Theory and simulations of beam dynamics and radiation emission in plasma-based devices

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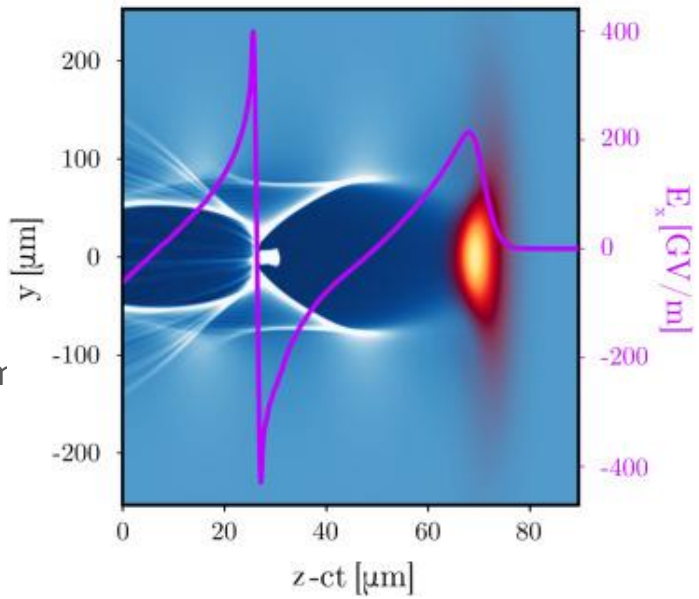
Co-Supervisors: Alessandro Cianchi, Massimo Ferrario

Outline

- **Context:** plasma acceleration, EuPRAXIA and EuAPS projects
- **Thesis work steps:**
  - **Radiation code development**, validation and usage in numerical spectra evaluation and theoretical radiation accuracy analysis
  - Code extension, now with full relativistic beam dynamics
  - **Betatron radiation studies**: self injection and extreme regim in ion channel emission
  - **Plasma discharge beam bending device study**: theoretical modelling, numerical simulations and measures



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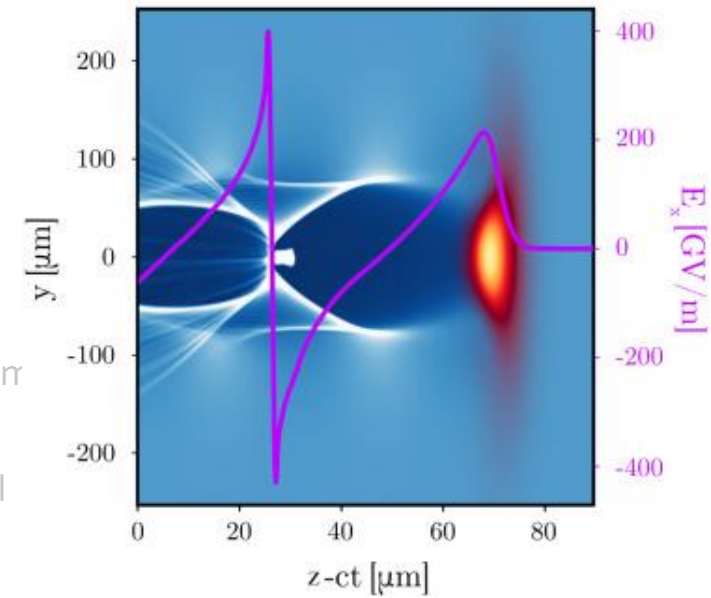
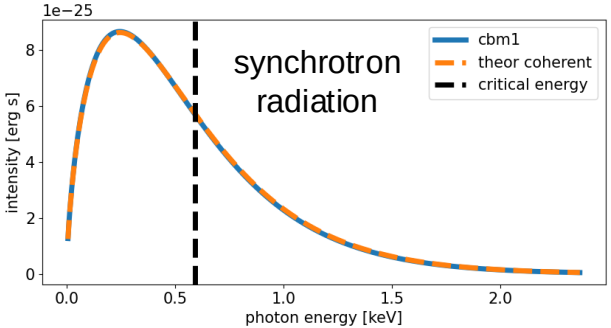
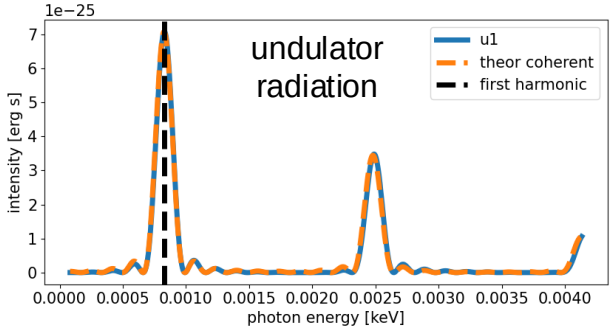
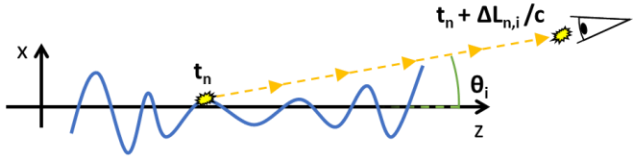


