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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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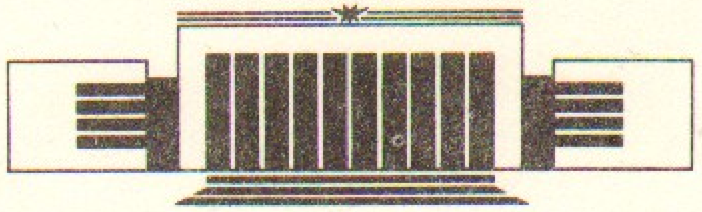

НОВОСИБИРСК

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

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ABSTRACT

The lasing in visible and ultraviolet ranges was reached in the optical klystron installed on VEPP-3 storage ring in 1988 [1] with minimum relative linewidth $\Delta\lambda/\lambda=10^{-4}$. In order to decrease the linewidth we have performed these experiments.

The optical cavity on VEPP-3 storage ring optical klystron was up-dated to install intracavity selective elements. We used the simplest selective element - a glass plate with parallel planes as natural interferometer.

With the use of a 1.2 mm thick glass plate installed inside the optical cavity we have reached lasing with a very narrow linewidth. The minimum relative lasing linewidth, $2.7\cdot10^{-6}$ (λ=6250Å, $\Delta\lambda$=0.017 Å), was 30 time narrower than the minimum one without the plate ($\Delta\lambda$=0.6 Å). The average power was the same in both cases.

The experiments on lasing linewidth narrowing with the use of the plates with different thickness are under way.

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1. INTRODUCTION

The optical klystron (OK) was proposed in 1977 by Vinokurov and Skrinsky [2] as 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 the lasing was reached in visible and ultraviolet ranges (λ = 2400 Å - 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 a quite big for spectroscopy and any other applications. This is the reason for our experiments on lasing linewidth narrowing. In recent experiments the $2.7\cdot10^{-6}$ relative lasing linewidth was reached with the use of an intracavity 1.2 mm thick glass plate.

2. THE BASIC PRINCIPLES

The short wavelength FEL usually operates in the so called synchronization mode when an electron and a lased bunches are much shorter in comparison with an 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 [3]:

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

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}.

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 $\lambda=2\pi/k$:

$$I_r = I_0 R \left| \frac{1-\exp(ikD)}{1-R\exp(ikD)} \right|^2 ,$$

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

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

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

$$p \approx p_0 + 4\cdot R\,(1-\cos kD) , \qquad (2)$$

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

Let an wavepacket pass in optical cavity:

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

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 transfer is the following

$$a_{out}(z) = (1-R)\sum_{n=0}^{\infty} a(z-nD)\cdot R^n\cdot e^{ikD} \approx$$

$$\approx (1-R)\cdot a(z) + R\cdot a(z-D). \qquad (4)$$

If we can not 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-lenth 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 [4,5]. Here we just point out some important facts and formulae. The following assumptions are used:

i) the maximum FEL gain corresponds to the wavelength $\lambda=D/M$, where $M \gg 1$ is any integer;

ii) the optical syncronization between the optical and electron bunches is chosen (see [4]);

iii) the lased spectral density is much higher (for few orders of magnitude) in comparison with the spontaneous one;

iv) $D \ll \sigma_s$ and $D \gg \Delta$, where Δ is the FEL slippage.

The lased field is the superposition of longitudinal supermodes:

$$a(z) = \sum a_n \cdot H_n(z/\sigma_r) \cdot \exp(-z^2/2\sigma_r^2) , \tag{7}$$

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, $H_n(x)$ is the n-th Hermits polynomial of x. The supermodes remain unchanged in the shape throughout the roundtrip of the optical cavity, except the only multiplication by some complex parameter:

$$a_n(m+1) = a_n(m) \cdot \exp(\gamma_n/2+i\delta\varphi) , \tag{8}$$

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

where m is the pass number.

