Optimization of the density down-ramp scheme for the LFWA injector

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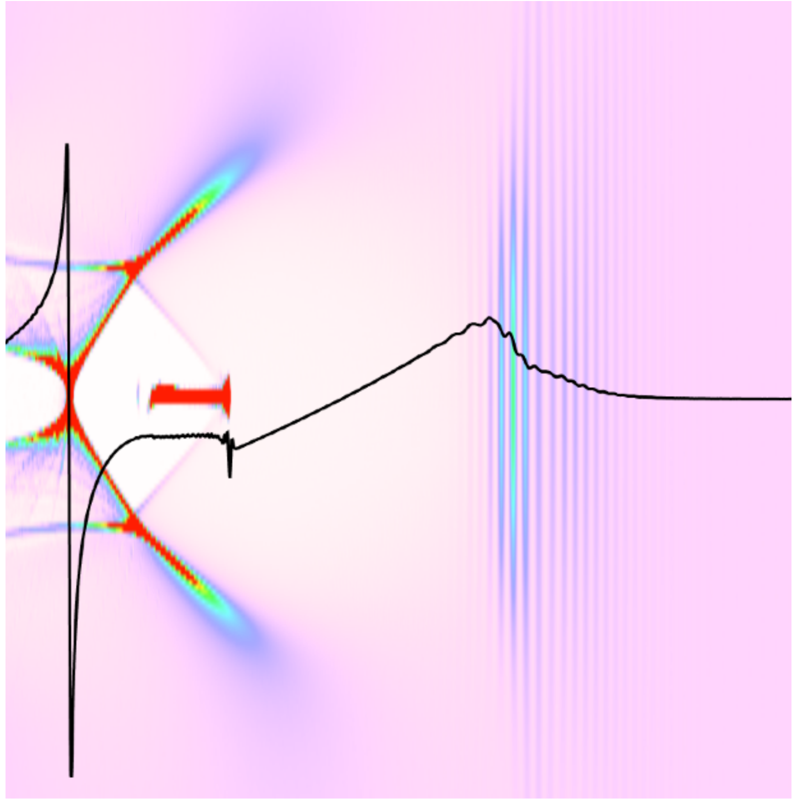

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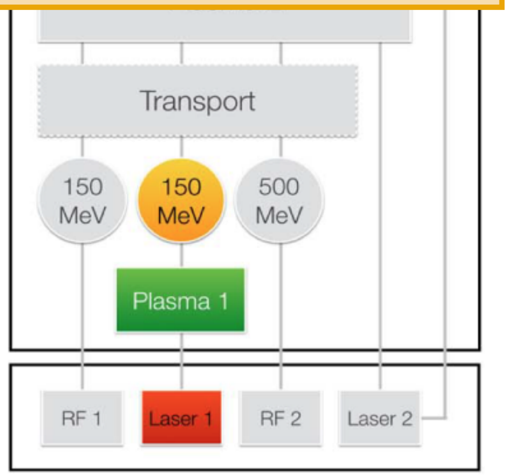
Context within EuPRAXIA

LWFA injector



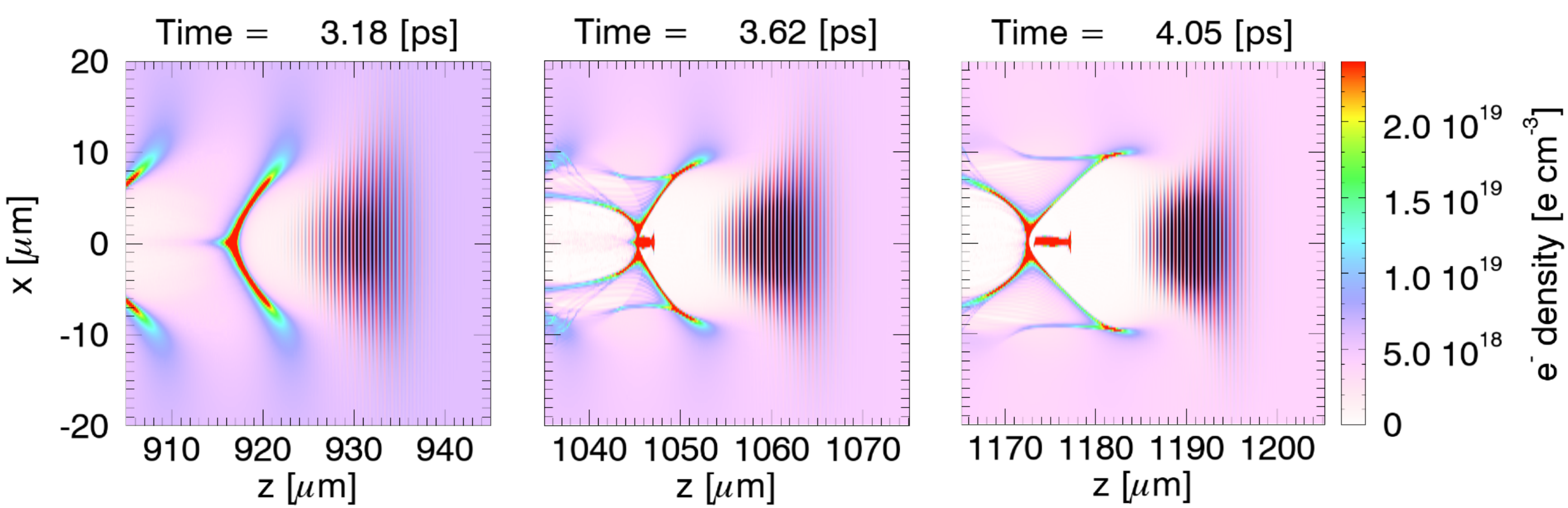
Beam requirements

- Energy ~150 MeV
- Energy spread < 5% (or < 1%)
- Charge ~ 30 pC
- Emittance < 1 mm mrad
- Gamma (Twiss) @ plasma exit < 200m^{-1}

