

Experimental demonstration of Flying-Focus enhanced Thomson scattering



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LaserNetUS

BELLAHTT



LABORATORY FOR
LASER ENERGETICS



Flying-Focus enhanced Thomson scattering

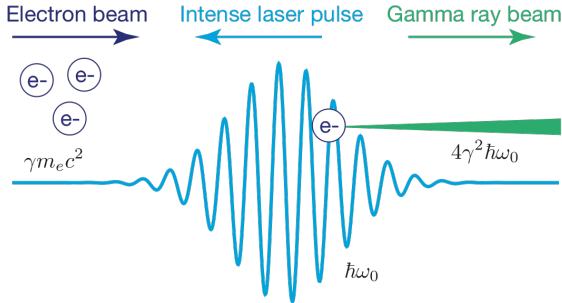
All-optical Thomson scattering

Flying-Focus Thomson scattering

Experimental Results

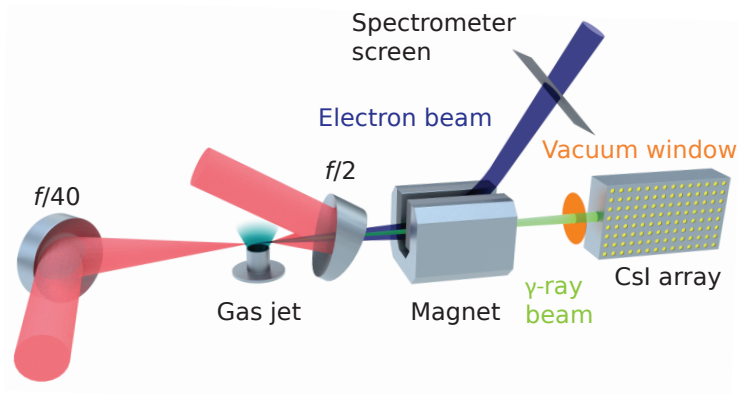
All-optical Thomson scattering

All-optical Thomson scattering is a compact source of x-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)

A typical experimental setup

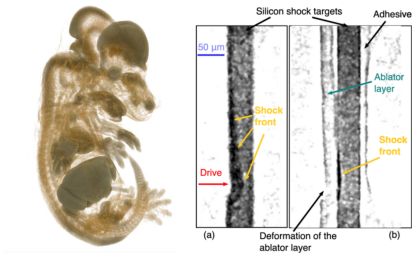


Cole et al., *PRX* 8 (2018)

Examples of applications: imaging and HEDP experiments

Small source size :

► Phase Contrast Imaging

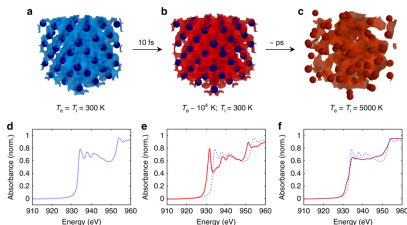


Cole et al., *PNAS* **25** (2018)

Wood et al., *Sci. Rep.* **8** (2018)

Short pulse duration and bright
broadband X-ray source:

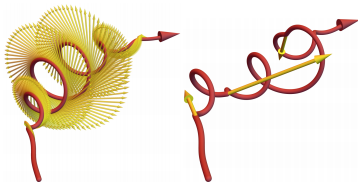
► (Time resolved) X-ray absorption spectroscopy



Mahieu et al., *Nat. Comms.* **9** (2018)

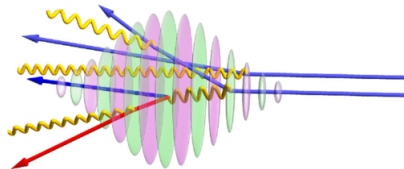
Examples of applications: (Strong-field) QED

