Inter-stage coupling of plasma accelerators

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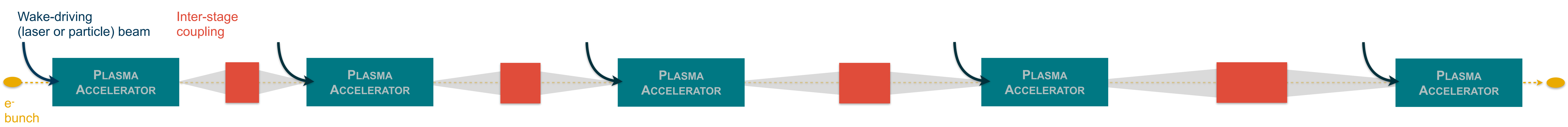
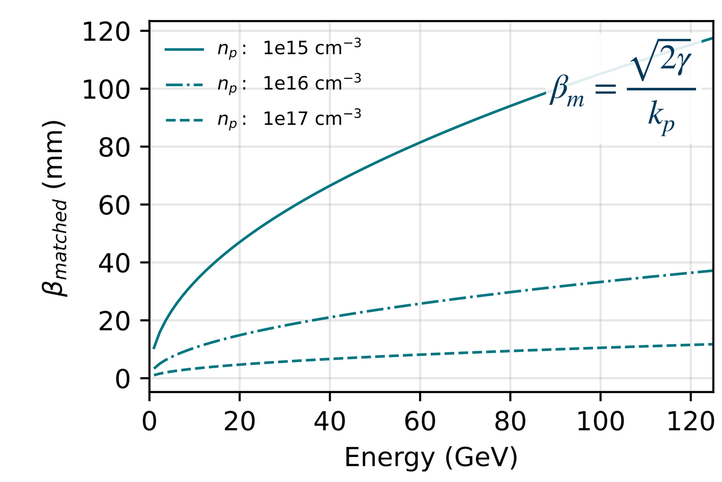


Motivation: Reaching collider-relevant beam energies

> Plasma wakefields exhibit GV/m electromagnetic fields promising:
  > Compact accelerator stage
  > Excellent beam-quality: nm-level emittance, fs-level bunch duration, $\mathcal{O}(100\,\mathrm{pC})$ charge
> Ultimate limit of the acceleration process: **driver depletion**
> Beam energies beyond ~10 GeV require **driver replenishing**
> Inter-stage coupling must provide:
  > **Incoupling** of new wake-driving beam
  > **Beam-quality-preserving transport** of accelerated bunch
> Metric for a compact design of future linear accelerator facilities:
  Effective acceleration gradient including beam delivery systems

The challenge

> Strong in-plasma focusing forces:
  → **Matching conditions** requires strong focusing into plasma
  → Strongly divergent beam after acceleration
> Micron-sized wake:
  → **Tight tolerances** (synchronisation and alignement)
  → Non-negligible energy spread causing **chromaticity**



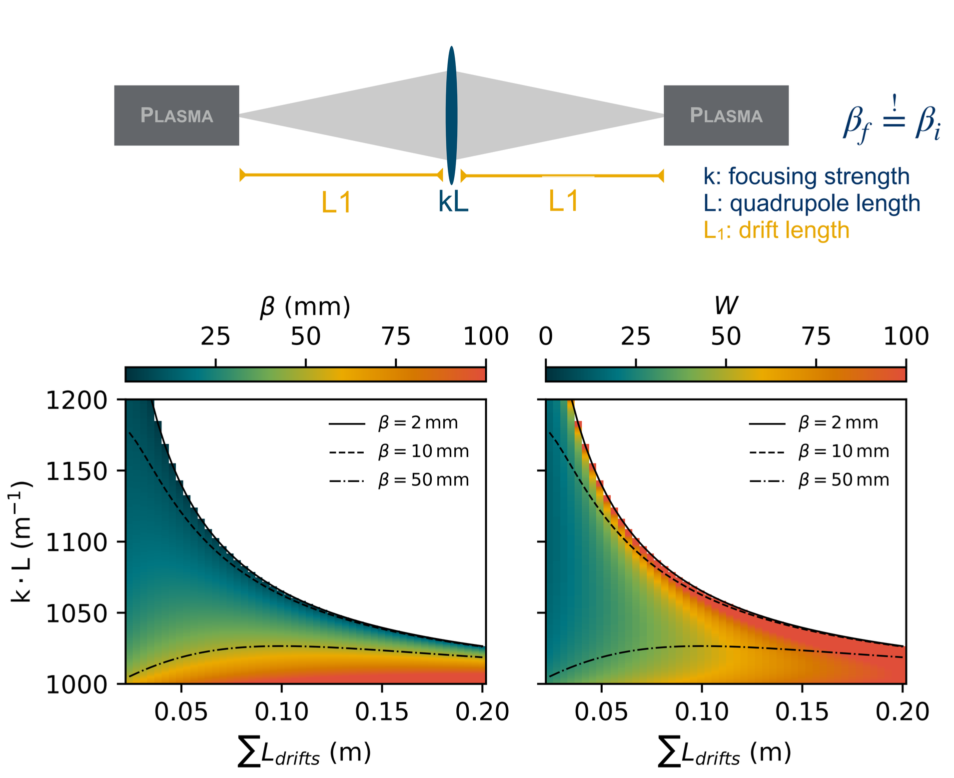
The scale of the inter-stage coupling is determined by:
> Achievable gradient of focusing optics
> Demand on chromatic focus correction

