The Results of Lasing Linewidth Narrowing on VEPP-3 Storage Ring Optical Klystron

V. N. Litvinenko, M. E. Couprie, N. G. Gavrilov, G. N. Kulipanov, I. V. Pinaev, V. M. Popik, A. N. Skrinsky, and N. A. Vinokurov

***Abstract*—Lasing in the visible and ultraviolet ranges was reached in the optical klystron installed on a VEPP-3 storage ring in 1988 [6] with minimum relative linewidth $\Delta\lambda/\lambda = 10^{-4}$. In order to decrease the linewidth we have performed the experiments reported here. The optical cavity on VEPP-3 storage ring optical klystron was updated to install intracavity selective elements. We used the simplest selective element—a glass plate with parallel planes as a natural interferometer. With a 1.2 mm thick glass plate installed inside the optical cavity we have reached lasing with a vary narrow linewidth. The minimum relative lasing linewidth, $2.7 \cdot 10^{-6}$ ($\lambda = 6250$ Å, $\Delta\lambda = 0.017$ Å), was 30 times narrower than the minimum one without the plate ($\Delta\lambda = 0.6$ Å). The average power was the same in both cases. Experiments on lasing linewidth narrowing with the use of the plates with different thickness are underway.**

I. Introduction

The optical klystron (OK) was proposed in 1977 by Vinokurov and Skrinsky [1] as a modification of the free-electron laser (FEL). It has a much higher gain in comparison with a conventional FEL due to the use of a special device—a buncher located between two undulators. The experiments with OK have been carried out in our institute since 1979.

In 1988 lasing was reached in the visible and ultraviolet ranges ($\lambda = 2400$–6900 Å) with a fine tunability inside the reflection bandwidth of the mirrors we used. The minimum lasing linewidth $\Delta\lambda/\lambda = 10^{-4}$ was obtained. This value was the best for a short wavelength FEL but quite big for spectroscopy and any other applications. This is the reason for our experiments on lasing linewidth narrowing. In recent experiments, $2.7 \cdot 10^{-6}$ relative lasing linewidth was reached with the use of an intracavity 1.2 mm thick glass plate.

II. The Basic Principles

The short wavelength FEL usually operates in the so-called synchronization mode when the electron and optical bunches are much shorter than the optical cavity length. The reason is that in this case the gain is proportional to a peak current instead of an average one. The natural lasing linewidth is here defined generally by the FEL gain bandwidth (or period). The FEL gain bandwidth (period) narrowing is limited by the existing energy spread in an electron beam [2]:

$$\delta\lambda_g/\lambda \geq \frac{\sigma_E}{2\pi \cdot \mathbb{E}}.$$

It means that the gain bandwidth $\delta\lambda_g/\lambda$ is usually more than 10^{-3} and the natural FEL lasing linewidth $\delta\lambda/\lambda$ is 10^{-3}–10^{-4}, if it is not limited by electron bunch length.

It is quite natural to use an intracavity selective element to decrease the lasing linewidth. The simplest one is the Fabry–Perot etalon consisting of two parallel faces with a thickness d, refraction index n, and reflection coefficient R. The reflected intensity depends strongly on the wavelength $\lambda = 2\pi/k$:

$$I_r = IoR \left| \frac{1 - \exp(ikD)}{1 - R \exp(ikD)} \right|^2$$

where $D = 2nd$ is the optical overpass length and we have assumed that there is no absorption in the bulk. The reflected field is not synchronized with the electron bunch and will be lost. This means that the overpass cavity losses will also be modulated with the period of $d_\lambda = \lambda^2/D$:

$$p = p_0 + 2 \cdot R \left| \frac{1 - \exp(ikD)}{1 - R \exp(ikD)} \right|^2 \tag{1}$$

where p_0 is the loss in cavity mirrors and we take into account that light passes twice through the F–P etalon per pass. The simplest natural F–P etalon is an uncoated glass plate with parallel faces and $R = (n-1)^2/(n+1)^2 << 1$. In this case,

$$p \approx p_0 + 4 \cdot R(1 - \cos kD) \tag{2}$$

and the plate does not give any additional losses when the wavelength is $\lambda = D/M$, where M is any integer.

