NON-INVASIVE DIAGNOSTICS ON FEL PHOTON BEAMS: GENERAL REMARKS AND THE CASE OF FERMI@ELETTRA

M. Zangrando#, Istituto Officina dei Materiali CNR, Trieste, I-34149, Italy
D. Cocco, Sincrotrone Trieste SCpA, Trieste, I-34149, Italy

Abstract

The advent of FEL sources has brought new possibilities for experimentalists performing measurements that are challenging in terms of time resolution, flux, coherence, and so on.

One of the most important points, however, is the capability of characterizing the FEL photon beam so to determine the different parameters of each pulse hitting the system under investigation. For this reason it is mandatory to realize diagnostics sections along FEL user facilities recording beam pulse-resolved features such as the absolute intensity, the energy spectrum, the beam position, the time arrival, and the wavefront. For other parameters like the coherence and the pulse length, on the other side, a direct and online detection is not possible.

At FERMI@Elettra, the Italian FEL facility, a dedicated diagnostic section called PADReS (Photon Analysis Delivery and Reduction System) will be installed after the undulators' exit, and it will serve as a source of pulse-resolved informations for end-users.

In this talk the instruments that are part of typical FEL diagnostic sections will be described using PADReS as a real example to see the roles of the different diagnostic tools.

INTRODUCTION

In the last two decades an increasing number of new Free Electron Laser (FEL) facilities has been foreseen, designed, and actually realized [1-5] all around the world. In this moment, about five of them are either already operating, or in the building phase. They can differ from each other with respect to several parameters like generation/amplification scheme (SASE, HGHG, etc.), energy, peak power, photon emission wavelength, temporal pulse length, and so on. Nonetheless, they share the unique feature of representing a new class of lightsources, capable of delivering pulsed light of unprecedented brilliance, energy, coherence, etc.

The unique characteristics of such light pulses represent a major improvement in the quality of the possible experiments as well as a challenge for potential users who are called to think, design and realize new experiments that can thoroughly exploit FEL light.

It is then obvious that, in order to perform such challenging and state-of-the-art experiments, it is mandatory to fully characterize FEL radiation so to give end-users the possibility to properly handle the experimental data obtained with FEL radiation. Most of the photon beam parameters needed by the experimentalists are listed and briefly discussed in the next section.

USERS' REQUESTS

The first, and sometimes most challenging, general request by the users of a FEL facility is to have all the possible informations about the beam both online and resolved pulse by pulse. That means that ideally each pulse should be characterized in terms of the parameters that will be discussed later, and that information should be given, possibly, in real time. The final result should be a set of experimental data where the user can immediately couple each light pulse with the experimental evidences measured in the endstation. This of course poses some technical constrains that will be briefly discussed afterwards.

The parameters that users typically need to know (online and pulse-by-pulse) are:

- intensity (number of photons);
- pulse energy (μJ);
- photon energy (eV);
- spectral distribution (meV-resolution);
- beam (angular) position (μrad);
- pulse length (fs);
- time arrival (fs-resolution);
- focus size (μm);
- coherence;
- polarization (%);

Each of them calls for dedicated instrumentation that should work in a non-destructive way, letting the beam travel (almost) undisturbed to the experimental station. In order to fulfill this stringent constrains, fortunately, some physical process like the atomic photo-ionization or the grating diffraction come to help. In the following, some examples of such instrumentation will be reported and discussed. As a reference to a real-life situation the Photon Analysis Delivery and Reduction System (PADReS) [6] that will be installed at FERMI@Elettra will be used as an example, when possible.

PADRES

The FERMI@Elettra project at the Sincrotrone Trieste Laboratory (Italy) is based on a seeded scheme employing multiple undulators up-shifting an initial seed signal (conventional pulsed laser) in a single-pass [4]. As the seed laser determines the duration, bandwidth, and wavelength of the output radiation, all are tunable and controllable, covering a wide spectral range. Two FELs (1 and 2), in fact, will be employed delivering radiation in the 100–20 and 20–3 nm wavelength ranges. Other parameters such as pulse length and energy bandwidth will vary depending on the FEL used in that moment. The photon radiation expected parameters of the two FELs can be found in [6].

