PROPOSALS FOR EXPERIMENTAL STUDY OF WAKEFIELD UNDULATOR RADIATION

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The possibility of detection of a wake-field undulator radiation generated by short bunches of relativistic charged particles, moving through a periodic rf structure, is estimated.

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1. INTRODUCTION

Recent research [1-5] into a novel wake-field undulator (WFU) radiation mechanism has specified new potential opportunities for generating an ultra-short wavelength light. The mechanism consists in photon emission by a short bunch of relativistic charged particles undulating at nonsynchronous harmonics of a wake-field (WF) induced by the bunch moving through a periodic corrugated waveguide without external fields. The basic theoretical results of studies into the WFU radiation include the following.

- In a relatively long-wave spectral region of the periodic structure (where diffraction of generated waves is essential) the radiation manifests itself in a coherent interference of the WF and WFU radiation. The pure WFU radiation takes place only within the relatively ultra-short wave range, where the wave diffraction of the WFU radiation can be neglected [1, 2].
- The power of the coherent WFU radiation emitted by the bunch of N particles is proportional to N^4 [1].
- The power of the incoherent WFU radiation is proportional to N^3 [2].
- Since the WFU radiation power is proportional to the electron energy squared, it can become comparable with the WF power or even exceed it [2, 3].
- The creation of the WF undulator with sub-millimeter periods may open up the possibilities of generation the hard X-rays employing the relatively low electron energies without external alternative fields [4, 5].

On ground of above-mentioned we can conclude that experimental studies into the WFU radiation predicted are of great benefit. The goal of the present paper is to estimate the possibilities of carrying out proof-of-principle experiments on observing the WFU radiation.

2. WFU RADIATION CHARACTERISTICS

The WFU radiation has a line spectrum with resonant wavelengths

$$\lambda^{(p)} \approx D/\left(2\gamma^2 p\right), \qquad (1)$$

where p =1, 2,... is a non-synchronous spatial harmonic's number, D is the rf structure period, γ is the Lorentz factor (γ>>1).

Let $F^{(p)}$ be a spectral flux (photons/s) into a small bandwidth $\Delta\omega$ of the *p-th* harmonics. Then, by analogy with Ref. [6,7], the spectral-angular flux density emitted non-coherently by the bunch in a forward direction is given by

$$\frac{dF^{(p)}}{d\Omega} = \alpha N_u^2 N f_{aver} \left\langle \gamma^2 \left|K^{(p)}\right|^2 \frac{\Delta\omega}{\omega^{(p)}} \right\rangle, \qquad (2)$$

where Ω is the solid angle, α is the fine-structure constant, N_u is the number of the rf structure periods, $K^{(p)}$ is the WF undulator parameter [4,5,8], f_{aver} is the average bunch repetition frequency, $\langle\ldots\rangle$ denotes an averaging.

The formula for the full flux of the *p-th* harmonics in a central cone $\Delta\Omega = 2\pi\sigma^2_{r\breve{y}}$ (with an angular rms width $\sigma_{r\breve{y}} = 1/\left(\gamma\sqrt{N_u}\right)$) into a FWHM bandwidth $\Delta\omega/\omega^{(p)} \cong 1/N_u$ [7] is very useful for experimental estimations and given by

$$F^{(p)}_{full} = \frac{\pi}{2}\alpha N f_{aver} \left\langle \left|K^{(p)}\right|^2 \right\rangle. \qquad (3)$$

2.1. WFU RADIATION FROM AN S-BAND WAVEGUIDE

Let us consider the possibilities of detection the WFU radiation from the WF undulator being an axisymmetric disk loaded waveguide (DLW) schematically depicted in Fig.1.

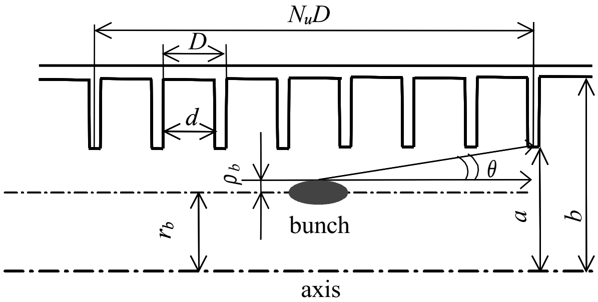

Fig.1. DLW as WF undulator

In this figure: a is the aperture radius, D-d is the disk thickness, b is the cell radius, r_b is the bunch distance from the DLW axis, ρ_b is the bunch radius, θ is the maximum possible angular spread of the bunch.

At first we will perform an under-estimation of the full fluxes of the WFU radiation out of both a conventional SLAC-type rf section [9] and a STRUM90 section designed and fabricated at the NSC KIPT (Ukraine) [10]. The dimensions of these sections are shown in Table 1.

