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EAAC2025 · EUROPEAN NETWORK FOR NOVEL ACCELERATORS EuroNNAc4 NPACT supported by EU via I-FAST · I.FAST

Non-linear Inverse Compton Scattering Experiments using a Self-reflecting Collision Geometry

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Introduction

- A relativistic electron will absorb multiple n photons from an intense laser before emitting a single scattered photon through the Non-linear Inverse Compton Scattering (NLICS) process [1].

$$e^- + n\gamma \rightarrow e_s^- + \gamma_s \quad (1)$$

- The energy relation of these photons is given by

$$E_\gamma = \frac{n\hbar\omega\gamma^2(1+\beta\cos\theta)}{1+\gamma^2\theta^2+n\hbar\omega/(m_e c^2)} \quad (2)$$

where γ is the electrons Lorentz factor and θ is the photon emission angle to these relativistic electrons.

- NLICS experiments have been carried out at the PW-class facilities ZEUS in TA1 and TA3, Michigan and ELI-NP in area E5, Romania.
- Multi-GeV electrons are self-guided and accelerated in a gas jet. Laser light which is not depleted from the wakefield are reflected at a small collision angle onto the electrons.
- Advantage of self-reflecting experimental design increases the number of successful collisions compared to dual-beam experiments [2] as well as single beam capability constraint at major PW-class facilities.

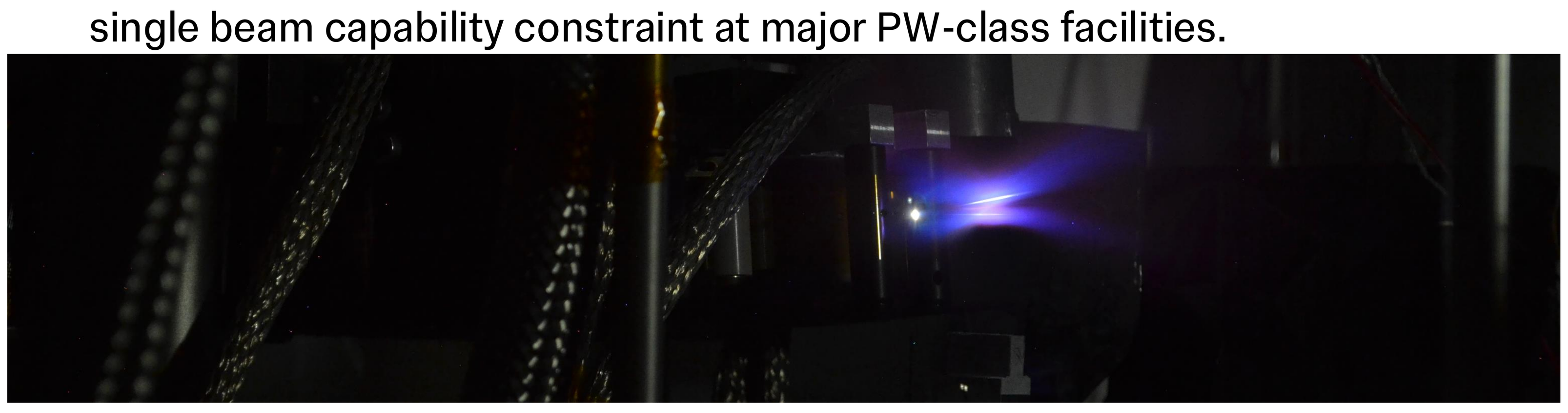

Figure 1: Two plasma channels are formed from ionization by the incident and reflected laser beams.

- Application of this work includes compact source development, fundamental strong-field quantum electrodynamics (SFQED) and laboratory studies of extreme astrophysical environments like black holes and pulsars [3].

