Optimizing Plasma-Downramp Profiles and Beam Transport for Emittance Preservation in Multi-Stage Plasma Accelerators

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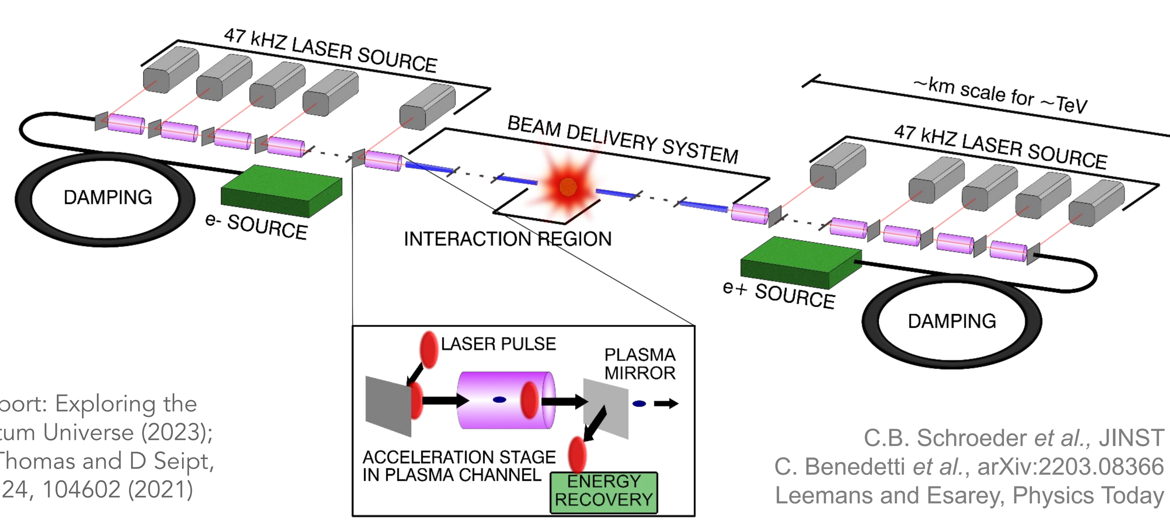
Simulations for Design of Next-Gen Colliders



P5 Report: Exploring the Quantum Universe (2023); AGR Thomas and D Seipt, PRAB 24, 104602 (2021)

C.B. Schroeder *et al.*, JINST (2023)
C. Benedetti *et al.*, arXiv:2203.08366 (2022)
Leemans and Esarey, Physics Today (2009)

- Designing a 10 TeV pCoM collider is a **complex task**
- HEP community expects **robust start-to-end designs** before construction
- **Modeling**: first exploratory LPA elements, now **operation in beamlines**
- Exploration & optimization **workflows**: params **depend on previous stage**

Preservation of Beam Quality is Challenged by Chromatic Emittance Growth

Realistic inter-stage transport lengths complicate things!

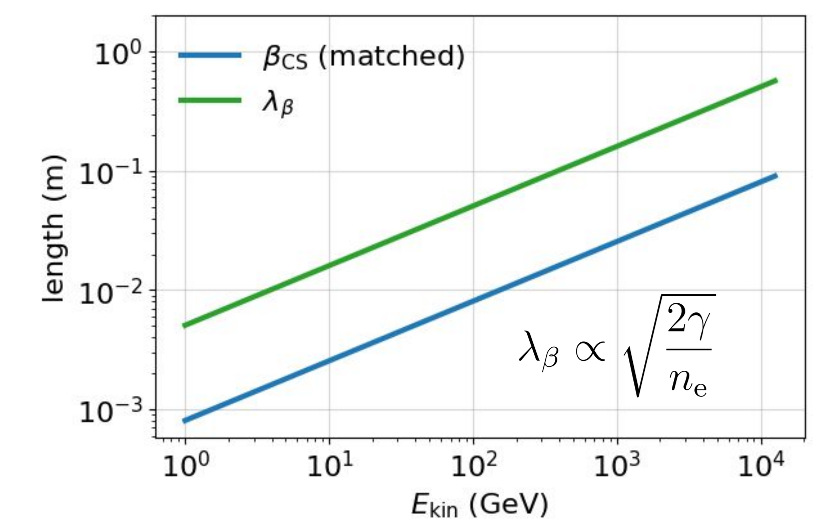
→ energy spread, matching, space charge effects

Emittance growth from chromaticity in drifts [1, 2]:

$$\Delta\epsilon = \left(\frac{\epsilon_0}{\sigma_0}\right)^2 \frac{\sigma_\gamma}{\gamma_0}\frac{s}{\gamma_0}$$

- ϵ_0 .. transverse emittance
- σ_0 .. transverse beam size
- σ_γ .. energy spread
- γ_0 .. Lorentz factor
- s .. drift distance

$$\beta_{\mathrm{matched}} = \frac{\lambda_\beta}{2\pi} = \frac{\sqrt{2\gamma}}{k_p}$$



Exit ramps can address the issue!

