# Design and tolerance studies of the Undulators for the EuPRAXIA@SPARC_LAB Free-Electron Laser lines


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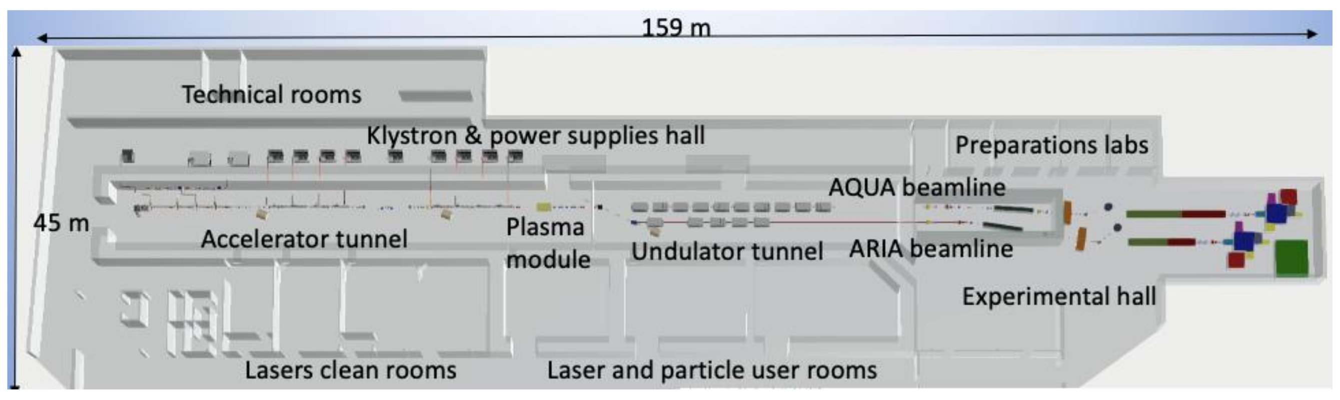
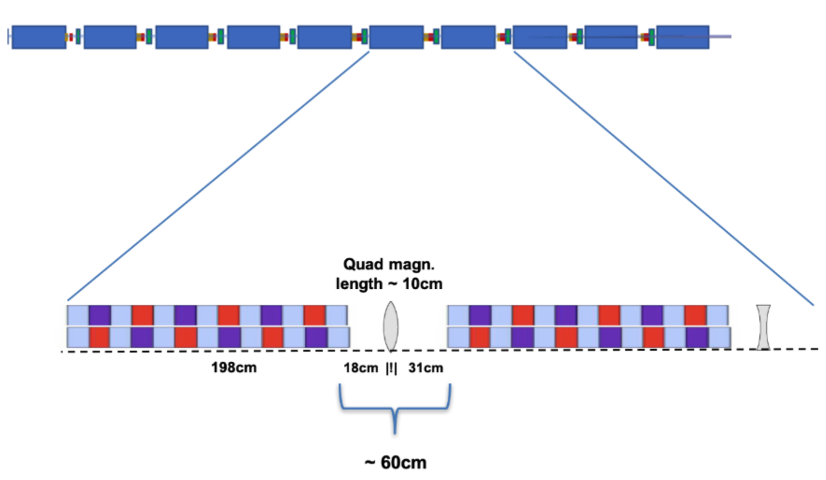



The future EuPRAXIA@SPARC_LAB FEL facility will host two FEL beamlines driven by the X-band LINAC and a PWFA stage. The two foreseen FELs will deliver short pulses with selectable polarization:

- **AQUA**, a soft X-ray FEL operated in Self-Amplified Spontaneous Emission mode and optimized for in the water window around 3-4 nm wavelength, i.e. 410-310 eV photon energy
- **ARIA**, an EUV-VUV seeded FEL in High Gain Harmonic Generation configuration for gas phase (50-180 nm) providing coherent pulses with continuous tunability

