FINAL PUBLISHABLE SUMMARY

The main goal of the NEPTUNE project ("**Ne**w generation of ion sources: from dee**p** space missions **t**o **u**pstream **n**ano-t**e**chnologies") was to enhance the understanding of the physics and exploit the benefits of bipolar charged particle extraction from low temperature plasma. The project was focused on coincident extraction and acceleration of ions and electrons from a low temperature plasma using an inverted RF self-bias effect. The flows are accelerated to high and low energy for the purpose of: i) space propulsion applications, ii) deep reactive ion etching (DRIE) for the microelectronics and semiconductor industry; iii) surface treatments of different materials including polymers.

Two scenarios of broad bipolar beam generation have been considered: i) The NEPTUNE concept where simultaneous extraction and acceleration of positive ions and electrons from a plasma using a so-called self-bias effect formed in a gridded RF-biased extraction system; ii) the PEGASES concept where alternate acceleration of positive and negative ions from an electronegative plasma using a gridded extraction system biased with bipolar square voltage waveforms. During the project full proof-of-concept for both ion-electron and ion-ion acceleration was achieved.

A patent for the NEPTUNE concept applied in space propulsion was filed in April 2014. For the first time, a broad coincident ion-electron beam was generated using a multi-grid extraction systems. The experiments on simultaneous ion-electron extraction showed that the ion-electron extraction from the plasma provides stabile generation of an ion-electron flow with controlled energy and flux. In addition, it was found that both ion and electron fluxes at the source exit are directed along the system axis, thus the NEPTUNE source can be considered as a new source of flowing plasma or plasma accelerator. This has many interesting properties for fundamental plasma research and applications. For example, the TRL of a NEPTUNE thruster prototype can now rapidly increase due to the strong technology heritage from classical gridded thrusters.

In the PEGASES thruster development, the bipolar extraction of the positive and negative ions from the ion-ion plasma was thoroughly investigated, showing that alternating beam packets accelerated from plasma can be self-compensated (by space charge) at frequencies of the extraction voltage above few hundreds of kilohertz. In addition, these investigations showed that pure electron-less broad negative ion beam could be formed if the ratio between the negative ion and electron densities in the plasma (the plasma electronegativity) exceeds a few thousands.

The challenging goals of this project required also to develop new beam and plasma diagnostic tools and methods, such as Magnetically Filtered Retarding Field Energy Analyzer (MRFEA), Dipole Impedance Matched (DIM) probe, multi-channel induced charge probe, various RF-compensated analyzers and other electrostatic and RF diagnostics. These diagnostic methods are new powerful instruments useful for specific bipolar extraction characterization and for general plasma and ion beam researches.

Complete characterization of both the ion-ion and the ion-electron bipolar extraction scenarios allowed us to map the operating parameters space and to mark out the most preferable applications for both beam extraction schemes. The ion-ion extraction process at low energies is found to be attractive for deep reactive ion etching for microelectronics and semiconductor industry and surface treatments in particular for porous sulfur deposition for LiS battery electrodes. For high-energy acceleration this concept is well adapted for space debris removal systems using a ion beam shepherd system, this led us to be a partner in a larger FP7 cooperation project called LEOWSEEP. The most attractive and promising application of the NEPTUNE concept, using coincident ion-electron extraction and acceleration from plasma, is in the space propulsion domain, where this new concept of particles acceleration can be implemented within very short term due to a strong technology heritage with existing ion thruster, providing significant increase in the propulsion system efficiency, mass/volume cost and allowing new possibilities of the plume control.

The scientific results obtained within the project have been described in 9 papers published in peer-reviewed journals and 11 contributions to international scientific conferences (including 5 invited talk). In order to protect intellectual property one patent application has been filed and one is in preparation.

We participated in communication actions for the general public in order to disseminate information about Marie Curie fellowships under FP7 and Horizon 2020 programs. These actions are: “Journée de l’Espace 2013/2014 à l'X” and “La Nuit des chercheurs » in 2013 and 2014” organized at the Ecole Polytechnique and at the University of Pierre and Marie Currie in Paris. An international seminar was given at V.N. Karazin Kharkiv National University (Ukraine), where the fellow presented the main objectives of the NEPTUNE project and key advantages for non-EU scientists from participating in the various EU Framework programs, particularly in the Marie Curie actions under Horizon 2020 program. A film crew from “Canal-U” made an educative film about our activities and the fellow, the scientist in charge and two other members of the research group were interviewed. The film will be broadcasted in May – June 2015, and will be firstly published on the web site of laboratory (www.LPP.fr) and later hosted on YouTube. The Scientist in charge was also interview by a large French newspaper L’OBS where the article can be read here (http://tempsreel.nouvelobs.com/sciences/20141103.OBS3947/les-debris-de-l-espace-menacent-la-terre-la-chasse-est-ouverte.html)

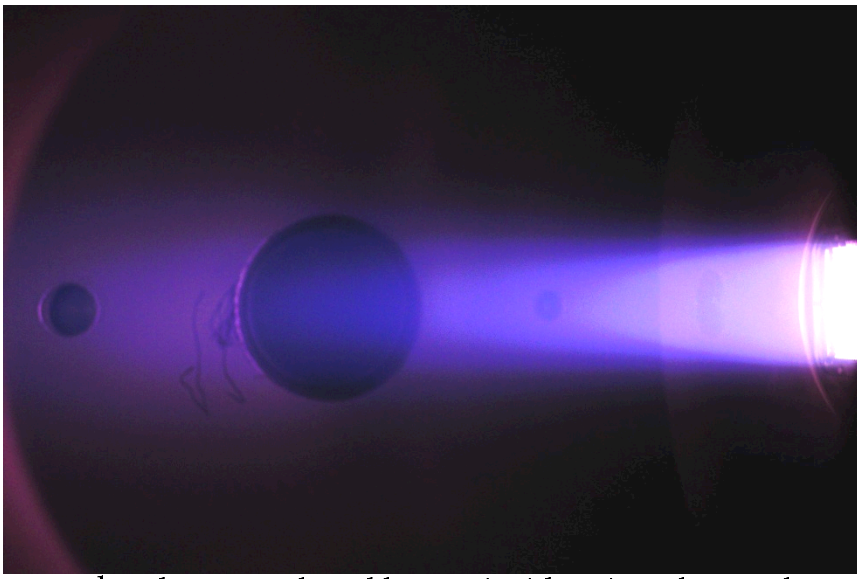

Figure 1. View on the plume produced by a coincident ion-electron beam accelerated from a NEPTUNE prototype.

NEPTUNE