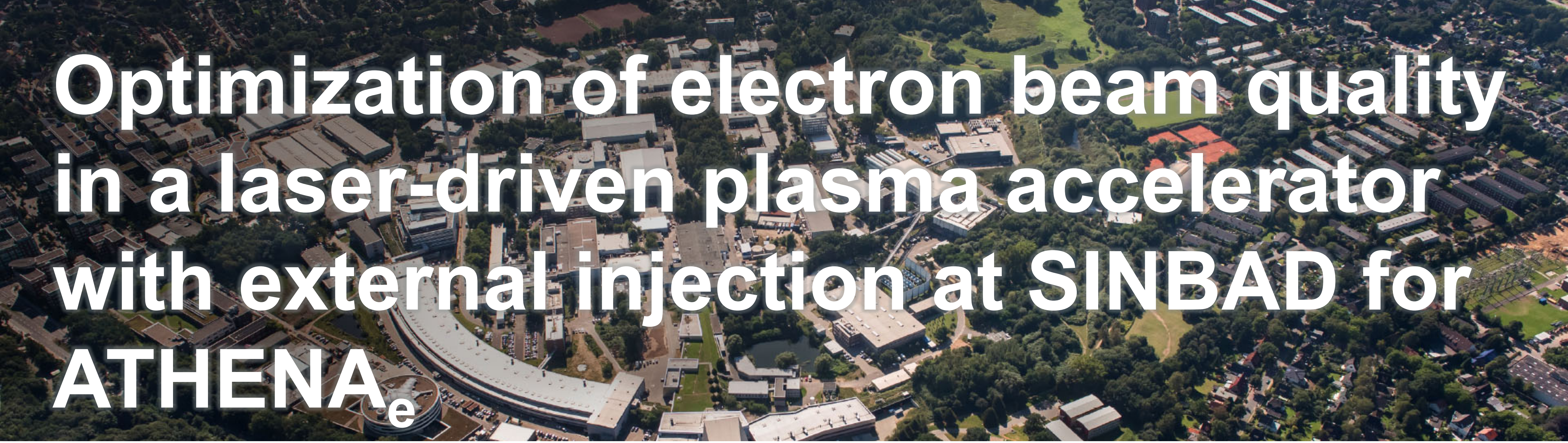


Optimization of electron beam quality in a laser-driven plasma accelerator with external injection at SINBAD for ATHENA$_e$

Elena Svystun, Ralph Assmann, Ulrich Dorda, Barbara Marchetti, Maria Weikum

Deutsches Elektronen-Synchrotron DESY

XXVI Russian Particle Accelerator Conference
October 1–5 2018, Protvino, Moscow Region , Russia

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

MTARD MATTER AND TECHNOLOGIES ACCELERATOR RESEARCH AND DEVELOPMENT

SINBAD

HELMHOLTZ GEMEINSCHAFT | ATHENA Accelerator Technology HElmholtz iNfrAstrcuture

DESY.

Outline

Potential experimental setup for laser-driven plasma acceleration with external injection:

2D simulations with the PIC code OSIRIS

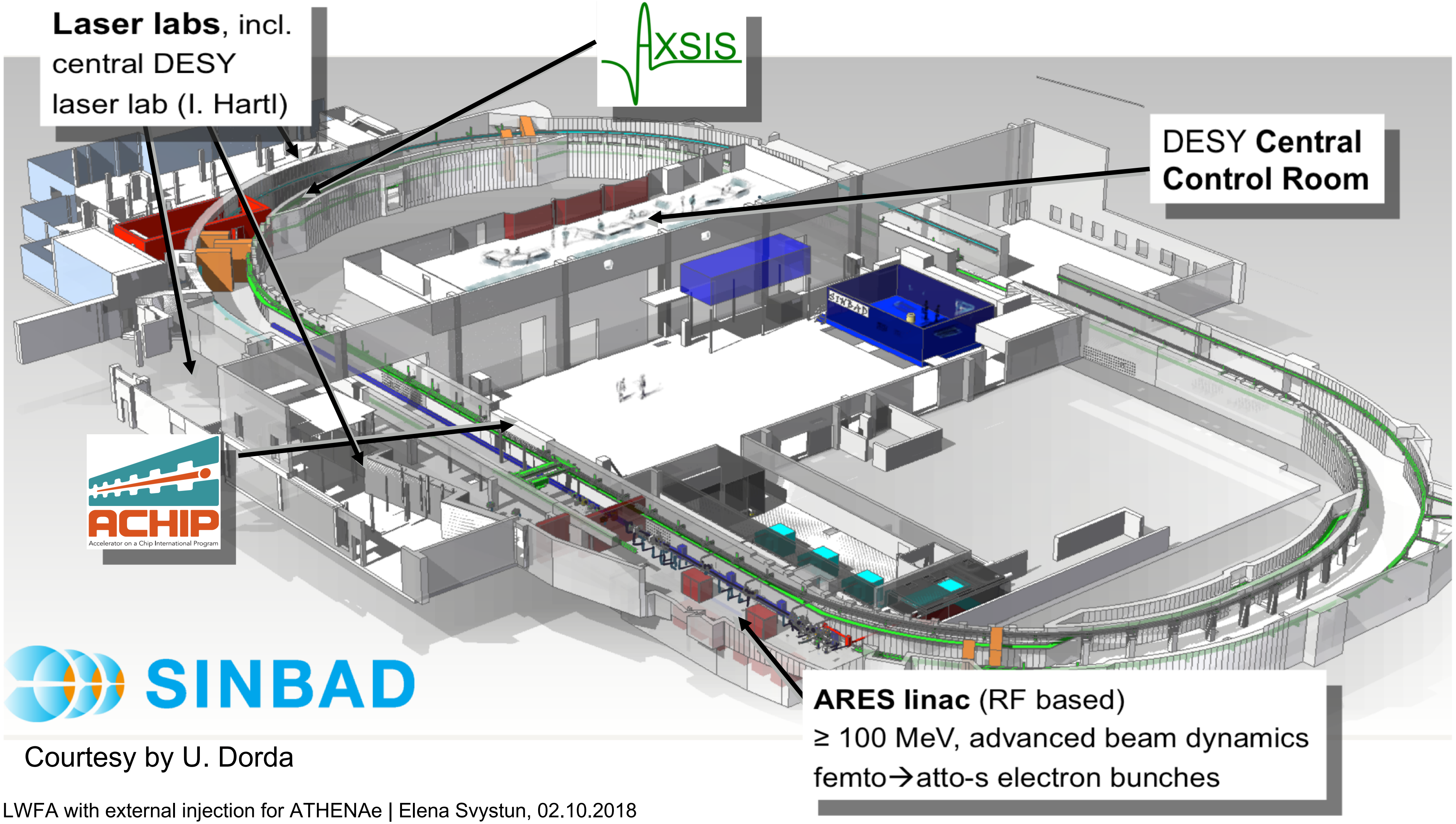
Start-to-end simulations with the PIC code FBPIC

- ✓ Emittance growth mitigation by tailoring the longitudinal density profile of the plasma entrance and exit with smooth vacuum-plasma and plasma-vacuum transitions (realistic plasma ramp profile)
- ✓ 3D simulations with the full 6D beam distributions
- ✓ Tolerance studies on the arrival time jitter between the electron beam and the external laser.

