1. Publication Nº	2. Version	3. Date	5. Distribution
INPE-4383-PRE/1203		*Sept. 1987*	☐ Internal ☒ External ☐ Restricted

4. Origin *LAP* Program *PTOR*

6. Key words - selected by the author(s)

REPORT OF ACTIVITIES
PLASMA PHYSICS

7. U.D.C.: *533.9*

8. Title *INPE-4383-PRE/1203*

RECENT RESULTS OF PLASMA RESEARCH ACTIVITIES AT THE INSTITUTO DE PESQUISAS ESPACIAIS

10. Nº of pages: *9*

11. Last page: *8*

12. Revised by

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14. Abstract/Notes

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15. Remarks

Published in the Proceedings of the V Japan-Brazil Symposium on Science and Technology, Tokyo, Japan (1986), p. 163.

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RECENT RESULTS OF PLASMA RESEARCH ACTIVITIES AT THE INSTITUTO DE PESQUISAS ESPACIAIS

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Abstract

Recent results obtained in different experiments at the Institute for Space Research (INPE) are reported. An enrichment of 390% of carbon isotopes has been achieved in the plasma centrifuge. The role of ion-acoustic turbulence in the formation of double layers has been experimentaly investigated. The turbulent spectrum has been measured and agrees quite well with the prediction of the modified Kadomtsev's renormalized theory. The characteristics of the gyrotron that is presently being built at INPE and new techniques for gyrotron design are discussed. Theoretical results on the generalized Spitzer-Härm problem, current drive in the start-up phase of tokamaks, and quasilinear theory of beat-wave current drive are also presented.

Introduction

The Associated Plasma Laboratory (LAP) is the outgrowth of a small Plasma Physics Group established in 1978 at INPE. Presently, the research activities of LAP are divided in three main areas: basic plasma physics, technological applications of plasmas, and thermonuclear fusion research. The experimental work in basic plasma physics is mainly carried out in quiescent plasma devices with surface magnetic confinement. A small reversed field pinch is being currently constructed to study basic problems related to magnetic reconnection. The technological applications are concentrated on the operation of a plasma centrifuge for isotope separation, the development of ion micro-thrusters for space applications, and the design and construction of a 35GHz gyrotron for plasma heating and current drive in tokamaks. The effort in thermonuclear fusion research is currently concentrated on the design of a new tokamak to be built in collaboration with the University of São Paulo, the development of diagnostic techniques for tokamaks, and theoretical studies on plasma heating and current drive by electromagnetic waves.

In this paper we briefly report the main results obtained in the current year.

Plasma Centrifuge

The plasma centrifuge is a device in which a plasma column is put to rotate at high angular velocities by means of electromagnetic forces. Its main application is isotope separation in gas and metal plasmas[1,2]. Krishnan has recently reported rotational velocities above the Alfvén critical velocity and high separation factors in fully ionized metal plasmas[1]. The plasma centrifuge of INPE is schematically shown in Fig. 1. The stainless steel vacuum vessel has a diameter of 22cm and is 85cm long, evacuated to 10^{-7}mbar by a diffusion pump. A set of eight coils produces a peak magnetic field $B = 1.3T$, with a 185ms L/R decay time. The discharge current is produced by a low voltage overdamped RLC network with 1-10kA peak value and 1-5ms duration depending on the shot conditions. The discharge is triggered in vacuum by a high power laser.

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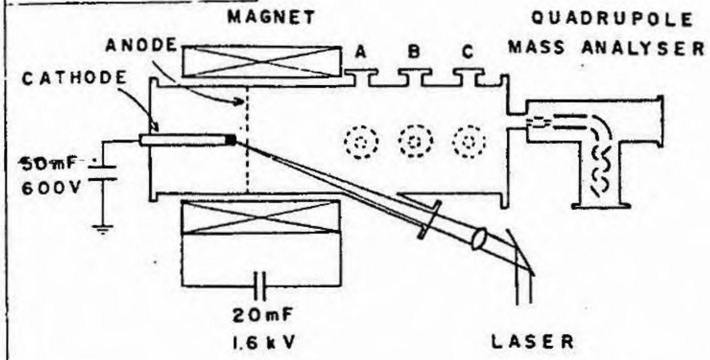


Fig. 1 - Schematic diagram of the INPE vacuum-arc centrifuge.

