EuPRAXIA Doctoral Network

LPA-based EUV FEL Start-to-End Modelling

Mihail Miceski

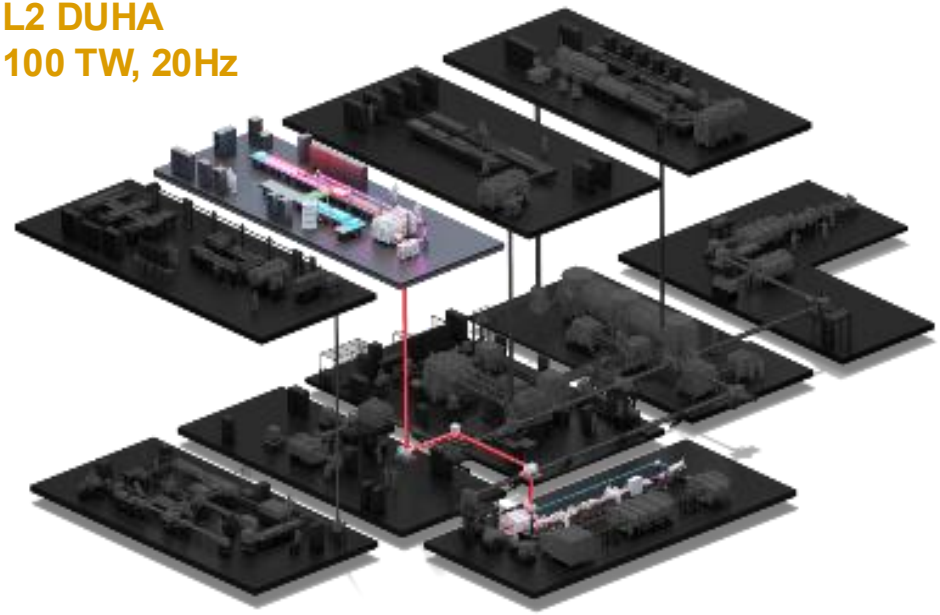
ELI ERIC

Czech Technical University in Prague

UK Research and Innovation

Content

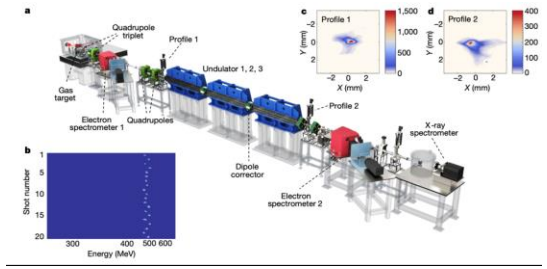
- FEL framework
- LPA modelling
- Optimized electron beam from LPA-PIC simulation
- Electron beam transport
- LPA-based EUV FEL
- Conclusion



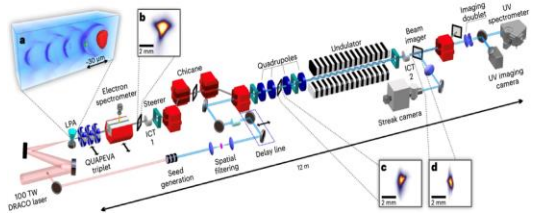
LPA-based FELs: Current state of art

EuPRAXIA Doctoral Network

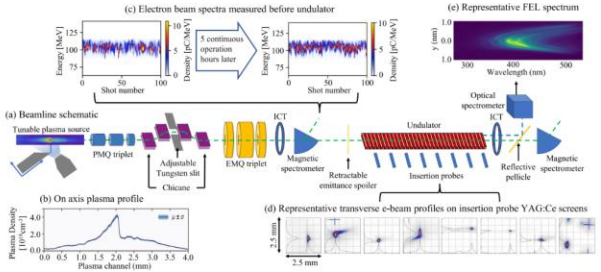
2021 2022 2025 2026



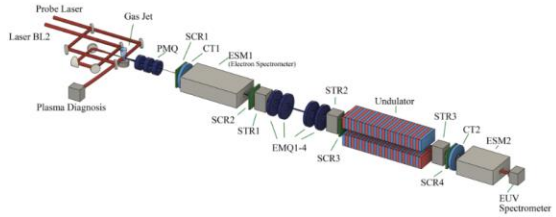
SIOM (China)
W_e ~ 500 MeV
SASE FEL
Lasing 27 nm



COXINEL
(SOLEIL/France+HZDR/Germany)
W_e =188 MeV
Seeded FEL
Lasing 240 nm



BELLA (USA)
W_e ~ 100 MeV
SASE FEL
Lasing 420 nm



OSAKA (Japan)
W_e ~ 400 MeV
SASE FEL
Lasing 40 nm

FEL framework

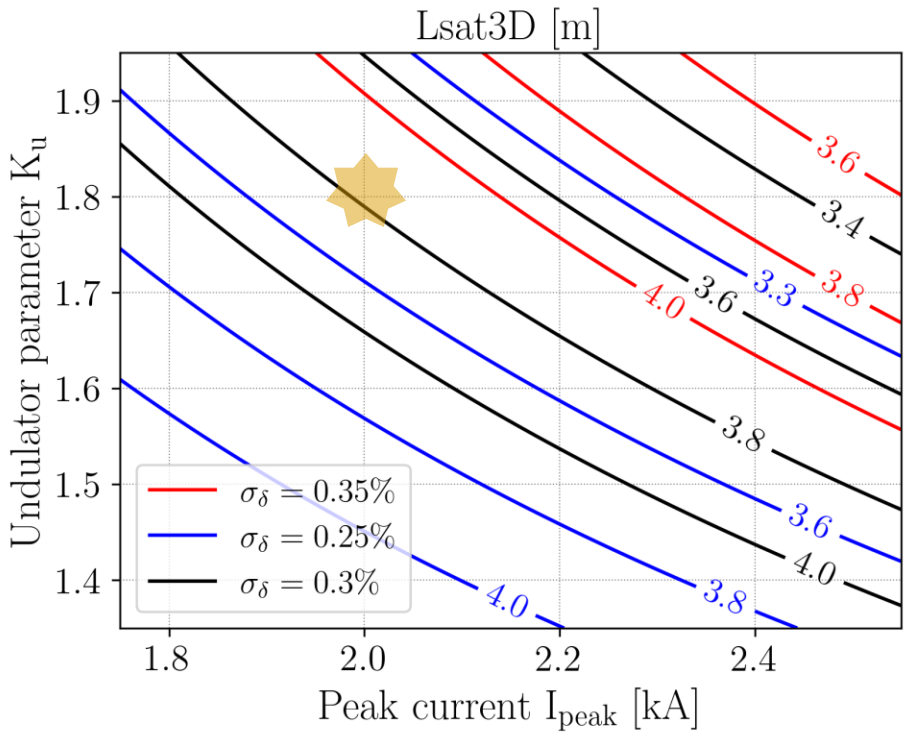
Low energy case ~300 MeV.

Constraint:

- Saturation within 4 meters.

