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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

VEPP-3 optical klystron lasing in a confocal optical resonator

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In the 18.68 m long confocal resonator at 6380 Å wavelength various combinations of transverse eigenmodes were excited by the VEPP-3 optical klystron misaligned with the resonator axis. Extracted from the resonator as two separated beams, the laser radiation was observed as well as the astigmatism and unconfocality effects. A confocal resonator seems to be suitable to use the "hole extraction" of either the FEL radiation or the electron beam microbunched in a FEL.

Experiments with an optical klystron (OK) [1] are being carried out on the VEPP-3 storage ring in our Institute since 1979. In late 1985 it was decided to upgrade VEPP-3. This modernization was aimed to install an additional straight section (bypass) dedicated for the OK operation. In 1988 the bypass was successfully installed on VEPP-3 and the lasing was achieved in visible and ultraviolet ranges ($\lambda = 2400$–6900 Å) [2] with a fine tunability inside a reflection bandwidth of dielectric multilayer mirrors we used. Later in the experiments on a lasing linewidth narrowing [3] by means of an intraresonator 1.2 mm thick glass plate, a lasing linewidth $\delta\lambda/\lambda$ of 2.7×10^{-6} was achieved. The smallest linewidth obtained previously had been 10^{-4}. In all these previous experiments we obtained the OK lasing in a near concentric optical resonator of 18.68 m length with 10 m radius of curvature mirrors.

In this paper we describe recent experiments on the OK lasing at the 6380 Å wavelength in a symmetric confocal resonator with the multilayer mirrors with the precise radii of curvature specially manufactured and checked [4,5]. Such optical resonator has a minus-unity round-trip matrix and thus the spectrum of its eigenmodes is degenerate [6]. Therefore an arbitrary radia-

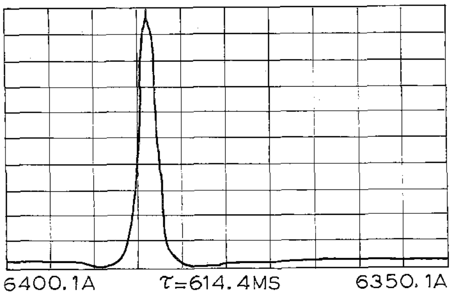

Fig. 1. The typical spectrum of the lased radiation.

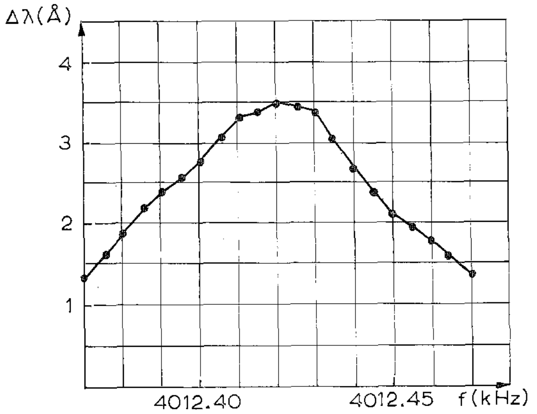

Fig. 2. The observed lasing linewidth $\Delta\lambda$ dependence on the VEPP-3 electron revolution frequency f.

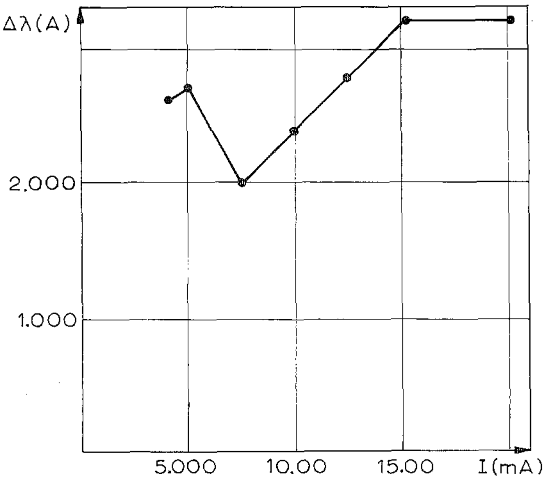

Fig. 3. The observed lasing linewidth $\Delta\lambda$ dependence on the VEPP-3 average electron current I.

