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МЕТОДИКА ФИЗИЧЕСКОГО ЭКСПЕРИМЕНТА

THz WIGGLER APPLIED FOR MEASUREMENTS OF ELECTRON BUNCH LONGITUDINAL STRUCTURE IN FEL

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The infrared undulator manufactured at JINR and installed at FLASH in 2007 is used for longitudinal bunch shape measurements in the range of several tenths of a micrometer.

The presented electromagnetic wiggler is intended for generating a narrow-band THz radiation to measure the longitudinal electron bunch structure in FELs with an electron energy of several tens of MeV. This is a planar electromagnetic device with six regular periods, each 30 cm long. The K parameter is varied in the range 0.5–7.12 corresponding to the range $B = 0.025 - 0.356$ T of the peak field on the axis. The wiggler is simulated for 19.8 MeV/c corresponding to the possible FEL option at PITZ. The wavelength range is 126 μm – 5.1 mm for this electron beam momentum. The 3D Opera simulations of the THz wiggler are discussed.

A new PITZ photocathode laser system is proposed for the optimized performance of the high-brightness electron beam. The main goal is a production of 3D ellipsoidal electron bunches with homogeneous charge density. The electromagnetic wiggler is supposed to be used for measuring the longitudinal shape of these electron bunches.

Инфракрасный ТГц-ондулятор, изготовленный в ОИЯИ и установленный в 2007 г. на ЛСЭ FLASH, используется для измерения продольной структуры электронных банчей.

Представленный в работе электромагнитный виглер предназначен для генерации ТГц-излучения и измерения продольной структуры электронного банча в ЛСЭ с энергией несколько десятков МэВ. Это плоский виглер с шестью регулярными периодами и длиной каждого периода 30 см. Параметр ондуляторности K в нем варьируется в диапазоне 0,5–7,12 в соответствии с диапазоном магнитного поля $B = 0{,}025 - 0{,}356$ Тл на оси виглера. Расчеты виглера приведены для импульса электронов 19,8 МэВ/c, соответствующего ЛСЭ PITZ. Диапазон длин волн излучения в этом случае составляет 126 мкм – 5,1 мм. Трехмерные расчеты виглера с помощью кода Opera обсуждаются ниже.

Новая лазерная система для фотоинжектора PITZ предложена для формирования электронных пучков высокой яркости. Основная цель данной системы — формирование трехмерных эллипсоидальных электронных банчей с однородной плотностью распределения. Предложено использовать электромагнитный виглер для измерения продольной структуры этих банчей.

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JINR FAR INFRARED UNDULATOR AT FLASH

The FLASH was equipped with an infrared electromagnetic undulator, tunable over a K-parameter range from 11 to 44, and capable of producing radiation up to 200 μm at 500 MeV and up to 50 μm at 1 GeV [1–5]. The undulator is used for longitudinal electron bunch measurements. It was designed and constructed at JINR according to the FLASH requirements. The undulator period is 40 cm, the number of periods is nine, and the magnetic field is varied in the range of 0.1–1.1 T. The output undulator radiation has the following parameters: the wavelength in the range of 5–200 μm, the peak power of $\sim$ 4 MW, the micropulse energy of 1 mJ, and the micropulse duration of 0.5–6 ps.

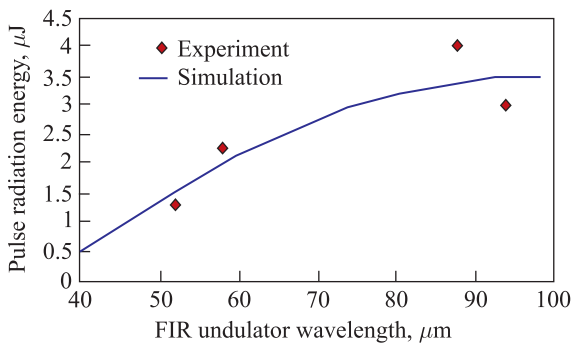

Fig. 1. Dependence of the FIR undulator pulse radiation energy on the wavelength

The energy radiated by the FIR undulator is determined by the number of electrons per bunch N and the form factor of an electron bunch $F(\lambda)$:

