(some) Theory and simulation related challenges for particle physics (plasma colliders)

J. Vieira, expert panel advanced accelerators

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Acknowledgements

Contributions from theory/simulation talks from previous expert panel town-hall meeting

A. Beck, R.A. Fonseca, M. Thévenet, J.-L. Vay

Also contributions from our

expert panel on advanced accelerators

our **community**

What are the requirements for a particle physics collider?

Parameter	Units	CLIC-like (e-/e+)	ILC-like (e-/e+)
bunch charge	pC	833	3200
polarization	-	80% e-	80% e- / 30% e+
initial energy	GeV	**175**	**235**
final energy	GeV	**190**	**250**
initial relative energy spread	%	0,6	1
final relative energy spread	%	0,35	0,1
initial bunch length	µm	70	300
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initial normalized emittance H/V	µm / nm	0.890 / 19	9.5 / 25
emittance growth budget H/V	µm / nm	0.010 / 1	0.5 / 5
final normalized emittance H/V	µm / nm	0.900 / 20	10 / 30
bunch separation	ns	0,5	554
number of bunches per train	-	352	1312
rep rate	Hz	50	5
beamline length	m	250	600
Efficiency: wall-plug to drive beam	%	58	-
Efficiency: drive beam to main beam	%	22	-
Luminosity	10^34 cm-2 s-1	1,5	1,8

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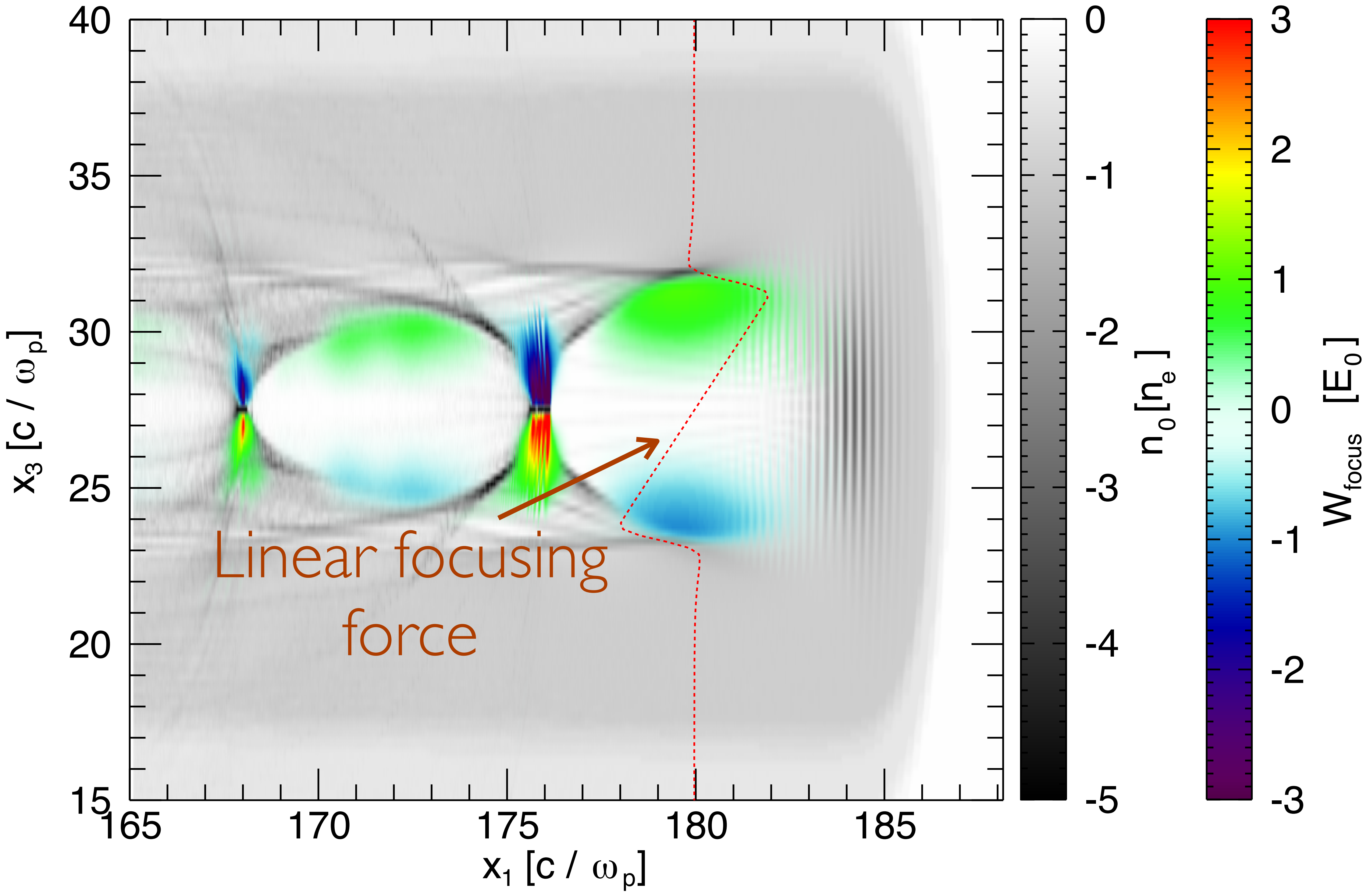
- Can we do it?

Emittance preservation in linear focusing force

Laser wakefields in blowout regime



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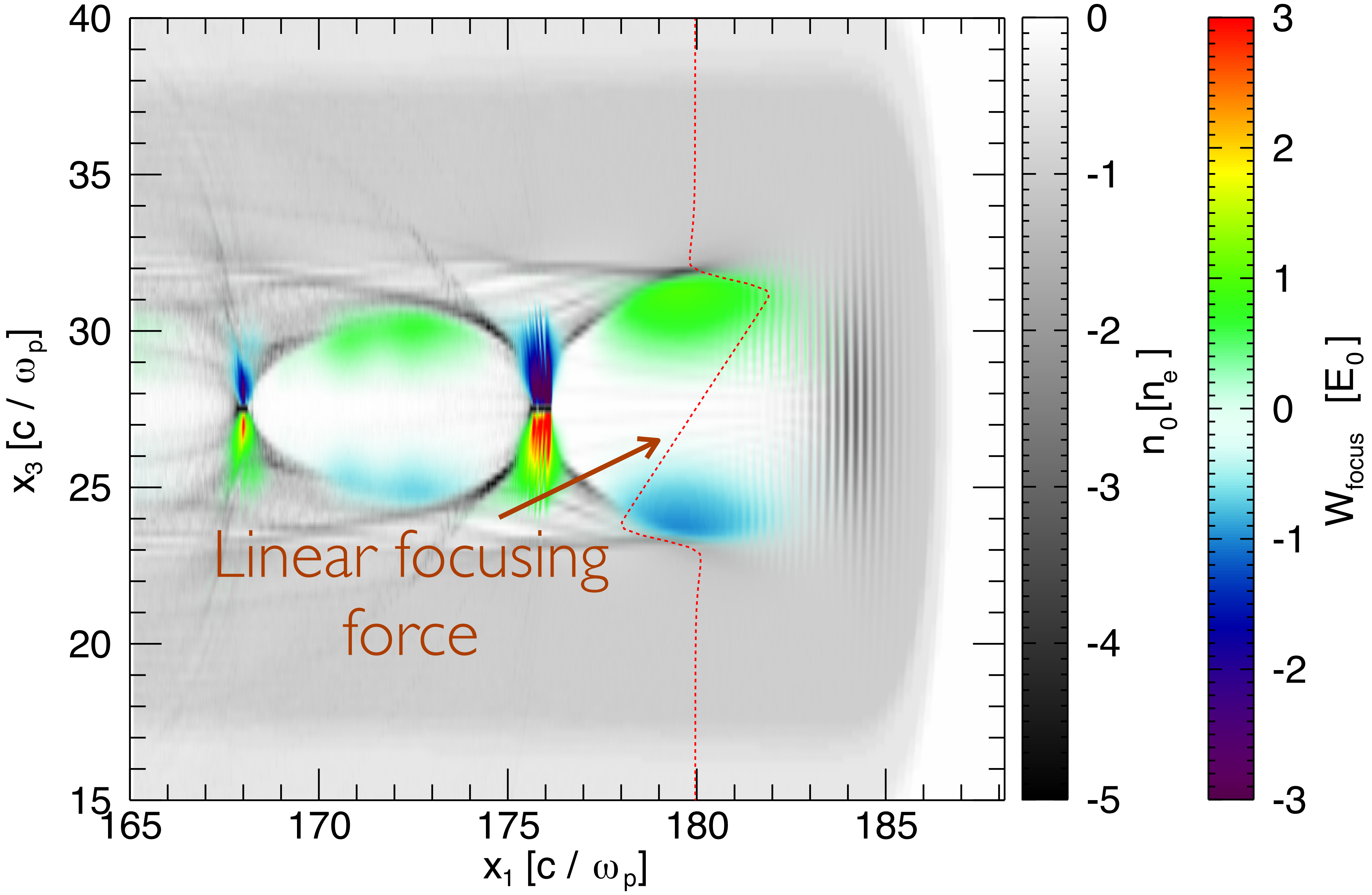

