Letters to the Editor

Pulsed Coherent Generation of Millimeter Radiowaves by Nonrelativistic Electron Bunches

G. A. ASKAR'IAN
P. N. Lebedev Physical Institute
Academy of Sciences, USSR
(Submitted to JETP editor August 10, 1955)
J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 584-586
(March, 1956)

THE proposed[1,2] and partly realized[3] methods of coherent generation of millimeter waves by electron bunches possess a number of properties limiting their applicability and efficacy. Thus, for instance, a complicated experimental set-up containing an accelerator and buncher of relativistic electrons is necessary for the wave generation through relativistic transformation of emission frequencies taking place during the passage of the bunch through the field of the undulator[1-3] or the accelerator[1]. The difficulty of formation of compact, strong, relativistic bunches and preservation of their size during sufficiently long flight in fields in the presence of Coulomb divergence and spread of the trajectories of the electrons forming the bunch prevent the actual realization of the method and its application.

The proposed methods of microwave generation by nonrelativistic electron bunches radiating during accelerated or oscillatory motion (under the influence of applied electromagentic fields) or uniform Cerenkov motion in a narrow channel in a dielectric or close to a dielectric surface[1] are in practice inconvenient, since the condition of the proximity to the dielectric (the cross section of the channel or the distance to the dielectric surface should be smaller than the wavelength of the generated radiation) together with the necessity of safeguarding a long path of flight bring about heavy current losses and limitations connected with the necessity of strong collimation and the impossibility of employing strong compact bunches.

The method of generation of microwaves proposed here makes use of the radiation emitted during the bombardment of a metallic or dielectric anticathode with electronic bunches or by rebounding of the bunches from a strong localized field. The possibility of employing compact (during the short timed interaction), strong electronic bunches constitutes the main advantage of the pulsed method, permitting the placing of the interaction region in the focus of the buncher. Although pulsed bunches create radiation having a continuous spectrum, the minimum wavelength of intensively emitted radiation, determined by the compactness of the bunch at the moment of action, can be shifted into the spectral region where the use of methods employing long-acting bunches is not very effective or altogether impossible.

We shall estimate the angular distribution and the total energy of radiation for the case of normal incidence of a nonrelativistic bunch upon a layer of metal. For a bunch consisting of N electrons, moving with the velocity v, the distribution of radiation accompanying the annihilation of a bunch and its image in the frequency region in which the emitted wavelength is greater than the bunch dimensions

$$\mathcal{E}^{\text{ann}}(\theta)\, d\omega\, d\Omega \approx (N^2 e^2 v^2 / \pi^2 c^3) \sin^2\theta\, d\omega\, d\Omega$$

(θ is the angle between the direction of reception and the velocity vector of the bunch image) and

$$\mathcal{E}^{\text{ann}}_{\omega} d\omega \approx (4N^2 e^2 v^2 / 3\pi c^3)\, d\omega\,.$$

The main advantages of metallic anticathodes are larger value of thermal and electrical conductance and high thermal endurance, enabling the use of strong currents without impairing the stability. With a pulsed current $I \sim 300$ mA, $N \sim 10^9$ and the kinetic energy of electrons in the bunch $T_{\text{kin}} \sim 30$ kev, the pulsed power of radiation in the bandwidth $\Delta\lambda \sim \lambda \sim 0.1$ cm

$$w_{\text{pulsed}} \approx 8INe\beta^2 / 3\lambda \sim 130 \text{ W}.$$

Among the deficiencies of metallic anticathodes should be noted the small efficiency coefficient of transformation of the bunch energy into radiation and inconvenient angular distribution of the radiation.

A second method of generation consists in pulsed generation of radiation, arising through incidence of the beam on an indentation on the surface of a dielectric, transparent for the millimeter waves, but possessing sufficient conductivity for the direct current.

The energy of the radiation in the dielectric is:

$$\mathcal{E}^{\text{brems}}_{n\omega}(\theta')\, d\Omega\, d\omega = c'\varepsilon\, |\mathbf{E}_\omega|^2 R_0^2\, d\Omega\, d\omega$$

($c' = c/\sqrt{\epsilon}$; θ' is the angle between the direction of reception $\mathbf{n}$ and the initial bunch velocity $\mathbf{v}_0$).

Summing the Fourier components of the wave fields of all electrons, and using the formulas for the case of infinite dielectric (neglecting the boundary effect of reflection is obviously permissible in the case of $v_0 \approx c'$, i.e., in the case of prevalence of the radiation in the forward direction) we shall obtain, while the coherence condition

$$\omega\left(\frac{x}{v_0}+\frac{y\sin\theta}{c'}\right) \ll 1,$$

is satisfied (x and y denote the longitudinal and the lateral dimensions of the bunch, respectively),

$$\mathbf{E}_\omega = \sum_{i=1}^{N}\mathbf{E}_{i\omega} = \frac{e}{2\pi\varepsilon c'^2 R_0}\sum_{i=1}^{N}\int\frac{[\mathbf{n}\,[(\mathbf{n}-\mathbf{v}_i/c')\,\dot{\mathbf{v}}_i]]}{(1-\mathbf{v}_i\mathbf{n}/c')^2}$$

$$\times\exp\left[j\omega\left\{t_1' + \frac{R_0}{c'} - \frac{\mathbf{r}_i(t_i')\,\mathbf{n}}{c'}\right\}\right]dt_i'$$

$$\approx \frac{(eN)\exp\{i\omega R_0/c'\}}{2\pi\varepsilon c'^2 R_0}\,\frac{[\mathbf{n}\,[\mathbf{n}\mathbf{v}_0]]}{(1-\mathbf{v}_0\mathbf{n}/c')}.$$