Injection Method

Self-injection using a plasma density down-ramp profile

Wakefield excited by the pulse	Injection at the density ramp	Beam acceleration



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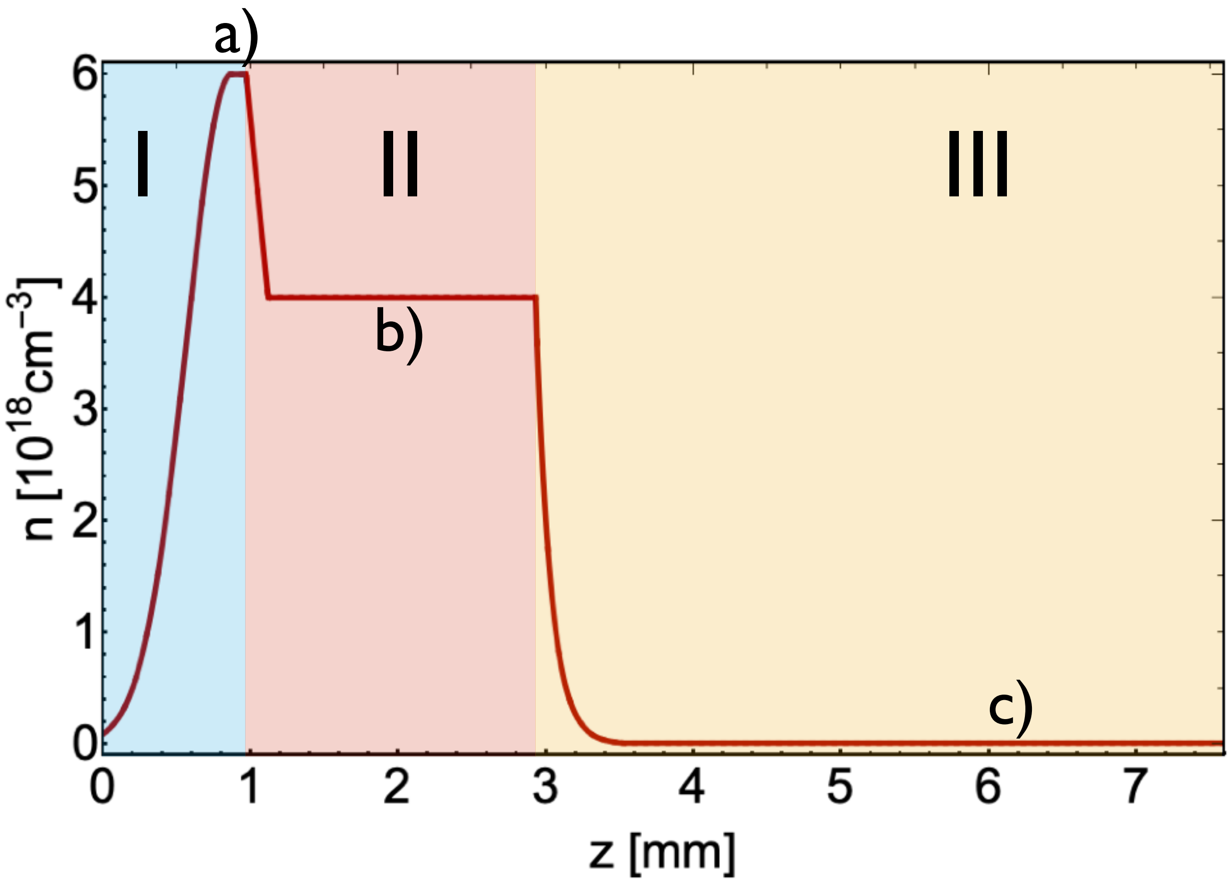
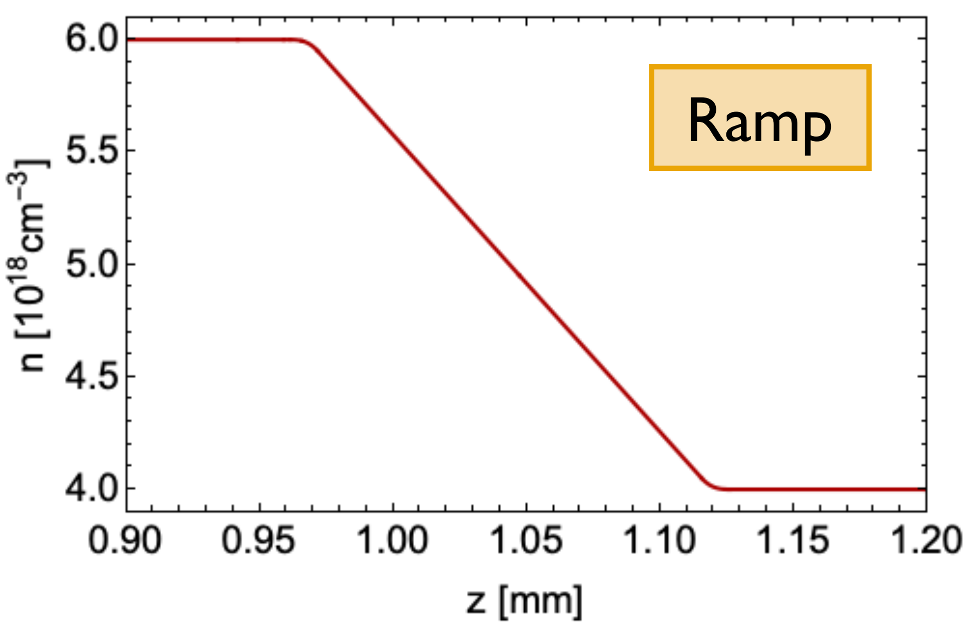
Plasma profile

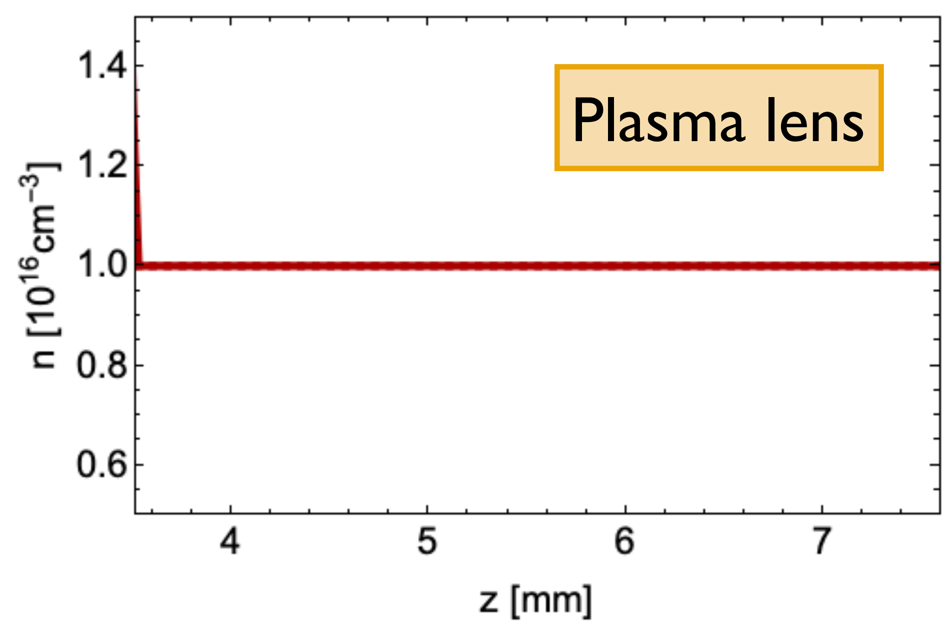
Plasma profiles and typical lengths*



Profile		Exploration range
I -	Up-ramp	~1 mm
II -	Down-ramp	~10 to 200 μm
	Acceleration length	~800 μm to 5mm
III -	Exit ramp	~600 μm to 6mm
	Plasma lens	~4 mm

Density	
a) before the ramp	6×10^{18}cm^{-3}
b) after the ramp	3 to 5×10^{18}cm^{-3}
c) plasma lens	1×10^{16}cm^{-3}





* Base parameters taken from H.Ekerfelt, et al., Scientific Reports **7**, 12229 (2017)

Laser parameters

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Laser parameters on par with requirements

LWFA injector laser (laser 1): for LWFA with controlled injection within plasma 1				
Wavelength	λ_1	800 nm	800 nm	
Energy	E_1	5 J	5 J	10 J
Pulse length (FWHM)	τ_1	30 fs	20 fs	40fs
Peak power	$P_{1,peak}$	167 TW	150-250 TW	
Average power	$P_{1,ave}$	50 W	5 W	1 kW