The rotation velocity of the confined plasma column is obtained from the phase difference of periodic signals detected by two electrostatic probes placed 90° apart at a distance of 34cm from the cathode and, also, from the azimuthal displacement of the material deposited behind a narrow slit. The angular rotation frequency for an induction B = 0.09T is found to be 1.2 x 10^{5}rad/s for carbon and 1.7 x 10^{5}rad/s for copper plasmas.

The ions at the end of the plasma column are mass scanned using a modified quadrupole mass spectrometer which determines, *in situ*, the relative abundance of isotopes. The relative abundance is shown in Fig. 2 for different times from the onset of the discharge at a radial position R = 6cm. The points are experimental results for zero magnetic field. The curves are a best fit to the experimental results with two Gaussians; the broken one corresponds to the zero magnetic field case and the continuous ones to B = 0.12T. The peaks at A = 12 are normalized to the same value. As time goes on, the enrichment of ^{13}C increases as can be seen from the ratio of the peak for A = 13 to the one of the natural isotope. At t = 4ms we obtain a α = 4.92 enrichment factor, implying an enrichment of 390%. However, at this time saturation has not yet been achieved. This is because the length of the device is not long enough to reach full saturation for the above operating conditions.

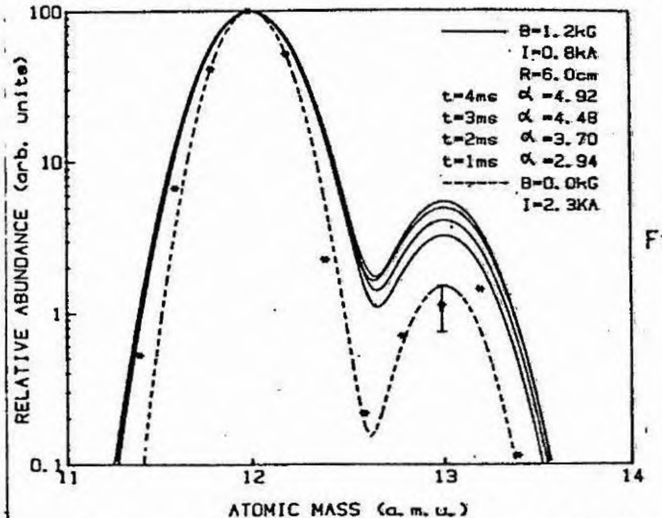


Fig. 2 - Mass scan of carbon plasma in logarithm scale for different times in the discharge.

The steady state behavior of the fully ionized magnetized plasma in the vacuum-arc centrifuge has been theoretically investigated in detail[3,4], using a multiple species fluid model which includes electromagnetic, pressure-gradient, centrifugal, and collisional forces, in cylindrical geometry. The parametric dependences of the various plasma variables, including the separation factor, under equilibrium conditions, have been determined. The numerical results were found to be in good agreement with experimentally measured plasma characteristics in the vacuum-arc centrifuge.

Investigation of the Bootstrap Action in Double Layers Driven by Ion-Acoustic Turbulence

Numerical simulations carried out by Sato & Okuda[5] have shown that double-layers can be formed by ion-acoustic turbulence excited by a drifting population of cold electrons in a background plasma. The corresponding anomalous resistivity gives rise to a localized potential step that further accelerates the cold electrons and maintains the ion-acoustic double layer. This bootstrap mechanism has been investigated in the double-plasma device of INPE[6]. The usual metal screen between the source and target plasmas has been replaced by a magnetic fence made of permanent magnets with a 0.15T superficial field[7]. The working pressure is 5×10^{-4}mbar (Argon) and typical parameters are: electron density $n_e = 10^9 cm^{-3}$, electron temperature $T_e = 2.5$eV, and ion temperature $T_i = 0.25$eV. The plasma potential is measured by an emissive probe and the electron drift velocity by double faced Langmuir probes.

