Recent experimental results on the optimisation of x-ray betatron sources

Gianluca Sarri

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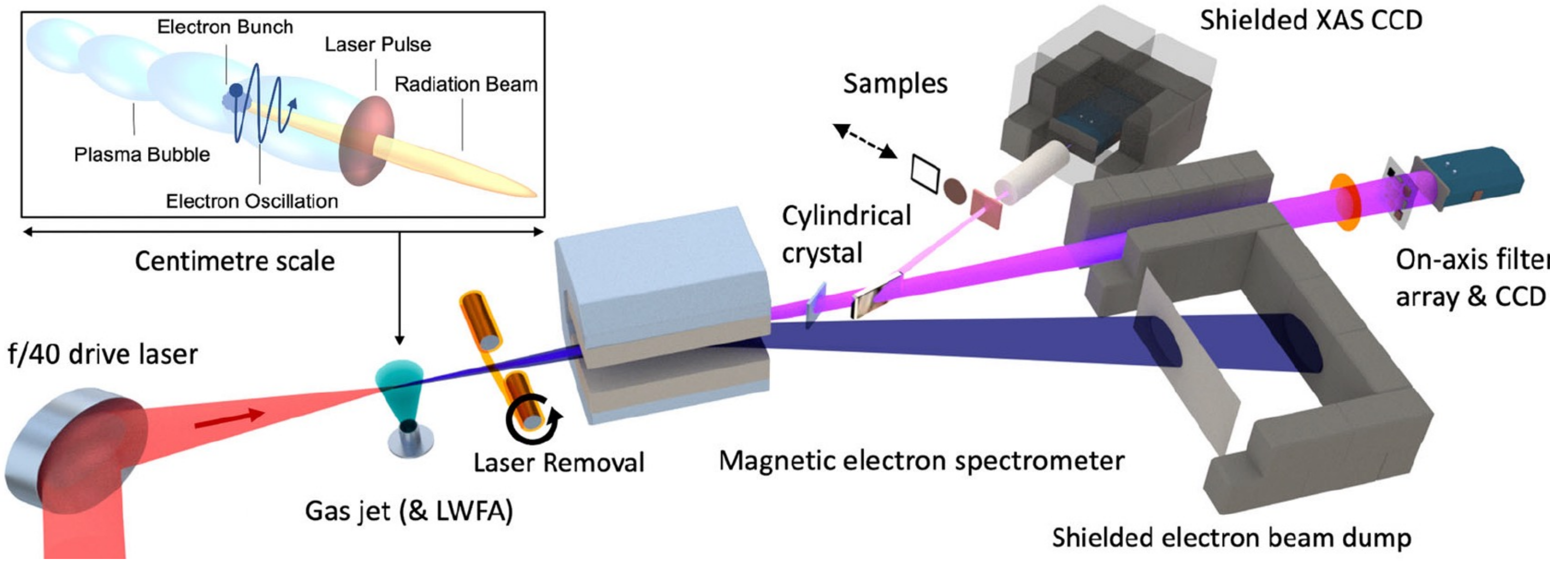
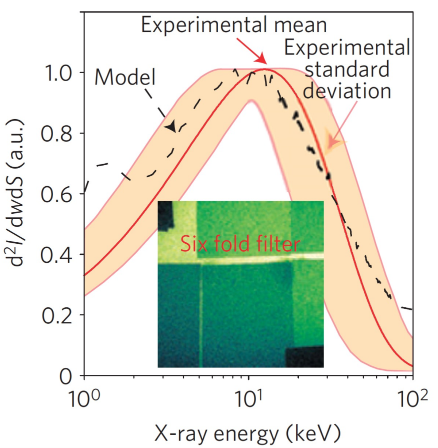
Introduction