Let a wavepacket pass in the optical cavity be represented as:

$$\mathbb{E}(t, z) = a(z - ct) \exp\{i(kz - \omega t)\} \tag{3}$$

where $\mathbb{E}$ is the electric field, z is the longitudinal coordinate along the cavity axis, $\omega = kc$, and c is the speed of light. After passing through the plate, the packet transformation function is the following:

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V. N. Litvinenko, N. G. Gavrilov, G. N. Kulipanov, I. V. Pinaev, V. M. Popik, A. N. Skrinsky, and N. A. Vinokurov are with the Institute of Nuclear Physics, 630090, Novosibirsk, USSR.

M. E. Couprie is with LURE, 91405 Orsay Cedex, France.

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$$a_{out}(z) = (1 - R) \sum_{n=0}^{\infty} a(z - nD) \cdot R^n \cdot e^{ikDn}$$
$$\approx (1 - R) \cdot a(z) + R \cdot a(z - D). \qquad (4)$$

If we cannot admit a significant decrease in FEL increment (i.e., the reduction in the gain per pass) we should assume that

$$D \ll \sigma_s \qquad (5)$$

where σ_s is a standard deviation of the longitudinal electron bunch density. It means that the electron bunch length practically limited the minimum lasing linewidth in the case when the FEL operates in synchronization mode:

$$(\delta\lambda/\lambda)_{min} \approx \lambda/\sigma_s. \qquad (6)$$

In optical range $\lambda \sim 0.5$ μm for typical electron bunch length of 5–50 cm, $(\delta\lambda/\lambda) = 10^{-5}$–$10^{-6}$ is acceptable without a substantial gain reduction.

You can find a detailed description of the longitudinal dynamics in [3], [4]. Here we just point out some important facts and formulae. The following assumptions are used:

1) The maximum FEL gain corresponds to the wavelength $\lambda = D/M$, where $M >> 1$ is any integer.

2) The optimal synchronization between the optical and electron bunches is chosen (see [3]).

3) The lasing spectral density is much higher (for few orders of magnitude) than the spontaneous one.

4) $D << \sigma_s$ and $D >> \Delta$, where Δ is the FEL slippage.

The lased field is the superposition of longitudinal supermodes

$$a(z) = \sum a_n \cdot H_n(z/\sigma_r) \cdot \exp(-z^2/2\sigma_r^2) \qquad (7)$$

where $\sigma_r = \sqrt{2\sigma_s D} \cdot \sqrt[4]{R/G_0}$, $G(z) = G_0 \cdot \exp(-z^2/2\sigma_s^2)$ is the longitudinal gain function, and $H_n(x)$ is the nth Hermits polynomial of x. The supermodes remain unchanged in the shape throughout the roundtrip of the optical cavity, except for multiplication by some complex parameter:

$$a_n(m + 1) = a_n(m) \cdot \exp(\gamma_n/2 + i\delta\varphi) \qquad (8)$$

$$\gamma_n = G_0 - p_0 - (2n + 1) \cdot D/\sigma_s \cdot \sqrt{G_0 \cdot R} \qquad (9)$$

where m is the pass number.

In steady-state lasing when the lased power P_1 is quite high as compared with the spontaneous radiation power on the basic harmonic P_{sp} (i.e., $D/\sigma_s >> q\lambda/\sqrt{2\pi}\sigma_s \cdot P_{sp}/P_1 \cdot \ln(D/\sigma_s)$, where q is the undulator period number) the basic supermode ($n = 0$) dominates. In this case, the longitudinal distribution of the lased power has a simple Gaussian form:

$$P_1(z) = P_0 \cdot \exp(-z^2/\sigma_r^2) \qquad (10)$$

and the corresponding form in k space:

$$P_1(k') = P_0 \cdot \exp(-(k' - k)^2 \cdot \sigma_r^2) \qquad (11)$$

with

$$\frac{\sigma_\lambda}{\lambda} = \frac{1}{2\pi}\sqrt{\frac{d_\lambda}{2\sigma_s}} \cdot \sqrt[4]{\frac{G_0}{R}} \qquad (12)$$

and the width at half height

$$\Delta\lambda/\lambda = 2\sqrt{2 \ln 2} \cdot \frac{\sigma_\lambda}{\lambda}. \qquad (12')$$

It is important to note that the difference in the increments between the basic and first supermodes

$$\Delta\gamma = 4D/\sigma_s\sqrt{RG_0}$$

can be big enough to reach basic supermode domination in the pulse mode of operation also if the number of passes $M \geq (3 - 6)/\Delta\gamma$. In our particular case, when $D \approx 0.4$ cm, $\sigma_s = 10$ cm, and $\sqrt{RG_0} \approx 5 \cdot 10^{-2}$, there are enough 400–800 passes (50–100 μs) to reach the minimum lasing linewidth.

