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THE FIRST EXPERIMENTS WITH AN OPTICAL KLYSTRON INSTALLED ON THE VEPP-3 STORAGE RING

A.S. ARTAMONOV, N.A. VINOKUROV, P.D. VOBLYI, E.S. GLUSKIN, G.A. KORNYUKHIN, V.A. KOCHUBEI, G.N. KULIPANOV, V.N. LITVINENKO, N.A. MEZENTSEV and A.N. SKRINSKY
Institute of Nuclear Physics, 630090, Novosibirsk, USSR

A layout of the magnetic system of an optical klystron (OK) installed on the storage ring VEPP-3 (Novosibirsk) is considered in the present work. The results of the experimental study of the OK spontaneous radiation spectrum are given. It is shown that the obtained results confirm the theoretical arguments.

1. Introduction

A modification of the free electron laser – the optical klystron (OK) – has been proposed in ref. [1] (see also ref. [2]). Its main difference from the conventional free electron laser is a considerably higher gain. This gain enables the OK to be installed on an electron storage ring (see refs. [3,4]). The present paper deals with a scheme for the installation of the OK on the VEPP-3 storage ring (Novosibirsk) and also with the construction of the OK magnetic system. The first results of a study of the OK spontaneous radiation spectrum are given as well.

2. Operation principles of the OK

The layout of the OK is schematically illustrated in fig. 1. As ultra-relativistic electrons with energy $E = \gamma mc^2$ move in the first plane magnetic snake (1) with period d under the action of a linearly polarized electromagnetic wave with length

$$\lambda = d\left(\frac{1}{2\gamma^2} + \frac{\alpha_0^2}{4}\right),$$

(where α_0 is the amplitude of oscillations of the angle

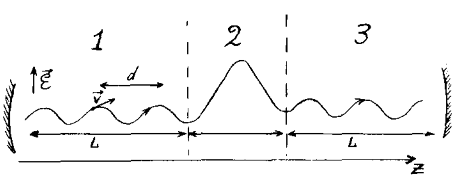

Fig. 1. Layout of the optical klystron.

between the velocity of an electron and its average velocity $\bar{V}_z$ directed along the z-axis) propagating parallel to the motion of the electrons, i.e. along the z-axis, the following energy modulation occurs:

$$E \to E + \tfrac{1}{2}e\epsilon L\alpha_0 \cos(Kz - K\bar{V}_z t + \varphi)\,,$$

where ϵ is the wavefield amplitude, and $K = 2\pi/\lambda$. After passage through the bunching magnets (2) with a path dependent on the energy described by the coefficient $\mathrm{d}z/\mathrm{d}E$, the energy modulation becomes the modulation of the longitudinal electron density, the amplitude of whose first (complex) harmonic is given by the expression

$$\rho_1/\rho_0 = \tfrac{1}{4}K\frac{\mathrm{d}z}{\mathrm{d}E}e\epsilon L\alpha_0 \exp\left[-\tfrac{1}{2}\left(K\frac{\mathrm{d}z}{\mathrm{d}E}\sigma_E\right)^2\right]$$

(where σ_E is the initial energy dispersion of the electrons). Electrons so bunched, on traversing the second snake (3) under the action of the same wave undergo a change in average energy of

$$\langle\Delta E\rangle = \tfrac{1}{8}(e\epsilon L\alpha_0)^2 K\frac{\mathrm{d}z}{\mathrm{d}E}\exp\left[-\tfrac{1}{2}\left(K\frac{\mathrm{d}z}{\mathrm{d}E}\sigma_E\right)^2\right]\cos\varphi_0\,, \tag{1}$$

where φ_0 is determined by the "path difference" of the wave and the electrons in the bunching section [see eq. (2)] and is controlled by a slight variation of the field in the bunching magnets. Thus electrons at $\cos\varphi_0 > 0$ give up part of their energy to the wave and amplify it. If two mirrors are placed in the path of the wave, i.e. if they are placed in the optical resonator, then feedback appears and electromagnetic radiation is generated. The condition for generation has the form $(1 + G)K_1K_2 > 1$, where K_1 and K_2 are the reflection coefficients of the mirrors and