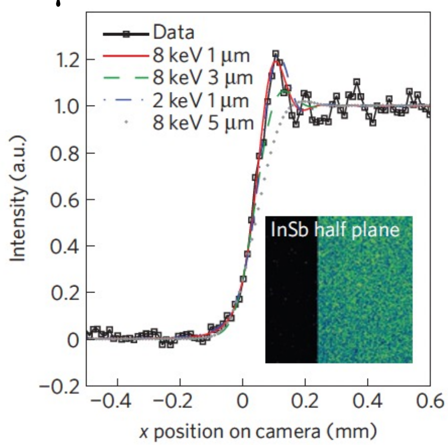
Typical source parameters



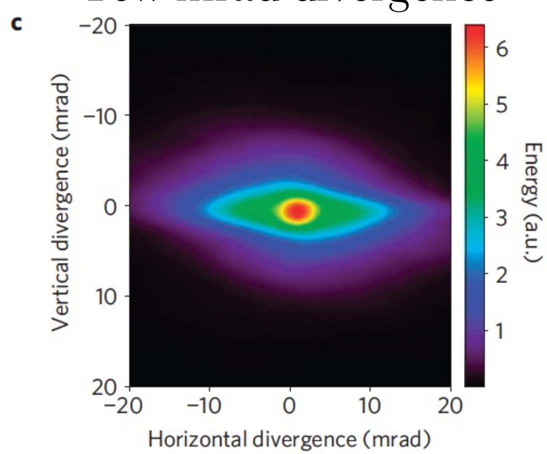
~ KeV-scale energy



μm-scale source size



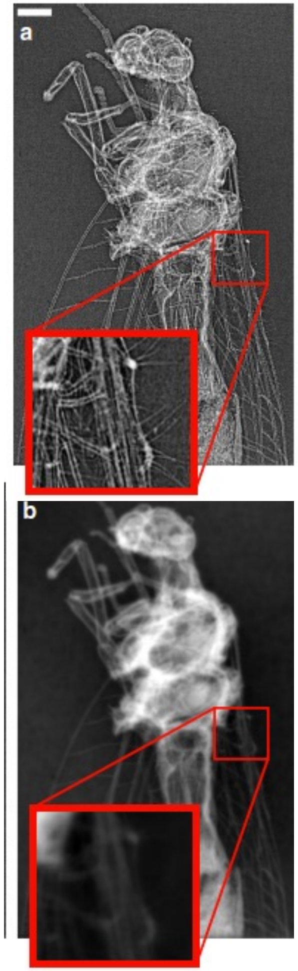
Few mrad divergence



S. Kneip et al., Nat. Phys. 2009

Typical applications

Phase-contrast imaging



J. Wenz et al., N. Comm. 2015

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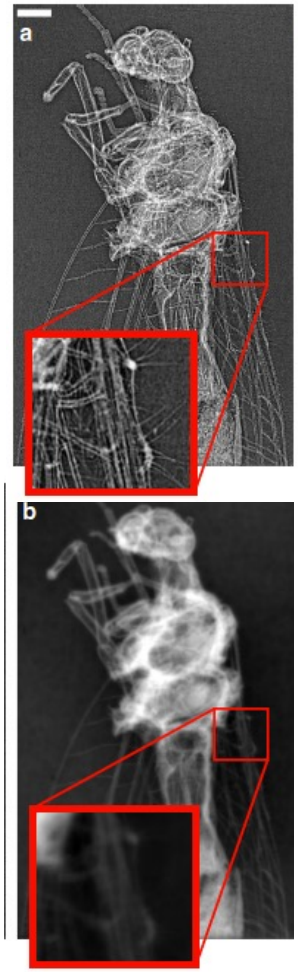

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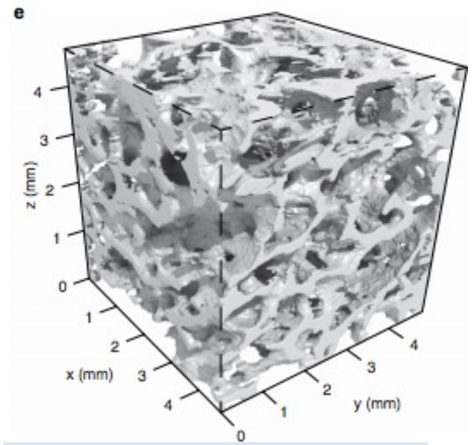
Tomography



J. Cole et al., Sci. Rep. 2015

J. Cole et al., PNAS 2018

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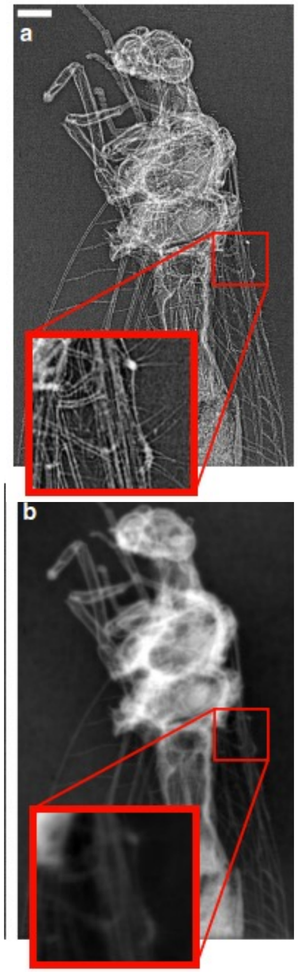

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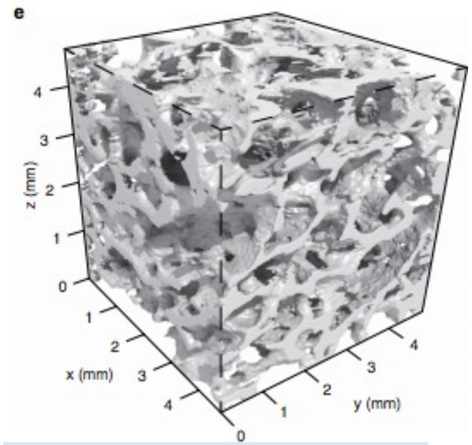

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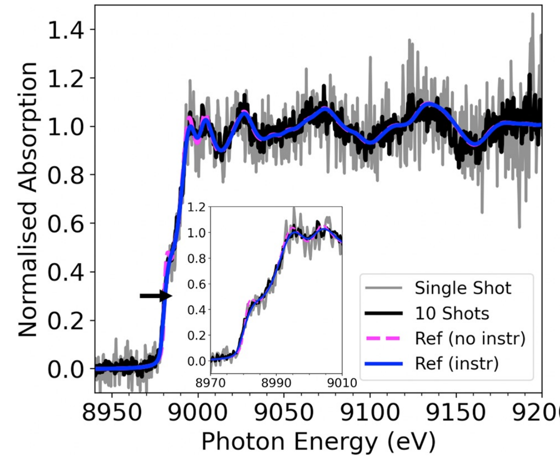
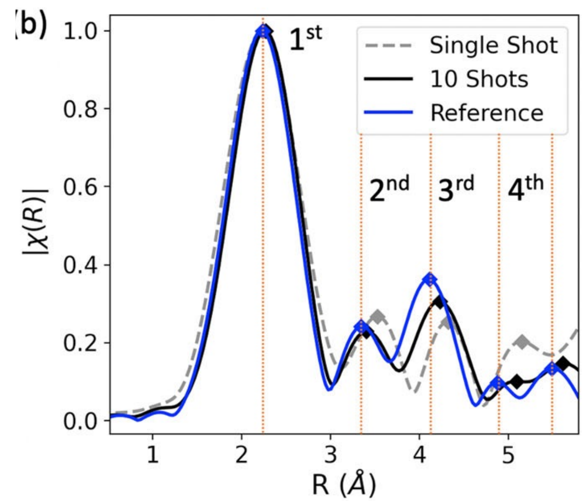
X-ray absorption

