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CYCLOTRON AUTORESONANCE MASER WITH HIGH DOPPLER FREQUENCY UP-CONVERSION

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Introduction

The cyclotron autoresonance maser (CARM) [1-3] is a promising variety of free-electron masers (FEMs) operated in the millimeter and long-wave submillimeter regions with high power [4-10]. In this range, CARM requires particle energies significantly lower than for the ubitron (a most popular FEM variety) and magnetic fields smaller than those for the gyrotron. Thus, according to calculations effective CARM variants of megawatt and higher levels of average power operating at the wavelength of about 1mm with electron energies only 300 keV are possible employing strong magnetic fields of about 100 kOe (the regime of low Doppler frequency up-conversion) or magnetic fields of only 30-40 kOe but relatively high particle energies of about 1 MeV (the regime of high Doppler frequency up-conversion). In this paper we present results of new model experiments on the creation of CARM of the second type, i.e. having a high frequency up-conversion. We realized CARM operating at middle millimeter waves with high efficiency and radiation power.

Being a FEM variety, the CARM, like the gyrotron, is also a modification of a cyclotron resonance maser (CRM), i.e., it is a device which uses stimulated radiation of an electron beam propagating along helical trajectories in a homogeneous magnetic field. Unlike in the gyrotron, electrons in CARM interact with an electromagnetic wave $\exp i(hz-\omega t)$ propagating almost along their translational velocities ($h \cong k$, where $k = \omega/c$) rather than transverse to them. Therefore, it is clear from the condition of electron resonance with the wave:

$$\omega - hv_{\parallel} \simeq \omega_H, \tag{1}$$

that due to the Doppler effect the wave frequency in CARM at relativistic translational velocities of electrons, $v_{\parallel}$, greatly exceeds the frequency of particle oscillations (here it is the cyclotron frequency $\omega_H = eH/mc\gamma$):

$$\omega \simeq \omega_H \gamma^2, \tag{2}$$

where $\gamma = (1-\beta^2)^{-1/2}$ is a relativistic factor of electrons.

Another consequence of the quasi-longitudinal propagation of the wave in CARM (when the phase velocity $v_{ph} = \omega/h$ is close to the velocity of light c) is partial autoresonance [11,12] compensation of the variation of the electron frequency $\Delta\omega_H$ by the Doppler shift $\Delta(hv_{\parallel})$. By virtue of this compensation electrons resonantly interact with the wave even at considerable changes in their energies and at large enough rotational velocities of particles $v_\perp$ ($\beta_\perp \sim \gamma^{-1}$, where $\beta_\perp = v_\perp/c$) the CARM efficiency may amount to some tens of percent even in the simplest cases (without magnetic field and phase velocity tapering).

Such a compensation makes CARM low-critical to particle energy spread $\delta\gamma$. But like other FELs and FEMs, CARM is very sensitive to the spread in the pitch angles of particles. Indeed, the spread is acceptable only when the phase shifts of various electrons $\Theta = (\omega - hv_{\parallel} - \omega_H)\frac{L}{v_{\parallel}}$ during their interaction with the wave differ one from another by less than 2π. This imposes the following restriction

$$\delta\beta_\perp/\beta_\perp \lesssim 1/2bN, \tag{3}$$

where N is the number of gyrorotations and $b = \beta_\perp^2/2\beta_{\parallel}\beta_{ph}(1-\beta_{\parallel}/\beta_{ph})$ is the parameter characterizing electron recoil during radiation.