$$G = \pi \frac{eJ}{Sc} (L\alpha_0)^2 K \frac{\mathrm{d}z}{\mathrm{d}E} \times \exp\left[-\tfrac{1}{2}\left(K \frac{\mathrm{d}z}{\mathrm{d}E} \sigma_E\right)^2\right] \cos\varphi_0 , \qquad (2)$$

is the gain per pass (J is the electron current and S is the effective cross-sectional area, which coincides with the cross-sectional area of the light beam if the transverse dimension of the latter exceeds the transverse dimension of the electron beam). Setting in eq. (2) that

$$\cos\varphi_0 = 1 , \quad S = \lambda L/2 , \quad K \frac{\mathrm{d}z}{\mathrm{d}E} \sigma_E = 1 , \quad \alpha_0\gamma \gg 1 ,$$

we find the highest gain:

$$G_{\max} \approx 7.4\, q \frac{mc^2}{\sigma} \frac{J}{J_0} , \qquad (3)$$

where q is the number of periods in each snake, and $J_0 = mc^3/e \approx 17$ kA. The gain, eq. (3), is approximately $E/q\sigma_E$ times higher than the gain of a conventional free electron laser of the same length, i.e. this ratio can significantly exceed unity (10^2–10^3).

3. The spontaneous radiation spectrum

As known, spontaneous radiation is related to the induced one (amplification) by the Einstein relations. For this reason, the gain G can be expressed through the spectral intensity of the spontaneous radiation [5] (see also [6], where this expression was derived without quantum representations). For the OK installed on an electron storage ring (see below), the gain can be written in the form:

$$G = -\frac{N\sigma}{S} \frac{\Pi}{l} , \qquad (4)$$

where N is the number of particles in the storage ring, Π the perimeter of the storage ring, l the bunch length, S the transverse cross-sectional area of the light beam (at small transverse dimensions of the electron beam) and σ the absorption (or induced radiation) cross section of an electron. As shown in [6], for a wide class of classical radiating systems,

$$\sigma \approx 2\lambda^2 \frac{d}{\mathrm{d}E} \frac{\mathrm{d}I_\omega}{\mathrm{d}\Omega}\bigg|_{\theta=0} , \qquad (5)$$

where $\mathrm{d}I_\omega/\mathrm{d}\Omega\,|_{\theta=0}$ is the spectral intensity of the spontaneous radiation in the direction of the incident absorbed (amplified) wave.

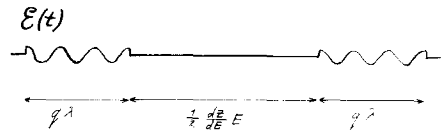

Fig. 2. Time dependence of the radiation field of an electron.

Let us derive now an expression for the OK spontaneous radiation spectrum for zero angle. The time dependence of the radiation field of an electron is shown in fig. 2. The time interval between the radiation pulses from the snakes equals the delay of an electron with respect to the pulse emitted by it in the first snake after its passage through the bunching section. We can readily show that this delay is given by the formula

$$\Delta t = \frac{E}{2c} \frac{\mathrm{d}z}{\mathrm{d}E} . \qquad (6)$$

The radiation spectrum is a result of the interference of radiation from the first and second snakes and, hence, is given by the expression

$$I(K) = 4I_1(K) \cos^2(cK\Delta t/2) , \qquad (7)$$

where $K = \omega/c = 2\pi/\lambda$ is the wave vector, $I_1(K)$ is the radiation spectrum of each snake (see, e.g. [9]).

