Beam Transport System for LPA-driven EUV FEL

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The project hase received funding form Eupropean Union's Horizon Europe research and inovation programme under the Marie Skłodowska-Curie grant agreement No 101073480.

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- Challenges for FEL
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FEL radiation in EUV regime

Requirements for FEL:

$$\epsilon_n < \epsilon_{coh,n} = \lambda_r / 2\pi$$

$$\sigma_\delta < \frac{1}{2}\rho$$

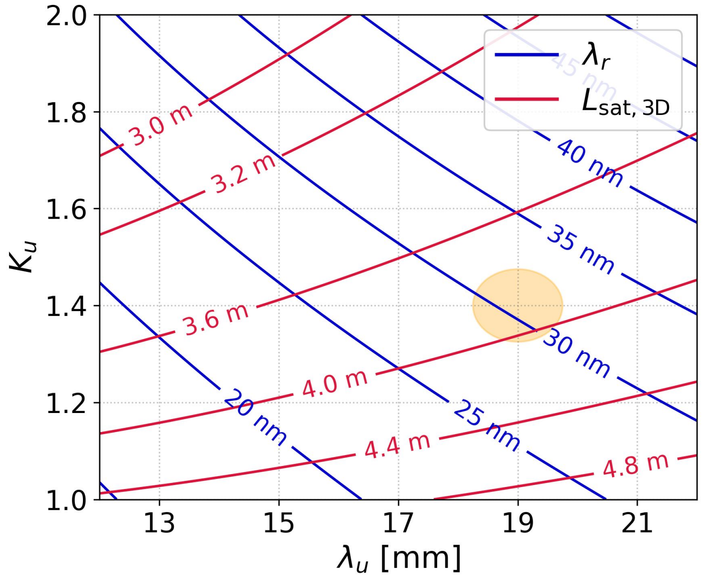
$$L_{g,1\mathrm{D}} < Z_R = \pi w_0^2 / \lambda_r$$

What do we have?

Parameter	Symbol	Specification
Undulator type		SwissFEL U19
Lattice		UND-QD-UND-QF
Undulator period	λ_u	19 mm
Undulator length	l_u	4 m (2 units of 2 m)
Undulator parameter	K_u	1.2 - 1.6 (by changing the undulator gap)

Slice electron beam we are considering?

Slice parameter		Value	Unit
Normalized emittance	ϵ_n	~0.3	π mm mrad
Relative energy spread	σ_δ	~ 0.2	%
Peak current	I_{peak}	~4.5	kA



LWFA electron beam

- Small initial normalized RMS transverse emittance
- Extremely short electron bunch (∼ fs)
- High peak current (few kA)

Challenges for FEL:

- High angular divergence (∼ mrad) ➡ Significant emittance growth in the first drift
- Large energy spread (few %) ➡ RMS normalized emittance not invariant anymore
- Significant space charge effect ➡ Halo formation
- Chromatic aberration effect
- Stability and repeatability

Initial electron beam parameters

- SIOM-like electron beam:

Parameter		Value	Unit
Energy	W	400	MeV
RMS relative energy spread	σ_δ	0.2	%
Peak current	I_{peak}	5	kA
RMS bunch duration	σ_τ	25	fs
RMS normalized horizontal(vertical) emittance	$\epsilon_{nx}(\epsilon_{ny})$	0.3(0.1)	π mm mrad
RMS horizontal(vertical) divergence	$\sigma_{x'}(\sigma_{y'})$	0.4(0.2)	mrad

High-quality electron beam generation from laser wakefield accelerators for driving compact free electron lasers

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Beamline layout

SOURCES ➡ CAPTURE BLOCK ➡ MATCHING SECTION ➡ UNDULATOR ➪ EUV RADIATION

LASER-PLASMA ACCELERATION

ACTIVE PLASMA LENS
OR
THREE PERMANENT QUADRUPOLE MAGNETS

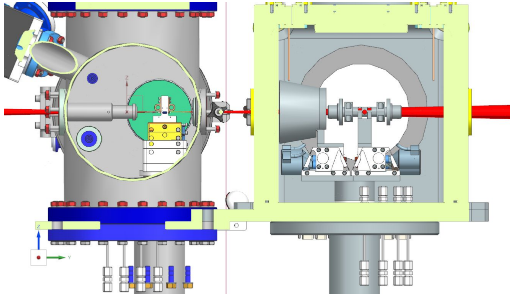
THREE ELECTRO QUADRUPOLE MAGNETS

SwissFEL U19

(two units of 2 meters)

