Plasma Kinetics Issues in the ESA 'Plasma Laboratory in Space' Study

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INTRODUCTION

The European Space Agency has initiated, in the context of its General Studies Programme, an investigation of the possible use of space for studies in pure and applied plasma physics, in areas not traditionally covered by "space plasma physics". A team of experts has been set-up to review the possible experiments that could be undertaken and the plasma phenomena they may address [1]. As broad a view as possible has been taken in order to address potential applications in plasma physics, industrial plasma physics and other terrestrial plasma domains including pure plasma physics, as well as astrophysical and solar-terrestrial areas. A preliminary discussion was performed in order to select the most promising experiments and to exclude those issues that can be studied on the International Space Station and therefore do not require a dedicated platform. As a result of this selection work, the following most promising experiments have been further investigated.

Type of experiment	Scientific study objectives	Approach
Active Magnetic Experiment	- reconnection, instabilities, and plasma body interactions in electron-magnetohydrodynamic regime and possibly in other regimes (including MHD) if enough magnetic expansion takes place - dynamics of magnetic bubble expansion	- active magnetic field and plasma source. - remote and situ diagnostics (possibly on more than 1 spacecraft)
Large Discharge Facility	- ion-neutral collisions on very large scales - high number Rydberg states	- gas release and RF antenna. - remote and situ diagnostics (possibly on more than 1 spacecraft)
Long Tether-Plasma Interactions	- application as an energetic electron source for upper atmosphere remote sensing - Alfven waves instabilities - adiabatic trapping of electrons	- wire of the order of 1 to 10 km. - remote diagnostic package on the same spacecraft

In the course of the subsequent investigation programme, which culminated in the final workshop held in the middle of July at ESA (Holland), kinetic plasma modelling techniques were adopted in order to identify the main physics issues in the novel plasma regimes under examination.

ACME (ACTIVE MAGNETIC EXPERIMENTS)

Space plasmas provide a natural environment for large-scale, control experiments in collisionless plasma regimes. Active experiments aimed at investigating basic nonlinear phenomena such as magnetic field-line reconnection, magnetic field generation, magnetic vortex dynamics and particle acceleration can be performed under essentially boundary-free conditions that cannot be realized in the laboratory. Besides, this is a very interesting new environment where to test wave scattering plasma diagnostics techniques.

A space plasma experiment is proposed which consists of a magnetized plasma bubble interacting with the ambient (ionospheric) plasma. In addition, artificial plasmas can be produced by a plasma source (inflated bubble). Numerical simulations are essential for understanding the dynamics of the plasma bubble: 2d and 3d Particle In Cell (PIC) models have been used here in the case of the non inflated and inflated bubble respectively. The requirements are very different in the two cases. The inflated bubble could also be used as a dynamically sustained solar sail.

In fig.1 an example of 2D PIC simulation of the non-inflated bubble [2] is shown: the simulation is performed in the (x,y) plane with Lx = 6□ and Ly = 2□ in electron skin depth units. The Debye length is 0.1. Open boundary conditions are used in the x direction, while periodicity is assumed in the y direction. The external magnetic field, periodic in y, is localized in the central region with typical dimension of the order of a few units. The plasma flows along the x direction at u = 0.05 in electron thermal velocity units. The simulation mesh grids is Nx = 128, Ny = 32 for both electrons and ions. The ion to electron mass ratio is 1000. The external magnetic field is generated by two opposite currents along z. The equations for the update of particle position and velocity under the effect of locally interpolated electric and magnetic fields

$$\frac{\mathrm{v}_\alpha^{n+1/2}-\mathrm{v}_\alpha^{n-1/2}}{dt}=\frac{q_\alpha}{m_\alpha}\left(\mathrm{E}^n(\mathrm{x}_\alpha^n,t)+\frac{\mathrm{v}_\alpha^{n+1/2}+\mathrm{v}_\alpha^{n-1/2}}{2}\times\mathrm{B}^n(\mathrm{x}_\alpha^n,t)\right)$$

$$\frac{\mathrm{x}_\alpha^{n+1}-\mathrm{x}_\alpha^n}{dt}=\mathrm{v}_\alpha^{n+1/2} \qquad (1)$$

are integrated with the Boris method.

