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FEL PERFORMANCE OF THE EuPRAXIA@SPARC_LAB AQUA BEAMLINE

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Abstract

The AQUA beamline of the EuPRAXIA@SPARC_LAB infrastructure consists of a Free-Electron Laser facility driven by an electron beam with 1 GeV energy, produced by an X-band normal conducting LINAC followed by a plasma wakefield acceleration stage, with the goal to deliver variable polarization photons in the 3-4 nm wavelength range. Two undulator options are considered for the AQUA FEL amplifier, a 16 mm period length superconducting undulator and an APPLE-X variable polarization permanent magnet undulator with 18 mm period length. The amplifier is composed by an array of ten undulator sections 2m each. Performance associated to the electron beam parameters and to the undulator technology is investigated and discussed.

INTRODUCTION

The EuPRAXIA project is expected to realize and demonstrate use of plasma accelerators delivering high brightness beams up to 1-5 GeV for users [1]. During the first phase, the Free-Electron Laser (FEL) facility EuPRAXIA@SPARC_LAB will be constructed at the INFN-LNF laboratory [2]. This will be driven by the beam accelerated to 1 GeV energy within the plasma wakefield accelerator (PWFA) scheme, where a properly tailored electron bunch is injected into the plasma wave [3].

The AQUA [1] FEL beamline of the project will be operated in Self-Amplified Stimulated Emission (SASE) mode with 3-4 nm target wavelength, *i.e.* 310-410 eV photon energy, where water is almost transparent to radiation, while nitrogen and carbon are absorbing and scattering. This range belongs to the so called *water window*, where for instance 3D images of biological samples can be obtained processing several X-ray patterns by means of coherent diffraction imaging experiments: an ideal technique that could allow to reconstruct images of viruses or cells in their native environment [4].

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CHOICE OF THE UNDULATORS

Table 1 shows the electron beam values expected and assumed for the undulators assessment and for evaluating the AQUA FEL performance. The Linac driving the AQUA FEL includes two pairs of eight X-band accelerating cavities, separated by a magnetic bunch compressor and followed by the PWFA module. The final design of the layout is still in progress, with the following main features:

Table 1: Electron Beam Parameters

Quantity	Value
Charge Q	30 pC
Energy E_{beam}	1 GeV
Peak current I_{peak}	1.8 kA
RMS bunch length σ_z	2 µm
Proj. normalized x, y emittance ε_n	1.7 mm mrad
Slice normalized x, y emittance ε_n	0.8 mm mrad
Proj. fractional energy spread $\sigma_{\delta,p}$	0.95 %
Slice fractional energy spread $\sigma_{\delta,s}$	0.05 %

- peak current from the S-band photoinjector;
- slice energy spread goal of 0.05 % or lower;
- energy spread and transverse quantities under control operating at 0.85 GeV/m accelerating gradient.

In addition to the coherent imaging opportunities mentioned before, the chance to have variable and selectable X-rays allows to study [5] chemical properties of materials by means of switchable FEL polarization. Thus, the main requests to the undulator configuration are the following:

- deflection strength $K \simeq 1$ at resonant $\lambda \simeq$ 3-4 nm;
- selectable linear and circular polarization;
- some contingency in the total active length;
- some flexibility in the wavelength tuning range.

Figure 1 shows the FEL saturation length as a function of undulator period and resonant wavelength, evaluated with

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the 1D FEL performance scaling laws [6] assuming the parameters of Table 1 for a planar permanent magnet out-of-

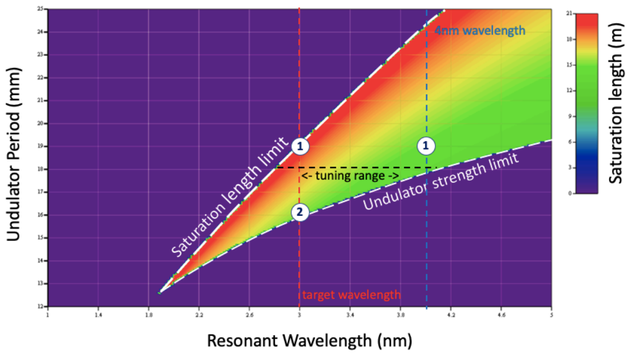

Figure 1: Saturation length contour plot as a function of undulator period and resonant wavelength.

vacuum undulator with remanent field strength $B_r = 1.2$ T and minimum gap of 6 mm. From Fig. 1 it results that:

(1) $\lambda_u = 18$ mm period implies some tuning range, plus a wide saturation length contingency, especially if operating at 4 nm resonant wavelength.

