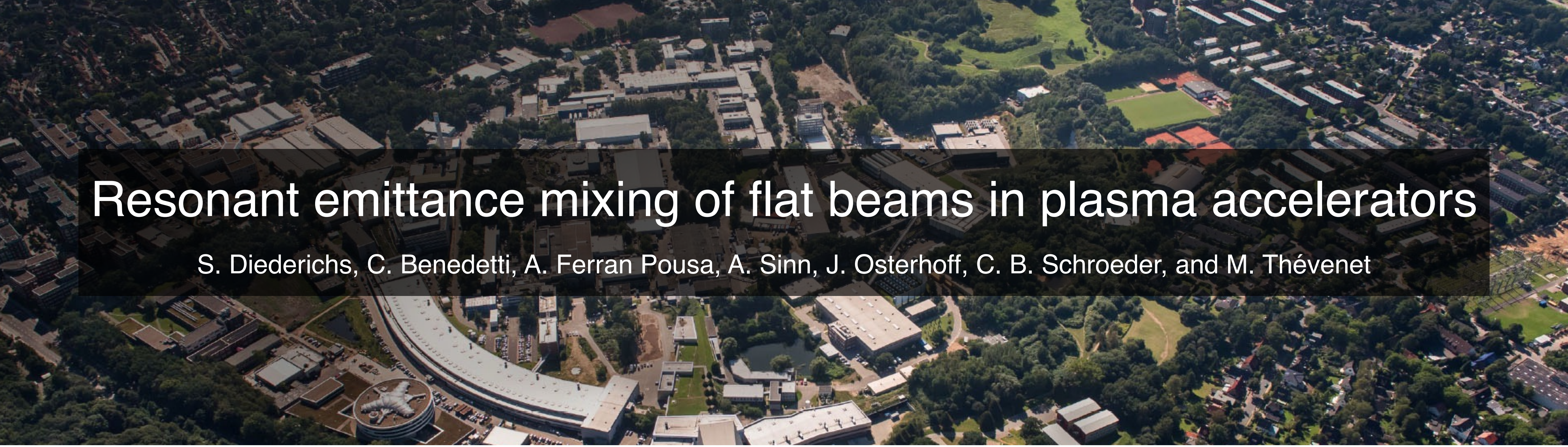

Resonant emittance mixing of flat beams in plasma accelerators

S. Diederichs, C. Benedetti, A. Ferran Pousa, A. Sinn, J. Osterhoff, C. B. Schroeder, and M. Thévenet

Maxence Thévenet – DESY

Theory & simulation for plasma acceleration

MPL

PHYSICAL REVIEW LETTERS **133,** 265003 (2024)

Resonant Emittance Mixing of Flat Beams in Plasma Accelerators

S. Diederichs,[1,2] C. Benedetti,[3] A. Ferran Pousa,[1] A. Sinn,[1] J. Osterhoff,[1,3] C. B. Schroeder,[3,4] and M. Thévenet[1,*]

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[2] *CERN, Esplanade des Particules 1, 1211 Geneva, Switzerland*

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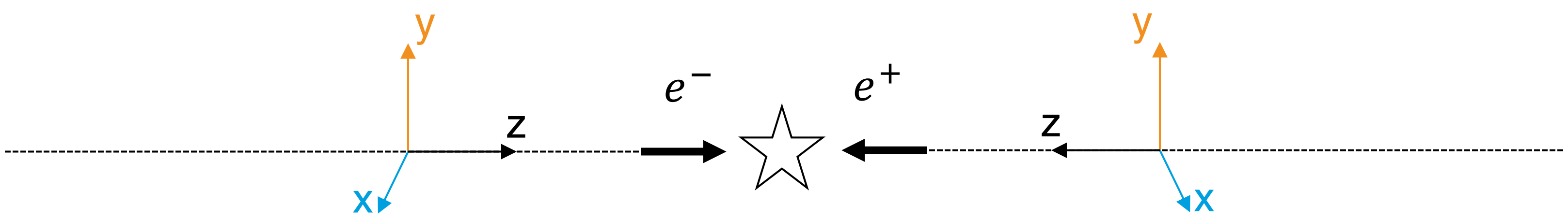
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Flat beams are preferred at the interaction point



Luminosity scales with[2] $\sim 1/(\sigma_x \sigma_y)$ or $\sim 1/\sqrt{\epsilon_x \epsilon_y}$

Beamstrahlung scales with[1] $\sim 1/(\sigma_x + \sigma_y)$

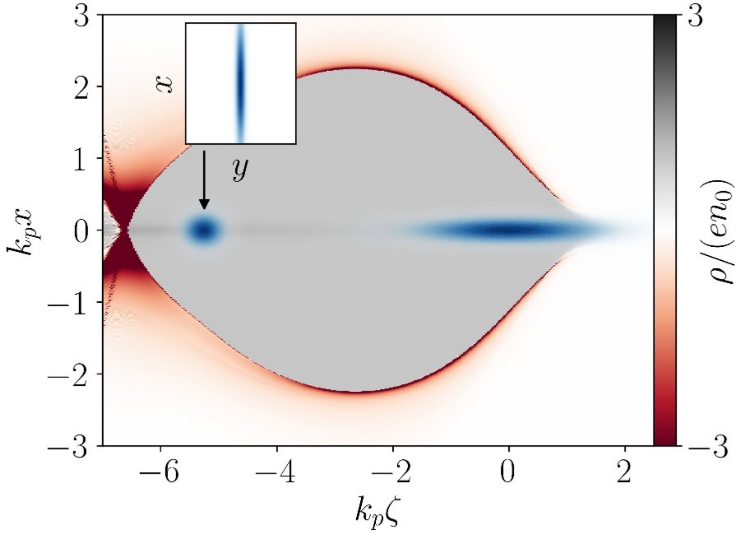
→ Flat beams with $\sigma_x \gg \sigma_y$ ($\epsilon_x \gg \epsilon_y$) **minimize beamstrahlung** and **maximize luminosity**

