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Lasing in visible and ultraviolet regions in an optical klystron installed on the VEPP-3 storage ring (invited)

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(Presented on 30 August 1988)

Since 1979, experiments on the storage ring VEPP-3 with an optical klystron (OK) have been performed at the INP Academy of Sciences of the USSR. In 1979, 1981, and 1983, three different OK magnetic systems based on SmCo permanent magnets undulators were installed at the VEPP-3 straight section at 6300-A wavelength. The following gains per pass have been obtained: 0.5% in 1980, 1% in 1982, and 2%–2.5% in 1984. In late 1985, we decided to improve the storage ring VEPP-3 and develop a dc bypass, a special straight section dedicated for OK operation. The bypass allowed us to install an OK magnetic system of 7.8 m length and significantly increase the gain per pass in March of 1988. The bypass was installed at the storage ring VEPP-3 on 3 June 1988. We obtained lasing in the red and yellow light spectral range from 5800 to 6900 A with 5%–10% gain per pass. After changing mirrors for new ones with minimum losses at 4150 A, lasing in the violet and near UV spectral range with 3%–6% gain per pass from 4500 to 3750 A was obtained on 8 July. All work is being carried out at an energy of 350 MeV. Threshold currents for lasing are 1–10 mA depending on the optical cavity mirror conditions. The maximum current is 80 mA at present. A set of measurements on studying lasing in various conditions is underway.

Since 1979, experiments with FEL modification—the optical klystron (OK) have been carried out in our Institute.[1–3] The first version of the magnetic system of the optical klystron OK-1 was employed in studying the spontaneous radiation spectrum[2,4] and for OK gain measurements.[2,5] In two subsequent versions, OK-2 (Refs. 2 and 6) and OK-3 (Refs. 7 and 8), use was made of hybrid (i.e., with steel pole concentrators) undulators based on samarium-cobalt permanent magnets which made it possible to obtain more than 2% gain per pass at a wavelength of 0.63 μm.

In late 1985 a decision was made to update the VEPP-3 storage ring. One of the most important tasks of this modernization was to install an additional straight section (bypass) dedicated to OK operation. In March 1988 the bypass was successfully installed on VEPP-3; in April a circulating electron beam was captured and spontaneous radiation from OK was obtained. In May the mirrors of the optical cavity were set up and on 3 June lasing was attained and a wavelength tunability from 0.58 to 0.69 μm with a linewidth less than 0.6 Å was observed. Lasing was also obtained within the ranges 0.38–0.45 and 0.24–0.27 μm.

The magnetic system OK-4 consists of two electromagnetic undulators with a buncher (3-pole wiggler) between them.

The cross sections of the undulator are schematically shown in Fig. 1 and the parameters are given in Table I.

The field in the undulator is excited by eight periodically bent copper buses with holes for water cooling. The buses are commuted on the ends of the undulator.

Each undulator has 68 poles; those on both ends are wound by one turn and they have half-magnetic potential. The undulators are installed on the bypass one after another and are bilaterally symmetric about the center of the section between them. This automatically provides the absence of distortion of the storage ring equilibrium orbit. Correction coils are put on both end poles and on three pairs of internal

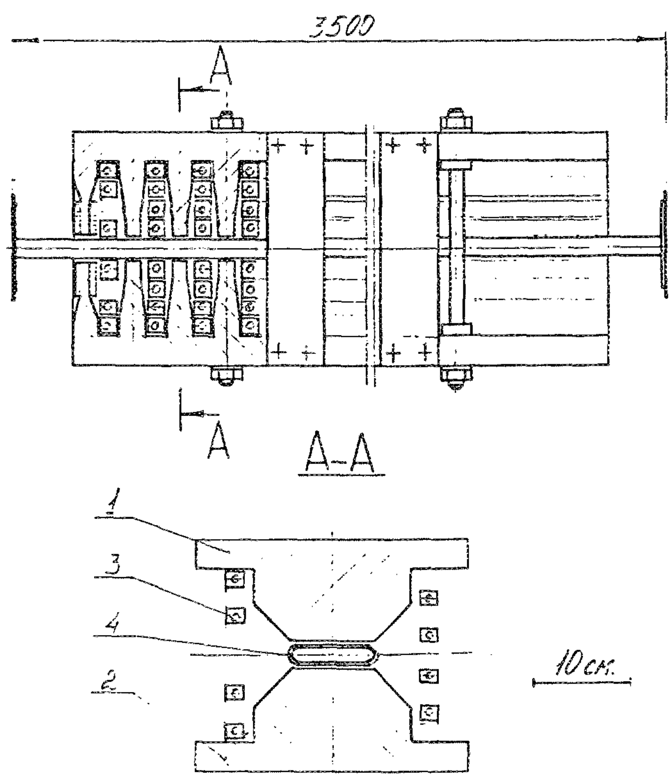

FIG. 1. Cross section of the undulator.