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

$$P_l(z) = P_0 \cdot \exp(-z^2/\sigma_r^2) \tag{10}$$

and the corresponding form in the k-space:

$$P_l(k') = P_0 \cdot \exp(-(k'-k)^2 \cdot \sigma_r^2), \tag{11}$$

with

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

and the width at halfheight

$$\Delta\lambda/\lambda = 2\sqrt{2\ln 2} \cdot \sigma_\lambda/\lambda. \tag{12'}$$

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

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

can be big enough to reach basic supermode domination in the pulse mode of operation too if the number of passes $M \geq (3-6)/\Delta\gamma$. In our particular case $D \approx$0.4sm, σ_s=10sm 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 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.

4. 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 [5, 6]. The schematic layout of the VEPP-3 storage ring with the bypass is shown on Fig.1.

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

The optical cavity consists of two dielectric mirrors with 10 meter curvature radii, located equidistantly from the OK center and 18.7 meter 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 meter in the OK center.

The average currents we used for operation in order of 20 mA, horizontal emittance $2\text{-}4\cdot10^{-6}$ cm·rad, the maximum peak current is 6 A, 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 ($\lambda\sim 0.4\mu$m) and 2.5% - in the UV ($\lambda\sim 0.25\mu$m).

The details about the lasing in visible and UV ranges can be found in [1].

The optical klystron gain wavelength dependence is described as follows:

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

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 $\Delta \gg q\lambda_r$. The maximum slippage is limited by the energy spread ($\sigma_E/E = 3\text{-}10\cdot10^{-4}$) 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.

4. 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 a little wedge-shaped and the incidence angle slightly differs from $\pi/2$. Let us consider the radiation corresponding to the basic TEM_{00} transverse mode of the optical cavity coming trough the plate located at a distance l from the cavity center. In this case, the reflected radiation intensity will be 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, $\vec{e}$ is the unit vector of radiation propagation. If $|\varphi|$ and $|\vartheta|$ is 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 $\vec{\vartheta}$ uncorralate and Δp_{max} is the maximum admissible additional losses the following tolerances are required:

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

In our particular case l=8 m, d=1.2mm, n=1.6, β_0=2.5m for Δp_{max}=0.5% should be

$$|\vartheta| < 3 \text{ arcsec}, \qquad |\varphi| < 0.4 \text{ degree}.$$

5. THE UPDATE OF THE OPTICAL CAVITY

In the late of 1989 the first up-date of the OK-4 optical cavity was made. The vacuum channal 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 were about 2 meter of empty space 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 the March of 1990 we installed a new mechanism of Brewster window 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 to not waste the time we have removed the Brewster window and have retuned the old vacuum channal to its native place. The new vacuum system for intracavity optical elements installation was designed and is now under construction.

Nevertheless, the good results on lasing linewidth narrowing have been obtained with the use of this configuration.

6. THE MEASUREMENTS OF THE CAVITY LOSSES MODULATION

For the experiments on lasing linewidth narrowing we used the glass plate 1.2mm thick and 20mm 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. Figure 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) according to the expected value of $d_\lambda = \lambda^2/D$. The depth of the intensity modulation also corresponds to the losses modulation.

7. THE SYSTEM FOR THE LASING LINEWIDTH MEASUREMENTS

According to our estimations, we need to measure the linewidth with $\Delta\lambda/\lambda = 3\text{-}7\cdot10^{-6}$. Our old system comprising a monochromator with the resolution of $\Delta\lambda/\lambda = 2\cdot10^{-5}$ was insufficient. To have the resolution of the order of 10^{-6} we have created the system schematically shown on 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 locates in the focal plane of the L3 lens with the 0.5m focal length.

The system gives a resolution of $\Delta\lambda/\lambda = 1.5\cdot10^{-6}$ when a 6mm 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 processing, saving in files or displaying. The spectral density diagram displayed in a linear scale of a wavelength.

