Characterization of LWFA with realistic laser profiles for ESCULAP project

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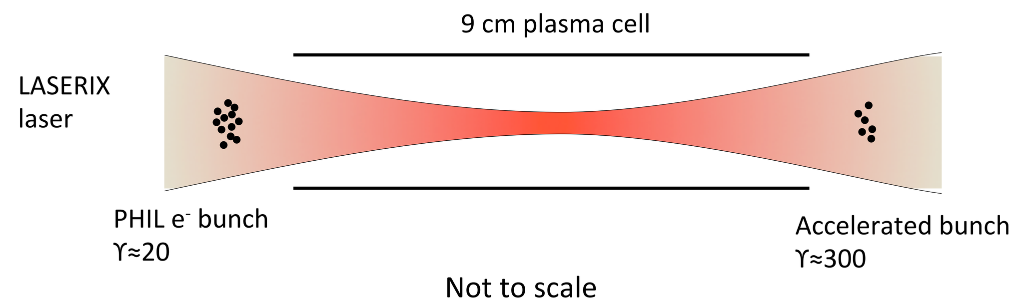
Introduction

A goal of ESCULAP [1-3] experiment is the external injection of photo-injector electrons bunch with consequent LWFA acceleration in the moderate density plasma cell. In our configuration small fraction of LASERIX laser is send to the photocathode, and the rest is delivered to the plasma cell for the wake excitation.

Stability of the laser beam, its shape, "flatness", duration, intensity etc. are crucial parameters for the reproducible shot-to-shot acceleration. We study numerically LWFA and evolution/propagation of flattened Gaussian profile of the laser approximating the experimental one.
The study is performed for 10, 20 and 50 MeV externally injected electron beam.

	Experimental parameters	Modelling parameters
PHIL	10 MeV electrons photoinjector, repetition frequency 5 Hz Bunch charge 10 pC Emittance FWHM 4 mm*mrad Bunch length rms 7–10 ps --> need of bunch compression (Ke Wang [4])	**Gaussian electron bunch / or one from Astra** Beam longitudinal rms size 5 µm Beam transverse rms size 10 µm Beam Gamma Mean = 19; Beam Gamma rms = 0.5% Normalised emittance 1 µm
LASERIX	2 J, 45 fs FWHM high-power Ti:Sa laser (800 nm)	**Gaussian Laser** Laser Duration 45 fs FWHM Laser Energy 2J Laser Waist ~50 µm, a_0=0.7
Plasma cell	2-4 e17 cm-3 variable density profile, total length of 9 cm (focal plane at 4 cm)	**Plasma density** Uniform 2e17 cm-3

Experimental setup scheme



Numerical Modelling

Features of FBPIC code [4]

- Cylindrical grids with azimutal decomposition and dispersion-free field solver.
- The simulation can be performed on CPU / GPU and in cluster environment.
- Moving window with boosted frame technique (crucial when plasma cell is several centimetres length).
- Post-processing: OpenPMDDiagnostics and LPATools modules.

Benchmarking

Total calculation time for 9 cm plasma cell.
FBPIC modelling was performed in boosted frame with γ_boost =5.
Moving window z: 4000 points = 120µm, r: 600 points = 600 µm

LPWA code	Hours x C(G)PU	Total, h
FBPIC CPU, OpenMP (48)	3456 HCPU	72
FBPIC CPU, OpenMP(20) MPI(7)	2730 HCPU	19.5
FBPIC GPU (2)	9 HGPU	4.5
WAKE-EP	9 HCPU	9