When only the source plasma is turned on, a stream of cold electrons ($T_e \approx 0.3$ev) diffuses through the magnetic fence and is detected in the target chamber. When the target plasma is also turned on, a density gradient between the two plasmas is formed and the relative density of the cold beam streaming into the target plasma becomes $n_b/n_e \approx 0.13$. The drift velocity v_d of the beam is much larger than the ion-acoustic velocity C_s. Under these conditions, strong ion-acoustic turbulence is generated in the target plasma. The corresponding spectrum is shown in Fig. 3 together with the predicted spectra from Kadomtsev's theory[8] (broken line) and from the modified renormalized theory of Choi and Horton[9] (heavy lines). The cutoff frequency is $f_c = 1.24$kHz and the ion plasma frequency is $f_{pi} = 1.49$MHz. The agreement between these theories and the experimental result is rather satisfactory. The turbulent anomalous resistivity is estimated to be $\eta_a \approx 7.7\Omega$m corresponding to an effective collision frequency $\nu \approx 3 \times 10^{-7} s^{-1}$. The measured potential step, $\Delta V \approx 0.4$V, is consistent with the measured anomalous resistivity.

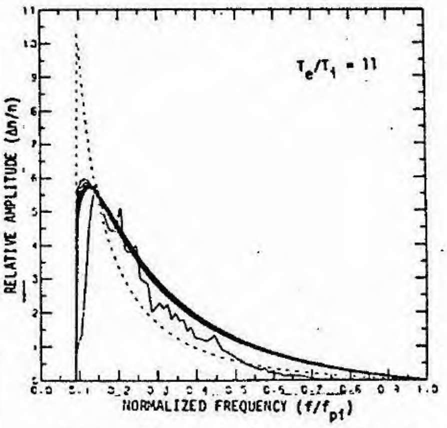
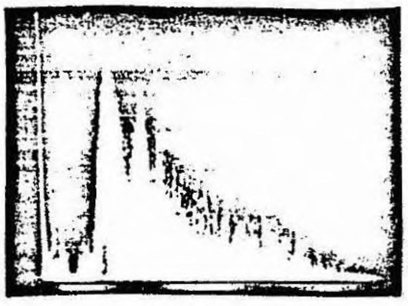


Fig. 3 - Spectrum of the ion-acoustic turbulence measured in the target plasma. The frequency is normalized to the ion plasma frequency. Broken line corresponds to Kadomtsev's theory and heavy continuous line to Choi and Horton's theory.

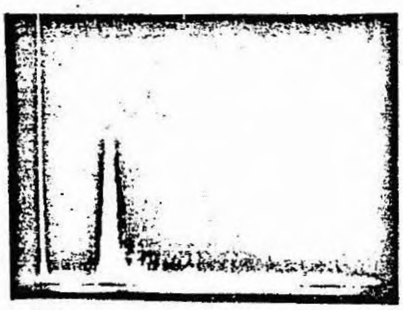
To check the role of the ion-acoustic turbulence on the formation of the double-layer, we have gradually quenched the ion-acoustic turbulence by introducing helium in the discharge to enhance Landau damping. In Fig. 4 we show the measured spectra for relative abundances of helium, $r = n_{He}/n_A$, equal to 0, 0.03, 0.09, and 0.25. The corresponding decrease in the potential step of the double layer is shown in Fig. 5. There is also a corresponding decrease in the value of v_d/C_s, and for $r \approx 0.25$ the ~~value~~

of the drift velocity is below the threshold for the excitation of ion-acoustic turbulence ($\approx 10C_s$). In this case a two-electron-temperature plasma is observed in the target chamber.

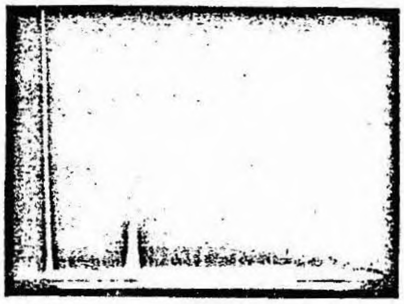


$r = 0$; $f_{pi} = 1.39$MHz; $v_d/C_s = 19.3$

$r = 0.03$; $f_{pi} = 1.41$MHz; $v_d/C_s = 17.1$



$r = 0.09$; $f_{pi} = 1.43$MHz; $v_d/C_s = 15.6$



$r = 0.25$; $f_{pi} = 1.48$MHz; $v_d/C_s = 7.0$

Fig. 4 - Ion-acoustic turbulent spectra for different helium concentrations $r = n_{He}/n_A$.

