Modeling of the Electron Beam Dynamics in Electron Beam Transport for Laser-Plasma Accelerator based FEL

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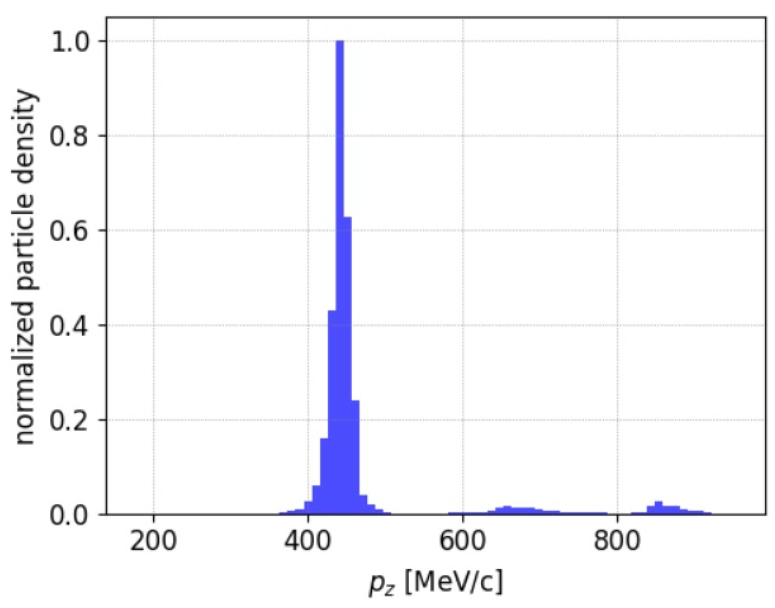
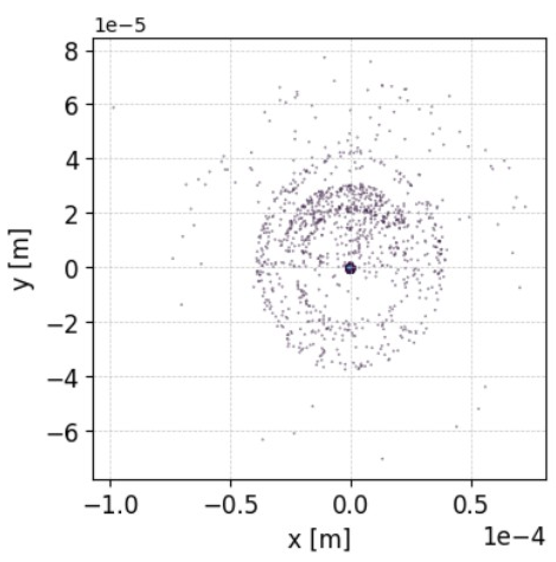
Achieving high-quality electron beam is crucial for the next generation Free Electron Laser (FEL) operating in the extreme ultraviolet (EUV) range of the radiation spectrum. In order to transport the laser-plasma-accelerator-based electron bunch without significant degradation in beam quality, the capture block of the electron beamline can be designed using either a set of quadrupole magnets or plasma-based focusing element, known as active plasma lens (APL). In the frame of this presentation, we compare the evolution of the electron bunch for both cases. The initial particle distribution was obtained from laser-plasma interaction code and serves as input for a start-to-end simulation. The obtained results demonstrate the active plasma lens as a suitable device for electron beam capture. Furthermore, the outcomes of the start-to-end simulations will be discussed in order to develop the entire electron beam transport suitable for a compact laser-plasma FEL, which will be developed at ELI-ERIC (ELI Beamlines).