8. THE RESULTS OF LASING LINEWIDTH NARROWING

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

Some measured lasing lines are shown on 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 a quite 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 formula (12′), where $G_0=3\%$, $n=1.6$):

$$\Delta\lambda/\lambda = 2.7\cdot10^{-6}.$$

After 20-30 hours 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 $\Delta\lambda/\lambda=5\cdot10^{-6}$ 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. It means that such a simple device as intracavity glass plate can dramatically improves the radiation quality, especially if we take into account that the transverse-distribution corresponds to the basic TEM_{00} mode too.

The tuning range for lasing was $|\Delta f_0|=30$ Hz and lasing linewidth varied within $3\text{-}10\cdot10^{-6}$.

The lased power was close to the same (there were no more than 10% difference) in both cases: with and without the intracavity plate. It 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].

9. CONCLUSIONS AND FUTURE PLANS

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

i. it gives a simple possibility to narrow the lasing line;
ii. a very narrow lasing line can be reached either in the steady state or in the pulse mode of operation;
iii. the lasing line is formed considerably faster;
iv. the longitudinal phase space volume is equal to the Fourier limit: $\Delta k\cdot\Delta z = 1$;
v. the requirements for the accuracy of the electron and light bunches synchronization is substantially simpler.

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

Acknowledgments. The INP optical klystron group would like to express the pleasure that in this experiment our colleague Marie-Emmanuelle Couprie (LURE, France) participated. We are looking forward for future fruitful collaborations with the Super-ACO FEL group and other FEL groups and laboratories in the world.

We would like to thank all the people who helped us to provide these experiments, especially A.I. Volohov and P.I. Ischenko.

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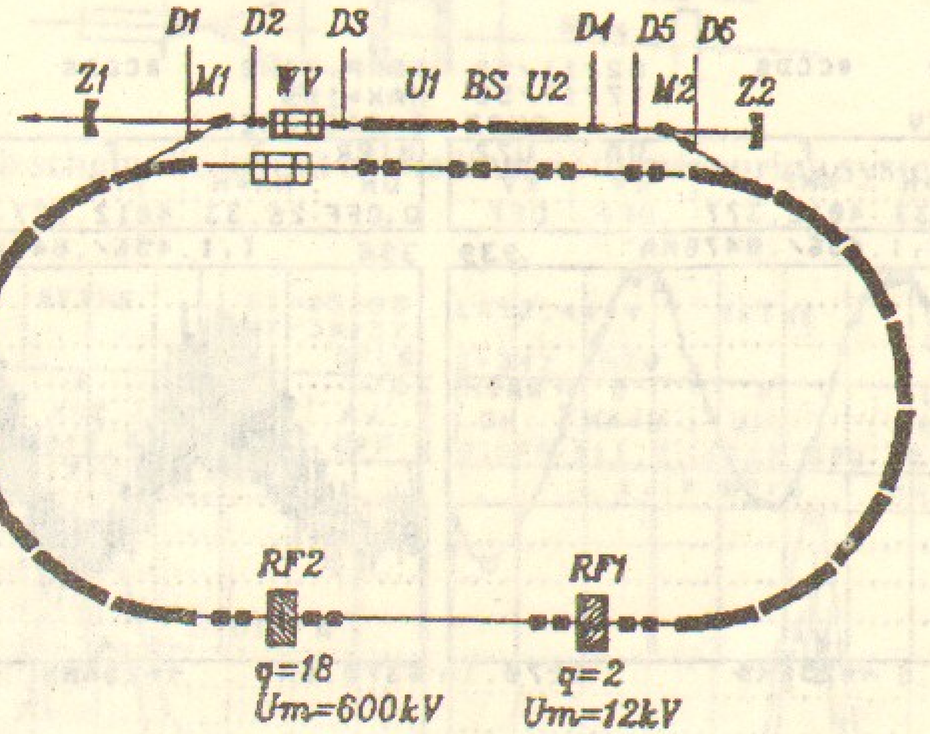

Fig 1. The layout of VEPP-3 storage ring with the bypass.