Each experimental station will receive the radiation emitted by both the FELs, and PADReS will be installed between the undulators and the beamlines to characterize the radiation on-line and pulse-by-pulse. This system will determine the absolute intensity of each pulse, the relative spatial movement of the photon beam, and the pulse-resolved spectral distribution. Moreover, it will be possible to attenuate the absolute intensity delivered to the beamlines reaching a maximum attenuation factor of 10^{-4}. Finally the angular acceptance of the photon beam will be determined and eventually controlled. The information gathered by the above-mentioned facilities will be stored and then delivered to the experimentalists in order to fully characterize each experiment carried out on the endstations.

The layout of PADReS, which is reported in Fig. 1, shows that, if multiple beamlines have to be installed, it is better (especially from the economical point of view) to put the diagnostics section into a common lightpath located as close as possible to the undulators. On the other side, the presence of multiple FEL undulatory lines calls for inevitably doubling some diagnostics.

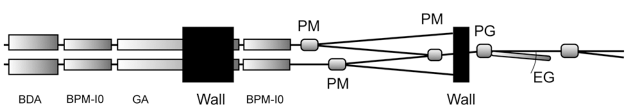

Figure 1: Layout of the PADReS. From left to right, duplicated, there is the section shutter-stopper-Beam Defining Aperture (BDA), the first section Beam Position Monitor (BPM)-Intensity Monitor (I0M), the Gas Absorber (GA), the second section BPM-I0M, the plane mirrors PMs, the plane grating PG, the Energy Spectrometer, (ES) and the first switching system.

PHOTON BEAM DIAGNOSTICS

In the following the different photon beam diagnostic tools will be discussed.

Beam Position Monitor

The Beam Position Monitors (BPM) of PADReS are based on the measurement of the drain current as the tails of the photon beam transversal intensity distribution intercept four metallic blades [6]. The distribution has been calculated and simulated by the FERMI@Elettra Machine Physics Group, and it results as Gaussian in both transverse directions [7]. Consequently, it is possible to calculate precisely the centroid of the horizontal-vertical transverse intensity distributions. The expected spatial resolution is determined by the resolution in measuring the currents generated on the blades and by the minimum mechanical step of the motors controlling the travel of the blades. The former is about 10^{-6} (AH401 picoammeter [8]), while the latter is about 1 μm (depending on the type of motor selected). This spatial displacement introduces a relative variation in the electrical current reading on the tails of the distribution (more than 3σ from the center) as low as 3E-6, detectable by the picoammeters.

Each blade can travel 30 mm transversally, and a complete closure in both directions is possible. All the four blades are electrically insulated and made of copper. By reading simultaneously the four currents, it is possible to determine pulse-by-pulse the relative displacement of each single pulse with respect to the others and the initial nominal position. The spatial resolution is expected to be better than 2 μm rms. Moreover, by the concurrent readings of the second BPM positioned about 9 meters after, it is possible to determine the angular movement of the photon beam shot-by-shot with sub-μrad precision.

Another possible solution to determine the beam position, used at FLASH [9], is based on the atomic photo-ionization of rare gas at low pressures (~10^{-5} mbar), which is described in detail in the next section. Split electrodes are used for ion and electron detection, as shown in [9]. Due to the homogeneous extraction field, the charged particles created within a single photon pulse represent, in the plane of the respective split electrode, a projection of the photon beam. At FLASH, two pairs of two perpendicularly oriented GMDs allow the determination of the horizontal and the vertical beam position at two different locations along the photon beam. Since the uncertainty in the beam position measurement amounts to about 20 μm and the two locations along the photon beam are separated by 15 m, the horizontal and the vertical beam direction can be determined online with an uncertainty in the μrad regime by means of the four FLASH GMDs.