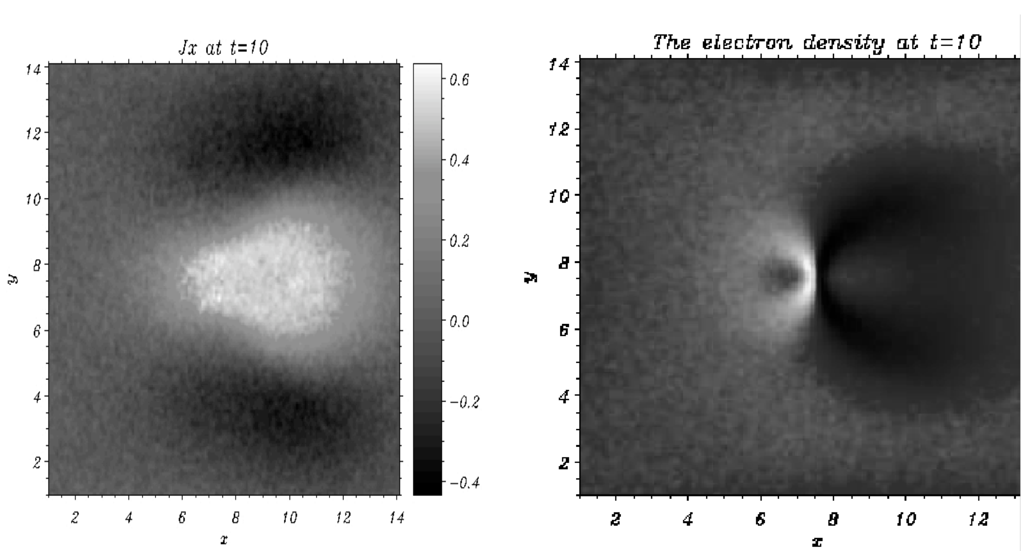

FIGURE 1. Sample of current density and charge density for 2D PIC modeling for the non inflated bubble.

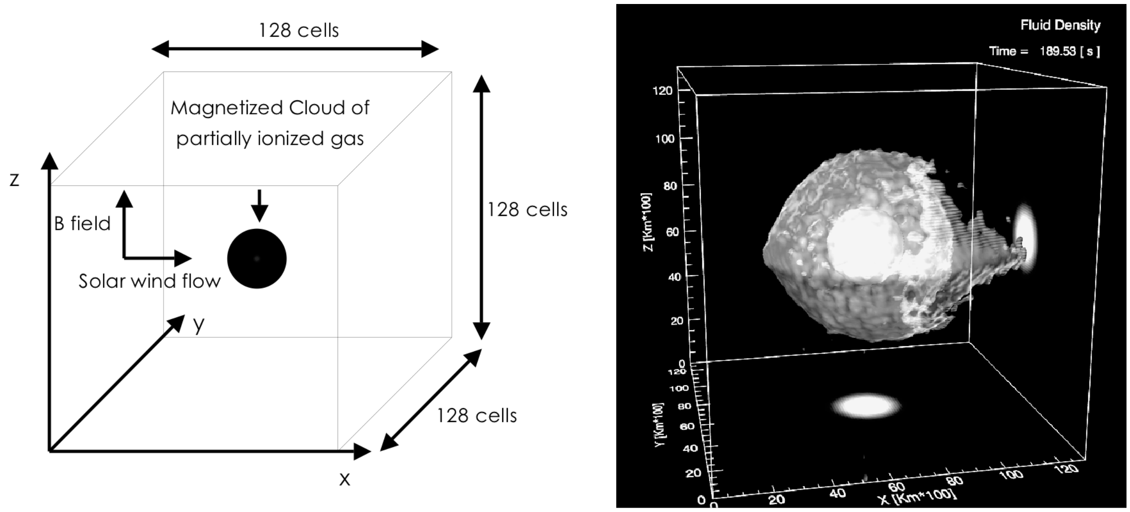

FIGURE 2. Computational domain and sample of results of 3D PIC simulation of the inflated plasma bubble

In Fig.2 an example of 3D hybrid simulation of the inflated bubble [3] is shown . The hybrid simulation used in this study is based on the description of the electron component as a fluid, while ions are treated by the PIC approach.

The interest of the more challenging inflated bubble configuration lies not only in the unprecedented large scale plasma physics (turbulence, instability, wave/plasma) made accessible, but also in the possibility of experimenting the concept of plasma bubble based sailing to produce thrust on a payload from solar radiation [5].

