Plasma Electronics Laboratory

Narrowband radiation in a plasma relativistic microwave generator

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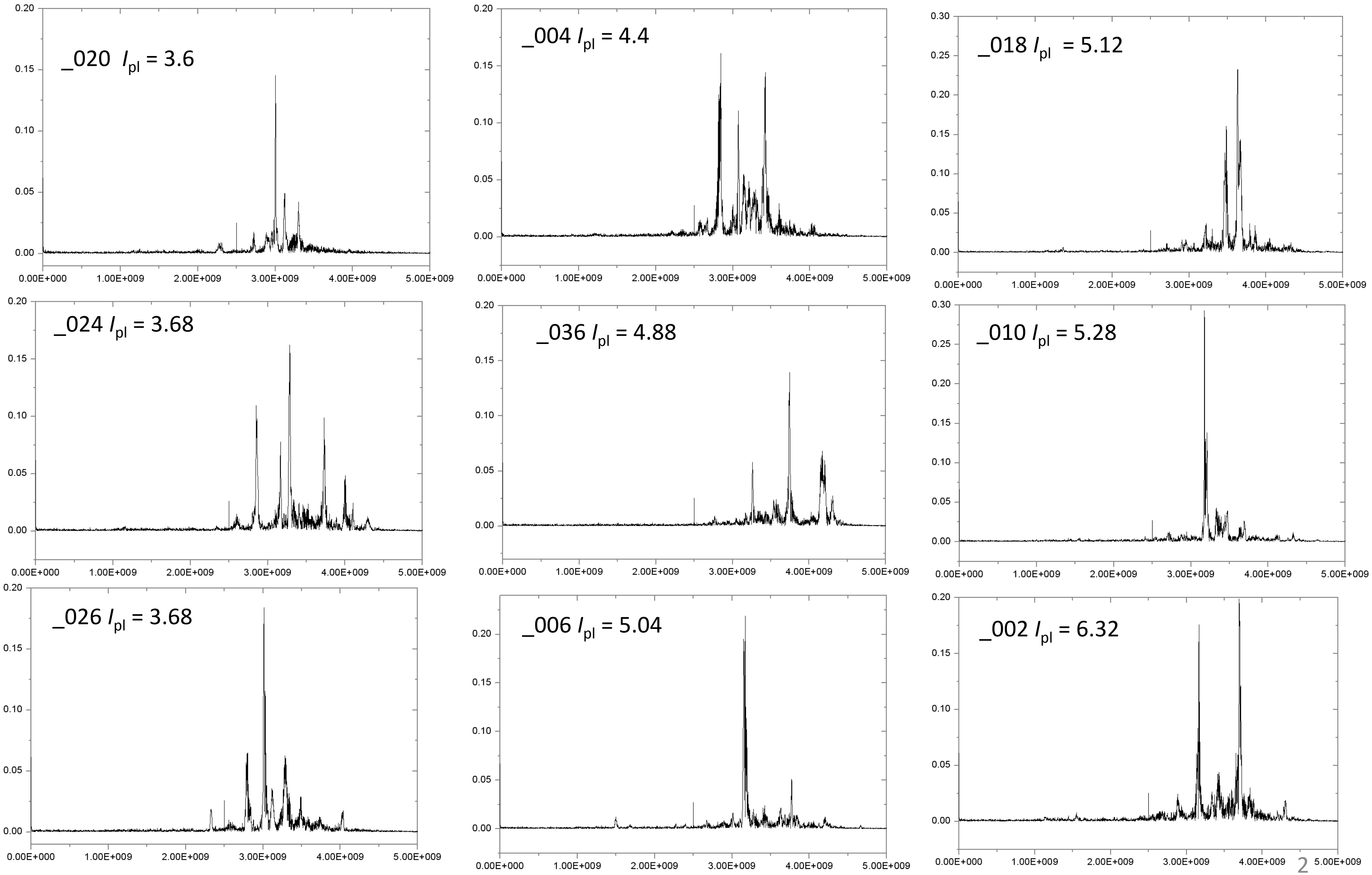
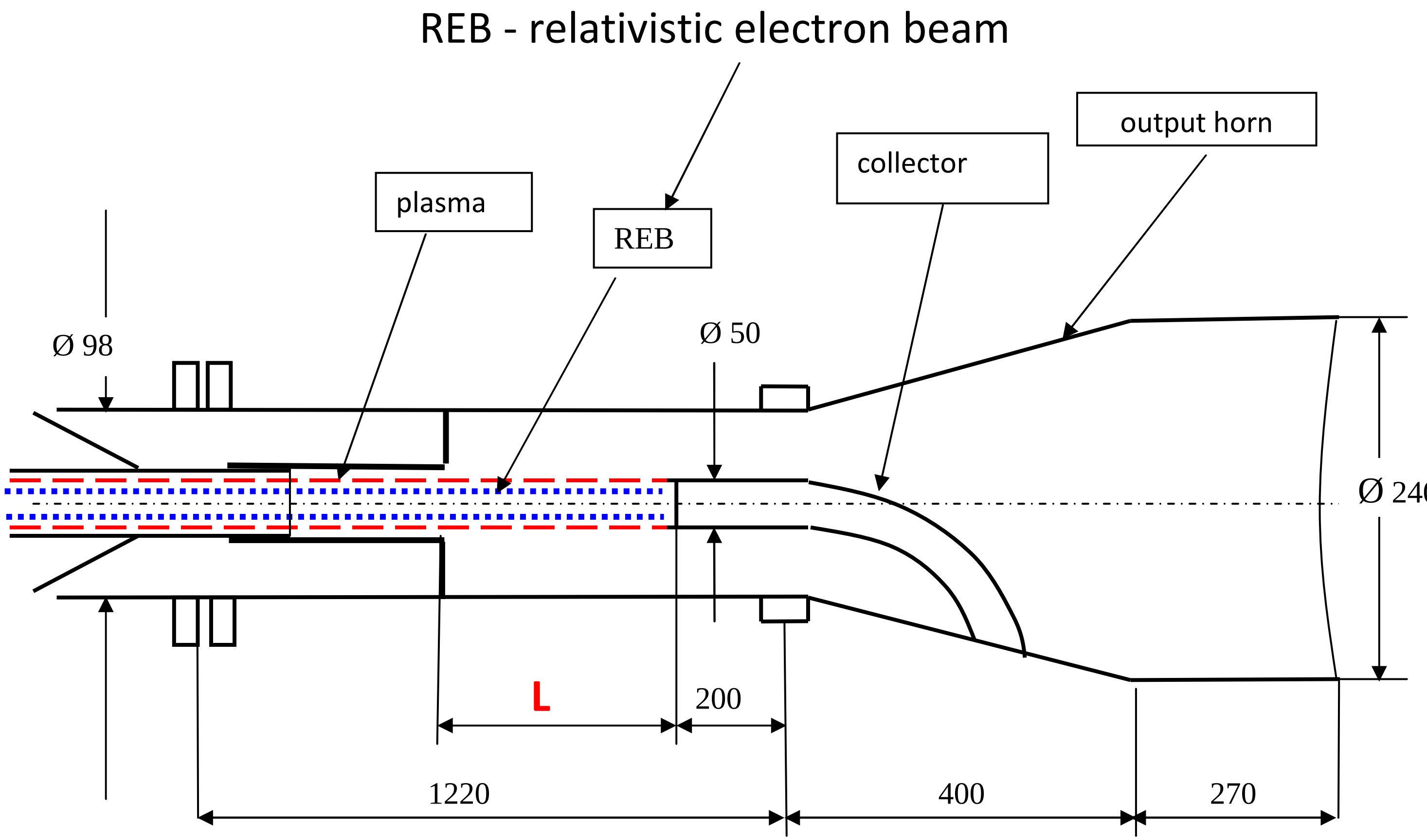
Radiation spectra of a relativistic plasma generator on a short baseline in a free lasing regime at different plasma densities

