Proton Beam Acceleration with Circular Polarized Laser Pulses

X.Q.Yan

Institute of Heavy Ion physics, Peking University, China

Center of Applied Physics and Technology, Peking Univeristy

Peking Univ.: J.E.Chen, X.T.He, C.Lin, H.Y.Wang, S.Zhao, J.Zhu, H.Z.Fu, Y.Shang, K.Zhu, Z.Wang, Y.R.Lu , Z.Y.Guo

Shanghai Jiaotong Uni.(China)/IOP: Z.M.Sheng, Y.T.Li, L.M. Chen, J.Zhang

MPQ/LMU: T.Tajima, J. Meyer-ter-Vehn , D.Habs, J. Schreiber,R.Hoerlein, A.Henig, D.Kiefer, D.Jung

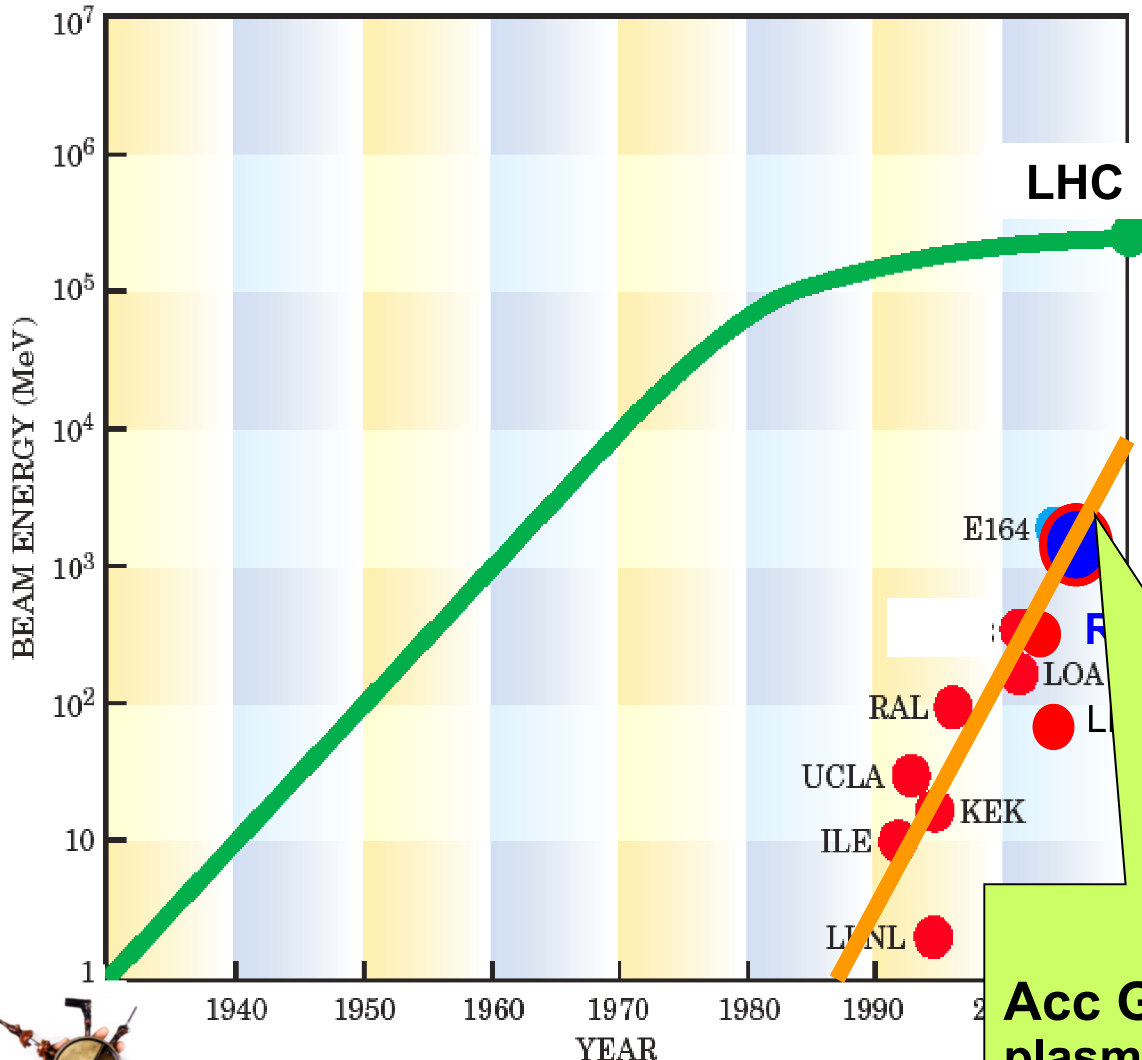
IZEST/LOA: G.Mourou

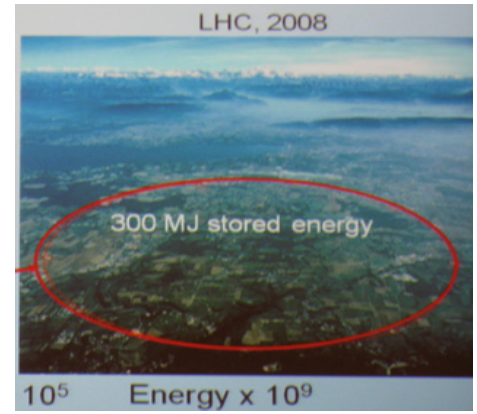
LANL: M. Hegelich, H.C.Wu, L.Yin

Outline

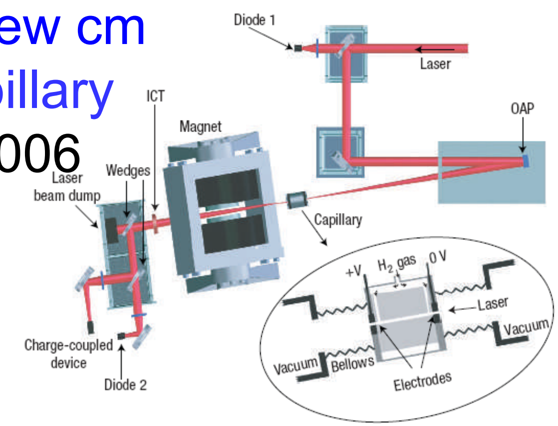
1. Why laser plasma accelerator
2. Phase Stability Acceleration (PSA) in a laser plasma accelerator
3. Challenges of PSA acceleration
4. Future plan at Peking University

Livinston Chart





LBL 1GeV
by few cm
Capillary
in 2006



Acc Gradient of Laser plasma accelerator is 100GV/m!

Laser Plasma Wake Accelerator (LWPA)

- 1979 Tajima and Dawson propose LWPA.

John M Dawson（1930-2001）

Toshiki Tajima

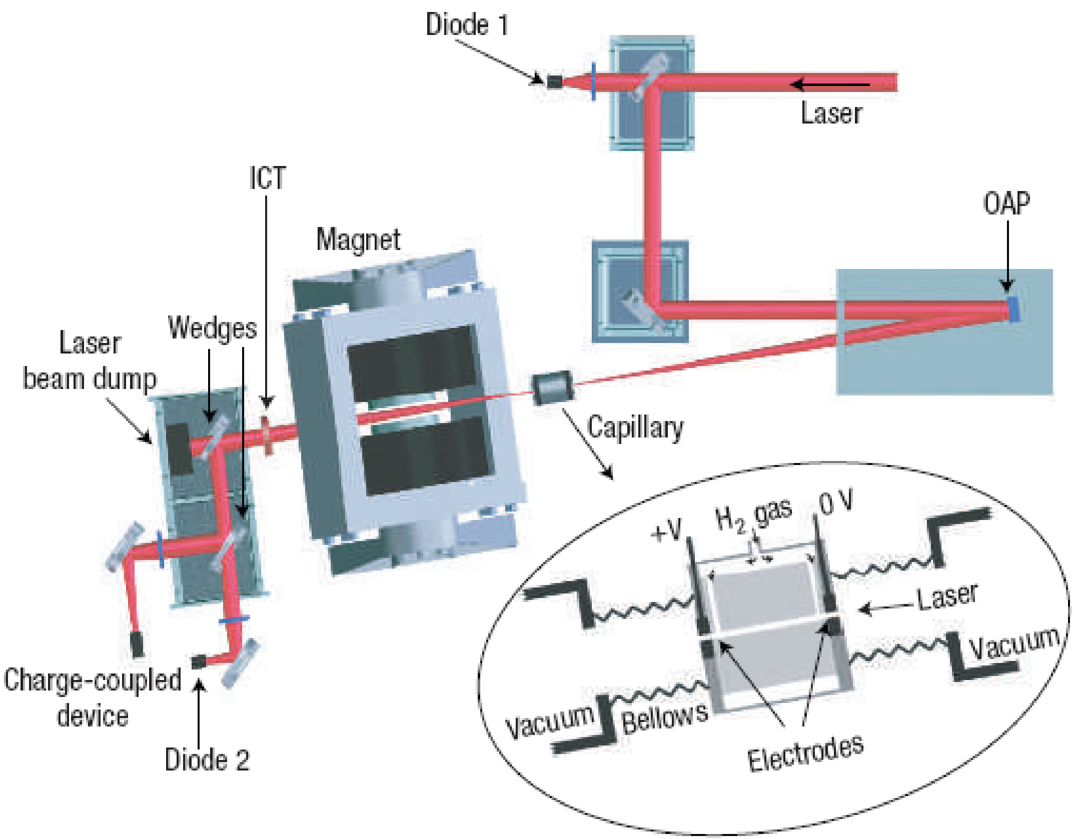
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

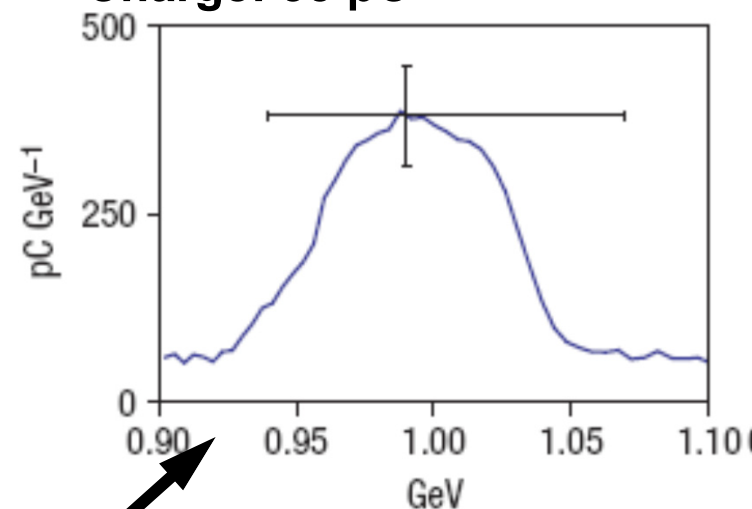
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

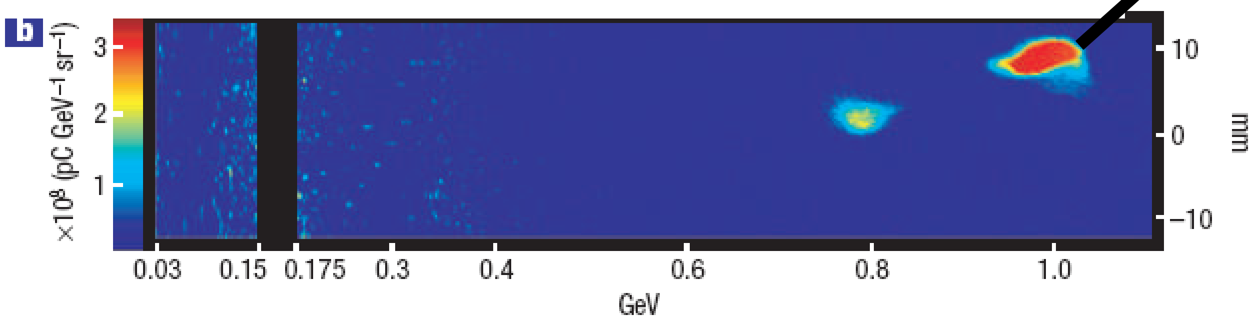
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

1GeV mono-energetic electron beam



- Divergence(rms): 1.6 mrad
- Energy spread (rms): 2.5%
- Resolution: 2.4%
- Charge: 35 pC