Thus, so as to attain high electron efficiency in CARM, the electron optical system must produce an electron beam with a sufficiently large rotational velocity of particles $\beta\sim\gamma^{-1}$ at small spread (the condition (3)). The electron efficiency of CARM is determined by the product of the so-called single-particle and orbital (transverse) efficiencies [2,3]:

$$\eta = \eta_{sp}\,\eta_{\perp}. \qquad (4)$$

The single-particle efficiency

$$\eta_{sp} = \frac{\beta_{\perp}^{2}}{2(1-\beta_{\parallel}/\beta_{ph})(1-\gamma^{-1})} \qquad (5)$$

is equal to the maximal portion of kinetic energy that can be withdrawn from a single electron in a homogeneous magnetic field by the wave of constant amplitude and phase velocity. The orbital efficiency $\eta_{\perp}$ characterizes the compactness of particle bunching. In the absence of spread in electron parameters, the value $\eta_{\perp}$ depends, in particular, on the amplitude of synchronous wave, its longitudinal structure and on the length of interaction space. For typical CARM parameters, the maximal values of $\eta_{\perp}$ without magnetic field profiling lie within the 0.3 - 0.6 range.

Linear Induction Accelerator. Evaluation of Design Parameters for CARM

CARM was studied on a LIA - unit [13] 180 cm long that consisted of 18 inductors with permalloy cores, fed

from a single modulator (Fig.1,2). Inside the unit, a strong magnetic field was produced to focus particles with the pulse duration 1.2 ms and the magnitude controlled within 0...15 kOe. The accelerator unit is connected through a transition chamber to an additional solenoid where the microwave device to be studied is placed. The magnetic field in the additional solenoid has the duration of 5 ms and controlled within 0...15 kOe.

The electron gun with explosive emission is installed directly in the accelerator unit. The graphite cathode and anode are situated in the first third of the accelerator unit, so that accelerating fields from the first 6 inductors are summarized. The maximal measured energy of accelerated electrons is 1.5 MeV at the current 1.5 kA and pulse duration about 60 ns. In this regime the accelerating gradient is equal to 10 kV/cm in the last 2/3 of the accelerator unit.

So far as the distance from the cathode to the HF section is about 2 m, high magnetic field homogeneity and precise alignment of the components are required for beam transportation in the electrodynamic system. In the experiment a thin axial electron beam with OD =3 mm (Fig.3) was transported through a metal tube with ID =10 mm d and up to 0.5 m long. By this the measurements of current and location of the electron beam in the HF section with a movable Faraday cylinder and a dielectric target showed that electron losses were practically absent and the beam position was controlled with 1 mm accuracy.

Based on the peculatities of the LIA, we set ourselves the task of creating a CARM-generator that would combine high Doppler frequency up-conversion and high efficiency. The design electron energy was taken to be in the range 1...1.2 MeV. When choosing the phase velocity of the wave in the region of $(1-\beta_{ph}^{-2})$ varying from $\gamma_\perp^{-2}$ to zero for

Figure 1. The induction linac-unit

such an energy and rotational particle velocity $\beta=\gamma_\perp^{-1}$, the Doppler frequency gain may amount to $\omega/\omega_H=$ 7...10.

Looking for the ways to minimize the role of particle velocity spread we chose a relatively short interaction space for electrons and the wave when the number of cyclotron rotations N=5...7. Correspondingly, the phase velocity of the wave was chosen not very close to unity β_{ph}=1.03...1.06, so that the length was almost optimal, when

for the parameter of inertial particle bunching [2,3]

$$\mu = \pi\beta_\perp^2 \frac{1-\beta_{ph}^{-2}}{(1-\beta_\parallel/\beta_{ph})^2} N \qquad (6)$$

