Simulation tools and performance for accelerator modeling

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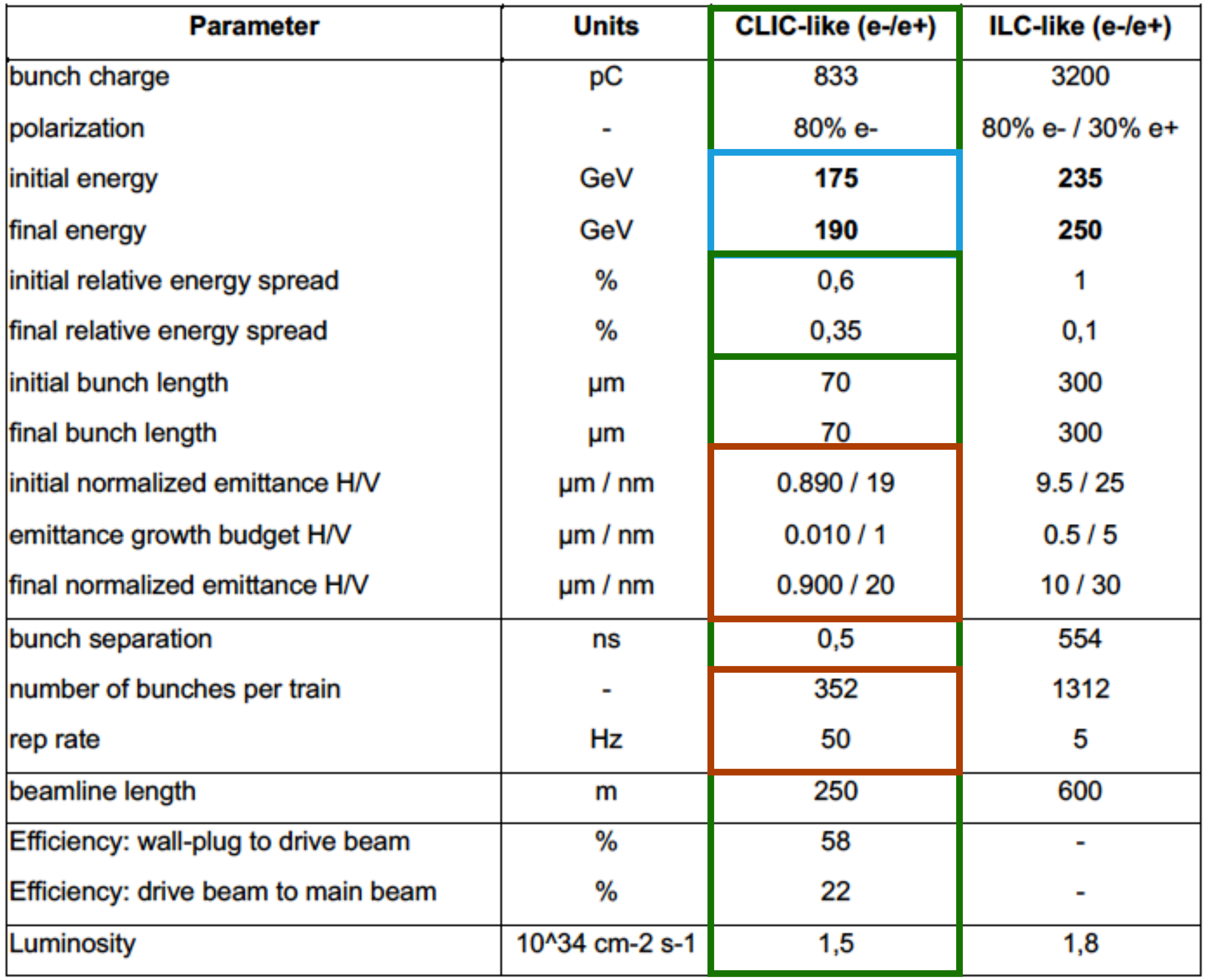
Contents

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
final bunch length	µm	70	300
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

Energy

- ✓ 15 GeV stages
- ✓ Up to 190 GeV
- ✓ High gradients have been established

Energy spread

- ✓ Recent results show we are on track
- ✓ Recent experiments demonstrated $\Delta E/E \lesssim 0.01$

Open questions

- ✳ Repetition rate $(352 \times 50\ \mathrm{Hz} \simeq 17\ \mathrm{kHz})$
- ✳ Average power ($\simeq 100\ \mathrm{MW}$)*
- ✳ Emittance ($\simeq 10\ \mathrm{nm}$) and emittance growth

Under which conditions can plasma accelerators meet HEP requirements?