SINBAD: Short Innovative Bunches and Accelerators at DESY

Dedicated accelerator R&D facility

- ✓ SINBAD will host multiple, independent accelerator R&D experiments



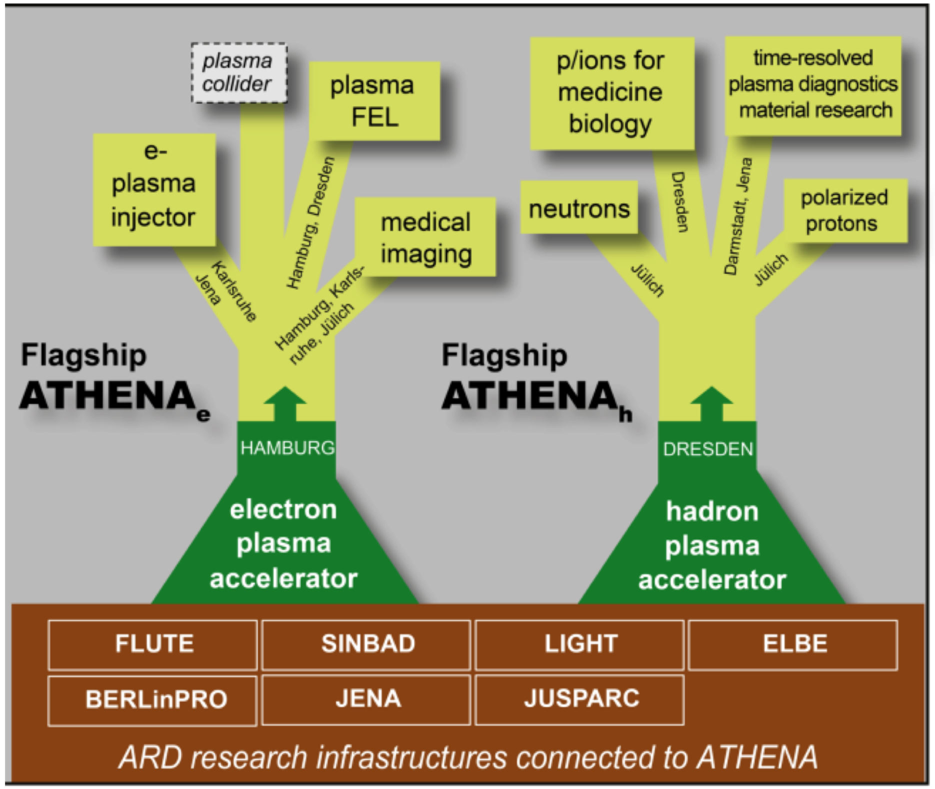
Courtesy by U. Dorda

ATHENA: Accelerator Technology HElmholtz iNfrAstructure

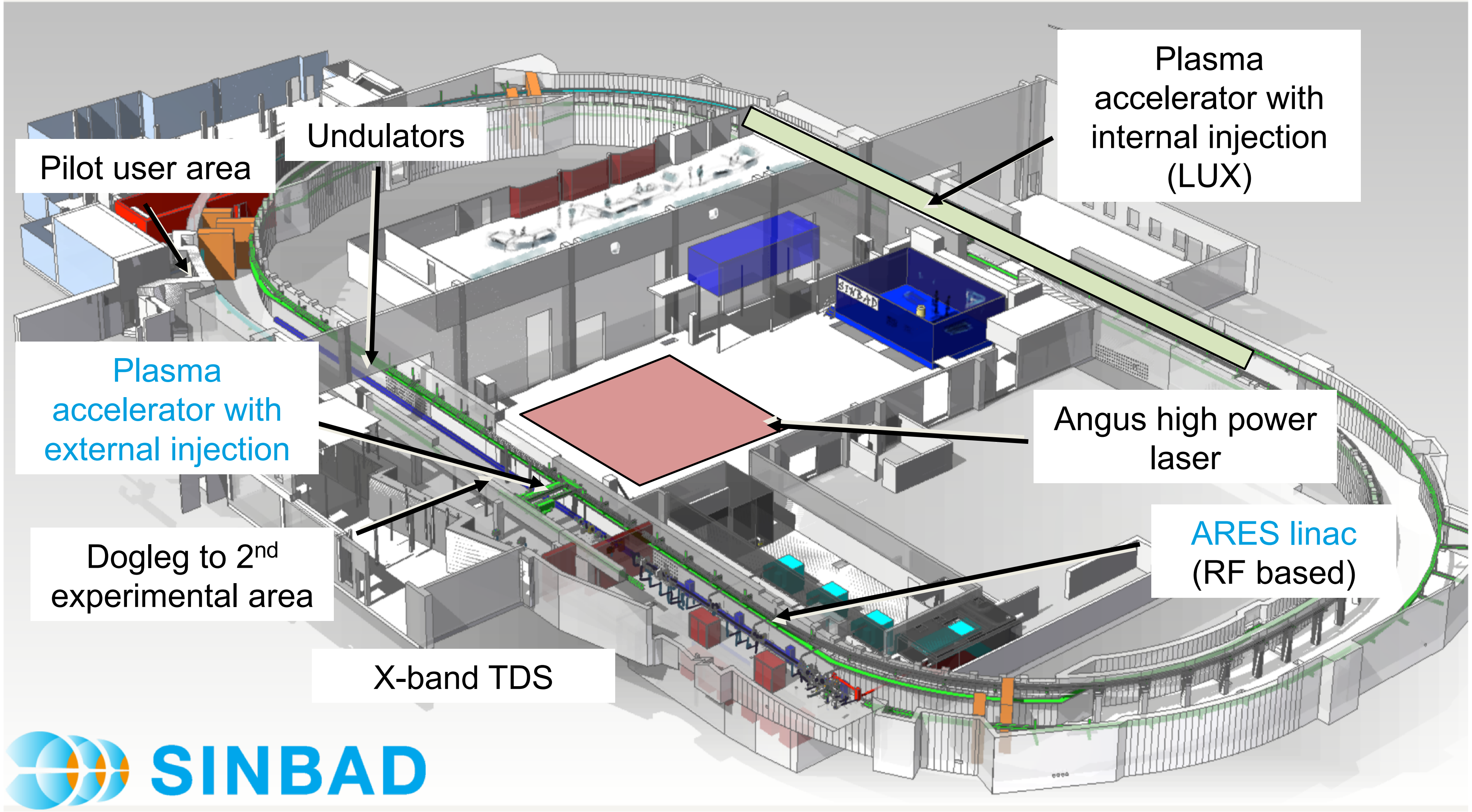
A new R&D platform focusing on accelerator technologies and drawing on the resources of 7 Helmholtz centers

HZB Helmholtz Zentrum Berlin · DESY · HZDR · HI Jena Helmholtz Institute Jena · KIT Karlsruhe Institute of Technology · JÜLICH FORSCHUNGSZENTRUM · GSI

- ✓ ATHENA **provides the infrastructure** required for **bringing compact and cost-effective plasma accelerators to user readiness**.
- ✓ Flagship projects will be set up in Hamburg (electrons - ATHENA$_e$) and Dresden (hadrons - ATHENA$_h$).
- ✓ Applications for science, medicine and industry will be developed in all centers.
- ✓ **ATHENA$_e$** flagship will be hosted at SINBAD.



ATHENA$_e$ @ SINBAD

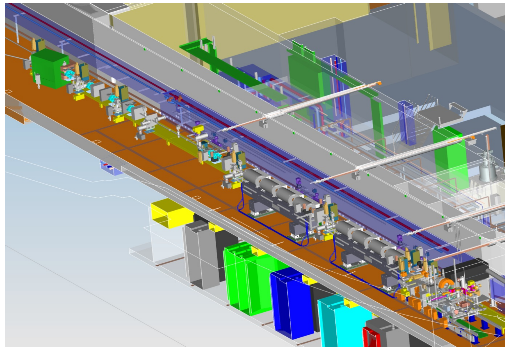


Simulation parameters

SINBAD-ARES-linac

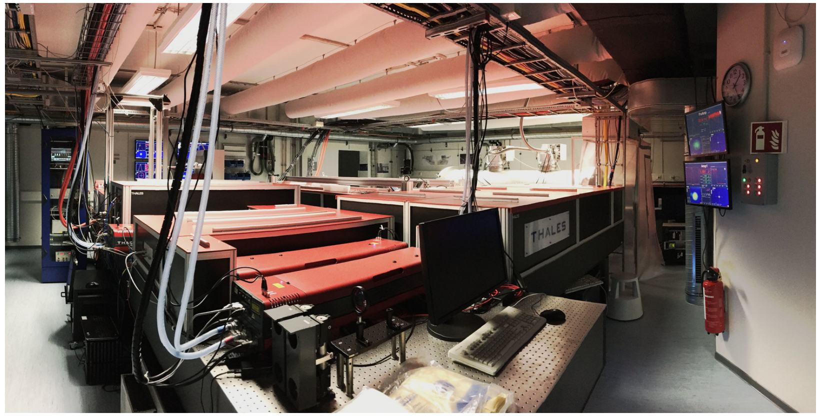
Normal conducting S-band electron linac for the production of ultra-short bunches

Single pulse @ 50Hz. Arrival time jitter stability < 10 fs RMS



	WP1 - I☆	WP1 - II☆☆
Charge [pC]	0.7	0.75
Energy [MeV] (incl. Bunch compression)	**99.7**	**99.9**
Relative energy spread [%]	**0.38**	**0.19**
σ_z (RMS) [μm]	0.238 (0.79 fs)	0.15 (0.5 fs)
σ_x (RMS) [μm]	5.0	0.7
σ_y (RMS) [μm]	5.3	0.7
Normalized transverse emittance, $\varepsilon_{n,x}$ [μm]	**0.138**	**0.09**
Normalized transverse emittance, $\varepsilon_{n,y}$ [μm]	**0.144**	**0.1**
β_x / β_y [mm]	33.7 / 38.2	1 / 0.99

ANGUS laser



- ✓ α_0 = 1.8;
- ✓ τ_l = 25 fs (FWHM);
- ✓ w_0 = 42.47 μm;
- ✓ 196.2 TW power;
- ✓ 5.2 J energy;
- ✓ repetition rate of 5 Hz

☆J. Zhu et al., *NIMA* 829, 229 (2016)

☆☆ J. Zhu, *Ph.D. thesis* (2017)

Simulation parameters

✧ Plasma channel:

- ✓ with a radially parabolic density profile of the form $n(r)=n_0+\Delta n(r/r_{ch})^2$,
- ✓ the channel depth $\Delta n=0.626 n_0$,
- ✓ the channel width $r_{ch} = 42.47$ µm,
- ✓ the on-axis plasma density $n_0 = 10^{17}$ cm^{-3}.
- ✓ Density up-ramp length: 1 cm;
- ✓ Acceleration region length : 9.5 cm;
- ✓ Density down-ramp length: 1 cm.

✧ Simulation window (OSIRIS) :

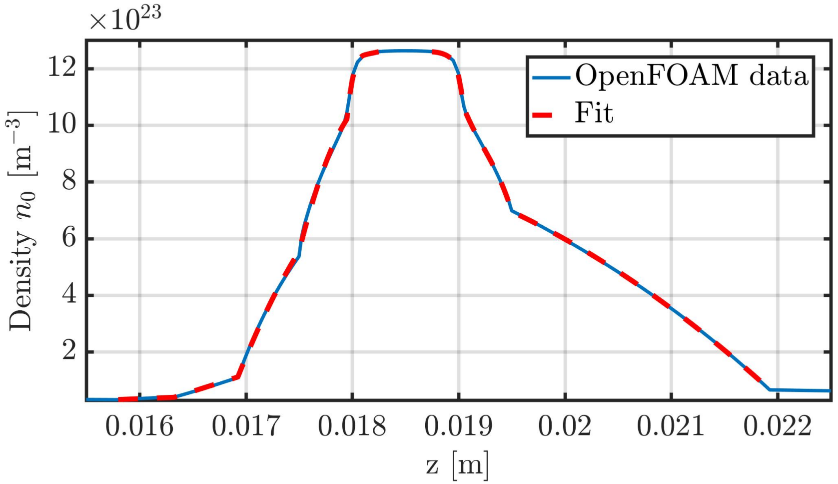
- ✓ 134.44 × 537.75 [µm^2] and 100.82 × 420.12 [µm^2];
- ✓ Resolution: 0.0127 µm × 0.98 µm;
- ✓ Yee field solver (Yee FS).

✧ Simulation window (FBPIC) :

- ✓ 118 × 420 [µm^2];
- ✓ Resolution: 0.0222 µm × 0.5 µm;
- ✓ Spectral field solver;
- ✓ Boosted frame, $\gamma_{bf} = 5$.

Longitudinal density profile of the plasma entrance and exit

Case 1



Realistic plasma target density profile simulated with OpenFOAM (C. Thornton) [solid line] and a piecewise polynomial fit of the up- and down-ramp [dashed lines] to be used for particle-in-cell simulations of a realistic plasma ramp shape.

M. Weikum, *Ph.D. thesis* (2017).

Case 2

$$f(z) = \frac{1}{\left(1 \pm (z - z_{0,d|u})/l_{d|u}\right)^2},$$

$z_{0,u}$ and $z_{0,d}$ are the longitudinal coordinates of the start of the up-ramp and the down-ramp respectively;
l_u and l_d are the optimized characteristic scale lengths of the plasma ramps given by

$$l_{d|u} = \beta_{p0}\sqrt{\left(\frac{\pi}{\ln(\beta_{goal}/\beta_i)}\right)^2 + \frac{1}{4}} = \frac{L_{d|u}}{\beta_{goal}/\beta_i - 1},$$

β_{p0} is the beta function of the matched electron beam in PBAs,

$$\beta_{p0} = \sqrt{\gamma_b c m_e/(ge)};$$

γ_b is the beam Lorentz factor;
g is the transverse focusing field in the plasma;
β_i is the initial beta function of the beam;
β_{goal} is the matched beta function of the beam;
L_u and L_d are the lengths of the plasma up-ramp and the down-ramp respectively.

X.L. Xu et al., Phys. Rev. Lett., 116 124801 (2016).

OSIRIS code

OSIRIS framework

- ✓ Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- ✓ Developed by the osiris.consortium: UCLA + IST

TÉCNICO LISBOA

UCLA

Osiris 3.0

http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/

Code features:

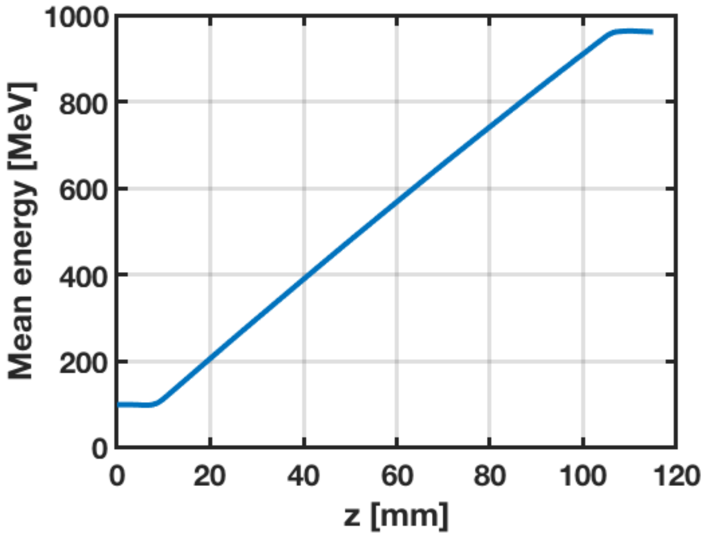
- ✓ Scalability to ~ 1.6 M cores
- ✓ Hybrid MPI/OpenMP parallelized
- ✓ SIMD hardware optimized
- ✓ Parallel I/O
- ✓ Dynamic Load Balancing
- ✓ QED module
- ✓ Particle merging
- ✓ GPGPU support
- ✓ Xeon Phi support

