JINR ACTIVITY IN MICROWAVE SOURCES FOR TeV RANGE LINEAR COLLIDERS

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Results of theoretical and experimental studies of the microwave radiation sources on the base of the induction linac LIU-3000 (JINR, Dubna) are presented. In particular, a FEM-oscillator with the reversed guide magnetic field and Bragg resonator as well as an electron beam buncher in the two-beam accelerator (TBA) driver was studied.

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1. INTRODUCTION

Research works on the creation of powerful pulse sources of the millimeter range coherent radiation were begun at JINR in 1983 by V.P. Sarantsev's initiative. Soon the applied implementation of these studies was formulated: development and creation of high-efficiency narrow-band free-electron lasers (masers) (FEL, FEM) on the base of JINR linear induction accelerators for their application as pulse microwave power sources suitable for tests (up to the nominal level) of the high-gradient accelerating structures of linear colliders. In the investigations another orientation has clarified itself. It is the creation of an electron beam buncher on the base of the FEM or travelling wave tube (TWT). Recently the frequency fixation (30 GHz) has been defined that corresponds to the frequency of the accelerating microwave field for the CLIC collider [1].

2. FEATURES OF FEM-OSCILLATORS USING DIFFERENT TYPES OF BRAGG RESONATORS

2.1. PROBLEMS OF OSCILLATOR FREQUENCY SETTING

In 1994–1996 theoretical and experimental investigations of the FEM-oscillators with the Bragg resonators and reversed guide magnetic field were carried out at JINR in collaboration with IAP (N. Novgorod) [2,3]. At such magnetic field orientation the direction of the electron cyclotron rotation is opposite to the direction of the electron rotation in a helical wiggler (this field direction is marked by the sign “–“ in the text).

In the initial experiments we used mainly the traditional optical Bragg resonator with a smooth tube between corrugated mirrors (Fig. 1,a). Generation of H_{11} mode radiation was carried out in the frequency interval of 30–40 GHz.

The computer simulation and the experiments showed that it was possible to obtain both the single-mode and multi-mode regimes of the generation in such FEM-oscillators with different resonator Q-factor values in the steady-state mode of operation. With the resonator Q-factor value about 300–400 the oscillator provided the single-mode generation with the efficiency 20 –25%. When the resonator Q-factor was increased up to 1000–1500, the radiation spectrum was multi-mode and the oscillator efficiency decreased down to 8–12%. The detailed description of the simulation results and experimental data contains in [3].

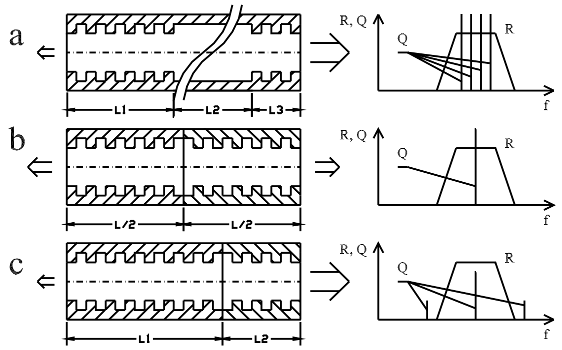

Fig. 1. *The schemes of the Bragg resonators (on the left): a) double-optical resonator with the section of the regular waveguide; b) symmetrical resonator with the corrugation phase step; c) asymmetrical resonator with the corrugation phase step. The reflection band and location of the frequencies of the resonator eigen modes (on the right).*

Comparison of the obtained experimental results with the parameters of the microwave power source required for the high-gradient accelerating structure of the CLIC collider is presented in Table. One can see that satisfactory results concerning the radiation pulse width and microwave pulse duration were obtained at the frequency close to the collider operating frequency. Low level of the output power was caused by the small electron beam power in the accelerator LIU-3000 (0.8 MeV, 200 A).

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Comparison of the microwave power source characteristics required for supply of the CLIC accelerating section with characteristics obtained for the FEM oscillator at JINR by 1997.

	CLIC demands	Obtained
Frequency, GHz	30	31
Spectrum width, %	0.3	0.25
Power, MW	200	35
Pulse duration, ns	140	40–100

However, for the utilization of such FEM-oscillator scheme for supply of the high-gradient accelerating structure some complicated technical problems must be resolved. First, the mode of operation of the single-mode generation in the stated FEM configuration is achieved at the final stage of interaction as a result of competition of several longitudinal modes being inside of the reflection band of the Bragg structures composing the resonator. These modes have the close Q-factors. Relative shift between them is about 0.5%, and they all grow at the linear stage of the oscillator operation. Consequently, to obtain the generation at the precisely fixed frequency, it is necessary to provide the stability of the electron beam energy and the FEM magnetic fields better than a part of percent.