TABLE I. Parameters of present undulators.

Undulator length, m	3.4
Number of periods	33.5
Period, cm	10
Magnetic gap, cm	2.2
Maximum magnetic field along the axis, kGs	5.3
Pole transverse width, cm	9
Number of separate buses	8
Cross section of a bus, mm^2	18×18
Current consumption, kA	2.2
Power consumption, kW	60

poles of each undulator; however, magnetic measurements and operations with electron beams showed that those were not necessary.

The undulators are connected in series and by conventional 2-kA 100-kW power supply. The maximum field obtained in them shown in Table I is limited not by the saturation in the poles but by the current of the power supply.

Making use of the undulators described above the lasing of coherent radiation was obtained at wavelengths from 0.69 to 0.24 μm. To increase the gain per pass in the ultraviolet the undulators are scheduled to be replaced by new ones. Their parameters are given in Table II and their cross sections are shown in Fig. 2. The period was successfully decreased by means of optimally shaped buses milled of a copper sheet and by increased power supply (undulators will be operated off two separate power supplies).

The optical cavity consists of two mirrors with curvature radii of 10 m located at a distance of 18.7 mm from each other. This distance amounts to a quarter of the VEPP-3 storage ring parameter for the laser to operate with mode synchronization (i.e., for the light bunch passing the optical cavity to interact with the electron bunch whenever the latter passes through the OK). The mirrors are equidistant from the center of the OK magnetic system. The optical β function can easily be calculated to be 2.5 m; the fundamental mode radius in the undulator centers equals 0.9 m and on the mirrors it is 2.8 m (for the wavelength 0.63 μm). The mirror reflectivity in the initial stage of operation was better than 99.9%.

Figure 3 shows the measured spectrum of spontaneous radiation (at a zero angle) from one undulator. Figure 4 illustrates the spectrum of the OK spontaneous radiation (i.e., from two undulators with the buncher switched on). The total spectral width can be seen to remain the same. The

TABLE II. Parameters of planned undulators.

Undulator length, m	2.8
Number of periods	39.5
Period, cm	7
Magnetic gap, cm	2
Maximum magnetic field along the axis, kGs	5.5
Pole transverse width, cm	8
Number of separate buses	8
Current consumption, kA	3
Power consumption, kW	90

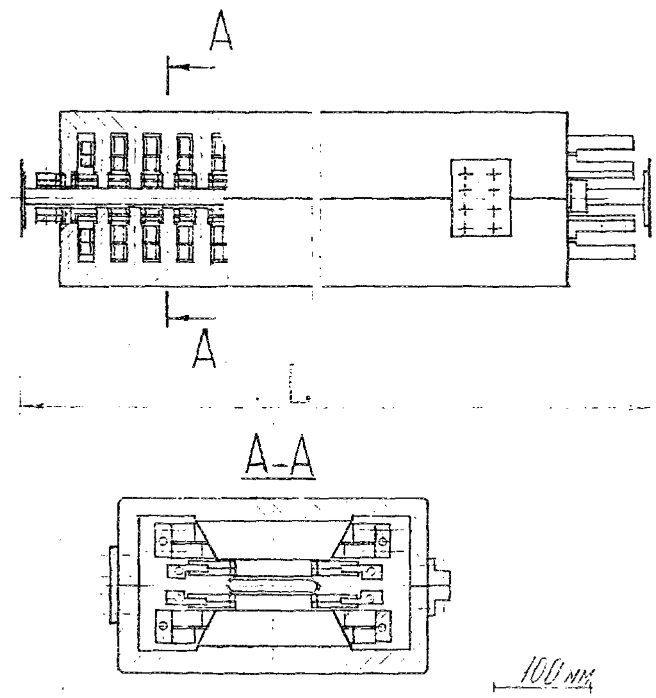

FIG. 2. Cross section of the undulator under construction.