Allowing for the fact that the length of the bunching section and the field in it are such that $c\,\Delta t K \gg 1$, we see that the spectrum, eq. (7), has a fine structure with period $\Delta K = 2\pi/c\,\Delta t$ (fig. 3). Then the dependence of $I(K)$ on the energy E at small variations in E is also periodic with period

$$\Delta E = \lambda(\mathrm{d}z/\mathrm{d}E)^{-1} . \qquad (8)$$

Due to the fine structure of the OK spectrum, the intensity derivative in energy in some of its points is quite large (essentially larger than that for the free electron laser of the same length). With the wavelengths corresponding to the highest amplification,

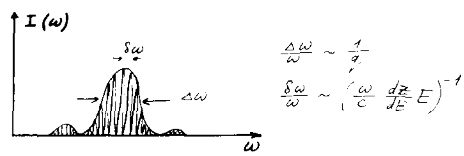

Fig. 3. The radiation spectrum as a result of the interference of radiation from the first and second snakes.

the gain can be written in the form:

$$G = \frac{8\pi\lambda}{S} \frac{dz}{dE} N \frac{dI_{1\omega}}{d\Omega} \frac{\Pi}{l} . \quad (9)$$

4. The influence of angular and energy spread in an electron beam

As has already been noted in the introduction, the energy spread in the beam limits the increase of dz/dE:

$$K\, dz/dE \lesssim 1/\sigma_E . \quad (10)$$

As seen from eq. (8), the violation of this condition leads to the vanishing fine structure of the spontaneous radiation spectrum.

If angular spread occurs in the electron beam, i.e. $\theta_x, \theta_y \neq 0$, then the spread over longitudinal velocities $\overline{V}_z$ also appears. In order that the above considerations be valid, the spread over longitudinal coordinate z after traversing a path of length L, should not exceed the wavelength $\bar{\lambda}$, i.e.

$$L(\Delta\theta)^2/2 \lesssim \lambda/2\pi . \quad (11)$$

There is no difficulty in showing that the non-fulfilment of this condition also leads to disappearance of the fine structure of the spontaneous radiation spectrum. If $\Delta\theta$ refers to the angle between the electron trajectory in the first snake and the trajectory in the second one, the appearance of which is due to the imperfect compensation of the magnetic field integral in the bunching section, then eq. (11) holds.

5. The magnetic system

The OK magnetic system consists of two plane magnetic snakes with the bunching section between. The latter has a similar period to that of the snake period with a larger period length and higher magnetic field in comparison with those in the main snakes. The measured dependence of the vertical magnetic field H_y in the OK versus the longitudinal coordinate is illustrated in fig. 4. The OK magnetic system is based on SmCo permanent magnets with magnetic energy $(BH)_{max} = 16 \times 10^6$ G Oe and saturation induction $B_s = 4\pi M_s = 8.3$ kG. In order to obtain a sufficiently homogeneous field, iron plates were used. An appropriate choice of the thickness of these plates makes it possible to correct the field value in the gap.

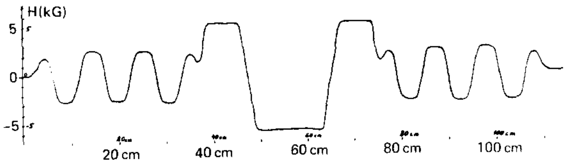

Fig. 4. The measured dependence of the vertical magnetic field H_y in the OK versus the longitudinal coordinate.

The OK magnetic system is controlled by a mechanism for varying the gap between the upper and lower parts of the magnetic system from 10 mm up to 800 mm (figs. 5–8). Each snake contains three periods of length $d = 10$ cm. The magnetic field value in the snakes ($H_{max} \approx 3$ kG) is chosen so that the wavelength of the first harmonic of radiation at zero angle (forward) corresponds to red light ($\lambda \approx 0.6$ μm) at an electron energy of 350 MeV. The longitudinal dispersion of the bunching section is given by the formula:

$$\frac{dz}{dE} = \frac{1}{48} e^2 H_0^2 \left(\frac{L_g}{E}\right)^3 , \quad (12)$$

where $L_g \approx 34$ cm is the length of the bunching section and $H_0 \approx 5.7$ kG the field in it. Then $\Delta E/E \approx 3 \times 10^{-3}$ [see formula (8)]. As both snakes and the bunching section are compensated

$$\int H_y(z)\, dz = 0 ,$$

the OK magnetic system thus does not distort the electron orbit in the storage ring, and the electrons travel along the same straight line in both snakes.