Focusing strength: $k = \frac{e}{p}\frac{B_z}{dx} \approx \frac{0.299}{\beta E\,[GeV]} \cdot G\,[T/m]$

Chromatic amplitude: $W = \sqrt{\left(\frac{\partial\alpha}{\partial\delta} - \frac{\alpha}{\beta}\frac{\partial\beta}{\partial\delta}\right)^2 + \left(\frac{1}{\beta}\frac{\partial\beta}{\partial\delta}\right)^2}$

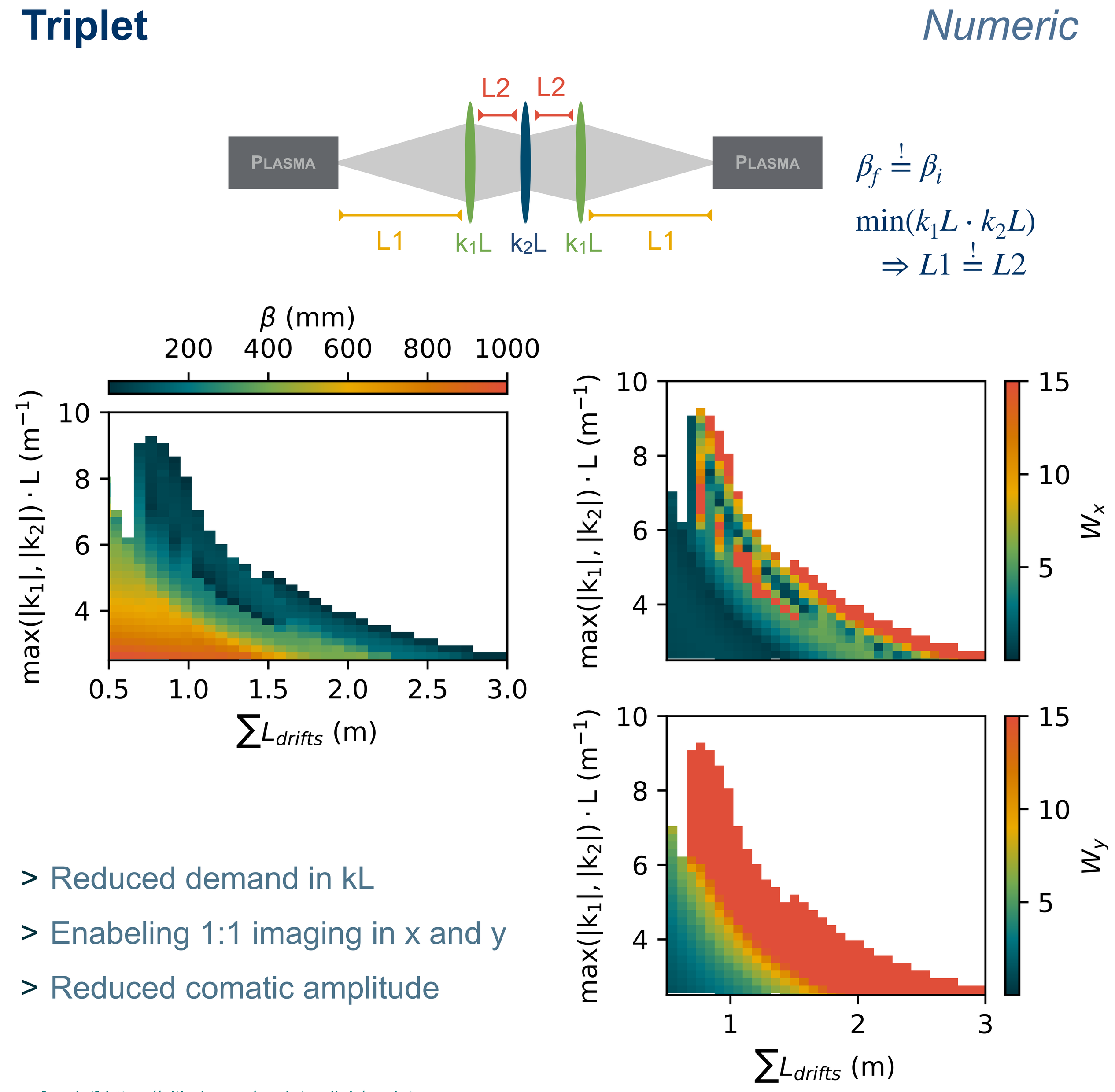
Stage length ↔ Focusing strength ↔ Chromatic acceptance

