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LASING IN VISIBLE AND ULTRAVIOLET REGIONS IN AN OPTICAL KLYSTRON INSTALLED ON THE VEPP-3 STORAGE RING

I.B. DROBYAZKO, G.N. KULIPANOV, V.N. LITVINENKO, I.V. PINAYEV, V.M. POPIK, I.G. SILVESTROV, A.N. SKRINSKY, A.S. SOKOLOV and N.A. VINOKUROV

Institute of Nuclear Physics, Siberian Branch of the USSR Academy of Sciences, Novosibirsk, USSR

Lasing in a wide 2400-6900 Å spectral range (from visible to ultraviolet) was reached in the optical klystron OK-4 installed on the VEPP-3 storage ring. OK-4 is the first FEL operating in UV.

1. Introduction

The optical klystron was proposed in 1977 by Vinokurov and Skrinsky [1] as a modification of a free electron laser (FEL). It has a much higher gain per pass than a FEL due to using a special device - a buncher located between two undulators. Experiments with an optical klystron (OK) have been carried out at our institute since 1979 [2].

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 [2,6] and OK-3 [7,8], 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 6300 Å.

In late 1985, it was decided 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 the OK was obtained, in May the mirrors of the optical cavity were set up and on June 3 lasing was attained and wavelength tunability from 5800 to 6900 Å, with a linewidth less than 0.6 Å, was achieved. In July and October 1988 lasing in the violet (3750-4600 Å) and ultraviolet (2400-2700 Å) ranges was also obtained.

2. A bypass on the VEPP-3 storage ring

The scheme of the VEPP-3 storage ring with the bypass is shown in fig. 1. The bypass consists of two bending magnets (with a maximum field of 21 kG), 12 quadrupoles, a vertical wiggler (1.2 m, 18 kG) and a 7.8 m long OK magnetic system. The bypass focusing system is very flexible and it gives us a possibility to optimize the electron beam parameters in the OK and to match β- and η-functions with VEPP-3 arcs under

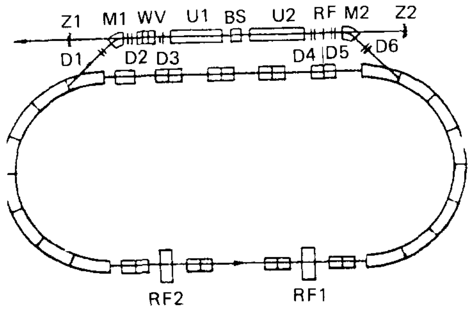

Fig. 1. Layout of the VEPP-3 storage ring with the bypass: M1, M2 - bending magnets; D1-D6 - quadrupole lenses; U1, U2 - undulators; BS - bunching section; WV - vertical wiggler; RF - 1.2 GHz passive RF cavity; RF1 - 8 MHz RF cavity ($q=2$, $U_m=12$ kV); RF2 - 72 MHz RF cavity ($q=18$, $U_m=600$ kV); Z1, Z2 - optical cavity mirrors.

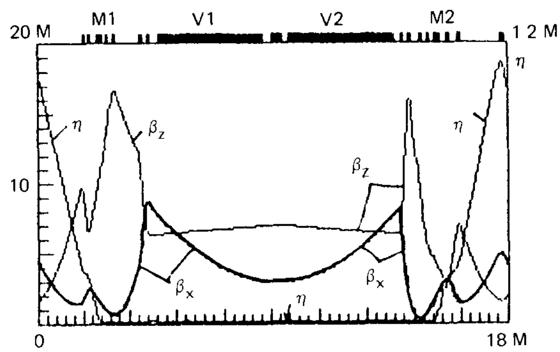

Fig. 2. Optimized β- and η-functions in the bypass for OK operation in UV.

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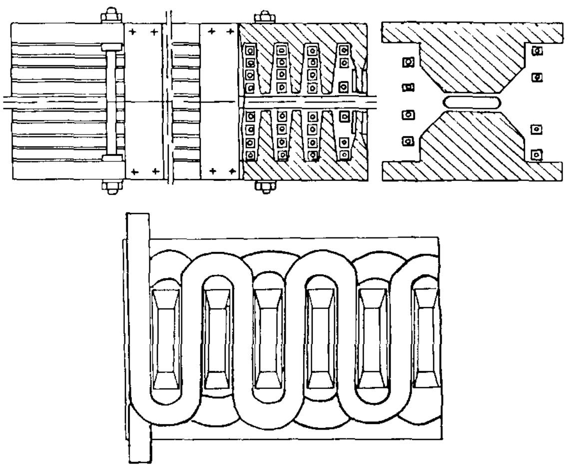

Fig. 3. Cross section of the OK-4 undulator.

different conditions (see fig. 2). The zero value of the η-function in the bypass straight section provides independence of the electron beam position in the OK of the revolution frequency, and significantly simplifies the synchronization procedure of the revolution times of electron and light beams.

