future

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Outline

1) Background

2) Past reach for proton acceleration @ SIOM
   a. Theory
   b. Experiment

3）Future plan for proton acceleration with 5-10 PW and 100 PW lasers

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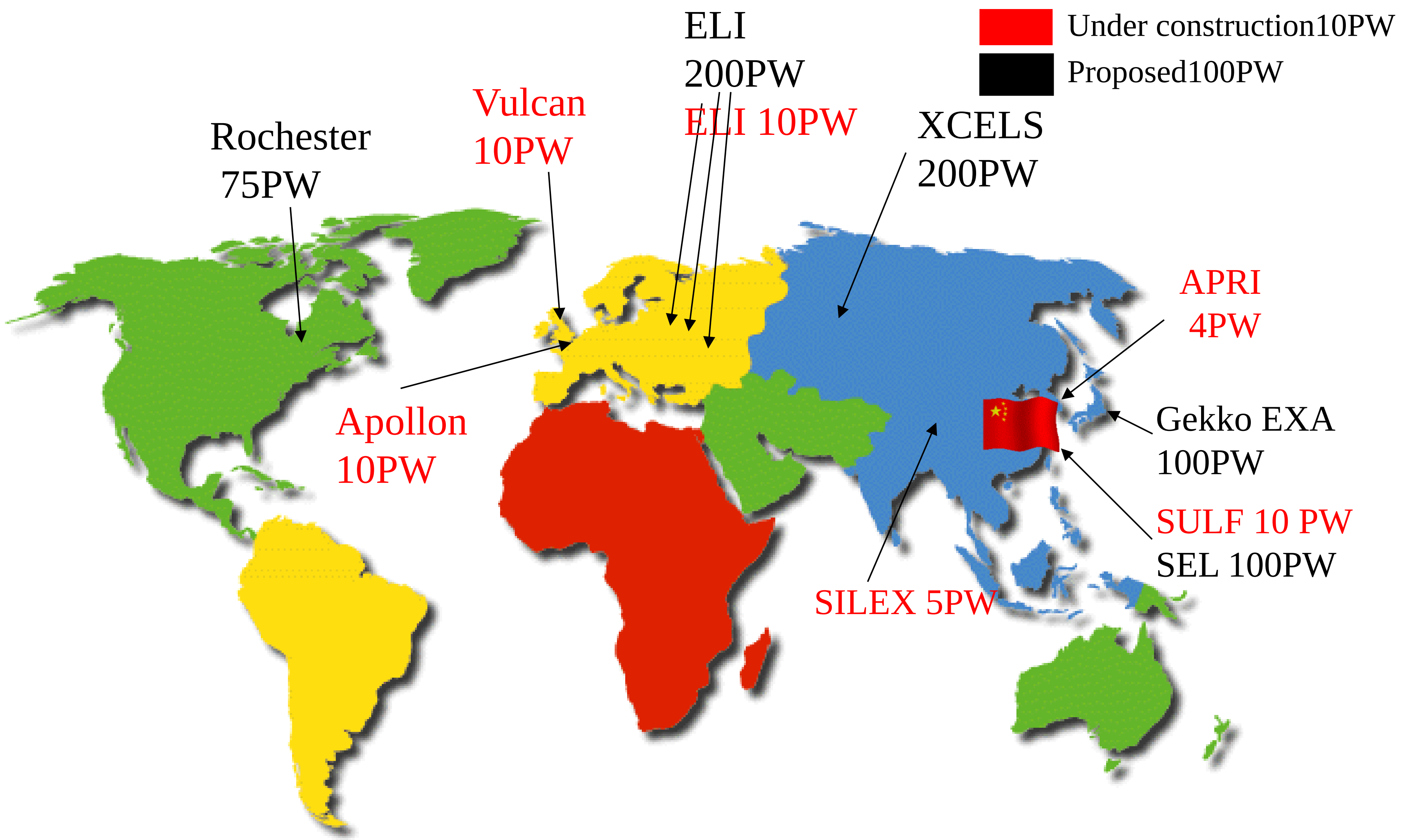
Laser parameters for proton acceleration

$I\lambda^2 = 10^{18}\mathrm{W/cm^2 \mu m^2}$ **Relativistic electrons** **TNSA**

$$\frac{d^2\phi}{d\xi^2} = \frac{v_g}{1-v_g^2}\left(\frac{n_e\Psi_e}{R_e} - \frac{n_{i1}\Psi_{i1}}{R_{i1}} - \frac{n_{i2}\Psi_{i2}}{R_{i2}}\right)$$

$a = \sqrt{m_p / m_e} \approx 43$ **Proton movement is important for wakefield**

$I\lambda^2 = 10^{24}\mathrm{W/cm^2 \mu m^2}$ **Relativistic protons in laser field**



Under construction10PW
Proposed100PW
ELI
200PW
ELI 10PW
Vulcan
10PW
Rochester
75PW
XCELS
200PW
APRI
4PW
Apollon
10PW
Gekko EXA
100PW
SULF 10 PW
SEL 100PW
SILEX 5PW

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PHYSICS OF PLASMAS VOLUME 8, NUMBER 3 MARCH 2001

High-density ($>10^{23}$/cm^3) relativistic electron plasma confined between two laser pulses in a thin foil

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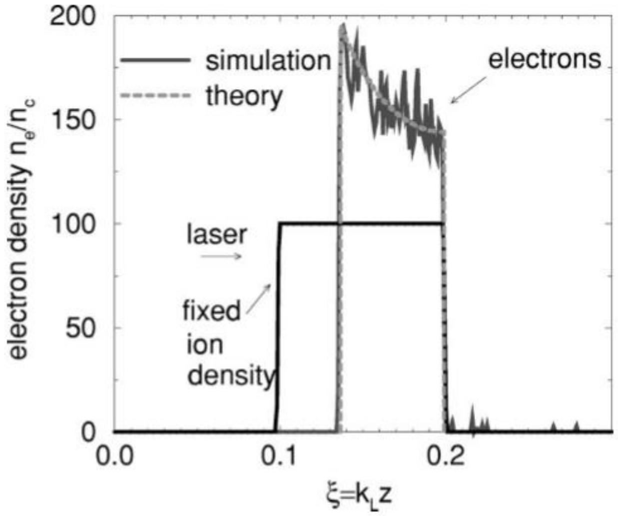
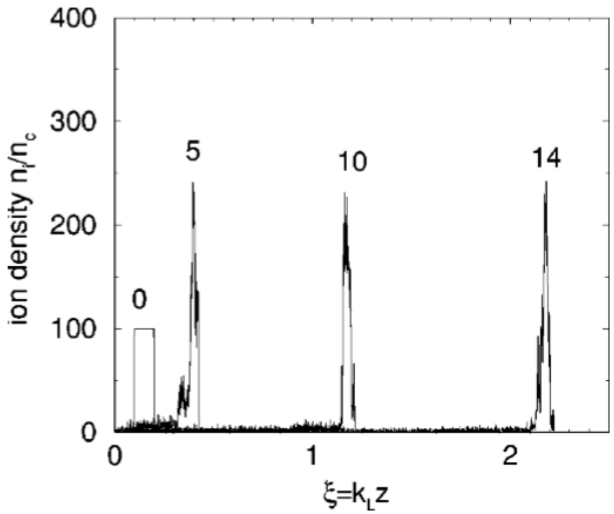
(Received 30 May 2000; accepted 10 November 2000)



Analytical solution was obtained for fixed ions



Thin foil could be pushed forward by laser

Theoretical Research on Proton Acceleration @ SIOM Light pressure acceleration

In 2001, we proposed light pressure acceleration of proton with ultra intense circularly polarized laser pulse.

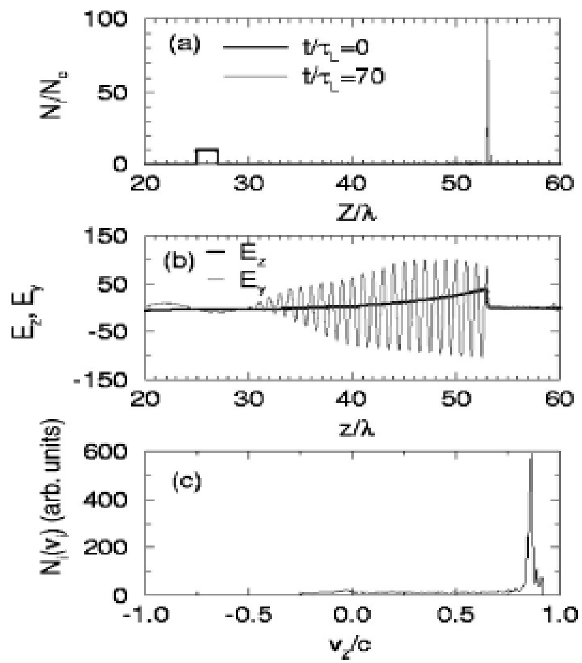
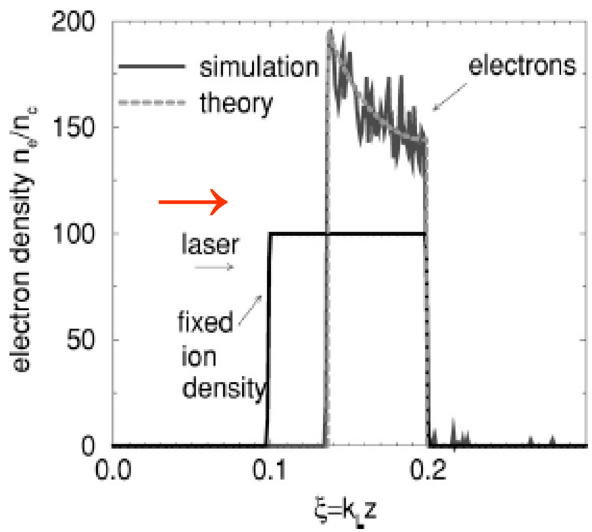


FIG. 6. The ion density distribution (a), normalized laser and static electric field (b), and ion velocity distribution (c) after 70 laser cycles. The plasma layer of density $N_i=10$ and thickness $2\lambda_L$ is initially at $\xi/2\pi=25$. The laser pulse is $a_1=100[\sin(\phi_1)\hat{x}+\cos(\phi_1)\hat{y}]\sin(\phi_1/80)$, $0<\phi_1=\omega_L t-k_L z\leq 80\pi$.