Witness beam matching condition

normalised emittance

$$\sigma_\perp = \frac{1}{k_p^{1/2}}\left(\frac{2\epsilon_n^2}{\gamma}\right)^{1/4}$$

transverse size

relativistic factor

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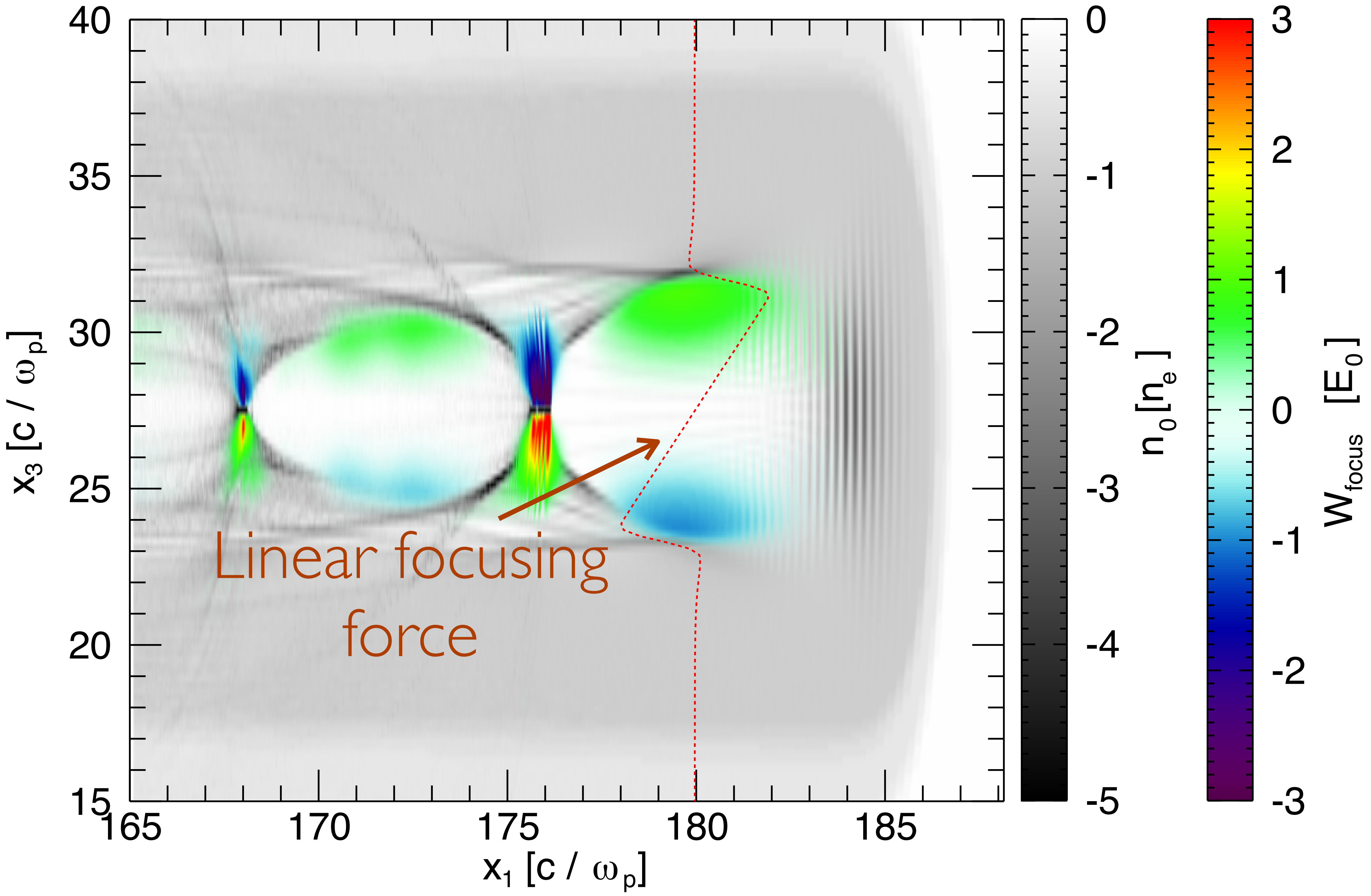

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E_{accel}

100 GeV/m

n_0

$10^{18}\ \mathrm{cm}^{-3}$

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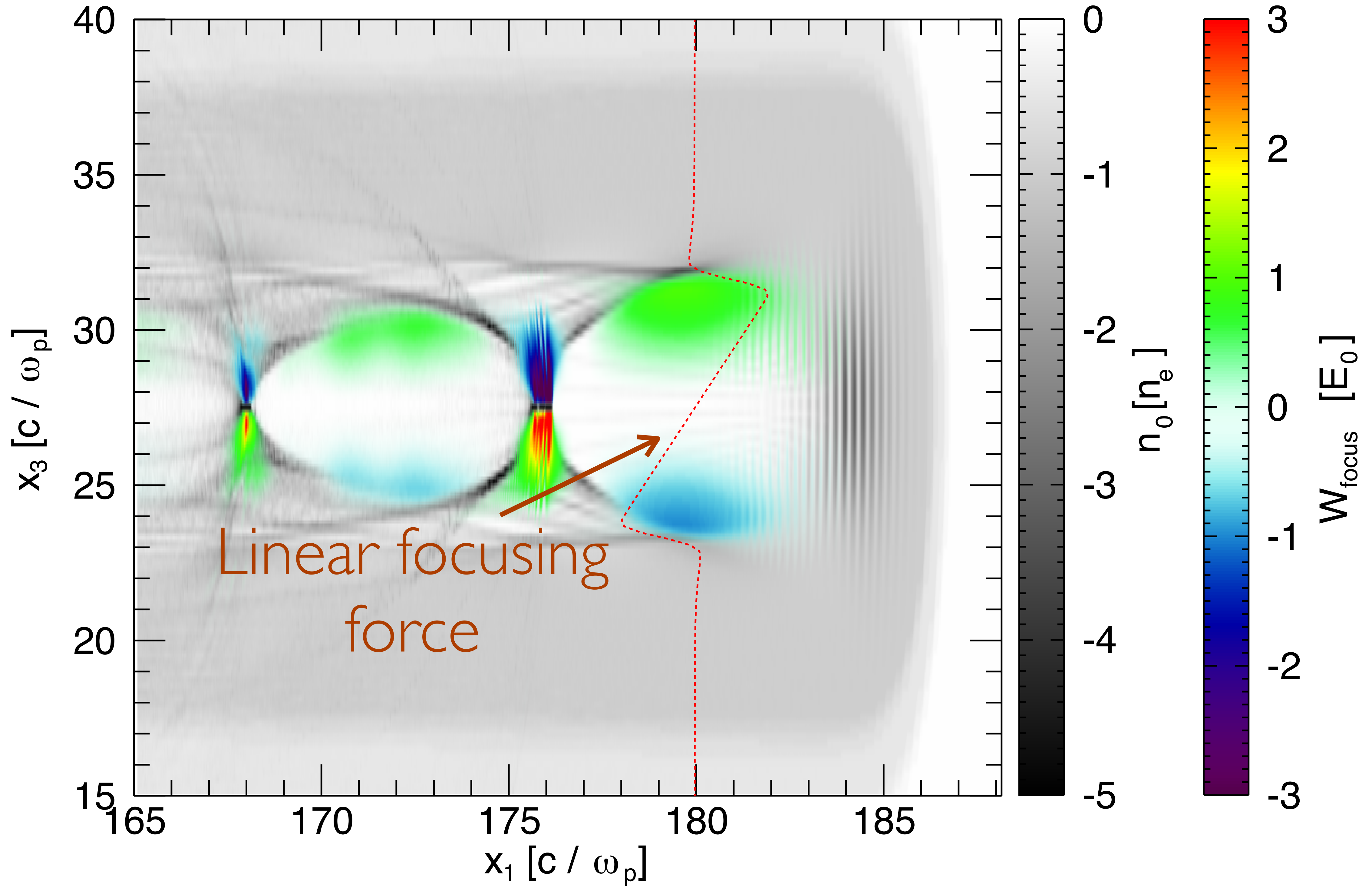