→ expand beam size, preserving emittance (if $k_p L_d \gtrsim 1$): **ϵ_0/σ_0 decreases!**

⇒ However, compactness is challenging

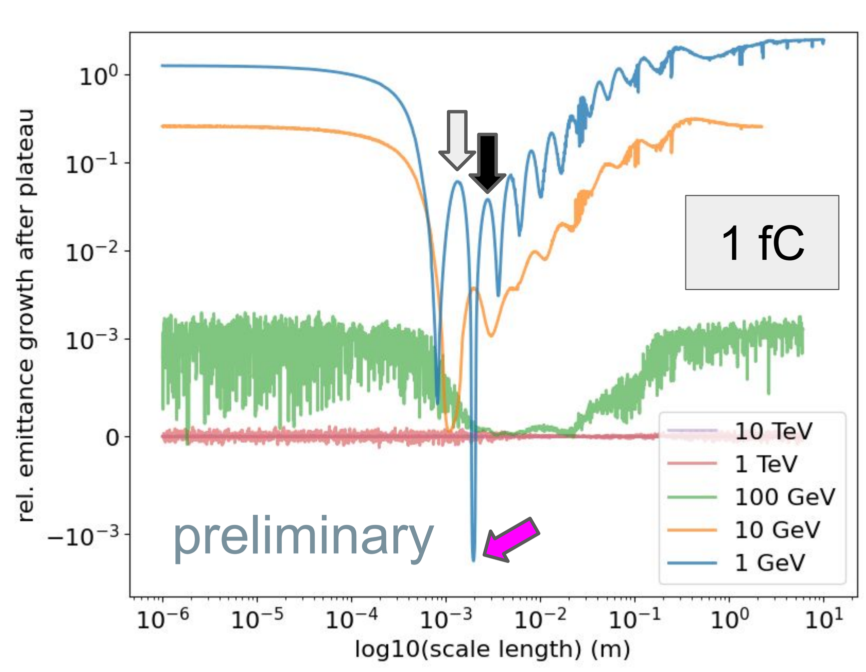
- Ramps become (too) long at high energy
- Development of a(po)chromatic focusing optics required [3]

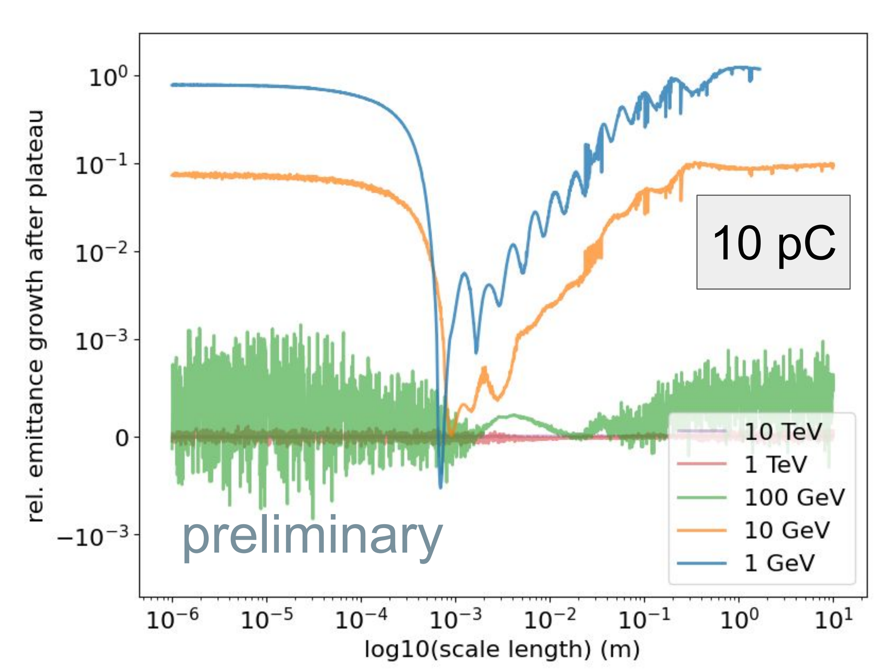
[1] P. Antici *et al.*, JAP (2012), [2] M. Migliorati *et al.*, PRAB(2013)