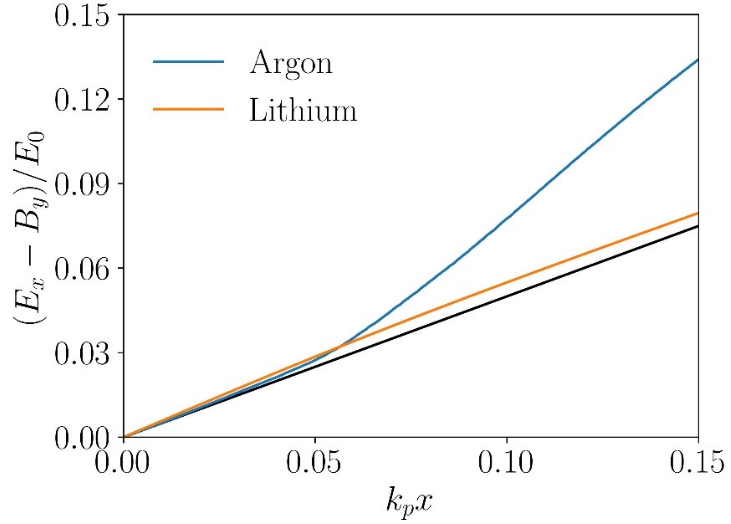
Acceleration of flat **beams not mentioned as a key R&D challenge** in ESPP

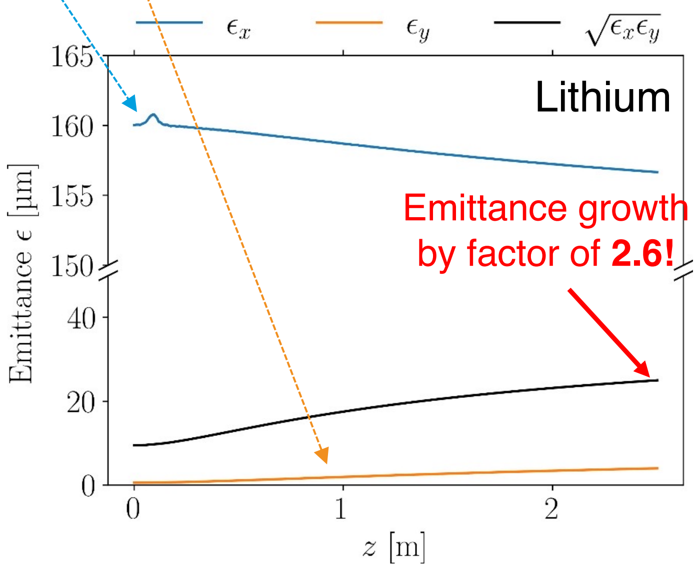
[1] Schroeder et al, JINST 2022
[2] Schulte, RAST 2016
[3] Raubenheimer, SLAC PUB 1993

Realistic plasma stage sees considerable emittance exchange

- **Drive bunch**: Charge: 4.28 nC, Length (rms): 42 μm, $\epsilon_{[x,y]} = [60, 60]\,\mu$m.
- **Witness bunch**: Charge: 1.6 nC, Length (rms): 18 μm, $\boldsymbol{\epsilon_{[x,y]} = [160, 0.54]\,\mu}$**m.**
- **Plasma**: $n_0 = 7\times10^{15}$ cm^{-3}, Length: 2.5 m, Lithium.







- Mild ion motion or ionization causes considerable emittance exchange

Mechanism: coupled wakefields give coupled x & y orbits

Consider the dynamics of a single beam electron in wakefield $\boldsymbol{W} = \boldsymbol{E} + c\boldsymbol{e_z}\times\boldsymbol{B}$

Ideal blowout regime
Axisymmetric and linear

$$\mathbf{W_r} = \mathbf{E_0}\frac{\mathbf{k_p r}}{\mathbf{2}}$$

$$W_x = E_0\frac{k_p x}{2}$$

$$W_y = E_0\frac{k_p y}{2}$$

→ ***x and y orbits <u>fully decoupled</u>***

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Example
Axisymetric non-linear wakefields

$$\mathbf{W_r} = \mathbf{E_0}\frac{\mathbf{k_p r}}{\mathbf{2}} + \boldsymbol{\alpha}\mathbf{r^2}$$

$$W_x = E_0\frac{k_p x}{2} + \alpha r x$$

$$W_y = E_0\frac{k_p y}{2} + \alpha r y$$

- Ion motion/ionization/... caused by an axisymmetric drive beam
- Guiding channel for LPA

→ ***x and y orbits are <u>coupled</u>***

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General
non-axisymmetric, non-linear fields

$$W_x = f(x, y)$$
$$W_y = g(x, y)$$

- Ion motion/ionization/… caused by a flat witness beam
- Laser misalignment in guiding channel for LPA

→ ***x and y orbits are <u>coupled</u>***

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Consider the dynamics of a single beam electron in wakefield $\boldsymbol{W} = \boldsymbol{E} + c\boldsymbol{e_z}\times\boldsymbol{B}$

