20th – 23rd March, 2017, Snezhinsk, Russia

Optimization of the combined proton acceleration regime by using a target composition scheme

Li Baiwen

李百文

Institute of applied physics and computational mathematics,
Beijing 100094, Haidian District, P. R. China

Contents

1) Introduction in high-energy density physics

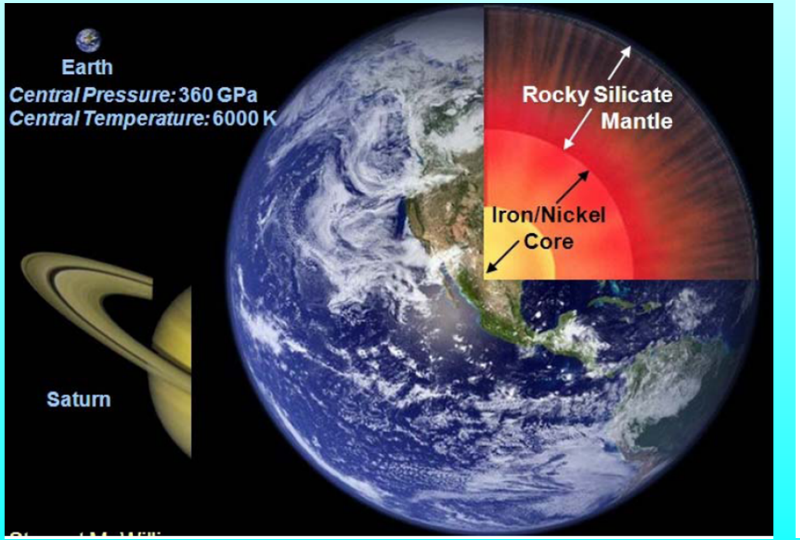
2) Recent works in our group

- 2.1) Target composition scheme of RPA and LWFA
- 2.2) Fast electron beam with manageable spotsize from laser interaction with the tailored cone-nanolayer target
- 2.3) Effect of inner-surface roughness of conical target on laser absorption and fast electron generation
- 2.4) 2D hybrid model for high-current electron beam transport
- 2.5) Kinetic Simulation research of gas-puff Z-pinch

3) Summary

1) Introduction in high-energy density physics

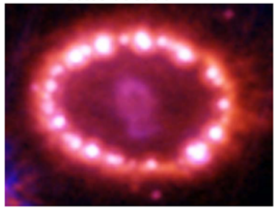
- Recently, high energy density physics (pressure > 1MBar, energy density > 10^{11}J/m^3) has become the frontier of plasma physics.
- Planets contain matter at quite high pressure (P>>100Gpa =1MBar) in high energy density condition, for example, the central pressure of earth is 360 Gpa, central temp. is 6000K.
- High energy density astrophysics involves strong shocks, high pressures,, intense radiations, strong fields and relativistic particles.



Crab Nebula

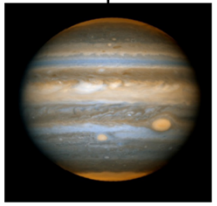
Magnetized RT instability

SNR 1987A



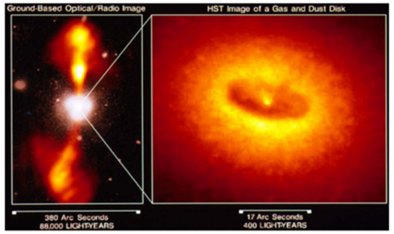
Radiative hydrodynamics

Jupiter



Matter at high pressure, density

NGC 4261

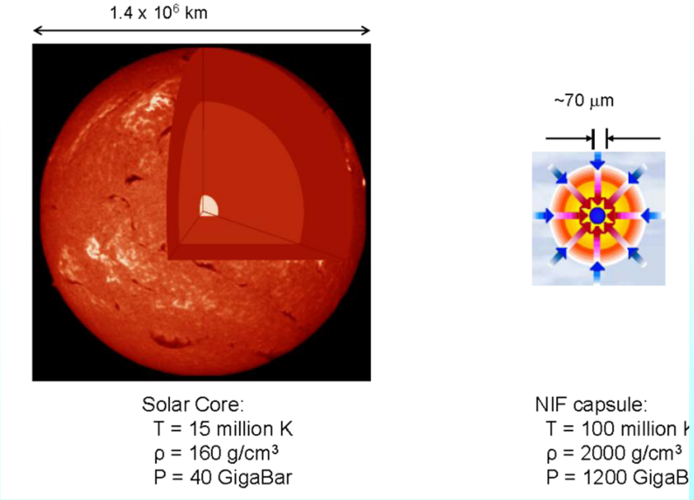


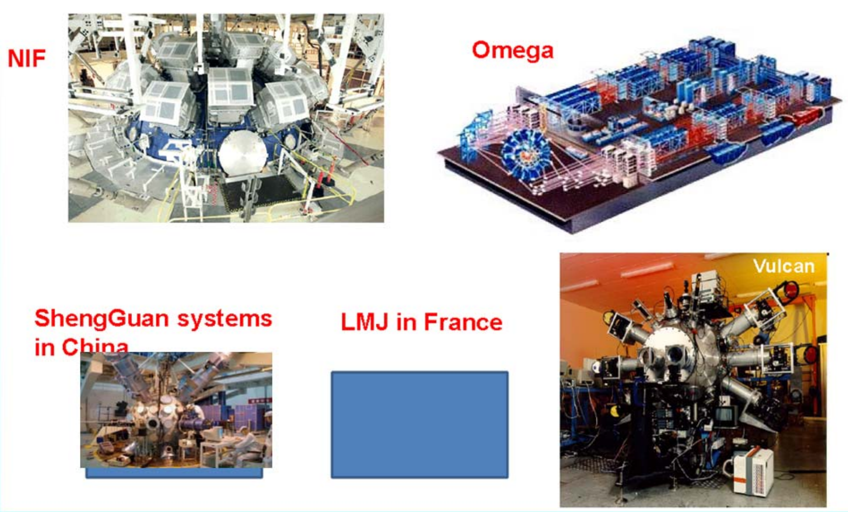
Relativistic plasmas

HH-47 jet

High Mach-# flows

- High energy density physics (HEDP) can explore many stellar relevant and fundamental problems of science.





- High energy density facilities such as NIF, Omega, LMJ and SG can generate astrophysics condition (strong shocks, high pressures, high Mach number flows, intense radiation, strong field, relativistic particles).
- Recent experiments with novel proton radiography resulted in a series of unique demonstrations and quantitative studies of the generation, evolution, instabilities and dissipation of the field.
  - In laser-foil interactions
  - in laser-driven ICF implosions
  - in laser-irradiated hohlraums

2) Recent works in our group

- **Our works mainly concentrate on**
  - Particle acceleration based on laser plasma interaction
  - Kinetic simulation research of gas-puff Z-pinch
  - Enhanced laser absorption, fast electron generation and control by intense short laser pulse interacting with structured target
  - Transport and energy deposition of high-current electron beam in a dense plasma in fast ignition condition
  - Laser plasma interaction in large-scale plasma in ICF condition
  - …….
- My Collaborators
  - Prof. Cao Lihua, Prof. Zheng Chunyang, Prof. Ni Cheng. IAPCM, China
  - Dr. Yao Weipeng, Dr. Wang Huan. Peking University, China
  - Prof. Seiji Ishiguro (Japan), Prof. M. M. Skoric (Serbia)

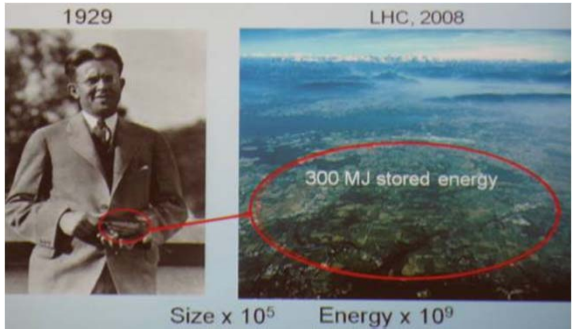
2.1) Target composition scheme of RPA and LWFA

- **Particle acceleration based on laser-Plasma interaction**

  Particle acceleration based on laser-plasma interaction has been of great interest to researchers over the past few decades because of its importance for a low-cost tabletop accelerators, fast ignition in ICF, high resolution radiographing, cancer radiation therapy and laboratory astrophysics and so on.