Requirements:

- $\varepsilon_n \leq \varepsilon_{n,coh} = \gamma \lambda/4\pi$
- $\sigma_\delta \leq \rho/2$
- $L_g \leq Z_R = 4\pi\sigma_x^2/\lambda$



Undulator – SwissFEL U19	
Undulator type	Planar hybrid
Magnet material	NdFeB
Gap range	≥ 4 mm
Undulator period	19 mm
Undulator parameter (Ku)	1.9 (max)
Undulator length	4 m

Required electron beam (Lsat<4 m, Ku=1.8)	
Reference electron energy	~ 308 MeV
Norm. RMS slice emittance	≤ 0.35 mm mrad
Total bunch length	~ 4 µm
Peak current	≥ 2 kA
Slice RMS energy spread	≤ 0.3%
Avg. RMS beam size	~ 35 µm

FEL scaling law (Ku=1.8)	
ħω	18.097 eV
λ	68.512 nm
Pierce parameter	0.0081338
Gain length ($L_{g,1D}$ / $L_{g,3D}$)	0.107 / 0.178
Saturation power (Psat)	2.934 GW
Saturation length (Lsat)	3.808 m

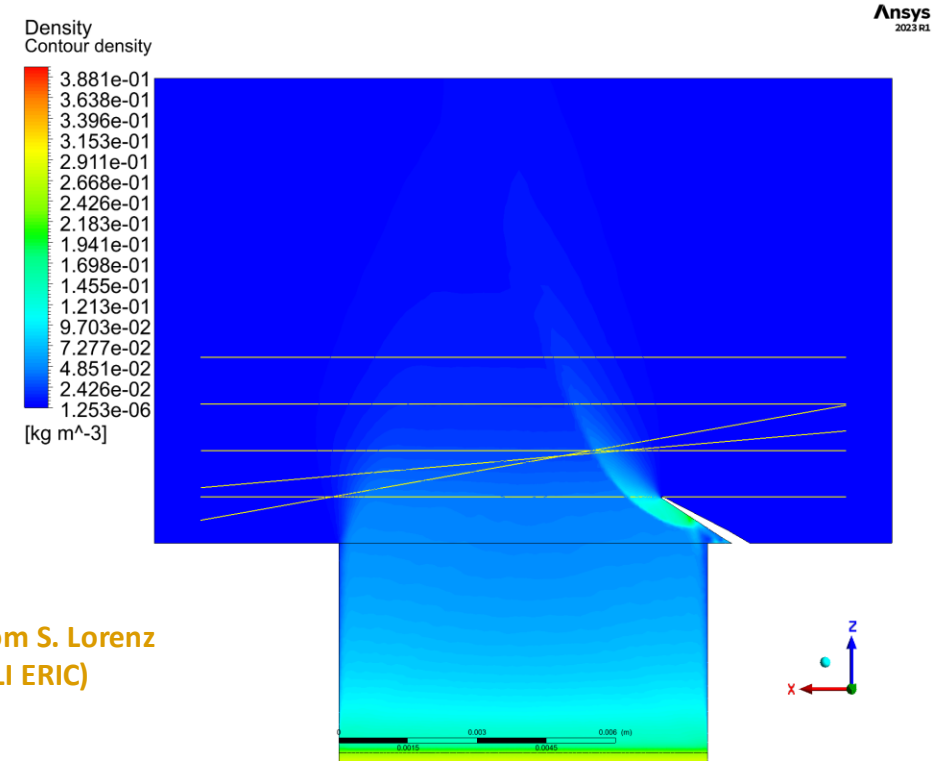
Challenges for LPA-based FEL

Parameters	Challenge	Feasibility	Solution
Energy	NO	OK	/
Emittance	YES	~ 0.5 mm mrad	Injection scheme + Preservation in beamline
RMS Energy spread	YES	~ 0.5%	Injection scheme + Beam loading
Energy chirp	YES	achievable	Beam loading
Charge	YES	OK	Injection scheme

Injection schemes with high TRL: Self-truncated ionization injection and **Shock injection**

Gas density profile

- Gas jet with a blade for shock injection.
- Gas density profile obtained from CFD code ANSYS Fluent.
- 5 mm slit nozzle
- The laser propagates 3 mm above the blade edge.



from S. Lorenz (ELI ERIC)

LPA modeling

- Laser-plasma acceleration modeled using a PIC code OSIRIS in quasi-3D geometry.
- Linearly polarized Gaussian laser pulse (vertical).
- Laser parameter based on L2 DUHA:

