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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

DIAGNOSTICS DEVELOPMENT AT JINR FOR ILC AND FEL ULTRASHORT ELECTRON BUNCHES

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Different methods for diagnostics of ultrashort electron bunches are developed at JINR–DESY collaboration within the framework of the FLASH and XFEL projects and JINR participation in the ILC project. The main peculiarity of these accelerator complexes is related to formation of ultrashort electron bunches with r.m.s. length 20–300 μm. Novel diagnostics is required to provide femtoscale time resolution in the modern FEL like FLASH and future XFEL and ILC projects. Photon diagnostics developed at JINR–DESY collaboration for ultrashort bunches is based on calorimetric measurements and detection of undulator radiation. The MCP-based radiation detectors are effectively used at FLASH for pulse energy measurements. 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. Two-color lasing in pump-probe experiments permits one to investigate dynamics of atomic and molecular systems with time resolution of 100–500 fs. A special magnetic spectrometer is planning to be used at ILC for measurements of average electron energy in each bunch. The first test spectrometer measurements were performed within the JINR–DESY–SLAC collaboration. A special synchrotron radiation detector applied for measurement of bunch average electron energy was constructed at JINR.

Диагностика ультракоротких электронных банчей, разрабатываемая в сотрудничестве ОИЯИ–DESY, предназначена для международного линейного коллайдера ILC, а также для лазеров на свободных электронах (ЛСЭ), таких как FLASH или рентгеновский лазер XFEL. Во всех этих ускорительных комплексах требуется диагностика ультракоротких электронных банчей с длиной 20–300 мкм. Детекторы на основе микроканальных пластин эффективно используются для измерения энергии излучения в импульсе из ультрафиолетового ондулятора FLASH. Инфракрасный ондулятор, изготовленный в ОИЯИ и установленный на FLASH, применяется для измерения длины электронных сгустков. Совместно с УФ-ондулятором он используется для двухцветной генерации излучения в ЛСЭ, что позволяет исследовать динамику атомных и молекулярных систем с временным разрешением 100–500 фс. Специальный магнитный спектрометр планируется установить на ILC для измерения средней энергии электронов в банче. Для отработки техники и методики эксперимента проведены первые тестовые эксперименты по измерению средней энергии электронов в банче на стэнфордском ускорителе при энергии электронов 28,5 ГэВ. Для этого в ОИЯИ сконструирован стриповый детектор синхротронного излучения, формируемый из магнитов спектрометра.

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INTRODUCTION

Development of new accelerator techniques applied for formation of ultrashort electron bunches with r.m.s. length 20–300 μm requires novel diagnostic methods. The use of diagnostic equipment for ultrashort bunches depends on the electron energy (Table). This energy is rather different at discussed above accelerator complexes: 1 GeV at FLASH, 17.5 GeV at XFEL and 250 GeV at ILC. Below we discuss several diagnostic systems for the FLASH, XFEL and ILC projects.

Parameters of FLASH, XFEL and ILC

Parameters	FLASH	XFEL	ILC
Electron energy, GeV	1	17.5	250
Bunch charge, nC	1	1	3.2
Normalized emittance, π·mm·mrad	2	1.4	10/0.04
Bunch length, μm	50	25	300
Bunch repetition rate, MHz	2	5	2.7

1. FLASH MCP-BASED PHOTON DETECTOR

The free electron laser FLASH has been in operation at DESY since the year 2000 [1, 2]. The electron energy now reaches 1 GeV, bunch length is 50μm, the radiation pulse duration is about 30 fs, the normalized emittance is $2\,\pi\cdot$ mm $\cdot$ mrad, the bunch charge is 1 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).

Successful operation of FLASH strongly depends on the quality of the radiation detectors. The key issues are: the wide wavelength range 6–100 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 FLASH bunch has non-Gaussian longitudinal distribution of electrons. 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 in accordance with the gamma distribution

$$P(W) = \frac{M^M}{G(M)}\frac{1}{\langle W\rangle}\exp\left(-\frac{MW}{\langle W\rangle}\right)\left(\frac{W}{\langle W\rangle}\right)^{M-1},$$

$$\sigma_w = \left[(W - \langle W\rangle)^2 \,/\, \langle W\rangle^2\right]^{1/2}.$$

Parameter $M = 1/\sigma_w^2$ characterizes the number of modes in the radiation pulse. This parameter 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 one to define the electron bunch leading spike length.