LWFA INITIAL PARTICLE DISTRIBUTION

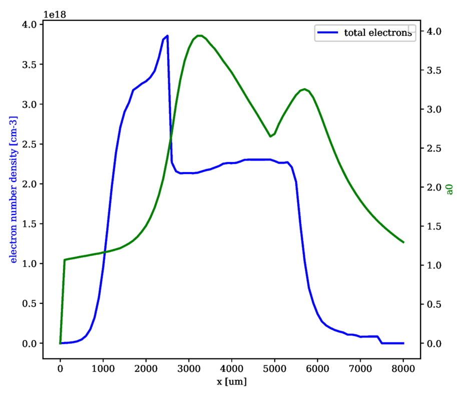
The initial particle distribution is generated using SMILEI. For the beam dynamics simulations, the full dataset from SMILEI is used without filtering. The plots illustrate the complete distribution and the corresponding parameters are listed in the table.

$E_{ref} =$	440 MeV	$\sigma_x =$	4.790 μm
$Q_{tot} =$	-81.82 pC	$\sigma_y =$	5.033 μm
$\sigma_\delta =$	0.191	$\sigma_{x'} =$	7.142 mrad
$\epsilon_{n,x} =$	19.87 π mm mrad	$\sigma_{y'} =$	7.012 mrad
$\epsilon_{n,y} =$	18.03 π mm mrad	$\sigma_z =$	1.246 μm





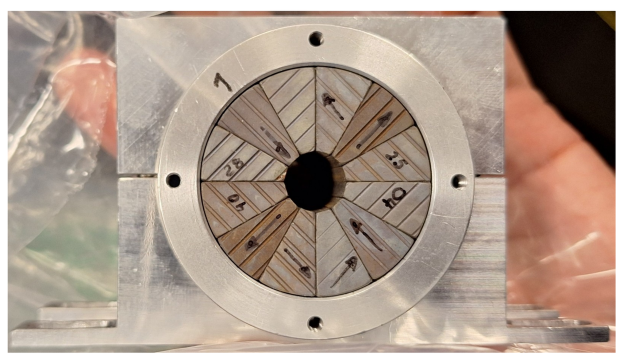
Plasma density distribution used in the simulation:



CAPTURE BLOCK TECHNOLOGIES

Configuration of the capture block employing permanent quadrupole magnets for required focusing:

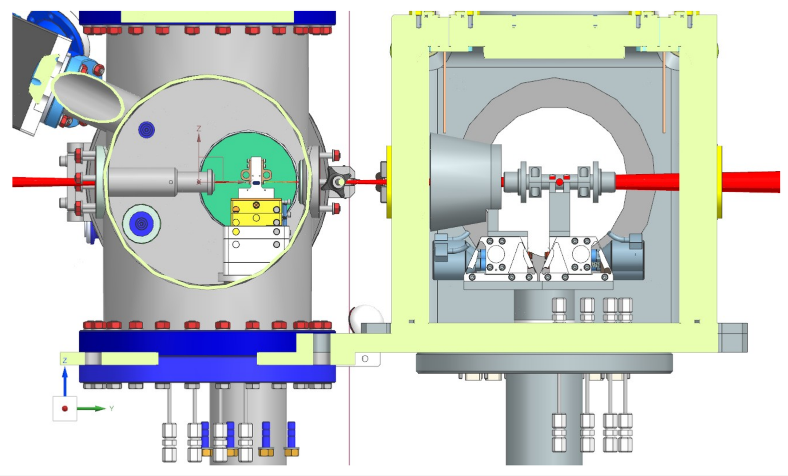
Parameter	Magnet 1	Magnet 2	Magnet 3
Type	Permanent	Permanent	Electric
G [T/m]	300	-275.107	70.178
ℓ_{eff} [cm]	4	5	10
r_i [mm]	3	6	
r_o [mm]	6.06	20.1	
B_r [T]	1	1.2	



Active Plasma Lens parameters for the required focusing:

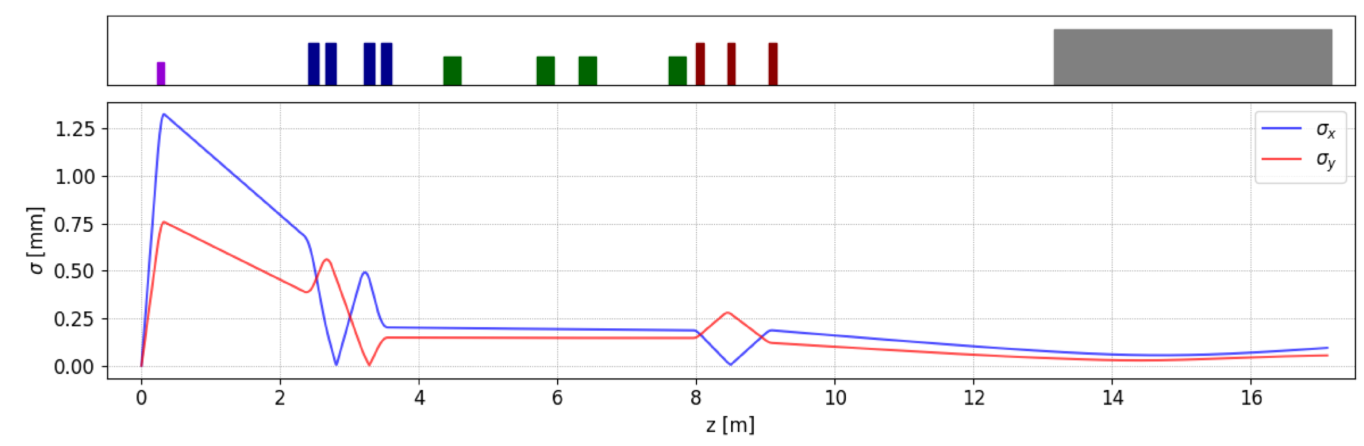
$G = 59.573$ T/m	$r = 2.3$ mm
$I = -1.576$ kA	$l = 100$ mm

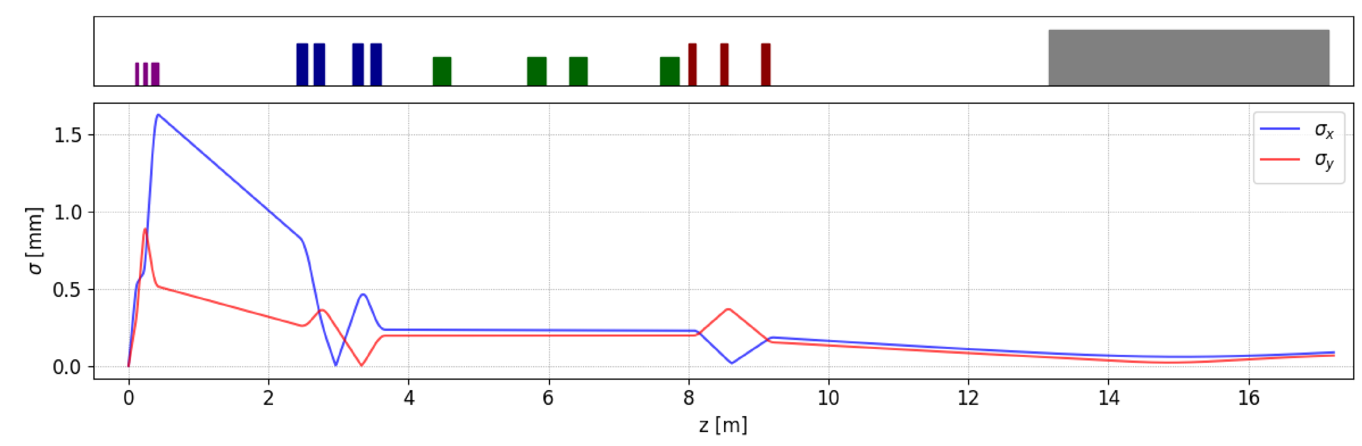
Schematic representation of the active plasma lens setup for LUIS beamline at ELI-ERIC, currently in preparation.