(2) $\lambda_u = 16$ mm period increases the saturation length limit, but with almost no wavelength tuning range, because of the deflection strength limit;

The adopted undulator solution is the Apple-X [7–9] with 18 mm period and remanent field strength $B_r = 1.35$ T. The design envisages a 5 mm external diameter vacuum chamber for electrons propagation. The minimum feasible gap is 1.5 mm, as the compromise between the requested field

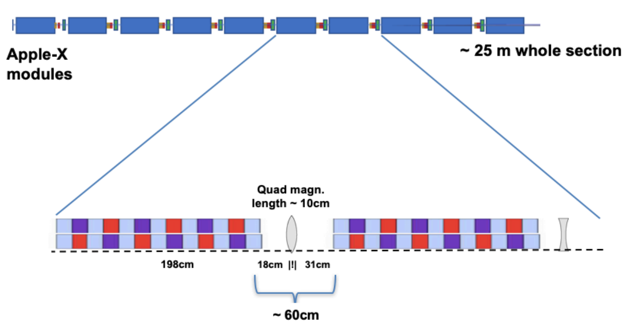

Figure 2: AQUA schematic undulator layout.

strength and mechanical constraints of the magnets. This structure allows to achieve $K_{\max} = 1.2$ ($K_{\max} = 1.7$) in case of circular (linear) polarization.

BASELINE UNDULATOR LAYOUT

The AQUA baseline SASE undulator section consists of 10 modules, each with a length of 110 periods ≃ 2 meters.

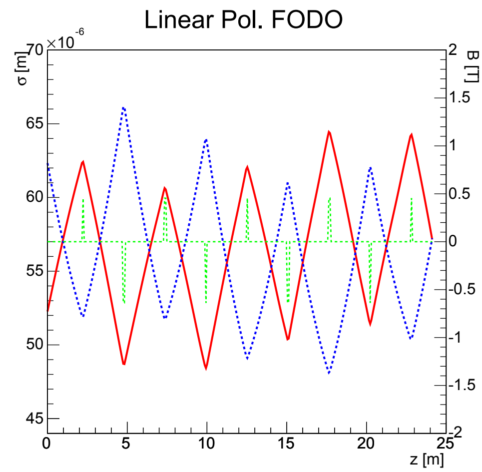

Figure 3: Horizontal (red solid line) and vertical (blue dotted line) profile of the electron beam inside the undulator plus FODO sections in LP mode: the green spots indicate the integral gradient field values specified on the right y-axis.

Figure 2 shows the scheme of the undulator line, featuring the inset zoom of the magnetic unit cell made of the undulator and FODO sections. The magnetic length of the quadrupoles is about 10 cm. For a 1 GeV electron beam energy, the choice to have the intra-undulator distance of about 60 cm, together with Twiss average $\beta_{x,y}$ parameter and K values constrain the quadrupole integral gradient fields requested to operate the Apple-X modules at 4 nm wavelength, in either linear (LP) or circular (CP) polarization.

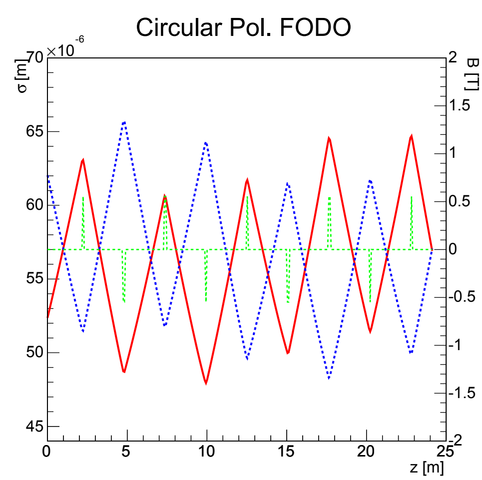

Figure 4: Horizontal (red solid line) and vertical (blue dotted line) profile of the electron beam inside the undulator plus FODO sections in CP mode: the green spots indicate the integral gradient field values specified on the right y-axis.

Figures 3 and 4 show the transverse profile of the electron beam subject to the undulator plus FODO sections in respectively LP and CP operations with $\langle \beta_{x,y} \rangle = 8$ m. The integral gradient field values are indicated by means of green spots indicating values on the y-axis specified on the right.

