Ion Acceleration in Strong Electromagnetic Interactions with Plasmas

A. Y. Wong and R. L. Stenzel
TRW Systems, Redondo Beach, California 90278
(Received 23 September 1974)

Energetic ions of energy up to $7kT_e$ are detected when an inhomogeneous plasma ($T_e/T_i \cong 10$) is irradiated by microwave pulses ($E_0^2/4\pi nkT_e \approx 10^{-2}$) of short durations ($\tau$ approximately twice the ion-plasma period). Time- and space-resolved analyses trace their origin to the generation of density cavitons by ponderomotive forces. The axially directed energetic-ion flux carries a significant fraction of incident electromagnetic energy.

Recent experiments of laser-pellet interactions[1] have demonstrated the existence of energetic ions of 10–30 keV which carry approximately half the energy absorbed by the plasma. These energetic ions could also be important in explaining the observation of neutrons. There are also a number of experiments[2] in which ion heating is observed when microwave fields are radiated upon the plasmas. Such an increase in ion temperatures has been described in terms of interactions between particles and a turbulent wave spectrum. In this paper we present experimental evidence to demonstrate a new mechanism which accelerates ions by sharply localized electric fields, a concept which should be applicable to a wide range of experiments involving strong fields $E^2/4\pi nkT_e \approx 1$ created by external electromagnetic (EM) fields or strong electron or ion beams. In our particular experiment where ionization effects are negligible the ponderomotive force $\nabla\langle E^2\rangle/8\pi$ which arises from the sharply localized electric field near the resonant layer $\omega_0 = \omega_p(z)$ in a nonuniform plasma is found to be mainly responsible for driving these ions out of the resonant layer, leaving a density cavity behind.[3]

The experiment is performed in QUIPS, the large TRW quiescent-plasma device (2 m diam and 4 m long). A 1-GHz 40-kW pulsed microwave source (Applied Microwaves) is used with a large horn antenna (14.4 dB gain, linear polarization) at one end of the chamber. Short microwave pulses of typical duration 0.4 μsec are radiated onto the plasma-density profile which rises from the antenna end to a maximum density near the opposite end (3 m away). The argon-plasma characteristics are 1.5 eV $< kT_e <$ 2 eV, $kT_i \cong 0.2$ eV, $5\times10^9 < n_e < 10^{11}$ cm^{-3}, and 100 cm $< (n_0^{-1}\partial n_0/\partial z)^{-1} <$ 1000 cm. By use of a box-car integrator in connection with probe diagnostics, the temporal development of the spatial density profile, the electron and ion distributions, and the plasma potential can all be taken before and after the incident rf pulse. Phase-space information can then be deduced.

The experimental arrangement and the main observations can be described best by the simultaneous spatial and temporal descriptions of the process in Fig. 1. The short electromagnetic pulse (0.4 μsec) is converted to an electrostatic pulse of high-field intensity near the resonant layer $\omega_0 = \omega_p(z_0)$, as a result of the much smaller group velocity and the resonant enhancement at that layer.[4,5] Observations with the aid of an ion-energy analyzer at several microseconds after the EM pulse show the presence of a large ion current (twice the normal saturation value) just outside the resonant region. This enhanced current is found to consist of ions of much higher energy than the ambient. This current peak is followed by a density depression ($\Delta n/n = 30\%$) which is a result of the expulsion of ions from the resonant region. As this ion structure travels down the density profile the peak consisting of a wide range of ion velocities quickly disperses while the density cavity (caviton) composed of background ions maintains its shape as a nonlinear ion perturbation for a much longer time.

By rotating the energy analyzer at various angles with respect to the axis we find that the ions move predominantly along the axial direction with a half-width angle of 40° as shown by the polar plot. The cross section over which ions are accelerated is as broad as the illuminated area of 7.5×10^3 cm^2. Using oppositely directed analyzers we observe accelerated-ion fluxes in both directions up and down the density profile with much stronger ion flux down the density profile ($-\partial n_0/\partial z$ direction). This most probably results because the profile of the intensity of the high-frequency field (measured by the electron-beam-deflection techniques[3]) has a steeper gradient to-

