Laser particle acceleration and accompanying nuclear processes: experimental and theoretical study

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Outline

- Experiments at $10^{17}$ W/cm$^2$ : polarization & target type dependence
- Experiments & PIC modeling at $10^{18}$ W/cm$^2$
- Nuclear excitation followed by IEC in $^{57}$Fe under fast ion bombardment
Intensities & mechanisms

- **Moderate intensity** – below \(5 \times 10^{16} \text{ W cm}^{-2}\)

- ??????????

- **Relativistic intensities** – above \(1.4 \times 10^{18} \text{ W cm}^{-2}\)

- **Ultrarelativistic intensities**

- At which intensity relativistic mechanisms become important or dominant?
- How different mechanism interplay?
- etc.
Femtosecond laser system

- Energy per pulse 1-25 mJ
- Energy stability 3% rms within 1 hour
- Pulse duration 50 fs
- Central wavelength 805 nm
- Spectral bandwidth 23 nm
- Repetition rate 10 Hz
- $M^2 = 1.7$
- Nanosecond contrast better $4 \times 10^6$
- Picosecond contrast better $10^5$
Target setup

Ga reservoir
thermocouple
Copper heater

Laser radiation

To x-ray detectors
10 Hz regime: X-ray yield stability

X-ray yield in spectral band $>2.5$ keV ($T_{Ga}=270^\circ C$)

$I=2 \times 10^{17}$ W/cm$^2$  \hspace{1cm} $\eta=(2.2\pm0.4) \cdot 10^{-4}\%$

$\sum E_{x-ray} \sim 2$ nJ per shot.  \hspace{1cm} In 10 Hz regime $P \sim 5$ nW.
1kHz regime: X-ray spectrum

Ga

$K_\alpha$ (Ga) – 9,3 keV
$K_\beta$ (Ga) – 10,3 keV
$K_\alpha$ (Cu) – 8,4 keV
Contrast, polarization and target type dependence

![Graph showing laser pulse contrast vs. energy for different target types and polarizations.]

- **p-polarized, melted Ga**
- **s-polarized, melted Ga**
- **p-polarized, SiO$_2$**
- **s-polarized, SiO$_2$**
- **p-polarized, Si**
- **s-polarized, Si**
Experimental data with different polarization direction

Si – $2.5 \times 10^{-7}$

Quartz glass – $10^{-2}$
Experimental data: hot electrons energy

<table>
<thead>
<tr>
<th>Target</th>
<th>Si, keV</th>
<th>SiO₂, keV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5 10⁻⁷</td>
<td>10⁻²</td>
</tr>
<tr>
<td>P/S, v, Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-1</td>
<td>18.2±1.1</td>
<td>16.8±1.0</td>
</tr>
<tr>
<td>P-10</td>
<td>14.2±0.9</td>
<td>11.5±0.8</td>
</tr>
<tr>
<td>S-1</td>
<td>16.0±0.9</td>
<td>14.3±0.9</td>
</tr>
<tr>
<td>S-10</td>
<td>11.4±0.8</td>
<td>10.6±0.8</td>
</tr>
</tbody>
</table>
Experimental data:

Intensity dependence

Si

$\text{P-polarized}$

$\text{S-polarized}$

SiO$_2$

$\text{P-polarized}$

$\text{S-polarized}$

Intensity, PW/cm$^2$

Mean energy, keV

Intensity, PW/cm$^2$

Mean energy, keV

$\sim 0.35 \pm 0.02$

$\sim 0.40 \pm 0.02$

$\sim 0.14 \pm 0.03$

$\sim 0.40 \pm 0.02$

$\sim 0.30 \pm 0.02$

$\sim 0.19 \pm 0.02$

$\sim 0.35 \pm 0.02$

$\sim 0.40 \pm 0.04$
Ions production from melted metal target

Fast ions

Slow ions

- p-polarization, along normal
- s-polarization, along normal
- p-polarization, pi/4
- s-polarization, pi/4
Optical shadowgraphy

Laser beam parameters:
- pulse duration – 55fs
- wavelength – 0.8μm
- pulse energy – 5mJ (200μJ on target)
- repetition rate – 10Hz
- angle of incidence – 45°
Optical shadowgraphy (plasma plume expansion)

Prepulse energy 200µJ, contrast 5
Optical shadowgraphy
(plasma plume expansion)

Prepulse energy 200μJ, contrast 5
Optical shadowgraphy (plasma plume expansion)

Prepulse energy 200μJ, contrast 5
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Experiments at relativistic intensities