► Radiation Reaction



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

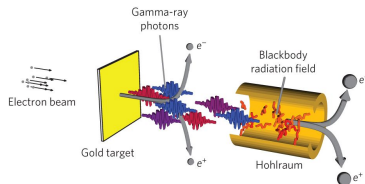
► QED Showers and Cascades



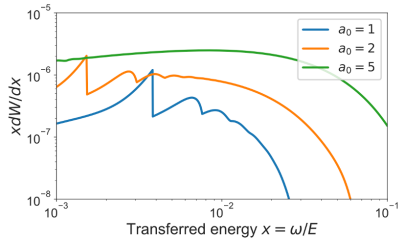
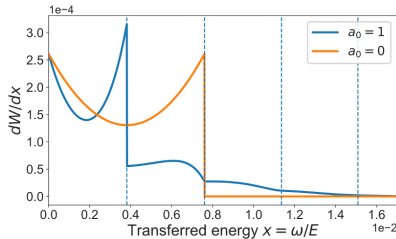
Blackburn et al., *PRA* **96** (2017)

► Photon-Photon scattering

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



Nonlinear electron motion modifies spectrum drastically

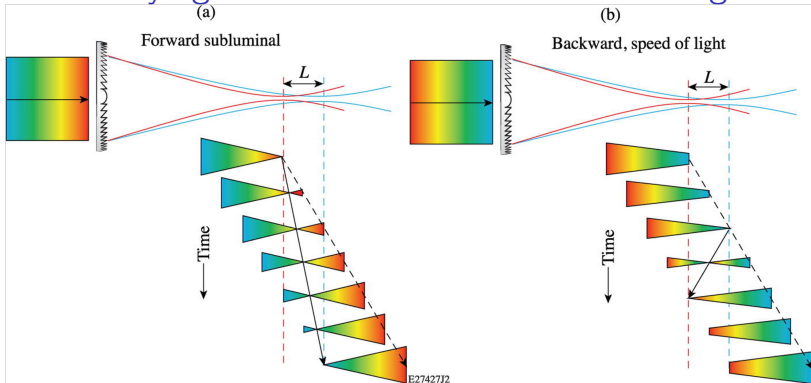


- ▶ Emitted x-ray energy

$$\hbar\omega' \approx 2n[1 - \cos(\alpha)]\gamma^2\hbar\omega/(1 + a_0^2/2 + (\gamma\theta)^2)$$
- ▶ Linear: $a_0 \ll 1$, narrowband, radiated energy increases with a_0^2
- ▶ Non-linear: $a_0 > 1$, broadband (higher harmonics/red shifting), harmonic order a_0^3 , energy increases as a_0
- ▶ Photon yield in linear case usually low ($a_0^2 \sim$ photon density)
- ▶ Extending interaction efficiently limited by diffraction

Flying-Focus Thomson scattering

Chromatic Flying Focus enables novel interaction geometries

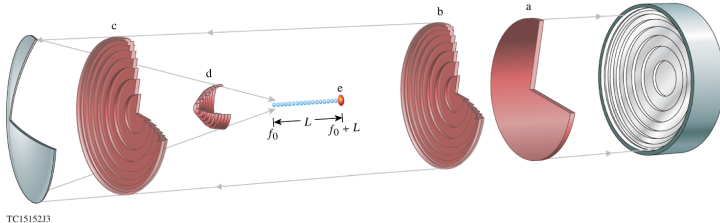


Froula et al., *Nat. Photon.* **12** (2018), *Phys. Plasmas* **26** (2019)

- ▶ Use chromatic focusing optic and chirp to control focal volume
- ▶ Maintain high intensity over extended distance (diffraction)
- ▶ Control focal velocity $\beta = \left[1 + \left(\frac{d\lambda}{dt} \right)^{-1} \left(\frac{dz}{d\lambda} \right)^{-1} c \right]$
- ▶ Provides additional control to optimise interactions

Reflective or pre-compressor optics enable high powers

PHYSICAL REVIEW LETTERS **124**, 134802 (2020)



Palastro et al., *Phys. Rev. Lett.* **124** (2020)

- ▶ Chromatic optics are typically transmissive → avoid high powers before compression: Jolly et al., *Opt. Expr.* **28** (2020)
- ▶ Reflective optics: Imprint radial delay with an echelon and focus with axiparabola: Arrowsmith et al., *Nat. Phys.* (2026)
- ▶ Dynamically: AO+SLM: Ambat et al., *Opt. Exp.* **31** (2023) and Plasma lens: Li et al., *Phys. Rev. Research* **6** (2024)

