Collective beam-plasma interaction for REB passed through inhomogeneous low-density plasma

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Two types of experiments on collective electron beam-plasma interaction are conducted at BINP. First one is plasma heating by relativistic electron beams (REB) in mirror magnetic field configuration, which is targeted on fusion application [1]. Second is series of fundamental plasma physics experiments on excitation of strong Langmuir turbulence [2]. For effective heating, according to initial theoretical prediction [3] the requirements for homogeneity of plasma density were considered rather tough to prevent convective stabilization of beam-plasma instability by drift of plasma waves out from resonance region of spatial spectrum. The minimal scale of longitudinal inhomogeneity of plasma density, which allows the growth of kinetic REB-plasma instability, is [3]:

$$L_L \le L_{L\min} = \frac{\theta_b \cdot c \cdot \ln\Lambda}{\omega_{pe}} \cdot \frac{E_B}{m \cdot c^2} \cdot \frac{n_P}{n_B}.$$

Under condition of plasma heating experiments ($E_b = 1$ MeV, $n_p = 4 \cdot 10^{14}$ cm^{-3}, $n_b = 10^{11}$ cm^{-3}, $\theta_b = 30°$) the minimal scale of inhomogeneity $L_{L\min}$ exceeds the total length of plasma (12 m). Still, the effective deposition of REB energy to plasma with $L_L \le 1\text{m}$ was observed experimentally with temperature of heated plasma in a keV range [1]. The simplest explanation of this result can be found in mutual role of longitudinal ∇_L and transversal gradients ∇_T of plasma density, which often co-exist in real plasmas. For long plasma column $\nabla_T >> \nabla_L$ so the normal to the resulting gradient $\nabla = \nabla_T + \nabla_L$ is slightly tilted from the REB direction and the instability grows rate is large for waves traveling along this normal. Another aspect of REB plasma interaction is delivering of REB from the vacuum high voltage diode to heated plasma through intermediate relative low-density plasma. Because of strong dependence of linear kinetic instability growth rate on densities ratio ($\Gamma \sim n_b/n_p$) deposition of considerable fraction of REB energy in the intermediate plasma might be a problem. Recently, this particular point got a fresh interest after suggestion to employ in fast ignition (FI) collective heating of dense core by REB [4]. The authors propose suppression of the REB energy loss in the transport channel by plasma density gradient in order to transport the REB through relatively rare plasma to the core. Although conditions of

BINP experiments are far from those in FI, but some dimensionless parameters (n_b/n_p, $L_p\omega_{pe}/c$, $\tau_b\omega_{pe}$, here L_p is the length of main plasma, τ_b is duration of REB) are similar (see Table).

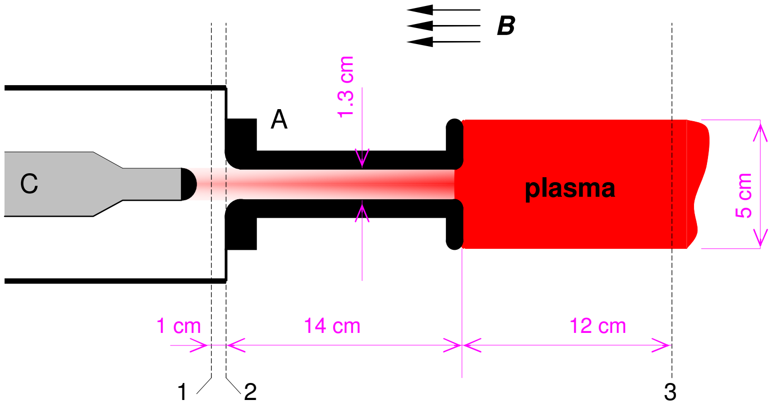

Fig.1 Geometry of experiment. Transport plasma size: L_{tr}=14cm, $2R_{tr}$=1.3cm

	Fast ignition [4]	Langmuir turbulence [2]	Mirror plasma [1]
n_p	10^{26}cm^{-3}	0.5-2.5·10^{15}cm^{-3}	2-10·10^{15}cm^{-3}
n_p/n_b	2·10^3	2.5·10^3-1.3·10^4	1.5·10^3-10^5
T_e	5000 eV	2eV (initial) 10-60 eV (final)	1-2 eV (initial) 2500 eV (final)
ω_{pe}/ν_e	300	150-350 (initial) 700-3500 (final)	50-350 (initial) 10^6 (final)
L_p	5 10^{-3}cm	250cm	1200 cm
$(L_p\omega_{pe})/c$	10^5	1-2.5·10^4	0.3-2·10^5
τ_b	10^{-11} s	2·10^{-7} s	8·10^{-6} s
$\tau_b\ \omega_{pe}$	6.10^6	2-5·10^5	0.6-4·10^7

In this publication we discuss some of related results obtained in the course of experiments on strong Langmuir turbulence driven by REB. The geometry of the experiments is shown in Fig.1. The REB produced in vacuum diode travels through graphite drift tube to the hydrogen plasma column where it drives Langmuir turbulence. Langmuir fluctuations are observed with CO_2 laser scattering [5] at section 3. Plasma is allowed to penetrate to the drift tube from the plasma column, produced by discharge in longitudinal magnetic field. In the considered experiments the plasma density in the diode gap (between sections 1 and 2) is kept below a few percent of the column plasma. In order to estimate the distribution of transport plasma in the drift tube we record the line-integrated density behind tubes of different lengths. The width of the probe beam of the interferometer is less than 1mm that enables evaluation of transversal plasma inhomogeneity from chord measurements. To determine the role of transport plasma in deterioration of the REB on the way to the plasma a separate test experiment was performed. In this experiment the drift tube was substituted to

