RADIO-FREQUENCY RADIATION OF HIGH ENERGY ELECTRONS

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Summary

The results of the experimentally investigated properties of the radio-frequency radiation generated by the relativistic electrons in the waveguide structures are reported. It is shown that the commensurability of the radiators sizes with the radiated wavelength is responsible for the appearance of characteristic peculiarities in the properties of electron bunch radiation which may have a number of practical applications.

The radio-frequency region of high energy electron radiation has a series of interesting properties and applications due mainly to the fact that in this frequency region the characteristic sizes of radiators are commensurable with the length of the radiated wave. Among the problems that arose our interest for this region of radiation spectrum we mention the possibility of diagnostics of the charged particle beams, the microwave generation, etc.

Below, we present some results of our works on the experimental study of the properties of the radio-frequency radiation generated by the relativistic electrons in the waveguide structures. These works are based on the theory developed by Ya.B. Fainberg and N.A. Khizhniak[1], K.A. Barsukov[2], L.G. Lomise[3] and our group[4].

Before proceeding with our report, the following circumstance should be mentioned. The point is that in the above-quoted works, they considered the radiation of a single charge, assuming that the radiation energy losses are less than the kinetic energy of the charge. As to the experiments, the charged particle beams are used here. Hence, the experimentally measured values of the energy losses will be determined by both the radiator characteristics and the beam formfactor $F(\omega)$.

When a continuous (density-uniform) charged particle flux traverses the radiator, a low radiation arises, whose intensity is determined only by the flux density fluctuations.

In case of using electron beams obtained at the waveguide linacs, these beams represent periodical repetition of electron bunches at the accelerating field frequency ω_0.

To estimate the factor $F(\omega)$, let us consider the following simple model. Let N cylindrical bunches $2r_0$ in diameter and $2d$ in height move 2ℓ spaced from each other at a velocity $v=v_z$ along the Z axis. Let each bunch contain n electrons. Then the beam formfactor $F(\omega)$ will have the form[3,4]:

$$F(\omega)=en\,\frac{J_1\left(\frac{\omega}{v}(1-\beta^2)r_0\right)}{\frac{\omega}{v}(1-\beta^2)r_0}\cdot\frac{\sin\frac{\omega}{v}d}{\frac{\omega}{v}d}\cdot\frac{\sin\frac{N\omega\ell}{v}}{\frac{\omega}{v}\ell} \qquad (1)$$

where e is the electron charge, J_1 is the Bessel function.

At frequencies satisfying the conditions

$$\frac{\omega}{v}\ell=p\pi \Rightarrow \frac{\omega}{\omega_0}=p\beta, \quad \text{where } p=1,2,3,\ldots,$$

$$\frac{\omega}{v}d \ll 1 \quad \text{and} \quad \frac{\omega}{v}(1-\beta^2)r_0 \ll 1$$

the radiated energy will be proportional to the square of the charge passed through the radiator, $(enN)^2$.

If the charged particle in its motion traverses a regular rectangular waveguide perpendicularly to its axis, then it induces in this waveguide TM and TE waves[3,6]. In case of excitation of the main wave, H_{10}, the radiation energy spectral distribution has the form as shown in fig. 1.

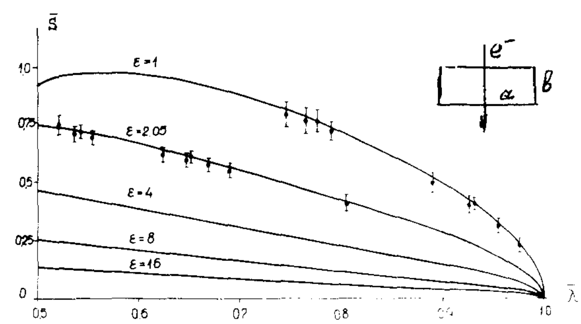

Fig. 1. Transition radiation energy as a function of the waveguide dispersion at homogeneous filling.