The key FLASH photon detector developed by the JINR–DESY collaboration is a micro-channel plate (MCP) detector intended for pulse energy measurements [3, 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 from 6 to 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 (88 and 79% open area), and one copper mesh (60% open area) (Fig. 1). 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.

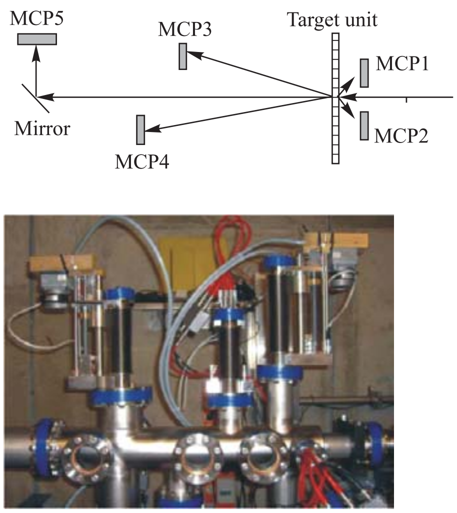

Fig. 1. Layout of the MCP detector with the extended wavelength installed at FLASH in 2007

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 other is calibrated attenuation of light: using the mechanical attenuator we can change the light intensity on the MCP several orders of magnitude. This construction permits overlapping of all radiation intensity ranges, from the level of spontaneous emission to the saturation level. The MCP has a very large dynamic

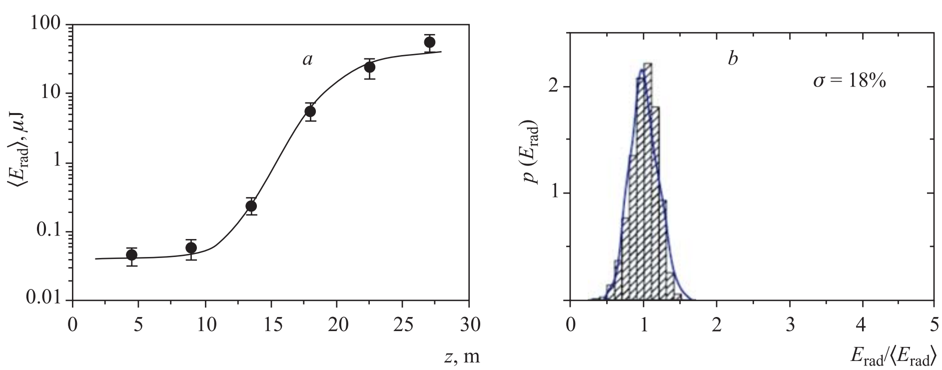

Fig. 2. *a*) Measured average energy in the radiation pulse versus the undulator length showing exponential growth and saturation. *b*) The probability distribution for the energy of the radiation pulses at saturation regime

range of six orders of magnitude. The electronics of the MCP detector itself has low noise, about 1 mV at the level of the signal of 100 mV (relative measurement accuracy 1%).

The dependence of the measured average energy in the FLASH radiation pulse on the undulator length is shown in Fig. 2. In the saturation regime the average pulse energy is 40 μJ and the wavelength is 13.7 nm. The measurements of the probability distribution of energy in the radiation pulses give information about r.m.s. leading spike length, which corresponds to $\sigma_{\rm ls} \cong 10$ μm.

2. FLASH FAR INFRARED UNDULATOR

The FLASH free electron laser is a running facility providing radiation in the vacuum-ultraviolet and soft X-ray ranges [1, 2]. In 2007 it was equipped with an infrared electromagnetic undulator (Fig. 3), 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 [5–7]. 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.

Fig. 3. FLASH far infrared undulator constructed by JINR

The undulator was designed and constructed by JINR to the FLASH requirements. The undulator period corresponds to $d = 40$ cm, the number of periods is 9, the magnetic field is varied in the range of 0.1–1.1 T. Output undulator radiation has the following parameters: wavelength 10–200 μm, peak power 1.5 MW, micropulse energy 4 μJ, micropulse duration 0.5–6 ps.

