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PLASMA HEATING AND ION ACCELERATION BY A RELATIVISTIC ELECTRON BEAM - REB ACCUMULATION

P.Šunka, K.Jungwirth, I.Kováč, V.Piffl, J.Stöckel, J.Ullschmied
Institute of Plasma Physics, Czechoslovak Acad. Sci., Prague 9

ABSTRACT: Results on REB interaction with an inhomogeneous magnetized plasma are reported. The maximum efficiency of plasma heating is found if a virtual cathode is created near the end of the system. In the virtual cathode regime also partial reflection and accumulation of beam electrons and ion acceleration from a free plasma boundary is observed.

Measurements were performed on the improved REBEX machine [1] (I_b= 10-20 kA, U_b= 450 kV, Q_b= 150-300 J, t_i= 70 ns). A gun (aperture diameter 7cm) placed 30cm apart the foil anode fills the whole interaction region (L=210 cm) with a hydrogen plasma ($n \lesssim 3.10^{13}cm^{-3}$) only after a time delay of 60μs. For time delays between plasma and beam injection $t_d \lesssim 35\mu s$ the plasma density remains negligible near the collector.

PLASMA HEATING

Plasma energy content Q after the beam injection is measured by three diamagnetic loops (placed at z=50,100,140 cm) at various t_d. In Fig.1 the z-dependence of transverse plasma energy $nE_\perp S$ is shown for t_d=40,80,200μs. Assuming an isotropic heating the REB-plasma energy coupling efficiency of about 50%,30%,20%, respectively, is achieved. As return current heating is negligible in our system ($I_b < I_A$, $L \ll t_i v_b$) excitation of strong plasma waves near the upper hybrid ($\omega_o^2 \approx \omega_{pe}^2 \gg \omega_{ce}^2$) represents the only effective channel for the REB-plasma energy coupling. Energy of these waves (localized within the beam channel) is rapidly absorbed by plasma electrons via parametric-decay instabilities. Rough estimates based on [2,3] suggest for the plasma core (3cm in diameter, $n=3.10^{13}$ ^{1}) heated by a propagating beam ($n_b/n=10^{-2}$) the following typical values: $t_i \nu_{eff} \approx 16\pi n E_\perp/E_o^2 \gg 1$, where the wave electric field $E_o \approx 100\ kVcm^{-1}$, threshold plasma length $L_{th} \approx 50$ cm, $nE_\perp \approx 3.10^{17}eVcm^{-3}$, $\nu_{eff} \approx 4.10^9\ s^{-1}$, $Q = 0,2Q_b$.

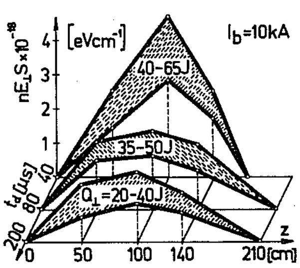

Fig.1

By shortening t_d ($t_d \lesssim 80\ \mu s$) the heating efficiency increases regardless the increase in the plasma density n and in its inhomogeneity dn/dz. The highest efficiency is measured at t_d=40μs when a virtual cathode is created and a significant part of the beam electrons multipasses the system. For t_d<40μs we were not able to determine the plasma energy content as strong r.f. oscillations ($\omega \lesssim 6.10^9 s^{-1}$) appear on diamagnetic loops placed in the virtual cathode region. Signal from the loop at z=50cm, however, continues to grow. The maximum value of $nE_\perp S \approx 5.10^{18} eVcm^{-1}$ is reached for magnetic fields B_o=4-6kG and 10μ thick aluminized mylar anode foil. (Most measurements were done with 30μ Al foil at B_o= 4,7 kG.)

The plasma core is overheated at the end of the beam injection ($\beta_i = 8\pi nE_\perp/B_o^2 \gtrsim 1$) and tends to expand radially towards a new pressure equilibrium. If a dense plasma is heated rapidly ($f_{ac} \lesssim \min(f_{ci}, 1/2t_i)$) a strong magnetoacoustic wave with frequency $f \approx f_{ac}$ is expected to be excited by the expansion. Its presence is demonstrated by regular damped oscillations of the diamagnetic signals (Fig.2). By decreasing the plasma density f_{ac} approaches the ion gyrofrequency f_{ci} and the oscillations become strongly damped. Then, energy of the magnetoacoustic wave $Q_{ac} \approx \beta_i\, Q/2(2+\beta_i)$ should be effectively absorbed by plasma ions and heat them to keV energy. (For n=$5.10^{13}cm^{-3}$, B_o= 4,7kG and $nE_\perp S=5.10^{18}eVcm^{-1}$ it is β_i=3/2, $Q_{ac} \approx Q/5$, el. field E_{ac}=300Vcm^{-1}.)

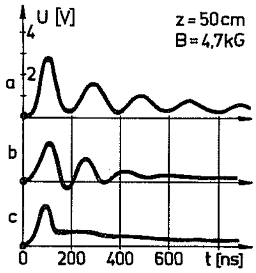

Fig.2: Oscillograms of diamagnetic signals $nE_\perp S$
a) t_d=40μs, n=$6.10^{13}cm^{-3}$
b) 60μs, $4.10^{13}cm^{-3}$
c) 160μs, $2.10^{13}cm^{-3}$

Measurements of fast neutrals escaping radially indicate that the ions are heated up to keV "temperatures". At higher densities an appreciable part of ions is heated to several hundreds eV, whereas at lower densities only a small part of ions is heated, but to higher energies (T_i=8-10 keV) Ions can get comparable energy also in radial electric fields arising in the hot electron plasma due to its expansion as well as due to longitudinal losses of overthermal electrons.

ACCUMULATION OF REB ELECTRONS AND ACCELERATION OF IONS

To detect the accumulated beam electrons X ray bremsstrahlung from the foil anode was monitored. It increases with the decreasing plasma length. The maximum observed enhancement was about 6times for the foil-terminated plasma and about 3times for a longer plasma column with a free boundary relative to the beam propagation mode. A similar result was obtained by measuring the current from a foil placed closely (2mm) to the terminating foil, indicating that the number of fast electrons increases 3-4times. The multipassage of these electrons through the anode foil results in an increase in the net diode current.

In the virtual cathode regime energetic ions (E_i > 100keV) accelerated from a free plasma boundary both axially and radially were detected. The total number of axially accelerated ions $N_{i\parallel}$ as well as their energy $E_{i\parallel}$ is maximum if the beam multipasses a short plasma column (L_p<50cm, max $E_{i\parallel}$=1MeV, $N_{i\parallel}$ = 2.10^{13} detected 2m downstream). If the plasma boundary becomes smooth (L_p>50cm) the radial dependence of potential in virtual cathode region causes the radial acceleration of ions to be more effective than the longitudinal one. The initial focusation of ions towards the axis leads to a drastic change of the potential distribution and ions with energies comparable to eU_b can then be ejected. Bursts (20ns) of such ions with transverse energy $E_{i\perp}$>400keV were registered. The total number of ions accelerated from a smooth boundary should exceed significantly that from a sharp boundary. Thus, at least for low density plasmas, this direct conversion of energy from REB to the plasma ions could be of practical interest.

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