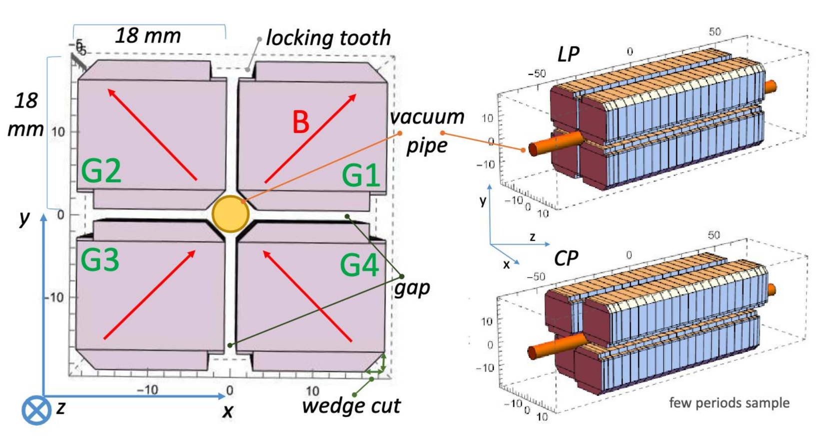
## AQUA: APPLE-X Undulator Design

The AQUA beamline, with a total magnetic length of 20 meters, is composed by ten APPLE-X permanent magnet Undulator Modules (UM) with 18 mm period length.




UM main parameters

| | |
|---|---|
| Br (T) | 1.35 |
| # blocks / period | 4 |
| Bmax (T) (in LP) | 0.935 |
| Kmax (in LP) | 1.572 |
| Kmax (in CP) | 1.111 |
| max $\lambda 0$ (nm) @1 GeV | 5.25 |



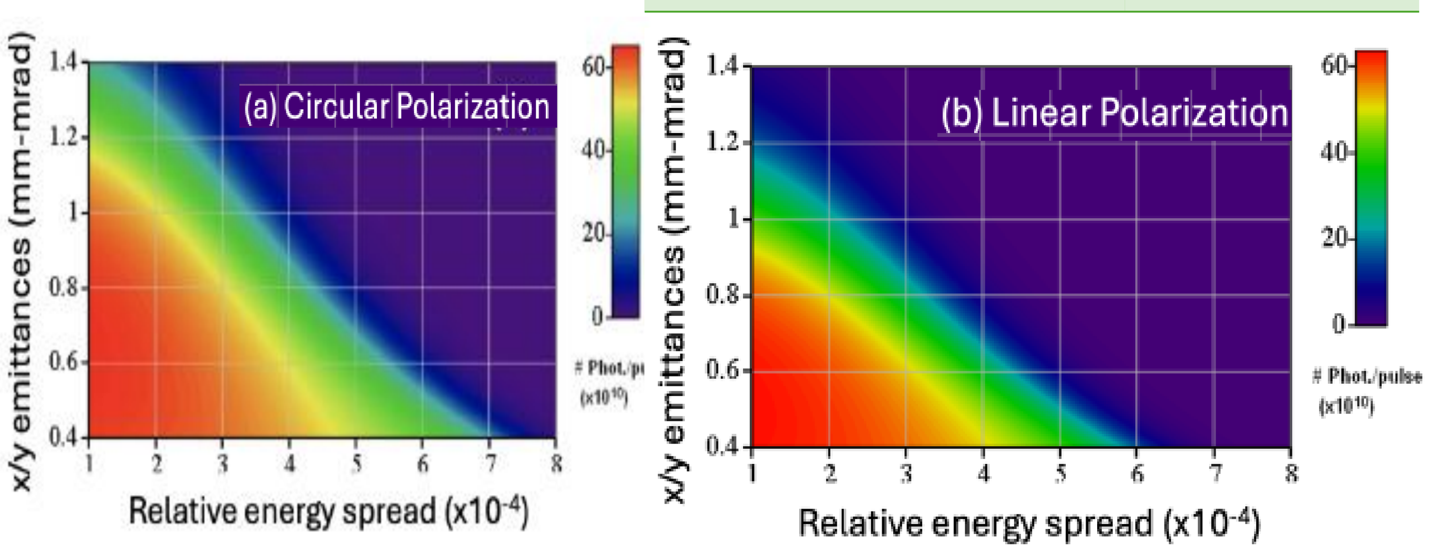

Cylindrical vacuum chamber

| | |
|---|---|
| Pipe ext. diam. (mm) | 5.6 |
| Pipe inner diam. (mm) | 5.0 |
| Wedge cut (mm) | 2.8 |
| ϕ aperture (mm) | 6.0 |