Singlet (focusing plane) — *Analytic*



> Longer coupling stages implicate:
  > Lower k-values for small beta values
  > Larger absolute chromatic amplitude
  > Larger k-sensitivity of focus spot size
  > Smaller k-sensitivity of chromaticity

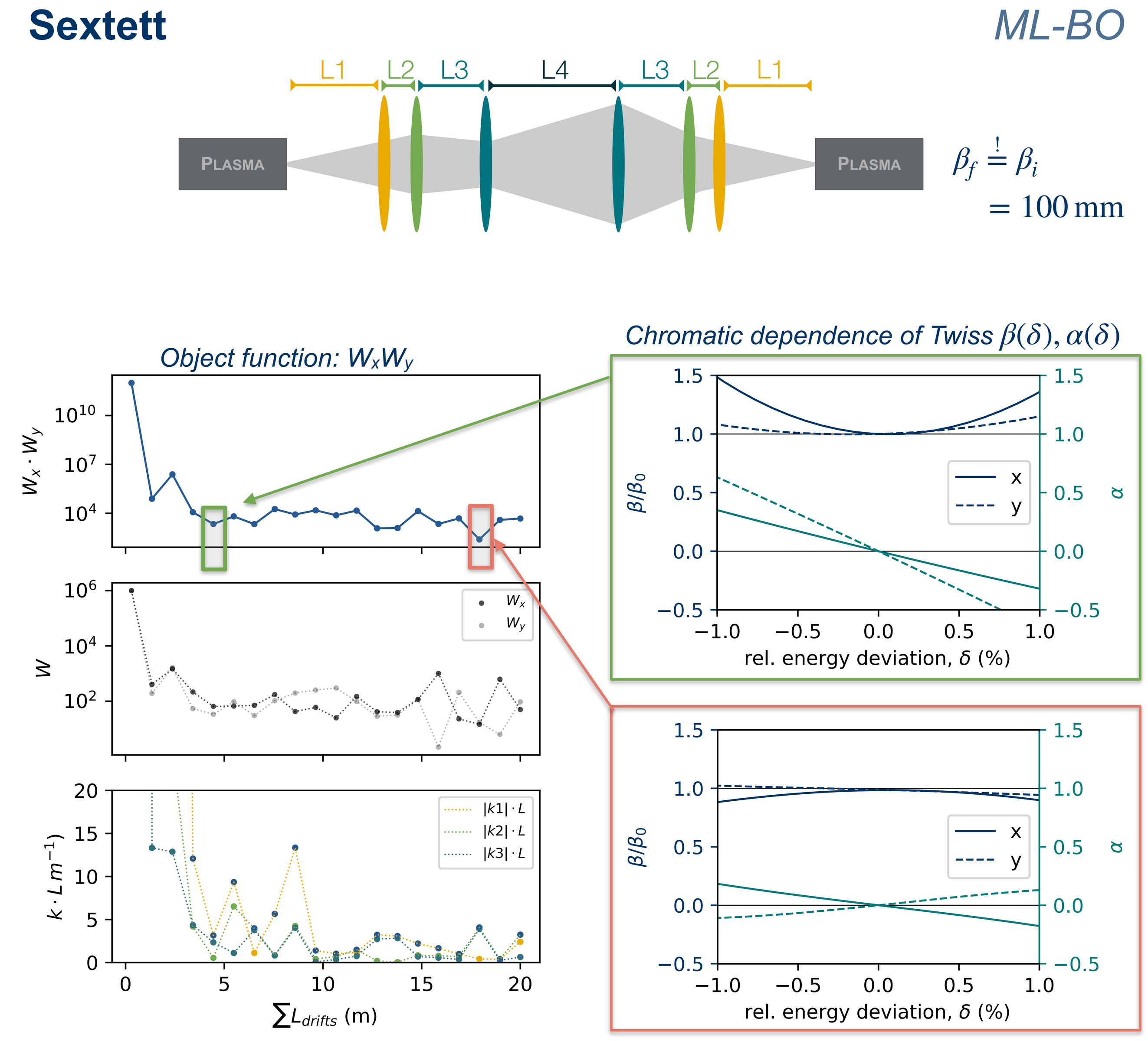
Triplet — *Numeric*



> Reduced demand in kL
> Enabeling 1:1 imaging in x and y
> Reduced comatic amplitude

[ocelot] https://github.com/ocelot-collab/ocelot

Sextett — *ML-BO*



[optimas] A. Ferran Pousa, et al. Phys. Rev. Accel. Beams 26 (2023)
S. Hudson et al., IEEE Transactions on Parallel and Distributed Systems (2022)

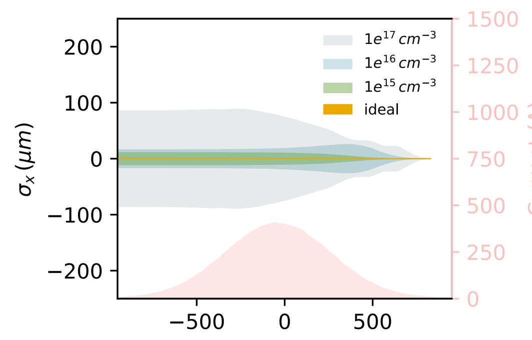
Plasma lens

> Exceptional focusing strength (kT/m)
> Axisymmetric focusing in single device
> Emittance degradation through wake excitation

$$\varepsilon^2 = \varepsilon_0^2 + \frac{\hat{H}}{45}\frac{I_b^2}{I_A^2}\left(k_p L_b\right)^4 L_c^2$$