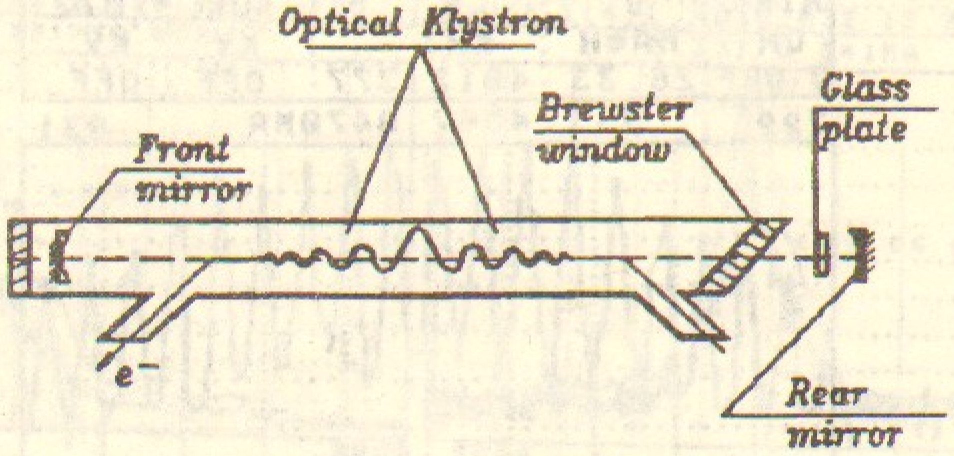

Fig 2. The updated optical cavity for lasing linewidth narrowing experiments.