6. Installation of the OK on the VEPP-3 storage ring

Installation of the optical klystron in the VEPP-3 straight section is schematically demonstrated in

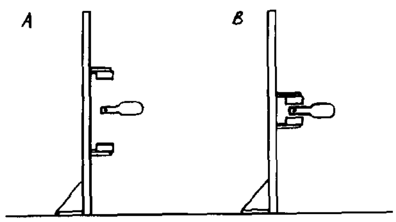

Fig. 5. Mechanism for varying the gap between the upper and lower parts of the magnetic system from 10 mm up to 800 mm.

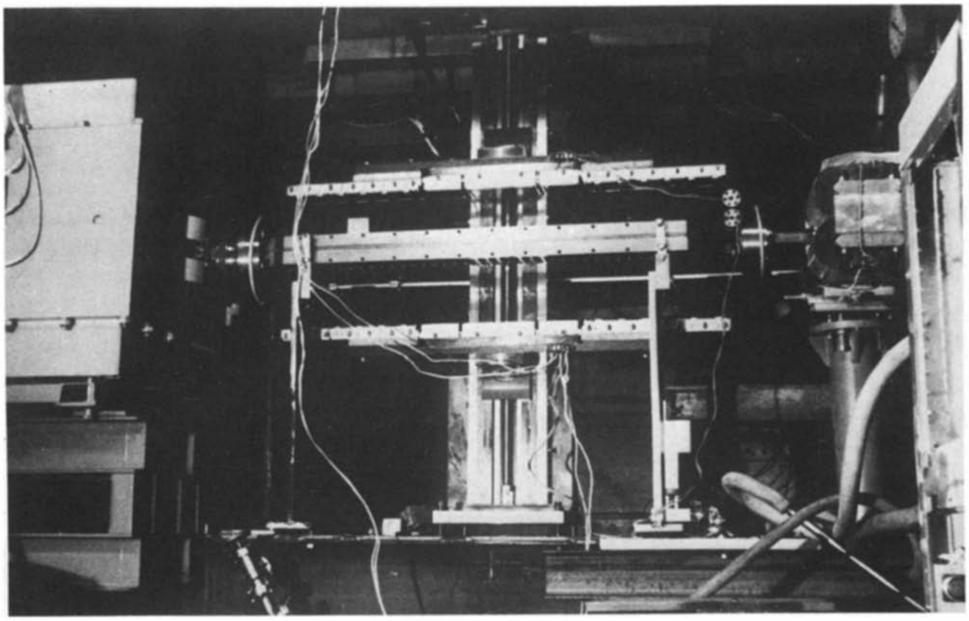

Fig. 6. Magnetic system with the gap in the wide position.

fig. 9. The VEPP-3 electron energy was 350 MeV. The transverse dimensions of the electron beam at the place where the OK was mounted, are $\sigma_x \approx 0.2$ mm and $\sigma_y \approx 0.1$ mm, and the angular spreads $\overline{\theta_x^2}^{\,1/2} \approx 5 \times 10^{-5}$ and $\overline{\theta_y^2}^{\,1/2} \approx 4 \times 10^{-5}$. From our measurements [7], $\sigma_E/E \approx 1.5 \times 10^{-4}$. From a comparison of this value with

$$\left(KE \frac{\mathrm{d}z}{\mathrm{d}E}\right)^{-1} \approx 5 \times 10^{-4}$$

