MEASUREMENTS OF ULTRASMALL CHARGES WITH MCP DETECTOR IN FLASH ACCELERATOR

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Abstract

Structure of the dark current passed through the undulator is a matter of great concern. Two effects can contribute to the dark current: emission of electrons from "hot" spots in the gun, and generation of "ghost" bunches due to possible leakage of the photoinjector laser. MCP based photon detector has been used for measurements of radiation energy from electron bunch. For small radiation densities the light is detected by direct illumination of the MCP plate, and for large densities a small angle scattering scheme is realized when metallic mesh scatters tiny fraction of light on the MCP plate. In the present experiment we used geometry of direct illumination of MCP plate aiming detection of "ghost" bunches which may generate parasitically from the laser driven electron gun. Reduction of background conditions allowed us to detect light produced by electron bunches with extremely small charges, on a subfemtocoulomb values. We measured for the first time structure of the dark current passing through the FLASH undulator. We have also been able to measure a high contrast of radiation produced by the photoinjector laser pulses switched on and off by a 1 MHz repetition rate Pockels cells.

INTRODUCTION

The Free Electron Laser FLASH at DESY is the first FEL user facility in the world operating in the soft x-ray wavelength range [1–3]. Five scientific instrumented beamlines have been in use since the commissioning of the facility in 2004. Second stage, FLASH2 is under commissioning now. First lasing at FLASH2 has been obtained in August, 2014 [4]. FLASH facility is also used for the development and testing of technology for the European XFEL and for the International Linear Collider (ILC) [5, 6].

Layout of the FLASH facility is shown in Fig. 1. It consists of 1.125 GeV superconducting linear accelerator operating in the burst mode (10 Hz repetition rate with 0.8 ms pulse duration). Number of electron bunches in the pulse may vary from 1 to 800. Electron beam drives two FEL beam lines, FLASH1 (in operation since 2005), and FLASH2 (in operation since 2014). Present experiment has been performed at FLASH1 branch of the facility equipped with fixed gap undulator with period 2.73 cm, peak field 0.48 T, and total magnetic length of 27 m.

Overall experience of the technology developed during two last decades was very positive: the FLASH facility demonstrated excellent operational characteristics and potential for the development of pioneer electron and photon beam diagnostics. In this report we describe application of photonics methods for measurements of the dark current in the undulator and detection of possible leakage of the seed light from the photoinjector laser which may generate unwanted "ghost" bunches.

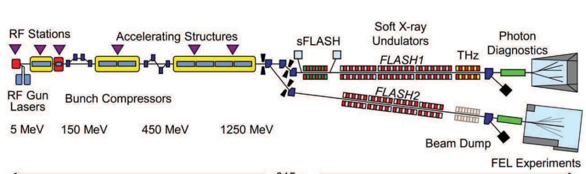

Figure 1: Layout of FLASH facility. Accelerator is on the left side. Top and bottom branches correspond to FLASH1 and FLASH2. MCP detectors are located in the photon diagnostics area behind beam dumps (green boxes).

MCP-BASED PHOTON DETECTOR

Scheme of microchannel-plate (MCP) detector is shown in Fig. 2 [7,8]. We implemented small/large angle reflection geometry of MCPs which demonstrated to be reliable solution for detection of the radiation with wavelengths above 10 nm. Four different targets can be used to scatter light on the detector: gold mesh (65% open area), two iron meshes (88% and 79% open area), and one copper mesh (60% open area). This helps us to operate the detector in the range below 10 nm. For tuning SASE at very short wavelengths or measurements ultra-low photon flux, we use movable MCPs directly facing photon beam. Reduction of the light intensity is provided with mechanical attenuator of light (perforated Ni foil located in the target unit, 2% open area). To have control on the photon beam image in the wide range of intensities, we installed side visual MCP which detects the light reflected by SiC mirror.

Gain of MCP detector has nearly exponential dependence on applied voltage (see Fig. 3).

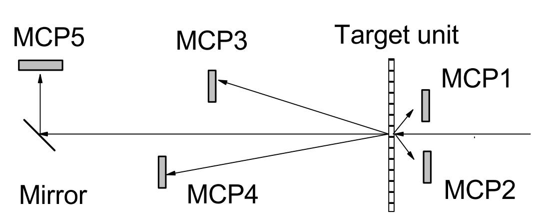

Figure 2: Scheme of MCP detector at FLASH1. MCP1 and MCP2 detect backward scattered radiation. MCP3 and MCP4 are movable, and allow to operate in a small angle geometry, or to measure direct light when positioned on-axis.

