All-optical, self-aligned Compton source using a PW-scale laser-wakefield accelerator and a plasma mirror

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Self-aligned Compton scattering at ELI-NP and ZEUS

All-optical Compton scattering

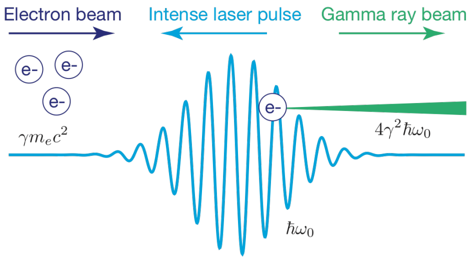
ELI NP: Self-reflecting Compton scattering
Gerstmayr et al., arXiv:2506.23718

ZEUS: Self-reflecting Compton scattering with density tailoring

All-optical Compton scattering

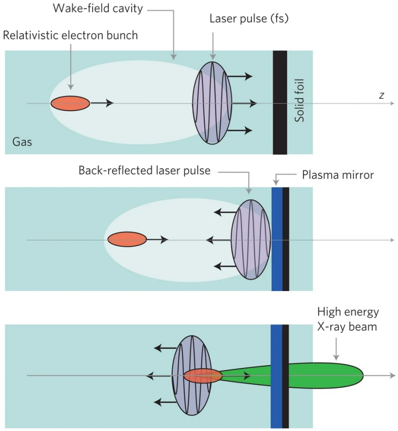
Inverse Compton scattering is a compact source of γ-rays

- Advantages:
  - Length and time scales are matched and synchronised
  - Co-location of accelerator and intense laser pulses
- Challenges:
  - Reproducibility of source
  - Spatio-temporal overlap (drift and jitter)
  - Beam quality



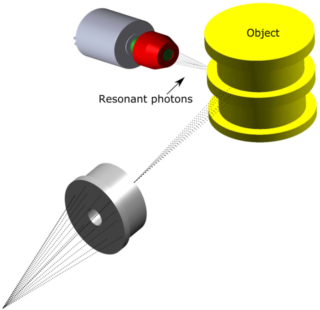
Self-reflecting schemes enable higher collision rates

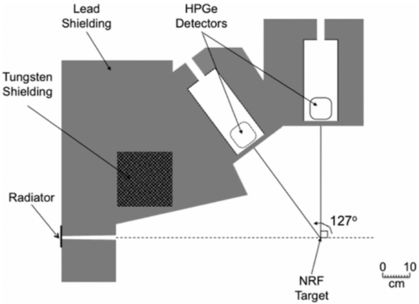
- Plasma mirror reflects driving laser pulse back onto electron beam
- High collision rate as self aligned (in time and space)
- Requires only one laser beam $\rightarrow$ more accessible
- No independent control of scattering beam (typically lower intensities)
- Consider debris and back-reflection



Ta Phuoc *et al.*, *Nat. Photon.* **6** (2012)

Examples of applications: Industry



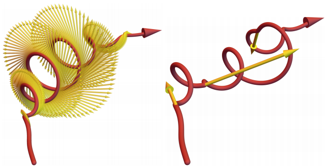


Zilges et al., *Prog. Part. Nucl. Phys* **122** (2012); Quiter et al., *PRC* **86** (2012)

- Interrogation of hazardous materials (e.g. spent nuclear fuel)
- Transmutation of nuclear waste
- Imaging applications for high-Z materials

Examples of applications: (Strong-field) QED

- Radiation Reaction



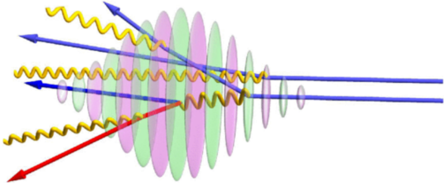
Blackburn, *Rev. Mod. Plas. Phys.* **5** (2020)

- Photon-Photon scattering

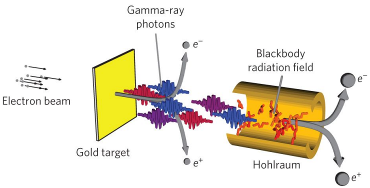
Pike et al., *Nat. Photon.* **8** (2014)

Drebot et al., *PRAB* **20** (2017)