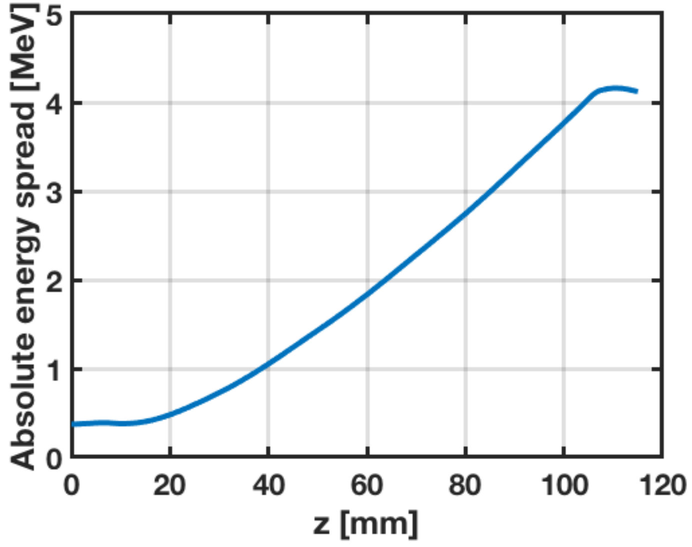
Main limitations in 2D simulations of LWFA with external injection:

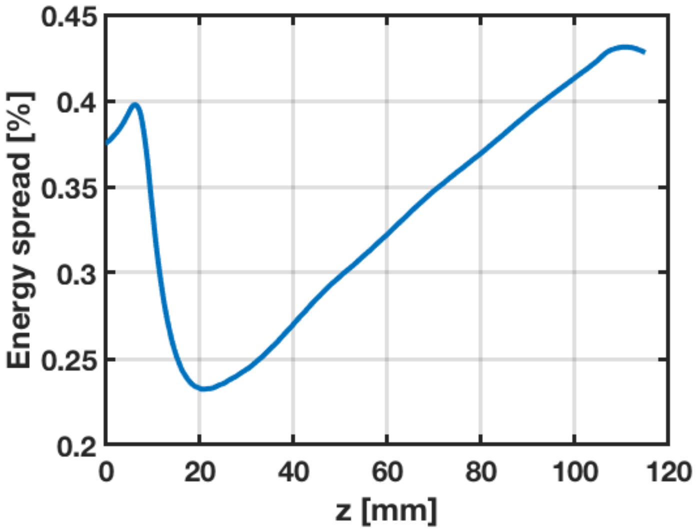
- ✓ the read-in of full 6D beam distributions in 2D is not available ⇒ initial symmetric Gaussian distribution of the injected beam in coordinate and momentum;
- ✓ Numerical Cherenkov radiation (NCR) with the Yee FS;
- ✓ In the NCR-suppressing FS (Lehe FS) the laser group velocity is higher than the speed of light ⇒ numerical electron beam-laser dephasing;
- ✓ Beam loading effect is stronger than in 3D simulations.

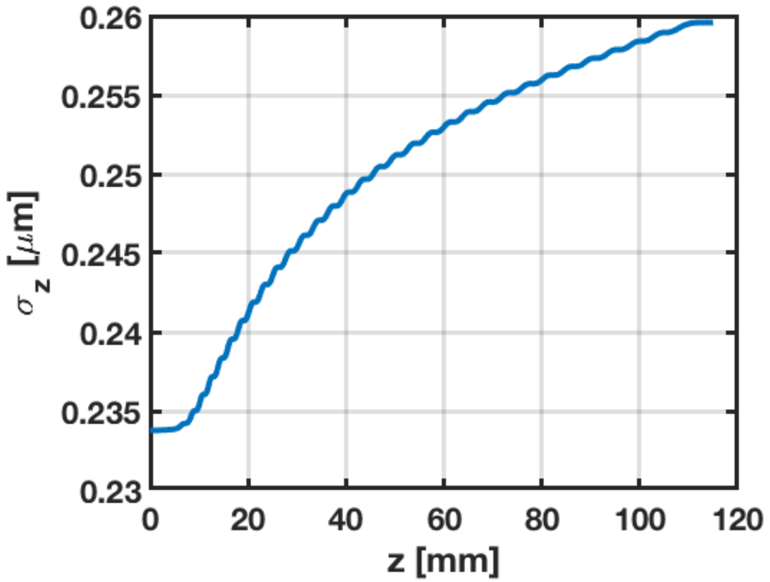
Evolution of the electron beam properties (WP1 - I)

Plasma ramps: case 1, electron beam-laser offset = 52.79 µm



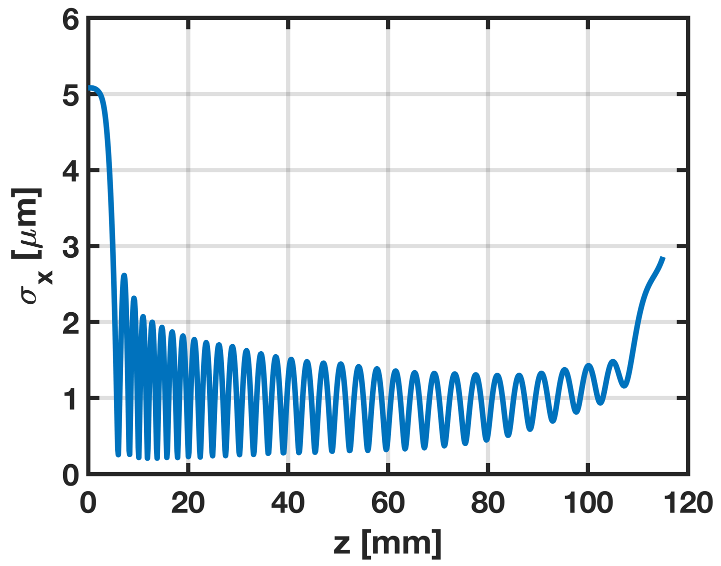


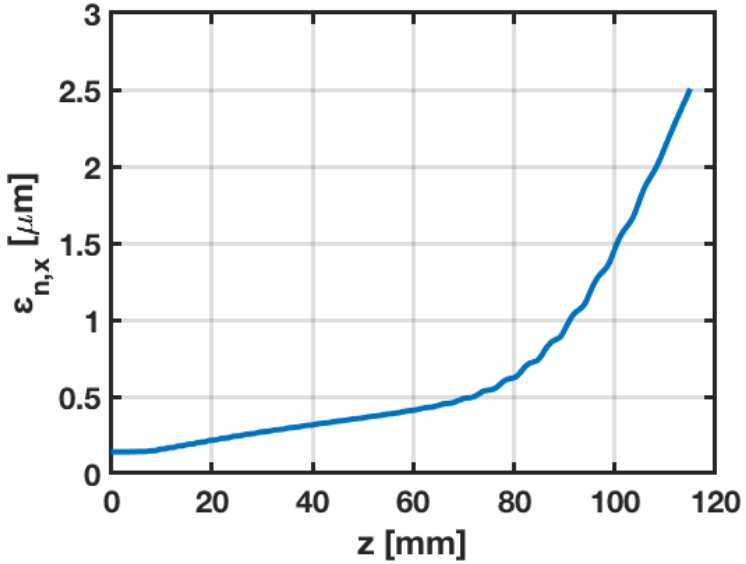


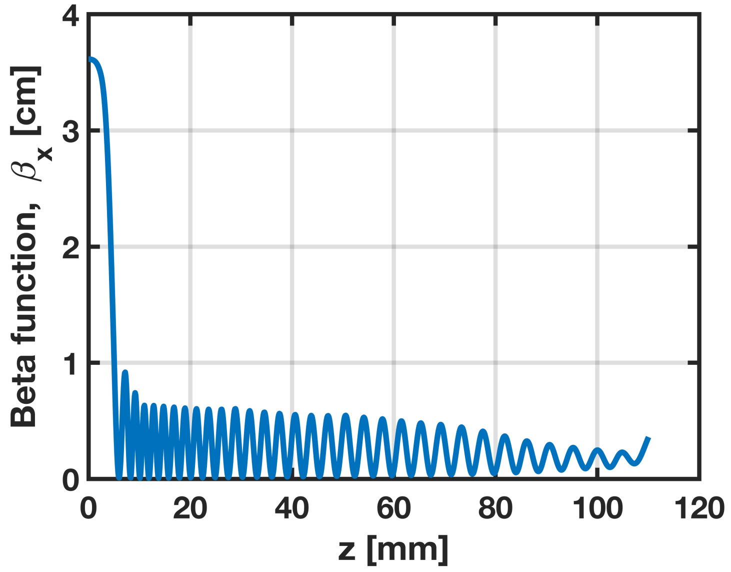


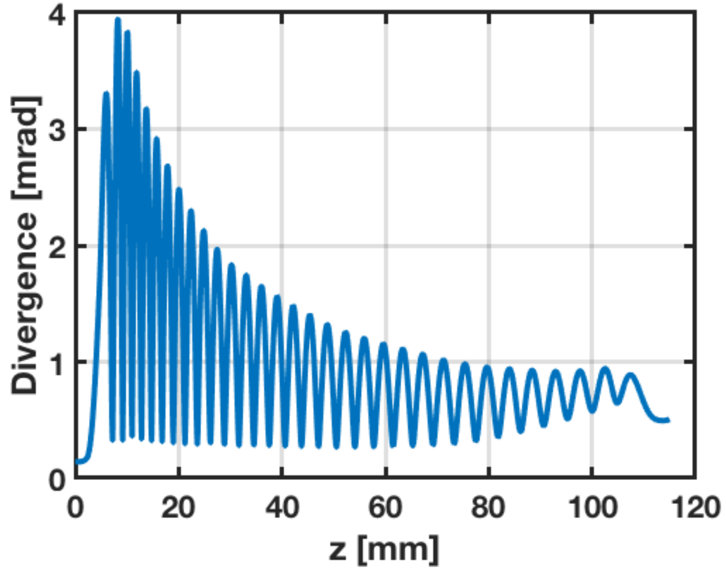
Evolution of the electron beam properties (WP1 - I)

Plasma ramps: case 1, electron beam-laser offset = 52.79 μm





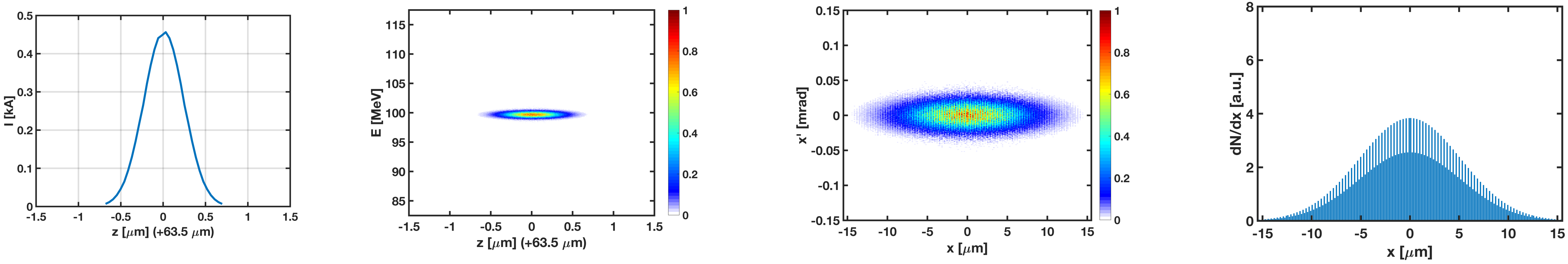




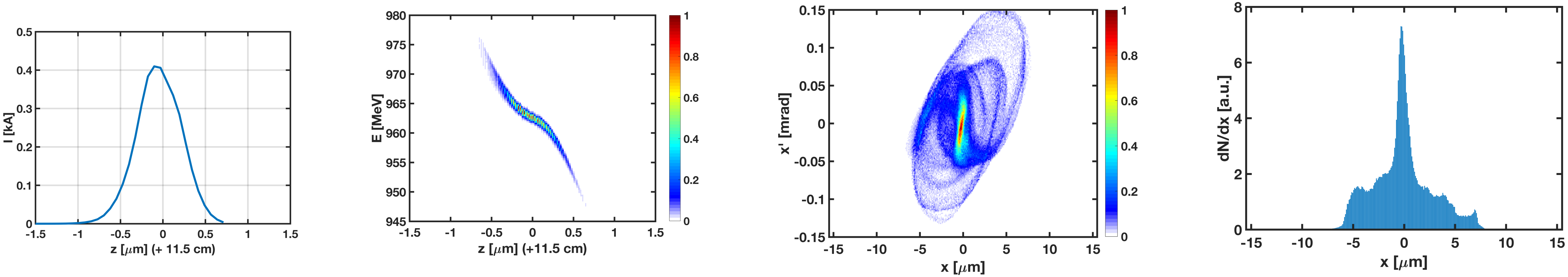
Current distribution, longitudinal and transverse phase-spaces of the accelerated electron beam (WP1 - I)