3. OK magnetic system

The OK-4 magnetic system comprises two electromagnetic undulators with a buncher (3-pole wiggler) between them. The cross sections of the undulator are schematically shown in fig. 3 and its parameters are given in table 1.

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; the ones on both ends are wound by one turn and they have half the magnetic potential. Undulators are installed on the bypass one after another and are bilaterally symmetric about the centre of the section between them. This automatically provides absence of any equilibrium orbit distortion in the storage ring. Correction coils are put on both end poles and on three pairs of internal poles of each undulator; however, magnetic measurements and operations with electron beam showed that these coils were not necessary.

Undulators are connected in series and are fed by a commercial 2 kA, 100 kW power supply. Their maximum magnetic field is limited by the power supply current rather than by the iron saturation in the poles (see table 1).

Table 1
Parameters of the OK-4 undulator

Undulator length [m]	3.4
Number of periods	33.5
Period [cm]	10
Magnetic gap [cm]	2.2
Maximum magnetic field along the axis [kG]	5.3 (5.7)
Pole transverse width [cm]	9
Number of separate buses	8
Cross section of a bus [mm^2]	18×18
Current consumption [kA]	2.2 (3)
Power consumption [kW]	60

4. Electron beam parameters

The maximum energy of the bypass, limited by the magnetic system (bending magnets and quadrupoles), is 500 MeV. For OK experiments, an injection energy $E = 350$ MeV) of the VEPP-3 storage ring was chosen. For injection, only the cavity RF1 (8 MHz, see fig. 1) is used, and the cavity RF2 (72 MHz) must be switched off and detuned. After injection, in order to increase the peak current (and OK peak gain, which is directly proportional to the peak current), we use the RF2 cavity. In this case, a turbulent bunch lengthening and a strong dependence of the other electron beam parameters on the peak current value are observed. In table 2 the measured electron beam parameters for low (~ 0.1 mA) and average (20 mA) current with RF2 switched on are given. For low current the measured electron beam parameters are in perfect agreement with calculations.

In March 1989 a vertical wiggler was installed on the bypass. It will be used to control the electron beam vertical emittance and to increase the damping rates. The increasing of the vertical emittance to a calculated value of 1.6×10^{-6} cm rad will suppress the Toushek effect and increase the beam lifetime. In this case, a

Table 2
Measured electron beam parameters for low and high average current (energy $E = 350$ MeV)

Parameter	Low current	$I = 20$ mA
Relative energy spread σ_E/E	3×10^{-4}	9×10^{-4}
Emittance [cm rad]		
ϵ_x	1.8×10^{-6}	4×10^{-6}
ϵ_y	1×10^{-6}	1×10^{-6}
Bunch length [cm]	3.3	10
Peak current [A]	–	6
Beam size [mm]		
σ_x	0.35	0.45
σ_y	0.2	0.2
Angular spread [mrad]		
σ_x'	0.11	0.24
σ_y'	0.04	0.04
76 mHz rf voltage [kV]	100	100

significant improvement of the electron beam quality is expected.

5. Optical klystron gain

According to the measured electron beam parameters for an average current of 20 mA, the OK-4 gain per pass was calculated. In fig. 4 calculated and measured values of the gain per pass vs the wavelength are shown. The gain values were measured by comparing with the optical cavity losses on the edges of the reflection bands, where lasing was stopped: 10% at 6000 Å, 5.5% at 4000 Å and 2.5% per pass at 2500 Å. Because of the bunch lengthening and respective energy spread growth, beginning from 3–4 A peak current, the maximum peak gain did practically not increase with increasing average current.