Intensity Monitor

As the BPM used at FLASH, described in the previous section, also the Intensity Monitors (IMs) take advantage of the atomic photo-ionization. As a matter of fact, in the FLASH case, they are hosted in the same vacuum chamber [10], while at FERMI@Elettra they are separated in a dedicated chamber [6].

The working principle is based on the travel of the photon beam through a rare gas-filled chamber, where it generates ions and electrons that are then extracted and collected separately. Using the currents generated this way it is possible to derive the absolute number of photons per pulse shot-by-shot. The advantages are the transparency, due to the low pressure used for the rare gas, the wide dynamical range, and the absence of saturation effects. Moreover, they are independent from the beam position fluctuations and are usable on the whole wavelength range (both soft and hard x-rays [10]). They can be used continuously for online shot-to-shot intensity measurements, and they can be calibrated absolutely providing the absolute number of photons per single pulse. This procedure can be made on different sources by using cross-calibrated photodiodes, and different gases can be used within this instrument, going from nitrogen to neon and xenon. The spectral responsivity, defined as the ration between the signal current (ions or electrons) and the radiant power, may be expressed in terms of known or tabulated quantities like the gas pressure, the temperature, the photo-ionization cross-section, and the mean charge generated per absorbed photon [10]. The only true calibration parameters are the acceptance length along the photon beam and the ion detection efficiency. The spectral responsivity, then, can be calculated with a relative standard uncertainty of less than 7%.

Moreover, the pulse mode for electron detection can be used for fast quantitative FEL pulse energy measurements with 30 ns-temporal resolution. The electron pulse signal is calibrated by online comparison to the calibrated ion current and averaged over many FEL shots. In this way it is possible to obtain the pulse energy (in μJ) on a shot-to-shot basis.

A similar GMD (X-GMD) has been developed for higher photon energies, up to 10 keV. With hard x-ray, in fact, the photo-absorption and the photo-ionization cross sections generally decrease, and so an open electron multiplier as a signal amplifier (up to 10^6) for ion detection has been chosen [10] to work with low-pressure gas targets. The performances of this instrument are currently under evaluation and test, moving it among different sources such as FLASH, LCLS in Stanford, and Spring-8 in Japan [11].

Energy Spectrometer

In order to determine the spectral distribution of each photon pulse it is necessary to analyze its energy components by means of a diffraction grating. The advantage of such approach is that every diffraction grating reflects most of the radiation, about 95-98%, into the so-called 0-order (basically the grating is behaving like a mirror). Only a fraction of the incoming beam is diffracted into higher diffraction orders, so to prevent the reduction of the flux going to the following beamlines. In this way it is possible to determine the spectral distribution of each pulse online, pulse-by-pulse.

At FERMI@Elettra, PADReS hosts the energy spectrometer as its last element, placed at the beginning of the beamlines [6]. The optical layout is such that the radiation coming from both FELs is directed to the same, single, spectrometer. It is designed to acquire the FEL spectrum in the wavelength range of 100–3 nm. The optical part is made by three identical plane silicon substrates. Two of them have the central part ruled in order to realize a variable line spacing diffraction grating, while the third one is a simple plane mirror.

Each grating is designed to deliver and focus a very small part of the incoming radiation onto a YAG crystal, imaged by a CCD detector, while most of the incoming photons are reflected to the following beamlines (see Fig. 2). The grazing angle of incidence is fixed to 2.5°, while the distance from the source slightly depends on the selected wavelength, and is about 45 m. The focus position changes as a function of the photon energy for both angle and distance. The minimum and maximum collectable diffraction angles are limited by the mechanical system and are 9° and 19°, respectively, while the focal distance ranges from 2500 to 3100 mm. The gratings parameters are reported in Table 1 (D0, D1, and D2 are the groove density variation parameters). The following energy resolutions are expected: about 0.4 meV for the first harmonic of FEL 1 and 1.7 meV for the third harmonic, 1.1 meV for the first harmonic of FEL 2, and 4.6 meV for the third harmonic.