Laser parameters in vacuum*

$\lambda = 800nm$

$a_0 = 1.8$

$\tau = 30fs$

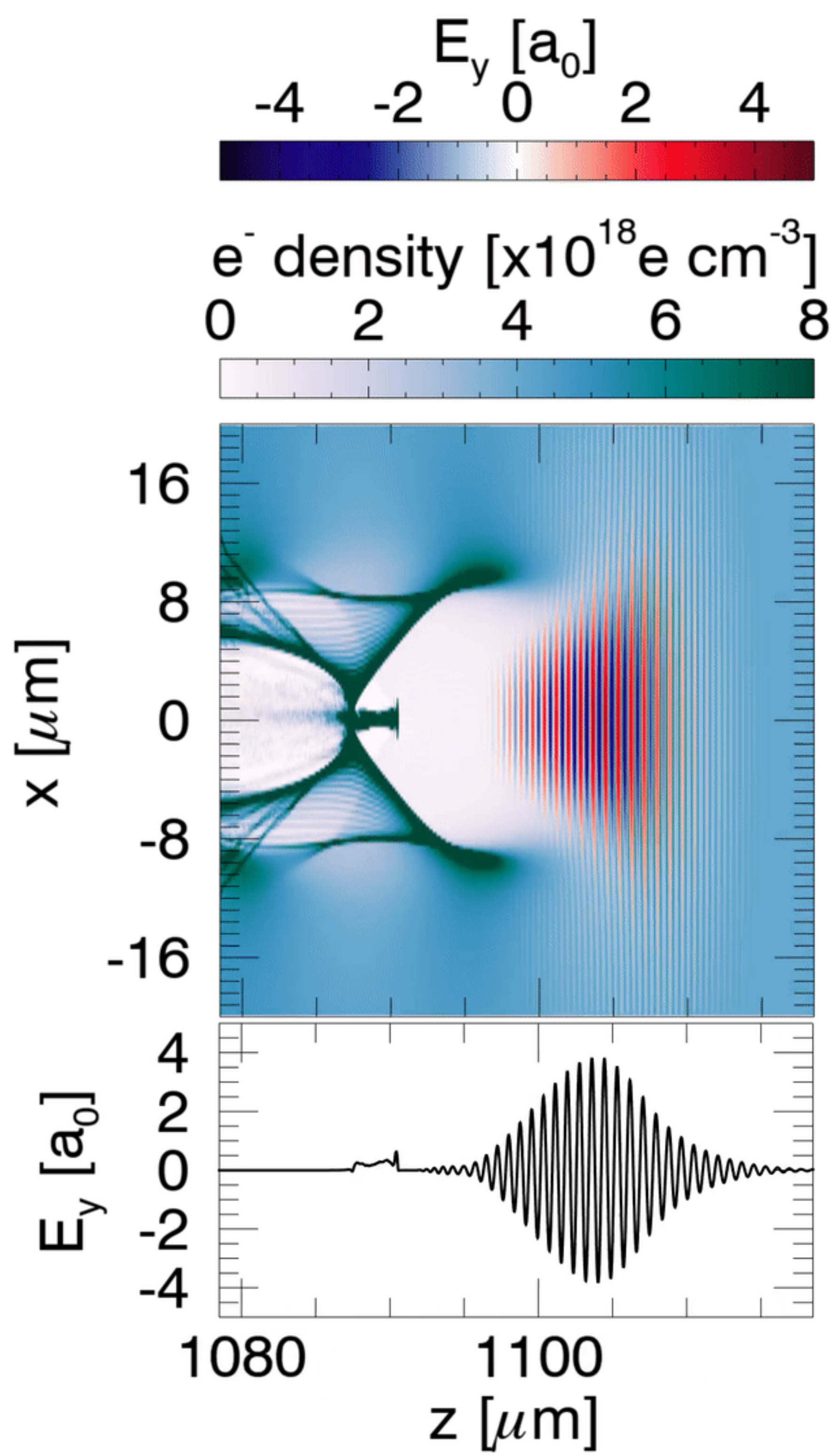
$w_0 = 18\mu m$

$P_{peak} = 35TW$

$E = 1.05J$

The laser will self-focus inside the plasma, which more than doubles a_0 at the time of injection

Self-focus increases a_0



* Base parameters taken from H.Ekerfelt, et al., Scientific Reports **7**, 12229 (2017)

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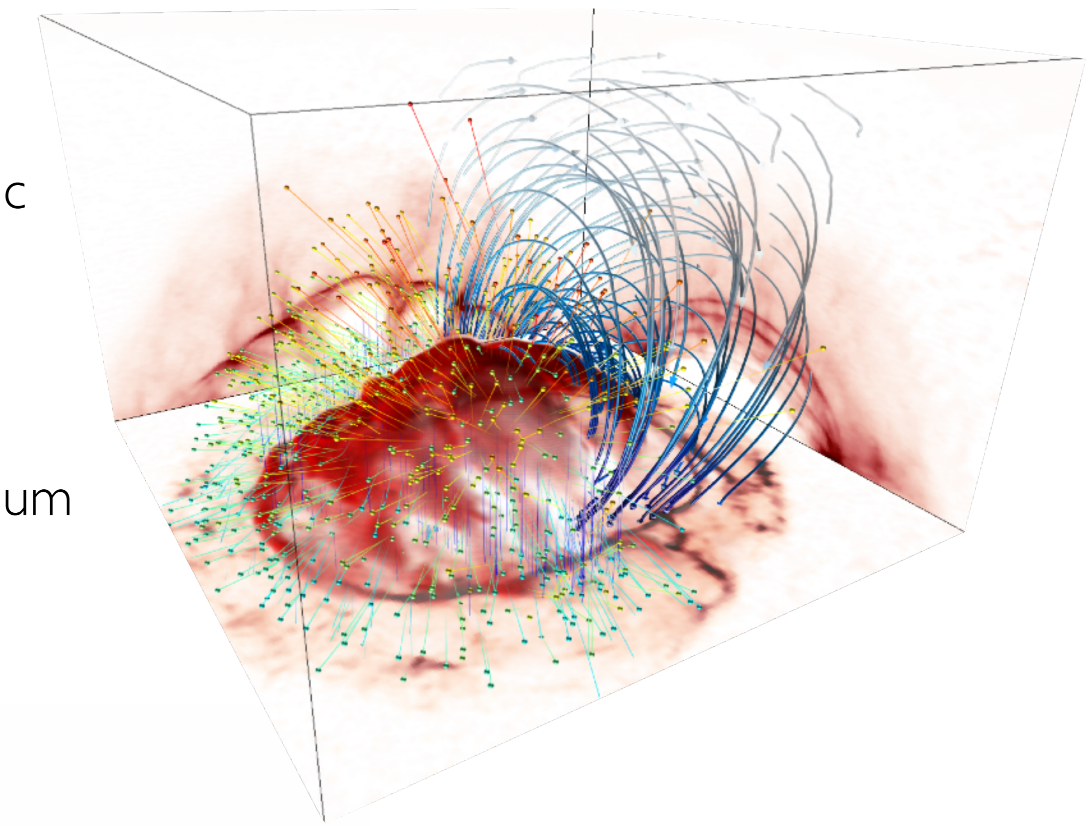
OSIRIS 4.0