If we try to reach the minimum lasing linewidth, the demands for the synchronization accuracy in the case of the intracavity plate used is also more realistic in comparison with a conventional mode of FEL operation. In our particular case, the requirement for an accuracy of the cavity length is 10–20 μm with the plate as compared with 10–20 Å without the plate (see [3] for details).

III. The Main Parameters of the Optical Klystron

A detailed description of the OK-4 optical klystron installed on the VEPP-3 storage ring bypass is given in [4], [5]. The schematic layout of the VEPP-3 storage ring with the bypass is shown in Fig. 1.

The electron energy for OK operation is $E = 350$ MeV. The OK-4 (7.8 m long) comprises two electromagnetic undulators (3.4 m long, 10 cm period, magnetic field up to 5.6 kG) and the buncher (35 cm long, three-pole electromagnetic compensated wiggler). The undulators allow a fundamental harmonic wavelength tunability from 0.1–1.5 μm by varying the magnetic field.

The optical cavity consists of two dielectric mirrors with 10 m curvature radii, located equidistantly from the OK center and 18.7 m from each other. This distance is a quarter of the VEPP-3 storage ring circumference to operate in synchronization mode. The optical β function is 2.5 m in the OK center.

The average currents we used for operation in order of 20 mA, horizontal emittance $2 - 4 \cdot 10^{-6}$ cm · rad, the maximum peak current is 6 A, and σ_s is 10–100 cm depending on the RF voltage.

The maximum measured gain is 10% per pass in the red spectral range, 5.5% in the violet ($\lambda \sim 0.4$ μm) and 2.5% in the UV ($\lambda \sim 0.25$ μm). The details about lasing in visible and UV ranges can be found in [6].

The optical klystron gain wavelength dependence is described as follows:

$$G(k) = G_0 \cdot (\sin\psi/\psi)^2 \cdot \sin(k\Delta + \varphi)$$

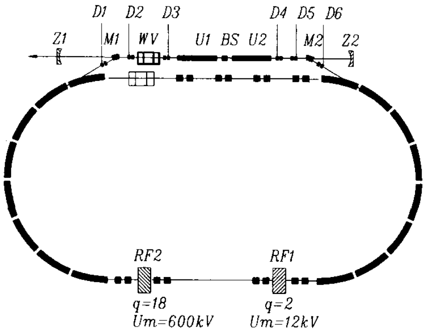

Fig. 1. The layout of VEPP-3 storage ring with the bypass.

where Δ is the slippage in the OK buncher, $\psi = \pi q(k - k_r)/k_r$, $\lambda_r = 2\pi/k_r = d/2\gamma^2 \cdot (1 + K^2/2)$ is the resonant wavelength, d is the undulator period, K is the undulator deflection parameter, q is the number of periods in each undulator and $\Delta >> q\lambda_r$. The maximum slippage is limited by the energy spread ($\sigma_E/E = 3 - 10 \cdot 10^{-4}$) and the gain has a fine structure with a period $\delta\lambda_g = \lambda^2/\Delta =$ 20–40 Å in the red range. The value of slippage Δ can be varied very precisely to choose the wavelength where the gain is maximum.

The experiments on lasing linewidth narrowing were done generally with the use of only one electron bunch in the storage ring. It means that the maximum admissible losses were 5% per pass.

IV. Requirements for the Intracavity Plate

The plate with exactly parallel faces installed on the normal incidence is absolutely transparent at a wavelength of $\lambda = D/M$. But a real plate is somewhat wedge shaped and the incidence angle differs slightly from $\pi/2$. Let us consider the radiation corresponding to the basic TEM_{00} transverse mode of the optical cavity coming through the plate located at a distance l from the cavity center. In this case, the reflected radiation intensity is given by the following expression:

$$I_r = I_0 \cdot 2R \cdot \{1 - \cos Kd(1 - \varphi^2/2n^2)\}$$
$$\cdot \exp\{-k/4[\vartheta^2\beta_0 + (l\vec{\vartheta} + 2\vec{\varphi}d/n)^2]\}$$

where β_0 is the optical β function in the optical cavity center; $\vec{\vartheta} = \vec{e}_1 - \vec{e}_2$, $\vec{\varphi} = (\vec{e}_1 + \vec{e}_2)/2 - \vec{e}$, $\vec{e}_1$, and $\vec{e}_2$ are the normal vectors to the front and rear plate surfaces; and $\vec{e}$ is the unit vector of radiation propagation. If $|\varphi|$ and $|\vartheta|$ are small enough, the minimum additional losses per pass are

$$\Delta p = R \cdot k \cdot [\vartheta^2\beta_0 + (l\vec{\vartheta} + 2\vec{\varphi}d/n)^2].$$