PIC output postprocessing

- EuPRAXIA Advanced Photon Source, exploits laser-driven self-injection for ultra-short high intensity **x-ray pulses production**
- **Highly nonlinear process**, requires heavy numerical simulations (PIC) and postprocessing for radiation evaluation and working points exploration
  - ➢ First step was to develop a **dedicated Liénard-Wiechert based code** for PIC output analysis, here are presented some accuracy checks on known devices

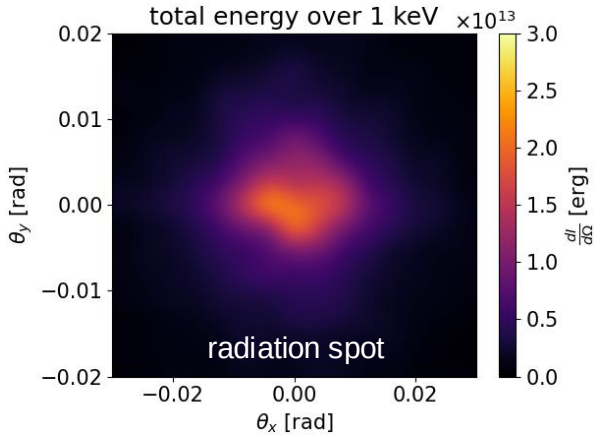


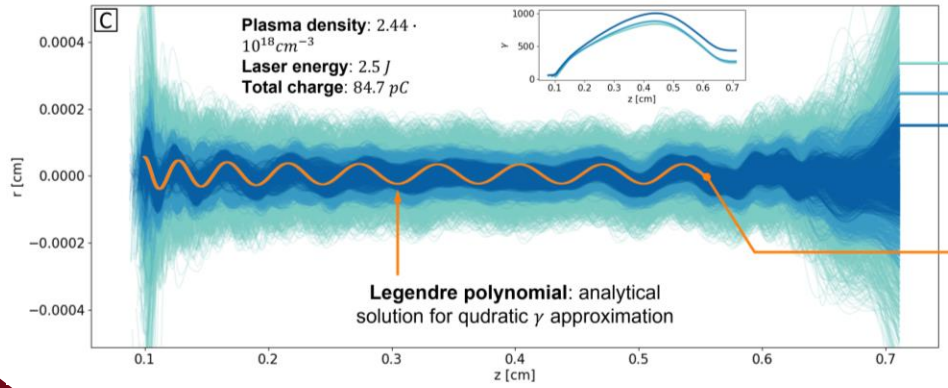


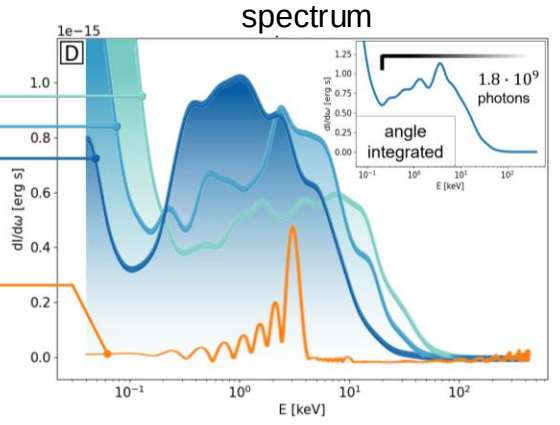


Radiation code: radyno part 1

- **PIC output postprocessing**: particle selection and ordering algorithm
- **Overcoming field timestep misalignment** at detector: total field interpolation algorithm or parallel FT calculation
- Easing **layered spectrum analysis** for core radiation features extraction
- Details published in PAHBB workshop proceedings [1]

