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

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Lasing in the visible and ultraviolet ranges was achieved in the optical klystron installed on the VEPP-3 storage ring in 1988 [1] with a minimum relative linewidth of $\Delta\lambda/\lambda = 10^{-4}$ In order to decrease the linewidth we have performed the following experiments. The optical cavity on the VEPP-3 storage ring optical klystron was updated by installing intracavity selective elements. We used the simplest selective element – a glass plate with parallel planes as a natural interferometer With the use of a 1.2 mm thick glass plate installed inside the optical cavity we have achieved lasing with a very narrow linewidth. The minimum relative lasing linewidth, 2.7×10^{-6} ($\lambda = 6250$ Å, $\Delta\lambda = 0.017$ Å), was 30 times narrower than the minimum without the plate ($\Delta\lambda = 0.6$ Å). The average power was the same in both cases Experiments on lasing linewidth narrowing using plates of different thicknesses 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. Experiments with the OK have been carried out in our institute since 1979.

In 1988 lasing was achieved in the visible and ultraviolet ranges ($\lambda = 2400$–600 Å) with a fine tunability inside the reflection bandwidth of the mirrors we used. A minimum lasing linewidth of $\Delta\lambda/\lambda = 10^{-4}$ was obtained. This value was the best for a short-wavelength FEL but was quite large for spectroscopy and any other applications. This is the reason for our experiments on lasing linewidth narrowing. In recent experiments a 2.7×10^{-6} relative lasing linewidth was achieved 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 the electron and lased bunches are much shorter than the optical cavity length. The reason is that in this case the gain is proportional to the peak current instead of the average current. The natural lasing linewidth is defined here 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]:

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

This 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 (F–P) etalon consisting of two parallel faces with 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 is no absorption in the bulk. The reflected field is generally not synchronized with the electron bunch and will be lost. This means that the overpass cavity losses will also be modulated with a period $d_\lambda = \lambda^2/D$:

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

where p_0 is the losses 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 un-

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coated glass plate with parallel faces and $R=(n-1)^2/(n+1)^2 \ll 1$. In this case,

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

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

Let a wave packet pass through the optical cavity:

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

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 transfer is given by

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

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

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

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

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

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

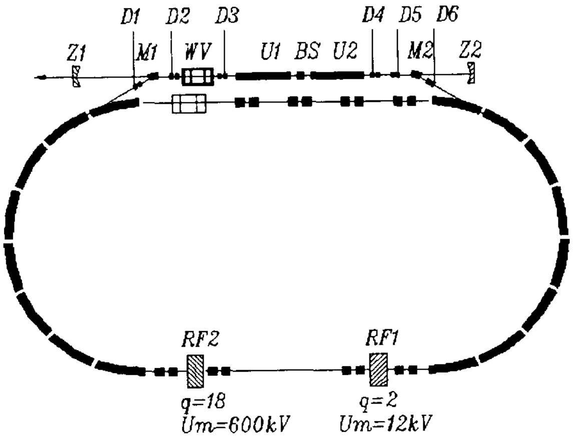

Fig. 1. Layout of the VEPP-3 storage ring with the bypass.

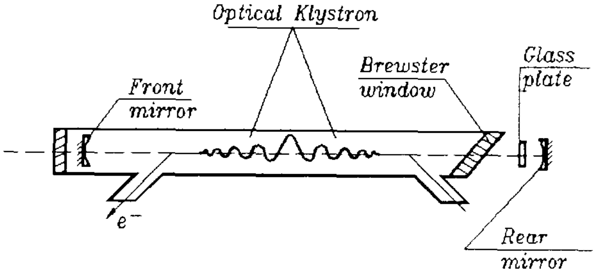

Fig 2 The updated optical cavity for lasing linewidth narrowing experiments.

A detailed description of the longitudinal dynamics can be found in refs. [4,5]. Here we will only 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 (by a few orders of magnitude) than the spontaneous spectral density;

(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, and $H_n(x)$ is the nth Hermite polynomial of x. The supermodes remain unchanged in shape throughout the round-trip of the optical cavity, except for a multiplication by some complex parameter:

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

$$\gamma_n = G_0 - p_0 - (2n+1)2D/\sigma_s\sqrt{G_0R}, \tag{9}$$

where m is the pass number.

In a 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. $D/\sigma_s \gg q\lambda/\sqrt{2\pi}\,\sigma_s \cdot P_{\mathrm{sp}}/P_l \cdot \ln(D/\sigma_s)$, where q is the number of undulator periods) 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 k-space:

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

with

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

and the width at half height

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

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

If we try to achieve the minimum lasing linewidth, the demands for the synchronization accuracy in the case of the intracavity used are also more realistic in comparison with a conventional mode of FEL operation. In our particular case, the accuracy requirement for the cavity length is 10–20 μm with the plate, as compared to 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 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 – a 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 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 when operating in the synchronization mode. The optical β-function is 2.5 m in the OK center.

