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Plasma Discharge Undulator: a novel concept for plasma-based radiation sources

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SAPIENZA UNIVERSITÀ DI ROMA | iFAST

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INTRODUCTION

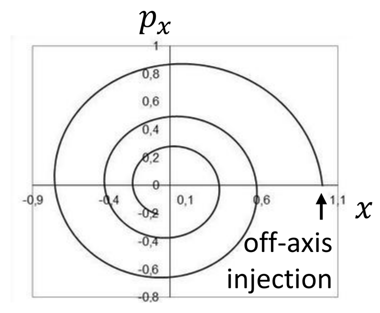
Plasma discharge devices have recently demonstrated their potential for compact particle beam manipulation. Building upon the Active Plasma Lens [1] and its extension to curved geometries (Active Plasma Bending [2]), new studies have revealed that chicane-like configurations can support sub-betatron oscillations of the beam. Motivated by this observation, the novel concept of the Plasma Discharge Undulator (PDU) is introduced. The PDU consists of a sequence of transversely displaced jointed plasma capillaries, carrying a high-current discharge. The resulting azimuthal magnetic field focuses the beam, while the periodic transverse displacement of the equilibrium axis acts as a geometric forcing term. This yields a well-defined oscillation at a wavelength λ_{PDU} distinct from the natural betatron wavelength λ_β. By proper injection, collective betatron oscillations can be suppressed, leaving only the forced λ_{PDU} beam centroid oscillation. This approach eliminates the intrinsic K-spread limitation of plasma undulators, achieving a narrow undulator strength distribution while preserving strong plasma focusing for beam matching. The theoretical framework, single-particle and beam dynamics analyses, first estimates of radiation emission from the PDU and preliminary particle-in-cell studies of segmented capillaries are presented. The PDU thus offers a pathway toward miniaturized, tunable, full-plasma-based radiation beamlines, with enhanced control over beam quality and radiation properties.

MOTIVATION

Betatronic plasma undulators limitations:

- On axis injection: **K-spread constraint**
- Off axis injection: less K-spread but possibly **unstable + oscillation damping** and/or **emittance growth**
- Possible solution? **Add driving term** How? **Geometrically**

$$\frac{\sigma_K}{\langle K\rangle} = \sqrt{\frac{4}{\pi} - 1} \approx 0.523 \quad \text{(Gaussian beam)}$$



