Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: F Villa *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012039

4th European Advanced Accelerator Concepts Workshop IOP Publishing
Journal of Physics: Conference Series **1596** (2020) 012039 doi:10.1088/1742-6596/1596/1/012039

Photon beam line of the water window FEL for the EuPRAXIA@SPARC_LAB project

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Abstract. A proposal for building a new Free Electron Laser facility at the Laboratori Nazionali di Frascati, EuPRAXIA@SPARC_LAB, is at present under consideration. This FEL facility will exploit plasma acceleration to produce ultra-bright photon pulses with durations of few femtoseconds down to the wavelengths between 2 and 4 nm, in the so called “water window”. The main class of experiments to be performed will include coherent diffraction imaging, soft X-ray absorption spectroscopy, Raman and photofragmentation measurements. In this article we present the updates on the photon beamlines design for the facility.

1. Introduction

The advent of Free Electron Lasers (FELs) opened up the way for an unprecedented, wide class of experiments exploiting the peculiar features of these radiation sources [1, 2, 3, 4, 5, 6, 7]. Key elements are the high peak brilliance higher than $10^{30}\, photons\, s^{-1}\, mrad^{-2}\, mm^{-2}\, 0.1\%\, bandwidth$, the short pulse duration of the order of tens of femtoseconds or even less, and the source tunability in the energy range of VUV - X-ray spectrum. FELs allow ultrafast time resolution measurements and provide a high signal-to-noise ratio [8, 9, 10]. Thus, a large number of X-ray FEL facilities is currently in operation, with an increasing number of new facilities planned or under active phase of realization.

One of the major disadvantages of X-ray FEL facilities is the large space required for electron acceleration, undulators and photon beamlines, in the order of many hundreds of meters to few km, thus making the realization of the present FELs possible only in large scale laboratories.

Plasma Wakefield Acceleration (PWFA) is known as a promising technique to essentially reduce the required space for beam acceleration [11, 12, 13, 14, 15, 16, 17]. The PWFA high accelerating gradient larger than 1 GV/m allows reducing both the dimension and cost for the whole facility. Up to now, the produced beam quality in terms of emittance as well as energy spread is not yet comparable to conventional Radio Frequency (RF) acceleration methods, while many attempts to close the existing gap have been planned and are ongoing.

In particular, the EuPRAXIA Design Study is aimed at realizing a FEL facility driven by plasma acceleration. In the framework of the EuPRAXIA project, the Frascati National Laboratories are proposing to host of a new facility, named *EuPRAXIA@SPARC_LAB* [18], capable to satisfy those requirements. The facility consists of a high brightness X-band linac, a plasma acceleration stage and a FEL. In Figure 1 the possible schematic layout of the EuPRAXIA@SPARC_LAB facility is presented.

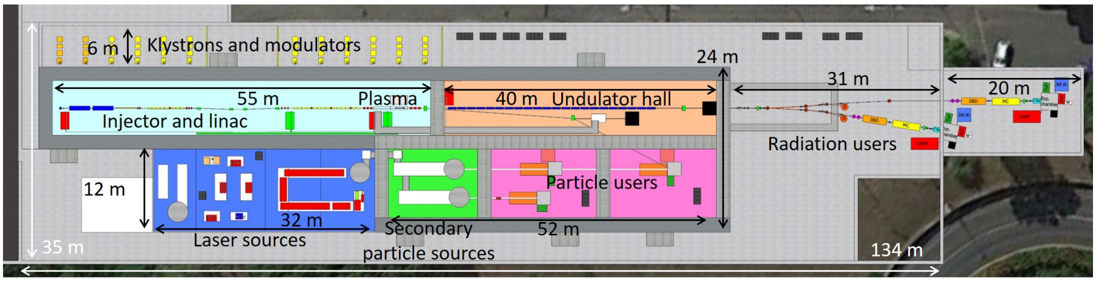

Figure 1. Scheme of the EuPRAXIA@SPARC_LAB facility.

The experimental activity will be focused on the realization of a plasma driven short wavelength FEL with two user beamlines, as required by the EuPRAXIA Design Study, according to the beam parameters reported in Table 1.

