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A review of low pressure expanding plasmas applied to electric propulsion, astrophysical objects and nanotechnology.

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The density gradient in low pressure expanding plasmas creates an electric field that accelerates positive ions out of the plasma. Generally, the total potential drop is similar to that of a wall sheath allowing the plasma electrons to neutralise the ion beam. An expansion dominated by a magnetic field can result in the formation of electric double layers which produce a very directed neutralised beam of ions. Applications of these phenomena can be found in satellite electric propulsion (ion and plasma engines), space science (solar and auroral double layers), neutral beam injection sources and materials processing (microelectronics, optoelectronics, nanotechnology and fuel cells). Recent interest has centred around the use of a radiofrequency (13.56 MHz) helicon plasma sources operating with various gases (neutral, reactive), in various operating (continuous, pulsed) and coupling (capacitive, inductive, wave) modes, with various magnetic field configurations (uniform, diverging field) and geometries (cylindrical, conical, asymmetric). This review will illustrate the basics of low pressure plasma physics (plasma sheath, plasma expansion, plasma-surface interaction) referring to a number of experiments around the world.

Characterisation of the various generated plasmas (density, potential, ion and electron energy distribution function) using electric, optical, photographic, mechanical probes diagnostics is a critical procedure in optimizing each application and will be described. Theoretical models and computer simulation play an important role in understanding mechanisms such as power transfer, particle transport and effect of boundaries. An overview of some of these models and simulations will be given and their relevance to terrestrial and spatial phenomena discussed. The demand for plasmas with a high degree of parameter control also results in the necessity of detailed spatial mapping (1, 2 and 3 D) of plasma parameters.

1. Introduction

There are a number of groups around the world who have reported beams of ions being accelerated in the density gradient of a radio-frequency (rf) produced plasma, sometimes with an axial magnetic field and sometimes without [1-7]. There has also been a concerted effort in modeling and simulation aimed at investigating the formation of the plasma potential and the acceleration of the ions [8-10]. At low pressures, where the mean free path for ion collisions is comparable to the plasma dimensions, a beam of ions with energies of a few 10s of volts has been observed [1]. Possible applications of this energetic ions beam have been investigated in the areas of space physics, satellite propulsion and surface activation and processing [1,11,12,13].

2. Ion acceleration in expanding plasmas

Geometrically expanding low pressure plasmas lead to ion acceleration. When this expansion is modified by application of an expanding magnetic field, e.g. by using a helicon or an inductive plasma source, electric double layers can spontaneously form to produce energetic ions beams with low divergence in a situation where there is no applied driving current (Fig.1).

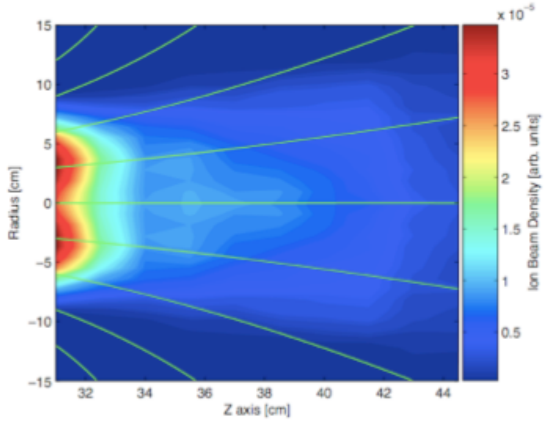

Fig.1: A spatially mapped ion beam downstream of a helicon double layer plasma.

Simplified analytical models and Particle In Cell computer simulations show that current-free solutions exist. The structure of the applied magnetic field induces the presence of plasma regions with specific electron dynamics (Fig 2.).

1D PIC simulations provide useful information on directional EEPFs along the main expansion axis.

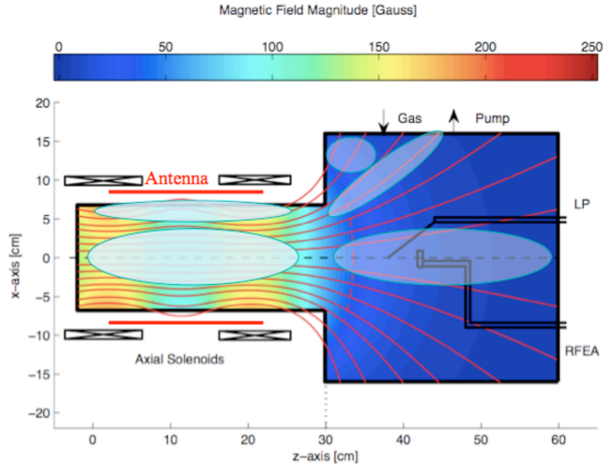

Fig.2: Regions of the Helicon double layer source and exhaust with distinct electron dynamics

3. Application to space plasmas

This current free double layer has been experimentally created for a various molecular gases (H2, O2, CO2…). The CO2 double layer extends outside the helicon source in a U-shape (Fig.3). Its relevance to space plasmas such as oblique double layers in the auroral cavity of the Earth and in the expanding plasma of the solar coronal funnels is discussed.

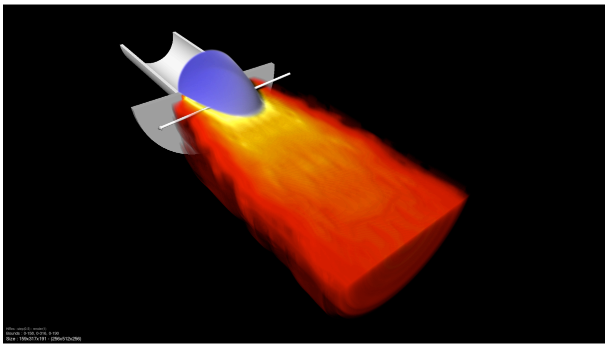

Fig.3: A U-shape helicon double layer (blue dome) and its accelerated ion beam (yellow to red flame).

4. Application to electric propulsion

The double layer mode and other expanding modes previously characterized in expanding plasmas can be applied to electric propulsion under the general umbrella of Helicon Double Layer Thrusters (HDLT). Direct measurement of thrust produced by various HDLT prototypes immersed in a small vacuum chamber (Fig.4) has been carried out and some modeling has been performed [8-10].

Fig.4: An HDLT prototype mounted on a thrust balance and firing into vacuum

5. Application to nanotechnology

Some preliminary experiments related to the use of the low energy ion beam for the soft treatment of polymers using in hydrogen fuel cells have been carried out with the aim of controlling the hydrophobicity of the surface[11].

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