FEL Performance of the APPLE-X Undulators for the EuPRAXIA@SPARC_LAB AQUA Beamline

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ID #269

Introduction

The **AQUA** FEL beamline of the EuPRAXIA@SPARC_LAB project [1] will be operated in Self-Amplified Spontaneous Emission mode for experiments around 3-4 nm wavelength, i.e. 410-310 eV photon energy, where water looks transparent differently from N or C

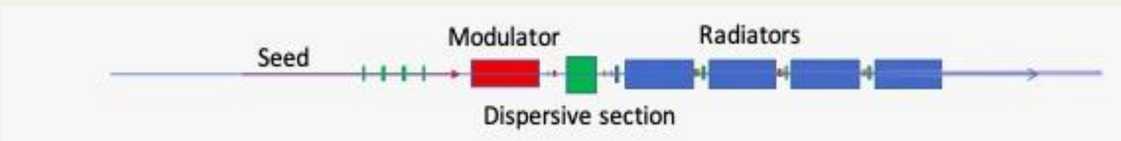
→ water window relevant to study biological samples with coherent imaging

The project baseline includes a second seeded FEL beamline, named ARIA.
Longer wavelength radiation in the VUV spectral range (50-200 nm), relevant to gas phase studies, should be produced in this case [2].

1) AQUA: Soft X-ray SASE FEL - optimized for 4 nm

Apple-X Permanent Magnet Undulator and planar Super-Conducting Undulator under study

