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# ARIA, A VUV BEAMLINE FOR EUPRAXIA@SPARC_LAB

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*Abstract*

EuPRAXIA@SPARC_LAB is a new Free Electron Laser (FEL) facility currently under construction at the Laboratori Nazionali di Frascati of the INFN. The electron beam driving the FEL will be delivered by an X-band normal conducting LINAC followed by a plasma wakefield acceleration stage. It will be characterized by a small footprint and include two different plasma-driven photon beamlines. In addition to the soft-X-ray beamline, named AQUA and delivering to the user community ultra-bright photon pulses for experiments in the water window, a second beamline, named ARIA, has been recently proposed and included in the project. ARIA is a seeded FEL beamline in the High Gain Harmonic Generation configuration and generates coherent and tunable photon pulses in the range between 50 and 180 nm. Here we present the potentiality of the FEL radiation source in this low energy range, by illustrating both the layout of the FEL generation scheme and simulations of its performances.

## INTRODUCTION

Free Electron Laser (FEL) light sources are capable of generating high quality and tunable pulses in the VUV-X-ray energy range, characterized by a peak brilliance larger than $10^{30}$ photons $s^{-1}$mrad$^{-2}$mm$^{-2}$, 0.1 % bandwidth and a short pulse duration, of the order of tens of femtoseconds or even less, which are needed for a wide class of experiments [1–7]. Thanks to such output pulse properties, FELs allow ultrafast time-resolved measurements and provide a high signal-to-noise ratio [8–10]. Due to the required space for electron acceleration, undulators and photon beamlines (in the order of many hundreds of meters up to few km), the present X-ray FEL facilities can only be realized in large scale laboratories and few of them are currently in operation.

Plasma Wakefield Acceleration, either laser- or particle-driven, is recognized as one of the most promising techniques for novel high-gradient accelerating structures: very high accelerating gradients beyond 1 GV/m can be achieved [11–17], *i.e.* about one order of magnitude larger than the ones of a normal-conducting LINAC structure, thus leading to an essential footprint and cost reduction for the whole facility. The EuPRAXIA Design Study [18] aims at realizing a new FEL facility driven by plasma acceleration. In this framework, the INFN Frascati National Laboratories, as a part of the EuPRAXIA project, will host EuPRAXIA@SPARC_LAB [19], a compact facility based upon a high brightness X-band LINAC, a particle-driven plasma acceleration stage and a FEL. The layout of its acceleration stage and FEL undulator lines is shown in Fig. 1. Before being matched and injected into the undulator line, the electrons are accelerated in two pairs of eight X-band accelerating cavities, separated by a magnetic bunch compressor (BC in Fig. 1) and followed by the plasma module.

This facility is able to fulfill the 1 GeV beam energy foreseen by EuPRAXIA in a low charge configuration by using particle- or laser- driven plasma acceleration, but it also can achieve the same energy at an higher charge from the X-band RF LINAC without the plasma module. The electron beam parameters at 1 GeV for FEL operation in both beam modes are reported in Table 1.

Table 1: EuPRAXIA@SPARC_LAB Electron Beam Parameters. The Normalized Emittance Is Here Reported

| | **LINAC** | **LINAC+PWA** |
|---|---|---|
| Charge (pC) | 200 | 30 |
| Bunch length (rms, μm) | 34 | 2 |
| Energy (GeV) | 1 | 1 |
| Peak current (kA) | 0.7 | 1.8 |
| Slice energy spread (%) | 0.01 | 0.05 |
| Slice emittance (mm mrad) | 0.5 | 0.8 |

As required by the EuPRAXIA Design Study, a first FEL beamline called AQUA [20–22], operating in the water window at 3-4 nm, was funded and included in the project baseline. It will use the full undulator length available to the project and requires very high quality electron beams.

A second lower photon energy FEL beamline in the VUV range (around 50-180 nm), called ARIA [23], has been recently considered and included in the project baseline, although not yet fully funded. In comparison with AQUA, such VUV beamline is highly flexible, with a larger input parameter acceptance, and requires a shorter magnetic length to lase.

