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AN ICRF-DRIVEN INVERSE FILAMENTATION INSTABILITY

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ABSTRACT

One source of bandwidth broadening in ion acceleration at cyclotron resonance has been found to be the occurrence of random pulses in plasma potential. We propose an instability mechanism which, in the absence of detailed calculations, seems to account for most of the observed features of this type of noise.

Noise measurements with both hot and cold probes during the application rf inductive drive have shown two types of noise: 1) a broad spectrum of rf noise on either side of the drive frequency corresponding to the spectrum of low frequency noise seen in the filtered low frequency signal, and 2) random pulses in plasma potential, always with positive polarity, occurring on msec time scales and with amplitude up to 40 V. We propose a mechanism for the latter phenomenon. Note that the amplitude of these pulses is 10 – 100 times the electron temperature, much larger than would be expected of any type of unstable wave in the plasma.

The reference conditions for the measurements will be taken as follows; we assume that U^{235} is resonantly heated and U^{238} is nonresonantly heated, and that the observations are made near the midplane.

$B = 18.67$ kG	
$KT_e = 1$ eV	$r_{Le} = 1.8 \times 10^{-4}$ cm
$KT_5 = 500$ eV	$r_{L5} = 2.7$ cm
$KT_8 = 100$ eV	$r_{L8} = 1.2$ cm
$f_{ci} = 121$ kHz	$t_c = 8.2$ μsec
$p_o = 1\text{-}50$ μTorr	$n_o = 3\text{x}10^{10} - 1.6<10^{12}$ cm^{-3}
$E_{rf} \simeq 2$V/cm	

Here p_o, n_o refer to the neutral argon pressure and density, and all numbers are given for the Z=1 charge state.

The main features of the noise pulses are as follows:

1) They are always positive excursions in potential, never negative.

2) They are of order 0.5 msec in width.

3) The rise and fall times are about equal.

4) They occur at intervals of several msec, on the average.

5) The intervals are not regular.

6) The amplitude ($\lesssim$ 40 V) is >> KT_e/e.

7) They occur more frequently when E_{rf} is large, up to a certain point. At very large E_{rf}, the pulses are suppressed.

8) The rise and fall times are longer when E_{rf} is small.

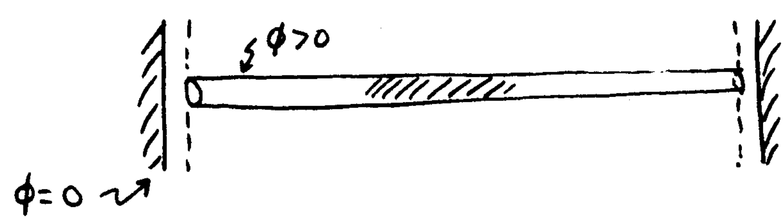
9) The transverse correlation length is of order 1 cm and changes in the same direction as r_{Li} when B and KT_i are changed.

10) The longitudinal correlation length exceeds 200 cm, as if the entire flux tube fluctuates as a whole.

11) When the sputter voltage is increased, KT_e decreases and the U^{++} fraction decreases. If U^+ is driven, the noise then increases; if U^{++} is driven, the noise decreases. Vice versa if the sputter voltage is decreased. This suggests that the noise is suppressed by the presence of a non-resonant species.

12) Argon density greatly increases the noise.

We now propose a model for these noise pulses. Consider a tube of force, as shown below. Let the tube terminate in ion sheaths in front of conducting end



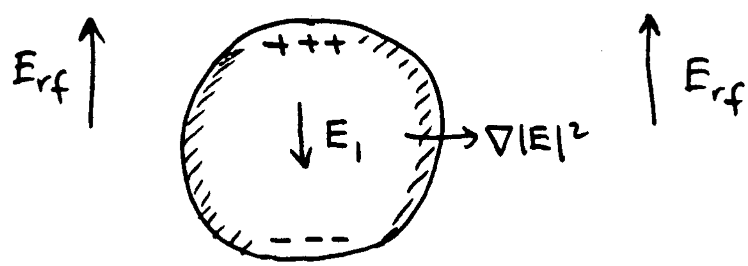
boundaries. The sheath drop is independent of density. This is because the ion flux into the sheath is $\Gamma_i = nv_B$, and the electron flux is $\Gamma_e = nv_r \exp(-e\phi/KT_e)$, where $v_B = 0.5(KT_e/M)^{\frac{1}{2}}$ and $v_r = (KT_e/2\pi m)^{\frac{1}{2}}$. Sheath equilibrium requires $\Gamma_i = \Gamma_e$, giving $e\phi = KT_e \ln(v_r/v_B)$, with n cancelling out. Thus, the sheaths fix the potential at the ends of the tube of force.