At the relation $b/a \approx 0.5$, the energy spectral density in the $0.5 \leq \lambda_0/\lambda_c \leq 0.8$ range (i.e. in the waveguide operating range) has a good (~15%) uniformity. We have used this circumstance for measuring the phase length of bunches ($\frac{\omega}{v}d$) of the electron beam accelerated up to 50 MeV in the linac[7]. The number of bunches N per linac current pulse was ~ 3000, therefore, with a good approximation ($\Delta\omega/\omega = 10^{-3}$), we could consider the transition radiation spectrum discrete. The radiator was a set of rectangular waveguides whose transverse sizes were chosen so that the k-th harmonic of the pulse repetition rate should be excited in the k-th waveguide, while the (k-1)-th harmonic should be limiting. Having chosen the same ratio b/a and λ_0/λ_c for each waveguide we ensure the same value of $R(\omega)$. Since the (k+1)-th harmonic can excite the k-th waveguide, all the waveguides were loaded with rejector filters providing the (k+1)-th harmonic attenuation ~ 20 db. The radiator construction provided a good current passage (up to 90%) of the beam through the hole 2 mm in diameter. A diagram of the experimental arrangement is shown in fig. 2.

The performed measurements allowed to establish that the most stable acceleration mode is achieved at the bunches phase length from 5° to 30°. At lesser and larger values of $\frac{\omega}{v}d$ the acceleration mode was unstable.

After determining the bunch formfactor, $F(\omega)$, we could proceed with the investigation of the properties of different radiators.

At the beam traversal through the dielectric plate in the waveguide a wave is generated whose occurence is due to both the Čerenkov and transition radiation. Both the Čerenkov and transition radiation power dependences calculated by the formulae of ref. 9 are presented in fig. 3.

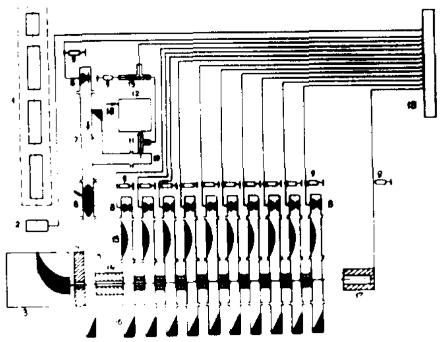

Fig. 2. 1. Accelerator. 2. Resonator. 3. Beam-turning magnet. 4, 14. Collimators. 5. Controlling waveguide. 6, 15. Attenuators. 7. Directional coupler. 8. Detector. 9. Load. 10. Waveguide-coaxial junction. 11, 13. Divider. 12. HF generator. 16. Matched loading. 17. Faraday cylinder. 18. Indicator unit.

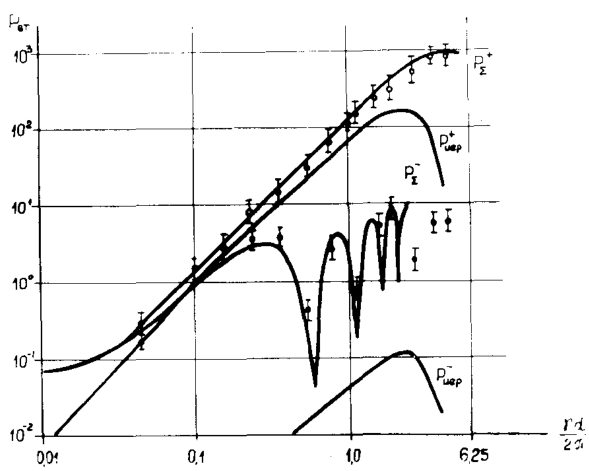

Fig. 3. The summary power of the transition and Čerenkov radiation $P_\Sigma^\pm$ in the waveguide with dielectric plate (ε = 2.05) as a function of the plate electrical length. P_{uep} is the theoretical power dependence of the Čerenkov forward radiation "+" along the beam motion, and backward one "-".

It was impossible to separate experimentally the Cerenkov and transition radiation for the given radiator. Therefore, a summary power of the forward P_Σ^+ and backward P_Σ^- radiation was measured. The $P_\Sigma^\pm$ radiation for the small thicknesses γd increases by the quadratic law, and $P_\Sigma^+ = P_\Sigma^-$, what is characteristic of the transition radiation. With increasing γd, the contribution of the Čerenkov forward radiation increases and P_Σ^+ grows almost linearly. In the backward radiation P_Σ^-, which is due mainly to the transition one, there are observed distinct maxima and minima caused by the wave interference from the front and back boundaries of the plate.