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The behavior of the integral gradient field values is investigated with raising the electron beam energy, while keeping constant all other parameters. In order to accommodate the same focusing factors, integral gradient fields have to be increased. Figure 5 shows that field values stay on the order

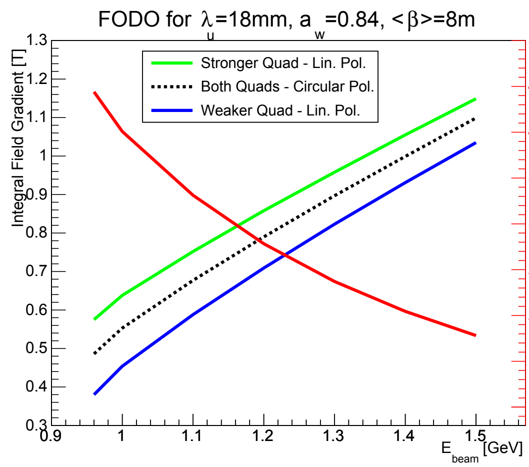

Figure 5: Integral gradient field values and resonant wavelength as a function of electron beam energy.

of about 1 T, or even smaller for both polarization modes, with asymmetric quadrupole field strengths in the LP FODO configuration, as expected. The following considerations are drawn:

- quadrupole field strengths are such to sustain even higher beam energies, and so shorter wavelengths with the same undulators;
- if $E_{\text{beam}} = 1.2\,\text{GeV}$, it is possible to operate at 3 nm wavelength with the same quadrupole and undulator devices, and with larger saturation length and pulse energy contingencies than with $E_{\text{beam}} = 1\,\text{GeV}$.

FEL performance can be enhanced with respect to the baseline design by adding upstream the planar NbTi superconducting undulator prototype under development in collaboration with the Fermi National Accelerator Laboratory [10].

FEL PERFORMANCE

With the electron beam parameters of Table 1 and same FEL scaling laws, the number of photons per pulse N_γ/pulse is evaluated for both polarization modes. Figure 6 shows the number of photons per pulse, evaluated as a function of resonant wavelength and electron beam energy for LP (top) and CP (down). Tunability is achieved in both beam energy and undulator gap:

- undulator gap gives limited lever arm;
- wider tunability in CP than in LP mode;
- by increasing the beam energy, there is the chance to probe water window with $N_\gamma/\text{pulse} \sim 10^{11}$ yields at 4 nm (LP) and 3 nm (CP) wavelengths.

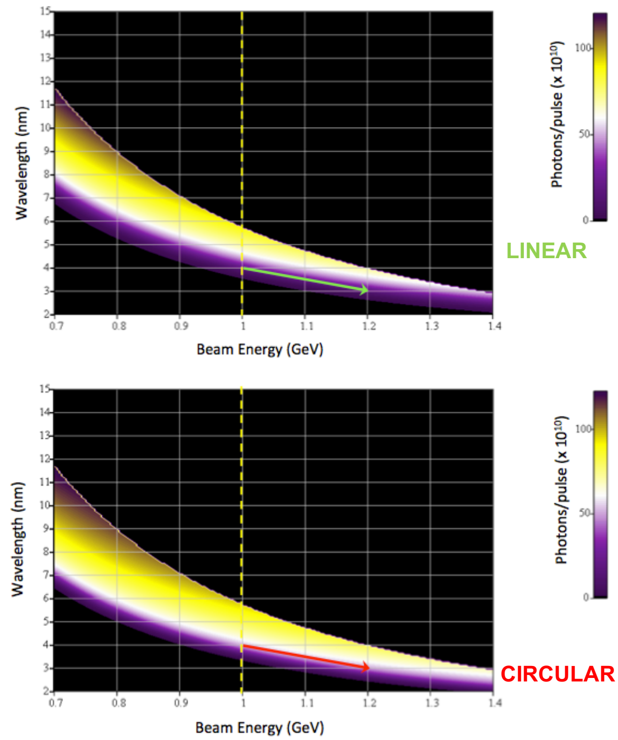

Figure 6: Number of photons per pulse contour plot as a function of resonant wavelength and electron beam energy for linear and circular polarizations.

The average electron beam slice parameters are used to perform 3D time dependent simulations with the `Genesis1.3` code [11] assuming four undulator plus related FODO magnetic lattice configurations: linear and circular polarizations

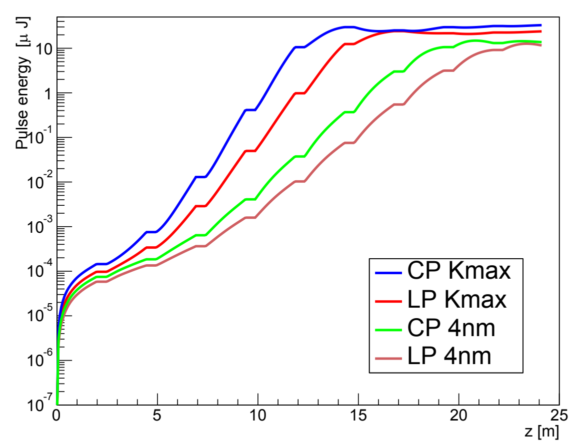

Figure 7: Growth of the FEL pulse energy along the propagation coordinate for the specified working points.