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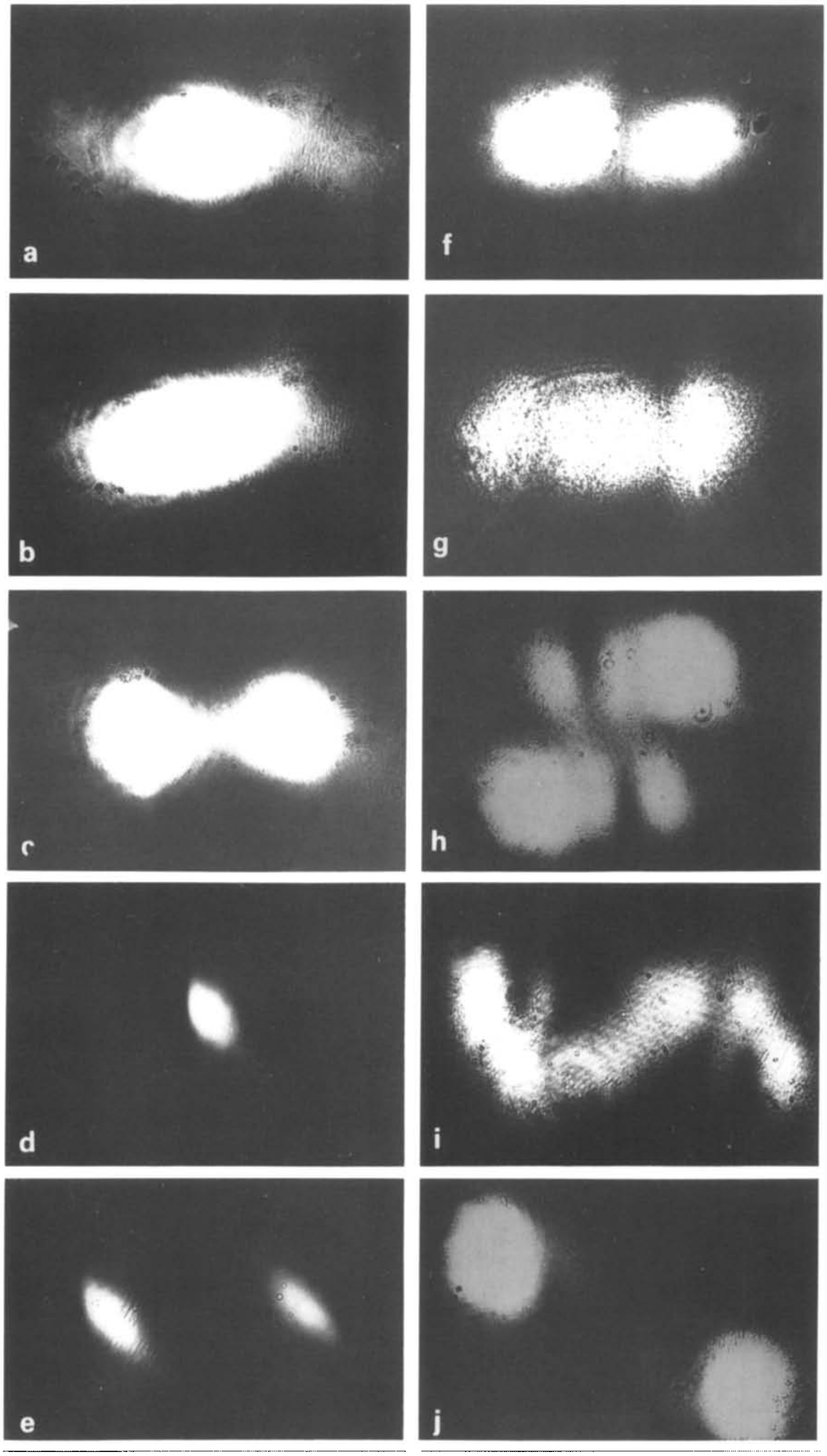

Fig. 4. The transverse distribution of the radiation lased in the R_3-R_4 unstable resonator (a), (b), (c), the R_2-R_3 slightly unstable resonator (d), (e) (in a scale about two times larger) and the R_2-R_4 stable resonator (f)–(j).

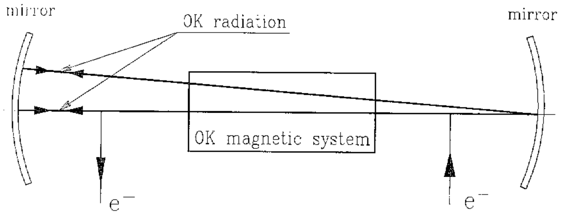

Fig. 5. The scheme of detuning the resonator rear mirror.

tion field will be reproduced after two round-trips of the radiation through the resonator (four reflections). This mode of FEL operation allows one to misalign the optical resonator with respect to an electron beam equilibrium trajectory. Moreover, in the confocal resonator the sizes of the stored light beam adapt to the sizes of the electron beam and the resonator apertures, so they are "self-optimized". These features are very promising for use of very long optical resonators.