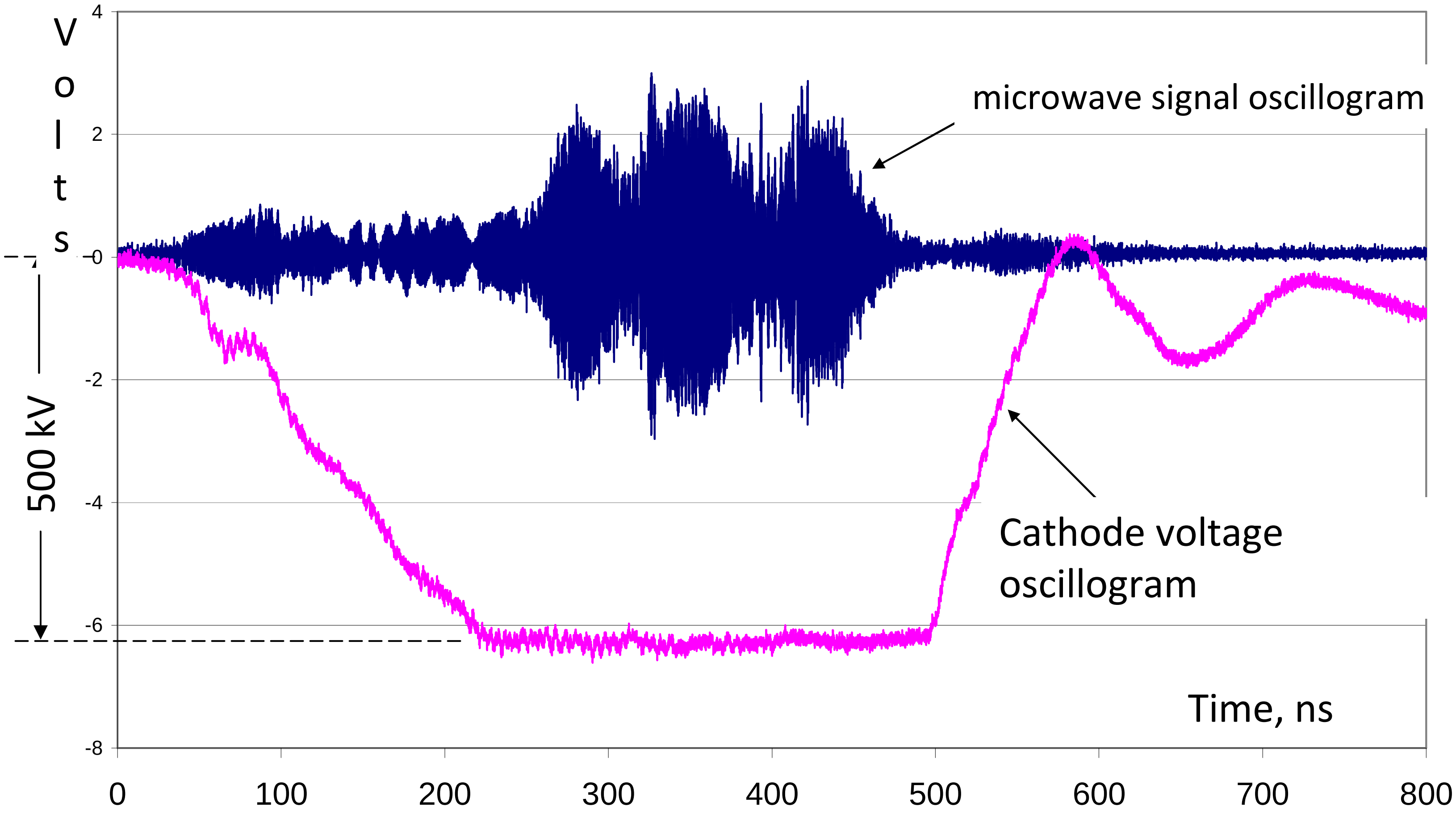


Plasma Relativistic Generator Device



U_k = 500 кВ, I_{REB} = 2.5 kA, plasma $5 \cdot 10^{11} \div 2{,}6 \cdot 10^{12} cm^{-3}$