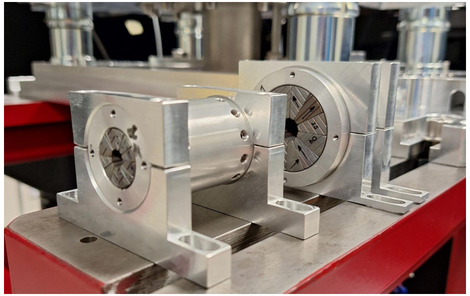
Capture block

Active plasma lens



Parameter	Value	Unit
Length	70	mm
Radius	1	mm
Gradient	~77	T/m
Discharge current	~385	A

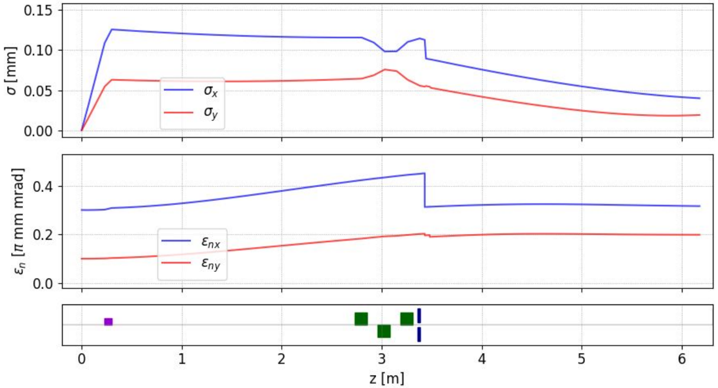
Set of three permanent quadrupole magnets

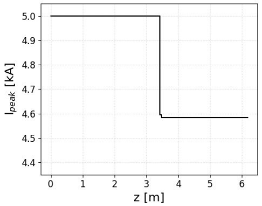


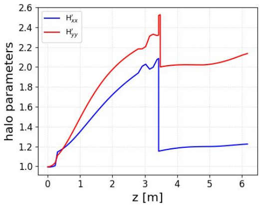
	Parameter	Value	Unit
First magnet	G_1	~300	T/m
Second magnet	G_2	~250	T/m
Third magnet	G_3	~100	T/m

Beam dynamics

Active plasma lens







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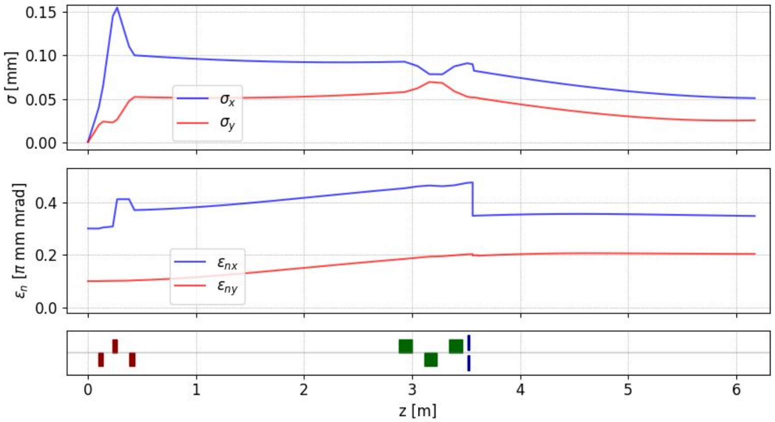
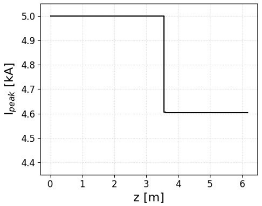
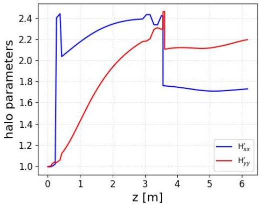