In a single bunch operation of VEPP-3 we obtained the OK lasings in the confocal resonators consisting of all possible pairs of three mirrors with their measured curvature radii: $R_2 \approx 18.64$ m, $R_3 \approx 18.70$ m and $R_4 \approx 18.55$ m; and their reflection losses about 1%. Such three combinations correspond to the R_2–R_4 stable open resonator, the R_2–R_3 slightly unstable open resonator and the R_3–R_4 unstable open resonator [6]. For all pairs of our mirrors there were no significant differences observed in corresponding spectra of the laser radiation. The minimum observed lasing linewidth (with no a synchronization detuning between the electron bunch and the optical pulse) was about 2 Å corresponding to a relative lasing linewidth of 3×10^{-4}. The laser radiation spectrum is shown in fig. 1 for the R_2–R_4 pair of our mirrors. The observed lasing linewidth $\Delta\lambda$ dependence on the electron revolution frequency f (the synchronization detuning) and an average electron current I of VEPP-3 are shown in figs. 2 and 3 respectively.

More interesting pictures (see fig. 4) could be observed in the angular distribution of the OK radiation lasing with the confocal resonators. The first confocal pair of our mirrors with which we obtained lasing was an unstable open resonator consisting of R_3 as the front mirror and R_4 as the rear one. Observed through the front mirror, the transverse distribution of the radiation, lasing with a well aligned R_3–R_4 resonator, is shown in fig. 4a. For all confocal pairs of mirrors used, an angular width of such distributions was always close to that of a $\mathrm{TEM}_{00\mathrm{p}}$ transverse eigenmode of an open symmetric confocal resonator [6].

In a single bunch operation of VEPP-3 there is only one electron–light interaction per two radiation round-trips of the optical resonator. Therefore in an ideal symmetric confocal resonator of an infinite aperture the VEPP-3 OK lasing conditions do not require the mutual alignment of the electron equilibrium orbit and the resonator axis. To observe this property of the confocal resonators we tried to keep the OK lasing while detuning the rear mirror of the resonator by changing the angle (see fig. 5). For the R_3–R_4 resonator, the slightly misaligned lasing picture and the maximum misaligned lasing picture are shown in figs. 4b and 4c respectively. The biggest observed detuning while lasing was obtained with the R_2–R_3 slightly unstable resonator (see for example the aligned R_2–R_3 lasings and the maximum misaligned R_2–R_3 lasings in figs. 4d and 4e. The scale is approximately twice the others of fig. 4). Furthermore we observed an essential difference in the angular structure of the misaligned lasings in the unstable resonators and the R_2–R_4 stable one. In the unstable resonators this angular structure always looks like a misaligned single mode of the lowest transverse order TEM_{00}, whereas in the R_2–R_4 stable resonator it may contain one or a few modes of a higher transverse order (see: TEM_{01} in fig. 4f; TEM_{02} in fig. 4g; TEM_{11} and "misaligned TEM_{00}" in fig. 4h; a complicated mode combination in fig. 4i; maximum "misaligned TEM_{00}" and the weak tail, caused by the resonator unconfocality, in fig. 4j). In all confocal pairs

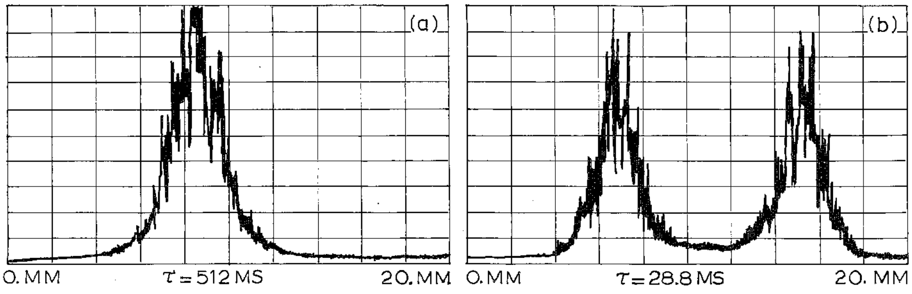

Fig. 6. Obtained by CCD, the horizontal distribution of the aligned TEM_{00} lasing (a) and the maximum "misaligned TEM_{00}" lasing (b) (from fig. 4j) in the R_2–R_4 resonator.