Osiris 4.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



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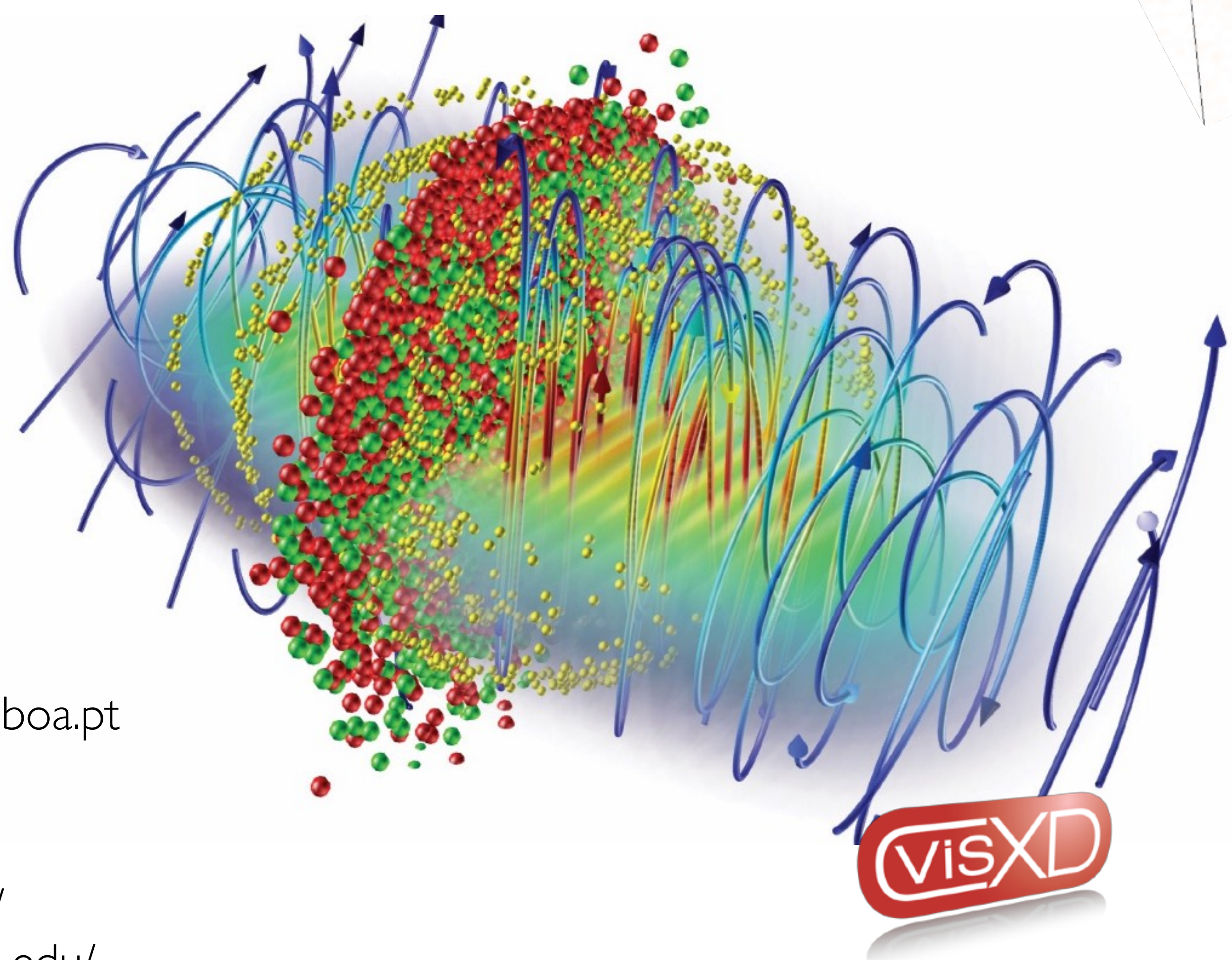
UCLA



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU & Xeon Phi support

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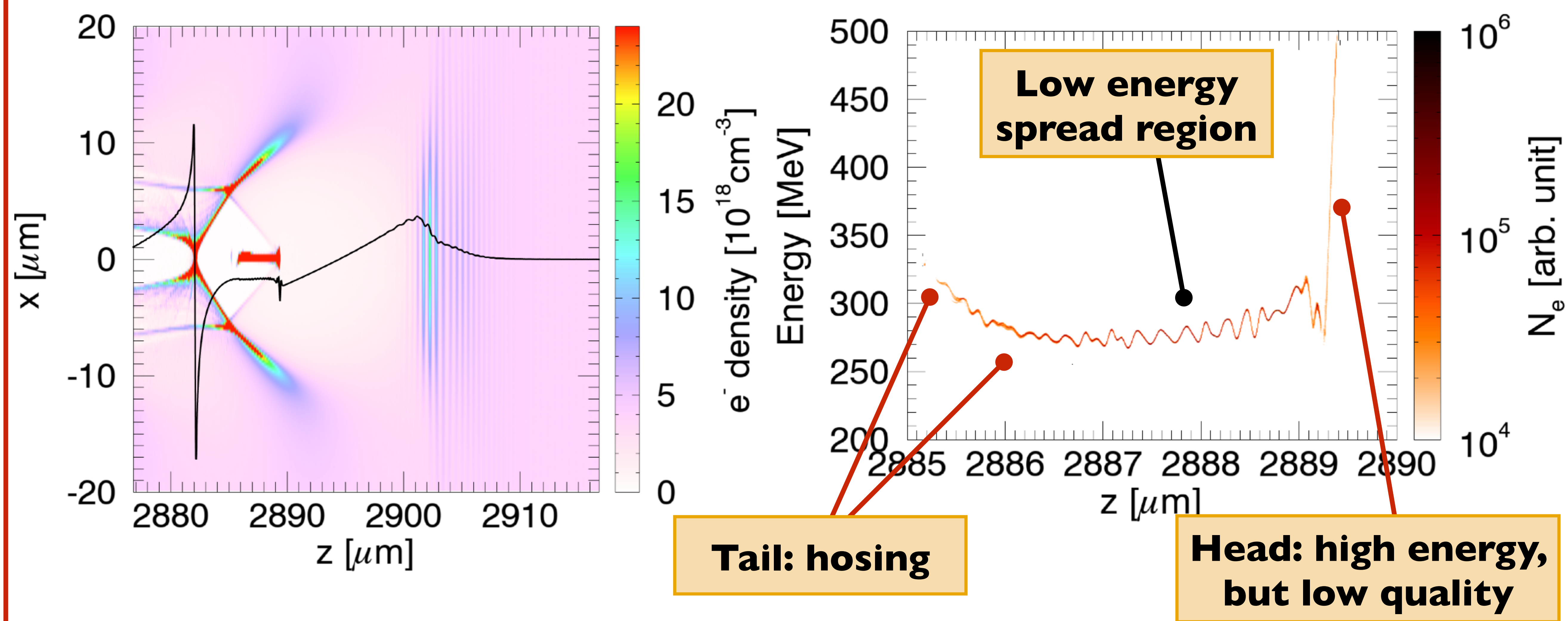
Removal of the head and tail can lead to high quality beams



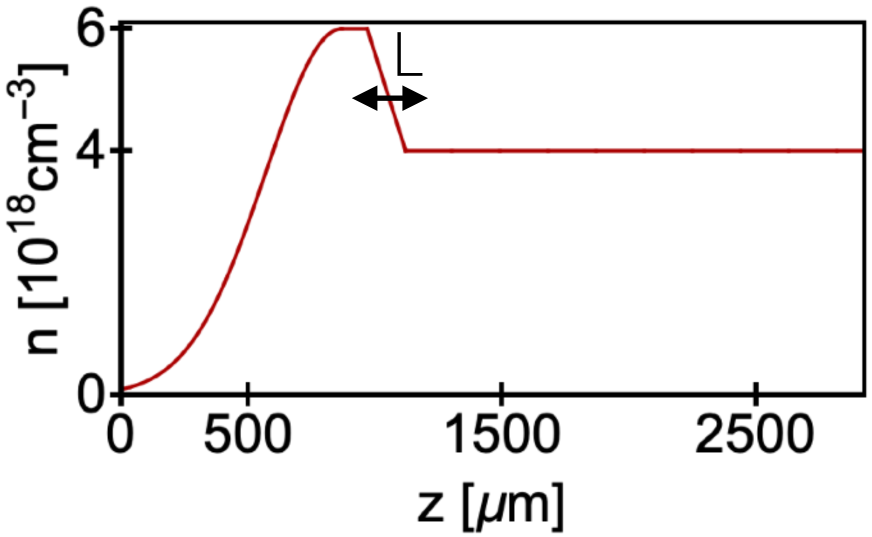
Beam parameters

- Energy = 296 MeV
- Energy spread (rms) = 13%
- Charge = 163 pC
- Emittance x/y (rms)= 0.25/0.14 mm mrad
- Bunch duration = 14fs