we obtained μ =5...8. The magnetic field allowed for the

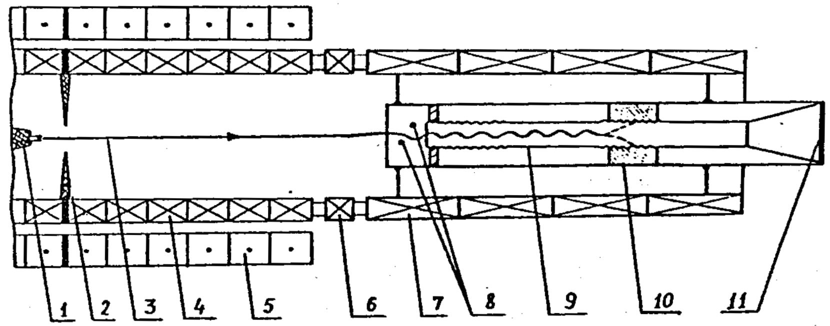

Figure 2. Scheme of the experimental setup: 1 - explosive-emission cathode, 2 - anode, 3 - axial electron beam, 4 - LIA-unit solenoid, 5 -inductors, 6 - transition chamber, 7 - sectioned additional solenoid, 8 - kicker loop, 9 - Bragg resonator, 10 - copper ring (magnetic screen) for magnetic field attenuation that provides electron collection, 11 - RF window

operation at millimeter waves. For experimental studying we chose two regimes with λ=4.4 mm and λ=6.0 mm which were determined by electrodynamic system. The corresponding magnetic field values were 10 kOe and 7 kOe.

For the parameters given above, the single-particle efficiency is rather high: η_{sp}= 0.5. Under a

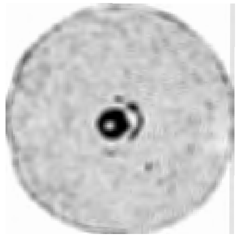

Figure 3. Trace of the electron beam on a dielectric film

constant amplitude of synchronous wave, the orbital efficiency without velocity spread is $\eta_\perp$=0.35 and total electron efficiency amounts to η=0.17. Calculations show a two-fold decrease in efficiency with a rather large spread in rotational velocities $\delta\beta_\perp/\beta_\perp \sim 0.2$, in this case the starting current of the generator increases by two times.

The Formation of a Helical Electron Beam with Low Velocity Spread

So as to produce in experiment a helical electron beam, at first we form a dense rectilinear beam and then put to the particles rotational velocity in an inhomogeneous magnetic field of a kicker (Fig.4). The rectilinear beam is produced in an explosive-emission injector in the form of a co-axial diode with magnetic insulation. In such a system the

initial (parasitic) rotational velocity that is caused by particle drift in crossed electric and magnetic fields changes from zero to $\beta_\perp = E/H$, where E is the maximal transverse electric field in the emitter region. In our experiment the parasitic electron velocity in the beam was estimated to be less than 0.01. On the formation of a rectilinear beam it is necessary to put to the particles equal rotational velocities. To ensure against spread it is essential that electrons in the beam of finite thickness should pass through the region of a perturbing magnetic field, preferably homogeneous in the transverse direction.

The simplest way to excite a thin continuous axial beam used in the experiment is to employ a kicker that consists of two current-carrying linear conductors perpendicular to the focused field and located on both sides of electron trajectories (Fig.4)[14]. In this case the sensitivity to the position particle spread is minimum when the distance between the currents in the direction of the focused magnetic field is equal to half a Larmor step $L_H = 2\pi v_\parallel/\omega_H$ and the currents have opposite directions. Then,

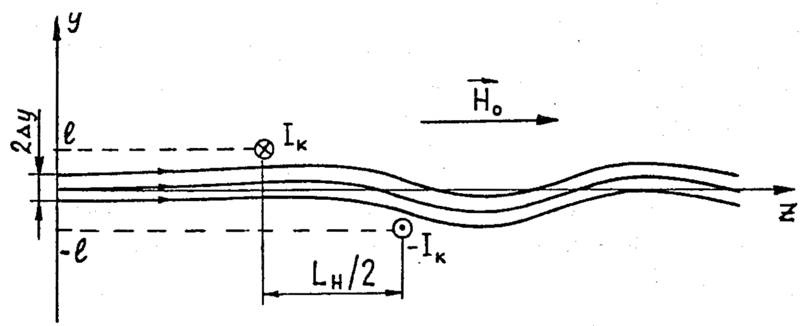

Figure 4. Electron trajectories in the kicker

in the transition between the conductors with relatively low currents I_k at a distance l from the plane $y=0$, the electron having the initial coordinate y_0 acquires a rotational velocity [14]:

$$\beta_\perp = \frac{4\pi I_k}{\gamma mc^3} \exp\left(-\frac{2\pi l}{l_H}\right) \mathrm{ch}\left(\frac{2\pi}{l_H} y_0\right). \tag{7}$$