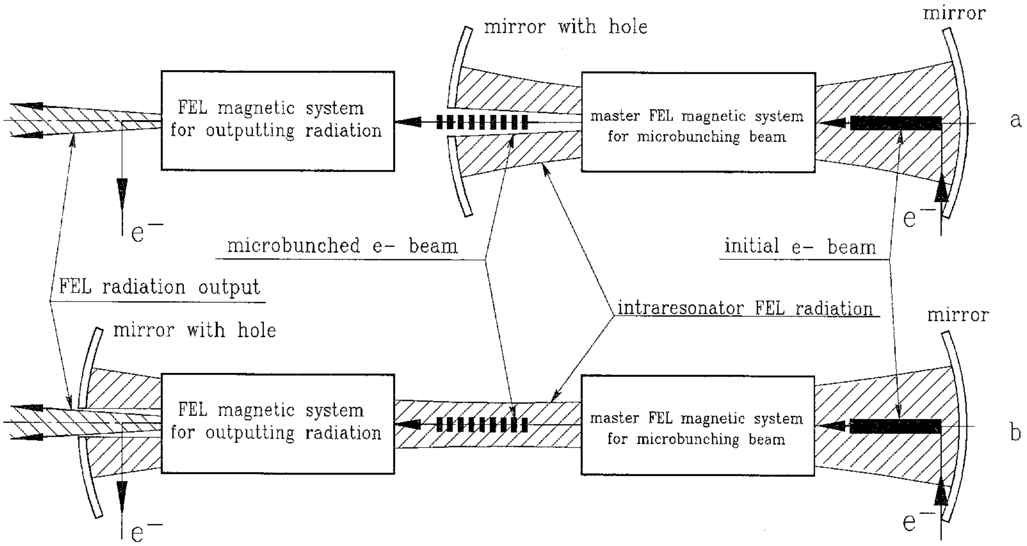

Fig. 7. The proposed FEL scheme using the "hole extraction" of either the microbunched electron beam (a) or the FEL radiation (b).

used we also noted a resonator astigmatism indicated by an anisotropy of the misalignment direction.

To obtain the spatial distribution of the laser radiation we used a one-dimensional charge coupled device (CCD). In figs. 6a and 6b we show the horizontal distributions of the aligned TEM_{00} lasing and the maximum "misaligned TEM_{00}" lasing (the same as in fig. 4j) in the R_2–R_4 resonator. Using a photomultiplier we observed that both misaligned lasing spots, like the ones shown in figs. 4e or 4j, have similar temporal structures, mutually delayed by one period of the resonator round-trip and consisting of periodic pulses separated by two periods of the resonator round-trip.

A confocal resonator seems to be suitable for obtaining the FEL lasing with a macroscopic hole centered in the front mirror of the resonator. Such a resonator may simplify the extraction of radiation from high-power FELs with opaque optical resonator mirrors. To solve this problem, one way called an "electron extraction of radiation" has already been suggested in our institute [7]. As in that method, the one proposed here is to use the electron beam passed through the master FEL magnetic system (MS) (an undulator or an optical klystron) in order to microbunch the electron beam at the radiation wavelength. An additional undulator is used to output the radiation. But unlike the "electron extraction of radiation", which uses an achromatic bend between the master FEL MS and the extraction undulator, it is possilbe by means of the a hole in the front mirror, to output either the microbunched electron beam (see fig. 7a) or the radiation from the additional undulator (see fig. 7b) whose fundamental radiation wavelength is scarcely longer than that of the master FEL MS. Like the "electron extraction", the "hole extraction" offers the possibility of greatly reducing the intraresonator radiation power as compared with the extracted power.

In the present experiments we also tried to obtain the confocal lasing with an intraresonator absorbing screen, about 1 mm of diameter, centered on the front mirror for simulating the macroscopic hole. But we could observe only the spontaneous radiation spectrum changes, caused by the OK gain, which did not exceed the lasing threshold. The question of the OK gain for the eigenmode of such hole confocal resonator needs careful analytic and numeric investigations, taking into account the electron beam emittance and the mirrors curvature radii deviations.

Acknowledgement

In conclusion we thank the staff of NPO "Astrophysica", which manufactured these precise curvature radii mirrors for the experiments presented above.

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