damped oscillator

ANALYTICAL MODEL : DRIVEN OSCILLATOR

$$x_0 = \frac{\Delta x}{2}\frac{k_\beta^2}{k_\beta^2 - k_{PDU}{}^2}$$

sub-oscillation amplitude

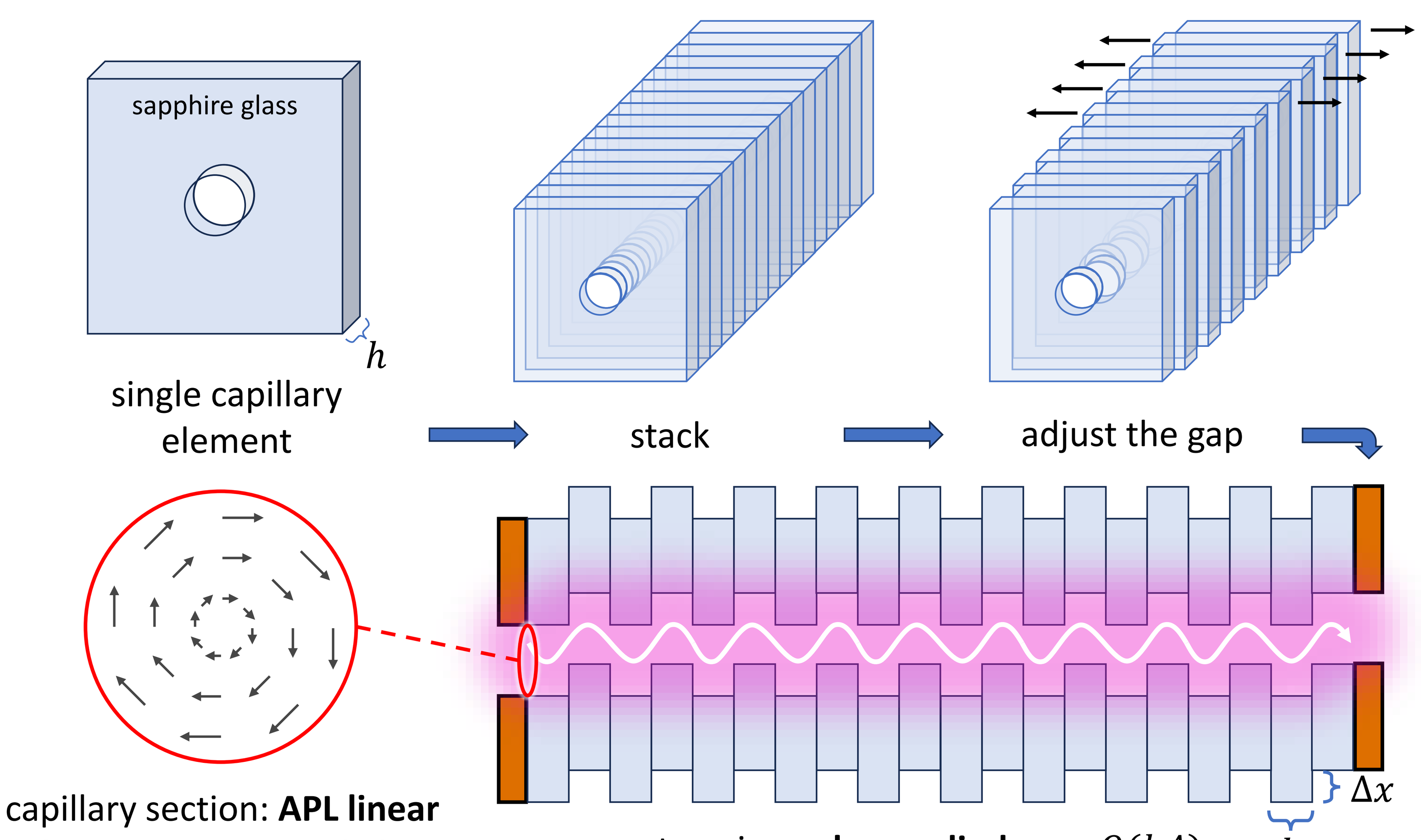
$$K_{PDU} = \frac{\gamma\,\Delta x}{2\frac{h}{\pi} - \frac{4 m_e c\gamma}{e\mu_0 J}\frac{\pi}{h}}$$

undulator strength

$$\sigma_M = \left(\frac{2 m_e c \gamma \epsilon_{rms}^2}{e\mu_0 J}\right)^{\frac{1}{4}}$$