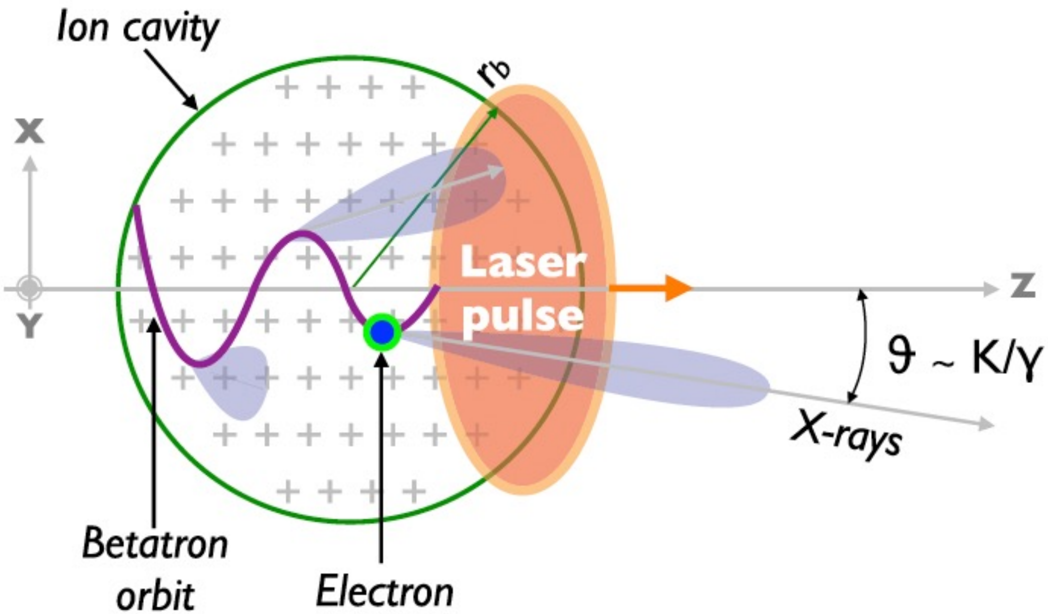




B. Kettle et al., Comm. Phys. 2024

Laser-driven betatron sources

During wakefield acceleration, the electrons are also subject to a transverse restoring force due to a positive background in the bubble. Electrons injected off-axis will experience oscillations and, thus, emit radiation.



Critical frequency

$$\omega_c = \tfrac{3}{2} K \gamma^2 2\pi c / \lambda_u$$

Number of emitted photons

$$N_\gamma = \frac{5\sqrt{3}\pi}{6} \alpha K.$$

Divergence

$\vartheta \sim K/\gamma$

S. Corde et al., Rev. Mod. Phys. 2013

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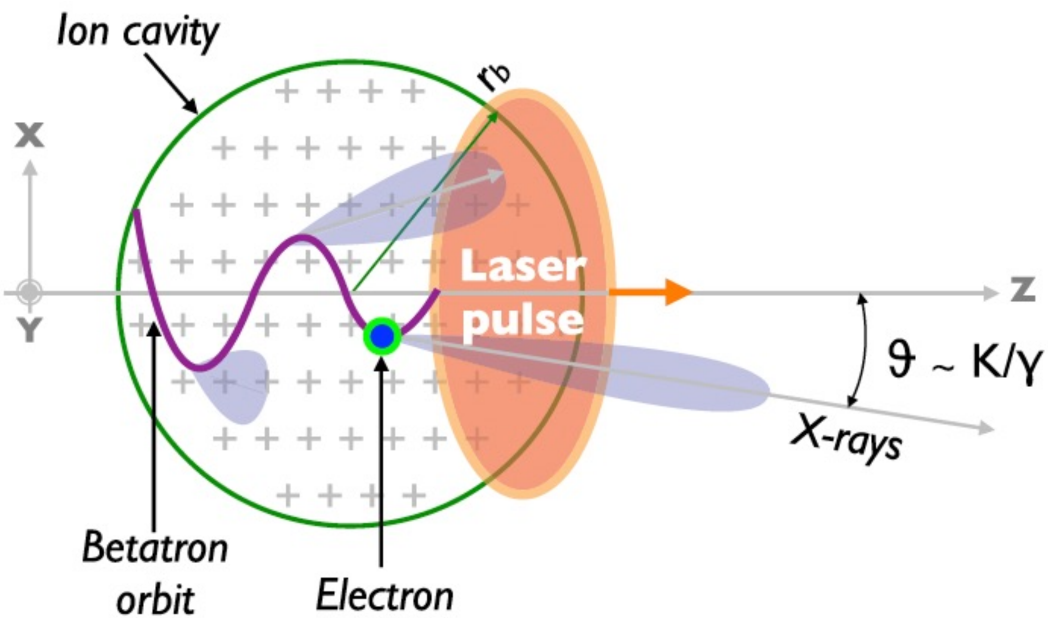

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The x-ray beam parameters mainly depend on the strength parameter K and λ_u

$$K(t) = r_\beta(t) k_p \sqrt{\gamma(t)/2}, \qquad \lambda_u(t) = \sqrt{2\gamma(t)}\lambda_p,$$

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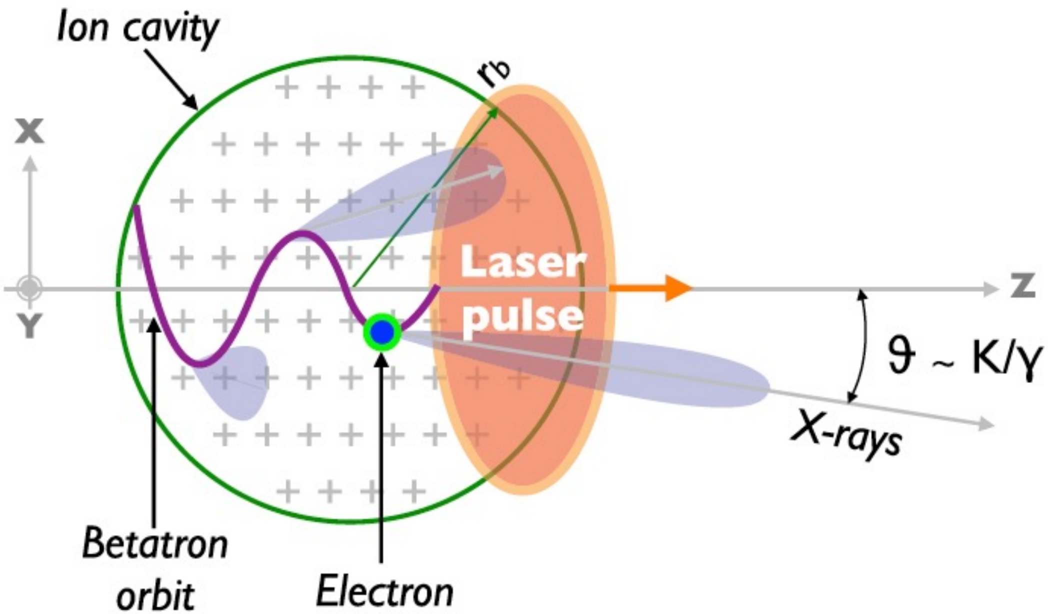

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How to work on K and λ_u to increase performance?