## Parameter Acceptance and Tuning Range

- FEL performance at 4 nm vs. electron beam parameters

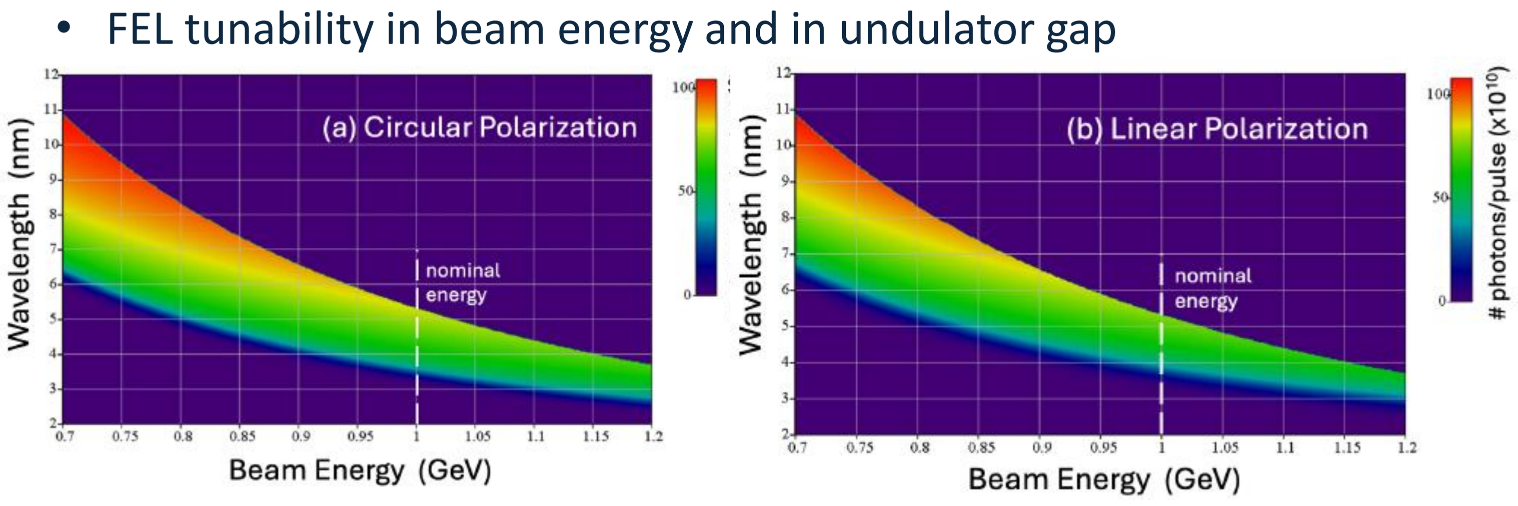
| Energy E=1 GeV | $\beta_x=\beta_y$=10 m |
|---|---|
| Ipeak=1.5 KA, σt=15 fs | $\varepsilon_x=\varepsilon_y$ |




**Circular polarization operations can be sustained even with non-optimal beam parameters**

**Non-optimal parameters can be partially mitigated by decreasing the Twiss b values**

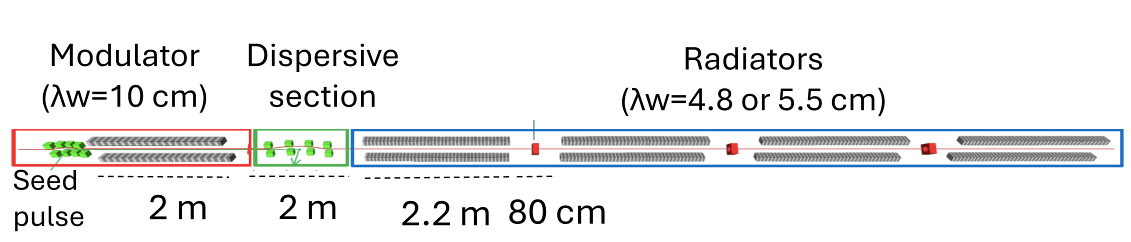
- FEL tunability in beam energy and in undulator gap




**"Water window" probed with higher photon yields and shorter saturation lengths**

**Shorter wavelengths imply lower K values → lower power and smaller tunability**

## ARIA baseline layout




APPLE-II and APPLE-X undulator technologies, already built by KYMA and respectively similar to the FERMI FEL-1 and to the AQUA undulators, are under investigation for the radiators

