DIAGNOSTIC TECHNIQUE WITH FEMNTO SECOND RESOLUTION APPLIED FOR FEL ELECTRON BUNCHES

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Abstract

Diagnostic technique applied for FEL ultrashort electron bunches is developed at JINR-DESY collaboration within the framework of the FLASH and XFEL projects. Photon diagnostics developed at JINR-DESY collaboration for ultrashort electron bunches are based on calorimetric measurements and detection of undulator radiation. The infrared undulator constructed at JINR and installed at FLASH is used for longitudinal bunch shape measurements and for two-color lasing provided by the FIR and VUV undulators. The pump probe experiments with VUV and FIR undulators provide the bunch profile measurements with resolution of several femtosecond. The MCP based radiation detectors are effectively used at FLASH for VUV pulse energy measurements. The new three MCP detectors operated in X-ray range are under development now in JINR for SASE1-SASE 3 XFEL.

FLASH MCP-BASED PHOTON DETECTOR

The free electron laser FLASH has been in operation at DESY since the year 2000. The maximal electron energy since 2007 up 2009 was equal 1 GeV, rms bunch length is 50 µm, the FWHM radiation pulse duration is about 30 fs, the normalized emittance is 2 π·mm·mrad, the bunch charge is 0.5 nC, the peak power is up to 1 GW, the peak brilliance is of 10^{28} ph/s/mrad^2/mm^2/(0.1%bw). In 2010 FLASH was upgraded to maximum electron energy 1.25 GeV and third harmonic RF system was installed which provides by few times longer the VUV pulse radiation comparing with the previous FLASH operation.

Successful operation of FLASH strongly depends on the quality of the radiation detectors. The key issues are: the wide wavelength range 4-100 nm, the wide dynamic range (from the spontaneous emission level to the saturation level), and the high relative accuracy of measurements which is crucial for detection of radiation amplification and characterization of statistical properties of the radiation.

The key FLASH photon detector developed by the JINR-DESY collaboration is a micro-channel plate (MCP) detector intended for pulse energy measurements [1-4]. The MCP detector is used for measurement of statistical properties of the radiation allowing determination of the pulse length. Key element of the detector is a wide dynamic MCP which detects scattered radiation from a target. With four different targets and MCPs in combination with optical attenuators, the present FLASH detector covers an operating wavelength range 4 -100 nm, and a dynamic range of the radiation intensities, from the level of spontaneous emission up to the saturation level of SASE FEL.

The gold target is perfect for the wavelength range above 10 nm, however its reflectivity falls dramatically for shorter wavelengths, and different targets and geometries of the detector are used. We added three more targets to gold mesh: two iron meshes, and one copper mesh. This helps us to operate the detector in a range below 10 nm.

For tuning SASE at very short wavelengths we use movable MCPs directly facing photon beam. Light intensity variation by a factor of 50 is controlled by a mechanical attenuator of light located in the target unit. To have full control of light intensity in a wide range we installed a side MCP which detects radiation reflected by the iron mirror. The mirror serves for two purposes. One is to deflect the photon beam off- the axis, which allows placing the MCP in better background conditions.

The FLASH bunch has non-Gaussian longitudinal distribution of electrons at operation in 2007-2009. The bunch edge or so named leading spike has a high peak current that is cable of driving the high intensity lasing process. Energy in radiation pulse and integrated spectral density fluctuate accordance with the gamma distribution with an energy width σ_w. Parameter $M=1/\sigma_w^2$ characterizes the number of modes in the radiation pulse. This parameters corresponds to a ratio of the electron bunch leading spike length σ_z to the coherence time τ_c at a saturation of the radiation in the SASE mode: $M=\sigma_z/c\tau_c$. The measurements of the integrate spectra density in radiation pulse permit to define the VUV pulse duration.

The r.m.s. VUV radiation pulse length was equal to τ_{VUV}= 8±1 fs at the end of the regime of exponential growth for wavelength radiation of 13.7 nm and bunch charge 0.5 nC at electron energy 1 GeV [1]. After 2010 upgrade the r.m.s. VUV pulse radiation time corresponds to τ_{VUV}= 41±8 fs at electron energy 1.25 GeV and bunch charge 0.5 nC [5].

DESIGN OF THE XFEL MCP DETECTOR

An important task of the photon beam diagnostics at the European XFEL is providing reliable tools for measurements aiming at the search for and fine tuning of the FEL creating SASE process. The problem of finding SASE amplification is crucial for the XFEL because of a large synchrotron radiation background. This requires a detector with a wide dynamic range, controllable tuning to the required wavelength range, and suppression of the unwanted radiation background. The JINR-XFEL

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collaboration proposes to design, manufacture, and install MCP-based photon detectors [6] as a primary tool for the search and fine tuning of the SASE process. Three MCP devices will be installed after each SASE undulator of the European XFEL (SASE1, SASE2, and SASE3).