(This is true since for the plane boundary and for $\beta' \approx 1$ in the coherent region $\mathbf{E}_\omega^{brems} \approx -\mathbf{E}_\omega^{trans}$ in order to prevent the vanishing of the Fourier component of interest of the resulting wave field it is necessary to attenuate the bremsstrahlung or the transitional radiation at least in the desired bandwidth, or to create the needed phase shift between radiation pulses. This can be done, for instance, making narrow axial channels in the dielectric, about 1 cm deep, which should be sufficient for destroying the longitudinal condition of coherence of the bunch or a part of it at one end of the channel, or for the desired phase shift between the radiation pulses.)

Using the obtained expression for $\mathbf{E}_\omega$, we shall write down the formulas for the spectral-angular and the spectral distributions of the energy of the transitional or the bremsstrahlung radiations:

$$\mathcal{E}_{n\omega}(\theta')\,d\Omega d\omega = \frac{\sqrt{\varepsilon}\,(eN)^2 v_0^2\sin^2\theta'}{4\pi^2c^3\,(1-\beta_0'\cos\theta')^2}\,d\Omega d\omega;$$

$$\mathcal{E}_{n\omega}(\theta'_{max}) = \frac{\sqrt{\varepsilon}\,(eN)^2 v_0^2}{4\pi^2c^3\,(1-\beta_0'^2)};$$

$$\mathcal{E}_\omega d\omega = \frac{\sqrt{\varepsilon}\,(Ne)^2 v_0^2}{\pi c^3\beta_0'^3}\left\{\ln\frac{1+\beta_0'}{1-\beta_0'} - 2\beta_0'\right\}d\omega,$$

where θ'_{max} is the angle corresponding to the maximum intensity ($\cos\theta'_{max} = \beta_0'$).

These formulas should coincide with the radiation distribution formulas for the sudden stopping of a point charge in dielectric[4], since in the spectral region of interest the wavelength of the emitted radiation exceeds the dimensions of the braking region and of the bunch.

Obviously, the use of dielectric anticathodes, permitting only moderate currents due to their thermal limitations will be purposeful in the region $\beta_0 \approx c'$ in which the intensity and direction of radiation rise sharply on entering the dielectric.

We shall compare the bremsstrahlung radiation in the dielectric anticathode with the "annihilation" radiation, following the head-on incidence of a nonrelativistic electron bunch upon a metallic anticathode: for $\sqrt{\epsilon} \sim 3$ ($T_{kin} \sim 30$ kev) and the mean value of $1/(1-\beta'^2) \approx 10^2$:

$$\frac{\mathcal{E}_{n\omega}^{brems}(\theta'_{max})}{\mathcal{E}_{n\omega}^{ann}(\theta_{max})} = \frac{\sqrt{\varepsilon}}{4\left(1-\beta_0'^2\right)} \approx 75; \qquad \frac{\mathcal{E}_\omega^{brems}}{\mathcal{E}_\omega^{ann}} \approx 9.$$

The mean yield of radiation energy $w = 4\,W$ in $\Delta\omega \sim 2\times10^{12}$ ($\Delta\lambda \sim \lambda \sim 0.1$ cm) for the total current intensity of the bunches entering the channels of a thermally stabilized dielectric anticathode $I_b \sim 1$mA, and for the number of electrons in the bunch $N \sim 10^9$

It should be noted that the cited values of radiation energy in the region $\Delta\lambda \sim \lambda \sim 0.1$ cm are obtained for the continuous distribution spectrum, which allows the energy to be redistributed in the spectrum, e.g., phase-shifted bremsstrahlung radiation or employing bunches with periodically modulated charge density.

The final choice of the anticathode will depend on the specific conditions and purposes of the tube. The separation of the millimeter waves from the x-ray background can be done using, for instance, bent waveguides bringing out the radiation from behind the protecting screens or using a dielectric transparent for the microwaves as a filter.

The idea of construction of a millimeter wave generator simple in production and use and sufficiently intensive, seems to be promising, since its realization will enable wide application of millimeter waves.

---

[1] V. L. Ginzburg, Izv. Akad. Nauk SSSR, Ser. Fiz. 11, 165 (1947).

[2] H. Motz, J. Appl. Phys. 22, 527 (1951).

[3] H. Motz, J. Appl. Phys. 24, 826 (1953).

[4] V. L. Ginzburg and I. M. Frank, J. Exptl. Theoret. Phys. (U.S.S.R.) 16, 15 (1946).

Translated by H. Kasha
110