We investigated the possibility to fulfill the 1 GeV EuPRAXIA scenario by using plasma acceleration driven by laser or electron bunches, but also the possibility to drive the FEL with higher charge per bunch (100 - 200 pC) in a conventional configuration, exploiting the full X-band RF linac energy (1 GeV) without using the plasma module.

The first foreseen FEL operational mode is based on the Self Amplification of Spontaneous Radiation (SASE) mechanism [19]. Other FEL schemes, like seeded and higher harmonic generation configurations, will be also investigated.

Electron and undulator parameters		**Radiation parameters**	
Energy	0.8–1.2 GeV	Wavelength	2–4 nm
Energy spread	0.1%	Bandwidth	0.15–0.23%
Emittance	0.5 mm mrad	Dimensions	0.14–0.20 mm
Peak current	2–3 kA	Divergence	27–51 μrad
Und. period	15 mm	Photon per pulse	$0.4–2.6 \cdot 10^{12}$
K	0.9–1.45	Duration	5–50 fs rms

Table 1. EuPRAXIA@SPARC_LAB parameters.

In this article we present the photon beamlines of the *EuPRAXIA@SPARC_LAB* FEL.

2. Photon beamlines

Two beamlines will be realized: the first one, the longer in Figure 2, will be realized with all the elements described below and will deliver the beam to the experimental chamber.

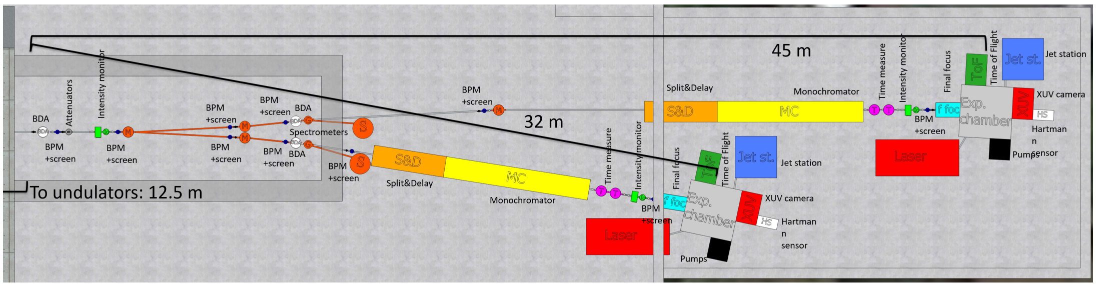

Figure 2. Scheme of the two photon beamlines.

In a second phase, the second beamline will be finely tailored to the future experimental requirements, while at the moment it is planned to use the same scheme of the other one, as many elements will be needed independently of the user experiments, e.g. energy, spectrum, transport and dimensions measurements. A safety hutch will enclose the first part of the beamlines to guarantee radiation protection, e.g. from gas bremsstrahlung, to the user area.

2.1. Transverse measurement and control

A beam defining aperture (BDA) is placed at the beginning of the beamlines. This aperture, composed by two pyramid trunks independently movable, can be closed to finely tune its size to let pass the beam almost unperturbed while preserving the beamlines from large fluctuations or beam misalignments. This aperture also remove the broad spontaneous radiation propagating along the beam with a larger angular divergence, acting as a collimator. In addition to the first aperture, described in [20], a second aperture will be inserted before the spectrometer grating to better collimate the beam. For this second aperture we plan to use a plate with a series of round holes with diameters ranging between few hundred microns and few mm, with a remotely controllable actuator on the two transverse directions with micrometric resolution.

Several Beam Position Monitors (BPMs) will be installed along the line to monitor the trajectory of the photons. The BPMs we plan to use are composed by four metallic blades collecting a drain current from intercepting the very edges of the beam [20]. The expected spatial resolution of such devices are about 2 microns RMS [21] displacement from the reference, without affecting too much the beam shape and energy.

We will measure the transverse dimension of the photon beam via scintillating screens, with a YAG:Ce crystal that is cost-effective, commonly used in FEL lines, has a high yield of light (about 8 photons/keV [22]) and will make it a perfect replica of the electron diagnostic to increase modularity and reduce the needs of different controls and spare parts. We will also consider other scintillating materials for higher photon fluxes that may damage YAG:Ce, such as pc–CVD diamond [22].