APL matching

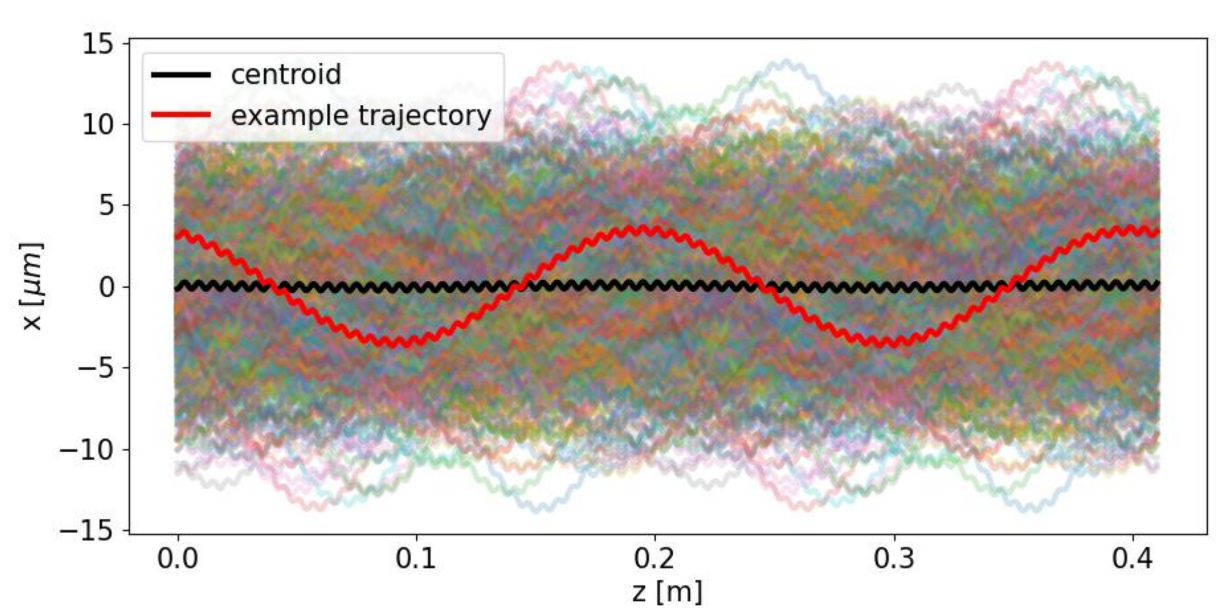
CONCEPT

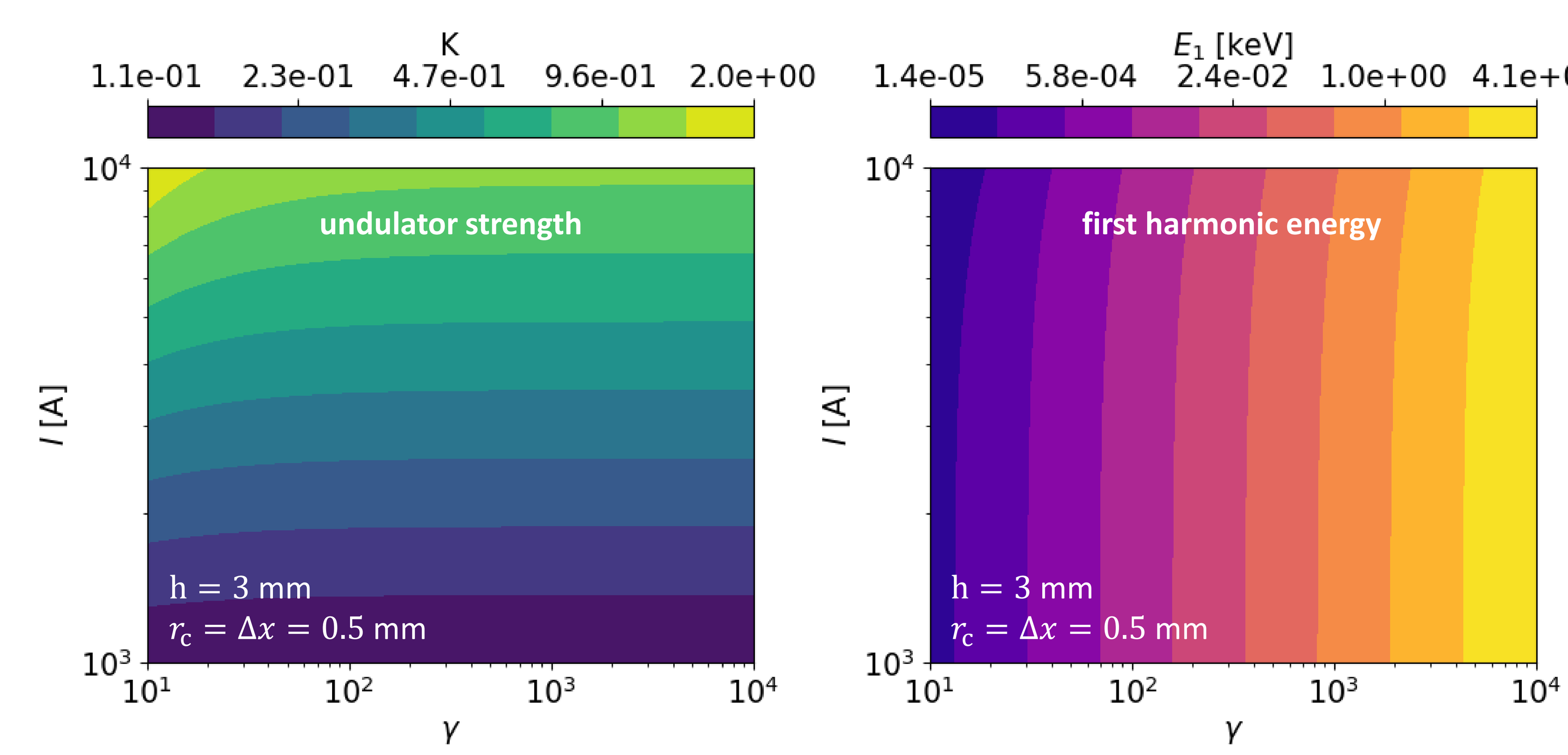


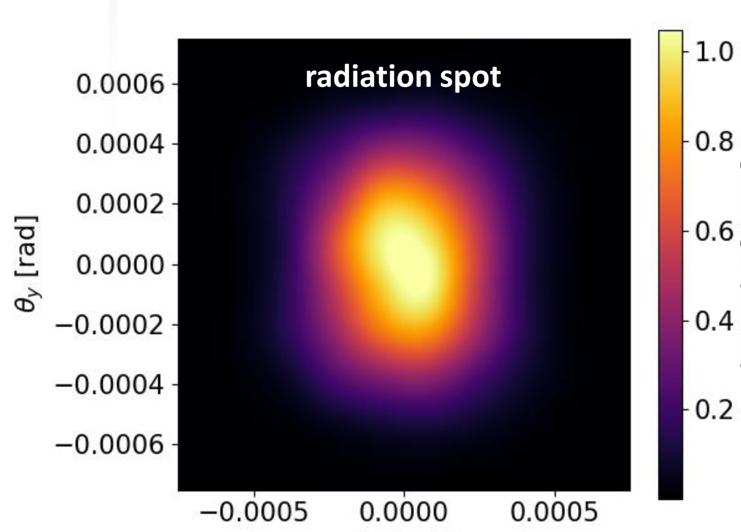
DYNAMICS AND RADIATION SIMULATIONS

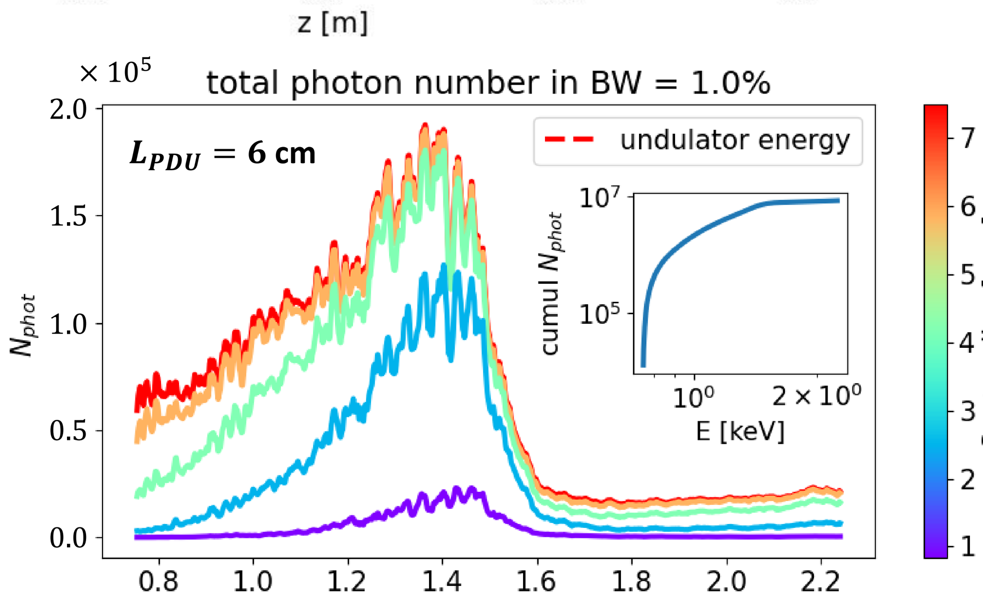
Beam parameters:
$\gamma = 2000$,
$\epsilon_n = 1$ mm mrad,
$\sigma_r = 4$ μm,
$Q = 10^2$ pC,
$n_{\mathrm{part}} = 10^3$

PDU parameters:
h = 3 mm,
$r_c = \Delta x = 0.5$ mm,
I = 4 kA,
$K = 0.45$,
$E_1 = 1.5$ keV