The energy radiated by the undulator is defined by the number of electrons per bunch N and a form-factor $F(\lambda)$ characterized by a ratio of the bunch length to the wavelength [5]:

$$\varepsilon_{\rm coh} = \frac{\pi e^2 A_{jj}^2 \omega K^2}{c\,(1+K^2/2)} \left[N + N(N-1)\left|\bar{F}(\lambda)\right|^2\right],$$

where $A_{jj} = J_0(q) - J_1(q)$, J_0, J_1 are the Bessel functions, $q = K^2/(4(1+K^2/2)$. The energy radiated by the undulator is divided into two parts. The first term is the incoherent part which is proportional to the number of electrons. The second term shows the coherent part of the spectrum proportional to $N(N-1)$. The form-factor $|F(\lambda)|$ determines which part is dominant. If the emitted wavelength is much smaller than the bunch length, the form-factor is negligible and the spectrum consists mainly of incoherent radiation. When the wavelength is comparable with or longer than the bunch length, the coherent radiation dominates. The form-factor is equal to $|F(\lambda)|^2 = \exp\left(-2\pi\sigma/\lambda\right)^2$ for Gaussian bunch with r.m.s. length σ.

The measured spectrum of FLASH infrared undulator radiation at different K parameters is presented in Fig. 4. The experimental value of maximum pulse radiation energy corresponds

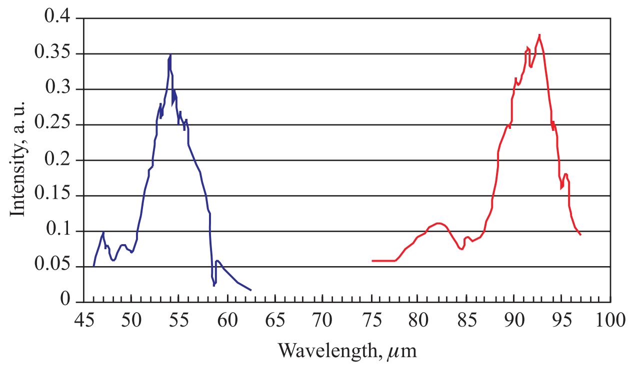

Fig. 4. Spectra of FLASH infrared undulator radiation at different K parameters

to 4 μJ at bunch charge of 0.5 nC and the electron energy of 700 MeV [8]. The experimental dependence [8] of pulse radiation energy on the wavelength is shown in Fig. 5. The bunch leading spike has a high peak current that provides the high intensity lasing process. The Gaussian fit (solid line) corresponds to the r.m.s. leading spike length of $\sigma_{\rm ls} = 12\,\mu$m (Fig. 5). This value has a good agreement with data obtained in MCP measurements (Fig. 2).

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 broad spectral range that opens new perspective for two-color pump-probe experiments at FLASH. In the first pump-probe experiment [8] 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 a few ps in

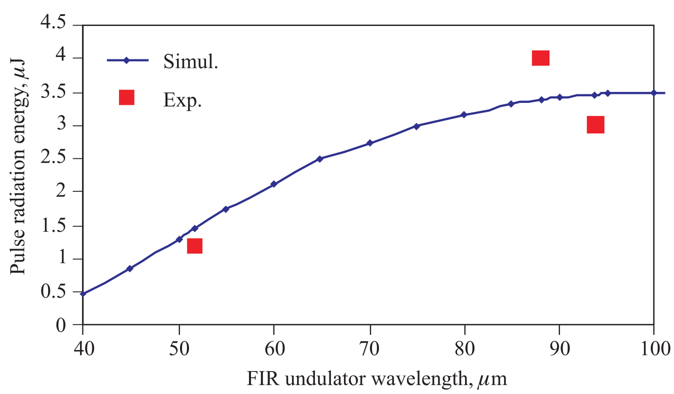

Fig. 5. Dependence of the pulse radiation energy emitted into central cone of the FIR undulator on the wavelength