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* C.B. Schroeder et al, PRSTAB 13 101301 (2010)

Contents

“First” plasma accelerator physics challenge: average power

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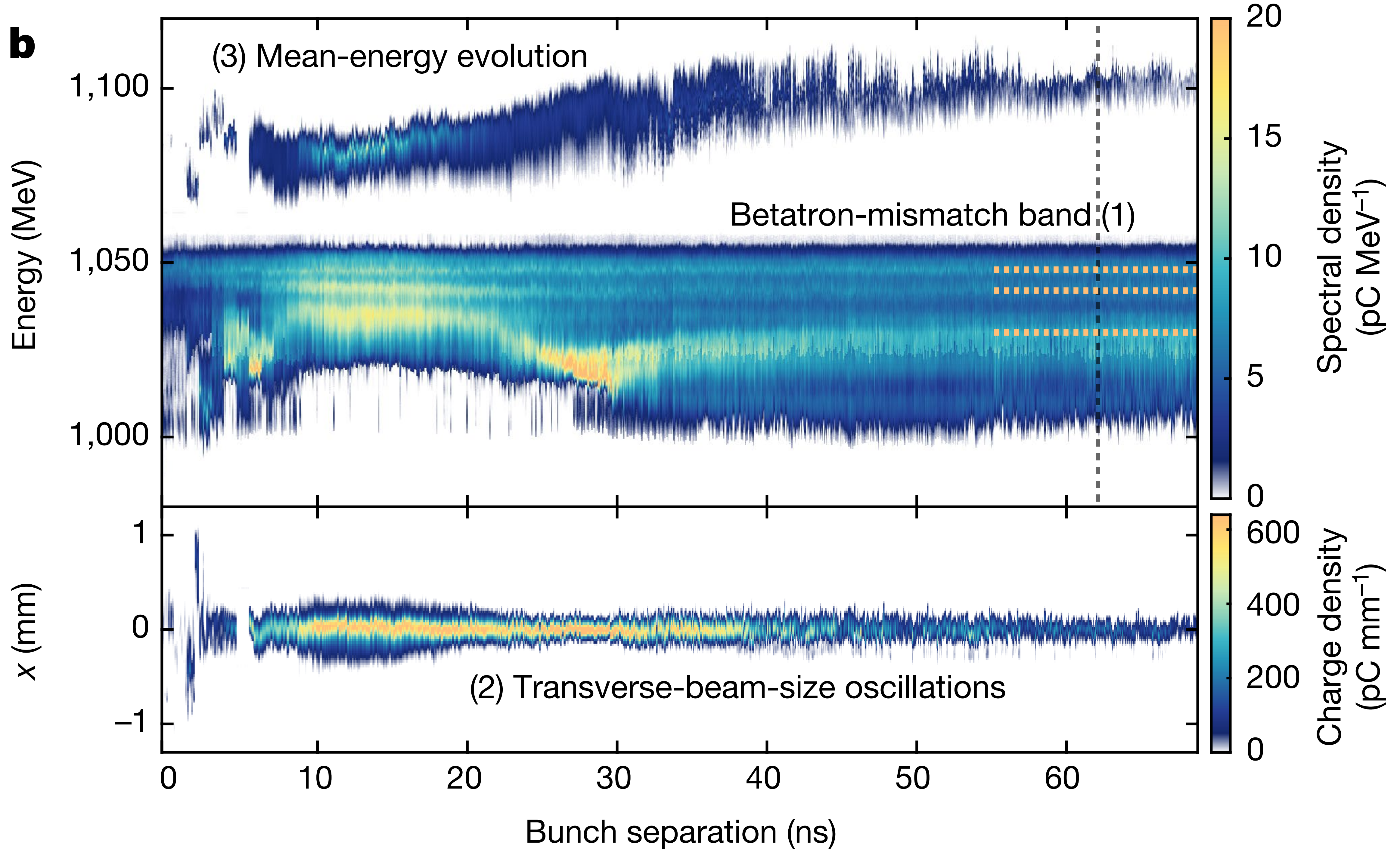
Plasma e- could become relativistically hot after 1s of operation