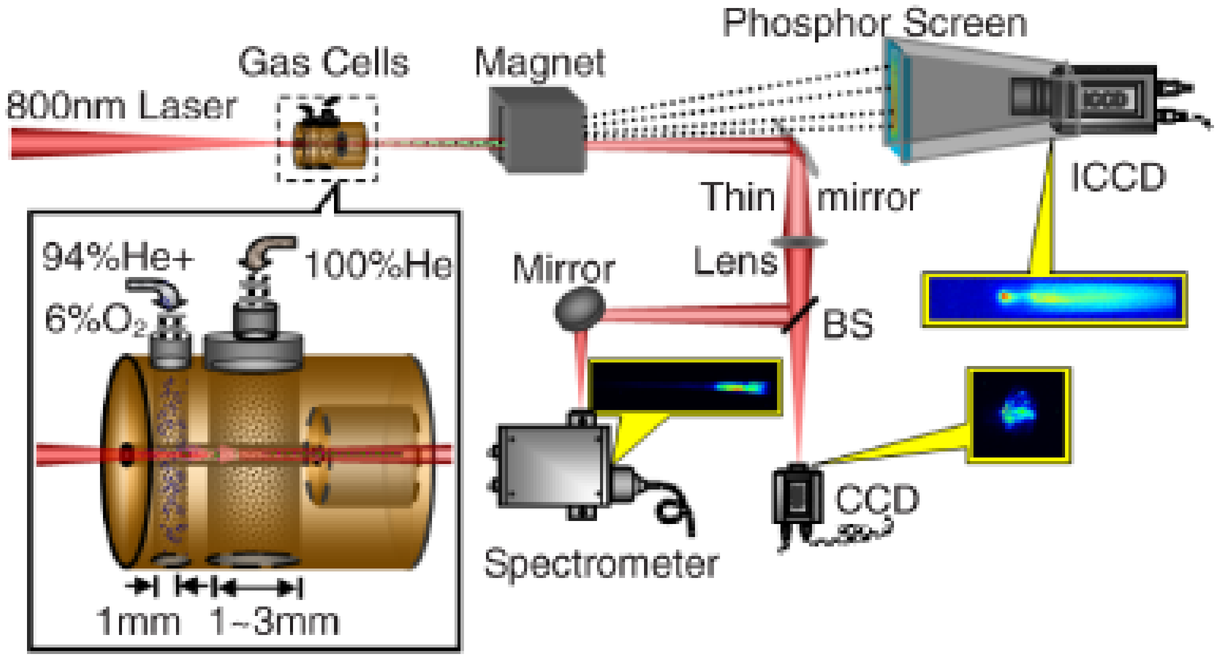


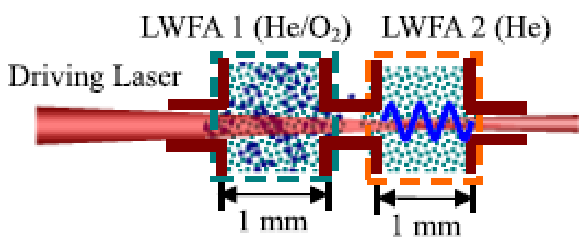


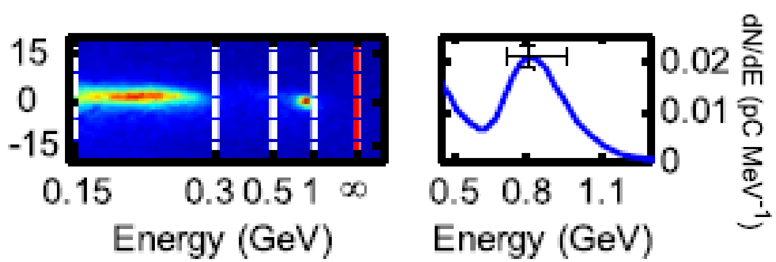
Nature physics VOL.2 , 2006

（Leemans et al）

0.8 GeV mono-energetic electron beam







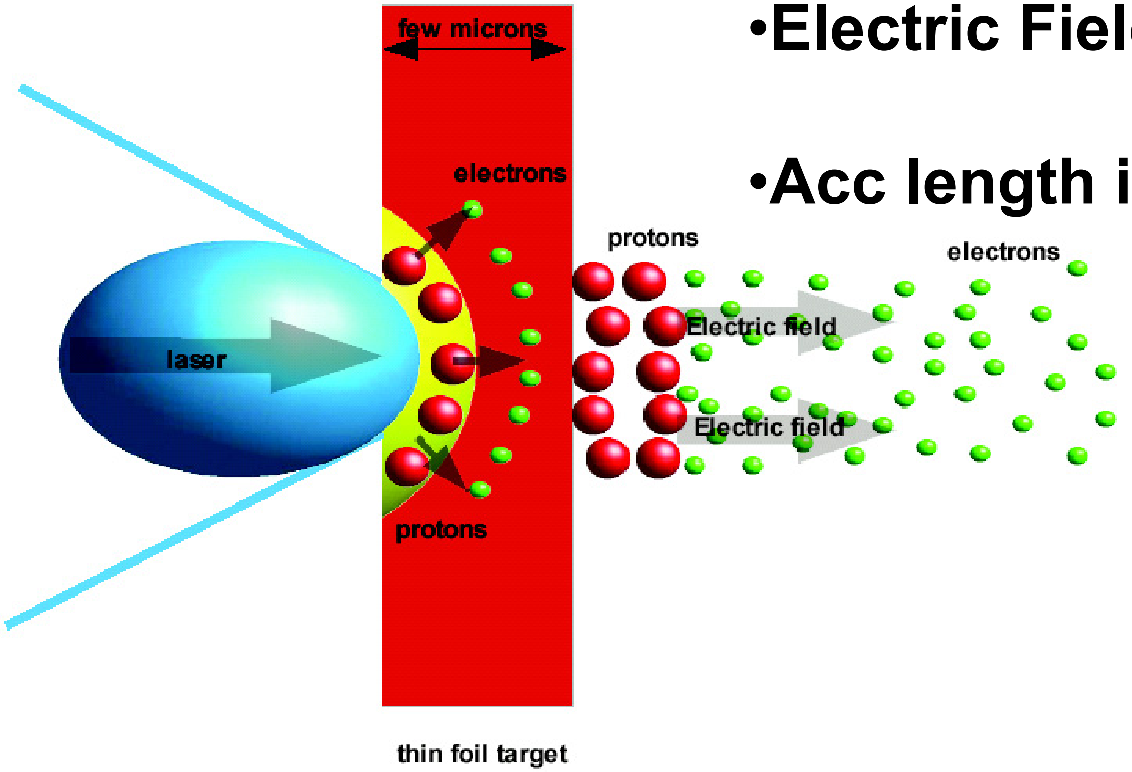
Cascaded Laser Wakefield Acceleration Using Ionization-Induced Injection

Z. Z. Xu et al. PRL 107, 035001 (2011)

Shanghai Institute of Optics and Fine Mechanics

Target Normal Sheath Acceleration (TNSA)

Ions are much more heavier than electrons, the plasma wake field can hardly trap and accelerate slow ions! They are mainly accelerated from solid targets by TNSA so far.

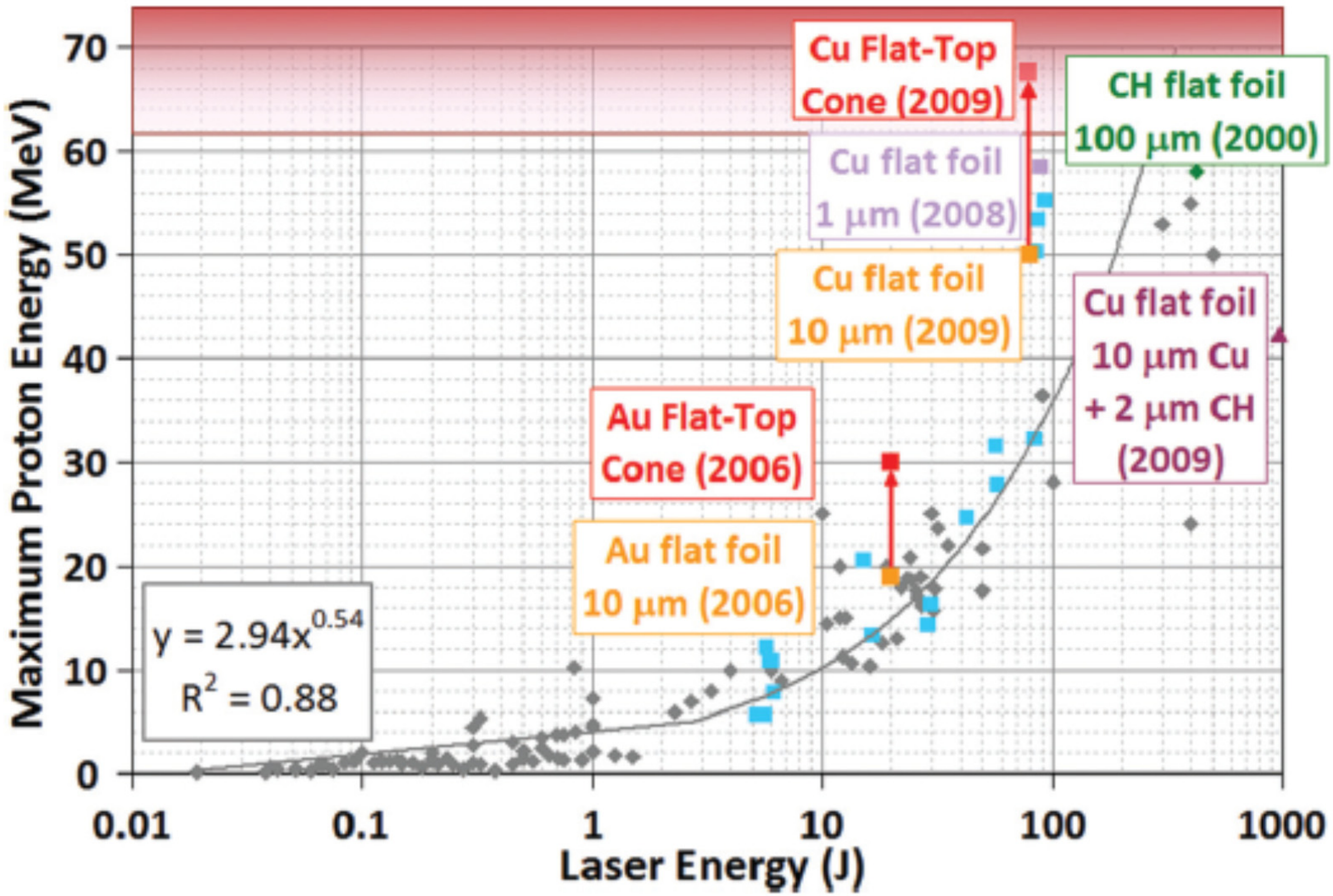


- Electric Field: >TV/m!!!
- Acc length is only few microns

Phys. Rev. Lett. **85**, 2945 (2000).

Phys. Plasmas 18, 056710 (2011)

Target Normal Sheath Acceleration (TNSA)



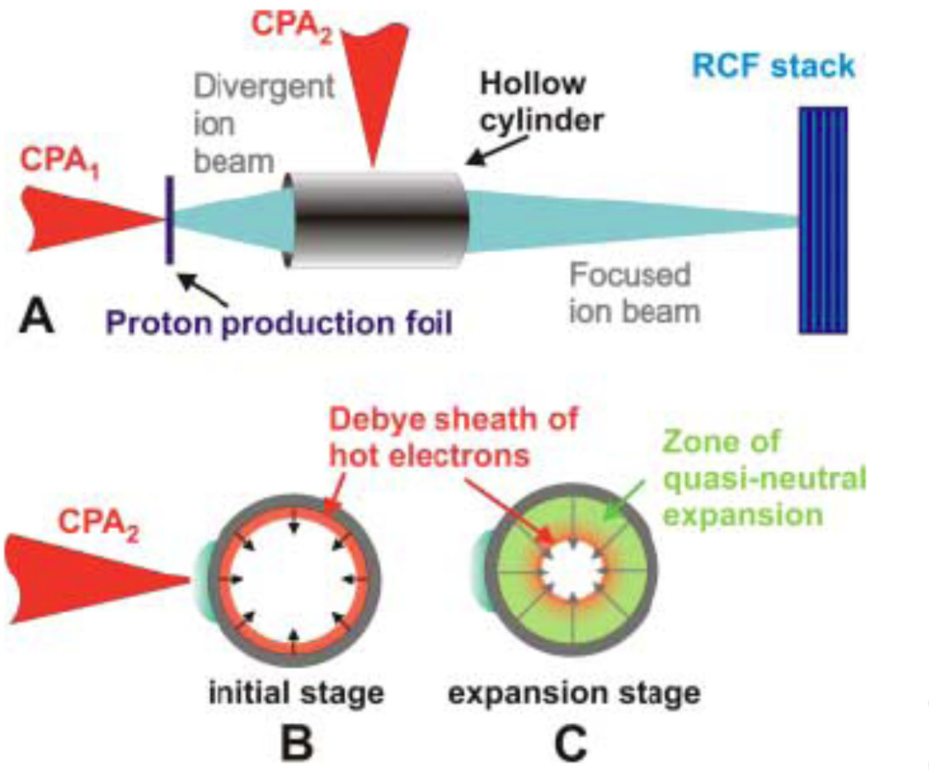
Maximum proton energy 60 MeV in 2000 and 68 MeV in 2011, moreover the spectrum is still exponential!

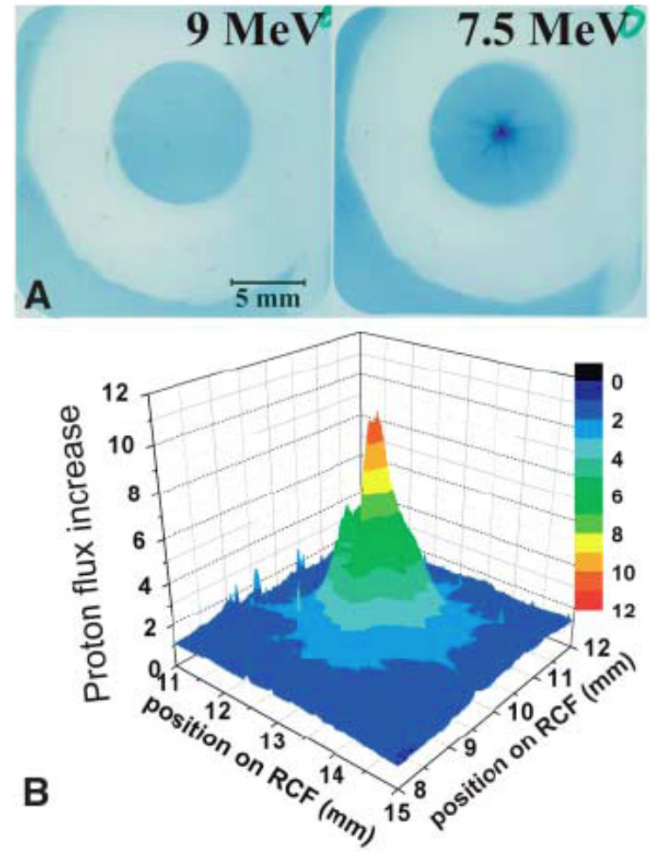
Phys. Rev. Lett. **85**, 2945 (2000). Phys. Plasmas 18, 056710 (2011)

Laser–Driven Microlens

T.Toncian et al., SCIENCE, 312,**410, 2006**

Focus and Energy-Select Mega–Electron Volt Protons



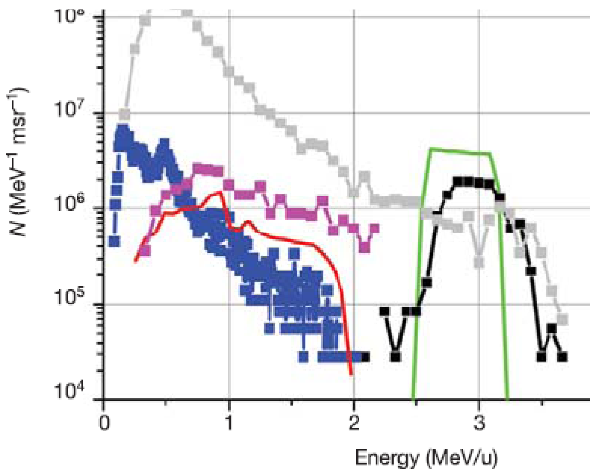


High energy and low energy spread?

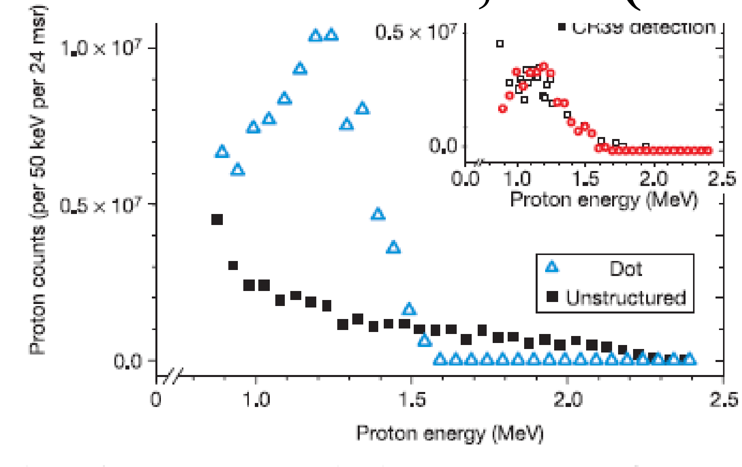
Micro-structured target

reducing the energy spread, still MeV energy

Hegelich et al., Nature 439, 441 (2006)



H. Schwoerer, et al. Nature 439, 445 (2006).



High energy and low energy spread?