Before injection into the plasma:

Plasma ramps: case 1, electron beam-laser offset = 52.79 µm



After extraction from the plasma:

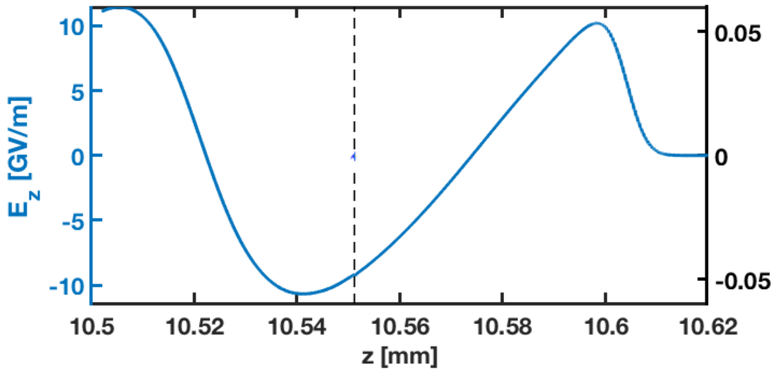


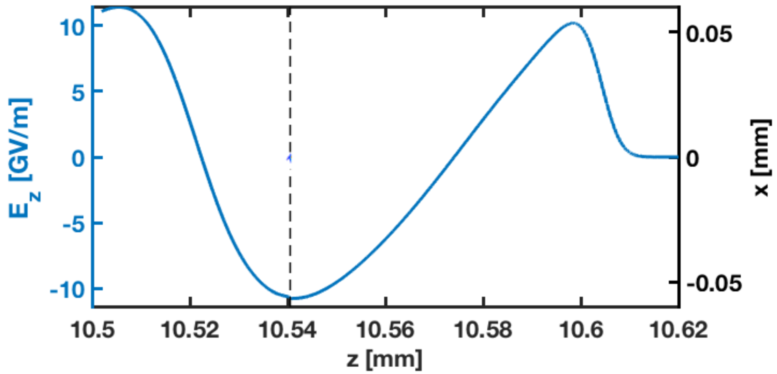
The colormap describes normalized charge.

Electron beam parameters (WP1 - I)

Parameters	at the plasma entrance	after acceleration		
Plasma ramp		Case 1	Case 2	
Electron beam-laser offset [μm]		52.79	52.79	63.43
Charge [pC]	0.7	0.7	0.7	0.7
Energy [MeV]	99.2	963	941.2	1169.6
Relative energy spread [%]	0.376	0.428	0.381	**0.315**
σ_z (RMS) [as]	780	866	830	829
σ_x (RMS) [μm]	5.1	2.86	4.5	5.6
Normalized transverse emittance, $\varepsilon_{n,x}$ [μm]	0.14	0.41 (z = 6 cm) | 2.5* (z = 11.5 cm)	5.1*	8.4*

*due to numerical Cherenkov radiation.





FBPIC code

Open source electromagnetic Particle-In-Cell code

Quasi-3D geometry
- ✓ 3D accuracy at 2D costs.

Spectral electromagnetic solver
- ✓ Highest precision
- ✓ No numerical artifacts

Boosted frame
- ✓ Accelerate simulations by orders of magnitude
- ✓ Instability-free solver

Highly parallel & written in Python
- ✓ CUDA GPU acceleration
- ✓ Multi-GPU domain decomposition

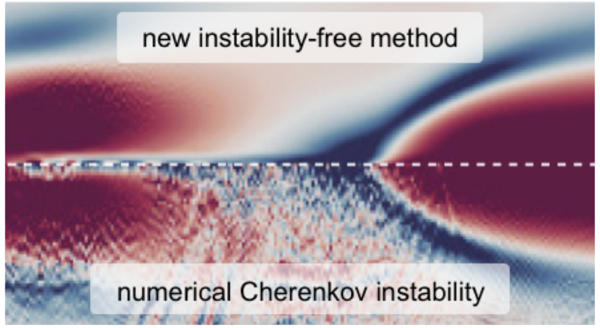
R. Lehe et al., Comput. Phys. Commun. 203, 66-82 (2016).

High accuracy spectral solver
Spectral solvers mitigate the common numerical errors of traditional simulation codes

S. Jalas et al., Phys. Plasmas 24, 033115 (2017).

Stability of Lorentz-boosted frame simulations
A novel method enables stable boosted frame simulations

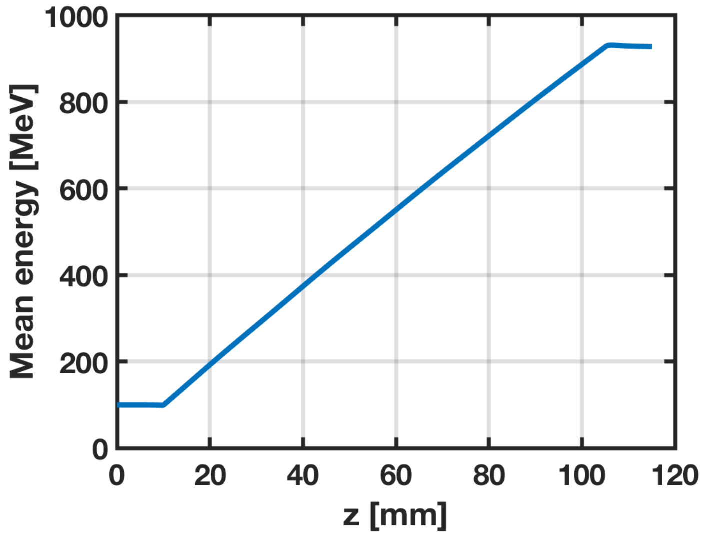
Boosted frame technique
- ✓ Orders of magnitude speed up of simulations
- ✓ Application was limited by severe instability
- ✓ New solver intrinsically eliminates the instability

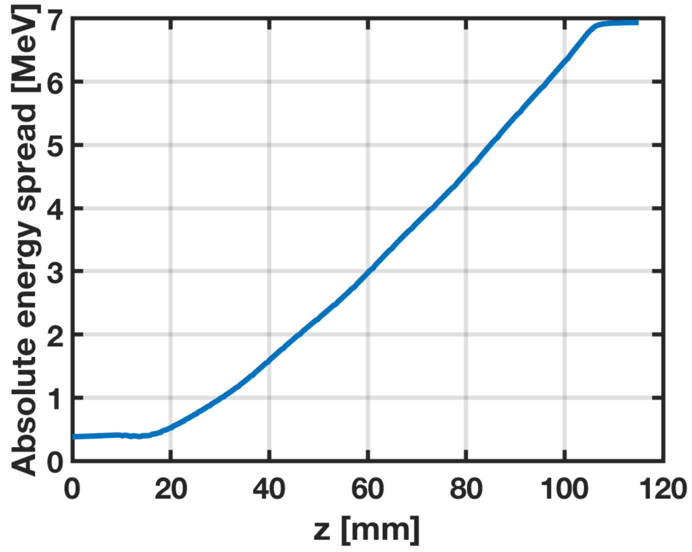


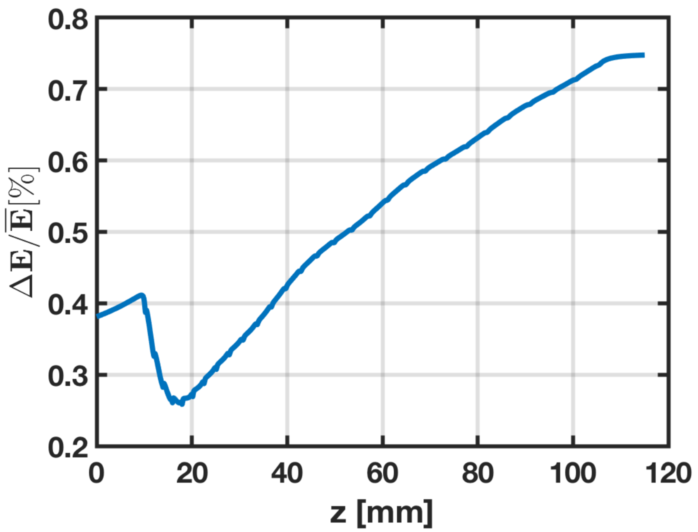
M. Kirchen et al., Phys. Plasmas 23, 100704 (2016).

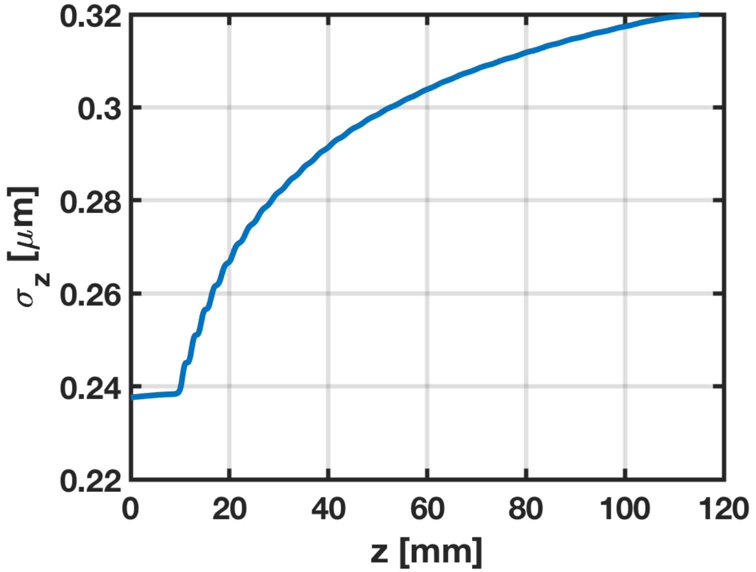
Evolution of the electron beam properties (WP1 - I)

