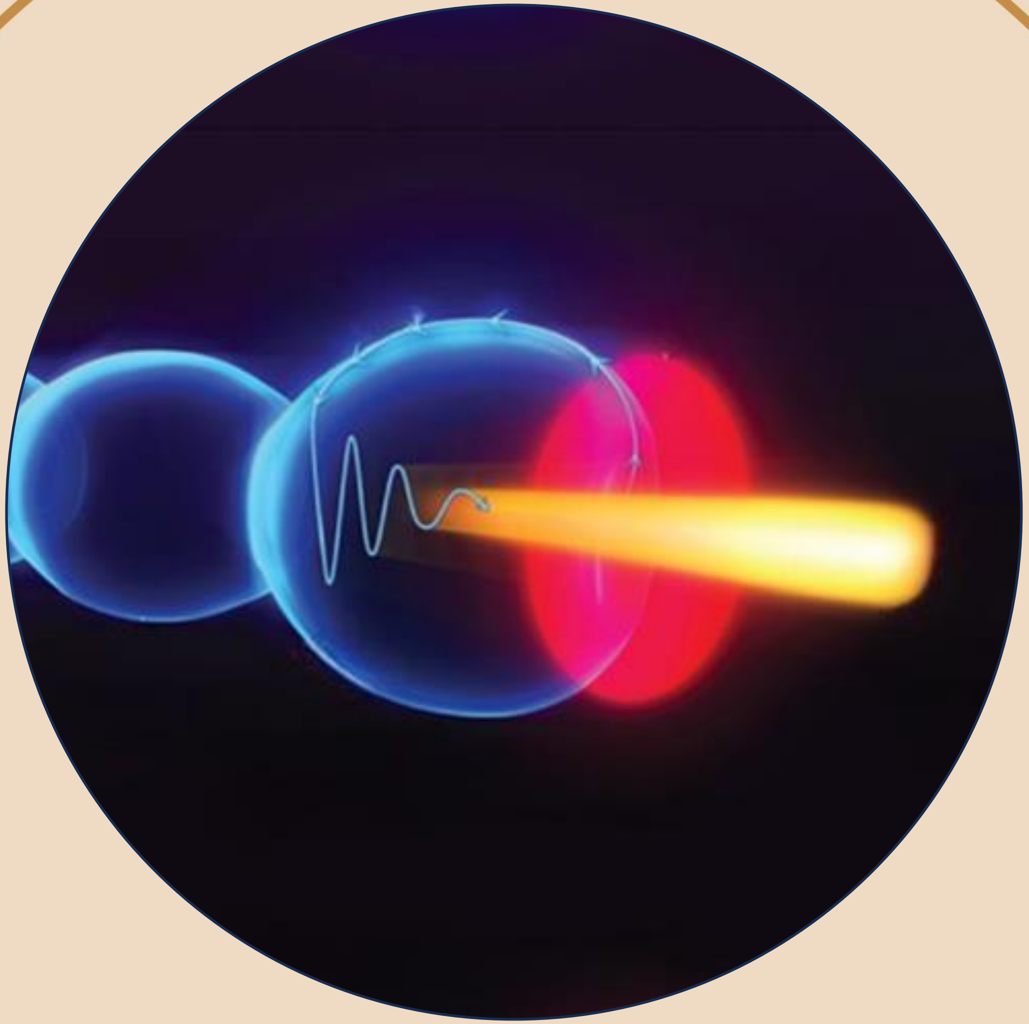
Sources:
Betatron Radiation



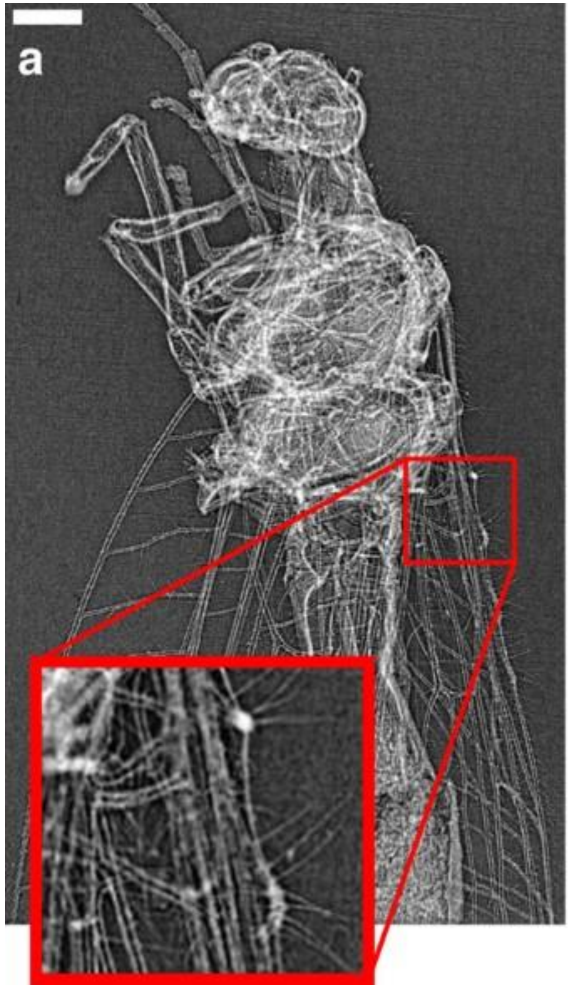
Andrea Frazzitta

INFN Milano

Sapienza University of Rome

Outline

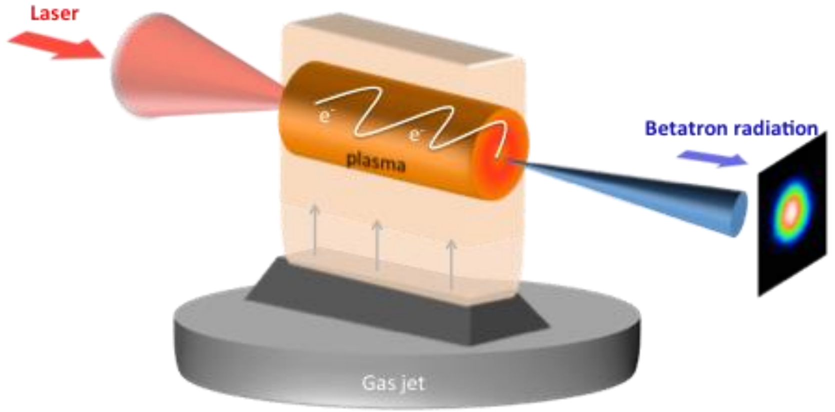
- Betatron radiation: emission principles
- Betatron radiation: spectral features
- The EuAPS source: expected performance



Betatron radiation based phase contrast imaging. “Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source” J. Wenz et al.

What is betatron radiation?

- We refer to a **compact**, **soft X-rays**, **laser wakefield based** source
- Not the most stable method, but it's **easy to set up**, and gives **high photon fluxes** and **ultrashort pulses**, filling a gap between synchrotrons and FELs
- Thanks to the small source size, it features a good level of spatial **transverse coherence**, that can be exploited for effective imaging

