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FREE ELECTRON LASERS BASED ON HIGH CURRENT ELECTRON BEAM

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Summary. The stimulated radiation generation of intense electron beam with 1 MeV energy and current to 13 kA has been investigated. The radiation to 20 MW power in 7 ÷ 13 mm band with the pump by helical magnetic field of the undulator and to 6 MW in 3 cm band with the pump of 10 cm electromagnetic wave has been received. The dependences of output power on pump field, transverse focusing magnetic field and interaction field length have been studied.

Electromagnetic radiation generators, using the stimulated scattering phenomenon of pump wave on the electron beam and having received the title of Free-Electron Lasers (FEL) are intensively being investigated both theoretically and experimentally nowdays. The theory of FEL on the basis of intense electron beams when the collective effects are very important has been carried out by several authors.[1÷3] In the series of the experimental works the generation in the millimetre and submillimetre bands has been obtained. In these works the pump was either the powerful electromagnetic wave [4,5] or a static spatially periodic magnetic field [6,7].

The results of the experimental study of stimulated radiation of the intense beam of "TONUS" accelerator relativistic electrons[8] for the cases of pumping by magnetostatic field of a helical undulator and by the powerful electromagnetic wave are presented in this report. The experimental device scheme with helical undulator pumping is shown in Fig.1. 6 kA electron beam 60 ns duration has been accelerated in the diode gap of "TONUS" to 1 MeV energy and was propagated along the drift tube having 35 mm inner diameter. The experiment has been performed with a solid beam of 8 mm radius amd with the annular one of 10 mm outer radius and 8 mm inner radius. At 15 cm distance from the anode on the drift tube was placed 80 cm long helical undulator.

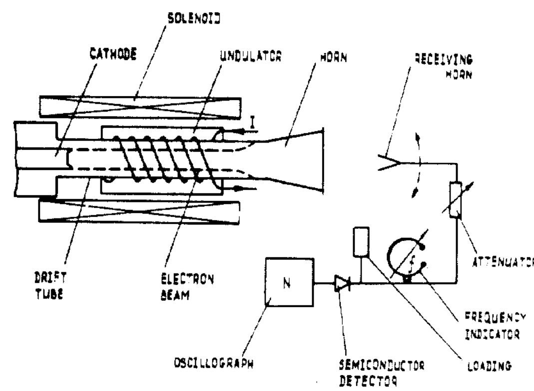

Fig.1

The undulators with periods $\ell_0 = 4$ cm and 2,8 cm were used in these experiments. The diode and undulator were placed in a longitudial uniform magnetic field of a solenoid with a value up to 1,2 T. The generated radiation was being brought out through a conical transmitting antenna. The part of this radiation entered the receiving antenna input and through the waveguide to the creogenic Ge detector. The radiation frequency was measured by the waveguide filters.

The dependences of the microwave radiation power v.s. the guiding magnetic field B_z and the undulator field $B_\perp$ are shown in Fig.2. The radiation power increase with the growth of the guiding magnetic field (Fig.2a) is provided by the beam current increase. The radiation power decrease at the high magnetic field may be explained by the fact that the saturation length becomes greater than the undulator length.[3]

The radiation power increase due to the undulator field growth (Fig.2b) is provided by the increase of increment instability, and the following decrease of the radiation power is apparently explained by the decrease of the electron current through the undulator due to the growth of the transverse rate. The guiding field growth increases the optimum value of the pump field and the maximum radiation power (Fig.2b).

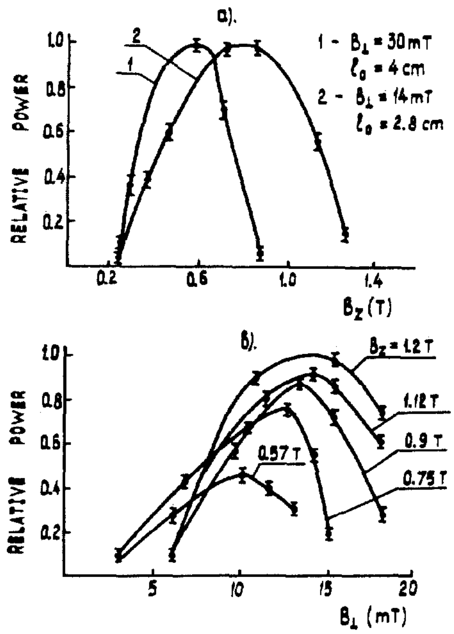

Fig.2

In a given experiment the dependence of the radiation wave length on the guiding magnetic field value is not found. At the same time the electron density increase in the beam provided the radiation wave length growth. It is possible the interaction is supposed to occur at the space charge mode. For the solid beam in the undulator with 4 cm period the generation of 2 MW power at 13 ± 1 mm wave length has been obtained and in the undulator with 2,8 cm period - 2,5 MW the same process takes place at the wave length 7,5 ± 1 mm. The generation with the annular beam was investigated only in the second undulator and for this case 20 MW power was received at 11 ± 1 mm wave length. Radiation pulse duration was equal to 50 ns.