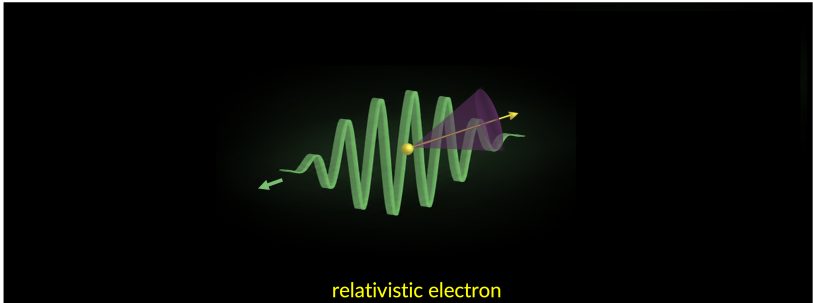
Conventional focusing limits the useful interaction length



- ▶ Diffraction limits overlap between electron bunch and laser pulse (unless externally guided)
- ▶ Optimum pulse duration depends on focusing ($\tau \sim z_R$)
- ▶ Counterpropagating geometry reduces interaction length

Conventional focusing limits the useful interaction length

laser pulse and x-rays



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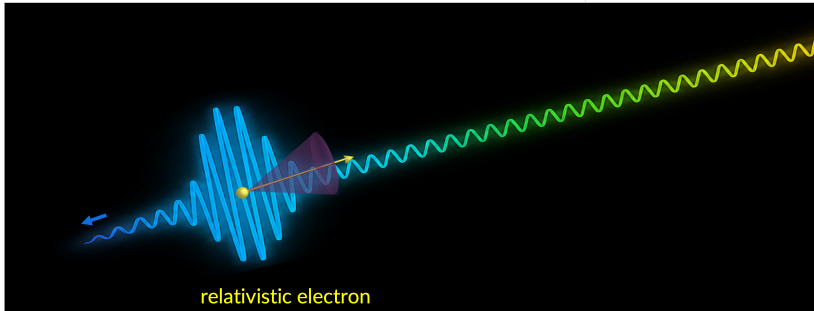
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A co-propagating flying focus can extend the interaction

laser pulse and x-rays

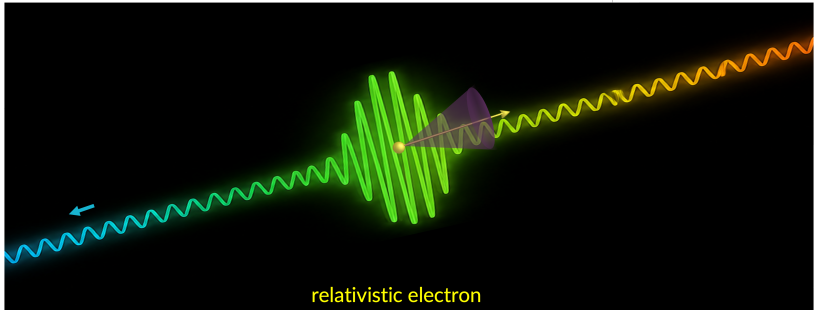


Ramsey et al., *Physical Review E* **105** (2022)

- ▶ Maintains high intensity beyond conventional Rayleigh length
- ▶ Co-propagating focus ($\beta = -1$) extends interaction length
- ▶ Increase photon yield while preserving linear electron motion