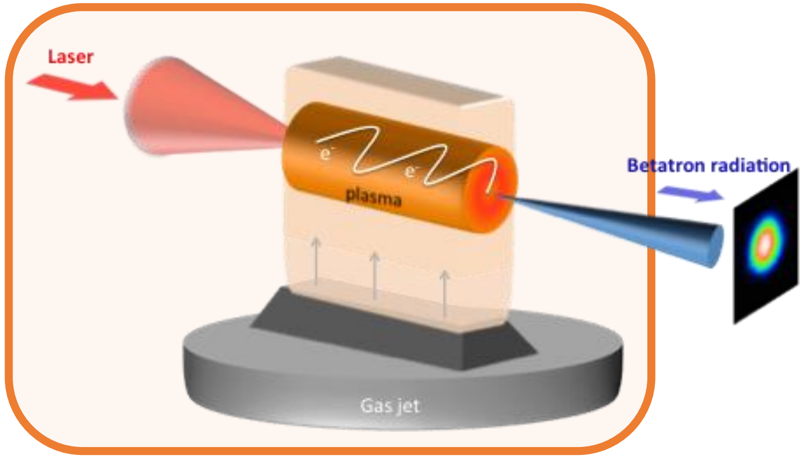


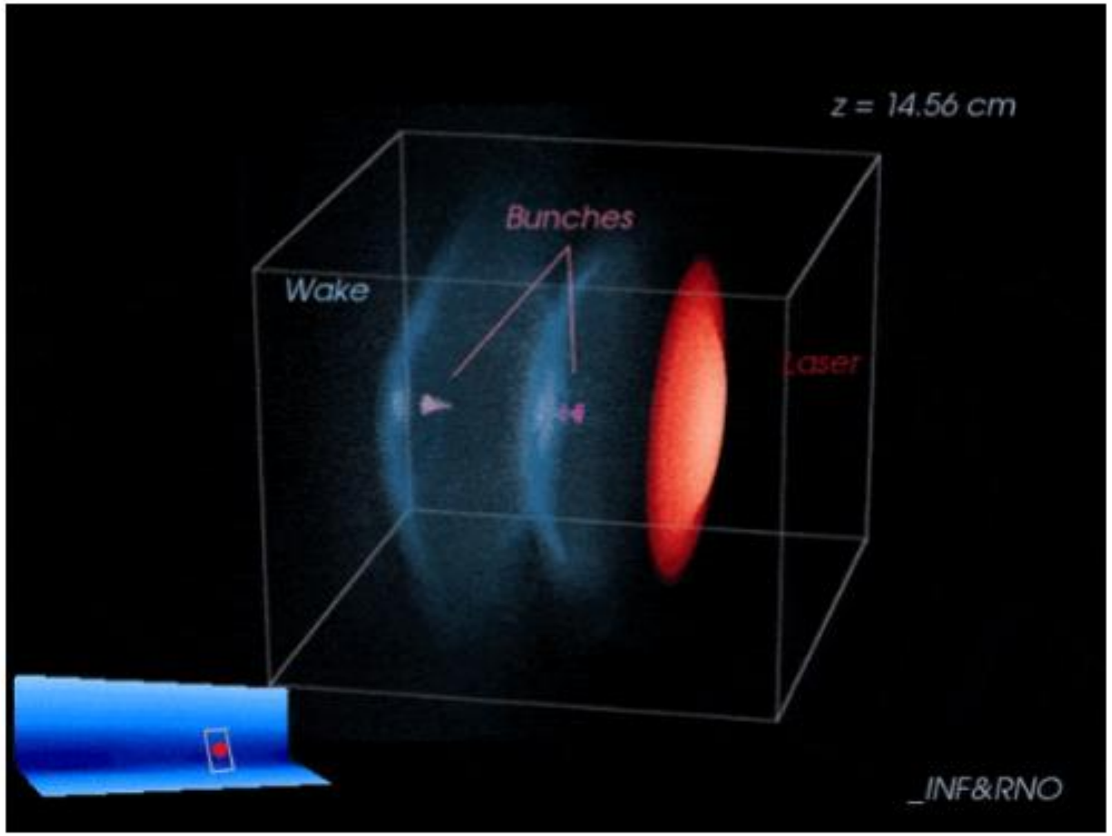
✓ up to **10^9 photons/shot**

✓ down to ***O*(10) fs pulse duration**

Providing radiators: self-injection

- **High power laser pulse** ionizes neutral gas and creates a **plasma wake** (bubble regime)
- **Electrons get injected in the wake,** undergoing relativistic accelerations in a few millimeters





Plasma waves (blue) excited by a petawatt laser pulse (red) at Berkeley Lab's BELLA Center as it propagates in a plasma channel. Caption and credit: Carlo Benedetti/Berkeley Lab

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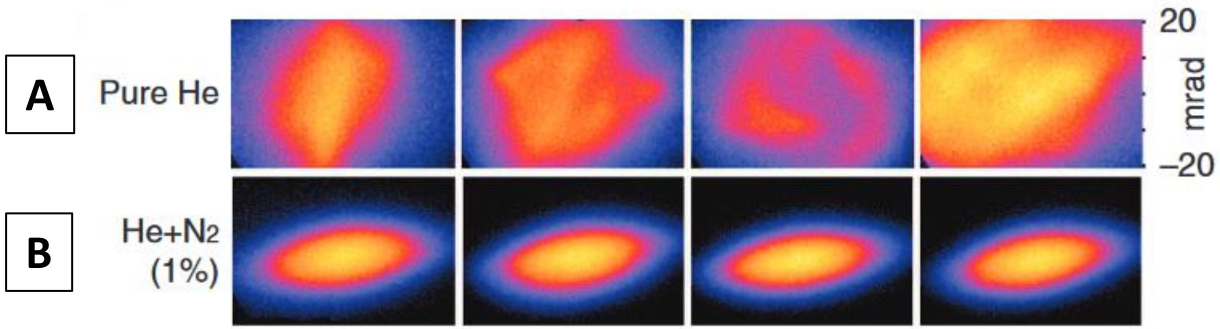
Self-injection VS Ionization injection