The beamlines will require few mirrors for steering the beam away from the undulator line and to make the two beamlines, for a split and delay system, for the monochromator and for the final beam focusing. Each mirror will have two angular degrees of freedom and an insertion control. The mirror will be grazing the beam to an angle of about 3° in the horizontal plane to ensure high reflectivity and large beam area, useful to decrease the surface intensity well below the damage threshold (see Figure 3).

We used the results from start-to-end simulations in each of EuPRAXIA@SPARC_LAB acceleration configurations (PWFA, LWFA or purely x-band linac acceleration) and compared to literature reported mirror damage thresholds [23, 24]. We found that we have a relatively large safety margin, one order of magnitude from the lowest material threshold value reported in [23] and a factor 20 to 60, depending on wavelength, from the higher, at distances longer than

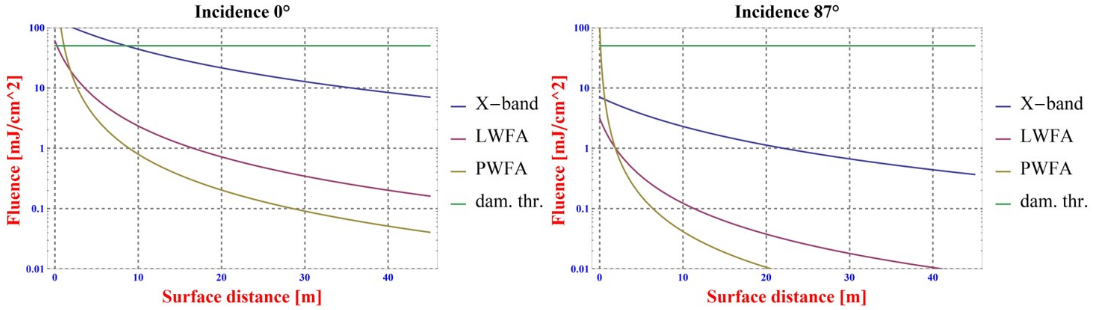

Figure 3. FEL intensity on the mirrors for the three simulated cases. The mirror damage threshold is expected to be in the range of many tens to few hundreds mJ/cm^2 [23], the green line correspond to 50 mJ/cm^2.

about 12 m from the undulator end.

Reflectivity of the mirrors is on the order of 50-80% [20] depending on the coating material, surface roughness, that should be less than few nm rms, and incidence angle, that increases as the beam is near to be parallel to the surface. The damage threshold and reflectivity will thus strongly depend on the manufacture of the surface, so a more precise value will be specified in the EuPRAXIA@SPARC_LAB TDR after discussion with the suppliers of the mirrors.

In order to focus the beam on the experimental target, we plan to use two mirrors (spherical or plane elliptical) in a Kirkpatrick-Baez configuration. The curvature can be manufactured or implemented directly by slightly bending the mirrors [25] (as a reference, the bent mirror at FERMI can have a minimal focal length of ∼1.2 m[26]). The expected final RMS spot size will be in the order of some micrometers for every considered configuration, with an equivalent focal length of about 1 to 2 m. We calculated the parametric spot dimension for the 3 configurations with the foreseen distance between the undulator and the focal spot in the experimental chamber and with a range of possible focal lengths in Figure 4.

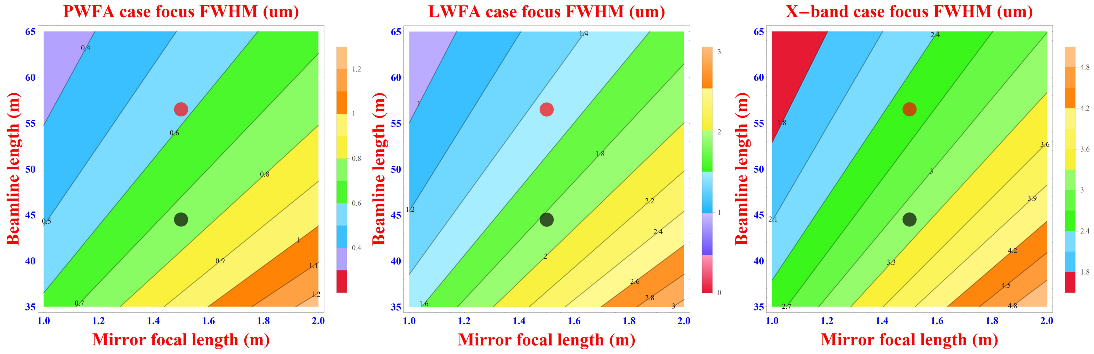

Figure 4. Preliminary focal spot dimensions, calculated with ideal Gaussian beam and aberration free focusing, as a function of mirror focal length and distance from the undulators for the three cases. The black dot represents the working point for the shorter beamline, while the red one is for the longer beamline. With 1.5 m focal length, we expect spots of less than 4 microns FWHM in every configuration.