A co-propagating flying focus can extend the interaction

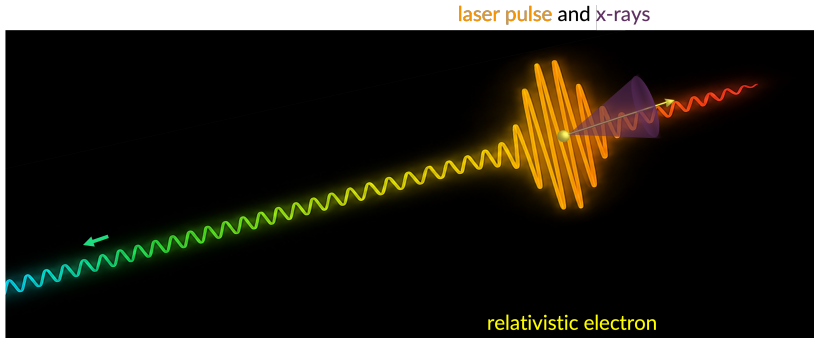
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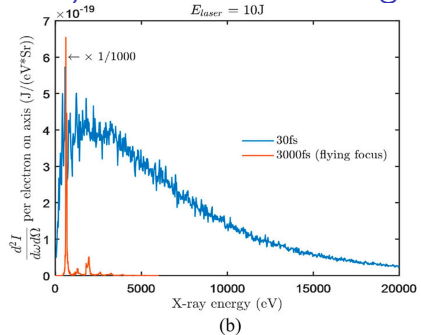
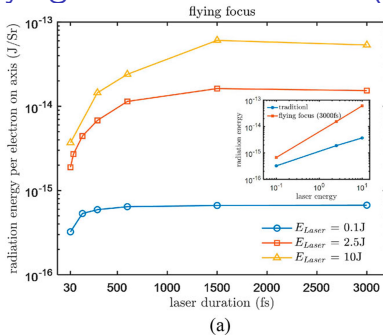
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A flying focus can enhance (linear) Thomson scattering

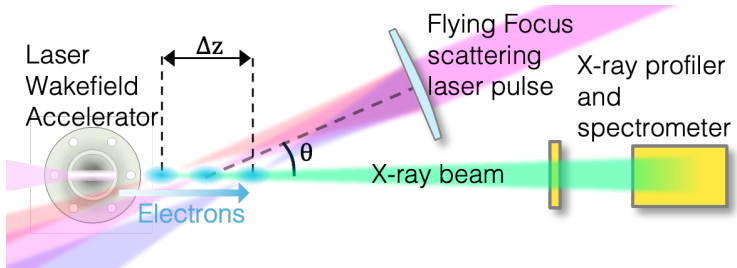


Ye et al., *AIP Advances* **13** (2023)

- ▶ Linear electron motion:
reduced divergence and spectral bandwidth
→ increased spectral brightness
- ▶ Enhancement increases with laser energy
(electron motion increasingly nonlinear at higher intensities)

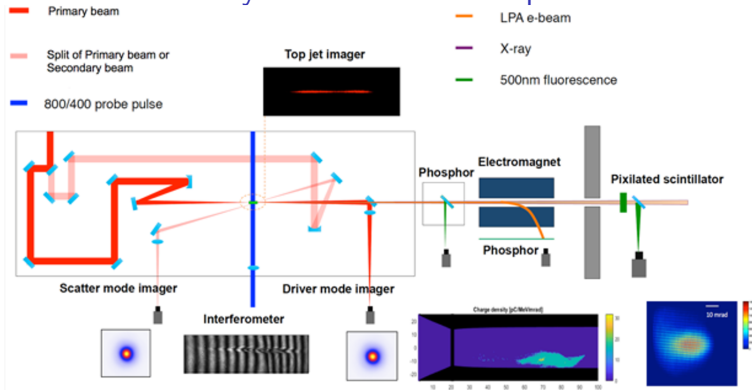
Flying-Focus Thomson scattering at BELLA HTT

Enhanced Thomson scattering with two-dimensional control



- ▶ Match trajectory of LWFA electrons with laser pulse
- ▶ Chromatic flying focus with two-dimensional control:
 - ▶ Longitudinal chromatism introduced by a singlet lens
 - ▶ Tune velocity (chirp) and angle (angular dispersion)
- ▶ Observables: electron and X-ray spectrum/profile
- ▶ Demonstrate enhanced X-ray yield with matched flying focus

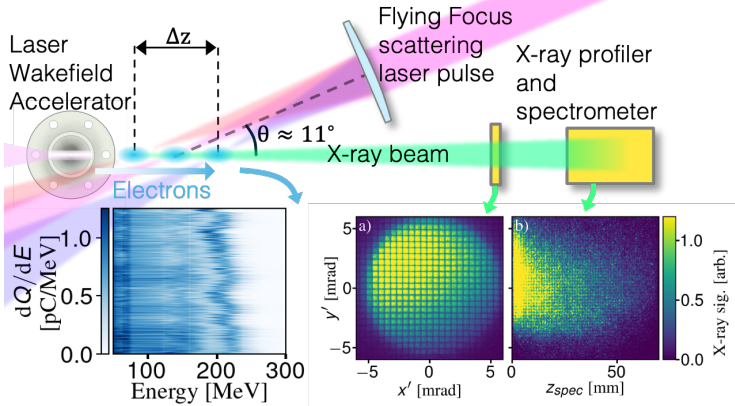
BELLA HTT is ideally suited for this experiment