1. **Double detector**
   - PMT+Nal(Tl) 5mm thick

2. **Calibrated x-ray energy measurements**
   - PMT+Nal(Tl) 5mm thick

3. **Single quantum x-ray detection**
   - PMT+Nal(Tl) 5, 32 or 60 mm thick

\[ E_h = 2.5 - 100 \text{ keV} \]

\[ E_h = 2.5 - 100 \text{ keV} \]

\[ E_h = 10 - 5000 \text{ keV} \]
Off-axes parabolic mirror focusing
Contrast dependence at $10^{18}$ W/cm$^2$

P-polarized
15 mJ
$10^{18}$ W/cm$^2$
Pre-pulse:
13 ns – $10^{-2}$- $2.5 \times 10^{-7}$

Tungsten 13 ns – $2.5 \times 10^{-7}$

Contrast dependence at $10^{18}$ W/cm$^2$
Experimental data: contrast dependence

P-polarized
2 - 15 mJ
1.5x10^{18} W/cm^2
Experimental data:
energy (intensity) dependence

\[ T_2 \sim (73 \pm 10) \lambda^{0.39 \pm 0.02} \text{ keV} \]

\[ T_2 = 4 \lambda^{0.33} \text{ keV} \]

\[ \lambda = 59 \text{~} \]

Experimental data: energy (intensity) dependence

\[ P_{cr} = 7 \frac{n_c}{n_e} \text{ GW} \]

ns \( \to \) \( L \sim 100\text{-}200 \mu\text{m} \)

ps \( \to \) \( L \sim 0.1\text{-}1 \mu\text{m} \)

3D PIC code MANDOR

- the fully electromagnetic, relativistic three dimensional particle-in-cell code

- C99, UNIX (GNU/Linux, IRIX), MPI-2

- the flexible setup for the initial and boundary conditions

- Maxwell equations: explicit scheme (second order accurate both in space and in time (Yee scheme))

- The kinetic (Vlasov) equation: relativistic modification of the Boris scheme.

- particle shape factor - a well compensated self-force and suppressed self-heating

- parallelization is specially optimized to handle strongly non-uniform distribution of markers over the simulation domain to proper address the accuracy in modeling of laser-target interactions.
2D PIC data with 4 mcm gradient
2D PIC data with 100 mcm gradient
2D PIC data with varying gradient

- 100 mcm gradient
- 4 mcm gradient
Recent data

2.5 MeV
3D PIC simulation of laser pulse interaction with overdense plasma jet

Laser pulse: duration 50 fs, $I = 10^{19}$ W/cm$^2$, 4 μm FWHM focal spot
Target: cylinder which consists of electron-proton plasma, $n_p = 20 n_c$, l=5μm, r=0.5μm

3D effects at the diffraction limit - formation of electron jets
Max electron energy $\sim 14$ MeV (electron temperature $\sim 1$ MeV)
Max proton energy $\sim 2$ MeV
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Low energy nuclear isomers excitation

- **Photoexcitation**

- **NEES**

- **NEEC**

- **NEET**

\[
y_e, \varepsilon_i = - \varepsilon_f \quad \text{if} \quad n_e, \varepsilon_f \neq Y
\]
Low energy nuclear isomer decay

- $\gamma$ decay
- Internal electronic conversion (inverse NEEC)

Detection of a single electrons at plasma afterglow background

Partial IC coefficient

IC electrons energy, keV

Fe

K

L
Experimental arrangement
Raw data: single trace
Raw data: average current
Raw data: ion spectrum
Electron spectrum (low statistics)
Results (high statistics)
Key conclusions

The differences in hot electron production between the cases of P- and S- polarized femtosecond laser pulses become small if intensity of these pulses approaches $10^{17}$W/cm$^2$. This behavior is characteristic for initially both opaque and transparent targets as well as for melted metal one.

The decrease in nanosecond contrast causes dramatic increase in hard x-ray yield and mean hot electron energy if the melted metal target is used. Fast ions are accelerated preferentially along the reflected laser pulse by the contrast to slow ions accelerated along the target normal.

At relativistic intensities and peak laser power above 0.1TW mean hot electron energy rises up twofold if the nanosecond pre-pulse is applied with arbitrary amplitude more than $2\times10^{-3}$.

The internal electronic conversion of Fe-57 14.41 keV level has been observed. Excitation is due to inelastic collisions of ions accelerated during femtosecond laser-plasma interaction with fe-57 nucleus.