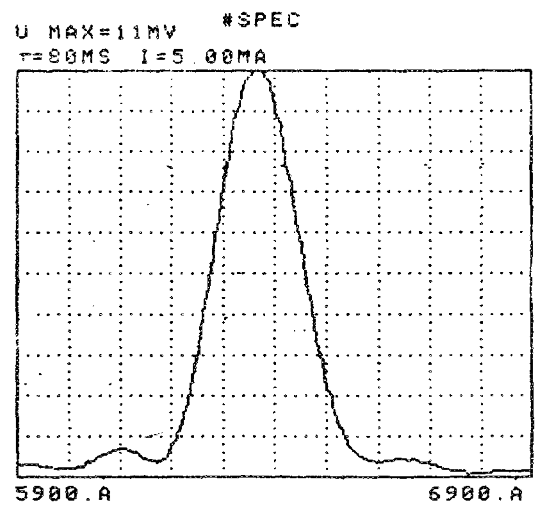

FIG. 3. Spontaneous radiation spectrum from one undulator.

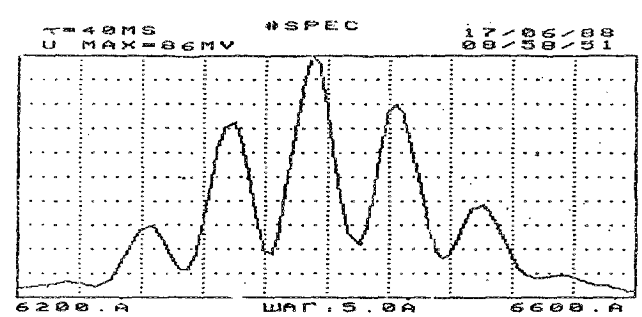

FIG. 4. OK spontaneous radiation spectrum.