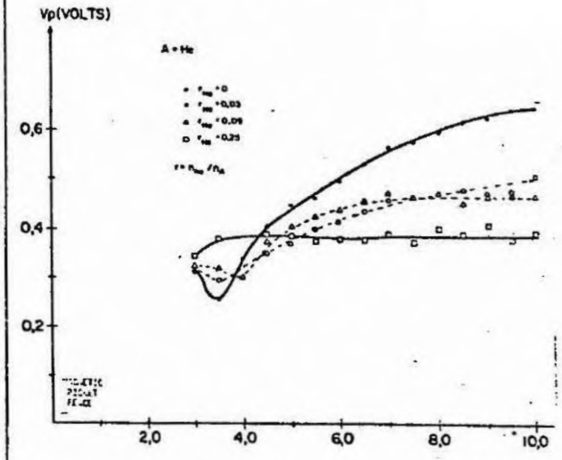


Fig. 5 - Decrease of the potential step of the double layer with the increase in the helium concentration.

Gyrotron Development

The first prototype of the Brazilian gyrotron is being designed to operate at 35GHz, mode TE_{02}, with an electron beam voltage of 50kV and current of 5A. In the cavity region, the magnetic induction is $B_0 \approx 1.35$T and the velocity components ratio is $\alpha = v_\perp/v_\parallel = 1.5$. The radiation power will depend upon the efficiency but must fall in the range 50 to 100kW, with a pulse duration of 10ms.

A critical element in the construction of a gyrotron is the electro-optical system, which must be optimized to generate an electron beam with high transverse energy and low velocity spread. One of the main causes of velocity spread is the space-charge force, enhanced by the intersection of electron paths. To avoid this problem, a synthesis method has been used to design an electron gun capable of producing a laminar electron flow. A systematic procedure for the design of axisymmetric electro-optical systems has been developed and is fully described in Ref. 10. This procedure allows the derivation of the synthesis parameters from the required characteristics of the electron gun. In Fig. 6 we show the final configuration of the synthesized gun and electron trajectories, obtained for the design parameters specified above. The perpendicular velocity spread for this configuration has been calculated to be approximately 1%.

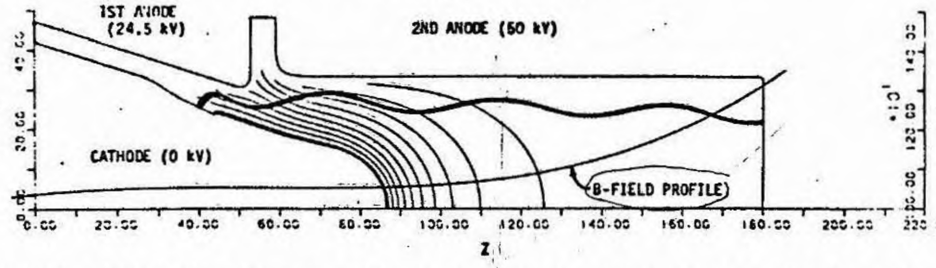


Fig. 6 - Final electrode configuration and electron trajectories for the 35GHz gyrotron.

Another important aspect of gyrotron design is the determination of the optimum RF field axial profile for the generation of different modes and cyclotron harmonics and the cavity geometry required for its setting up. It is well-known from theory and experiments that the shape of the longitudinal profile of the electric field plays a crucial role in the determination of the interaction efficiency. High efficiency is obtained by weakly pre--bunching the electron beam, allowing the electrons to remain bunched for a sufficiently long time in a high field region, in such a way as to favour the transfer of beam energy to the RF field. An electric field profile that can give rise to these desirable features has been obtained[11] and is shown in Fig. 7a, together with the associated resonant cavity geometry (Fig. 7b). In addition to higher interaction efficiency, this cavity requires a smaller starting current and minimizes reflections and mode conversion.