ISBN 978-3-95450-147-2

POTENTIAL OF MCP DETECTOR FOR CHARGE MEASUREMENTS

In the case under study we deal with spontaneous radiation from the undulator. The simplest way to derive required quantities is to use notion of the central cone [9]. Radiation within the cone of half angle $\theta_{\mathrm{con}} = \gamma^{-1}\sqrt{(1 + K^2)/N_{\mathrm{w}}}$ has relative spectral bandwidth $\Delta\lambda/\lambda \simeq 1/N_{\mathrm{w}}$ near resonance wavelength. Radiation energy of single electron into the central cone is

$$E_{\mathrm{rad}} \simeq 4\pi^2 e^2 K^2 A_{\mathrm{JJ}}^2/[\lambda(1 + K^2)] \ .$$

Here K is rms undulator parameter, $A_{\mathrm{JJ}} = 1$ and $A_{\mathrm{JJ}} = [J_0(Q) - J_1(Q)]$ for a helical and a planar undulator, respectively, $J_n(Q)$ is a Bessel function of nth order, and $Q = K^2/2/(1 + K^2)$. Number of photons radiated by electron into the central cone is equal to:

$$N_{\mathrm{ph}} \simeq 2\pi\alpha K^2 A_{\mathrm{JJ}}^2/(1 + K^2) \ ,$$

where $\alpha = 2\pi e^2/hc \simeq 1/137$ is the fine-structure constant, and h is the Planck constant. For FLASH1 undulator rms value of the undulator parameter is equal to 0.89, and $A_{\mathrm{JJ}} = 0.88$. In the experiment electron energy was equal to 1140 MeV which corresponds to the resonance wavelength 6.3 nm (200 eV photon energy). Full angle of the central cone is equal to 40 μrad. Number of photons within central cone radiated by single electron in FLASH undulator is about 0.016 (which corresponds to one photon per 60 electrons). FLASH1 undulator consists of 6 modules of 4.5m length. Photons were detected by MCP detector, which was operated with a 10-mm diameter aperture and was located 18.5m from the undulator. Assuming source position in the center of undulator, we find that angle acceptance of the detector is 300 μrad, and number of photons radiated by single electron in the detector aperture is about one. Electron bunch with 1 fC charge brings 6250 electrons which radiate approximately the same number of photons in the detector aperture. Detection efficiency of uncoated MCP in the photon energy range around 200 eV is about 10% which allows to perform measurements of 1 fC charges with statistical accuracy about 5%. We estimate lower level of charges for reliable detection to be a few attocoulomb.

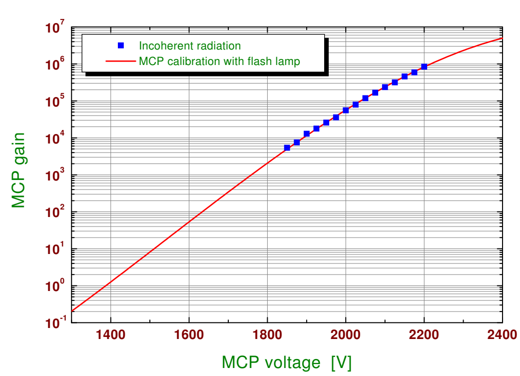

Figure 3: Gain curve of MCP detector versus voltage.

MEASUREMENTS OF THE DARK CURRENT IN THE UNDULATOR

The problem of monitoring of the dark current in the FLASH accelerator has high practical priority since uncontrolled currents may bring a set of problems with radiation doses on critical components. The dark current is mainly originates from the gun. Relevant diagnostics available by now are Faraday cup installed just after the gun [10], and dark current monitor (rf cavity based dark current monitor (DaMon)) installed in the bunch compressor area [11, 12]. From practical point of view it is important to know properties of that fraction of the dark current which is able to pass through the undulator. We performed such measurements with MCP detector measuring light produced electron beam in the undulator.

Signal from DaMon detector is shown in Fig. 4. DaMon detector allows to resolve features of the dark current on a scale of about 150 ns, but during our measurements it has been sampled with 1 MHz frequency.

Calibration of MCP has been performed at the MCP voltage of 1400 V for the bunch charge of 10 pC which can be measured reliably with charge monitors at FLASH (toroids). Calibration curve shown in Fig. 3 has been used for derivation of the bunch charge. Measurements of the dark current have been performed at the MCP voltage of 2100 V. We performed set of test measurements with different apertures installed in front of detector: 0.5, 1, 3, 5, and 10 mm. Signal of the detector exhibited quadratic dependence on the aperture diameter which convince that the detector observe light from the undulator. No signature of gamma background due to possible losses in the beamline has been detected after optical blocking of the detector. In this case signal is just usual electronic noise (a few tens of μV) induced on long cables. Typical value of MCP signal is 100 mV, and we estimate noise level of the measurements to be well below 10^{-2}. At the value of charges of 1 femtoCoulomb this noise level corresponds to the values about a few attoCoulomb.