Three different tasks can be fulfilled with the XFEL MCP-based photon detectors [6]: study of the initial stage of the SASE regime; measurement of the photon pulse energy; and measurement of the photon beam image. The MCP detector will resolve each individual pulse at a repetition rate of 4.5 MHz. The following wavelength ranges are to be covered by three MCP stations: 0.05-0.4 nm for MCP1 and MCP2, 0.4-5 nm for MCP3.

MCP detector for SASE1&SASE2 [6] consists of three MCPs equipped with the anode as a pulse energy monitor and one MCP detector for imaging the photon beam and silicon semiconductor photo detector (Fig.1). The first MCP detector port houses silicon photo detector and two F4655 Hamamatsu MCPs 18 mm in diameter, which are used for measuring the pulse energy and for searching for initial indication of SASE regime. The second detector port houses two MCPs: F4655 Hamamatsu for measurement of the pulse energies, and beam observation system (BOS) MCP (model BOS-40-IDA-CH/P-47) of 40 mm diameter with a phosphor screen.

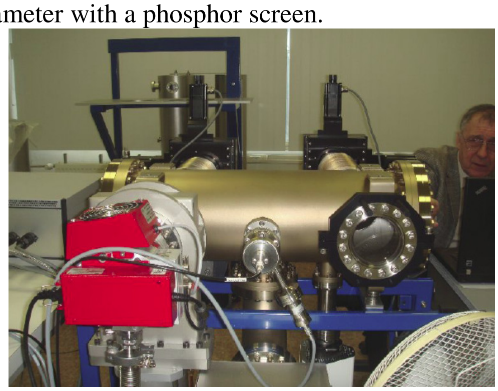

Figure 1: XFEL SASE1&SASE2 MCP detector.

MCP detector for SASE3 will have an additional port with movable semitransparent mesh and wire targets for production of scattering FEL radiation similar to those used at FLASH [1-4].

JINR FAR INFRARED UNDULATOR AT FLASH

The FLASH was equipped with an infrared electromagnetic undulator (Fig.2), tunable over a K–parameter range from 11 to 44, and producing radiation up to 200 µm at 500 MeV and up to 50 µm at 1 GeV [2-4, 6-7]. The purpose of the device is two-fold: firstly, it is used for longitudinal electron bunch measurements, secondly, it is a powerful source of intense infrared radiation naturally synchronized to the VUV FEL pulses, as both are generated by the same electron bunches and being therefore well suited for precision pump-probe experiments.

The undulator was designed and constructed by JINR to the FLASH requirements [6]. The undulator period corresponds to 40 cm, the number of periods is 9, the magnetic field is varied in range of 0.1-1.1 T. Output undulator radiation has the following parameters: wavelength 5-200 µm, peak power 4 MW, micropulse energy 1 mJ, micropulse duration 0.5-6 ps.

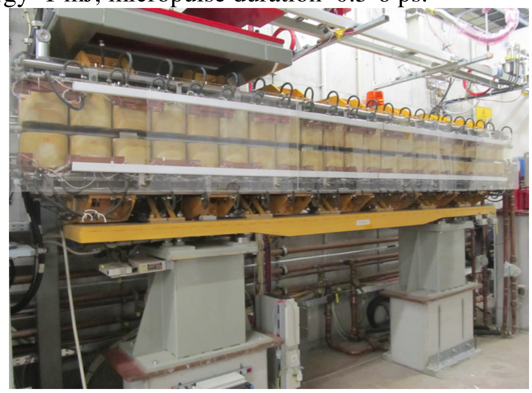

Figure 2: FLASH far infrared undulator constructed by JINR.

The energy radiated by the FIR undulator is defined by the number of electrons per bunch N and a form-factor F(λ):

$$\varepsilon_{coh} = \varepsilon_e \times \left[N + N(N-1)\left|\bar{F}(\lambda)\right|^2\right],$$

where ε_e is energy radiated by single electron. The form-factor is equal to $|F(\lambda)|^2 = \exp(-2\pi\sigma/\lambda)^2$ for Gaussian bunch with r.m.s. length σ. When the wavelength is longer than the bunch length, the coherent radiation dominates. Measuring the spectrum that regime one can extract the form-factor and thus the charge distribution and the bunch leading spike length. The Gaussian fit (Fig.3) corresponds to the r.m.s. leading spike length of σ_{ls}= 12 µm. The r.m.s duration of FIR pulse radiation is equal to $\tau_{FIR}=\sigma_{ls}/c$=40 fs, it is few times larger than r.m.s. pulse duration of the VUV pulse radiation.

After 2010 upgrade the detailed measurements of form-factor for FIR radiation were performed (Fig.4) [6]. The form-factor permits to reconstruct the time distribution of the electron current in the electron bunch (Fig.5) [6]. The reconstructed electron current pulse has complicated shape with two peaks at electron energy 1.25 GeV and bunch charge 0.5 nC.

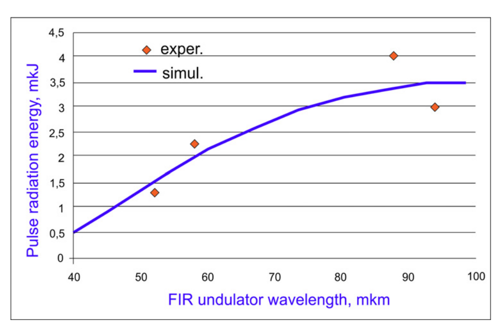

Figure 3: Dependence of the FIR undulator pulse radiation energy on the wavelength.