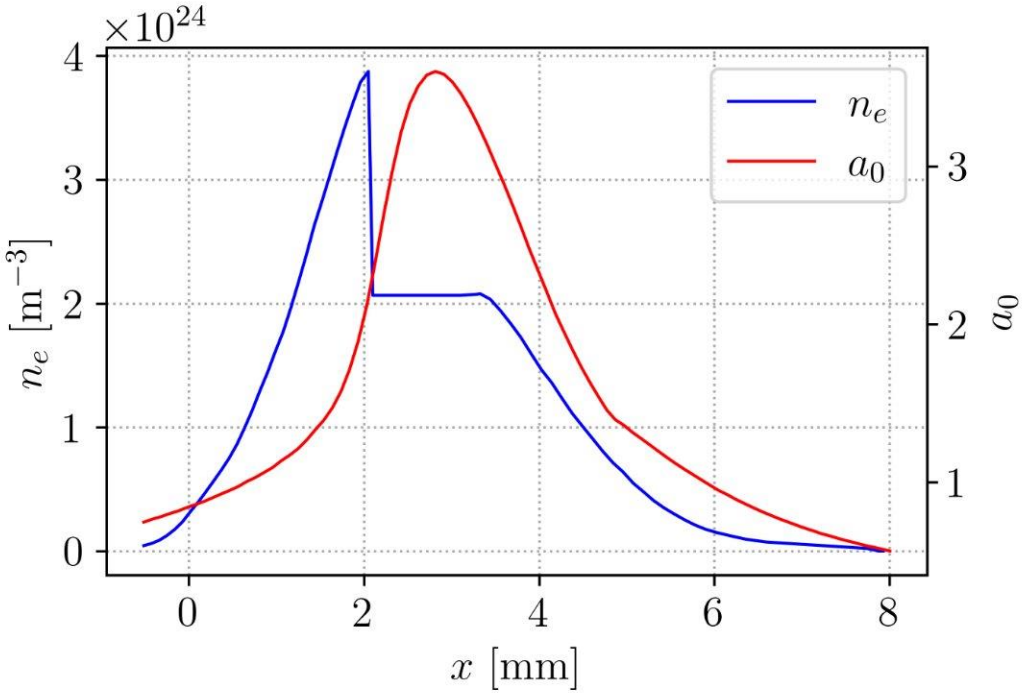
$$E(r) = E_0\, e^{-r^2/w_0^2}$$

$$a_0 = \frac{eE_0}{m_e c\, \omega_0}$$

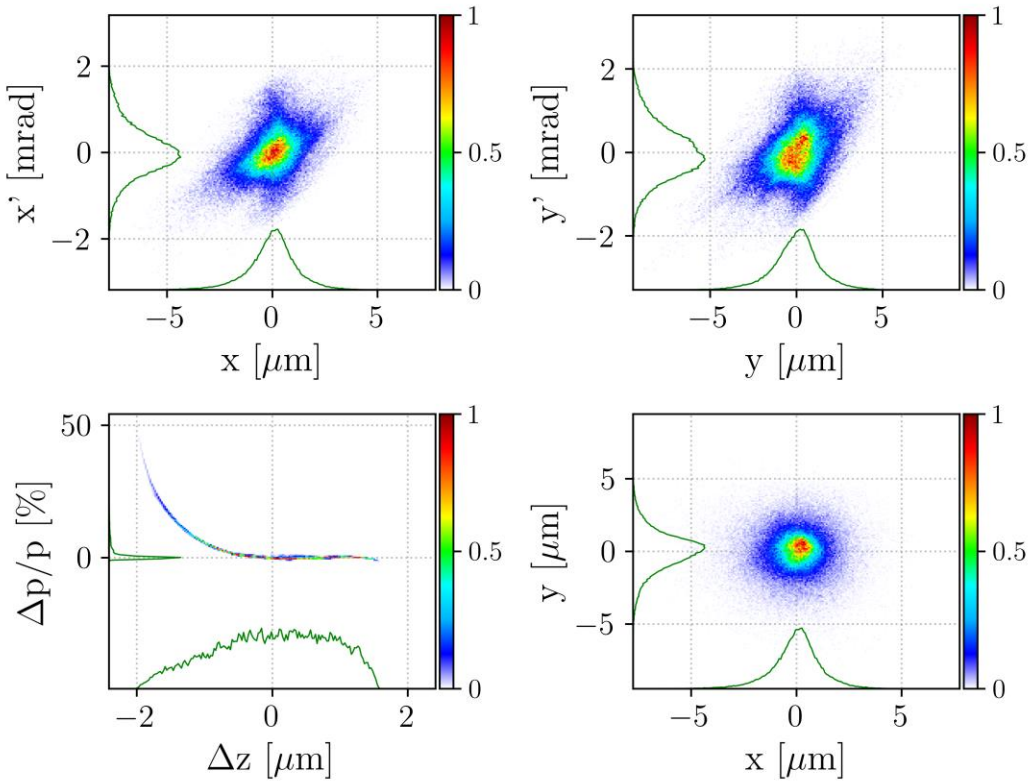
$\lambda = 820$ nm $\quad \tau = 27.4$ fs
$w_0 = 20.5$ µm (1/*e* field radius)
$\boldsymbol{a_0} = 1.96$ (normalized field strength in vacuum in focus)
$E = 1.43$ J $\quad P_{peak} = 49.13$ TW

Optimization:

- **Acceleration plateau length** – to stop acceleration at the point where beam loading minimizes the energy chirp
- **Focal position** – to inject sufficient electron charge
- **Laser energy** – to drive efficient acceleration
- **Plasma ramp exit** – to minimize beam divergence
- **Final re-optimization with density profile from CFD** – focal position, plasma density, plateau length, and laser energy



Electron beam from PIC after optimization



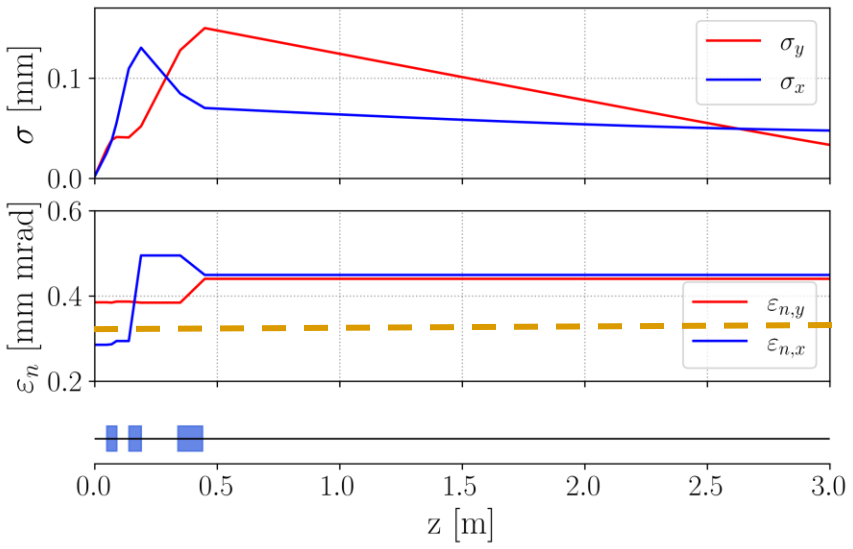
Electron beam parameters at the exit of the plasma:

Reference energy	=	307.5 MeV
RMS beam size (σ_x/σ_y)	=	1.190 / 1.399 μm
RMS divergence ($\sigma_{x'}/\sigma_{y'}$)	=	0.564 / 0.629 mrad
Projected norm. RMS emittance ($\varepsilon_{n,x}/\varepsilon_{n,y}$)	=	0.359 / 0.476 mm mrad
Projected RMS energy spread	=	0.42 % (-0.5 μm $\leq \Delta z \leq$ 1.5 μm)
Bunch core charge	=	25.639 pC (-0.5 μm $\leq \Delta z \leq$ 1.5 μm)
Total bunch charge	=	36.189 pC
RMS bunch length (total length)	=	0.837 μm (2.5 μm)
Beam current	=	4342.68 A
Energy chirp (dE/dz)	=	-0.609 MeV/μm (-0.5 μm $\leq \Delta z \leq$ 1.5 μm)

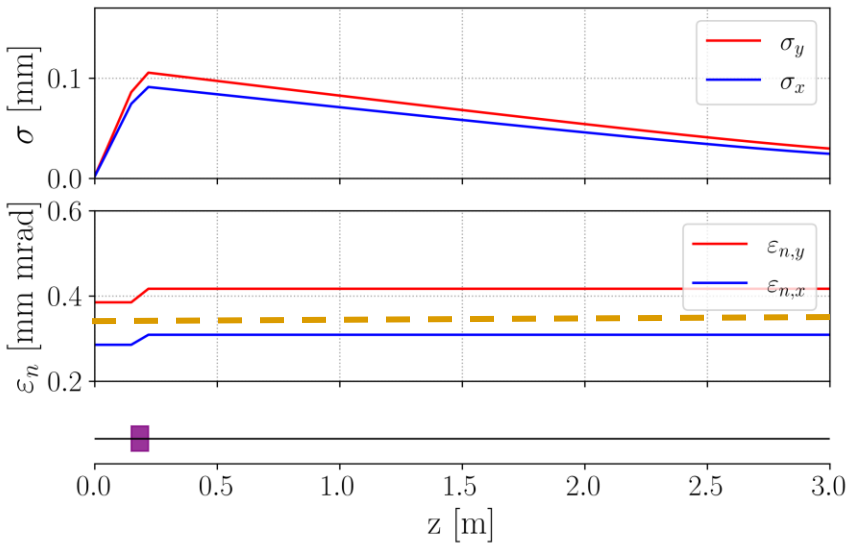
Important parameters	Satisfaction
Norm. RMS slice emittance	✅
RMS Divergence	✅
Projected RMS energy spread	😐 🤷
Peak current	✅

