Betatron Radiation Diagnostics for AWAKE Run 2

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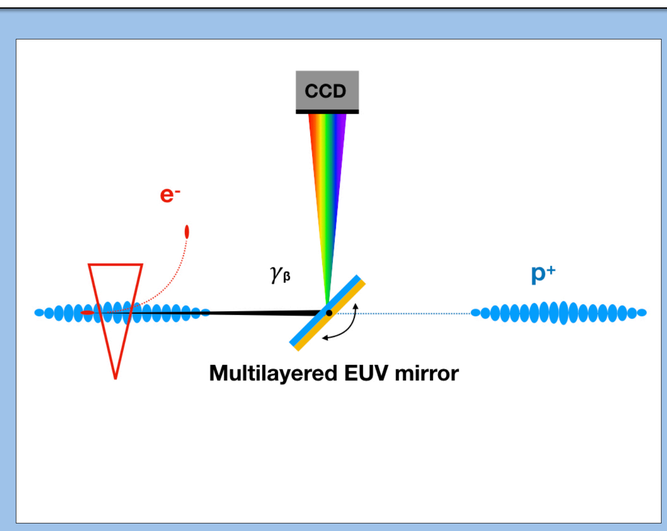
- The AWAKE experiment is a GV/m-class plasma wakefield accelerator (PWFA) at CERN
- Proof-of-concept experiments in AWAKE Run 1 have demonstrated electron acceleration in a proton-driven wakefield [1]
- AWAKE Run 2 aims to preserve witness beam quality throughout acceleration
- New, non-intercepting diagnostics are required to measure the emittance of the accelerated electron beam
- Core and defocused protons remain on axis and with a 1 mrad divergence, making a direct measurement challenging
- We study betatron radiation spectroscopy as a possible solution, which may also provide information on injection dynamics



Ion channel dynamics & betatron radiation

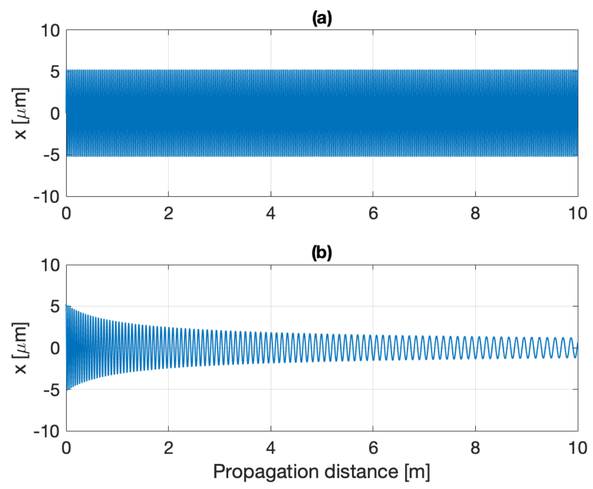
- An electron in an ion channel undergoes transverse oscillations due to focusing forces from the ion column, governed by the equation:

$$\frac{d^2x}{dt^2} + \frac{1}{\gamma}\frac{d\gamma}{dt}\frac{dx}{dt} + \frac{\omega_p^2}{2\gamma}x = 0$$

*Ignoring radiation reaction effects

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

- This motion has a linear sinusoidal solution in the case of constant energy and a decaying amplitude and betatron frequency for a non-zero accelerating field [2], via the WKB approximation



$E_z = 0$

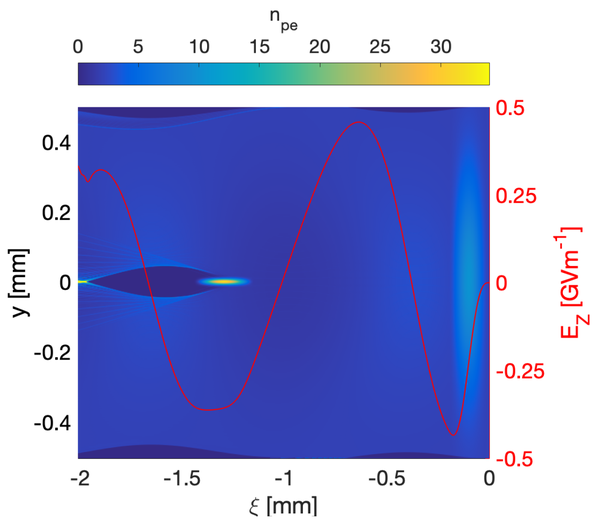
$E_z \neq 0$

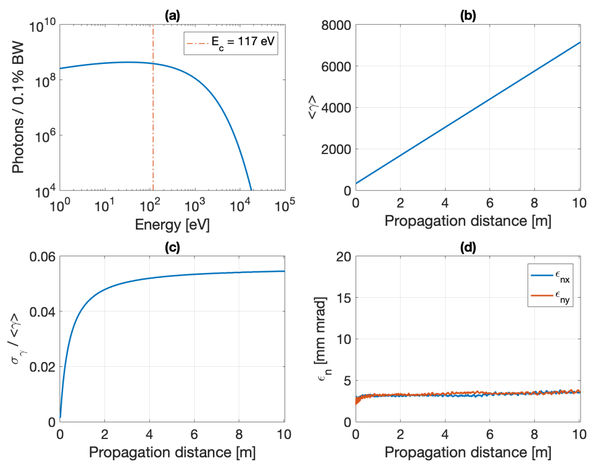
$$x \simeq C\sqrt{\omega_\beta(t)}sin\left(\int \omega_\beta dt\right)$$

