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The results of lasing linewidth narrowing on the VEPP-3 storage ring optical klystron

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Lasing in visible and ultraviolet ranges was obtained using the optical klystron installed on VEPP-3 storage ring in 1988 [I B. Drobyazko et al., Nucl. Instr. and Meth. A282 (1989) 424] with minimum relative linewidth $\Delta\lambda/\lambda = 10^{-4}$. To decrease the linewidth we have performed the following experiments. The optical cavity of the VEPP-3 storage ring optical klystron has been updated to install intracavity selective elements. We used the simplest selective element – a glass plate with parallel faces as a natural interferometer Using 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, 2.7×10^{-6} (λ = 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 under way

1. Introduction

The optical klystron (OK) was proposed in 1977 by Vinokurov and Skrinsky [2] 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 the OK have been carried out in our institute since 1979.

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

2. The basic principles

The short-wavelength FEL usually operates in the so called synchronized mode where the electron bunches and optical pulses are much shorter than the optical cavity round trip time. The natural lasing linewidth here is defined generally by the FEL gain bandwidth. The FEL gain bandwidth narrowing is limited by the existing energy spread of the electron beam [3]:

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

This means that the gain bandwidth, $\delta\lambda_g/\lambda$, is usually greater than 10^{-3} whereas the natural FEL lasing linewidth, $\Delta\lambda/\lambda$, is 10^{-3}–10^{-4}.

It is quite natural to use an intracavity wavelength selective element to decrease the lasing linewidth. The simplest one is the Fabry–Perot etalon consisting of two parallel faces separated by a thickness d, with a 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 path length and we have assumed that there is no absorption in the etalon. The reflected field is generally not synchronized with the electron bunch and will be lost. This means that the round trip cavity losses will also be modulated with the period of $d_\lambda = \lambda^2/D$:

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

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

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

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

Let a wave packet passing through the optical cavity be represented by

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

where 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 transmission function is the following

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

If we do not admit a significant decrease in the FEL gain per pass, we should also assume that

$$D \ll \sigma_s, \tag{5}$$

where σ_s is a standard deviation of the longitudinal electron bunch density. This means that the electron bunch length in practice limits the minimum lasing linewidth in the case when the FEL operates in a synchronized mode:

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

In the optical range ($\lambda \sim 0.5$ μm) for typical electron bunch lengths 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 refs. [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 optimal synchronization between the optical and electron bunches is chosen (see ref. [4]);
(iii) the lased spectral density is much higher (a 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:

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

where $\sigma_r = \sqrt{2\sigma_s D}\ \sqrt[4]{R/G_0}$, $G(z) = G_0 \exp(-z^2/2\sigma_s^2)$ is the longitudinal gain function, $H_n(x)$ is the nth Hermite polynomial of x. The supermodes remain unchanged in the shape throughout the round trip of the optical cavity, except for a complex multiplicative factor:

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

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

where m is the pass number.

In steady-state lasing when the lased power P_l is quite high compared with the spontaneous radiation power on the basic harmonic P_{sp} (i.e. $D/\sigma_s \gg (q\lambda/\sqrt{2\pi}\,\sigma_s)(P_{sp}/P_l) \ln(D/\sigma_s)$, 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:

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

and the corresponding form in the k-space:

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

with

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

and the full width at half maximum of

$$\Delta\lambda/\lambda = 2\sqrt{2 \ln 2}\, \sigma_\lambda/\lambda. \tag{12a}$$

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

It we try to reach the minimum lasing linewidth the demands for the synchronization accuracy in the case of the intracavity etalon 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.

3. 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

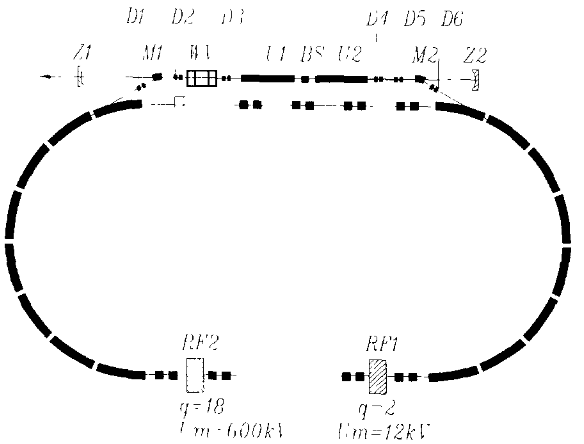

Fig. 1. The layout of the VEPP-3 storage ring with the bypass.

refs. [5,6]. 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 a buncher – 35 cm long three-pole electromagnetic compensated wiggler. The undulators allow a fundamental harmonic wavelength tunability from 0.1 to 1.5 μm by varying the magnetic field.