- **A – Self-injection:** some of the main gas component ionized electrons oscillate around the bubble and get **trapped inside the** wake, with a typically **unstable *transverse injection*.**

- **B – Ionization injection:** adding a **doping gas** with higher atomic number (e.g. nitrogen) some of the dopant electrons are **ionized directly inside the bubble**. This gives an intrinsically **more stable *longitudinal injection***.



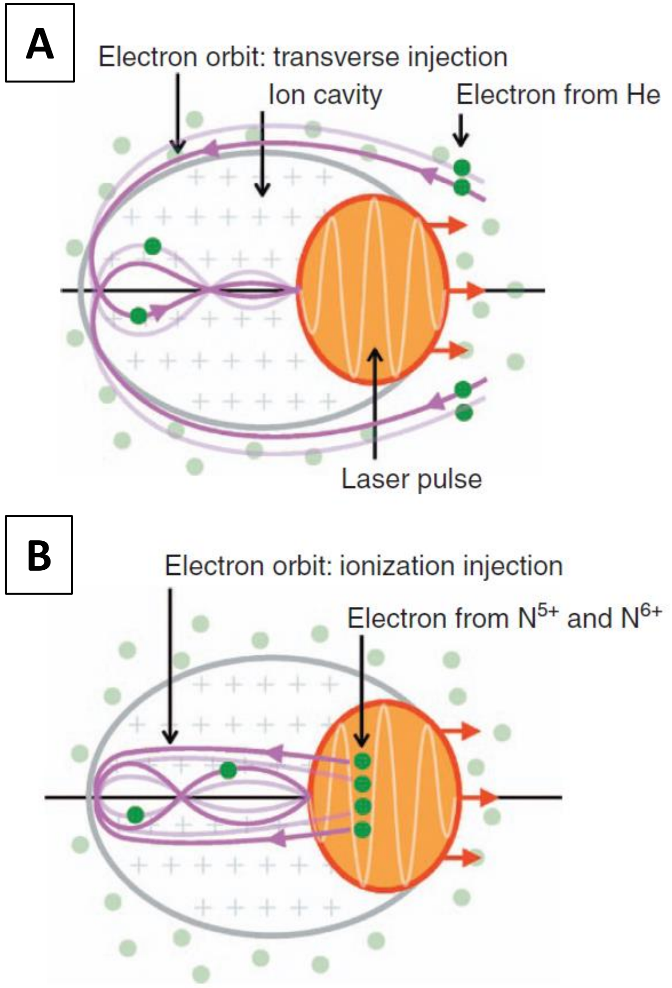
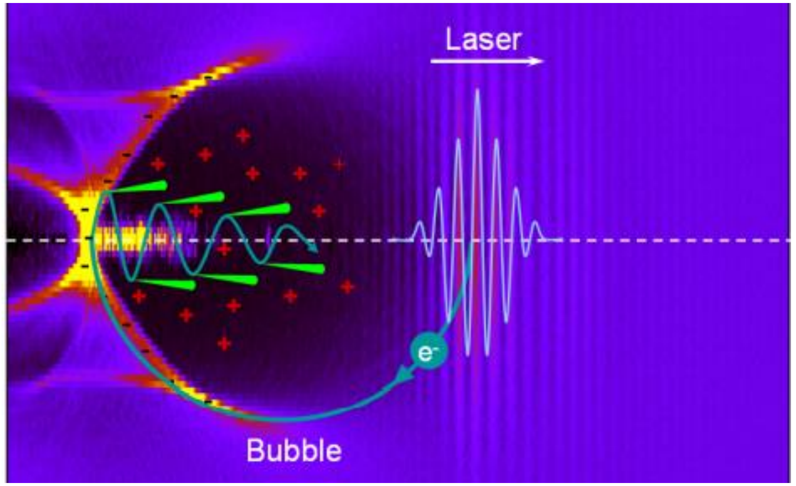
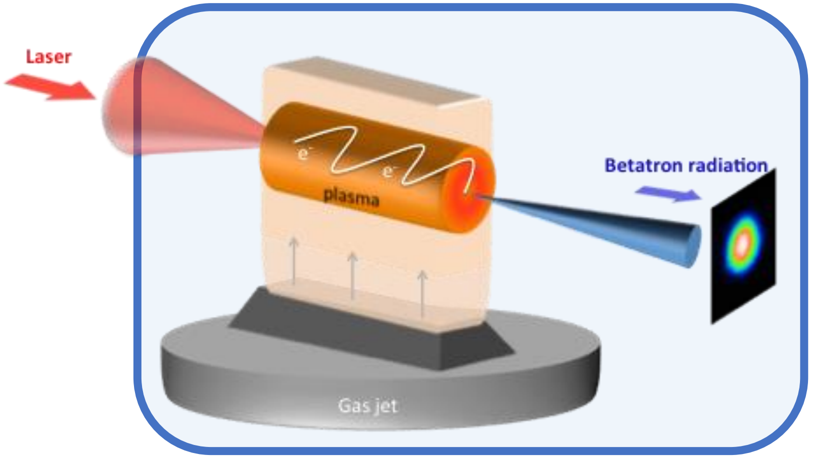