Foil: density n=10n_c

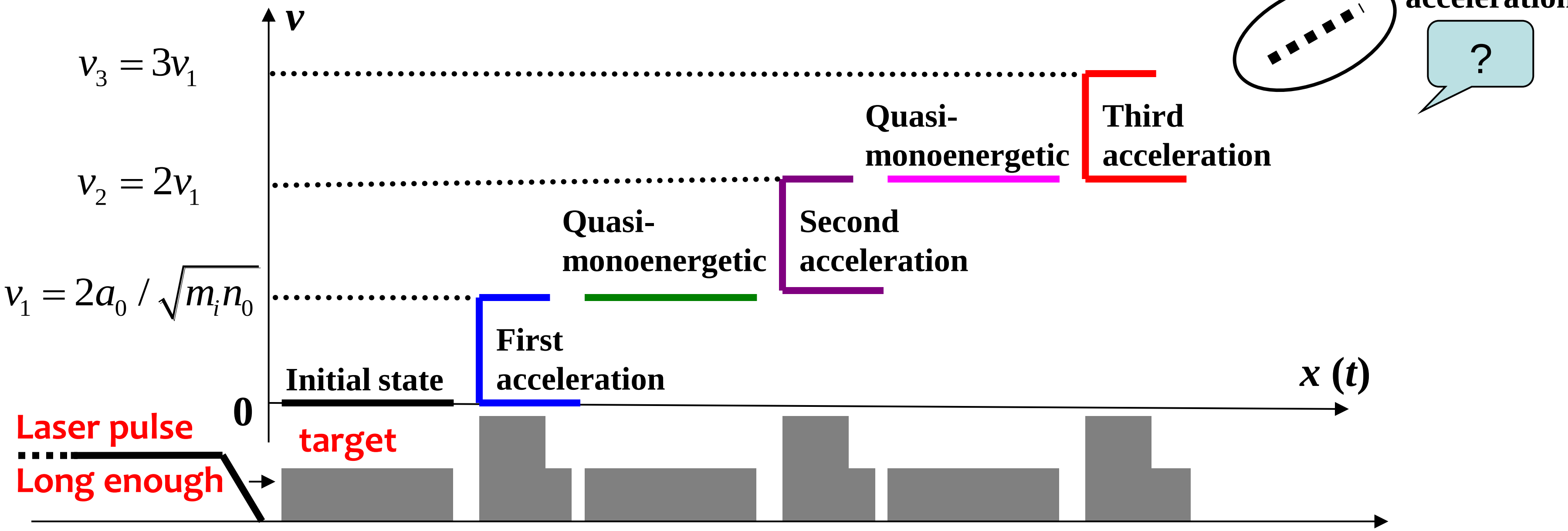
thickness=2λ_L

Laser: a=100

20 laser cycles

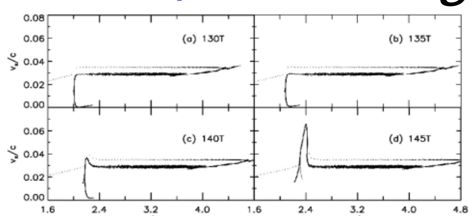
Baifei shen et. al., Phys. Rev. E, 64, 056406(2001)

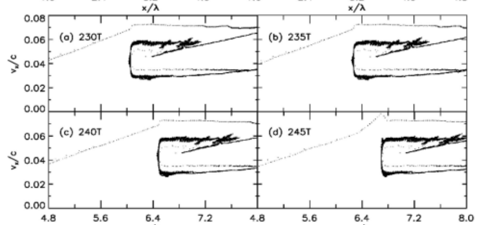
Multi-staged acceleration by electrostatic shock

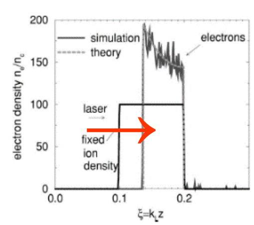


Simulations:

For *normal intense* laser pulse *and/or thick* target







For *ultra-intense laser pulse or/and ultra-thin foil*

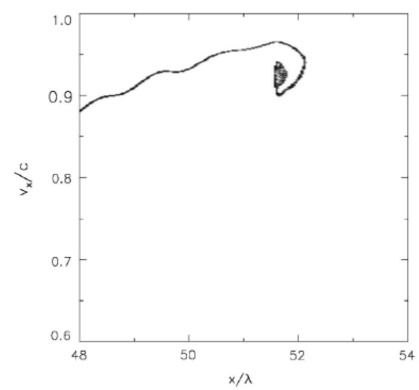


FIG. 7. Ion phase space (x, v_x) at t=60T from 1D PIC simulation for the

Xiaomei Zhang, Baifei Shen et al., Phys. Plasmas 14, 073101 (2007)
Xiaomei Zhang, Baifei Shen et al., Phys. Plasmas 14, 123108 (2007)

The acceleration scheme for the quasi-monoenergetic heavy ions proposed by SIOM

PRL 101, 164802 (2008) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2008

Generating Monoenergetic Heavy-Ion Bunches with Laser-Induced Electrostatic Shocks

Liangliang Ji,[1] Baifei Shen,[1,*] Xiaomei Zhang,[1] Fengchao Wang,[1] Zhangyin Jin,[1] Xuemei Li,[1] Meng Wen,[1] and John R. Cary[2,3]

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(Received 22 May 2008; published 16 October 2008)

A method for efficient laser acceleration of heavy ions by electrostatic shock is investigated using particle-in-cell (PIC) simulation and analytical modeling. When a small number of heavy ions are mixed with light ions, the heavy ions can be accelerated to the same velocity as the light ions so that they gain much higher energy because of their large mass. Accordingly, a sandwich target design with a thin compound ion layer between two light-ion layers and a micro-structured target design are proposed for obtaining monoenergetic heavy-ion beams.

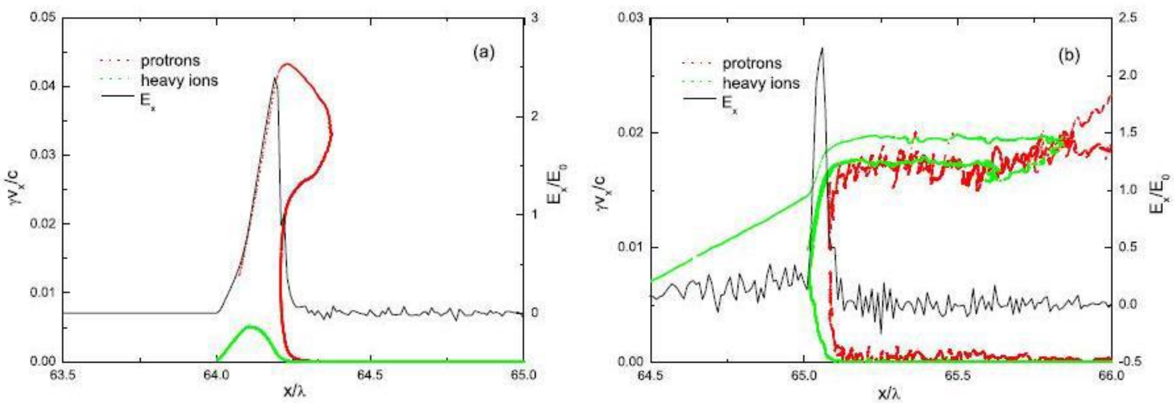
Under the electrostatic collisionless shock acceleration, heavy ions in the mixed target can be accelerated together with the protons with the same velocity, accordingly heavy ions have higher energy. Quasi-monoenergetic heavy ions can be obtained by using microstructured target.

Liangliang Ji, Baifei Shen et al., Phys. Rev. Lett., 101, 164802 (2008)

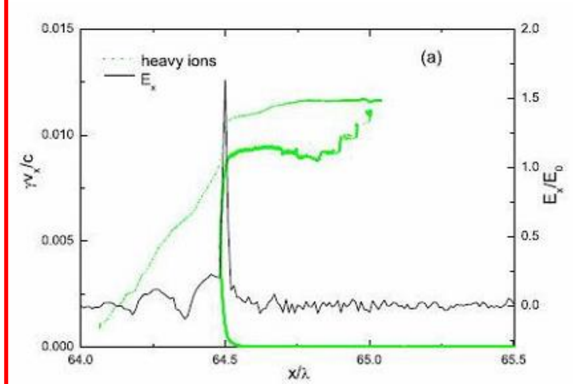
Shock acceleration for mixed plasmas

$$a=2, n_{e0}=10, m_{i1}=1836, m_{i2}=18360, n_{i1}=8, n_{i2}=2, T_e=T_i=0$$

The target is between *x*=64μm and *x*=72μm



The ratio of number density of proton and heavy ion is *n*i1:*n*i2=8:2. (a) *t*=80T (b)160T.