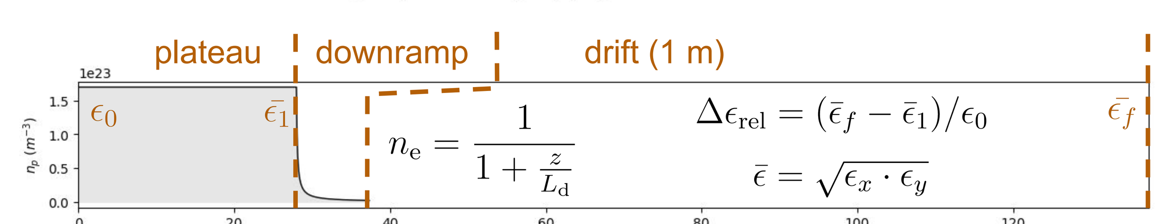
[3] C. Lindstrøm *et al.*, PRAB (2021)

Fast-turnaround optimization studies revealed that **chromatic emittance growth** during simplified **inter-stage transport** can be **strongly decreased** through **tailored plasma downramps.**

Emittance Preservation via Tailored Density Ramps



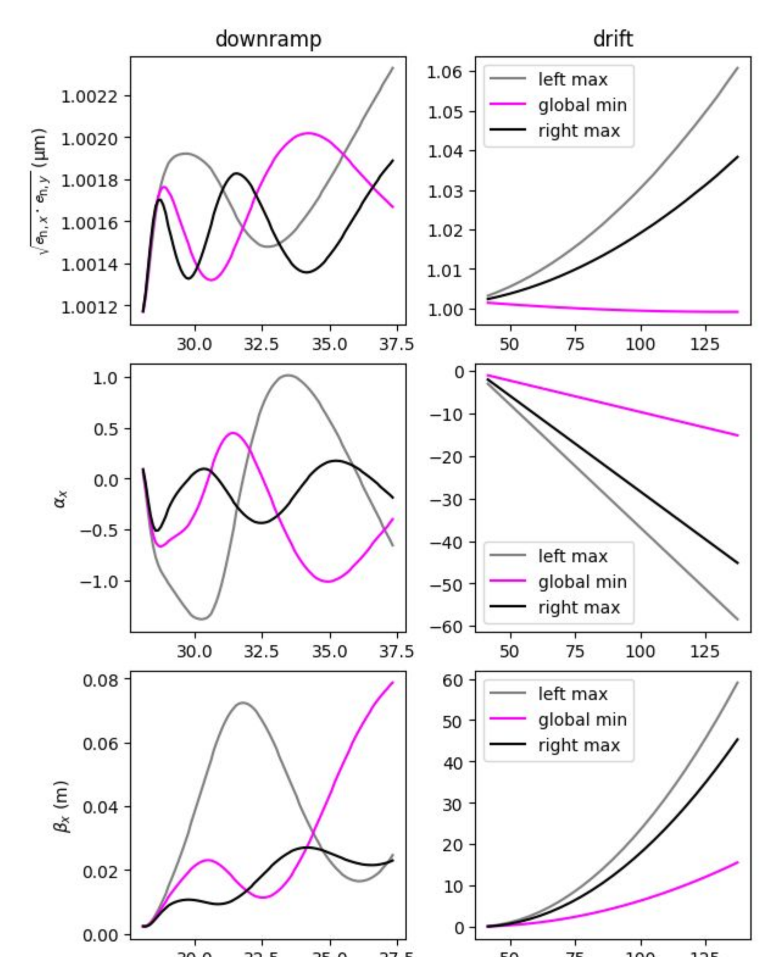




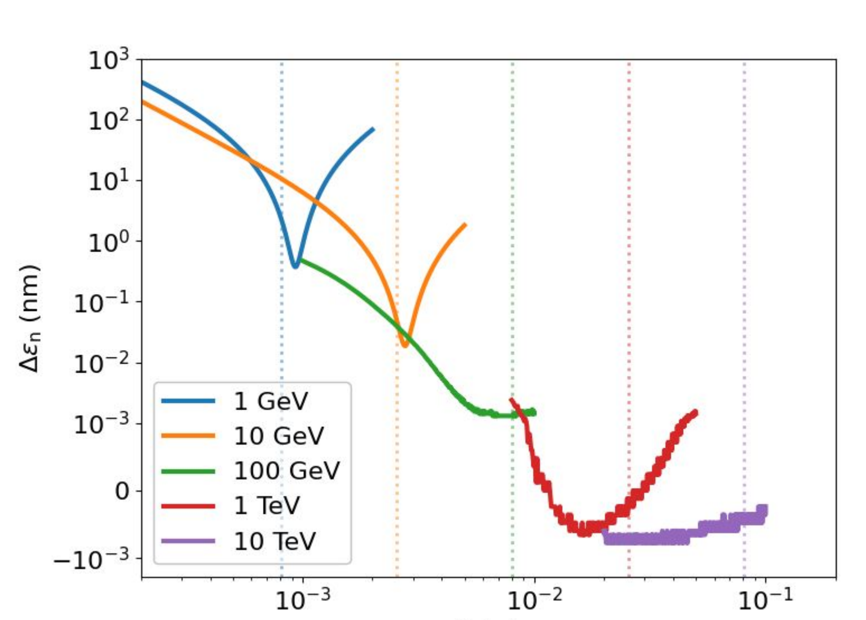