6. Optical cavity

The optical cavity consists of two mirrors with curvature radii of 10 m, located at a distance of 18.7 m from each other. This distance amounts to a quarter of the VEPP-3 storage ring circumference for the OK to operate in synchronization mode (i.e. for a light bunch passing the optical cavity to interact with an electron bunch whenever the latter passes through the OK). The mirrors are equidistant from the centre of the OK magnetic system. The optical β-function can be easily calculated to be 2.5 m; the fundamental mode radii are 0.9 mm in the undulator centres and 2.8 mm on the mirrors (for a wavelength of 6300 Å). The mirror reflectivity in the initial stage of operation was better than 99.9% at 6300 Å wavelength. The mirror degradation under VUV and soft-X-ray radiation from the OK magnetic system was observed. After three weeks of operation the front mirror, affected by direct radiation, had only 98% reflectivity, but lasing did not stop because of the high OK gain.

The other pairs of mirrors, which were used for lasing in the violet and UV spectral ranges, had a maximum initial reflectivity of 99.6% and 99.4% at 4150

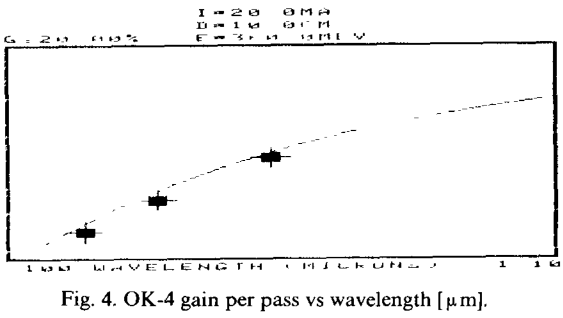

Fig. 4. OK-4 gain per pass vs wavelength [μm].

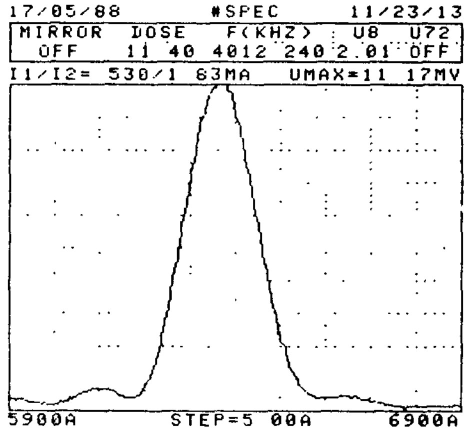

Fig. 5 Spontaneous radiation spectrum from one undulator.

and 2500 Å wavelength, respectively. The VUV degradation of these mirrors was less because the magnetic field in the undulators was lower.

7. OK spontaneous radiation spectrum

The electromagnetic undulators allow a wavelength of fundamental harmonics tunability from 1000 up to 15000 Å by changing the magnetic field (at 350 MeV fixed energy), i.e. by changing the K-factor.

The OK spontaneous radiation spectrum is the result of an interference of wave packets radiated from two undulators and shifted each from the other due to the delay of electrons in the bunching section. Fig. 5 shows the measured spectrum of spontaneous radiation (at zero angle) from one undulator. Fig. 6 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 "fine structure" of the spontaneous radiation spectrum

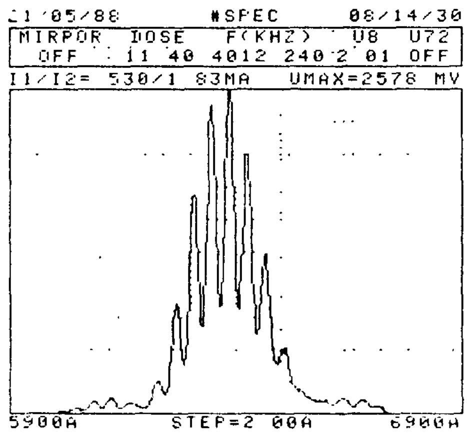

Fig. 6. OK spontaneous radiation spectrum.

is the result of interference of radiation from two undulators. The spectra are measured at an electron energy of 350 MeV, the field in the undulators being 3.4 kG.

It is well known that the gain is proportional to the derivative of the spontaneous radiation intensity over energy. It means that the "fine structure" is the cause of the OK high gain.

8. Lasing in OKs

Because the OK gains have different signs on the left- and right-hand slopes of the spectrum, a variation of the radiation spectrum was observed, with the OK tuned below the threshold ($G_{OK} \lesssim 1 - R_1 R_2$, where $R_{1,2}$ are the reflection efficiencies of the optical cavity mirrors). Fig. 7 shows the change of the spectrum of the radiation from the optical cavity as the peak current increases (the spectra are normalized to the maximum spectral density).