S. Corde et al., Rev. Mod. Phys. 2013

A brute-force approach

A formally straightforward approach to maximise the x-ray parameters (mainly flux per shot) is to adopt **Bayesian optimization** on the laser and plasma parameters

R. Shalloo et al., Nat. Comm. 2020

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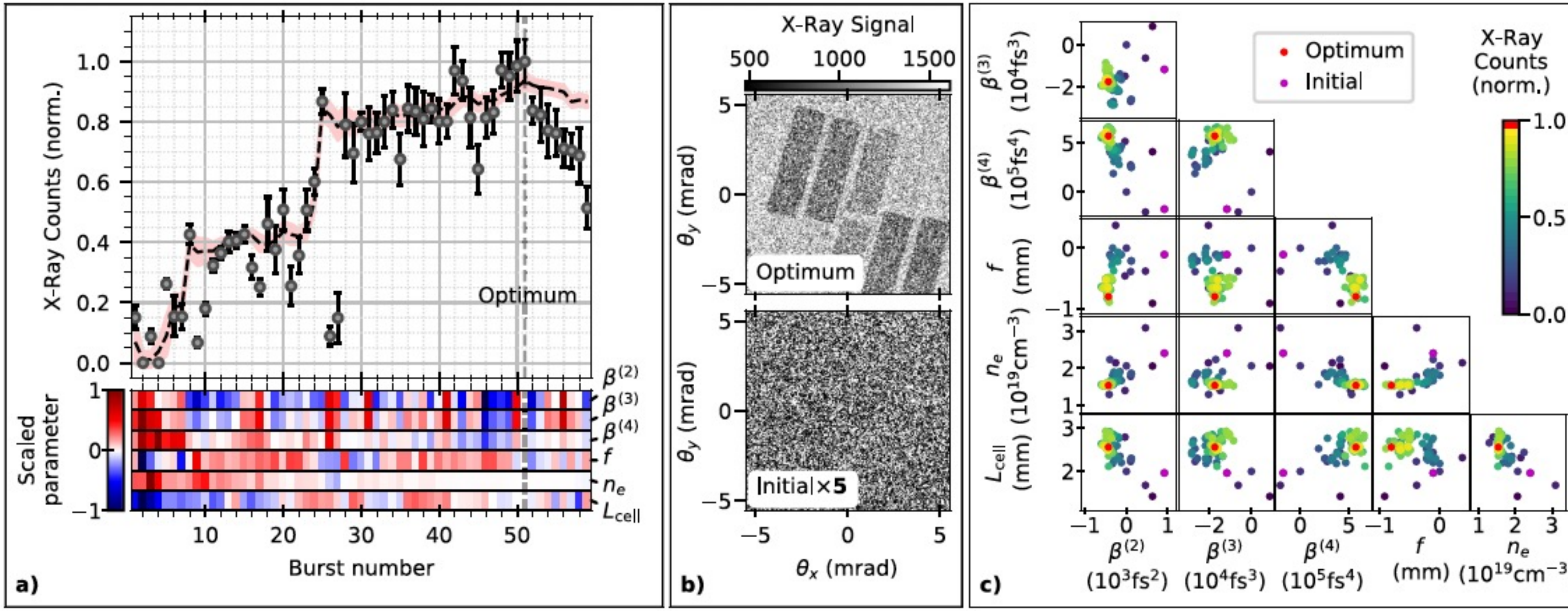
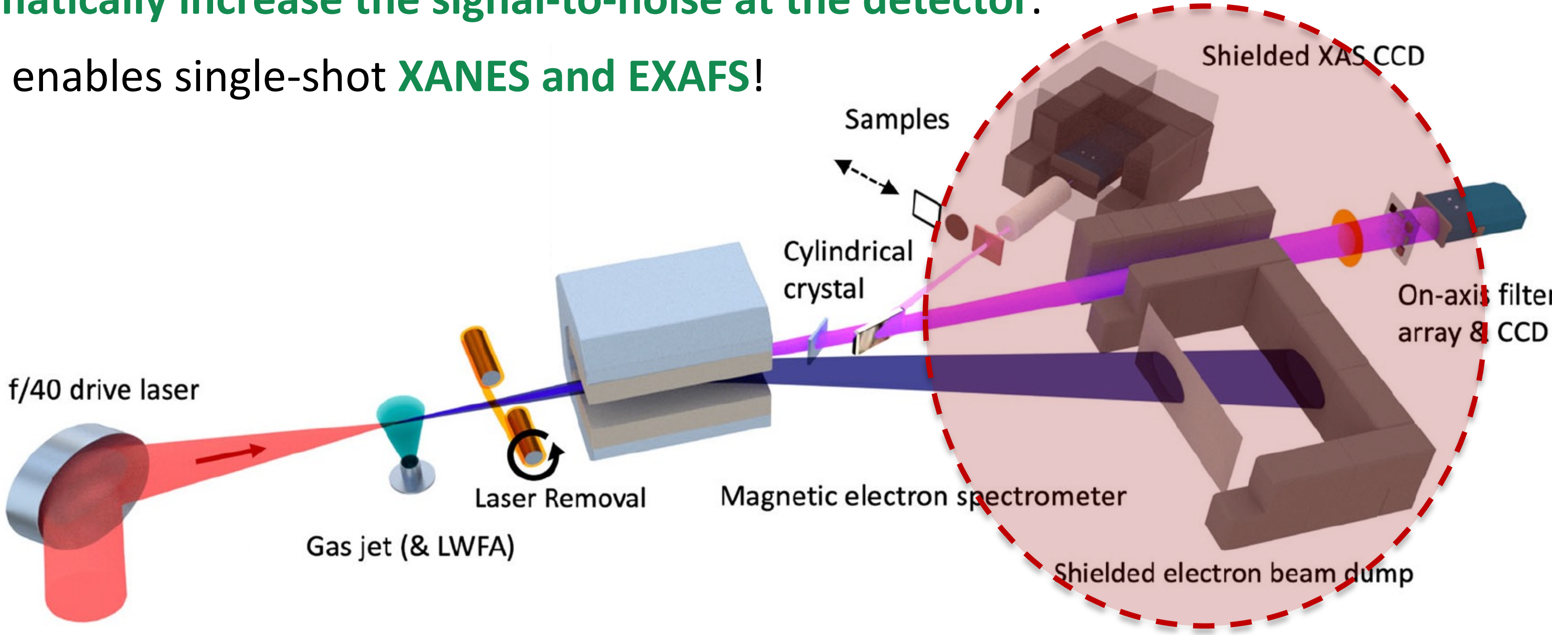


5.4 TW laser operating at 1 Hz! By only varying the length of the gas-cell, the electron density, the focal position, and three orders of spectral phase, a significant increase in flux can be automatically achieved in only 40-50 bursts

R. Shalloo et al., Nat. Comm. 2020

Signal-to-noise enhancement

- Careful consideration of the noise produced during the x-ray generation allows to **dramatically increase the signal-to-noise at the detector**.
- This enables single-shot **XANES and EXAFS**!