Other focusing devices, as multi channel plates (MCPs) [27, 28], can be considered for further improvements.

2.2. Longitudinal measurement and control

Time length is a very critical measure for the ultrashort FEL pulses and many recent developments are ongoing, such as those reported in [29].

Many technologies and methods have been considered [30] for the characterization of short X-ray pulses such as, for example, streak cameras (for pulses longer than few hundreds fs), measuring the FEL-induced lasing effects on the spent electron beam [31], interferometry [32, 33], transient reflectivity [34], cross-correlation [35] or ionization time-of-flight streaking with THz [36] or IR [37, 38, 39] wavelengths. We plan to use angular streaking of gas ionization from a circularly polarized laser pulse, that has been deployed in X-ray FEL facilities and achieved sub-fs resolution on single-shot measurements, and can potentially be operated in a non-intercepting configuration. Depending on the time length of the expected pulse regime, THz or IR wavelengths will be chosen, as the time window scales with the laser wavelength (e.g. $\sim$ 35 fs for 10.6 μm laser wavelength [38]), while time resolution is inversely proportional to the wavelength (e.g. $\sim$ 500 as for the same 10.6 μm wavelength [38]).

Commercially available fast photodiodes have temporal resolution of few tens of ps, that are useful for electronic synchronization of the instruments, but other techniques are required for a higher resolution arrival time monitor of the photons. To increase the time resolution, we plan to develop the above streaking measurement to obtain also the arrival time [36], comparing the electron time-of-flight to the streaking pulse.

The FEL pulse wavefront can be tilted by the beamline, in particular when a monochromator is used, increasing significantly the time length of the pulse on the target. It will be measured with a Hartmann sensor (routinely implemented at FELs facilities [40]) to check the alignments of the beamlines to avoid unwanted tilts.

We will include in the beamlines a split and delay system for pump-probe experiments. This system (like those in [41] or [42]) uses the edge of a mirror to split transversally the beam and recombines on a final mirror, with a tunable geometric separation of the pulses typically ranging from 0 to few hundreds of fs. The mirror actuators will be long enough to put the mirrors out of the beamline if the experiments don't require such feature to avoid their losses.

We plan to measure also the transverse coherence length of the beam using an interferometer in Michelson [43] or Fizeau configuration. The interferometer will be set inside or just after the final experimental chamber only for the coherence measurement, as the method is multi-shot and intercepting.

2.3. Spectral measurement and control

We will measure the pulse spectrum with a spectrometer based on diffraction gratings [44, 45]. We plan to use a mirror at near grazing incidence (3°) to shift the beam from the undulator line. This mirror will also choose which beamline will be fed by the FEL radiation, so its mount will include a 360° horizontal rotational stage.

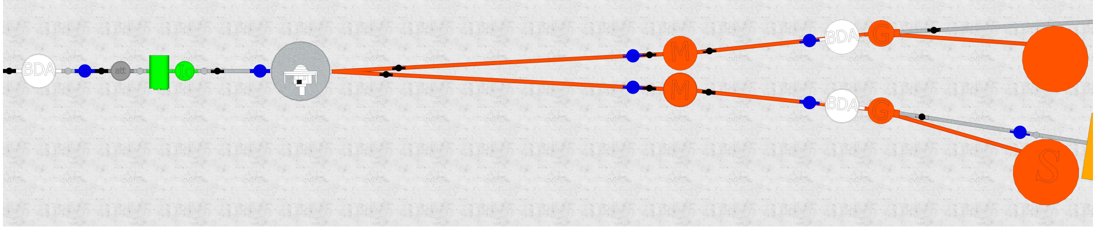

Figure 5. Scheme of the beamline selection mirror and spectrometers.