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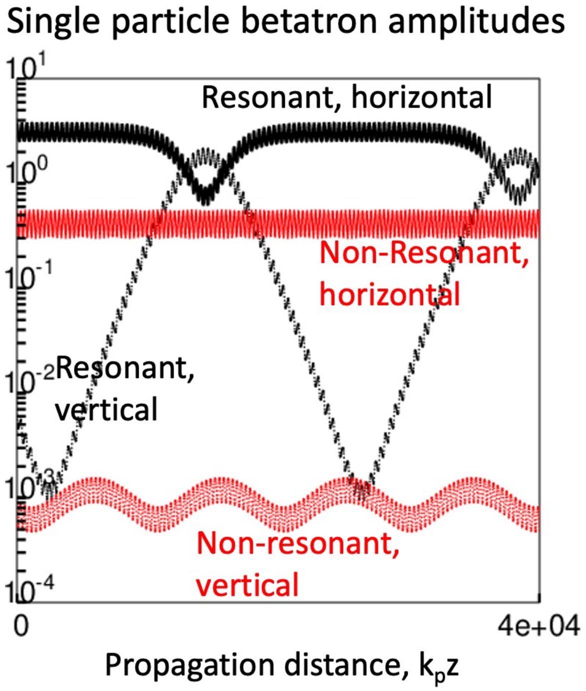
$$W_{[x,y]} = \frac{k_p[x,y]E_0}{2}\left[1 + \alpha_{[x,y]}H\left(\frac{r^2}{2L^2_{[x,y]}}\right)\right]$$
$$H(q) = [1 - \exp(-q)]$$

C. Benedetti *et al.*, PRAB 20, 111301 (2017)

A fraction of beam particles are trapped in a resonance



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- Electron has different $k_{\beta x}$ and $k_{\beta y}$ depending on initial conditions.
- The resonance is located on the diagonal $k_{\beta x} = k_{\beta y}$.
- Electrons in a specific area are trapped in the resonance.
- Resonant electrons see periodic exchange in x and y orbits.
- They are responsible for the emittance exchange.

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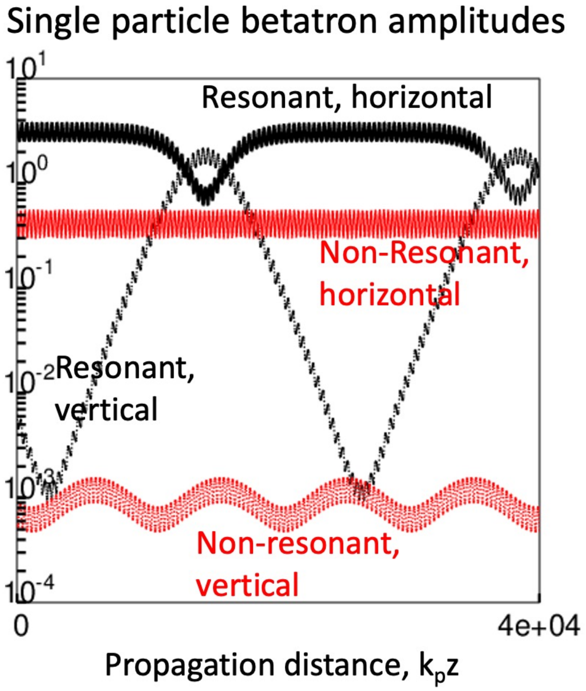

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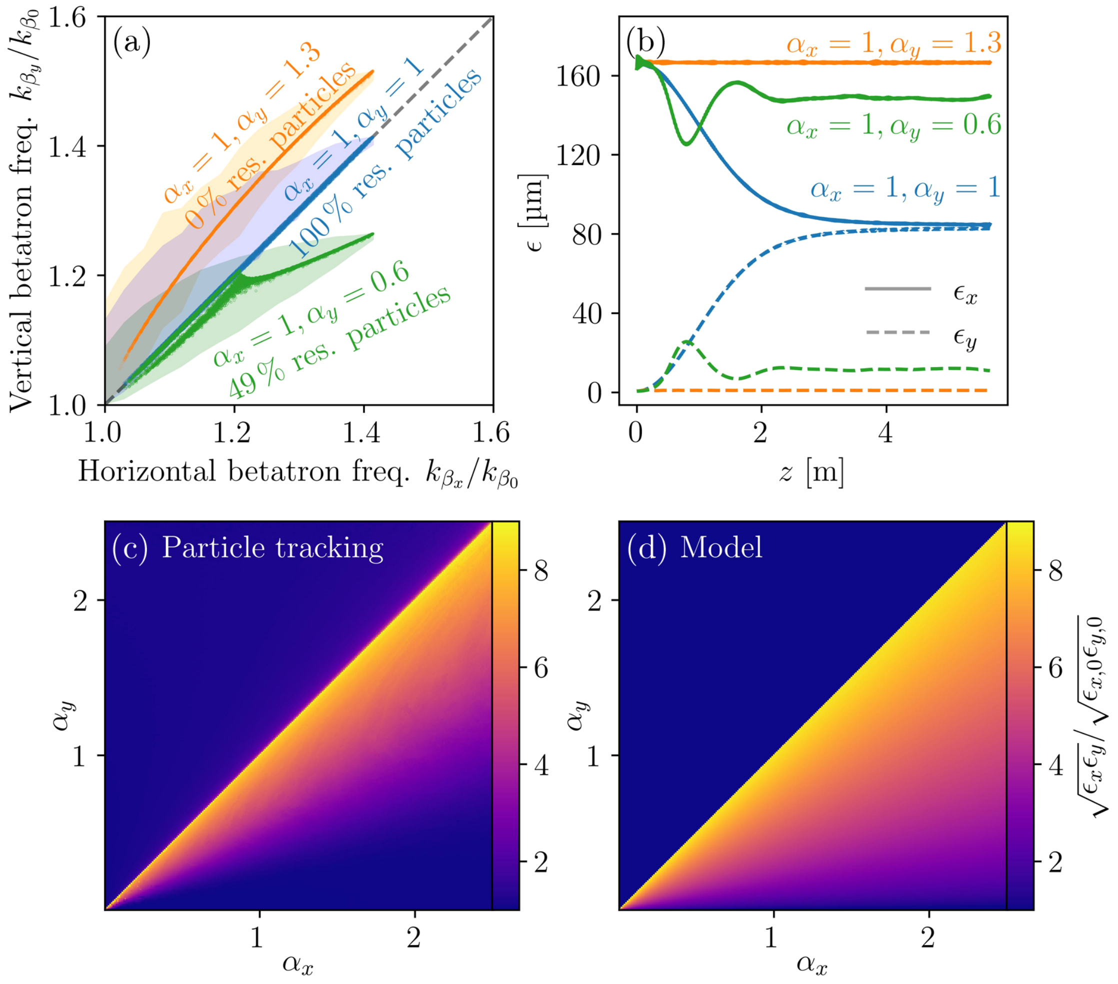