Outline

1. Why laser plasma accelerator
2. Phase Stability Acceleration (PSA) in a laser plasma accelerator
3. Challenge of PSA acceleration
4. Future plan at Peking University

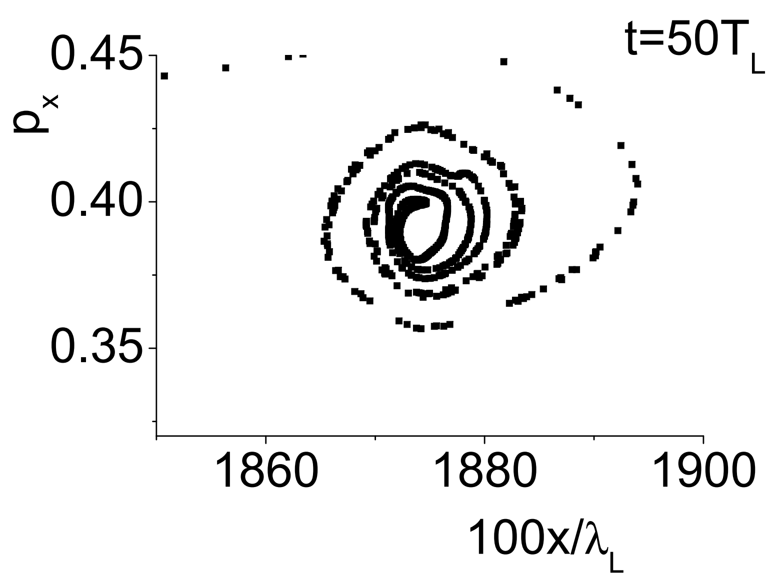
2. Phase Stability Acceleration (PSA)

Radiation Pressure Acceleration

- B.Shen et. al., PRE, VOLUME 64, 056406(2001)
- A. Macchi, et al, Phys. Rev. Lett. 94, 165003 (2005)
- Xiaomei Zhang, et al, PHYSICS OF PLASMAS 14, 123108 (2007)
- X.Q.Yan et al , PRL, 100, 135003 (2008)
- Rykovanov, et al, NJP. 10, 113005 (2008)
- Klimo et al, PRST 11, 031301 (2008)
- Robinson et al, NJP 2008
- M. Chen et al., Phys. Rev. Lett. 103, 024801 (2009).
- A.Henig et al. PRL 103, 245003 (2009)

Circular Polarized (CP) pulse + nanometers foil

Mono-energetic ion beam



Synchrotron oscillation

Ponderomotive force

- **Linear polarized laser**

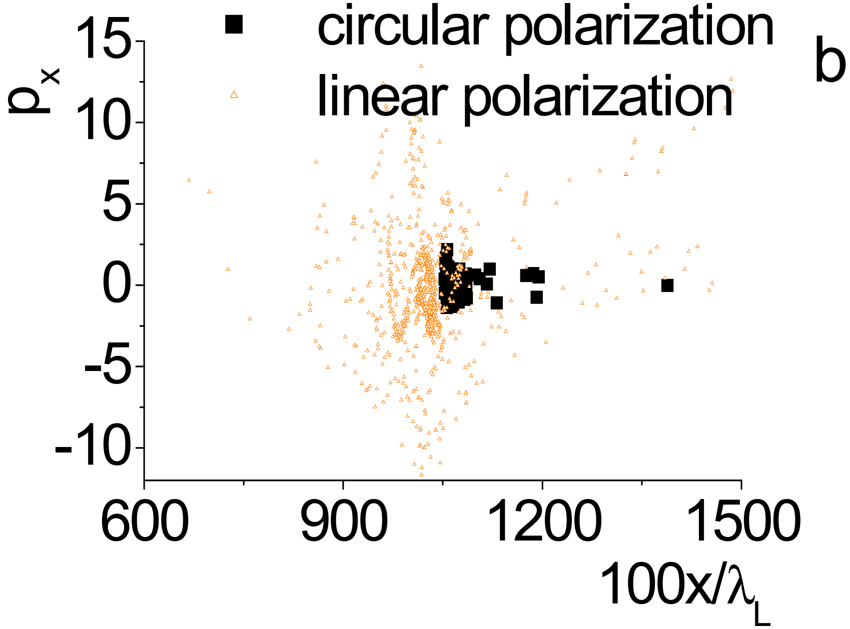
$$v_L(x) = eE_L / m\omega_L$$

$$f_p = -\frac{m}{4}\frac{\partial}{\partial x} v_L^2(x)(1-\cos 2\omega_L t)\hat{x}$$

Circular Polarized laser

$$E = E_L(x)(\sin(\omega_L t)\hat{y} + \cos(\omega_L t)\hat{z})$$

$$f_p = -\frac{m}{4}\frac{\partial}{\partial x} v_L^2(x)\hat{x}$$

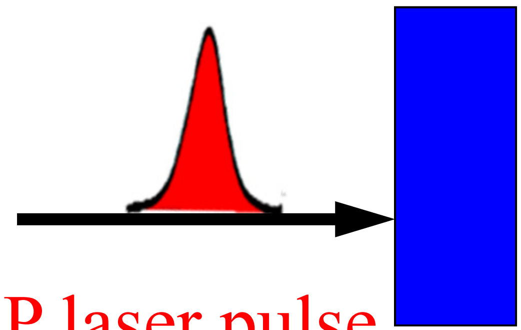


1D simulation

$a=5$, $n_0/n_c=10$, $L=0.2\lambda$

No oscillation component, it pushes electrons forward!

Phase Stable Acceleration model

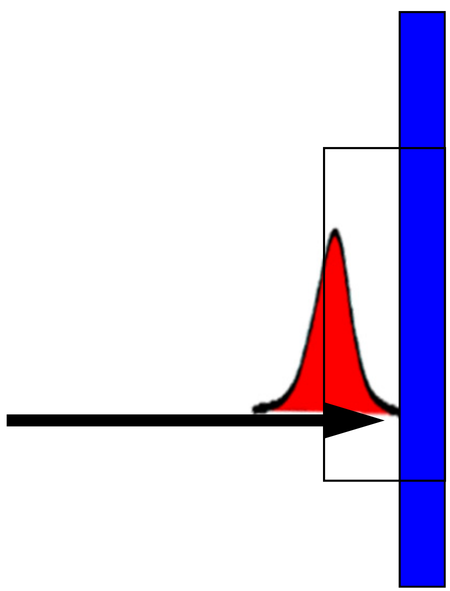


electron

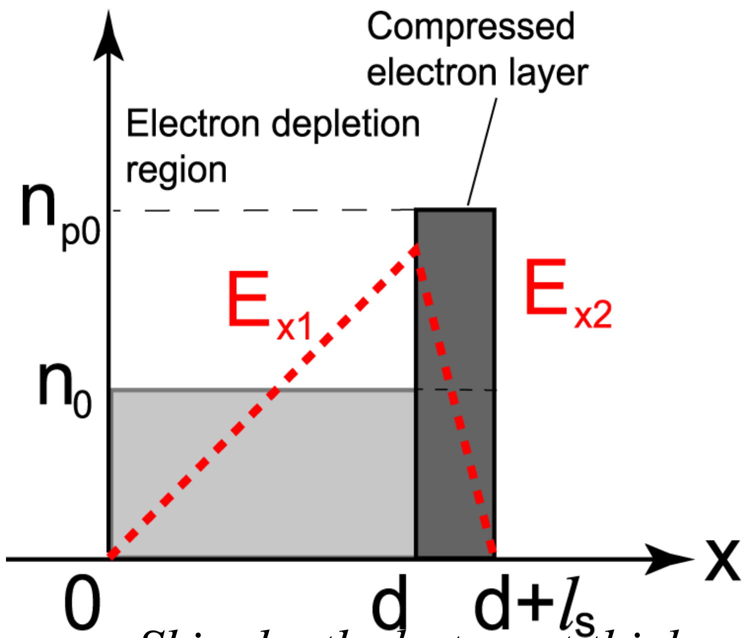
proton

CP laser pulse

- Electrons are pushed forward and pile up in the front of a CP laser pulse .



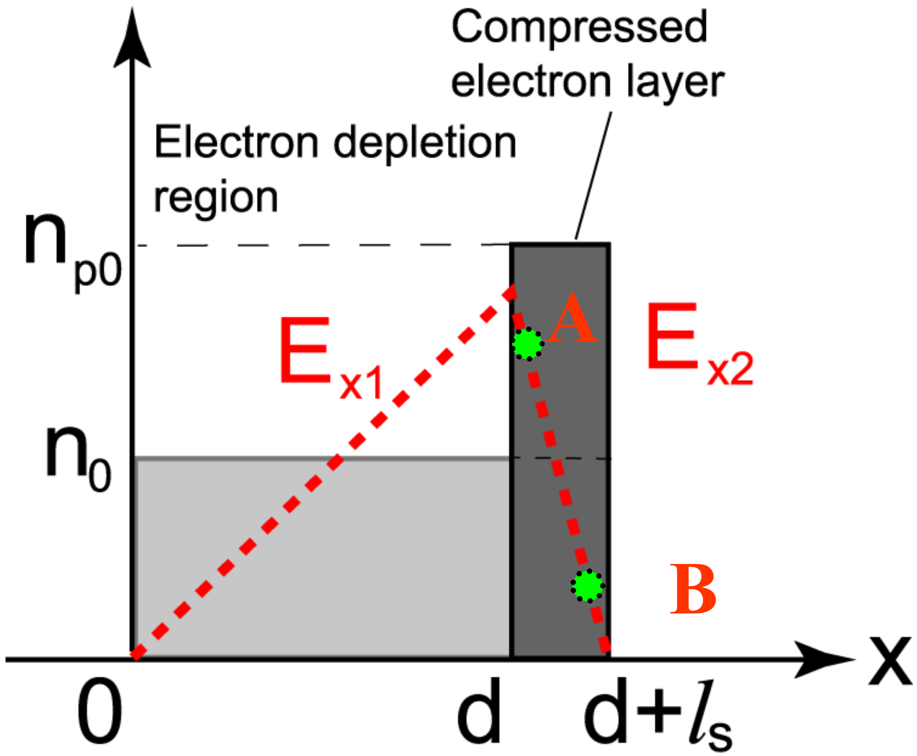
Protons are nearly fixed

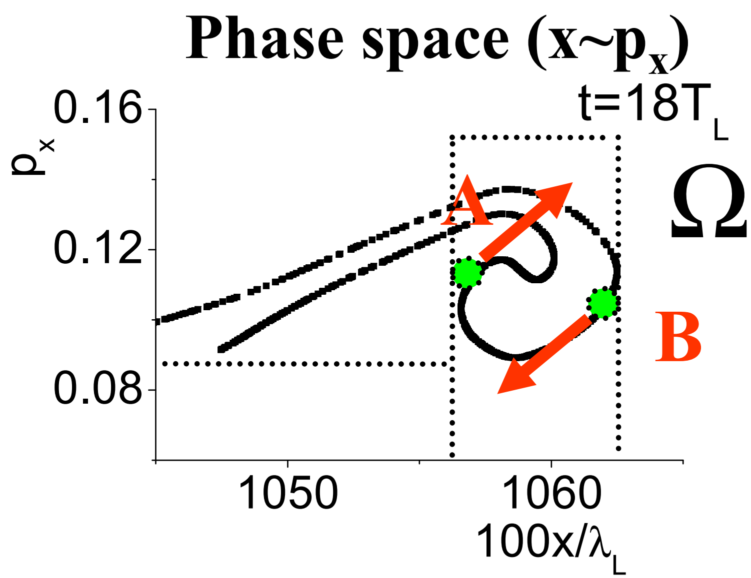


Skin depth: l_s, *target thickness* $d+ls$

Phase Stability Acceleration when

$$a \sim (n_0 / n_c) D / \lambda_L$$





$$E_{x1} = E_0 x / d, (0 < x < d) \qquad E_0 = 4\pi n_0 d$$

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

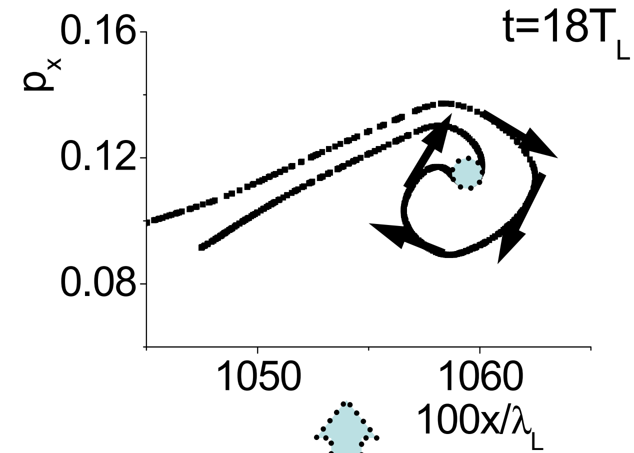
X.Q.Yan et al, PRL 100, 135003 (2008)

Phase motion is harmonic

Motion equations:

$$\frac{d^2x_i}{dt^2} = \frac{q_iE_0}{m_i\gamma^3}(1-(x_i-d)/l_s)$$

$$\frac{d^2x_r}{dt^2} = \frac{q_rE_0}{m_i\gamma^3}(1-(x_r-d)/l_s)$$



Phase motion equation:

$$\ddot{\xi} = -\Omega^2\xi, \Omega^2 = \frac{q_iE_0}{m_il_s\gamma^3}$$

$$\xi = \xi_0 \sin(\Omega t)$$

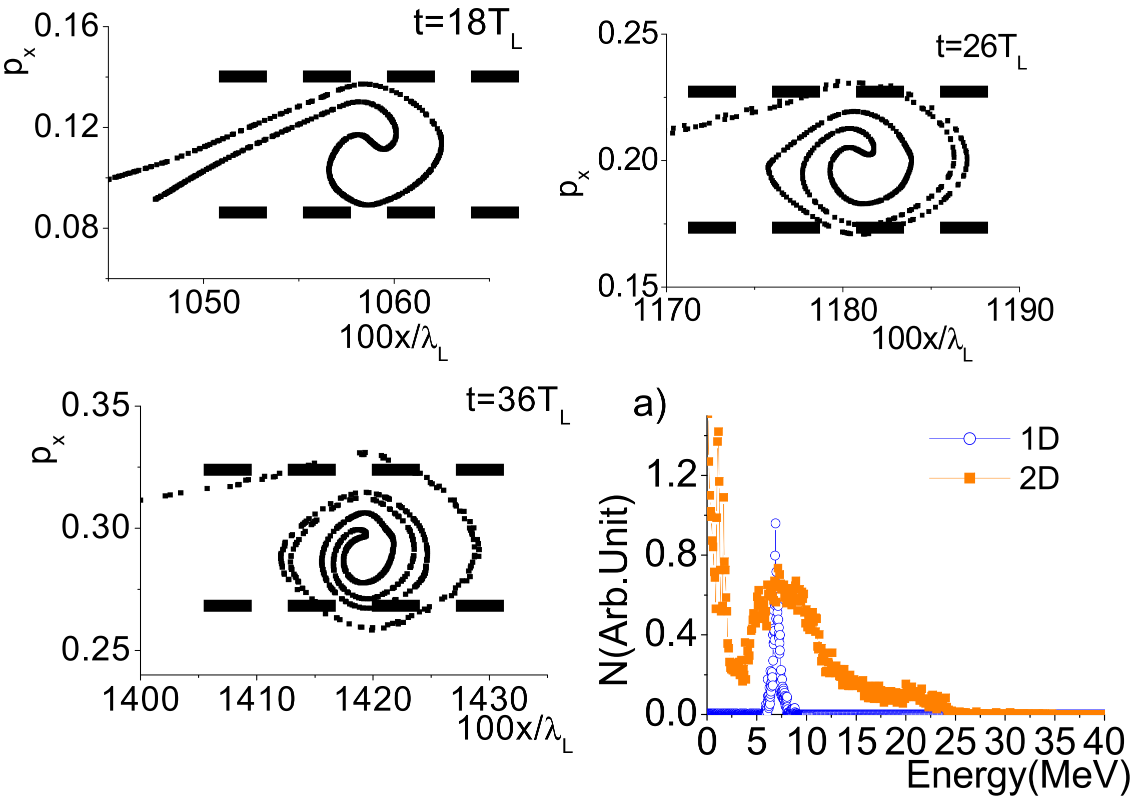
For proton/ions $\gamma \sim 1$, The phase motion is harmonic with frequency Ω