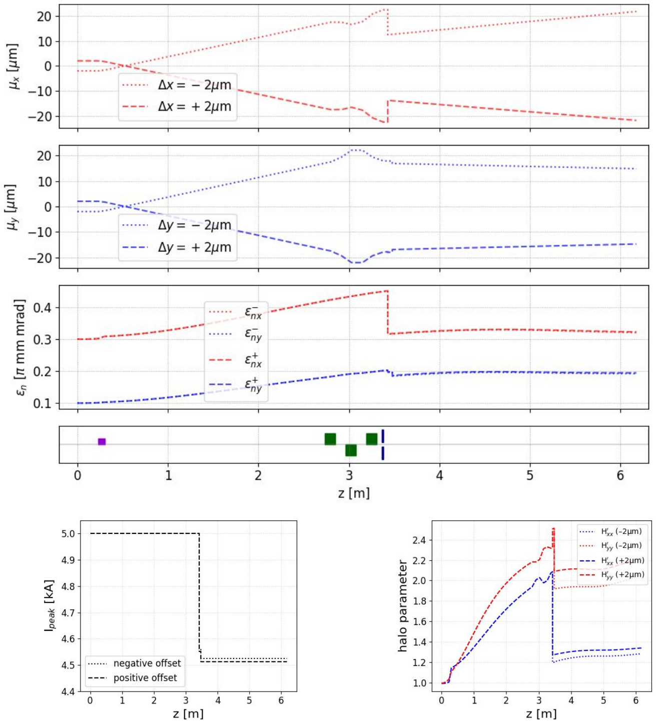
Transmission efficiency and emittance degradation affected by injection error

Restriction:
Shift of the beam center at the undulator position should be less than a half of the transverse sigma beam size.

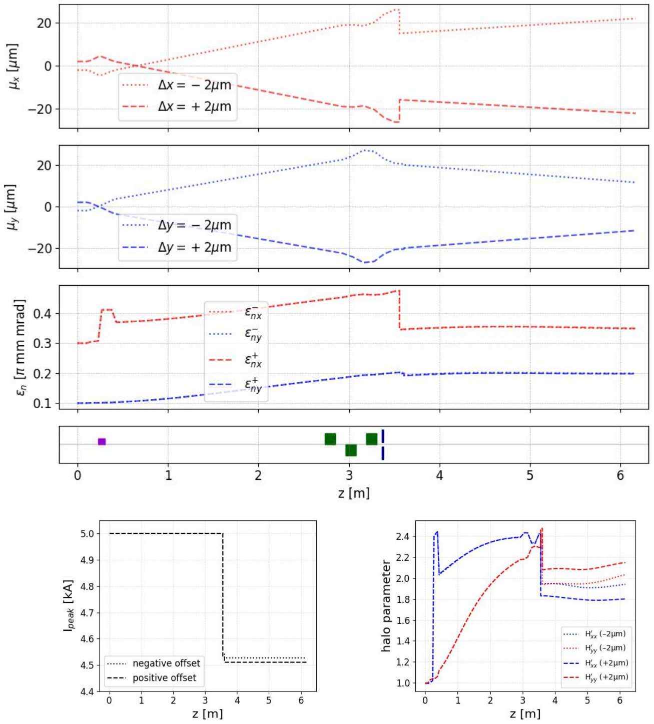
Result:
The injection error should not exceed ± 2 μm

Note:
Random injection error cannot be corrected by using correctors along the beamline.

Active plasma lens



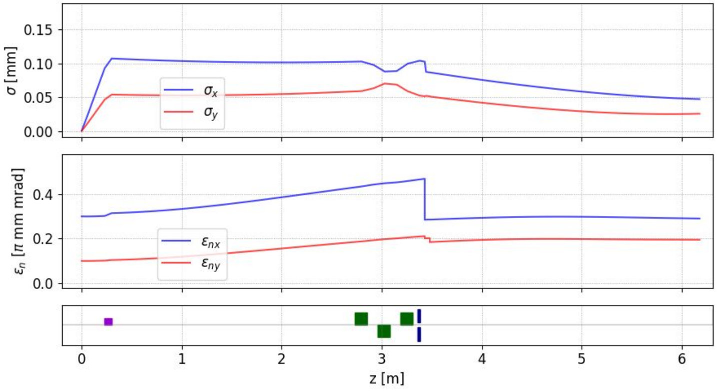
Set of three permanent quadrupole magnets