Experimental technique
Acquisition of waveforms on a high-speed oscilloscope
Tektronix TDS 7404. Pulse _024



Mechanism of formation of microwave radiation
Phase synchronism

The transfer of the energy of a relativistic beam to an electromagnetic wave occurs with phase synchronism, i.e. when the phase velocity of the wave υphases and the relativistic beam u are equal. The presence of plasma leads to the formation of a plasma waveguide, in which slow electromagnetic waves can propagate at speeds lower than the speed of light.

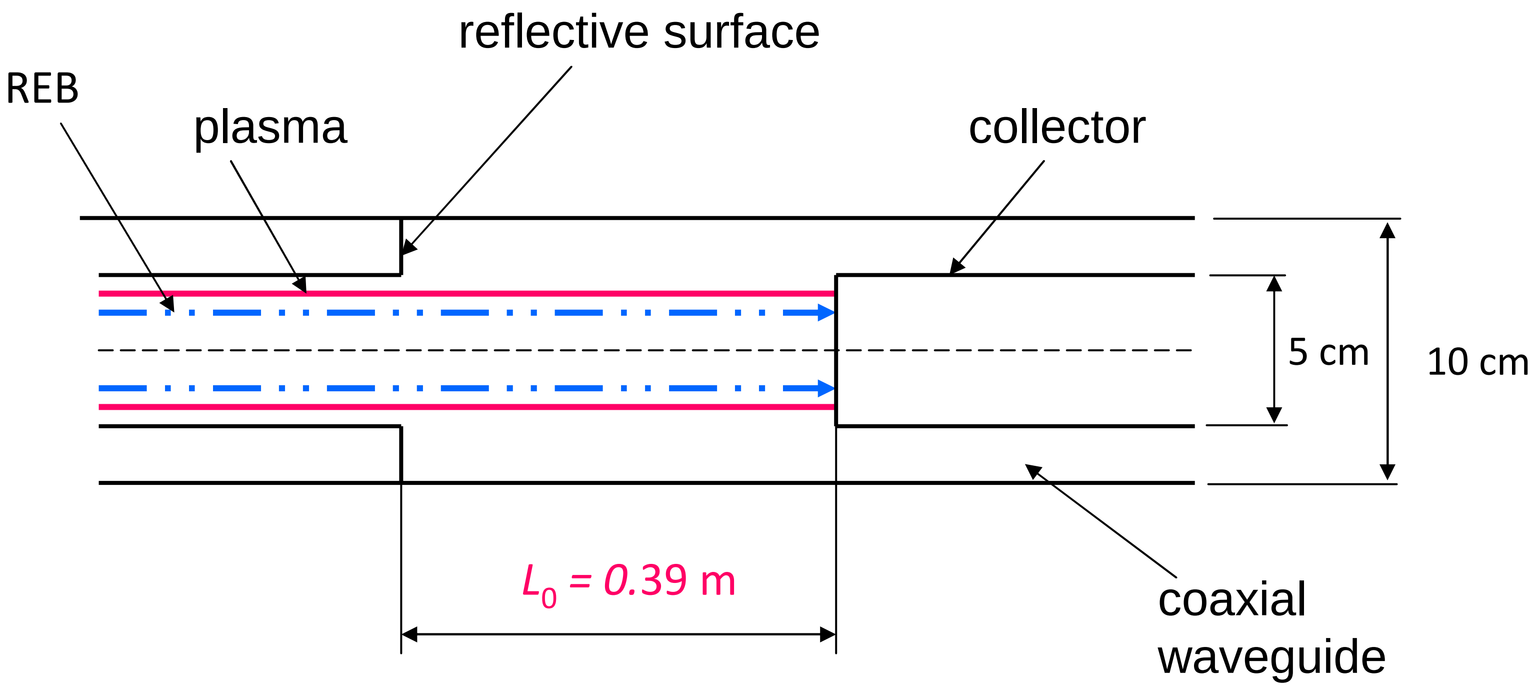
(1) $$\upsilon_{ph} = \frac{\omega}{k_z} = u = \lambda \nu$$

An integer number N of half-waves should fit over the cavity length L.

(2) $$\Delta \nu = \frac{u}{2L}$$ – intermode distance of longitudinal modes in the cavity

(3) $$\nu_N = \Delta \nu N$$ – position of resonance frequencies ν_N

Experiment. Resonator length L_0 = 39 cm



The size of the resonator elements is comparable to the wavelength λ_N in the resonator. When reflected, the wave will partially enter the coaxial waveguide (right) and the hole in the reflecting surface (left). Therefore, each longitudinal mode will have its own effective cavity length L_{eff}. We assume that the wave during reflection cannot penetrate beyond the reflection plane by more than ½ the wavelength.