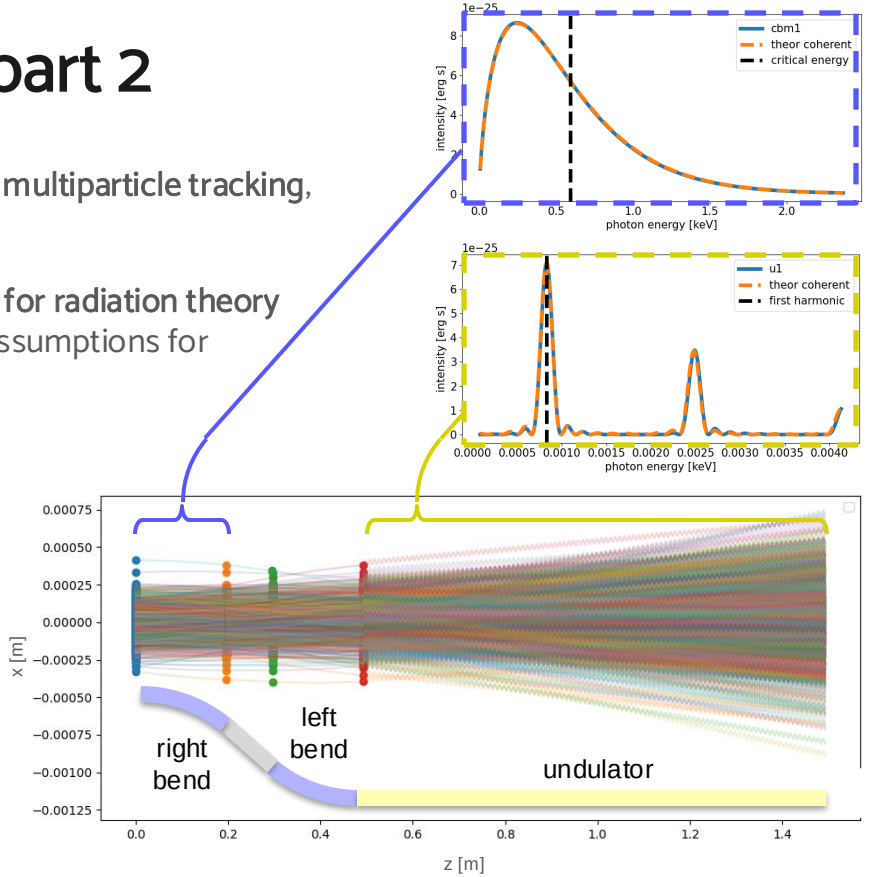






Particle tracking: radyno part 2

- Urge for new integrated features: **full relativistic multiparticle tracking**, soon with transfer matrix option as well
- At first developed to give a prompt **support tool for radiation theory** advancement, easily customizable with model assumptions for prediction validation
- Ready for **multi-device beamline simulation**, both on the dynamics and the radiation side.
- **WIP modules** for radiation recoil, coherent synchrotron radiation effects and space charge



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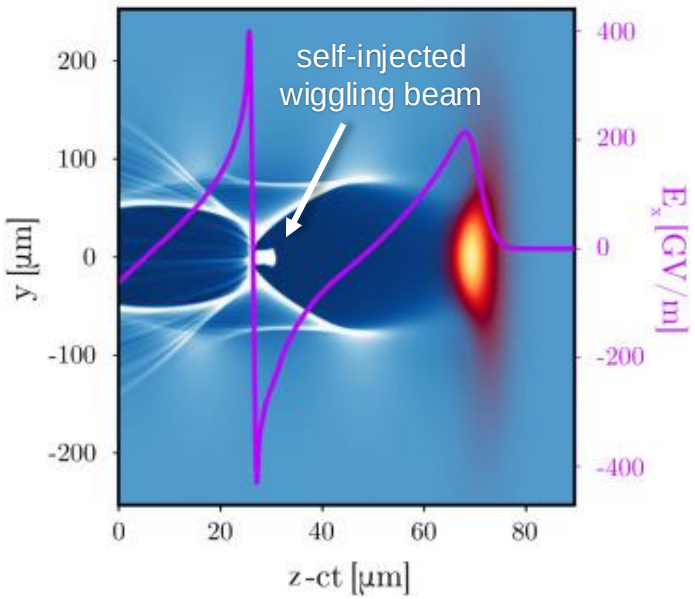
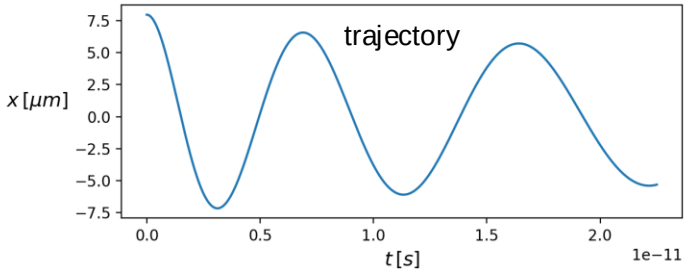
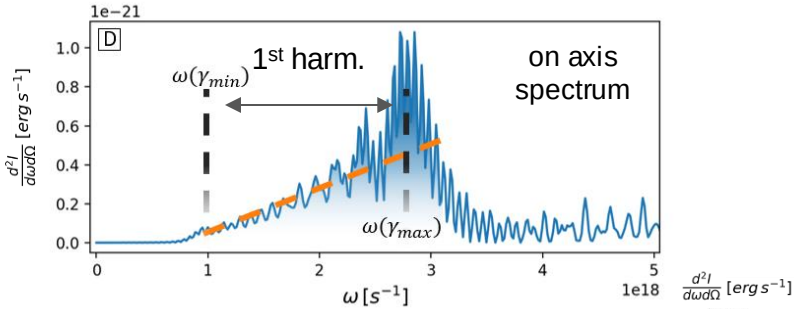