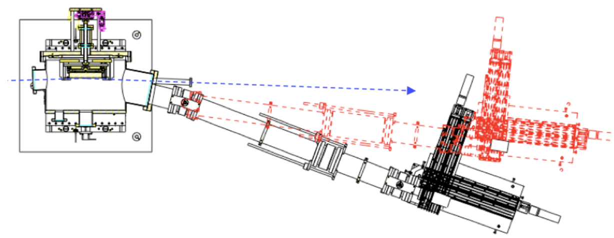

Figure 2: Top view of the energy spectrometer. The beam is coming from the left (dashed line) and impinges at 2.5º on the grating. The ES can be moved to track the focal line (see text): solid and dashed images. The 0-order radiation continues to the beamlines.

Table 1: Parameters of the ES Gratings

Margin	**G1**	**G2**
Energy range (eV)	12-90	30-360
Coating material	Graphite	Gold
D0 (lines/mm)	500	1800
D1 (lines/mm^2)	0.35	1.26
D1 (lines/mm^3)	0.000175	0.000628

TOF-based Diagnostics

Rare gas photo-ionization coupled to time-of-flight spectrometry is the process used also in two other diagnostic tools already existing and being under tests at FLASH.

The first is a combined ion- and electron-TOF (iTOF and eTOF) spectrometer that is particularly well fitted for SASE FELs (like FLASH) where the photon energies fluctuate pulse-to-pulse due to the stochastic nature of the SASE process. It works online giving pulse-by-pulse informations about the photon beam like the energy, the existence of higher harmonics, the presence of multiple wavelengths, etc. [12]. As the other instruments based on photo-ionization described before, also in this case the instrument is almost completely radiation transparent, and does not degrade the beam in any way. It takes advantage of the already tabulated data about total and partial photo-ionization cross sections of various substances [see 10]. There exists, in fact, a well determined value of the ratio between the partial cross sections of n- to single-ionized states, and it depends strictly on the photon energy. As a consequence, the iTOF can determine the photon energy with a precision better than 1% up to 150eV, while for higher energies the uncertainty increases (at least using the single and double ionizations). The robustness of the instrument, and the fact that it is supposed to work out of focus (to avoid multi-photon ionization) confirm its versatility and ease of use [12]. The eTOF, on the other side is faster (ns vs. ms of the iTOF), has a better energy resolution (0.1 eV vs. ~0.5 eV of the iTOF), and gives informations about the spectral-resolved distribution of the pulse (instead of the average photon energy given by the iTOF).

The second instrument that uses the TOF spectrometry to give informations about the photon beam is the so-called "universal online diagnostic unit", developed at DESY [14]. This instrument performs angle-resolved photoelectron spectroscopy on rare gases using 16 eTOF spectrometers to reconstruct the Stokes parameters. In this way it is then possible to determine the polarization degree of the photon beam with an accuracy of about 1%. Moreover, it is possible to extract also the photon flux (accuracy 1% absolute, 0.1% relative), the beam position (accuracy about 1µm), and the photon energy (resolving power ~10000). Successful tests were made at FLASH demonstrating the possible application of such kind of instrument as a diagnostic tool for a soft x-ray FEL source. Moreover, preliminary results in the photon energy range 4-8 keV show promising evidences also for operations in the hard x-ray regime.

Focus Size

An interesting application of the previous-mentioned GMD is the determination of the focus size of a FEL beam. The major problem when determining the size of a focused FEL beam is the very high energy of the radiation that prevents the use of fluorescent screens and any solid irradiated surface (unless a "post-mortem" microscopic analysis of target samples is used as in [14]). As a consequence, a method employing saturation effects upon photo-ionization of rare gases was developed [15]. A GMD chamber movable along the beam waist collects the number of ions generated by the FEL illumination of the gas target. This experimental number is related to the photon number per pulse with a sub-linear dependence, due to a considerable reduction of target atoms within the interaction zone by ionization with a single photon pulse. Fitting this relationship yields the beam cross-section and consequently the focus diameter as a fit parameter. Moving the GMD along the photon beam, then, it is possible to reconstruct the beam waist, the focus position, and diameter with µm-resolution.