The energy spread is derived:

$$\Delta w / w_r \approx 2\xi_0\Omega / p_r$$

Phase oscillations in Simulations

a=5, n_0/n_c=10, L=0.2λ, τ=100 T_L



Ions are trapped in the bucket!

$$v_{i,\mathrm{buc}} = \zeta\Omega = \sqrt{\frac{m_e}{m_i}\,a_0\,c\,N^{-1/4}}$$

$$\frac{\Delta W}{W_r} \cong 2\xi_0\Omega / p_r = l_s\Omega / p_r$$

The periods are 8, 8 and 10 T_L

X.Q.Yan et al CHIN.PHYS.LETT. Vol. 25, No. 9 (2008) 3330

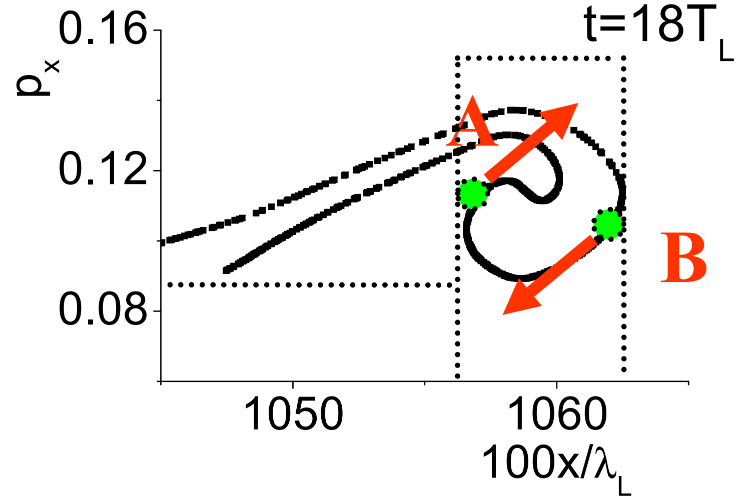
•Phase stability

1945: E. McMillan and V.J.Veksler （1944） discover the principle of phase stability

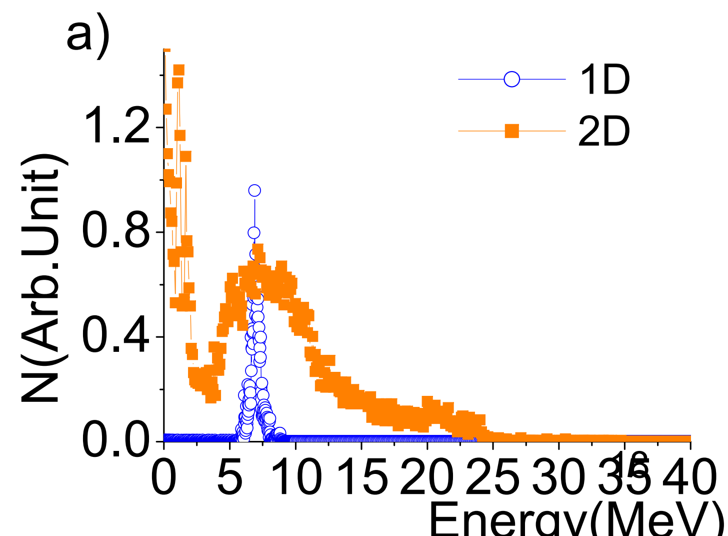
Photo by U. Amaldi

1959: Veksler visits McMilan at Berkeley

Phase space ($x \sim p_x$)



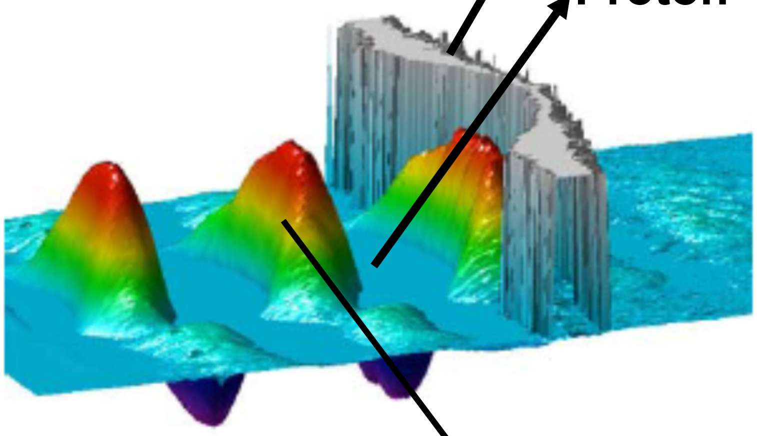
Particles are compressed in the phase space!



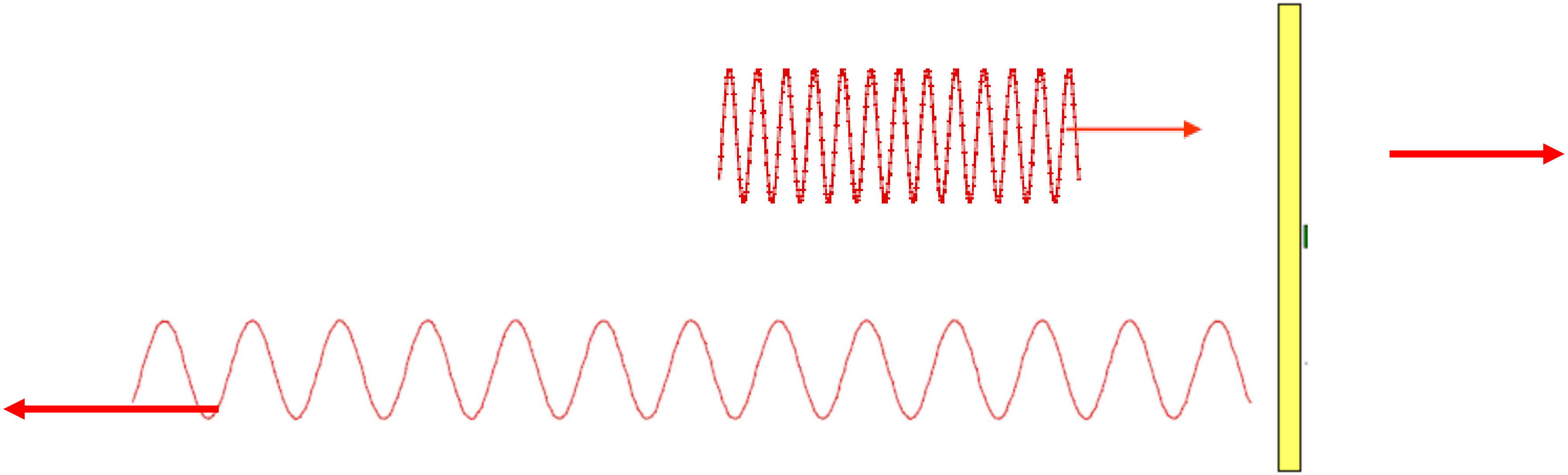
Sail model for PSA acceleration

Sailboat

PSA



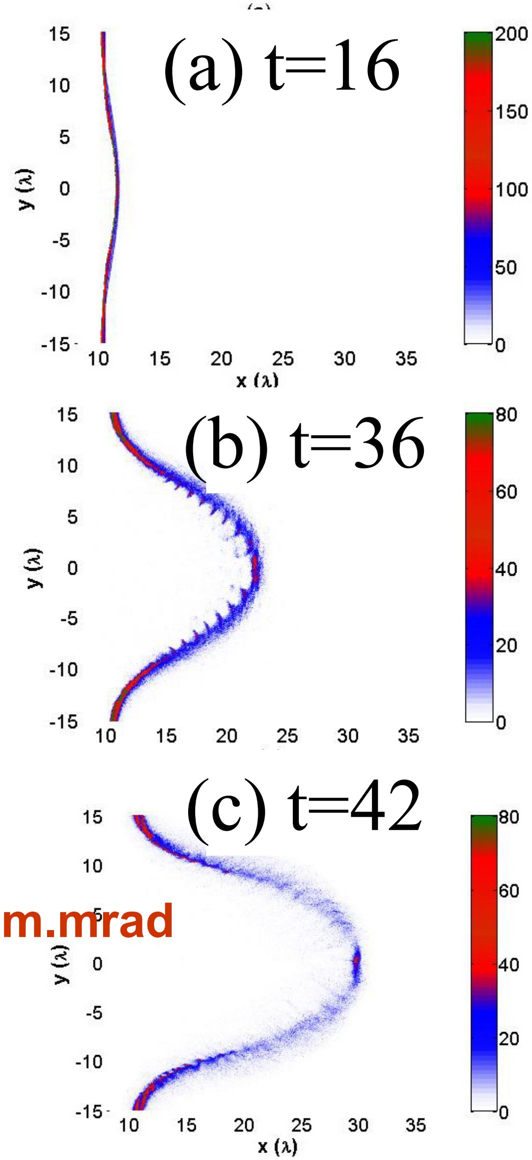
Conversion Efficiency (CE)



$$CE = 1 - \frac{1}{4\gamma^2} \sim 100\%$$

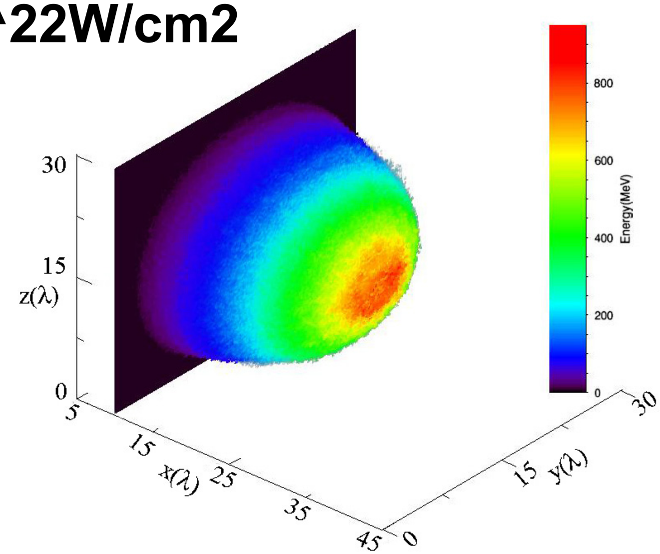
A. Einstein, Annalen der Physik 17, 891 (1905)

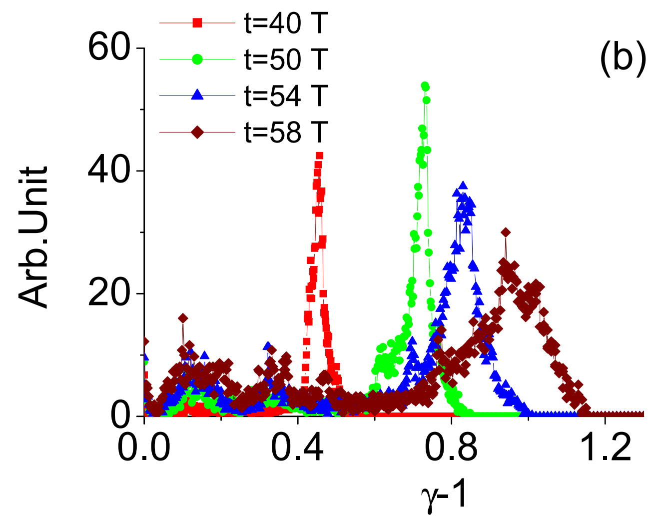
Self-organizing GeV proton in Phase Stable regime



ε_r~0.5 mm.mrad

I~10^22W/cm2





X.Q.Yan, W.H.C, Z.M.Sheng,J.E.Chen, J.MtV, et al., PRL, 103, 135001, (2009)

Demonstration of PSA

PRL **103,** 245003 (2009) PHYSICAL REVIEW LETTERS

$a \sim (n_0/n_c)D/\lambda_L$

Radiation-Pressure Acceleration of Ion Beams Driven by Circularly Polarized Laser Pulses

A. Henig,[1,2,*] S. Steinke,[3] M. Schnürer,[3] T. Sokollik,[3] R. Hörlein,[1,2] D. Kiefer,[1,2] D. Jung,[1,2] J. Schreiber,[1,2,4] B. M. Hegelich,[2,5] X. Q. Yan,[1,6,†] J. Meyer-ter-Vehn,[1] T. Tajima,[2,7] P. V. Nickles,[3] W. Sandner,[3] and D. Habs[1,2]