Simulating self-reflection in a PIC code

- 2D particle-in-cell code simulations using the relativistic laser – plasma code EPOCH [4] have been performed to understand our experiments.
- A 4.0 µm aluminium (Z=13) foil is placed at 50 micron and angled by 20 degrees as shown in Figure 2.
- The 800 nm, 30 fs, 5x10^{19} Wcm^{-2} laser is then focused onto the front the foil and reflected onto the electron bunch which starts at the same boundary but delayed by 200 fs in Figure 3.

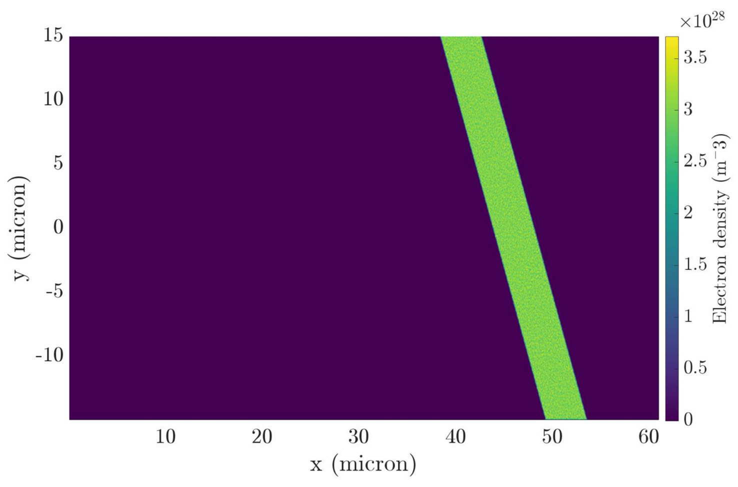

Figure 2: A 4.0 µm Aluminum target is placed at 50 micron into the simulation domain at an angle using the rotation matrix.

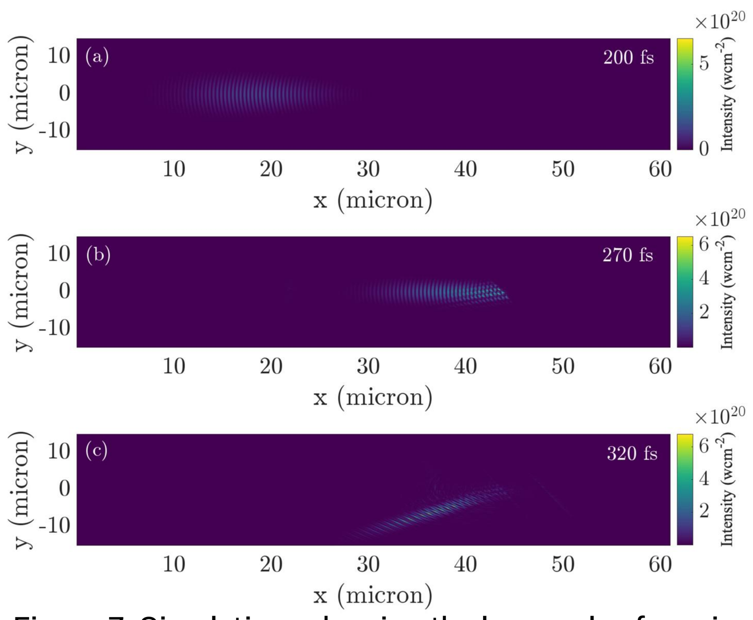

Figure 3: Simulations showing the laser pulse focusing onto the target in (a) interacting with the front surface in (b) and getting reflected at an angle in (c) as the laser pulse collides with a 600 MeV electron beam.

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} x-x_0 \\ y-y_0 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \quad (3)$$

$$\begin{aligned} x' &= (x-x_0)\cos\theta + (y-y_0)\sin\theta \\ y' &= -(x-x_0)\sin\theta + (y-y_0)\cos\theta \end{aligned} \quad (4)$$

- Eqn (3) and expanded version in (4) are the equations used for rotating the target. Plasma density = 100n_{crit}.
- Numerical heating is reduced using 5-th order B-spline particle shape fn.