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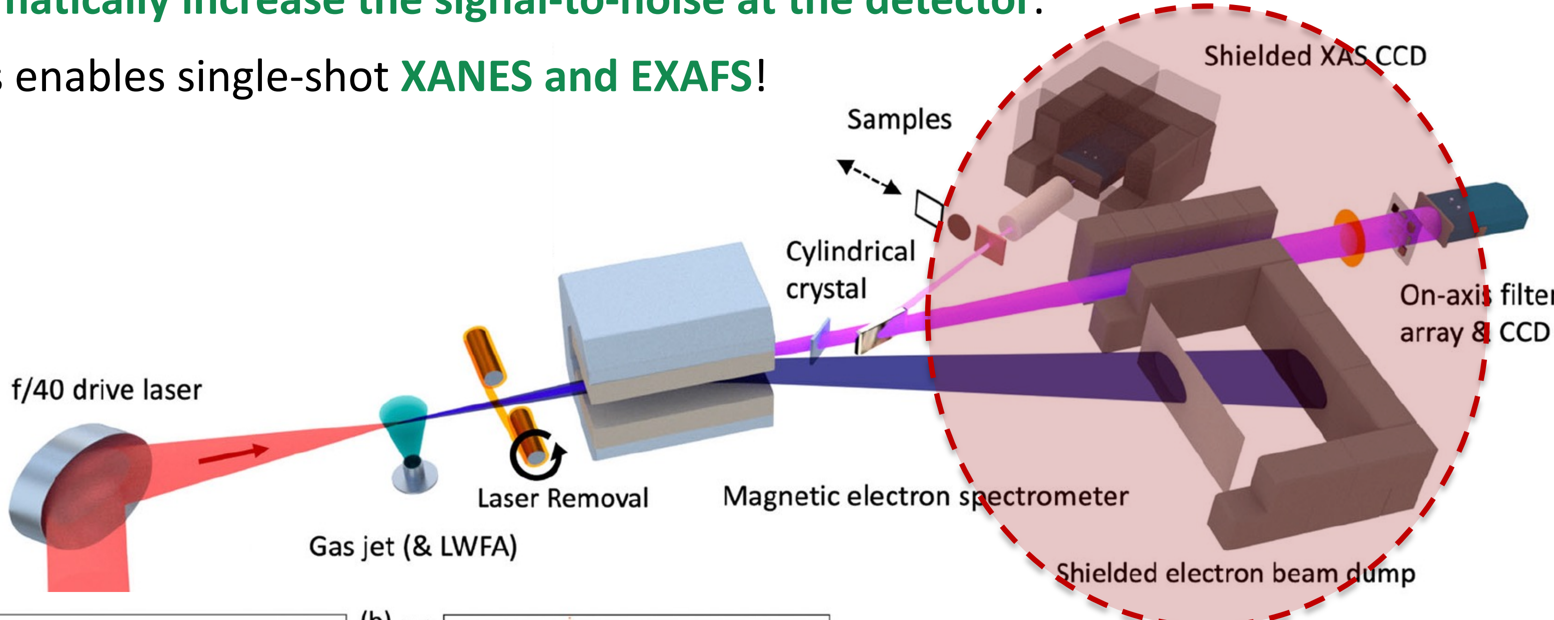

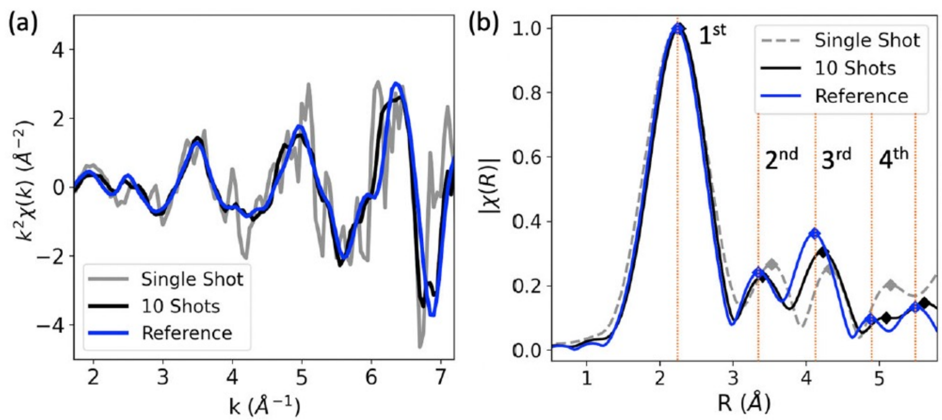

- XANES and EXAFS features on femtosecond timescales.
- Pump-probe experiments in extreme conditions

B. Kettle et al., Comm. Phys. 2024

Acceleration beyond dephasing

- Operating the wakefield acceleration **beyond dephasing**, allows for rapid bubble expansion and acceleration of secondary electron bunches with a much a wider transverse oscillation
- This, in turn, results in a much higher photon flux: $K(t) = r_\beta(t) k_p \sqrt{\gamma(t)/2},$