It is clear from this expression that for a thin beam the spread in rotational velocities depends rather weakly (quadratically) on the beam thickness $2\Delta y$:

$$\delta\beta_\perp / \beta_\perp = \frac{1}{2}\left(\frac{2\pi\Delta y}{l_H}\right)^2. \tag{8}$$

According to calculations this estimate is also valid for relatively large kicker currents I_k, when the kicker imparts to the particles the rotational velocity $\beta_\perp \sim \gamma^{-1}$ needed for effective operation of CARM.

So as to decrease velocity spread and to simplify beam alignment in the experiment, the cathode diameter was chosen rather small: precisely, 3 mm and, correspondingly, the diameter of the electron beam was close to 3mm (Fig.3). The current I at operating voltages was measured to be 0.3...0.5 kA.

For the design electron energy and magnetic field, the unperturbed Larmor step was 3.3 cm. Consequently, the longitudinal distance between the kicker conductors was 1.7 cm. In order to obtain the needed rotational velocity $\beta_\perp \sim 0.3$ and prevent the beam from brushing against the conductors the transverse distance between them $2l$ was chosen to be 6 mm. The design current in the kicker was I_k=2.6 kA. With

exact beam alignment the design spread acquired by electrons in the kicker is very small: $\delta\beta_\perp/\beta_\perp$=3%; however, taking into account the initial spread acquired in the region of explosive-emission gun, the spread in the transverse velocities of the drived beam may amount to 9% , which is two times lower than the admissible value.

Selective Feedback

In our experiment, like in the most previous investigations of CARM [15-18], a lower $\mathbf{H}_{1,1}$ mode of a regular circular waveguide was chosen for an operating mode. An important feature of our experiment is that we used a thin axial electron beam instead of a hollow one. Such a beam is able to excite only the waves with the azimuthal index m=1. Operation at the $\mathbf{H}_{1,1}$ wave (or at a higher $\mathbf{H}_{1,n}$ wave) that has almost homogeneous distribution of a HF field in the axial region, is also convenient because we have low sensitivity of the system to the position of the electron beam.

For the chosen parameters of the electron beam and of the phase velocity of the wave , their dispersion curves intersect at two points or are tangential (Fig.5). High-frequency intersection with the parameters of the wave λ=4.4mm and β_{ph} =1.035 fit the first design regime (point 1 in Fig.5). Parasitic LF intersection corresponds to λ =11 mm, β_{ph} =1.31 and to a relatively small group velocity β_{gr}=0.76 (point 3 in Fig.5).

To ensure single-frequency operation, the electrodynamic system should provide selective excitation of