Recovery time of a beam-driven plasma wake

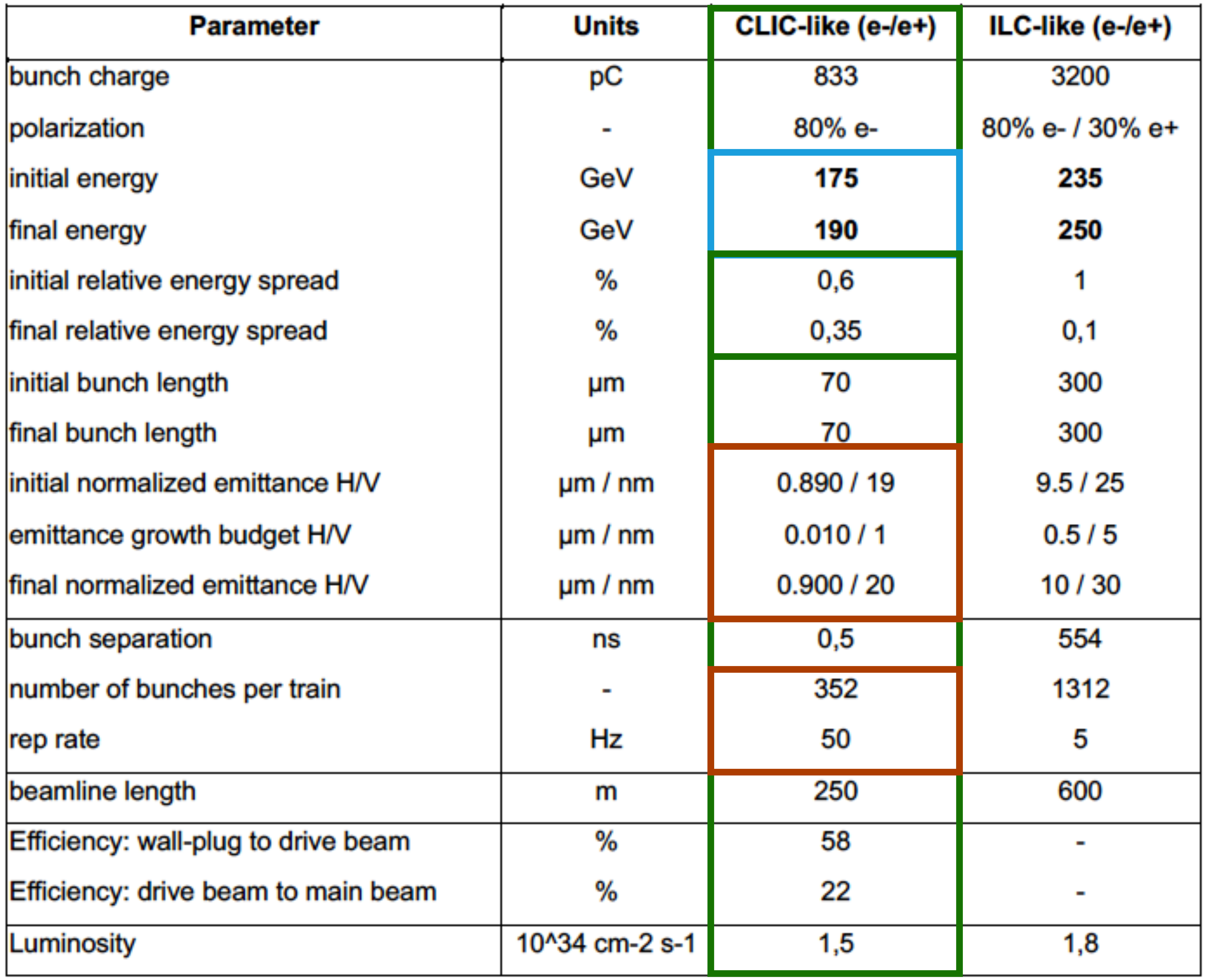


R. D'Arcy et al, Nature **603**, 58 (2021)

Quantity	Units	Value
Average power	MW	9,60E+00
Total distance (including inter-stages)	m	1,00E+02
Transverse cross-section	m^2	2,46E-07
Plasma density	m^{-3}	1,00E+23
Electron number	-	2,46E+18
Energy deposited / e- / (10 ns)	MeV	2,44E-07
Energy deposited / e- / s	MeV	**2,44E+01**

- Without dissipation, assumed 100% driver energy deposition into plasma
- plasma relativistically hot
- Need for multi-physics (with radiation), multi-scale models
- Tools are not ready yet

“Second” plasma accelerator physics challenge: emittance



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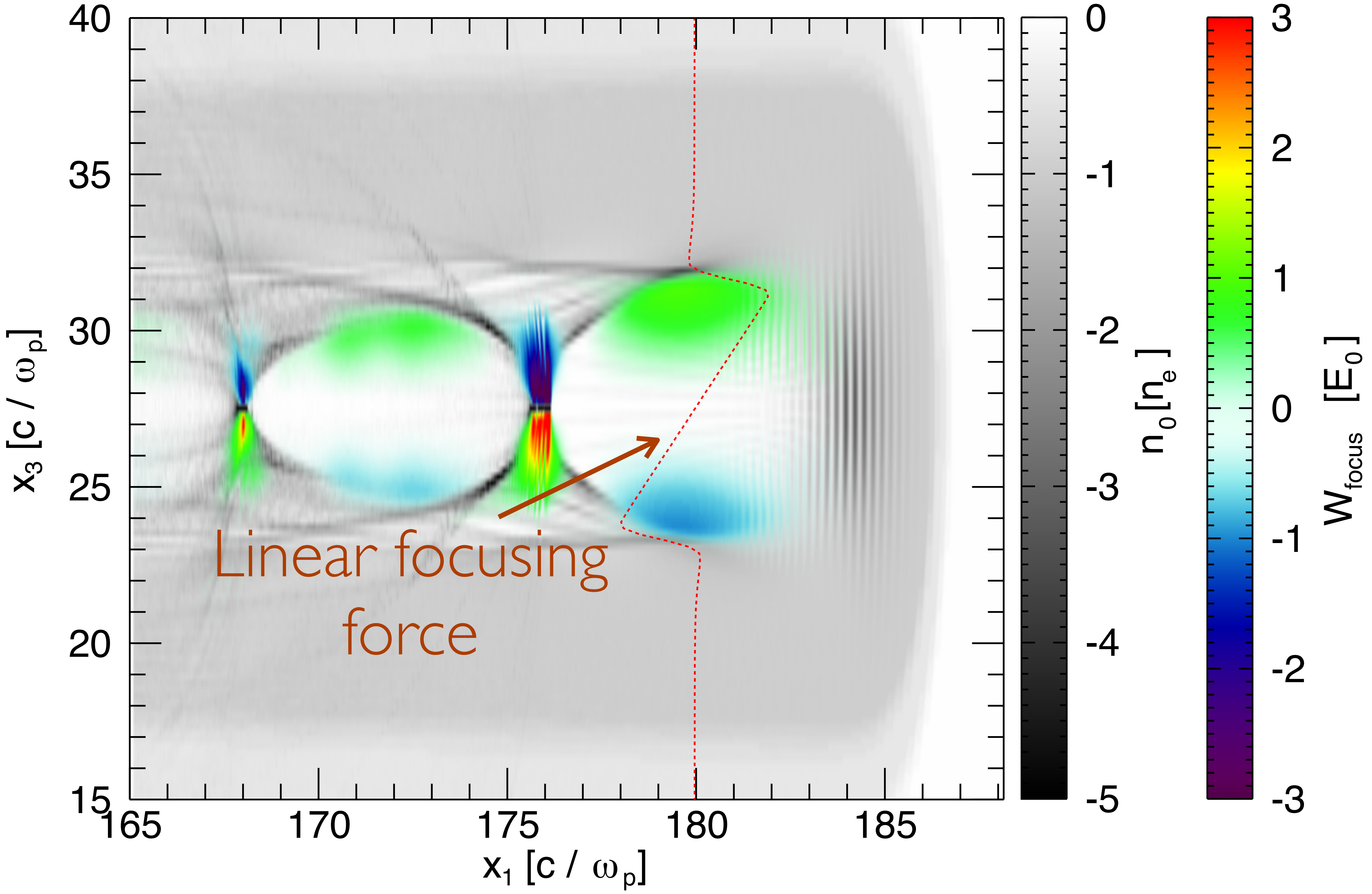
Emittance preservation in linear focusing force