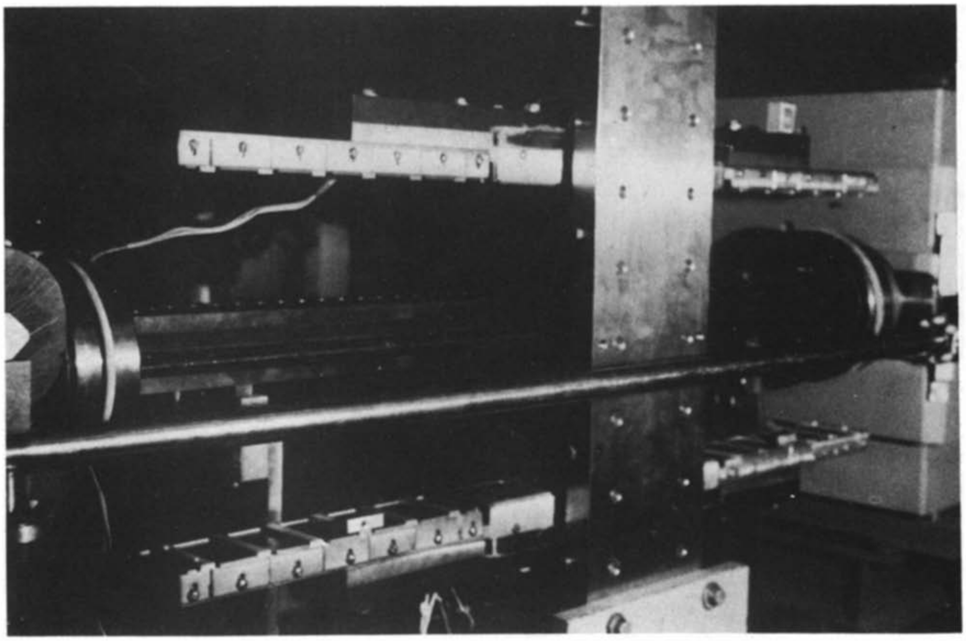

Fig. 7. Magnetic system with the gap in the wide position.

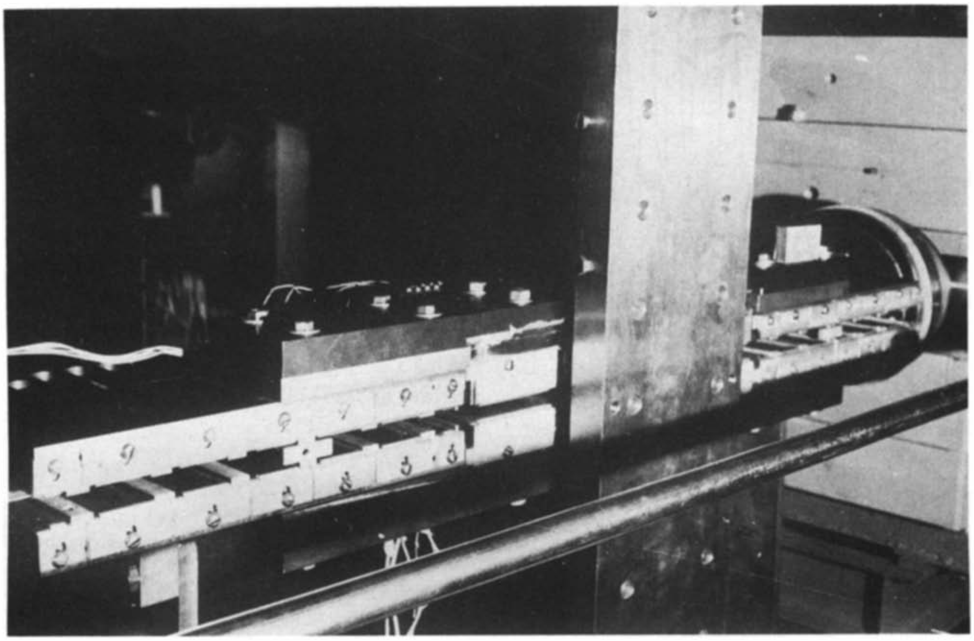

Fig. 8. Magnetic system with the gap in the narrow position.

we can readily see that we could increase the longitudinal dispersion dz/dE by a factor of 2.9; it follows from eq. (2) that G would become a factor of 2 higher. The underestimated value of dz/dE enables the energy spread in all our considerations to be neglected. Moreover, since in the generation regime the OK power will be limited by the growth of the energy spread, such an underestimated dz/dE will allow the attainment of higher power [3].