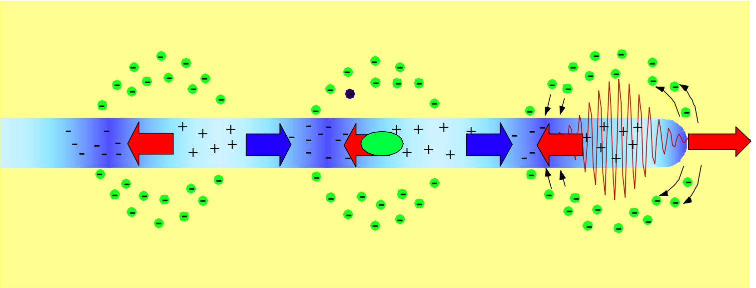
- **The advantages of laser plasma accelerators**

	Laser-plasma accelerators	**Traditional accelerators**
Acceleration Gradient:	> 100GV/m	< 100MV/m
Size of particle beam:	mm / um	km
Width of particle beam:	10fs	ps
Energy spread:	small	large

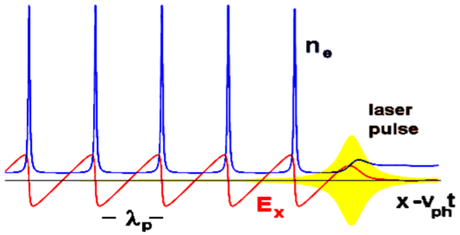


LWFA (Laser Wakefield Acceleration)

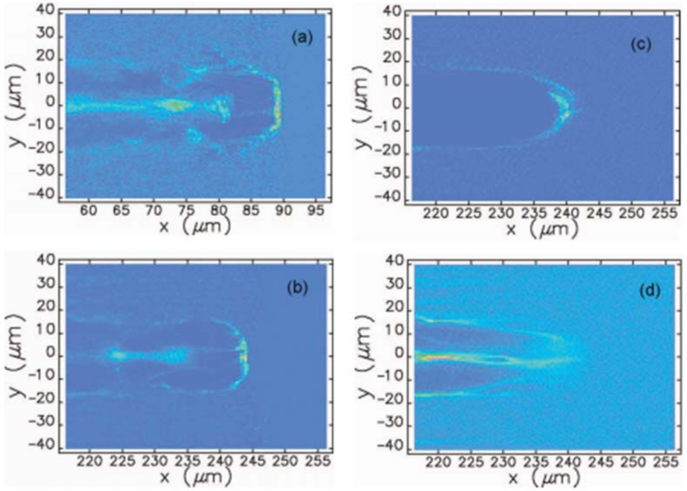
Mechanism: An intense Laser EM pulse can create plasma oscillations through the action of the nonlinear ponderomotive force. Electrons/protons trapped in the wakefield can be accelerated to high energy (charge-separation ES field).



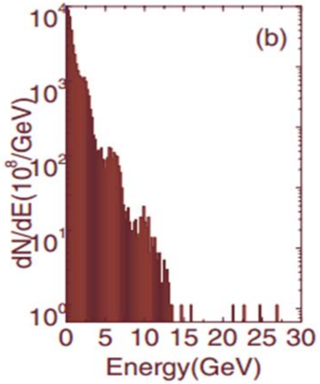
Tajima and Dawson, Phys. Rev. Lett. 43, 267 (1979)



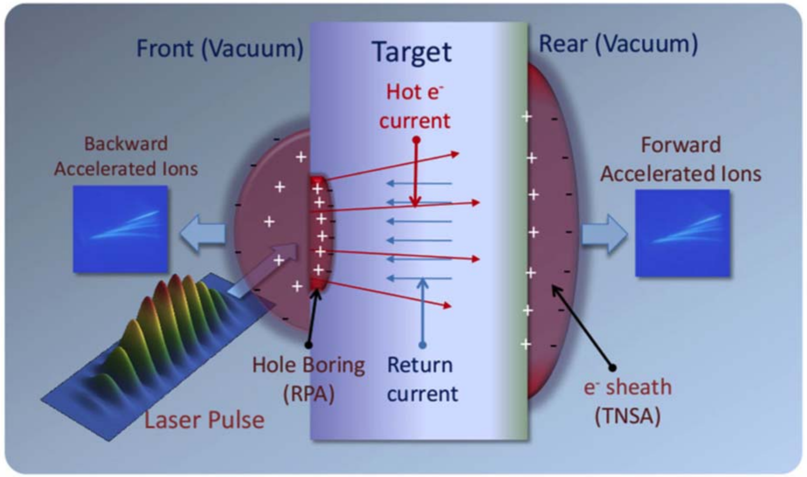
$$v_p = \sqrt{1 - n_0/n_c} \approx c$$



B. F. Shen, et al., PRE 76, 055402 (2007)



TNSA (Target Normal Sheath Acceleration)

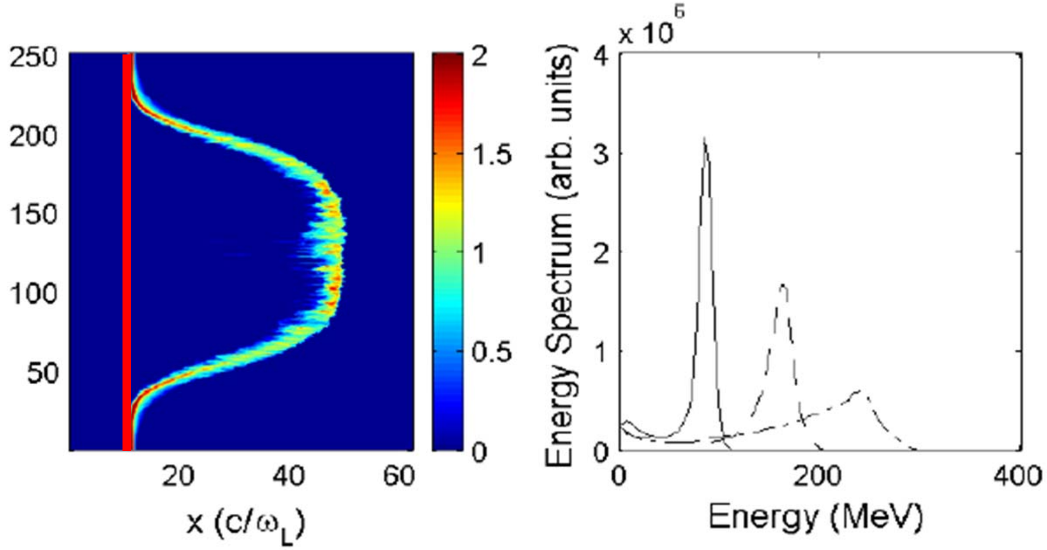


- In the past years, high energy protons were first observed and found in ground experiments. Clark et al., PRL 84, 670 (2000); Maksimchuk et al., PRL 84, 4108 (2000); Snavely et al., PRL 85, 2945 (2000).
- In order to explain this phenomenon, the mechanism of target-normal-sheath-acceleration (TNSA) has been proposed. Wilks et al., Phys. Plasmas , 542 (2001).
- Experiments and simulations indicate that the energy spread of proton beam was relatively large.

