Recent progress in the Studies of Laser Plasma Proton Acceleration

X.Q.Yan, L. Chen, H.Y.Wang, S.Zhao, J.Zhu, H.Z.Fu, X.T.He, J.E.Chen

State Key Laboratory of Nuclear Physics and Technology
Institute of Heavy Ion Physics, Peking University, China

SHJU/IOP: Z.M.Sheng, Y.T.Li, L.M. Chen, J.Zhang
MPQ/LMU: J. Meyer-ter-Vehn, D.Habs, J. Schreiber, W.J.Ma, J.H.Bin
IZEST: T.Tajima, G.Mourou
Ecole Polytech: J.Fuchs
LANL: M.Hegelich, H.C.Wu, L.Yin
Institute of Heavy Ion Physics @Peking U. China

Found in 1983

- nuclear physics
- accelerator physics
- ion beam physics
- medical physics and imaging

- 2*6 MV tandem, AMS/material facility
- 4.5 MV electrostatic AMS facility
- RFQ neutron radiography
- 2*1.7 MV tandem
- Linac
- Laser proton accelerator
- 3D printed proton physics
- 9-cell helix

- 4.5 MV electrostatic
Outline

1. TNSA, Shock acceleration and RPA mechanism
2. Laser plasma lens for pulse cleaning and ion acceleration
3. Recent experiments
4. How to go higher proton energy
5. New project: LAPA
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
- Conversion Efficiency CE~1%

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

Phys. Plasmas **18**, 056710 (2011)
Challenges: proton energy is proportional to square root of laser intensity!
Shock acceleration

$10^4$ protons per shot, $CE \sim 10^{-9}$

Haberberger, NATURE PHYSICS, VOL 8, JANUARY 2012, P96
Radiation Pressure Acceleration

- X. Q. Yan et al., PRL, 100, 135003 (2008)
- Klimo et al, PRST 11, 031301 (2008)
- Robinson et al, NJP 2008
- M. Chen et al., PRL 103, 024801 (2009).
- B. Qiao et al., PRL 102, 145002 (2009)
- X. Q. Yan, et al., PRL. 103, 135001 (2009)

RPA (CP + nanometers)
Mono-energetic ion beam

Synchrotron oscillation
Sail model or light sail

Sailboat

PSA

Electron—Sail

Proton—Boat

Laser—Wind

PRL 102, 145002 (2009)

PRL 100, 135003 (2008)
Conversion Efficiency (CE)

\[ CE = 1 - \frac{1}{4\gamma^2} \approx 100\% \]

A. Einstein, Annalen der Physik 17, 891 (1905)
Phase Stable Acceleration regime

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

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

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

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

1959: Veksler visits McMillan at Berkeley

Particles are compressed in the phase space!
Self-organizing nc GeV proton in Phase Stable regime

\[ \varepsilon_r \approx 0.5 \text{ mm.mrad} \]

(a) \( t=16 \)

(b) \( t=36 \)

(c) \( t=42 \)

I \( \approx 10^{22} \text{W/cm}^2, \ CE > 10\% \)

X.Q.Yan, ..., J.MtV, et al., PRL, 103, 135001, (2009)
overall efficiency

- wall-plug efficiency of ICAN fibre laser: 30%

- overall efficiency: 30% * 10% ~ 3%

- Overall efficiency of contemporary RF proton accelerators?
CSNS GeV accelerator
### CSNS GeV accelerator