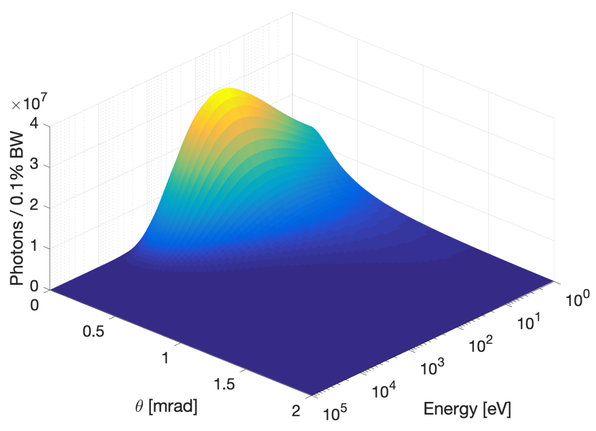
- This motion results in synchrotron radiation, which has spectral characteristics determined by the distribution of single-electron orbits within the beam envelope [3]
- The emission at AWAKE is not straightforward to characterise with analytics for a number of reasons: the wiggler parameter $\alpha_\beta \sim 1$; the radiating electron beam evolves significantly over 10 m; and the beam does not sit fully within the ion channel it generates

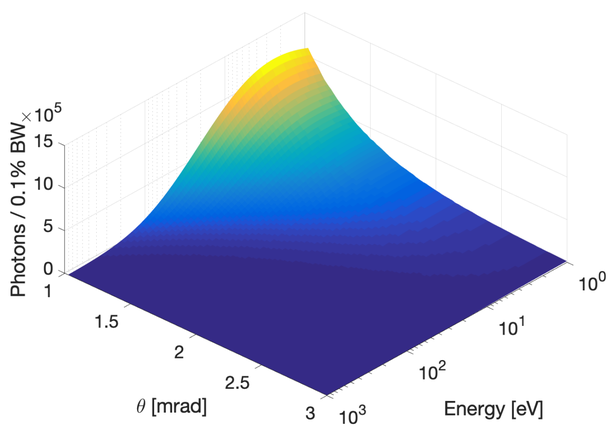
Simulated emission for AWAKE

- A simulation approach can provide more accurate estimates for the betatron emission
- The Run 2 model developed by Olsen et al. [4], that determines matching and beam loading conditions, is adopted with the added consideration of betatron radiation
- QV3D is a quasi-static 3-dimensional PIC code that includes betatron radiation [5]
- A significant number of EUV photons fall at angles above 1 mrad for the matched baseline case, propagated over 10 m



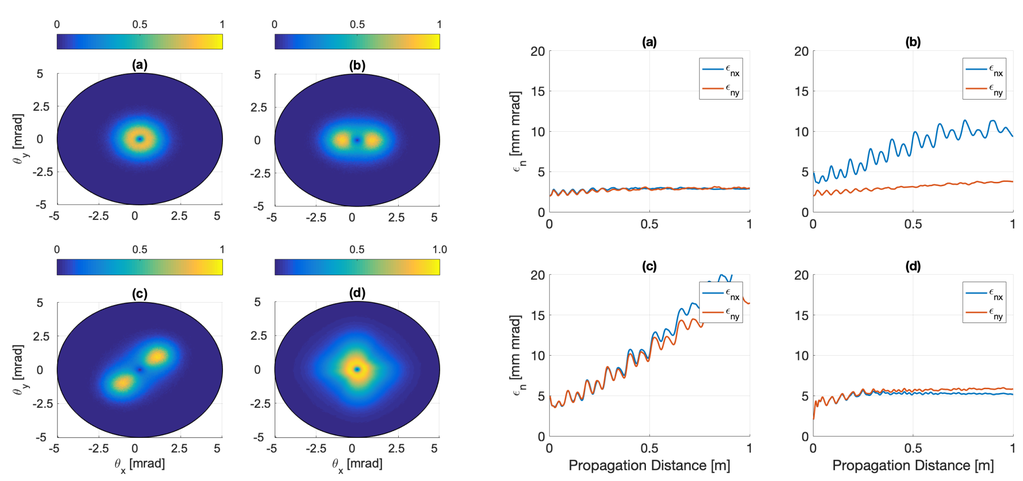






Injection scans

- Electron orbits map directly to radiation emission patterns [6]
- The matched baseline case is scanned between 1 and 2-dimensional offsets, and a wide mismatched beam
- The corresponding emittance evolution over 1 m is also shown
- These different injection scenarios could therefore be discriminated between with a betatron measurement



Conclusions

- The betatron radiation from accelerated witness electrons at AWAKE Run 2 will, in the ideal matched case, be highly collimated (< 1 mrad) with the majority of photons falling between 10-1000 eV
- A significant number of EUV photons (10-100 eV) remain above 1 mrad. This could facilitate a partial measurement of the betatron spectrum, despite a background of defocused protons, using a rotating multilayered mirror with a central hole
- This measurement could also reveal the injection dynamics for each acceleration event

1. E. Adli et al. (The AWAKE Collaboration), Acceleration of electrons in the plasma wakefield of a proton bunch, Nature **561**,7723 (2018)
2. E. Esarey et al., Synchrotron radiation from electron beams in plasma-focusing channels, Physical Review E **65**, 056505 (2002)
3. P. Michel et al., Radiative damping and electron beam dynamics in plasma-based accelerators, Physical Review E **74**, 026501 (2006)
4. V. Oslen et al., Emittance preservation of an electron beam in a loaded quasilinear plasma wakefield, Physical Review Accelerators and Beams **21**, 011301 (2018)
5. A. Pukhov, Particle-in-cell codes for plasma-based particle acceleration, CERN Yellow Reports **1**, 181 (2016)
6. K.T. Phuoc et al., Imaging electron trajectories in a laser-wakefield cavity using betatronx-ray radiation, Physical Review Letters **97**, 225002 (2006)

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