Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (27–28 February 1985)

Usp. Fiz. Nauk **146**, 709–718 (August 1985)

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR took place in the conference hall of the P. N. Lebedev Physics Institute of the Academy of Sciences of the USSR on February 27 and 28, 1985. The following papers were presented at the session:

27 February

1. *Ya. B. Faĭnberg*. Some problems of plasma electronics.

2. *M. V. Kuzelev, A. A. Rukhadze, P. S. Strelkov and A. G. Shkvarunets*. Relativistic plasma UHF electronics.

28 February

3. *G. T. Zatsepin and O. G. Ryazhskaya*. Program for the search for star collapse in the Galaxy.

4. *V. N. Gavrin, G. T. Zatsepin and O. G. Ryazhskaya*. Present status and prospects of the problem of detecting solar neutrinos.

5. *V. S. Berezinskiĭ*. High energy neutrino astrophysics.

A brief summary of three of the papers is given below.

M. V. Kuzelev, A. A. Rukhadze, P. S. Strelkov and A. G. Shkvarunets. *Relativistic plasma* UHF *electronics*. 1. Introduction. Plasma UHF electronics as a science was born in 1949 in the papers of A. I. Akhiezer and Ya. B. Faĭnberg,[1] and D. Bohm and E. Gross,[2] who predicted the phenomenon of stimulated Cherenkov radiation of electromagnetic waves in a plasma by a beam of fast electrons. This phenomenon opens up the possibilities of effective amplification and generation of electromagnetic waves in the centimeter and millimeter ranges, the obtaining of high currents in electron beams and the attainment of high powers of radiation. The parameters of plasma devices according to estimates exceeded by far the analogous parameters of devices of vacuum UHF electronics.

The very first experiments demonstrated that electron beams in a plasma indeed are effective in exciting electromagnetic fields of large amplitude. But these fields turned out to be locked in within the plasma and were not strongly emitted outside the plasma. This obstacle due to the low phase velocities of the waves being excited turned out to be difficult to overcome and negated all the advantages of plasma electronics. The results of the investigations up to the middle of the 1960's were summarized in the monograph of Ref. 3 which, although expressing optimism, noted the inability as yet of plasma electronics devices to compete successfully with devices used in vacuum UHF electronics. And this situation did not change with time.

In the beginning of the 1970's plasma UHF electronics was reborn, but now in relativistic form. This rebirth is associated with the name of M. S. Rabinovich who proposed using the powerful relativistic electron beams that appeared at the time in order to generate electromagnetic radiation.[4] Below we discuss the achievements of this science during the last decade and its prospects following References 4–14.

2. Advantages of relativistic plasma UHF electronics. In vacuum UHF devices the beam current is lower than the limiting vacuum current[5]

$$I_0 = 17\frac{(\gamma^{2/3}-1)^{3/2}}{(\Delta/r_b)+2\ln(R/r_b)}\ (\text{kA}); \qquad (1)$$

here $\gamma = 1 + (\varepsilon/mc^2)$ is the relativistic factor, R is the resonator radius, r_b is the average radius of the cylindrical electron beam of thickness $\Delta \ll r_b$. The limiting current (1) restricts the power of vacuum UHF devices. But in plasma UHF devices beams can be utilized with currents up to

$$I_{b,\max} = \gamma\left(\frac{1-\gamma^{-2}}{1-\gamma^{-2/3}}\right)^{3/2} I_0. \qquad (2)$$

When $\gamma = 3(\varepsilon = 1\ \text{MeV})$ the current $I_{b,\max} \approx 7I_0$ exceeds by a large amount the value utilized in relativistic vacuum UHF electronics.