**Electricity Power 35MVA, overall efficiency ~1.5%**

<table>
<thead>
<tr>
<th>Phase</th>
<th>I</th>
<th>II</th>
<th>II’ or III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power on target [kW]</td>
<td>100</td>
<td>200</td>
<td><strong>500</strong></td>
</tr>
<tr>
<td>Beam energy on target [GeV]</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Ave. beam current [μA]</td>
<td>63</td>
<td>125</td>
<td>315</td>
</tr>
<tr>
<td>Pulse repetition rate [Hz]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Protons per pulse $[10^{13}]$</td>
<td>1.6</td>
<td>3.1</td>
<td>7.8</td>
</tr>
<tr>
<td>Linac energy [MeV]</td>
<td>80</td>
<td>132</td>
<td>250</td>
</tr>
<tr>
<td>Linac type</td>
<td>DTL</td>
<td>DTL</td>
<td>DTL+SCL</td>
</tr>
<tr>
<td>Target number</td>
<td>1</td>
<td>1</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Target material</td>
<td>Tungsten</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderators</td>
<td>H₂O (300K), H₂(20K, coupled &amp; non)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of spectrometers</td>
<td>3+1</td>
<td>20+1</td>
<td>&gt;=20</td>
</tr>
</tbody>
</table>
Overall efficiencies:

- GeV laser proton accelerator: 3%
- GeV RF proton accelerators: 1.5%
Outline

1. Introduction of TNSA and RPA mechanism
2. Laser plasma lens for pulse cleaning and ion acceleration
3. Recent experiments
4. How to go higher proton energy
5. New project: LAPA
Demonstration of RPA

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
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. Habs1,2

1Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
2Department für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
3Max-Born-Institut, D-12489 Berlin, Germany
4Plasma Physics Group, Blackett Laboratory, Imperial College London, SW7 2BZ, United Kingdom
5Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

\[ a \sim \left( \frac{n_0}{n_c} \right) D / \lambda_L \]

[Graphs showing particle distribution with linear and circular polarization]

I\approx5\times10^{19} \text{W/cm}^2, 5 \text{nm DLC foil}
13 \text{MeV proton; 30 MeV carbon} \quad \text{CE}\sim10\%
RPA Challenge (I): High laser intensity


- 200 MeV proton beam,
- $I \sim 10^{21} \text{W/cm}^2$
- Contrast $> 10^{10}$ @ $\sim$ ps

**Graph:**
- Maximum Proton Energy (MeV) vs. Laser intensity $I$ (W/cm$^2$)
- Experimental demonstration with 13 MeV proton at $10^{19}$
It is very difficult to have a contrast $>10^{10}$ @10ps,ns and an intensity of $10^{20}$W/cm$^2$ at the same time!

<table>
<thead>
<tr>
<th></th>
<th>Power TW</th>
<th>Intensity W/cm$^2$</th>
<th>Contrast in ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>SILEX-I</td>
<td>300</td>
<td>$10^{19}$</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>QG-III (Shanghai)</td>
<td>890</td>
<td>$10^{19}$</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>LANL, USA</td>
<td>100</td>
<td>$10^{20}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>MBI, Germany</td>
<td>40</td>
<td>$10^{19}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>JAERI, Japan</td>
<td>800</td>
<td>$10^{19}$</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>XL-II</td>
<td>20</td>
<td>$10^{19}$</td>
<td>$&lt;10^6$</td>
</tr>
<tr>
<td>Astra</td>
<td>500</td>
<td>$10^{20}$</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

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


A P L Robinson et al 2008 New J. Phys. 10 013021
Challenge(IV): Short rise time is required


B.Qiao, et al., PRL 102, 145002 (2009)

M.Chen et al., PRL 103, 024801 (2009)

Step pulse with $I > 10^{21} \text{W/cm}^2$ for RPA!
Challenges in RPA-PSA regime

• High laser intensity $>10^{21}$W/cm$^2$
• High contrast $>10^{10}$@10ps,ns
• Hole boring and instabilities
• Short rise time (1~3T)

Quasi-Step function pulse profile!!!
Plasma mirror

Laser Plasmas lens

A. Pukhov and J. Meyer-ter-Vehn, PRL 76, 3975, 1996

Focus and steepening at the same time

Near critical plasma  nm foil

intensity 20 times higher

Steepened!!!
Universal of Plasma Lens

\[ \frac{l_s}{\lambda} = (\frac{a_{c}}{n_e})^{0.5} \sim 2.6 \]

H. Y. Wang et al., PRL 107, 265002 (2011)
Plasma lens to generate high quality laser pulses
The Gas-Filled Cone Target (GCT)

The plasma lens can be implemented by a GCT target.