Tsai et al., *Sci. Rep.* (2026)

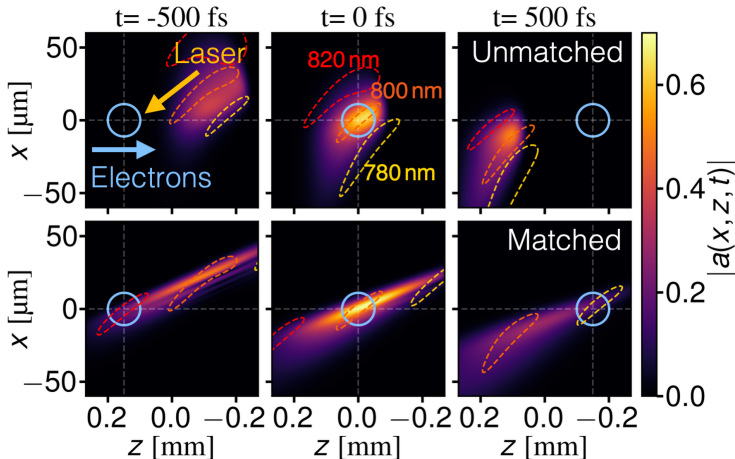
- ▶ Designated Thomson beam line (LWFA+scattering beam)
- ▶ Existing suite of laser, plasma, x-ray and electron diagnostics
- ▶ High-repetition rate system allows for scans at Hz scale
- ▶ Replace reflective scatterer with chromatic flying focus

Experimental campaign at BELLA HTT (LaserNetUS)



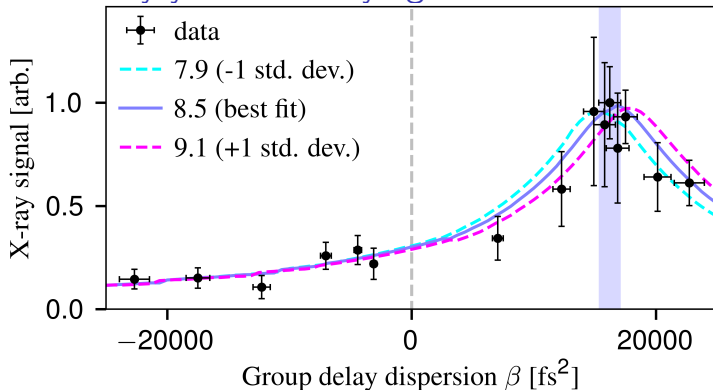
- ▶ LWFA electrons: 140 ± 40 pC, 210 ± 20 MeV (95th percentile)
- ▶ Scattering beam: 0.5 J, focused with f/5 UV fused silica lens
- ▶ Scintillator-based x-ray profiler and spectrometer

Matched 2D Flying Focus extends interaction length



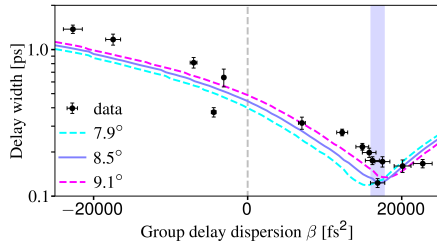
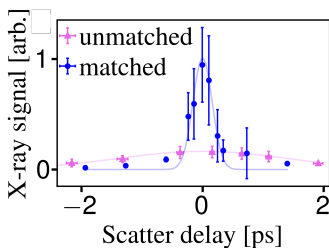
- ▶ For $f(\lambda = 800\text{nm}) = 254$ mm, $\Delta\lambda = 21$ nm $\rightarrow \Delta f \approx 210\mu\text{m}$
- ▶ At $\tau = 1\text{ps}$, $a_0 = 0.7$ (compared to $a_0 = 5.2$ fully compressed)