N – the number of half-waves in the resonator

Thus $L_0 < L_{eff}(\lambda_N) < L_0 + \lambda = L_{max}$

$L_{eff}(\lambda_N)$ – effective cavity length

Purpose of work

Associate the value of the observed frequency with the main parameters of the longitudinal mode of the resonator: 1) the phase velocity of the wave, 2) the wavelength, 3) the number of half-waves, 4) the length of the effective resonator, 5) the amount of entry behind the reflecting surface

Understand,

1) why there is no repeatability in the frequency arrangement

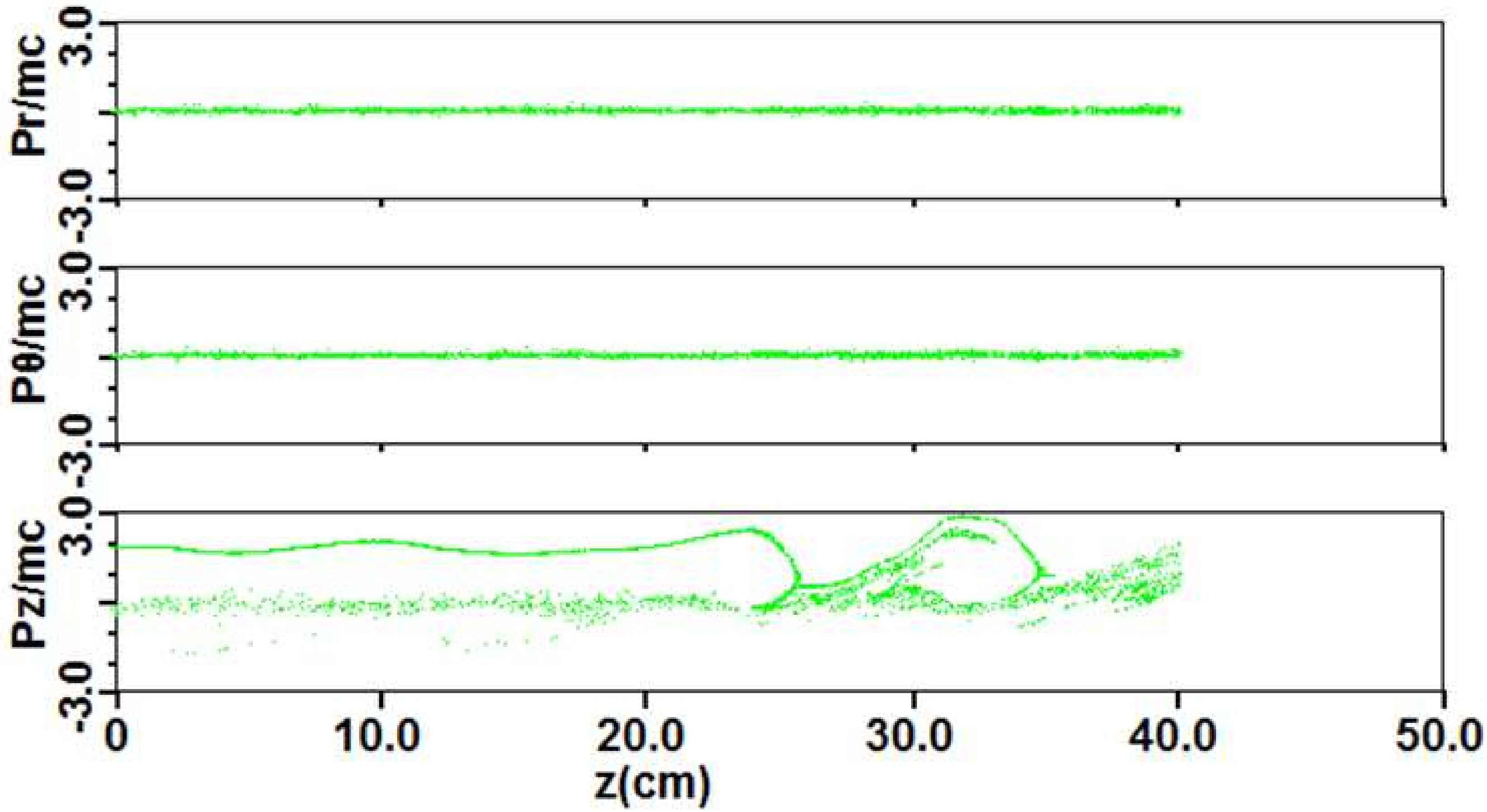
2) why is there no generation on equidistant allowed modes

3) why generation occurs at one frequency, and not at several simultaneously.

Determination of the electron velocity *u* of a relativistic electron beam

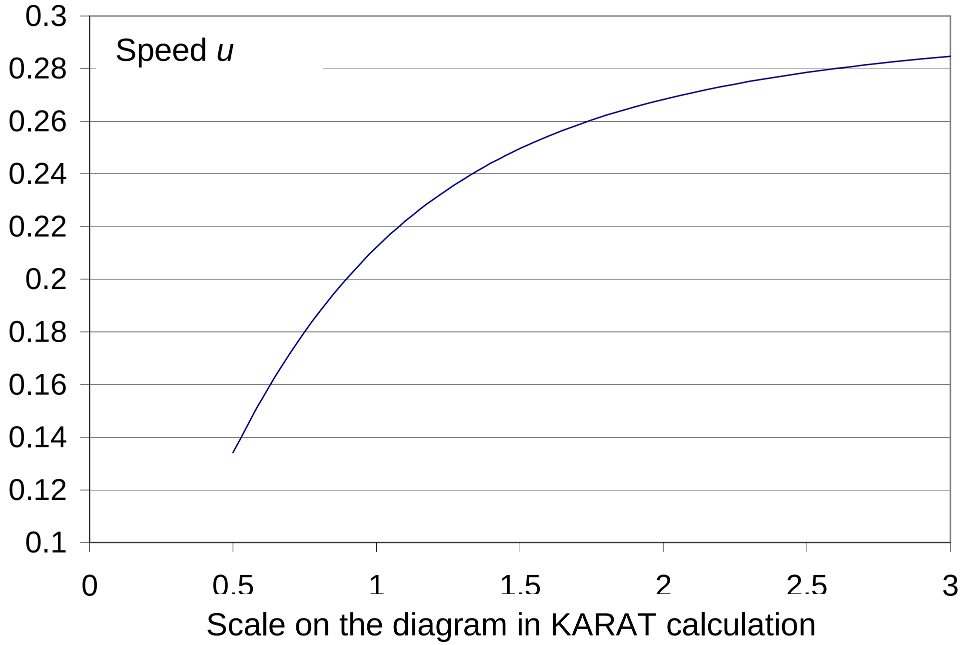
Calculation of the movement of electrons REB in the KARAT code
(Tarakanov V.P.)