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

where ε_e is the energy radiated by a single electron. The form factor is determined by the temporal profile of the electron beam and, e.g., for Gaussian bunches with the r.m.s. length σ it yields $|F(\lambda)|^2 = \exp{(-2\pi\sigma/\lambda)^2}$. When the wavelength is larger than the bunch length, the coherent radiation dominates. In this case measuring the spectrum can yield the form factor and thus the charge distribution and the bunch leading spike length. The Gaussian fit (Fig. 1) corresponds to the r.m.s. leading spike length of $\sigma_{\text{ls}} = 12$ μm. The r.m.s duration of pulse radiation is $\tau_{\text{FIR}} = \sigma_{\text{ls}}/c = 40$ fs.

3D ELLIPSOIDAL ELECTRON BUNCH

A new photocathode laser system [6–8] is proposed for the high-brightness electron beam. The main goal is a production of 3D ellipsoidal electron bunches with charge density close to the homogeneous one. This corresponds to an almost linear space charge forces within the bunch and therefore to the minimization of the space charge contribution to the overall beam emittance budget.

Beam dynamics simulations demonstrated a significant reduction in the transverse emittance of electron bunches produced by applying 3D ellipsoidal laser pulses to the rf photo gun [9]. Such a system capable of producing 3D quasi-ellipsoidal pulses is under development at the IAP RAS, Nizhni Novgorod, Russia. The Photo Injector Test facility at DESY, Zeuthen site (PITZ) develops high-brightness electron sources for modern Free Electron Lasers, like FLASH and the European XFEL. The photocathode laser system is one of the key issues for the photo injector optimization. Currently, the PITZ photocathode laser can generate cylindrical pulses with flattop temporal profiles. Tests of the new photocathode laser system with 3D shaped pulses are considered to be the next step in the high-brightness electron source optimization. The laser system developed at IAP RAS is intended to be installed at the PITZ accelerator for experimental tests with electron beam production. The electron bunches with mean momentum of up to 19.8 MeV/c and r.m.s. pulse duration of ~ 7.2 ps are expected in the PITZ accelerator with the new laser system. Installation of a magnetic chicane in PITZ permits the r.m.s. electron bunch duration reduced down to ~ 0.66 ps, which corresponds to the bunch length of 200 μm. Below we assume that the electron bunches will be compressed in the PITZ magnetic chicane.

The wiggler [10, 11] is proposed for measuring the longitudinal shape of the 3D ellipsoidal electron bunch. As done at FLASH, we plan to estimate the form factor of a 3D ellipsoidal electron bunch on the basis of the radiation energy measurements. For small angles, typical of radiation of PITZ relativistic electrons, transverse effects are strongly suppressed. For the 3D ellipsoidal bunch shape $(x^2+y^2)/5\sigma_x^2 + (ct)^2/5\sigma_z^2 \leqslant 1$, $S(x,y,t) = 1/(4\pi \times 5^{3/2}\sigma_x^2\sigma_z^2)$ the form factor is defined by the relation $F(\omega) = \int dx\, dy \int S(x,y,t) \exp(i\omega t)\, dt$. After the integration one obtains $F(\varphi) = 3/(5\varphi^2) \times \{\sin(5^{1/2}\varphi)/(5^{1/2}\varphi) - \cos(5^{1/2}\varphi)\}$, where $\varphi = \omega\sigma_z/c$. As mentioned above, the form factor of the Gaussian beam is $F(\varphi) = \exp(-\varphi^2/2)$. The dependences of the squared form factor $F(\varphi)^2$ on φ are shown in Fig. 2 compared to the Gaussian and flattop cases. Though dependences for flattop and 3D ellipsoidal bunches show qualitatively similar behavior, they differ significantly from the Gaussian case.

The first experimental tests with the new photocathode laser system [6, 7] showed deviation of the generated laser pulses from the ideal 3D ellipsoidal shape. Finite border sharpness is one of such imperfections. In order to investigate the influence of the finite border sharpness on the electron beam emittance, beam dynamics simulations were performed [9]. Evaluations for the border thickness of 10% yield $\sim 10\%$ emittance growth [9].