The optical cavity consists of two dielectric mirrors with 10 m radii of curvature, 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 synchronized mode. The optical β-function is 2.5 m in the OK center.

The average currents used for operation were approximately 20 mA, the horizontal emittance was $(2-4) \times 10^{-6}$ cm rad, the maximum peak current 6 A and σ_s was 10–100 cm depending on the rf voltage.

The maximum gain measured 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 of lasing in the visible and UV ranges can be found in ref. [1].

The optical klystron gain wavelength dependence is described as follows:

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

where Δ is the slippage in the OK buncher, $\psi = \pi q(k - k_r)/k_r$, $\lambda_r = 2\pi/k_r = (d/2\gamma^2)(1 + K^2/2)$ 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 ($\sigma_E/E = (3-10) \times 10^{-4}$) 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.

Experiments on lasing linewidth narrowing were generally done using only one electron bunch in the storage ring. This means that the maximum admissible losses were 5% per pass.

4. Requirements for the intracavity plate

A 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 normally slightly wedge-shaped and the incidence angle differs slightly from normal. Let us consider the radiation corresponding to the TEM_{00} transverse mode of the optical cavity passing 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:

$$I_r = I_0 2R\left\{1 - \cos kd\left(1 - \varphi^2/2n^2\right)\right\} \times \exp\left\{-k/4\left[\vartheta^2\beta_0 + (l\vartheta + 2\varphi d/n)^2\right]\right\},$$

where β_0 is the optical β-function in the optical cavity center, $\boldsymbol{\vartheta} = \boldsymbol{e}_1 - \boldsymbol{e}_2$, $\boldsymbol{\varphi} = \frac{1}{2}(\boldsymbol{e}_1 + \boldsymbol{e}_2) - \boldsymbol{e}$, $\boldsymbol{e}_1$ and $\boldsymbol{e}_2$ are the vectors normal to the front and rear plate surfaces, $\boldsymbol{e}$ is the unit vector of radiation propagation. If $|\boldsymbol{\varphi}|$ and $|\boldsymbol{\vartheta}|$ are small enough the minimum additional losses per pass are

$$\Delta p = Rk\left\{\vartheta^2\beta_0 + (l\vartheta + 2\varphi d/n)^2\right\}.$$

If $\boldsymbol{\varphi}$ and $\boldsymbol{\vartheta}$ are uncorrelated and Δp_{max} is the maximum admissible additional losses the following tolerances are required:

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

In our particular case $l = 8$ m, $d = 1.2$ mm, $n = 1.6$, $\beta_0 = 2.5$ m, so that for $\Delta p_{max} = 0.5\%$ we should have:

$$|\boldsymbol{\vartheta}| < 3'', \qquad \boldsymbol{\varphi}| < 0.4°.$$

5. The update of the optical cavity

Late in 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 to install different optical elements inside the optical cavity. The position of the rear mirror was changed to compensate for the difference in the optical path length.

A 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 saw a very fast degradation of the

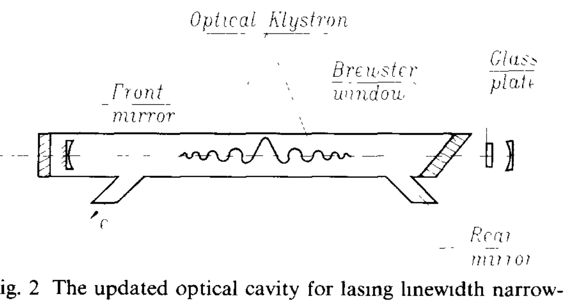

Fig. 2 The updated optical cavity for lasing linewidth narrowing experiments.