Increase in x-ray yield when flying focus is matched



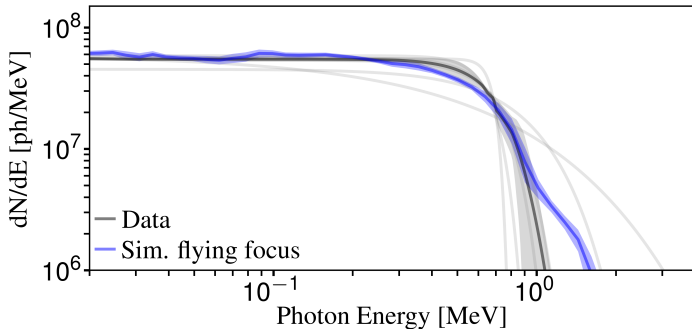
- ▶ Set angle and vary GDD to match focal velocity
- ▶ Establish spatial and temporal overlap at each position
- ▶ Good agreement with modelling within FF angle and errors
- ▶ Peak a_0 remains within $\approx 10\%$ for this GDD range

Increased synchronisation sensitivity when FF is matched



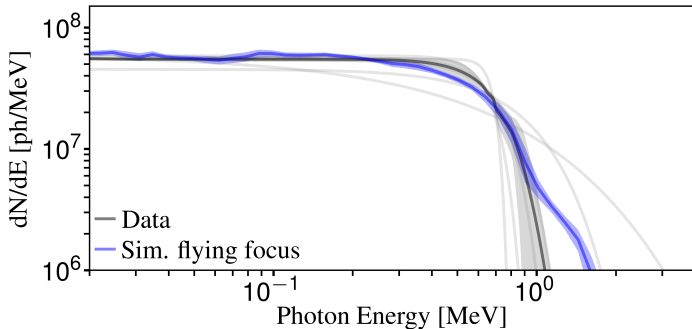
- ▶ Matched velocity results in higher synchronisation sensitivity
→ 1 ps pulse duration but ~ 100 fs delay width
- ▶ Unmatched pulses interact with some part of the beam
- ▶ Highest sensitivity around maximum x-ray yield (within errors)
- ▶ Deviations from modelling due to higher order effects such as nonlinear chirp, aberrations in the beam, electron bunch size

Enhanced photon density on detector when FF is matched



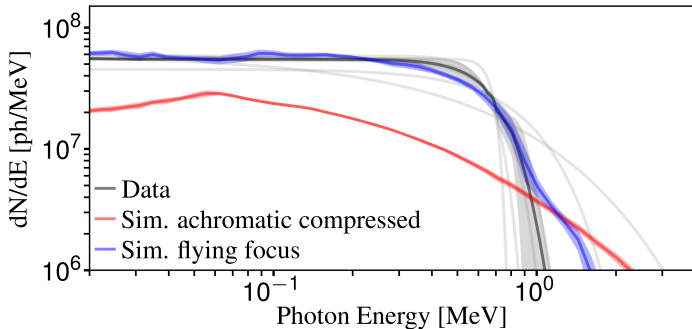
- ▶ Broadband electron spectrum and high divergence result in broadband x-ray spectrum (even for linear electron motion)
- ▶ Spectral shape measured with x-ray spectrometer in good agreement with ptarmigan simulations (linear scattering)
- ▶ Angular cut based on detector acceptance

Enhanced photon density on detector when FF is matched



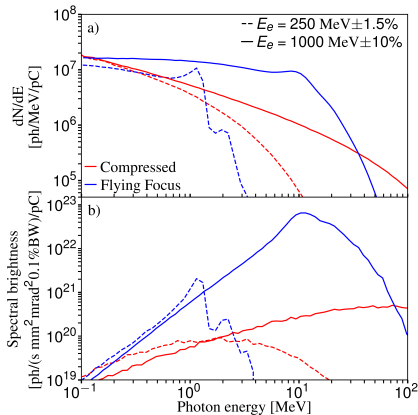
- ▶ Average photon yield $(3.6 \pm 1.0) \times 10^7$ photons > 20 keV
Maximum photon yield $(5.8 \pm 2.0) \times 10^7$ photons > 20 keV
- ▶ 5% of maximum photon number expected for zero-size bunch
→ Inferred electron bunch size of $8 \mu\text{m}$ at interaction plane
- ▶ Spectral brightness $\sim 3 \times 10^{20}$ ph/(s mm² mrad² 0.1% BW)