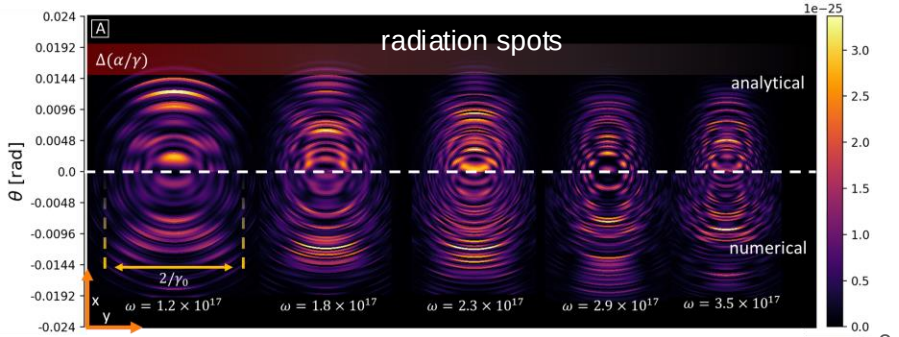
Betatron radiation studies

Accelerated self-injection

- Fully analytical theory for radiation spectrum in case of **linear particle energy growth,** extending a work from Pukhov et al.*
- Spectrum analysis shows that **single harmonics spread out** as energy changes, and **the envelope mimics the energy variation trend**
- This behavior **holds for arbitrary energy variation** and may be useful as self-injected beam energy diagnostics principle
- Side to side comparison with the **numerical radiation spots**, showing good accuracy, poster on the topic presented at EAAC 2023



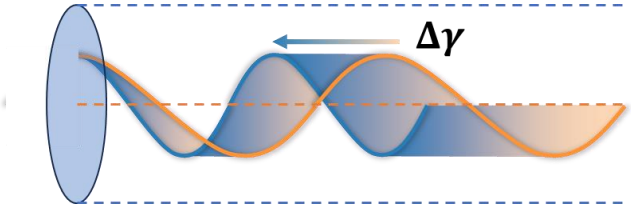


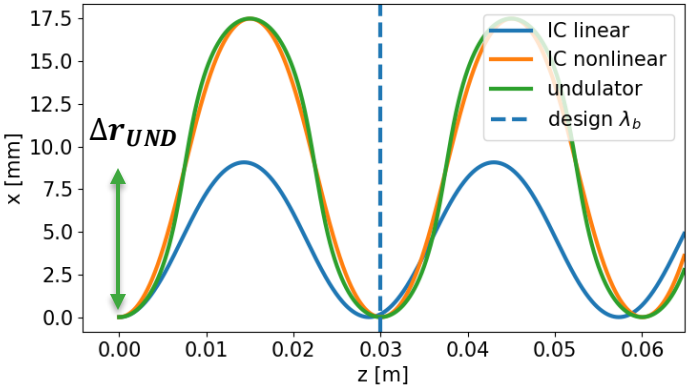


Betatron radiation studies

Nonlinear Ion Channel study

- Ion channel are **wakeless plasma devices**, were pure electrostatic linear focusing is exploited in radiation production
- One more test bench for the code, a **fundamental comparison between magnetic undulator and ion channel radiation** properties, in extreme focusing strength (K/γ) regimes.
- A wide theory correction has been performed, to account for strong energy oscillations and properly **match nonlinear IC and UND trajectory**
- In the process, a **new general expression for magnetic undulator strength** was found, showing the theoretical limit $K/\gamma < 1$