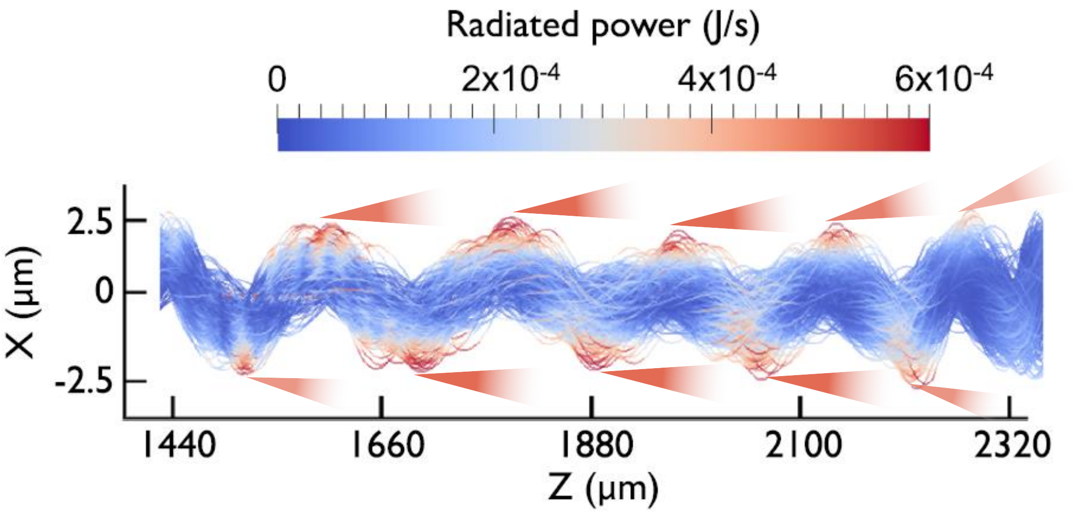
Image credits: A. Döpp et al. “Stable femtosecond X-rays with tunable polarization from a laser-driven accelerator” https://doi.org/10.1038/lsa.2017.86

Providing radiation: betatron motion

- The randomized injection results in **transverse betatron oscillations**, driven by the intense **plasma focusing**
- **Acting as an undulator**, this gives **ultrashort x-rays emission** in a wide broadband spectrum







Betatron motion: trajectory crossing

- While in a magnetic undulator the oscillation amplitude is given by particle energy and **undulator strength *K***, inside the bubble it's given by the axial offset

