DIAGNOSTICS OF ULTRASHORT ELECTRON BUNCHES DEVELOPED AT JINR

O. Brovko, D. Kharlamov, O. Kozlov, S. Kostromin, R. Makarov, E. Matyushevskiy, N.Morozov, E. Syresin*, B. Zalikhanov, M. Yurkov, JINR, Russia.

Abstract

Different methods for diagnostic 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 are 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. A special magnetic spectrometer is planning to be used in ILC for measurements of average electron energy in each bunch. The first test spectrometer measurements were performed within the JINR-DESY-SLAC collaboration.

INTRODUCTION

Development of new accelerator techniques 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 also depends on the electron energy. 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.

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, rms bunch length is 50 μm, the radiation pulse duration is about 30 fs, the normalized emittance is 2 π·mm·mrad, the bunch charge is 1 nC, the peak power is up to 1 GW, the peak brilliance is of 10^{28} ph/s/mrad2/mm2/(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 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. 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 the 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.

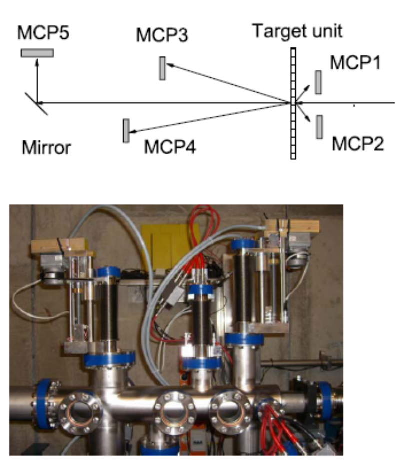

Fig. 1 Layout of the MCP detector (version MCP07) with the extended wavelength installed at FLASH in 2007.

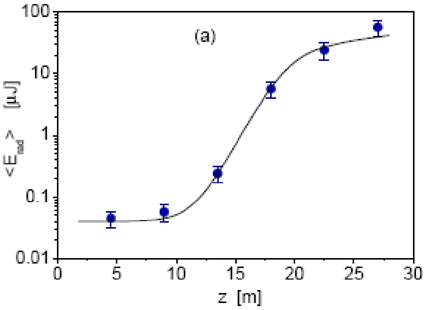

Fig.2 Measured average energy in the radiation pulse versus the undulator length showing exponential growth and saturation .

The MCP has a very large dynamic 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.

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.

The undulator was designed and constructed by JINR to the FLASH requirements. 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 50-200 µm, peak power 100 MW, micropulse energy 1 mJ, micropulse duration 1,5-7 ps.

Fig. 3 FLASH far infrared undulator constructed by JINR.

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

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

where $A_{jj}=J_0(q)-J_1(q)$, J_0, J_1 are the Bessel functions, $q=K^2/(4(1+K^2/2))$.

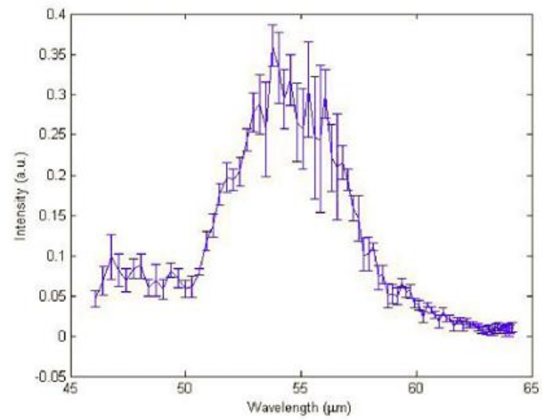

Fig. 4 Spectrum of FLASH infrared undulator radiation.

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(ω) 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. Measuring the spectrum (Fig.4) that regime one can extract the form-factor and thus the charge distribution and the bunch length. The bunch length measurements based on infrared radiation are in progress now.

XFEL DYAGNOSTICS

A bunched electron beam of extremely high quality is needed in the XFEL to get coherent radiation in sub-nanometer wavelength [8]. 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.

ILC DYAGNOSTIC

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 with an energy resolution $\Delta E/E=5\cdot10^{-5}$ was proposed for the ILC beam energy calibration [9]. 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 $2\cdot10^{-5}$.

A prototype spectrometer chicane employing four dipole magnet is currently under development at SLAC [10]. 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 [10,11]. 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.5 [11]. The resolution of the energy measurement per bunch is determined by the BPM resolution of ≈ 1 μm giving a relative energy determination error $2.5\cdot10^{-4}$. The accuracy of the magnetic field integral with NMR monitoring corresponds to 100 ppm.

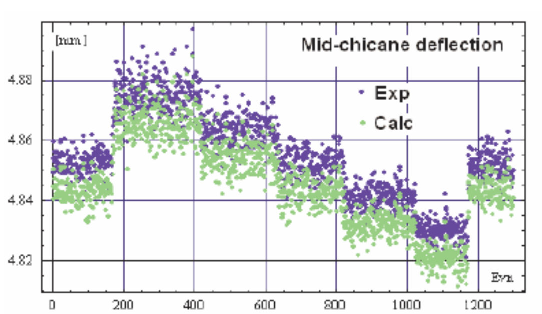

Fig. 5 Experimentally measured and calculated mid-chicane beam deflection at energy scan.

The electrons/positrons which pass through the ILC spectrometer magnets produce synchrotron radiation. A complementary method of beam energy measurement with an uncertainty of $\Delta E/E \cong 5\cdot10^{-5}$ based on synchrotron radiation (SR) at photon energy 1-20 keV emitted in the dipole magnets of the energy spectrometer is proposed [12]. Measuring the SR fan (Fig.6) 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.

The SR stripe detector with 2-3 μm resolution consists of about 2500 independent 2 μm Si layers, each separated by 0,05 μm SiO dielectrics. 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.

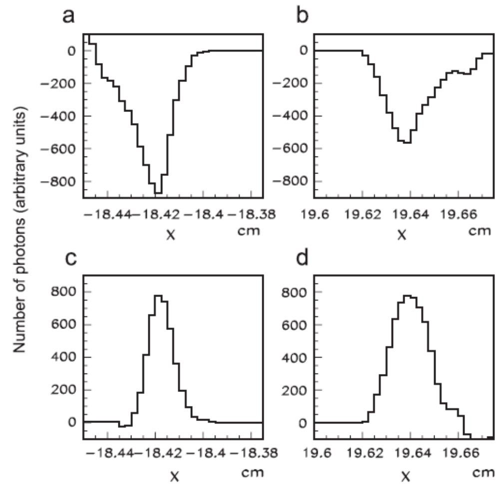

Fig. 6 Simulated differences of SR spectra versus the x-coordinate close to the right (a) and (c) and left (b) and (d) fan edges at the electron energies of 250 GeV and 250 ±0.025 GeV.

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