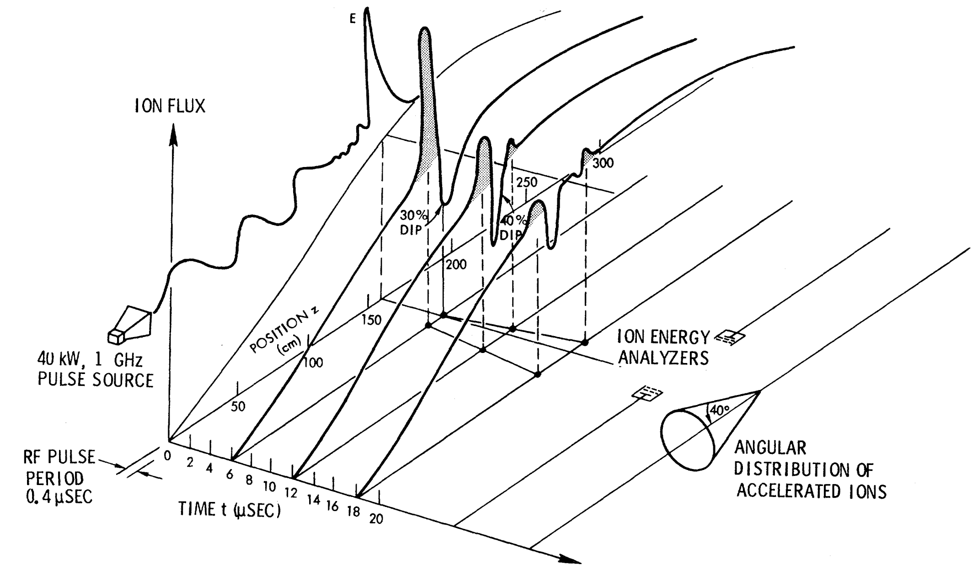

FIG. 1. Space-time representation of ion bursts (shaded) driven by the ponderomotive force. Density cavities are created as a result of ion expulsion. The polarization of ion trajectories is represented by the cone with a half-width of 40° with respect to the z axis.

wards the antenna.

The temporal behavior of the ion-saturated current following the short 0.4-μsec rf pulse is displayed together with the ion temperature and plasma potential in Fig. 2. The diagnostics consist of radially and axially movable ion-energy analyzers and Langmuir probes all located outside the resonant region, at 2 cm down the density gradient from the resonant location. These locations not only avoid the interference of the probes with the development of the rf field and density cavities at the resonance, but also allow the ion signal to be well separated in time from the rf pulse. The ion current is observed to increase to a peak value 1.7 times its normal saturated value in the first 8 μsec after the rf turn-on because of the presence of energetic ions. The energy spectrum of the ions was measured with an ion-energy analyzer which discriminates against ions below a certain energy by a grid placed in front of the collector (a third grid left at floating potential is placed in front of the discriminator grid to reduce the disturbance of the analyzer on the ambient plasma). This energy analysis corrobates well the time-of-flight measurements as shown in Fig. 2(a). The faster ions with energy > 7 eV arrive earlier than the bulk of fast ions represented by the main peak. Ion oscillations propagating at the ion-acoustic velocity $c_s = (kT_e/M_i)^{1/2}$ ($\Delta n/n = 5\%$, $\omega \approx 0.1\omega_{pi}$) are observed in the vicinity of the source of these energetic ions. We believe that these oscillations, which persist even after the pump is turned off, are generated by interactions between the accelerated ions and the background plasma. The beam density and velocity ($\frac{1}{2} < n_b/n_0 < 1$, $v_b/c_s > 1$) to which these fast ions contribute satisfy the instability criteria of ion-beam–plasma interactions.[6]

The sampled results of the ion-energy analyzer show a broader ion distribution or a higher ion temperature at earlier times which then cools off to the ambient value when the ion-acceleration process is terminated. These curves also reveal the systematic increase in plasma potential at times when the ion temperature and density both increase. The increase in plasma pressure in the hot region just outside the density cavity causes an increase in the plasma potential which, together with the decay of the resonant field due to convective loss, ultimately limits the ion acceleration by the ponderomotive force.

