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Ion acceleration in non-equilibrium plasmas driven by fast drifting electron

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ABSTRACT

We hereby present results on ion acceleration mechanisms in non equilibrium plasmas generated by microwaves or high intensity laser pulses. Experiments point out that in magnetized plasmas X–B conversion takes place for under resonance values of the magnetic field, i.e. an electromagnetic mode is converted into an electrostatic wave. The strong self-generated electric field, of the order of 10^7 V/m, causes a $E \times B$ drift which accelerates both ions and electrons, as it is evident by localized sputtering in the plasma chamber. These fields are similar (in magnitude) to the ones obtainable in laser generated plasmas at intensity of 10^{12} W/cm^2. In this latter case, we observe that the acceleration mechanism is driven by electrons drifting much faster than plasma bulk, thus generating an extremely strong electric field $\sim 10^7$ V/m. The two experiments confirm that ions acceleration at low energy is possible with table-top devices and following complementary techniques: i.e. by using microwave-driven (producing CW beams) plasmas, or non-equilibrium laser-driven plasmas (producing pulsed beams). Possible applications involve ion implantation, materials surface modifications, ion beam assisted lithography, etc.

1. Introduction

The need of intense beams of ions at moderate energy for industrial or scientific applications is constantly growing. At the same time, the exceptional improving in plasma physics understanding, including non-linear mechanisms in laser plasma interaction, has provided absolutely new methods for particles acceleration. In laser-plasma-based ion acceleration, the energy scales with the laser intensity; in the case of table-top lasers operating at moderate intensities ($I < 10^{12}$ W/cm^2) and in a nanosecond domain ions are typically accelerated up to some keV. Laser Produced Plasmas (LPP) are employed in several fields of matter and nuclear physics, such as thin film deposition, ion acceleration and nuclear fusion [1,2]. In a low energy domain, like that of laser plasmas produced in irradiance regime of 10^{12} W/cm^2, the density is very low (on the order of 10^{19}–10^{21} cm^{-3}) if compared with stars, but temperature and density can be rescaled to simulate phenomena of astrophysical interest.

Spontaneous formation of a high-speed plasma flow has been recently observed at LNS when the plasma was ignited through non-linear microwave plasma interaction. Microwave ignited plasmas are largely employed as powerful injectors for particles accelerators or like high intensity proton sources and in industrial applications. The plasma ignition is usually obtained by means of microwaves at 2.45 GHz [3,4], axially launched inside the plasma chamber, where a strongly non uniform magnetostatic field exists (with 0.1 T of maximum value). If the wave is properly launched, in under-resonance regions the X–B conversion is possible [5], i.e. the incoming electromagnetic extraordinary mode is converted into an electrostatic Bernstein wave. Signs of BW generation are the transition from an underdense to overdense plasma state, and specially the appearance of high energy electrons. In the new setup designed at LNS clear signatures of BW generation have been observed. During BW heating regime, the plasma transits from an equilibrium to a strongly non-equilibrium regime governed by turbulence. The strong electric field associated with the nascent EBW drives $E \times B$ drifts causing ion and electron acceleration.

We also designed a novel setup to study nuclear astrophysics by employing LPP [6]. By studying the evolution of single expanding plasma, we observed, other than the classical hydrodynamics expansion, some non linear processes driven by the formation of

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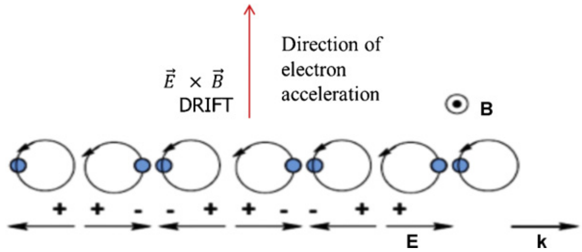

Fig. 1. Description of the charge bunching creating the EBW waves and direction of $E \times B$ drift.

Double or Multi-layers. Mechanisms of ion acceleration have been observed, based on the "blow-off" of prompt electrons which in turn drive instabilities, producing finally the Coulomb-like explosion and a multi layered plasma bulk. Similar electric fields have been found in microwave driven and laser driven plasmas at intensity of 10^{12} W/cm^2.

2. Theory of X–B conversion mechanism

ECR plasmas are density limited [7], in facts the electromagnetic waves cannot propagate above the so-called cut-off density: $n_{\text{cut-off}} = (\varepsilon_o m_e/e^2)\omega^2$. Electron Bernstein Waves (EBW) [8] are able to propagate in overdense plasmas, and thus they are an option to increase the density over the cut-off limit [7,9]. They are crucial for plasma ignition in nuclear fusion experiments, and represent a promising technique to improve the performances of existing plasma-based ion sources, which are critically dependent on the plasma density. EBW are generated at Upper Hybrid frequency (UHR) [9,10], i.e. the resonance of X wave, where the condition: $\omega_{\text{RF}} = \sqrt{\omega_p^2 + \omega_c^2}$ is valid, being ω_c the cyclotron frequency and ω_p the plasma frequency, and propagate perpendicularly to the magnetic field as layers of electron density accumulation and rarefaction sustained by the cyclotron motion (Fig. 1).

