Laser-plasma electron accelerator for all optical inverse-Compton x-ray source

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OUTLINE

- ALL OPTICAL INVERSE-COMPTON X-RAY SOURCES
- LASER-PLASMA ELECTRON ACCELERATORS
  (WAKEFIELD ACCELERATORS)
  PRINCIPLE AND CHARACTERISTICS
- STABILIZATION OF WAKE-FIELD ACCELERATORS
Inverse Compton x-ray source

Inverse Compton scattering provides a monochromatic x-ray pulse by Doppler upshifting of an intense laser pulse.

\[ h\nu_s \approx h\nu_L \frac{2\gamma^2 (1 + \beta \cos \psi)}{1 + (\gamma \theta)^2} \]

\[ h\nu \ll mc^2, \theta \ll 1, a_0 \ll 1 \]

\[ \Delta \theta = 1/\gamma \]
Inverse Compton x-ray source II

Duration of x-ray pulse $\propto$ e$^-$-bunch length + laser pulse

Intensity of x-ray pulse $\propto$ number of interaction e$^-$ $\times$ hv-density

Laser wakefield accelerator can deliver a sub-nC, fs-bunch of e$^-$. 

K.Koyama ; ICFA Workshop on Compton Sources for X/$\gamma$ Rays: Physics and Applications, Alghero, Italy 2008
Inverse Compton x-ray source III

\( \approx 10^7 \) X-ray photons per shot

\( \approx 100\text{pC}, 10^{17} \text{ W/cm}^2, \ 5 \times 10^{-9} \text{cm}^3 \)

to produce a few-MeV photons ( @ 1eV)

\[ h\nu_s \approx 4\gamma^2 \cdot h\nu_L, \quad (\psi \approx 0, \theta \approx 0) \]

<table>
<thead>
<tr>
<th></th>
<th>Accel. gradient</th>
<th>Length for 500MeV</th>
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<tbody>
<tr>
<td>rf-linac</td>
<td>10–40 MeV/m</td>
<td>( \approx 25\sim50 \text{ m} )</td>
</tr>
<tr>
<td>LWFA</td>
<td>96 GeV/m</td>
<td>( \approx 5 \text{ mm} )</td>
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Laser wakefield electron accelerator

1. Electrons are expelled by the laser pulse. 
   ponderomotive force
2. Displaced electrons are pulled back by the Coulomb force. 
   plasma wave is excited behind the laser pulse (wakefield) 
   traveling at the speed of light
3. Electrons riding the wakefield are accelerated.

\[ f_{NL} = -\frac{e^2}{4m\omega^2} \nabla E_s^2 \]

\[ \left( \frac{\partial^2}{\partial t^2} + \omega_{pe}^2 \right) \phi = \frac{mc^2}{4e} \omega_{pe}^2 a^2 \]

\[ \frac{E_{WB}}{E_0} = [2(\gamma_{ph} - 1)]^{1/2} \]

\[ E_0 = cm\omega_{pe}/e \]

\[ E_0 = 96 \text{ GV/m} \text{ for } n_e = 10^{18} \text{ cm}^{-3} \]
Mono-energetic electron acceleration

1. Electrons should be accelerated by a single well.
   - excitation of single well
   - electron injection to one of wells

2. Initial electrons must be injected in a small portion of the phase space.
   - self-trapping
   - external injection

3. Acceleration length
   \[ \approx \] dephasing length
Amplitude of plasma wave

Energy-distribution of electrons

Forward scattering spectrum
IR-visible spectrometer

Gas jet
Electron energy
Angle
Electron energy spectrum

Trace of laser pulse
Short pulse shadowgraph (50fs)
Length of laser channeling
Side scattering image (800nm)

K. Koyama; ICFA Workshop on Compton Sources for X/γ Rays: Physics and Applications, Alghero, Italy 2008
Recent activities of LWFA experiments at AIST and U.Tokyo

- Empirical scaling law of LWFA.
- Electron injection at a density step.
  - Density jump formation by the shock wave
- Axial magnetic to stabilize LWFA.
  - Deep capillary formation by the expanding shock in B-field
  - Electron injection and post acceleration
  - \( \approx 0.5 \text{ GeV} \) by 8 TW laser pulse
Scaling and achieved parameters in quasi-monoenergetic electron beam generation

(by courtesy of E. Miura, AIST)
Stable generation of quasi-monoenergetic electron beam by self-injection scheme

Laser : 8.5 TW / 50 fs
Electron density : 1.6x10^{19} cm^{-3}

Statistics of quasi-monoenergetic beams in consecutive 20 shots

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean (± s.d.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak energy</td>
<td>55 ± 16 MeV</td>
</tr>
<tr>
<td>Energy spread ((\Delta E_{FWHM}/E))</td>
<td>21 ± 11 %</td>
</tr>
<tr>
<td>Charge in peak</td>
<td>15 ± 10 pC</td>
</tr>
<tr>
<td>Beam divergence (FWHM)</td>
<td>7.6 ± 3.5 mrad</td>
</tr>
<tr>
<td>Beam pointing</td>
<td>± 7.6 mrad</td>
</tr>
<tr>
<td>Probability of generation</td>
<td>80%</td>
</tr>
</tbody>
</table>

(by courtesy of E. Miura, AIST)
For increasing stability

Energy
Energy width
Electronic charge
Emittance
Beam pointing

- Amplitude of the wakefield
- External injection of initial electrons
- Acceleration-length
- Laser guiding

K.Koyama; ICFA Workshop on Compton Sources for X/γ Rays: Physics and Applications, Alghero, Italy 2008
Electron injections

Locally increased ponderomotive force produced by colliding laser pulses

The laser pulse crosses the wakefield


Beatwave injection


Standing wave


Local wavebreaking at the density ramp

Wavebreaking at the density ramp

- The local wave number of the plasma wave, which propagate from high-density to low-density, i.e. from large $\omega_{pe}$ to small $\omega_{pe}$, increases in time.

\[ \frac{\partial}{\partial t} k_{pe}(t, z) = -\frac{\partial}{\partial z} \omega_{pe}(t, z) \]

- The phase velocity of the plasma wave $v_{ph} = \omega_{pe}/k_{pe}$ decreases.