The two bubble concepts ask for very different external environment: a strongly elliptic *GTO (Geostationary Transfer Orbit)* solution (fig.3) fits the different ambient plasma requirements with a single payload.

A detached daughter satellite separated by a few hundred meters carries additional diagnostic systems.

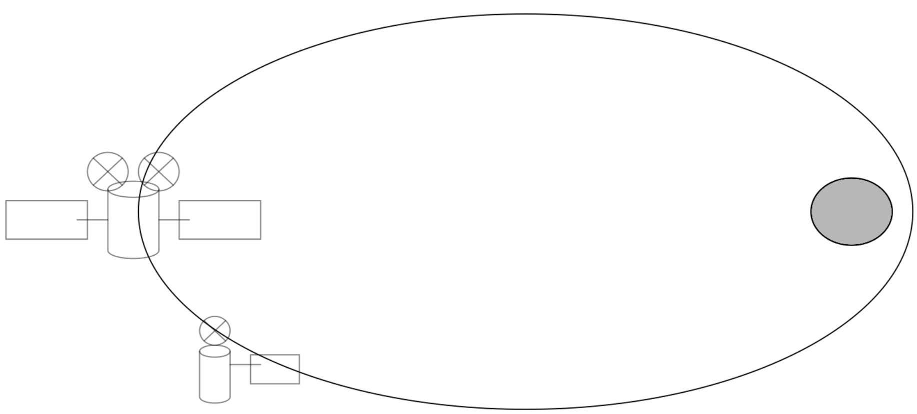

FIGURE 3. GTO orbit, main payload and detached diagnostic sub-satellite (not in scale)

LDF (LARGE DISCHARGE FACILITY)

The experiment is devoted to the production and study of large scale (10-100 m) discharge plasmas in open space, including hydrodynamics and atomic physics issues. The peculiarity of these experiments towards already performed active plasma experiments is the role played by ionization processes and the stress on cold plasma physics, where the collisions of charged species with neutrals are most relevant. Because of this last circumstance, atomic physics and hydrodynamics strongly affect the system, while the variety of collective plasma phenomena is drastically reduced. Basic physics: large volume associated to low gas density.

Typical laboratory low T plasmas are characterized by p = 10-100 mTorr, T = 300 K, L (discharge gap) = a few cm, n ~ 10^{15} cm^{-3} , low ionization degree about $\alpha \sim 10^{-7}$.

The analogous space plasma is set up based on a choice of scaling: for example one can keep approximately the same Knudsen number and α. As a results one gets the following specifics L = 100 m, n = 10^{11}-10^{13} cm^{-3}, matter quantity ~ a few moles. The expansion timescale: ~ 0.1 s for He at 100 K. Mass requirement are evaluated elementarily based on the scaling of sound speed and n, and at fixed n ~ $M^{1/2}$ (M = molar mass).

Skin depths issues are the essential factor to account for antenna heating, this can be studied by a simple radial model assuming collisional plasma heating, He as a neutral component, and free expansion of neutral particles:

$$dP/dr = -\frac{1}{2}\alpha n_g \frac{e^2}{m_e \nu}\frac{1}{1+(\omega/\nu)^2}\left(\frac{3}{4\pi\varepsilon_0 c}P\right)$$
$$\nu = n_g(r)\sigma_{e-He,el}(v_{th,e})v_{th,e} \qquad (2)$$
$$v_{th} = \sqrt{8kT/\pi m} \qquad n_g = \frac{m.f.r./m_{He}}{4\pi r^2 \cdot v_{th,He}}$$
$$m.f.r. = 1\,g/s \quad T_e = 1\,eV \quad T_{gas} = 100\,K \quad \omega = 10^4\,s^{-1}$$

where P is the angle-averaged dipole antenna e.m. power, α is the ionization degree, *m.f.r.* is the mass flow rate. The radius r is cut off at the lower value of 1m to account for deviations from free expansion of the gas and the dipole field for the antenna. As a result (fig.4) most heating occur in the plasma centre, better results for low ionization degree (like 1e-8).