Time 300 ns



REB electron velocity range
Numerical simulation data in the KARAT system

1. The presence of plasma screens the field of the relativistic beam - the potential energy of the beam decreases, and the velocity increases
2. Numerical modeling indicates the presence of electrons in the beam with velocities exceeding 0.26×10^9 m / s (corresponding to the accelerating voltage U = 500 kV, the relativistic factor $\Gamma = 2$)
3. To analyze the spectra, we consider the velocity range 0.16 - 0.28×10^9 m / s
4. Hereinafter, relativistic velocities will be expressed in units of $\times 10^9$ m / s



Spectrum frequency analysis. Basic Provisions

1. Narrowband generation occurs due to resonant effects - multiple passage of a wave in the interaction space zone.
2. The interaction space is the area where the REB energy is transferred to the microwave energy. In this case, it coincides with the base resonator length L_0.
3. The effective resonator length L_{eff} is greater than the base one, since the wave partially penetrates the reflecting surfaces during reflection.
4. L_{eff} - different for different frequencies of the spectrum.
5. The reflected wave cannot penetrate into the coaxial resonator for more than ½ the wavelength. We have two reflection zones. Therefore, the effective length L_{eff} is contained within $$L_0 < L_{eff} < L_0+\lambda = L_{max}$$
6. For the analysis, the velocities of the electrons of the relativistic beam are considered, which lie within the limits $0.16 < u < 0.28$. Their velocities can exceed 0.261, which corresponds to the relativistic factor $\Gamma = 2$.

Experimental Results Processing Technique

Basic position - narrow-band radiation occurs due to resonance effects

To explain the origin of the experimental frequencies of the spectra, we must use the formulas

(1) $\upsilon_{pf} = \frac{\omega}{k_z} = u = \lambda \nu$ (2) $\Delta\nu = \frac{u}{2L}$ (3) $\nu_N = \Delta\nu N$

The velocity of relativistic electrons *u* must lie within the limits

(4) $0.16 < u < 0.28$

The effective resonator length must satisfy the condition

(5) $L_0 < L_{эфф} < L_0 + \lambda = L_{max}$

The calculation algorithm is based on determining an integer *N* of the number of half-waves that fit on the length of the effective resonator L_{eff}. By varying *u* and L_{eff}, we get non-integer values as the value of *N*. We are looking for those values of *u* and L_{eff}, at which an approximation to the integer value of *N* with a minimum deviation is obtained. We assume that these values of *u* and L_{eff} correspond to the given experimental value of the frequency ν_1.

Calculation Algorithm

The experimental value of the frequency ν_1

initial velocity u

initial value $L_{eff} = L_0$

value $L_{eff} = L_{эфф} + \Delta L$,
limitation $L_0 < L_{eff} < L_0 + \lambda = L_{max}$

finding $N, \lambda, \Delta N, L_{эфф}$

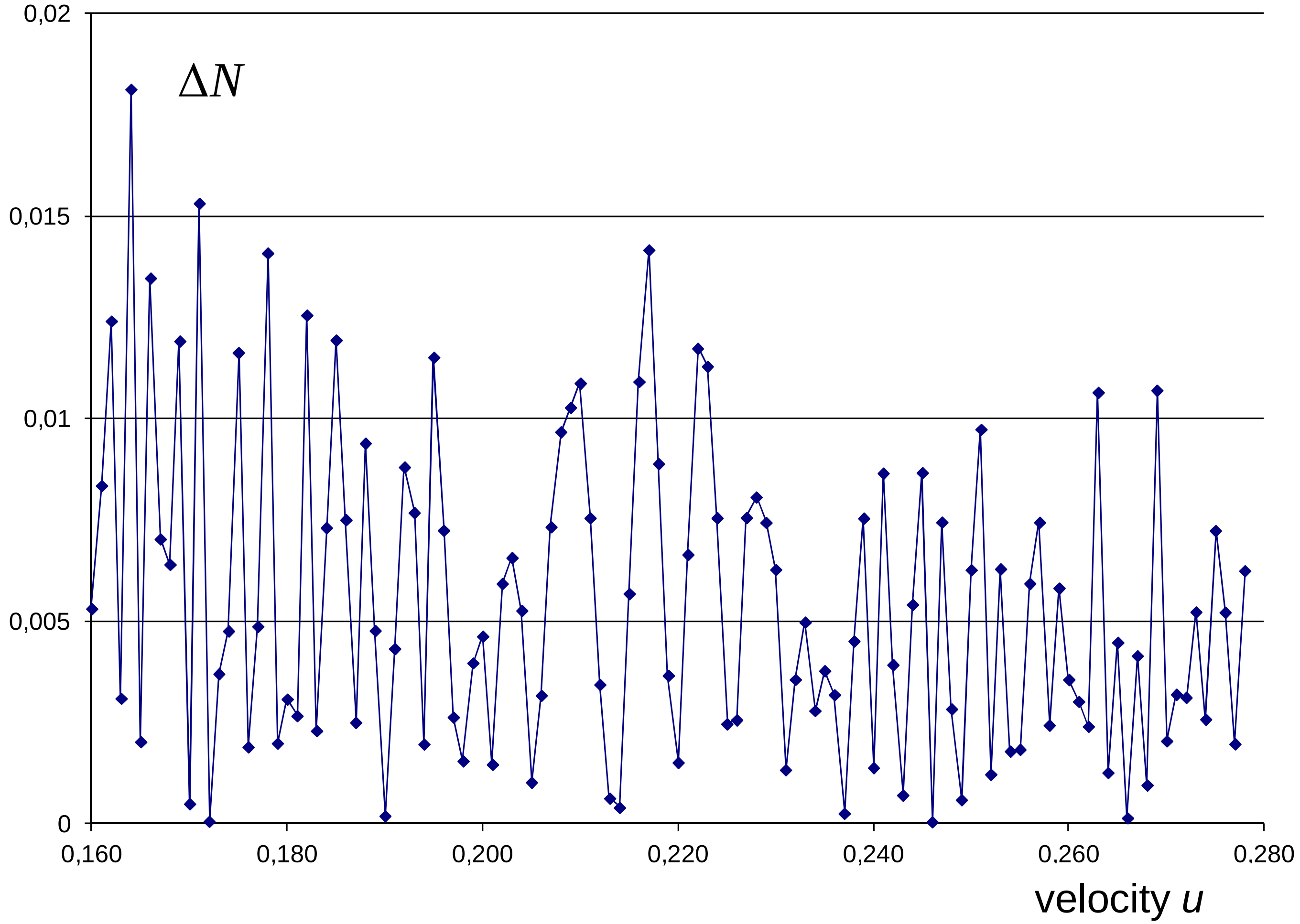
First cycle result : found ΔN_{min} for the velocity u, determined all mode parameters under the condition $L_0 < L_{eff} < L_0 + \lambda = L_{max}$