$$n_e = \frac{1}{1+\frac{z}{L_d}} \qquad \Delta\epsilon_{\mathrm{rel}} = (\bar{\epsilon}_f - \bar{\epsilon}_1)/\epsilon_0 \qquad \bar{\epsilon} = \sqrt{\epsilon_x \cdot \epsilon_y}$$

2048 simulations each
laser a_0 = 2.36, w_0 = 36e-6
n_p = 1.7e23 m^-3
parabolic guiding channel
28 cm plasma stage, 9.33 cm downramp,
1m drift, $\epsilon_{n,0}$ = 1 μm

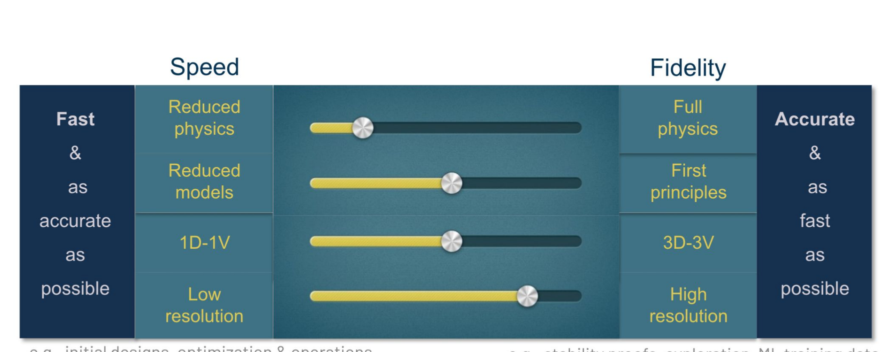
BLAST · WakeT · optimas · libEnsemble · Perlmutter