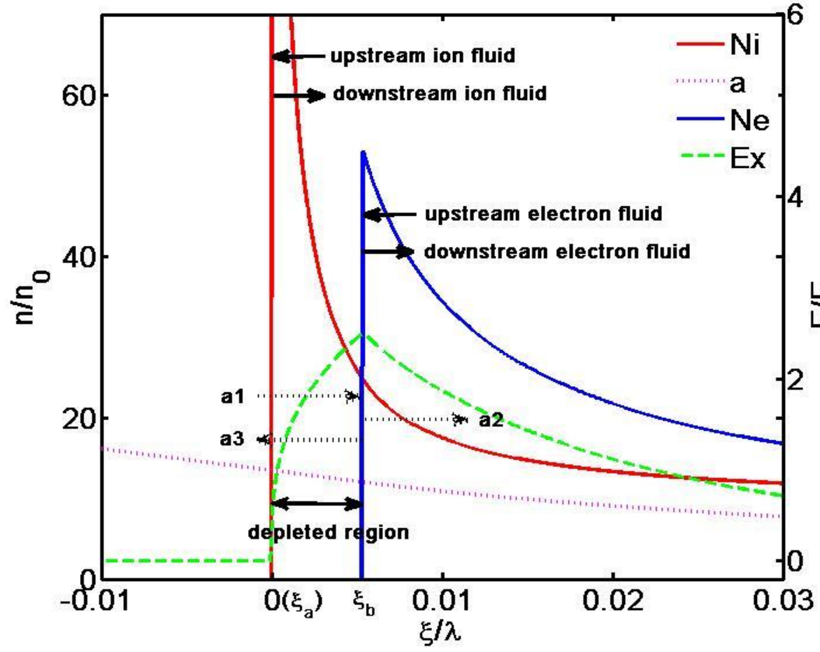


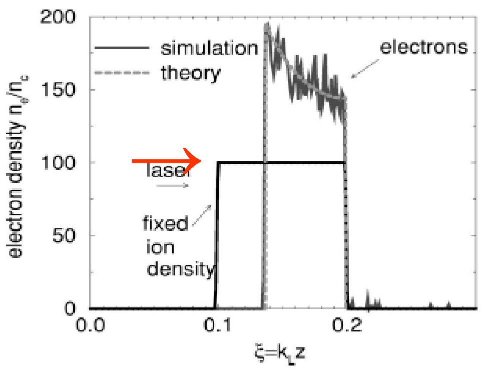
Pure heavy ions

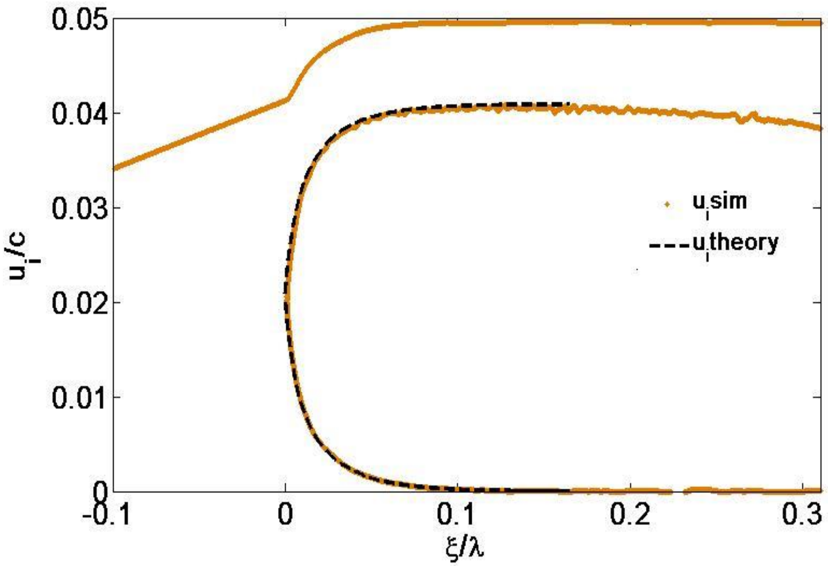
- **Initially protons are accelerated to 0.0295 c, then protons and heavy ions reach a same velocity 0.018 c.**

$u_s \approx \sqrt{a^2/(m_i n_i)}$ **For pure protons，0.0295c；For pure heavy ions，0.0094c**

Quasi stationary solution for hole boring







Physics of Plasmas 23, 043107 (2016)

Theoretical Research on Proton Acceleration @ SIOM Light pressure acceleration

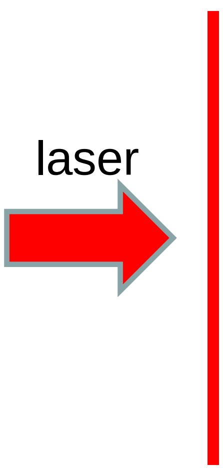
PRL 105, 025001 (2010)   PHYSICAL REVIEW LETTERS   week ending 9 JULY 2010

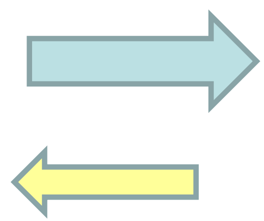
Relativistic Single-Cycled Short-Wavelength Laser Pulse Compressed from a Chirped Pulse Induced by Laser-Foil Interaction

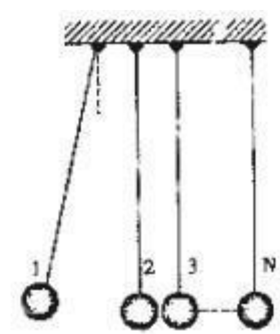
L. L. Ji (吉亮亮), B. F. Shen (沈百飞),* D. X. Li (李冬雪), D. Wang (王丁), Y. X. Leng (冷雨欣), X. M. Zhang (张晓梅), M. Wen (温猛), W. P. Wang (王文鹏), J. C. Xu (徐建彩), and Y. H. Yu. (郁亚红)

State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, P.O. Box 800-211, Shanghai 201800, China

(Received 9 April 2010; published 8 July 2010)







Simulation for driving pulse of a=50, the scattered pulse of a=5, T=30 T_0, and the foil of $n=100n_c$, $d=0.2\lambda$

In this example, the intensity of the driving pulse is 3.5×10^{21}W/cm^2, while the intensity of the source laser is 3.5×10^{19}W/cm^2. After compression, the intensity is 8.8×10^{22}W/cm^2, 25 times higher than the driving pulse and the central wavelength is 200 nm. If the focal size is reduced to one fifth, the intensity would be 2.2×10^{24}W/cm^2, 625 times higher than the driving pulse.

Therefore, it may be a good way to approach the Schwinger limit.

Advantages of RPA with relativistic laser

Radiation pressure is proportional to the laser intensity (a^2), so it is helpful to scale to ultra-high intensity. When the moving velocity of the whole target is close to the light speed, nearly all the laser energy can be transferred to ions due to the Doppler effects. That is, the efficiency is close to 100%.

Problems in the relativistic laser radiation pressure acceleration

1. Circularly polarized laser pulse is required for RPA and pre-pulse is required to be well controlled.

   * these technological problems are expected to be resolved.

2. Transverse instabilities

   *using super-gaussian pulse, appropriate pulse profile and optimal transverse profile of foil is helpful to suppress these instabilities.

3. Can protons be accelerated to 100GeV or even TeV by RPA?

   * laser pulse can be guided in the plasma channel and propagates much longer distance.

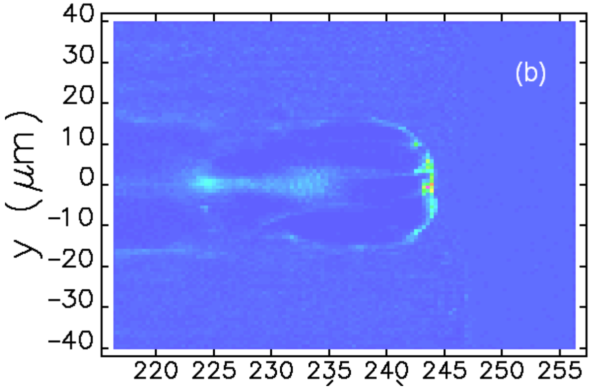
   * thinner foil can be used to decrease the acceleration distance.

When $p \gg 1$, $dp/dt \propto (1/p^2)$, So $p \propto t^{1/3}, x^{1/3}$

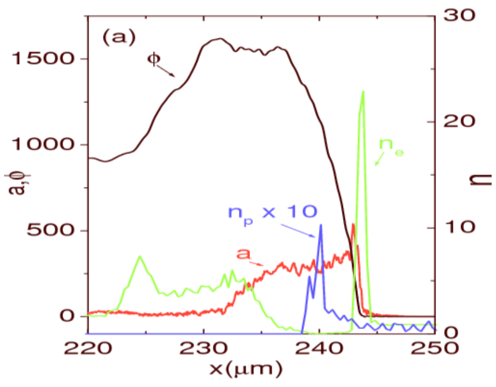
$a=316$, $\lambda=0.8$ μm, $n = 1.5\times10^{21} cm^{-3}$

$n_p=1\times10^{20} cm^{-3}$ (proton), $n_t=1.4\times10^{21} cm^{-3}$ (tritium)