20 μ Ti foil and the REB is directly injected from the diode to dense main plasma. The foil diode configuration yields more than fivefold REB current relative to standard foilless configuration but of shorter duration (Fig.2). Scattering of electrons in 20 μ Ti foil spreads the REB angular distribution up to θ_b=25° about the propagation direction. Observations of Langmuir waves excited by REB show clear peaks near the resonant longitudinal wave number $k_L = \omega_{pe}/v_B$ (Fig.3). Spectral widths of the peaks are close to instrumental width in both configurations. About one order higher spectral density of Langmuir oscillations per unit beam current evidences that REB retains its low divergence after passing the transport plasma. The total level of Langmuir turbulence that is estimated from plasma heating by collisional damping of Langmuir oscillations [2] appears higher for foilless configuration as well. Longitudinal distribution of plasma density in the drift tube is shown in Fig.4. Plasma density at zero was determined from line density behind a wire grid of known transparency. It agrees with localized measurement of plasma density by ruby Thomson scattering at section 3 (see Fig.1). It is seen from figure 4, that the longitudinal gradient is somewhat larger than n_p/L_{tr} at time 80 ms after start of the discharge. The same is true for transversal gradient that is larger than n_p/R_{tr}. As it follows from the experimental data the density gradients increase with time that can be explained by plasma loss near the tube walls. With the observed density gradients the violation of the theoretical requirements on plasma homogeneity in this experiment is not stronger than in the mentioned above mirror plasma

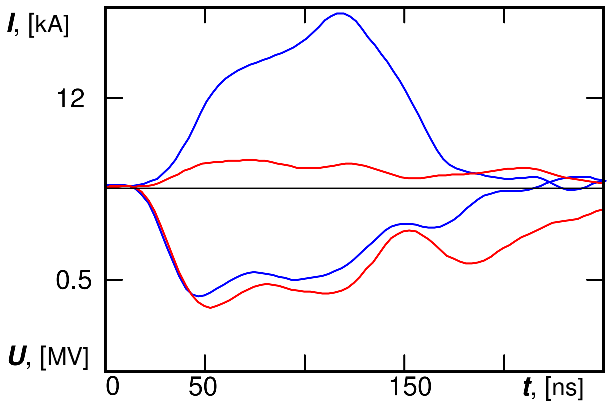

Fig.2. Current and diode voltage for REB injected through transport plasma (red) and Ti foil (blue).

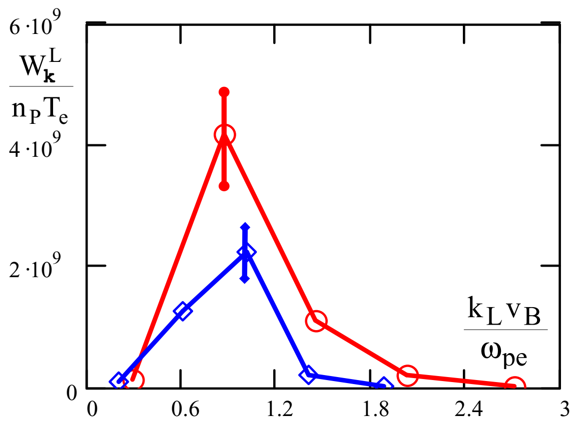

Fig.3. Frequency integrated k-spectra for foilless REB injection (red) and injection through Ti foil (blue).

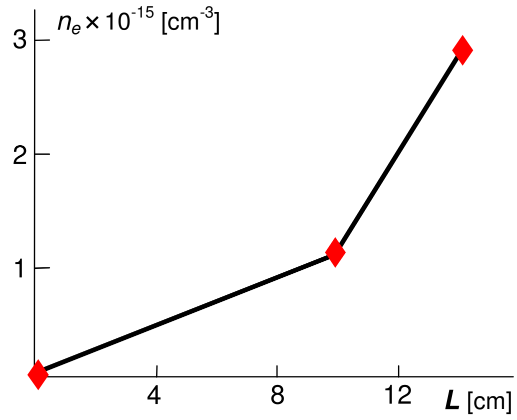

Fig.4. Longitudinal distribution of transport plasma at 80 µs after discharge start. L=0 corresponds to section 2 in figure 1.

heating experiments. It does not provide enough reasons to attribute revealed in the experiment weak degradation of the REB in transport plasma to density gradients. The relative short length of the transport plasma is not the only explanation of weak REB degradation. The scale for distinct decline in effectiveness of cold REB interaction with optimized plasma typically is of order of a few lengths of present drift tube [6]. The decrease of REB energy loss in plasma with decrease of plasma density was observed in early experiment [6] and was explained by excitation of ion-acoustic turbulence that suppresses the beam-plasma instability. This effect might be significant in case of transport of REB in FI plasma as well. It should be noted however that described experiment differs from FI in two important aspects: i) strong ambient magnetic field ($B_0 >> B_{REB}$) prevents REB from filamentation and coalescence; ii) relative low initial temperature T_o enables fast plasma heating and relate increase of the ratio Γ/ν_e. in the present experiment. It is well established experimentally [6] that condition of weak collisional damping $\Gamma/\nu_e >> 1$ is vital for collective REB-plasma interaction. The important result of present work is that the REB is not deteriorated in low-density transport plasma and retains capability for effective interaction with more dense plasma.

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