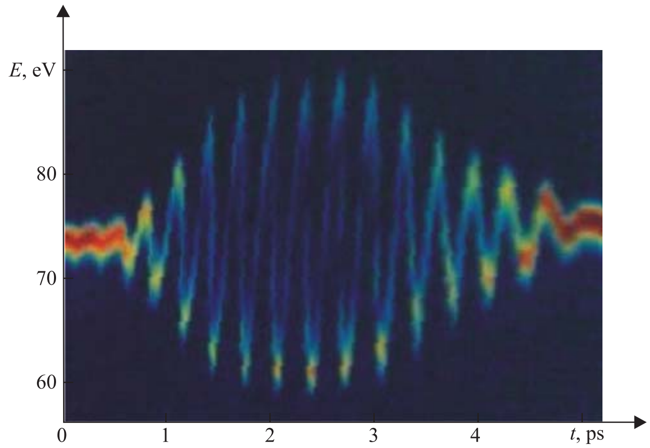

Fig. 6. Dependence of electron energy versus time in FLASH pump-probe experiment

the electric field of IR light. The spectrum measurements of the electron energy (Fig. 6) versus tunable time delay between VUV and FIR pulses permit one to reconstruct the pulse of FIR undulator electric field. The FIR electric field has harmonic time structure similar to image of the electron trajectory within infrared undulator. In FLASH experiment [8] the electric field of the infrared pulse has Lorentz-transformed image (Fig. 6) of the electron trajectory caused by 10% band pass application. The FIR undulator in this pump-probe experiment operates in regime of a streak camera with hundred femtosecond resolution. The internal envelope phase stability of infrared pulse in combination with femtosecond synchronized VUV pulse permits one to investigate dynamics of atomic and molecular systems with time resolution shorter than the period of infrared undulator radiation of order of 50–500 fs.

3. XFEL DIAGNOSTICS

A bunched electron beam of extremely high quality is needed in the XFEL to get coherent radiation in sub-nanometer wavelength [9]. JINR proposes for realization of several XFEL diagnostic systems. The laser heater consists of a magnet chicane 2 m long with an undulator magnet which the electron beam traverses together with a laser beam. The XFEL laser heater makes it possible to avoid electron beam instabilities driven by space charge and coherent synchrotron radiation. JINR proposes to design and construct the Optical Replica Synthesizer (ORS). Its operation is based on a production of optical replica of the electron bunch with subsequent use of modern optical techniques for deriving properties of the electron bunch (current profile, emittance, energy spread) with a femtosecond resolution. The ORS consists of a seed optical laser, two undulators, a dispersion section, and an optical diagnostic station. JINR proposes to design and construct MCP-based detectors for SASE XFEL. JINR also plans to participate in construction of the XFEL Hybrid Pixel Array Detector [10].

4. ILC MAGNETIC SPECTROMETER

The ILC physics program requires to measure particle masses of, e.g., the Higgs boson and top quark with uncertainties of about 50 MeV. Since the beam energy uncertainty has a major impact of the accuracy of the mass measurements, a precision of 100 ppm for beam energy measurements is needed.

A magnetic spectrometer (Fig. 7) with an energy resolution $\Delta E/E = 5 \cdot 10^{-5}$ was proposed for the ILC beam energy calibration [11]. The measurement is based on precise determination of the beam positions with a resolution of 100 nm and the spectrometer B-field integral with a relative accuracy of $2 \cdot 10^{-5}$.

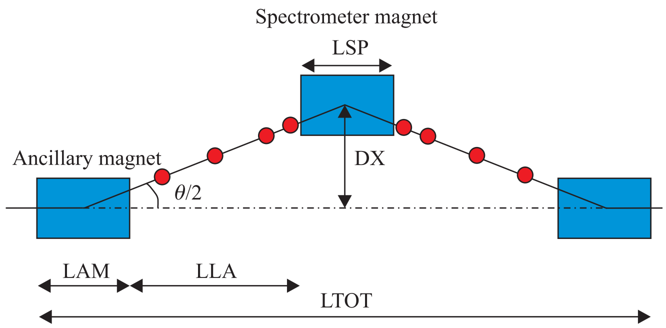

Fig. 7. Scheme of magnetic spectrometer proposed for ILC beam energy measurements

