Kinetic modelling of the jet extraction mechanism in spherical IEC devices

Type of activity: Standard study

1 Background & Study Motivation

1.1 Introduction

Inertial Electrostatic Confinement (IEC) devices were originally developed and used for fusion research purposes [1]. The simplest IEC type of set-up contains a spherical cathode grid, which is co-centrically placed within in a spherical anode (represented as the vacuum chamber in see Fig. 1.)

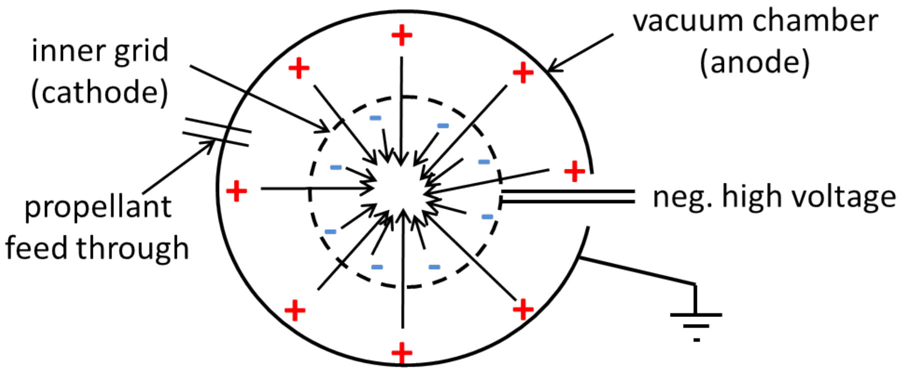

Figure 1: Scheme of a so-called Farnsworth – Hirsch Fusion Reactor.

The cathode, made of stainless steel wires, is negatively charged (typically several kV) while the anode is grounded. The vacuum chamber contains a highly rarefied neutral gas with a pressure matched to the electrode distance in order to provide a glow discharge. The produced ions are accelerated by radial electric fields towards the centre of the sphere where they collide with other ions building a positively charged ion cloud. This ion cloud itself accelerates electrons towards the centre of the sphere, which can lead to the creation of a virtual cathode. Due to an effect called micro-channelling the ions are pushed away from the grid wires such that the effective grid transparency can exceed 95% [2]. An in-depth description of the working principle and the physics of the IEC confinement can be found in [1-3] and references therein.
It has been shown recently (see e.g. [4, 5]) that it is possible to extract a plasma jet from the confinement. Figure 2 shows exemplarily such a plasma jet extraction. The jet was obtained by creating in both grids an opening in the confinement, i.e. the grid openings were locally enlarged in order to provide a lower potential barrier for the confined charges to escape. The extraction has been experimentally observed though its properties, working mechanism, key parameters are still not well understood. A schematic of the grid openings is depicted in Fig. 3.
Depending on the literature, the creation of a quasi-neutral beam is described as a consequence of initially escaping electrons from the confinement. Those electrons induce strong electric fields, thereby attracting and accelerating confined ions such that both species form a particle jet. In order to keep the operation steady neutrals

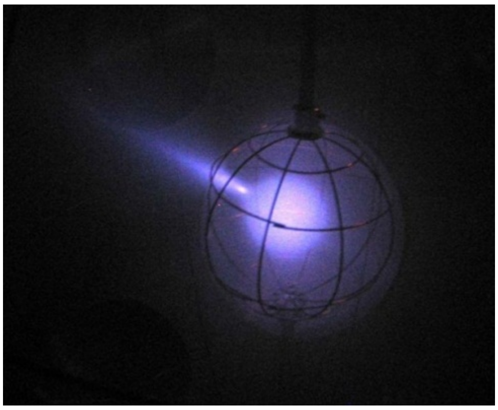

Figure 2: IEC in so-called jet mode [5].