- QED Showers and Cascades

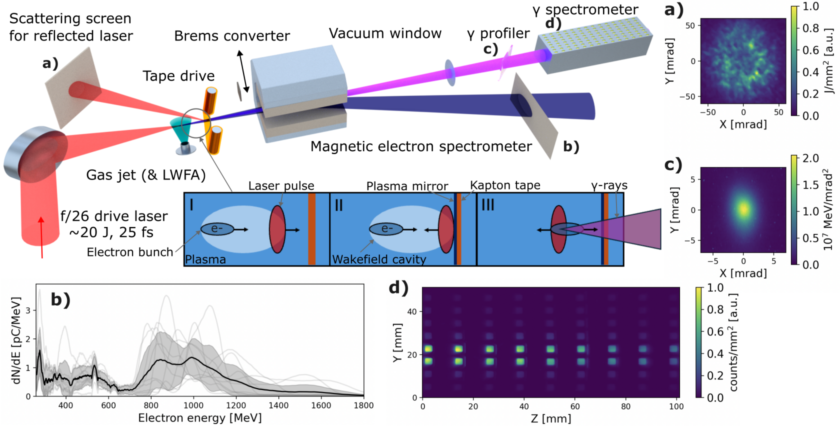


Blackburn et al., *PRA* **96** (2017)



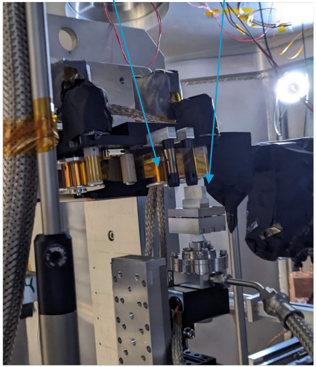
Self-reflecting Compton scattering

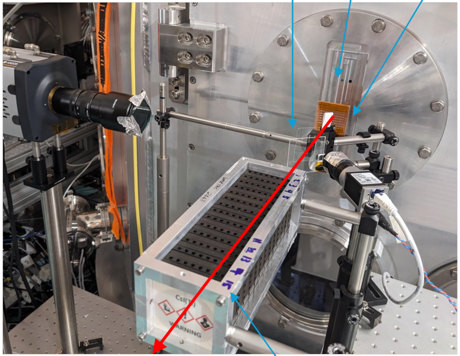
Self-reflecting Compton scattering at ELI-NP



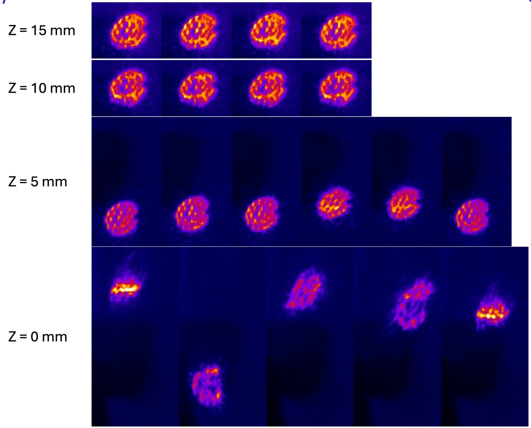
- $\langle E \rangle = 900 \pm 30$ MeV; $\langle Q \rangle = 0.9 \pm 0.4$ nC; see arXiv:2506.23718 for details

Close-up of the diagnostics and interaction point



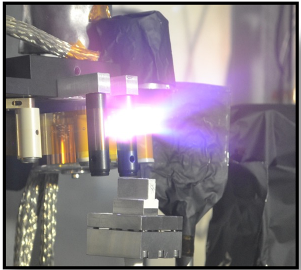
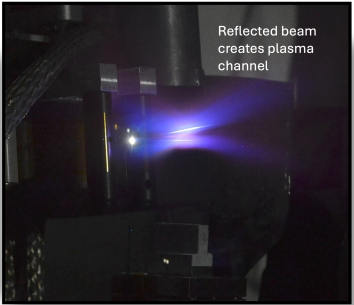


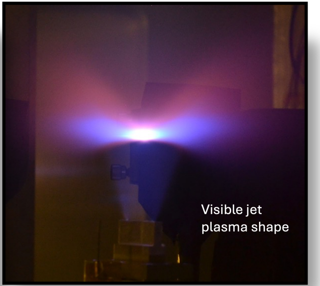
Gas flow affects tape/laser reflection when close to the jet