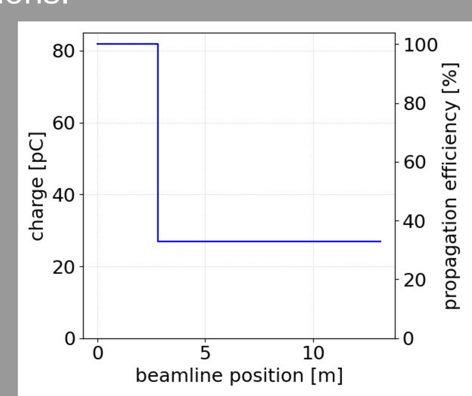
ELECTRON BEAM DYNAMICS IN THE TRANSPORT LINE

Sigma matrix formalism (energy spread and space charge not taken to account) is used to optimize the configuration of the beamline components to achieve the desired Twiss parameters at the entrance of the undulator. The beamline consists of a capture block for collecting and focusing of the initial beam, followed by a momentum filter designed to remove the beam halo, reduce energy spread, and produce a nearly collimated beam for the CHIC section. Finally, a matching section adjusts the beam optics to meet the required parameters for efficient injection into the undulator. Thus, the beamlines designed using Permanent Quadrupole Magnets (PQMs) and Active Plasma Lenses (APLs) are as follows:

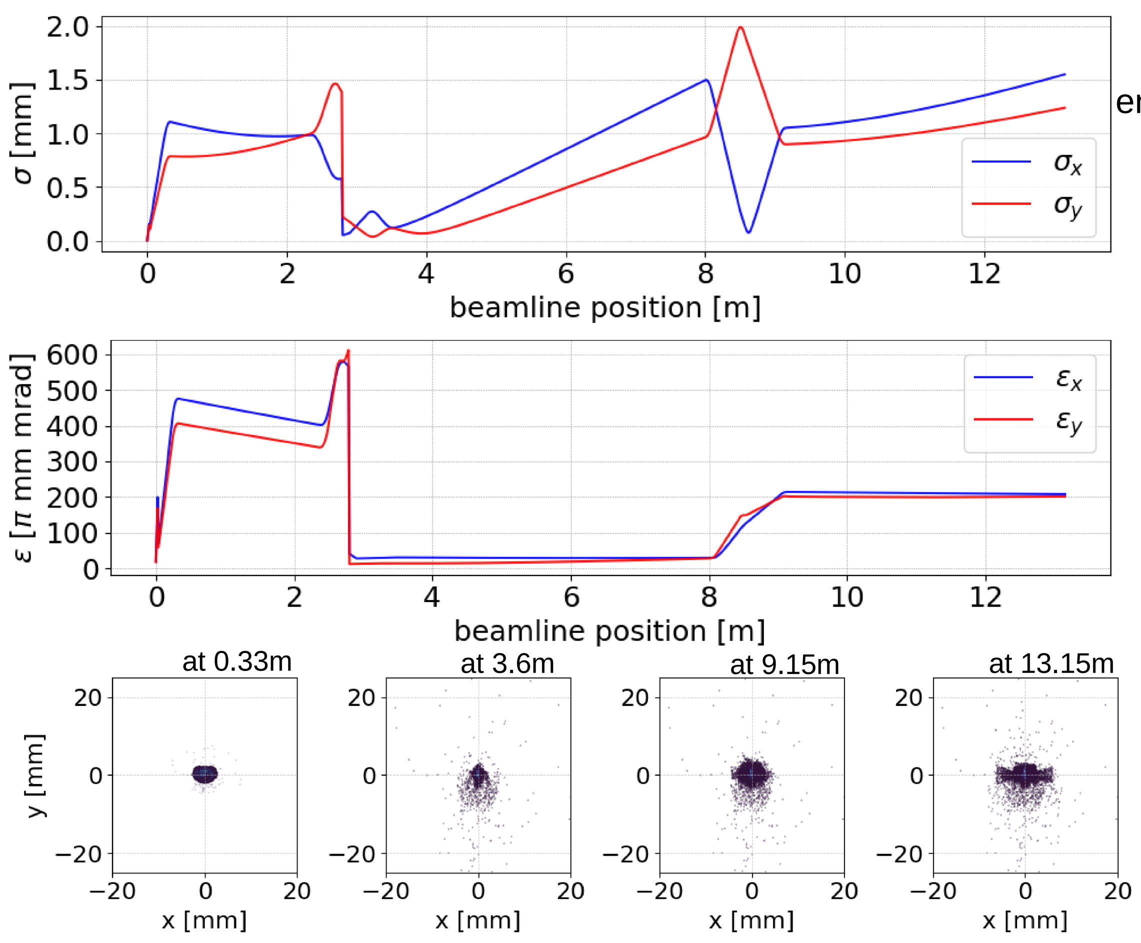




At the center of the momentum filter, horizontal and vertical collimators with apertures of ±0.15 mm and ±0.5 mm, respectively, were placed to filter out halo particles. The resulting propagation efficiency was evaluated for both the APL and PQMs configurations.



Multi-particle tracking performed with ASTRA, including energy spread and space charge effects, reveals that the messy electron beam distribution produced by laser-plasma acceleration, commonly encountered in practice, leads to significant beam enlargement due to chromatic aberrations caused by the large energy spread. By filtering out the halo particles, the emittance can be effectively controlled.