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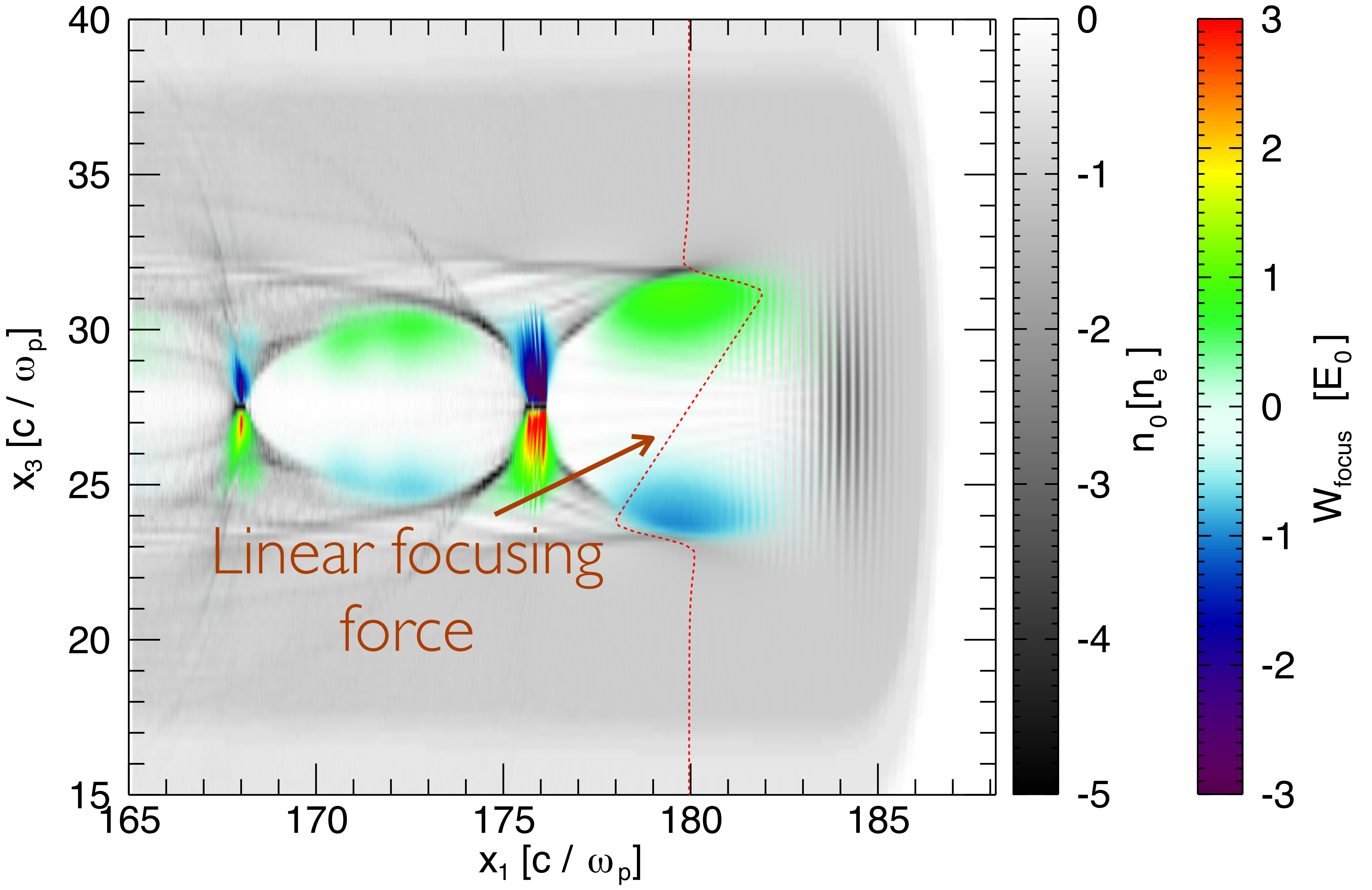

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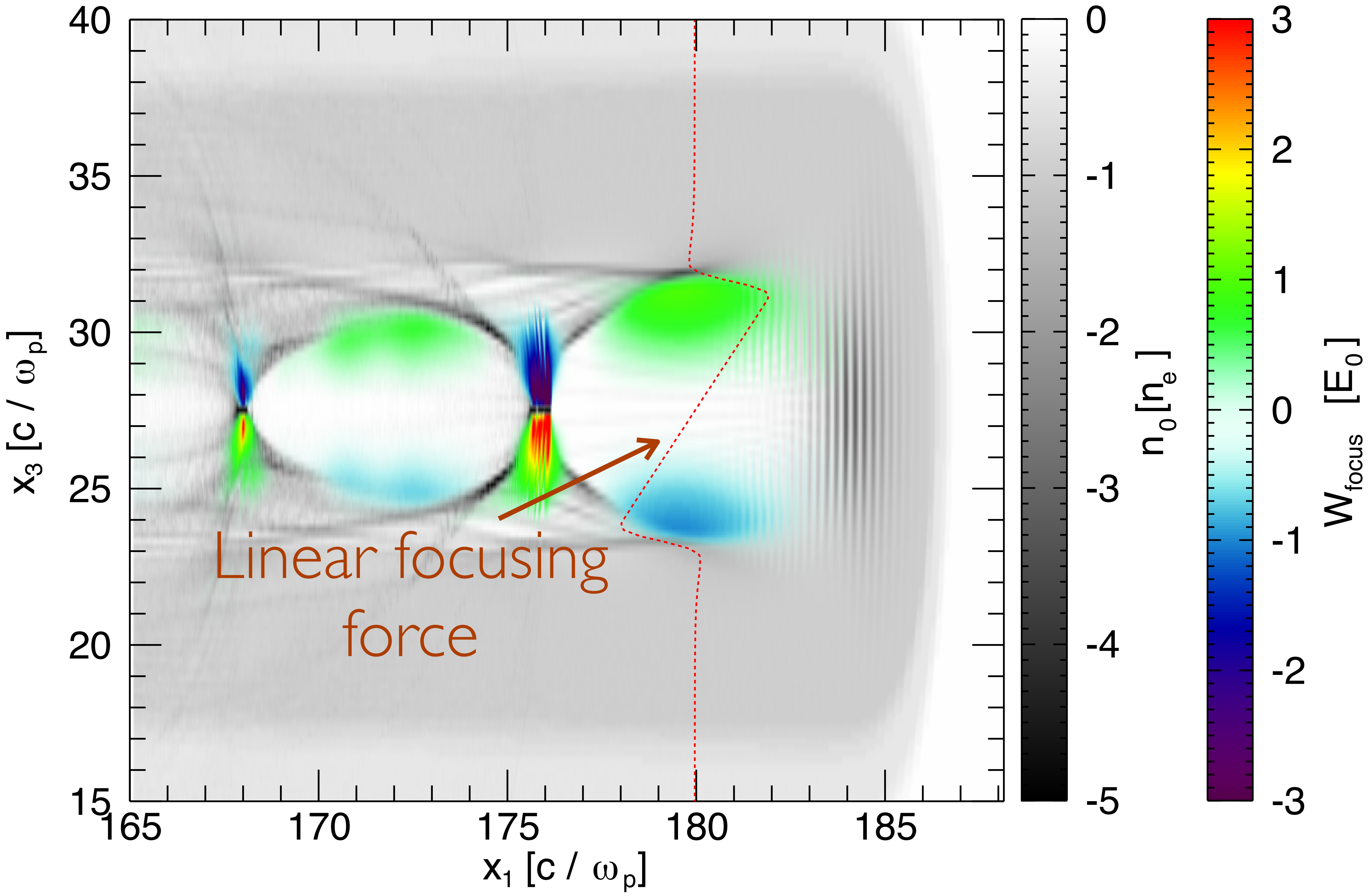

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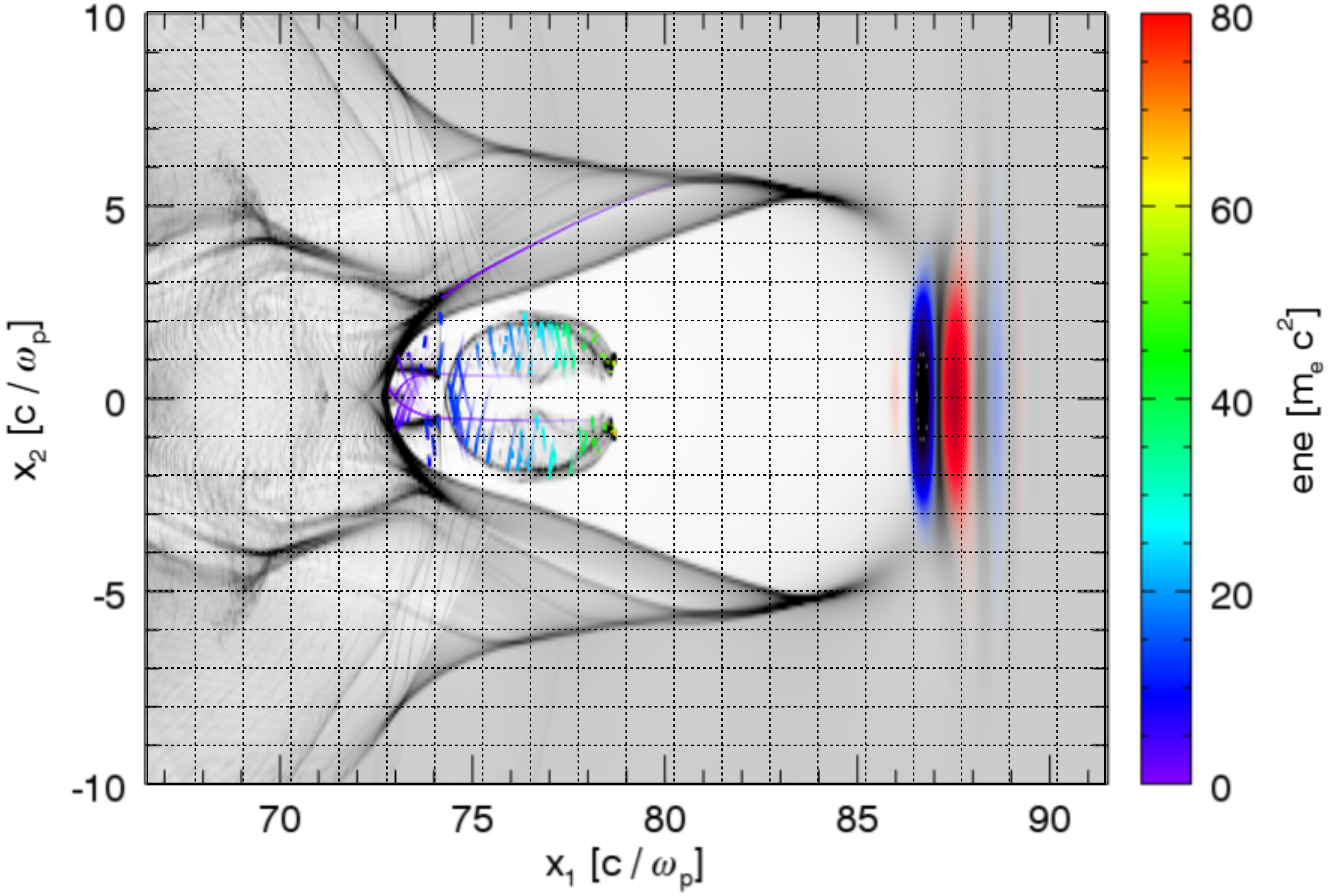

