TERAHERTZ ELECTRON MASERS WITH FREQUENCY MULTIPLICATION *

A.V. Savilov#, I.V. Bandurkin, V.L. Bratman, N.Yu. Peskov, Institute of Applied Physics, Russia
A.K. Kaminski, S.N. Sedykh, Joint Institute for Nuclear Research, Russia

Abstract

Various schemes of low/moderately relativistic electron masers operating in the THz frequency range in the regime of frequency multiplication, are discussed. The use of this approach makes possible the realisation of high-harmonic cyclotron masers, which operate at low accelerating voltages in long-pulse and CW regimes. As for realisation of pulsed high-power THz masers, it is attractive to use the regime of frequency multiplication in moderately-relativistic high-current free-electron and Smith-Purcell autooscillators.

SELF-EXCITED GYROMULTIPLIER

In electron cyclotron masers with frequency multiplication (gyromultipliers) [1-5], an electron beam is bunched by a relatively low-frequency (LF) wave, which acts at a low cyclotron harmonic and imposes a frequency and a spatial structure of the electron bunching. This provides a selective excitation of a high-frequency (HF) wave at a multiplied frequency and a high cyclotron harmonic, even if a relatively low-current electron beam is used. Cirtainly, a sufficiently powerful LF signal, as well as exact coincidence between the harmonic of LF frequency and the resonant frequency of the HF mode are required. It is attractive to excite both the LF and HF waves by the same electron beam inside the same cavity [5]. In such a scheme, the operating cavity should have a pair of LF and HF eigenmodes applicable for frequency multiplying. However, a simple smooth-wall cavity with circular cross-section (which is conventional for cyclotron masers) has a non-equidistant mode spectrum and does not provide necessary pair of modes.

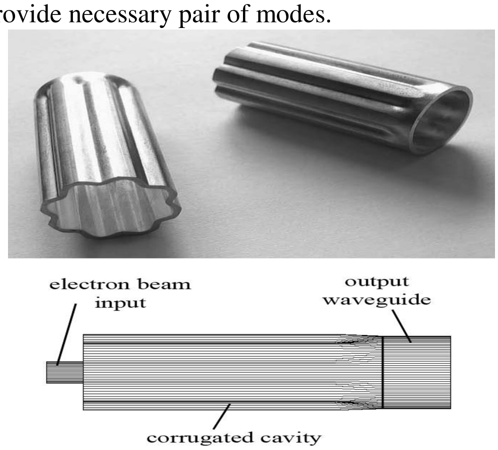

Figure 1: Photo and schematic view of the cavity.

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#savilov@appl.sci-nnov.ru

This problem is solved by using a more complicated cavity; namely, a resonator with periodic $2m$-fold azimuthal corrugation of the wall [6]. Such a corrugation has a maximal effect on the modes with azimuthal index m since it resonantly couples two degenerate counter-rotating waves of such a type. Taking the corrugation index resonant for the HF mode and selecting corrugation depth, one can provide the desired pair of the modes.

This method was realized in a mm-wavelength range experiment. A thin axis-encircling electron electron beam with an electron energy of 60 keV, a current of up to 6 A, and pitch-factor close to 1 excited simultaneously the $TE_{2,2}$ and $TE_{4,3}$ near-cutoff modes at the second and fourth cyclotron harmonics, respectively. In a circular cavity, the ratio of cutoff frequencies for these modes (1.89) is less than the necessary value (2). In the corrugated cavity with the length of 40 mm (Fig. 1), the LF-mode eigenfrequency is $f_{\rm LF} = 37.5$ GHz , whereas the HF-mode one is exactly twice higher, $f_{\rm HF} = 75$ GHz .

The experiment demonstrated the possibility of stable two-mode operation. The measured frequencies of the LF and HF radiation differed exactly by a factor of two, and the output field pattern of the HF radiation was consistent with the $TE_{4,3}$ mode structure. The dependence of the HF power on the beam current was close to quadratic (Fig. 2), which was in good agreement with the theory. However, the problem of providing exact coincidence between the "hot" eigenfrequency of the LF mode and the resonant frequency of the HF mode was essential. This problem was partially solved by search among several cavities of slightly different lengths, but it became clear that some rapid mechanism of frequency adjustment should be provided for high-frequency gyromultipliers.