- **Driven by PWFA or LINAC only, 15-100 fs duration FEL pulses close to Fourier transform limit are expected → selectable polarization VUV light will allow to explore chirality and dichroism in biotic media**
- **Less demanding electron beam parameter space → user operations at early stage**
- **No other seeded FEL facility covers the full 50-180 nm range, except for the DALIAN light source**
- **Overlap with HHG sources, but without limitations on polarization, wavelength tuning and intensity**

## Tolerance studies

To accumulate sufficient statistics, the tolerance of the AQUA undulators to different sources of degradation has been simulated with longer electron bunches →

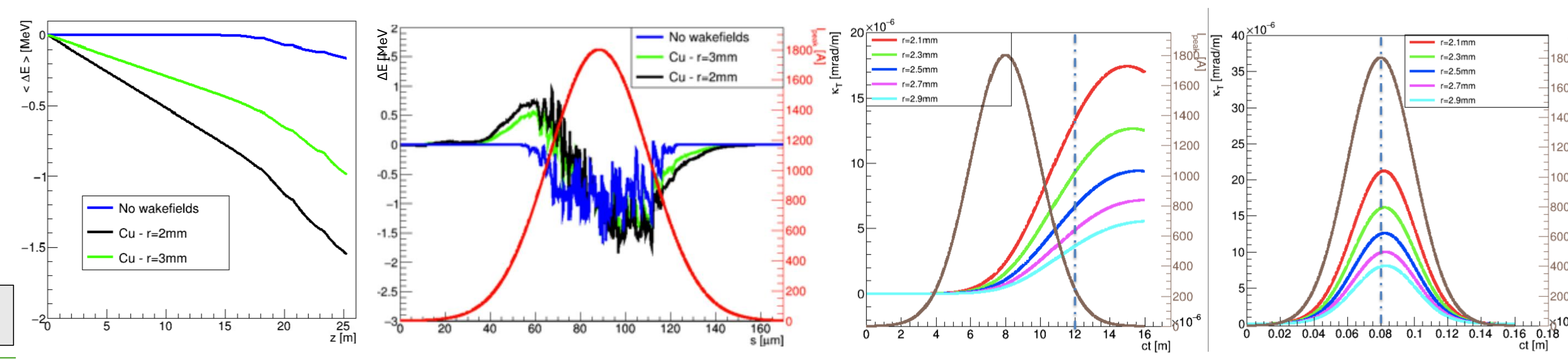
| E=1 GeV | Q=200 pC, σz=20 μm |
|---|---|
| ΔE/E=0.05% | $\varepsilon_{x,y}$= 0.8 mm mrad |

### Resistive-wall wakefields

Analysis assuming a copper vacuum chamber (VC) of different inner radii and a higher charge beam of 300 pC