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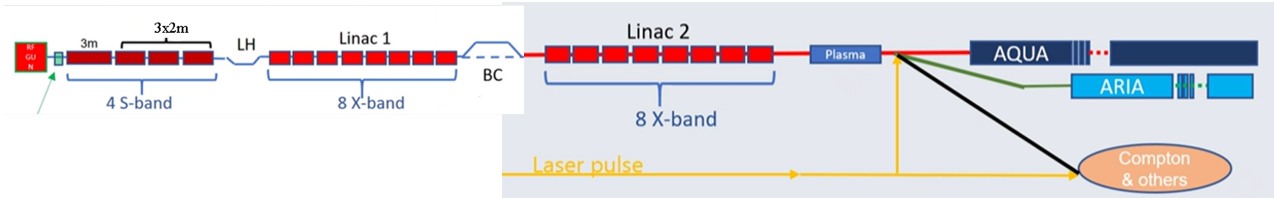


Figure 1: Layout of the EuPRAXIA@SPARC_LAB acceleration and undulator chain.

In this proceeding we will discuss the ARIA FEL line, including its layout, operating modes and performances, and give an overview of its scientific case.

## FEL SIMULATIONS

ARIA is a seeded FEL beamline in the standard High-Gain Harmonic Generation (HGHG) configuration, delivering continuously tunable pulses in the VUV wavelength spectrum between 50 and 180 nm [24]. Figure 2 shows its compact layout: the laser seed pulse modulates the electron bunches in a three meter-long modulator, followed by a dispersive section for electron density modulation at higher harmonics of the seed and a final amplification stage made up of four radiators. Table 2 lists the main characteristics of the undulators and the seeding source.

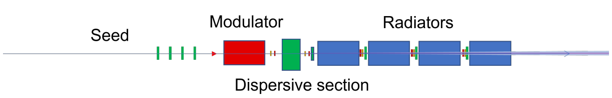


Figure 2: Layout of the ARIA HGHG FEL. The seed pulse is superimposed on the electron bunches at the modulator entrance; the dispersive section is a four-dipole chicane which converts the energy modulation into a density modulation. Its length ~2 m is kept constant and the dispersion strength is tuned by varying the dipoles' magnetic fields. The amplification stage is made up of four radiators.

Table 2: ARIA Line: Undulator (Top) and Seed Laser (Bottom) Specifications

| Undulator | Modulator | Radiator |
|---|---|---|
| Length (m) | 3 | 4 x 2.1 |
| Period length (cm) | 10 | 5.5 |
| Type | Apple-II | Apple-II |
| **Seed** | **Range** | **Simulated** |
| Wavelength (nm) | 410-560 | 460 |
| Pulse energy (µJ) | 1-30 | 6-30 |
| FWHM Duration (fs) | 150-200 | 170 |

The electron bunches entering this line are seeded by a long near-UV/blue laser, which can be realized with commercial OPA amplifiers. The main seed parameters considered in the following simulation results are reported in the third column of Table 2. The choice of a long wavelength seed simplifies the switch between two OPA processes, allowing to cover the full wavelength range (after second harmonic generation) with harmonic orders 3-9, while the use of APPLE-II undulators allows amplification of pulses with variable polarization.

The flexibility associated to the two-fold electron acceleration in the conventional LINAC or through the beam-driven plasma module enables FEL operation in the long and short beam modes. The electron beam parameters for both operating modes are summarized in the third and fourth column of Table 1, respectively. On one hand, long and high-charge electron bunches from the LINAC generate narrow linewidth photon pulses suitable for spectroscopic applications in the first case. On the other hand, short and low-charge electron bunches amplify a single longitudinal mode [25], whose shot-to-shot stability and second-order coherence are ensured by the presence of the seed.

The Xie model [26] gives an estimate of the expected performances in terms of photon pulse energy. Short electron bunches provide pulse energies below 20 µJ in the 50-70 nm range, while up to 60 µJ are obtained at longer wavelengths. The circular polarization may allow to reach slightly larger (>20 µJ) photon energies for intermediate wavelength values around 100 nm. Besides, pulse energy levels of the order of hundreds-µJ are obtained in the long beam mode.

