Basics of electron beam-plasma interactions; experiment and simulation

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SP3’s activities: summary

SP3 undertakes research into low temperature plasmas and their applications.

PIC simulations and plasma modeling, plasma processing of surfaces, atmospheric pressure plasmas, fuel cells, space physics and space plasma thrusters.

INDUSTRY

EADS-ASTRIUM (propulsion)
LAM RESEARCH (microelectronics)
OREGON PHYSICS (focused ion beams from Ar, Xe plasma source not metals)
SP3 (Helicon source manufacturing)
Interaction of electron beams with plasmas

If a charged particle passes through a medium with a velocity greater than the phase velocity then waves are emitted (Heavyside, Čerenkov)
Boats moving faster than surface water waves create a similar wake.
Electron beams interact with plasmas in a similar manner, the instability is convective rather than absolute in that it grows along the direction of the beam velocity rather than growing everywhere in time. (from Briggs)

Figure 2.1. Evolution of pulse disturbance in an unstable system.
Electron beams support fast and slow waves, propagating with and against the beam direction, these waves interact with the electron plasma (Langmuir) waves to produce instabilities.
For unmagnetised plasmas (or for $\omega_{pe} \ll \omega_{ce}$) the interaction occurs near the plasma frequency.
In a magnetised plasma the beam interacts with oblique waves on the upper hybrid and whistler resonance cones.

Figure 1.1: The dispersion relation of Simpson and Dunn (1966) for a beam-plasma interaction in cylindrical geometry. The circles show the regions where the fast and slow beam waves may couple with the Trivelpiece-Gould modes of the plasma.
Rocket experiments launched electron beams along a field line to the earth’s conjugate point, beam plasma discharge postulated to explain rocket neutralisation (and Hall Effect neutraliser used!)

Fig. 1. Schematic representation of the experimental arrangement.
Bernstein et. al. in 1978 observed two types of BPD, low density ($\omega_{pe} < \omega_{ce}$) and high density ($\omega_{pe} > \omega_{ce}$).
WOMBAT (Waves On Magnetised Beams And Turbulence) was constructed at the ANU to simulate the Space Shuttle environment and active experiments with charged particle beams.

Figure 2.1: Schematic diagram of the WOMBAT apparatus.
Four types of BPD were discovered in WOMBAT
BPD1 when \((\omega_{pe} < \omega_{ce})\)
BPD2 when \((2\omega_{ce} > \omega_{pe} > \omega_{ce})\)
BPD3 and BPD4 \((\omega_{pe} \gg \omega_{ce})\)

Figure 2.8: Typical spectra of the first four BPD's, when \(E_0 = 300\) eV and \(B_0 = 36\) G.
As the beam current was increased, the frequency of the BPD1 bursts increased and the deduced plasma density increased linearly with beam current (ie. ionisation rate).

Figure 2.11: a) Frequency of the BPD1 bursts with increasing $I_b$. b) Plasma density estimated by assuming that the oscillations are at $f_e$. 
The bursts grew axially away from the electron gun at a rate approximately \( \sim (n_{\text{beam}}/n_{\text{plasma}})^{1/4} \omega_{\text{pe}} \). They were axially modulated by the finite number of wavelengths that could fit in the system (Pierce).

![Figure 2.13: Envelopes of the 30-40 MHz bursts measured with 16 probes spaced 6 cm apart along the axis of the electron beam.](image)
Figure 4.1: The dispersion relation for the original Pierce instability. The solid lines are the real part of $\gamma$, i.e. the growth rate, and the broken lines are the imaginary part of $\gamma$, i.e. the frequency.
Figure 2.10: Correlation between a) envelope of the RF burst, b) current to a photomultiplier tube, and c) current reaching the collector of the energy analyser with $V_3 = -15$ volts, for BPD1 bursts.
For large amplitude bursts, the beam produced waves with sufficient amplitude reverse the motion of the electrons, i.e. the beam was stopped by its own instability!

Figure 2.14: Envelopes of the bursts of about 50 MHz measured with 16 probes spaced 6 cm apart along the axis of the electron beam.
The electron beam is severely perturbed by the instability, scattering and phase mixing down to lower energies. The additional Beam Plasma Discharge produced an excess of low energy electrons which increase the ionisation rate.

Fig. 2. Electron energy distributions obtained from the differentiated time averaged energy analyzer results, (a) just before BPD, $I_b \sim 3$ mA; (b) just after BPD, $I_b \sim 6$ mA; (c) developed BPD, $I_b \sim 12$ mA. As the potential on the analyser affects the plasma, the beam currents are accurate only to a factor of two.
Waves generated by the beam can become sufficiently high to parametrically decay into lower frequency waves.

Figure 1. Schematic diagram of the experiment.
In this experiment, the beam convectively excites waves at the upper hybrid frequency (A) which then decay to a non-propagating wave at the electron cyclotron frequency and a whistler on the resonance cone (B) and finally to broad band waves by cascading (C). The spatial evolution of the pump, sideband and daughter are shown in (D).

Figure 2. Wave spectra in the beam at 35 cm (a), 50 cm (b), and 75 cm (c) and (d) amplitude as a function of distance from the gun for waves at 1.3, 1.01 and 0.3 \( \omega_{ce} \).
References