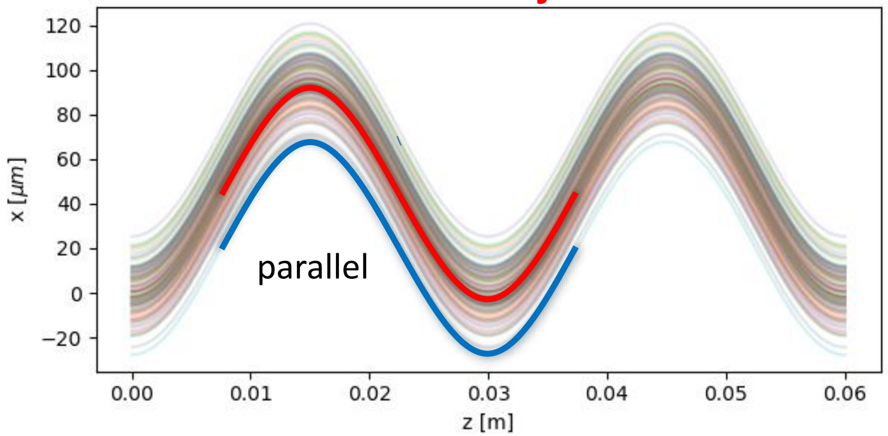
- This gives an **intrinsic *K*-spread** due to the source size (beam spot), greater in case of on axis injection

- The **nearly continuous *K* distribution** reaches very low values, **enhancing low energy spectral intensity**

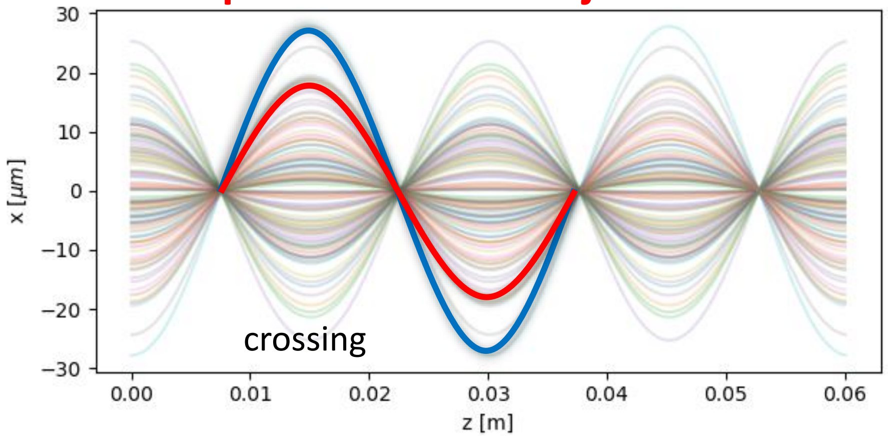
$$K = \gamma \, k_\beta \, r_\beta$$

particle energy (γ); betatron wavenumber (k_β); oscillation amplitude (r_β)