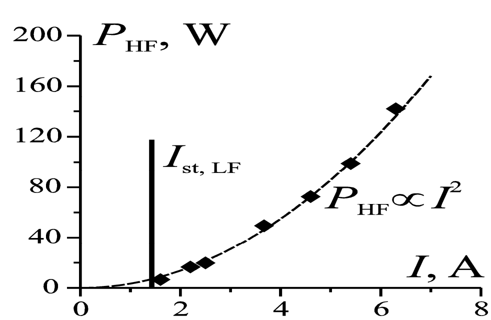

Figure 2: Measured dependence of the HF power on the beam current, as well as the calculated starting current of the self-excitation of the LF wave.

After a certain modification, the studied gyromultiplier scheme can presumably be realized in the THz frequency range. According to preliminary calculations, use of the electron beam with a lower and more practical particle energy (30 keV) but a greater pitch-factor (1.4) can provide generation in the azimuthally corrugated cavity at the fourth cyclotron harmonic with a frequency of 0.5-1 THz and a power of tens watts when the electron current is as small as 0.5-1 A. Several methods of rapid frequency adjustment are now under consideration.

TWO-WAVE FREE-ELECTRON MASER

An attractive solution of the problem of realization of a THz Free-Electron Maser (FEM) driven by mildly relativistic electron beam is an FEM-scattron, which is capable to operate at THz frequencies if a GHz pumping wave is applied. We propose to realize an inter-cavity scattering regime in Bragg FEM operating in two-wave (ubitron and scattron) resonance conditions [7]. In the "ubitron" regime, electrons interact with the forward GHz wave, whereas the backward GHz wave is used for the feedback and, simultaneously, operates a secondary wiggler to provide stimulated scattering into a THz forward wave (Fig. 3). To increase efficiency of the THz generation we proposed operation at a multiple frequency. In this case no feedback (resonator) is needed for THz wave.

FEM with Bragg resonator is investigated during the last decade in collaboration between JINR and IAP RAS. At the present stage 30 GHz / 20 MW / 200 ns have been achieved [8]. This project is aimed to generate THz radiation in this FEM. A schematic diagram of this experiment is shown in Fig.3. The induction linac LIU-3000 (JINR) generates a 0.8 MeV / 150 A / 250 ns electron beam with a repetition rate of 1 Hz, which is injected into the FEM-oscillator immersed in a solenoid. A helical wiggler of 6 cm period pumps transverse velocity into the beam. This electron-optical system was tested in the FEM experiments at 30 GHz [8]. A reversed guide field regime was chosen for the FEM-ubitron operation. This regime provides high-quality beam formation in the tapered wiggler section with a low sensitivity to the initial beam spread and leads to high efficiency energy extraction from the beam that was corroborated in the performed experiments.

In the "ubitron" regime, electrons interact with a 30 GHz circularly polarized $TE_{1,1}$ wave (LF wave). The two-fold helically-corrugated Bragg mirrors provide feedback loop with the feedback counter-rotating LF $TE_{1,2}$ wave, which is close to the cut-off. Scattering of the backward wave into the forward HF waves is calculated to be at 360 GHz for the $s = 12$ harmonic. Proper rotation and small group velocity of the backward LF wave is needed to increase coupling with the electrons in the process of "scattron" interaction.

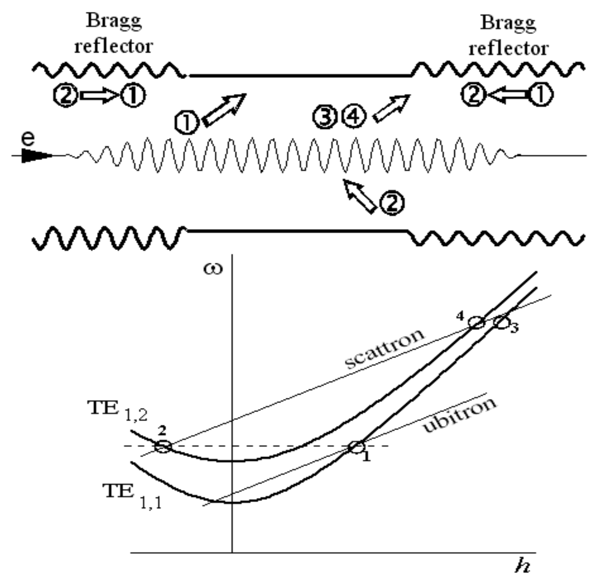

Figure 3: Schematic and dispersion diagramm of the two-wave FEM: the GHz ubitron wave (1) is reflected into the feedback backward wave (2), which is scattered on the electron beam into THz wave (3) and (4).

The first experiments on THz generation were carried out. Acceptable for THz generation the electron beam quality and quality of pumping GHz wave were realized. At the frequency of 30 GHz output LF power up to 20 - 30 MW and frequency spectrum width of ~ 6 MHz were achieved with stability of the output power and the radiation frequency demonstrated during ~ 10^5 pulses.