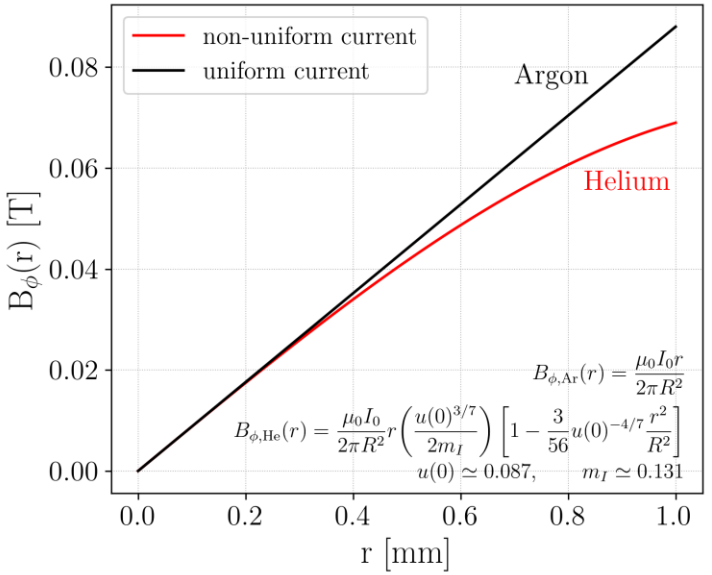
Capture block

Permanent quadrupole magnets:



Active plasma lens:





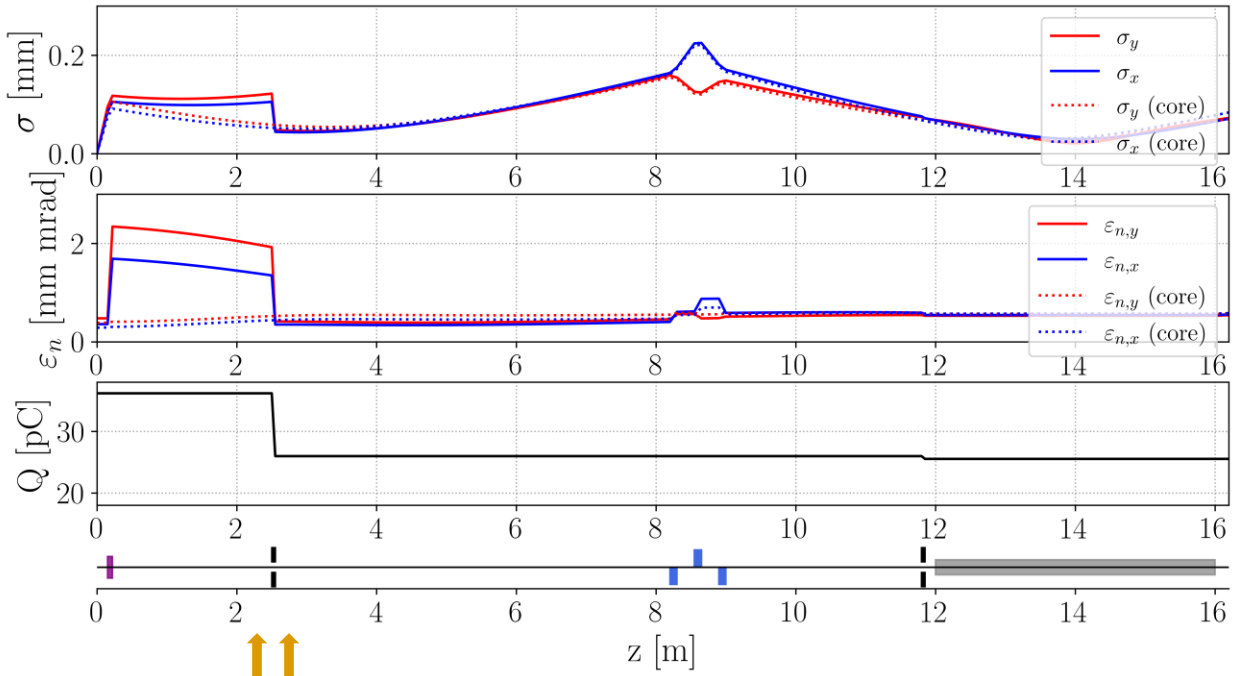
$$\varepsilon_{tr,n} = \beta_r \gamma_r \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

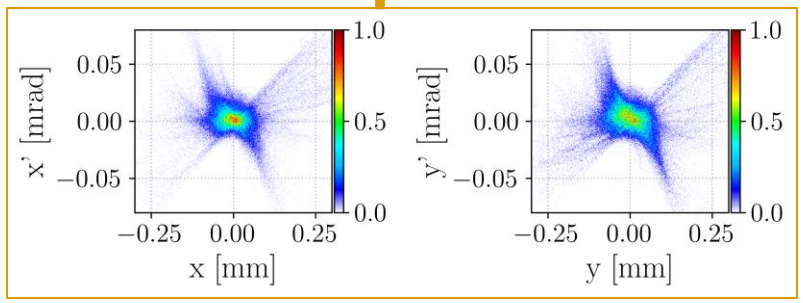
$$\varepsilon_{tr}^2 = \varepsilon_{tr0}^2 + \sigma_{x0}^4 (KL)^2 \sigma_\delta^2$$

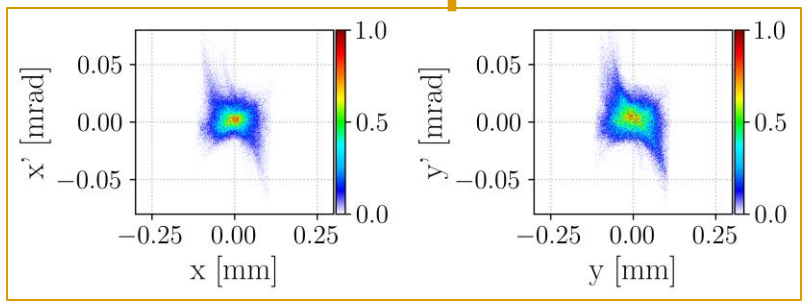
- **Azimuthal symmetry** – focuses both transverse planes simultaneously
- **Linear focusing field** – uniform, low-aberration focusing
- **High field gradients**
- **Tunability** and **Compactness**