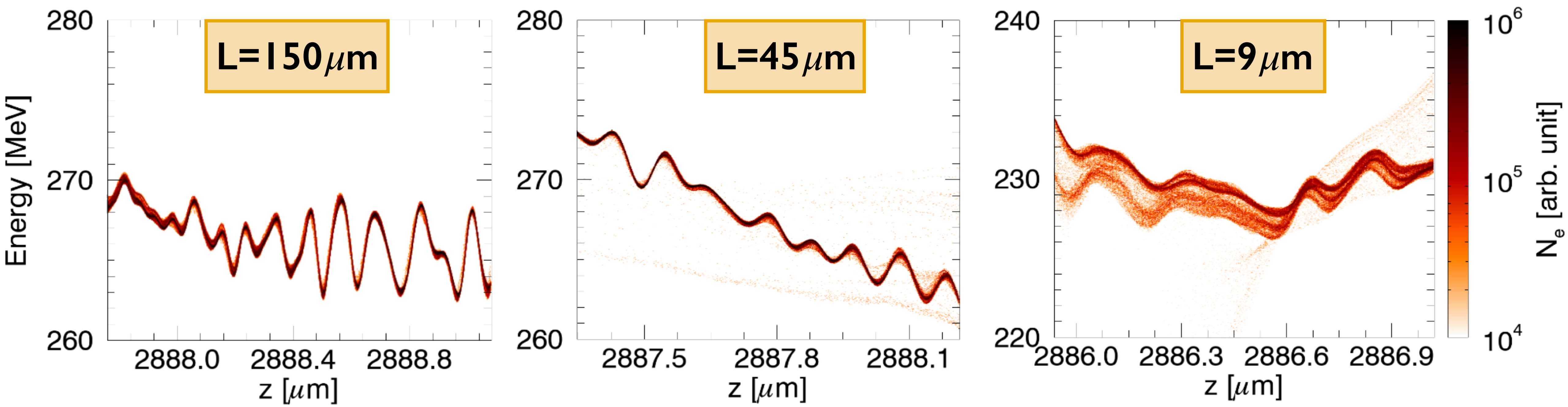
- Numerical artefacts: use of Lehe* solver to mitigate the growth of numerical Cherenkov, limiting non-physical growth of the beam emittance

* R. Lehe, et al., Phys. Rev. ST Accel. Beams **16**, 021301 (2013)

A few examples of simulation results

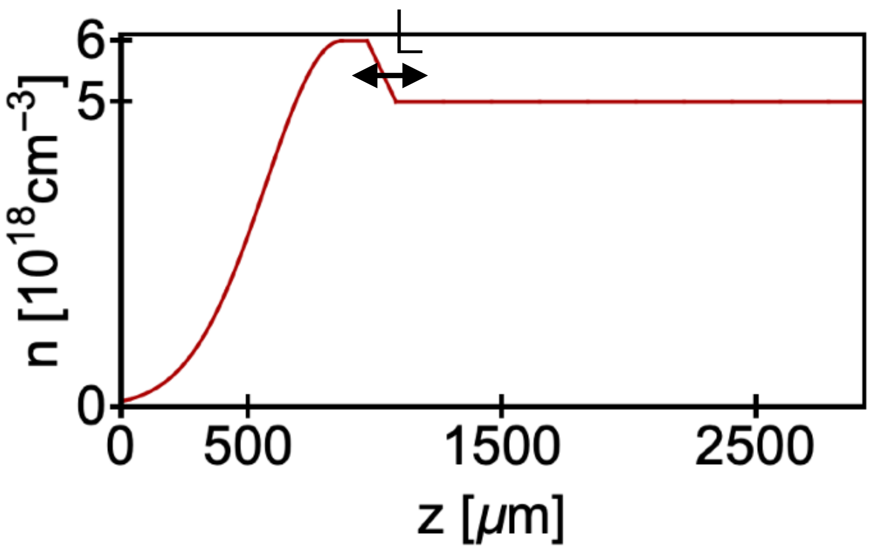


- Density of the acceleration stage $n_0=4\times10^{18}cm^{-3}$
- Varying length of the down-ramp L
- Beam parameters calculated after ~1.8mm acceleration

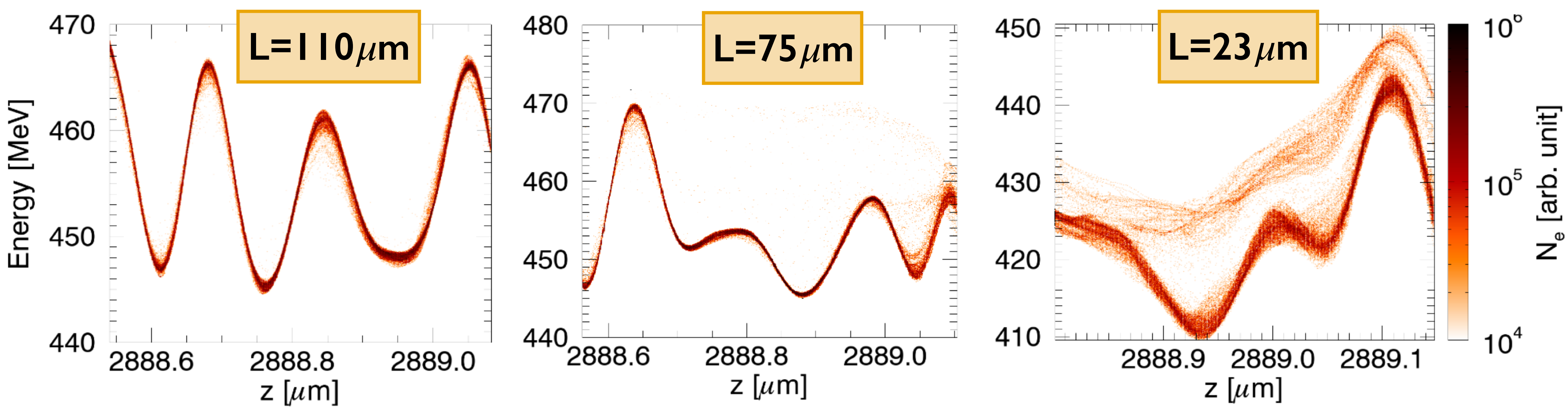


Energy = 266 MeV	Energy = 267 MeV	Energy = 229 MeV
Energy spread (rms) = 0.66%	Energy spread (rms) = 1.15%	Energy spread (rms) = 0.65%
Charge = 42 pC	Charge = 29 pC	Charge = 41 pC
Emittance x/y(rms)=0.04/0.06μm	Emittance x/y(rms)=0.10/0.09μm	Emittance x/y(rms)=0.85/0.68μm
Bunch duration = 4.4fs	Bunch duration = 3fs	Bunch duration = 3.6fs

A few examples of simulation results



- Density of the acceleration stage $n_0 = 5 \times 10^{18} cm^{-3}$
- Varying length of the down-ramp L
- Beam parameters calculated after ~1.8mm acceleration



Energy = 455 MeV
Energy spread (rms) = 1.43%
Charge = 29.62 pC
Emittance x/y(rms)=0.05/0.05µm
Bunch duration = 1.8fs

Energy = 454 MeV
Energy spread (rms) = 1.27%
Charge = 29.55 pC
Emittance x/y(rms)=0.09/0.07µm
Bunch duration = 1.8fs

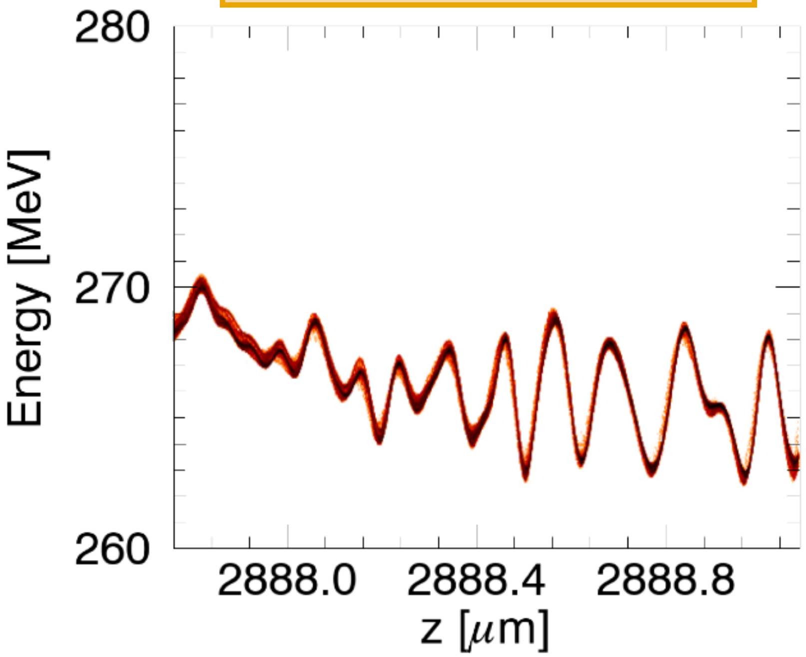
Energy = 427 MeV
Energy spread (rms) = 2.22%
Charge = 31.28 pC
Emittance x/y(rms)=0.50/0.40µm
Bunch duration = 1.15fs