Original diffraction grating was used for separation of HF and LF wave beams. The spectrum measurement was performed by means of waveguide cut-off filters. The HF radiation with a frequency higher than 300GHz was registered (Fig.4). The HF power was estimated (from calibration of the THz detector sensitivity and output horn transmission) at 100 kW level. Thus, operability of novel two-wave FEM scheme was demonstrated.

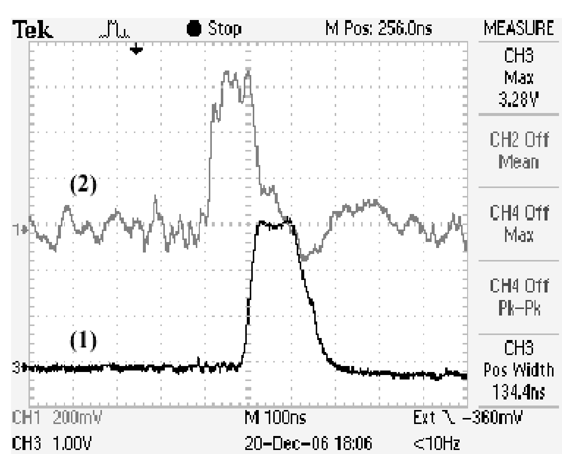

Figure 4: Typical oscilloscope traces of (1) LF pulse and (2) HF pulse (100 ns / div.).

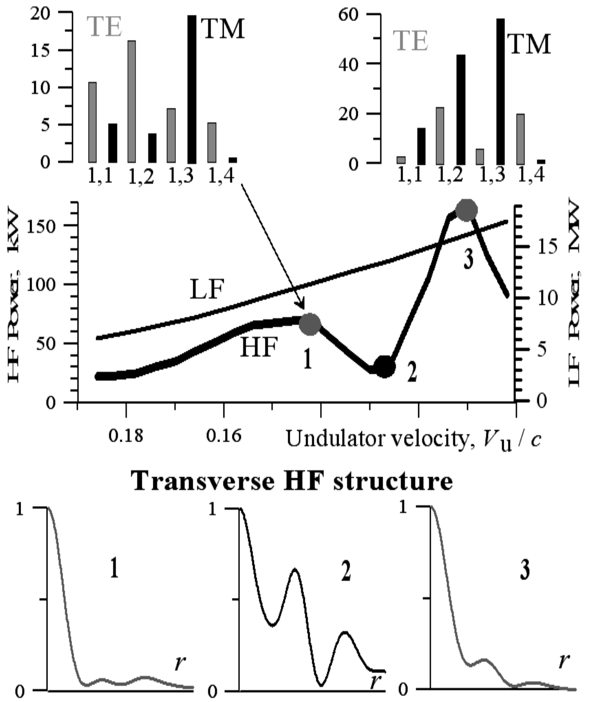

Figure 5: Output power of LF anf HF waves versus the undulator velocity, mode spectra of the HF radiation in optimal regimes 1 and 3, as well as the transverse structure of the HF field $\left|E^2(r)\right|$ in regimes 1, 2, and 3.

Numerical simulations have confirmed the 100 kW level of the output HF power (Fig. 5). In addition, they predict a multi-mode character of the HF radiation. The mode interaction results in a complicated character of the depencence of the output HF power on the electron undulator velocity. In optimal regimes (the regimes 1 and 3 in Fig. 5), the total electric field of the HF radiation is concentrated basically close to the waveguide center, which is the point of the electron beam injection. This effect of the mode cooperation is similar to the known effect of canalization of the microwave radiation.

CYCLOTRON RADIATION IN SMITH-PURCELL BWO

The cyclotron frequency multiplication can be organized in a Smith-Purcell Backward-Wave Oscillator (BWO) to produce a secondary HF radiation. Namely, we propose to use the regime of the cyclotron absorption of the forward LF wave, which arises due to reflection of the backward LF wave from the input end of the operating waveguide. This absorption results in transverse cyclotron oscillations of electrons, and makes possible a stimulated emission of a HF wave at a multiplied frequency and a high cyclotron harmonic.This can be a way to obtain a powerful THz-range radiation from a high-current moderately-relativistic rectilinear electron beam in a system, which does not require both strong magnetic fields and small-scale elements of the microwave system.