2) ARIA: VUV seeded FEL beamline for gas phase

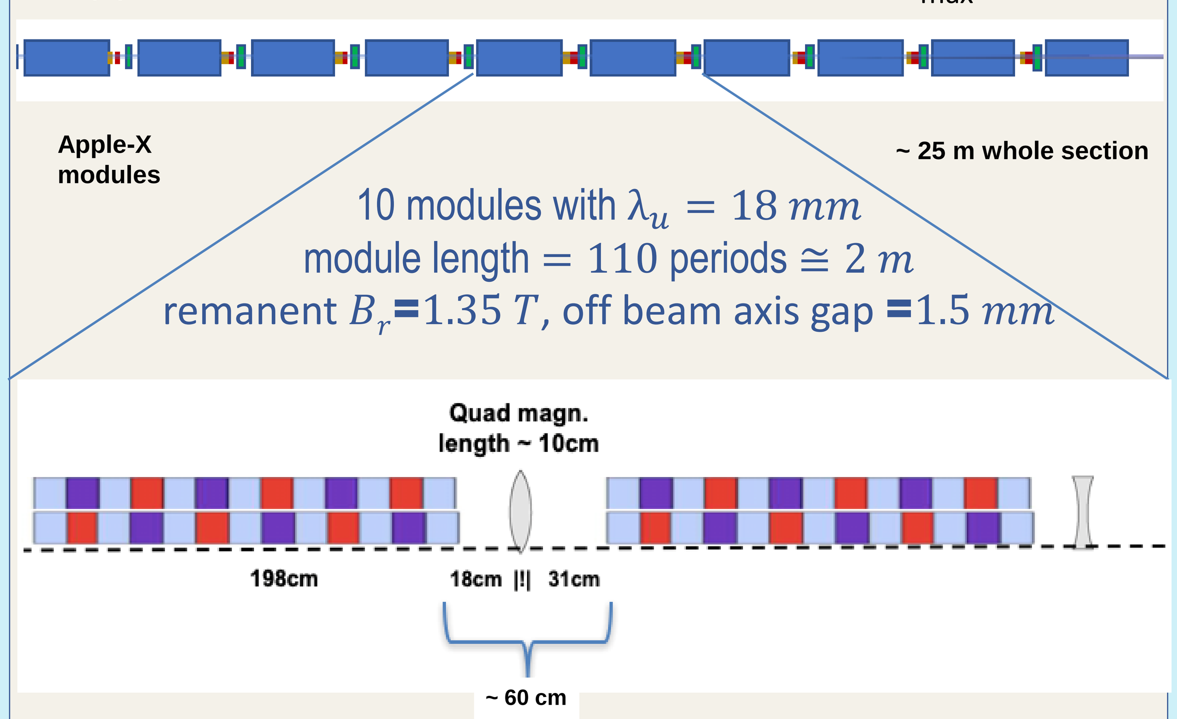


Modulator 1 m + 4 Radiators (APPLE II, 2.2 m each)
Undulator based on consolidated technology
Seeded in the range 290 - 430 nm

Baseline undulator layout

The **AQUA** baseline consists of 10 2m-long Apple-X permanent magnet undulator modules.

Apple-X: 5 mm round vacuum chamber → K_{max} = 1.7



A tolerance study of two possible sources of degradation of the FEL performance is here presented: undulator field errors and longitudinal resistive wall (RW) wakefields.
Their theoretical models as well as their effects on the expected FEL performance are presented.

Electron beam driving AQUA

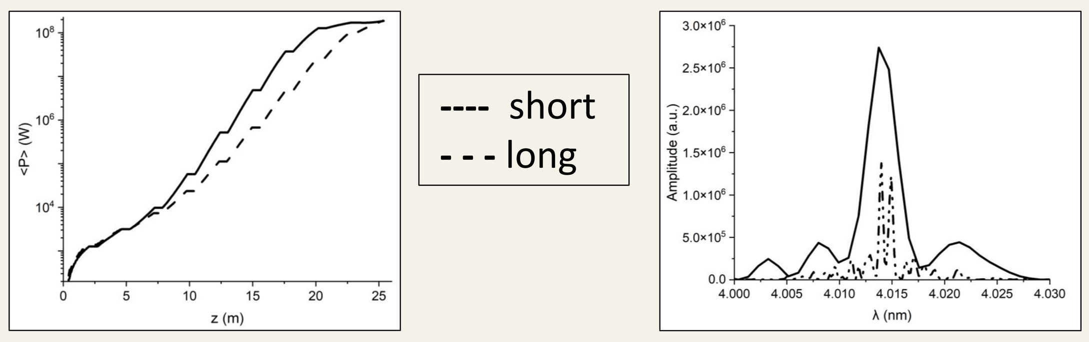
The AQUA beamline is driven by the EuPRAXIA@SPARC_LAB accelerator, composed by an X-band Linac followed by a plasma stage.

Parameter	Units	PWFA	Linac
Charge Q	pC	30	200
Energy E	GeV	1	1
Peak current I_{peak}	kA	1.8	1.2
Bunch length σ_z	μm	2	20
Proj norm. emittances $\varepsilon_{n,x,y}$	mm-mrad	1.7	1.7
Slice, norm. emittances $\varepsilon_{n,x,y}$	mm-mrad	0.8	0.8
Proj. energy spread $\sigma_{\delta p}$	%	0.95	0.95
Slice Energy spread $\sigma_{\delta s}$	%	0.05	0.05

Plasma wakefield acceleration (PWFA) provides low-charge electron bunches.
Longer bunches can be delivered by employing the X-band RF Linac only. 36