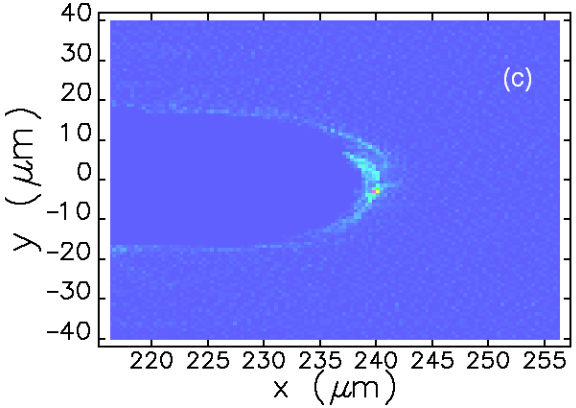
Electron density



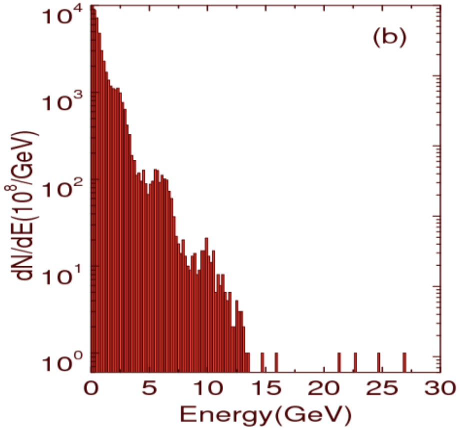
Plasma density and field



Proton density

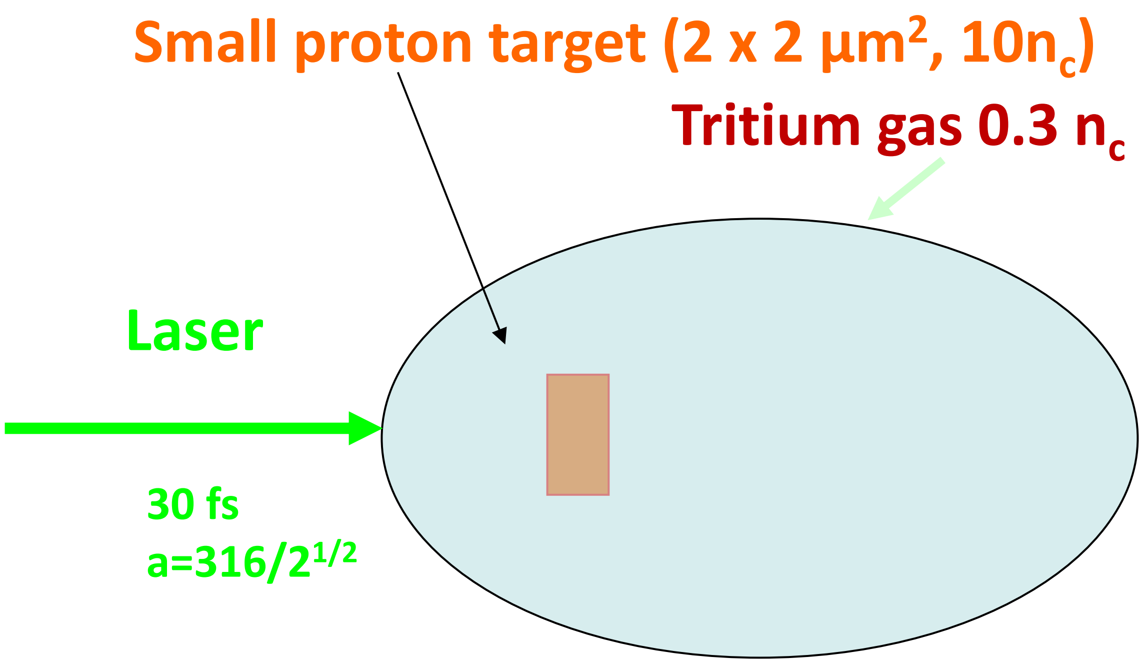


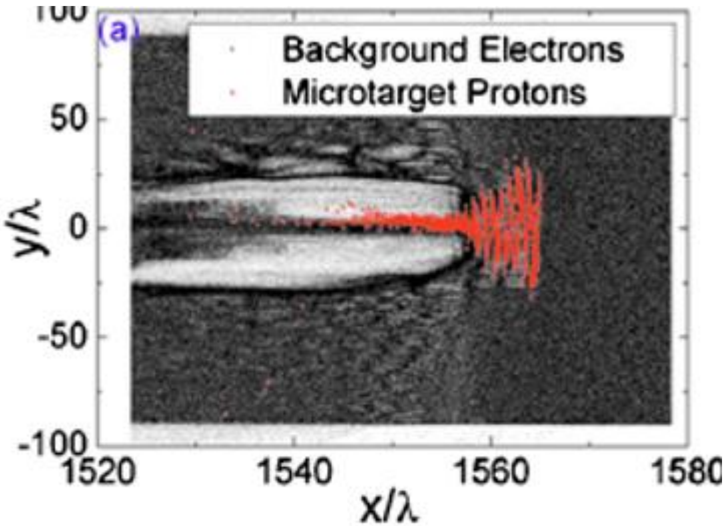
Energy spectrum of proton

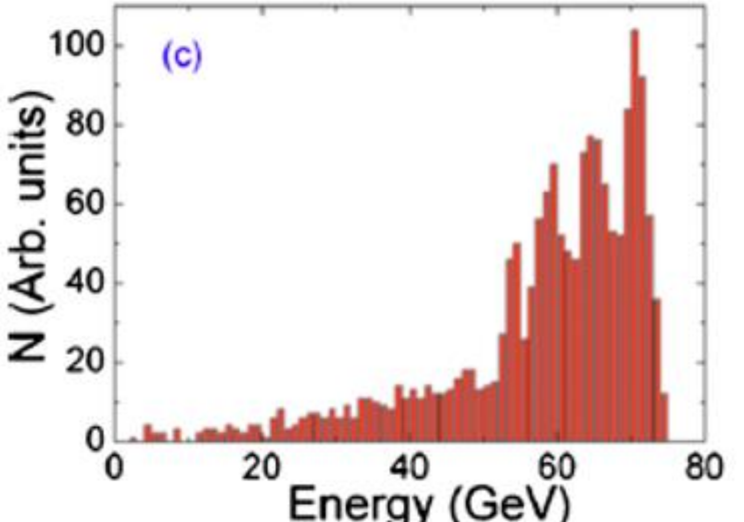


Baifei Shen et al., Phys. Rev. E(R）, 055402（2007）

Sequential radiation pressure and bubble acceleration regime



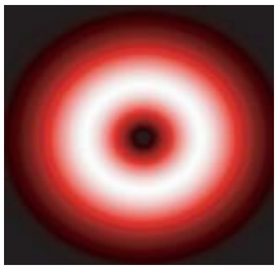


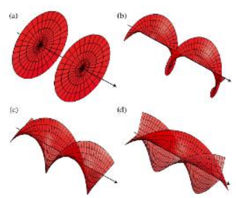


Baifei Shen et al., Physical Review Special Topics-Accelerators and Beams, 12, 121301 （2009）

X. Zhang, Baifei Shen, PHYSICS OF PLASMAS 17, 123102(2010)

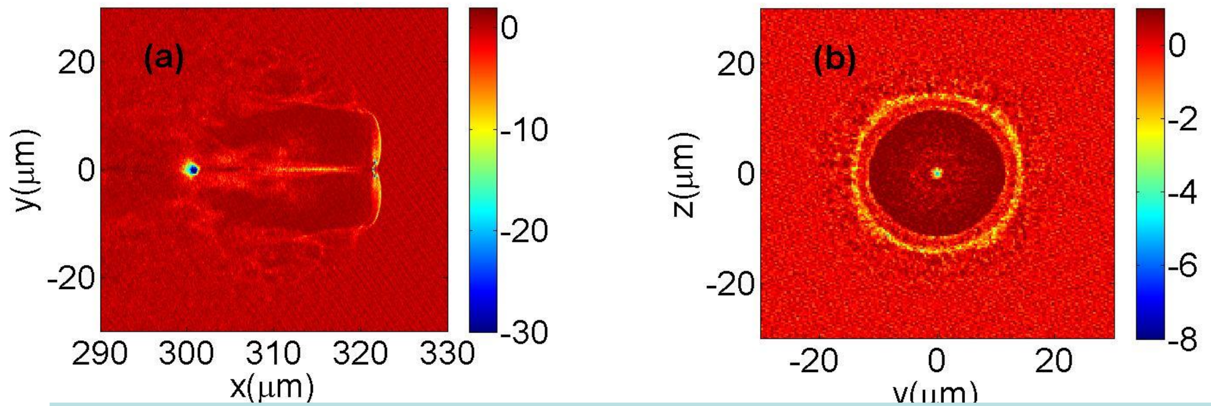
Proton acceleration in the bubble regime driven by intense LG pulse



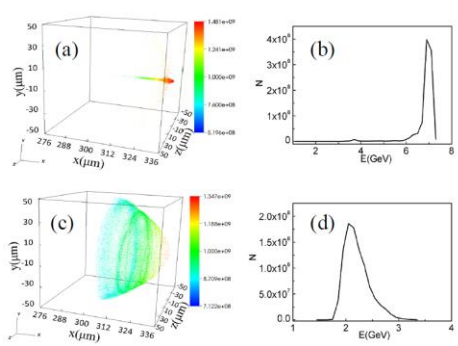


Helical phase fronts for (a) $\ell = 0$, (b) $\ell = 1$, (c) $\ell = 2$, and (d) $\ell = 3$.

Electron density



A electron cylinder is found in the middle of the bubble.



Underdense plasma of density 2.4×10^{20} /cm^3 driven by the CP LG laser pulse of intensity of 1.7×10^{22} W/cm^2 (a=70)