The ARIA line is therefore capable of producing FEL pulses characterized by an energy of 10-100 µJ and very short pulse durations, determined by the short electron bunch length and the large gain bandwidth. The FEL gain bandwidth is proportional to the Pierce parameter $\rho_{3D}$ as well as to the ratio $\sqrt{L_{tot}^{SASE}/L_u}$ between the SASE saturation length and the actual undulator length, when $L_u < L_{tot}^{SASE}$: a large $\rho_{3D}$ parameter (of the order of $10^{-2}$) in this long wavelength range and the presence of the seed, especially when driving the FEL with short and high-current electron bunches from the plasma acceleration module, enable the generation of ultra-short femtosecond-class pulses.

Simulations of the ARIA FEL has been carried out by using the 3D FEL code GENESIS 1.3 used in time-dependent mode, with the maximum available precision [27] and considering an ideal electron beam, characterized by a Gaussian current profile and seeded by a FT-limited laser pulse. The main e-beam and seed properties are listed in Tables 1 and 2, respectively. The electron beam is matched to the modulator, with an average Twiss beta function of 8-9 m. The harmonic FEL emission is optimized by finely tuning both the seed intensity and the dispersion strength $R_{56}$, representing the particle longitudinal displacement per unit momentum error.

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Starting from the 460 nm seed pulse, the optimized values of seed energy Es and dispersion strength $R_{56}$ vs harmonic number (HN) are shown in Fig. 3: short electron bunches were considered at first, but these results are valid for both beam modes. The achieved pulse energies and FWHM pulse durations at different harmonics of the seed are reported in Fig. 4: for each case, the considered seed energy and dispersion strength are the ones presented in Fig. 3.

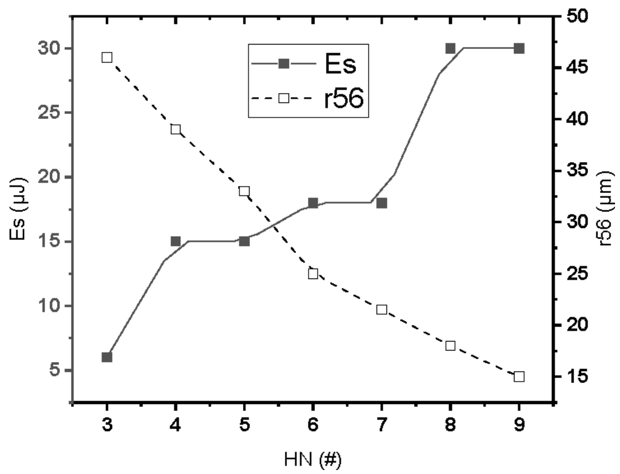
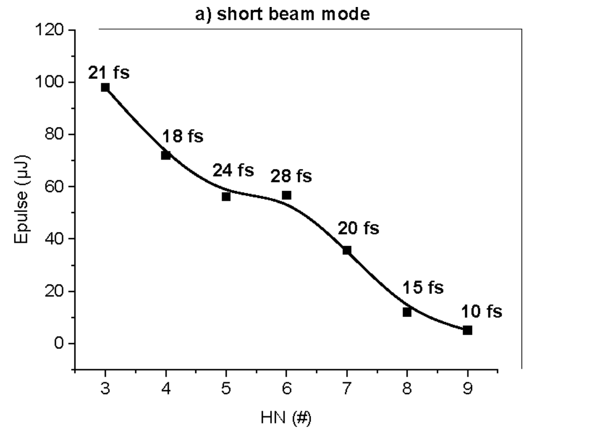



Figure 3: Seed energy Es (solid line, black squares) and dispersion strength $R_{56}$ (dashed line, white circles) vs harmonic number HN of the 460 nm seed.