The process of ion acceleration could be understood as follows: After the external EM pulse arrives at the resonant region, the electric-field component in the direction of the axial density gradient is greatly enhanced by the plasma resonance. Under this highly localized electric field the anharmonic motion of electrons gives rise to a time-averaged force field $-\nabla\langle E^2\rangle/8\pi$ (derived from the $\vec{v}\cdot\nabla v$ term in the electron equation of

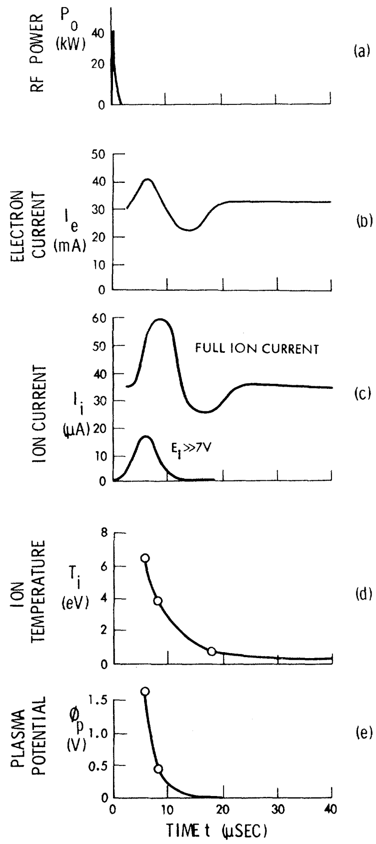

FIG. 2. Temporal behavior of argon ions collected by energy analyzer at various times after the termination of the exciting rf pulse of 0.4 μsec. The analyzer is located at 2 cm below the resonant region, monitoring ions accelerated towards the lower-density side. (a) Duration of rf excitation pulse. (b) The electron saturation current collected by a Langmuir probe at the same location as the ion-energy analyzer. Note the earlier arrival time of the electron response with respect to the ion response in (c). (c) Higher-energy ions observed with a discriminating grid arrive earlier. (d), (e) Ion temperatures and plasma potentials obtained from ion-energy analyzer.

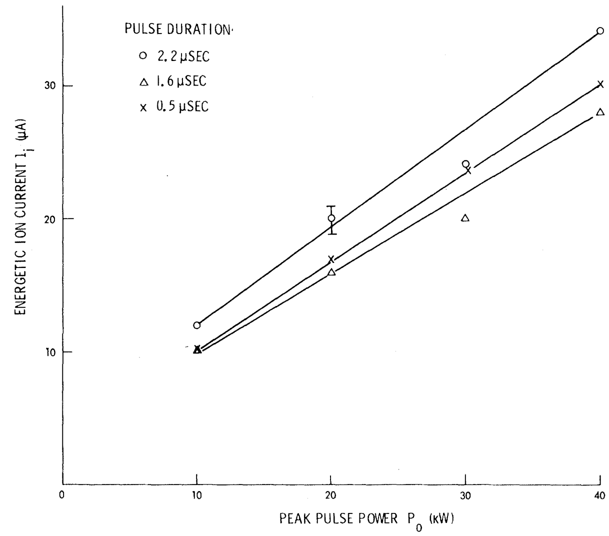

FIG. 3. Energetic ion flux [maximum ion current in Fig. 2(c)] versus incident power P_0 for three different pulse durations.

motion) which pushes electrons down the field gradient. As the electrons are accelerated they pull the ions with them by means of self-consistent fields.

This process is indeed confirmed by our experimental observations of both the electronic and ionic responses to the ponderomotive force. As shown in Figs. 2(b) and 2(c), the electron response first comes out of the resonant region followed by the ionic response as monitored by a Langmuir probe and an ion-energy analyzer all mounted on the same movable shaft located 2 cm away. The ions eventually catch up with the electrons and they travel together.

The above process requires an rf pulse of sufficient duration ($\tau > \Delta z/v_e \approx 0.1$ μsec) to set up the initial electron drift and displacement away from the resonant layer ($\Delta z \lesssim 2$ cm). Once this duration is exceeded the net electron drift and the field necessary to accelerate the ions depend mainly on the peak rf power. As shown in Fig. 3 the energetic ion flux bears approximately the same linear relation to the peak power, even though the pulse duration changes by a factor of 5. The insensitivity to the total energy content of the applied pulse distinguishes this process from that of turbulent wave-particle interactions; the turbulent-ion-wave spectrum must depend on the energy input into the system and the pulse duration should be many times the ion-plasma-wave period for a turbulent-wave spectrum to develop.