Synchrotron spectrum is [5]

$$\frac{dN_\gamma}{dE} \propto AE_\gamma^{-2/3}\exp(-E_\gamma/E_c) \quad (5)$$

N_γ = number of photons
A = spectrum amplitude
E_γ = photon energy
E_c = critical energy

- The conserved electron spread before and after collision shows a negligible loss of energy as the quantum parameter χ_e is low.

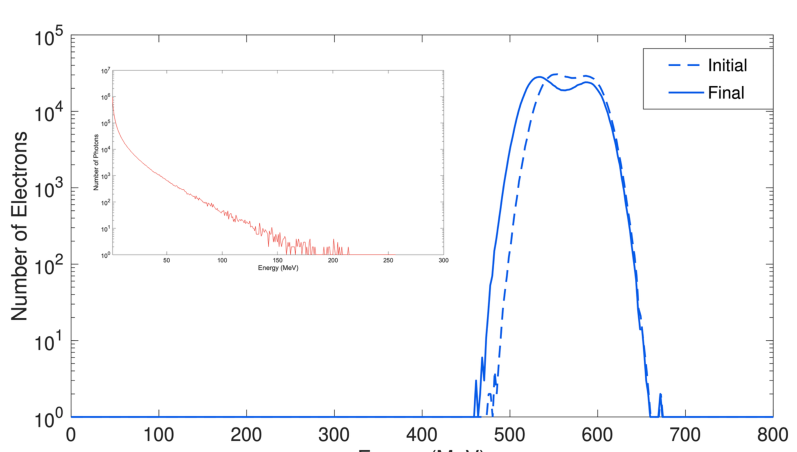

Figure 4: Electron distributions showing the initial (dashed) and final distribution (solid). Inset: photon synchrotron-like spectrum.

ELI-NP E5

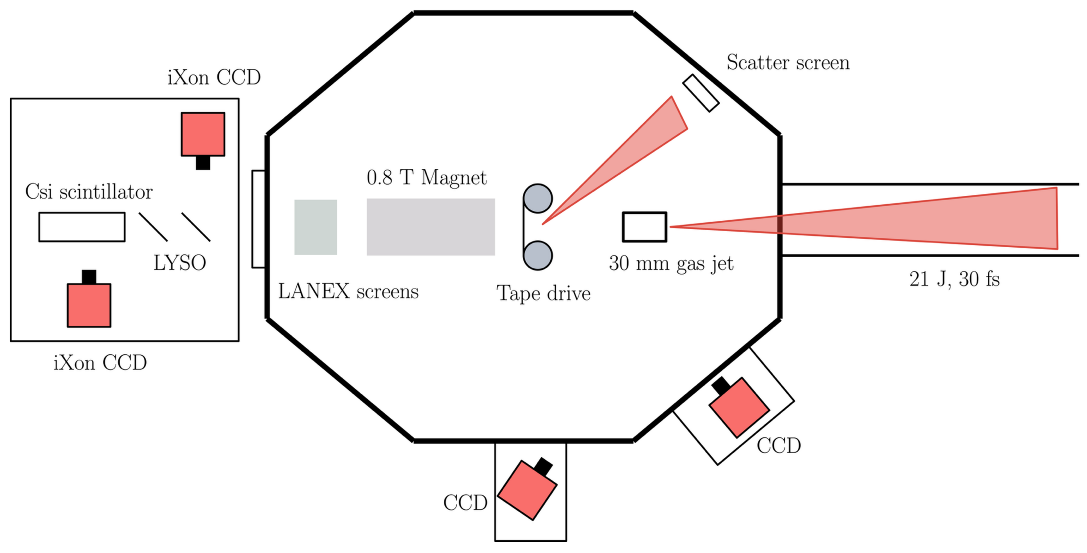

Figure 5: Experimental setup of the interaction chamber in E5 at ELI-NP showing the f/25 (21 J, 30 fs) focused at the front of a 30 mm helium-nitrogen gas to accelerate electrons to GeV energies. Diagnostics include the electron spectrometer, CsI detector and LYSO profilers. A scatter screen camera and spectrometer measures the reflection.