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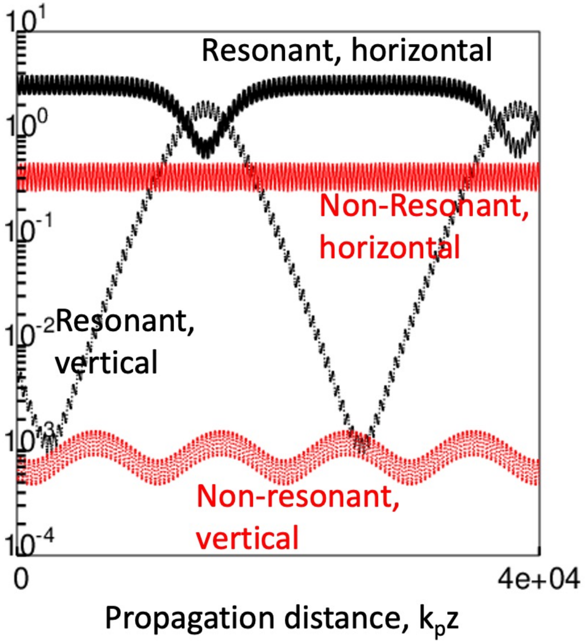
A fraction of beam particles are trapped in a resonance

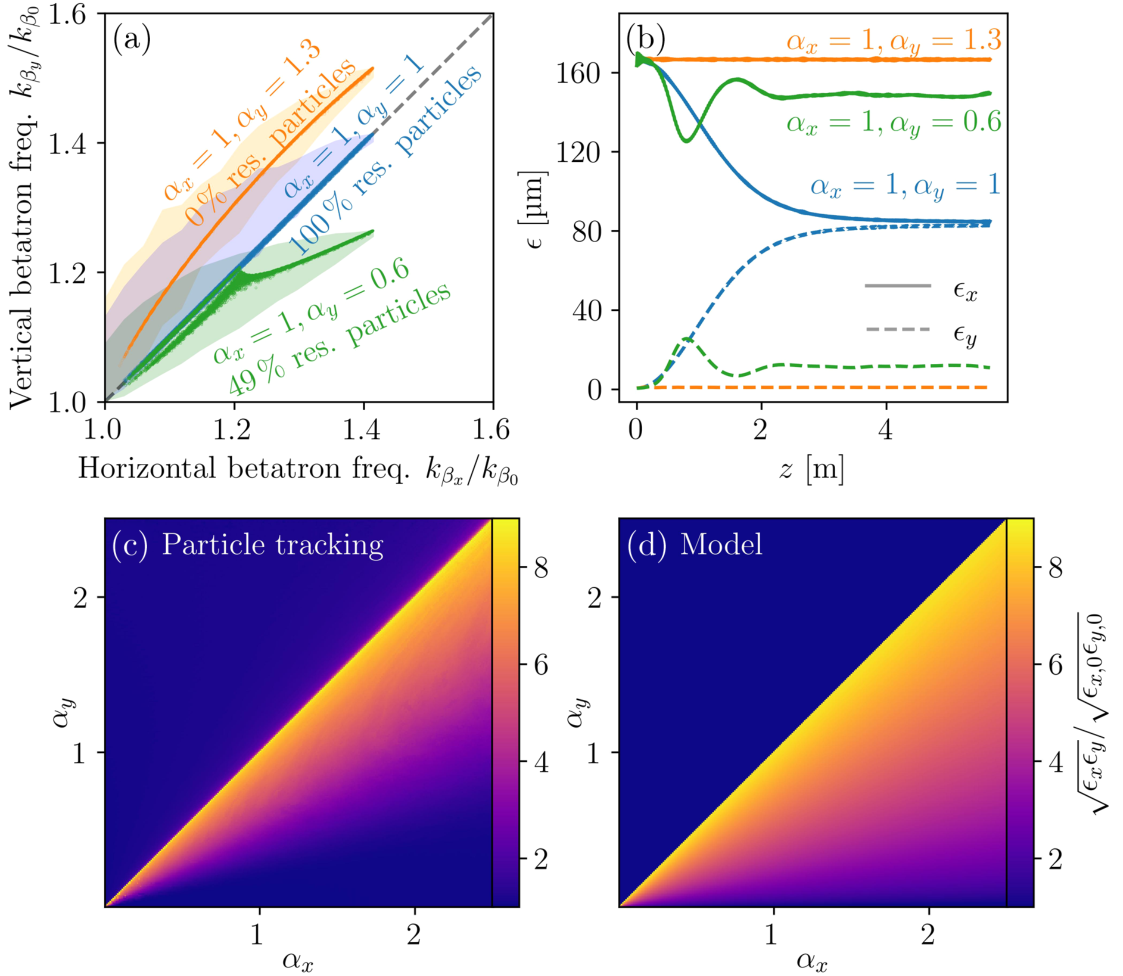
Single particle betatron amplitudes



$$W_{[x,y]} = \frac{k_p[x,y]E_0}{2}\left[1 + \alpha_{[x,y]} H\left(\frac{r^2}{2L^2_{[x,y]}}\right)\right]$$