RPA (Radiation Pressure Acceleration)

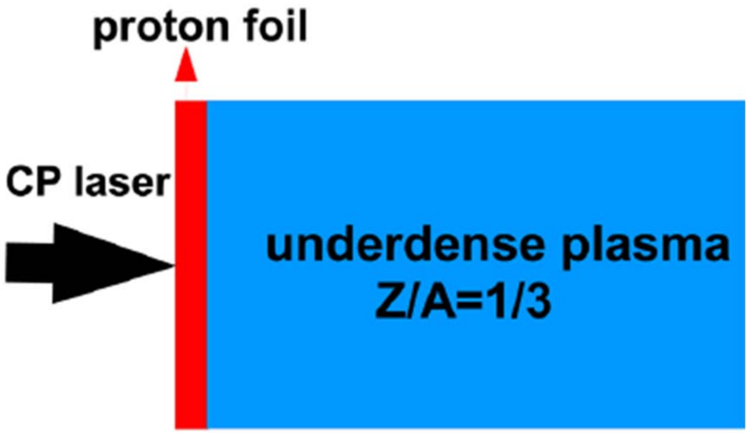
$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + \mathbf{f}_R,$$

$$\mathbf{f}_R = \frac{2r_c^2}{3}\left\{ -\gamma^2\left[\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right)^2 - \left(\frac{\mathbf{v}}{c} \cdot \mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c} + \left[\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) \times \mathbf{B} + \left(\frac{\mathbf{v}}{c} \cdot \mathbf{E}\right)\mathbf{E}\right]\right\},$$



- To limit the energy spread in TNSA, the radiation pressure acceleration (RPA) mechanism has been proposed. Esirkepov et al., PRL **92**, 175003 (2004); Zhang et al., POP **14**, 123108 (2007); Chen et al., POP **15**, 113103 (2008); Yan et al., PRL **100**, 135003 (2008); Qiao et al., PRL **102**, 145002 (2009).
- Physics mechanism: when laser is strong enough its radiation pressure can accelerate protons to high energy.

Combined Scheme of RPA and LWFA



- ✓ Shen et al., Phys. Rev. ST Accel Beams 12, 121301 (2009);
- ✓ Yu et al., New J. Phys. 12, 045021 (2010);
- ✓ Zheng et al., POP 19, 023111 (2012).
- ✓ ……

- ➢ In order to accelerate protons to a much higher energy, the combination of RPA and LWFA mechanism were proposed.
  - In this scheme, protons together with electrons in the overdense target are firstly pre-accelerated under the laser irradiation.
  - As laser penetrates into target and propagates through underdense plasma, a fast-moving wakefield can be excited. Some pre-accelerated protons can be injected into the wakefield and further accelerated over a long distance to an extremely high energy.
- ➢ However, due to the difficulty in controlling the proton injection process, the energy spread of proton beam is still larger, and it needs to be further reduced.

Differences of three Proton Acceleration Mechanism

Proton Acceleration Mechanism	**Pros and Cons**	**Some Former works**
TNSA	- Tens of MeV - 100% energy spread	Wilks et al., 2001, etc
RPA	- Few GeV - ~10% energy spread	Esirkepov et al., 2004 M.Chen et al., 2008 X.Q.Yan et al., 2008 B.Qiao et al., 2009, etc
Combined Scheme of RPA and LWFA	- Hundreds of GeV energy - ~10% of energy spread - Very high requirement of the laser intensity	Shen et al., 2009 Yu et al., 2010 Zheng et al., 2012, etc

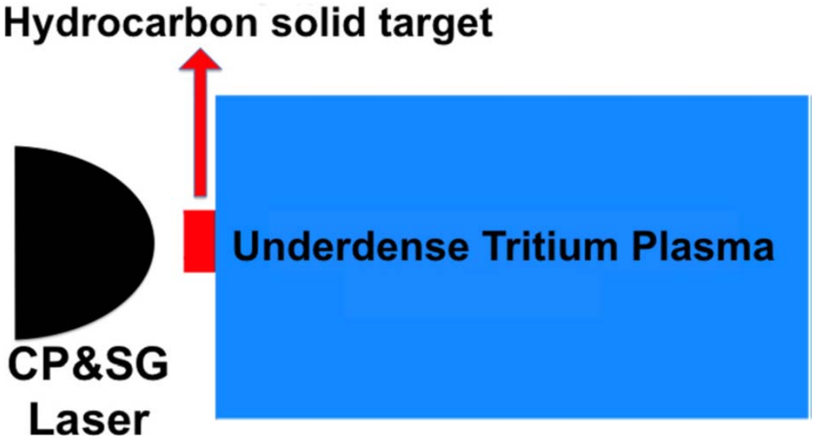
The quality of proton beam needs to be optimized

Target composition scheme proposed by our group

- In order to optimize and generate high-quality proton beam, instead of pure proton target by hydrocarbon target, a target composition scheme, were proposed by our group.
  - Energy spread < 10%
  - To reduced the requirement for laser intensity
  - To reduced the size of proton beams in space

1，Yao W P, Li Baiwen et al., Physics of Plasmas 23, 013107（2016）；

2，Yao W P, Li Baiwen et al., Laser and Particle Beams 32,593 (2014)



Simulation Parameters

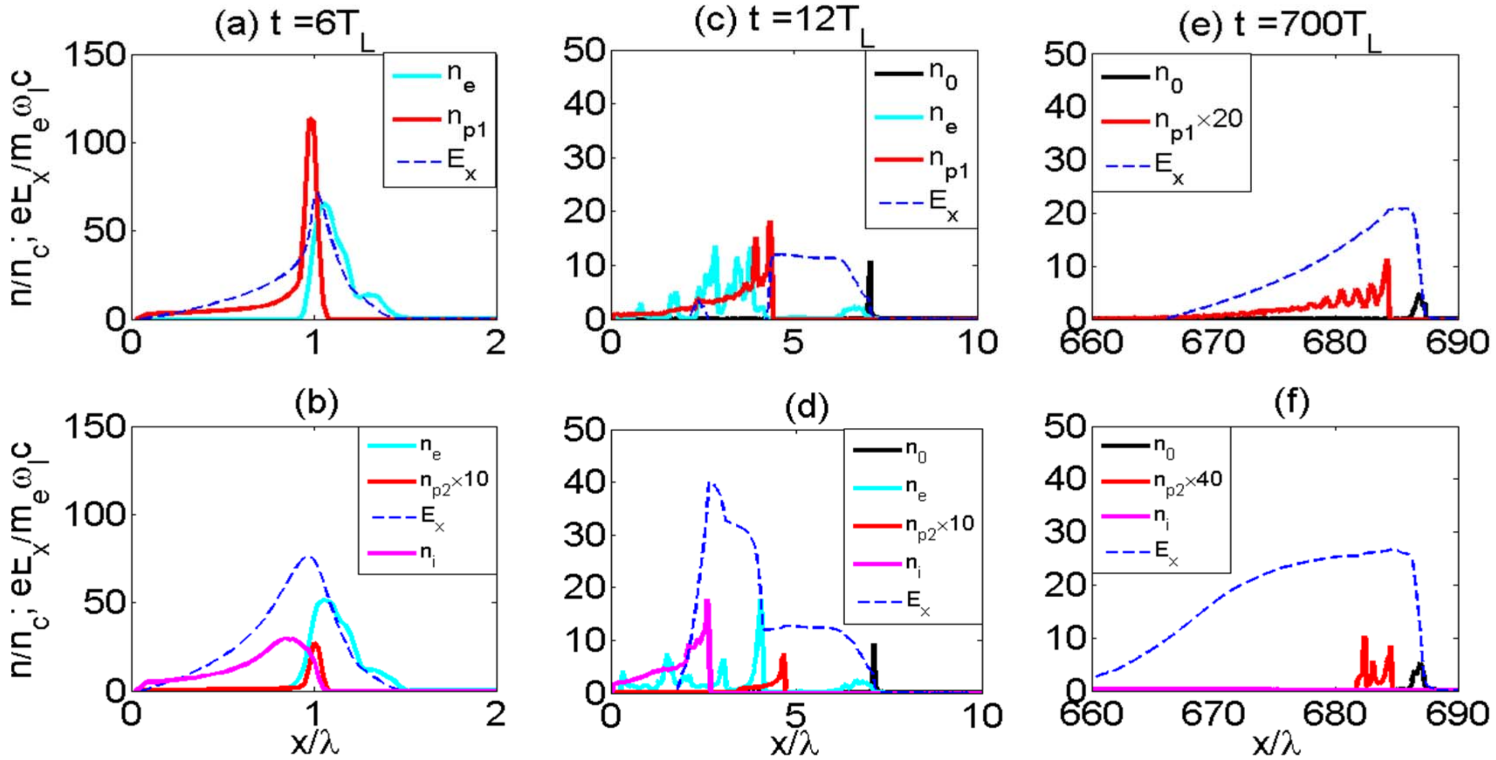
- **Laser Pulse** Circular-Polarized
- **CH Target** 1um, n_e=15n_c, n_p+Xn_i=15n_c
- **Plasma Gas** 1000um, n_0 = 0.1n_c