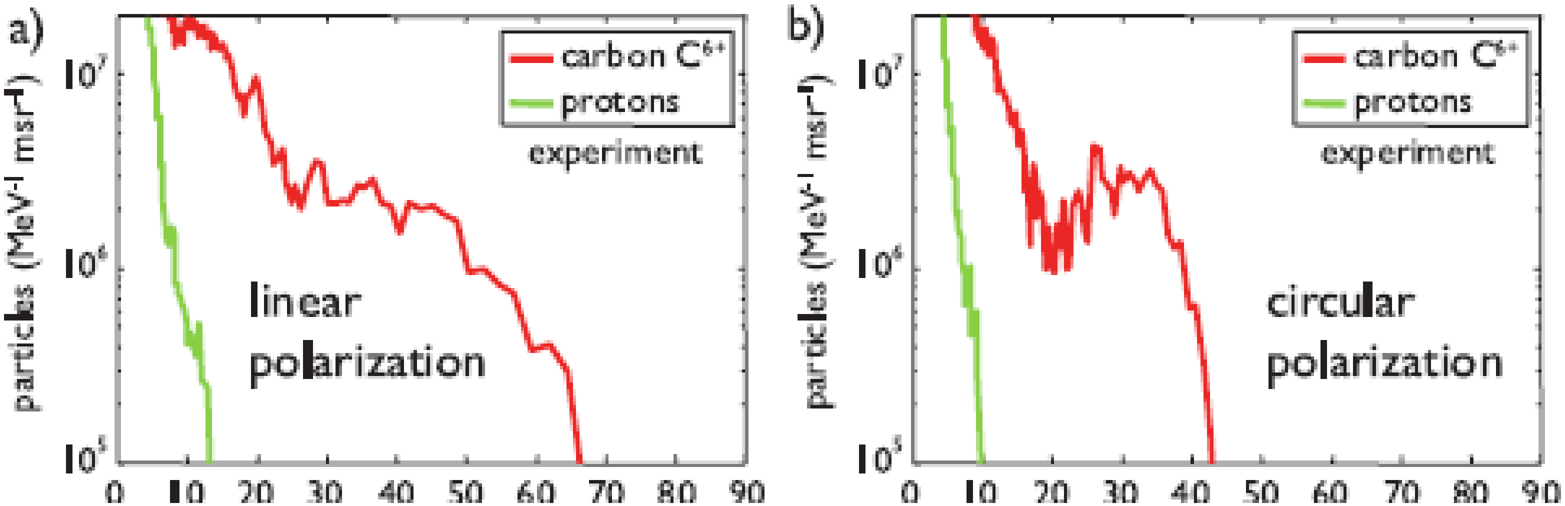
[1]*Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*

[2]*Department für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*

[3]*Max-Born-Institut, D-12489 Berlin, Germany*

[4]*Plasma Physics Group, Blackett Laboratory, Imperial College London, SW7 2BZ, United Kingdom*

[5]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

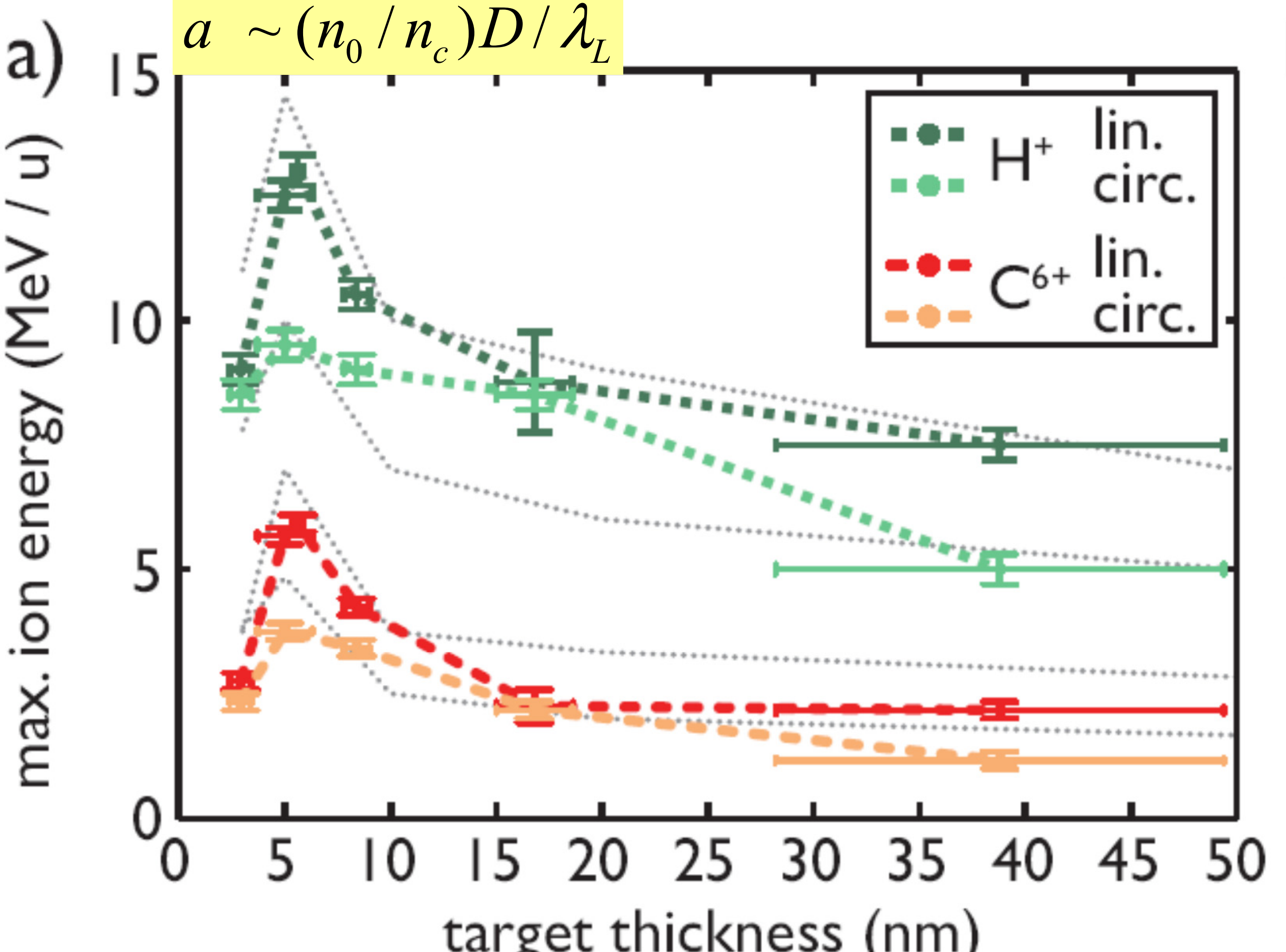


I~5*10^19W/cm2,5nm DLC foil

13MeV proton; 30MeV carbon

Optimum thickness of DLC is 5nm

$a \sim (n_0 / n_c) D / \lambda_L$



PSA has rigorous request on laser contrast!

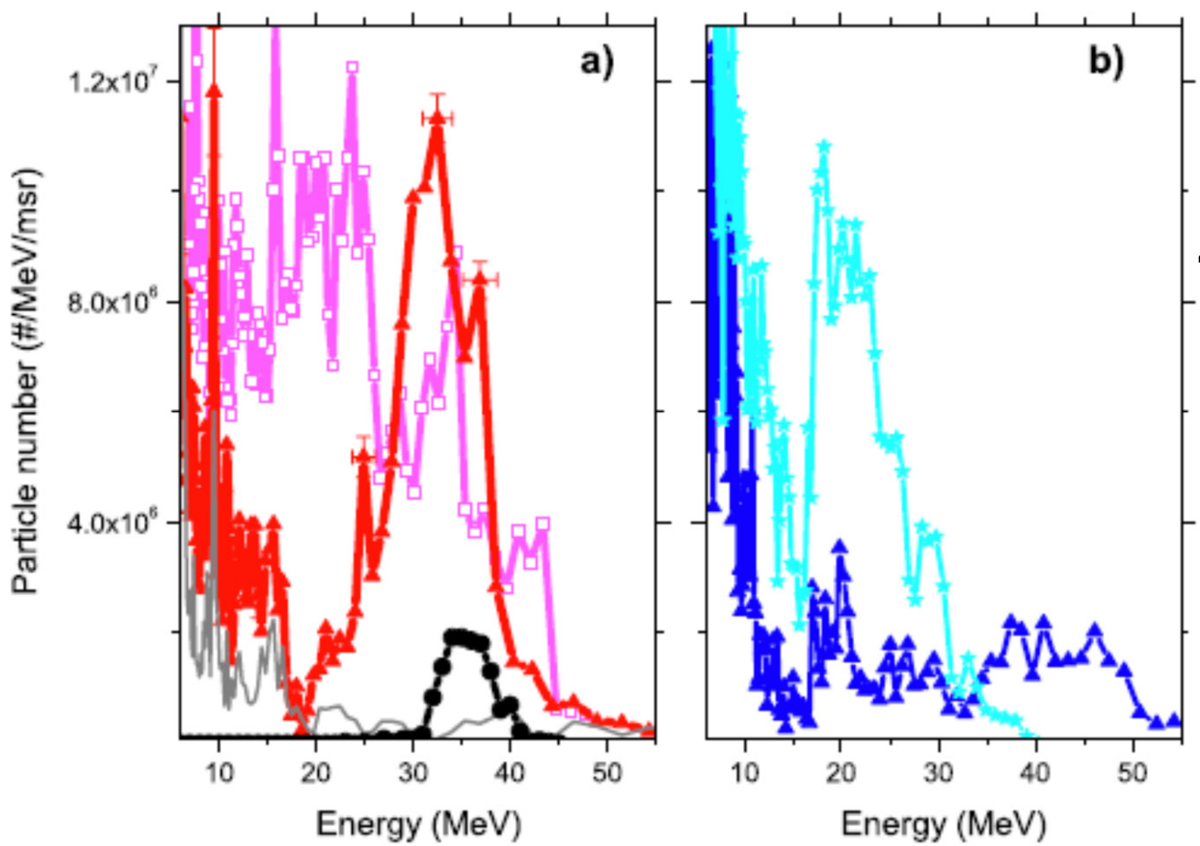
Demonstration of PSA

PRL 107, 115002 (2011) PHYSICAL REVIEW LETTERS

$a \sim (n_0 / n_c) D / \lambda_L$

Monoenergetic Ion Beam Generation by Driving Ion Solitary Waves with Circularly Polarized Laser Light

D. Jung,[1,2,3,*] L. Yin,[1] B. J. Albright,[1] D. C. Gautier,[1] R. Hörlein,[2,3] D. Kiefer,[2,3] A. Henig,[2,3] R. Johnson,[1] S. Letzring,[1] S. Palaniyappan,[1] R. Shah,[1] T. Shimada,[1] X. Q. Yan,[3] K. J. Bowers,[1] T. Tajima,[2] J. C. Fernández,[1] D. Habs,[2,3] and B. M. Hegelich[1,2]

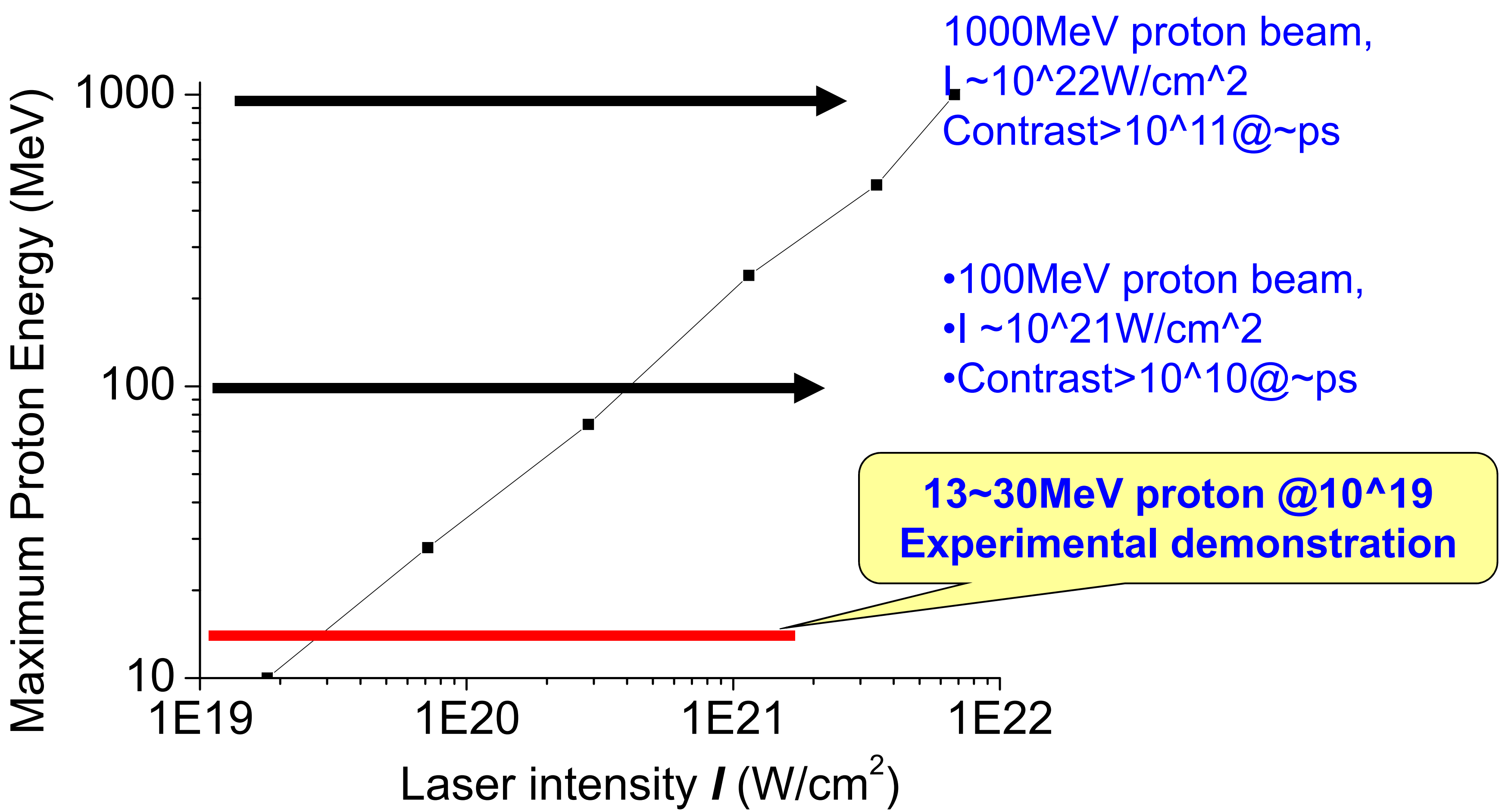


I~10^20W/cm2
5nm DLC foil
40MeV carbon

Outline

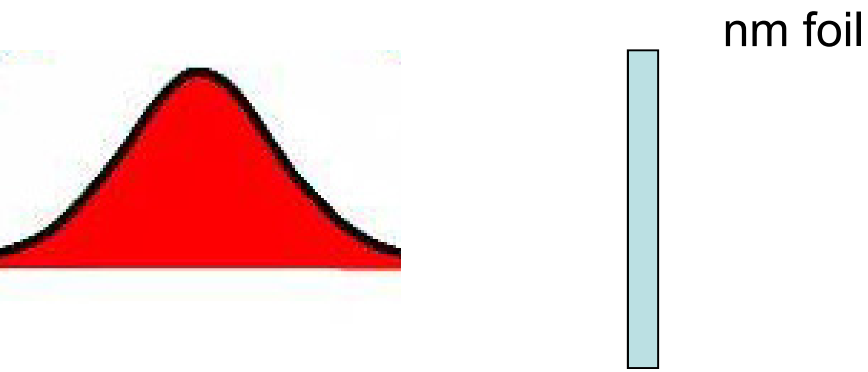
1. Why laser plasma accelerator
2. Phase Stability Acceleration (PSA) in a laser plasma accelerator
3. Challenges of PSA acceleration
4. Future plan at Peking University

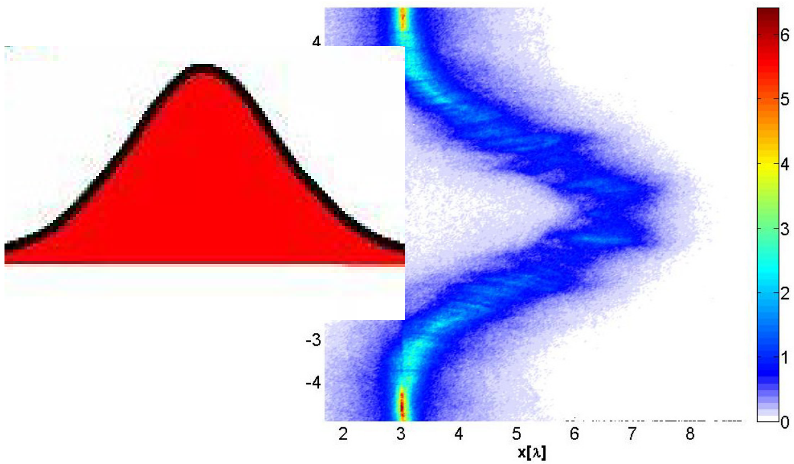
RPA Challenge (I): High Laser Intensity



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

Laser pulse front breaks the foil



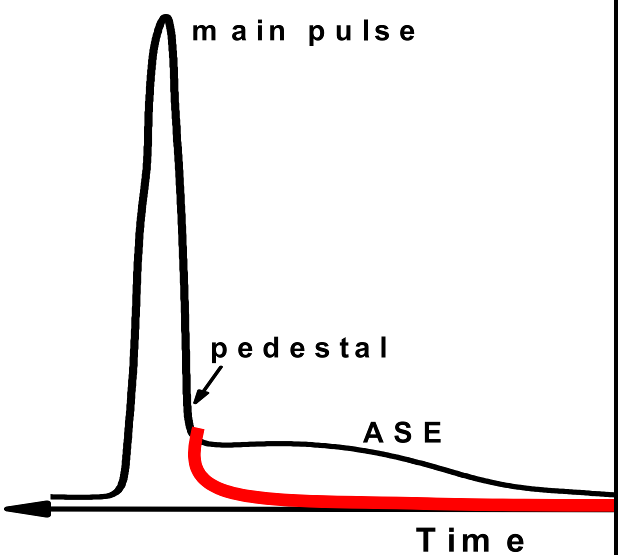


Laser front Breaks the foil!!!

