Development of Photon Beam Diagnostics for VUV Radiation from a SASE FEL

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Abstract

For the proof-of-principle experiment of self-amplified spontaneous emission (SASE) at short wavelengths on the VUV FEL at DESY a multi-facetted photon beam diagnostics experiment has been developed employing new detection concepts to measure all SASE specific properties on a single pulse basis. The present setup includes instrumentation for the measurement of the energy and the angular and spectral distribution of individual photon pulses. Different types of photon detectors such as PtSi-photodiodes and fast thermoelectric detectors based on YBaCuO-films are used to cover some five orders of magnitude of intensity from the level of spontaneous emission to FEL radiation at saturation. A 1 m normal incidence monochromator in combination with a fast intensified CCD camera allows to select single photon pulses and to record the full spectrum at high resolution to resolve the fine structure due to the start-up from noise.

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1. Introduction

In 1995 DESY proposed to make use of the unique electron beam properties of the TESLA Test Facility (TTF) and to construct a VUV FEL based on self-amplification of spontaneous emission (SASE) [1]. Since the initial work of Kondratenko et al. [2,3], Bonifacio et al. [4] and Pellegrini [5], the SASE theory has been elaborated for short wavelength radiation down to 0.1 nm ([6,7] and references therein). These calculations serve as a sound basis for the experimental verification of the SASE principle. For given electron beam and

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undulator parameters they predict the gain, the photon beam profile and the SASE-typical fine-structure in the temporal and energy distribution which is caused by the startup from noise [8].

2. Experimental Setup

The first phase of the DESY project is considered a proof-of-principle experiment for SASE at VUV wavelengths. For the complete characterisation of the photon beam a multi-facetted experiment has been designed (Fig. 1), providing all the instrumentation necessary to measure the photon pulse intensity and its angular, spectral and temporal distribution. Due to the unique properties of the VUV FEL beam, particularly the extremely high power, the short pulse length and the unusual pulse timing (Table 1), new concepts have been developed to measure the SASE specific properties on a single pulse basis. The present part of the experiment required for the initial commissioning and characterisation of the FEL has been designed, constructed and installed by HASYLAB. It comprises all the components shown in Fig. 1 except the left-hand branch (10) (looking downstream) and the very last little chamber in the straight direction which will be added later for a regenerative amplifier FEL experiment[9]. Due to the strong absorption of VUV radiation by any material, all devices for beam diagnostics are operated under ultra-high-vacuum (UHV) conditions, and no windows can be used to separate the diagnostics from the undulator and the accelerator vacuum. Therefore all components have been cleaned appropriately and assembled under cleanroom conditions to avoid dust particles which could migrate to the accelerator cavities. In addition the experiment is fully remote controlled because the radiation background in the accelerator tunnel prevents access during operation.

An external HeNe-laser, coupled in through a Suprasil (fused silica) viewport (Fig. 1, No. 2), is used to pre-align optical and other diagnostics components. A set of apertures (Fig. 1, No. 3) attached to a water cooled frame can be scanned across the beam profile and defines the photon beam cross section impinging on the detectors (No. 4) and the optical components downstream. A second set of apertures and detectors (No. 9) is available further downstream in the straight forward direction and can be used to determine the FEL beam direction and to align the HeNe-Laser. For the commissioning phase this second aperture/detector unit has actually been moved out of the direct beam into the left-hand branch in order to protect it from the hard γ radiation due to beam loss in the accelerator and from bremsstrahlung produced in the long undulator. Later this second set of apertures and detectors will be moved back into the position shown in Figure 1 and additional equipment will be added in the left-hand beamline (No. 10).

To cope with beam intensities varying over roughly five orders of magnitude, different types of detectors have been mounted on a cooled frame just behind the apertures (Fig. 2), including simple, electrically insulated metal plates and thin tungsten wires (50 μm diameter), PtSi-photodiodes[10] and thermopiles[11,12] based on the "Seebeck-Effect" of YBaCuO high-T_c superconductors (HTSCs)[12].