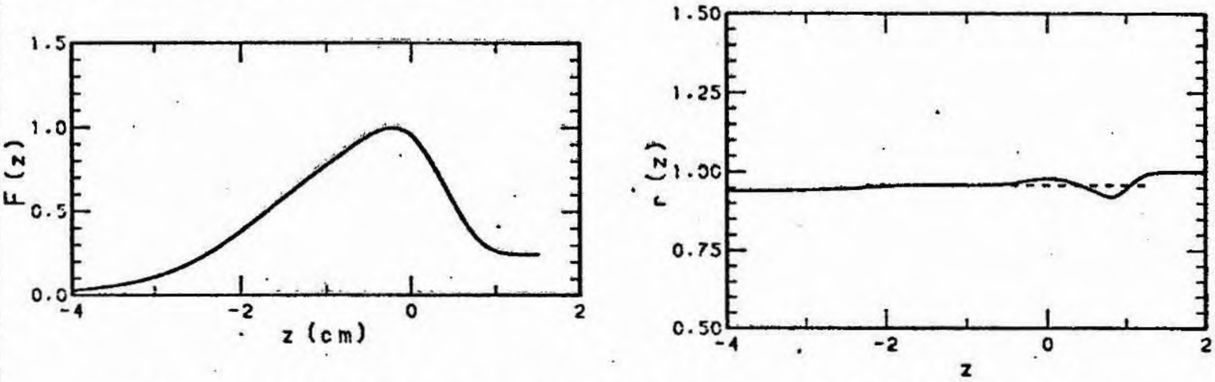


Fig. 7 - Electric field (a) and cavity (b) profiles for the 35GHz gyrotron.

The construction of the gyrotron described above is under way and the testing is planned to start by the end of 1987.

Current Drive in the Start-Up Phase of Tokamak Discharges

We have investigated the possibility of current drive in the start-up phase of tokamak discharges using electron Bernstein waves. These waves can be generated by mode conversion at the upper hybrid resonance surface of extraordinary waves launched from the high magnetic field side of the device. Electron Bernstein waves can drive currents by the Fisch-Boozer mechanism, i.e., selective heating of electrons moving in one direction[12]. To calculate the local figure of merit j/P_d, where j is the generated current density and P_d the locally absorbed power density, we have solved the steady-state Fokker-Planck equation including only electron-ion collisions and quasi-linear diffusion caused by EBW. We find[13]

$$\frac{j}{P_d} = -\frac{24\pi\varepsilon_0^2}{e^3}\,\frac{k_BT_e}{Zn_e\ell n\Lambda_{ei}}\,\frac{u_0 I(u_0,\, k_\perp^2 r_e^2)}{(4/k_\perp^2 r_e^2)\exp(-k_\perp^2 r_e^2/2)I_1(k_\perp^2 r_e^2/2)}\,, \tag{1}$$

where

$$I(u_0,\, k_\perp^2 r_e^2) = \frac{4}{k_\perp^2 r_e^2}\int_0^\infty dx(x + u_0^2)^{1/2} e^{-x} J_1^2(k_\perp r_e\sqrt{x}) \tag{2}$$

and $u_0 = (\omega - \Omega_e)/k_\parallel v_e$. All the quantities are given in MKS units, $k_\parallel$ and $k_\perp$ are respectively the parallel and perpendicular wave numbers, n_e, T_e, and Ω_e are respectively the electron density, temperature, and cyclotron frequency, $v_e = (2k_B/T_e/m_e)^{1/2}$, $r_e = v_e/\Omega_e$, and $\ell n\Lambda_{ei}$ is the Coulomb logarithm. The above expression for j/P_d has been incorporated in a ray-tracing code[14] to calculate the current profile in realistic tokamak conditions. In Fig. 8 we show the ray trajectories calculated for the conditions of the COMPASS tokamak (R_0 = 0.55m, a = 0.22m, $n_e = 2 \times 10^{18}m^{-3}$, T_e = 50eV, B_T = 1.07T, f = 28GHz). The extraordinary waves penetrate up to the upper hybrid resonance surface, where they are mode converted into Bernstein waves, and travel back toward the electron cyclotron resonance surface, where they undergo strong electron cyclotron collisionless damping. The generated current profile is shown in Fig. 9 for not self-consistent parabolic density and temperature profiles. We obtain an overall efficiency of I/P = 0.11A/W, indicating that this mechanism is capable of substantial current drive in the start-up phase of tokamak discharges.

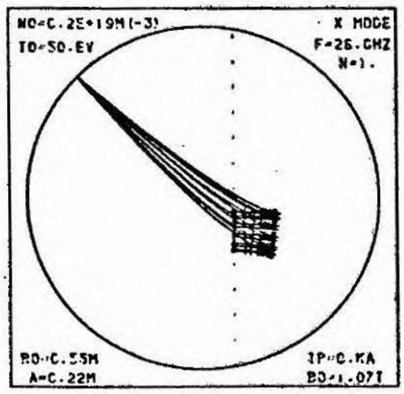


Fig. 8 - Minor cross section projection of ray trajectories.