Typical cell sizes in most (*not all!*) published results

- Longitudinal $\Delta x_{||} \propto \lambda_L$
- Transverse $\Delta x_{\perp} \propto \lambda_p$

cells (order of magnitude)
1000x100x100

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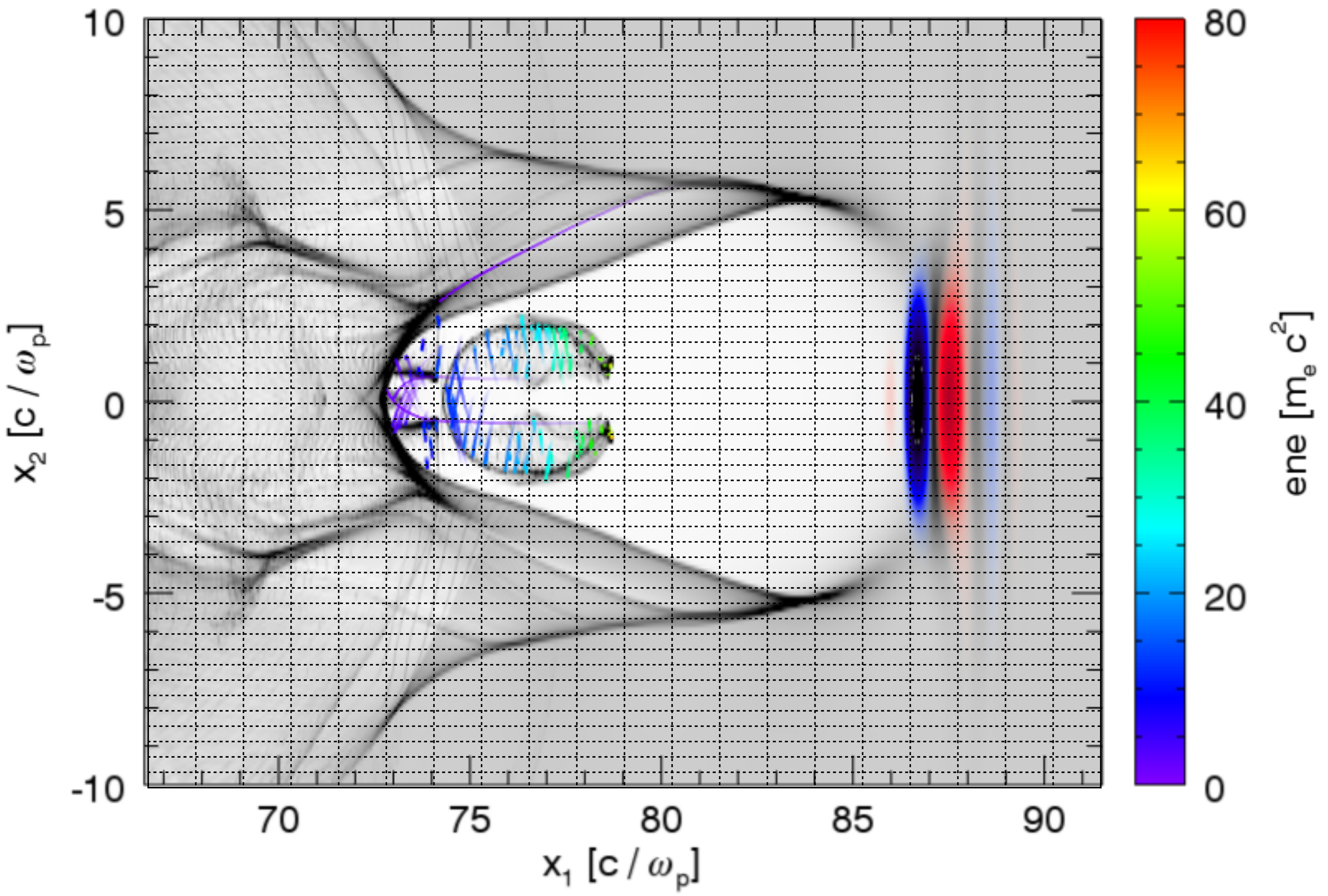

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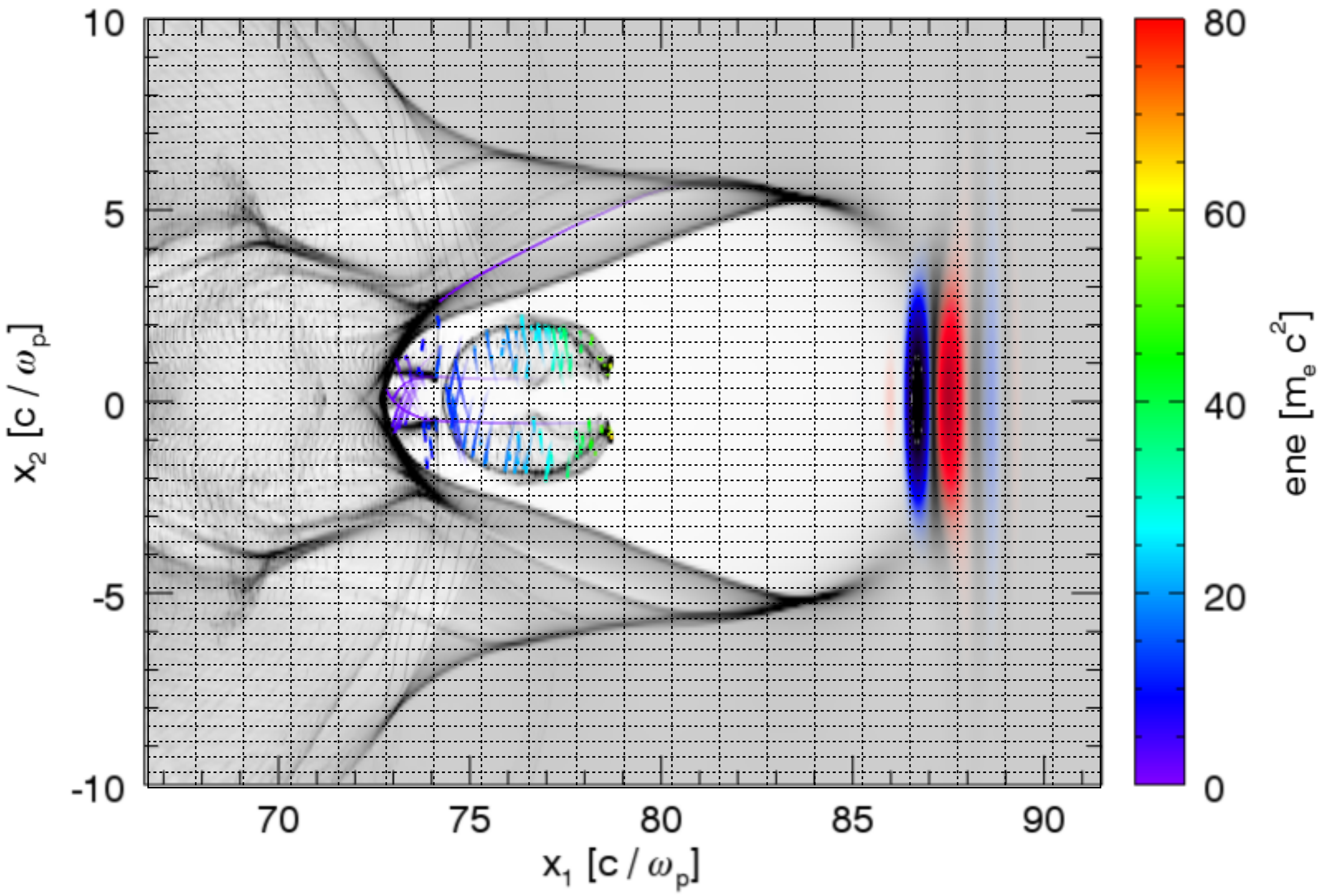

Resources are critical! **Community** based effort!