Active plasm lens	
Length	7 cm
Radius	1 mm
Discharge current	440 A

Beam transport using 6D data from OSIRIS

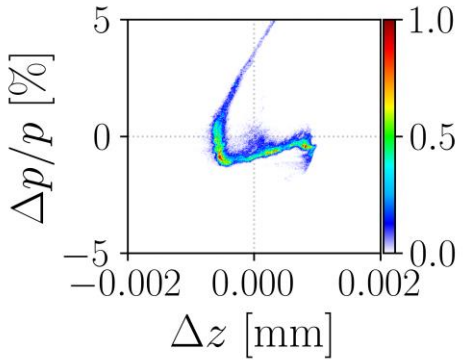




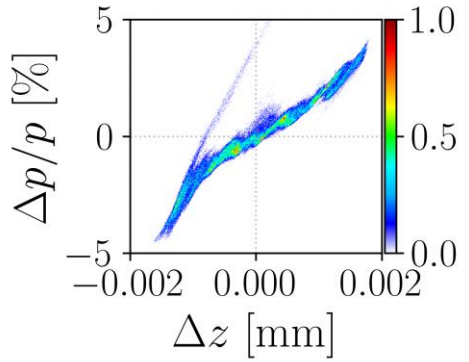


Longitudinal phase-space of the electron beam at the entrance of the undulator

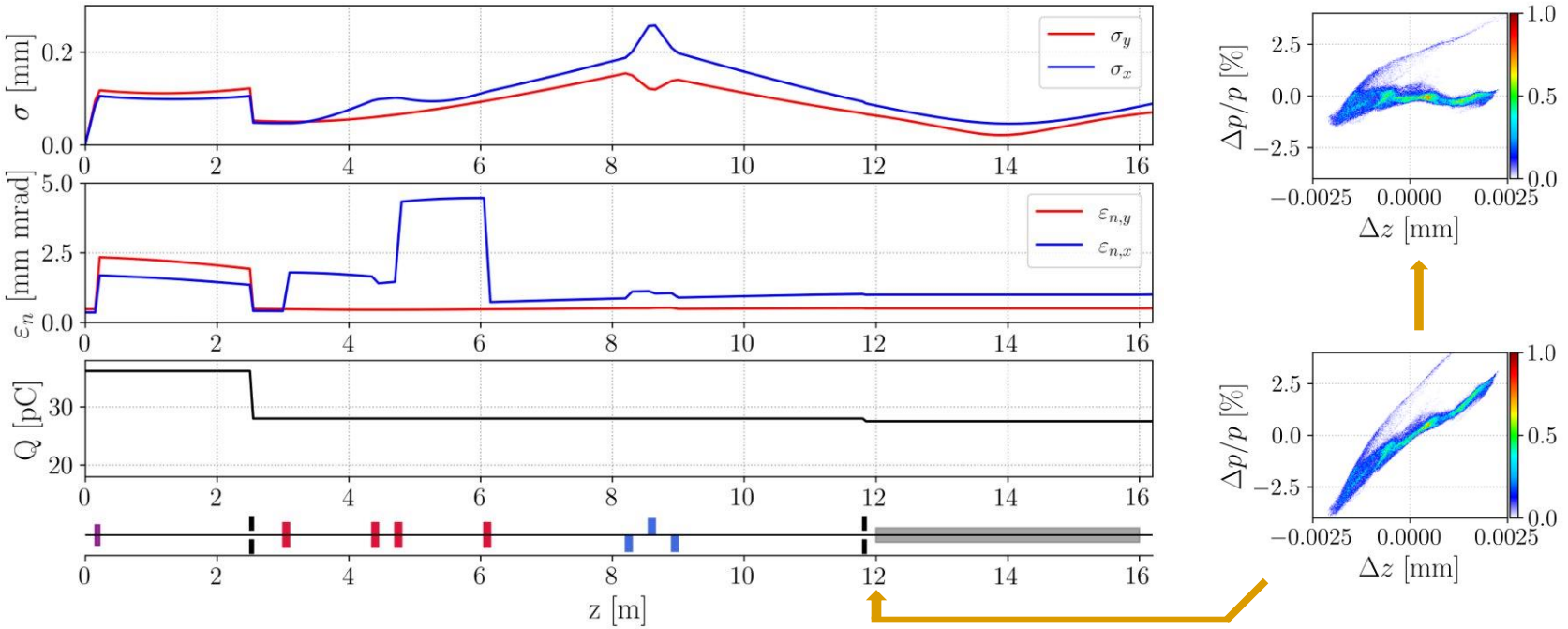
if space-charge effect is neglected:



if space-charge effect is included:



Beam transport using 6D data from OSIRIS with Chicane



Possible solution:
active plasma dechirper

[1] F. Pousa et al., 2022

Resonance condition for FEL:

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2}\right)$$

Pros:

- **Reduce slice energy spread**
- **Remove laser beam**

Cons:

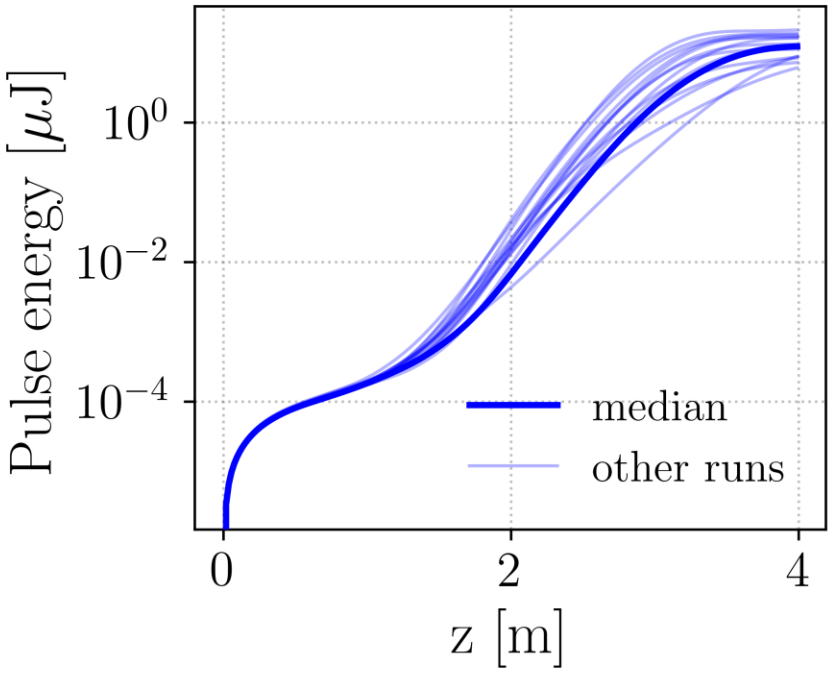
- **Emittance growth from CSR –** for small bending angle it is negligible
- **Reduction of the peak current –** the electron bunch is stretched

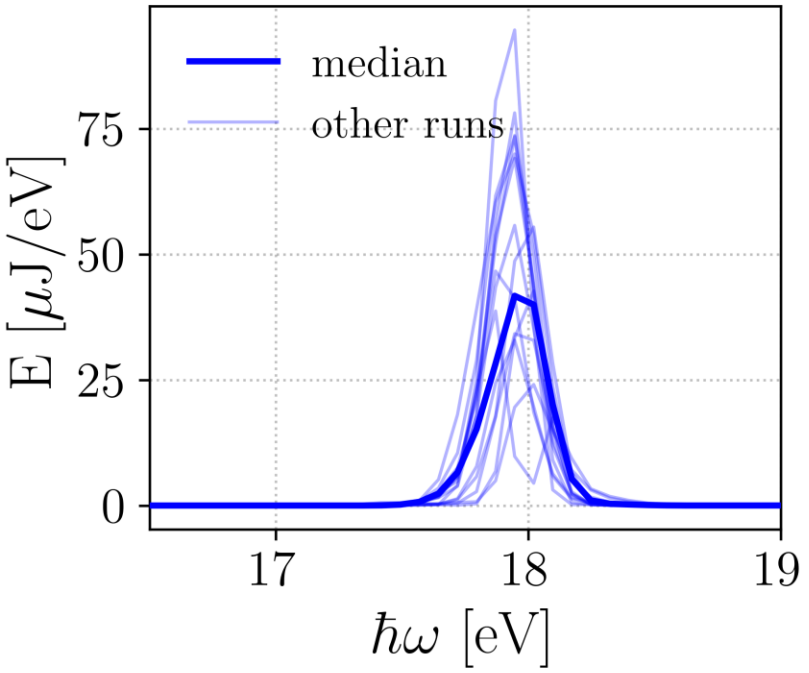
Chicane magnet	
Bending angle	0.2 deg
Magnetic field	35.78 mT
Leg length (L_{12})	1.25 m
R_{56}	32 µm
Displacement (Δx)	4.54 mm
Bending radius	28.667 m

EUV FEL

- Space-charge effect in the undulator is not consider.
- Fifteen runs with different shot-noise seeds.