Contrast = peak intensity / intensity at laser front

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

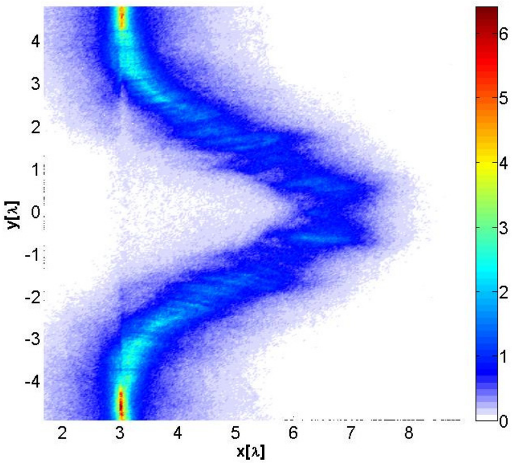
It is very difficult to satisfy a contrast >10^{10} @10ps,ns and an intensity of 10^{20}W/cm^2 !



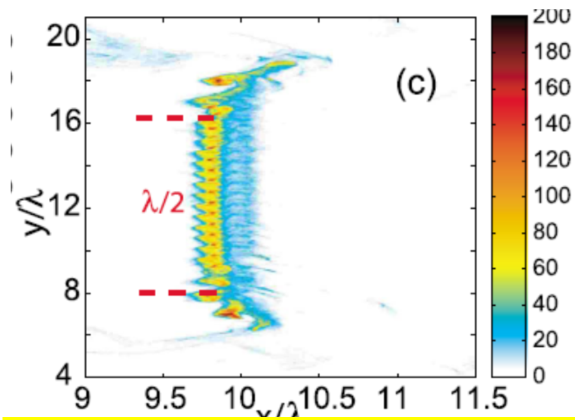
	Power TW	Intensity W/cm^2	Contrast in ps
SILEX-I	300	10^{19}	<10^6
QG-III (上海)	890	10^{19}	<10^6
LANL, USA	100	10^{20}	10^{10}
MBI, Germany	40	10^{19}	10^{10}
JAERI, Japan	800	10^{19}	<10^6
XL-II	20	10^{19}	<10^6
Astra	500	10^{20}	10^7

1. **Amplified Spontaneous Emission**
2. **Pedestal：100ps before the main pulse**

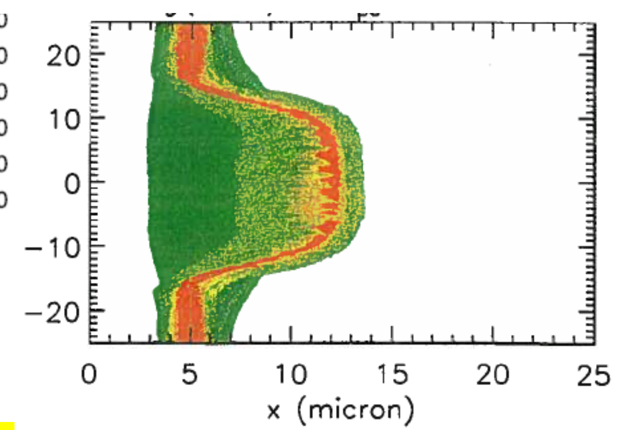
RPA Challenge (III): Hole boring and Instabilities



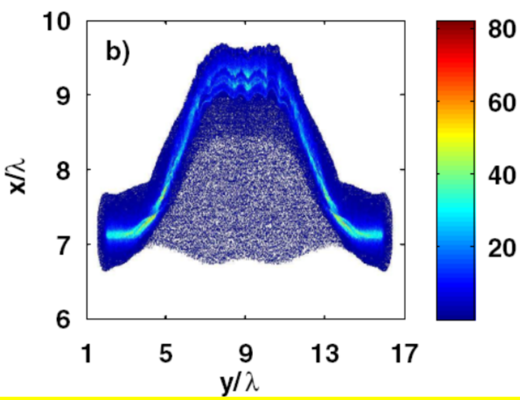
Hole boring



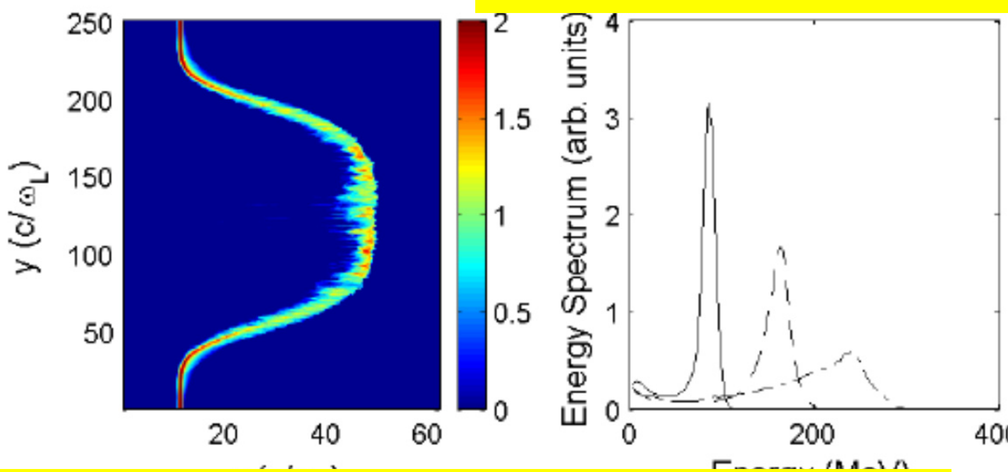
M.Chen et al PoP, 15, 113103, 2008



M.Hegelich and L.Yin



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



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

Challenges in PSA regime

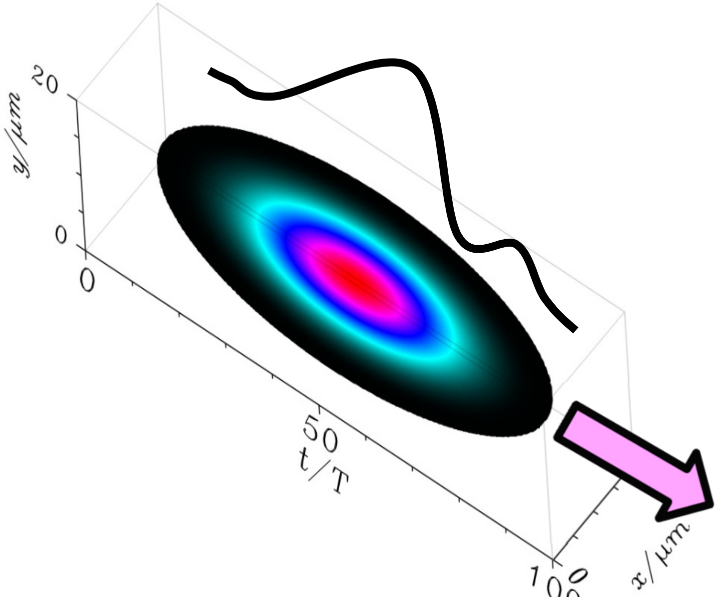
- **High laser intensity** **>10^21W/cm2**
- **High contrast** **>10^10@10ps,ns**

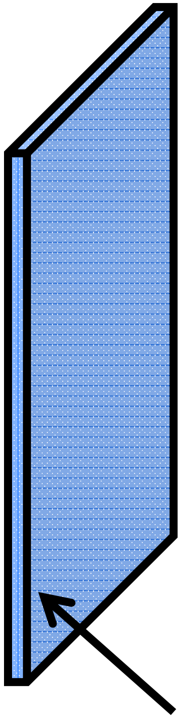
- **Hole boring and instabilities:**

Short rise time (1~3T) is required

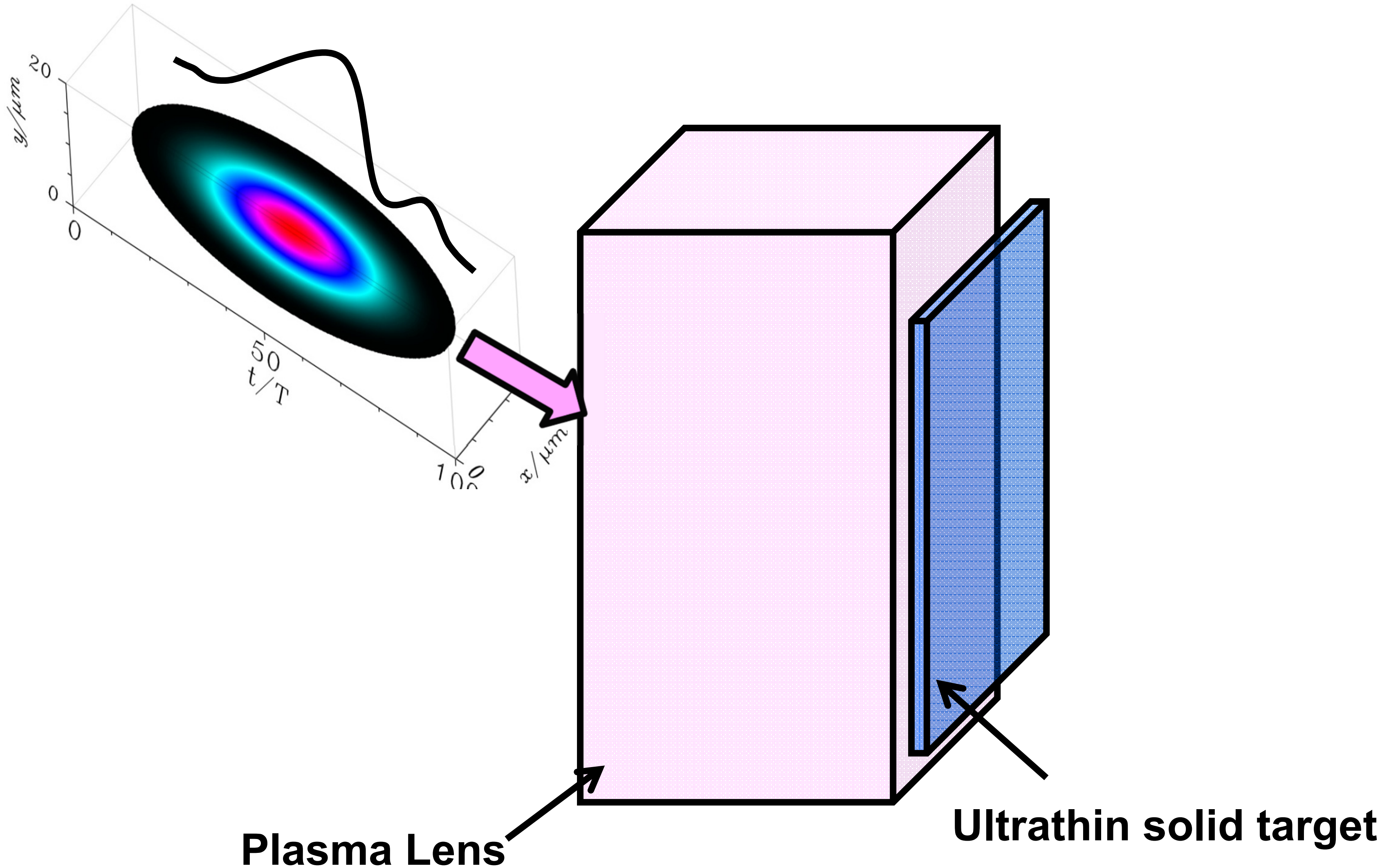
Quasi-Step function pulse profile!!!

How can we accelerate proton more efficiently ?