- When the phase velocity is equal to the quivering velocity of the plasma wave $v_q$, the portion of the wave breaks.

\[ v_q = \xi_m \omega_{pe} \sin(k_{pe} z_0 - \omega_{pe} t) \]

\[ k_{pe} \xi_m = 1 \quad (v_{ph} = v_q) \]

The wave breaking occurs at the density discontinuity of the plasma.

The density of injected electron.

\[ n_{inj} \approx n_{e0} \frac{\xi_m}{\Delta X} = n_{e0} \frac{1}{k \Delta X} \]


Methods for producing density ramps in plasmas

Shock front of the laser heated cavity

Laser machining of the plasma

Oblique shock wave in a supersonic flow
K. Koyama; ICFA Workshop on Compton Sources for X/γ Rays: Physics and Applications, Alghero, Italy 2008
The density ramp was produced by the oblique shock.

\[ \frac{n_2}{n_1} \approx 3, \quad L_n \ll 100 \mu m, \quad n_1 \approx 10^{19} \text{ cm}^{-3} \]
Preliminary result

Shock wave

Gas flow

80  40  (MeV)  20
Repeatable LWFA with external B-field


Axial B-field ~ 0.20T

He Gas ~4x10^{19} cm^{-3}
F# = 3.5 (f = 178 mm)
Laser 6 ~ 12 TW
Focal spot ~ 5-7 \mu m(1/e^2)
Rayleigh length ~ 50 \mu m

T.Hosokai Dept. of Energy Sciences, Tokyo inst. of Tech.
Repeatable LWFA with external B-field


He Gas \(~4 \times 10^{19}\) cm\(^{-3}\)

F\# = 3.5

Laser \(6 \sim 12\) TW

Focal spot \(~5-7\) \(\mu\)m (1/e\(^2\))

Rayleigh length \(~50\) \(\mu\)m

T. Hosokai Dept. of Energy Sciences, Tokyo Inst. of Tech.
Repeatable e-Beam profiles (@ 300mm from focus point)

**B = 0** (Ejection angle ~10°)

**B = 0.2T** (Ejection angle ~0.6°)

(Transverse geometrical emittance ~0.02π mm mrad)

T.Hosokai Dept. of Energy Sciences, Tokyo Inst. of Tech.
Enhanced e-Beam parameters

Beam size ~ x 1/20
Total charge ~ x10
Charge density ~ x 200

Total Charge

Electron Charge [pC]

Laser Intensity [Wcm^{-2}] (x10^{19})

Laser Power [TW]

Electron Energy [MeV]

Energy Spectra

Electron Signal [arb.units]

Detector Position [mm]

T.Hosokai Dept. of Energy Sciences, Tokyo Inst. of Tech.
Formation of transient plasma micro-optics (TPMO)
TPMO suppress laser diffraction

B=0 1.2ps before main pulse

Laser
Focus point
Gas jet 1.2 mm

Laser
Focus point
Gas jet 1.2 mm

Wave-breaking
Electron bunch

Shadowgraph image

B=0.2T

Laser
Focus point
Gas jet 1.2 mm

Laser
Focus point
Gas jet 1.2 mm

Strong wave-breaking
Electron bunch


T. Hosokai Dept. of Energy Sciences, Tokyo inst. of Tech.
Stronger B-field experiment (1.2 mm gas-jet) with channel formation by ps pre-pulse tuning

Pre-pulse case (a), B=1T

Pre-pulse case (b), B=1T

1.2ps before main pulse

T. Hosokai Dept. of Energy Sciences, Tokyo inst. of Tech.
1.2 mm gas-jet experiment (e-Spot & energy spectra)
Demonstration of 2-staged acceleration


Typical electron spot image
(300 mm from focal point)

Electron Signal [arb.units]

Electron Energy [MeV] (x10^3)

Position [mm]

Intensity [arb.units]

3.5 mm (FWHM)

Screen Position [mm]
1.2 mm gas-jet experiment (e-Spot & energy spectra)
Demonstration of 2-staged acceleration


Typical electron spot image
(300 mm from focal point)

Electron Signal [arb.units]
(a)
(b)

Electron Energy [MeV] (x10³)

Screen Position [mm]

T. Hosokai Dept. of Energy Sciences, Tokyo Inst. of Tech.
4.0 mm gas-jet experiment (e-Spot & energy spectra)
Demonstration of 2-staged acceleration

T. Hosokai, Dept. of Energy Sciences, Tokyo Inst. of Tech.

*Shadowgraph:
1.2 ps before main pulse

Typical e-beam profile

Evolution of energy spectrum (Staged Acc.)

No channel (a) 700μm channel (b) 2 mm channel (c)

Thermal ~50 MeV ~100 MeV

~20pC

Highest energy electrons measured

Peak energy $\sim 0.45\text{GeV}$
(Detection limit)
$\sim 1\text{pC/shot}$
$0.02\pi\text{m mmrad}$

Drive laser only $\sim 7\text{TW}$
Prepulse (b)
4.0 mm nozzle (He)
Gas density $\sim 4 \times 10^{19}\text{cm}^{-3}$

Submitted (Aug. 2008)
Table-top MeV-class Compton x-ray source can be possible by using the LWFA.

Present problems of the LWFA is the stability of the output beam.

Electron injection as well as capillary formation in the B-field are effective.