Laser-driven ion acceleration on LFEX for fast ignition:
State of the art and applications

Akifumi YOGO
Institute of Laser Engineering (ILE), Osaka University, Japan
Institute of Laser Engineering, Osaka University


Kansai Photon Science Institute, QST

A. Sagisaka, K. Ogura, M. Nishikino, S. V. Bulanov, A. S. Pirozhkov, T. Zh. Esirkepov, and K. Kondo

Hiroshima University

T. Johzaki

National Institute for Fusion Science

T. Ozaki and H. Sakagami

Institute of Laser Technology

A. Sunahara

Institute of Physics, Chinese Academy of Sciences

Z. Zhang

The Graduate School for the Creation of New Photonics Industries

K. Mima
Fusion fast ignition driven by ions.
Laser-accelerated protons as an alternative igniter

10 kJ ion-energy deposition onto the ~500 g/cm³ fuel

100 kJ is the technically manageable energy of the driving laser

Energy conversion efficiency
\[
\text{Energy of driver laser} 
\begin{align*}
\text{Kinetic energies of ions having } & 10-30 \text{ MeV/u} \\
\geq 10\%
\end{align*}
\]
Fusion fast ignition driven by ions.
Laser-accelerated protons as an alternative igniter

**STEP 1**  
Ion acceleration test

**STEP 2**  
Ion delivery test

**STEP 3**  
Ion driven Fast Ignition
Fusion fast ignition driven by ions.
Laser-accelerated protons as an alternative igniter

**STEP 1**
Ion acceleration test

To improve ion energy and conversion efficiency

**STEP 2**
Ion delivery test

**STEP 3**
Ion driven Fast Ignition

**NEWLY DEVELOPED SCHEME**
Temporally evolution of electron temperature in pico-second region

**THIS WORK**
Summary of Achievement
30 MeV proton generation with 5% conversion efficiency

LFEX
kJ, ps, High-contrast laser

30 MeV on ion kinetic energy

Our results

5% on energy-conversion eff.

Laser energy: 1 kJ
Gross kinetic energies of proton: 50 J

We have achieved these results with $10^{18}$ Wcm$^{-2}$ laser intensity.
c.f. In previous works, similar results were obtained with $10^{19-20}$ Wcm$^{-2}$ lasers.
Ion acceleration with $10^{18}-10^{20}$ Wcm$^{-2}$ laser intensity
TNSA model: ion acceleration from the target rear surface.

1. The laser pulse is focused on a thin foil (nm-μm).
2. Fast electrons (> 0.511 MeV) are generated.
3. Charge separation field (~MV/μm) is induced on the rear side.
4. Protons (originating from the surface contaminants) are predominantly accelerated.


In this model, the electron temperature is never evolved as time.

Maximum ion energy predicted by 1 dimensional (1D) isothermal model

$$E_{max} = 2T_h \left[ \ln \left( t_p + \sqrt{t_p^2 + 1} \right) \right]^2$$

Experimental conditions

Ion energy distributions are measured at the rear side of thin-foil targets.

**LFEX: ps laser**
- 1.5 ps, 1 kJ on target
- $1.2 \times 10^{19}$ Wcm$^{-2}$
- 60 μm spot (FWHM)
- 4 beams in total.

The arrival timing of 4 LFEX beams can be set independently of each other.

**Thin-foil target**
- 5 or 10-μm-thick AL

**Spot size >> target thickness**
- (60 μm)
- (5-10 μm)

**Pulse-train**
- $2.5 \times 10^{18}$ Wcm$^{-2}$

**Thomson parabola Ion spectrometer**
- at the laser propagation direction

**Target**
- Al 0.8 μm

**Electron energy spectra**
- are measured simultaneously with ions.

**Target Chamber**
- 1 m

**Gekko-XII: ns laser**
- for fuel implosion
- 12 beams in total.

**Electric deflection**
- Magnetic field

**Magnetic deflection**
- Electric deflection

**Target energy**
- $< 6.3$ MeV/u
- is stopped by the front filter of 100-μm-thick Al foil

**Target : Al 0.8 μm**

**H$^+$**

**C$^6^+$**

**C$^5^+$**
Proton energy increases with the pulse duration. Our experimental results clearly exceed the prediction of usual model.