PtSi-photodiodes were preferred to Si- or GaAsP-diodes due to their radiation hardness. For $\lambda \leq 150$ nm, Si- and GaAsP-photodiodes deteriorate already at low exposure doses of several mJ/cm^2, i.e. after a few "shots" of the FEL, while PtSi does not even show significant damage at a hundred times higher irradiation[10]. The PtSi-photodiodes will be used for low to intermediate power densities of the FEL, starting with the spontaneous emission of the undulator. From investigations with a picosecond Nd:YLF laser at 527 nm wavelength we deduced that for pulses shorter than their response time of ≈ 500 ps the onset of saturation for PtSi-photodiodes lies around 1-2 μJ, i.e. two orders of magnitude below the saturation power of the VUV FEL. Using pinholes to reduce the cross section of the FEL beam, the range of operation of the photodiodes might be slightly extended.

The HTSC thermopiles fill the gap from intermediate power to saturation of the FEL (325-707 μJ in a 564 fs pulse, cf. Table 1). They work at room temperature and are insensitive to temperature changes (0.5%/K). These especially designed thermopiles[11] combine a fast response time of ≈ 1 ns with linearity over 12 decades up to megawatts of power delivering an output signal of 1 V/mJ for short pulses. In addition to single thermopile elements, a special matrix detector with 4×4 elements, 2×2 mm^2 each (Fig. 3) has been developed for a coarse but fast measurement of the intensity distribution of individual photon pulses.

The matrix readout is done through delay lines with delays of 0, 25, 50, and 75 ns, respectively, so that each full column (4 elements) of the matrix can be combined and fed into one out of four channels of a 1 GHz digital oscilloscope (Fig. 3). Fast amplifiers are employed which also compensate for the signal drop due to the damping of the delay lines made from coaxial cables. The memory of the oscilloscope is sufficiently large to store the data from a high resolution sample of a full pulse train of 800 μs.

The detectors are complemented by fluorescence screens viewed by external CCD-cameras through Suprasil viewports. We have chosen Ce:YAG and $\mathrm{PbWO_4}$ crystals, because they have a fast fluorescence channel (80 ns and 2 ns lifetime, respectively), emit visible light (matching viewport transmission and camera sensitivity), and are very homogeneous, radiation hard and UHV compatible. $\mathrm{PbWO_4}$ crystals are key materials for future use in enormous quantities in scintillation detectors for high energy particle calorimeters, e.g. at HERA (DESY) and at LHC (CERN). Like the Ce:YAG crystals[13], they have also been investigated for applications based on photon excited fluorescence[14]. The fluorescence screens are intended to be used for a coarse adjustment of the detectors and optical components with respect to the FEL beam and, in particular, to investigate the beam profile and its statistical fluctuations.

For the spectral characterisation, the photon beam is deflected by a plane mirror (Fig. 1, No. 5) into a commercial 1m normal incidence monochromator (Fig. 1, No. 7) in the right-hand branch-line. The monochromator contains a 1200 lines/mm spherical grating which will be replaced by one with 3600 lines/mm for high resolution measurements to resolve the details of the spectral fine structure. For technical reasons the latter grating is mounted on the holder at an angle in order to make the full spectral range of the Phase I VUV FEL (42-122 nm) accessible, and it is no longer possible to adjust the grating and calibrate the photon wavelength using the 0th order reflection. Therefore, a hollow cathode lamp[15] will be used for monochromator alignment and calibration: a noble gas discharge at well defined operating conditions yields a calibrated photon source covering the relevant range for Phase I FEL operation with a number of narrow lines of known flux.

The 3600 l/mm grating, in conjunction with a precise piezo-actuated entrance slit that can be closed down to less than 10 μm, results in a maximum resolving power of $\mathrm{E}/\Delta\mathrm{E} = 2\times10^4$ at $\lambda = 120\,\mathrm{nm}$, which should be sufficient to fully resolve the fine structure in the spectral distribution[8]. The complete FEL spectrum with a relative bandwidth of 0.3–0.5 % rms can be recorded by a CCD-camera mounted in the focal plane of the spherical grating. Presently a thinned, back-illuminated UV-sensitive CCD with a pixel size of 24 μm is used[16], directly attached to the monochromator vacuum. Tests at an identical monochromator, using a laser produced plasma source with varying targets, revealed the potential of the camera (Fig. 4). This camera with its low electronic noise is ideally suited for the commissioning phase of the FEL at low to medium beam intensity.