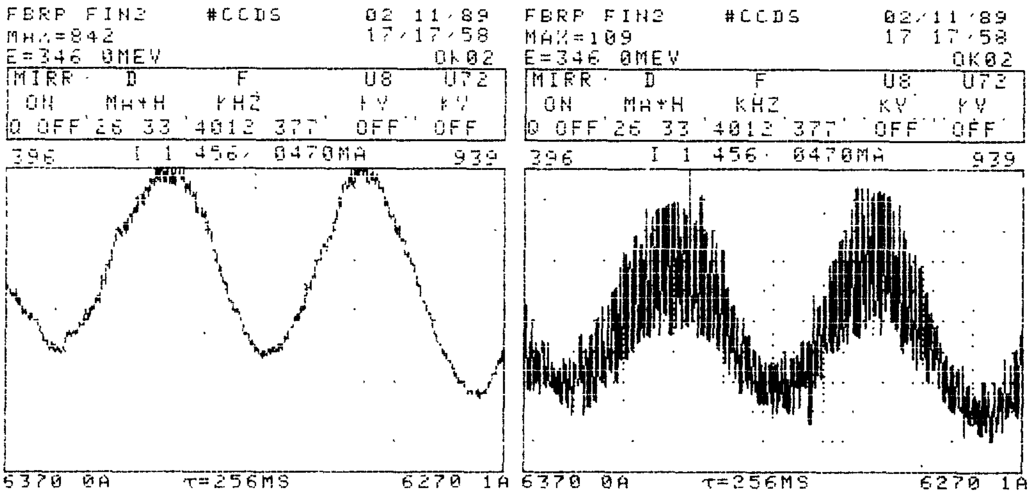

Fig. 3 The measured spectra of spontaneous radiation captured in the optical cavity: (right) with and (left) without the intracavity plate.

Brewster window transparency caused by a very weak UV and VUV radiation reflected by the front mirror. This is quite strange because the degradation of the front mirror reflectivity affected by the direct VUV and XUV radiation from the OK magnetic system was very small.

In March 1990 we installed a new mechanism of a Brewster window in conjunction with an indium sealing to have a possibility for changing the window.

Using 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 reinstalled the old vacuum channel. A new vacuum system for intracavity optical element installation was designed and is now under construction. We are planning to install it in autumn 1990.

Nevertheless, good results on lasing linewidth narrowing have been obtained using this configuration.

6. The measurements of the cavity losses modulation

For the experiments on lasing linewidth narrowing we used a glass plate 1.2 mm thick and 20 mm in diameter. The parallelism between two faces was better than 2″. 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 (right) the plate in the optical cavity. As can be seen, 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 estimate, we need to measure the linewidth with $\Delta\lambda/\lambda = (3–7) \times 10^{-6}$. Our old system comprising a monochromator with the resolution of $\Delta\lambda/\lambda = 2 \times 10^{-5}$ was insufficient. To have a resolution

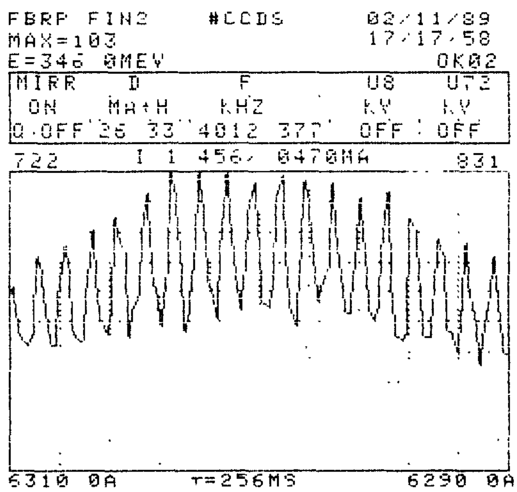

Fig. 4. The fine structure in the spectrum of the radiation captured in the modified cavity.

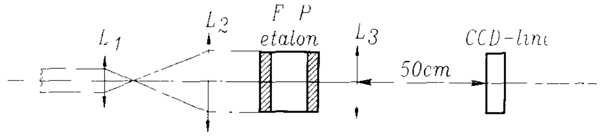

Fig 5. The schematic layout of the linewidth measuring system.

of the order of 10^{-6} we have made the system schematically shown in fig. 5. It comprises three optical lenses, an IT-51 Fabry–Perot interferometer (with the set of standard reference spacers) and a computer-controlled 1024 pixel CCD-array. 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 $\Delta\lambda/\lambda = 1.5 \times 10^{-6}$ when a 6 mm F–P etalon is used. The conventional He–Ne laser was used for resolution measurements.

The CCD-array measures the distribution of the interference rings. The data from the CCD can be processed and saved in files or displayed. The spectral density diagram displayed has a linear wavelength scale.

8. The results of lasing linewidth narrowing

As was mentioned above, lasing with the intracavity plate was 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 maximum gain.

Some measured lasing lines are shown in fig. 6. In 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 it was