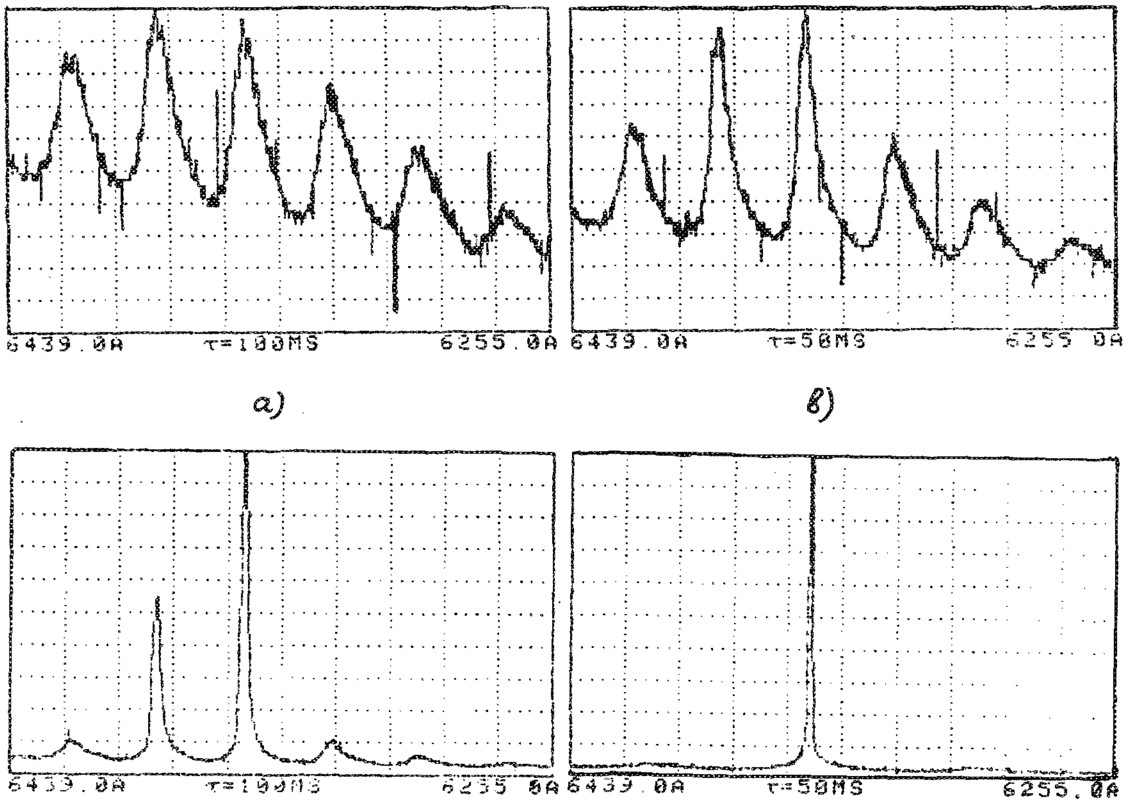

FIG. 5. The change of the radiation spectrum outcoming from the optical cavity as the peak current increases.

"fine structure" of the spontaneous radiation spectrum is the result of interference of radiation from two undulators. The spectra are measured at an electron energy of 350 MeV, the field in undulators being 3.4 kGs.

Figure 5 shows the change of the radiation spectrum outcoming from the optical cavity as the peak current increases (the spectra are normalized to the maximum spectral density). The lasing linewidth above the threshold varied within the range of 2–0.6 Å depending on the detuning of revolution frequency of the electron beam, the beam current length of electron bunches, and other parameters.

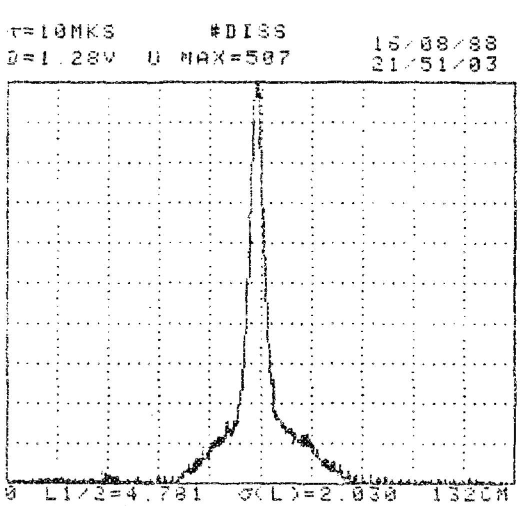

FIG. 6. The time structure of the electron beam (wide peak) and lased beam (narrow peak) on top of the electron beam.

The transverse distribution of radiation intensity corresponded to the basic mode (TEM_{00}) of the optical cavity. When the optical cavity was slightly detuned lasing was observed in TEM_{01} mode.

Continuous tunability of lasing wavelength was attained by field change in the undulators. Its limits (0.58–0.69 μm) corresponded to the reflection band of the mirrors.

Figure 6 shows the time structure of the electron beam (with peak) and lased beam (narrow peak) on top of the electron beam. The measurements were taken by a dissector.[9] The pulse duration of the spontaneous radiation is equal to that of the electron bunch and the duration of the lased beam pulse is considerably shorter. This is quite natural since the gain is proportional to the instantaneous value of electron current and, consequently, is at its maximum in the center of the bunch. Over many passes, the light interacting with the center of the electron bunch is amplified much more than the light interacting with its ends. The bunch repetition frequency is $c/2L$ 8 MHz ($L = 18.7$ m is the length of the optical cavity). The time structure of the lased power averaged over the period $2L/c$ (macrostructure) is shown in Fig. 7. The observed process is similar to relaxation auto-oscillations (light interacting with electron beam increases the energy spread of the latter, which results in a gain drop below the threshold gain and the light intensity decreases; due to radiation damping the energy spread decreases and the gain increases over the threshold gain, and then the radiation power increases again and the cycle is repeated). The maximum measured average energy spread increase was 40% of the initial one (9×10^{-4}).