Second, it is necessary to have a precise matching of the FEM-oscillator and mentioned structure frequencies for supply of the collider accelerating structure. The typical Q-factor values of the structure are equal to 300. So the upper limit of the admissible frequency mismatch composes $\delta\omega/\omega \approx 0.3\%$. The admissible error of the corrugation period must not exceed 0.1%, i.e. 5 μm if the corrugation period of the Bragg mirrors is about 5 mm. It is extremely difficult to meet so rigid requirements on the accuracy of the mirror fabrication, the magnetic field values and electron energy.

To solve the problems of fixing and smooth tuning the FEM frequency we investigated a FEM scheme, where the feedback was carried out with the help of the Bragg resonators with the phase step of the mirror corrugation (Fig. 1,b,c) [4,5]. The resonator consists of two Bragg mirrors of lengths $L_1 = L_2 = L/2$ (Fig. 1,b) (without the regular waveguide between them) with the corrugation phase step between the mirrors. There is the only high-Q oscillation in a resonator with the phase step equal to π in the reflection band of the Bragg structures, located in the middle of this band (the central mode). The Q-factors of the other oscillations, being close to the reflection band boundary (so-called side modes), is much less the Q-factor of the central mode. Thus, the electrodynamic selection in a resonator with a corrugation phase step provides such conditions in a FEM-oscillator when only the central mode excites and the single-mode mode of operation occurs already at the linear stage of the process.

The equality of the energy fluxes from the resonator in the forward (along the electron beam movement) and in the backward directions is the shortcoming of the symmetrical Bragg scheme (Fig. 1,b). One-way output of the radiation in the collector direction can be provided in the asymmetrical resonator with unequal lengths of the Bragg structures that is for shorter output structure (Fig. 1,c).

As a result of optimization of the corrugation depth and lengths of the Bragg mirrors very high for FEM-sources efficiency (up to 35%) was obtained in this scheme of the FEM-oscillator [6].

2.2. PRECISE FREQUENCY TUNING IN FEM-OSCILLATOR

In the FEM-oscillator with the corrugation phase shift there is a possibility not only to fix the oscillation frequency but also provide the precise tuning of this frequency. The results of the computer simulation of the FEM-oscillators with three different values of the corrugation phase steps (on π, π/2 and 3π/2) between the Bragg structures are presented in Fig. 2.

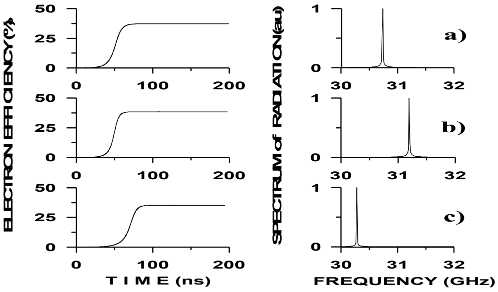

Fig. 2. *Simulation results for dynamics in the FEM oscillator for different values of the corrugation phase step φ: a) $\varphi = \pi$; b) $\varphi = \pi/2$; c) $\varphi = 3\pi/2$.*

Changing the step of the corrugation phase by π (that is the value corresponding to the half of the corrugation period) results in the oscillator frequency shift of ~ 1 GHz. We have the frequency shift $\delta\omega/\omega \sim 5–6\%$ when the length of the Bragg structure changes on 5 mm. So the range of the frequency tuning in the resonator with the step of corrugation phase is sufficiently larger than for the traditional resonator scheme.

It is important to note that under definite conditions the oscillator efficiency may be maintained practically constant when the phase step changes (see Fig. 2,a-c).

The scheme of the experimental setup was similar to one used in [5,7]. The electron beam energy of the accelerator LIU-3000 was increased up to 1.0 MeV. The electron beam currents before the injection into the FEM waveguide and at its output were measured to be 200 A and 160–180 A respectively. The beam pulse duration was about 250 ns.