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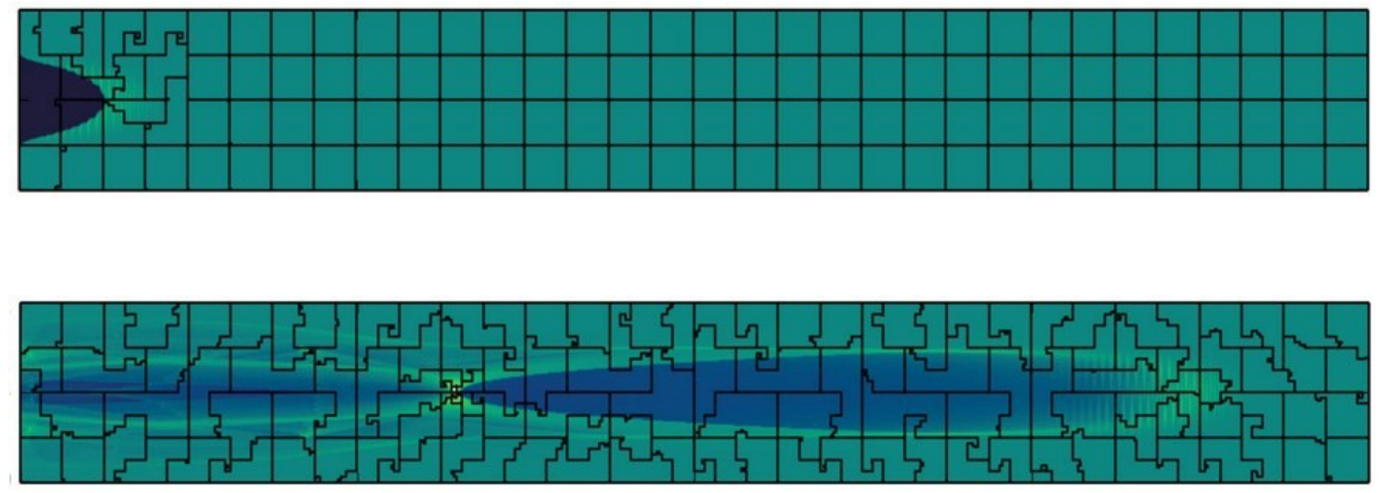
Computational developments

Efficiency

Parallel efficiency, domain decomposition, AMR, CPU, GPU, ML/AI, …



Courtesy A. Beck

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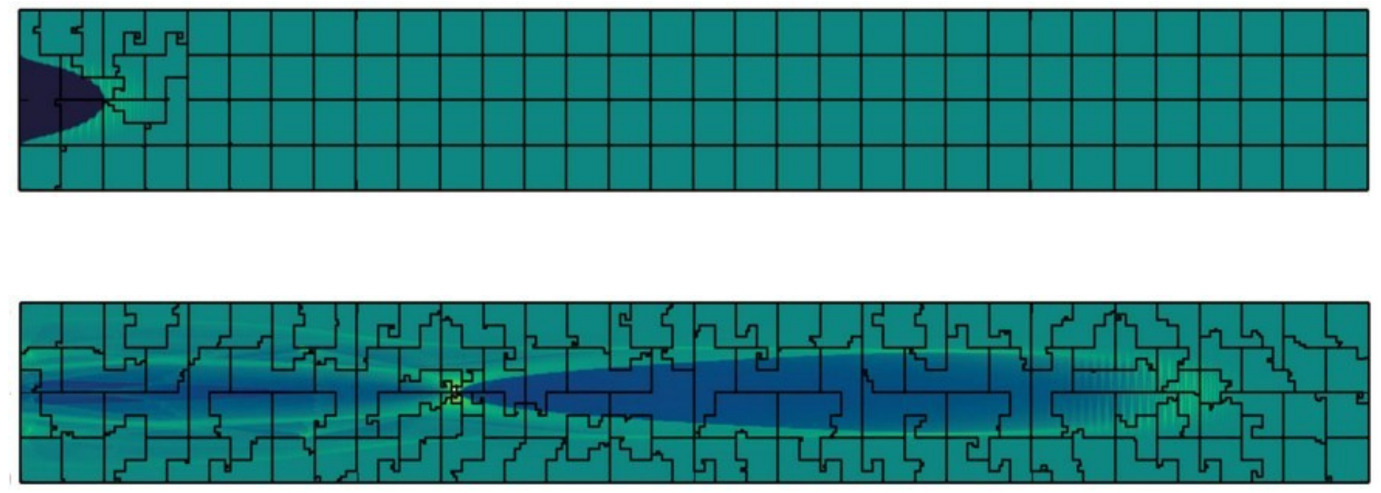

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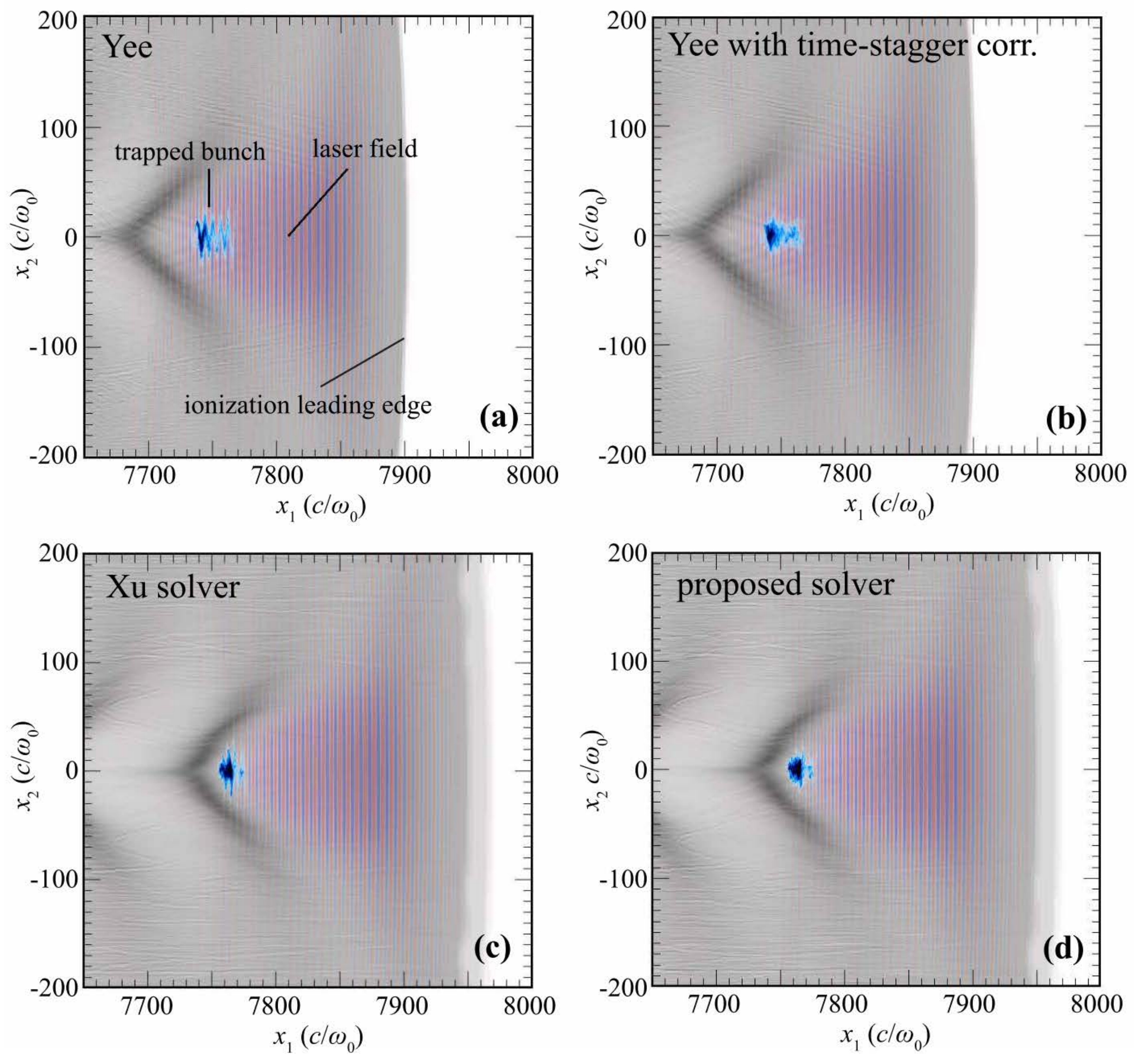
Accuracy

Control/suppress numerical instabilities, correct dispersion, accurate particle pushers,…



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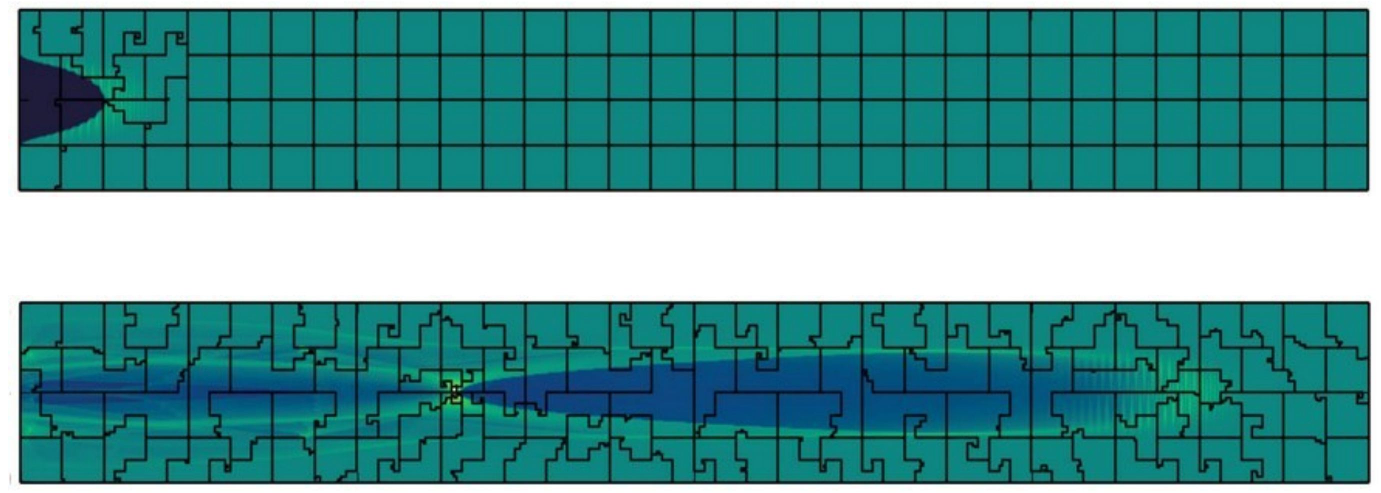