speed value $u + \Delta u$
limitation $0.16 < u < 0.28$

The result of the second cycle: the dependence (direct spectrum) $\Delta N_{min}(u)$ for the experimental frequency ν_1

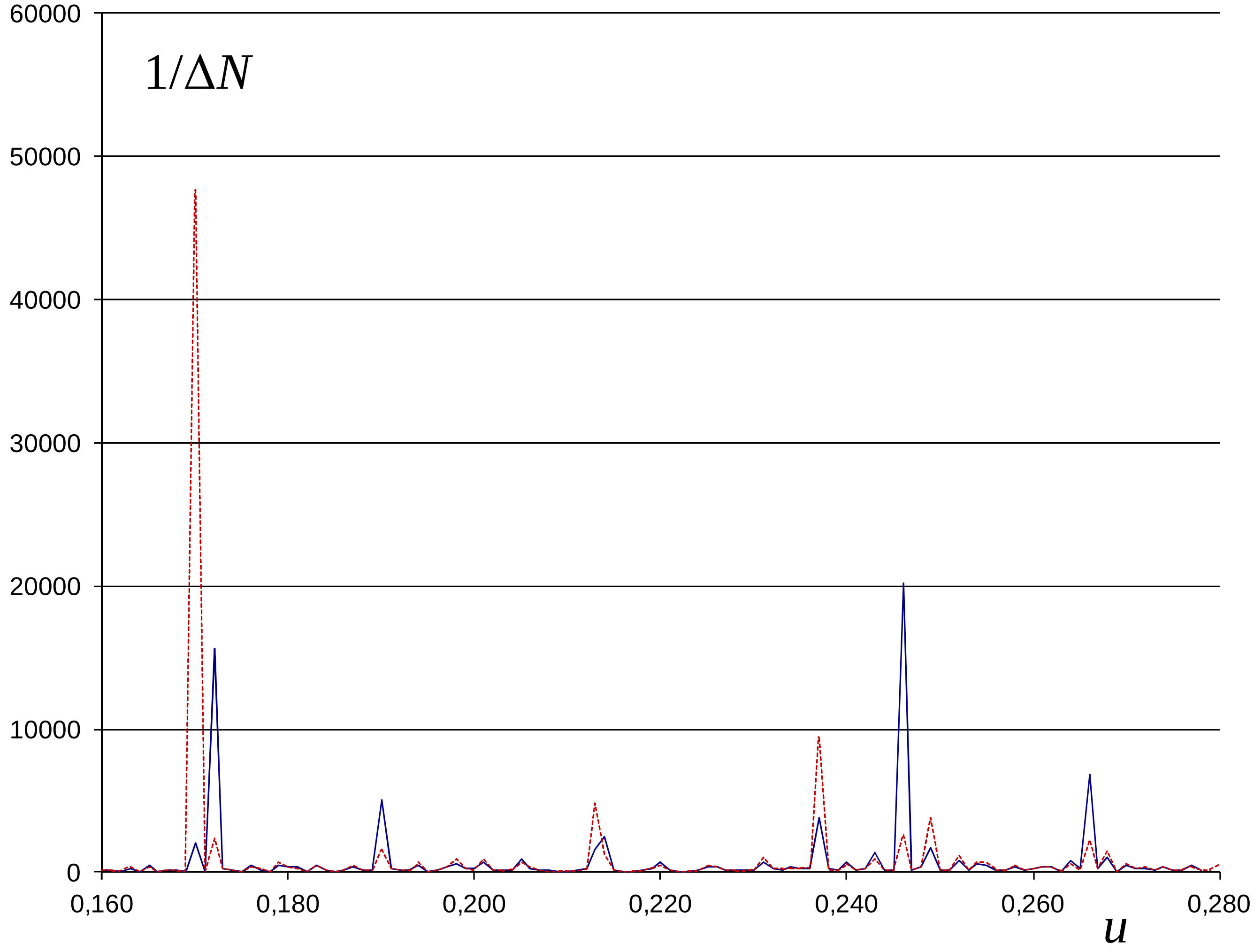
Graph of dependence $\Delta N = \left| N - Int(N) \right|$ on velocity *u* for frequency ν_1 = 3.284 GHz