Laser: $I = 2.6 \times 10^{20} \text{W/cm}^2$

Target:
- Cone: $n/n_c = 10$
- Gas: $n/n_c = 0.8$
- Foil: C:H=1:1
  - $n/n_c = 40$
  - $D = 0.35 \mu\text{m}$

Experimental manufacture also in process…

H. Wang, et al., POP, 18, 093105 (2011)
High-quality Proton Bunch from GCT Target

<table>
<thead>
<tr>
<th></th>
<th>GCT</th>
<th>Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Energy</td>
<td>181 MeV</td>
<td>65 MeV</td>
</tr>
<tr>
<td>Energy transfer rate</td>
<td>2.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>36%</td>
<td>100%</td>
</tr>
<tr>
<td>Emax (a.u.)</td>
<td>3.3</td>
<td>1</td>
</tr>
<tr>
<td>Ne (a.u.)</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

H. Wang, C. Lin, et al., POP, 18, 093105 (2011)
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Experiments with the DLC and Al Targets

**XL-III**

XL-III laser system @ Institute of Physics
Chinese Academy of Science

- Laser pulse duration: 80 fs
- $I=1 \times 10^{18} \text{ W/cm}^2$ to $4.6 \times 10^{18} \text{ W/cm}^2$
- ns/ps contrast $10^{-5}$ to $10^{-6}$
- 20 min per shot
DLC Target Manufacture System

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

Image of DLC foil

Measurement of atomic force microscope
DLC Target fabrication at PKU

5~40nm self-standing foil target is ready!

FCVA

5nm free-standing DLC foil
Proton Beam was Observed in Both Directions

Laser direction

Target normal direction
DLC Target Images

Before Experiment

After Experiment

Proton $E_{\text{max}} \sim 1\text{MeV}$

Count (a.u.)

Energy (MeV)

0.05 0.5 1 1.5 2

0.1 0.5 1 1.5 2

0.60J
0.23J
0.44J
Experiment with 2.5um Al target
Proton energy scaling in TNSA

I~5*10^18 W/cm²

TNSA 1~2 MeV
Lens+TNSA 8 MeV

Why????

J. FUCHS et al., nature physics, 2, 48, 2006
Prepulse of IOP laser XL-III

2*10^{12} W/cm^2

\sim 2*10^{13} W/cm^2

80fs

2*10^{18} W/cm

Pedestal 1-5ns

Pedestal 20ps

2*10^{12} W/cm^2

\sim 2*10^{13} W/cm^2
Hydrodynamics simulation

2.5um I=10^{13}W/cm^2, 2ns t=0

Done by Dengfeng Fan and Hongbo Cai from IAPCM
DLA acceleration in Plasma lens

energy distribution of electrons in gas at t=100T

Laser incident

Al target
Electron temperature and proton energy

S. Zhao, et al., submitted, 2012
Theoretical prediction of $>100\text{MeV}$ at $\sim 10^{20}\text{W/cm}^2$

proton energy in plane of plasma density and length D

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100GeV Laser proton accelerator?