When the OK is tuned above threshold, i.e. the OK gain is more than the optical cavity losses and the revolution frequencies of the electron and light beams are synchronized, the lasing appears on a wavelength where the OK has a maximum gain. Some of the measured spectra are shown in fig. 8.

The relative lasing line width $\Delta\lambda/\lambda$ varied within the 10^{-4}–5×10^{-4} range, depending on the detuning of the electron beam revolution frequency from the exact synchronism, on the beam current and on other parameters.

The transverse distribution of the radiation intensity corresponded to the basic mode (TEM_{00}) of the optical cavity. When we worked in the red spectral region, the OK gain was high enough to reach lasing with an electron beam slightly shifted from the optical cavity axis, and lasing in TEM_{10} mode was observed.

Continuous tunability of the lasing wavelength was attained by changing the field in the undulators. Its boundaries (5800–6900 Å, 3750–4600 Å and 2400–2700 Å) corresponding to the reflection bands of the mirrors were used. The threshold current for lasing was 1–10 mA, depending on the optical cavity mirror conditions.

The average lasing power is limited by electron beam energy spread growth and is proportional to the full synchrotron radiation power and to the maximum ad-

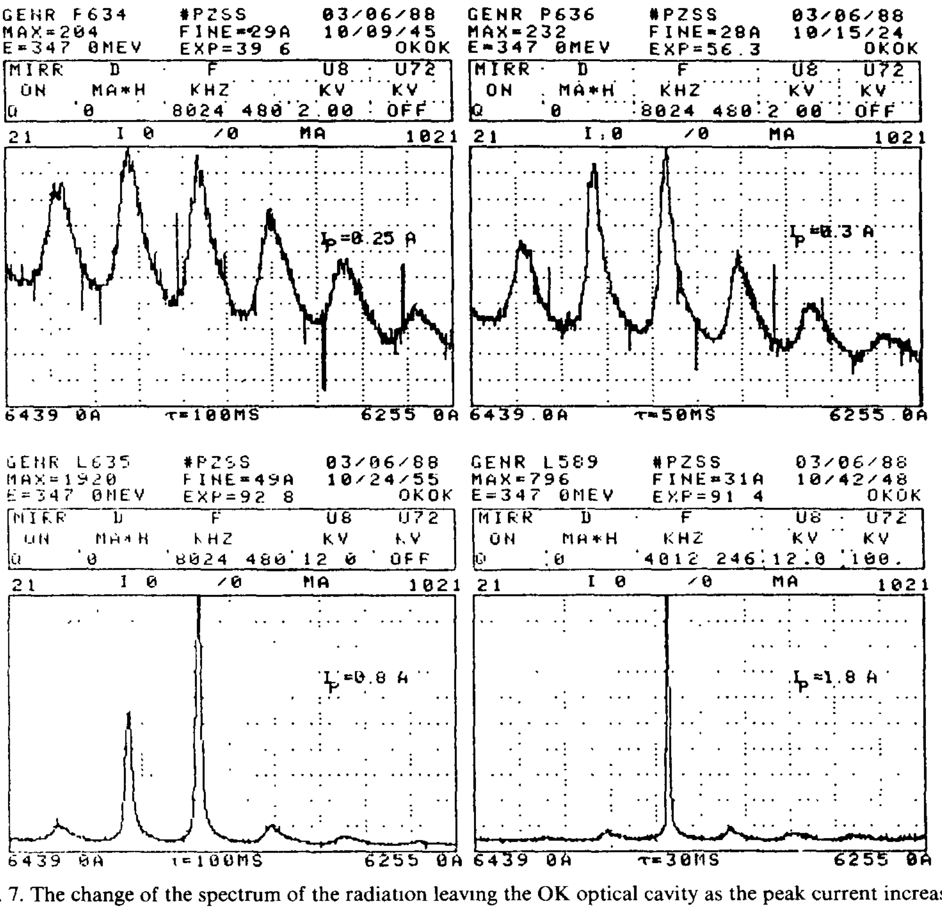

Fig. 7. The change of the spectrum of the radiation leaving the OK optical cavity as the peak current increases.