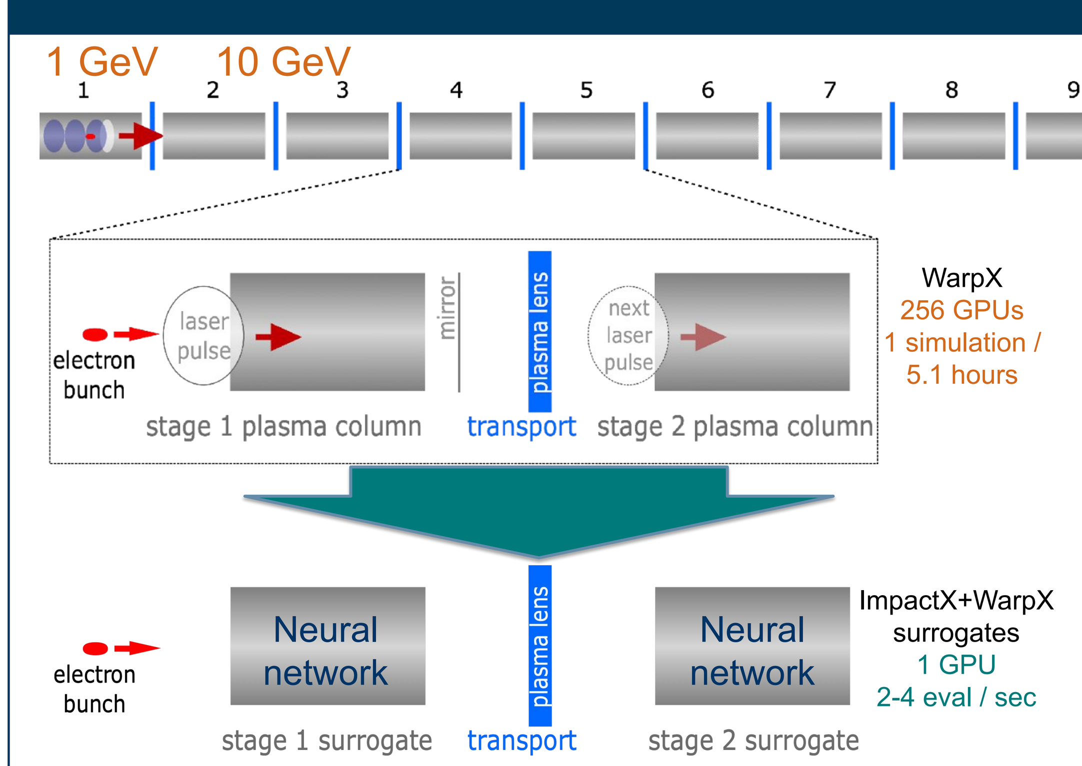
- Beam expansion faster than adiabatic matching
- Plasma cutoff at right betatron phase



- Matching beta-function to partially blown-out plasma accelerator cavity



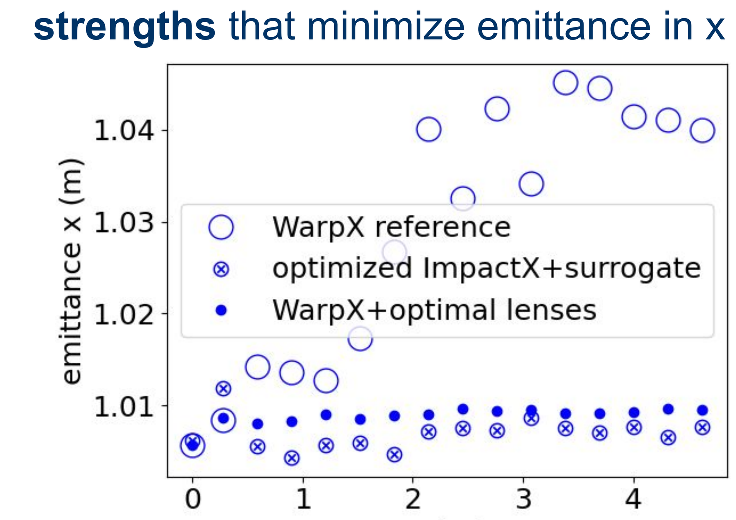
ML Optimization of Simplified Transport Parameters



Awarded PASC'24 Best Paper - R. Sandberg et al., *Synthesizing Particle-In-Cell Simulations through Learning and GPU Computing for Hybrid Particle Accelerator Beamlines*

Open challenge: ML workflow for space-charge beam w/ collective effects

Optimization for **lens positions** and **strengths** that minimize emittance in x



- Optimization: 100s-1000s of iterations
- Before: optimization workflow > 100,000 GPU hours
- After: optimization workflow ~ 1-3 GPU hours

Summary & Conclusions

- **Emittance growth reduced by several orders of magnitude as opposed to sharp density cutoff for all energy ranges up to ~TeV**
- **Optimum ramp scale length appears to grow with beam energy**
- **Scale length can be shorter than predicted by adiabatic matching**
- **Sensitivity to scale length drops with lower emittance growth for higher energies**
- **Combination of low- and high-fidelity codes, and ML methods for surrogate models make BLAST suite a powerful toolbox for collider design studies**

Outlook

- Optimize **upramps** and plasma lenses / **apochromatic transport**
- Include **beam-loading** (100s of pC) and repeat studies
- Reproduce in **high-fidelity** (3D WarpX), and continue to train surrogate models
- Refine **workflows** for full accelerator chain and enable quick configuration changes

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