Laser wakefields in blowout regime



Linear focusing force

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

Eaccel [GeV/m]	100
Density [cm^{-3}]	1,00E+18
Q [nC]	0,833
Beam length [µm]	10

Energy [GeV]	ε_n [nm]	$\sigma_{x/y}$ [nm]	n_b/n_0
15	10	**21**	**1,20E+06**
15	100	**66**	**1,20E+05**
190	10	**11**	**4,27E+06**
190	100	**35**	**4,27E+05**

HEP requirements in terms of peak witness-bunch density and transverse size will lead us towards (nearly) unexplored territories in theory and modelling

Unexplored plasma accelerator physics questions

nm-emittance-preservation-driven research on the fundamentals of plasma accelerators

🟧 **Extremely dense electron and positron acceleration**

Hosing, beam loading, efficiency, ion motion, long term plasma dynamics, collisions, …

🟦 **Inject and extract electrons to/from plasma**

Vacuum-plasma-vacuum transitions

🟩 **Other key physics**

Spin polarisation, disruption, radiation-cooling, …

⬛ **Coupling to conventional beam lines**

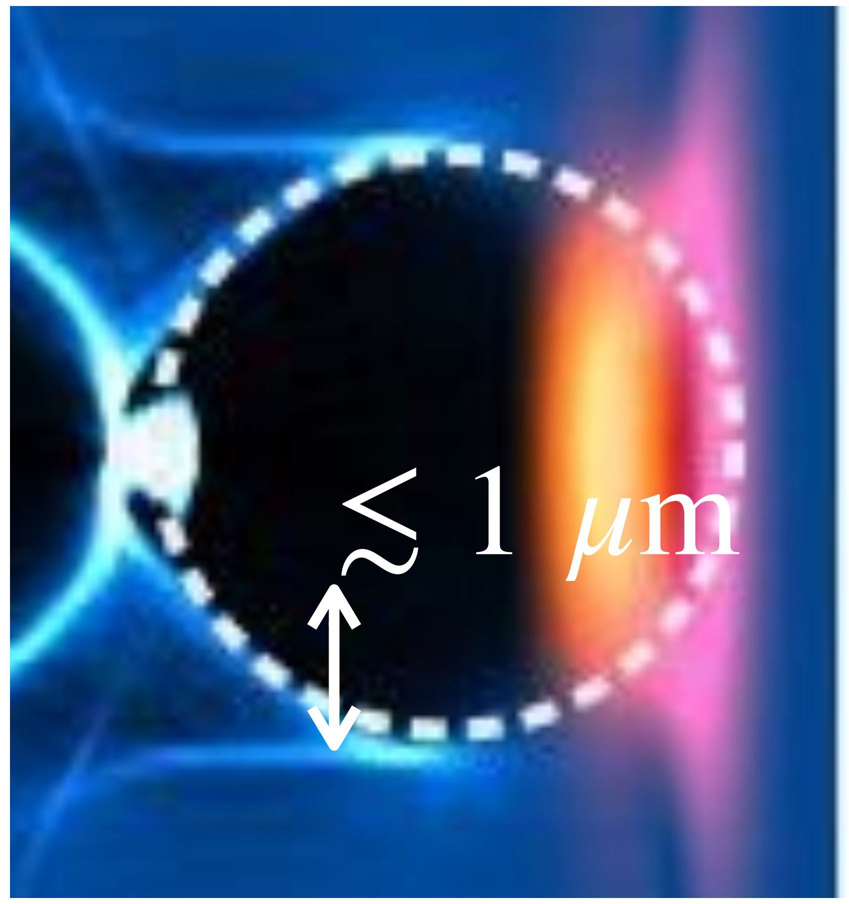
Contents

- Collider needs - where we stand
- Theory and modelling physics challenges
- (some) essential ingredients to design a single stage
- Computing requirements/resources
- Conclusions