High resolution measurements at high intensities will be carried out using a different camera equipped with a fast fluorescent screen in the focal plane of the monochromator, and a multi-channel-plate (MCP) intensifier[17]. While the pixel size of the CCD is 6.7 μm, the "effective" pixel size of the whole system (including the MCP and some lenses) amounts to $\approx 12\,\mu$m. This results in a spectral resolution twice as large as that of the back-illuminated CCD camera and close to the aberration limit of the monochromator. The MCP is used as a fast shutter enabling exposure times down to 5 ns. This makes it possible to select a single pulse from a sequence of pulses and to study a possible change of electron beam parameters for the first couple of bunches in a bunch train (macrobunch), even at the minimum bunch/pulse separation of 111 ns.

The left-hand beamline (Fig. 1, No. 10) will accomodate different experiments which will be installed after the initial characterisation of the FEL beam using the diagnostics in the other two beamlines.

Groups from the Research Centre Jülich and the University of Jena are presently designing two separate autocorrelation experiments to study the properties of the FEL beam in the time domain [18]. Later on it is intended to investigate the radiation damage of materials such as optical components in a specially designed UHV chamber containing a focusing mirror and time-of-flight spectrometers for electrons and ions. This experiment is in preparation at the Polish Academy of Sciences, Warszawa. The groups from Jülich, Jena and Warszawa will also be involved in the more detailed characterisation of the FEL radiation, together with groups from Dublin City University, Hamburg University, LURE (Orsay, France) and MAX-Lab/Lund Laser Centre (Lund, Sweden).

3. Summary

New concepts of photon beam diagnostics have been developed to measure the unique properties of the VUV radiation from a SASE FEL on a single pulse basis. A variety of detectors is employed to cover the full range of intensity from spontaneous undulator emission to SASE in saturation. Apart from the photon beam diagnostics task this will also be a benchmark experiment for several new types of detectors. The knowledge gained with the present setup will be very valuable to develop instrumentation for online photon beam characterisation which is indispensable at future FEL user facilities.

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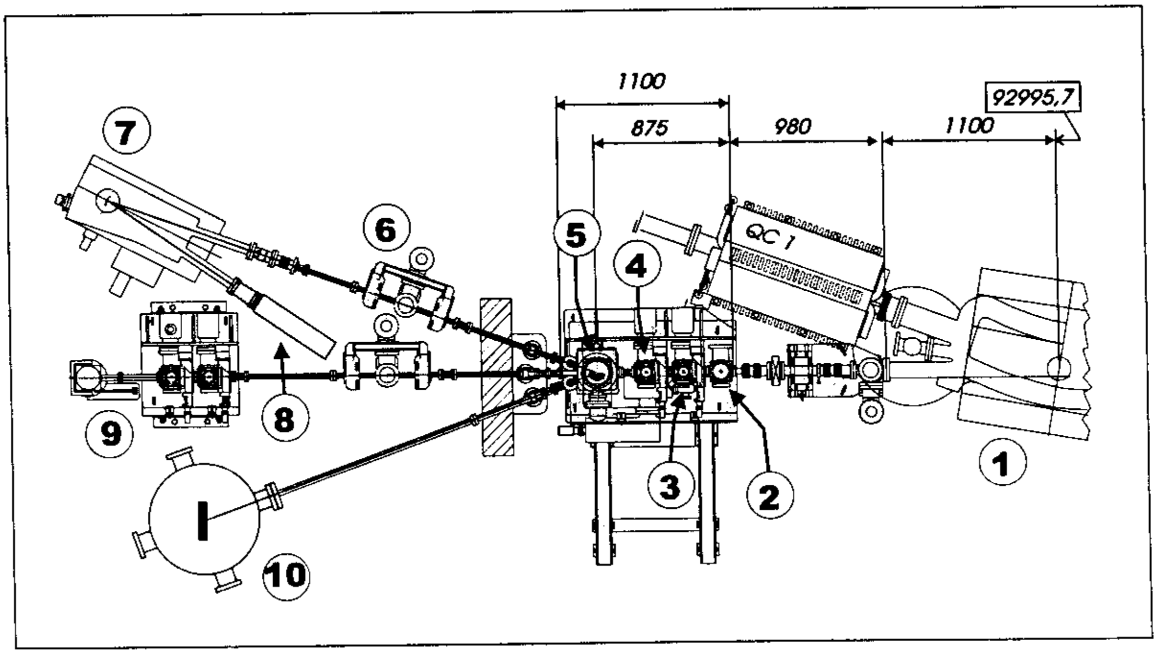