Snapshots of Density and Ex field

Before Penetration **Injection Process** **LFWA**

H

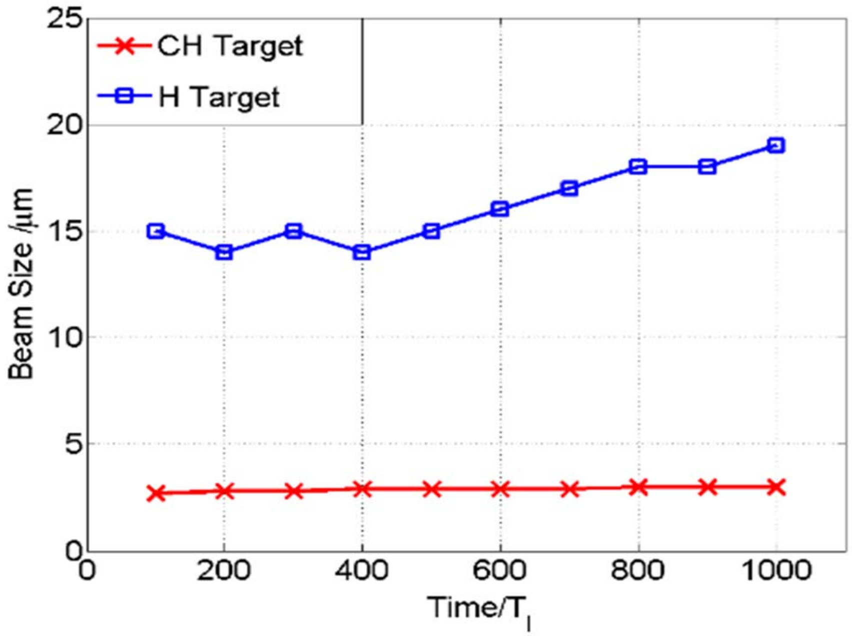
CH (9:1)



Stable Pre-acceleration **Much Compressed Beam**

Stable Pre-acceleration → Better Injection →
Compressed Proton Beam → Lower Spread

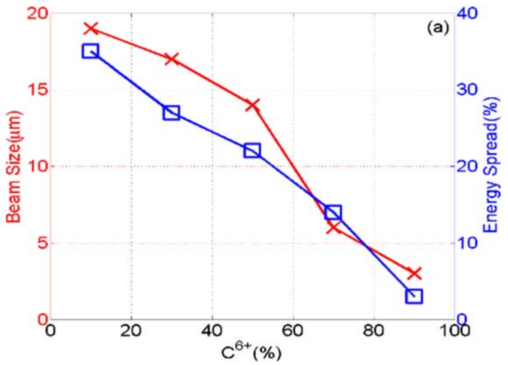
Time evolution of the length of proton beam

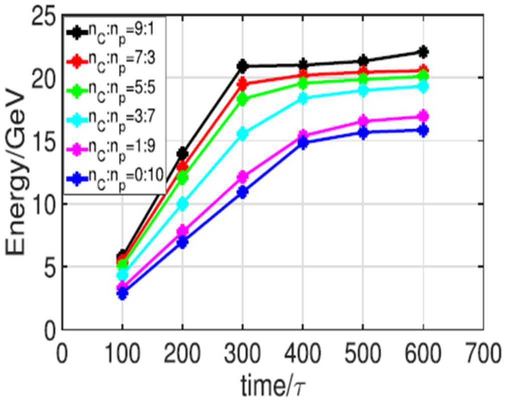


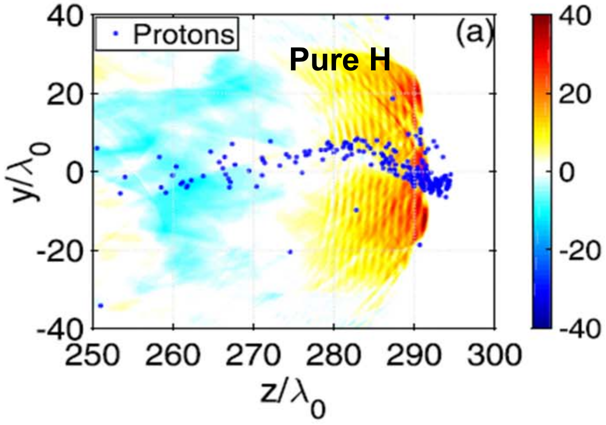
The advantages of high-quality proton beam in the case of CH composition target

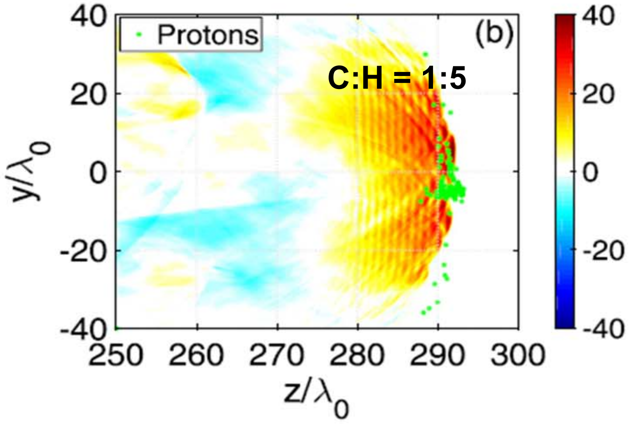
- **The space size of proton beam less than that of pure H case**
- **The space size of proton beam is more stable with time evolution**