- Pulse duration:
  - 1.5 ps ⇒ 3 ps ⇒ 6 ps
  - 1 pulse, 2-pulse train, 4-pulse train

The intensity is fixed on $2.3 \times 10^{18} \text{ W cm}^{-2}$

Our proton energy is close to $10^{19} \text{ W cm}^{-2}$ line by results of conventional lasers.

- References:
  - Present study: $2.3 \times 10^{18}$
Conversion Eff. increases with the pulse duration.

The intensity is fixed on $2.3 \times 10^{18} \, Wcm^{-2}$

Similar efficiency was obtained with $10^{20} \, Wcm^{-2}$ conventional lasers.

Energy conversion efficiency

$$\text{Conversion eff.} = \frac{\text{Kinetic energies of ions}}{\text{Laser energy}}$$

Electron temperature increases with pulse duration. The temperature exceed a usual scaling law.

Conventional scaling law
Ponderomotive energy

\[ T_0 = m_e c^2 (\gamma - 1) \]

\[ \gamma = \sqrt{1 + a_0^2/2} \]

\[ a_0 = 0.85 \sqrt{I[W/cm^2][\lambda^2[\mu m]]/10^{18}} \]

\[ T_0 = 0.2 \text{ MeV} \]
for \( I = 2.3 \times 10^{18} \text{ Wcm}^{-2} \)

(No time dependency)

However, in our experiment,
0.45 \( \Rightarrow \) 1.10 \( \Rightarrow \) 0.96 MeV

Never explained by the ponderomotive scaling
Comparison btw experiment and PIC simulation

The PIC results quantitatively agree with the experiments.
Mechanism underlying the heating
Electrons are heated during recirculating the target.

The electron motion above never happens when a seriously large plasma expansion is made by low-contrast laser.
We introduce the temporally evolved temperature into analytical model, based on self-similar solutions.

\[ \xi = \frac{x}{R(t)}, \quad R(t) = \int_0^t c_s(t')dt', \]

We newly introduce time dependency onto the self-similar variable.

**Self-similar solution of the electric field**

\[ e\phi = -T(t)(\xi + 1) \]
\[ E_{ss} = -\partial_x \phi = T(t)/eR(t). \]

**Electric field on the ion front Assumed by Mora**

\[ E_f(t) \approx 2E_{ss} = \frac{2T(t)}{eR(t)}. \]

**Normalization**

\[ \tau = \omega_{pi0}t/\sqrt{2eN}, \quad \bar{c}_s^2(\tau) = T(\tau)/T_0. \]

**Ion velocity at the front**

\[ v = 2c_{s0} \int \frac{\bar{c}_s^2(\tau)}{\sqrt{1 + R^2(\tau)}}d\tau, \quad c_{s0} = \sqrt{ZT_0/m_i} \]

**Ion kinetic energy at the front**

\[ \mathcal{E} \approx \frac{1}{2}m_iv^2 = 2T_0 \left[ \int \frac{\bar{c}_s^2(\tau)}{\sqrt{1 + R^2(\tau)}}d\tau \right]^2 \]
Maximum proton is analytically reproduced. We find a fairly well agreement with the experiments.

The temporal evolution of electron temperature enables to improve proton energy up to 30 MeV.
Energy absorption into ions increases as time in PIC.

The PIC simulation qualitatively predicts the temporal evolution of the conversion eff.

The temporal evolution of electron temperature enables to improve conversion eff. up to 5%.
**Conclusion**

**THIS WORK**

**STEP 1**
Ion acceleration test

30 MeV protons with 5% conversion eff. with the temporally-evolution effect.

**STEP 2**
Ion delivery test

**STEP 3**
Ion driven Fast Ignition

**Final requirement**
30 MeV, ≥10% with 100 kJ laser
Conclusion

**THIS WORK**

1. **STEP 1**
   - Ion acceleration test
   - 30 MeV protons with 5% conversion eff. with the temporally-evolution effect.