After the mirrors a grating will reflect the beam toward the experimental chamber in its 0^{th} order, whereas its 1^{st} diffracted order will send a small portion of the FEL pulse toward a

CCD camera for spectral measurement. For a 2400 grooves/mm grating and 3 m of propagation [20], one camera pixel (about 13 microns for a back illuminated soft X-ray camera) will cover 2.4 10^{-4} nm (about 1/12 of the expected spectral width) at an angle of about 4.5° from the reflected beam. The high quantum efficiency (in the order of 30%) and the signal-to-noise ratio of commercial x-ray cameras require only a small fraction of the photon beam to be diffracted.

In case of narrow band experiments, a monochromator will be used. Also in this case, the diffraction elements will be gratings, with particular care to have the monochromator in a configuration of closed dispersion [46] in order to avoid pulse front tilt. This configuration can properly take care of the induced pulse front tilt (checked by the Hartmann sensor) but with the disadvantage of higher losses due to the grating diffraction efficiency (that is in the order of few tens % even with high performance gratings [47]). Therefore, the monochromator will be moved outside the beam line if the experiment doesn't require it.

2.4. Energy measurement and control

We will measure the number of photons per pulse, e. g. the beam energy, using gas-based intensity monitors similar to those used at FLASH [48] and FERMI [44], with an expected precision of about 3%. We plan to have two of such detector, one at the beginning of the beamlines and one in front of the experimental chamber to accurately measure the shot-by-shot energy sent to the target, an useful information for experiments that require a normalization of the results to the incoming photons. The ionization cross-section of nitrogen, most commonly used gas in those devices, is low in the water window spectral region, so the photocurrent can be low and affecting the measurement precision. Possible alternatives require other gases (such as xenon [48]) or other methods of energy detection, e.g. using the spectrometer to obtain a relative intensity measurement. For the purpose of commissioning and first alignment of the FEL, we will also use a removable photodiode and the scintillating screen nearer the undulators to be able to measure very low energy. Similar schemes for FEL beam lines have been successfully used at FERMI [49].

The beamlines require also an attenuator for the FEL photons to have better control of the average intensity sent to the experimental target. In the first phase of the beamlines construction we will have thin films attenuator of different thickness, as the photons used in the experiments are in a relatively narrow bandwidth, while, in a second phase, a gas attenuator can be added at the beginning of the beamlines to have better tunability of the energy but with an increase in the cost for the device and the pumping system.

3. User end station

The FEL properties (energy range, time resolution and brilliance) can be exploited in several branches of physics, chemistry, material science and biology [50]. The experimental endstation of EuPRAXIA@SPARC_LAB FEL will be designed and built to allow performing a wide class of experiments. Some fields of application of such radiation pulses are coherent diffraction imaging, soft X-ray absorption spectroscopy, Raman spectroscopy, Resonant inelastic X-ray scattering and photofragmentation measurements.

A multi-purpose experimental chamber will be installed at the end of each beamline in order to allow performing the widest possible class of experiments. The chamber will host different kind of targets, from solid samples on motorized stages to liquid and gaseous samples delivered by micro-jets, in particular to maintain the hydrated state of biological samples. We plan to have a high resolution CCD camera located inside the chamber to allow performing imaging experiments. A time of flight spectrometer connected to the experimental chamber will be used to analyze the molecules produced by the sample-beam interaction [51]. High power synchronized optical laser from the EuPRAXIA@SPARC_LAB facility will be also available, with its harmonics, to allow performing laser pump-FEL probe experiments. Space for a supporting laboratory, in particular for biological/chemical preparations and manipulations, will be allocated in the building or in the nearby area to allow last-minute sample preparations and characterizations.

4. Conclusions

We expect that the building realization time will require about 5 years. Construction and commissioning of the the accelerator, undulator and beamlines will require approximately two additional years. Finally, the first pilot user experiments will be roughly a year later.

We consider that the length of the beamlines before the experimental apparatus required to host the above described diagnostics will fit in the allocated space, with a distance from the undulators not smaller than 10 – 15 m, mainly depending on photon intensity and optics damage thresholds.

The expected total transmission of the beamlines, when no intercepting devices are inserted in line, is ∼18%, eventually reduced to ∼6% when split and delay line is used. The monochromator will additionally reduce the transmission of about two orders of magnitude.

Acknowledgments

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 653782.

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