Let us call this graph *the direct spectrum* of detuning Δ*N* in the coordinates of the velocity *u*

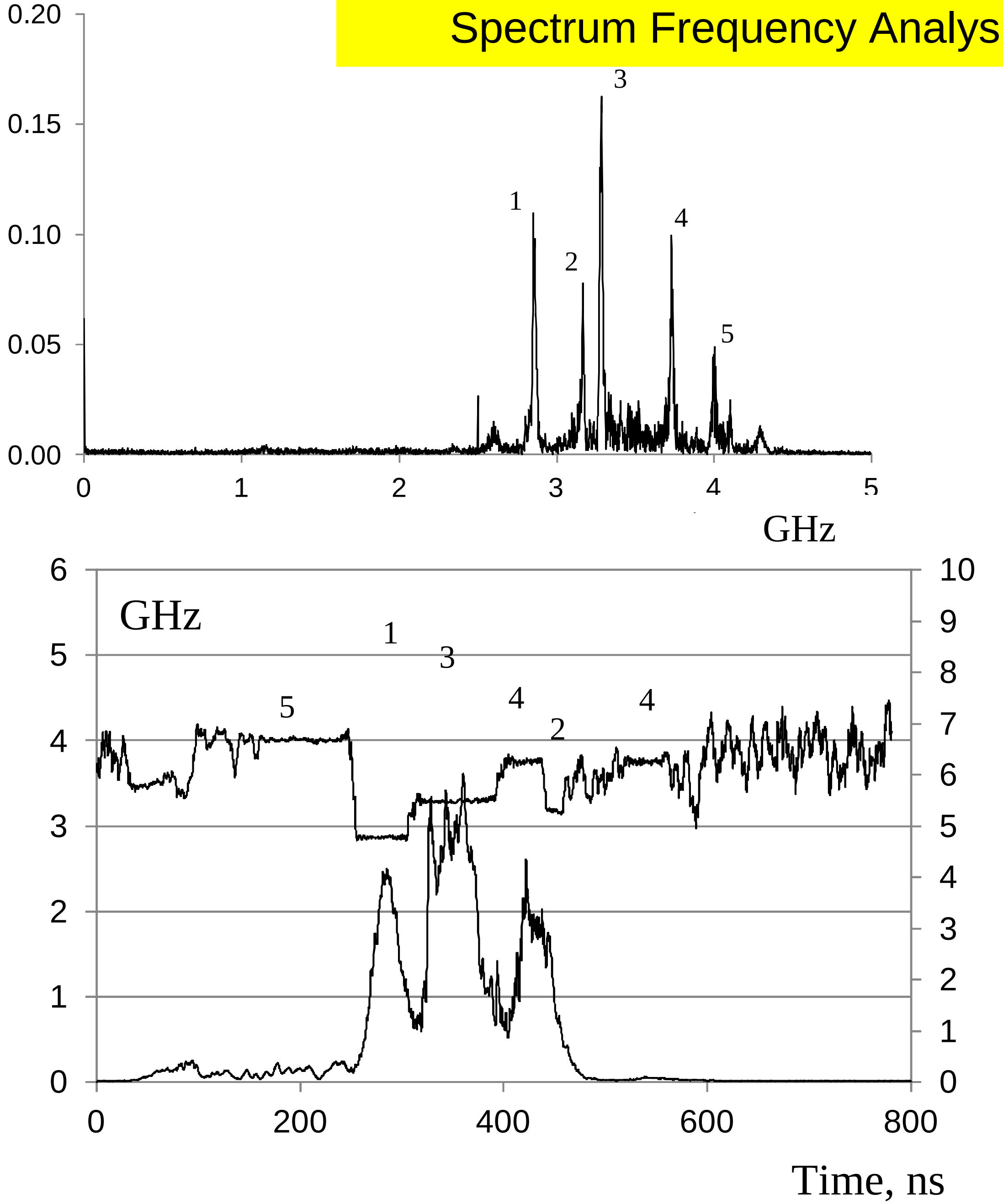


Graphs of $1/\Delta N$ versus velocity u for frequencies $\nu_1 = 3.2840$ GHz (solid blue line) and $\nu_2 = 3.2841$ GHz (dashed red line)

Let us call these graphs *the inverse spectrum* of detuning ΔN in the coordinates of the velocity u



Spectrum Frequency Analysis (spectrum _024)