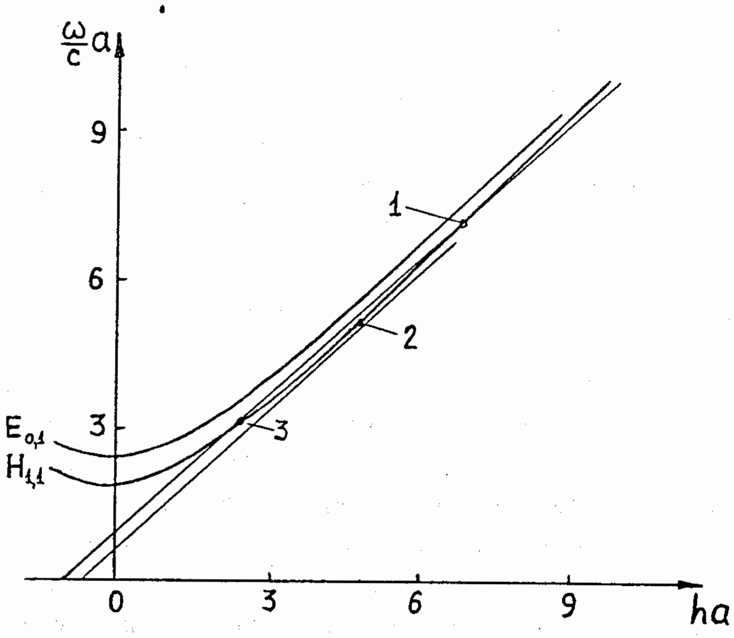

Figure 5. Brillouin diagram for CARM

a HF mode and discriminate LF oscillations. Like in [8], this task may be solved using for the operating mode a Bragg resonator with reflectors in the form of waveguide with periodically corrugated wall (Fig.6) [16,17,15]. We would like to note that Bragg resonance re-reflection $H_{1,1}$ of the wave into itself in an oversized waveguide with admissible corrugation depth and with the above specified phase velocity of the wave that is very close to the velocity of light (which corresponds to small Brillouin angles of wave $\varphi = 14^{\circ}...19^{\circ}$) has a fairly small coupling coefficient. Therefore such a reflector is too long and it is unsafe to

use it on the cathode side of the resonator because of possible excitation of parasitic LF modes. The coupling coefficient can be increased and the reflector length shortened almost by two times using the corrugation with resonant reflection of the operating wave into higher modes (in our case $E_{1,1}$ and $E_{1,2}$ for wavelengths 6 mm and 4.4 mm, correspondingly). In the regular section of the resonator with such a reflector, a synchronous wave $H_{1,1}$ propagates in the direction of electron propagation, and a nonsynchronous feedback wave travels in the opposite direction (Fig.6). At the output reflector the wave $H_{1,1}$ is transformed into the wave $E_{1,2}(E_{1,1})$ that is converted into $H_{1,1}$ at the cathode reflector.

The desired values of reflectivity are found from the following requirements: the electron current I should be close to the optimal current I_{opt} that corresponds to the maximal value of orbital efficiency $\eta_{\perp}$ for design beam parameters. The value I_{opt} is found from the numerical solution of equations of electron motion in a self-consistent wave field [18].

The optimization was made under the assumption that because of a sharp droop of the guiding magnetic field at the collector end, the electron-wave interaction ceases after passage of the input mirror and of the smooth resonator section. Electrons perform seven cyclotron oscillations at this length. On the basis of calculations we chose the reflection coefficients at which the start oscillation current was about 120 A and the optimal current I_{opt} was about 4 times greater than the start one. These optimal conditions were achieved only for the regime with the

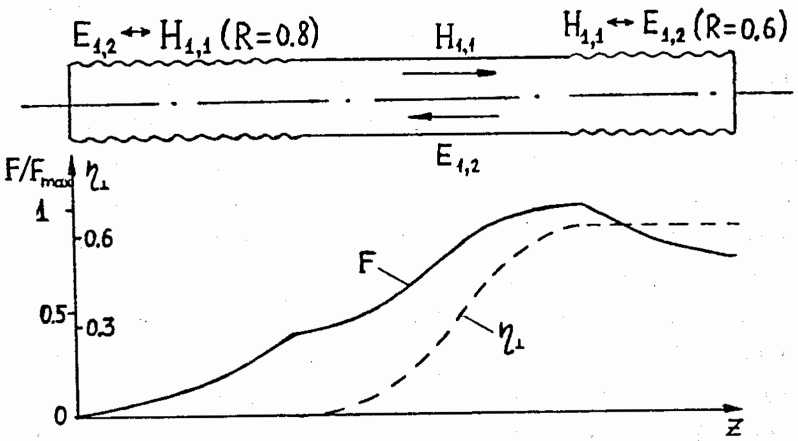

Figure 6. Bragg resonator: scheme of feedback and "hot" field and efficiency structure

wavelength λ=4.4 mm. In this case the field structure of a synchronous wave, like the field structure in TWT, grows towards the output (Fig.6), which favors a substantial increase in transverse electron efficiency up to $\eta_\perp$=0.57 (cf. the case of constant-amplitude wave where $\eta_\perp$=0.35). Taking into account velocity spread of 9% and the fact that part of the power of operating wave passes towards the cathode, the design efficiency for the first regime is η=20%. The final values for design parameters of a CARM-generator are listed in the Table.