Plasma ramps: case 2, electron beam-laser offset = 52.79 µm



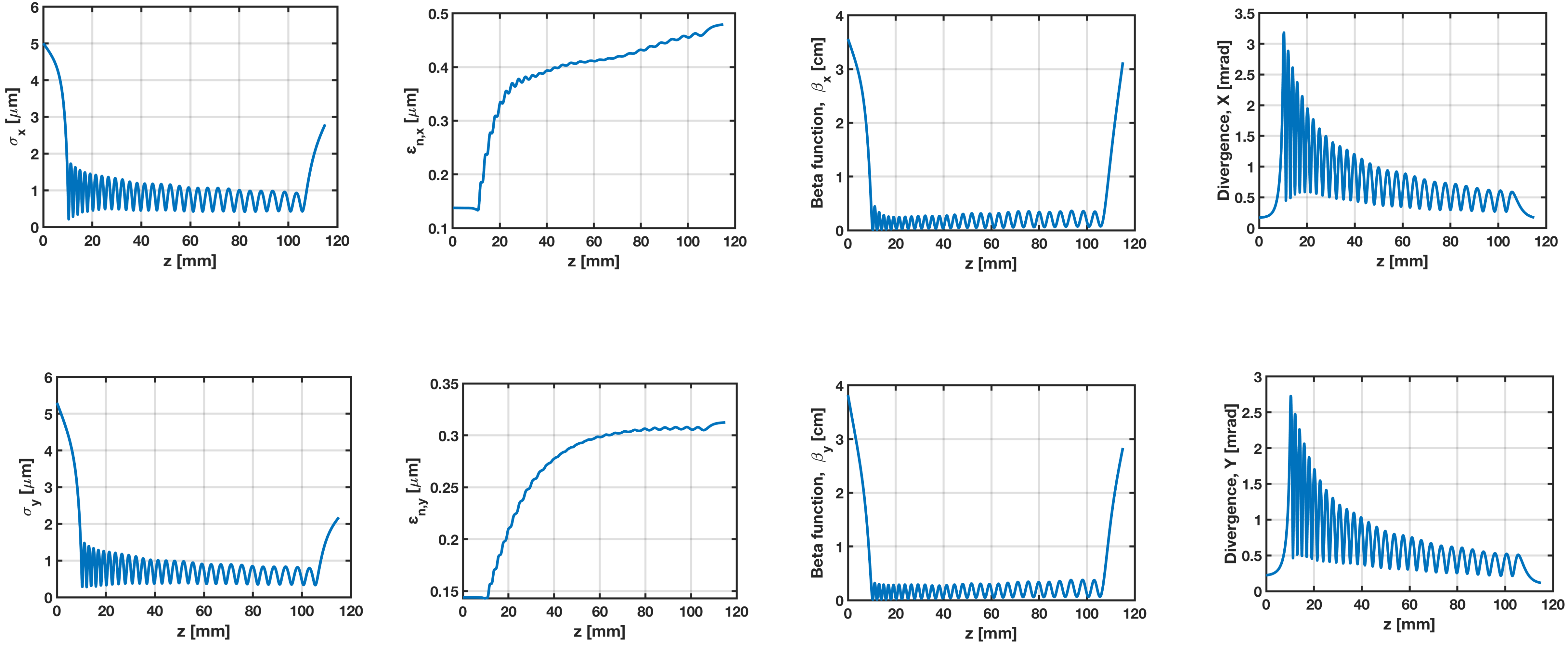






Evolution of the electron beam properties (WP1 - I)

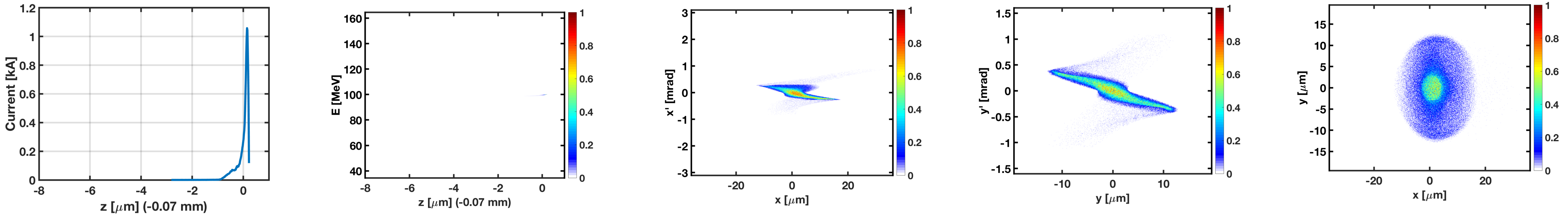
Plasma ramps: case 2, electron beam-laser offset = 52.79 µm



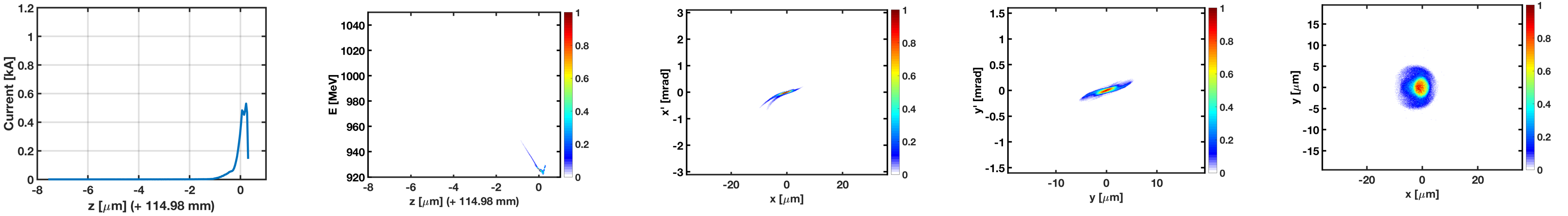
Properties of the accelerated electron beam (WP1 - I)

Plasma ramps: case 2, electron beam-laser offset = 52.79 μm

Before injection into the plasma:



After extraction from the plasma:

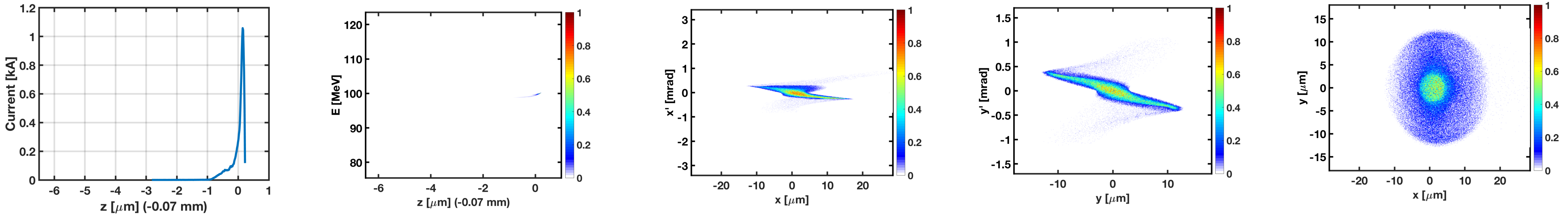


The colormap describes normalized charge.

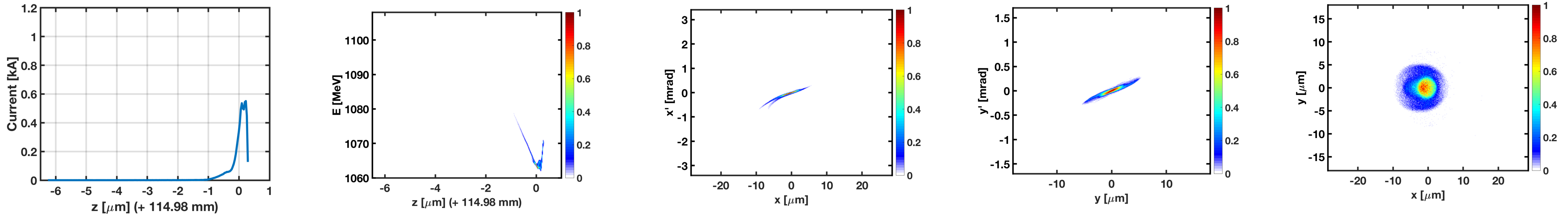
Properties of the accelerated electron beam (WP1 - I)

Plasma ramps: case 2, electron beam-laser offset = 58.1 µm

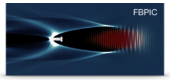
Before injection into the plasma:



After extraction from the plasma:



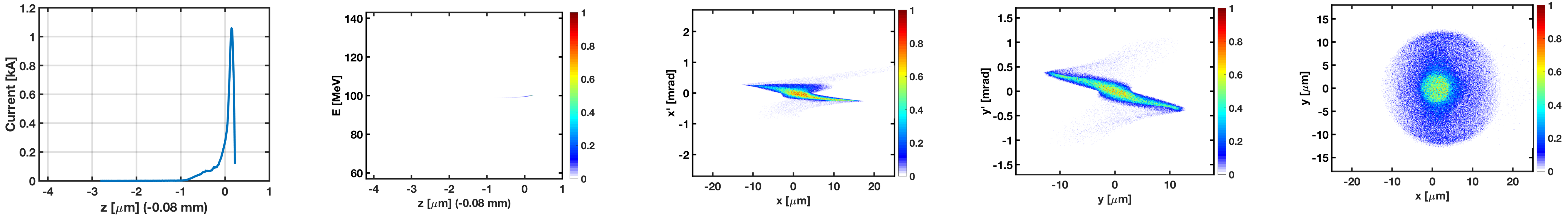
The colormap describes normalized charge.



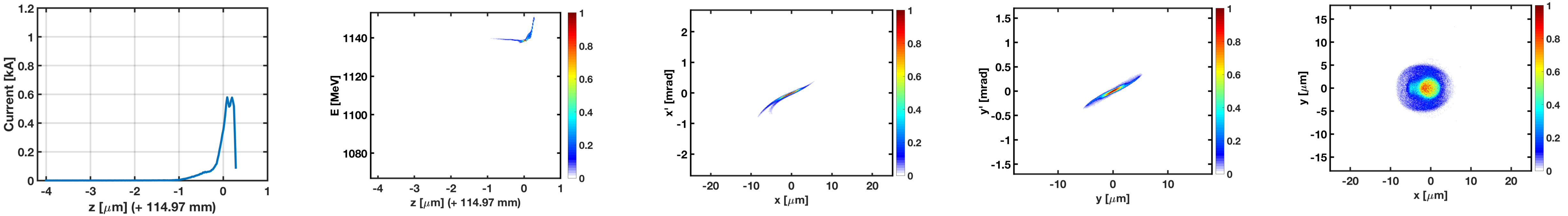
Properties of the accelerated electron beam (WP1 - I)

Plasma ramps: case 2, electron beam-laser offset = 63.43 μm

Before injection into the plasma:

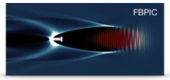


After extraction from the plasma:

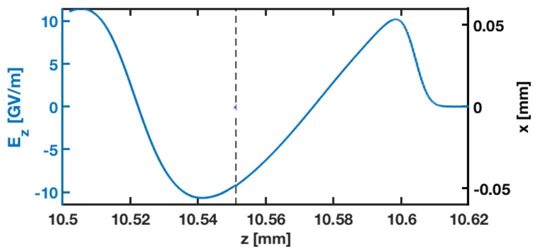


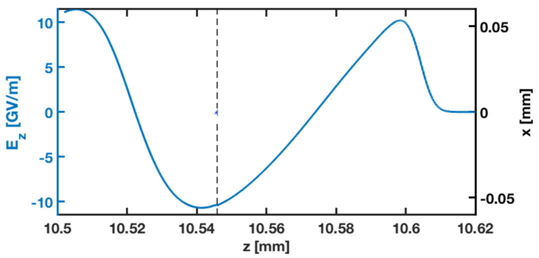
The colormap describes normalized charge.