ZEUS TA1

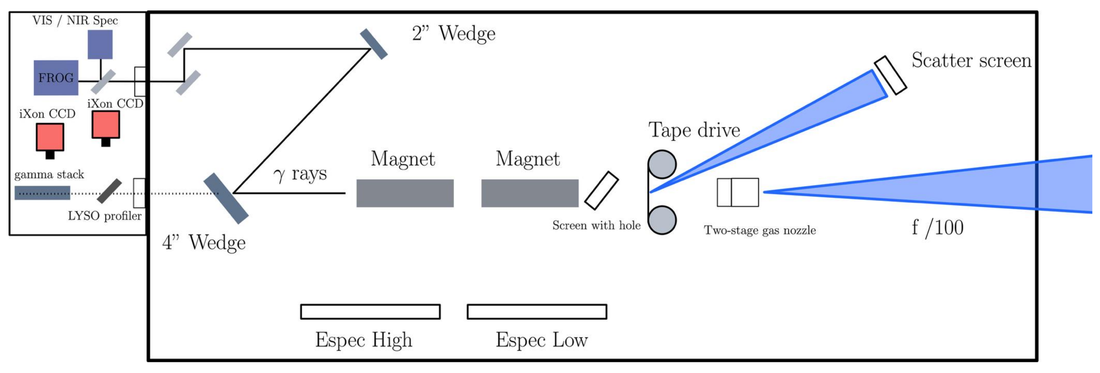

Figure 6: TA1 ZEUS experimental campaign using a two-stage gas jet for independently varying the plasma densities to control self-focusing and the a0 before the collision.

Method & Preliminary Results

- Electron spectrometer used measures 3 GeV electrons but reproducibly 1 GeV . Gamma-ray diagnostics, explained in [6] produce transverse profile of gamma-rays with LYSO profilers.
- Scans of the tape drive position in Z moving toward the gas jet and therefore closer to the laser focus show an increase in the Compton signal for Z = 2.5.
- Figure 9 shows the pressure dependency on both the laser spot size and the intensity. i.e self-focusing causes the beam to diffract at higher densities as well as lose more energy the plasma.