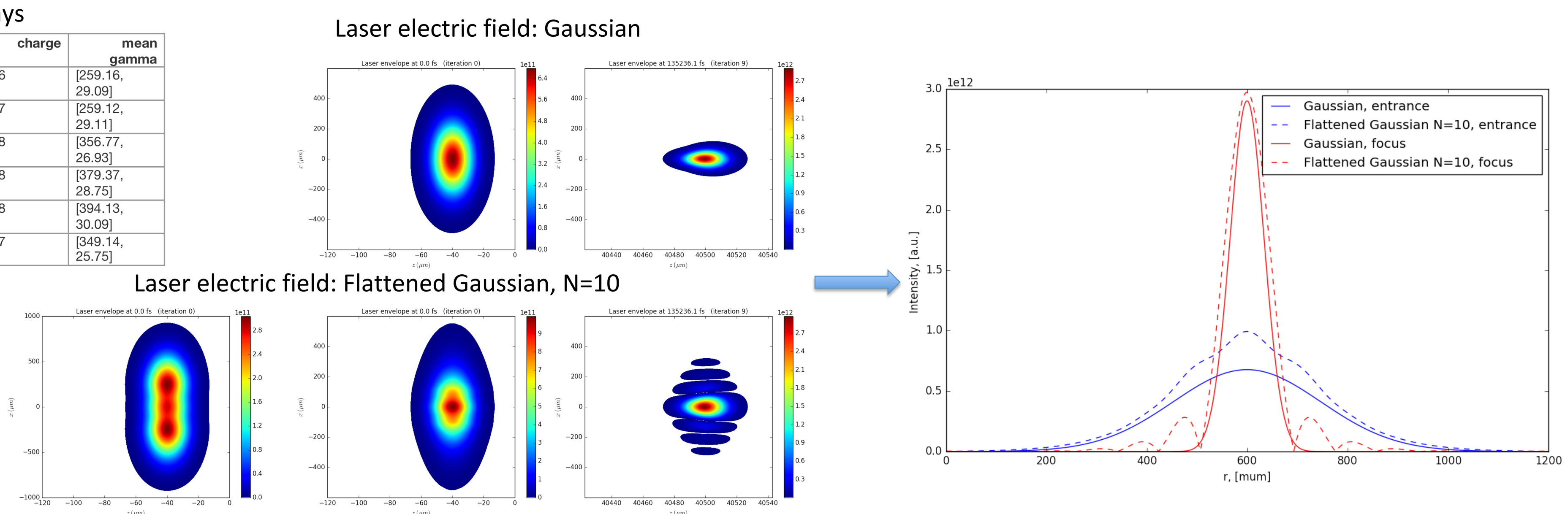
Results and discussion

Gaussian vs Flattened Gaussian beam.
Physical properties of the accelerated electron bunch (gamma>100) at optimal delays

Name	Energy	emittance	divergence	charge	mean gamma
Gauss	10	[5.01e-06, 4.32e-06]	[9.20e-04, 8.60e-04]	78.6	[259.16, 29.09]
N=0 (Gauss)	10	[4.94e-06, 4.35e-06]	[9.13e-04, 8.61e-04]	78.7	[259.12, 29.11]
N=3	10	[2.85e-06, 2.23e-06]	[6.98e-04, 6.36e-04]	99.8	[356.77, 26.93]
N=6	10	[2.59e-06, 1.89e-06]	[7.64e-04, 6.41e-04]	99.8	[379.37, 28.75]
N=10	10	[2.59e-06, 1.84e-06]	[8.02e-04, 6.64e-04]	99.8	[394.13, 30.09]
waist X1.25	10	[3.04e-06, 2.23e-06]	[7.90e-04, 7.09e-04]	99.7	[349.14, 25.75]