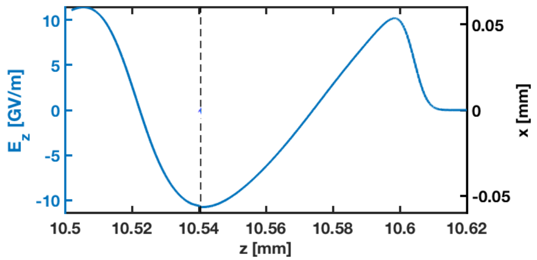
Electron beam parameters (WP1 – I)

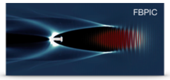


Parameters	**at the plasma entrance**☆	**after acceleration**		
Plasma ramp		Case 2		
Electron beam-laser offset [µm]		52.79	58.1	**63.43**
Charge [pC]	0.7	0.7	0.7	**0.7**
Energy [MeV]	**99.7**	928	1065.7	**1140.7**
Relative energy spread [%]	**0.38**	0.747	0.357	**0.287**
σ_z (RMS) [µm]	0.238	0.32	0.3	**0.28**
σ_x (RMS) [µm]	5.0	2.8	2.7	**2.58**
σ_y (RMS) [µm]	5.3	2.2	2.15	**2.15**
Normalized transverse emittance, $\varepsilon_{n,x}$ [µm]	**0.138**	0.48	0.42	**0.41**
Normalized transverse emittance, $\varepsilon_{n,y}$ [µm]	**0.144**	0.31	0.29	**0.28**



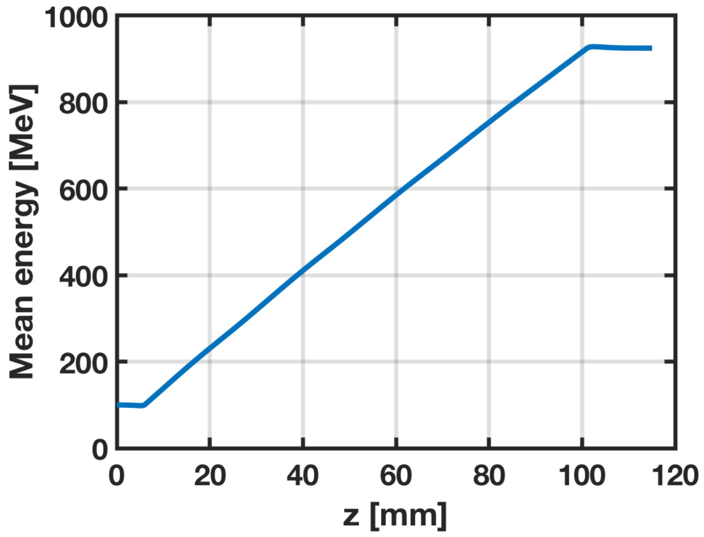


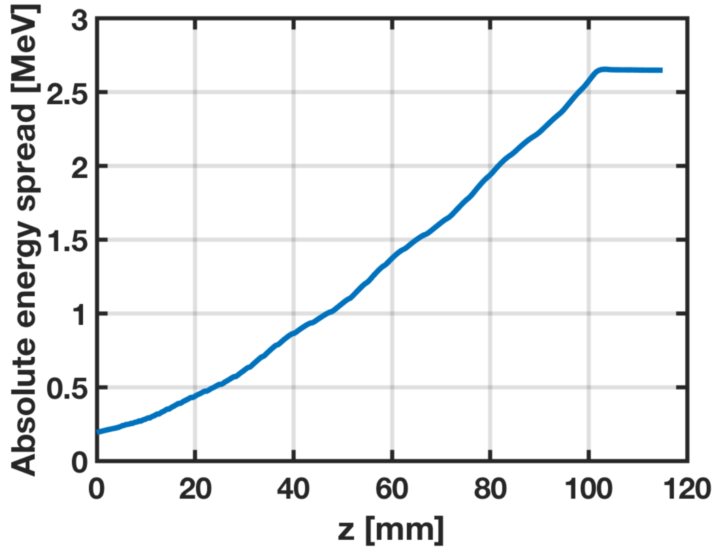


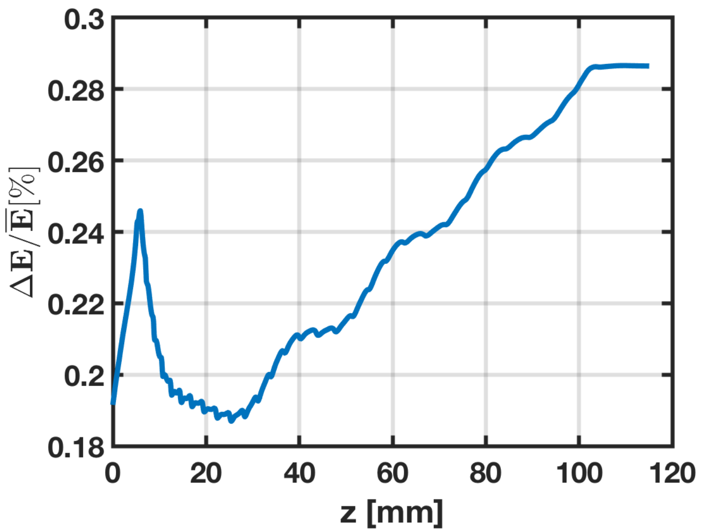


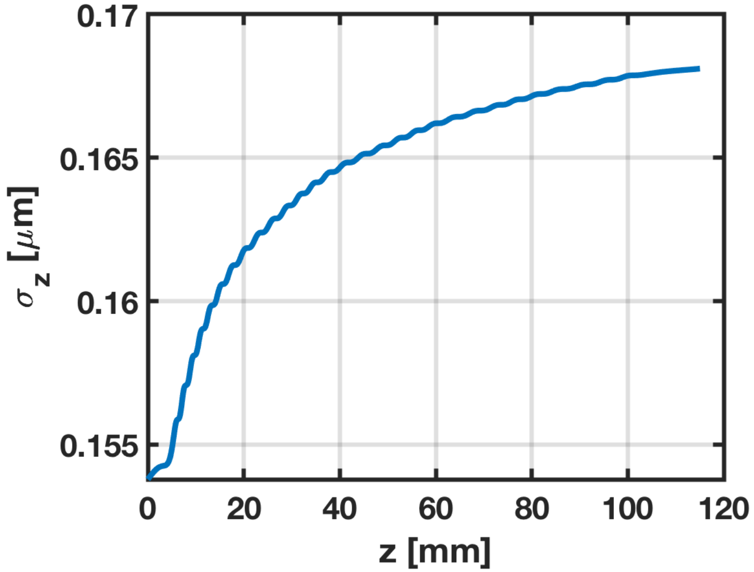
Evolution of the electron beam properties (WP1 - II)

Plasma ramps: case 2, electron beam-laser offset = 52.79 µm



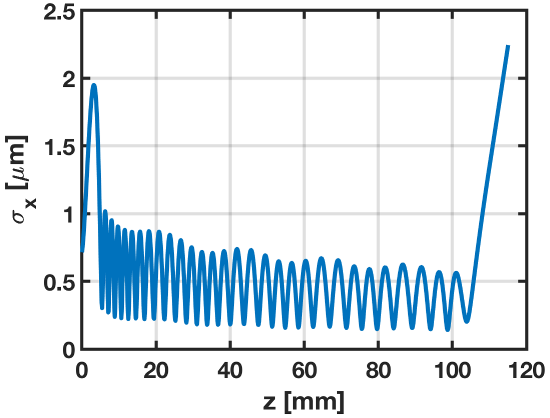


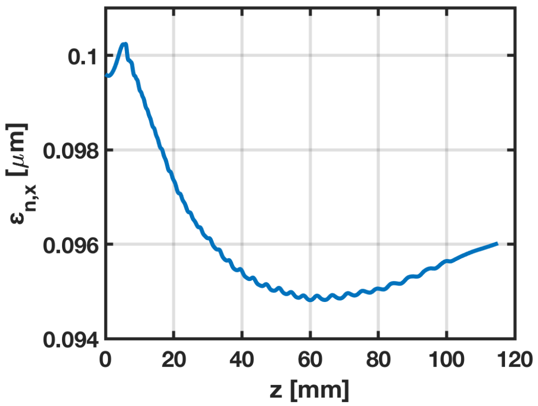


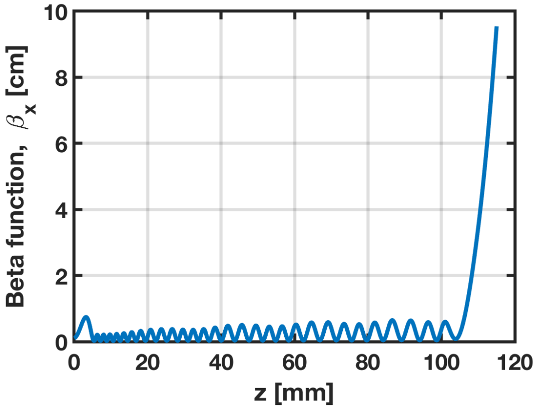


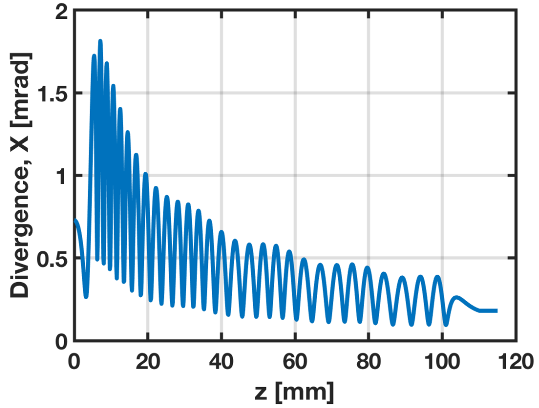
Evolution of the electron beam properties (WP1 - II)

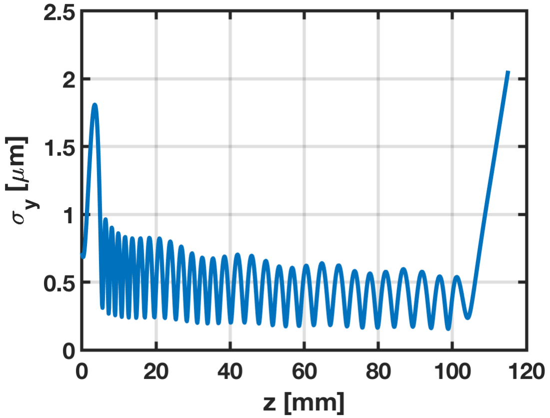
Plasma ramps: case 2, electron beam-laser offset = 52.79 μm