- Determine safe working distance at low power to avoid harmful back-reflections

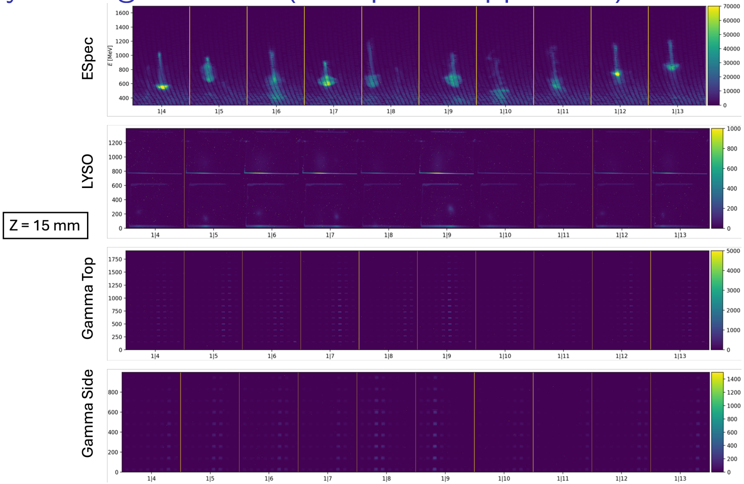
Plasma mirror in action



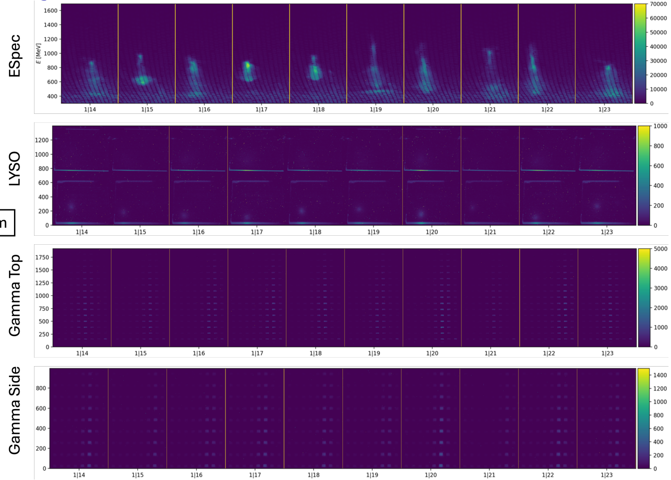
- Reproducible reflections using tape drive (Scitech/CLF, UK)
- Occasional EMP issues resolved by maximising distance to gas nozzle
- Shots 1/40 s due to gate valve/to check tape spooled (can operate at 1 Hz)

Tape 'far' away from gas nozzle (Compton suppressed)