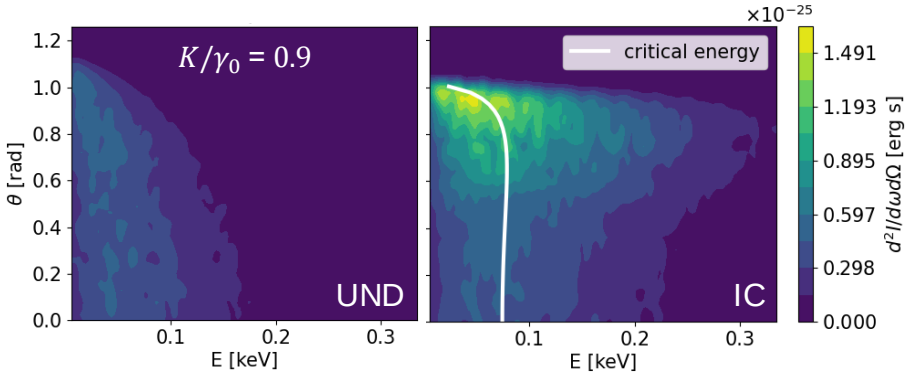


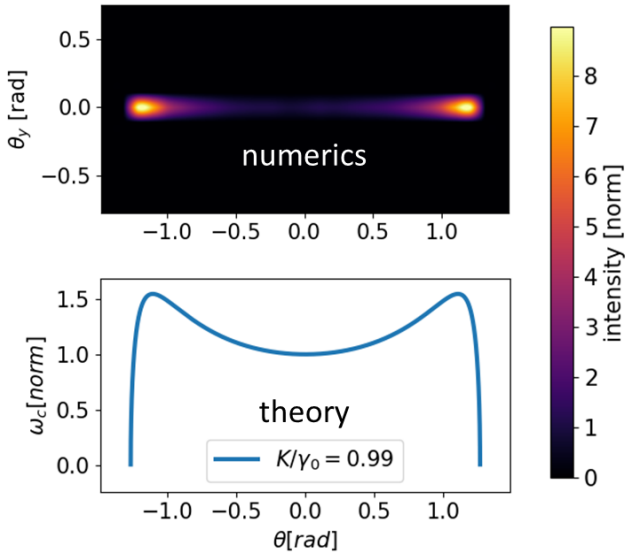
$$\Delta r_{UND} = \frac{\operatorname{arctanh} K/\gamma}{k_b} \xrightarrow[K/\gamma \to 0]{} \frac{K}{\gamma k_b}$$

Betatron radiation studies

Nonlinear Ion Channel study

- Core differences were predicted and numerically verified with radyno, as **relativistic dipole emission** in ion channel for extreme oscillations, while undulator still features relativistic doppler shifted spectrum
- High intensity radiation at wide polar angle may be exploited as an **emittance damping mechanism** through radiation recoil, still under investigation

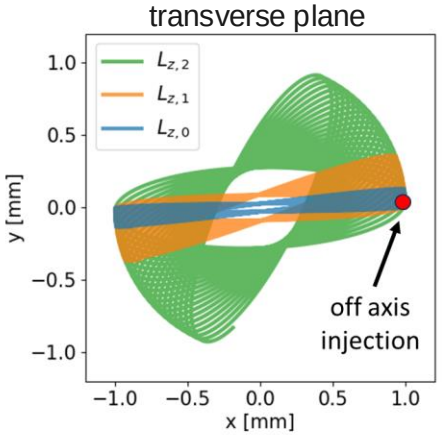


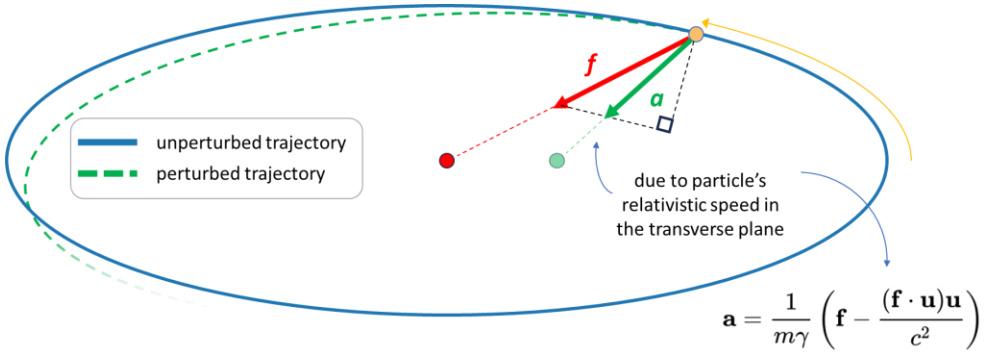


Betatron radiation studies

Nonlinear Ion Channel study

- Transverse plane **trajectory precession** in ion channel was numerically observed and analytically described
- Trajectory precession is a **pure relativistic dynamics effect**: often negligible, it becomes relevant in high K/γ regimes, where transverse speed component gives a misalignment between force and acceleration
- WIP to include precession as an **rms envelope equation term**
- Paper on arXiv, about to be submitted [2], and topic discussed at EuPRAXIA_PP meeting in September