J. Wood et al., *submitted* (2024)

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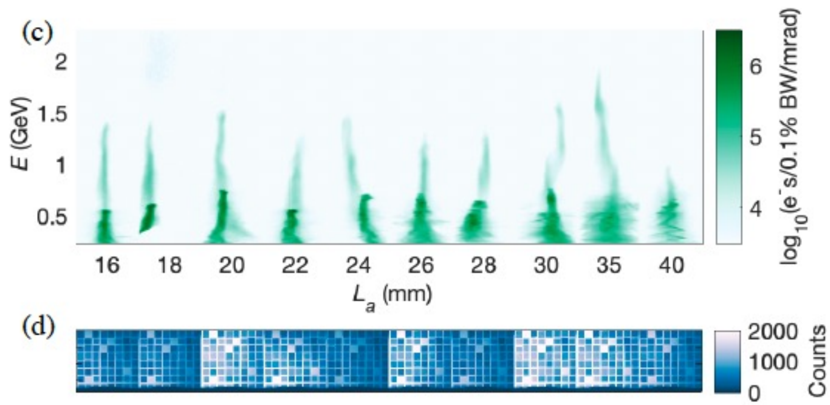

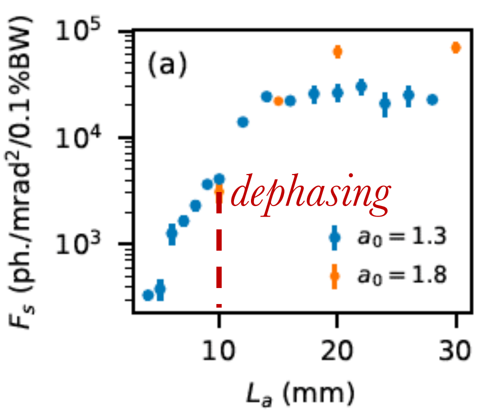

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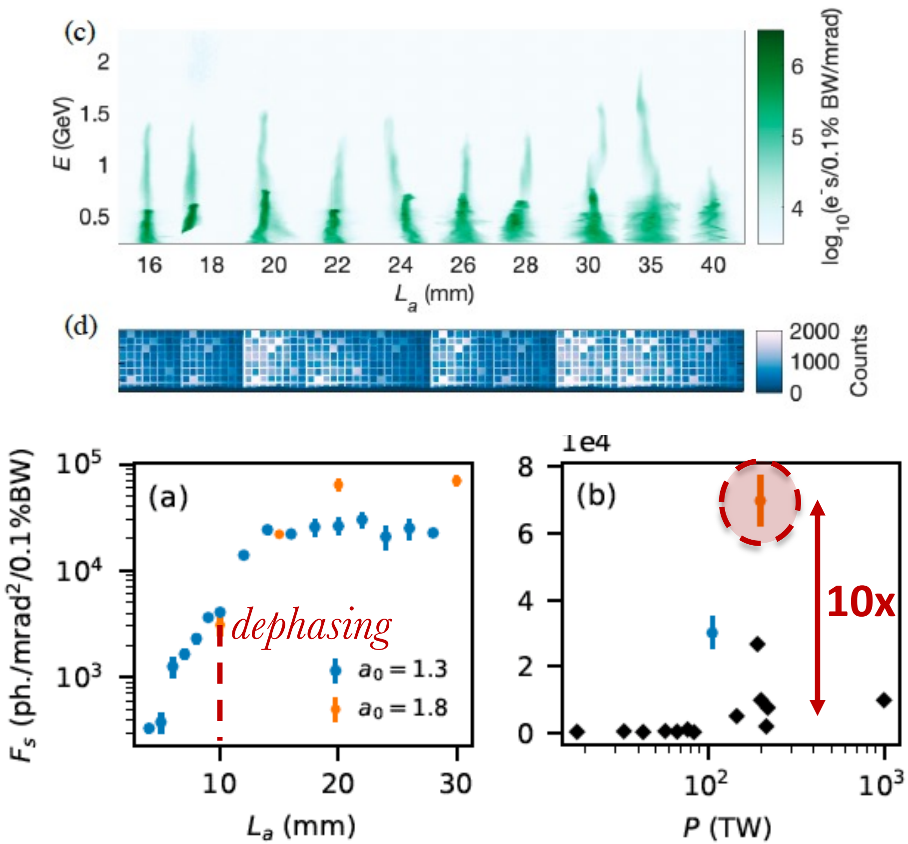

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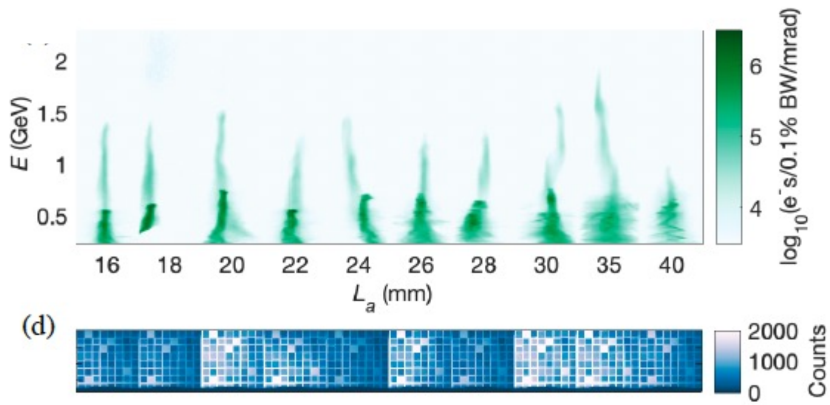
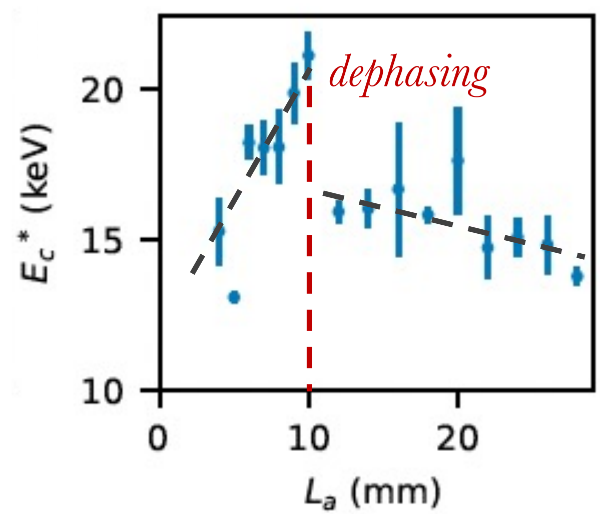
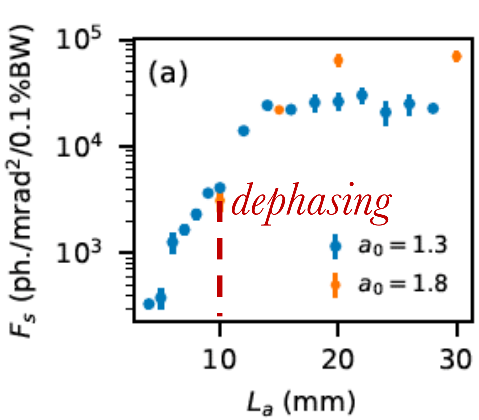
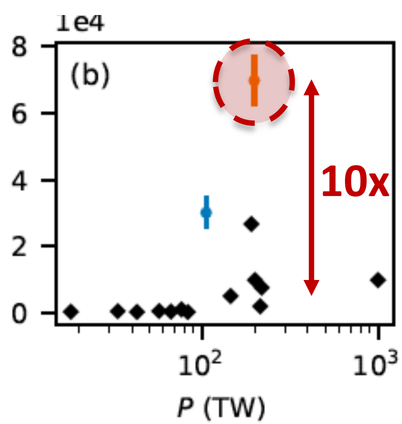