Ku =1.8 ϕ=0.2deg





E = (13.021 ± 4.667) µJ

λ = (69.096 ± 0.172) nm

Conclusion

- Start-to-end simulation of a ~300 MeV LPA-driven FEL

  → From LPA beam, through multiparticle tracking, to FEL output.

- Beamline design controlling electron beam quality.
- **FEL saturation achieved**, at ~69 nm with ~13 µJ pulse energy.
- Key next step for a fully self-consistent model:

  → Include space-charge effects in the undulator with undulator tapering

  → Investigate active plasma dechirper

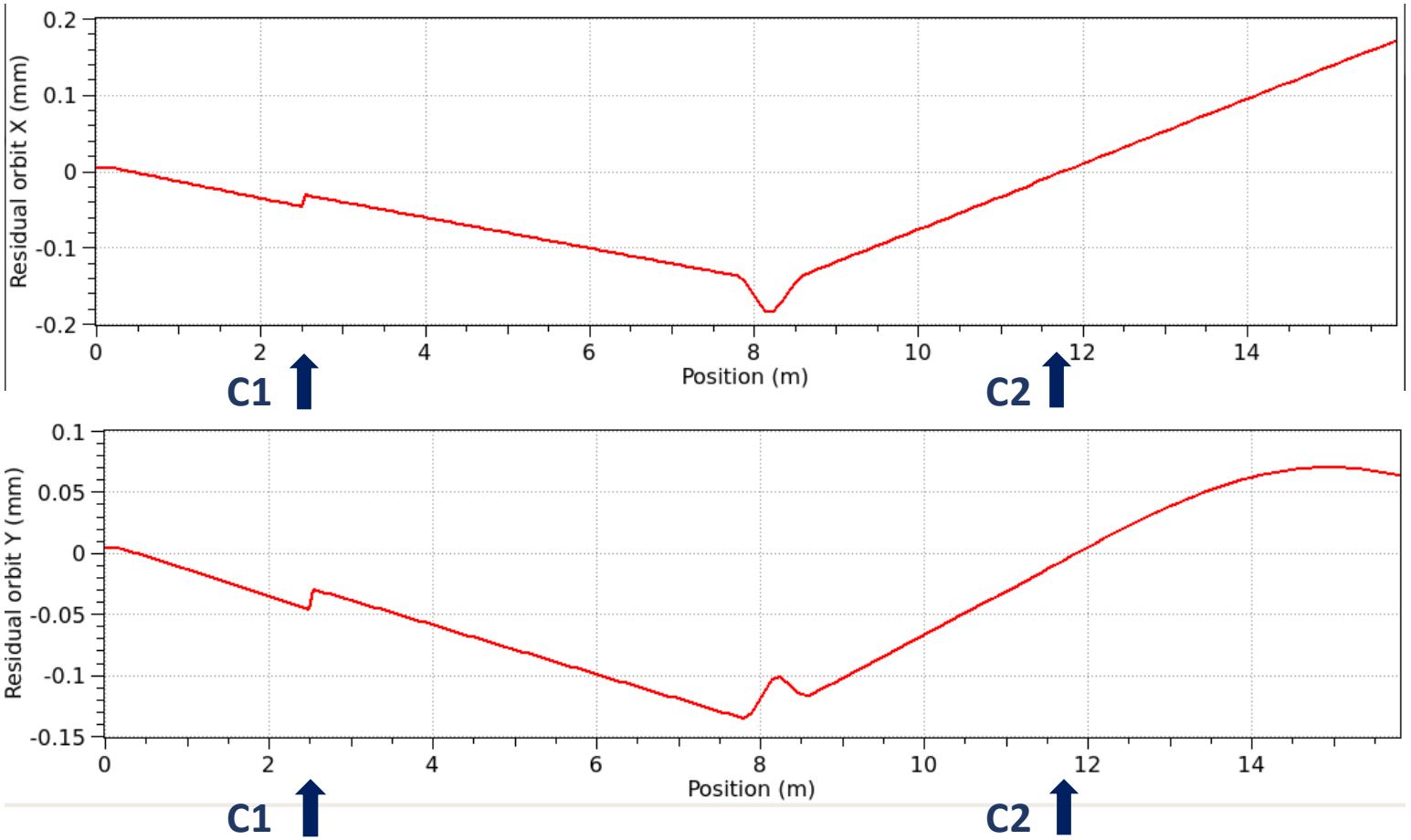
EuPRAXIA

Doctoral Network

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement no. 101073480.