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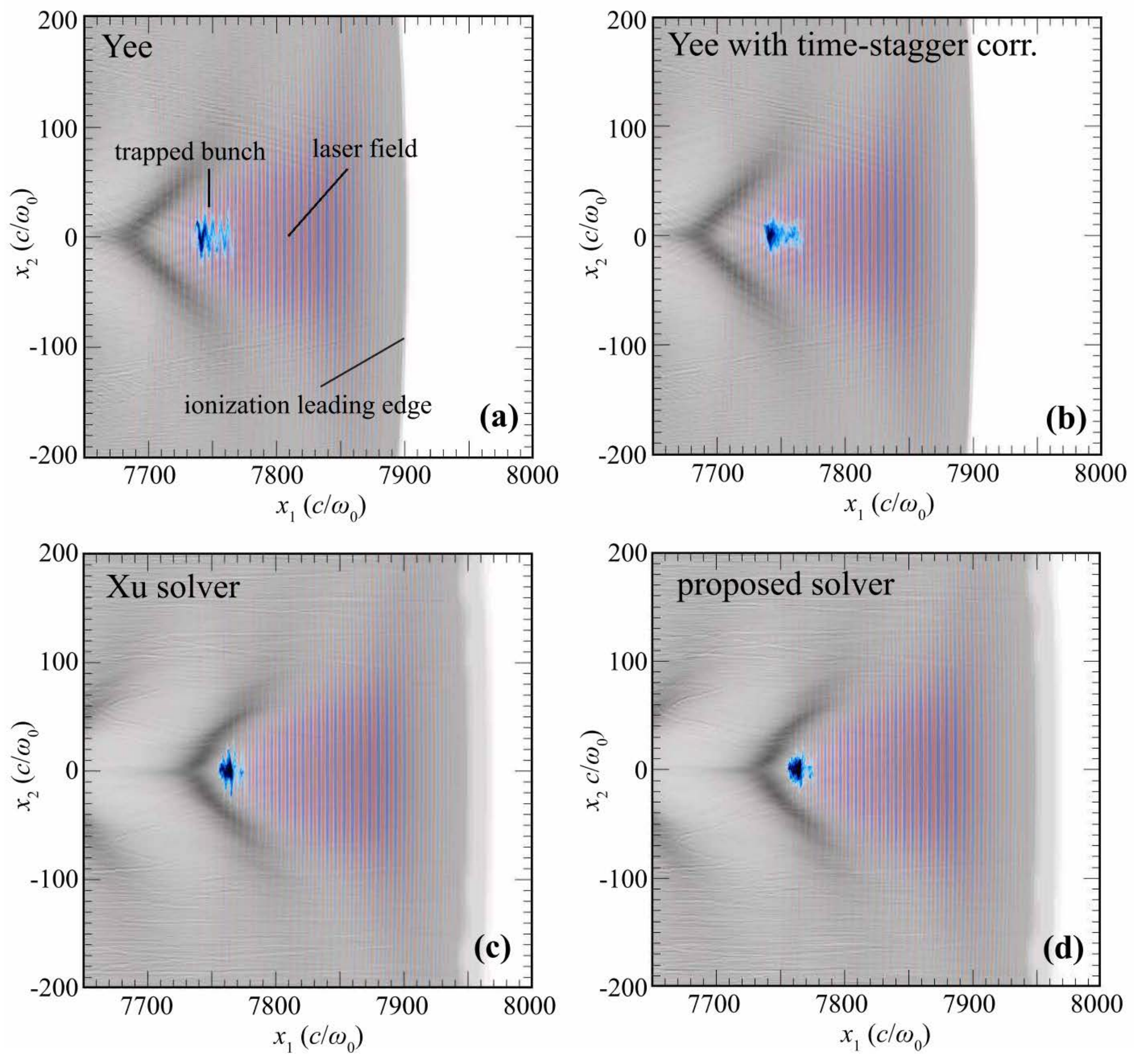

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Multi-physics

Hydrodynamics, MHD, radiation reaction, spin, disruption, …

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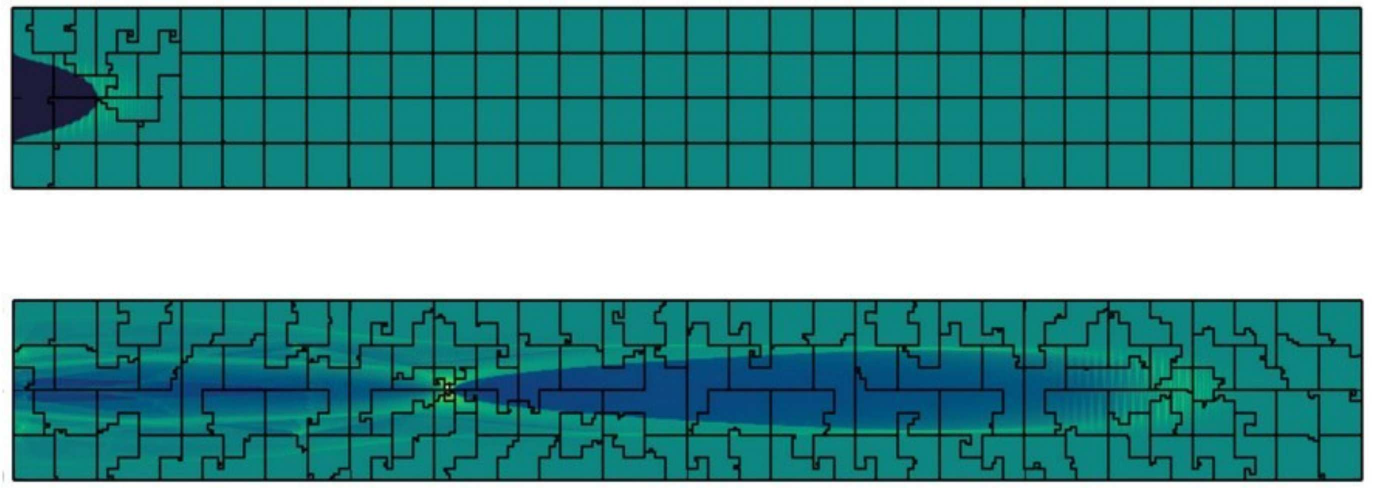

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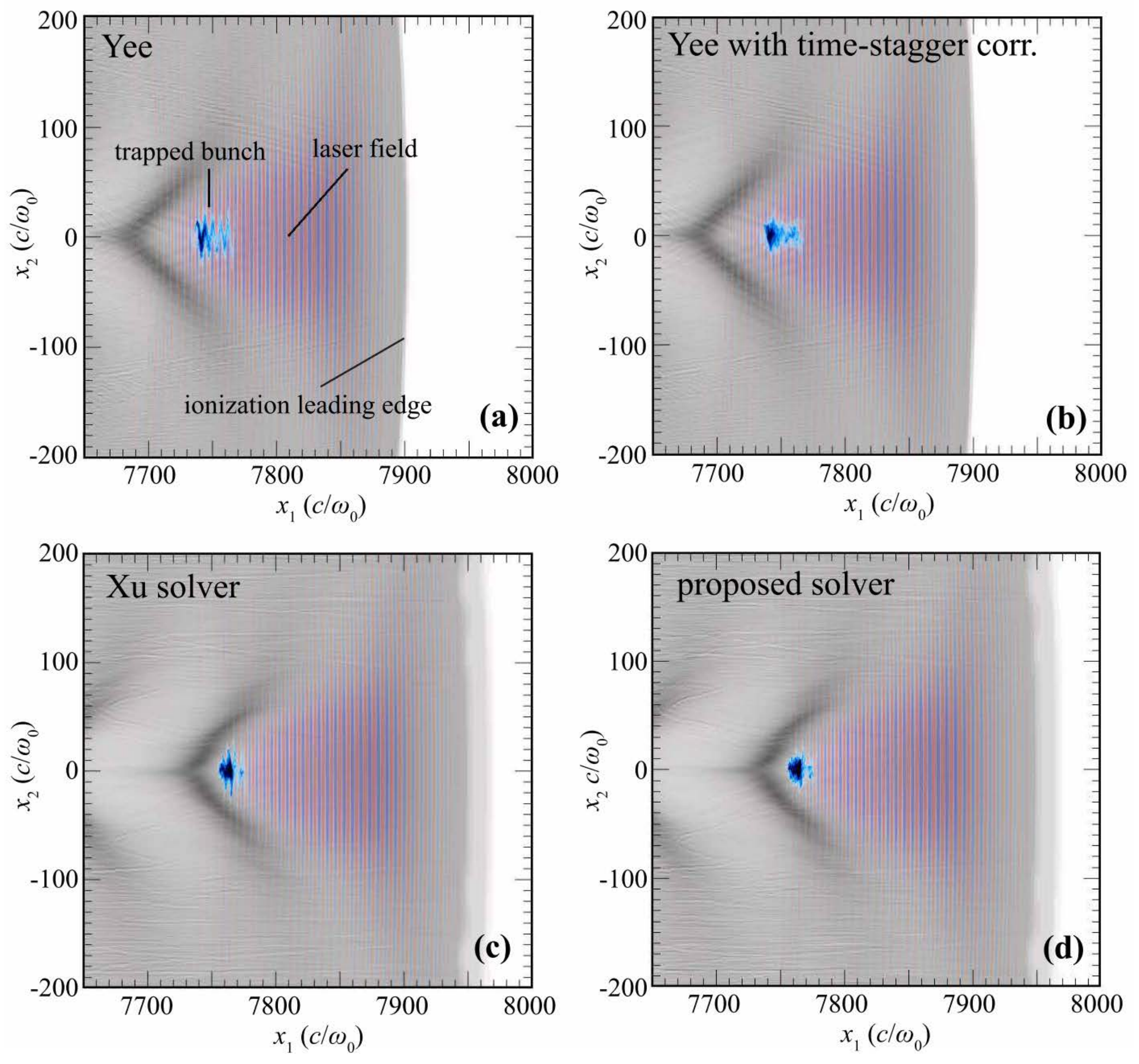