Table 1. *The DLW parameters*

DLW	*D*	*d*	*a*	*b*	*Nu*
STRUM90	7.1	6.7	1.5	4.1	24
SLAC-type	36	3	1.3…0.1	4.2…4.1	85

Note: the dimensions are given in cm

Let us look at the wavelengths of the WFU radiation, obtained at the above-mentioned rf structures, as a function of the electron energy (the dependence is presented in Fig.2). It shows that for the S-band rf structures the electron bunches with the energies not less than 100 MeV are required for generating the well-detectable WFU radiation (below infrared light).

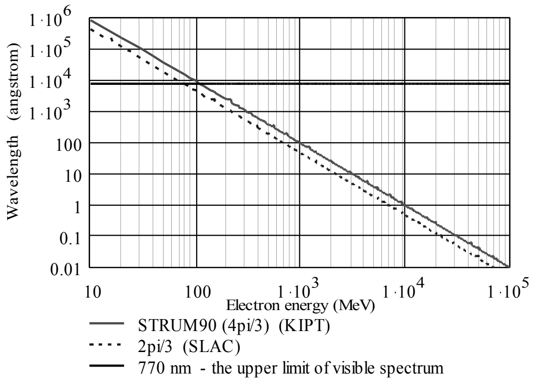

Fig.2. The wavelength of WF undulator radiation versus electron energy

In order to estimate the magnitudes of the photon fluxes emitted by the bunch in the DLW, we have used analytical relations for the WFU parameter derived in Ref.[8] for the wake-fields excited in the lowest passband (TM_{01}-type mode). The full fluxes in the central cone into the FWHM bandwidth as functions of the bunch charge are shown in Fig.3. Here we consider the ultra-relativistic single bunches with a 6D phase volume typical for the SLAC beams that follow through the given rf sections at a distance equal $r_b=0.75a$ from the axis (see Fig.4) with a repetition rate 120 Hz. It is easy to notice that the full flux under-estimated, $10^4…10^5$ ph/sec, can be achieved at the bunch charge about 10 nC.

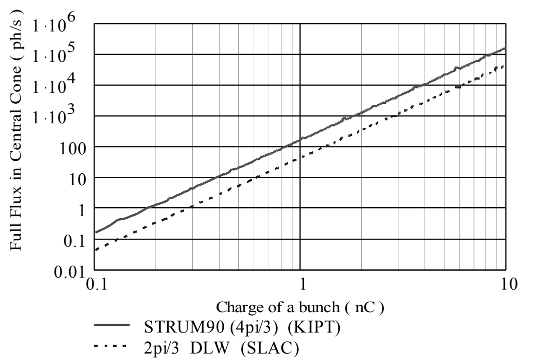

Fig.3. The full flux of the WFU radiation in the central cone into the FWHM bandwidth versus bunch charge

Let us consider the upper estimation of a beam transverse phase dimension required for the experiments. Let us assume that there are none of additional focusing elements along the rf structure, and there is a bunch crossover at the structure half-length. Then, supposing $\rho_b=2\sigma_r$ and $\theta=2\sigma_\theta$ (where σ_r and σ_θ are the rms radius and angular spread of the bunch, respectively), see Fig.1, the maximum normalized rms emittance can be estimated as

$$\varepsilon_n = \gamma\sigma_r\sigma_\theta = \gamma\sigma_r 2\frac{a - r_b - 2\sigma_r}{N_u D}, \qquad (4)$$

with the maximum magnitude

$$\varepsilon_{n,\max} = \gamma\frac{(a - r_b)^2}{4N_u D}, \text{ at } \sigma_r = \frac{a - r_b}{4}. \qquad (5)$$

So, for the STRUM90 section Eq.(5) results in $\varepsilon_{n,\max}$ ≈400 mm·mrad at σ_r ≈1 mm, whereas for the SLAC section we have $\varepsilon_{n,\max}$≈150 mm·mrad at σ_r≈0.7 mm. In the given section the bunch is moving at r_b= 0.75*a*.

2.2 WFU RADIATION FROM SUB-MM PERIODIC WAVEGUIDE

Further, we will analyze conditions, under which the WFU radiation emitted by the ultra short bunches obtained at the so-called table-top accelerators, could be detected. As an example we consider a photo-injector developed at Eindhoven Technical University [11]. The parameters of the photo-injector are given in Table 2.

Table 2. *The parameters of TU/E photo-injector*

Energy	10 MeV
Emittance	1 mm mrad
Length	100 fs
Charge	0.1 nC

As follows from Eq.(1), the rf structure periods required for photon generation, by 10 MeV electron bunches, in the visible spectrum that can be detected easily by multiplier phototubes, lie within 0.3…0.6 mm.