The Bragg resonator consisted of two contiguous corrugated waveguides 26 cm and 13 cm long with the bore diameter 19 mm. The period of the corrugation and its depth were equal to 5.4 mm and 0.6 mm respectively. Changing the length of the initial section of the output Bragg structure we modified the value of the corrugation phase step. The power measurements were carried out with the help of two pulse crystal microwave detectors (measuring and monitor ones). The narrow-band filter set in the measuring detector scheme was used for the RF frequency defining in contrast to the cut-off filters used in the earlier experiments. The transmission bandwidth of the filter at the level of 3 dB was about 0.4 GHz. The measured output RF power in the frequency range 29–31 GHz (H_{11} mode) was at the level of 25–35 MW. The power level was not optimized. The radiation pulse duration was equal to 70–130 ns. The results of the frequency tuning measurements are given in Fig. 3.

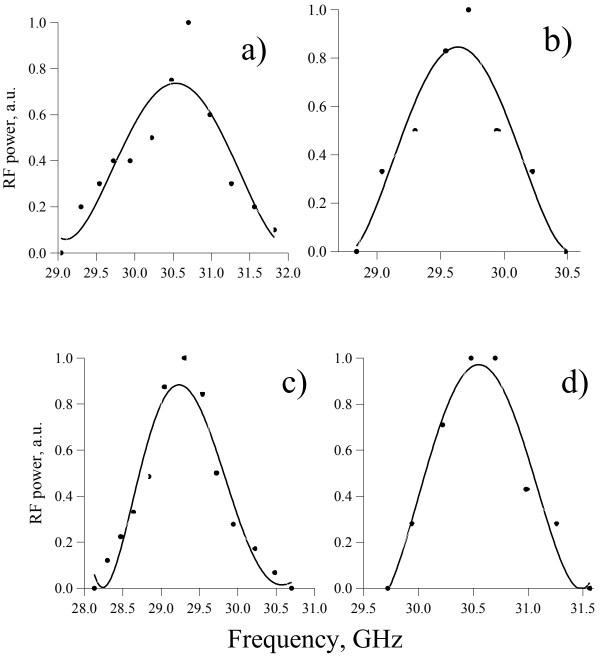

Fig. 3. *Output RF power versus the frequency for different values of the corrugation phase step φ: a, b) φ = π; c) φ = 3π/2; d) φ = π/2.*

Dependencies in Fig. 3,a and 3,b correspond to the phase step π between the Bragg reflectors and were obtained at the wiggler field values of .1550 T and .146 T respectively. The guide magnetic field was equal to –.206 T. Fig. 3,a corresponds to the excitation of the central mode of the Bragg resonator, and Fig. 3,b corresponds to the side mode, i.e. mode shifted on the half of width of the resonator reflection band. Measurement of the frequency of the FEM-oscillator central mode in the case of the phase step 3π/2 (Fig. 3,c) yields the frequency value close to the measured one for the side mode for the phase step π (Fig. 3,b). When the phase step was equal to π/2 (Fig. 3,d) the oscillator was not started up at the central frequency though the generation on the shifted downward frequency was observed.

From the comparison of the obtained results with the data of the computer simulations it follows:

– measured values of the central frequency and the frequency shift coincide with a good precision with the simulation results;

– the experimentally obtained spectral distributions have the broader frequency spectrum in comparison with the simulations results. Reasons of the spectrum broadening may be connected with the used method of measurement and demand a separate examination.

It is worth noting that the oscillator parameters in the given results of the computer simulations were chosen so that the single-mode generation rose already at the linear stage of the oscillator operation. However, in the experiment both the multi-mode and single-mode regimes of the generation were possible at the linear stage.

The electron beam bunching corresponding to the frequency of 30.6 GHz was registered with the help of a picosecond streak camera in these experiments as well as in the TWT experiments (see Section 3).

3. INVESTIGATION OF THE BEAM BUNCHING IN THE TWT AMPLIFIER

A novel scheme of two-beam accelerator driver is being currently studied at JINR [8]. In this scheme a synchronous microwave accompanies the electron beam along the whole driver. It should provide the high spatial phase stability of the output radiation. The scheme of the TWT amplifier is being studied for creation of the buncher for the low-energy electron beam.

The electrodynamic structure of the amplifier had the length about 45 cm and main radius 9.1 mm. The scheme of the experiments is shown in Fig. 4.