Ya.B. Fainberg and N.A. Khizhniak[1] have shown that at the particle passage through the laminated dielectric, a radiation arises that differs from a usual Čerenkov one by a number of peculiarities. The authors called this radiation parametrical because of the nature of resonance between the frequency of the particle exciting field and the one of the laminated medium natural oscillations.

If the particle moves at a velocity v along the axis of a circular waveguide filled with infinite laminated dielectric of the structure period L = $a+b$, where a is the air gap thickness (ε_1=1, μ_1 =1), is the layer thickness with the dielectric constant $\varepsilon(\omega)$, then the particle energy total losses will consist of the polarization losses, the usual Vavilov-Cerenkov radiation losses and the parametrical radiation ones.

Ref. 10 presents the experimental data on the E_{01} wave excitation in the circular waveguide. The experiment was performed with the above-described arrangement. The laminated medium was created of the alternating air and teflon layers. The power of the excited forward and backward E_{01} wave was measured. The calculational results of ref. 1 and of the experiment are presented in fig. 4.

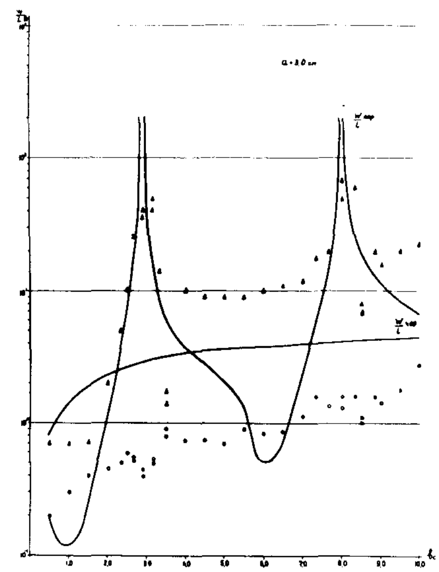

Fig. 4. The radiation power in the laminated medium as a function of the dielectric plate thickness at the fixed value of the air gap a = 3 cm. ▲ - forward radiation along the bunches motion direction; o - backward radiation.

The calculations have shown that for the above-given parameters of the beam and radiator the parametrical radiation dominates over the usual Cerenkov one which occurs in the plate due to $\varepsilon\beta^2 > 1$.

The range of the values a =3.7 ÷ 5.1 cm corresponds to the waveguide non-transparency band. A comparatively high level of power registered in this band is explained by the fact that since the number of periods of the structure filling the waveguide is finite, then the forward and backward transition radiations at the structure boundaries always take place. Fig. 4 illustrates the dependence of the radiation intensity on the teflon plate thickness at the fixed value a =3.0cm. Two parametrical maxima are pronounced, corresponding to the first and second spatial harmonics. Unfortunately, the limitations in the experimental arrangement length made it impossible to investigate the higher-order resonances. The experiment was done with the radiator, the total length of which was 160 cm, what enabled one to take the number of layers N no less than 12 for the largest L.

It became clear from the investigation done that the finite sizes of the laminated medium impose a number of characteristic peculiarities. In ref. 11 they have calculated a radiation arising in the waveguide at the charged particle traversal through the finite stack of dielectric plates, and ref. 12 presents the experimental results. They measured the dependence of the radiated energy on both the waveguide dispersion and the number of periods of the laminated medium. The measurement of the quoted dependences in the laminated medium transparency and non-transparency bands was of interest. In the transparency band, the parametrical resonance condition being fulfilled[1], the energy losses in the stack of N plates exceed N^2 times those in single plate, and the resonance width is inversely proportional to N. This is illustrated well by the calculational and experimental dependences shown in fig. 5.