UK Research and Innovation

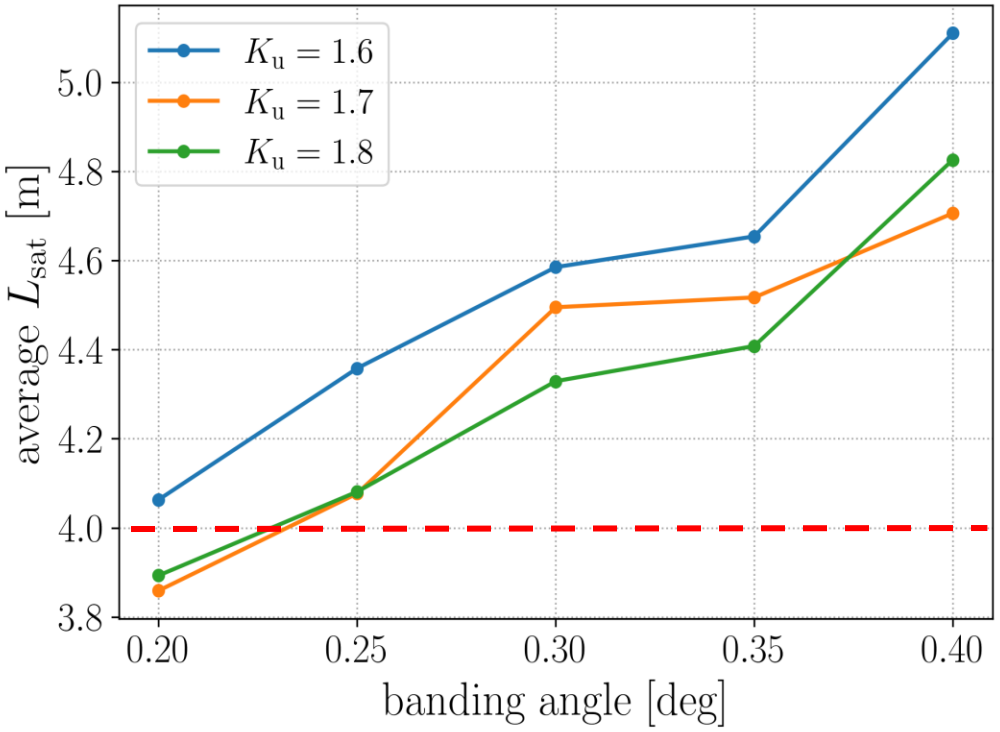
Injection error

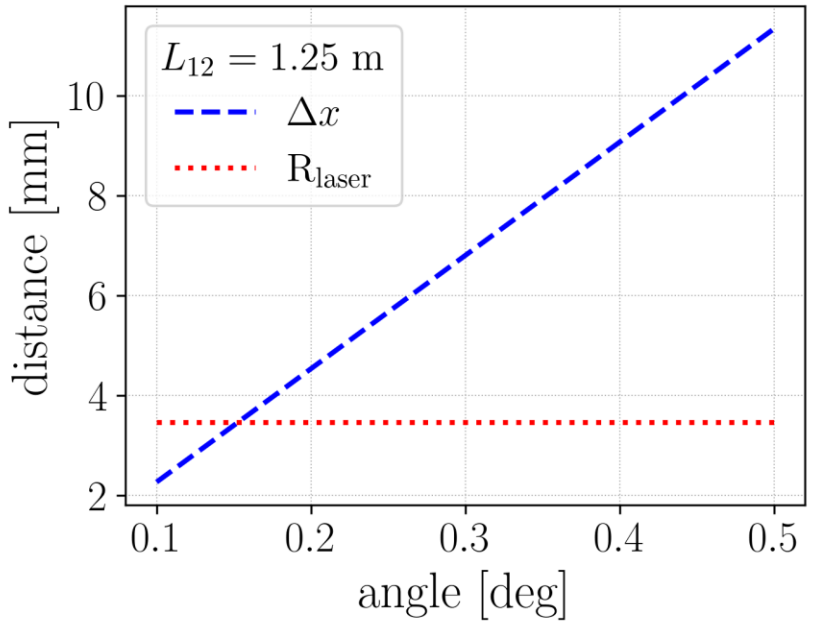


- Injection error of 2 µrad
- ~90% propagation compare to no injection error
- The beam propagates inside the undulator without problem.

Saturation within 4 meters

- For each chicane angle, ran 10 random-seed realizations in GENESIS.
- Detected saturation point per curve using relative growth rate d(ln E)/dz.
- Saturation defined where growth rate drops below 10% of its peak.
- Calculated mean value of the obtained such saturation length

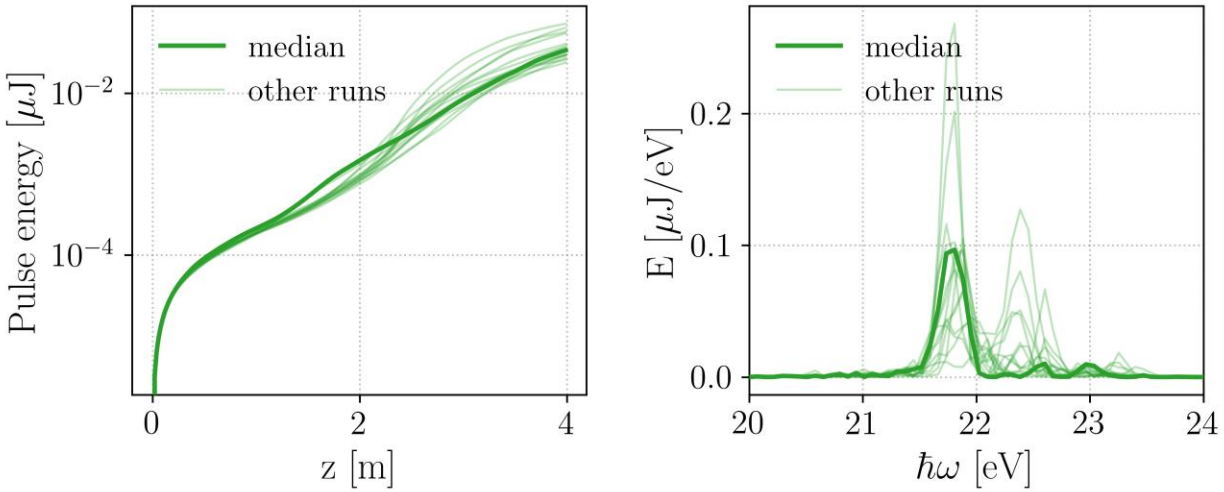




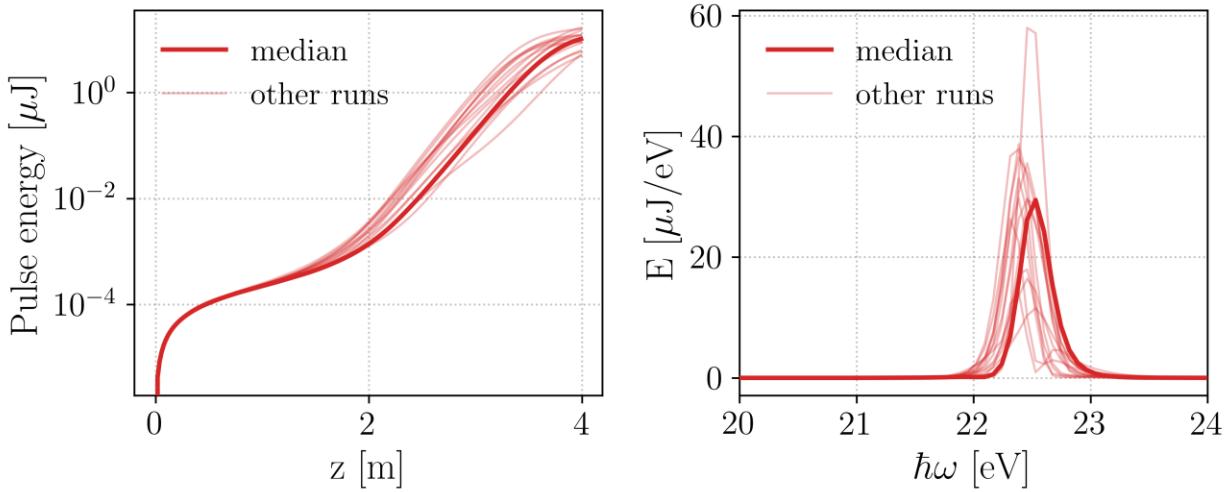
EUV FEL (without CHIC)

Ku =1.5

Without compensation of the energy chirp but including collimators:



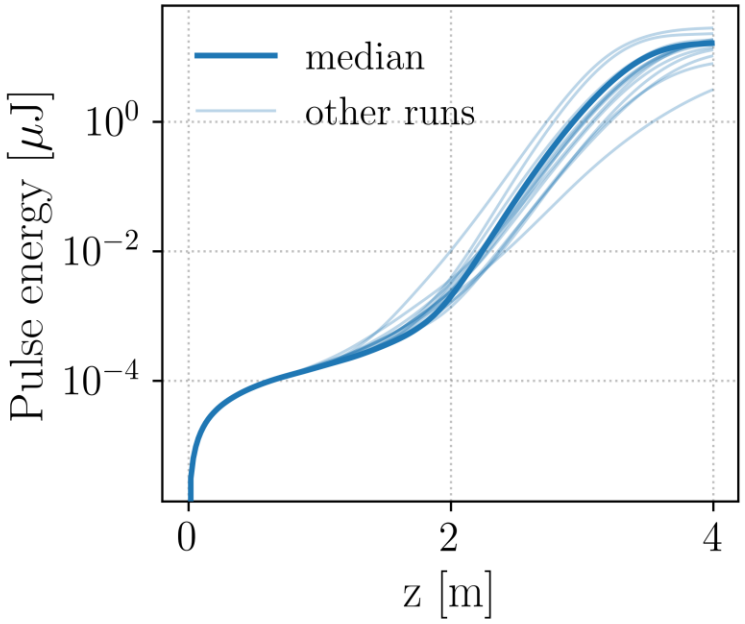
Without collimators but with compensation of the energy chirp:

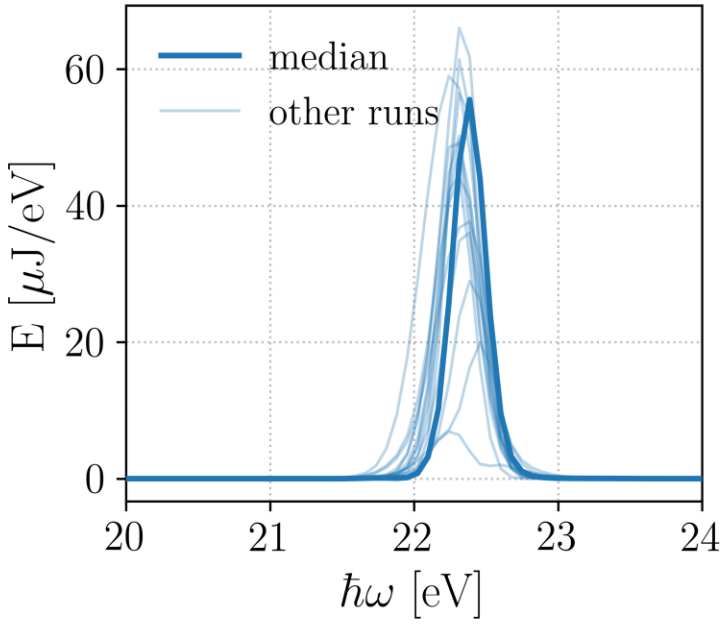


EUV FEL (without CHIC) Ku =1.5

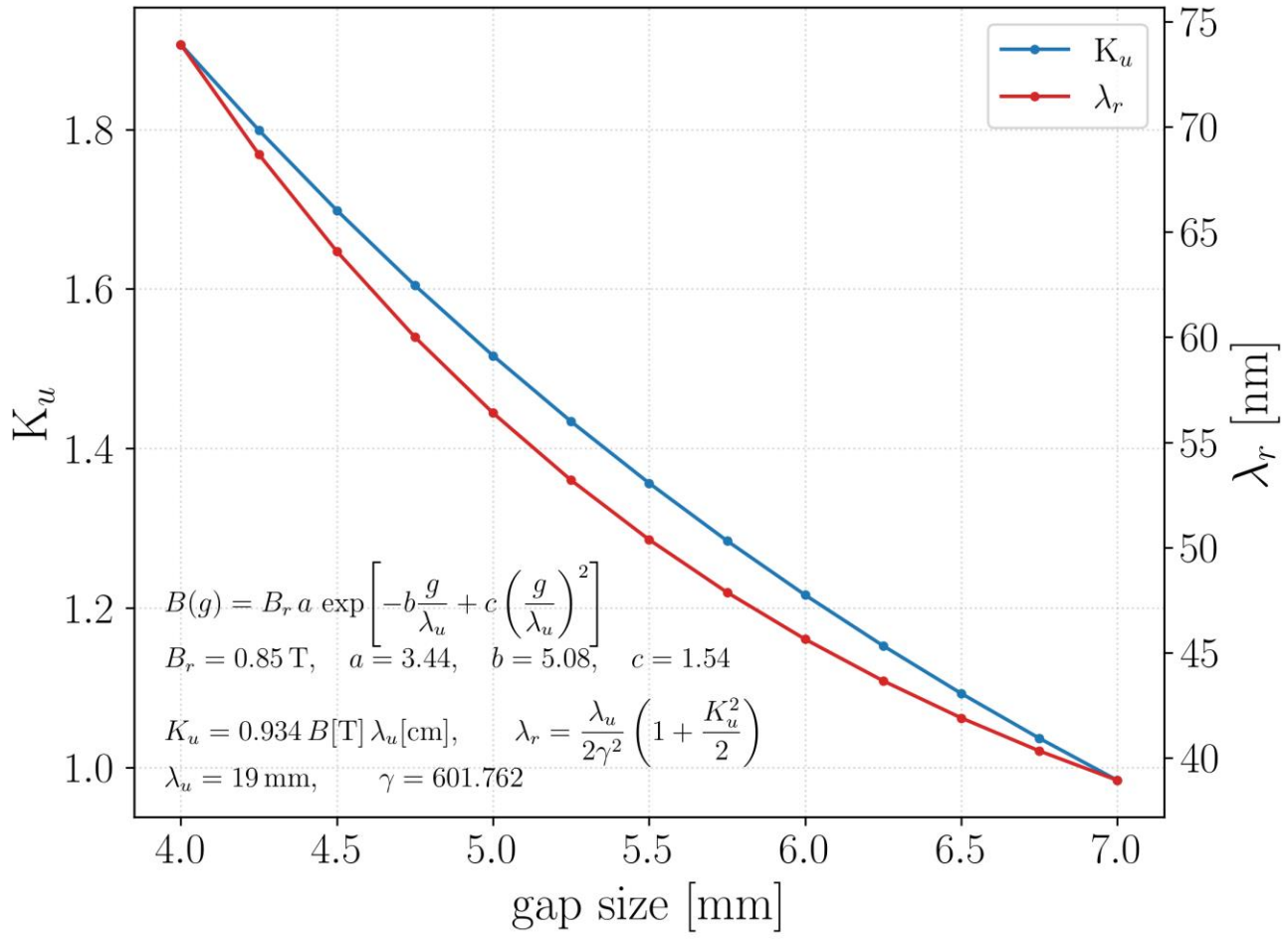
- Space-charge effect in the undulator is not consider.
- Fifteen runs with different shot-noise seeds.

Compensation of the energy chirp and using collimators:





E = (15.69 ± 5.89) μJ

λ = 55.45 nm

Ku and λu for different gap size