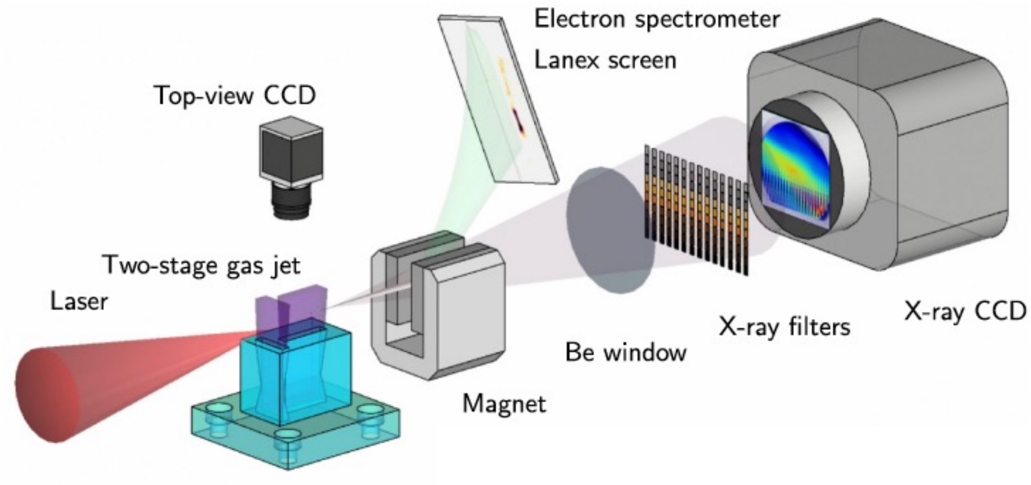


- ~10x increase in photon flux, at the cost of a slight softening of the photon spectrum

J. Wood et al., *submitted* (2024)

Betatron streaking

- A tilt in the gas-jet induces a curved trajectory in the accelerating electron beam, which allows for a **"light-house" effect** on the betatron photon beam



Y. Ma et al., Phys. Rev. Lett. (2024)

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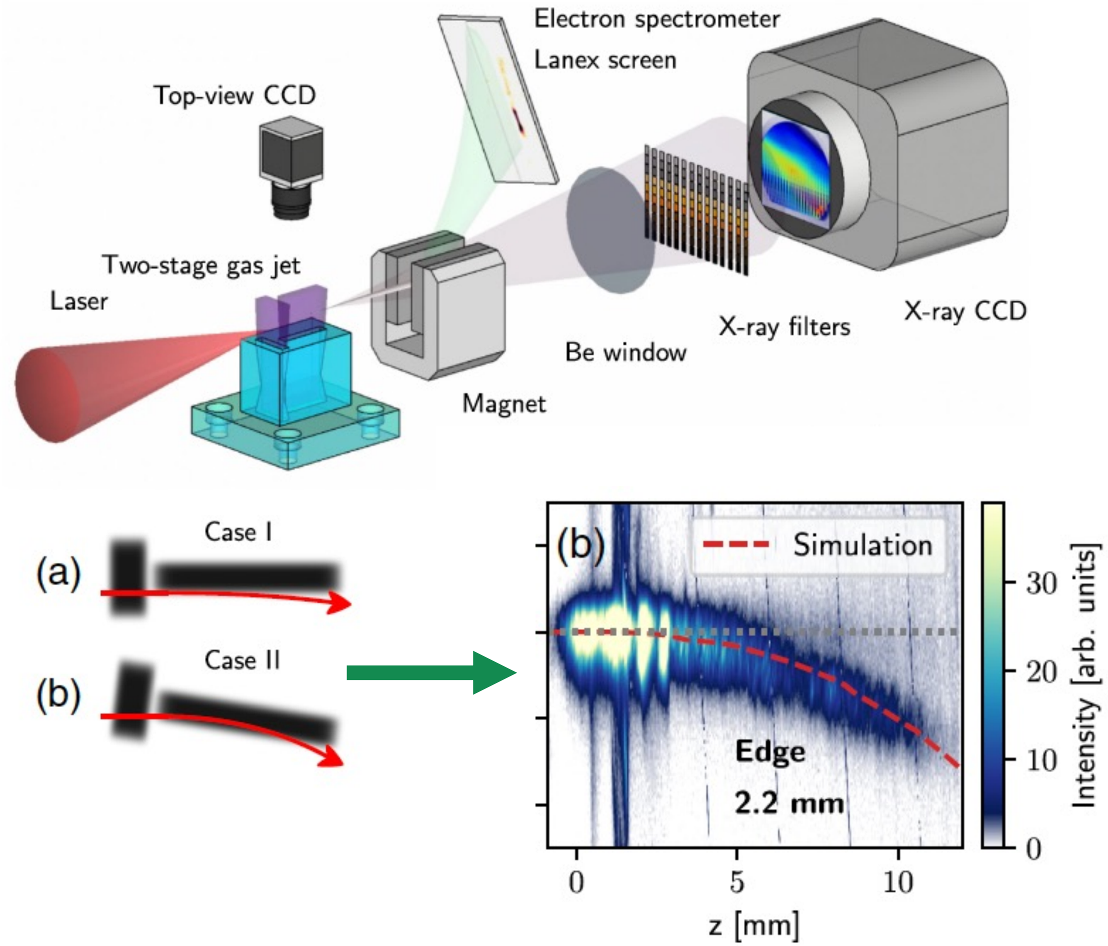