"Cold" electrodynamic measurements of Bragg resonator parameters showed that the Q-factor of the operating mode coincided to an accuracy of 10% with design values.

Experiment

The scheme of the experimental setup is presented in Fig.2. A thin axial beam produced in the LIA-unit acquires rotational velocity in the kicker, passes through Bragg resonator and it is settled near the output mirror by means of a bulky conducting cylinder shielding the pulsed magnetic field of a solenoid. The generated wave is radiated out of the horn through the output dielectric window. The microwave radiation was diagnosed by means of a calibrated semiconductor detector and visually by a neon light panel. Besides, the radiated power allowed for the air breakdown at the focus of a parabolic mirror at atmospheric pressure. The extent of the microwave breakdown enables one to estimate the level of output power. The radiation wavelength was determined by means of waveguide filters, as well as an echelette that provided an accuracy of about 5% in the range λ=3.6 5.8 mm.

Experiment performed with the parameters close to the calculated values ($\mathcal{E}$=1.2 MeV, I=500 A and H=10 kOe) yielded the $H_{1,1}$ wave generated with predominant radiation at the desired wavelength λ=4.4 mm and with the maximal output power of 50 MW. The efficiency amounted to about 8%. A significantly lower efficiency, compared to the calculation is explained evidently by parasitic radiation with a rather broad spectrum (about 40%) at a frequency close to the operating one . The power of this parasitic superluminiscence depends weakly on the parameters of electrodynamic system and in the absence of resonator reaches a value comparable with the radiation power at the operating frequency in the

A M parameters	λ=4.4 mm design	λ=4.4 mm experiment	λ=6.0 mm design	λ=6.0 mm experimen
electron energy $\mathcal{E}$(MeV)	1.2		1.0	
electron current I(kA)	0.5		0.3	
Doppler frequency up-conversion ω/ω_H	7.7		8.3	
magnetic field H_0(kOe)	10		7	
transverse velocity $\beta_\perp$	0.3	0.25	0.25	0.25
velocity spread $\delta\beta_\perp/\beta_\perp$	0.09	----	0.1	----
operating mode (feedback wave)	$H_{1,1}$ ($E_{1,2}$)		$H_{1,1}$ ($E_{1,1}$)	
reflection coefficients	R_1=0.80	R_2=0.60	R_1=0.56	R_2=0.37
starting current I_{st}(kA)	0.12	----	0.14	----
efficiency %	20	8	12	10
output power P_{out}(MW)	120	50	36	30

Table. CARM Parameters

presence of resonator (Fig.7a). As it is seen from the experimental dependence drawn in Fig.7a for the radiation power versus electron driving, the resonator is excited effectively when the transverse electron velocity is rather

small and the level of parasitic noise decreases. However, this value of transverse velocity is lower than the optimal one. The powerful superluminiscence observed in experiment is evidently caused by a sufficiently high level of parasitic input signal that is contained in the noise modulation of the electron beam produced by means of explosive emission, as well as by a rather high gain and a wide amplification band. Thus, according to calculations, energy modulation of the beam at the operating frequency with a relative amplitude only 0.5% at the operating length of the interaction space causes the microwave signal with the power of about 10 MW.

