A Plasma-Assisted High-Brightness X-Ray Source via Inverse Compton Scattering

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Compton (Thomson) Scattering as an X-ray Source

- mechanism well-studied since 1960s
- large cross-section (600 mb)

\[ \lambda' = \frac{\lambda_0}{4\gamma^2} \]

- photon energy upshift from Doppler factor

- radiation opening angle \( \sim 1/\gamma \)
- considered for short-pulse x-ray and gamma ray sources (synchrotron light sources are broadband, long-pulse)

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Current Experimental Programs/Results

• Field rebirth after advent of CPA lasers
• Generally requires TW laser, 800 nm to 10 µm
• Need either compressed e-beam or 90° incidence
• Focus on ultrashort pulse generation
  - LBL, 90° scattering, 300 fs pulses at 30 keV
    roughly 10^5 photons/pulse (1997)
  - LLNL, 90°-180° scattering, pulses from 100 fs
to 5 ps at ~100 keV, 10^8 photons/pulse (ongoing)
  - KEK/Sumitomo, 90° scattering, 300 fs at 3 keV
  - BNL-ATF, 90° scattering, ≥10^7 photons/pulse, 3 keV (2000)
• Some interest in high-flux gamma sources
  - JLC collaboration
Obstacle to high brightness: Spatial overlap problem

- Photon production $\sim \sigma_T \frac{N_b N_\gamma}{\text{Area}} \left(\frac{\sigma_{t,\gamma}}{\sigma_{z,b}}\right)$

- Want high photon density, but tight focus gives **strong diffraction**
- Beam limited by emittance $\beta = \sigma_r^2 / \varepsilon \leq 0.5 - 1 \text{ cm}$
- Laser limited by diffraction $Z_R = \pi r_0^2 / \lambda_0 \leq 1 - 2 \text{ mm}$

- Result: **basic limitation** on photons/pulse for Compton sources: must have beam lengths $\leq$ diffraction length; - large laser fields and beam space charge effects

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Emittance, field are limiting factors

Particle beam has (approximately) $\varepsilon_n = \gamma \sigma_x \sigma_{x'} = \text{constant}$
Brightness comes at expense of divergence

Laser has wavelength-limited product of $\sigma_r$ and $\theta$
Can’t simply add more energy to short pulse without increasing $a_L = eE_L/mc\omega$
If $a_L \geq 1$, transverse relativistic motion becomes important and e-beam disruption is an issue
Only solution is to increase interaction volume
Guiding Channel: beat the diffraction limit

- **Plasma channels**: region of plasma with low electron density, positive ion background
- Created by intense laser pulses or electron beams
- Laser guiding over many Rayleigh ranges has been demonstrated
- Matched electron beam can be transmitted over many $\beta$
- Full beam length available for interaction even for small spot size

- Can do this using a *pre-formed* channel
  (BNL-ATF, current work using capillary discharge tubes)
  … but potentially easier to exploit *self-guiding*:
- both laser and e-beam will self-guide under correct conditions
- no need for timing 2 laser pulses or spark devices
Beam Self-Guiding: PWFA in blowout

• Field of beam pushes plasma electrons away from axis
• Rarefaction forms behind beam
• Long beam needed: the head erodes as the channel forms
• Middle/tail of beam is focused and guided
• Very high axial fields created in rarefaction
Self-Guiding Results

Recent demonstrations include

- Argonne AWA: 70% of 14 MeV, 25 ps, 10 nC beam transmitted intact through 12 cm plasma (= 8\(\beta\)) forming 280 \(\mu\text{m}\) channel
- SLAC FFTB: Beam tail propagation through 1.4 m plasma (overfocused) using 28 GeV, 2 ps, 3 nC beam — observed steering
Plasma Blowout: Theory

- Blowout efficiency depends on the ratio \( n_b/n_p \) as long as beam is relativistic (must be > 1 for blowout; usually ~ 5 to 10)
- but density decrease still observed for \( n_b/n_p < 1 \)
- Focusing strength of channel is fixed: this sets the depth of focus for the e-beam
  \[ \beta_{eq} = \sqrt{\gamma / 2\pi r_e n_0} \]
  - Match the beam to this gradient to avoid overfocusing
    - set \( \sigma_r^2/\varepsilon = \beta \); then focus onto plasma boundary
- Beam distribution near head expands radially; the head electrons are focused less due to finite plasma response time
- Beam body transverse size is near stationary
Laser Self-Guiding: Relativistic Self-Focusing

- Intense laser fields produce relativistic quiver velocity in plasma electrons near laser axis
- Plasma refractive index increases:
  \[ n^2 = 1 - \frac{1}{\gamma} \left( \frac{\omega_p}{\omega} \right)^2 \]