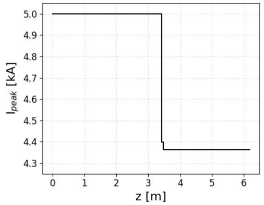


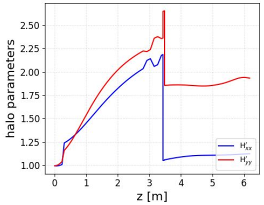
Transmission efficiency and emittance degradation affected by mismatch

- Assumed **15% mismatch** in initial Twiss parameters (β and α increased by 15% from ideal values).

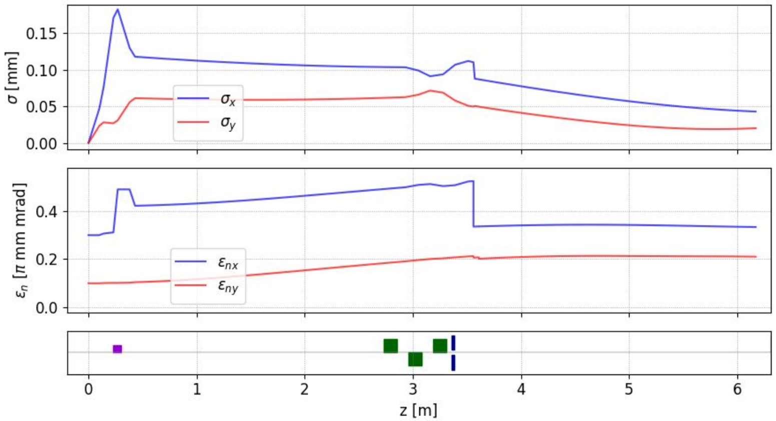
Active plasma lens

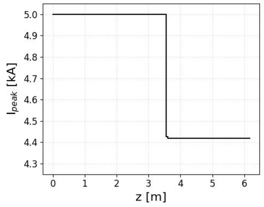


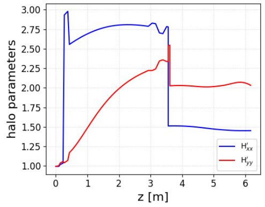




Set of three permanent quadrupole magnets







Simulated FEL radiation

- Time-dependent SASE FEL simulation using **GENESIS**.
- Input beam parameters from the multiparticle tracking transport analysis.
- Central wavelength: **30.7 nm**
- Pulse energy at saturation: **∼ 40 μJ**
- Peak power: **∼ 9 GW**
- Averaged on 15 shot noise seeds for statistics.

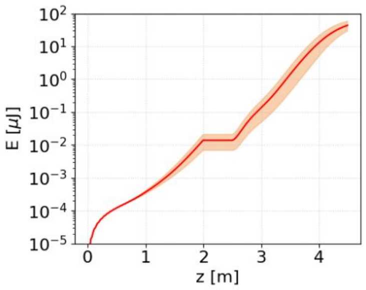


Figure 3: Radiation gain over the undulator length. The solid line represents the mean of the 15 shots with different shot noises and the shaded region is the standard deviation.

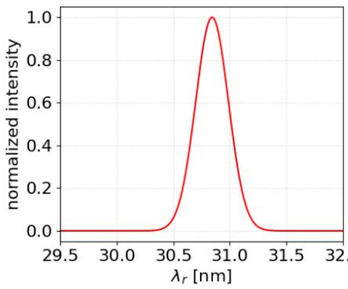


Figure 4: Gaussian fit of the averaged spectrum of the produced EUV photon pulses for a 15 shots with different shot noises.

Conclusion

- Designed a compact beamline using APL and PQMs for beam transport.
- APL and PQMs deliver comparable performance.
- APL offers greater flexibility and its focusing strength is tunable via current (prototype under development).
- Preserve low emittance (∼ 0.3 mm·mrad) and high peak current (∼ 4.5 kA).
- Beam mismatch simulations show no significant emittance growth and no significant beam loss.
- Injection error within the specified range does not lead to significant losses.
- FEL saturation reached at 30.7 nm.

Thank you !

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