By varying the parameters (electron energy, magnetic field , current in the kicker) in the experiment we found the second regime of single-frequency operation in which the $\mathbf{H}_{1,1}$ mode was excited at the wavelength λ=6.0 mm in the same resonator. This wavelength corresponds to the mode formed due to the resonant re-reflection of the $\mathbf{H}_{1,1}$ and $\mathbf{E}_{1,1}$ waves at the Bragg reflectors. Although the Q-factor of the resonant oscillations at λ=6 mm is almost twice lower than at λ=4.4 mm, the gain was higher at a lower frequency and, consequently, at a smaller group velocity of the wave. Therefore the start oscillation current at λ=6 mm is only slightly higher than that at λ=4.4 mm. At a lower accelerating voltage, when the electron energy was 1 MeV, a smaller current, of about 300 A, was read at the cathode. The experimental dependence presented in Fig.7b for superluminiscence power and resonant generation power as a function of electron beam pumping show that because of parasitic superluminiscence , the resonator can be excited effectively only at relatively small values of transverse

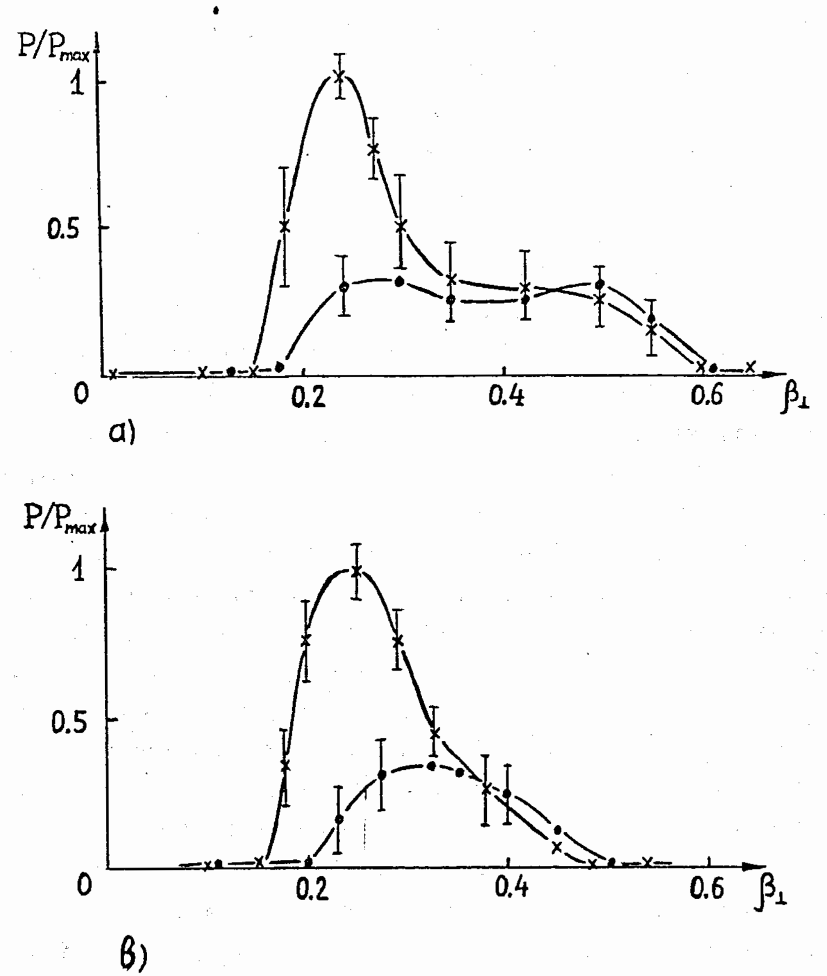

Figure 7. Output radiation power (in arbitrary units) vs transverse electron velocity at fixed magnetic field and electron energy : • -superluminiscence, × -radiation of CARM with Bragg resonator

a) λ = 4.4 mm   b) λ = 6.0 mm

electron velocities, similar to the case of generation at λ=4.4 mm. Measurements of the wavelength showed that when the radiation without resonator almost vanished (the dispersion characteristic of the beam is lower than the dispersion characteristic of the wave, see Fig.5), only a resonant wavelength λ=6.0 mm was present in the radiation spectrum. A rather small transverse electron velocity and the current lower than the optimal value yield a relatively small design efficiency of 12% , with spread taken into account. In experiment at a single-frequency generation the CARM efficiency amounted to 10%, which is close to the calculated value, and the maximal radiation power was 30 MW.