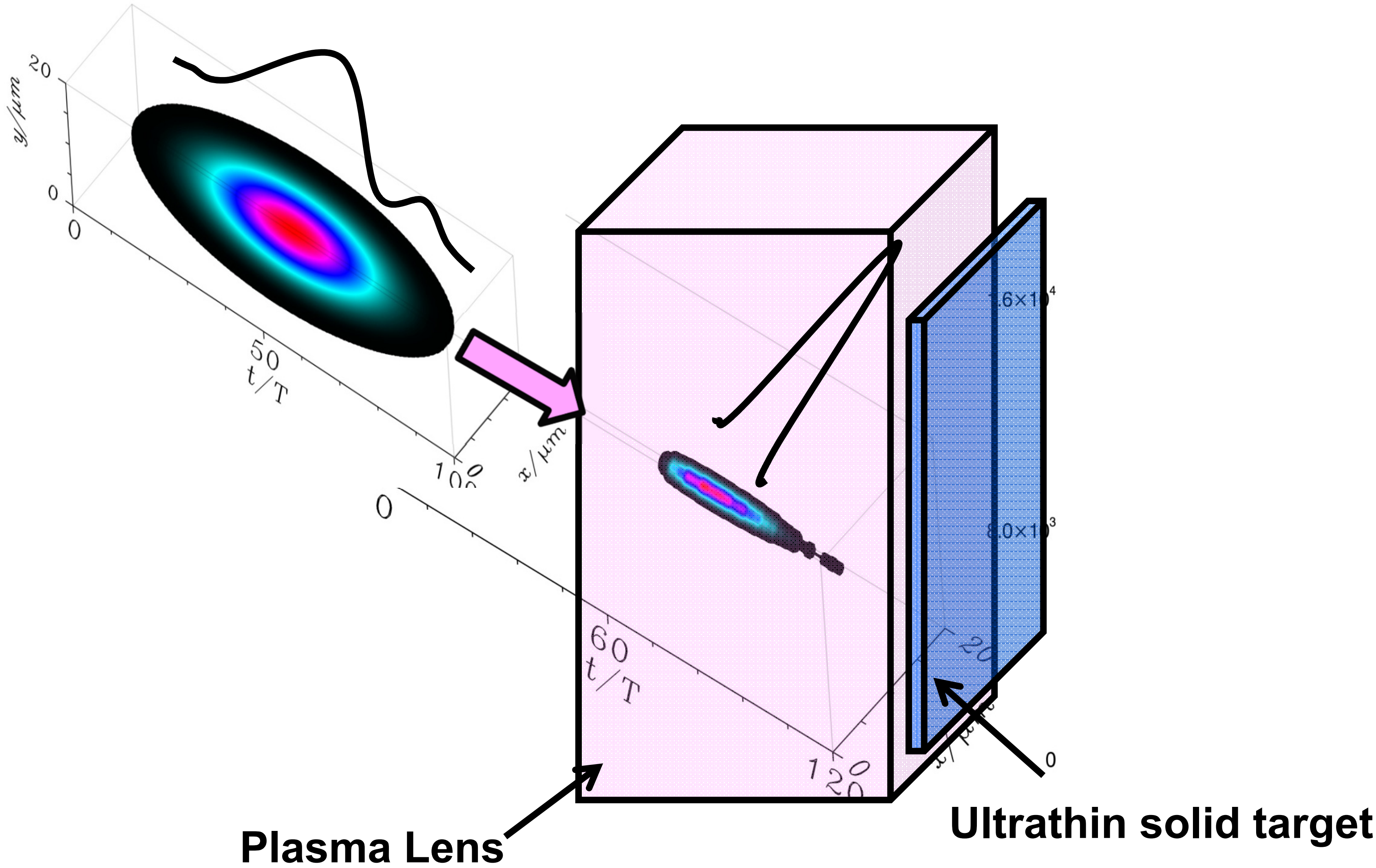


use a critical dense plasma as a lens



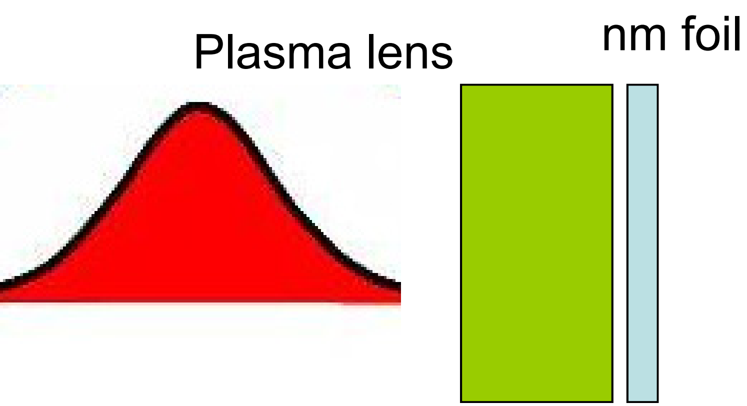
H. Y. Wang, C.Lin et al., PRL 107, 265002 (2011)

Plasma lens to generate high quality laser pulses

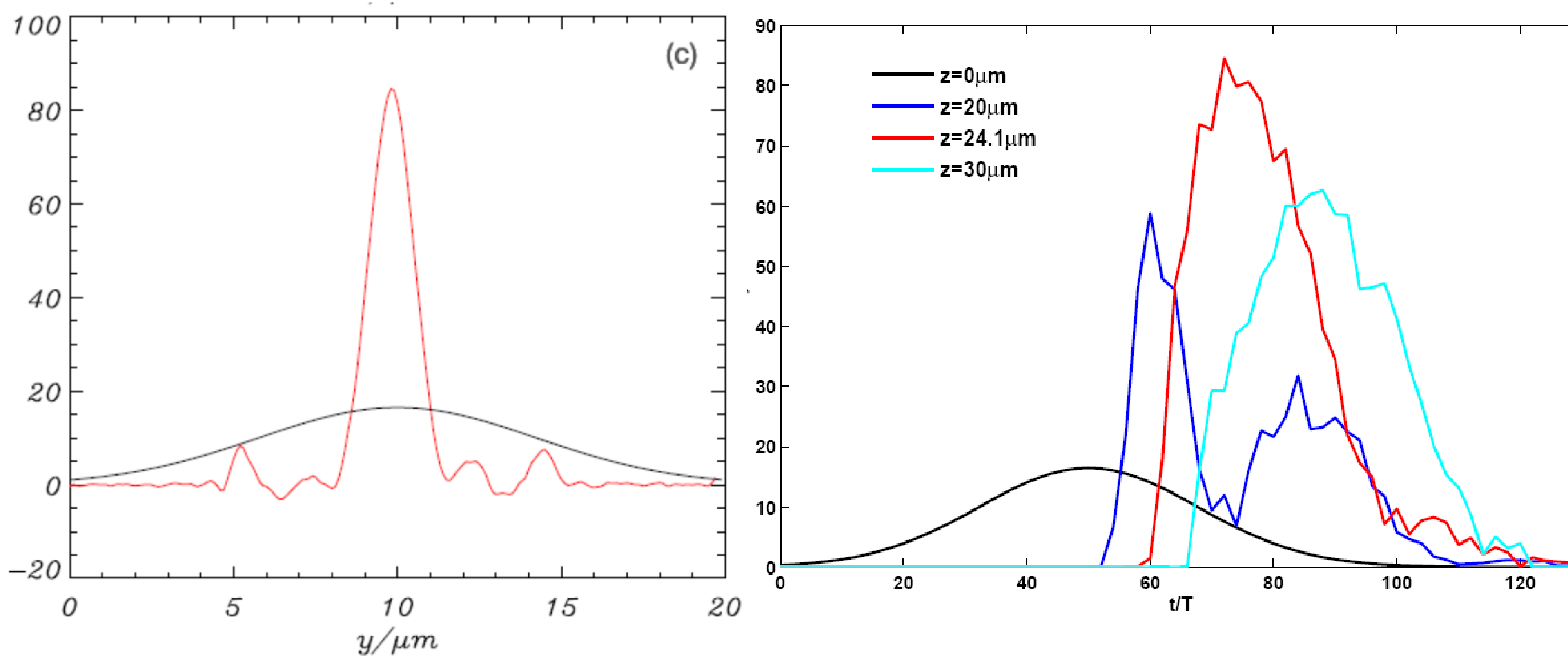


H. Y. Wang et al., PRL 107, 265002 (2011)

Laser driven plasma lens

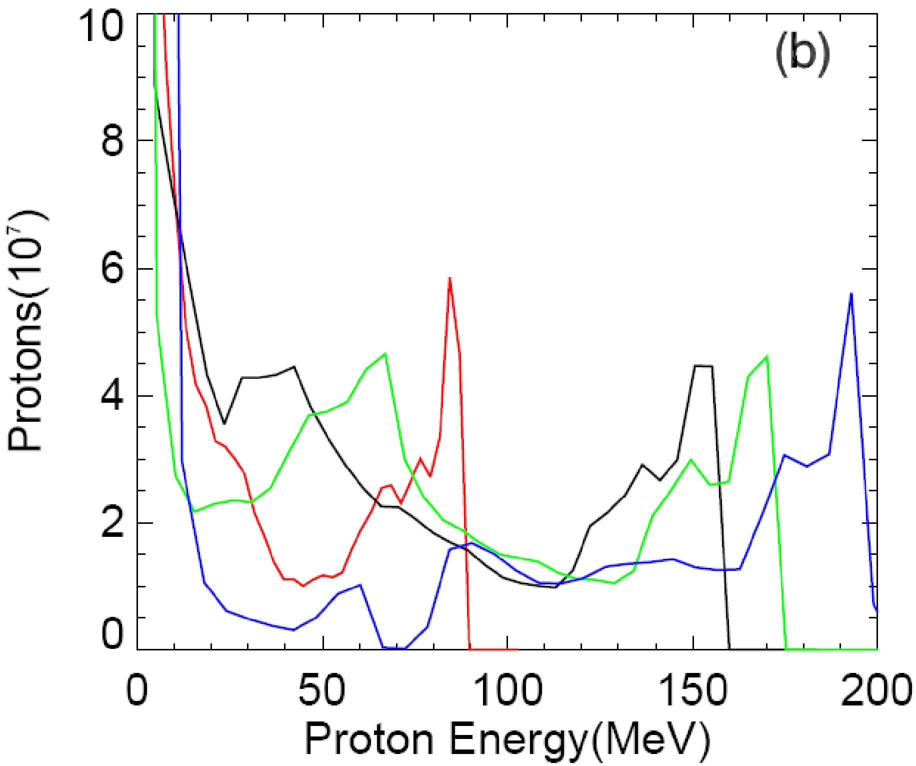


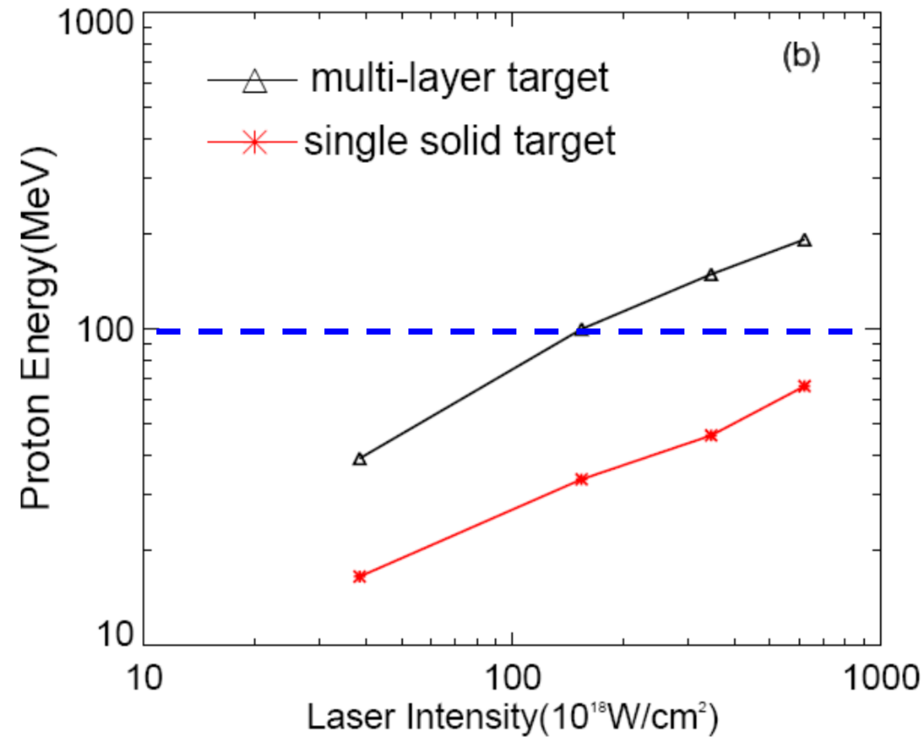
1. Pulse cleaning
2. Intensity 20 times higher
3. pulse steepening
at the same time for a short pulse!!!



Theoretical prediction: >100MeV

>200TW, 25fs,5~25J laser



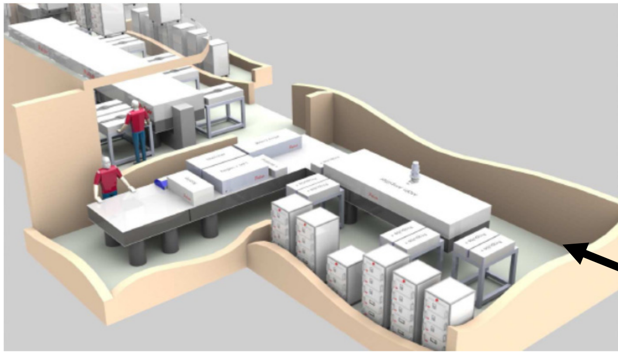


H.Y.Wang, X.Q.Yan, et al., submitted (2012)

Outline

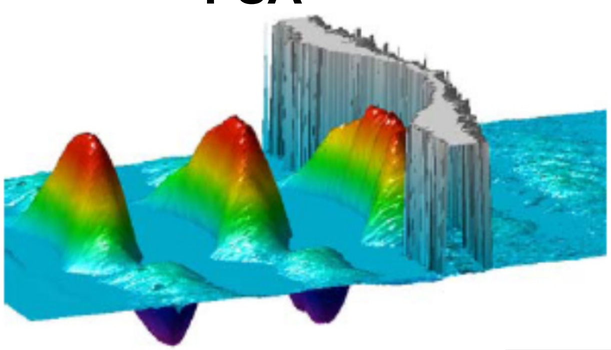
1. Why laser plasma accelerator
2. Phase Stability Acceleration (PSA) in a laser plasma accelerator
3. Challenges of PSA acceleration
4. Future plan at Peking University