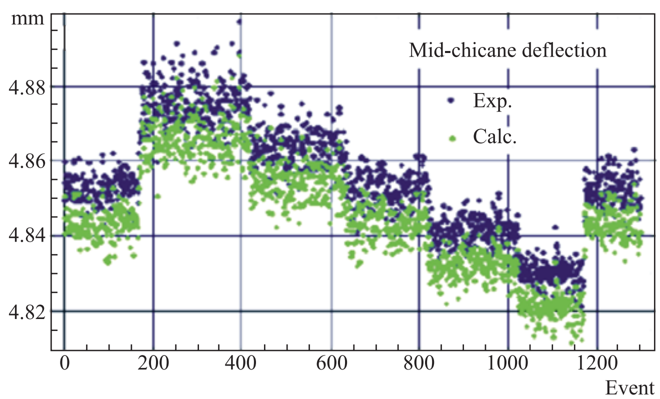

Fig. 8. Measured and calculated mid-chicane beam deflection at energy scan

A prototype spectrometer chicane employing four-dipole magnet is currently under development at SLAC [12]. The ILC energy measurement technique was tested in the JINR–SLAC–DESY joint research at T-474 project to demonstrate performance of the spectrometer with a 28.5-GeV beam [12, 13]. The comparison of the experimentally measured and simulated values of bunch deflection in the mid-chicane region during 5 steps of energy scan in the range ± 0.2 GeV is given in Fig. 8 [13]. The resolution of the energy measurement per bunch is determined by the BPM resolution of $\approx 1\,\mu$m giving a relative energy determination error $2.5 \cdot 10^{-4}$. The accuracy of the magnetic field integral with NMR monitoring corresponds to 100 ppm.

5. ILC SYNCHROTRON RADIATION DETECTOR

The electrons/positrons which pass through the ILC spectrometer magnets produce synchrotron radiation. A complementary method of beam energy measurement with an uncertainty of $\Delta E/E \cong 5 \cdot 10^{-5}$ based on synchrotron radiation (SR) at photon energy 1–20 keV emitted in the dipole magnets of the energy spectrometer is proposed [14]. Measuring the SR fan (Fig. 9) at far distances downstream of the spectrometer provides precise independent beam energy monitoring when both horizontal edge positions of the fan are known with the micrometer precision.

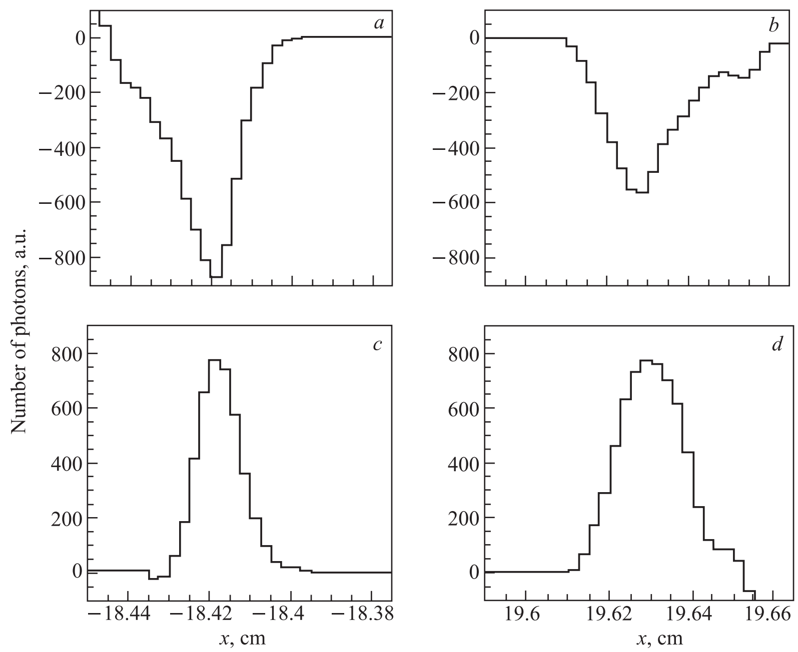

Fig. 9. Simulated differences of SR spectra versus the x coordinate close to the right (a, c) and left (b, d) fan edges at the electron energies of 250 GeV and (250 $\pm$ 0.025) GeV

The SR stripped detector with 2–3 μm resolution consists of about 2500 independent 2 μm Si layers, each separated by 0.05 μm SiO dielectrics [14]. The appropriate electronics can be made simple and compact.

As an alternative a plane-parallel avalanche detector might be used as a high resolution detector. A prototype of a gas amplification stripped detector with 47 channels and resolution of 3 μm was constructed at JINR. The first test experiments with this detector are under realization now. Schematically, the avalanche detector is a flat capacitor filled with xenon at a pressure of 100 atm. The anode plane of the detector comprises Ni layers of 1 μm thick separated from each other by dielectric of 2 μm thick. To eliminate edge effects, the sensitive elements are placed inside a plastic frame $\approx 10 \times 10$ mm covered by Al. The 10 mm by 10 mm entrance window of the detector is made of 1 mm thick beryllium (Be) foil. High voltage is applied to the beryllium cathode foil. The mean path of 20-keV γ-quanta in xenon is about 0.2 mm at a pressure of 100 atm. The distance between the anode and the cathode of the detector may be less than 1 mm at this pressure. At the gas amplification about 10 the transverse dimension of the avalanche will be within the mean free path of electrons which is 1 μm long.

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