Suppose now that there is a temporary increase in density somewhere in the tube of force away from the ends. We shall show that this density increase is unstable in the presence of ICRF and will grow. Since electrons along each flux tube follow the Boltzmann relation

$$n_r = n_o e^{e\phi/KT_e} ,$$

an increase in density will cause ϕ to rise by an amount $(KT_e/e)\ln(n/n_o)$. This is in the right direction but is insufficient to explain the amplitudes of order 40 V that are observed. Fortunately, our mechanism allows for the direct accumulation of excess ion charge in the dense region.

Consider a filament of plasma with density higher than average at a

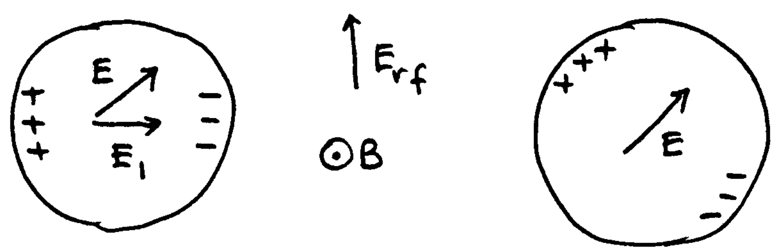


time when the rf electric field is upward, as shown. Two separate processes occur. First, on a time scale short compared with $2\pi/\omega$, ω being the rf frequency, electrostatic charges will build up on the edges of the filament to create a field $\underline{E}_1$ opposing $\underline{E}_{rf}$. The net field inside the filament will be weaker than that outside. Second, on a slow time scale, the resulting gradient $\nabla|E|^2$ will exert a ponderomotive force on the ions, causing them to be pushed into the filament, making its density even larger. These two processes will now be discussed in more detail.

The buildup of the electrostatic field $\underline{E}_1$ occurs in a way that depends on ω/Ω_c. For $\omega << \Omega_c$, there is a polarization drift in the direction of $\underline{E}_{rf}$, and the resulting charge separation gives rise to the low-frequency dielectric response of the plasma:

$$\varepsilon = 1 + c^2/v_A^2 \approx c^2/v_A^2 \quad .$$

In this case, $\varepsilon \approx 10^4$, so that the E-field inside the filament would be reduced by a factor of 10^2 if $\Delta n/n = 1\%$. As ω approaches Ω_c, this picture breaks down; in fact, for $\omega > \Omega_c$ the ions move in the opposite direction to $\underline{E}_{rf}$. The field $\underline{E}_1$ then builds up entirely from the motion of electrons. Imagine that $\underline{E}_{rf}$ is suddenly turned on. Before the ions can move, the electrons will $\underline{E} \times \underline{B}$ drift sideways, creating a horizontal $\underline{E}_1$ and a net $\underline{E}$ at an angle, as shown. The resulting $\underline{E}$ will cause an $\underline{E} \times \underline{B}$ drift perpendicular to itself,



and the surface charges will rotate as in the second figure. It is clear that the charges will continue to move until $\underline{E}_1$ is opposite to $\underline{E}_{rf}$ and the net $\underline{E}$ is nearly zero. If $\underline{E}$ is not ≈ 0 inside the filament, there is no steady state on the fast time scale, and the polarization charges will keep moving until $\underline{E}$ is zero.

The time required for this to happen can be estimated as follows. Let the density inside the filament be $n_o + n_1$, and let the diameter be 2a.

The field E_1 due to two charge sheets separated by 2a is

$$E_1 = \sigma/\varepsilon_o \quad ,$$

where σ is the surface charge density (in MKS). In practice, E_1 will be somewhat weaker than this and there will be a dependence on 2a because of the finite vertical dimension. Now we write

$$\frac{d\sigma}{dt} = n_1 e v_E = n_1 e \frac{E_{rf}}{B} = \frac{\sigma}{t_1} \quad .$$

Setting $E_1 \approx E_{rf}$ gives

$$E_{rf} = \frac{\sigma}{\varepsilon_o} = \frac{n_1 e}{\varepsilon_o} \frac{E_{rf}}{B} t_1 \quad ,$$

or

$$t_1 = \frac{\varepsilon_o B}{n_1 e} = \frac{\varepsilon_o m}{n_o e^2} \cdot \frac{eB}{m} \cdot \frac{n_o}{n_1} = \frac{\omega_c}{\omega_p^2} \frac{n_o}{n_1} \quad .$$

For the assumed condition, this gives the polarization time

$$t_1 = 1.5 \times 10^{-10} \; n_o/n_1 \text{ sec.}$$

Requiring this to be much shorter than the cyclotron period t_c yields the threshold condition

$$\frac{n_1}{n_o} >> 1.8 \times 10^{-5} \quad .$$

Thus, we can expect that $\underline{E}$ inside the filament will be largely cancelled within a fraction of a cyclotron period anytime there is a density fluctuation greater than 0.01%. This assumes that the perturbation is so long in the $\underline{B}$ direction that the polarization charges cannot escape by flowing along $\underline{B}$. Note that this effect is independent of the sign of n_1 and of the relative orientation of $\underline{E}_{rf}$ and $\underline{B}$. This is because $\underline{v}_E$ is perpendicular to $\underline{E}_{rf}$ and $\underline{B}$, and changing the direction of either merely changes the direction of rotation of $\underline{E}$. Similarly, a density depression instead of a density rise would merely change the rotation direction. Note also that a two-dimensional structure is required; this cannot happen in slab geometry.

