350 and 500°C the value of S_2/S is zero, and the values of δ_2 coincide with the positions of the centers of these spectra. As seen from Fig. 3, the area under the second line is maximal after annealing at 400° and 800°, and the values of the chemical shift are maximal after annealing at 400 and 700°. The relative value of the area under the second line is proportional to the fraction of the iron atoms leaving the solution, and the character of its dependence on the annealing temperature obviously corresponds to the proposed decay scheme. The value of the chemical shift δ_2 apparently changes in accordance with the change of the composition, structure, and dimension of the segregations. The same Fig. 3 shows a plot of the critical current density in a field $H = 0.9H_{c2}$ (i.e., in a field corresponding to ahe peak of J_c for curves 1, 3, and 6 of Fig. 1) against the annealing temperature. We see that this dependence is in full correlation with the $\delta_2(t)$ dependence. It can be proposed that the value of the chemical shift for the iron atoms in the segregations and the value of the critical current density are determined by the same factors. A more detailed evaluation of the results will be published by us later.

[1] R.R. Hake and J.A. Cape. Phys. Rev. 135, A1151 (1964).
[2] V.S. Shpinel', Rezonans γ-luchei v kristallakh (Gamma-ray Resonance in Crystals), Nauka, 1969.
[3] D.A. Prokoshkin and E.V. Vasil'eva, Splavy niobiya (Niobium Alloys), Nauka, 1964.
[4] A.F. Prokoshin, Pretsizionnye splavy (Precision Alloys), in: Sb. trudov TsNIIChM (Coll. Papers of Central Research Inst. of Ferrous Metals) 71, 161 (1969).

PLASMA HEATING BY OPPOSING BEAMS OF COHERENT RADIATION

Ya.B. Zel'dovich and E.V. Levich
Applied Mathematics Institute, USSR Academy of Sciences
Submitted 18 March 1970
ZhETF Pis. Red. 11, No. 10, 497 - 500 (20 May 1970)

The possibility of plasma heating by coherent radiation was noted immediately after the development of lasers. It is customary to consider heating and absorption of radiation resulting from the interaction between electrons and nuclei at temperatures such that full ionization is already reached, i.e., free-free absorption is considered (cf., e.g., [1, 2]). Kovrizhnykh [3] proposed a method of heating nuclei in a plasma, based on stimulated nonlinear scattering by nuclei of narrow-spectrum opposing radiation beams ($\Delta\nu \ll \nu_0$, ν_0 is the Langmuir frequency). Peyraud [4] considered heating of electrons by stimulated Compton scattering of light in a focused laser beam with spectrally-narrow radiation, $\Delta\nu/\nu \sim 10^{-4}$.

The possibility of observing the effect of stimulated Compton scattering in the presence of crossed beams was first pointed out by Dreicer [5].

In this paper we propose the use of opposing beams, one or both of which are spectrally broad ($\Delta\nu/\nu \geq v/c$, where v is the thermal velocity of the electrons). Strictly speaking, light with this $\Delta\nu$ cannot be called coherent, but the required intensity can be attained only by somehow broadening the coherent radiation (by a method not considered here).

Only with such a spectrum do the electrons have a Maxwellian distribution with respect to the longitudinal velocity as a result of interaction with light without collisions [6].

The heating rate is proportional in this case to the product of the intensities of the two beams and does not depend on the charge of the nucleus or on the plasma density. At high intensity, and particularly for a substance with low density and with small nuclear charge, the proposed method should be substantially more effective than the usual one.

We shall discuss here the heating of free electrons by the Compton mechanism and compare it with the bremsstrahlung mechanism. The electron heating should be accompanied by plasma expansion, during the course of which the thermal energy of the electrons is converted into kinetic energy of the nuclei. The latter becomes thermalized when the jets collide [7]. We also present a classical interpretation of heating by stimulated scattering and compare it with acceleration of waves by opposing beams [8].

The expression for the energy gain of Maxwellian electrons in an isotropic radiation field with a broad spectrum was given by Kompaneets [9]; the kinetic equation for the electrons was considered by Dreicer [5]. Makhan'kov and Tsitovich considered electrons in a stochastic and classical electromagnetic field [10]. Peyraud presented an expression for the rate of heating of Maxwellian electrons. In our earlier paper [6] we gave a similar expression. We are grateful to A.E. Kazakov who pointed out to us the existence of the earlier paper by Peyraud [4] after our paper [6] was published.

We note that Peyraud regards the electron as being isotropically Maxwellized, say as a result of collisions, and then the expressions for the heating rate and for the stationary temperature follow directly from [9].