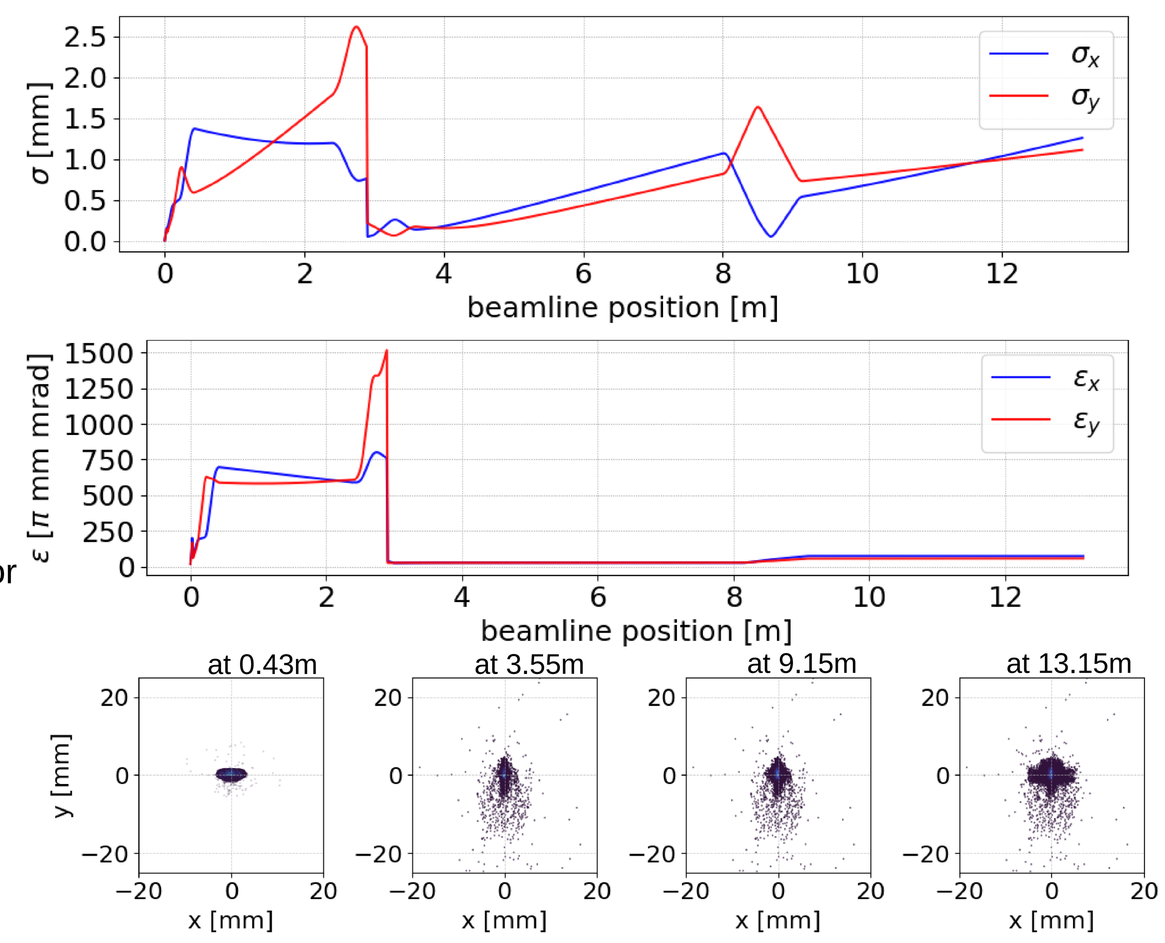


Electron beam parameters at the entrance of the undulator in case of APL:

E_{ref}	440 MeV
Q	-26.88 pC
σ_δ	0.06
σ_x	1.546 mm
σ_y	1.237 mm
$\epsilon_{n,x}$	207 π mm mrad
$\epsilon_{n,y}$	201 π mm mrad
σ_z	9.297 μm

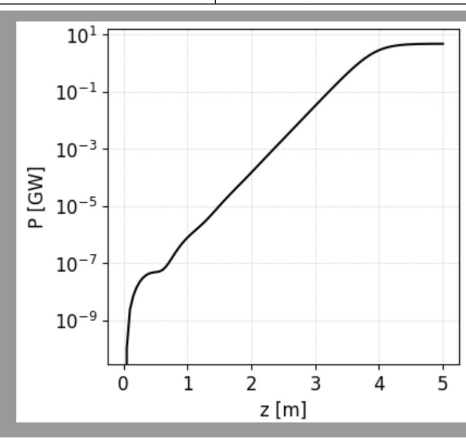
Electron beam parameters at the entrance of the undulator in case of PQMs:

E_{ref}	440 MeV
Q	-30.92 pC
σ_δ	0.03
σ_x	1.258 mm
σ_y	1.111 mm
$\epsilon_{n,x}$	72.9 π mm mrad
$\epsilon_{n,y}$	56.9 π mm mrad
σ_z	6.069 μm



The following presents the beam parameters required to drive an EUV FEL obtained from 3D FEL analysis, along with the corresponding saturation power achievable under these conditions.

$\lambda_u =$	15 mm	$\lambda_r =$	16.2 nm
$K =$	1.1	(slice) $\epsilon_n =$	0.2 π mm mrad
$g =$	5 mm	$\sigma_x =$	25 μm
$l =$	4 m	(slice) $\sigma_\delta =$	0.2 %
$\epsilon_{n,coh} =$	1.11 π mm mrad	(slice) $I_c =$	3 kA
$\rho =$	0.00534	$L_{sat,3D} =$	4.04 m



CONCLUSION

This study investigates the beam dynamics of an electron beam with significant energy spread in beamlines designed with a capture block composed of permanent quadrupole magnets (PQMs) and an active plasma lens (APL). Multi-particle tracking with ASTRA reveals that the large energy spread induces halo formation due to chromatic aberration, resulting in emittance degradation. The introduction of a collimator at the center of the momentum filter effectively controls the emittance while maintaining reasonable propagation efficiency. However, this represents only an initial step, **further optimization of the beamline is essential** to achieve improved control of the beam size and matching conditions at the entrance of the undulator. In order to meet the requirements of an EUV FEL, not only the beam dynamics be optimized, but **the intrinsic properties of the LPA-based electron beam such as energy spread and emittance, must be significantly improved**. Achieving this level of control is crucial for ensuring efficient FEL amplification.

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