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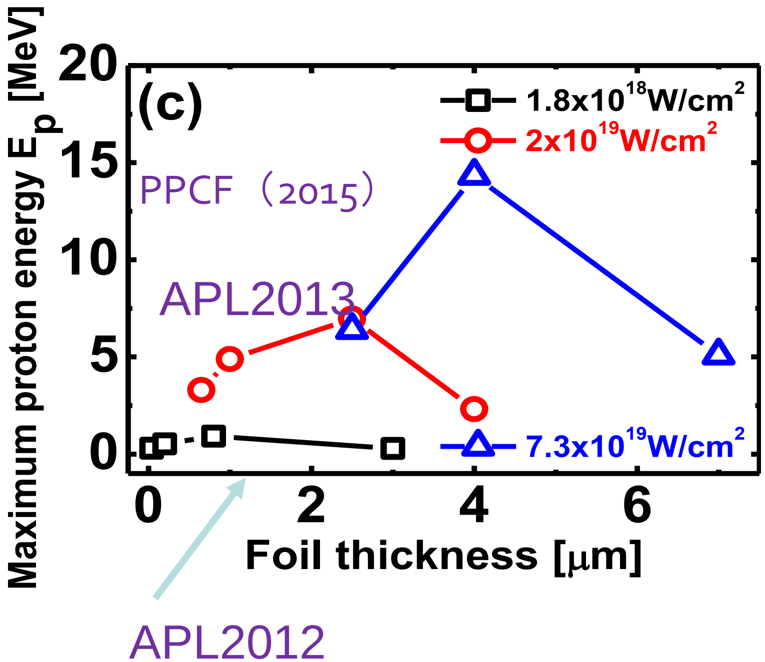
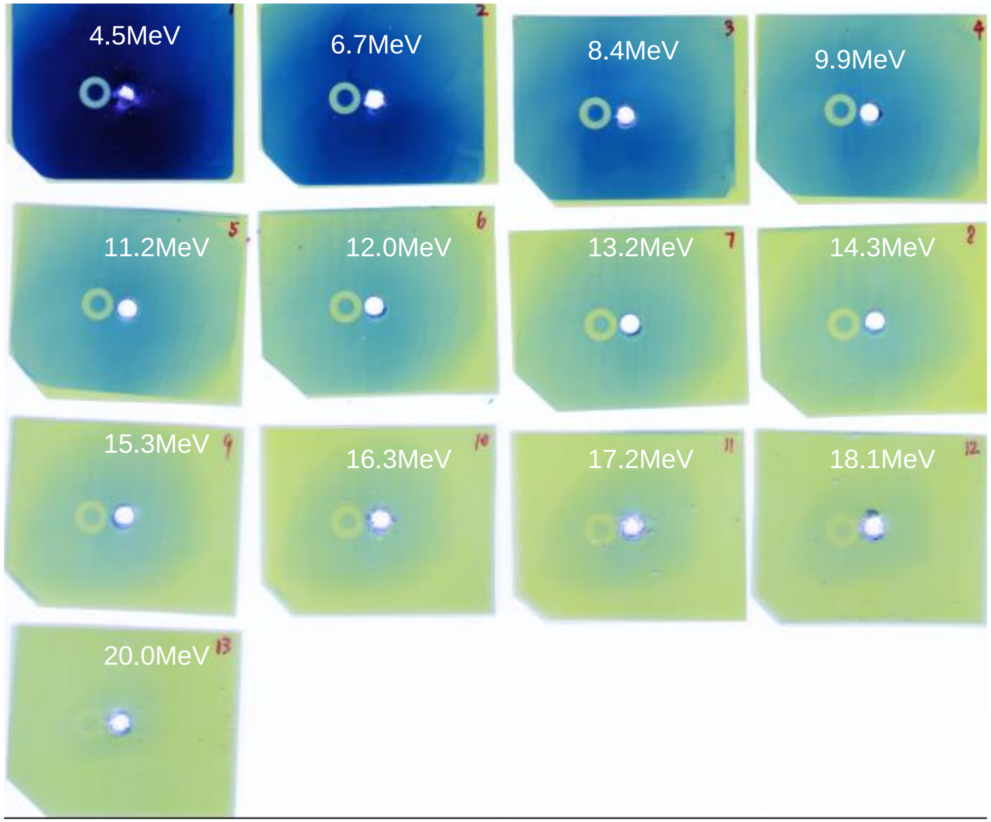
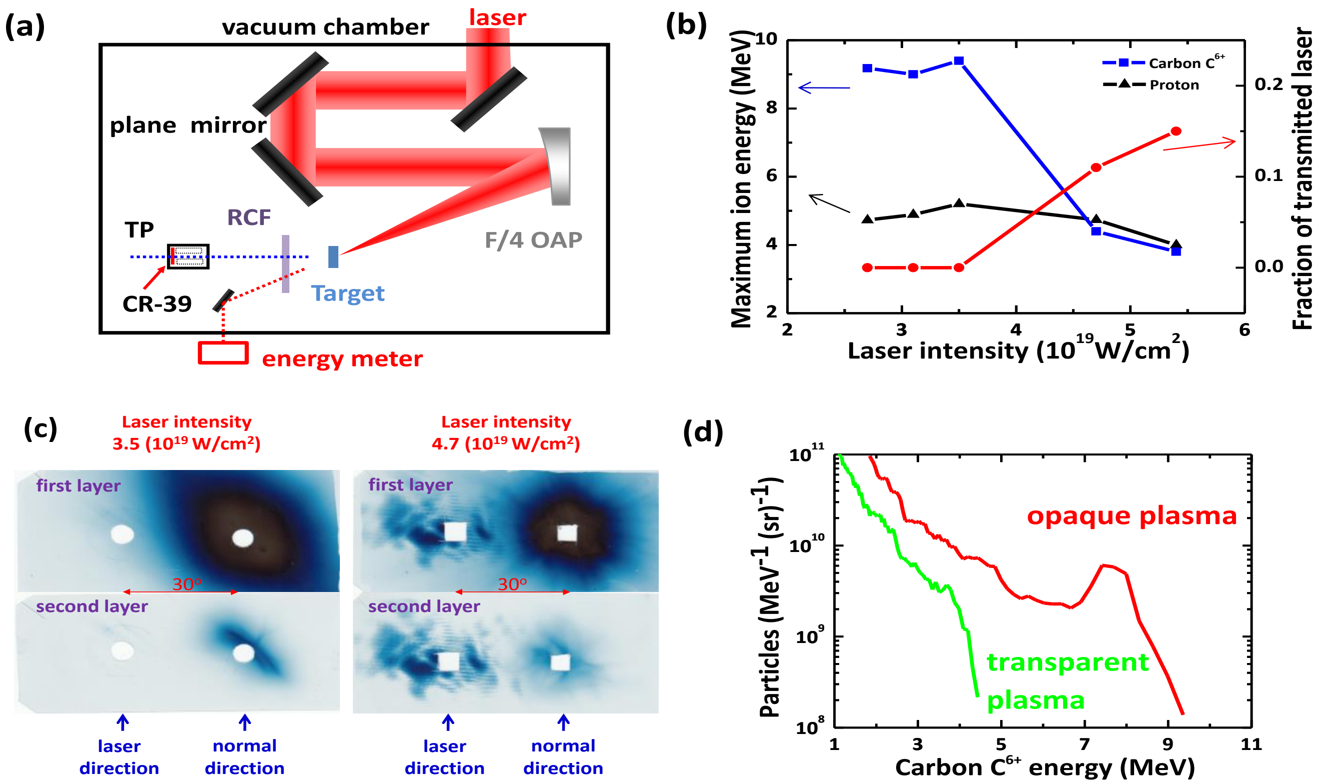


Maximum proton energy of published result is 14.3 MeV



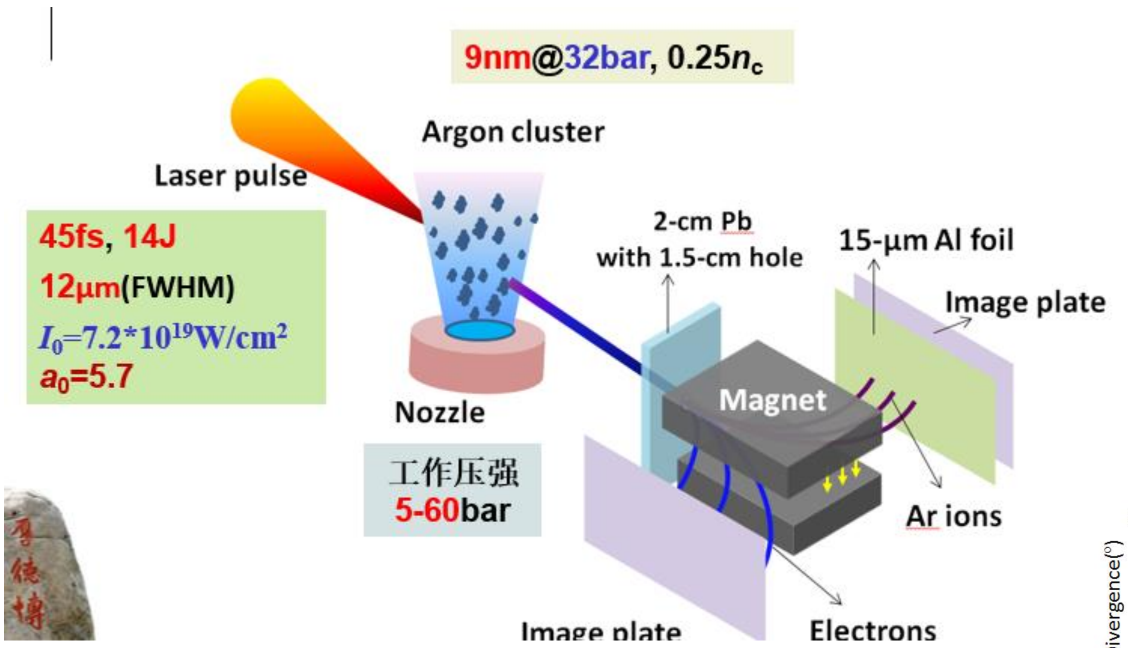
Proton energy of our recent result is larger than 20 MeV

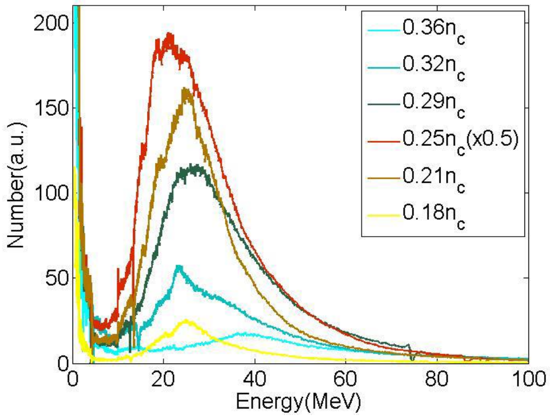
Collisionless shocks driven by 800 nm laser pulses generate high-energy carbon ions