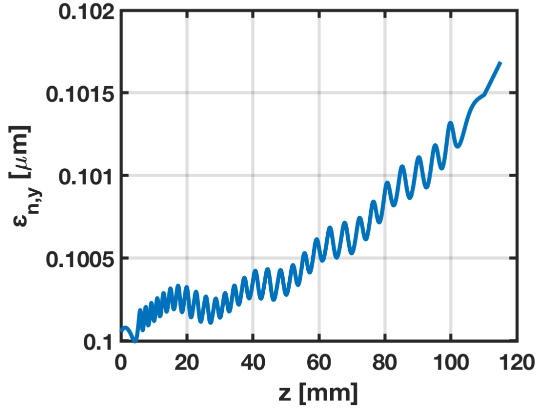


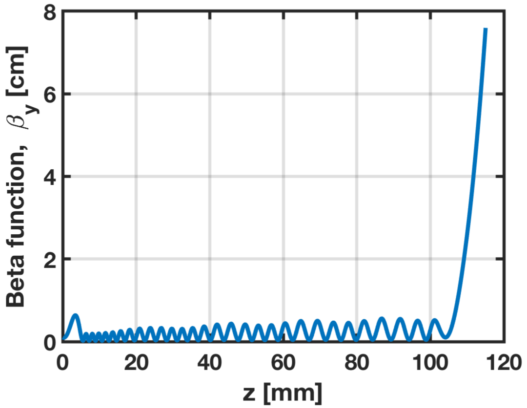


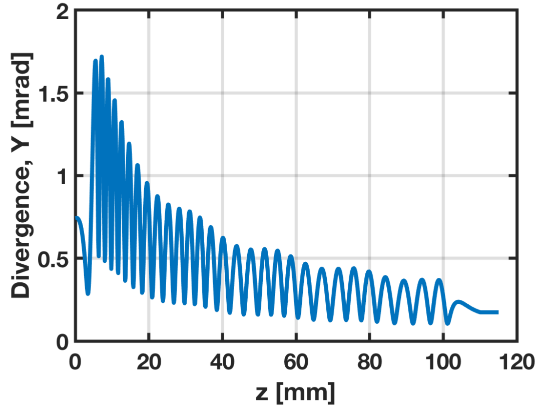








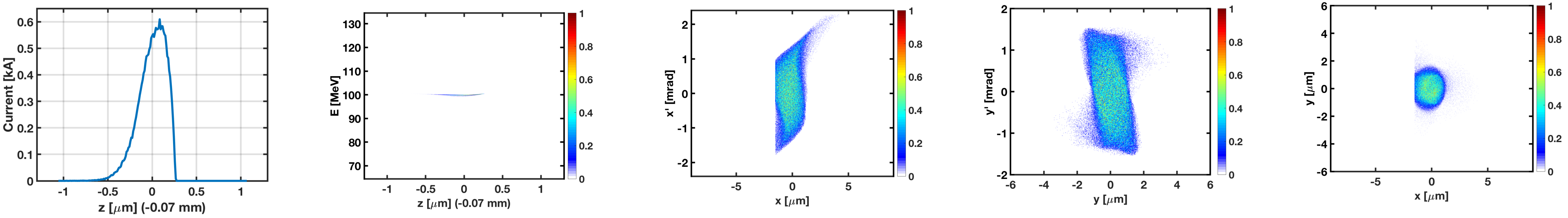




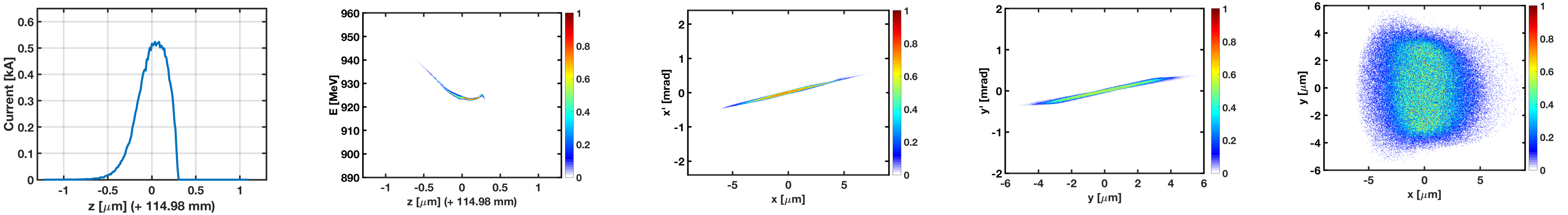
Properties of the accelerated electron beam (WP1 - II)

Plasma ramps: case 2, electron beam-laser offset = 52.79 µm

Before injection into the plasma:



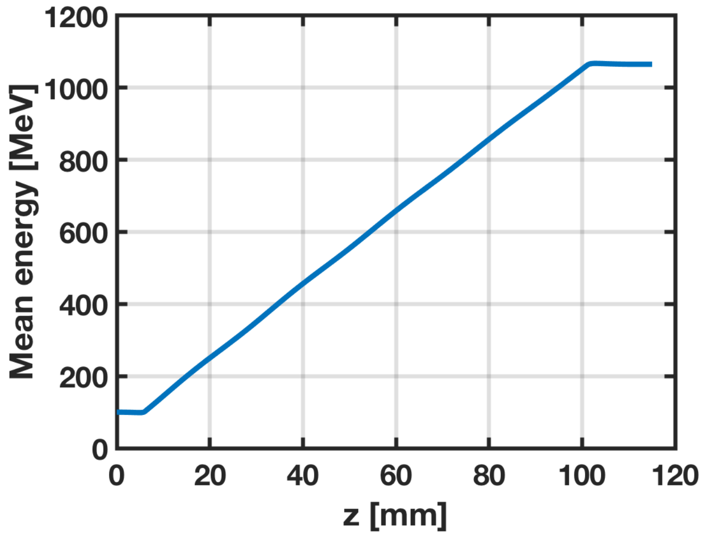
After extraction from the plasma:

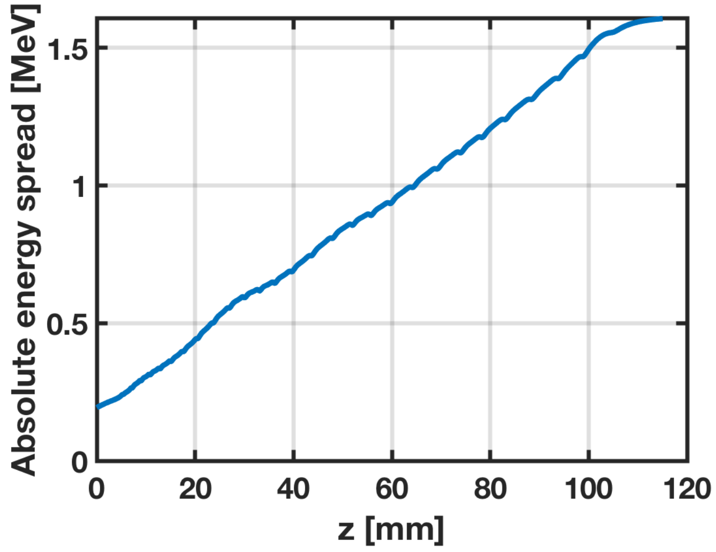


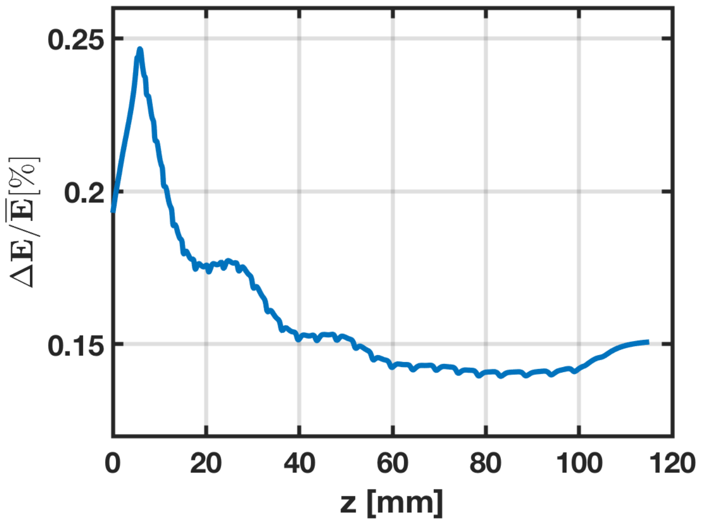
The colormap describes normalized charge.

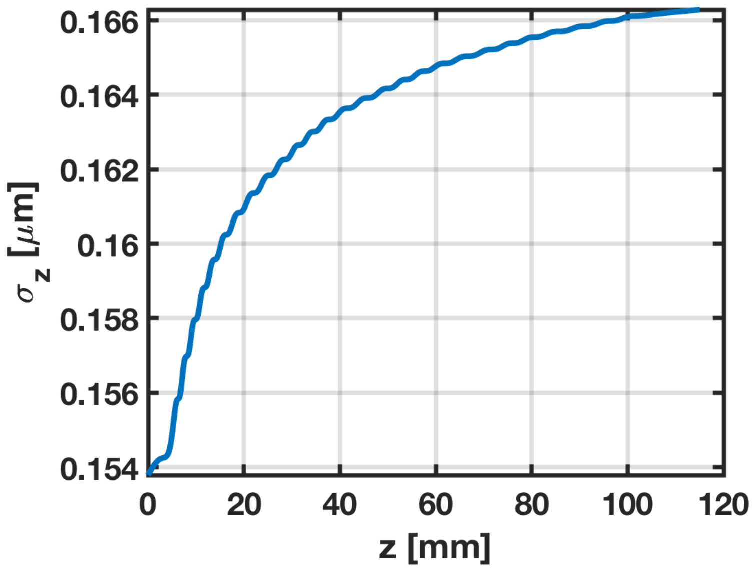
Evolution of the electron beam properties (WP1 - II)

Plasma ramps: case 2, electron beam-laser offset = 58.1 μm



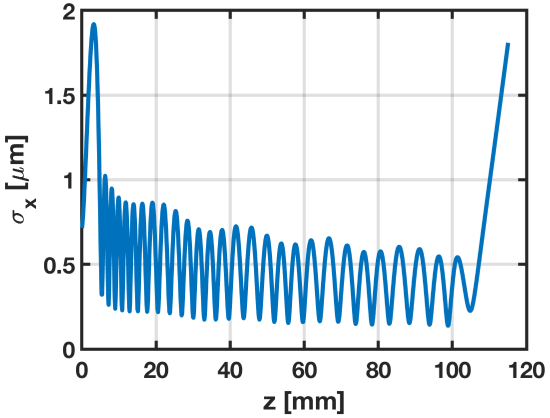


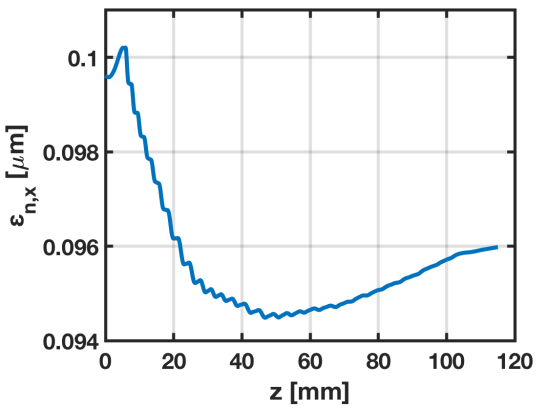


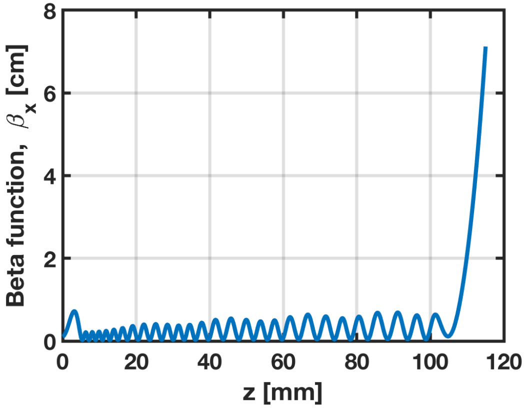


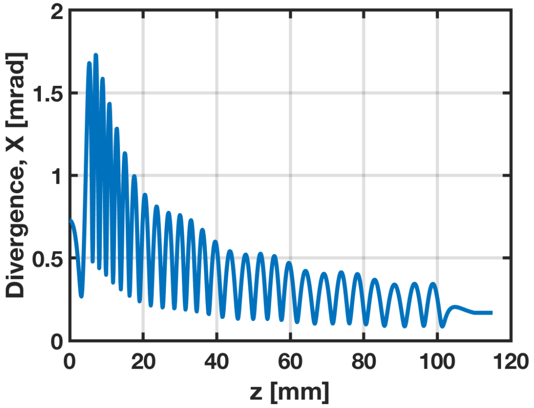
Evolution of the electron beam properties (WP1 - II)

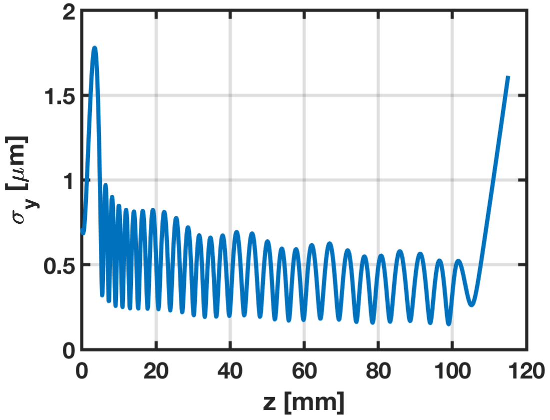
Plasma ramps: case 2, electron beam-laser offset = 58.1 µm