Energy and energy spread





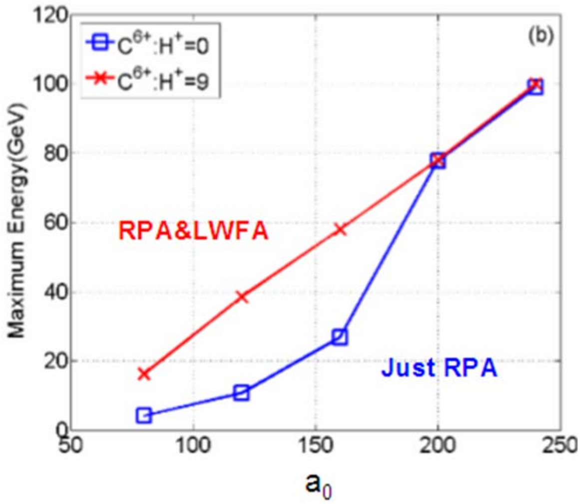




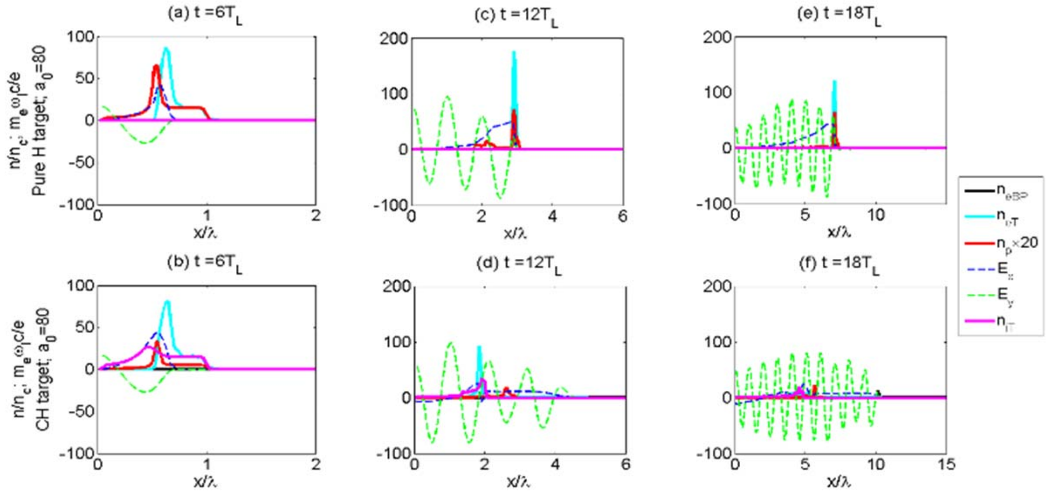
With the increasing of C number density, we fount that

- The size of proton beam becomes more smaller (from 19um to 3um)
- Energy spread were decreased (from 35% to 3%)
- The maximum proton energy were increased

The scaling of laser amplitude



In the case of laser amplitude a = 80



- If laser amplitude is low, in pure H case, protons and electrons were compressed double-layer like structure, laser is hard to penetrate H target, protons get accelerated only by RPA. However, In the CH case, heavy C ions were hard to followed electrons to form double-layer like structure, laser can penetrate CH target, protons can be accelerated to high energy by RPA and LWFA.
- If we want to accelerate proton to the tens of GeV level, it can effectively reduced the requirement of laser amplitude by using our target composition scheme.

2.2) Fast electron beam with manageable spotsize from laser interaction with the tailored cone-nanolayer target

- In Fast Ignition research, the efficient absorption of intense short laser energy by solid targets and the quality of electron beams are the basic and key physics issues.
- Theory and experiment researches have indicated that the targets with various structured surfaces can enhanced energy coupling efficiency.
- In past years, by 2D-PIC simulation and analysis, the generation of fast electron beam with manageable spotsize and its control are studied by our group.

- we found that the tailored cone-nanolayer target, can not only improve the laser absorption but also can enhance the rate of production of hot electron effectively.

Huan Wang, Lihua Cao et al., Laser and Particle Beams (2012), 30, 553–558

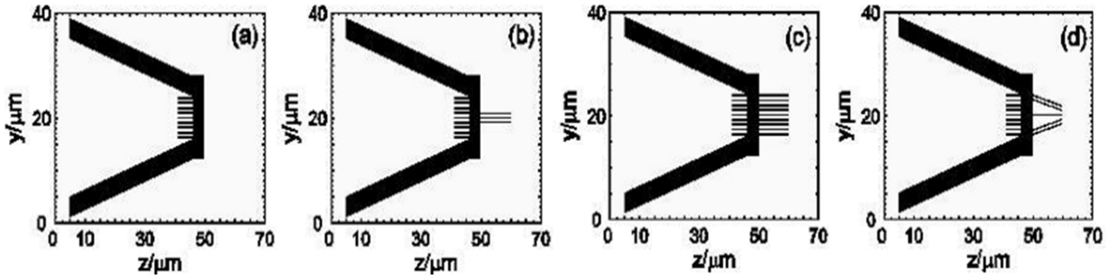


Fig. a) Classical target T1; tailored targets b) T2, c) T3, and d) T4. The cone has a 30^{o} opening angle and the nanolayers are of length 5λ, width 0.4λ, and interlayer spacing 0.4λ.

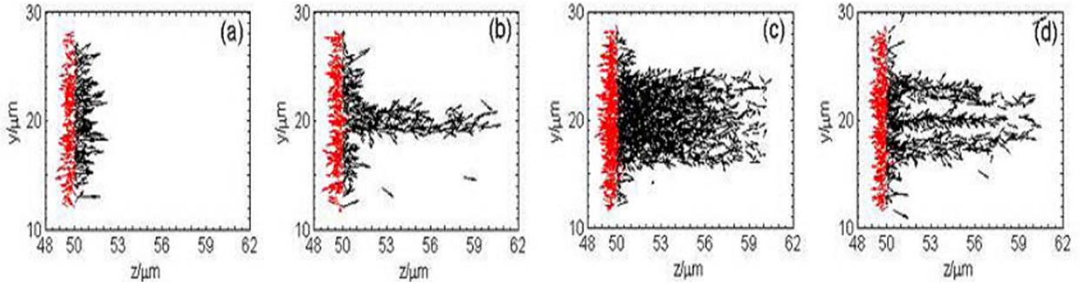


Fig. The momentum vectors of the forward (black) and backward (red) fast electrons with electron energies ≥1 MeV for (a) T1, (b) T2, (c) T3, and (d) T4 at t= 145T.

- Compared to the classical target, the tailored targets can efficiently limit the spotsize of fast electron beams and increase propagation distance beyond the cone tip, and the laser-to-beam conversion efficiency has also been enhanced.

The spotsize T1~13μm, T2~2μm, T3~7μm. For the focused target T4, spotsize T4 ~ 3μm. The maximum efficiency for T2 is about 2.5%, for T3 is 7.5%, for T4 is 4.4%, compared with 1.1% for T1

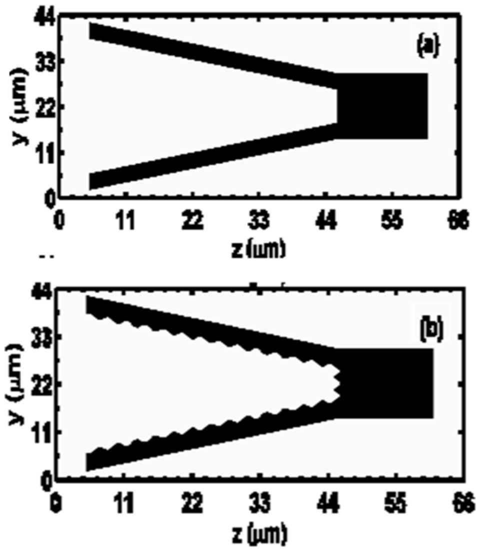
- Reasons of improvements: total absorption area enhanced due to the increasing of interaction region; laser focuses inside cone duo to non-linear deflection/refection of EM wave; and the confining EM field formation due to the fast electron propagation along plasma layers behind the cone tip.