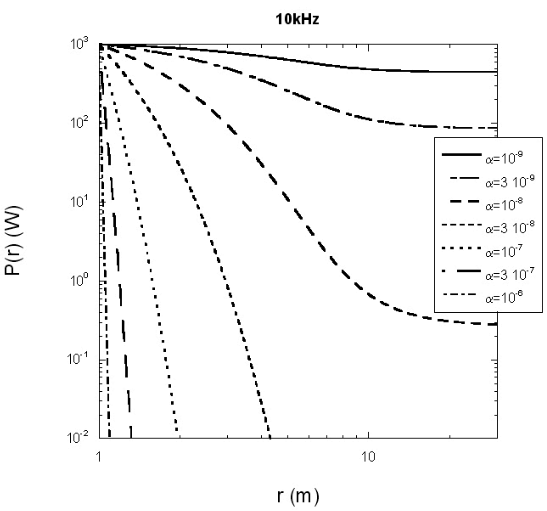

FIGURE 4. Results from the simple absorption model (eq.2)

The necessity of a low ionization degree increases the sensitivity of LDF to ionospheric plasmas, and a result the experiment cannot be performed in LEO, but it can be run on most of the GTO orbit (fig.1).

A comparison can be attempted between the proposed experiments and recent plasma space experiments, in particular CRRES and AMPTE [5]. Both are, like the one proposed, composite experiments involving collisional and transport features in a weakly ionized medium, of a kind we could define as "plasma chemical physics in space", e.g. a special attention to impurity transport in a weakly ionized media.

The difference between this new experiment and its precursors is rooted in a different philosophy behind: the present experiment focus on the properties of artificial plasmas as well as magnetic perturbation of the ambient plasma, and it is not limited to atom transport in the ambient plasma. In fact, impurity transport here is not a central issue, while we are considering the global aspects of the cloud, including rarefied hydrodynamics, which were neglected in previous studies.

The focus here is discharge physics on unprecedented scale and not simply impurity transport, with a view of future space technology where large scale plasmas could play a role in open space, ‘solar winds’, and other ambitious plasma treatments. So the releases of previous experiments evolves in ambient plasma, while here we consider additional ionization and large discharge features.

In the former experiments the impurity traced were mostly low IE (ionization energy) metal atoms like barium and lithium, while here considerations based on hydrodynamic losses as well as plasma chemical and molecular physics interest of the produced data suggest the dispersion of rare gases, hydrogen, methane, CO: the special attention posed here on the problem of collisional produced non-equilibrium ion and electron distribution and neutral species spectroscopy is expected to improve our knowledge of weakly ionized plasmas artificially produced in open space.

In terms of application, the LDF experiment can in particular help to understand the kinetics of extraterrestrial ionospheres and is a first step towards future large scale discharge-based applications in open space large scale surface processing connected to thermal protection, radiation protection. Furthermore, negative ion production in open space makes the way for energetic atom beam and their application to neutral particle/sail propulsion.

TETHERED EXPERIMENTS (ARTIFICIAL AURORA)

An electrically floating tether comes out biased highly negative over most of its length. Ambient ions impacting it with KeV energies liberate secondary electrons, which are locally accelerated by the tether voltage-bias, race down magnetic lines, and result in peak auroral emissions at about 120-160 km altitude.

Since no current flows at either tether end, a bare-tether e-beam is fully free of spacecraft charging problems. Also, the beam is free of plasma interaction effects: its very large cross section (about twice electron gyroradius times tether length) results in energy flux over 1000 times weaker than in standard beam sources. In addition, emission of such a weak flux has no significant effect on the local plasma, and takes place far from any instrument.

Beyond auroral effects proper, a floating bare-tether could provide values of neutral density along its E-layer footprint track, of interest in full numerical simulations of the atmosphere lying below, and in orbit decay and re-entry predictions [6].

FUTURE CHALLENGES FOR PLASMA MODELLING POSED BY THE PRESENT STUDY

The study focused on plasma regimes and scales that cannot be realized in earth-bound laboratories. As such, it requires the use of advanced modelling techniques and sets the arena for future studies and development.

In particular the following issues are raised: improvement of the quantitative understanding of instabilities and turbulences in the bubble dynamics, use of PIC models with fully realistic electron/ion mass ratio, inclusion of MC collisions, study of the limits of MHD approach for different orbit conditions, identification and numerical simulation of the main nonlinear plasma phenomena that occur in the wake of a magnetized plasma bubble streaming through an ambient plasma, modelling of the electron heating in the LDF, kinetic modelling of the flow of the neutral components.

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