The mirrors which form the optical resonator are shown in fig. 9. These mirrors will be used for obtaining the generation. The distance between them (9.3 m) equals one eighth of the perimeter of the storage ring. In this case, the gain G depends on the peak value of the electron current. The mirrors are located in the storage ring vacuum chamber and have radii $R_1 \approx 5.9$ m and $R_2 \approx 3.4$ m and reflection coefficients $K_1 \approx K_2 \approx 0.998$ [8].

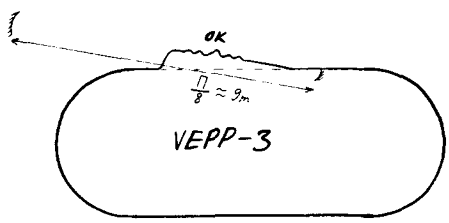

Fig. 9. Installation of the optical klystron in the VEPP-3 straight section.

7. The results of the experimental study of the spontaneous radiation spectrum

The radiation spectrum at zero angle was observed and photographed with a prism spectrograph. For more accurate quantitative measurements we used a spectrometer with a focusing diffraction grating. The pictures of the spectrum are shown in fig. 10. In

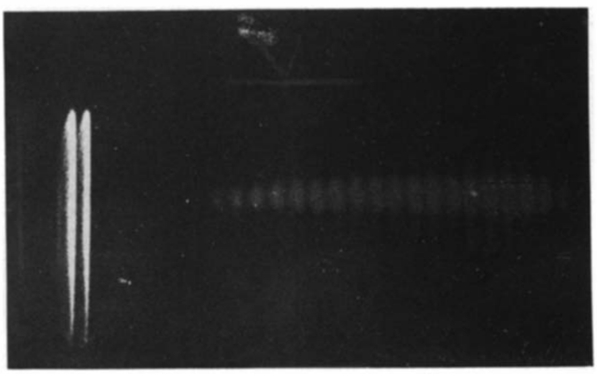

Fig. 10. The radiation spectrum at zero angle.

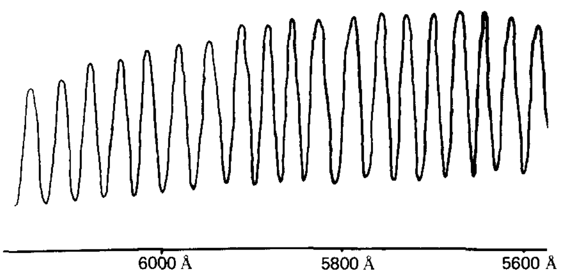

Fig. 11. A small part of the spectrum which is displayed with the spectrometer.

order to graduate the spectrograph and also to illustrate its resolution with the input diaphragm through the semi-transparent glass, the light from a mercury lamp was used. Its yellow lines (5769.60 Å and 5790.66 Å) are seen on the left of the OK spectrum. A small part of the spectrum which is displayed with the spectrometer is shown in fig. 11. At a wavelength of 6000 Å the fine structure period is $\Delta\lambda \approx 34$ Å, which corresponds to the electron delay in the bunching section $c\,\Delta t = \lambda^2/\Delta\lambda \approx 0.1$ mm. The spectrum is shifted with variation in electron energy. The energy variation corresponding to the shift of the spectrum during one period $\Delta E/E$ was approximately 3.3×10^{-3}. On the other hand, as follows from eqs. (7) and (8), $\Delta E/E = \Delta\lambda/2\lambda \approx 2.8 \times 10^{-3}$, which coincides with the measured value fairly accurately. Thus our two independent measurements are in good agreement with each other and also with the calculated value 3×10^{-3} (see section 5). Note, that with an increase of the energy spread by an integer factor we observed, as we should expect, the complete disappearance of the fine structure in the spectrum.

8. Conclusion

The results of our experiments have confirmed our theoretical considerations. We can now hope to obtain light generation in the OK.

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