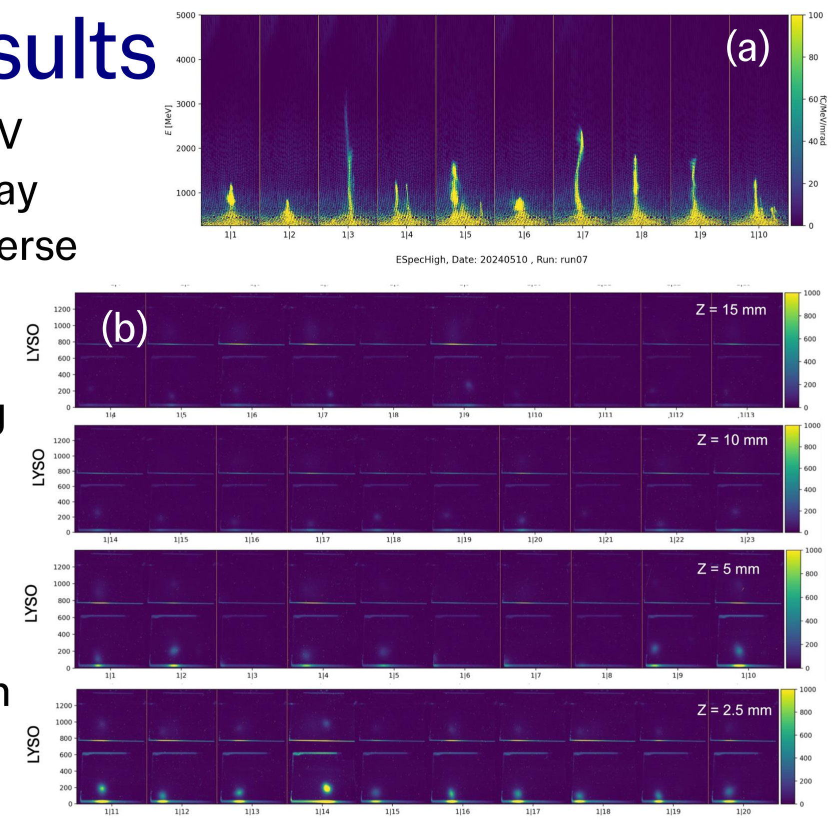

Figure 7: Electron beams produced at ELI-NP with energies up to 3 GeV but reproducibly 1 GeV in (a). Gamma LYSO profilers showing the transverse distribution of gamma rays getting brighter as Z moves closer to the focus.

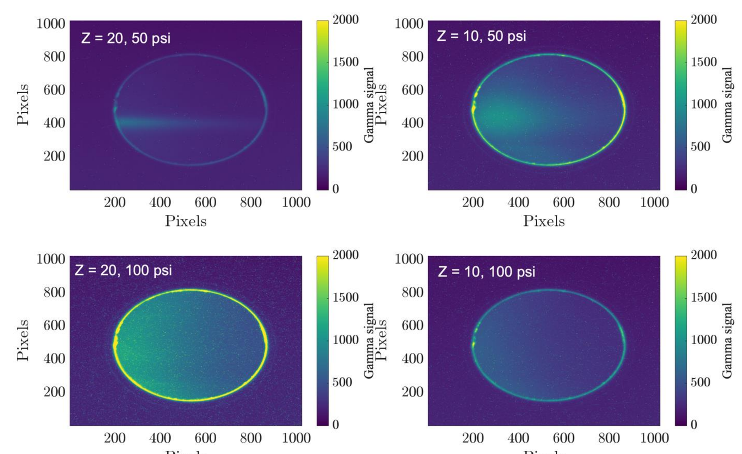

Figure 8: LYSO profiler used to diagnose the gamma-rays for Z = 10 and 20 and for gas pressures 50 psi and 100 psi.

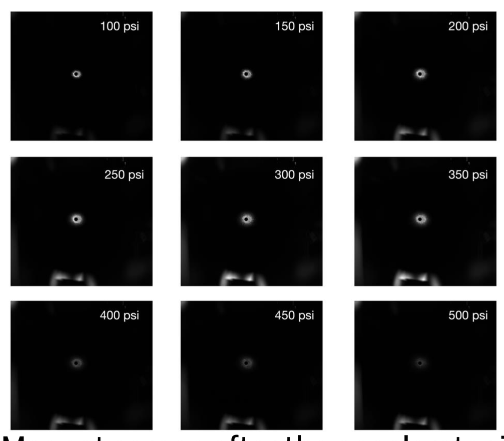

Figure 9: Magnet screen after the accelerator in ZEUS TA1 showing how the profile of the non-depleated laser light changes as a function of pressure in psi.

Conclusion

- Experiments have been conducted to investigate NLICS where GeV electron beams are produced from a laser wakefield and interact with the intense laser to generate Compton photons.
- Performing ICS experiments using a self-reflecting laser geometry is a useful technique to overcoming the challenges in dual beam collision experiments.

Outlook

- Future simulation campaigns may consider the effect that the tape has on both the electron beam as well as the laser spatial and temporal profiles.
- Understand experimentally how much the tape changes the properties of the laser.
- Analysis of the ZEUS TA1 experiment to understand how the laser a0 increases in the plasma and scaling with the signal of Compton radiation.

References

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Acknowledgements

ZEUS and ELI-NP collaborators and support staff.
Experimental support from Scitech Precision Ltd and the CLF Vulcan dark period fund.
This poster presentation has received support from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 10100473