LAser proton accelerator (LAPA) at PKU

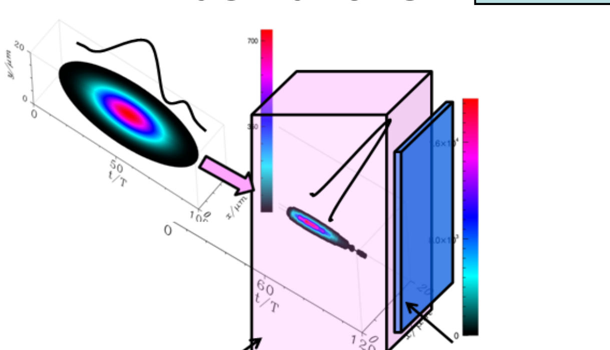


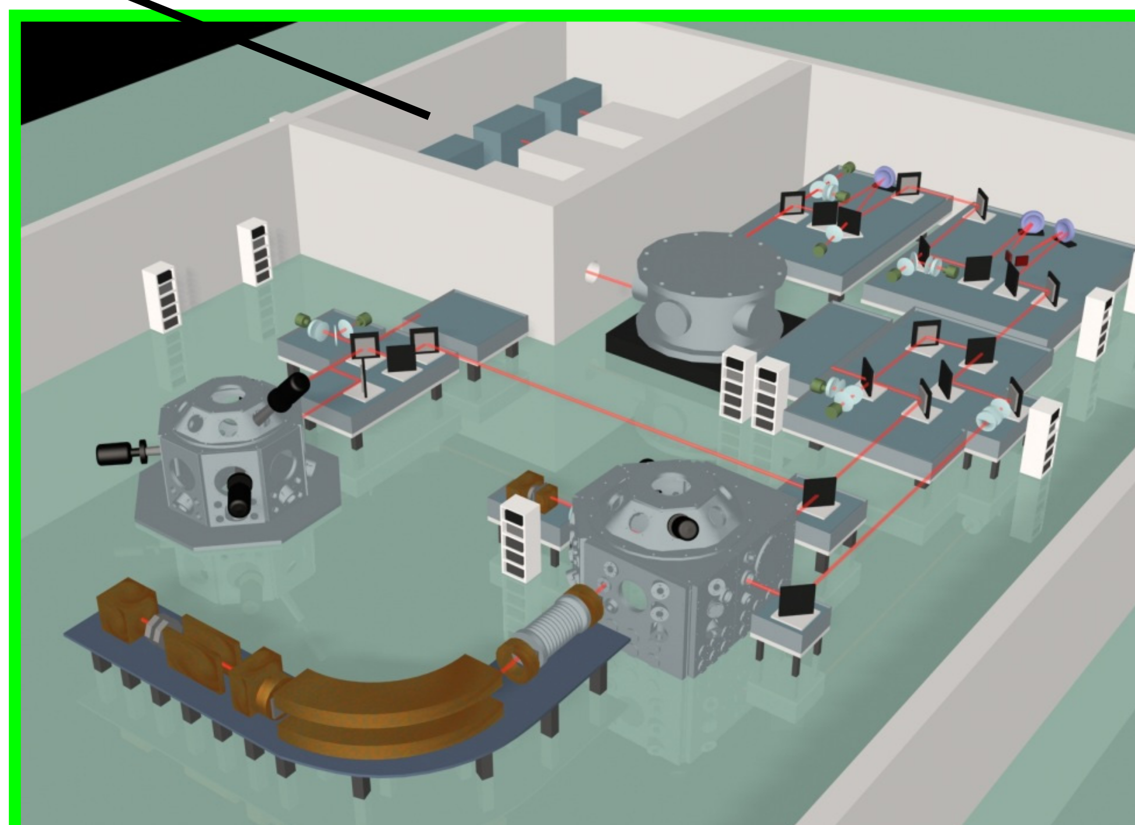
- Power supply: >200TW, 25fs,5~25J laser
- commercial product from Thales or AT company, costs ~2M$

PSA



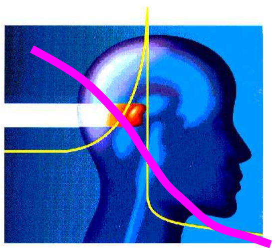
Plasma lens



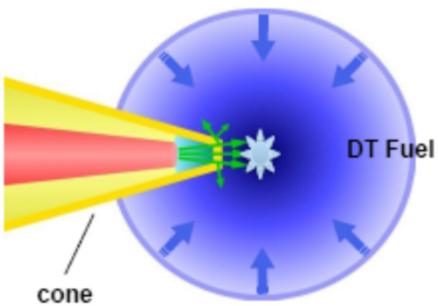


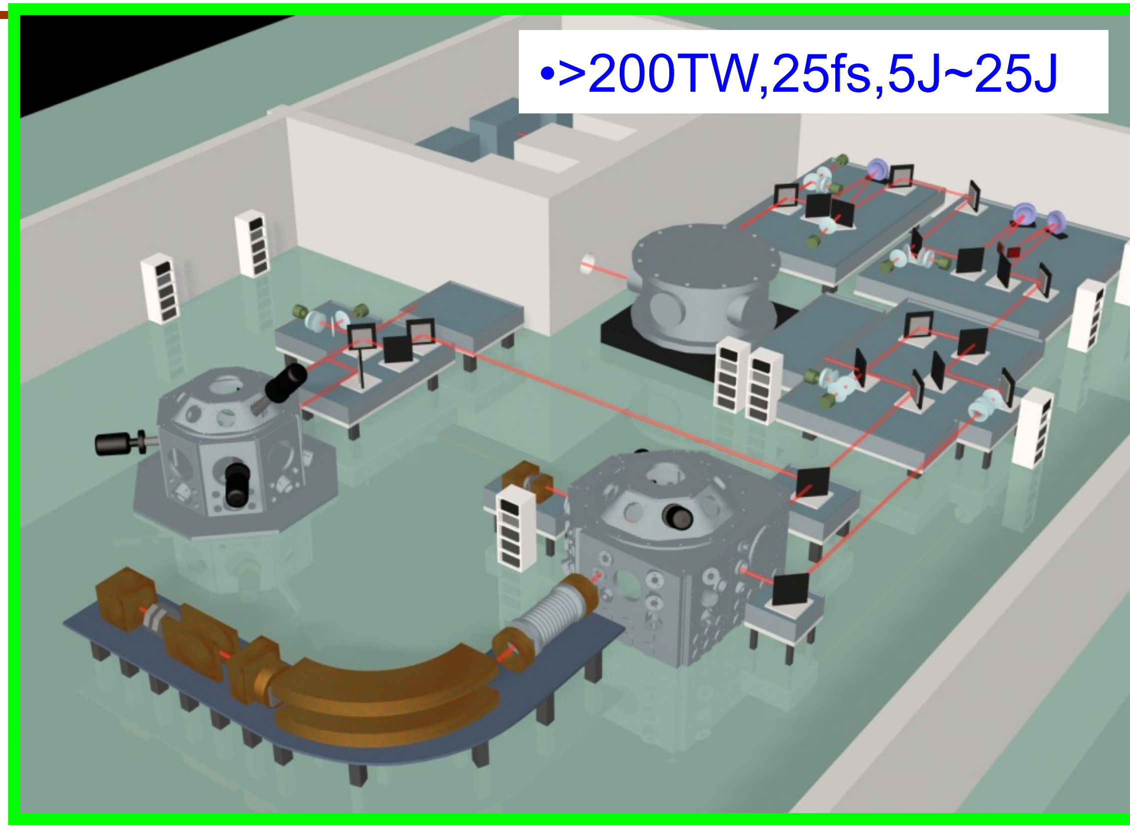
Applications of LAPA (10~100MeV)

1)Cancer therapy

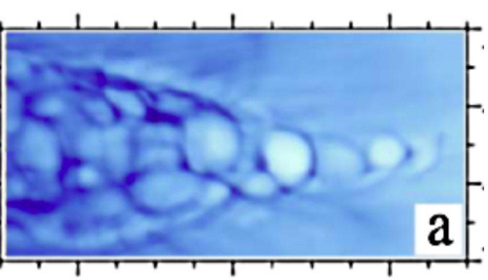


2)ICF fast ignition

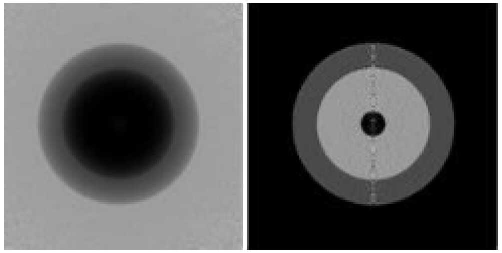




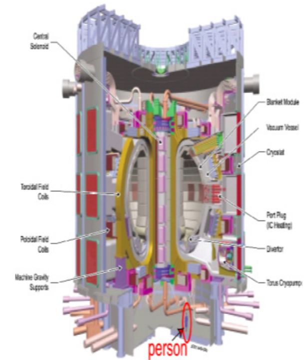
3) diagnostic for HEDP



4) Proton Imaging



5) HIB for ITER



6)Injector for HEP accelerator

DLC Target Manufacture System (CAD)

We have successfully manufactured Diamond-like Carbon (DLC) foil with thickness between 5～40nm.

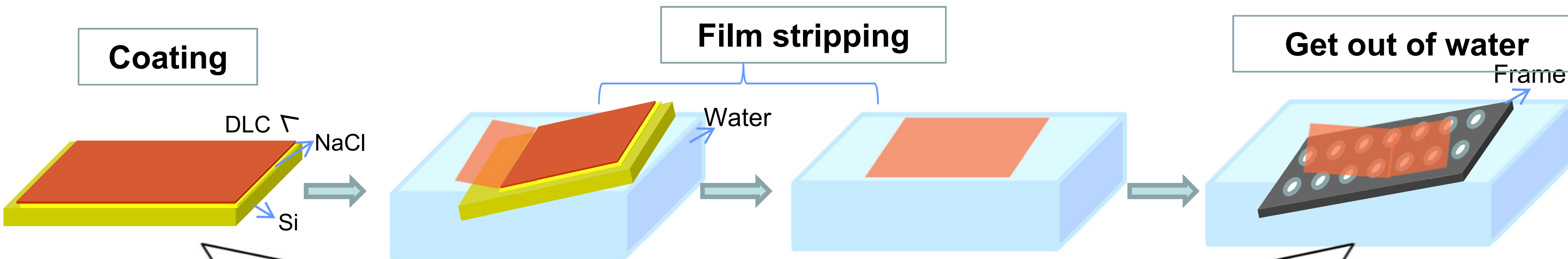
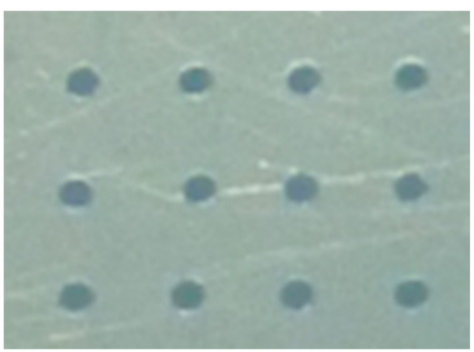
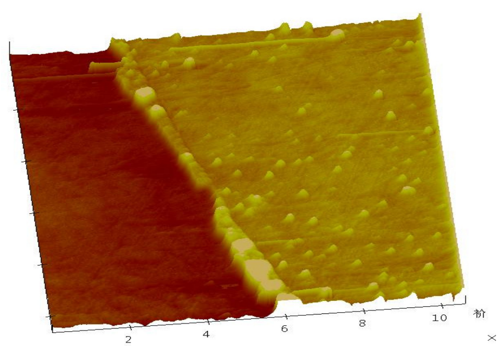
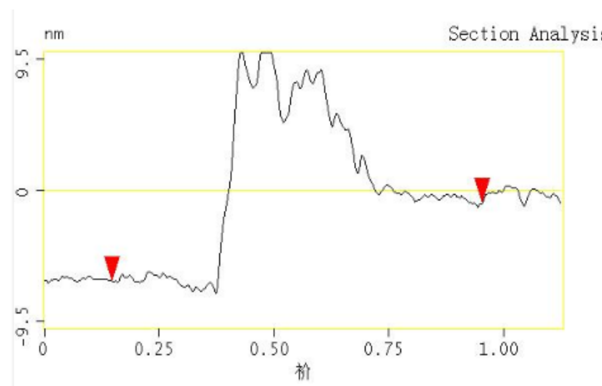


Image of DLC foil



Measurement of atomic force microscope



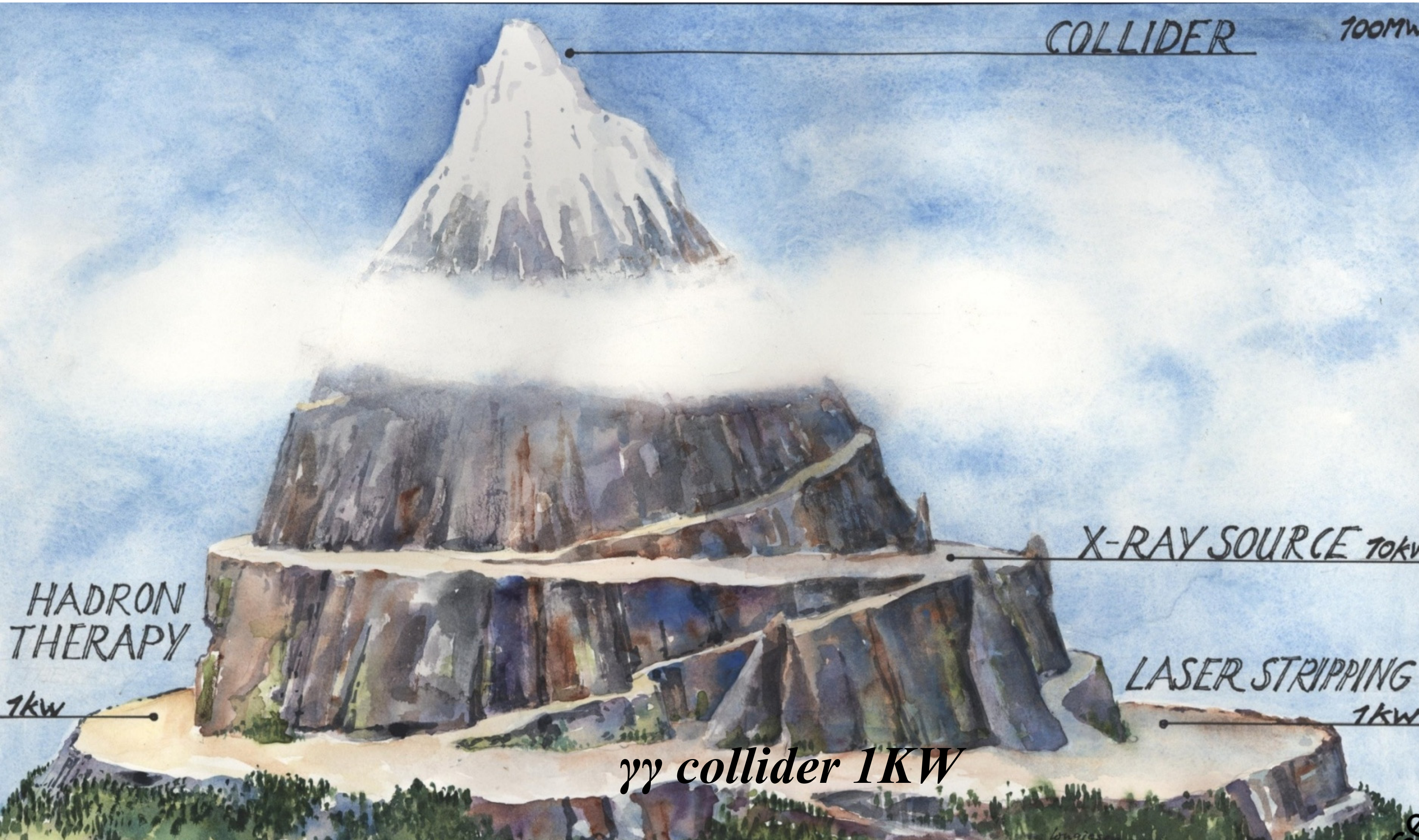


Summary

- Phase Stability Acceleration (PSA) can generate mono-energetic ion beam. 10~30MeV quasi-monoenergetic Carbon/proton beam were demonstrated in the experiments.
- Laser Plasma lens can be used to realize high laser intensity and high contrast!
- A prototype of 10~100MeV proton accelerator (LAPA) will be built at Peking University in the near future.

- Thanks for your attention！
- Thanks NSFC and Humboldt Foundation for financial support!

Mountain of Laser Plasma Accelerator



↑ average power

→ rep rate

↗ pulse shortness

By T.Tajima