AQUA FEL simulation: ideal und. lattice

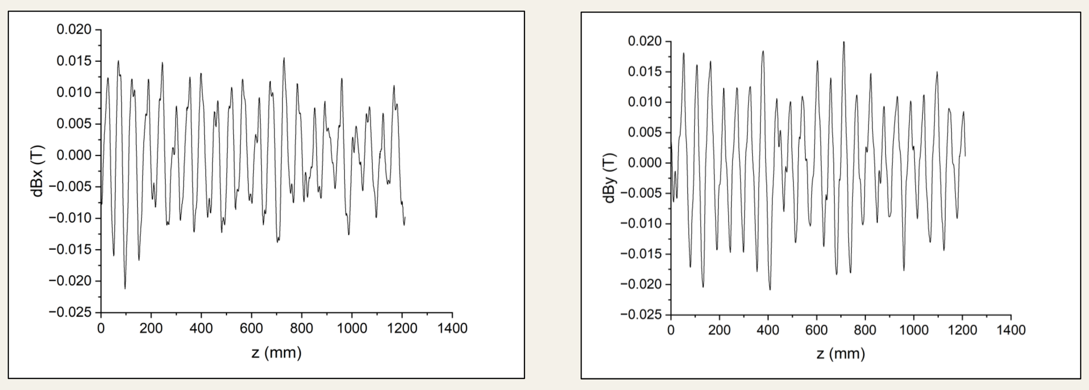
Beam slice parameters and Gaussian current profile are used for 3D time dependent FEL simulations with GENESIS1.3 [3]; on-axis injection is assumed.



The plots show the output average power and output spectrum. The short beam mode (short) leads to single-spike FEL pulses, unstable from shot to shot (here a single shot is reported).

Undulator field errors

The AQUA APPLE-X short-period undulator is similar to a longer period ($\lambda_u = 55\ mm$) undulator designed by KYMA for a THz FEL project at SPARC_LAB in Frascati, named SABINA [4].
Undulator field errors for the SABINA undulator were measured with a Hall probe method.
The differences $dB_{x,y}$ between the measurements and the ideal on-axis field amplitudes are

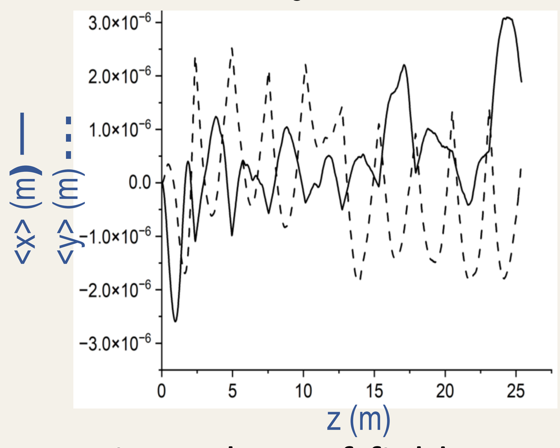


Apart from the period conversion, comparable field errors could be expected for the AQUA undulator.

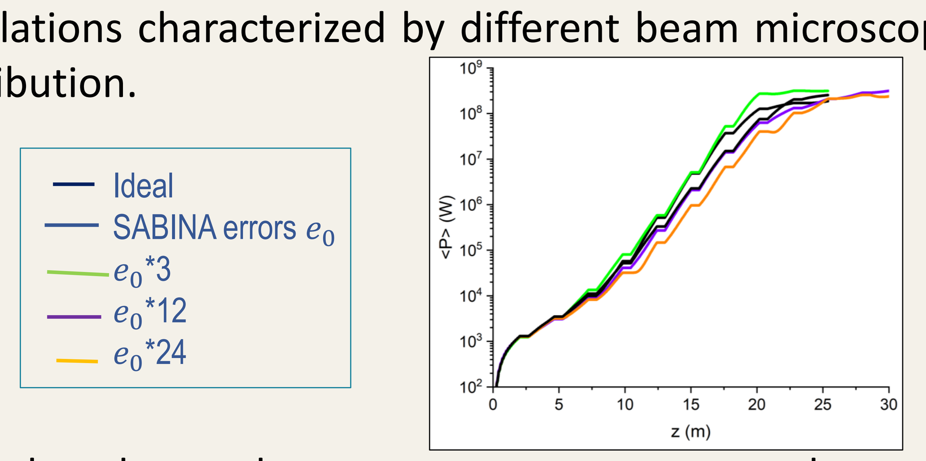
Model → dipoles d_i added to each AQUA module, with fields given by $d_i = 0.3\frac{dB_i[T]\Delta s[m]}{m_e c^2[GeV]}$

The undulator lattice for FEL simulations is built using a Gaussian random number algorithm generating sequences of dipoles with fields characterized by the same average/rms of the SABINA errors (e_0).