Wavefront

The knowledge of the impact of propagation through the FEL optical transport system on the photon beam wavefront is very important as many experiments are sensitive to the fringe visibility, including both transverse coherence and wavefront properties [16]. In particular, these experiments include coherent x-ray diffraction, phase contrast, photon correlation spectroscopy, and so on [17]. In order to characterize and measure the wavefront one possibility is to use the Hartmann principle described hereafter [18, 19]. The Hartmann sensor is based on a pinhole array that divides the incoming beam into an array of smaller beams, whose position and intensity are monitored with a CCD camera at a certain distance *l* from the array (see Fig. 3).

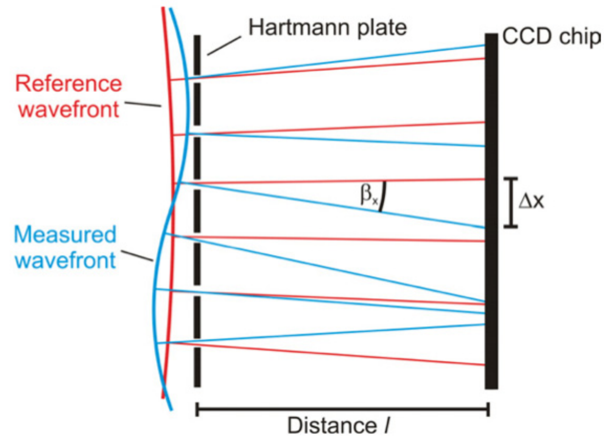

Figure 3: The incoming beam is divided into an array of beams by the Hartmann plate. The centroid deviation Δx from a known reference spot position divided by the distance *l* yields the local wavefront gradient β_x relative to the reference wavefront (from [20]).

The displacement of a spot centroid Δx divided by *l* yields the local wavefront gradient $\beta_{x,y}$ inside one subaperture relative to a known reference wavefront. In a modal approach using Zernike or Legendre polynomials, the wavefront *w*(x,y) is then reconstructed from the local gradients [21] and afterwards corrected for tip/tilt and defocus. In the case of coherent radiation, moreover, the knowledge of the beam profile and wavefront allows calculation of some beam parameters using the moments method like beam width, divergence, beam waist diameter, and waist position [18].

At FERMI@Elettra the wavefront analysis will be performed within a collaboration with FLASH in the framework of the IRUVX-PP European Project (FP7), using the Hartmann wavefront sensor used in [20].

The determination of the transverse coherence at FERMI@Elettra, on the other hand, will be realized through the diffraction from a simple double slit system. By measuring the visibility of the fringes and reconstructing its dependence on the transverse distance from the center of the beam it is straightforward to determine the coherence width. This technique, of course, cannot be used online and is not capable of providing informations pulse-by-pulse. The mechanical assembly hosting the double slits-detector system will be installed on one of the branchlines of FERMI@Elettra and is reported in Fig. 4.

A plate with a set of double slits with different spacings going from 0.2 to 12 mm is placed 8.5 meters before a YAG screen that will be imaged by a CCD camera with 6 µm-pixel size [22].

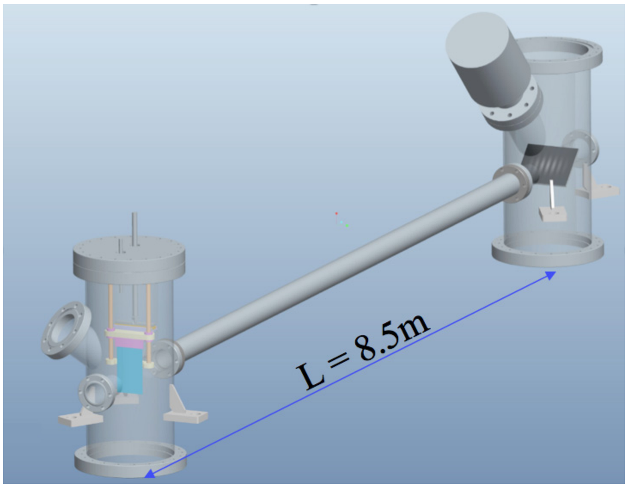

Figure 4: Section of a FERMI@Elettra branchline dedicated to spatial coherence measurements.