If $\vec{\varphi}$ and $\vec{\vartheta}$ uncorrelate and $\Delta p_{\max}$ is the maximum admissible additional losses, the following tolerances are required:

$$|\vartheta| \le \sqrt{\frac{\Delta p_{\max}\lambda\beta_0}{4\pi R(l^2 + \beta_0^2)}} \qquad |\varphi| < \frac{n}{2d}\sqrt{\frac{\Delta p_{\max}\lambda\beta_0}{4\pi R}}.$$

In our particular case $l = 8$ m, $d = 1.2$ mm, $n = 1.6$, and $\beta_0 = 2.5$ m for $\Delta p_{\max} = 0.5\%$ should be

$$|\vartheta| \le 3 \text{ arcsec} \qquad |\varphi| < 0.4°.$$

V. The Update of the Optical Cavity

In late 1989 the first update of the OK-4 optical cavity was made. The vacuum channel to the rear mirror was cut to install the Brewster window (see Fig. 2). A substantial part of the vacuum pipe was removed and the rear mirror was located in the atmosphere. There was about 2 m of empty space in which to install different optical elements inside the optical cavity. We changed the position of the rear mirror to compensate the difference in the optical pass. The Brewster window was welded to a stainless steel pipe and a special bellows gave the possibility for angular adjustment.

The first run with the new optical cavity has shown quite admissible losses in the Brewster window of the order of 0.5% per pass. But it was an unpleasant surprise for us when we have seen very fast degradation of the Brewster window transparency caused by a very weak UV and VUV radiation reflected by the front mirror. It is quite strange because the degradation of the front mirror reflectivity affected by the direct VUV and X-UV radiation from OK magnetic system was very small.

In March 1990 we installed a new mechanism of the Brewster window in conjunction with indium sealing to have a possibility for window changing. With the use of three Brewster windows all the recent results on lasing linewidth narrowing have been obtained. The Brewster window "lifetime" was extremely short and practically independent of the previous cleaning, heating, and so on. The nature of the Brewster window degradation is not so evident and in order not to waste time we have removed the Brewster window and have retuned the old vacuum channel to its original position. The new vacuum system for intracavity optical element installation was designed and is now under construction. We are planning to install it the autumn of 1991. Nevertheless, the good results on lasing linewidth narrowing have been obtained with the use of this configuration.

VI. Measurements of the Cavity Losses Modulation

For the experiments on lasing linewidth narrowing we used the glass plate 1.2 mm thick and 20 mm in diameter. The parallelism between two faces was better than 2 arcsec. For incidence angle adjustment we used the standard support with two adjusting screws for two directions. It was enough to reflect the light captured in the optical cavity to have quite admissible losses.

The spectrum of the radiation captured in the cavity was modified in the presence of the intracavity plate. Fig. 3 shows the measured spectra of spontaneous radiation captured in the cavity without (left) and with the plate in the optical cavity. As you can see, the very fine structure appears with approximately a 1 Å period (see Fig. 4) ac-

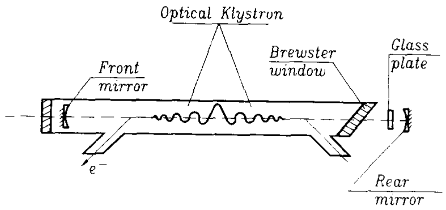

Fig. 2. The updated optical cavity for lasing linewidth narrowing experiments.