$$H(q) = [1 - \exp(-q)]$$

C. Benedetti *et al.*, PRAB 20, 111301 (2017)



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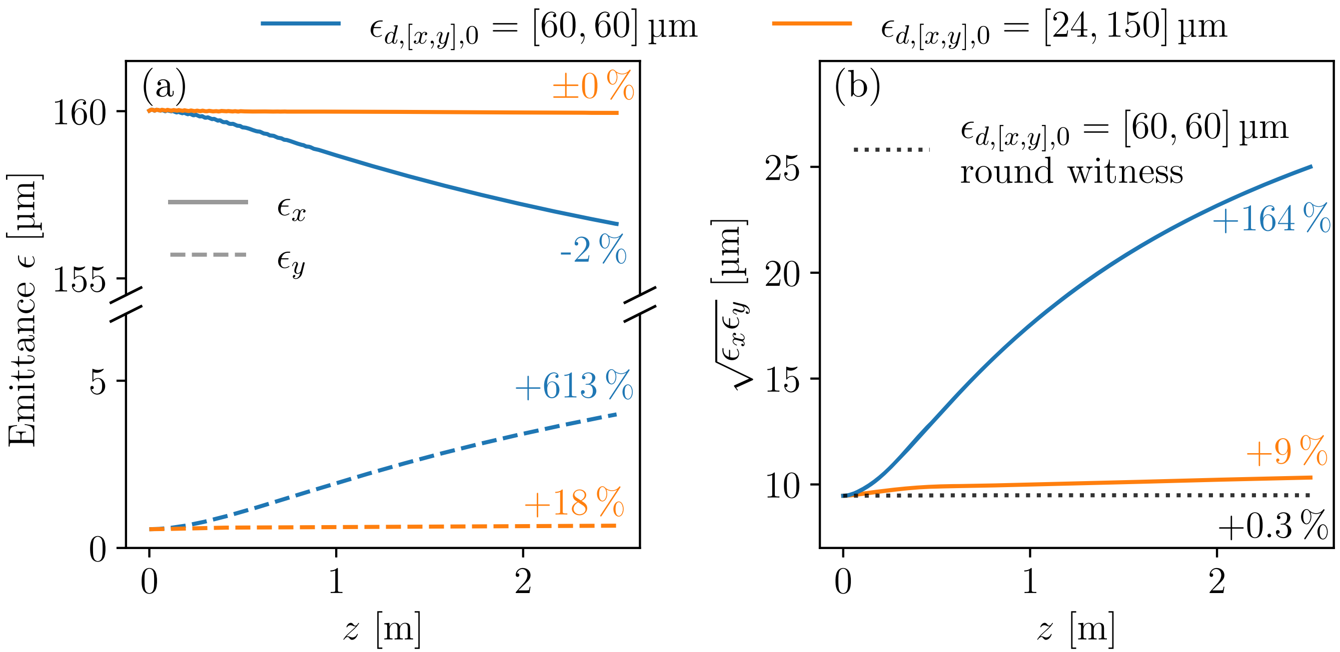
➢ Well-known (complex) phenomenon in RF accelerators

➢ Axisymmetric + non-linear is the worst case
  all particles are resonant → **full emittance exchange**

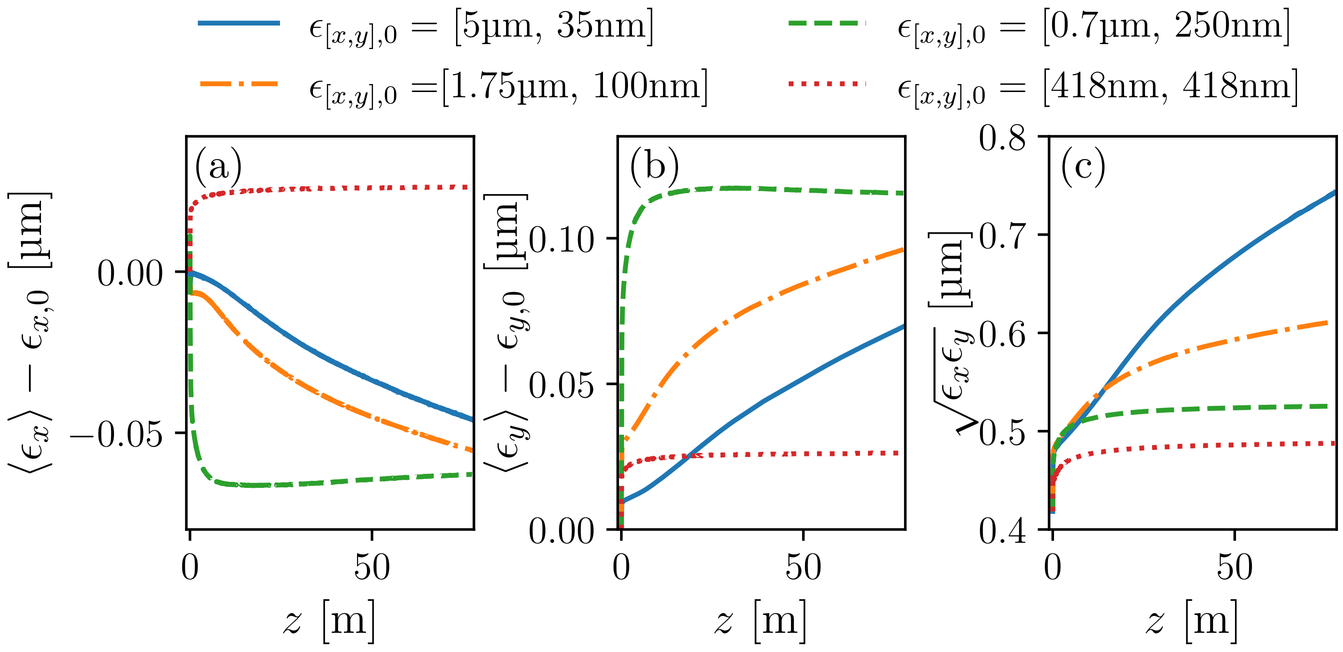
Ion motion from the driver can be solved with a flat driver



<u>Driver</u>: 4.28 nC, 42 μm, $\epsilon_{[x,y]} = [60, 60]\ \mu m$,$[24, 150]\ \mu m$
<u>Witness</u>: 1.6 nC, 18 μm, $\epsilon_{[x,y]} = [160, 0.54]\ \mu m$
<u>Plasma</u>: Sodium 1+, $n_0 = 7\times10^{15}$ cm^{-3}, 2.5 + 5*5 m.