The bunch border imperfection [6–8] is approximated by $(x^2+y^2)/5\sigma_x^2 + (ct)^2/5\sigma_z^2 \leqslant 1 + \delta \times \sin(2\pi mct/5^{1/2}\sigma_z)$, where $\delta \cong 0.1$ is the amplitude of the border oscillations, $m = 2$ or $m = 3$ is harmonic number. The square of form factor is equal to $F(\psi)^2 = \{3/(\psi^2) \times (\sin(\psi)/\psi - \cos(\psi))\}^2 + \{9\pi^2\delta^2 m^2 \sin^2(\psi)\}/\{\psi^2 - (2\pi m)^2\}^2$ at bunch border

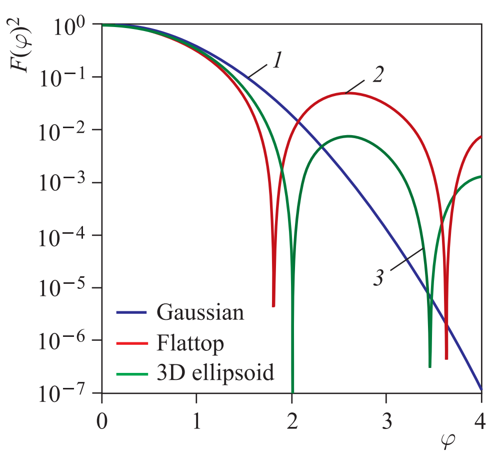

Fig. 2 (color online). Dependence of the squared form factor for the Gaussian (blue, *1*), flattop (red, *2*) and ellipsoidal (green, *3*) beams on $\varphi = \omega\sigma_z/c$

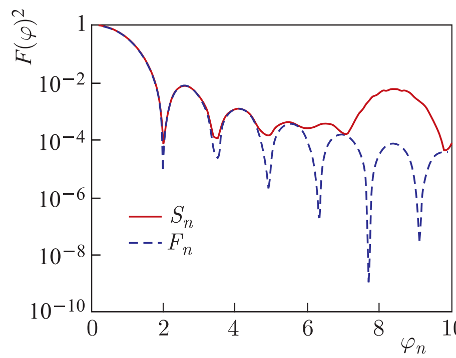

Fig. 3. Dependence of the squared form factor of the ellipsoidal bunch with an ideal 3D ellipsoidal shape (dashed line) and with border imperfection (solid line at $\delta = 0.1$ and $m = 3$) on $\varphi = \omega\sigma_z/c$

imperfection, where $\psi = 5^{1/2}\varphi$. The bunch border imperfection leads to large modification of square of the form factor at high $\varphi \cong 2\pi m/5^{1/2} \cong 8.5$ and $m = 3$ (Fig. 3). The square of the form factor is proportional to $F^2 \sim \delta^2$ at this φ.

The square of form factor and the longitudinal length of a 3D elliptic bunch can be found from the energy radiation measurements with different wavelengths [3–5]. To obtain the bunch length and extract the imperfection of the ellipsoidal bunch shape, the phase range should be about $10 > \varphi > 0.32$, where $F(0.32)^2 = 0.9$. This phase range corresponds to the wavelengths of $124\ \mu\text{m} < \lambda < 3.9$ mm for the bunch length of $\sigma_z = 200\ \mu$m after the compression.

THz WIGGLER FOR BUNCH SHAPE MEASUREMENTS

The design of the THz wiggler [10, 11] (Fig. 4 and the table) is based on the FLASH undulator constructed at JINR [1–5].