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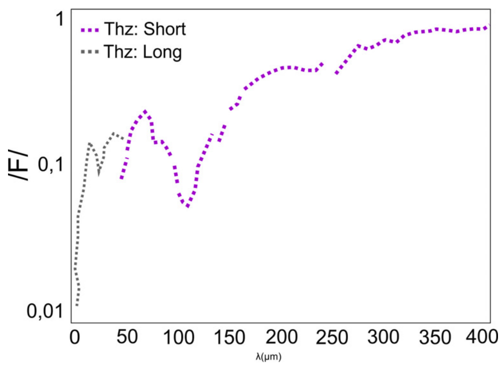

Figure 4: Dependence of form-factor on FIR radiation wave length.

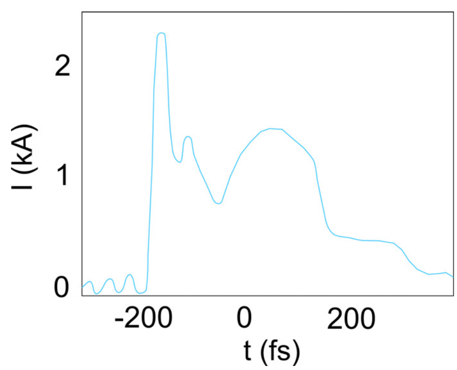

Figure 5: Reconstructed from form-factor of FIR radiation the time distribution of electron current in single short electron bunch.

PUMP PROBE EXPERIMENTS AT FLASH WITH JINR FIR UNDULATOR

The pump-probe experiments are very promising application of FLASH VUV and FIR undulators. The VUV and FIR undulator radiations are truly synchronized and tunable in a board spectral range that opens new perspective for two–color pump probe experiments at FLASH. In first pump probe experiments performed in 2009 [9] both FIR and VUV undulator radiations at wavelengths of 91 μm and 13.5 nm, correspondingly, pass through a krypton gas chamber. The 4-p krypton electrons are ionized in the gas chamber by the VUV photons generated during short pulse duration of 30 fs. The ionized electrons are accelerated during 3 ps in the electric field of IR light. The electron energy E_e is defined by VUV photon energy hω=91.8 eV, the krypton electron bind energy E_{bind}=14.1 eV and the vector potential of FIR electrical field A_{THz}: $E_e=h\omega-E_{bind}+evA_{THz}$, here v is the electron velocity. The difference of the electron energy spectrums along and across of the vector potential A_{THz} direction gives same information about the time structure of VUV radiation pulses. There is an asymmetry of the electron spectrums at small vector potentials $A_{THz}\to\pm0$ for two opposite directions of vector potential $A_{THz}\to+0$ and $A_{THz}\to-0$ (Fig. 6) .

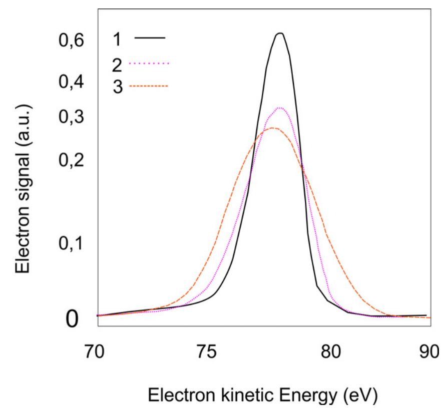

Figure 6: Dependence of electron intensity on its kinetic energy for three different vector potential of FIR radiation: 1 - $v\perp A_{THz}$, 2 - v// A_{THz}, $A_{THz}\to-0$, 3 - v// A_{THz}, $A_{THz}\to+0$.

The effective electron energy rate S_{eff} is defined by equation $S_{eff}^2=S^2\pm4SC$, where $S=veE_{THz}\cong100$meV/fs is the electron energy rate corresponded to FIR undulator electric field $E_{THz}=dA_{eff}/dt$, C=hdω/dt≅5±7 meV/fs is the VUV photon energy chirp related to the beam electron energy chirp produced in FEL lasing spike at bunch compression. The sign ± corresponds two cases of the vector potential $A_{THz}\to\pm0$. The r.m.s. VUV radiation pulse duration is equal to $\tau_{VUV}=(\sigma^2_{E\text{-}THz}-\sigma_E^2)^{0.5}/S_{ef}$ =15±3fs for measured 1000 FLASH micro pulses, where $\sigma_{E\text{-}THz}$ and σ_E are the r.m.s. widths of the krypton electron energy spectrum with and with out FIR radiation.

The FIR undulator in this pump-probe experiment operates in regime of a streak camera with 10 femtosecond resolution. The internal envelope phase stability of infrared pulse in combination with femtosecond synchronized VUV pulse permits to investigate dynamics of atomic and molecular systems with 10 femtosecond resolution.

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