We consider a Smith-Purcell BWO operating at the lowest symmetrical mode of the circular waveguide $TM_{0,1}$. The operating backward LF wave of this BWO $A^{(-)}$ is excited by a rectilinear tubular electron beam inside the corrugated section of the operating waveguide (Fig.6). For this wave, the Smith-Purcell resonance condition should be provided, $\omega_0 \approx (h_{cor} - h_0)V_z$.

At the input of the waveguide, this wave is reflected into the forward $TM_{0,1}$ wave, $A^{(+)}$, which is close to the fundamental-harmonic cyclotron resonance with rectilinear electrons, $\omega_0 \approx h_0 V_z + \Omega_c$. Cyclotron absorption of this LF wave results in transverse cyclotron oscillations of electrons. This fact makes possible a stimulated emission of a high-frequency (HF) $TE_{0,q}$ wave, A_m, at a multiplied frequency and a high cyclotron harmonic. This is possible, if the frequency multiplication factor coincides with the cyclotron harmonic number, $\omega_m = m\omega_0$, so that the resonance condition for the HF wave takes the following form:

$$\omega_m = m\omega_0 \approx h_m V_z + m\Omega_c \ .$$

According to these resonance conditions, axial wavenumbers of the two wave should be approximately divisible, $h_m \approx m h_0$. Therefore, group velocities of the waves, $V_{gr} \propto h/\omega$, approximately coincide, $V_{gr,m} \approx V_{gr,0}$. Transverse wavenumbers of the waves also should be approximately divisible, $g_m \approx m g_0$. Since they are determined by the waveguide ragius and the corresponding roots of Bessel function, $g = \mu / R$, approximate devisibility of eigenvalues of the waves, $\mu_m \approx m\mu_0$, is also required .

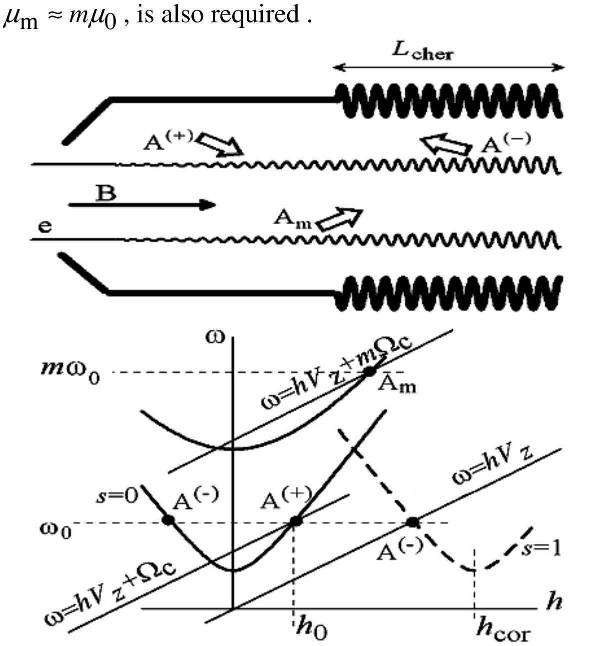

Figure 6: Schematic and dispersion diagram of a Smith-Purcell BWO with cyclotron frequency multiplication.

These conditions make significantly difficult the realisation of the two-wave co-generation. Condition $\mu_{\mathrm{m}} \approx m\mu_0$ limits the choice of the frequency multiplication factor. Condition $V_{\mathrm{gr,m}} \approx V_{\mathrm{gr,0}}$ is even more important, as the proposed method of the frequency multiplication strictly requires the use of a far-from-cutoff LF wave. Actually, since for the forward LF wave, $A^{(+)}$, the cyclotron resonance condition takes place, condition $h_0 \sim k_0$ is needed to avoid the cyclotron resonance for the backward LF wave, $A^{(-)}$. Otherwise, resonant cyclotron absorption of the backward wave can result in frustration of the Smith-Purcell LF generation. However, cyclotron generation of a travelling far-from-cutoff HF wave is very sensitive to the spread in electron velocity, especially in the case of the high-harmonic operation.

These problems can be solved by the use of a modified cyclotron resonance condition for the HF wave, which takes into account the non-resonant cyclotron interaction of electrons with the backward LF wave:

$$\omega_{\mathrm{m}} = m\omega_0 \approx h_{\mathrm{m}} V_{\mathrm{z}} + m\Omega_{\mathrm{c}} + Q h_{\sim} V_{\mathrm{z}} \ .$$

Hhere $-m < Q < m$ is an interger value, and $h_{\sim} = (\omega_0 - \Omega_{\mathrm{c}})/V_{\mathrm{z}} + h_0 \approx 2h_0$ is the wavenumber of non-resonant oscillations of the electron velocity in the field of the backward LF wave.