undulator trajectories



plasma bubble trajectories



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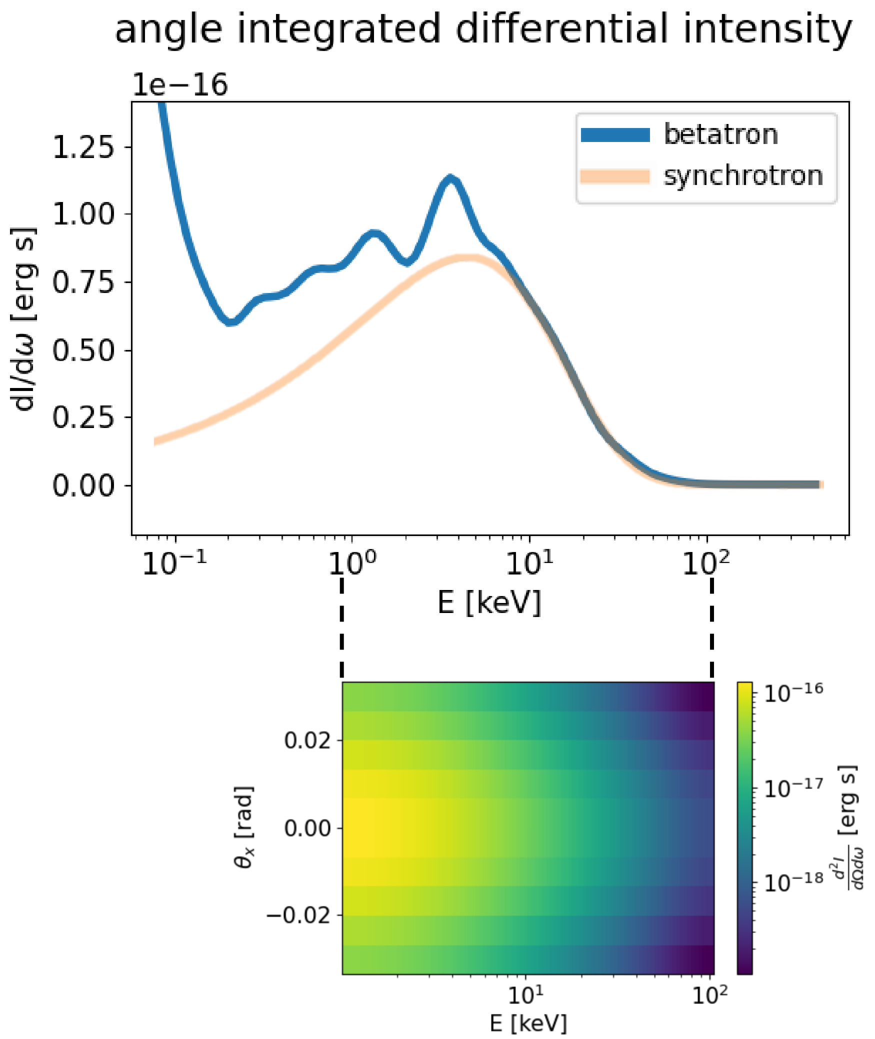
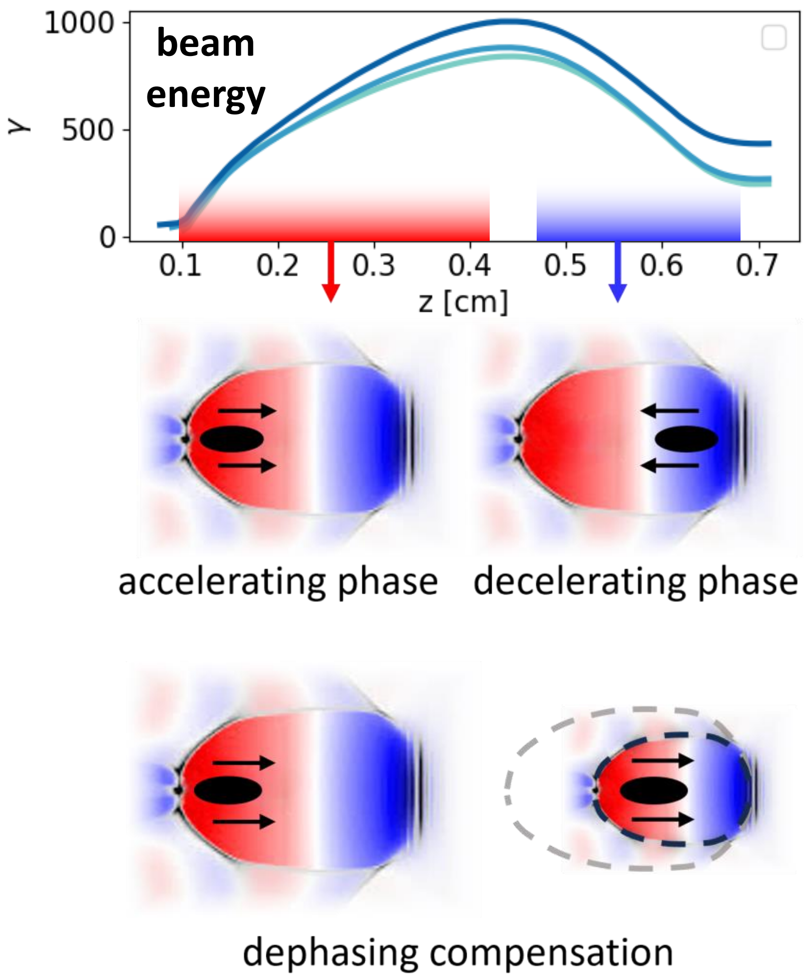
Spectral features

- **Broadband synchrotron-like** spectrum with **enhanced low energy intensity**: detailed features depend on beam evolution inside the wakefield
- In general, **beam energy evolution increases spectral broadening**
- It features **low energy-angle correlation**, due to the high average undulator strength ($K \approx O(10)$) that prevails over relativistic doppler shift