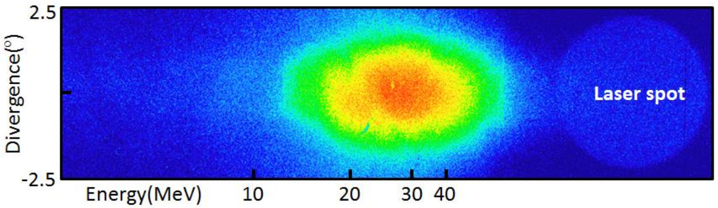


H. Zhang et al., PoP（2014）

Monoenergetic argon ions were produced







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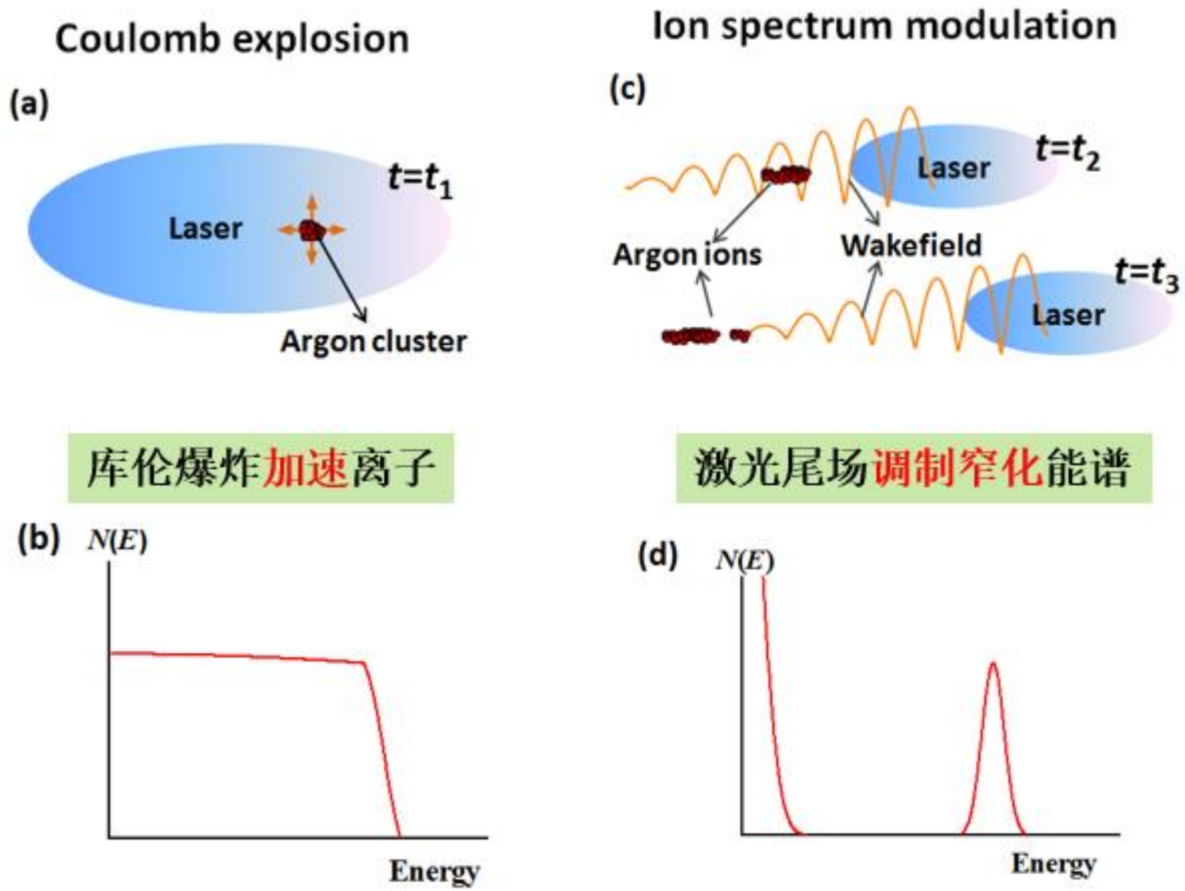
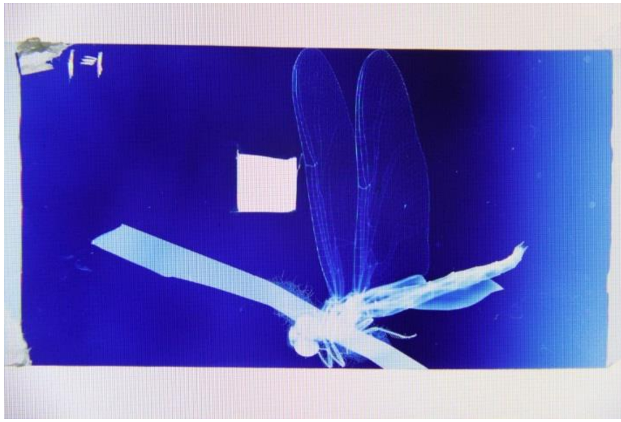
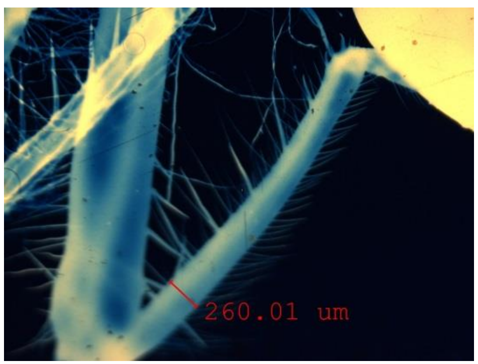
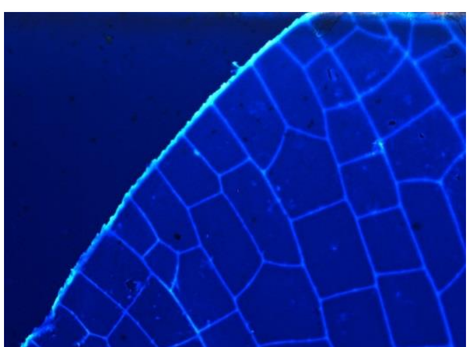


Experimental Research on Proton Acceleration @ SIOM   Proton radiograph







APPLIED PHYSICS LETTERS **108**, 214102 (2016)

CrossMark

Proton beam shaped by "particle lens" formed by laser-driven hot electrons

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[1]*State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
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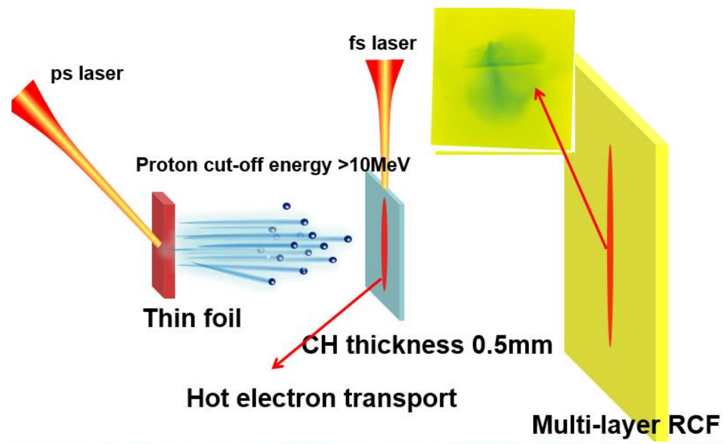