Changing the length of the beam interaction space with the undulator field by means of the Al tubes, located in the drift tube along the undulator part and creating the screen for its field it was possible to determine the undulator optimum length equal to 60 cm. These experiments were made with B_z = 1,1 T and $B_\perp$ = 24 mT.

The measured efficiency of the energy transformation of the electron beam to the radiation energy was equal to 0,4 % and it was less than the theoretical value for the nonmonoenergetic beam (10 %) because the electron energy spread was equal to 10 %.

The investigation of the stimulated radiation at the electromagnetic 10 cm wave pump has been carried out also. To obtain rather intense radiation a very high (10^9 - 10^{10} W) power of the pump wave [4,5] is required. The necessary power values in 10 cm wave length band can be reached in a relativistic magnetion [9].

For simultaneous generation of the electron beam and powerful UHF pump wave the accelerator worked with two loads connected in parallel with the forming line. A relativistic magnetron and a highvoltage diode represented the loads.

During accelerator explotation in such a regime microwave impulses with a power up to 5 GW, 30 ns duration 10,2 cm wave length and electron beam with 0,8 - 0,9 MeV energy,13 kA current and 80 ns duration were obtained. The electron flow was formed in the diode with magnetic insulation placed into the uniform quasi-stationary magnetic field of a solenoid. Generated microwave energy through the wave guide entered the interaction region represented by a circular waveguide 90 cm length and 9,2 cm diameter.

In the experiments the scattering electromagnetic waves of E_{01} and H_{11} modes on the electron beam was studied at the various magnitudes of the guiding magnetic fields and the pump power. The annual electron beams of two different diameters equal to 54 and 74 mm with 1 - 2 mm thickness, which current was equal to 13 kA , were used.

In Fig.3 are demonstrated the scattering radiation power dependence with a wave length of 3 ± 0,2 cm v.s. the wave pump power of E_{01} and H_{11} modes at the various solenoid fields. At the E_{01} mode the power pump (Fig.3a) the scattering radiation power maxima were being displaced to the side of the higher values of the pump wave power with the increasing of the guiding magnetic field. The scattering radiation power maxima correspond to the generation saturation level at the given device length. During the further increase of the pump power the scattering radiation level decreases, it is connected with the device optimum length decrease. The displacement of the radiation maximum can be explained by the fact that with the increase of the guide magnetic field for reaching the generation saturation level the optimum device length increased. Therefore, to coincide the optimum device length with the real one the pump wave power is necessary to increase.

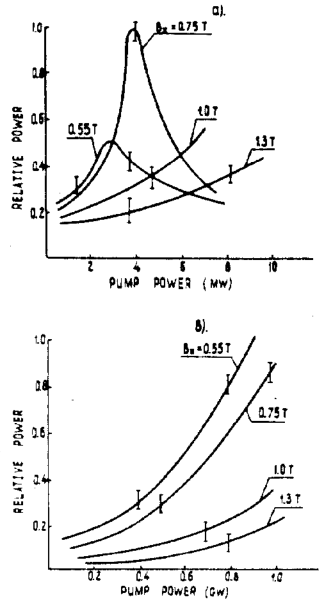

Fig.3

At H_{11} mode the power pump in the interaction space equal to 1 GW has been obtained. The maximum of the scattering radiation (Fig.3b) was not observed though the maximum level of the pump power greatly exceeded the E_{01} mode and the power of the scattered wave was comparable with the one at the wave pump of E_{01} mode. At the given device length the saturation level of generation was not evidently reached. The increment of the generation decreases with the growth of the guide magnetic field but increases with the growth of the pump wave power. This corresponds to the calculation data for the pump by the magnetostatic field [3].

As it is known, in the field of the pump wave the electrons of a relativistic beam make the transverse oscillations with a velocity $V_\perp$, which is directly dependent on the strength amplitude of the electrical field of the electromagnetic wave and is inversely proportional to the difference of the pump wave frequency according to the Doppler shift and the cyclotron frequency of the electron rotation [10]. It followes that for the effective usage of relativistic beam electrons representing in the magnetic field a set of oscillators for the scatteringwave it is necessary to keep the resonance condition $\omega_1 + k_1 V_0 \approx \omega_c$ where k_1 and ω are the wave vector and the pump wave frequency, respectively, $\gamma = [1 - (V_0/c)^2]^{-1/2}$; $\omega_c = eB_z/mc\gamma$ is a cyclotron frequency. As the made experiments show, if this condition is provided the wave transformation efficiency really increases (Fig.3a).

It shculd be also noted that the increase of the electron beam diameters leads to some power growth of the scattered wave by the pump with E_{01} mode and by the pump with H_{11} mode it leads to some decrease. Hence, the efficiency of the pump wave transformation is increased at the resonance condition. It is also found that the pump with the wave of E_{01} mode is more effective compared to H_{11} mode.

In our experiment the ratio of the scattered radiation frequency to the pump frequency is lower than the corresponding one by the scattering in a free space, equal to $4\gamma^2$. It can be explained by the larger efficiency of the high mode generation in a waveguide [5].

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