To obtain the under-estimated value for the photon flux generated at the rf structures with sub-millimeter periods, we have carried out optimization of the rf structure geometry. The mean-square of the WFU parameter modulus [8] was used as an efficiency function. First, we have found an optimal set for the dimensions of the S-band DLW by varying the appropriate sizes. Then, using a scaling approach we have determined the optimal dimensions for the rf structure with the sub-millimeter period required. The optimal DLW dimensions are presented in Table 3.

Table 3. *The optimal dimensions for the DLW*

n	mode	*D'*	*d'*	*a'*	*b'*
1	4π/3	71.45	39.46	20	41.2
150	4π/3	0.476	0.263	0.133	0.275
200	4π/3	0.357	0.197	0.100	0.206

Note: n=D/D'=d/d'=a/a'=b/b' is the reduction ratio, all the dimensions are given in mm

Further, let us compare the photon flux emitted by a single bunch at two optimal rf structures having different reduction ratio *n*=150 and 200, respectively. We suppose that in the each section the bunch moves at $r'_b=r_b/n=0.75a'$. The dependences of photon numbers in the central cone into the FWHM bandwidth per bunch transit through the section (see Eq.(3)) on the bunch charge are presented in Fig.4.

Fig.4 shows that the single 0.1 nC bunch can emit not less than 44…80 *photons* per one transit through the sub-mm structures with n=150 and 200; each structure consists only of 10 periods. Substituting the data from Table 3 into Eq.(5), we can obtain the upper-estimations for the normalized emittance $\varepsilon'_{n,\max}\approx1.2\ldots0.9$ mm·mrad at $\sigma'_r\approx8\ldots6$ μm corresponding to the structure with n=150 and 200, respectively. As follows from Eq.(5), to rise significantly the normalized emittance and bunch radius it is necessary to increase the transverse dimension of the waveguide in several times. Besides, considerable increase in the WFU radiation flux may be provided by both solving the repetition rate step-up problem and raising the bunch charge in several times.

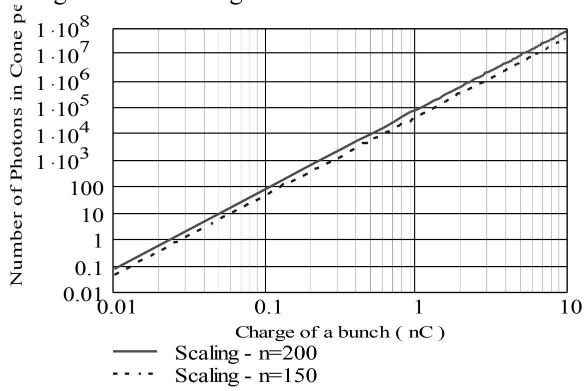

Fig.4. The photon number of the WFU radiation in the central cone into the FWHM bandwidth emitted by a single bunch versus the bunch charge

3. CONCLUSION

Because well-detectable wavelengths are located below infrared light, the electron energies not less than 100 MeV are required for observation of the WFU radiation from the S-band accelerator structures. The underestimation of the full flux, $10^4\ldots10^5$ ph/sec, emitted by the single bunches at a repetition rate 120 Hz from the S-band accelerator structures can be achieved at the bunch charge about 10 nC.

For observation of the WFU radiation emitted by the ultra-short electron bunches from the *TU/E* photo-injector it is necessary to solve the problems of increase in the repetition rate and/or the bunch charge.

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ПРЕДЛОЖЕНИЯ ПО ЭКСПЕРИМЕНТАЛЬНОМУ ИССЛЕДОВАНИЮ КИЛЬВАТЕРНО-ПОЛЕВОГО ОНДУЛЯТОРНОГО ИЗЛУЧЕНИЯ

А.Н.Опанасенко

Проведена оценка возможности регистрации кильватерно-полевого ондуляторного излучения, генерируемого короткими сгустками релятивистских заряженных частиц, движущихся в периодической резонансной структуре.

ПРОПОЗИЦІЇ, ЩО ДО ЕКСПЕРИМЕНТАЛЬНОГО ДОСЛІДЖЕННЯ КІЛЬВАТЕРНО-ПОЛЬОВОГО ОНДУЛЯТОРНОГО ВИПРОМІНЮВАННЯ

А.М.Опанасенко

Проведено оцінку можливості реєстрації кільватерно-польового ондуляторного випромінювання, що генерується короткими згустками релятивістських заряджених частинок, що рухаються в періодичній резонансній структурі.