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openPMD

Platform for multi-code cross-talk and benchmark

Courtesy M. Thévenet

Physics challenges

Figures of merit		
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Extreme conditions

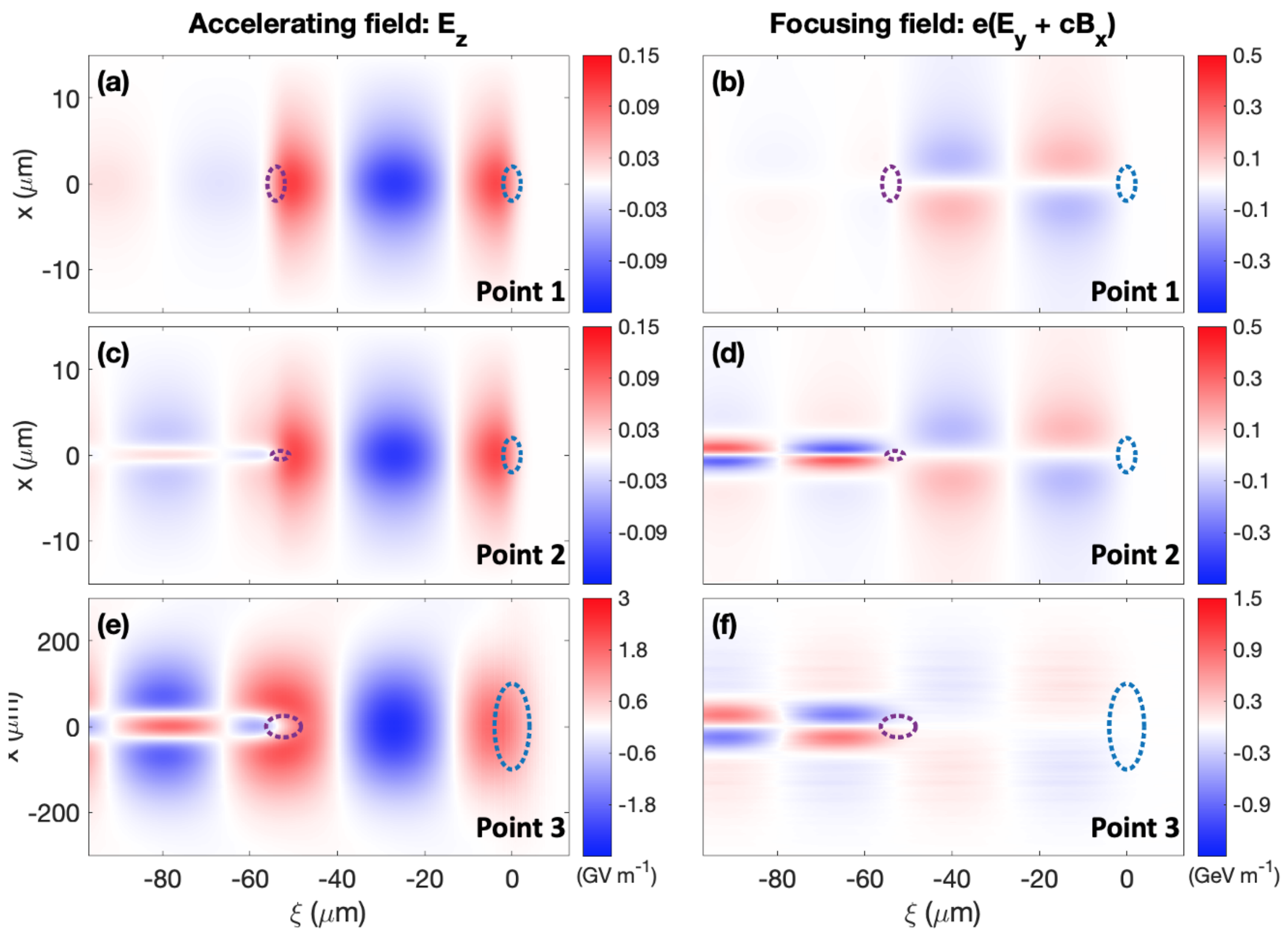
emittance preservation and **acceleration** under **extreme** witness bunch densities

- electrons
- positrons
- plasma vacuum matching

Positron acceleration

Positron acceleration schemes

Hollow channels, linear/mildly nonlinear regime, doughnut wakefields, …



example in linear regime
C.S. Hue *et al.* arXiv 2107.01145v1 (2021)

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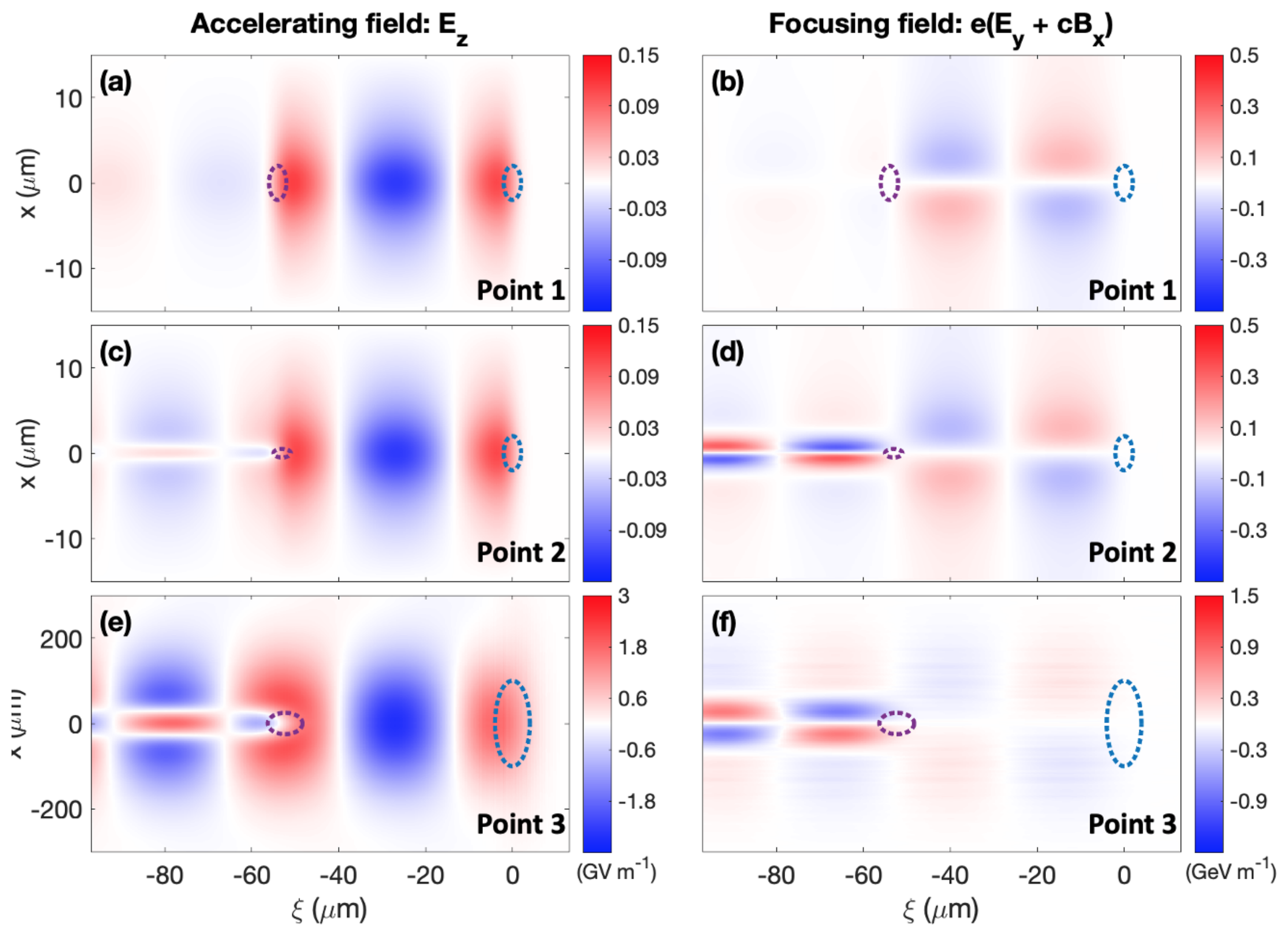

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New (?) questions?