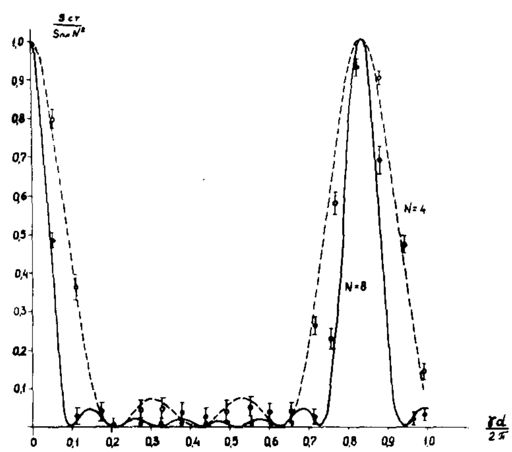

Fig. 5. Relative power of forward radiation in the stack of N plates as a function of the plate thickness γd and of the medium period $2\gamma d$ =2Γa at λ_0/λ_c =0.82 corresponding to the stack transparency condition.

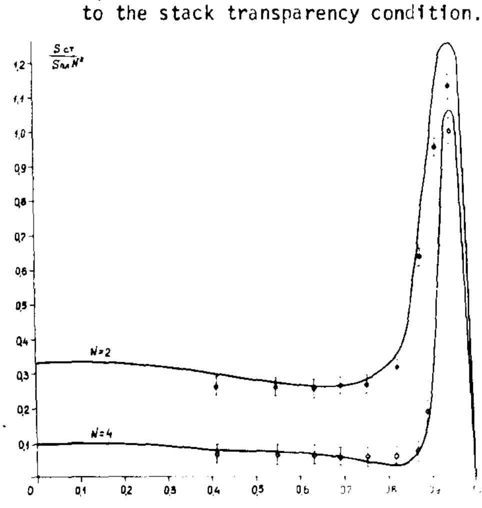

Fig. 6. Relative power of forward radiation in the stack of N plates as a function of the waveguide dispersion under the stack non-transparency condition $\gamma d = \Gamma a = \pi/2$

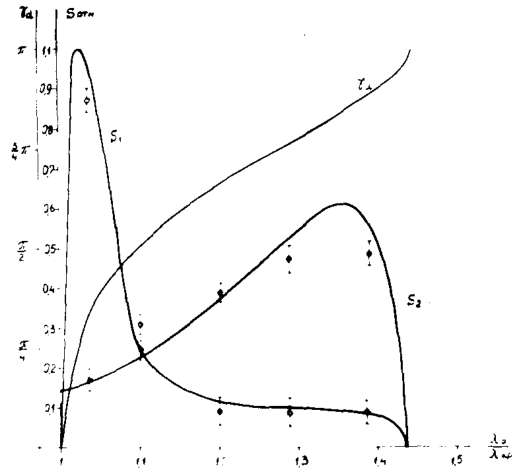

Fig. 7. The "locked" radiation power S in the dielectric plate and the radiation power S in the dielectric-filled resonator as functions of the waveguide dispersion. S is normalized in the power level 200 w.

For the non-transparent stack the radiation energy losses (fig. 6) in the wide range of values of λ_0/λ_c are approximately equal to the energy losses in single plate except for the region close to the critical wavelength, i.e. for those values of λ_0/λ_c where the stack reflection coefficient sharply increases. This case may be interpreted as the case of the "locked" radiation. The "locked" radiation is a phenomenon characteristic of radiation in any waveguide. It occurs when the wave propagation is impossible beyond the medium (plate), i.e. in the frequency range lying between the critical frequencies of the empty waveguide and that filled with dielectric[9,13]. At the charged particle passage through the plate the energy radiated in this frequency range is "locked" within the plate. In case of the axial passage the plate resonance length and the radiation energy can be calculated by the formulae of ref. 9. Note that at $\beta^2 < \beta^2\varepsilon - 1$ the Čerenkov radiation may occur, which also is "locked" in the plate, so the Čerenkov radiation peak appears in the quasi-continuous spectrum of the transition radiation. In case of the H_{m0} waves excitation (when the particle passes perpendicularly to the waveguide axis) the Čerenkov radiation is impossible, so all the energy of the "locked" radiation will be due only to the transition radiation[13]. The dependence of the "locked" radiation energy on the waveguide dispersion was measured experimentally[14]. Fig. 7 presents the calculational and experimental dependences on both λ_0/λ_c and the plate resonance optical length. The radiation peak due to the Vavilov-Čerenkov effect corresponds to λ_0/λ_c =1.02. In the wavelength λ_0/λ_c < 1.1 the "locked" radiation exceeds that in the resonator.

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