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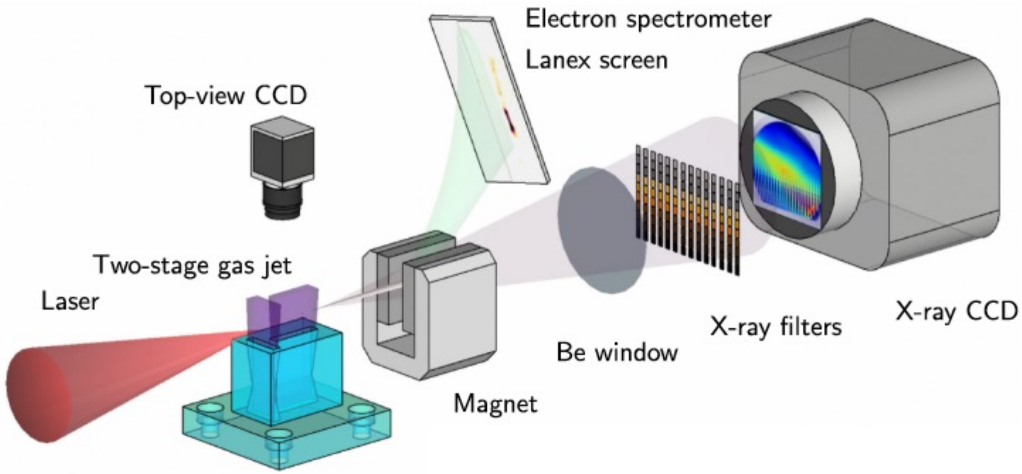

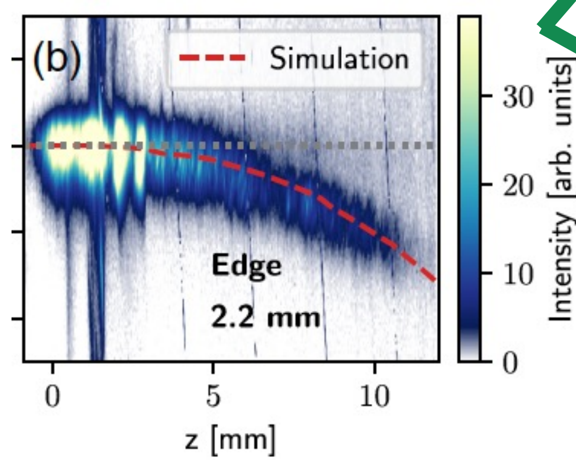

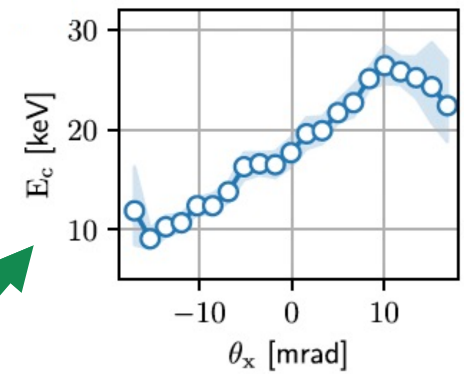

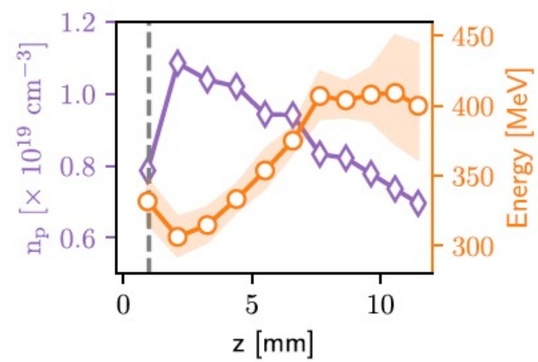

Y. Ma et al., Phys. Rev. Lett. (2024)

Conclusions

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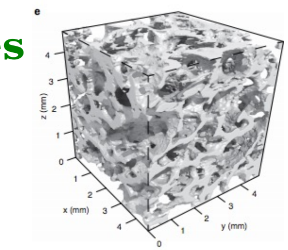
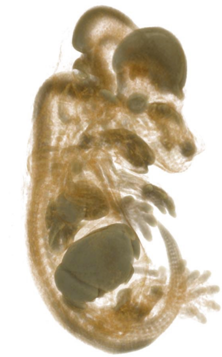
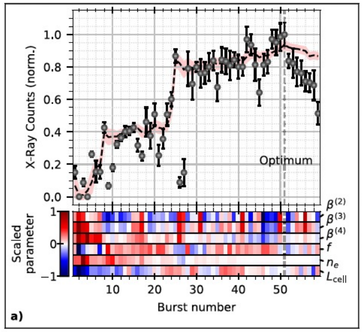
⇒ **Laser-driven betatron sources have unique properties** including small source-size (~μm), short duration (~ fs), and high brightness





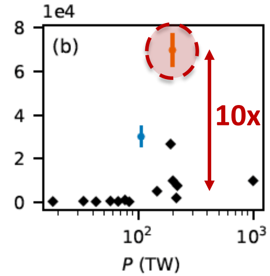
⇒ **Even a few TW laser** can produce x–ray beams suitable for applications

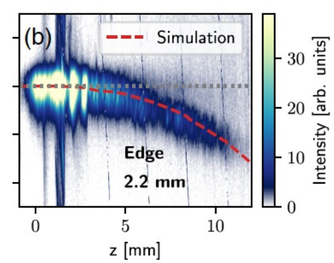
⇒ The unique properties allow for **a range of high-quality applications**, which could also provide a high temporal resolution



⇒ **Automatic self-optimized** wakefield accelerators have been demonstrated to quickly reach optimum conditions

⇒ The betatron radiation properties can be **further optimized** with specific regimes (e.g., wakefield beyond dephasing, bent channels)





Thanks for your attention!

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