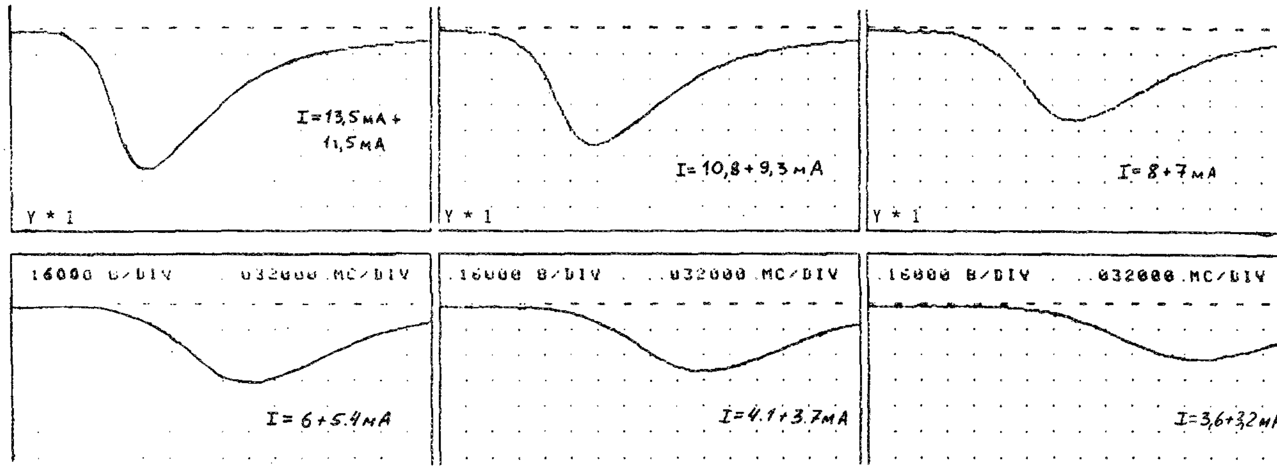

FIG. 7. Time dependence of outcoming radiation power of the OK under different values of electron bunch current.

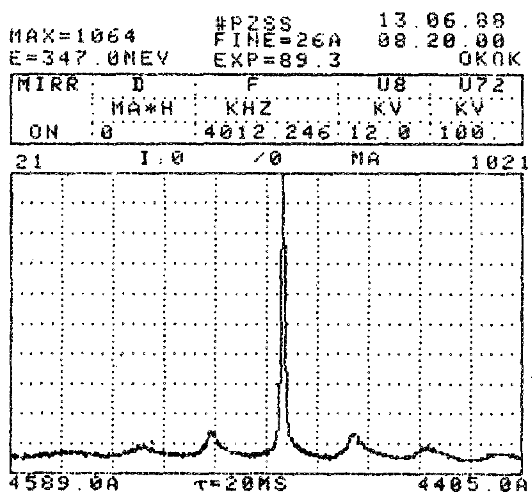

FIG. 8. Lasing in violet.

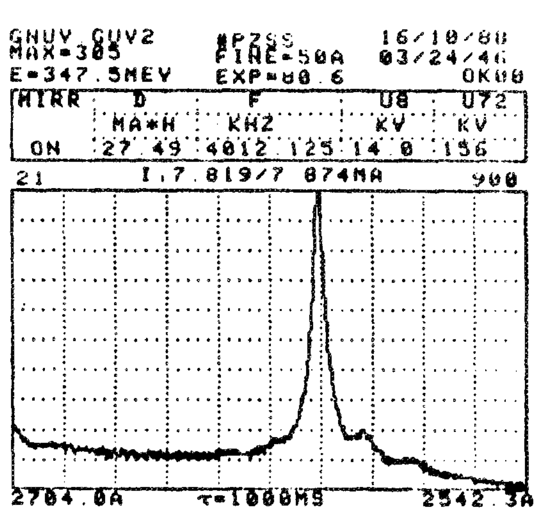

FIG. 9. Lasing in the ultraviolet.

Making use of the outcoming power from the optical cavity the power lased by the electron beam was estimated. With the mean current of the beam 20 mA, it was all of the order of 5 mW, which is in accordance with the observed change of energy spread. More precise measurements of the OK power will be carried out after the replacement of the front mirror (whose transmission is now of the order of 10^{-4}) for the mirror with transmission of the order of 1%.

Three weeks after the operation started, absorption per pass (two reflections) in the optical cavity increased to 0.5% but it did not stop the lasing as the gain per pass is 5%–10%.

After replacement of the mirrors, lasing was obtained in the violet and ultraviolet spectra ranges (0.45–0.30 and 0.27–0.24 μm). One of the measured spectra is shown in Fig. 8. Figure 9 shows one of the lasing lines in UV (0.24–0.27 μm) obtained in October 1988, OK-4 is the first FEL operating in the UV.

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