→ *A flat driver breaks the resonance and mitigates emittance exchange*

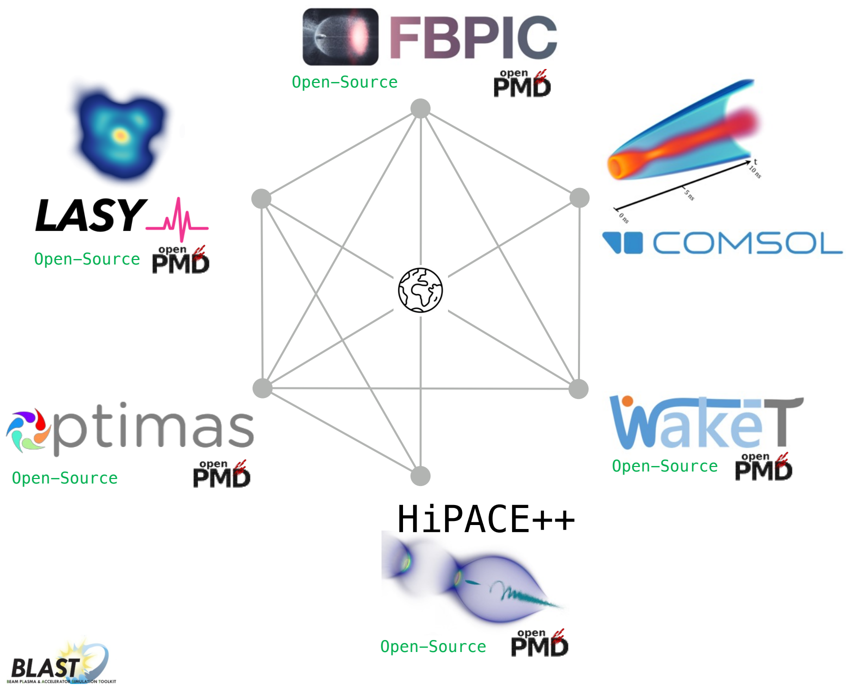
Ion motion from witness beam is not (yet) solved!



Driver: 4.28 nC, 42 μm, $\epsilon_{[x,y]} = [2.8, 2.8]$ mm, rigid
Witness: 1.6 nC, 18 μm, $\epsilon_{[x,y]} = [5, 0.035]$ μm
Plasma: Hydrogen, $n_0 = 7\times10^{15}$ cm^{-3}, length 77.5 m

→ *A flatter beam causes larger emittance exchange*

Studies made possible thanks to recent progress in simulations



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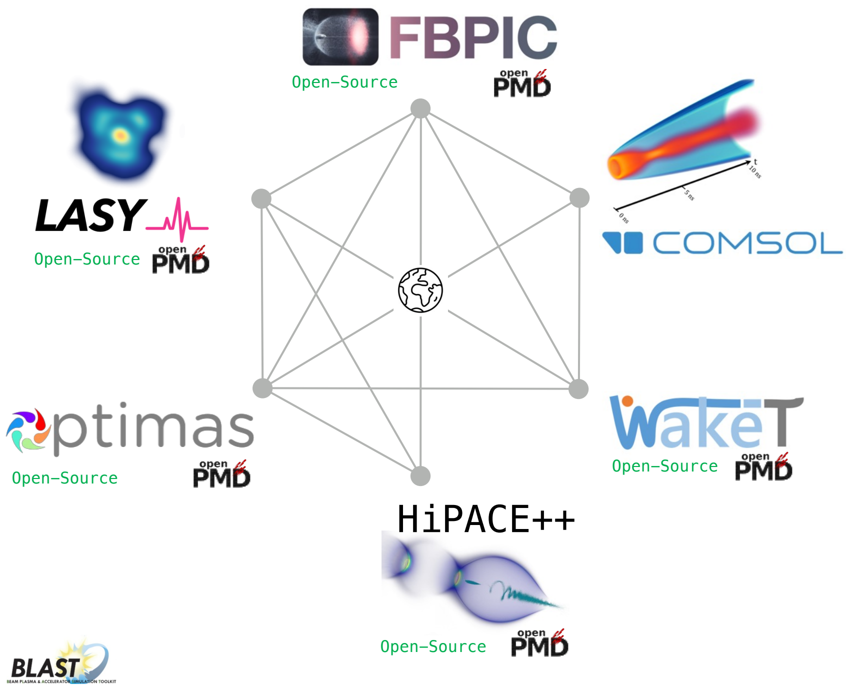
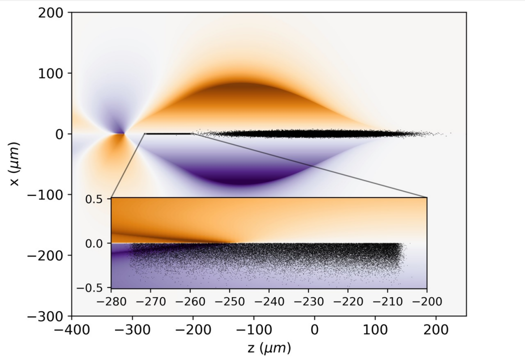


➢ HiPACE++

Optimized for large 3D simulations



…

- ➢ 3D quasistatic particle-in-cell
- ➢ Multi-physics
- ➢ C++, on top supercomputers
- ➢ Mesh refinement