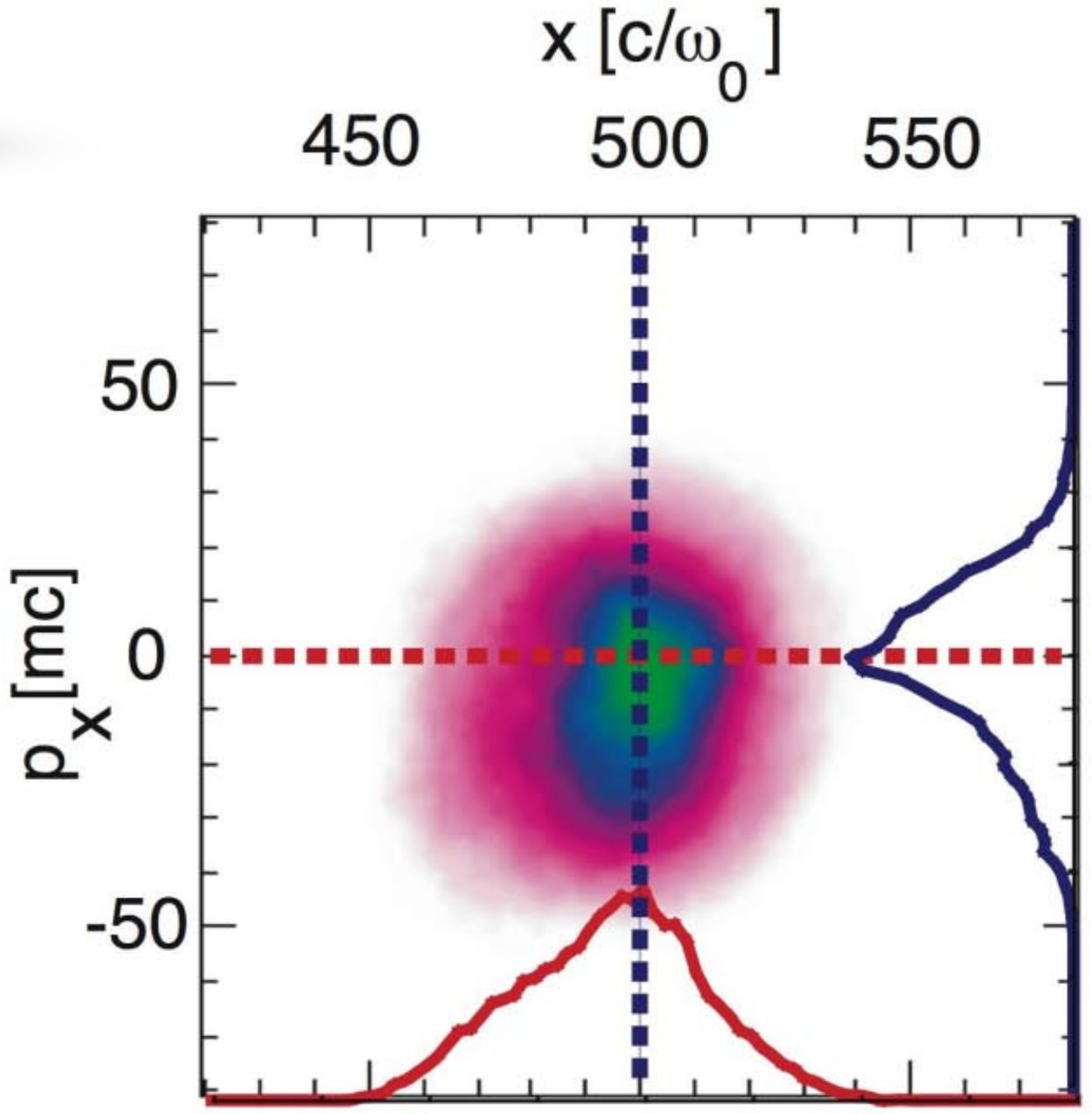
Towards the design of a single collider stage