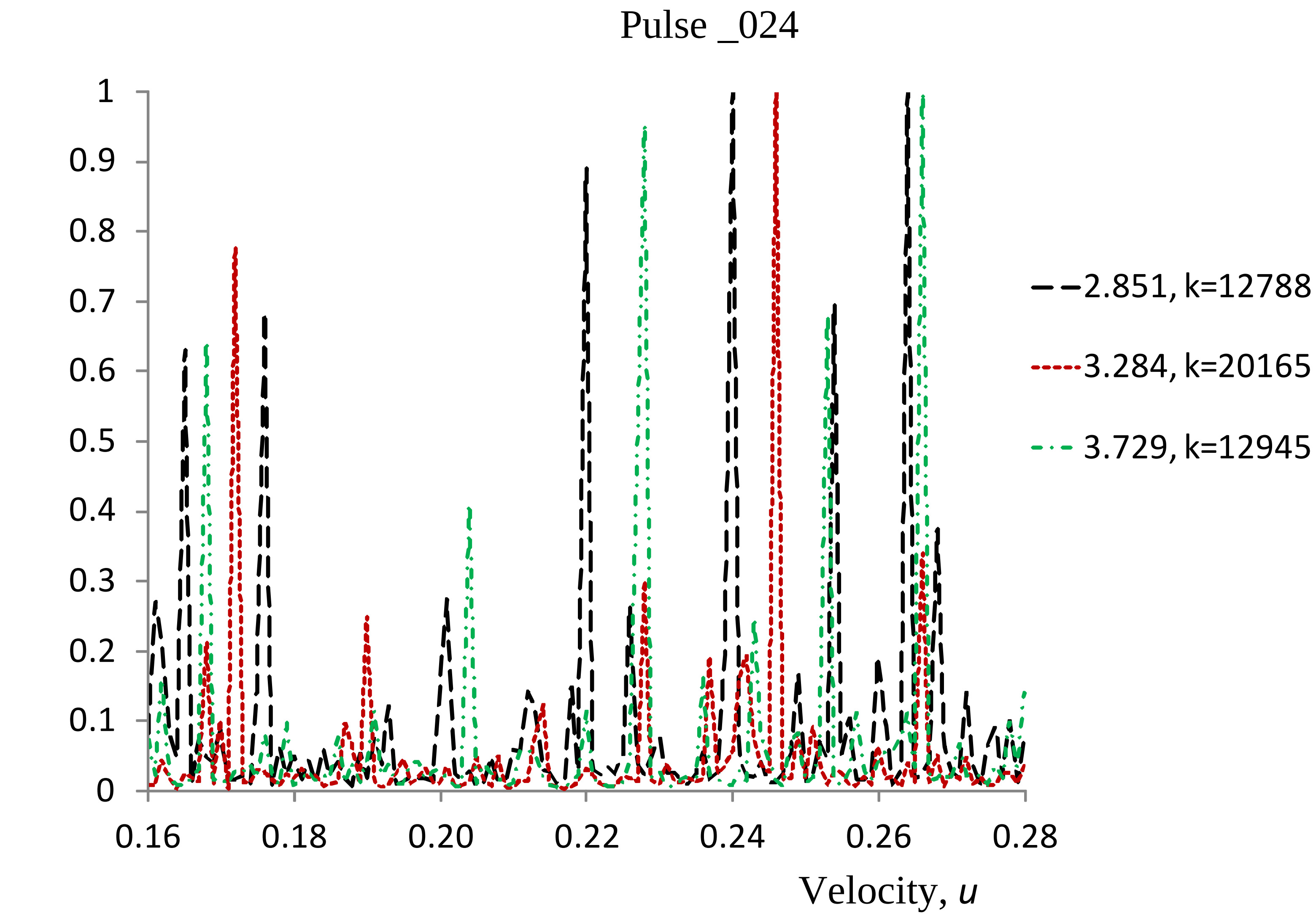


(a) the spectrum of the microwave radiation pulse received by the FFT over the entire duration of the oscillogram recording (800 ns, sampling step 16 ps);

(b) instantaneous frequency graph and (c) the square of the pulse waveform amplitude _024.

The numbers indicate the correspondence of spectrum frequencies and instantaneous frequencies.

Normalized inverse spectra for frequencies (1) 2.851 → (3) 3.284 → (4) 3.729 pulse _024. The coefficient k shows the value of the normalization coefficient when plotting graphs.



Conclusions

The main fact of the experimental results is based on two basic principles:
1) The experimental spectra of microwave pulses in the free mode indicate the resonant generation mechanism.
2) There is no repeatability of the position of frequencies in the generation spectra.

First conclusion. Frequency spectrum inconsistency is an unavoidable and fundamental feature of free-mode generation. This is due to the non-repeatability of the injection of the relativistic electron beam.
Second conclusion. Plasma density instability is not the reason for the non-repeatability of the frequency spectrum.
Third conclusion. When generating at a fixed frequency, the beam electrons with different velocities are involved. Two groups of electrons participating in the formation of microwave radiation have been identified: fast electrons with velocities in the range 0.22 - 0.27 and slow electrons in the range 0.16 - 0.19.
The generation mode is degenerate, energy is taken from different groups of electrons at different speeds. Several longitudinal modes with different numbers of half-waves N in the cavity correspond to one frequency.
The fourth conclusion. The study of resonance effects requires an extremely accurate frequency measurement, namely with an accuracy of 10^{-4}. Thus, it is desirable to measure frequencies in the gigahertz range with an accuracy of ± 0.1 MHz. The arrival of the wave behind the reflecting plane does not exceed $\lambda / 2$, and in most cases $\lambda / 4$.

Rezalt

An algorithm has been developed to determine the main characteristics of longitudinal modes (phase velocity of a wave, length of an effective resonator, number of half waves, wavelength, amount of entry behind the reflecting plane). The input data are the experimental oscillation frequencies (obtained by Fourier analysis, a measurement accuracy of 10^{-4} in the gigahertz range is required) and the basic resonator length (a sufficient measurement accuracy of ± 1 cm). The range of relativistic velocities of the REB electrons is also specified. The electron velocities of the relativistic beam can exceed the velocities determined by the accelerating voltage. New terms are introduced to demonstrate the calculated data: *the direct spectrum* and *the inverse spectrum* of the detuning ΔN in the coordinates of the velocity u of the electrons of the relativistic beam. It has been shown that obtaining an inverse detuning spectrum is a delicate tool for analyzing small frequency changes associated with resonance effects. The normalized inverse spectra are used to determine the velocities of relativistic electrons participating in the formation of fine-structured generation.

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