Enhanced photon density on detector when FF is matched



- ▶ Enhancement of photons on detector compared to computed spectrum for compressed pulse without spatiotemporal control
- ▶ Overall radiated energy is higher for compressed pulse
- ▶ Measured photon beam divergence is (5.7 ± 1.1) mrad, increases to 16 mrad in polarisation axis for compressed pulse

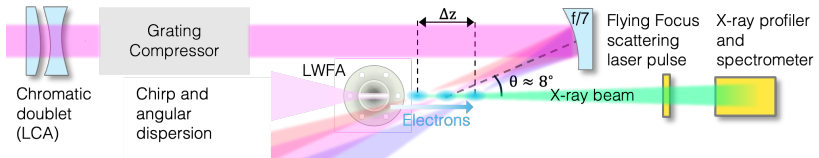
Enhancement scales favourably with laser energy



- Pulse energy: $0.5 \text{ J} \rightarrow 10 \text{ J}$
- Compressed $a_0 \approx 5.5 \rightarrow 16.6$

- Improve performance with high-quality electron beams (energy spread, divergence)
- Increase photon yield linearly with laser energy
- Increase energy $E_f \propto \gamma^2$
- Enhancement in photon density for angular integrated spectrum
- 10J-scale system could yield orders of magnitude enhancement in spectral brightness at 10 MeV scale

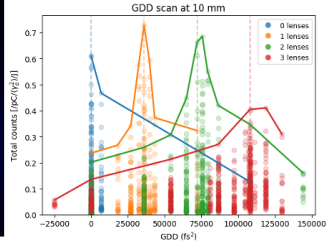
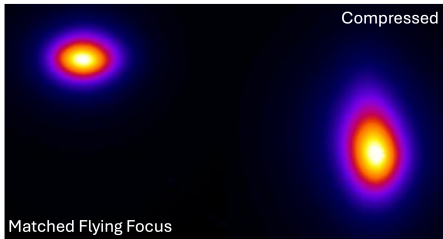
Enhanced Thomson scattering at Gemini ($\sim 2 \times 10$ J)



Jolly et al., *Opt. Express* **28** (2020), Kabacinski et al., *Nat. Photon.* **17** (2023)

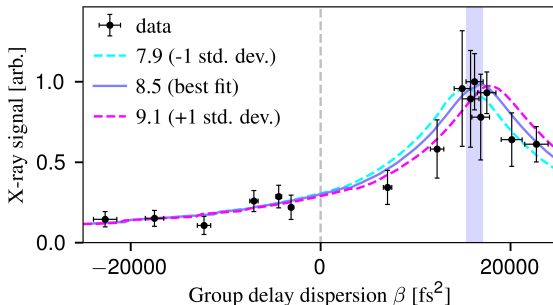
- ▶ Chromatic optics placed before compression to avoid damage
- ▶ LCA added in discrete steps to generate mm-scale line focus
- ▶ Removing optics altogether allows for direct comparison of matched flying focus with conventional focusing
- ▶ GeV-scale electrons from LWFA collided with optical pulse
→ few-10 MeV photons at linear edge

Enhanced Thomson scattering at Gemini ($\sim 2 \times 10$ J)



- ▶ Similar behaviour as for BELLA for each set of lenses
- ▶ Without lenses, highest yield when compressed (0 GDD)
- ▶ Comparable yield on detectors as electron divergence lower
→ all photons typically in detector range
- ▶ Analysis needed to translate yield on detectors into gamma spectra, photon numbers and spectral brightness
- ▶ High-power setup, can be integrated with existing geometries

Thank you for your attention!



- ▶ Flying focus can enhance Thomson scattering in terms of yield, spectral control and spectral brightness
- ▶ Flying-focus Thomson scattering with 2D control at BELLA
- ▶ High-power compatible setup demonstrated at Gemini at 10-J
- ▶ Path towards brighter sources:
higher laser energies and improved electron properties



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LaserNetUS

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