Two example cases of output pulses at saturation, namely the third (HN=3, ~153 nm) and ninth (HN=9, ~51 nm) harmonics of the seed, are shown in Figure 5. The simulated FEL pulse temporal profiles (HN=3 yellow, HN=9 orange) in the two beam modes (see Table 1) are here presented: the low-charge, short beam operation mode is shown on the left, while the results on the right are obtained by operating with the higher charge and long electron beams. The corresponding spectral amplitudes are also shown. Lower harmonics (≤ 5) in the short beam mode (30 pC case) saturate after two or three radiators only: early saturation deteriorates and stretches the output pulse. Larger seed intensities may help avoiding it, or the radiation can be extracted beforehand, eventually using the last radiator for pulse gymnastics or double pulses' generation [28, 29]. The radiation pulse properties in the short (a) and long (b) beam modes are summarized, for the odd harmonic orders in the range 3-9, in Table 3. The performances in terms of pulse energy agree with the expected ones from the Xie scaling relations. The longitudinal coherence of the FEL radiation is described by the time-bandwidth product reported in Table 3: FEL pulses close to the Fourier-Transform limit are produced in the short beam mode. Stable FEL pulses, characterized by few tens to hundreds-μJ pulse energies and ~15-100 fs pulse durations can be produced in the whole spectral range.

## SCIENTIFIC GOALS

Many different experimental opportunities may be provided by the ARIA beamline. Its photon energy range may



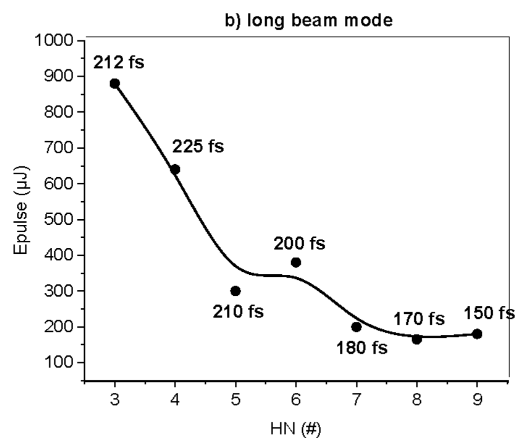




Figure 4: Output pulse energy at saturation vs harmonic number, starting from the 460 nm seed pulse. Top plot a): short beam mode, 30 pC case. Bottom plot b): long beam mode, 200 pC case. The FWHM pulse duration is specified on top of each point.

give access to the photo-ionization thresholds and to the valence ionic states of atmospheric constituents. The ability of the VUV-FEL to shift the wavelength of the scattered light from the visible into the deep UV will allow to probe new electronic transitions within the 7-20 eV range for classes of cluster materials such as nano-carbons and potential gap dielectrics. Its pulsed time structure makes it an ideal source for spectroscopy and studies of the light-induced dynamics in such complex media with state-of-the-art mass spectrometric and electron spectrometry techniques [30]. The possibility of changing the polarization of the FEL light allows to obtain important information, e.g., correlating chirality and natural dichroism in biotic media. The high brightness of this FEL source may enable the first direct analysis of low density systems as well as spectroscopic studies of exotic species. Due to the extremely low number of target particles in cluster experiments, great advances are also expected at a VUV FEL such as the ARIA beamline. The implementation of resonant techniques in the VUV range can enable studies on aggregates of elements with high vaporization temperatures, allowing to look at the formation of free clusters of varied chemical nature [31]. A VUV monochromatic beam-