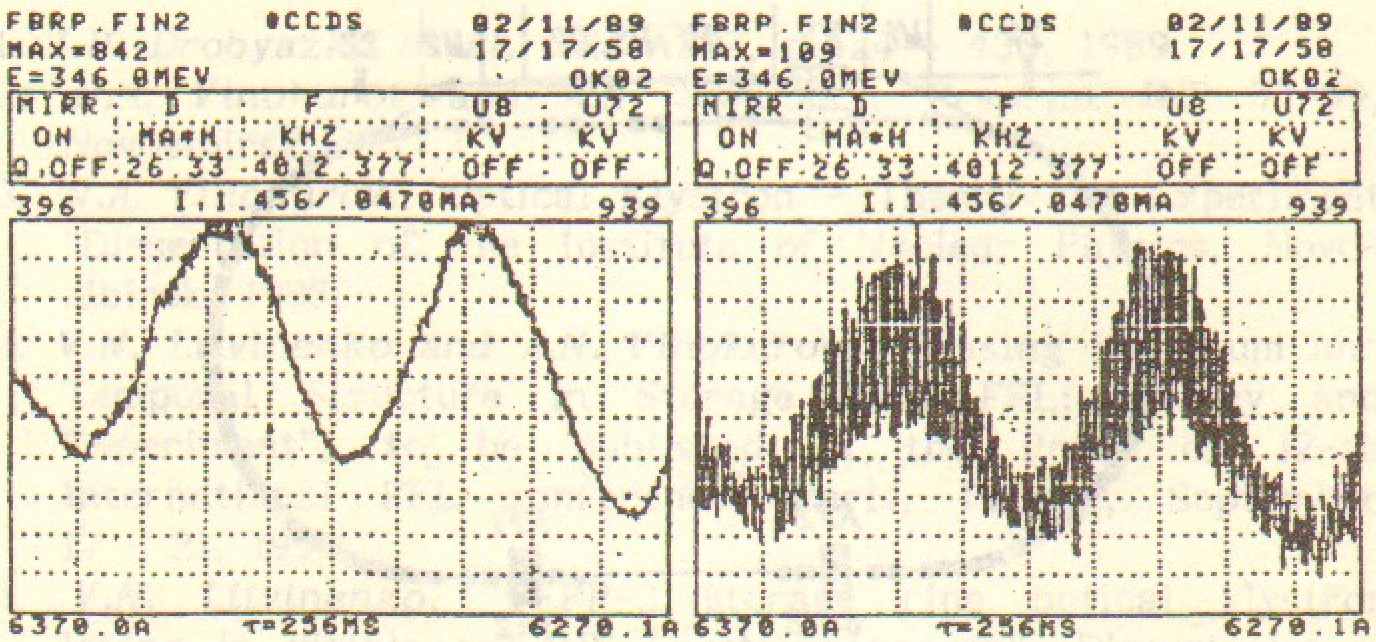

Fig. 3. The measured spectra of spontaneous radiation captured in the optical cavity: with (right) and without the intracavity plate.

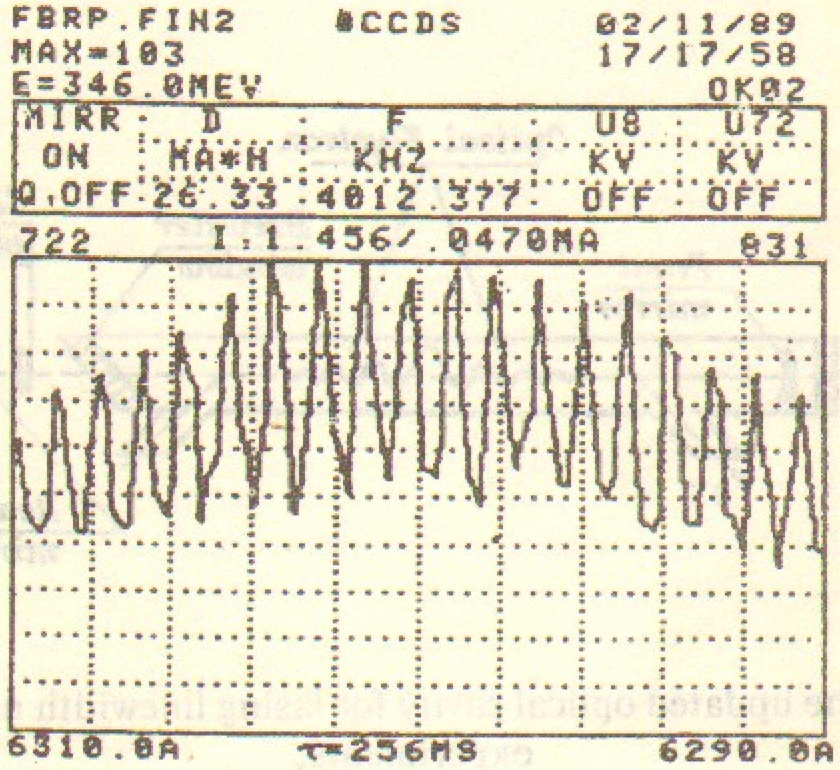

Fig. 4. The fine structure in the spectrum of the radiation captured in the modified cavity.