targeting 4 nm and 5.75 nm wavelengths, the latter being associated to the K_{max} deflection strength parameter. The ideal Gaussian current profile is assumed with $I_{\text{peak}} = 1.8\,\text{kA}$ and $Q = 30\,\text{pC}$. Figure 7 shows the growth of the FEL pulse energy along the propagation coordinate, and Table 2 lists the

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Table 2: FEL Performance Summary of the 4 nm and 5.75 nm Wavelengths Working Points for both polarizations

Working point	**LP K_{max}**	**LP 4 nm**	**CP K_{max}**	**CP 4 nm**
resonant λ [nm]	5.75	4.01	5.75	4.01
photon energy [eV]	215	309	215	309
matching $\langle\beta\rangle$ [m]	6	8	6	8
Pierce ρ_{1D} [10^{-3}]	1.8	1.4	2.0	1.5
gain length$_{1D}$ [m]	0.56	0.79	0.41	0.57
satur. length [m]	16.8	23.4	14.3	20.8
satur. ⟨power⟩ [GW]	0.39	0.24	0.49	0.28
exit E_{pulse} [μJ]	23.9	11.6	33.0	13.7
exit bandwidth [%]	0.15	0.09	0.22	0.12
exit pulse length$_{\text{RMS}}$ [fs]	6.10	3.50	6.12	3.76
exit divergence [mrad]	0.032	0.023	0.031	0.022
exit trans. size [μm]	200	130	190	130
exit N_γ/pulse $\left[10^{11}\right]$	6.9	2.3	9.5	2.8

main parameters characterizing the FEL performance of the AQUA beamline for the working points under investigation.

CONCLUSION

The AQUA undulator section and related magnetic lattice targeting 3-4 nm wavelengths are designed, and they are able to sustain $E_{\text{beam}} > 1$ GeV energies. This consideration paves the way to operate at the water window range with enhanced contingency in terms of saturation length and pulse energy. Reference beam parameters are used for time dependent simulations for both linear and circular polarizations, at 5.75 nm and 4 nm working points: the goal to produce a photon yield of N_γ/pulse $\simeq \mathcal{O}(10^{11})$ is within reach.

REFERENCES

[1] R. W. Aßmann *et al.*, "EuPRAXIA Conceptual Design Report" *Eur. Phys. J. ST*, vol. 229, no. 24, p. 3675, 2020.doi:10.1140/epjst/e2020-000127-8 [erratum *Eur. Phys. J. ST*, vol. 229, p. 11, 2020. doi:10.1140/epjst/e2021-100018-5]

[2] M. Ferrario *et al.*, "EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 909, p. 134, 2018. doi:10.1016/j.nima.2018.01.094

[3] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, "Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma", *Phys. Rev. Lett.*, vol. 54, p. 693, 1985. 10.1103/PhysRevLett.54.693 [erratum *Phys. Rev. Lett.*, vol. 55, p. 1537, 1985. doi:10.1103/PhysRevLett.55.1537]

[4] A. Balerna *et al.*, "The Potential of EuPRAXIA@SPARC_LAB for Radiation Based Techniques", *Condens. Matter*, vol. 4, p. 30, 2019. doi:10.3390/condmat4010030

[5] E. Roussel *et al.*, "Polarization Characterization of Soft X-Ray Radiation at FERMI FEL-2", *Photonics*, vol. 4, p. 29, 2017. doi:10.3390/photonics4020029

[6] Ming Xie, "Design Optimization for an X-Ray Free Electron Laser Driven by SLAC Linac", in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper TPG10, pp. 183–185.

[7] P. Li, T. Wei, Y. Li, and J. Pflueger, "Magnetic design of an Apple-X afterburner for the SASE3 undulator of the European XFEL", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 870, p. 103, 2017. doi:10.1016/j.nima.2017.07.023

[8] T. Schmidt and M.Calvi, "APPLE-X Undulator for the SwissFEL Soft X-ray Beamline Athos", *Synchrotron Radiat. News*, vol. 31, p. 35, 2018. doi:10.1080/08940886.2018.1460174

[9] A. Petralia *et al.*, "Short Period Apple-X Undulator Modeling for the AQUA Line of the future EuPRAXIA@SPARC_LAB Facility", presented at the 40th International Free Electron Laser Conference (FEL'22), Trieste, Italy, Aug. 2022, paper WEP38, this conference.

[10] C. Boffo *et al.*, "Design of the Superconducting Undulator for EuPRAXIA@SPARC_LAB"', presented at the 40th International Free Electron Laser Conference (FEL'22), Trieste, Italy, Aug. 2022, paper WEP39, this conference.

[11] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 429, p. 243, 1999. doi:10.1016/S0168-9002(99)00114-X