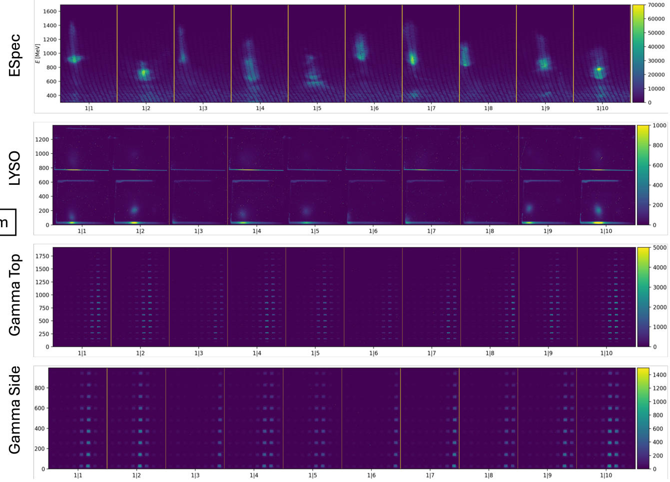
Moving closer to the jet

Z = 10 mm

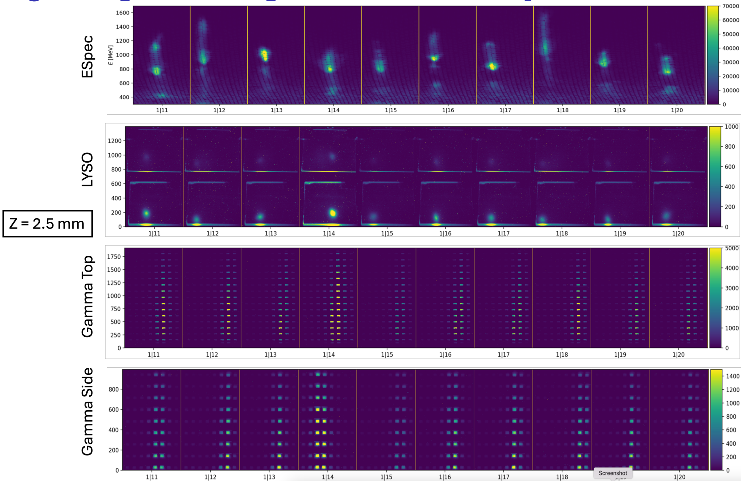


Increasing gamma/Compton signal as we approach

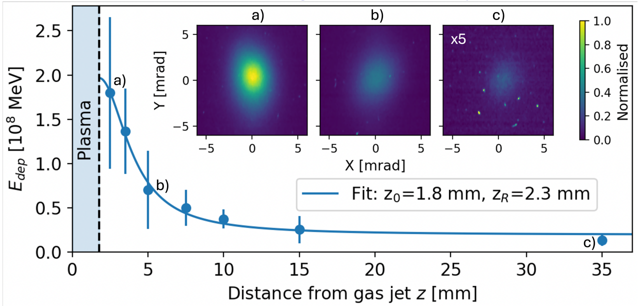
Z = 5 mm



Significantly brighter gamma signal close to the jet

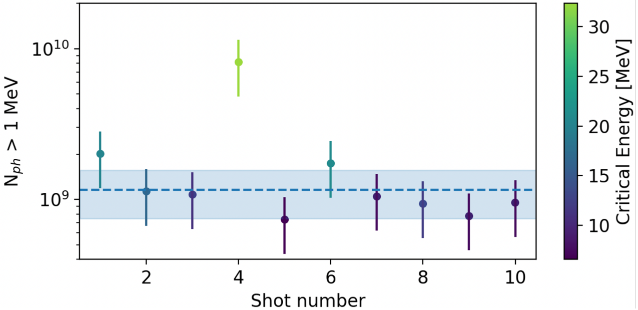


Gamma signal increases when moving closer to jet



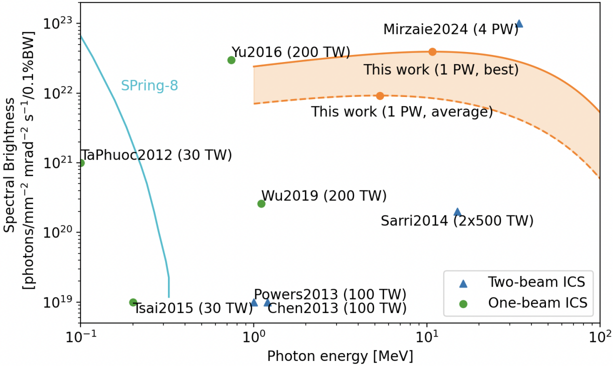
- Decrease in gamma yield consistent with ICS
- Simple fit of Gaussian waist consistent with input parameters
- Brems (kapton) and betatron signal negligible at close distance
- Divergence of photon beam is $\sim 4.0 \pm 0.5$ mrad FWHM

Shot-to-shot variations in performance (close shots)



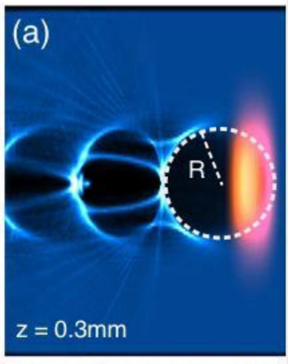
- Forward fitting using $dN_\gamma/d\epsilon_\gamma \sim \epsilon^{-2/3} e^{-\epsilon_\gamma/\epsilon_{crit}}$
- Average photon energy is few MeV ($\epsilon_{crit}/3$)
- Combine charge and brems calibration with ϵ_{crit} for N_{ph}
- Outlier: potentially variations in laser/plasma properties

Photon source in context



- Combine measured ϵ_{crit}, N_{ph} and θ, with simulated source size
- Source not fully optimised yet (energy, divergence...)
- Photons in bandwidth and average flux might be more important than brightness

Simple model describes ICS yield for a given laser energy



Total radiated energy = Classical radiated power × Beam charge × Interaction duration

$$W_{ICS} \approx \frac{2}{3}\frac{e^2 m_e^2 c^3}{4\pi\epsilon_0 \hbar^2}\chi^2 N_b \frac{\tau}{2}$$

$$W_{ICS} \approx \left[\frac{1024}{405\pi^2}\frac{r_e^2}{m_e c^4}\right]\omega_0^2 W_L^2 \frac{2a_0^2}{(a_{g,0})^3}$$