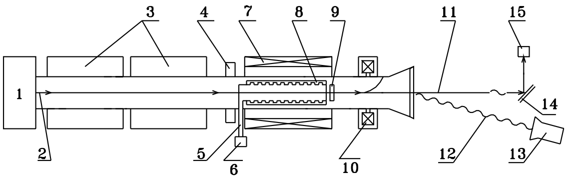

Fig. 4. *Scheme of the experiment: 1–electron gun; 2 –electron beam; 3–accelerating sections; 4–tuning magnetic lens; 5–microwave transmission line; 6–magnetron; 7–solenoid; 8–corrugated cylindrical waveguide; 9–quartz strip; 10–deflecting magnets; 11–optical Cherenkov radiation; 12–microwave radiation; 13–RF detector; 14–optical mirror; 15–streak camera IMACON-500.*

The slow electric type wave E_{01} of the oversize cylindrical waveguide with corrugated wall was chosen as an operating wave. The entrance signal was transmitted into the operating waveguide (8) from the magnetron (6) with the help of the quasi-optical system previously used in [9]. The microwave losses from the magnetron to the TWT input were ~ 13 dB. The electron beam parameters were as follows: 660 keV, 200 A, 200 ns. The uniform guide field of 0.1–0.2 T was used in these experiments and the input beam radius was tuned equal to 4–5 mm to reach the maximal output RF power.

The phase wave velocity value $\beta_{ph} = 0.86$ at the operating magnetron frequency $f = 36.4$ GHz was close to the electron beam velocity. The measured maximum of the amplified microwave power was equal to ~ 5 MW with the gain ~ 30 dB. Coincidence with the corresponding calculations was rather good.

We used a quartz strip with the thickness of 3 mm, width of 3 mm and refractive index $n = 1.46$ for the beam bunching measurements. The target was placed on the accelerator axis at the distance ~ 80 mm from the

TWT output. The electron bunches moved from the TWT exit to the quartz strip accompanied by the microwave, passed through the strip and generated Cherenkov radiation which was taken out through the vacuum window. Hereupon Cherenkov radiation was directed to the input slit of the streak camera with the help of the optical mirror.

The registered set of bunches is shown in Fig. 5. Sweep speed is equal to 13.3 ps/mm. Measured distance between bunches corresponded to the wavelength about 8.2 mm that coincides rather well with the working TWT frequency 36.4 GHz.

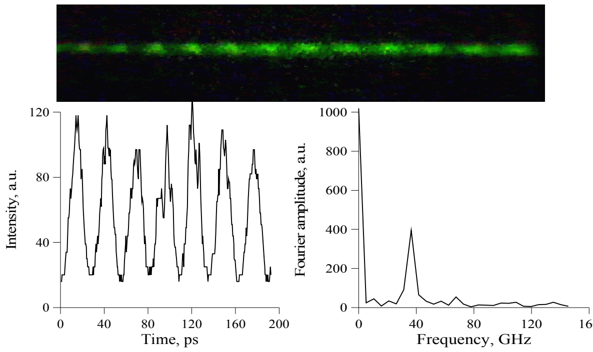

Fig. 5. *Temporal profile of the bunched electron beam recorded by the streak camera (top). Digitized intensity of streak-camera image (in arbitrary units) plotted versus time (bottom, left). The corresponding Fourier spectrum (bottom, right).*

The experimental bunching parameter was defined as the ratio of the Fourier components at 36.4 GHz and zero frequency, respectively. The measured value was ~ 0.4. It is close to the value obtained in [10] at the beam energy of 2.2 MeV.

The numerical simulation shows that the beam bunching completely disappears at ~ 4 cm after the TWT output if the amplified microwave does not accompany the beam. At the same time, the fulfilled experiments confirmed that the electron bunches keep high level of the bunching parameter at the distance ~ 10 cm from the TWT exit being accompanied by the amplified microwave.

4. CONCLUSIONS

As a result of the computer simulation and experimentally it was proved a possibility of creating a high-efficiency ($\eta \sim 25–30\%$), precisely tunable, narrow-band ($\delta\omega/\omega \sim 0.1–0.3\%$) FEM-oscillator using the reversed guide magnetic field and Bragg resonator.

The power of 5 MW in the E_{01} mode with the bunching parameter about 0.4 was obtained in the first set of the experiments aimed at the development of the TWT amplifier used as the electron beam buncher in the new scheme of the TBA driver.

The electron beam bunching was registered with the help of Cherenkov radiation in the FEM oscillator and TWT amplifier at the frequencies of 30.7 and 36.4 GHz respectively.

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