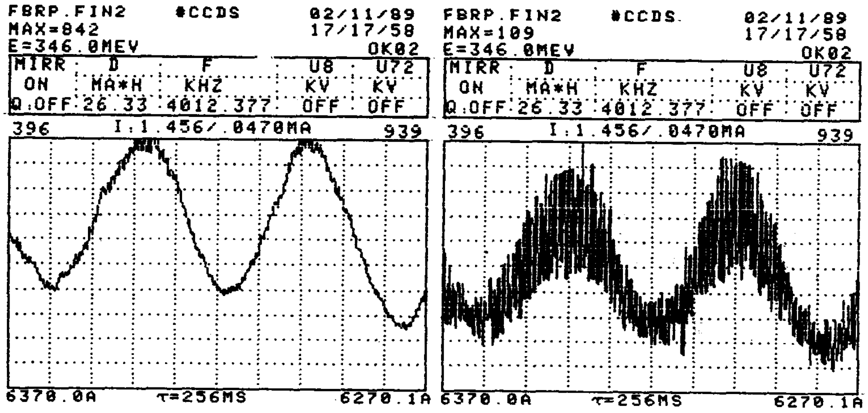

Fig. 3. The measured spectra of spontaneous radiation captured in the optical cavity: with (right) and without (left) the intracavity plate.

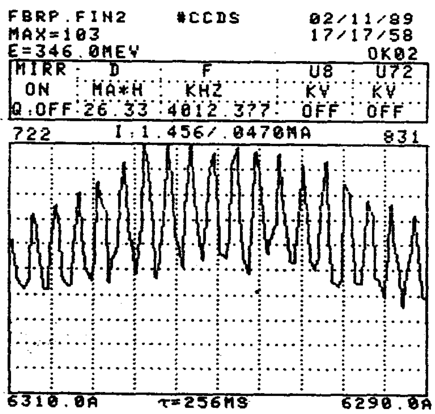

Fig. 4. The fine structure in the spectrum of the radiation captured in the modified cavity.

cording to the expected value of $d_\lambda = \lambda^2/D$. The depth of the intensity modulation also corresponds to the loss modulation.

VII. System for Lasing Linewidth Measurements

According to our estimations, we need to measure the linewidth with $\Delta\lambda/\lambda = 3\text{–}7 \cdot 10^{-6}$. Our old system, consisting of a monochromator with the resolution of $\Delta\lambda/\lambda = 2 \cdot 10^{-5}$, was insufficient. To have the resolution of the order of 10^{-6} we have created the system schematically shown in Fig. 5. It comprises three optical lenses, a IT-51 Fabry–Perot interferometer (with the set of standard reference spacers), and a computer-controlled 1024 pixels CCD line. The CCD is located in the focal plane of the L_3 lens with the 0.5-m focal length.

The system gives a resolution of $\Delta\lambda/\lambda = 1.5 \cdot 10^{-6}$ when a 6 mm F–P etalon is used. The conventional He-Ne laser was used for resolution measurements.

The CCD line measures the distribution in the interference rings. The data from the CCD can be processed, saved in files, or displayed.

VIII. Results of Lasing Linewidth Narrowing

As mentioned earlier, lasing with the intracavity plate has been obtained in three runs (with the use of three different Brewster windows) in April, May, and June 1990. The OK operated in the red spectral range to have the maximum gain.

Some measured lasing lines are shown in Fig. 6. On the initial stage after the Brewster window replacement the optical cavity losses were 1–1.5% per pass and the threshold current was 4–7 mA. In this case we had the possibility to reach lasing with quite a long electron bunch (up to $\sigma_s = 35$ cm) and the minimum lasing linewidth of $\Delta\lambda = 0.017$ Å ($\lambda = 6250$ Å). This linewidth is in very good agreement with the predicted one (see (12′), where $G_0 = 3\%$ and $n = 1.6$):

$$\frac{\Delta\lambda}{\lambda} = 2.7 \cdot 10^{-6}.$$

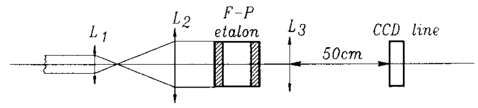

Fig. 5. The schematic layout of the linewidth measuring system.