Beam orbit is corrected by means of an extra inter-module dipole.

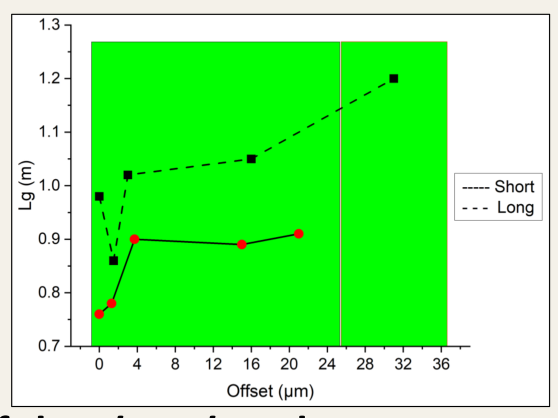


Different simulations for increasing values of field errors with respect to the SABINA undulator ones (up to 40 times e_0) are performed.
Each result of the short beam mode is the average of simulations characterized by different beam microscopic distribution.



The plot shows the average output power along the undulator line of a single shot in the short beam mode for increasing magnetic error intensities.

For both long and short beams, FEL performance begins to degrade for error intensities 1 order of magnitude larger than e_0.



FEL performances of the *short,long* beam

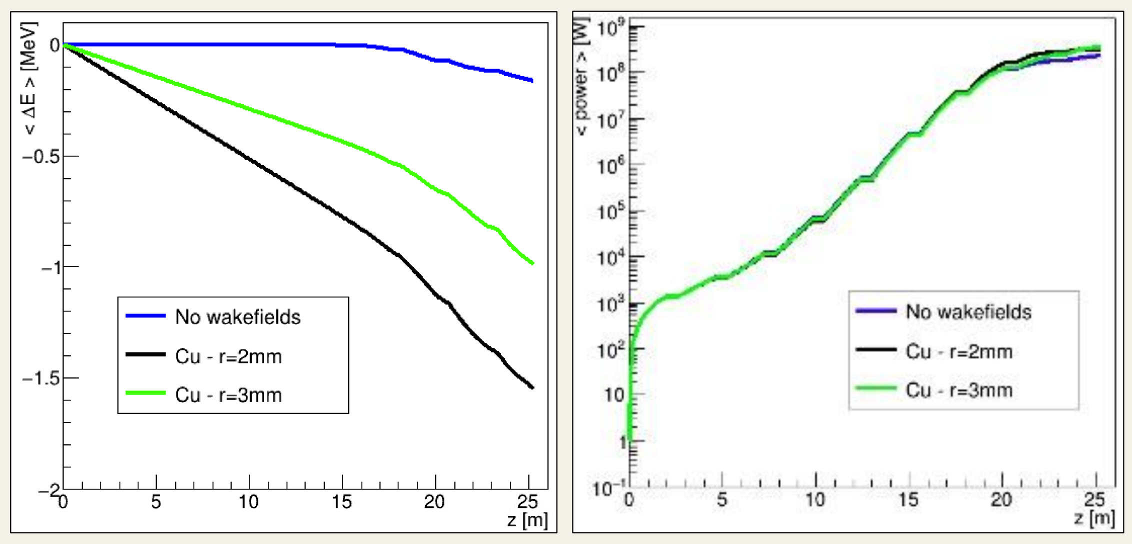
Increase (*e_0)	0	1	3	12	24
Offset (μm)	0.03,0.013	1.3,1.5	3.7,3	15,16	21,31
L_{sat} (m)	25,25	25,25	25,25	25,26	28,28
E_{sat} (μJ)	15.2,65.7	12.3,74	14,63	15.6,87	13,65
L_g (m)	0.76,0.98	0.78,0.86	0.9,1.02	0.89,1.05	0.9,1.2

Longitudinal resistive wakefields

Beams propagating inside a vacuum chamber (VC) with finite conductivity experience self-induced fields, described by the resistive wall (RW) impedance model.