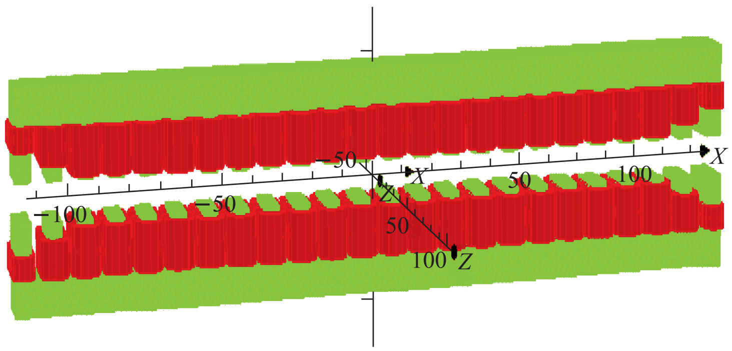

Fig. 4. TOSCA 3D simulation of the THz wiggler

Technical characteristics of the wiggler

Parameter of THz wiggler	Value
Period length, mm	300
Number of full periods	7
Number of poles including end-pieces	$14 + 4$
Maximum wiggler parameter $K_{\rm rms}$	7.12
Peak field on axis, T	0.356
Minimum field on axis, T	0.025
Electron momentum, MeV/c	19.8
Maximum wavelength, mm	5.1
Minimum wavelength, mm	0.12
Clear gap, mm	100
Position accuracy of magnetic axis, mm	0.5
Angular precision of magnetic axis, mrad	0.5
Field flatness at ± 20 mm off-axis (horizontally), %	–0.1–+0.5
First field integral $I1$, $\mathrm{G \cdot cm}$	50
Second field integral $I2$, $\mathrm{G \cdot cm^2}$	500
Stability and reproducibility of magnetic axis, mm/μrad	$\pm 0.1/\pm 50$

It follows from the 3D TOSCA simulations of the magnetic field (Fig. 5) that its transverse component is smaller than –0.1% at the aperture of 20 mm (Fig. 6).

The first wiggler peculiarity is related to a large clear gap between its main coils. The diffraction spot size of the radiation determines the diameter of the vacuum chamber and the wiggler gap. The diffraction angle and the spot radius of wiggler radiation are $\theta_d \cong (\lambda/2L)^{0.5}$ and $r_d \cong (\lambda L/2)^{0.5}/\pi$, respectively, where $L = 2.1$ m is the wiggler length and λ is the wavelength. The diffraction parameters θ_d/r_d are 29 mrad/2.1 cm at the wavelength of 3.9 mm.

The angle spread of the photon radiation $r = L\theta/6$ gives the same input in transverse size at the wiggler exit, where $\theta = K_{\rm rms}/\gamma N_w^{1/2}$, γ is the relativistic factor, and N_w is the number of the wiggler periods. This size is 1.2 cm at the maximum field.

The second peculiarity of the wiggler is related to the trim coils. Four trim coils with individual power supplies should be installed in the wiggler. These trim coils permit the first and the second integrals to be compensated over the full wiggler length. However, it does not permit compensation of the integral over the period length. The first integral over the

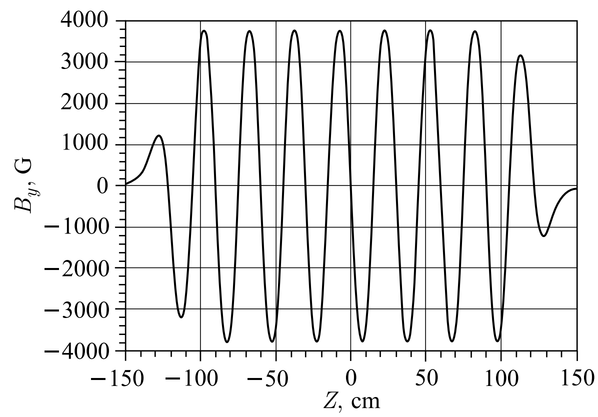

Fig. 5. Dependence of the wiggler magnetic field on longitudinal coordinate

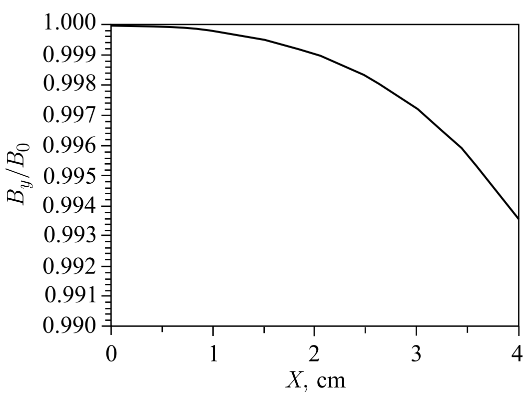

Fig. 6. Dependence of the normalized wiggler magnetic field at $I_w = 21.5$ kA · turns on the transverse coordinate

period length should be smaller than 50 $G \cdot cm$, and the second integral should be as low as 500 $G \cdot cm^2$. To meet both the requirements, it is proposed to install an additional correction coil in each regular coil.

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