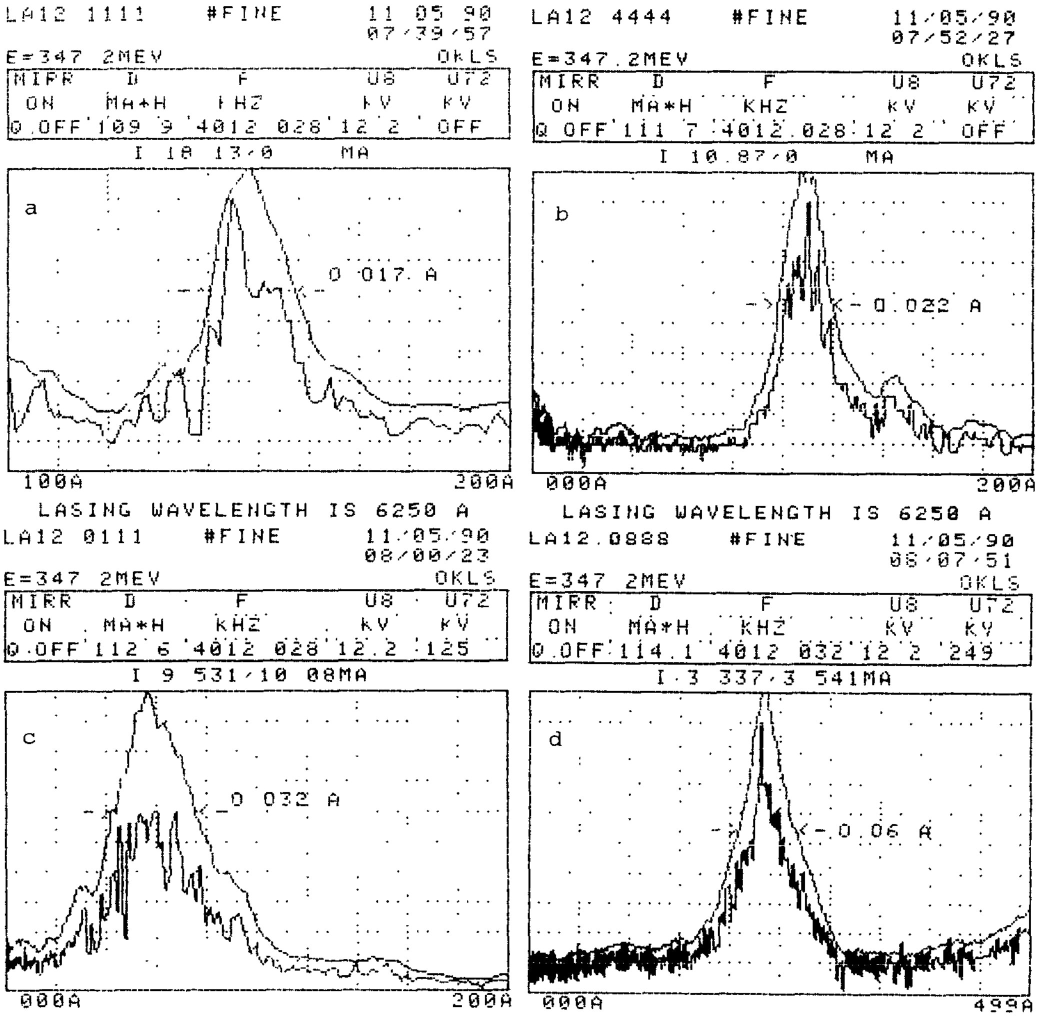

Fig. 6. The measured lasing lines: (a) $\Delta\lambda = 0.017$ Å, $\sigma_s = 35$ cm; (b) $\Delta\lambda = 0.022$ Å, $\sigma_s = 30$ cm; (c) $\Delta\lambda = 0.032$ Å, $\sigma_s = 10$ cm; (d) $\Delta\lambda = 0.060$ Å, $\sigma_s = 8$ cm, and synchronization slightly detuned in this case. A linear scale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

possible to reach lasing with quite a long electron bunch (up to $\sigma_s = 35$ cm) and minimum lasing linewidth of $\Delta\lambda = 0.017$ Å ($\lambda = 6250$ Å). This linewidth is in very good agreement with the predicted one (see eq. (12a), where $G_0 = 3\%$, $n = 1.6$):

$$\Delta\lambda/\lambda = 2.7 \times 10^{-6}.$$

After 20–30 h of operation the losses grew to 3–4% per pass and lasing was only observed with a high peak gain when the bunch length was quite short ($\sigma_s = 10$ cm). The minimum lasing linewidth in this case was $\Delta\lambda/\lambda = 5 \times 10^{-6}$ 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 $\sigma_r\sigma_k = 1$ corresponding to the Fourier limit. The typical value of $\sigma_r\sigma_k$ for conventional FEL operation is a few hundreds or thousands. It means that such a simple device as an intracavity glass plate can dramatically improve 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 the lasing linewidth varied within $(3–10) \times 10^{-6}$.

The lased power measured was the same to within 10% in both cases: with and without the intracavity plate. This is quite normal because the average lased power in the storage ring FEL is limited by the electron bunch energy spread growth induced by multipass interactions 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 important from different points of view:

(i) it gives a simple possibility to narrow the lasing line;
(ii) a very narrow lasing linewidth can be obtained 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: $\Delta k \Delta z = 1$;
(v) the requirements on the accuracy of the electron and light bunch synchronization is substantially simpler.

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

Acknowledgements

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.

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