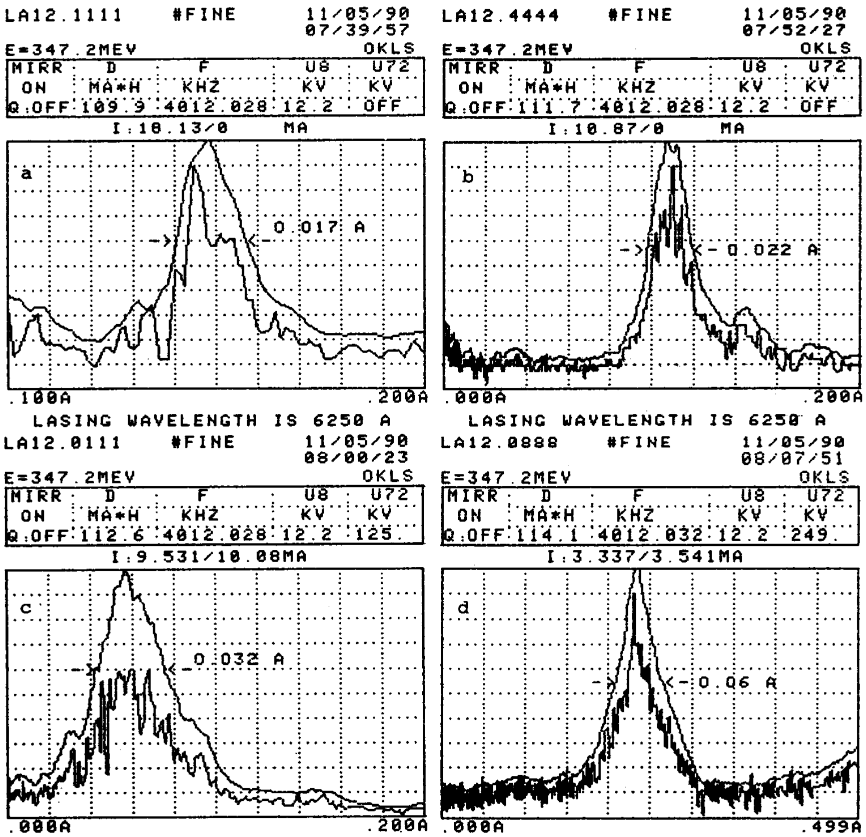

Fig. 6. The measured lasing lines. (a) $\Delta\lambda = 0.017$ Å, $\sigma = 35$ cm; (b) $\Delta\lambda = 0.022$ Å, $\sigma = 30$ cm; (c) $\Delta\lambda = 0.032$ Å, $\sigma_s = 10$ cm; (d) $\Delta\lambda = 0.060$ Å, $\sigma_s = 8$ cm, and synchronization slightly detuned in this case. The linear scale in both directions: vertical in arbitrary units, horizontal λ-λ_0 in Å, where $\lambda_0 = 6250$ Å.

After 20–30 h of operation the losses grew up to 3–4% per pass and lasing was observed only with a high-peak gain when the bunch length was quite short ($\sigma_s = 10$ cm). The minimum lasing linewidth in this case $\Delta\lambda/\lambda = 5 \cdot 10^{-6}$ was also in perfect agreement with the prediction. The accuracy of the revolution frequency tuning required for the minimum linewidth was $|\Delta f_0| = 2$ Hz ($f_0 = 4.012$ MHz). In this case the lased radiation had a minimum phase space volume $\sigma_r \cdot \sigma_k = 1$ corresponding to the Fourier limit. The typical value of $\sigma_r \cdot \sigma_k$ for conventional FEL operation is a few hundreds or thousands. This means that such a simple device as an intracavity glass plate can dramatically improve radiation quality, especially if we take into account that the transverse distribution also corresponds to the basic TEM_{00} mode. The tuning range for lasing was $|\Delta f_0| = 30$ Hz and lasing linewidth varied within $3 - 10 \cdot 10^{-6}$.

The lased power was close to the same (there was no more than a 10% difference) in both cases with and without the intracavity plate. This is quite natural because the average lased power in the storage ring FEL is limited by the electron bunch energy spread growth induced by multipass interaction with the lased radiation [3].

IX. Conclusion and Future Plans

The recent experiments have shown that the use of the intracavity glass plates in FEL is very perspective from different points of view:

1) It gives a simple possibility to narrow the lasing line.

2) A very narrow lasing line can be reached either in the steady state or in the pulse mode of operation.
3) The lasing line is formed considerably faster.
4) The longitudinal phase space volume is equal to the Fourier limit: $\Delta k \cdot \Delta z = 1$.
5) The requirements for the accuracy of the electron and light bunches synchronization is substantially simpler.

We are planning to continue the experiments on the lasing linewidth narrowing with the use of thicker plates and longer electron bunch.

ACKNOWLEDGMENT

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