Evidence of the conversion from Electromagnetic to Electrostatic waves is given by parametric decay, which can be visualized by means of the presence of sidebands (due to the creation of ion waves in the process) in the E.M. spectrum at UHR position. Dispersion relation of the Bernstein waves [11] is:

$$1 - \left(\frac{k_B v_{\text{th}}}{\omega_p}\right)^2 = e^{-k_B^2 r_L^2} I_0(k_B^2 r_L^2) - \left(\frac{\omega}{\omega_c}\right) \frac{\sum_q e^{-k_B^2 r_L^2} I_q(k_B^2 r_L^2)}{q^2 - \frac{\omega}{\omega_c^2}} \quad (1)$$

where k_B is the wave number of the Bernstein wave, v_{th} is the electron thermal velocity, r_L is the electron Larmor radius, ω_p and ω_c are plasma and cyclotron frequencies, ω is the pumping frequency, I_q is the Bessel function, $q = 1, 2, \ldots, N$. BWs exhibit a resonance when the denominator of equation 1 vanishes, i.e. when:

$$B_{\text{resonance}} = \frac{1}{q}\left(\frac{m}{e}\omega_{\text{RF}}\right) = \frac{1}{q}B_{\text{ECR}} \quad q = 1, 2, \ldots N. \quad (2)$$

corresponding to cyclotron harmonics. The absorption mechanism can be explained by the Segdeev–Shapiro damping model [11]. The maximum energy available by the electron W_{MAX} depends by the electric field E of the Bernstein waves and by the magnetic field B in the point where absorption takes place [12]:

$$W_{\text{MAX}} = \frac{1}{2} m_e \left(\frac{E}{B}\right)^2 \quad (3)$$

where m_e is the electron mass. It can be shown [12] that if the magnetic field is directed along the z axis and the wave propagates along the x axis, the electrons are accelerated along the y axis because of the $\vec{E} \times \vec{B}$ drift acting on electrons. In a cylindrical symmetry these electrons will be accelerated into concentric circles, creating an azimuthal flow rotating around the plasma chamber axis. Experimental results [13] show that also a radial component of motion can arise because of a $\vec{F} \times \vec{B}$ drift, where F is a friction force due to the collisions. The result is the formation of a "typhoon-shaped" plasma vortex [13,14]. Thus EBW-heated Plasma can be represented as made of a series of vortex-like energetic electron layers at the cyclotron harmonics positions (where EBW are absorbed) separate by bulk plasma regions.

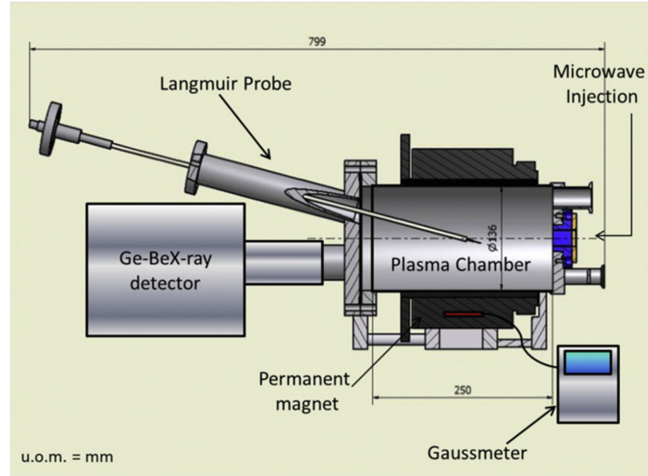

Fig. 2. Render view of experimental set-up.

3. Experimental setups

Parts of the tests have been carried out in a small-size plasma reactor (a stainless-steel cylinder 24 cm long, 14 cm diameter) that is essentially a Microwave Discharge Ion Source usually working at 2.45 GHz. A NdFeB permanent magnets system generates an off-resonance magnetic field along the plasma chamber axis (with a maximum of 0.1 T on axis). Microwaves have been generated using a Traveling Wave Tube (TWT) working in the range 3.2–4.9 GHz. Most of the experimental results were collected at 3.7478 GHz. Nitrogen has been flowed inside the reactor, keeping constant the pressure at 10^{-4} mbar. The microwaves were axially launched inside the chamber and, due to the formation of standing waves, extraordinary waves (with non parallel $\vec{k}$ vectors with respect to the B axis) can be generated [15]. The measurements of plasma temperature and density have been carried out using a movable Langmuir Probe (LP). The same system can host a small wire used as a local electromagnetic antenna, which can be connected to a Spectrum Analyzer (SA) for the plasma spectral emission analysis. A Ge–Be X-ray detector has been used for the measurement of X-rays spectra. The detector was placed in the extraction flange and it was separated by the plasma only by a 75 μm thick kapton layer, in order to allow the detection of X rays in the energy range 1–30 keV. A CCD camera has been used to visualize plasma structure within the chamber at different powers. A gaussmeter enabled us to measure variations of magnetic field linked to internal currents in the plasma. A render view of the experimental set-up is shown in Fig. 2.

The experimental set-up used to characterize the laser produced plasmas is shown in Fig. 3 and is fully described in [16,17]. It consists of a compact cylindrical stainless steel vacuum chamber, having a diameter of 250 mm and being 240 mm high. Four DN40 flanges are located at 90° with respect to the chamber axis, while additional DN25 and DN16 form angles going from 15° to 45°. The plate where the chamber is located was designed and made at LNS and has lateral dimensions of 600 mm The laser is a Quanta