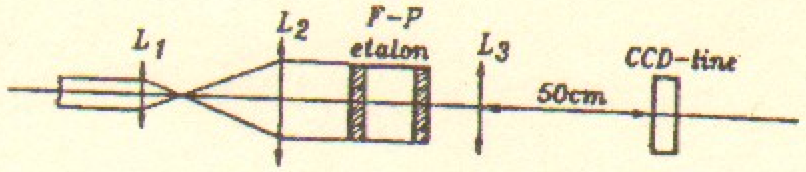

Fig. 5. The schematic layout of the linewidth measuring system

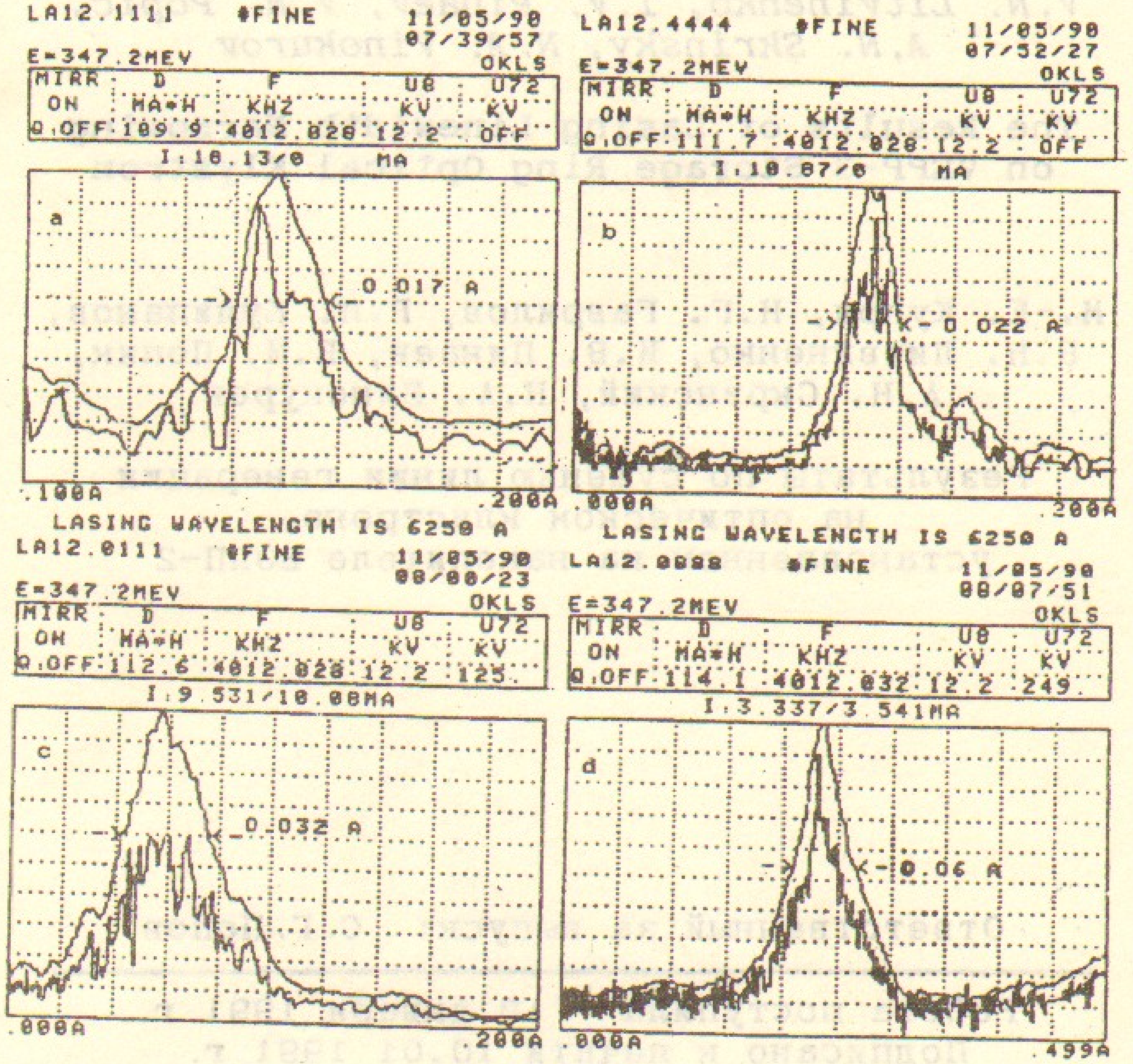

Fig. 6. The measured lasing lines:
a) $\Delta\lambda = 0.017$ Å, $\sigma_S = 35$ cm; b) $\Delta\lambda = 0.022$ Å, $\sigma_S = 30$ cm; c) $\Delta\lambda = 0.032$ Å, $\sigma_S = 10$ cm; d) $\Delta\lambda = 0.060$ Å, $\sigma_S = 8$ cm, and synchronization slightly detuned in this case. The linear scale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

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