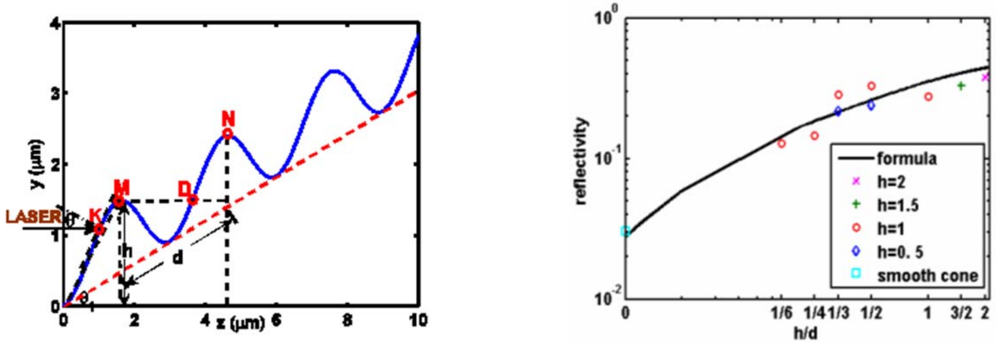
2.3) Effect of inner-surface roughness of conical target on laser absorption and fast electron generation

- ➢ In Fast Ignition research, in order to effectively guide or transport the energetic electrons to a suitable ignition point in dense compressed plasma over hundreds of micrometers, a practical scheme is to impinge a laser driving pulse on the cone inserted into the pre-compressed fuel.
- ➢ To improve the laser-to-electron energy conversion efficiency and the electron propagation, targets with different surfaces have been proposed and studied.

- ➢ **Our works:** By assuming a periodic corrugated surface, the effect of inner surface roughness on laser absorption, fast-electron generation and transport are investigated by 2D-PIC simulations, and a scaling law for the laser reflectivity based on the vacuum-heating model were obtained analytically.

Huan wang, Lihua cao, et al., Chin. Phys. B, 23, 055202 (2014).





Scaling of reflectivity

$R/\psi = 1 - \ln(1 + 4\zeta/\chi)/\zeta + 4/\{\chi(\chi + 4\zeta)\}$

Fig. Corrugated conical target surface and dependence of laser reflectivity with h/d

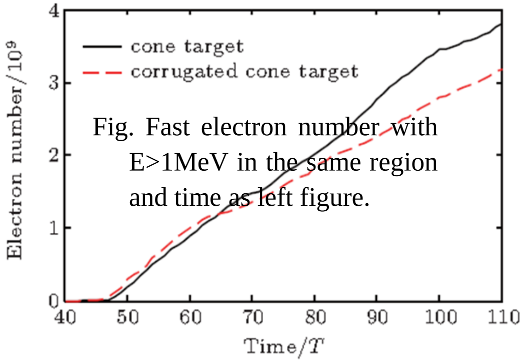


Fig. Fast electron number with E>1MeV in the same region and time as left figure.

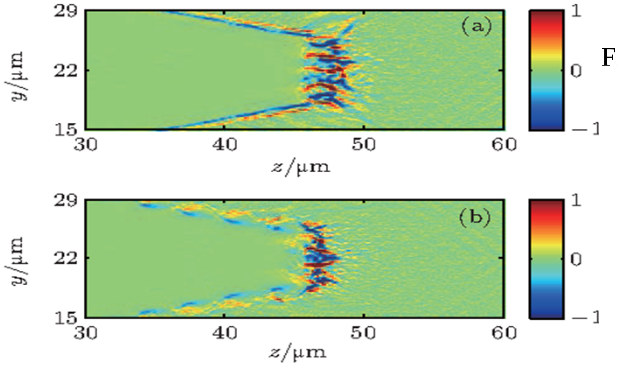


Fig. Snap shots of current component Jz which is averaged over five laser cycles and normalized by n_0ec at time 110T

- With the corrugated surface, the laser generated fast electrons in the skin layer of the inner wall are trapped and slowed by the induced electric and magnetic fields.
- A scaling law for the laser reflectivity is derived using a vacuum-heating model. Theory and simulation show that laser reflection increases with the height-to-width parameter k of the periodic corrugation, and it approaches the smooth surface case in the limit k✸0.
- Our results indicate that the smoothness of the inner surface should be taken into account in the fabrication of cone targets for ICF.

2.4) 2D hybrid model for high-current electron beam transport

- By considering the effect of background plasma on EM field, a 2D hybrid code is developed to model the transport of a high-current electron beam in a dense plasma target.

  Cao Lihua, Li Bawen et al., Plasma Science and Technology 16, 1007 (2014).

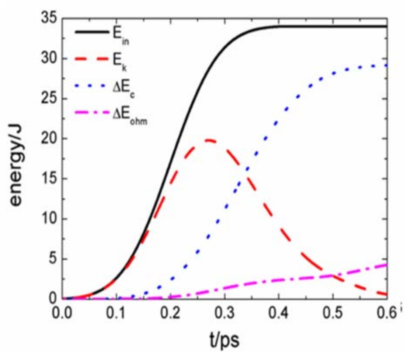
  - Assuming that $n_f << n_b$ and kinetic density >> background averaged temperature, then to treat the dense plasma as high density background and to describe it by using three quanta of temperature, density and ionization state.
  - To treat the electrons of electron beam as particles and to describe it by using PIC method in the case that electron collision effect with the background plasma were taken into account.
  - Electron beam transport model proposed by Davies is used. The total current density is the sum of beam and return current densities.

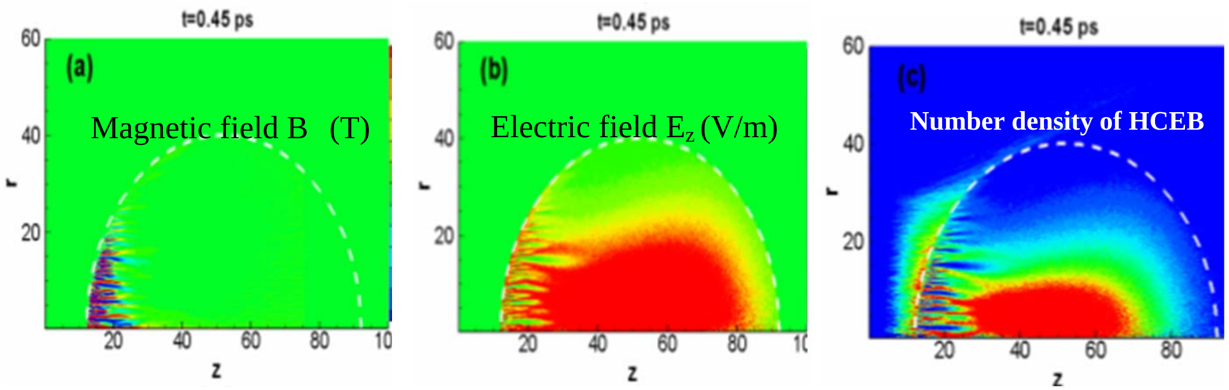
$$\mathbf{E} = -\eta \mathbf{J}_f + \eta \nabla \times \mathbf{B} / \mu_0 、\quad \frac{\partial \mathbf{B}}{\partial t} = \eta \nabla \times \mathbf{J}_f + \nabla \eta \times \mathbf{J}_f + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B} - \frac{1}{\mu_0} \nabla \eta \times \mathbf{B}$$

  - The changes in the momentum and scattering angle due to collisions are treated as follows:

$$dp = < \Delta P > \Delta t \approx -\frac{Z^* n_p e^4 \gamma^2 m}{4\pi \varepsilon_0{}^2 P^2} L_d \Delta t 、\quad d\theta = \left(\frac{Z^{*2} n e^4}{2\pi \varepsilon_0{}^2} \frac{\gamma m}{P^3} L_s \Delta t\right)^{1/2} \Gamma(t)$$

- The processes of transport and energy deposition of electron beam in background bulk DT plasma were simulated.
  - Uniform DT plasma ball with radius 40um, density 300g/cm^3, initial temp. 300eV, ionization state $Z^*=1$。
  - Electron beam generated by intense laser $I_p \, e^{-r^2/R_L^2} \, e^{-4(t-t_L)^2/t_L^2}$, peak laser intensity 10^{20}W/cm^2, spot size 20um, pulse duration 0.4ps, the converse efficiency from laser to beam electrons is assumed to be 30%.