Actually, in the case of anisotropic radiation, the temperature is also anisotropic[1], and in the case of intense spectrally-narrow radiation the distribution differs from Maxwellian in such a way that the heating rate is smaller than given in [4] and tends to zero. In the high-intensity radiation beams needed for effective heating, the collisions do not change the situation appreciably. In this case, if at least one of the beams is spectrally broad in order of magnitude, the energy acquired $(dE/dt)_c^+$ is given by

$$(dE/dt)_c^+ \approx \frac{8I_1I_2}{\nu^2\,\Delta\nu}(1-\cos\theta)\frac{\sigma}{m},$$

where E is the electron energy, I_1 and I_2 the beam powers per unit cross sections (erg/cm^{2}sec), σ the Thomson cross section, and θ the angle between the beams.

It is important that the influence of stimulated scattering on the inverse process, the deceleration of the electrons by the radiation, is small up to relativistic energies.

A similarity can be seen between the proposed heating method and the suggested coherent acceleration of plasmoids and particles in opposing radiation beams (see [8] and the literature cited therein).

At large quantum occupation numbers n, the electromagnetic field admits of a classical description. In classical language, the heating mechanism consists in the fact that one wave (labeled by the index 1) applies to the electrons a field $v_1 = \vec{e}\cdot\vec{E}_1/2\pi\nu_1 m$, while the second wave produces a Lorentz force $\vec{F} = e^2\vec{E}_1 \times \vec{H}_2/2\pi c\nu_1 m$ or else a force that depends on the field inhomogeneity $\vec{X}_1 = -\vec{e}\cdot\vec{E}/4\pi^2 m\nu_1^2$

[1] A detailed article will be published in Zh. Eksp. Teor. Fiz. [Sov. Phys.-JETP].

$$f = e(X_1, V)E_2 = -\frac{e^2}{(2\pi)^2 \nu_1^2}\left(E_1, \frac{k_2}{k_2}\right)E_2 .$$

The two effects are of the same order of magnitude. One wave or two waves having the same direction cannot accelerate, since $\vec{v}_1$ and $\vec{H}_2$ are shifted 90° in phase and $\vec{E}_1 \perp \vec{k}_2$. The frequency condition imposed on $\Delta\nu$ is necessary in order that the scattering be not only by the electrons at rest, but also by electrons having thermal velocities.

In the cited acceleration investigations [8], monochromatic radiation was used to produce standing waves and the plasmoids were retained in the nodes. If ν_1 or ν_2 is varied smoothly, the nodes move and drag the plasma with them. The difference between the proposed method and [8] lies in the fact that in a broad and random spectrum the nodes move rapidly, the plasma becomes distributed in space uniformly (within the range of several wavelengths), and heating is therefore produced instead of acceleration.

When radiation of sufficient intensity is applied to cold matter, multiquantum ionization first sets in [11], followed by a cascade [2] and finally the principal role in the ionized plasma is played by stimulated scattering by the electrons.

We emphasize once more that the main problem, to which we wish to call attention, is the need for using radiation with a broad spectrum. It should also be noted that the insufficient power of the broad-spectrum can be offset to a certain degree by raising the intensity of the second coherent source.

In conclusion, we present numerical estimates.

Let the total energy of each beam be 50 J, the focusing cross section $\sim 10^{-5}$ cm^2, the flash time $\sim 10^{-11}$, the flux density 5×10^{17} W/cm^2, and the carrier frequency $\nu \sim 3 \times 10^{14}$ Hz. The electron energy is in keV, and accordingly dE/dt is in keV/sec (the subscript c stands for Compton scattering, ff stands for free-free absorption or emission, + means energy gain and - means energy loss).

z	N_e	E	$\Delta\nu$	$\left(\frac{dE}{dt}\right)_c^+$	$\left(\frac{dE}{dt}\right)_{ff}^+$	$\left(\frac{dE}{dt}\right)_c^-$	$\left(\frac{dE}{dt}\right)_{ff}^-$
1	10^{20}	1	$3\cdot10^{13}$	$4\cdot10^{17}$	$2\cdot10^{12}$	$1,5\cdot10^{7}$	$3\cdot10^{5}$
—	—	100	$3\cdot10^{14}$	$4\cdot10^{16}$	$2\cdot10^{9}$	$1,5\cdot10^{9}$	$3\cdot10^{6}$

It is seen from the table that the described mechanism is more effective than ordinary heating by deceleration absorption also at lower radiation intensity.