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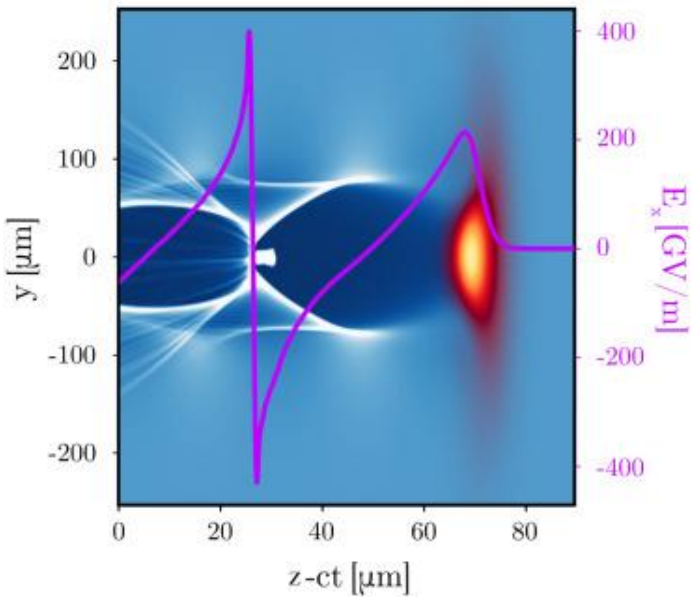
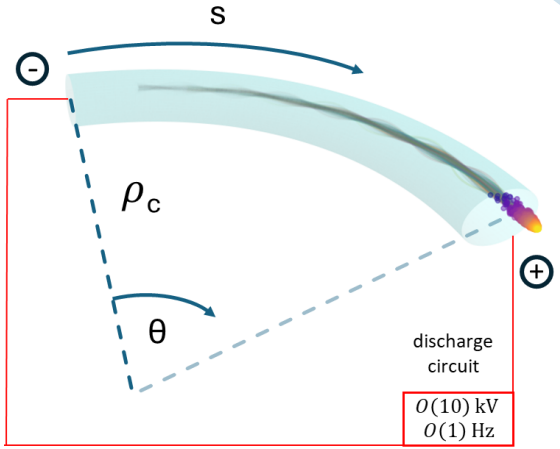
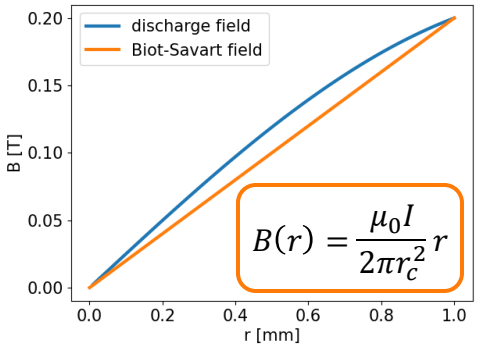


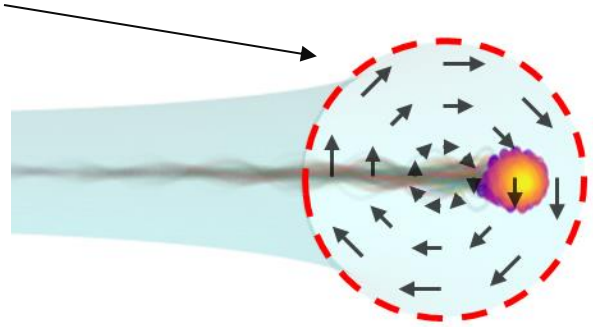
Plasma beam bending

ABP theoretical and numerical study

- **Full theoretical characterization** of a novel device, where focusing azimuthal magnetic field generated during plasma discharge are exploited to obtain beam bending (dipolar error)
- Optimal **injection offset** and **discharge current requirements** were outlined
- Detailed analysis of **transfer matrix**, **dispersive properties**, **transition energy** and **beam quality** evolution
- Numerical checks supported by `radyno` code



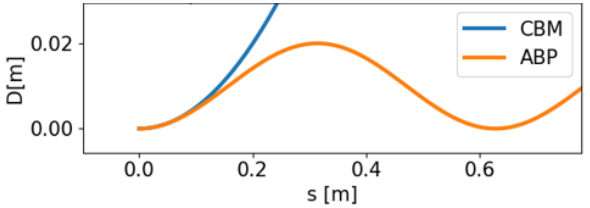




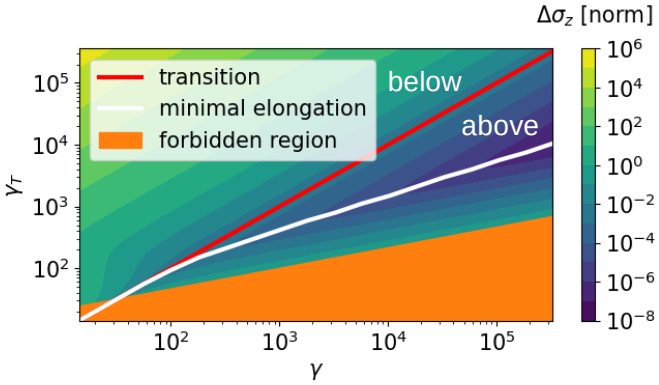
Plasma beam bending

ABP theoretical and numerical study

$$L_c \geq \frac{2}{k_x}\sqrt{6\left(1-\sqrt{\frac{D_{\mathrm{ABP}}}{D_{\mathrm{CBM}}}}\right)}.$$