The temporal coherence of a FEL beam, finally, can be evaluated through the two-beam interference pattern generated by overlapping two partial beams obtained splitting the FEL photon beam. Changing the time delay between both partial beams, the temporal coherence properties of the FEL pulses can be measured plotting the interference fringe visibility against the time delay.

Pulse Length

Though the pulse temporal length is one of the most important parameters of the FEL radiation, a direct online determination of it is not possible up to now. Streak cameras optimized in the EUV/Soft x-ray regions can provide time resolution of the order of some hundreds of fs, typically much bigger than the actual FEL pulse length (some tens of fs). As a consequence, invasive methods like, for instance, auto-correlation should be preferred to determine the pulse lengths. In this kind of experiments, the FEL photon beam must be first split, and then part of it delayed with respect to the other. After, the two beams are focused in the same region (*e.g.* 5 µm-diameter) and ionize a rare gas (e.g. He, using λ = ~50 eV). The He^{2+} ions produced in the ionization region are then extracted and measured. Varying the delay between the two beams (passing through 0-delay) it is then possible to reconstruct the correspondent ion signal (due to double ionization) response curve that gives an indication of the pulse length. The resolution of this kind of measurement has been proven to be around 1 fs. [23].

REFERENCES

[1] V. Ayvazyan, et al., Eur. Phys. J. D 37 (2006) 297.

[2] P. Emma, et al., Nature Photonics, Adv. Online Pub. (2010)

[3] T. Shintake and SCSS Group, EPAC'06, Edinburgh 2006, THOPA02, p. 2741; http://www.JACoW.org.

[4] E Allaria, et al., New J. of Phys. 12 (2010) 075002.

[5] The Technical Design Report of the European XFEL (2007), http://xfel.desy.de/tdr/tdr.

[6] M. Zangrando, et al., Rev. Sci. Instrum. 80 (2009) 113110.

[7] E. Allaria, et al., Elettra Scientific Advisory Council Meeting, Trieste 2009 unpublished.

[8] See: http://www.elettra.trieste.it/organisation/experiments/laboratories/instrumentation for a description of the instrumentation.

[9] M. Richter, et al., Appl. Phys. Lett. 83 (2003) 2970.

[10] K. Tiedtke, et al., J. Appl. Phys. 103 (2008)094511.

[11] N.Saito, et al., Metrologia 47 (2010) 21.

[12] P.N. Juranic, et al., J. Inst. 4 (2009) 09011.

[13] M. Braune, et al., J.of Phys.: Conf. Series 194 (2009) 032016.

[14] J. Chalupský, et al., Opt. Expr. 15 (2007) 6036.

[15] A.A. Sorokin, et al., Appl. Phys. Lett. 89 (2006) 221114.

[16] G. Geloni1, et al., New J. Phys. 12 (2010) 035021.

[17] K. Nugent, Adv. in Phys. 59 (2010), 1.

[18] B. Schäfer, et al., Rev. Sci. Instrum. 77 (2006) 053103.

[19] P. Mercère, et al., Opt. Lett 28 (2003) 1534.

[20] B. Flöter, et al., New J. Phys. 12 (2010) 083015.

[21] R. Cubalchini, J. Opt. Soc. Am. 69 (1979) 972.

[22] C. Svetina, 2nd Annual IRUVX-PP Meeting, Berlin 2010.

[23] R. Mitzner, et al., Phys. Rev. A 80 (2009) 025402.