1. Demonstration of 100MeV~1GeV proton

2. IZEST(PETAL), 100GeV proton

~100GeV proton

underdense gas

~1cm

100MeV~1GeV

IZEST(PETAL), 100GeV proton
multi-stage acceleration (RPA+wakefield)

a) proton foil

CP laser

underdense gas

$Z/A = 1/3$

b) snowplow field

matching condition:

$$l_0 < D < \frac{1}{2\pi} \frac{n_c}{n_c} a_0 \lambda \lambda_i,$$
500GeV proton predicted in 1D simulation

\[ W_{\text{max}} \simeq \frac{1}{6} \left( a_0^2 n_c / n_e \right) m_e c^2 \]

- $10^{23}$ W/cm$^2$, 133fs, sub-TeV proton beam

Small target + underdense gas

Laser

$I \approx 10^{22} \text{W/cm}^2$

55fs

underdense gas

$n_e = 0.15n_c$

$n = (n_1 + \Delta n(y^2/y_0^2))$

Proton-rich MLT foil, 0.5um, 20$n_c$

$n_1 = 0.15n_c$, $\Delta n = 2n_c$ and $y_0 = 50\lambda$. 
Monoenergetic and collimated Proton beam

Proton density

Angular distribution

Proton spectrum

<10um
100GeV proton beam in 2D Simulation

7GeV protons
$2^*2\mu m^2$

Laser
$I_0 = 1.7e23$

Nanofibre
$R=0.5\mu m$ $n=3n_c$

$n_0 = 0.04n_c$, $n(y) = 0.04*(1+(y/35e-06)^2)$

$r=20\mu m$
$t_v\sim 50fs$
$70KJ$

~cm preformed channel
100GeV proton beam

Proton Spectrum, t=1.40e-011 s

Peak ~ 102GeV, \( \Delta E/E \sim 11\% \)

Proton Phase Space, t=1.40e-011 s

Protons: n (n_p), t=1.40e-011 s

4x17 \( \mu \)m
0.07 mm.mrad

Proton Divergence, t=1.40e-011 s

\( \pm 1.3^\circ \)
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Compact Laser-driven Proton Accelerator (LAPA)

Compact laser-driven proton accelerator based on PSA+plasma lens

- High contrast (> $10^{10}$), high focus intensity (> $10^{20}$W/cm$^2$) fs laser system
- Nanometer-thickness target manufacture system
- Proton generation, transportation and diagnosis
- Proton irradiation research platform
- System integration and control program Development

Project of the Chinese Ministry of Science and Technology
Institute of Heavy Ion Physics @ Peking University

1) Proton imaging

2) Fast Ignition

3) Space physics

4) Proton therapy

5) GeV SNS/ADS accelerator

~100MeV laser proton accelerator

Chinese SNS
Space physics

1~15~100MeV proton:

Single particle effects for chip or electronic apparatus
Proton imaging and diagnostic for plasma

- High-resolution dynamic imaging (ps, μm)
- Laser 1
- Laser 2
- Plasma
- Electric field, magnetic field
- Detector

\[ t_1 = 7\text{ps} \]
\[ t_2 = 13\text{ps} \]
\[ t_3 = 25\text{ps} \]

PRL 97, 135003 (2006)
Cancer stem cells

LETTERS

Glioma stem cells promote radioresistance by preferential activation of the DNA damage response

LETTERS

Association of reactive oxygen species levels and radioresistance in cancer stem cells

肿瘤干细胞：
肿瘤中具有自我更新能力并能产生异质性肿瘤细胞的一类细胞。
Cancer treatment in the future

2008年国内医疗总费用1.13万亿元

肿瘤：1430亿
心脑血管：1300亿
环境疾病：1573亿
神经精神：3025亿

重大疾病“吃掉”3.3%GDP（9900亿元）

> 15亿人民币

后期升级版100MeV：1~2亿人民币
Thanks for your attention!

- Laser plasma lens can steepen and focus the laser beam at the same time, due to relativistic self-focusing and self phase modulation.
- Simulations show hundreds MeV proton maybe possible by <PW laser.
- 10~100GeV collimated proton beam can be generated in two stage acceleration (RPA+LPA)!

LAPA project:
- One tenure tack position is open!
- Looking for laser engineer!
twin wakes in 2D or donut in 3D

Positive ions are diverging in 2D wakefield

Defocusing