J. van Tilborg et al., Phys. Plasmas 25, (2018)
C. A. Lindstrøm arXiv:1802.02750 (2018)

> Chromatic focus



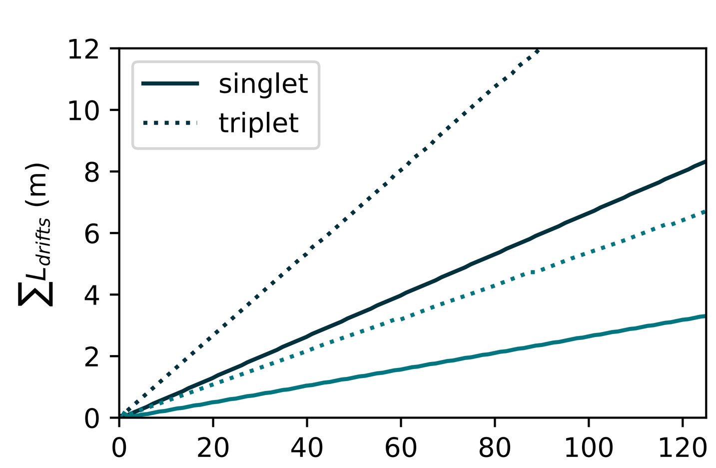
[Wake-T] A. Ferran Pousa, et al.J. Phys.: Conf. Ser. ***1350*** *012056 (2019)*

Scaling of coupling length with energy

Two maxmimal integrated field strengths are examined:

$G \cdot L = 200$ T
≙ 2 kT/m, 10 cm
≙ 200 T/m, 1 m

$G \cdot L = 500$ T
≙ 500 T/m, 1 m



Conclusion

> A systematic first-principle comparison of focusing systems showcases the complexity of the optimisation.

> ML is poised to take on the multi-dimensional optimisation.

> The development of advanced apochromatic high-gradient focusing stages is key to achieve the tight focusing requirements in a compact manner.

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