Open-source https://github.com/Hi-PACE/hipace

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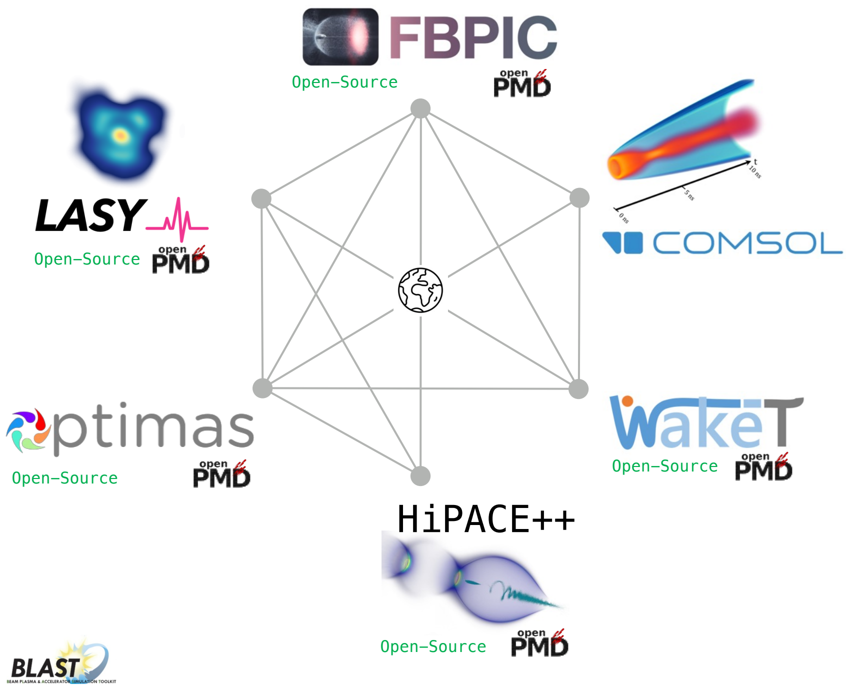

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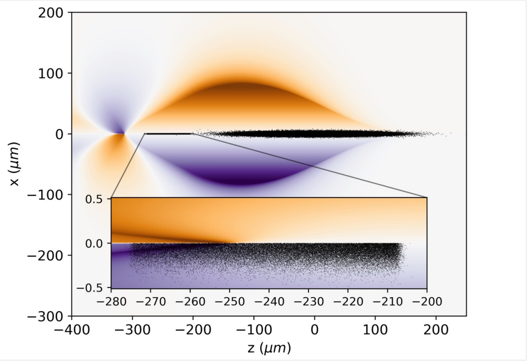

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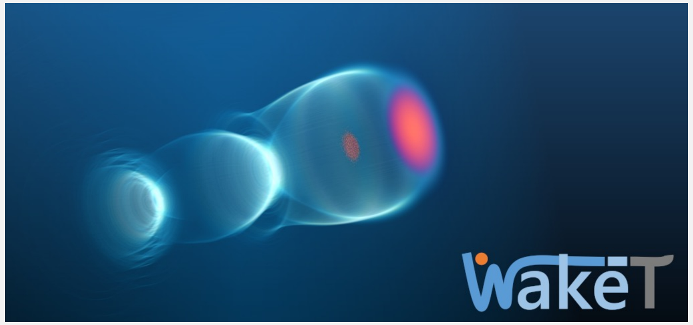
Open-source https://github.com/Hi-PACE/hipace

➢ Wake-T

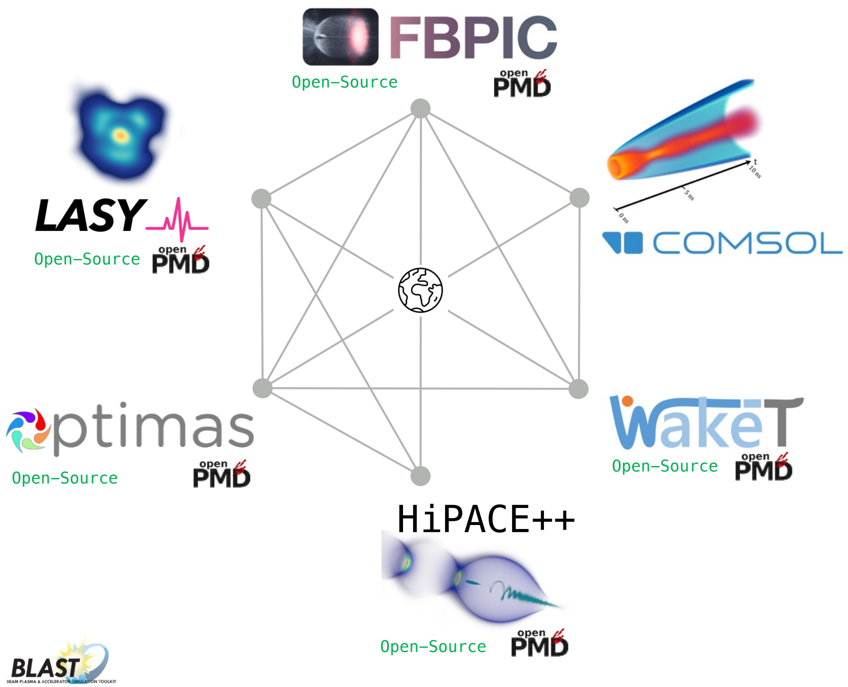
Quick simulations (benchmarked vs. FBPIC)



- ➢ 2D (axisymmetric) quasistatic
- ➢ Laser-driven or beam-driven
- ➢ Python, second/minutes on a laptop
- ➢ Adaptive grid & ion motion