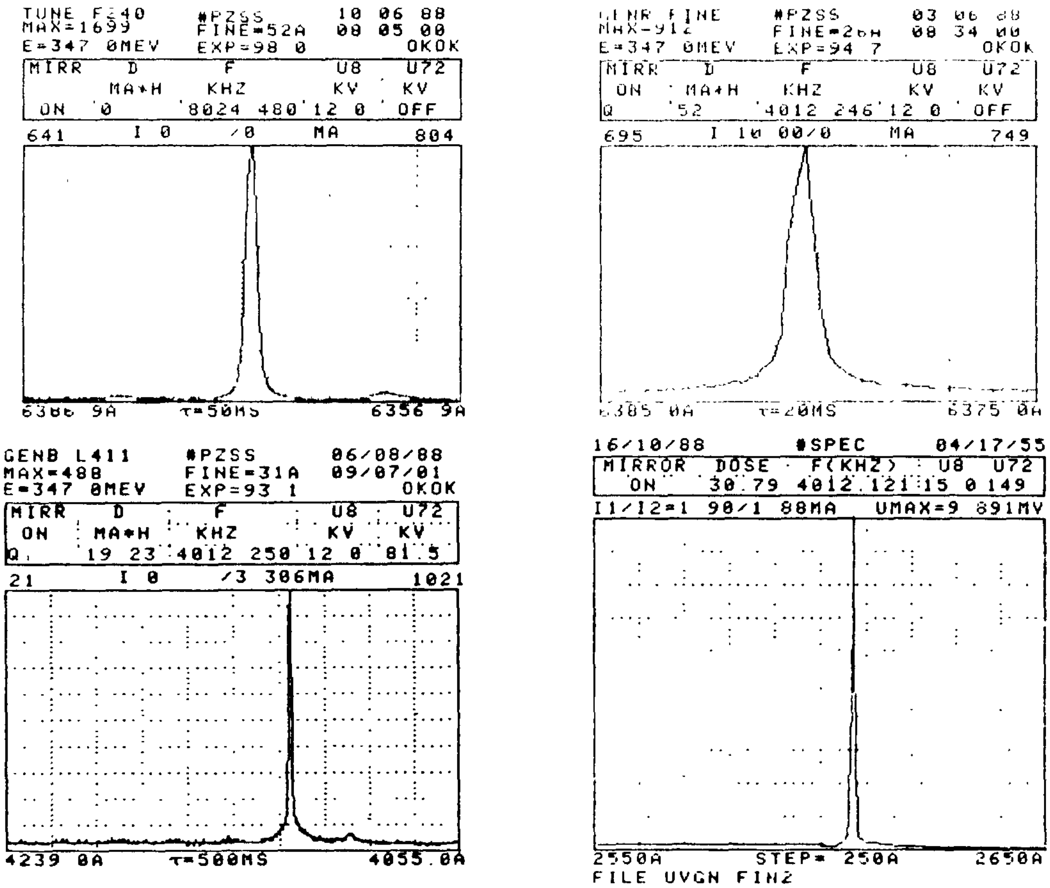

Fig. 8. Lasing lines in the red, violet and ultraviolet spectral regions, obtained on OK-4

missible energy spread. In our case the maximum energy spread σ_E/E was limited by the gain reduction above the threshold and varied within the $(0.6–2) \times 10^{-3}$ range. The measured power (6 mW at 6300 Å and 2.5 mW at 2500 Å) at 20 mA average current corresponded to the expected values. Because only the average lasing power is limited, we realized a G-switching mode of OK operation to produce high peak power. The electron beam was shifted from the optical cavity axis using electrostatic plates and was periodically returned to the initial position with 2–3 μs return time.

When we return the damped electron beam onto the

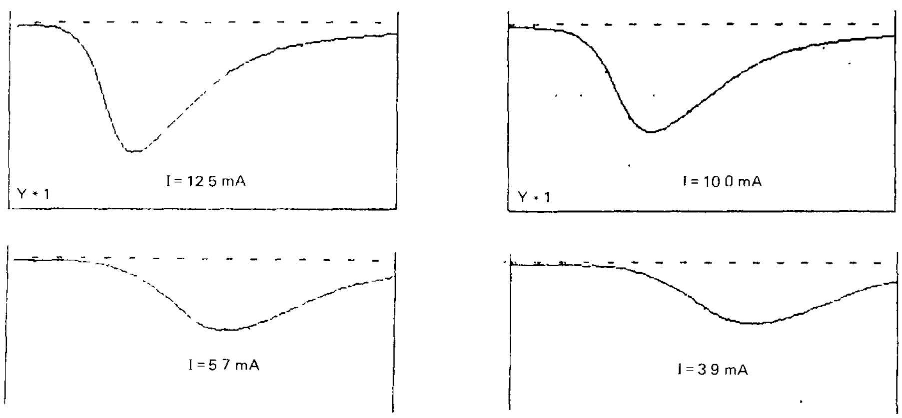

Fig. 9. Lased power pulses in G-switch mode for various beam currents; 32.000 μs/DIV.