- The magnetic field with a notable multiple filamentation structure appears near the incident surface, due to cB/E>>1, magnetic field plays important role in the transport process of electron beam. The positive longitudinal electric field hinders the propagation of electron beam.
- With continuous decreasing of the kinetic energy of electron beam, the field effect is suppressed, the energy deposition is dominated by Coulomb collision, so that the filament-like structure can be shown to exist only in the front part of plasma sphere and fades away gradually.
- The injected energy is 34J and about 98% of energy is lost or deposited. About 87% of the energy loss by Coulomb collisions, about 11% of the energy loss by electric field effect or Ohmic heating.

2.5) Kinetic simulation research of gas-puff Z-pinch

- The Z-pinch is self-pinch process that the current-carrying fluid is driven to move inwards by Lorentz force j×B. Recently, it has been again recognized due to the remarkable X-ray yield of wire-array implosion, the high neutron yields of capsule implosion in dynamic hohlraum and deuterium gas-puff Z-pinch experiments, and the measurement of plasma opacity.
- Z-pinch may become a promising approach in high energy density physics researches, especially, in the ICF (energy) research. More experimental and theoretical studies are further required for well understanding the physics of Z-pinch.
- **Kinetic PIC simulation of deuterium gas-puff Z-pinch**

Welch’s group first realized the kinetic simulation of gas-puff Z-pinch. They found that the neutron production and instability development happened in PIC simulations earlier than in the corresponding MHD simulations. Welch, et al., PRL 103, 255002 (2009); POP 17, 072702 (2010), etc.

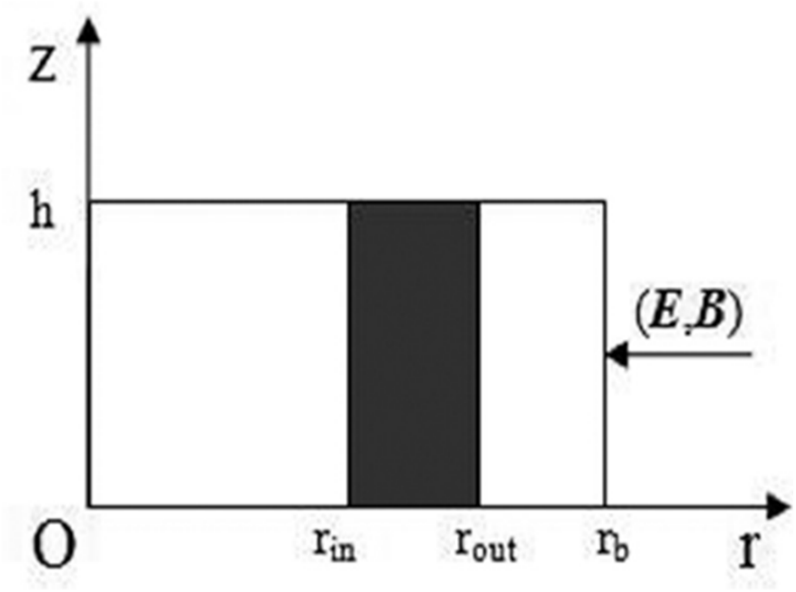
- **Gas-puff Z-pinch simulation in Our group**

A kinetic PIC code is developed in 2D cylindrical coordinates. We focus on revealing the micro dynamic process of Z-pinch, and simulate a rarefied deuterium plasma shell Z-pinch driven by a low current (433A).

C. Ning, Z.X Feng, C. Xue and Baiwen Li, POP 22, 022710（2015）;

C. Ning, Z.X Feng, C. Xue and Baiwen Li, Acta Phys Sin 63, 185203 (2014)

Simulation Model and Parameters



1) The gap between the cathode and the anode is 1cm

2) Inner radius $r_{in} = 0.6cm$

Outer radius $r_{out} = 1.0cm$

3) $r_b = 1.5cm$, the magnetic field is put here

4) Spacial resolution $\Delta_r = \Delta_z = 0.01cm$

Constant temporal resolution $\Delta t = 2\times10^{-13}s$

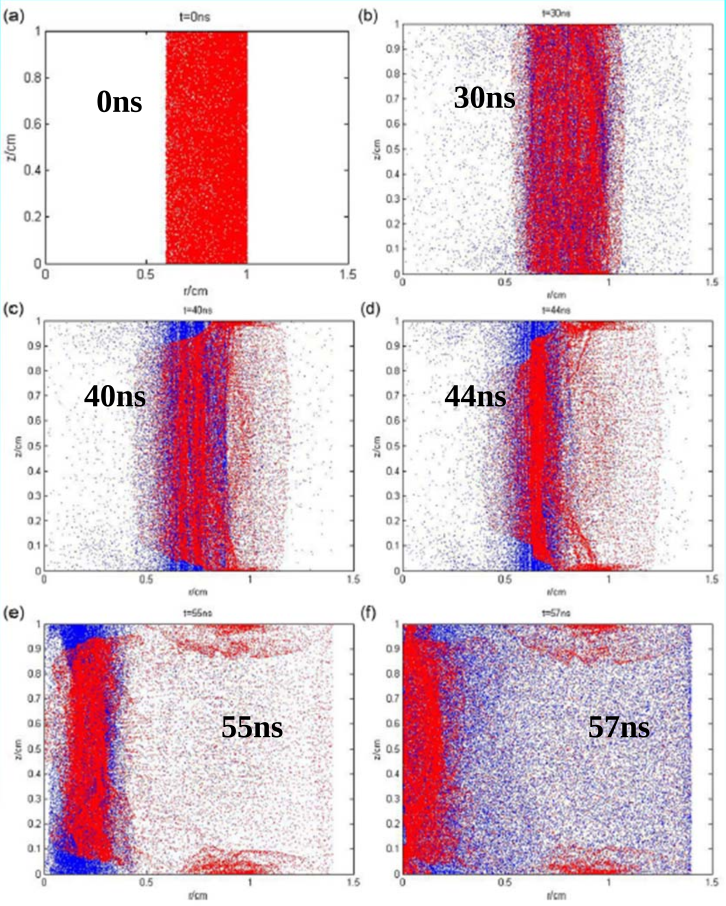
5) Linear mass of the plasma shell: $1\times10^{12}\mathrm{g/cm^3}$