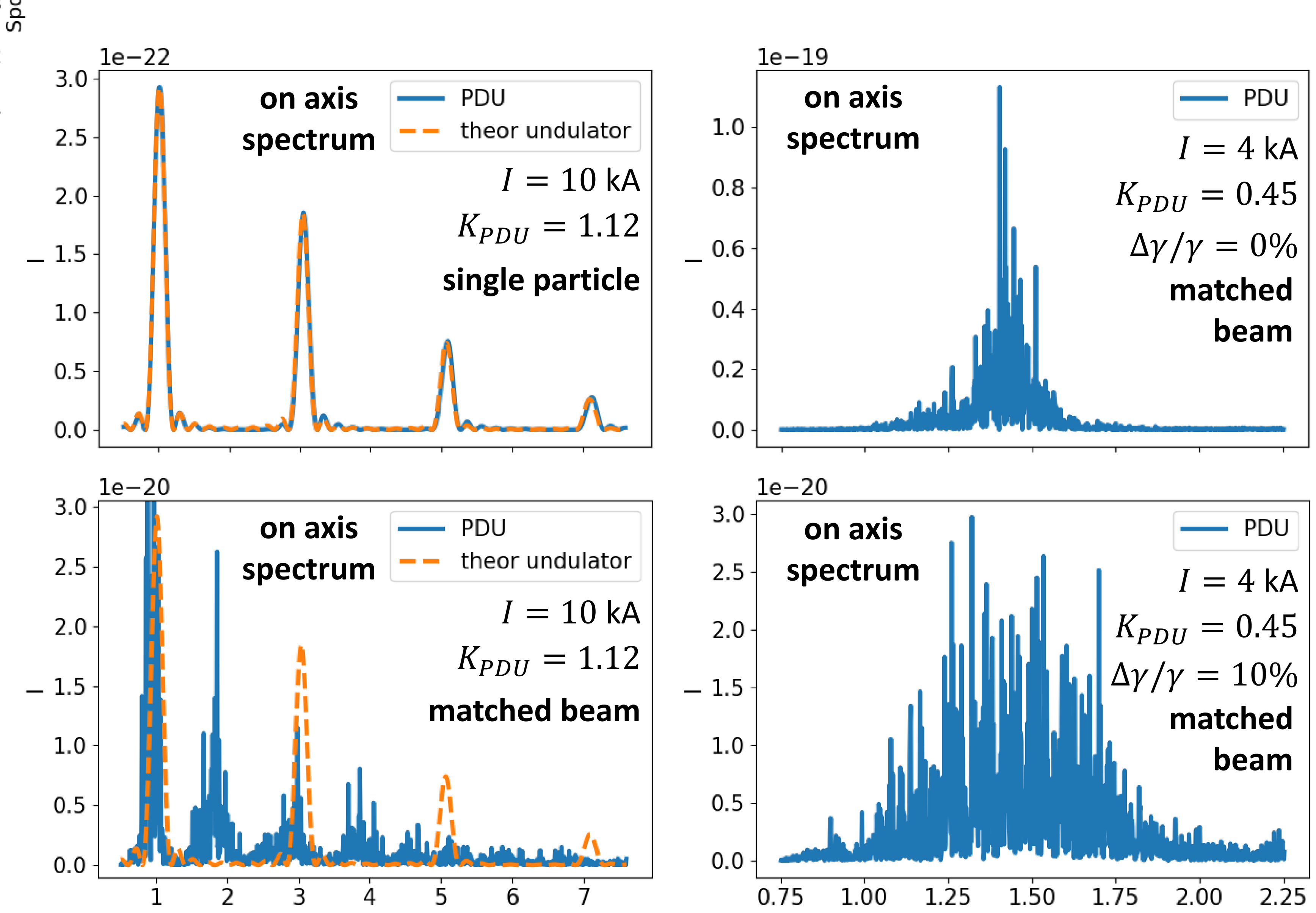






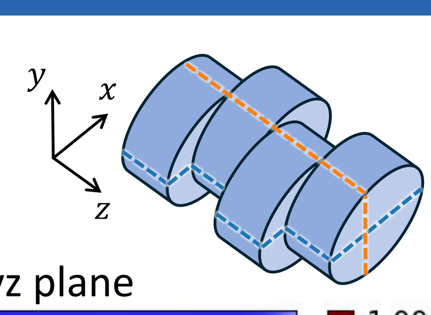


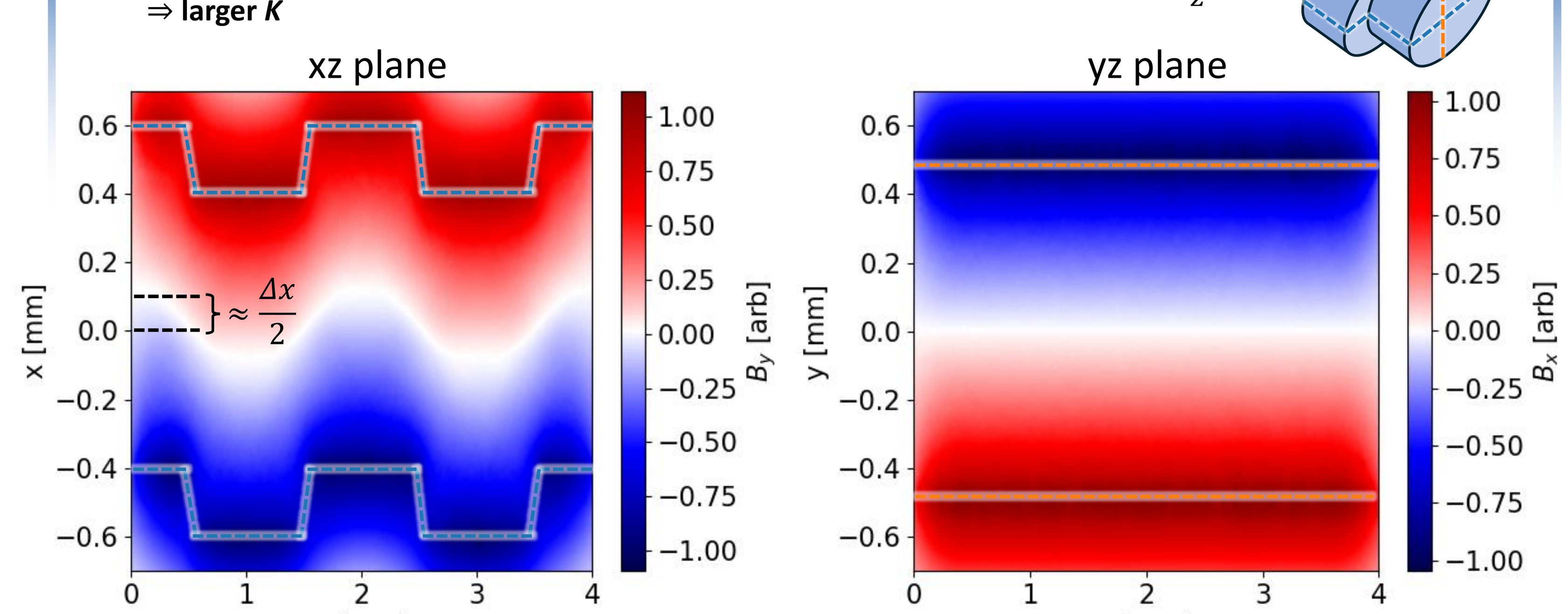
- Focusing magnetic field with oscillating zero: alternating dipolar error acts as effective undulator
- Magnetic field driven bending: the beam should feature longitudinal microbunching (transverse in ICL)
- Beam centroid injection at $x = x_0$ avoids λ_β collective oscillations, leaving just λ_{PDU} collective oscillations
- The wavelength λ_{PDU} appears as a modulation of amplitude x_0 over the main λ_β trajectory oscillation
- Intrinsically 2-color: λ_{PDU} acts as a conventional magnetic undulator while λ_β as a conventional plasma undulator
- Due to short λ_β, beam trajectories feature high average slope, so even harmonics contribution appear on axis too
- K gets greater for larger λ_{PDU} up to the threshold $\lambda_{PDU} = \lambda_\beta$, after which the behavior is opposite



PLASMA SIMULATIONS

- Just a preliminary pre-ionized, cold gas, short FBPIC simulation to evaluate current density evolution and magnetic field zero
- Thermal effects could help achieving larger field oscillation amplitude ⇒ larger *K*





h = 1 mm, r_c = 0.5 mm, Δx = 0.2 mm, $n_p = 10^{15}$ cm^{-3}, $E_z = 2.5\times10^5$ V/m, n_{modes} = 6

[1] "Direct measurement of focusing fields in active plasma lenses", DOI: https://doi.org/10.1103/PhysRevAccelBeams.21.122801
[2] "Guiding of Charged Particle Beams in Curved Plasma-Discharge Capillaries, "DOI: https://doi.org/10.1103/PhysRevLett.132.215001

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