$$a_{g,0} = 4$$

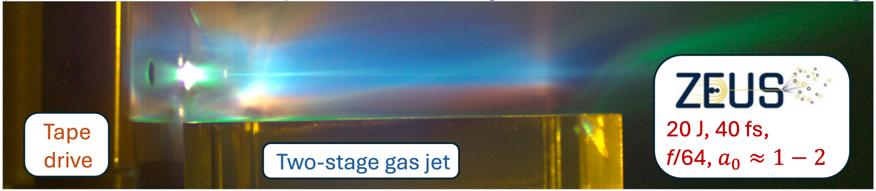
$$a_0 = \frac{a_{g,0}}{\sqrt{2}}$$

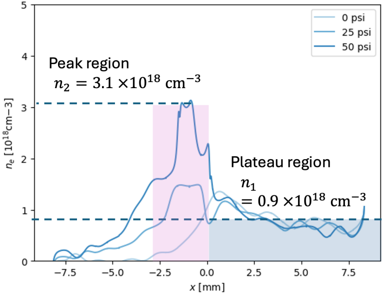
$$W_{ICS} \approx 4\times 10^{-4} W_L^2$$

Efficiency $\eta_{ICS} = 4\times 10^{-4} W_L$

- Assuming matched bubble regime (Lu et al. *PRSTAB* **10** (2007))
- Improve efficiency by enhancing a_0, e.g. density tailoring → arXiv:2408.13238

ZEUS Experiment to tailor plasma density and increase scattering intensity





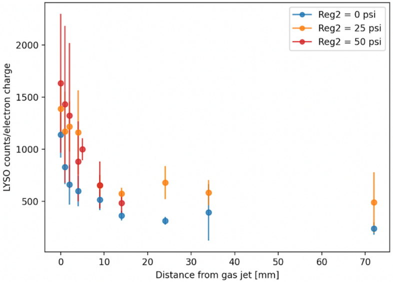
$$a_2 \approx a_1 \left(\frac{n_2}{n_1}\right)^{1/3}$$

$$a_2 \approx 1.5 a_1$$

$$W_{ICS} \propto a^2$$

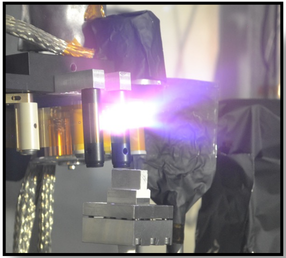
$$\frac{W_{ICS,2}}{W_{ICS,1}} \approx 2.3$$

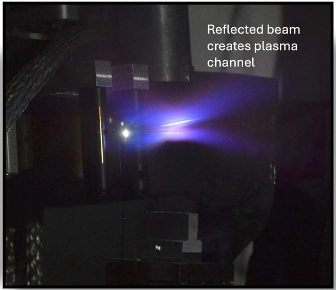
Assuming only self-focusing affected

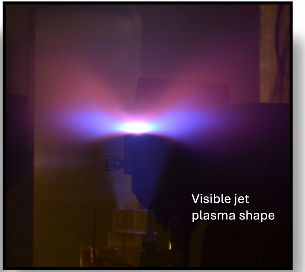


All-optical, self-aligned Compton source at ELI-NP and ZEUS

- High yield nonlinear inverse Compton scattering at ELI-NP
- Self-guiding at constant a0 in LWFA gives rise to simple scaling law
- Density tailoring can improve efficiency by increasing a_0 at the interaction
- see arXiv:2506.23718 for details







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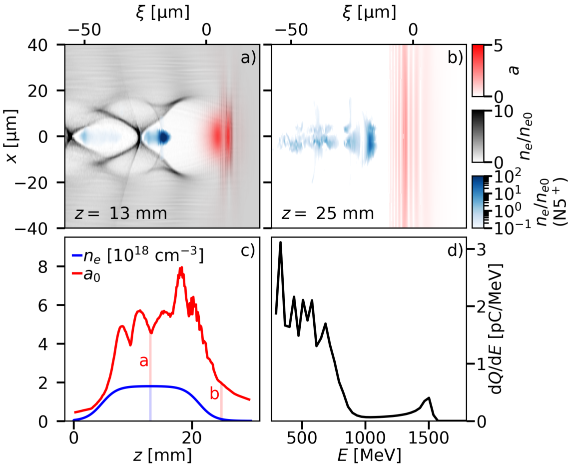
Backup slides

Simulations to check consistency of results



- FBPIC using measured density profile (offline) and focal spot to match electron beam performance
- Predicted intensity $a_0 \sim 2$ ($a_0 \sim 4$ in plasma)
- Electron beam size $\sim 5\mu m$
- Significant redshifting $\langle\lambda\rangle \approx 1\mu m$
- Ptarmigan simulations (Russell) match $a_0 < 2$
- A lot of variables, need more diagnostics