Short exit ramps are better for conserving the beam quality

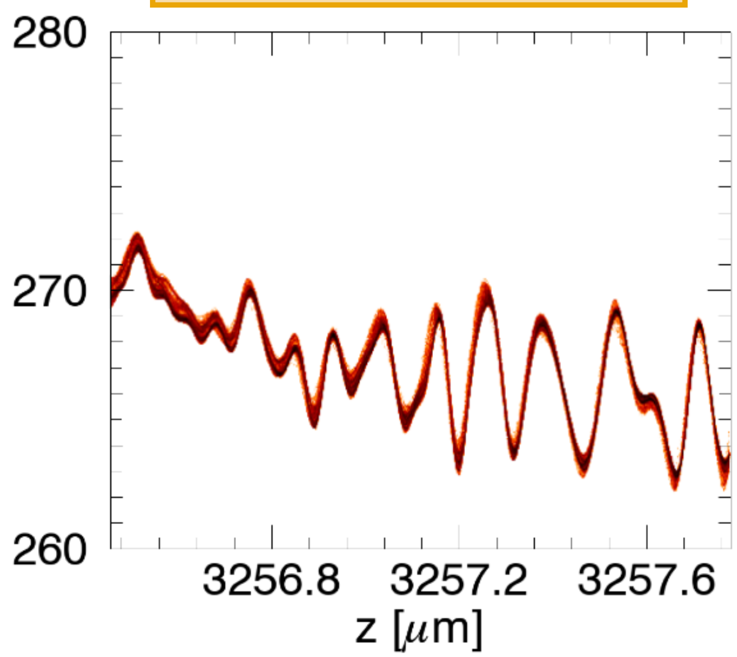
Plasma exit parameter scans

Exit ramp profile: $n(z) \propto \exp(-z/L_{exit})$

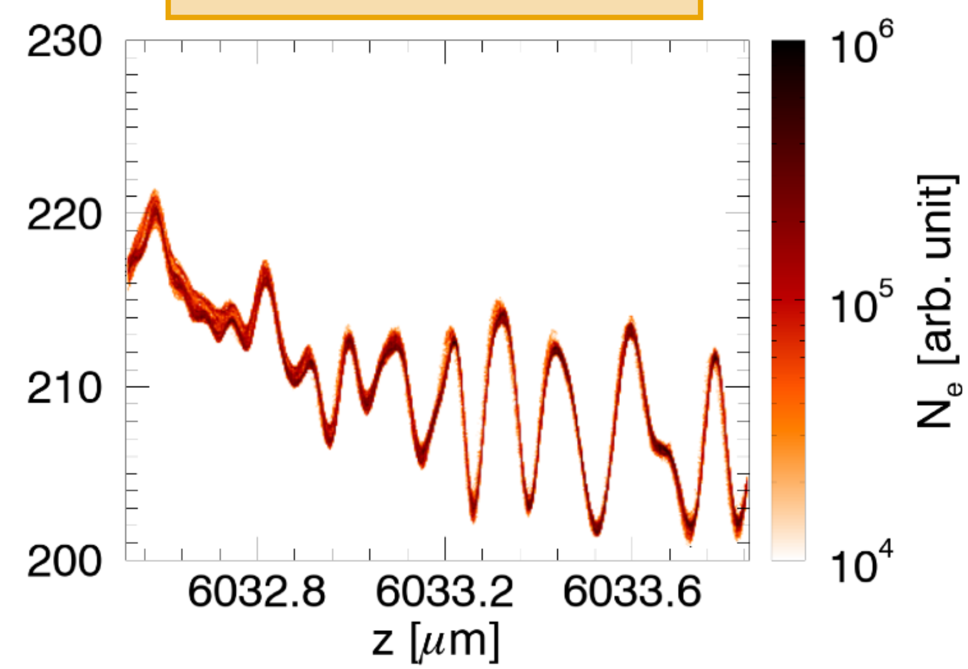
Inside the plasma



L_{exit}=100μm



L_{exit}=1mm



Energy = 266 MeV
Energy spread = 0.66%
Emittance x/y = 0.04μm/0.06μm
γ(Tw) x/y = 13900 m^{-1}/14300 m^{-1}

Energy = 267 MeV
Energy spread = 0.79%
Emittance x/y = 0.06μm/0.06μm
γ(Tw) x/y = 3900 m^{-1}/3700 m^{-1}

Energy = 210 MeV
Energy spread = 2.1%
Emittance x/y = 0.05μm/0.06μm
γ(Tw) x/y = 3160 m^{-1}/2850 m^{-1}