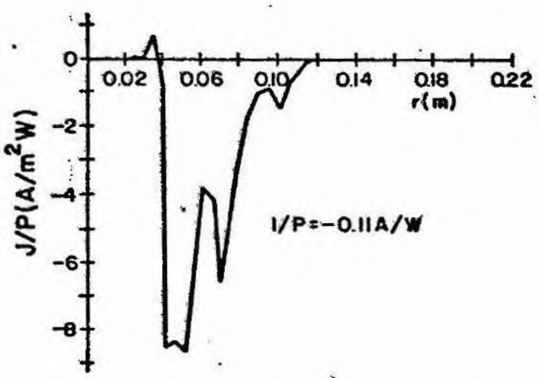


Fig. 9 - Current density profile.

Generalized Spitzer-Härm Problem

The determination of the current in problems of transport and current drive by particle beams and RF waves frequently requires solving a generalized form of the Spitzer-Härm problem, which can be symbolically stated as $S(v) = C(f_e)$. Here $S(v)$ is a known function of the velocity, determined by the acting force field, and C is an integrodifferential operator which describes the effect of electron-electron and electron-ion collisions on the distribution function f_e. It can be shown[15] that the original problem, with the help of an appropriate transformation of the dependent variable, can be reduced to the following second order differential equation

$$\Lambda(x)G''(x) + [\Lambda'(x) + (1/x + 2x)\Lambda(x)]G'(x) + [2x\Lambda'(x) - 4\Lambda(x) - 2Z]G(x) = \\ = 2x\Lambda'(x) - 4\Lambda(x) - 2ZR(x) \,, \tag{3}$$

where $\Lambda(x) = (4/\sqrt{\pi})\int_0^x y^2 \exp(-y^2)dy$, Z is the effective ionic charge,

$$R(x) = \frac{x^2 S(x) + 2\int_0^x y^3 S(y)dy}{2\int_0^\infty y^3 S(y)dy} \,, \tag{4}$$

and primes denote derivative with respect to the argument. The boundary conditions are $G(0) = 0$ and $G(\infty) = 1$.

All quantities of interest, such as the perturbed distribution function, the current and the heat flow can be obtained by simple operations of integration on $G(x)$. The current, in particular, is given by

$$\frac{j_\parallel}{j_\parallel^{(L)}} = \frac{1 + 2\int_0^\infty [1 - G(x)][1 - \Lambda(x)]x \exp(x^2)dx}{1 + 2\int_0^\infty [1 - R(x)][1 - \Lambda(x)]x \exp(x^2)dx} \,, \tag{5}$$

where $j_\parallel^{(L)}$ is the value of $j_\parallel$ when $G(x) = R(x)$, which corresponds to the Lorentz gas case ($Z = \infty$).

Theory of Beat-Wave Current Drive

The idea of generating current in magnetized plasmas by the beating of two strong electromagnetic waves has been put forward by Cohen[16] and Galvão and Tajima[17]. The basic scheme is to launch two strong electromagnetic waves in a plasma beating at a frequency close to some characteristic frequency of the plasma. The ponderomotive forces associated with the high frequency waves can then produce a low frequency electrostatic oscillation. The subsequent interaction of the electrostatic oscillations with nearly resonant particles can then lead to current drive. Using a multiple time scale technique, we have developed a quasilinear theory to calculate the generated current. For the one-dimensional case, we find that the generated current is given by[18]

$$\frac{j}{(-en_0 v_{th})} = \frac{4}{\sqrt{2\pi}}\, a w_0^2 \left(\frac{\Delta}{k_0}\right)^2 \exp\left(-\frac{3}{2} w_0^2\right) \,, \tag{6}$$

where $w_0 = \omega_p/k_0 v_{th}$, ω_p is the plasma frequency, k_0 is the wavenumber of the electrostatic oscillation, Δ is the spectral width of the electromagnetic waves, $a = 2\pi A/v_{th}^2\nu_0$, v_{th} is

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the electron thermal velocity, ν_0 is the electron-ion collision frequency, $A = (1/2\pi^2)(e/m)^4(\Delta^2 E_0^4/k_1^2 c^2)$, E_0 is the amplitude of the electric field of the electromagnetic waves, and k_1 is the largest wavenumber of the spectrum. Equation (6) shows that large currents can be generated by the beating of two CO_2 lasers at moderate intensities, i.e., $I \approx 10^{11} W/cm^2$.

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