If the high-harmonic cyclotron generation of the HF wave is organised in the regime of this combined resonance, axial wavenumbers of the LF and HF waves are related as $h_{\mathrm{m}} \approx (m-2Q)h_0$. Correspondingly, $V_{\mathrm{gr,m}} \approx (1-2Q/m)V_{\mathrm{gr,0}}$, and the Smith-Purcell generation of a far-from-cutoff LF wave can be combined with effective high-harmonic radiation of a close-to-cutoff HF wave. In addition, eigenvalues of LF and HF waves are related by the condition

$$\mu_{\mathrm{m}} \approx m\mu_0 \sqrt{1 + \frac{4Q(m-Q)}{m^2 (c^2 / V_{\mathrm{gr,0}}^2 - 1)}} \ ,$$

which can be fulfilled at any frequency multiplication factor, m, by means of chosing a proper value of $V_{\mathrm{gr,0}}$.

The factor of the cyclotron electron-wave coupling decreases very fast with the increase of cyclotron harmonic number: $\chi_{\mathrm{m}} \propto \beta_{\perp}^{\mathrm{m}}$, where $\beta_{\perp} = V_{\perp}/c$ is the oscillatory electron velocity. Therefore, in order to prolong the high-harmonic HF coupling, the operating waveguide may include, along with the corrugated Smith-Purcell section, also a smooth-wall section (Fig. 6). One more reason to use this smooth-wall section is organisation of the HF emission from the electron beam, which is not “spoiled” by the Smith-Purcell generation of the LF wave.

In simulations, we study a Smith-Purcell BWO with typical electron beam parameters 500 keV / 3kA. The electron beam is assumed to possess a spread in initial transverse (rotatory) electron velocity $0 \le \beta_{\perp,0} \le 0.1$. The length of the Smith-Purcell section is fixed as $L_{\mathrm{cher}} = 10\lambda_0$. As for the corrugation depth, it is chosen close to the limit of the stable operation of the BWO. In simulations, the efficiency of the Smith-Purcell operation amounts to 10-12%, which corresponds to the power of the backward LF wave $\sim 150\,\mathrm{MW}$. Almost whole this power is returned back to the electron beam due to the cyclotron absorption of the forward LF wave.

In the case of the frequency multiplication factor $m = 3$, simulations predict possibility to achieve as high efficiency of the high-harmonic generation of the HF wave as 5%. This corresponds to re-radiation of about a half of the LF power, which is generated in the Smith-Purcell BWO and, then, is returned back to electrons due to the cyclotron absorption. In this case, the optimal length of the smooth-wall section is comparable with the length of the Smith-Purcell corrugated section.

Naturally, an increase of the frequency multiplication factor (and, therefore, the cyclotron harmonic number) results in an increase of the optimal length of the the smooth-wall waveguide section, as well as in a decrease of the efficiency the HF wave generation. Nevertheless, simulations predict the efficiency the HF generation of 3% in the case of $m = 5$, and the efficiency of 1% in the case of $m = 7$ [9].

REFERENCES

[1] A. V. Gaponov, M. I. Petelin, and V. K. Yulpatov, Radiophys. Quantum Electron. 10 (1967) 794.

[2] V. I. Belousov, V. S. Ergakov, and M. A. Moiseev, Elektronnaya Tekhnika. Ser. 1. Elektronika **9** (1978) 41 [in Russian].

[3] D. B. McDermott, N. C. Luhmann, Jr. A. Kupiszewski, and H. R. Jory, Phys. Fluids **26** (1983) 1936.

[4] J. L. Hirshfield, Phys. Rev. A 44 (1991) 6845.

[5] I. V. Bandurkin, V. L. Bratman, G. G. Denisov et al, Terahertz Sci. Tech. 1 (2008) 169.

[6] I. V. Bandurkin, V. L. Bratman, A.V. Savilov, S.V. Samsonov, and A.B. Volkov, Phys. Plasmas 16 (2009) 070701.

[7] A. V. Savilov, N. Yu. Peskov, A. K. Kaminsky, Nucl. Instr. Meth. in Phys. Res. A507 (2003) 162.

[8] A. Kaminsky, S. Sedykh, N. Ginzburg, N. Peskov et al, “Development of powerful FEMs for X, Ka and W bands for physical and industrial application”, FEL’06, Berlin, Germany, August 2006, TUPPH032, p. 235 (2006); http://www.JACoW.org.

[9] A. V. Savilov, Phys. Plasmas 16 (2009) 063103.