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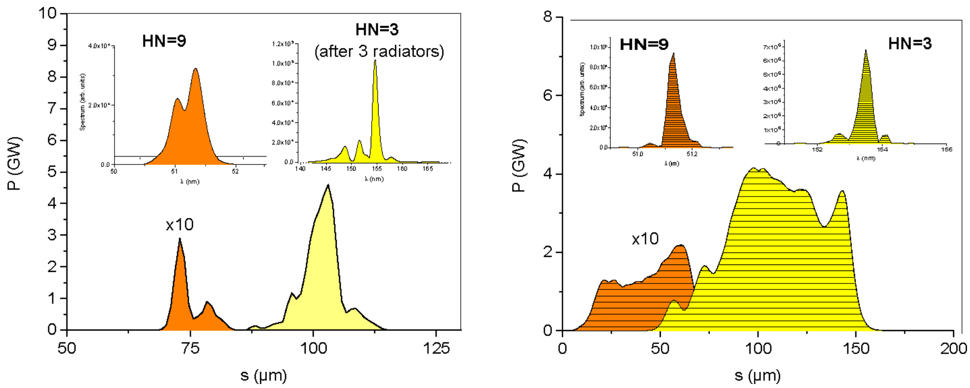


Figure 5: FEL emission at 51 nm (orange), 9$^{th}$ harmonic, and 153 nm (yellow), 3$^{rd}$ harmonic of the 460 nm seed. Output pulses' longitudinal power profile (GW) at saturation vs s(μm). The corresponding spectral amplitudes (arb. units) vs $\lambda$(nm) are shown above. Left: short beam mode. Right: long beam mode. The lower wavelength pulse profile (orange) is magnified and shifted with respect to the other one for a better visualization. In the short 30 pC beam mode, the longer wavelength saturates after 3 radiators only.

Table 3: Radiation Properties in the 50–150 nm Spectral Range at Saturation, in the Short (a) and Long (b) Pulse Mode

| Radiation properties / HN | 3a* | 3b | 5a | 5b | 7a | 7b | 9a | 9b |
|---|---|---|---|---|---|---|---|---|
| Wavelength (nm) | 153 | 153 | 92 | 92 | 65 | 65 | 51 | 51 |
| Seed energy (μJ) | 6 | 6 | 15 | 15 | 18 | 18 | 30 | 30 |
| Dispersion R56 μm) | 46 | 46 | 33 | 33 | 23 | 23 | 15 | 15 |
| Pulse energy (μJ) | 100 | 880 | 57 | 290 | 36 | 199 | 4 | 13 |
| Photons/shot ($10^{13}$) | 7.6 | 67 | 2.6 | 13 | 1.16 | 6.47 | 0.1 | 3.3 |
| FWHM Duration (fs) | 21 | 212 | 24 | 210 | 20 | 180 | 10 | 150 |
| Bandwidth BW (%) | 1.7 | 0.23 | 0.7 | 0.11 | 0.52 | 0.08 | 0.47 | 0.14 |
| Time-BW Product (#) | 1.88 | 2.57 | 1.5 | 2.03 | 1.3 | 1.8 | 0.69 | 3.33 |
| Pulse size (mm) | 0.74 | 0.85 | 0.63 | 0.56 | 0.51 | 0.45 | 0.35 | 0.43 |
| Pulse divergence (mrad) | 0.1 | 0.26 | 0.07 | 0.18 | 0.05 | 0.15 | 0.04 | 0.11 |

*saturation after 3 radiators.

line together with photo-emission techniques would allow the study of species of interest in the physics of the upper atmosphere and in combustion phenomena. The electronic structure of these species is not very well known in the region of photo-ionization due to the lack of high-intensity sources at wavelengths below 180 nm. Finally, ARIA represents a perfect source for two-photon photo-emission (2PPE) experiments, a technique that matches the advantages of direct and inverse photo-emission [32].

## CONCLUSIONS

The feasibility and expected performances of a compact, flexible and cost-effective FEL facility in the VUV spectral region have been investigated. We presented FEL simulations and some of the possible applications of the emitted radiation. This FEL line is capable of delivering close to Fourier-transform limit pulses [33] and gives the possibility of tuning the pulse duration in two different conditions: ultra-short pulses with a large gain bandwidth are generated by a low-charge, short electron bunches from the plasma wakefield acceleration, or intensity and spectrally stable, ultra-narrow bandwidth pulses by longer bunches

Scientific investigations in atomic, molecular and cluster physics may benefit from this beamline, broadening the possibilities offered by existing FELs or other sources, such as harmonics emitted in gas, in the VUV spectral region.

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