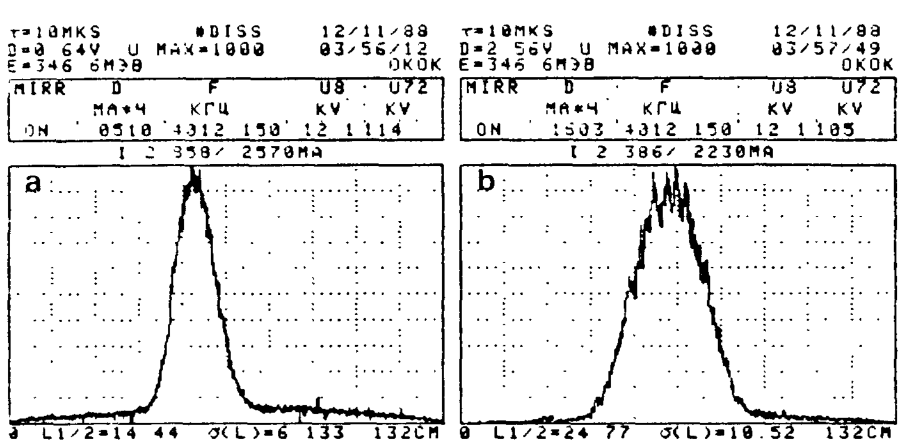

Fig. 10. Longitudinal distribution of the electron beam density (normalized to maximum density): (a) without lasing, (b) during lasing.

optical cavity axis, the gain is much higher than the losses. The radiation power in the optical cavity starts to increase fast. The radiation power increases till the gain remains above the threshold and then decreases. Fig. 9 shows the time structure of the lased power in the G-switch mode of operation. The typical pulse duration at 10 mA current was 0.1 ms and the power was about 50 W at 6300 Å and 18 W at 2500 Å wavelength. An increase in electron energy spread during lasing was observed in both cases (continuous and G-switch mode). The energy spread was calculated from the bunch length measured by a dissector [9] with 30 ps time resolution. Fig. 10 shows the lasing-induced bunch lengthening. The maximum measured relative energy spread (1.5×10^{-3}) was twice as large as the initial one.

9. Lased radiation time structure

For measurement of the radiation time microstructure we used a dissector. The radiation bunch repetition frequency is $c/2L = 8$ MHz, where $L = 18.7$ m is the length of the optical cavity.

Fig. 11 shows the time structure of the electron beam (wide peak) and the lased beam (narrow peak) on top of the electron beam. 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 less. This is quite natural since the gain is proportional to the instantaneous value of the electron current and, consequently, is maximum in the centre of the bunch. Over many passes, the light interacting with the centre of the electron bunch is amplified much more than the light interacting with its ends. The lasing micropulses have a duration time of about 200 ps. According to this duration, the lased peak power is about 25 and 9 kW on 6300 and 2500 Å, respectively, in G-switch mode. Within the optical cavity the peak power was 2.5 MW and 1 MW, correspondingly.

The time structure of the lased power averaged over the period $2L/c$ (macrostructure) is shown in figs. 12a,