The average current we use for operation is on the order of 20 mA, with a horizontal emittance of $2\text{–}4 \times 10^{-6}$ cm rad, maximum peak current of 6 A, and σ_s of 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).

Details regarding lasing in the visible and UV ranges can be found in ref. [1].

The dependence of the optical klystron gain on wavelength is described as follows:

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

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 ($\sigma_E/E = 3\text{–}10 \times 10^{-4}$) and the gain has a fine structure with a period $\delta\lambda_g = \lambda^2/\Delta = 20\text{–}40$ Å in the red range. The value of slippage Δ can be varied very precisely in order 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. This means that the maximum admissible losses were 5% per pass.

4. Requirements for the intracavity plate

A plate with exactly parallel faces installed at the normal incidence is absolutely transparent at a wavelength $\lambda = D/M$. But a real plate is slightly 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 will be given by the following expression:

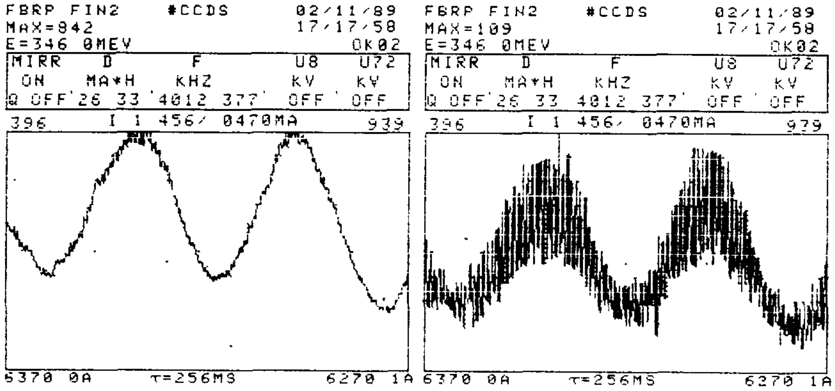

Fig. 3. The measured spectra of spontaneous radiation captured in the optical cavity, with (right) and without (left) the intracavity plate.

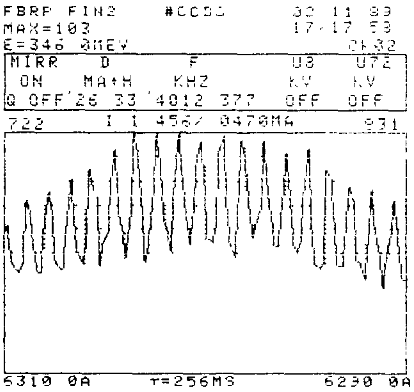

Fig. 4. The fine structure in the spectrum of the radiation captured in the modified cavity.

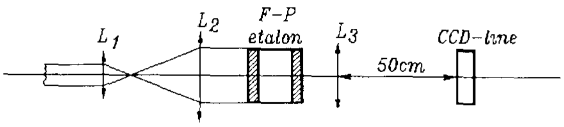

Fig. 5 The schematic layout of the linewidth measuring system

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

where β_0 is the optical β-function in the optical cavity center, $\phi = e_1 - e_2$, $\phi = (e_1 + e_2)/2 - e$, e_1 and e_2 are the normal vectors to the front and rear plate surfaces and e is the unit vector of radiation propagation. If $|\phi|$ an $|\vartheta|$ are small enough the minimum additional losses per pass are

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

If ϕ and ϑ are uncorrelated and $\Delta p_{\max}$ gives the maximum admissible additional losses, the following tolerances are required:

$$|\vartheta| < \sqrt{\frac{\Delta p_{\max}\lambda\beta_0}{4\pi R(l^2 + \beta_0^2)}},$$

$$|\phi| < n/2d\sqrt{\frac{\Delta p_{\max}\lambda\beta_0}{4\pi R}}.$$

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

$|\vartheta| < 3$ arc sec, $|\phi| < 0.4°$.