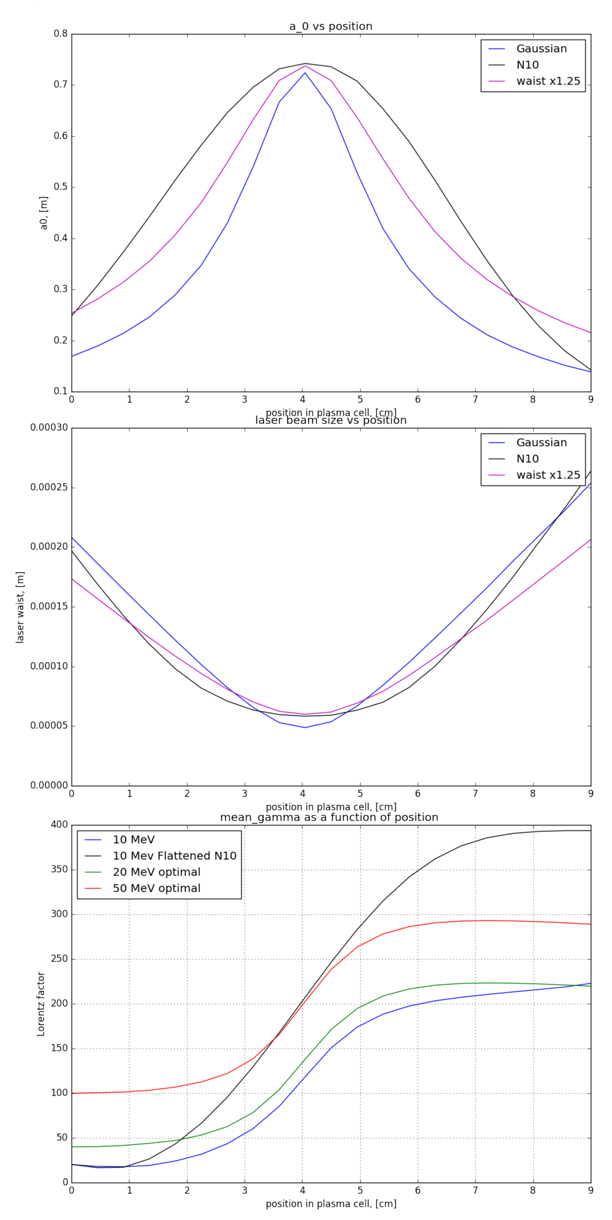
Laser electric field: Gaussian

Laser electric field: Flattened Gaussian, N=10

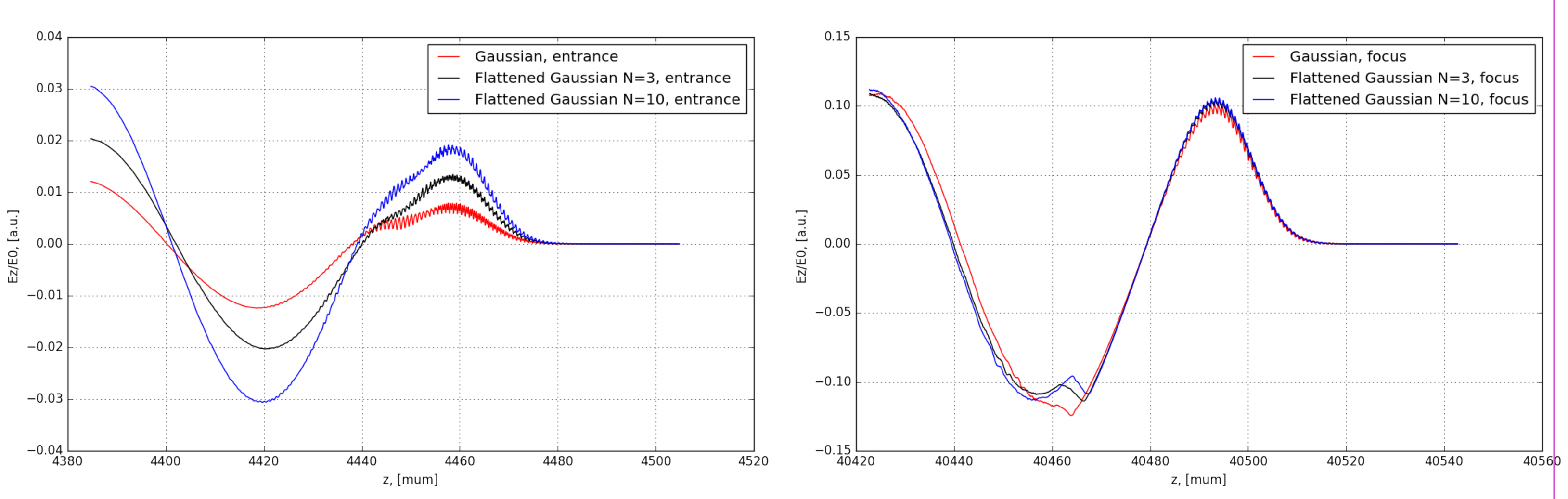


At -10 cm | At entrance to plasma cell | In the focal plane, at 4cm

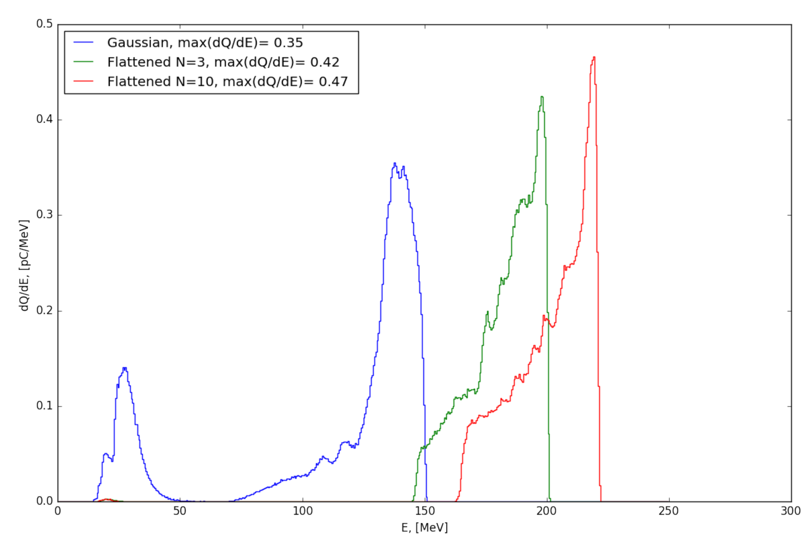
Laser a_0, waist, and Lorentz factor of accelerated electron bunch during propagation in plasma cell.



Plasma wake electric field



Energy distribution at the exit of plasma cell



Optimisation of delay between the electron bunch and the laser: 20 MeV and 50 MeV case.

Delay Optimisation	Energy	emittance	divergence	charge	mean gamma
Gauss	10	[5.01e-06, 4.32e-06]	[9.20e-04, 8.60e-04]	78.6	[259.16, 29.09]
Flattened N10	**10**	**[2.59e-06, 1.84e-06]**	**[8.02e-04, 6.64e-04]**	**99.8**	**[394.13, 30.09]**
0	20	[2.7e-06, 2.57e-06]	[1.05e-03, 1.03e-03]	96.3	[179.25, 21.39]
-10	20	[1.87e-06, 1.69e-06]	[9.63e-04, 9.24e-04]	99.8	[143.64, 13.58]
-20	20	[2.19e-06, 2.18e-06]	[1.25e-03, 1.28e-03]	100.0	[152.53, 25.97]
-30	**20**	**[8.98e-06, 8.84e-06]**	**[1.62e-03, 1.63e-03]**	**99.4**	**[220.13, 25.66]**
-40	20	[2.51e-05, 2.56e-05]	[2.32e-03, 2.36e-03]	49.5	[267.81, 61.76]
0	50	[3.9e-06, 3.32e-06]	[1.22e-03, 1.19e-03]	58.2	[155.21, 24.43]
-10	50	[1.91e-06, 1.8e-06]	[1.66e-03, 1.64e-03]	59.1	[112.15, 8.94]
-20	50	[3.13e-06, 2.98e-06]	[1.24e-03, 1.21e-03]	32.0	[145.54, 42.52]
-30	50	[3.9e-06, 4.42e-06]	[1.46e-03, 1.47e-03]	97.4	[213.58, 37.35]
-40	**50**	**[5.74e-05, 5.77e-05]**	**[2.89e-03, 2.90e-03]**	**99.3**	**[289.05, 57.87]**

Conclusions

We demonstrate that the external injection scheme, which consist in trapping electrons before laser focal plane with consequent acceleration in the focal plane is robust with respect to the laser radial profile. Acceleration in the wake from Flattened Gaussian laser is more efficient than with Gaussian beam of the same waist. This can be partly explained by increase of the effective waist, longer Rayleigh distance and consequently acceleration along longer distance. Moreover some optimisation on the laser radial profile can have some significant impact for LPA.

Increase of energy of injected electron bunch, without optimisation of initial electron bunch distribution does not seems beneficial for the ESCULAP experiment. Shaping of high energy electron bunch with plasma wake fields after capturing becomes difficult. No additional energy gain were observed for injection at higher energies, apart from the difference in the energy of injected bunches.

References

[1] E. Baynard et al., Nucl. Instrum. Meth. Phys. Res. A 909, 46 (2018).

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[4] R.Lehe et al., Comp. Phys. Com. 203, 66 (2016).