We take the opportunity to thank A.S. Kompaneets, L.M. Kovrizhnykh, V.N. Tsitovich, and A.E. Kazakov for interest and useful remarks.

[1] N.G. Basov and O.N. Krokhin, Zh. Eksp. Teor. Fiz. 46, 171 (1964) [Sov. Phys.-JETP 19, 123 (1964)].
[2] Ya.B. Zel'dovich and Yu.P. Raizer, ibid. 47, 1150 (1964) [20, 772 (1965)].
[3] L.M. Kovrizhnykh, ZhETF Pis. Red. 2, 142 (1965) [JETP Lett. 2, 89 (1965)].
[4] J. Peyraud, J. de Physique 29, 88, 306, 892 (1968).
[5] H. Dreicer, Physics of Fluids 7, 735 (1964).
[6] Ya.B. Zel'dovich and E.V. Levich, ZhETF Pis. Red. 11, 57 (1970) [JETP Lett. 11, 35 (1970)].

[7] H. Puell, H. Opower, and H.I. Neusser, Phys. Lett. 34, 4 (1970).
[8] M.A. Miller, Zh. Eksp. Teor. Fiz. 36, 1909 (1959) [Sov. Phys.-JETP 9, 1358 (1959)].
[9] A.S. Kompaneets, ibid. 31, 876 (1956) [4, 730 (1957)].
[10] V.G. Makhan'kov and V.N. Tsitovich, Preprint R9-4044, Dubna, 1968.
[11] L.V. Keldysh, Zh. Eksp. Teor. Fiz. 47, 1945 (1964) [Sov. Phys.-JETP 20, 1307 (1965)].

POSSIBILITY OF HEATING IONS IN A PLASMA BY EXCITING DRIFT-BEAM INSTABILITY WITH A FEEDBACK SYSTEM

V.V. Arsenin
Submitted 2 April 1970
ZhETF Pis. Red. 11, No. 10, 500 - 503 (20 May 1970)

The buildup of drift-beam (collisionless current-convective) instability [1 - 3] in a magnetized plasma broached by an electron beam is accompanied by heating of the plasma ions to a temperature on the order of the electron energy in the beam) [4]. This phenomenon is used to prepare a hot plasma in an open trap [5]. The concentration of the plasma that can be heated in this manner is limited. If n_1 and n_2 are the concentrations of the electrons in the beam and in the plasma at rest, a is the beam radius, and R is the transverse dimension of the plasma, then the instability develops (in full accord with the linear theory) only when the ratio n_2a^2/n_1R^2 is not too large [6] (see condition (2) below).

We shall show that by using special electronic circuity (a feedback system) that measures the oscillations of the electric field and controls the beam current it is possible to excite drift-beam instability in a plasma that is much denser than in the absence of feedback. Since the spatial structure of the oscillation is in this case the same, and the increment is of the same order, as in the "natural" instability (without the feedback), and since it is immaterial from the point of view of particle acceleration what causes the accelerating field, it follows that heating can be expected at sufficiently large oscillation amplitudes[1])

Let us determine the buildup conditions.

We direct the z axis of a cylindrical coordinate system along the axis of a compensated electron beam with concentration $n_1(r) = n_1(1 - r^2/a^2)$, passing through a plasma of concentration $n_2(r) = n_2(1 - r^2/R^2)$ along a magnetic field $\vec{H}$. Let us consider the instability of the beam against perturbations of the electric potential $\psi = \phi(r)\exp(i\ell\theta + ik_zz - i\omega t)$, where θ is the azimuthal angle, under the assumption that $\omega_{Hi} << |\omega| << \omega_{He}$ and $|\omega| << k_zu$, where ω_{Hi} and ω_{He} are the ion and electron cyclotron frequencies and u the electron velocity in the beam. In order not to write down the differential equations, we confine ourselves to quasiclassical perturbations $\phi(r) \simeq \exp(ik_rr)$, $k_ra >> 1$. For the large-scale oscillations of real interest, we should put $k_r \sim a^{-1}$.

We assume that electron sources with intensity $S = s\psi = -ic\ell n_1H^{-1}a^{-2}\Delta(\omega)\psi$ are distributed through the volume of the beam. The experimentally observed wave number of the unstable perturbation is $\bar{k}_z \simeq \pi L^{-1}$, where L is the length of

[1])Since there is no linear theory (nor is there one for the "natural" instability), the oscillation level required for the heating can be established only experimentally. It can be assumed that amplitudes sufficient for this purpose are of the order of amplitude observed under conditions when heating occurs without feedback.