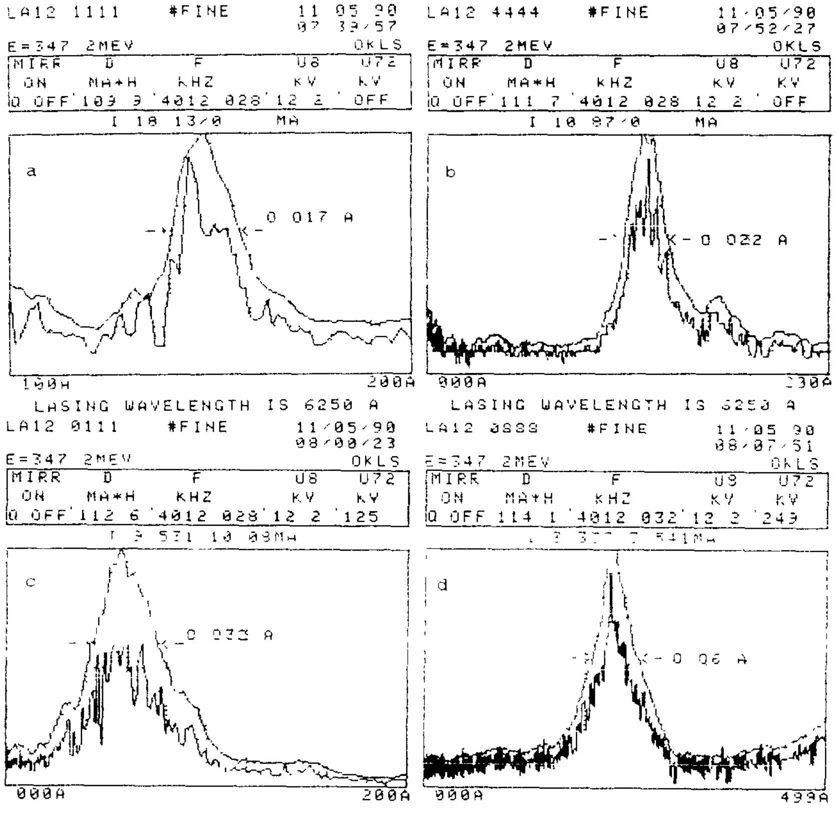

Fig. 6. The measured lasing lines (a) $\Delta\lambda = 0.017$ Å, $\sigma_s = 35$ cm; (b) $\Delta\lambda = 0.022$ Å, $\sigma_s = 30$ cm; (c) $\Delta\lambda = 0.032$ Å, $\sigma_s = 10$ cm; (d) $\Delta\lambda = 0.060$ Å, $\sigma_s = 8$ cm, and synchronization slightly detuned in this case. Vertical scale,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

5. 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 a 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. We changed the position of the rear mirror to compensate for the difference in the optical pass.

The Brewster window was welded to a stainless steel pipe and a special bellows provided the possibility of 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 observed a very fast degradation of the Brewster window transparency caused by 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 XUV radiation from the OK magnetic system was very small.

In March of 1990 we installed a new Brewster window conjunction mechanism with indium sealing to provide the possibility of 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 evident and in order not to waste time we have removed the Brewster window and returned the old vacuum channel to its original place. A new vacuum system for the installation of intracavity optical elements was designed and is now under construction. We are planning to install it in the autumn of 1990.

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

6. Measurements of the cavity losses modulation

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

The spectrum of radiation captured in the cavity was modified by 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 can be seen, a very fine structure appears with a period of approximately 1 Å (see fig. 4), in accordance with 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 lasing linewidth measurements

According to our estimations, we need to measure the linewidth to within $\Delta\lambda/\lambda = 3\text{–}7 \times 10^{-6}$. Our old system, comprising a monochromator with a resolution of $\Delta\lambda/\lambda = 2 \times 10^{-5}$, was insufficient. To obtain a resolution of the order of 10^{-6} we have constructed the system shown schematically in fig. 5. It comprises three optical lenses, a IT-51 Fabry–Perot interferometer (with a set of standard reference spacers) and a computer-controlled 1024 pixel CCD-line. The CCD is located in the focal plane of the L_3 lens with 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. A 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. The spectral density diagram is displayed on a linear wavelength scale.

8. The results of lasing linewidth narrowing

As mentioned above, lasing with an intracavity plate has been achieved in three runs (with the use of three different Brewster windows) in April, May and June of 1990. Operation of the OK in the red spectral range resulted in the maximum gain.

Some measured lasing lines are shown in fig. 6. At the initial stage, after replacement of the Brewster window, 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 achieve lasing with a rather long electron bunch (up to $\sigma_s = 35$ cm) and a 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. (12b), where $G_0 = 3\%$, $n = 1.6$):

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

After 20–30 hours of operation the losses grew to 3–4% per pass and lasing was observed with a high peak gain only when the bunch length was quite short ($\sigma_s = 10$ cm). The minimum lasing linewidth of $\Delta\lambda/\lambda = 5 \times 10^{-6}$ in this case 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 $\sigma_r\sigma_k = 1$ corresponding to the Fourier limit. The typical value of $\sigma_r\sigma_k$ for conventional FEL operation is a few hundreds or thousands. This means that such a simple device as an intracavity glass plate can dramatically improve the radiation quality, especially if we also take into account the fact that the transverse distribution corresponds to the basic TEM_{00} mode.

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 was almost the same (no more than a 10% difference) with and without the intracavity plate. This is quite natural because the average lased power in a 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 intracavity glass plates in a FEL is very promising from the following points of view:

(i) it provides a simple means to narrow the lasing line;
(ii) a very narrow lasing line can be achieved either in the steady state or in the pulsed 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 for the accuracy of the synchronization of electron and light bunches are substantially simpler.

We are planning to continue the experiments on lasing linewidth narrowing using thicker plates and longer electron bunches.

Acknowledgements

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