Fig. 1. *Layout of the experimental area for photon beam diagnostics.* **1**: *bending magnet to deflect the electron beam,* **2**: *alignment laser,* **3**: *aperture unit,* **4**: *detector unit,* **5**: *deflecting mirror,* **6**: *Titanium sublimation pump + ion pump unit,* **7**: *1 m normal incidence monochromator,* **8**: *CCD-camera,* **9**: *second chamber with aperture/detector unit and focusing mirror (optional),* **10**: *beamline for autocorrelation experiments and radiation damage investigations (schematic drawing)*

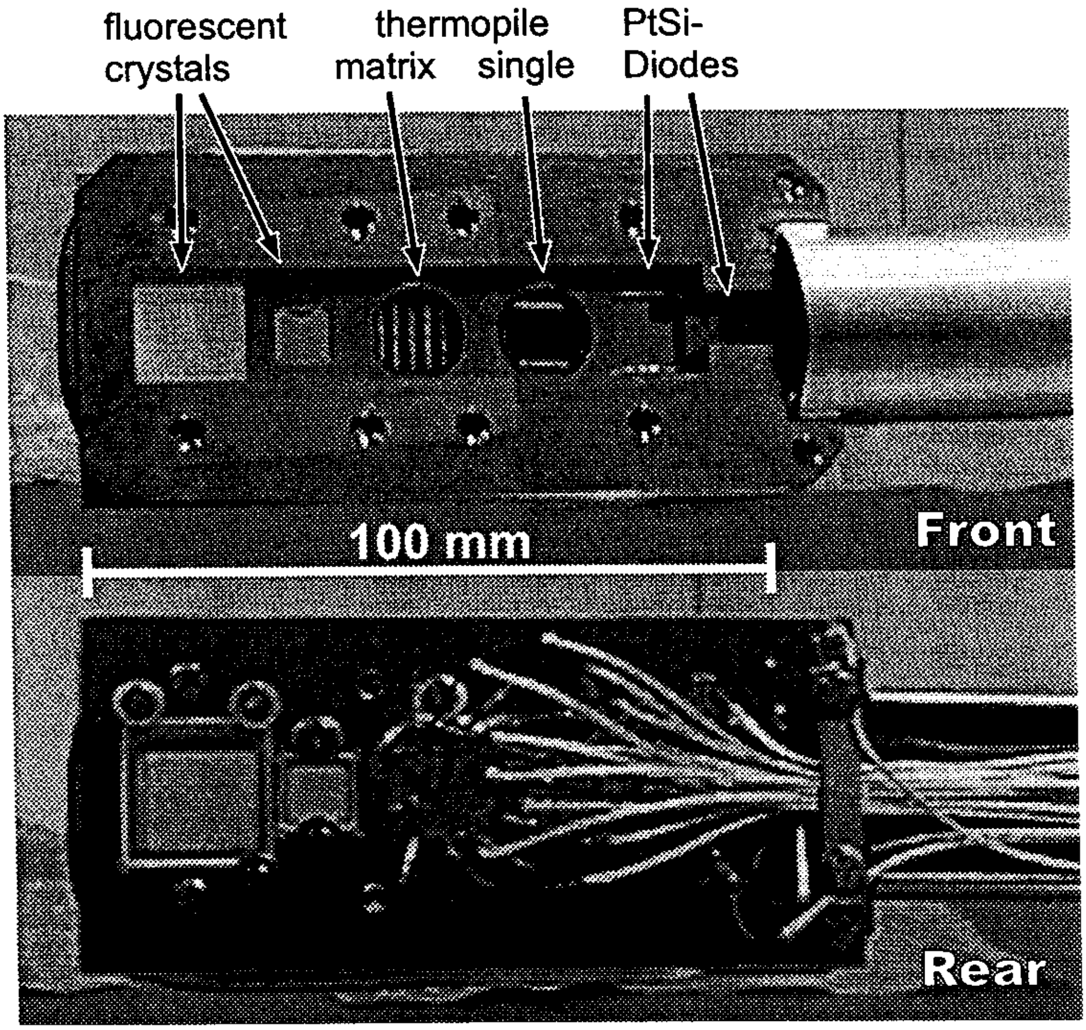

Fig. 2. *A set of detectors mounted on a water cooled Cu holder, ready for installation into the UHV chamber.*

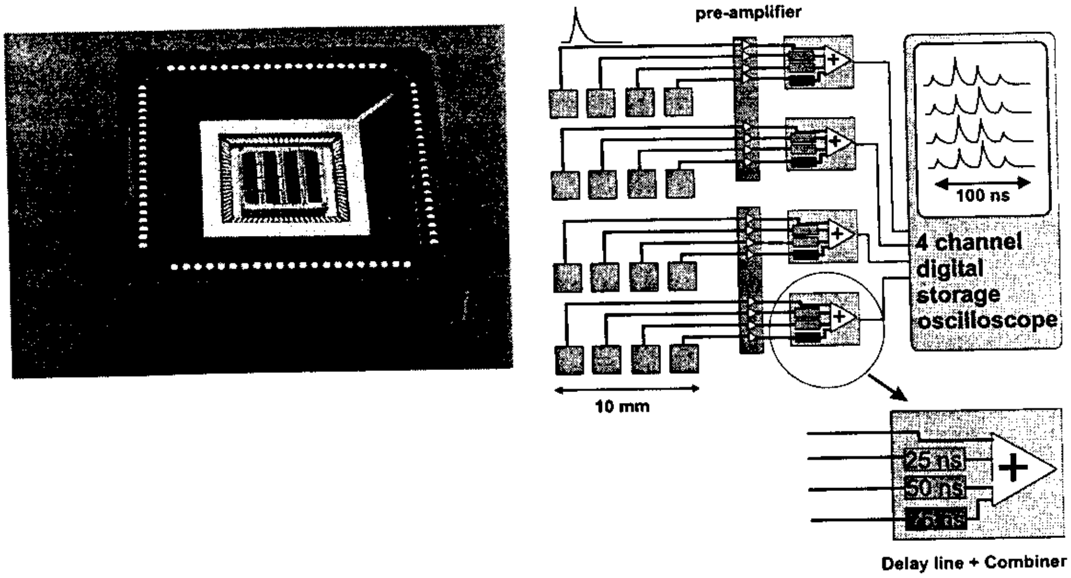

Fig. 3. *Thermopile 4 × 4 matrix detector and design of the readout scheme.*

	Energy	
	Minimum	**Maximum**
Electron Beam Properties:		
Energy [MeV]	230	390
Bunch Length (rms) [μm]	240 ≡ 800 fs	
Minimum Bunch Separation [ns]	111	
Max. No. of Bunches per Macropulse	7200	
Macropulse Repetition Rate [Hz]	10	
Undulator Properties:		
Length [m]	13.5	
Magnetic Gap [mm]	12	
Undulator Period [mm]	27.3	
Peak Magnetic Field [T]	0.497	
Photon Beam Properties:		
Energy [eV]	10.2	29.3
Wavelength [nm]	121.7	42.3
Spectral Bandwidth (rms) [%]	0.46	0.28
Pulse Length (rms) [fs]	564	
Photons per Bunch	2×10^{14}	1.5×10^{14}
Peak Power [GW]	0.23	0.5
Average Power (at 72000 pulses/s) [W]	23.5	51.1
Energy/Pulse [μJ]	325	707

Table 1
Parameters of the TTF Phase 1 VUV FEL at DESY. Photon intensities and power are saturation values calculated for a normalized electron beam emittance of 2π mm mrad (rms) and an electron energy spread of 500 keV (rms). Saturation is expected only for long photon wavelengths.