Use of a plasma lens to reduce γ-Twiss*

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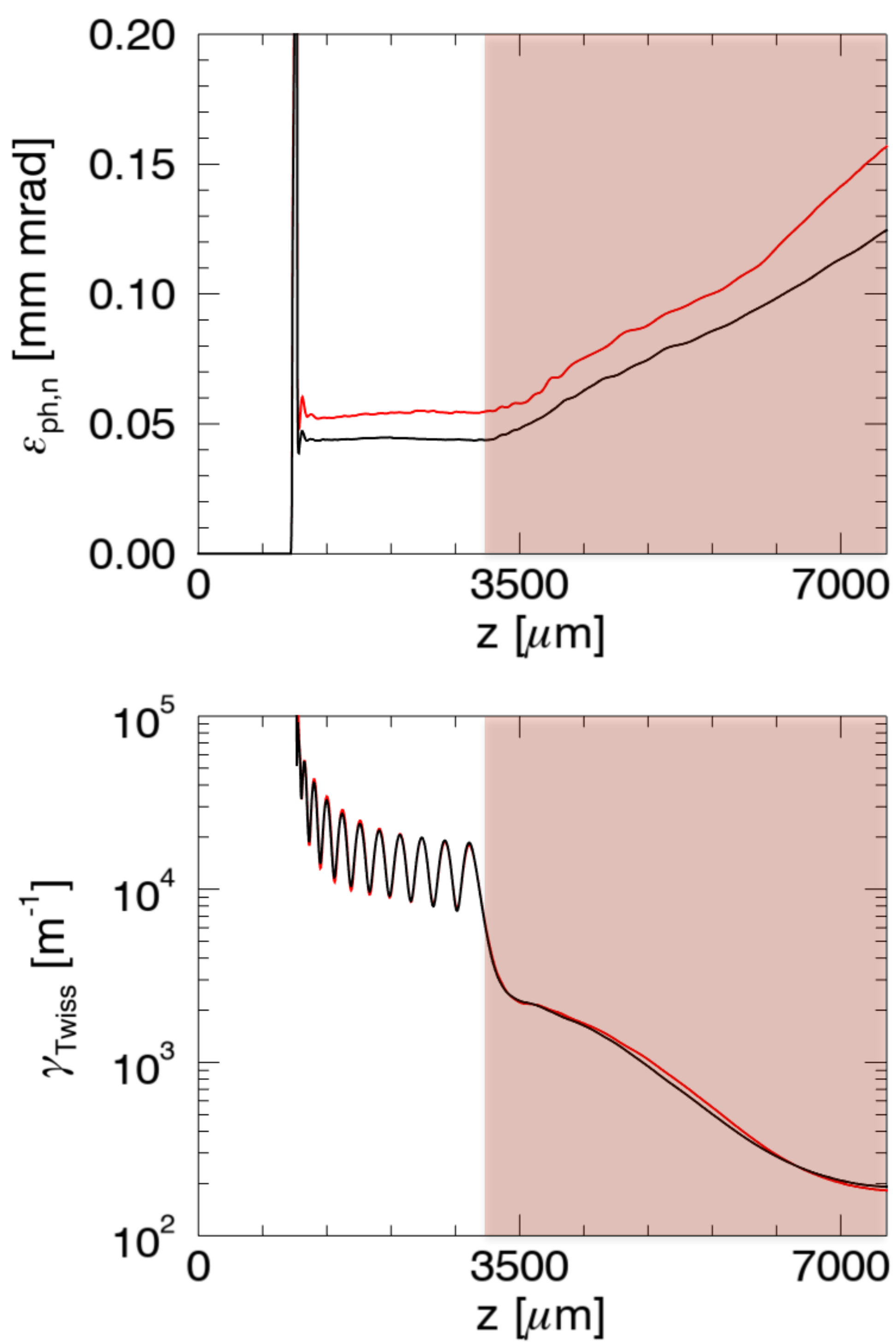
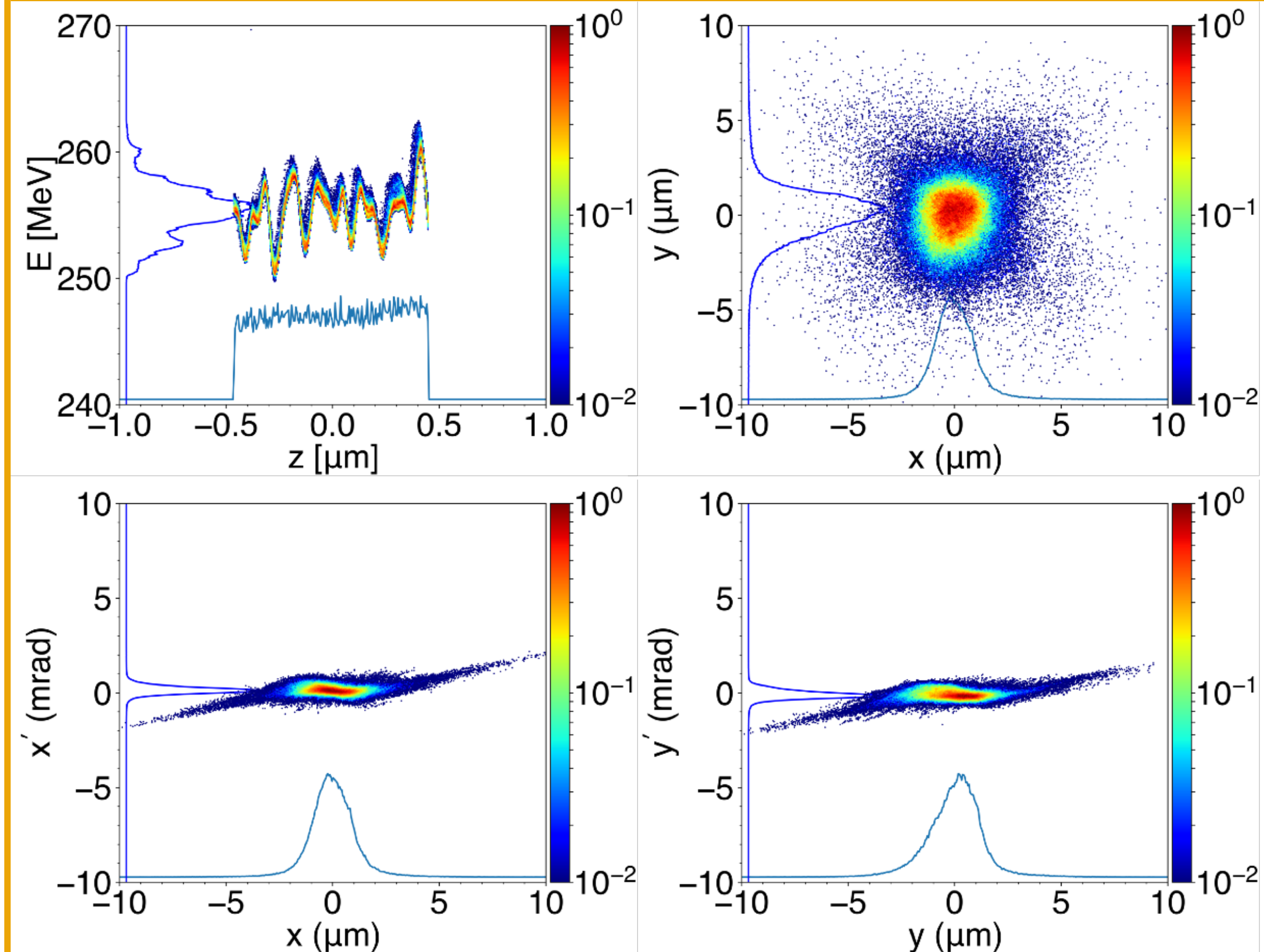
Emittance and γ-Twiss evolution