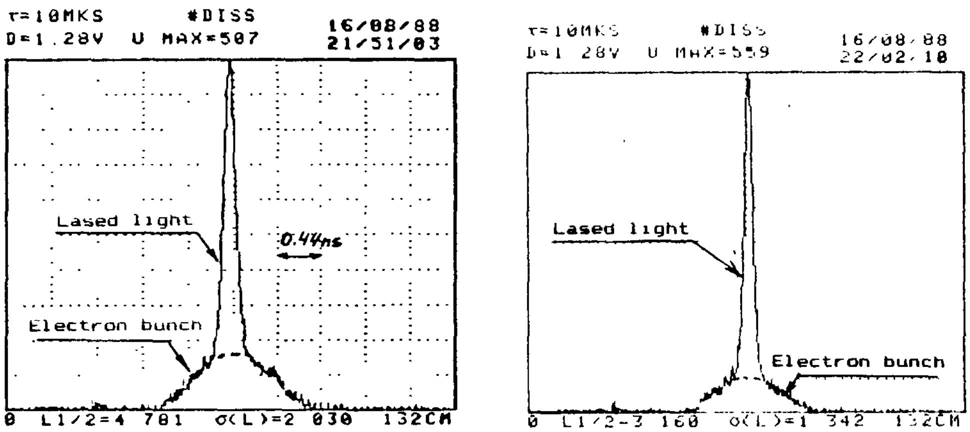

Fig. 11. The time structure of the electron bunch (wide peak) and the lased bunch (narrow peak) on top of the electron bunch.

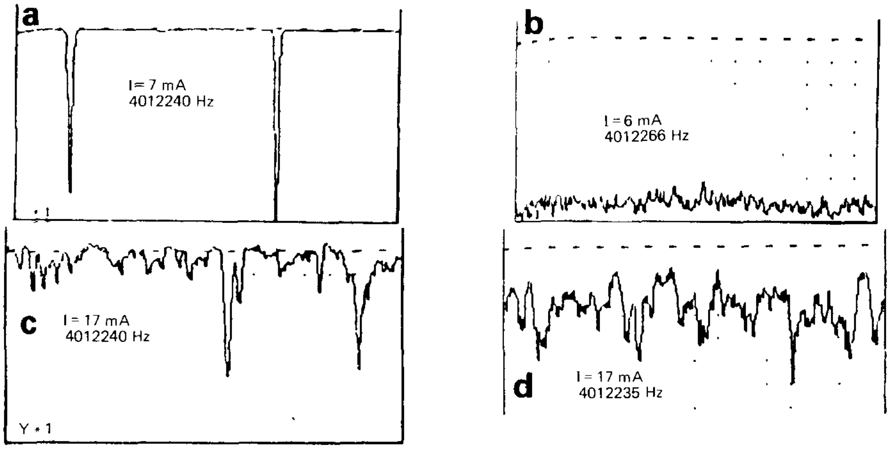

Fig. 12. Macrostructure of lased power under different conditions; 1600.00 μs/DIV.

c. The observed process is similar to relaxation autooscillations (the light interacting with an electron beam increases its energy spread, which results in a gain drop below the threshold, and the light intensity decreases; due to radiation damping, the energy spread decreases and the gain becomes higher than the threshold one, the radiation power increases again and the cycle is repeated). It can be shown that stable lasing is possible in principle, but it is very sensitive to small modulation of the gain value, which really always exists. In our case, 1% relative modulation of the gain value is enough to provide 100% modulation of lasing power. Stable lasing was realized when the synchronization was detuned, the lasing power was considerably lower and the linewidth was big enough (see figs. 12b,d). In this case the sensitivity to gain modulations is substantially lower.

10. Plans

Preparations for further increase of the lasing power and shortening of the lasing wavelength are in progress.

References

[1] N.A. Vinokurov and A.N. Skrinsky, Preprint 77-59 of the Institute of Nuclear Physics, Novosibirsk, 1977.

[2] N.A. Vinokurov and A.N. Skrinsky, in: Relativistic High-Frequency Electronics (Institute of Applied Physics, Gorky, 1981) p. 204.

[3] G.A. Kornyukhin et al., Preprint 83-137 of Institute of Nuclear Physics, Novosibirsk, 1983

[4] A.S. Artamonov et al., Nucl. Instr. and Meth. 177 (1980) 247.

[5] N.A. Vinokuron et al., in: Report on SR Operation in the Institute of Nuclear Physics, Siberian Division of the USSR Academy of Sciences (Institute of Nuclear Physics, Novosibirsk, 1981) p. 12.

[6] G.A. Kornkyukhin et al., Nucl. Instr. and Meth. 208 (1983) 189.

[7] G.A. Kornkyukhin et al, Nucl. Instr. and Meth. A237 (1985) 281.

[8] N.A. Vinokurov, Nucl. Instr. and Meth. A246 (1986) 281.

[9] E.I. Zinin, Nucl Instr. and Meth. 208 (1983) 439.

[10] V.N. Litvinenko, Synchr. Radiat. News 1 (1988) 18.