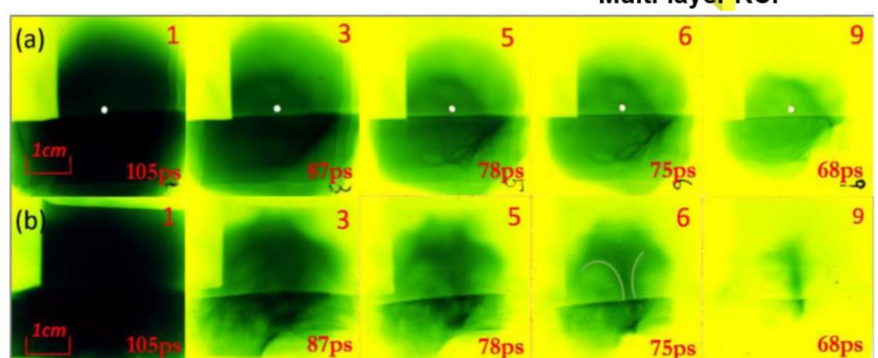

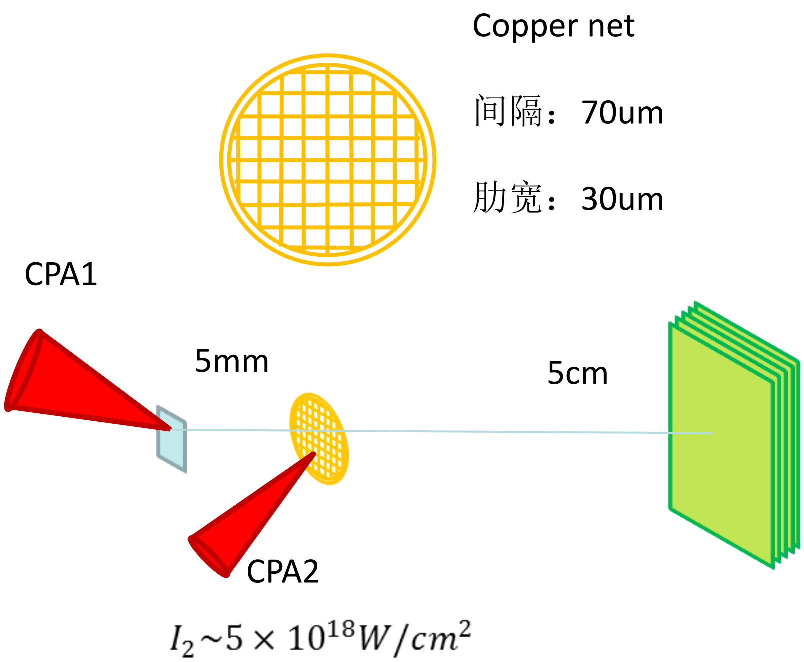

“Proton crystal” was formed

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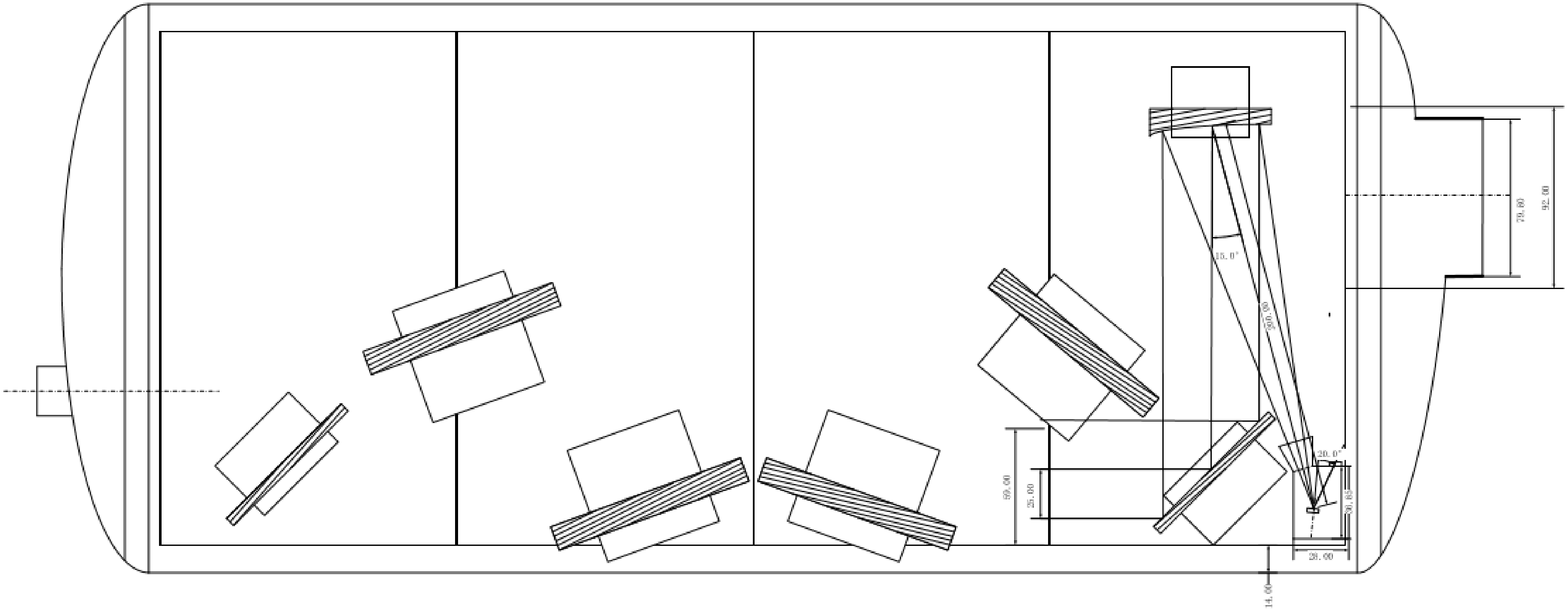
3）Future plan for proton acceleration with 5-10 PW and 100 PW lasers

Proton acceleration with 5 PW laser

Proton acceleration with 5 PW laser

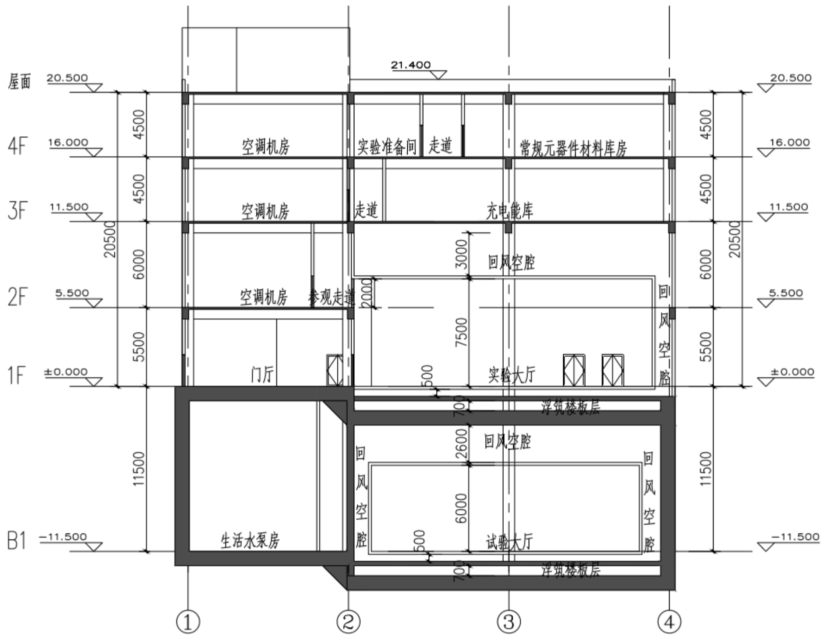


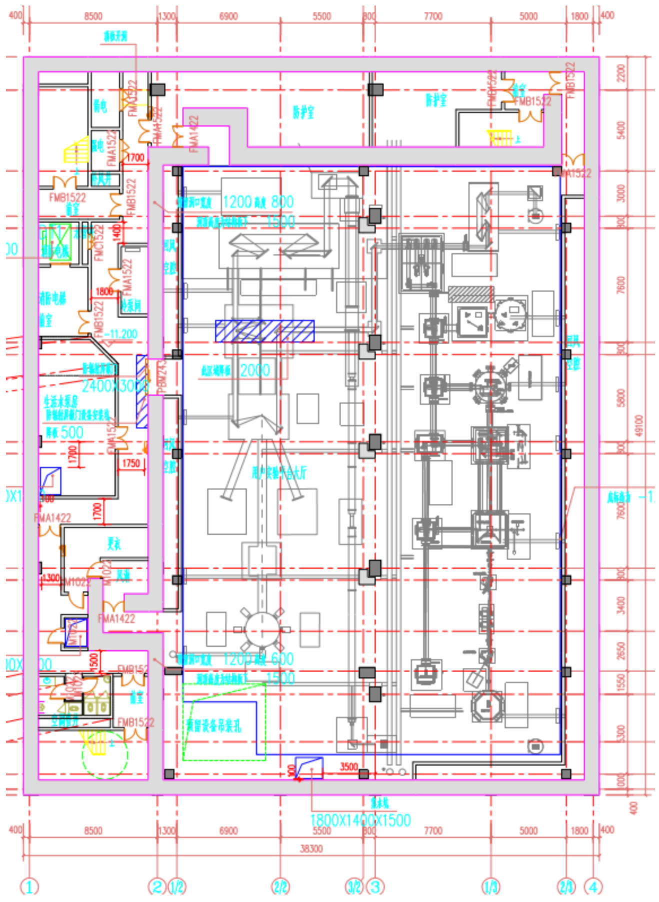
Test shots indider compression chamber in July, 2017

Shanghai Super-intense Ultrafast Laser Facility （SULF）

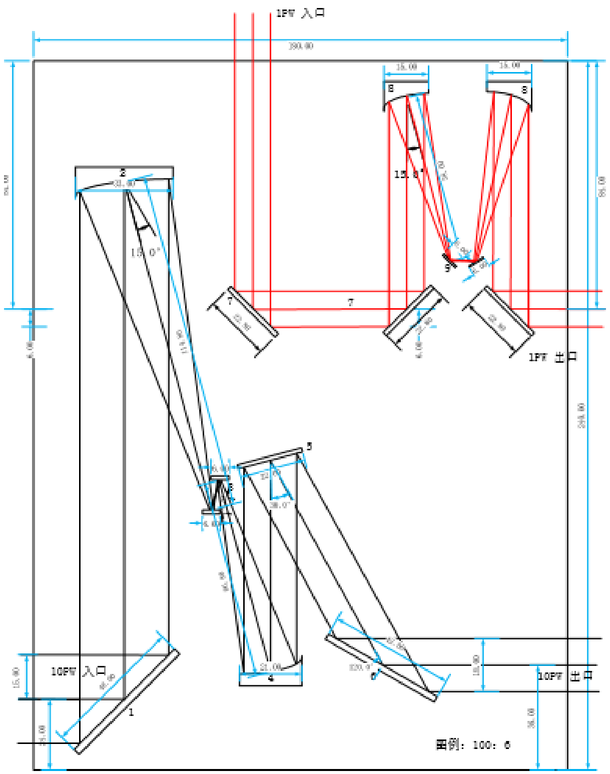
SULF will be finished in the end of 2018.

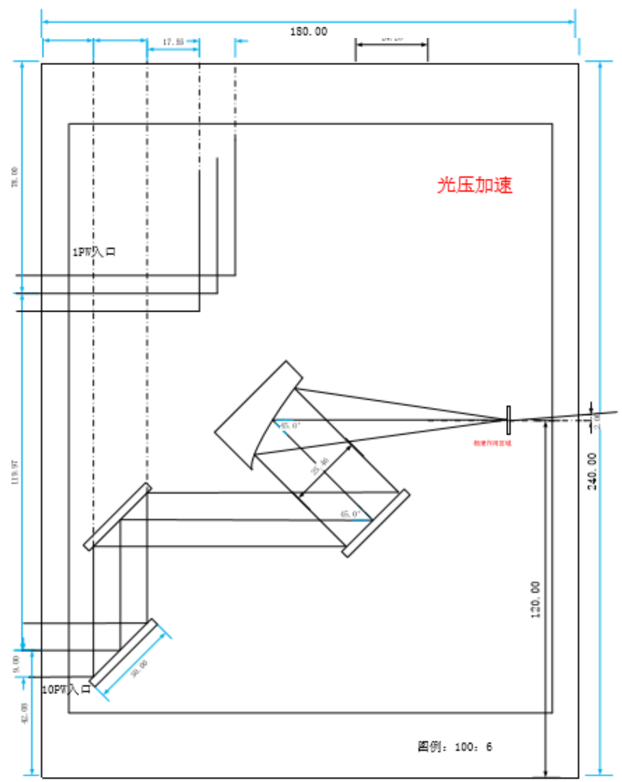
Shanghai Super-intense Ultrafast Laser Facility（SULF）