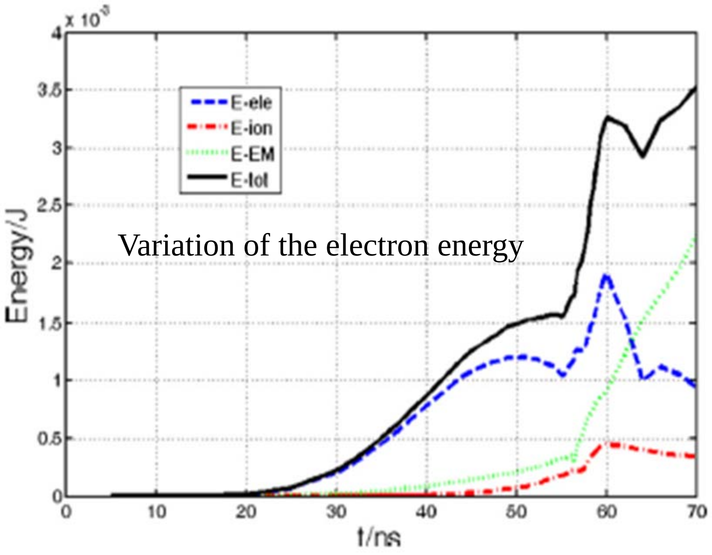
6) Matched current is taken as $I(t) = 433\sin^4\left(\pi t/2T_0\right)$

where the period is taken as $T_0 = 50ns$

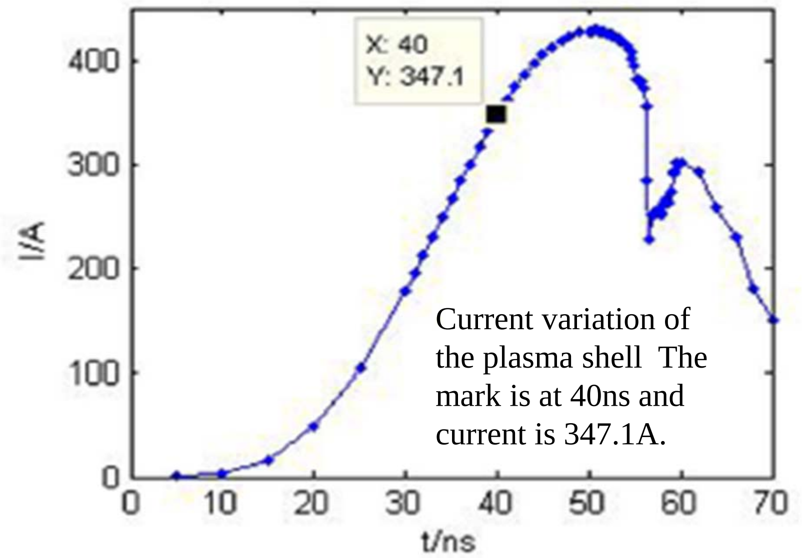
The particle phase-space snapshots

- The particle phase-space snapshots reveal the micro dynamic process of Z-Pinch clearly
  - The particles are moving self-consistently due to the particle motion in their integrated EM fields.
  - As time goes on, first the particles distribute broadly in radius; then the electrons and ions separate; finally, the nonuniformity of particle density appears.
  - With the driven current increasing, most of the particles are propelled inwards to the axis, but some particles have lagged back, especially at around the anode and cathode.
  - At about 56 ns, most of the particles get into stagnation phase and then return outwards.

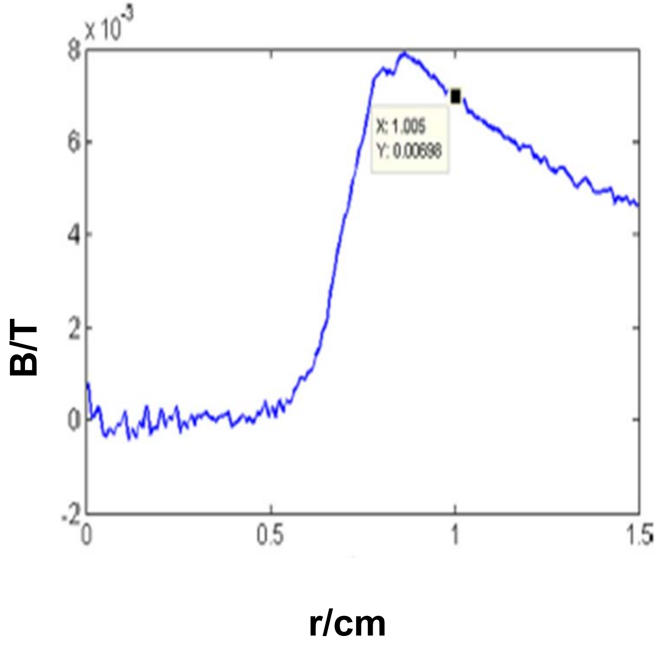




Variation of the electron energy

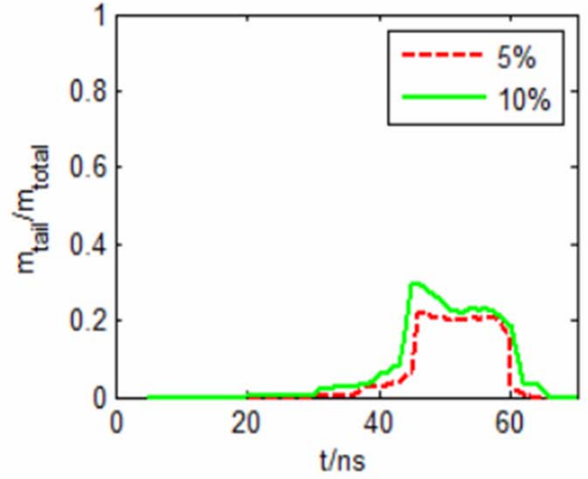


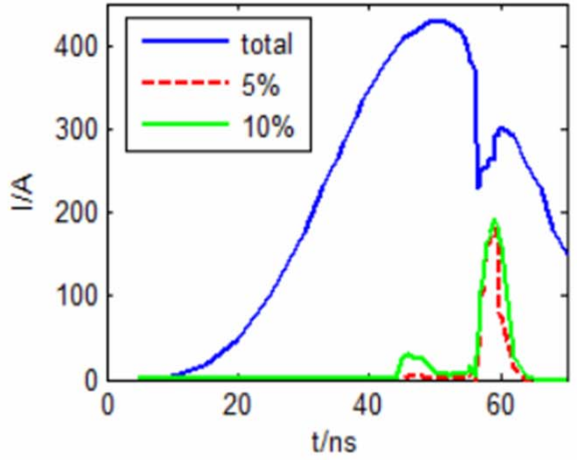
Current variation of the plasma shell The mark is at 40ns and current is 347.1A.



- The electron energy is dominating in the system energy before the Z-pinch stagnation.
- The current is almost the same as the driven current before peak current. After that, it reflects the plasma Z-pinch characteristic, it gets minimum when the plasma runs into the stagnation, and then, begins to increase after the plasma moves outwards.

The variations of the trailing mass and trailing current





- The trailing mass and current are accorded with observation result of experiment
  - At about 30ns, trailing mass begin to appear, they increase quickly and reach their peaks of 20~30% of the total mass of the shell. Then, they decrease, and later get roughly saturated.
  - At about 60ns, they drop fast because the ions move inversely and quickly distribute more uniformly, due to the ES repulsive interaction between ions.
  - At about 44ns, when the trailing masses increase abruptly, the trailing currents begin to form. Under the trailing criterion of 10%, the trailing current reaches its peak of 7% of the total driven current at 46ns and decreases to about 2% after 50ns.

3) Summary

- The high-energy density physics, its potential science importance of HEDP researches in astrophysics, ICF physics and particle acceleration, and the typical large-scale HEDP research facilities (NIF, LMJ, SG etc) are introduced briefly.
- Our recent works in the directions of target composition scheme for high-quality proton beam generation; simulation of Z-pinch dynamics; enhanced laser absorption, electron beam generation and control by structured target; and transport and energy deposition of high-current electron beam in a dense plasma in fast ignition condition, etc, are presented.

Thank you for your attention