We now consider the effect of a gradient $\nabla|E|^2$ on the ions. The ponderomotive force on the ions at the edge of the filament will push them inside. Thus, a density rise will increase, and a density depression will decay. This explains why the observed voltage spikes are always positive. Since normal filamentation causes channels of low density, this is an inverse filamentation phenomenon.

The ponderomotive force near ion cyclotron resonance has been studied by a number of authors, but the formula that we need is not at hand. Akama and Nambu[1,2] give most of the references and also the following formula for the α-component of the force:

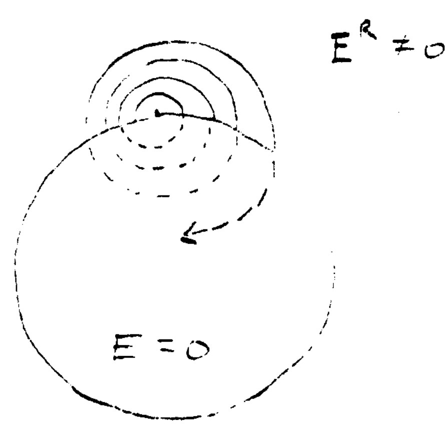
$$f_\alpha = \frac{1}{2} k_\alpha \varepsilon_0 K'' |E|^2 + \frac{1}{4} \varepsilon_0 (K'-1) \frac{\partial}{\partial x_\alpha} |E|^2 + \frac{1}{4} k_\alpha \varepsilon_0 \frac{\partial K'}{\partial k_\beta} \frac{\partial}{\partial x_\beta} |E|^2 + \frac{\partial g_\alpha}{\partial t} ,$$

where

$$g_\alpha = \frac{1}{4} k_\alpha \varepsilon_0 \frac{1}{\omega^2} \frac{\partial}{\partial \omega} \left[\omega^2 (K'-1) \right] |E|^2 ,$$

and K' and K" are the real and imaginary parts of ε. The first term above is the force due to Landau damping; the third term is connected with the heat flux; and the last term represents a force on the nonresonant particles. The second term is the classical ponderomotive force and goes to ∞ at $\omega = \Omega_c$ when $K' \to \infty$. This infinity has been removed by Lamb, et al.[3] by considering transit time effects. Here, the length of the filament means that transit times will be very long, and it is probably finite r_L that removes the infinity. Furthermore, Ref. 3 concerns the parallel component of f, which is not the one we need.

Though the appropriate theory is not at hand, it is not hard to see that ions will tend to accumulate in the region of low $|E|$. Consider a filament comparable in size to an ion Larmor radius. An ion whose orbit lies entirely inside the filament will feel no rf and will stay there. An ion which gyrates outside the filament in part of its orbit will be accelerated while it is outside and will re-enter with a larger Larmor radius. The effect will be to move its guiding center further in and for it to spend more time inside the filament.



It is clear that if $a \gg r_L$, there are no such particles that can contribute to the density at the center. If $a \ll r_L$, the ions pass through without appreciable change in their trajectory. This explains why $a \simeq r_L$ is required, and why it is the resonantly driven ion density that matters.

There is another effect that occurs once the positive potential inside the filament is built up. Then a large-orbit ion passing through will slow up on the potential hill and contribute more to the density there than it normally would. This, of course, contributes directly to bandwidth broadening. This last effect is probably not strong enough to cause instability by itself; the ponderomotive force is needed. Otherwise, the pulses would be seen all the time in rf heating, and negative pulses would also be seen. Since these effects occur on scalelengths comparable to r_L, it is doubtful that they can be treated by an analytic theory of ponderomotive forces. Computer simulation is probably required.

The picture so far explains qualitatively the sign of the potential spikes, the transverse and longitudinal dimensions of the filaments, and their dependence on drive amplitude and resonant-species fraction. The saturation level is clearly not related to KT_e but to E_{rf} or KT_5. From a ponderomotive force point of view, the radial dc E-field of the filament (40 V over $\frac{1}{2}$ - 1 cm) would reverse the sign of the field gradient when it exceeds that due to E_{rf}. The observed value seems too large for this. It is more likely that V_{sat} is related to KT_5. If V_{sat} is too large, ions don't make it to the center of the filament, and the build-up of ion charge must stop. As for the risetime, it should be somewhat slower than the gyration period, which it is. That the fall time should match the risetime may be accidental. We have not yet worked out the decay mechanism.

The effect of neutral argon can be explained by the fact that a charge exchange collision inside the tube would leave behind a cold ion which feels no accelerating field and therefore contributes greatly to the positive charge in the tube.

REFERENCES

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3. B.M. Lamb, G. Dimonte, and G.J. Morales, Phys. Fluids 27, 1401 (1984)