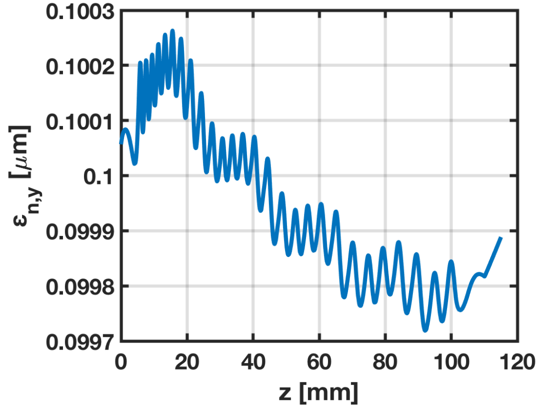


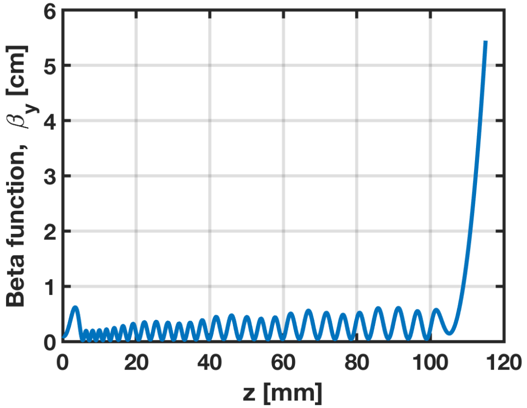


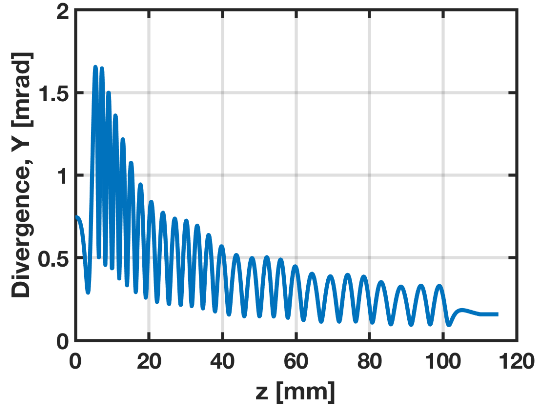








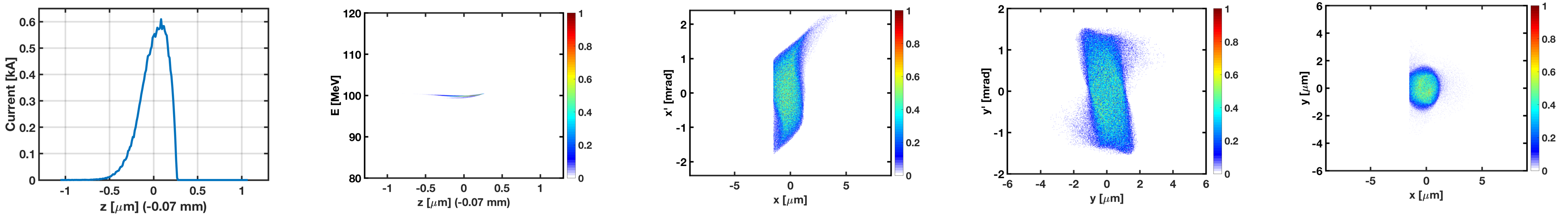




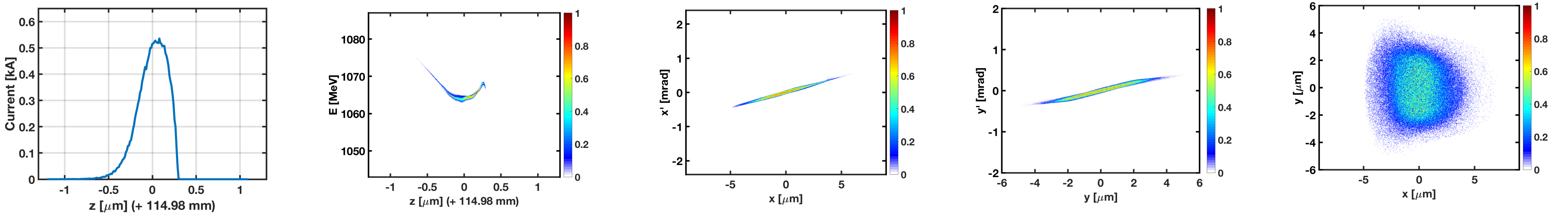
Properties of the accelerated electron beam (WP1 - II)

Plasma ramps: case 2, electron beam-laser offset = 58.1 µm

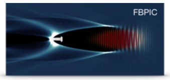
Before injection into the plasma:



After extraction from the plasma:



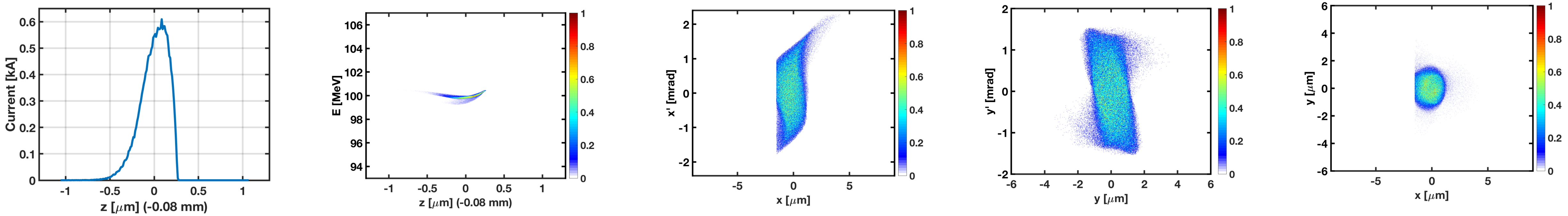
The colormap describes normalized charge.



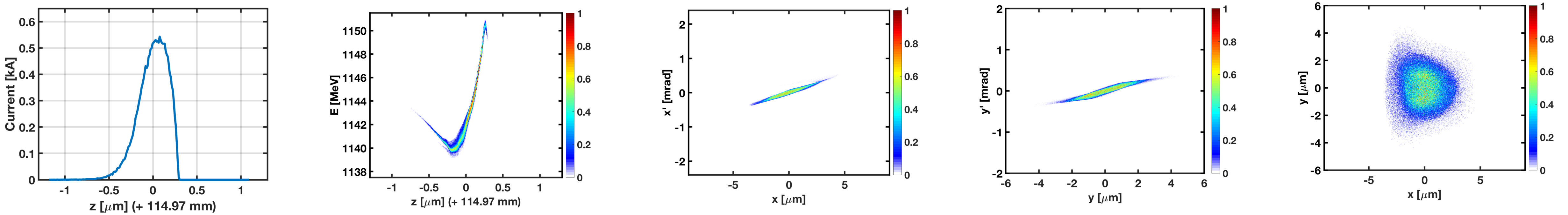
Properties of the accelerated electron beam (WP1 - II)

Plasma ramps: case 2, electron beam-laser offset = 63.43 µm

Before injection into the plasma:

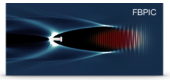


After extraction from the plasma:

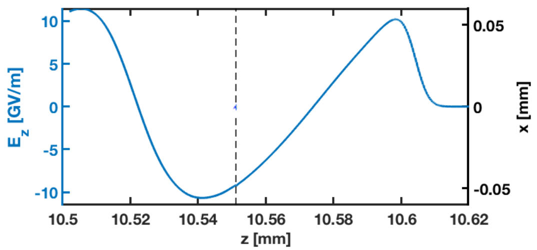


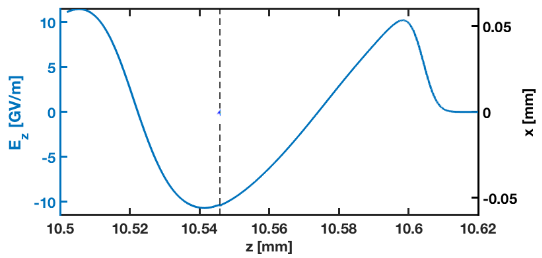
The colormap describes normalized charge.

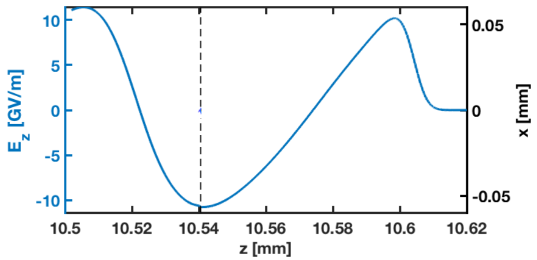
Electron beam parameters (WP1 - II)



Parameters	**at the plasma entrance☆**	**after acceleration**		
Plasma ramp			Case 2	
Electron beam-laser offset [µm]		52.79	**58.1**	63.43
Charge [pC]	0.75	0.75	**0.75**	0.75
Energy [MeV]	**99.9**	925	**1065.2**	1143
Relative energy spread [%]	**0.19**	0.28	**0.15**	0.25
σ_z (RMS) [µm]	0.15	0.17	**0.17**	0.165
σ_x (RMS) [µm]	0.7	2.2	**1.8**	1.32
σ_y (RMS) [µm]	0.7	2.0	**1.6**	1.15
Normalized transverse emittance, $\varepsilon_{n,x}$ [µm]	**0.09**	0.09	**0.09**	0.09
Normalized transverse emittance, $\varepsilon_{n,y}$ [µm]	**0.1**	0.1	**0.1**	0.1



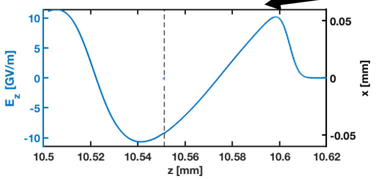


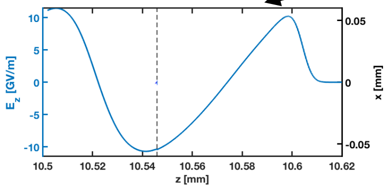


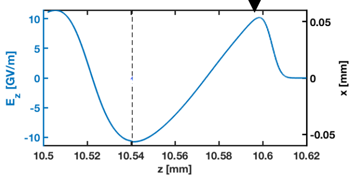
Summary

- ✓ The successful quality-preserving acceleration of an externally injected beam by a laser wakefield accelerator was demonstrated through the start-to-end 3D PIC simulations.
- ✓ Electron beam properties are preserved during the acceleration and extraction.
- ✓ A good working point has been found for the potential experimental setup for laser-driven plasma acceleration with external injection of an electron beam from an RF linac.
- ✓ The effect of the injection phase on the accelerated beam quality has been investigated through tolerance studies on the arrival time jitter between the electron beam and the external laser:
  - time jitter ≤ 35.5 fs does not have a significant influence on the final parameters of the accelerated electron beam.

Parameters	**at the plasma entrance**	**after acceleration**		
Electron beam-laser offset [μm]		52.79	**58.1**	63.43
Charge [pC]	0.75	0.75	**0.75**	0.75
$\bar{E}$ [MeV]	**99.9**	925	**1065.2**	1143
$\Delta E/\bar{E}$ [%]	**0.19**	0.28	**0.15**	0.25
σ_z (RMS) [μm]	0.15	0.17	**0.17**	0.165
σ_x (RMS) [μm]	0.7	2.2	**1.8**	1.32
σ_y (RMS) [μm]	0.7	2.0	**1.6**	1.15
$\varepsilon_{n,x}$ [μm]	**0.09**	0.09	**0.09**	0.09
$\varepsilon_{n,y}$ [μm]	**0.1**	0.1	**0.1**	0.1







Acknowledgements

- the OSIRIS Consortium (IST/UCLA) for providing access to the OSIRIS code.

- developers of the FBPIC: Remi Lehe (Berkeley Lab) and **Manuel Kirchen** (CFEL, UHH); also Soeren Jalas (CFEL), Kevin Peters (CFEL), Irene Dornmair (CFEL) and Igor Andriyash (Weizmann Institute).

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