Beam parameters before the transfer line

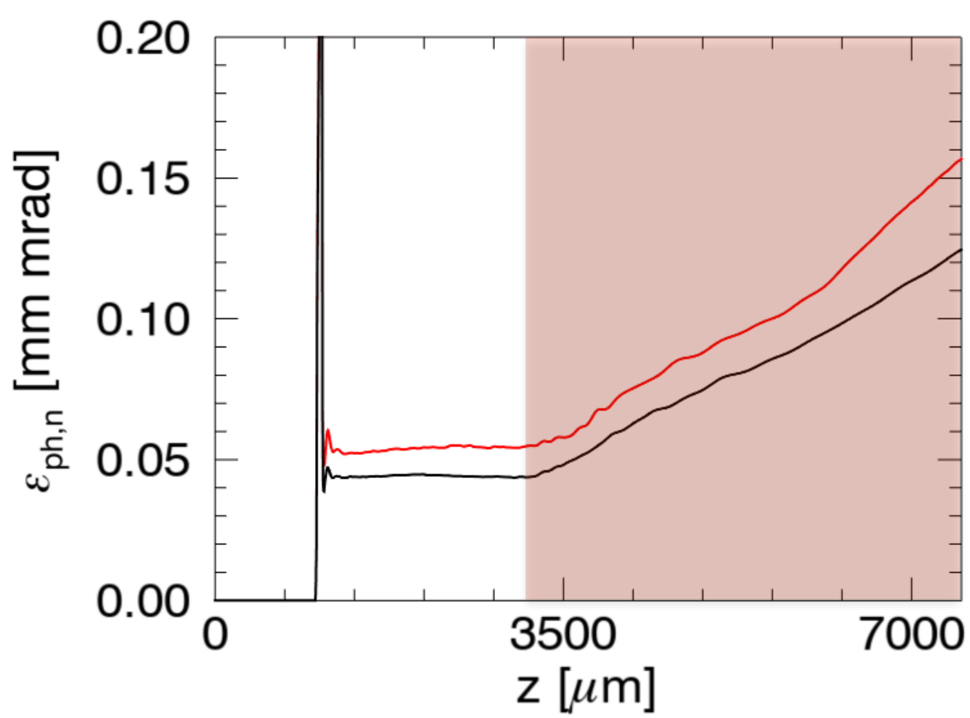


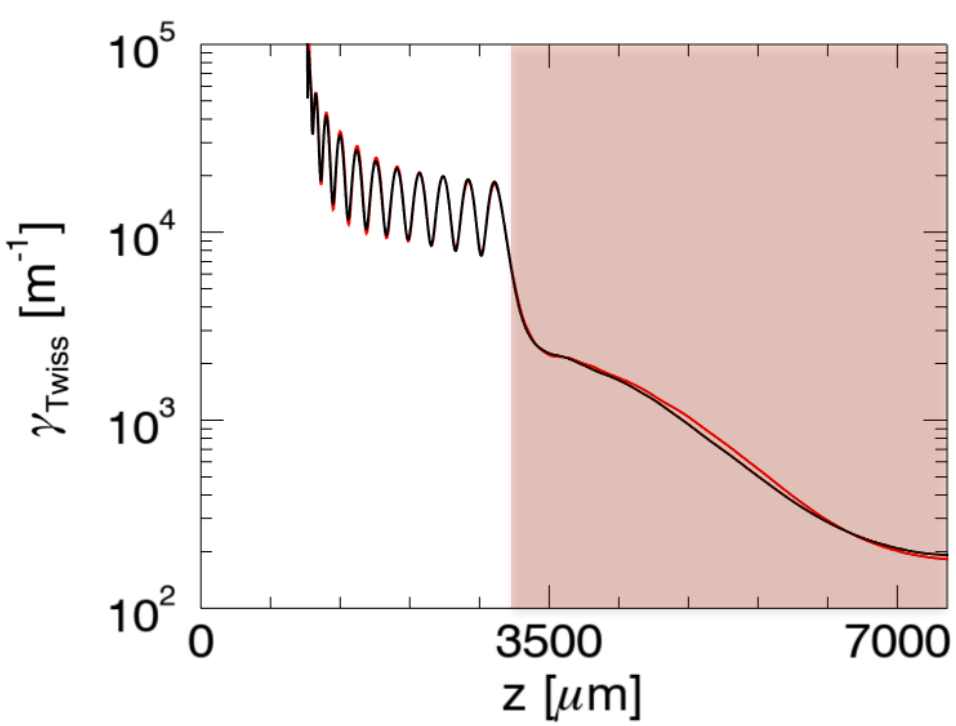
- E = 255.3MeV
- E_{spread} (rms) = 0.78%
- Q = 30.66pC
- $\epsilon_{x, phase, normalized}$ = 0.126 mm mrad
- $\epsilon_{y, phase, normalized}$ = 0.160 mm mrad
- s_x (rms) = 1.18μm
- s_y (rms) = 1.36μm
- s_z = 3fs
- $\gamma_{x,Twiss}$ (rms) = 190.6 m^{-1}
- $\gamma_{y,Twiss}$ (rms) = 181.9 m^{-1}

* Xiangkun Li, et al., Phys. Rev. Accel. Beams **22**, 021304 (2019)

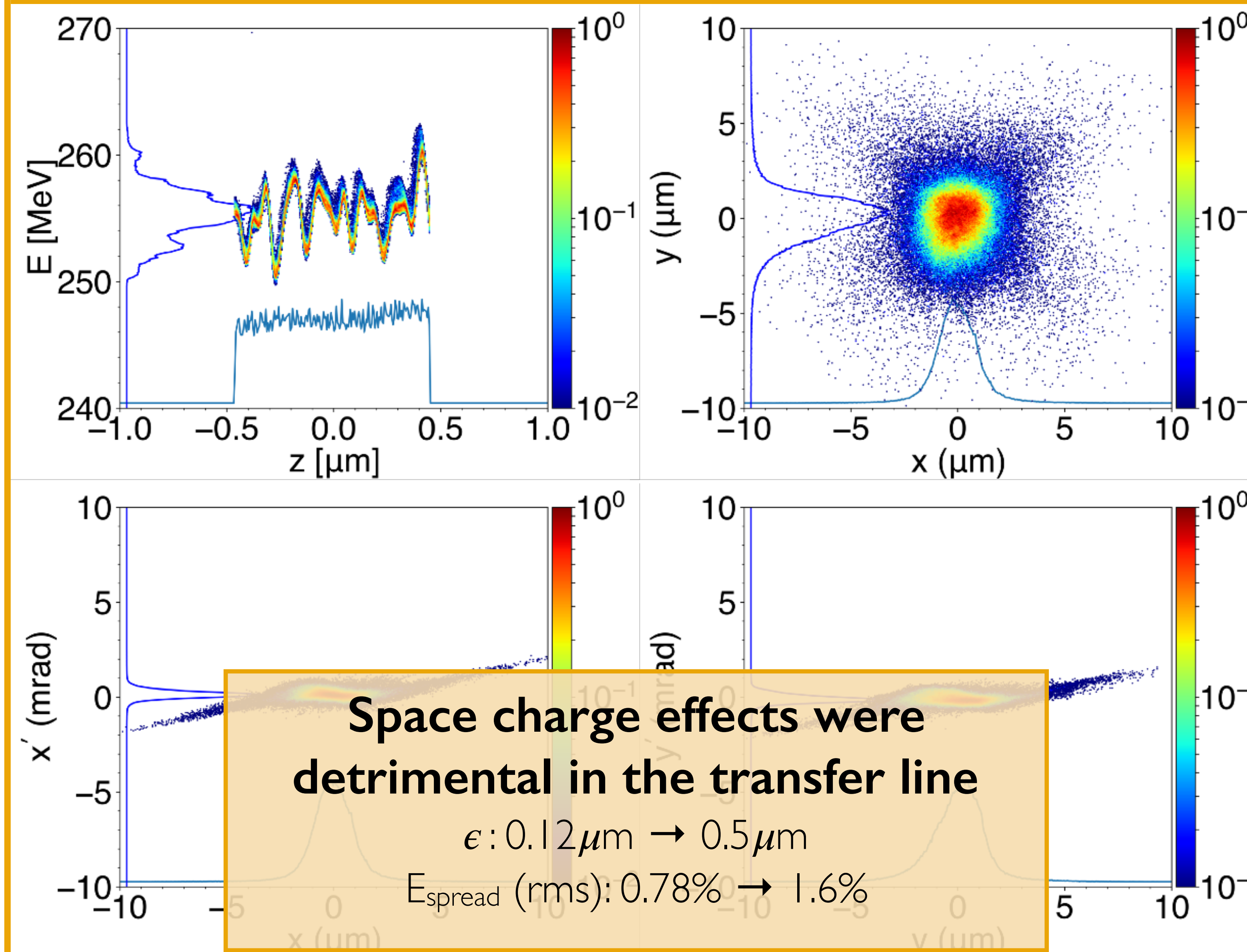
Use of a plasma lens to reduce γ-Twiss*

Emittance and γ-Twiss evolution





Beam parameters before the transfer line



Space charge effects were detrimental in the transfer line

ϵ: 0.12μm → 0.5μm

E_{spread} (rms): 0.78% → 1.6%

- E = 255.3MeV
- E_{spread} (rms) = 0.78%
- Q = 30.66pC
- $\epsilon_{x,\,phase,\,normalized}$ = 0.126 mm mrad
- $\epsilon_{y,\,phase,\,normalized}$ = 0.160 mm mrad
- s_x (rms) = 1.18μm
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- s_z = 3fs
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* Xiangkun Li, et al., Phys. Rev. Accel. Beams **22**, 021304 (2019)

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Conclusions

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The plasma density down-ramp injection method gives great controllability of the beam parameters

by varying the densities (before and after the ramp) and sharpness of the ramp

High beam quality if we we remove the beam head and tail

The use of a plasma lens helped lower the γ-Twiss parameters while preserving beam quality to acceptable levels

Space charge effects highly affected the beam dynamics in the transfer line.

Smoother ramps can help to inject less charge per unit of length.

Beam quality obtained still within range of EuPRAXIA's goals for the LWPA injector