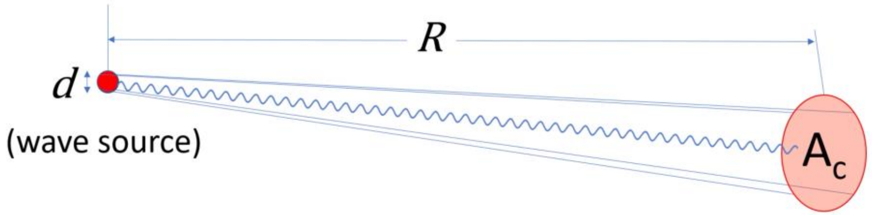


Spectrum shaping: dephasing control

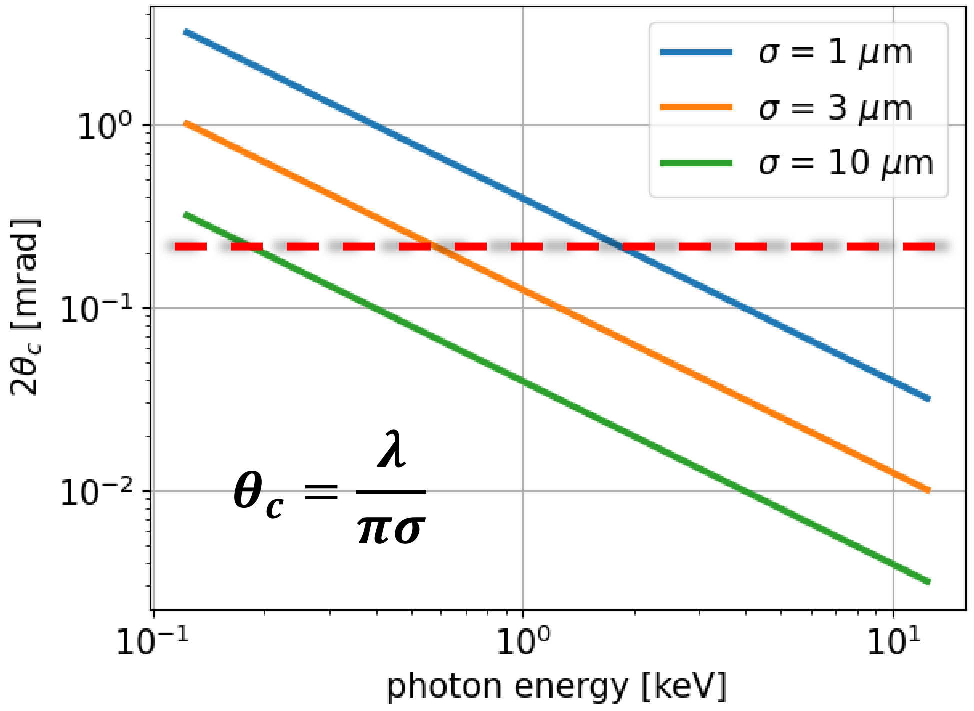
- **Dephasing:** laser pulse travels slower than the electron beam, due to plasma refractive index, causing a phase slippage from acceleration to deceleration
- Given the **radiation critical frequency** $\omega_c(t) \propto \gamma^{7/4}(t)$, the beam slowdown affects spectral shape, drifting from the synchrotron-like profile
- **Dephasing control** can be attained through gas density modulation: e.g. an "M" shaped profile should give beam injection followed by a **complying bubble size evolution**



Spatial coherence



- **Given the *K*-spread** and the **mix of betatron phases**, lower boundary of spatial **coherence angle is calculated from van Cittert–Zernike theorem.**
- Numerical simulations parametric scans also look for the smallest possible electron beam spot**, trying to reach *O*(1) mrad of coherence angle**
- Spatial coherence is a relevant parameter for **phase contrast imaging**: coherence size of at least 15x imaging resolution is required, threshold highlighted in dashed red



Expected Parameters

	Value	Unit
Electron beam Energy	100-500	MeV
Plasma Number Density	10^{18}-10^{19}	cm^{-3}
Photon Critical Energy	1 -10	keV
Number of Photons/pulse	10^{6}-10^{9}	-
Repetition rate	1	Hz
Beam divergence	10-20	mrad
Pulse duration	30-200	fs