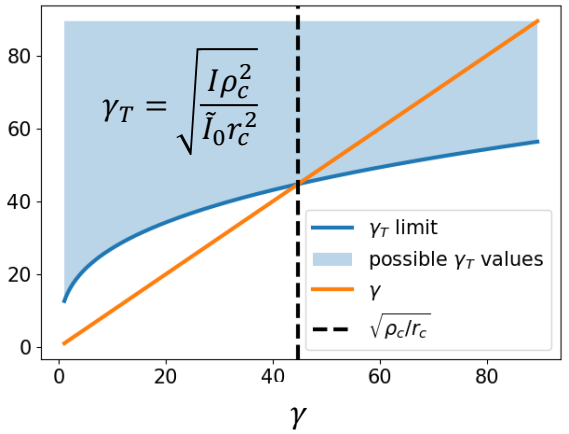


- Dispersion was thought to be absent, but it is not, and below some **geometry-given limit length** it's the same as in a CBM
- Given a **minimal usage current** as a function of beam energy, it's not always possible to place the beam above or below transition: **for beam energy below a geometric limit, the beam will be bounded below transition**
- This is relevant for beam length conservation. Above an emittance and geometry given energy, **minimal beam elongation is found above transition**



below transition only!

both above and below transition



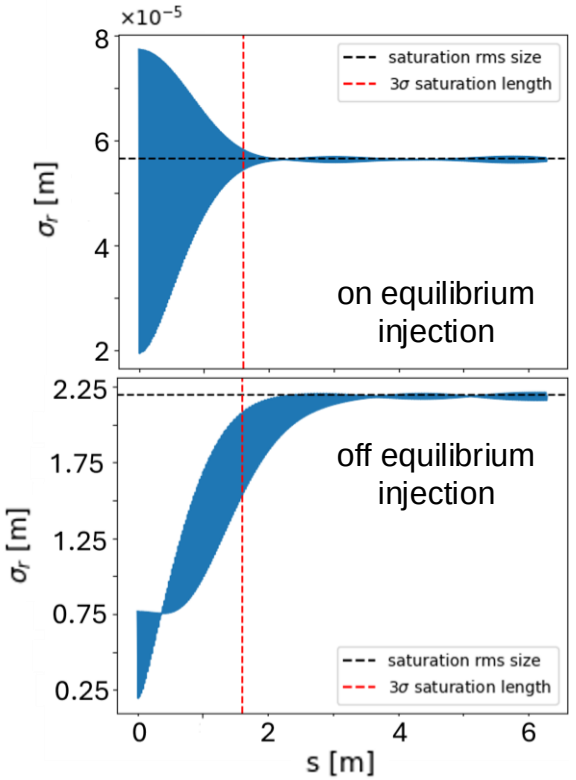
Plasma beam bending

ABP theoretical and numerical study

- One interesting result is a simple analytical prediction on **long-term beam spot degradation** as a function of beam parameters (emittance, energy spread) and injection, based on a statistical approach
- May be back-engineered for **energy spread and/or injection offset measurements**
- Calculated for the bent capillary case but appliable to **whatever focusing element**
- Paper recently published on PRAB [3] and topic discussed in UBA 24

$$\sigma_{sat}^2 = \frac{\Delta x_{inj}^2}{2} + \frac{\epsilon_{rms}}{k_b} + \frac{3}{2}\frac{\sigma_{\Delta\gamma/\gamma}^2}{\rho_c^2 k_b^4}$$

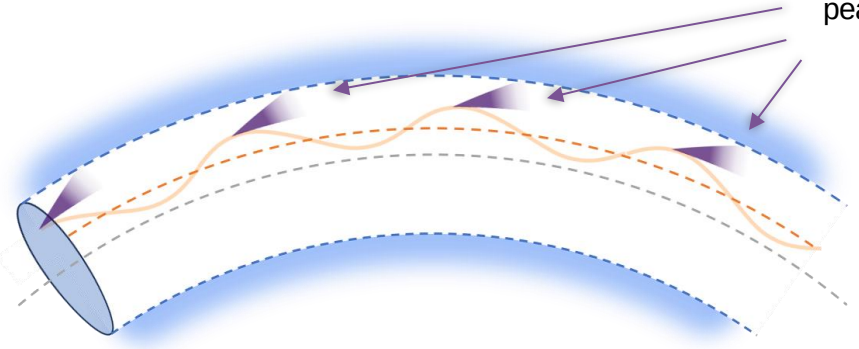
$$L_{sat} = \frac{\pi k_b}{(I/2\gamma\tilde{I}_0 r_c^2 - 1/\rho_c^2)}\frac{1}{3\sigma_{\Delta\gamma/\gamma}}$$