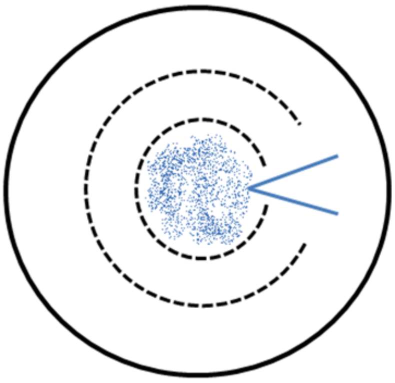

Figure 3: Scheme of grid openings for jet extraction. Outer grid is now the anode, both embedded in vacuum chamber. Blue: plasma within the IEC cathode.

are added according to the extracted plasma mass flow (see Fig. 1). IEC reactors in jet mode would thus be, in principle, usable for propulsion purposes. In fact, specific impulses of up to 4000s were estimated in [6]. While such devices have been proposed as space thrusters, arguing that

- the life time is increased due to a larger grid transparency,
- the set-up is simple and of low weight,
- it scales well with power,
- exhaust plasma modifications are possible to provide fast manoeuvrability, and that
- efficiency and thrust are good,

the mechanisms are still poorly understood as a comprehensive theoretical model of the underlying jet extraction physics is still lacking. This study therefore focuses on better understanding these mechanisms, in order to optimise them in a second step.

2 Study Objective

Given that IEC reactors with a steady jet extraction have been experimentally demonstrated, but their parameters have been set without an understanding of the underlying principles, it is very likely that the used configurations are far from optimal. Especially the mechanisms of the jet extraction are not understood. A parametric model is therefore needed, starting with the existing and well described experimental setup and then applying it to different IEC configurations. The understanding of the physical processes of the jet extraction process is crucial to this step. Representative mathematical/physical/numerical modelling needs to be done in order to identify the driving processes on a fundamental level. The main study objective is therefore the modelling and kinetic simulation of this extraction mechanisms and especially the jet particle interactions.

3 Proposed Methodology

IEC related publications superficially describe the IEC jet generation process in a 2-grid IEC set-up to be based on electrons overcoming the locally decreased potential barrier, which then leads to an acceleration of ions out of the plasma core. In trying to assess the relevant microscopic processes at the jet origin it is instructive to perform

kinetic particle simulations as it has been done e.g. in [5, 7, 8]. However, care has to be taken with respect to the modelling depth as model assumptions affect the outcome and, correspondingly, the interpretation of the simulation results. Exemplarily, the grid openings typically do not obey a symmetric structure, i.e. a rotational-symmetric 2D Particle-In-Cell code does not reproduce the correct electrostatic field distribution. Also, Particle-In-Cell codes are non-collisional, i.e. direct Coulomb collisions are ignored. Those interactions between the charged particles occur on scales smaller than the local Debye length and might become essential for understanding of the jet extraction, especially since space charging effects influence the Debye length as a measure of spatial resolution and, therefore, affect the general validity of the governing equations of the Particle-In-Cell codes. These examples illustrate the importance of kinetic modelling depth as it affects observable physics.
At this level of research engineering problems like e.g. grid erosion are considered of secondary priority only, since not adding to the understanding the underlying physics of jet extraction.
We propose to follow the outlined research path but highly welcome argued alternative approaches in proposals:

1. Identify an IEC set-up, its geometry in the jet extraction region, and its operating conditions, which will be the reference for the kinetic simulations. The IEC set-up described in [5] is proposed to be used as baseline since well described and with experimental data published. Universities are free to propose a different baseline if considered with relevant arguments as being more appropriate.

2. Define the simulation domain and the necessary physics. The implemented physics of the code should obey at least the following features:
    a. Particle-In-Cell code (i.e. Vlasov equation including Maxwell equations)
    b. 3D (not necessarily time accurate)
    c. Consideration of Coulomb collisions
    d. Consideration of neutral background

   Where appropriate, symmetry effects should be used in order to reduce computational load.

3. Visualise the results in a way that jet extraction is pinpointed on a molecular level.

4. Develop a model validated by reproducing the experimental parameters as observed in [5].

5. Tune the parameters of the model to derive how to increase propulsion related key characteristics of such a device.

4 ACT Contributions

The project will be conducted in close cooperation with ACT researchers that will be cooperating closely with the university's research group in the achievement of the respective milestones. The ACT will

- contribute to mathematical/physical/numerical modelling and
- contribute to the interpretation of the simulation results.

Also, the ACT will contribute in the definition if novel parameter settings for additional kinetic simulations in which thermalisation processes of high-energy ions can be studied in detail.

Bibliography

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