Explore positron acceleration under **extreme** conditions

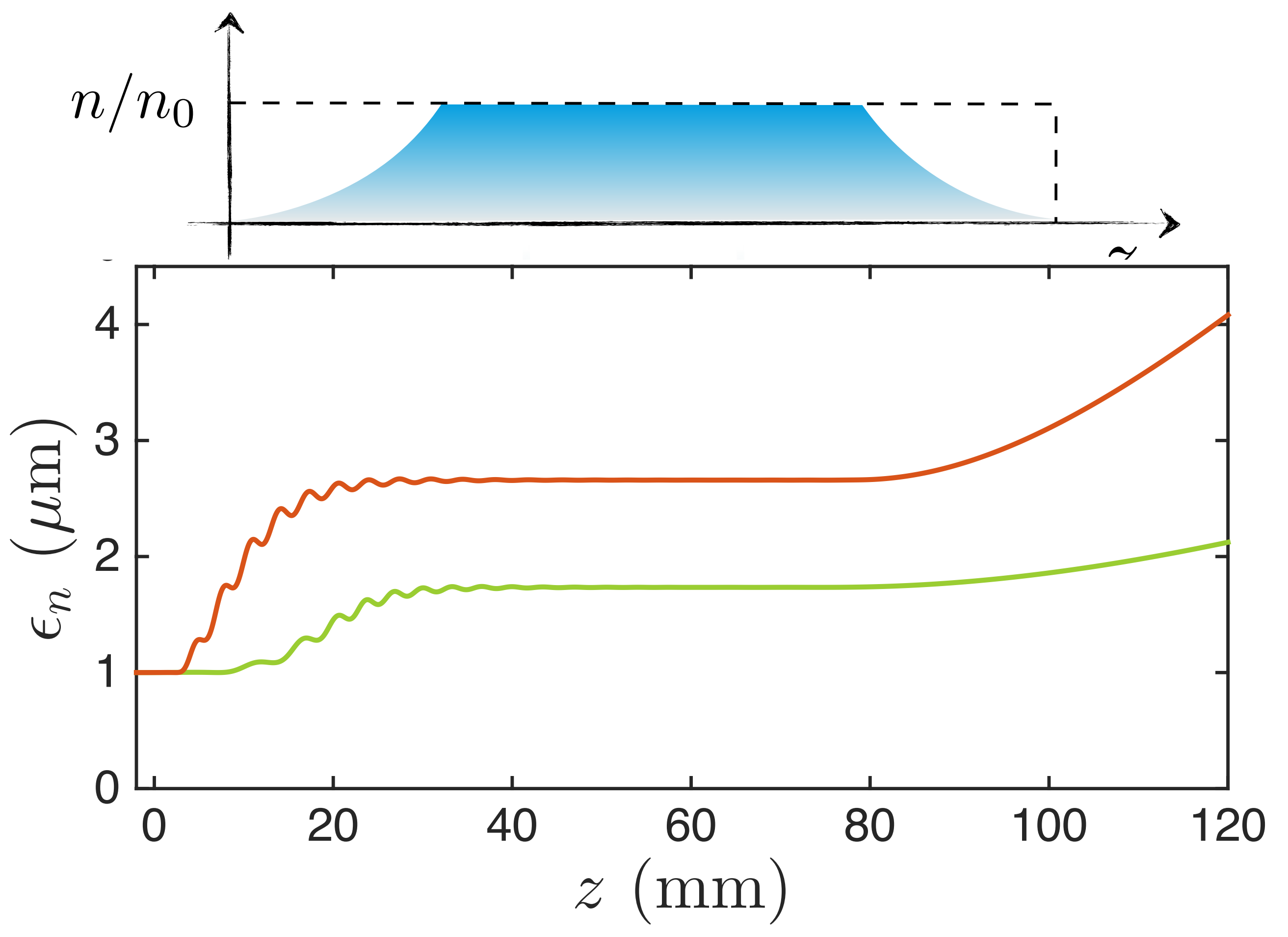
- Acceleration in linear regime: still possible?
- Ion motion: maybe beneficial for positrons?

Electron and positron acceleration under extreme conditions

Emittance preservation - plasma to vacuum transitions

Tailored plasmas and beams

T. Mehrling *et al*, ALEGRO 2018 workshop



Will these schemes hold under extreme conditions and in the possible presence of ion motion?

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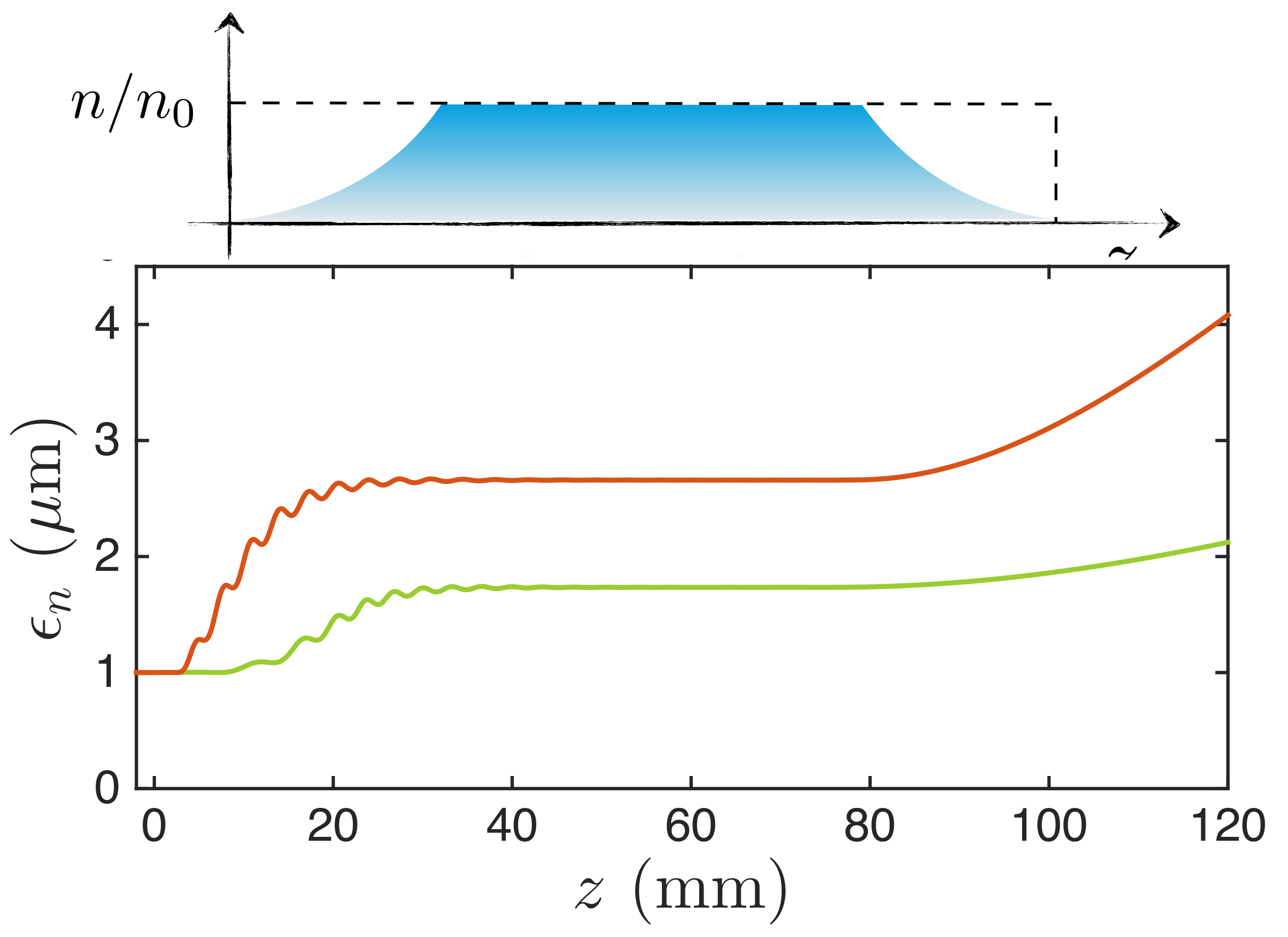

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Other key questions

- Hosing
- Asymmetric beams
- Disruption
- Spin conditioning
- Radiation reaction and synchrotron radiation
- Long term plasma dynamics
- Coupling with transport lines
- …

Conclusions and outlook

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Connection with collider physics brings new and exciting fundamental physics questions

Conclusions and outlook

- Creative field with tremendous progress in both theory and simulations
- Connection with collider physics brings new and exciting fundamental physics questions
- Prospects are exciting, and a lot of work is ahead of us to explore all we need for HEP at 100 GeV and beyond.