2. **STEP 2**
   - Ion delivery test

3. **STEP 3**
   - Ion driven Fast Ignition

**Requirement**
30 MeV, $\geq 10\%$ with 100 kJ laser

To achieve the requirement, we find the upper limit of the temporally evolution in a few 10s ps region, accompanied with the upgrade of LFEX laser.
The focal spot (60 μm) in our experiment leads to 1D plasma expansion. We try to explain the experimental results using 1D PIC simulation.

We have to evaluate the electron heating in the region up to 10 ps for the 4-pulse train case.

2D PIC simulation in the multi-ps time scale is time consuming, almost impossible.

We find that when the focal spot is set to be 60 μm, the 2D PIC results are well in agreement with the results obtained in 1D simulation, in the case of 1.5 ps pulse duration.

We evaluate the electron heating in multi-ps region by using 1D PIC simulation that probably reproduces the condition of actual experiment.

Proton energy spectra obtained with 2D PIC simulation assuming a 60 μm focal spot (blue) and 1D PIC (red). The laser pulse has 1.5 ps duration and 1X10^19 Wcm^-2 intensity.
FIG. 3. (a) Trace of typical electron trajectory in the 1D PIC simulation. The target foil is initially at the position $x = 50-55 \, \mu m$ and the laser (2-pulse train) is incident on the surface at $x = 50 \, \mu m$. (b) Time evolution of the Lorentz factor of the electron shown in (a).
シミュレーション結果:
電子・イオンエネルギー時間発展と相互作用の様子

エネルギー密度（吸収率）の時間発展

- Laser input $\varepsilon_{in}$
- e+i, e, i
- Time t [ps]

時間の経過に伴いエネルギー密度が増加し、最大値に達する。拡大図では拡大効果が確認できる。

パルスピーク開始時刻とパルスピーク終了時刻の比較

$t = 1.0\ ps$
$t = 3.3\ ps$
$t = 5.5\ ps$

電子密度と電場の変化が示され、特にレーザー軸方向での変化が顕著である。

Simulation system

77.1\ $n_c$

電場（レーザー軸方向）と電子密度の関係

Natsumi IWATA  ILE, Osaka Univ.

第71回 日本物理学会年次大会  March 21, 2016
Block diagram of LFEX laser system


cf. DA400S: square disk amplifier of 400mmx400mm clear aperture
Amplifier components of LFEX laser system

Main disk amp. (2x2)

Rod amp. (50mm)

4-pass rod amp. (50mm)

OPCPA

Fiber ML osc.

GVD adjuster

Deformable mirror (75mm, 125mm)

Faraday rotator (2x2)

NFP

Spectrum

LFEX  overview - 2

- 4-pass rod amplifier
- Spatial filter SF400S
- U-mirror
- Beam splitting optics
- OPCPA
- Rod amplifier R405
- DFM 75S
- DFM 125S
- Faraday rotator FR1200
- Focusing optics
- GVD adjuster
- Fiber ML oscillator
- 100 fs (A=16 nm)

1053 nm

1048 1050 1052 1054 1056 1058

Wavelength (μm)
Mechanical structure of rear-end subsystem

- Interaction chamber
- Pick-up mirror
- Deformable mirror
- Grating 1
- Grating 2
- Dielectric grating
- Monitor 1
- Monitor 2
- NFP
- OAP
Pulse contrast measurement at the front end

Optical system for pulse contrast improvement using saturable absorber

Dielectric multi-layer grating (40cm × 20cm)

Portable compressor (16-m path length)
Deterioration factors of pulse contrast

ASE (amplified spontaneous emission)
Rod amp./OS/Disk amp.
<100µJ, 40Fλ

AOPF (amplified optical parametric fluorescence)

Compressed pulse
~1 ps
<100 ps
~3 ns

Spectral modulation
- clipping
- shape
- phase

~5x10^{-14}

~20 ns

Time
A thin foil target attached inside the cone, developed in ILE, Osaka.