Typical e- acceleration modelling

Full PIC



$n_b/n_0 \lesssim 100$



$\epsilon_N \lesssim 10\ \mu m$

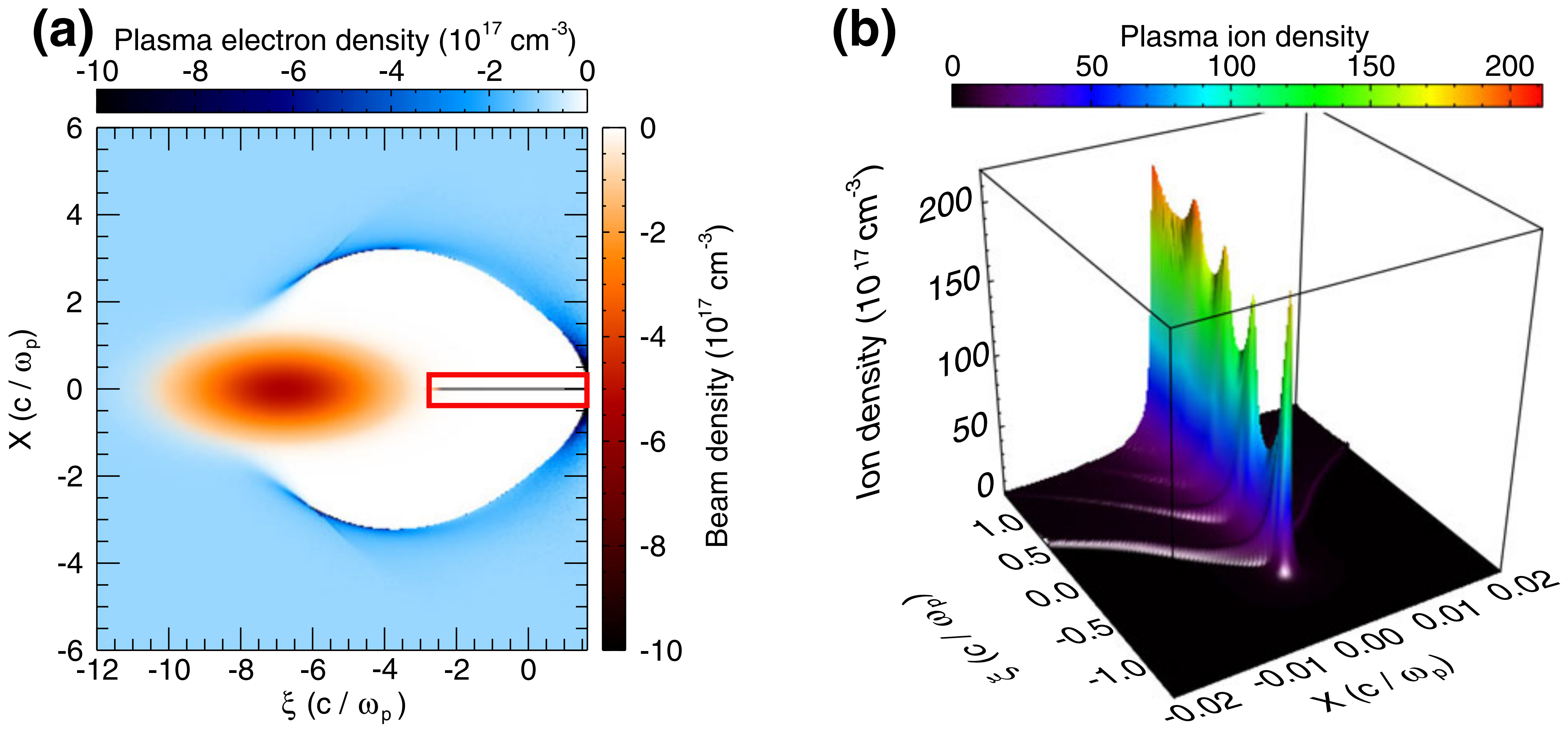
- **Positrons**
- Ion motion
- Efficiency and beam loading
- Hosing

W. Lu et. al, Phys. Rev. ST-AB **10**, 061301 (2007)

Example of work relevant for HEP in e- acceleration

Ion motion induced emittance growth on e- witness bunch

Quasi-static



Emittance growth solutions. Use:

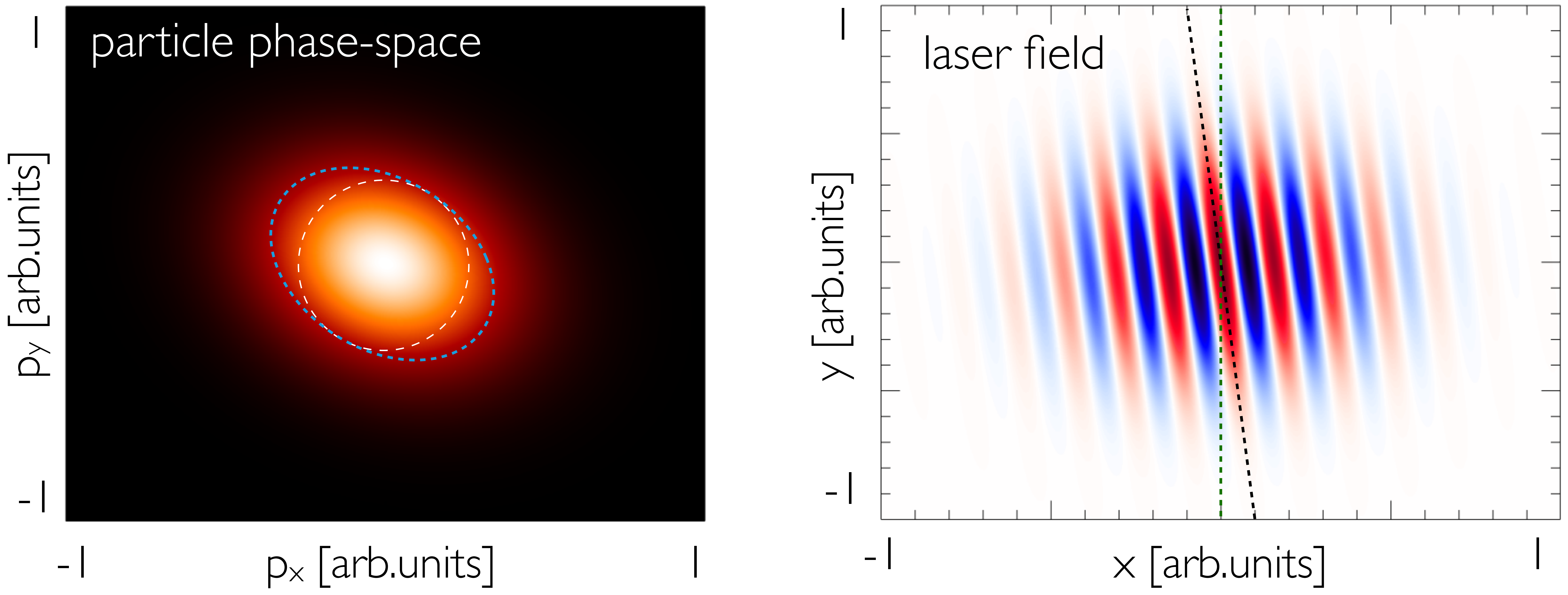
- asymmetric beams
- heavier ion species
- smaller than matched witness transverse size