**Longitudinal** | **Transverse** (trajectory transverse offset 50 μm)

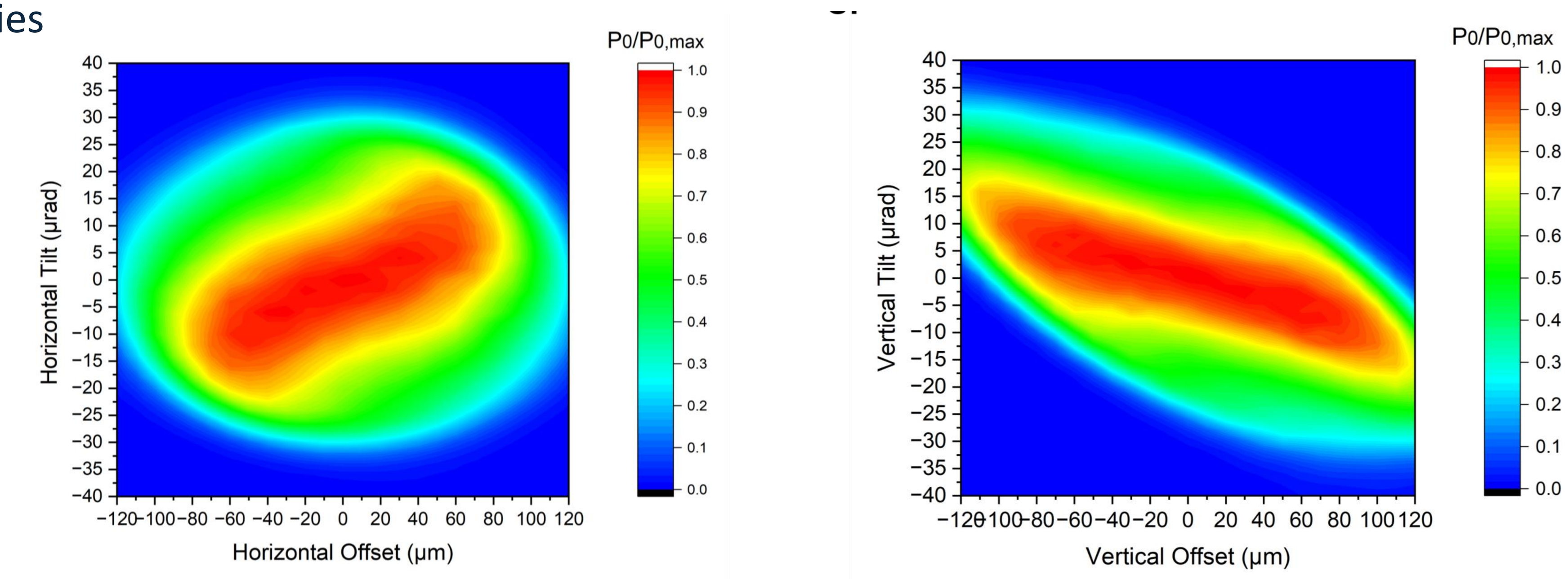
*Short 30 pC beam* | *Long 300 pC beam* | *Short 30 pC beam* | *Long 300 pC beam*




- The energy loss, so the average FEL power growth, are comparable to the case of no wakefields for both inner radii and beam modes
- For a VC inner radius of 2.5 mm, the peak current region of the bunch is affected by a potential kick angle per unit length of 5 nrad/m (10 nrad/m) in the low (high) charge case

### Trajectory and Injection

Electron beam transverse misalignments at injection, including trajectory offsets and tilts, can influence the FEL performances, drastically increasing the saturation length and reducing the achievable pulse energies




Nominal beam with β=8 m in circular pol.: Maximum achievable radiation power level $P_0$ normalized to the maximum FEL power $P_{0,max}$ achieved as a function of the initial horizontal and vertical tilt angles and offsets

- The AQUA undulator supports electron beam transverse offsets and tilts at injection below $\pm 40$ μm and $\pm$ 8 μrad respectively

### Magnetic Field errors

Undulator magnetic field errors can broaden the radiation bandwidth, shift the FEL resonance and reduce the radiation-electron transverse overlap, therefore affecting the overall FEL radiation growth

- Rms error values lower than 9 mT do not prevent the full radiation growth (>95% of saturation power in the absence of magnetic errors), provided that the conditions in Table are fulfilled:

| Quantity (unit) $\delta B_{x/y,rms}$ (T) | $3\times10^{-3}$ | $6\times10^{-3}$ | $9\times10^{-3}$ |
|---|---|---|---|
| $I_{1,rms}$ $(T\cdot m)$ | $7\times10^{-5}$ | $6\times10^{-5}$ | $5\times10^{-5}$ |
| $I_{2,rms}$ $(T\cdot m^2)$ | $5\times10^{-6}$ | $4\times10^{-6}$ | $3.1\times10^{-6}$ |
| $I_{1,max}$ $(T\cdot m)$ | $4.5\times10^{-5}$ | $4\times10^{-5}$ | $3.6\times10^{-5}$ |
| $I_{2,max}$ $(T\cdot m^2)$ | $3\times10^{-5}$ | $2.7\times10^{-5}$ | $2.5\times10^{-5}$ |
| $\langle I_1\rangle$ $(T\cdot m)$ | $2.1\times10^{-5}$ | $1.6\times10^{-5}$ | $1.1\times10^{-5}$ |
| $\langle I_2\rangle$ $(T\cdot m^2)$ | $2.5\times10^{-6}$ | $2.5\times10^{-6}$ | $2.5\times10^{-6}$ |

**Full time-dependent results with start-to-end electron beam distributions (from the cathode to the undulator entrance), accounting for electron beam fluctuations of two working points characterized b7 different bunch charges, show that AQUA will be able to deliver at least $10^{11}$ photons/pulse with narrow bandwidth and small deviations from the target performance**