In vacuum UHF devices the frequency of the waves being amplified is rigidly associated with the dimensions of the resonator, and it is practically impossible to vary it smoothly. But in plasma devices this frequency also depends on the plasma density[6]

$$\omega = \sqrt{\omega_p^2 - k_\perp^2 u^2\gamma^2}, \qquad (3)$$

where $\omega_p = \sqrt{4\pi e^2 n_p/m}$, while $k_\perp$ is the transverse wave number of the wave being amplified. By varying the plasma density n_p in the range

$$k_{\perp 1}^2 u^2\gamma^2 > \omega_p^2 > k_{\perp 0}^2 u^2\gamma^2, \qquad (4)$$

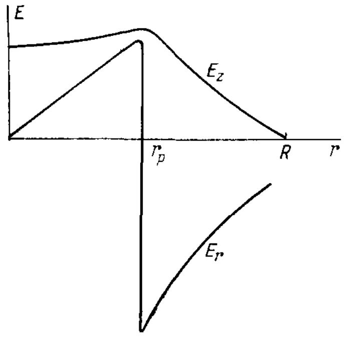

FIG. 1

where $k_\perp$ and $k_{\perp\perp}$ are the lowest transverse wave numbers one can vary the frequency ω over a wide range.

From (3) and (4) follows yet another advantage of relativistic plasma UHF electronics. Specifically, as γ is increased the critical density of the plasma increases above which amplification in the system is possible, and together with it the frequency of the wave being amplified also increases $\omega \lesssim \omega_p \approx k_\perp c\gamma$, which exceeds by a factor of γ the frequencies of waves being amplified in the vacuum systems. Moreover, if in vacuum parametric systems[7] one can obtain short-wave radiation with $\omega \approx k_\perp c\gamma^2$, then in corresponding plasma sources we have $\omega \approx k_\perp c\gamma^3$.

Finally, the phase velocity of waves being amplified by relativistic beams is $\omega/k \approx u \approx c$. The reflection coefficient for such waves from the plasma boundaries[8] is

$$\varkappa = \frac{1-(u/c)}{1+(u/c)} \approx \frac{1}{4\gamma^2} \ll 1. \qquad (5)$$

The smallness of the quantity $\varkappa$ eliminates the problem of extracting the UHF radiation from the plasma, not to mention the fact that high-current amplifiers and generators of UHF can be realized only using low-quality-factor resonators, and this is guaranteed when $\varkappa \ll 1$.

The realization of the above advantages of relativistic plasma UHF electronics requires the construction of systems with very high magnetic fields:

$$\Omega^2 = \frac{e^2 B_0^2}{m^2 c^2} \gg (\gamma^2 - 1)^2 \omega_p^2. \qquad (6)$$

With $\gamma \approx 3$ and $n_p \approx 4 \cdot 10^{11}$ cm^{-3} the condition (6) is satisfied when $B_0 > 50$ kG.

3. Achievements and prospects of relativistic plasma UHF electronics. Experimental achievements in obtaining

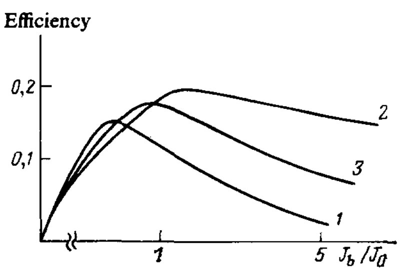

FIG. 2

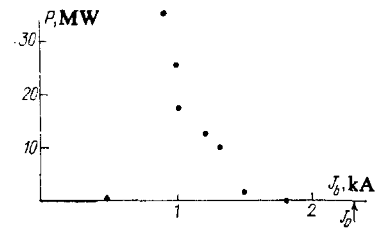

FIG. 3

single-mode generation in relativistic plasma UHF electronics are restricted to Refs. 8, 9 where two types of plasma UHF generators were realized using the TEM mode (the principal mode of a cable wave) of a plasma resonator with thin tubular plasma of radius r_p and of thickness $\Delta_p \ll r_p$ (Fig. 1). Both types of generators were working utilizing a relativistic beam of energy $\varepsilon \approx 450$ keV and a current of $I_b \approx 1-8$ kA. In the experiment of Ref. 8 the beam was injected within a plasma cylinder, i.e., $r_p > r_b$, while in the experiment of Ref. 9 the beam encompassed the plasma cylinder, i.e., $r_p < r_b$. A study was made of the structure of the mode excited by the beam, of the power of the radiation from the plasma, of the frequency spectrum, of the dependence of these quantities on the plasma density, on the beam current and the point of its injection, on the angular spread of the electrons in the beam. The existence of a critical plasma density, above which excitation of waves takes place, its magnitude, the dependence of the frequency of the radiation on the plasma density, the starting current of the beam (or the critical length of the resonator) for exciting the generator and the structure of the field of the mode being excited are in good agreement with the theory not only qualitatively but also quantitatively.[10]