The resulting longitudinal RW wakefield introduces a significant energy spread, affecting the FEL gain length and overall performance.

The average energy loss and FEL power are evaluated with the longitudinal RW wakefield model presented in [5], assuming different (VC) inner radii.



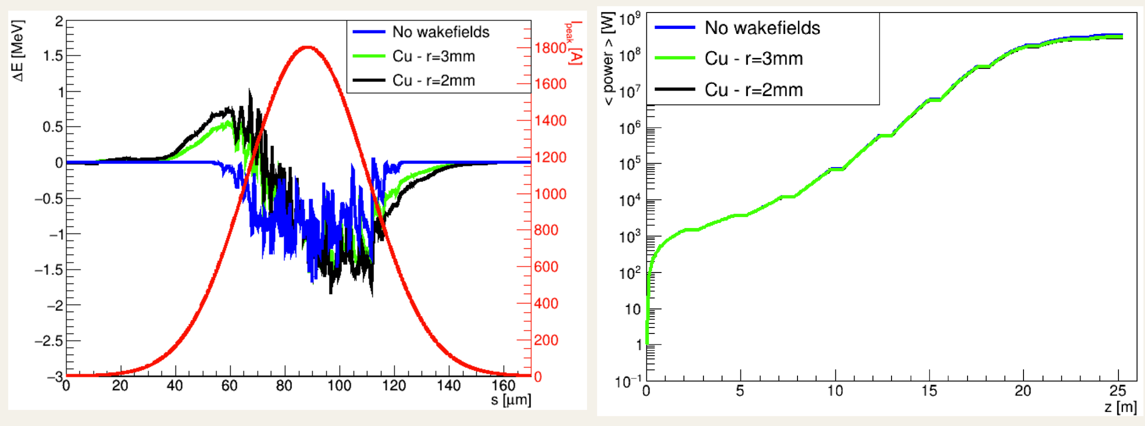
The left-side plot shows the average energy loss of the short beam along the FEL propagation coordinate.

The average FEL output power in logarithmic scale along the propagation coordinate is shown on the right.

- in the short beam case, longitudinal RW wakefields do not introduce significant effects on the FEL energy gain and saturation length

As shown below in the left plot, there is no significant difference on the average energy loss of the long beam at the undulator exit with and without longitudinal RW wakefields.

The plot on the right shows the corresponding average FEL output power along the propagation coordinate.



Conclusions and Outlooks

- ✓ The measured magnetic errors of the SABINA Apple-X undulator do not strongly affect the AQUA FEL performance
- ✓ Similar FEL performances without magnetic errors and with increased errors' intensities up to 25 times were observed

- ➢ A more detailed study will include undulator phase errors

- ✓ Longitudinal RW wakefields do not hamper the FEL lasing and their effects can be also attenuated by means of undulator tapering

- ➢ Transverse RW (plus other sources of) wakefields are under investigation.

References

[1] M. Ferrario et al., EuPRAXIA@SPARC_LAB Conceptual Design Report (2018)
[2] A. Balerna et al., "The Potential of EuPRAXIA@SPARC_LAB for Radiation Based Techniques", Condens. Matter 4(1) (2019) 30
[3] S. Reiche, GENESIS 1.3: A fully 3D time- dependent FEL simulation code
[4] J. Počkar et al., "Design of the Innovative Apple-X AX-55 for SABINA Project, INFN Laboratori Nazionali di Frascati", in Proc. FEL2022, Trieste.
[5] F. Bosco et al., "Modeling Short Range Wakefield Effects in a High Gradient Linac," in 12th IPAC, 2021. doi: 10.18429/JACoW-IPAC2021- WEPAB238.

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