Based on our model, the magnitude of the transient electric-field intensity or the ponderomotive potential $\langle E^2\rangle/8\pi$ can be directly estimated from the maximum energy gained by the ions since the change in ion energy $\Delta\frac{1}{2}nmv_i^2 \approx E^2/8\pi$. The experimental observation of ion energy up to $7kT_e$ indicates the presence of strong transient fields[7] $E^2/4\pi nkT_e \approx 7$ which is 700 times larger than the incident field $E_0^2/4\pi nkT_e \approx 10^{-2}$. This enhancement factor is confirmed by our separate electron-beam measurements[3] under similar situations. This strong-field condition could only be maintained before the plasma ions have time to move and before the change in plasma density shifts the resonant location, since equilibrium conditions require that $E^2/4\pi nkT_e \approx 1$. Even though the incident field is weak, resonant enhancement easily brings our experimental parameters into the strong-field regime.

The energy gained by these fast ions is of the same order of magnitude as the energy carried by the electron plasma waves out from the resonant layer:

$$\frac{\text{Energy carried out by ions}}{\text{Energy convected out by electron waves}} = \frac{n(\frac{1}{2}mv_i^2)v_i A\tau}{(nkT_e)v_g A\tau} \cong \frac{v_i}{v_g} \cong 1.$$

The measured group velocity v_g of electron-plasma waves near the resonant layer, $v_g \lesssim 10^6$ cm/sec, is in the same range as the speed of the energetic ions. The resonant enhancement of external fields are therefore limited by the convective losses of both waves and particles.

Our knowledge of the acceleration region ($\Delta z \approx 2$ cm, $\Delta r = 100$ cm) allows us to estimate the energy carried by the fast ions as 20% of the incident electromagnetic energy (4×10^3 erg) contained in the pulse.

This process of acceleration by localized high-frequency fields can occur over a much shorter time scale and impart more energy to the ions than the linear process of acceleration by ion-acoustic waves excited by the parametric process.[2] This latter process could be eliminated by applying the pump field over a duration shorter than the growth rate of the ion-acoustic wave. The plasma inhomogeneity which raises the thresholds in parametric processes and shortens the wave-particle-interaction region actually favors this localized field and its interactions with particles.

The ion acceleration by steep gradients of EM fields is to be distinguished from the ambipolar acceleration due to a steep density gradient. The latter case can only cause ion acceleration in the direction down the density gradient and not up the density gradient, as is permissible in the acceleration by the ponderomotive force.

We wish to thank Professor John DeGroot, Dr. W. Quon, Dr. Arnush, Professor B. D. Fried, and Mr. M. D. Plummer for their help. This work is supported by TRW independent Research and Development program.

[1]G. H. McCall, F. Young, A. W. Ehler, J. F. Kephart, and R. P. Godwin, Phys. Rev. Lett. 30, 1116 (1973), and Los Alamos Scientific Laboratory Report No. LA-UR 74-85, 1974 (unpublished).

[2]T. K. Chu, S. Bernabei, and R. W. Motley, Phys. Rev. Lett. 31, 211 (1974); H. W. Hendel and J. T. Flick, Phys. Rev. Lett. 31, 199 (1974); R. P. H. Chang and M. Porkolab, Phys. Rev. Lett. 32, 1227 (1974).

[3]H. C. Kim, R. L. Stenzel, and A. Y. Wong, Phys. Rev. Lett. 33, 886 (1974).

[4]J. P. Friedberg, R. W. Mitchell, R. L. Morse, and L. I. Rudsinski, Phys. Rev. Lett. 28, 795 (1972); G. Morales and Y. C. Lee, Phys. Rev. Lett. 33, 1016 (1974).

[5]R. L. Stenzel, A. Y. Wong, and H. C. Kim, Phys. Rev. Lett. 32, 654 (1974).

[6]B. D. Fried and A. Y. Wong, Phys. Fluids 9, 1084 (1966).

[7]E. J. Valeo, W. L. Kruer, and K. G. Estabrook, private communications.