W. Ann et. al, PRL **118**, 244801 (2017)

Tolerances at the nanometric level

Most previous work focuses on ideal conditions or consider non-ideal (yet real) setups that will (certainly) not preserve emittance to the nm level.

Ideal driver/witness phase-space profiles



What is the role of realistic elements on emittance preservation at the nm scale?

- Particle bunch phase-space
- Laser wavefronts
- Transverse/longitudinal jitter
- Plasma density uniformity

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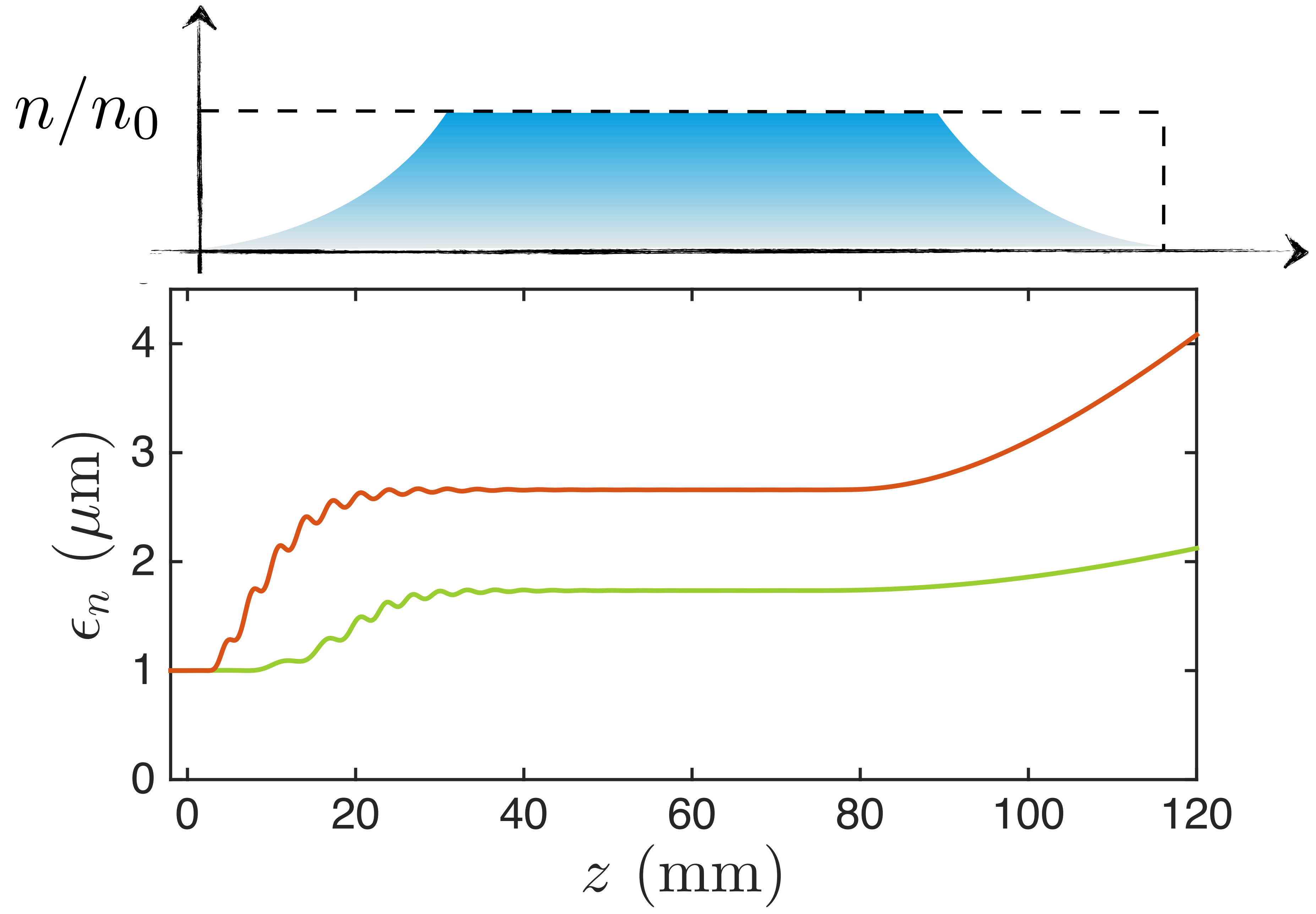
experimental/ technological conditions

Electron and positron injection and extraction to/from plasma

Emittance preservation - plasma to vacuum transitions

Tailored plasmas and beams



T. Mehrling *et al*, ALEGRO
2018 workshop

How can we **inject and extract electrons from plasma accelerator with nm emittance preservation** with ion motion, for electrons and positrons.