Here we present the dependence of the power of the radiation on the beam current, which is described only within the framework of a nonlinear theory developed in Refs. 11–13, and which opens up new prospects for high current plasma UHF electronics. In Refs. 11–14 it was shown that the nature of the interaction of a relativistic electron beam with plasma is determined by the parameter $\mu = (I_b/I_0)^{1/3}$. For $\mu \ll 1$ the mechanism of the interaction amounts to stimulated Cherenkov radiation of electromagnetic waves by the electrons of the beam. If in this case the instability is of a

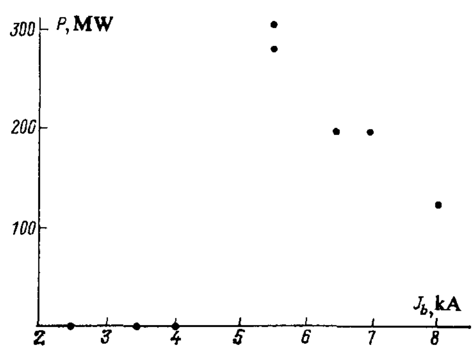

FIG. 4

single particle nature, then the efficiency of radiation increases with the current as $I_b^{1/3}$. However when $\mu > 1$ the mechanism of beam instability is essentially altered, it acquires the nature of a nonradiating phase transition and is accompanied by a deep modulation of the beam itself. As a result the efficiency of radiation falls as I_b^{-1} (curve 1 in Fig. 2).

In the papers of Ref. 12 it is shown that by choosing the point of injection of the beam one can diminish the effect of the HF space charge of the beam and even completely cancel it. In this case the instability remains a radiative one and for $\mu \gg 1$ the efficiency essentially increases and falls with the current in a limited manner as $I_b^{-1/3}$ (curve 2 in Fig. 2).

The slow decrease in the efficiency of radiation as a function of the current (curve 3 in Fig. 2) as $I_b^{-1/2}$ for $\mu \gg 1$ must also be observed in the case of a collective mechanism of beam instability which is realized in the case of injection of a high current beam into a plasma of subcritical density,[13] or when the beam and the plasma are greatly separated in space.[14]

The dependences of the radiated power on the beam current observed in the experiments of Refs. 8, 9 and shown in Figs. 3 and 4 respectively, are evidence rather of a single-frequency mechanism of instability with a large HF space charge of the beam in the high current range. Therefore it is necessary to conduct further studies with the aim of realizing the aforementioned high efficiency regimes of operation of plasma UHF generators.

4. Conclusion. Thus, relativistic plasma UHF electronics, in particular on the experimental side, has taken only the first steps. The theory already by now has formulated a number of difficult problems associated with the relativistic and high current nature of electron beams, which require experimental investigation. The theory also has many problems, for example the generalization of results obtained for devices with Cherenkov excitation of waves, to other mechanisms of excitation.

But already from the results of Refs. 8, 9 it follows that relativistic plasma UHF electronics can successfully compete with vacuum electronics. Evidence of this is not only the good agreement of experiments with theory, but also values of the obtained powers of radiation in the centimeter range of wave lengths ($\approx$200 MW) and efficiencies of radiation ($\approx$10–15%) compared with the corresponding values for vacuum devices. If one adds that in these experiments a considerable tuning of the frequency of radiation in the range of 1.8–3.2 cm has been realized, one can hope that the day is not too distant when new unique plasma amplifiers and generators of UHF radiation will be constructed and plasma UHF electronics will be firmly established in science and in technology.

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