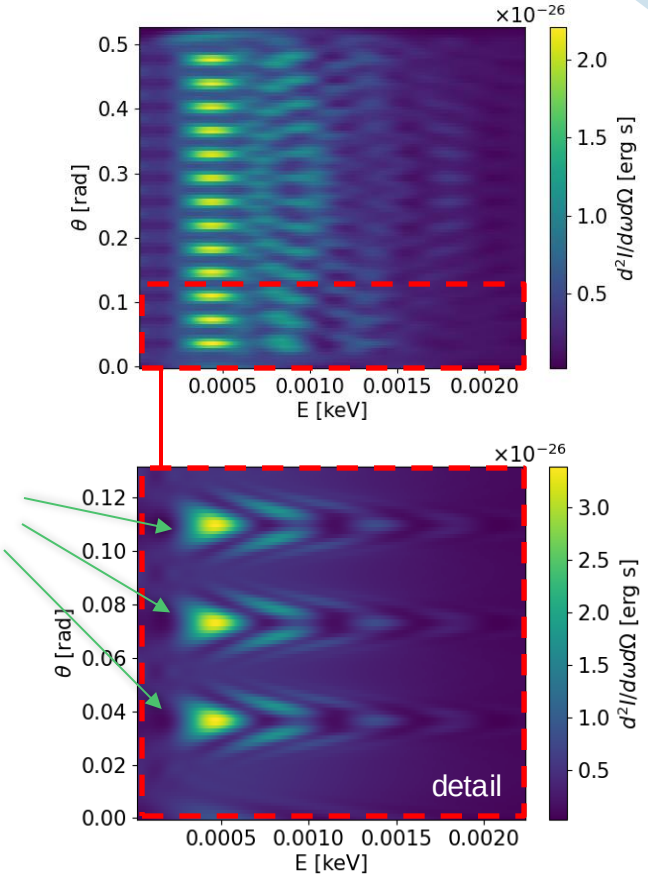
Plasma beam bending

ABP radiation

- ABP radiation analysis is now ongoing, featuring a **mixed undulator-synchrotron** spectrum that may be exploited as a diagnostic tool
- Off-equilibrium beam injection will give a collective bent betatron motion that will give **periodic peaks in the angle-resolved spectrum**, while correct injection should give uniform intensity



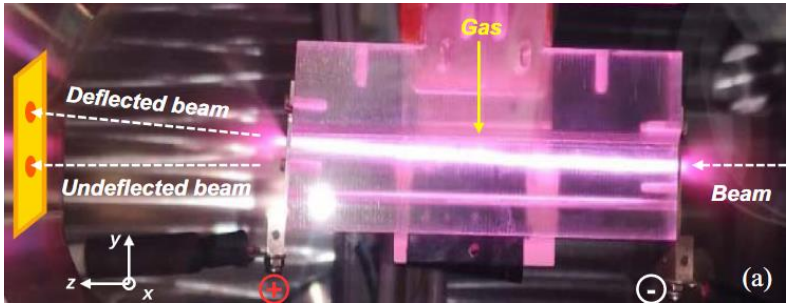
peak intensity

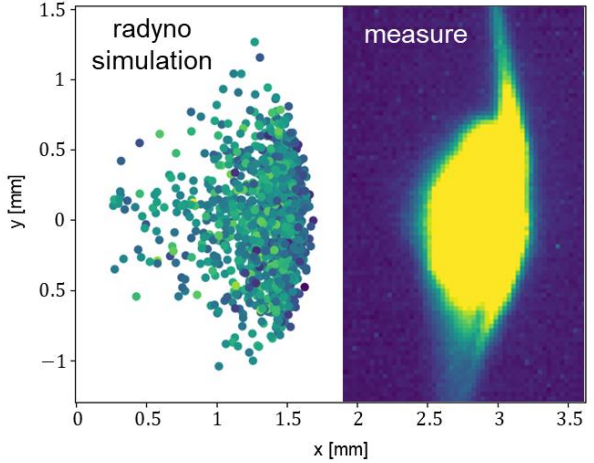


Plasma beam bending

ABP measurements @SPARC_LAB

- During the first part of my visit to LNF, numerical simulations were conducted to support ongoing **experimental beam dynamics measurements**
- By refining the field structure with nonlinearities, quantities like charge transport and beam pointing, could be accurately modelled
- Experimental paper published on PRL [4], radyno simulation on the cover!





Thank you for the attention!