Conclusion

On the way to CARM with high Doppler frequency up-conversion using an LIA-unit with explosive emission injector we came across a surprisingly high level of parasitic superluminiscence of the beam at short interaction space. We believe that this is caused by the background noise due to explosive emission, as well as by a very broad band of electron-wave interaction. By narrowing the interaction band by passing over to smaller magnetic fields and particle energies we decreased the superluminiscence down to acceptable values and obtained at single-frequency operation the efficiency close to the calculated value. At present only CARM with nanosecond electron beams produced by means of explosive emission has been realized. The CARM described in Sect.5 generates single-pulse radiation of about 0.1-1 J. When passing over from the single-pulse to the pulse-periodic regime with the repetition frequency of about 1 kHz that is the maximal attainable magnitude at present, we can expect that the CARM of interest will produce a kilowatt average power. Generation of significantly higher power will need considerable advance in the technology of powerful high voltage modulators and emitter operating with the high repetition frequency or in a continuous regime. On the basis of such electron sources the CARM varieties considered above could provide a rather high average power with acceptable level of heating of the walls of electrodynamic system caused by ohmic losses. Thus, for the CARM-generator considered in Sect.5 operated at the lower $H_{1,1}$-mode at the wavelength 4.4 mm with average radiation power 5 MW the thermal load would not exceed 1 kW/cm^2 .This power can be increased by an order of magnitude if a smooth waveguide is replaced by a corrugated waveguide with the operating $HE_{1,1}$-mode having [19] a small field at the wall, and if quasi-optical reflectors are used instead of Bragg mirrors. Estimations show that such a CARM with the electron energy $\mathcal{E}\sim 1$ MeV may be realized also at the 1-2 mm waves with the average power 5-10 MW for relatively low magnetic fields of 20-40 kOe.

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Архипов О.В. и др. E9-92-406
Мазер на циклотронном авторезонансе с высоким преобразованием частоты колебаний

На базе линейного индукционного ускорителя с использованием взрывоэмиссионного катода были проведены исследования мазера на циклотронном авторезонансе (МЦАР) с высоким допплеровским преобразованием частоты,когда частота волны в 7-9 раз превышала циклотронную частоту электронов. С помощью высокоизбирательного резонатора Брегга, использовавшегося в качестве электродинамической системы МЦАРа, были исследованы два режима его работы, имеющие существенно различные свойства. При этом дисперсионные характеристики электронного пучка и волны или пересекались, или касались друг друга.В первом случае генерируемая мощность достигала 50 МВт на длине волны, равной 4,4 мм с КПД 8%. То, что КПД оказался значительно меньше расчетного, объясняется высоким уровнем паразитных шумов пучка. Во втором режиме работы МЦАРа с излучением, имевшим длину волны, равную 6 мм, генерируемая мощность составляла 30 МВт при низком уровне паразитных шумов, а КПД - 10%, который был близок к расчетной величине.

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Cyclotron Autoresonance Maser with High Doppler Frequency Up-Conversion

A linear induction accelerator (LIA) unit with explosive emission was used as a basis for CARM with high Doppler frequency up-conversion when the wave frequency is greater up to 7...9 times than the cyclotron frequency of electrons. Using a high-selective Bragg resonator as an electrodynamic system of CARM we investigated two regimes having essentially different properties: the dispersion characteristics of the electron beam and the wave were either intersected or tangential to one another. In the first case, the radiation power amounted up to 50 MW at the wave length of 4.4 mm with efficiency 8%. The efficiency significanty smaller than the design value was evidently caused by a high level of parasitic superluminiscence of the beam. In the second regime of operation at 6 mm, the radiation power was 30 MW with a low level of parasitic superluminiscence and efficiency 10% which was close to the calculated value.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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