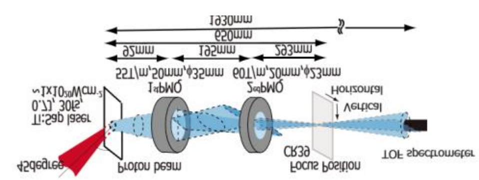




Shanghai Super-intense Ultrafast Laser Facility（SULF）







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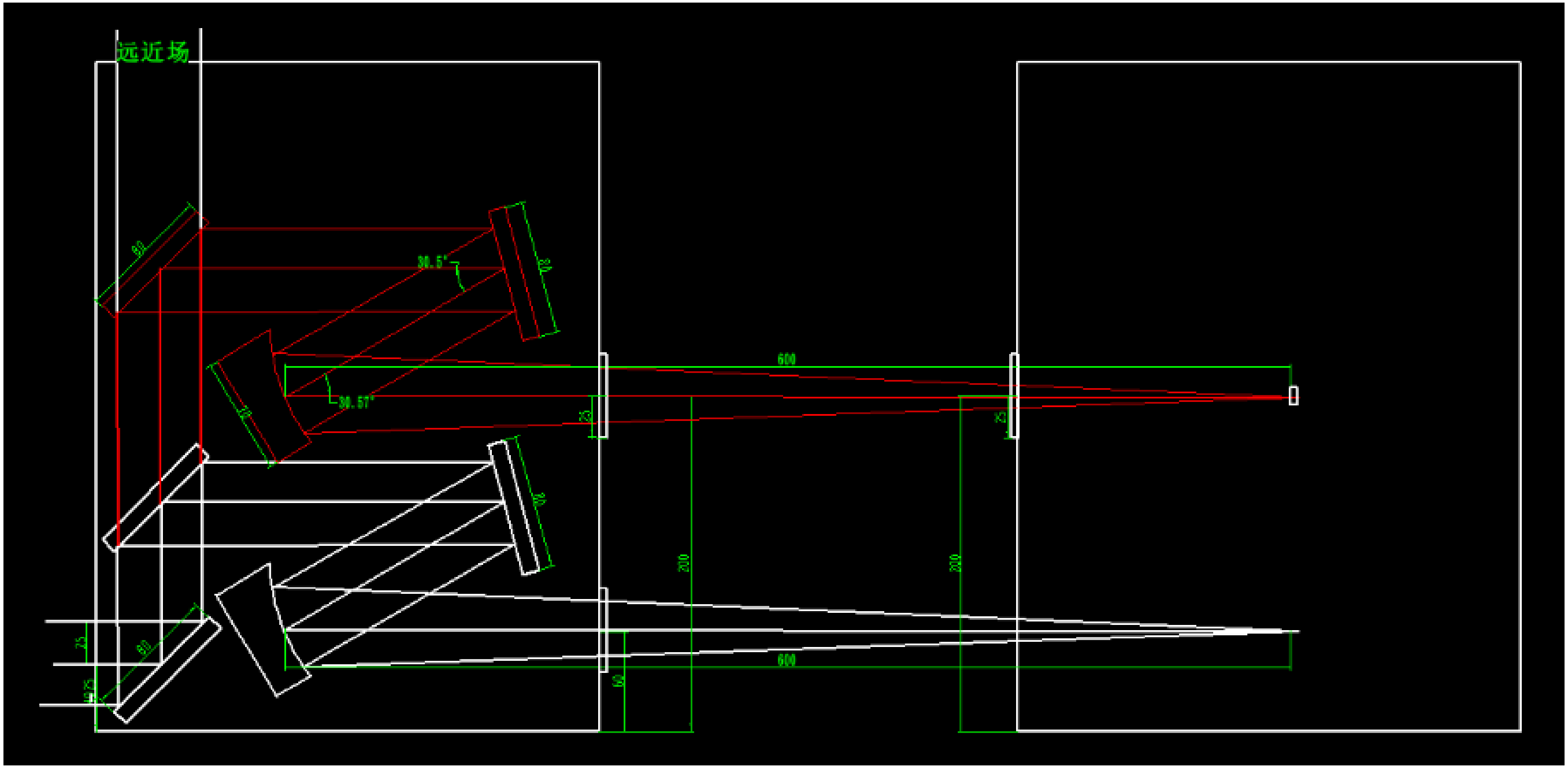
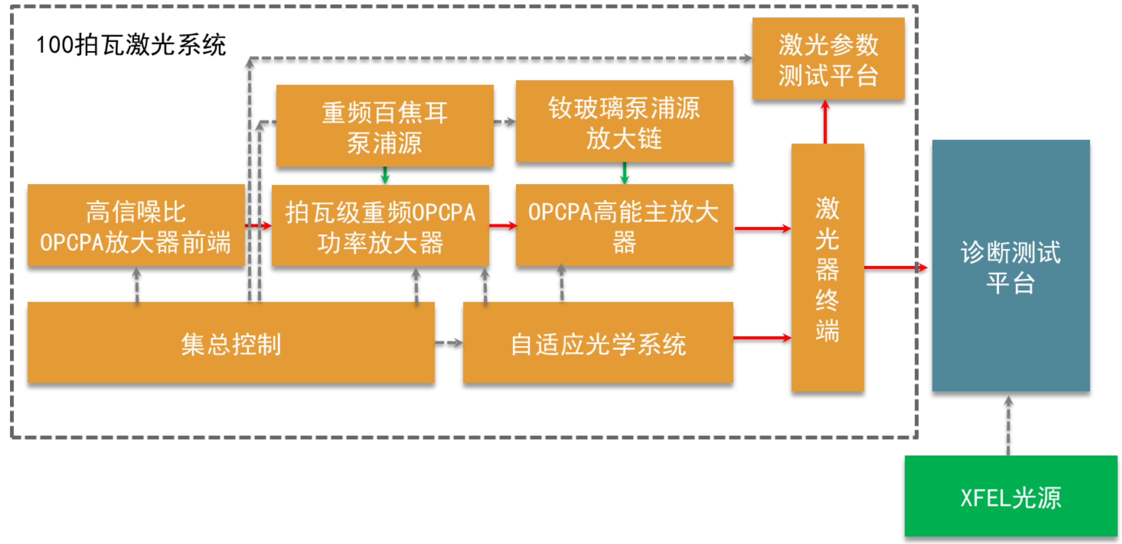


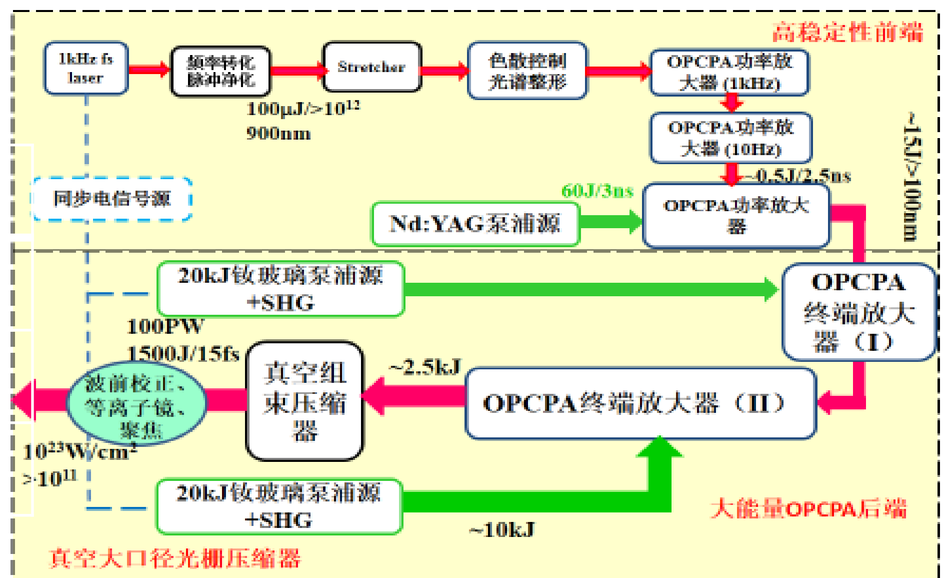
Future plan on Proton Acceleration @ SIOM — 100 PW

100 PW laser is planed to be finished before 2025.



- Parameter：

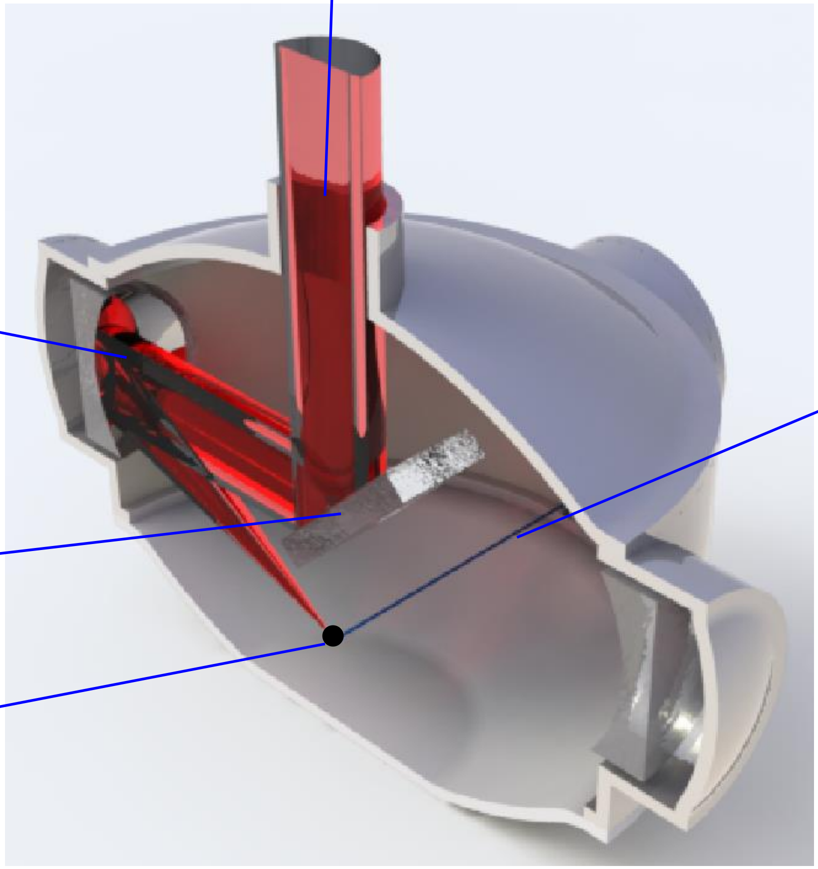
Intensity	1×10^{23} W/cm^2
Power	100 PW
Pulse duration	≥15fs
Spot size	~5µm



100PW激光系统原理图

- **100PW laser pulse (1500J/15fs, 1.4 m) is from up floor. It is focused to the middle of the 10m chamber where an XEFL go through.**

North Pole——Laser enters the chamber



Cylindrical Chamber

Height : 6 m
Diameter: 10m

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Thank you for your attention