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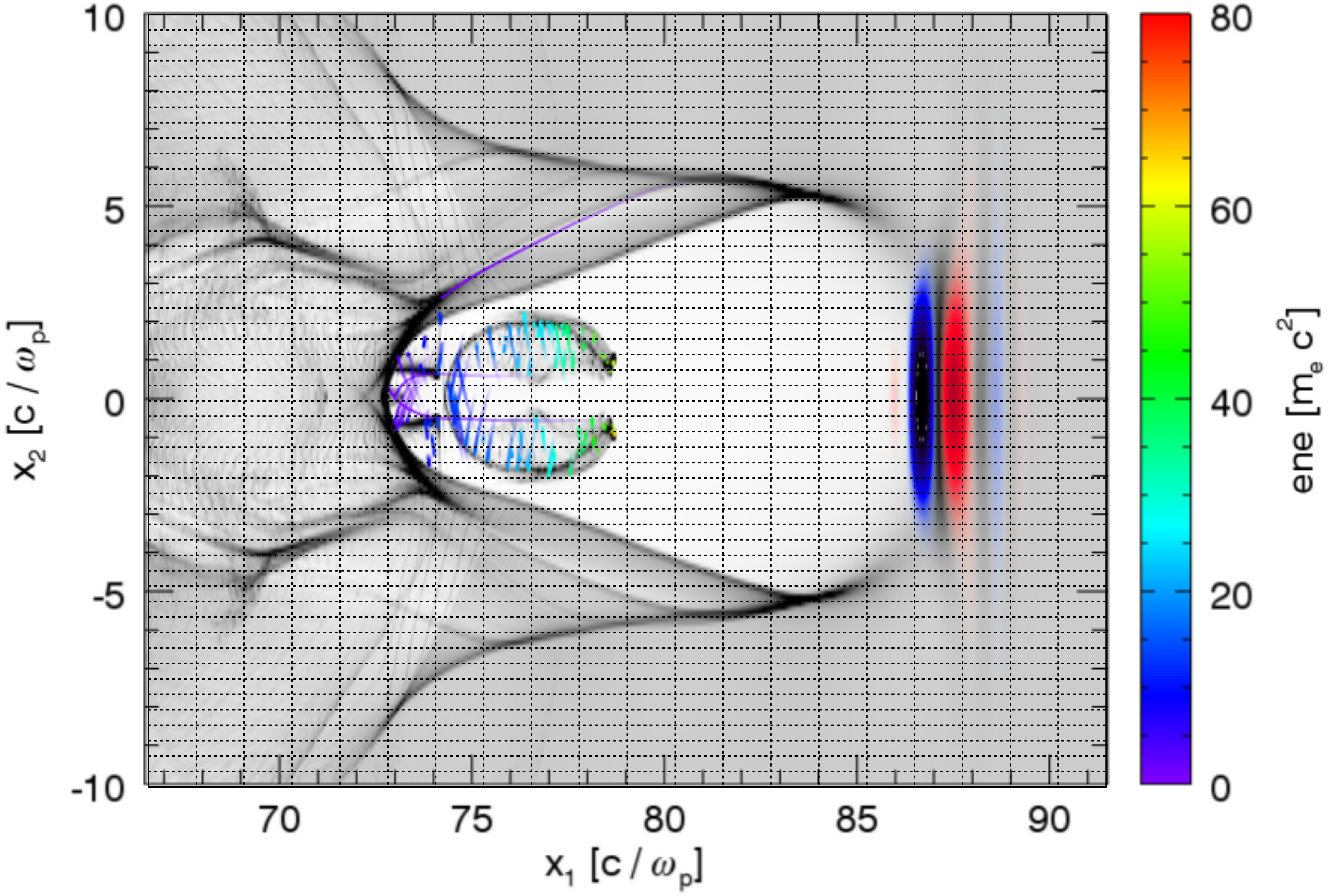
Computing requirements



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

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

Collider

- Longitudinal $\Delta x_{\|} \propto \lambda_L$
- Transverse $\Delta x_{\perp} \propto \sigma_{\perp} \propto \lambda_p/100$

\# cells (order of magnitude)
1000x10000x10000

Computing resources

E = 15 GeV; εN = 10 nm

Simulation mode	particle pushes	time steps	cells	core-hours
LWFA full PIC 3D	4,69E+23	3,18E+08	1,84E+14	6,51E+13
LWFA full PIC 2D	1,72E+18	2,25E+08	9,58E+08	2,39E+08
envelope/PWFA 3D	1,13E+22	3,18E+08	4,44E+12	1,57E+12
envelope/PWFA 2D	4,15E+16	2,25E+08	2,31E+07	5,77E+06

E = 15 GeV; εN = 100 nm

Simulation mode	particle pushes	time steps	cells	core-hours
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envelope/PWFA 3D	3,57E+20	1,01E+08	4,44E+11	4,96E+10
envelope/PWFA 2D	4,15E+15	7,11E+07	7,30E+06	5,77E+05

- **Quasi-static quasi-3D codes optimised for a few azimuthal modes** to account for non-cylindrically symmetric effects.
- **Boosted frames**, provided they can model emittance with nanometric precision

Contents

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Collider needs - where we stand

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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.