Open-source https://github.com/AngelFP/Wake-T

Studies made possible thanks to recent progress in simulations



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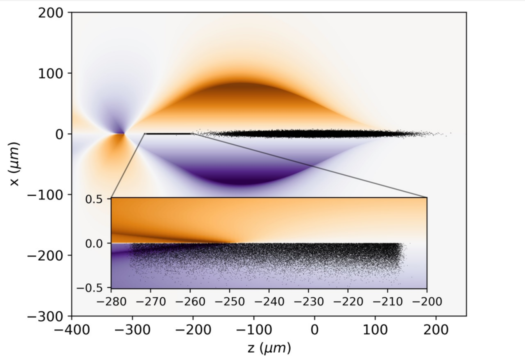

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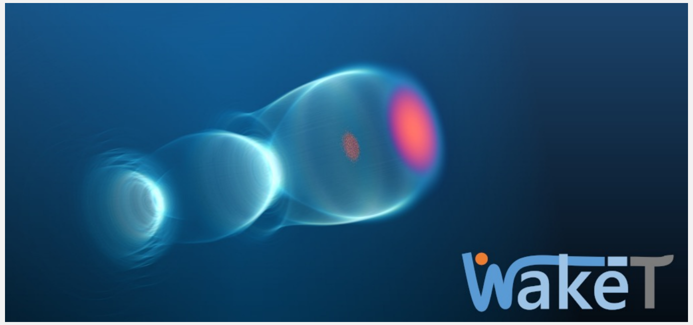

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- ➢ With mesh refinement, 3D simulations of a 20 GeV stage from 175 GeV, emittance 135 nm, are very affordable
  Numerical convergence with transverse resolution of **5 nanometers** to fully resolve ion motion effects

- ➢ Multi-stage simulation studies done routinely
  A. Ferran Pousa et al. Proc. IPAC'23 14: 1533-1536. ; S. Diederichs et al. arXiv:2403.05871 (2024).

- ➢ A collection of tools enables start-to-end multi-physics studies
  COMSOL-plasma for hydrodynamics simulations of HOFI, Optimas for scalable Bayesian optimization, LASY for laser manipulations

→ don't worry about simulations (anymore)

The DESY plasma group MPL

Andi Maier
group leader

Wim Leemans
division director









Paul Winkler
Coordinator
Plasma Injector

Manuel Kirchen
Team Leader
High Average Power LPA

Guido Palmer
Team Leader
Laser Development

Rob Shalloo
Team Leader
High Energy LPA

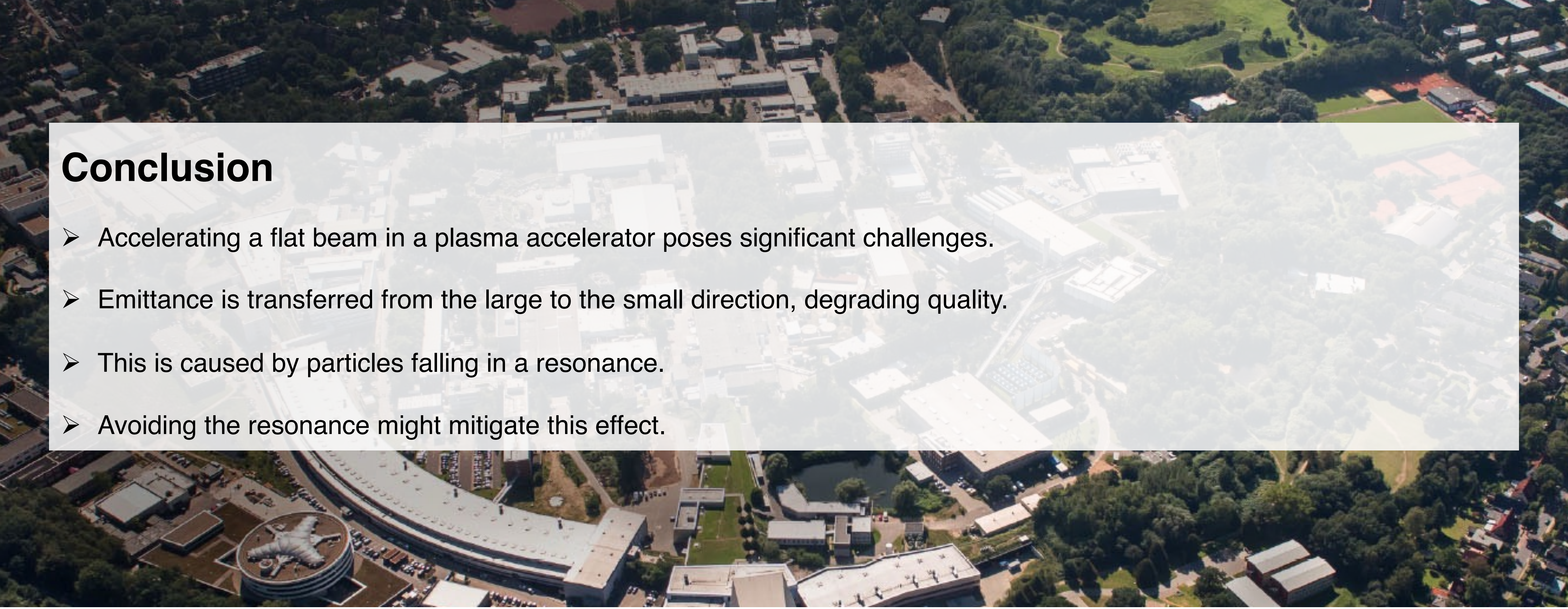
Maxence Thévenet
Team Leader
Theory & Simulations

Jon Wood
Team Leader
Beam-Driven Plasma Acceleration

Kris Põder
Team Leader
LPA Applications

Lutz Winkelmann
Team Leader
Scientific Engineering

Andi Walker
Coordinator
Scientific Infrastructure



Conclusion

- Accelerating a flat beam in a plasma accelerator poses significant challenges.
- Emittance is transferred from the large to the small direction, degrading quality.
- This is caused by particles falling in a resonance.
- Avoiding the resonance might mitigate this effect.

Thank you for your attention