Snapshots of oscilloscope signals from MCP detector are shown in Fig. 5. The reason for using oscilloscope was that standard sampling rate of control electronics at FLASH is 1 MHz, while temporal characteristics of the detector allow to see temporal features of the signal on a scale of several nanoseconds. Upper snapshot in Fig. 5 shows full temporal picture of the macropulse of 450 μs duration. Temporal scale is 50 μ s/div. MCP signal is negative. We see envelope of the dark current from MCP detector is similar to that from rf-cavity based monitor DaMon (see Fig. 4), and significant fraction of the dark current propagates through the whole accelerator beamline including collimation system.

Lower snapshot in Fig. 5 shows details of the temporal structure of the dark current on a scale of 6 microseconds. Here temporal scale is 500 ns/div. We observe rather complicated temporal structure of the dark current with period of 1 microsecond. This feature relates to operation of the dark current kicker installed in the gun. The idea behind this device is to kick out dark current in between main elec-

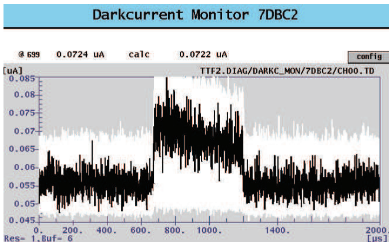

Figure 4: Dark current measured by DaMon detector located in the bunch compressor area. Sample frequency is 1 MHz.

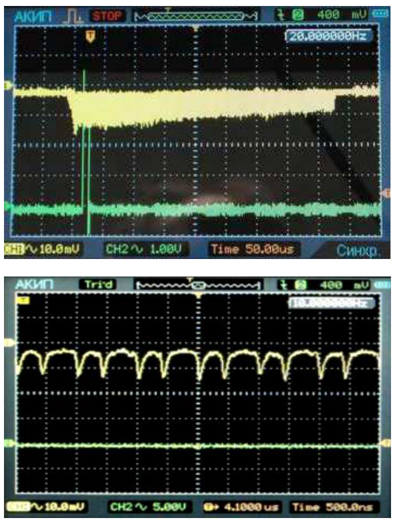

Figure 5: Dark current in the undulator measured by MCP detector. Two snapshots from oscilloscope show different time scale of 50 μs/div (top), and 500 ns/div (bottom). Dark current kicker of the gun (1 MHz frequency) is on.

tron pulses produced by photoinjector [13]. Technically it is realized as a strip line providing periodic beam deflection combined with collimator. The kicker runs with 1 MHz frequency, hence we have 2 zero crossings 500 us apart. In consequence, two pulses of the dark current originate from the zero crossing. Since the sine wave is not exactly symmetric, the distances between the zero crossings are not exactly half period, but 400 and 600 μs, respectively. Photoinjector pulse is synchronized with one of the zero phase of the kicker (maximum negative signal on the snapshot).

MCP voltage during dark current measurements was equal to 2100 V. From the MCP gain curve and dark current signal we derive the value of the bunch charge in 1.3 GHz buckets to be about 1 femto Coulomb (see Fig. 3). During this experiment electronics of MCP detector did not allow us to resolve single bunches in 1.3 GHz buckets. However, it can be possible in the future by means of optimization of MCP circuit: minimization of cable length and detection of the signal as close as possible to the detector. Relevant activity has been performed with early versions of MCP detector at FLASH [7]. Ultimately MCP detector can resolve single bunches in 1.3 GHz buckets. It is reported by Hamamatsu that FWHM width of MCP signal can be reduced to 300 ps with rise time about 150 ps, and fall time about 350 ps [14].

We have also been able to measure a high contrast of radiation produced by the photoinjector laser pulses switched on and off by a 1 MHz repetition rate Pockels cells which gives an estimate for suppression of bunches closed by the laser 2 Pockels cell to be much less than 10^{-6} (most probably 10^{-8}).

SUMMARY

Detection of light produced by electron bunches in the undulator is reliable method for detection of the dark current, and can be easily implemented at operating x-ray facilities. Sensitivity of the method is rather high, and is estimated to be on a level of a few electrons per rf bucket (attoCoulomb scale).

ACKNOWLEDGEMENT

We thank Dirk Lipka and Evgeny Schneidmiller for many useful discussions.

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ISBN 978-3-95450-147-2