- Higher index on axis gives guiding (“optical fiber”)
- If \( a_0^2 \gg 1 \), high efficiency

Once channel forms, propagation is very efficient:
e.g. guiding \( 10^{14} \text{ W/cm}^2 \) over 25 to 70 Rayleigh lengths with pre-formed channel! (Durfee et al., Maryland, 1995)
Relativistic Self-Guiding: Theory

Occurs above a critical power level: 17.4 \((\lambda_p/\lambda_w)^2\) [GW]
Guiding doesn’t work well for \(L \leq \lambda_p\)
(no plasma collective response)
⇒ Only long pulses can be considered

Long pulse can self-modulate due to wakefield formation
(especially at lower intensities)

(Reason for interest in pre-formed channels: see
Sprangle et al., PRL 1990, 1992)
Laser constraints make this a hard problem

- Choose long wavelength (10 µm), achievable power levels (~20 TW?) very dense plasma ($n_p = 10^{17}/\text{cm}^3$), $\lambda_p = 48$ µm

- To beta-match into this requires $\sigma_r = 2.3\mu\text{m}$ with low-emittance beam (4 mm mrad) at 80 MeV $n_b \sim n_p$ even with this focusing

**Option 1:** allow incomplete blowout, then use state-of-the-art electron beam with permanent-magnet focusing quads…

still very tough, and guiding through ~2 µm channel uncertain

**Option 2:** abandon effort to match laser at critical density and use beam to prepare channel for both, with $P_{\text{laser}} \ll P_{\text{crit}}$

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Possible scenario

• very long electron beam, high charge (~100 nC)
• laser pulse arrives when beam head exits plasma
• laser guiding over 5–10 $Z_R$ through plasma-formed channel

PIC simulations underway!

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Projected Photon Flux

Approximately:

\[ N_x = \sigma_T \frac{N_b N_\gamma}{A} f \]

A is transverse overlap area; \( f \) is ratio of lengths (\( \leq 1 \)); 
\( \sigma_T = 0.6 \) barn

Assume 800 nm laser, 1 TW, 500 fs, 20 \( \mu \)m spot:
- \( N_\gamma \sim 10^{18} \), \( N_b = 6 \times 10^{11} \), entire laser pulse is usable energy, \( a_L < 0.1 \)

\[ \text{photon yield near } 10^{10}/\text{pulse} \]

With 10.6 \( \mu \)m, \( N_\gamma \) goes up, can get over \( 10^{11}/\text{pulse} \), but \( a_L \sim 0.5–1 \)

More exact calculations in progress ...

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Provocation

• Compton scattering has been proposed for high-flux $\gamma$-ray source for e+/e- collider (multiple laser beams)
• Requires only high-energy e-beam ($\sim 2$ GeV)
• Plasma-assisted Compton source could greatly simplify this idea by extending useful pulse lengths
• Obtain small-angle, bright, polarized positron beam with only one laser?
γ-ray source I

- 800 nm YAG laser, 10 ps, 1.5 J/pulse, 60 MeV scattered photons
- 150 nC e-beam, 1.6 GeV, 20 ps length, in $10^{17}$ plasma
- Matched beam, $\beta = 800 \, \mu m$, $\sigma_x = 2.3 \, \mu m$, $n_b/n_0 \sim 5$ (like SLC)
- Laser guided over $7 \, Z_R$
- $6 \times 10^{11}$ scattered photons/pulse, with $a_L \sim 0.1$ (low is good)
- Average brightness $\sim 10^{22}$ photons/sec

*Competitive with proposed polarized positron sources, with much simpler laser setup!*
γ-ray source II

- 10.6 μm CO₂ laser, a few J/pulse
- Need 60 GeV electron beam to get 60 MeV photons
- Guiding over 30 $Z_R$
- Matched beam, $\beta = 1.5$ mm, $\sigma_x = 4$ μm, $n_b/n_0 \sim 3$
  - easier to achieve
- $6 \times 10^{11}$ scattered photons/pulse, but $a_L \sim 0.5$
- Transverse effects will begin to be important
Conclusion

• Self-guiding in plasma by electron beam has potential to create a high-brightness, long-pulse x-ray source through inverse Compton scattering
  - conceptually simple
  - easy to time
  - high photon number output

• Output looks competitive with other x-ray and γ-ray generation methods involving pre-formed channels or multiple lasers
  • Not necessary to use 10.6 µm laser!
    - increase in photon number offset by high $a_L$
    - similar performance from 800nm systems

• Simulation and yield calculations underway… stay tuned!

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