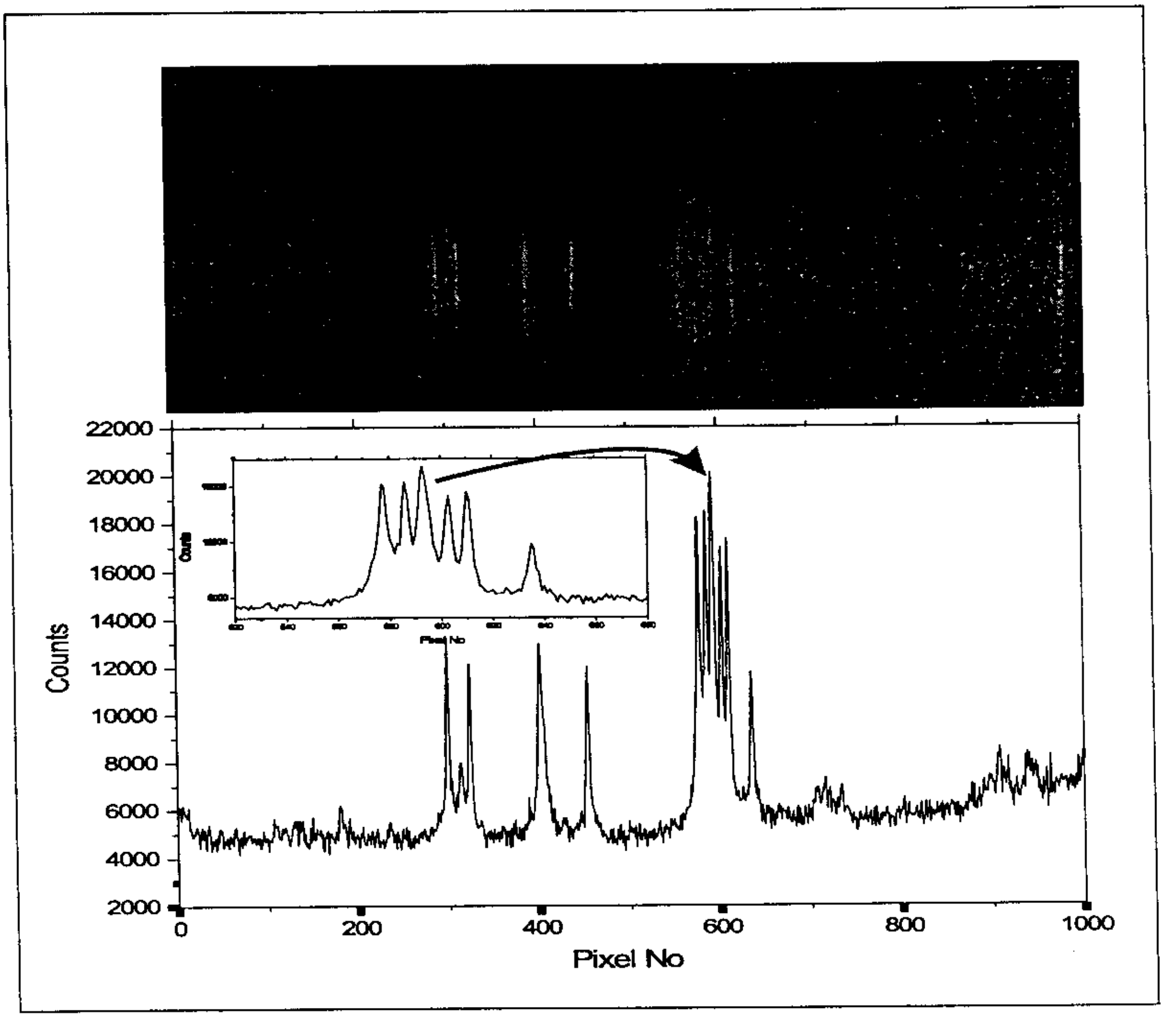

Fig. 4. *Typical spectrum of a laser produced plasma source measured with a 1 m normal incidence monochromator using a 1200 lines/mm grating and the back-illuminated CCD-camera. In this setup, the CCD covers a wavelength range of ± 10 nm, here centered around 147 nm. The experiments were performed in collaboration with the Centre for Laser Plasma Research, Dublin City University.*