Child-Langmuir-limited current in the negative ion source NIO1

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Abstract. Negative ion sources are the first stage of several types of accelerators, ranging from medical applications to materials testing and to heating systems for nuclear fusion devices. One of the most important aspects of these sources is the amount of extracted ion current, which depends on the extraction voltage and on the availability of ions inside the source plasma; this situation is usually described by the Child-Langmuir law, which can be extended to include an initial ion velocity. In the case of negative ions, plasma electrons also play a role in the definition of the maximum extractable ion current, which can be significantly decreased for the possibly combined effects of large electron current and magnetic field configuration; double species might also be included in an extended Child-Langmuir law. The present contribution describes the main issues of a theory of the electrostatic extraction of particles from the meniscus, the plasma boundary which forms at the apertures of a negative ion source in the aforementioned conditions. A normalised treatment might be adopted, which is suitable for application to different types of plasmas. Data from the flexible multi-aperture RF-based caesium-free negative ion source NIO1 are studied, which exhibit saturation in the extracted negative oxygen current depending on the plasma parameters.

INTRODUCTION

In the framework of the research on Neutral Beam Injectors (NBIs) for fusion reactors, the NIO1 (Negative Ion Optimization 1) negative ion source is operated by Consorzio RFX and INFN-LNL [1]. This experiment aims at optimising the production and acceleration of negative ions in the NBIs in view of future fusion reactors. NIO1 consists of an inductively coupled (2MHz) plasma ion source, cylindrically shaped (10 cm diameter × 21 cm length); the available RF power is up to 2.5 kW, irradiated by a solenoid. The negative ions produced in the plasma are extracted and accelerated by a set of grids: Plasma Grid (PG, facing the source; aperture radius 3.8mm), Extraction Grid (EG, aperture radius 3.2mm) 5mm after PG; Post Acceleration Grid (PA, at ground voltage, aperture radius 3.2mm) 24mm after EG; Repeller (aperture radius 4.4mm) 4mm after PA. The grids feature a square (14mm spacing) lattice of 3x3 apertures, through which as many beamlets are accelerated. With the future evaporation of caesium inside the source to enhance surface production of negative ions, NIO1 is expected to produce a maximum beam current of 130mA, composed by H^- ions accelerated at maximum 60keV, in continuous (>1000s) operation. The present paper describes the results of an experimental campaign aimed at measuring the beam current as a function of the extraction grid voltage; the operation gas was oxygen.

CHILD-LANGMUIR LAW

The Child-Langmuir (C-L) law that describes the thermionic emission phenomenon can be generalised in order to account for the initial kinetic energy particles of particles [2]. A model of the NIO1 ion source requires allowing also for the simultaneous presence of more than one species of electrically charged particles, as in [3], since in the first operations the amount of co-extracted electrons can be even larger than the negative ions [4].

In detail, the beam extracted in NIO1 faces two stages of acceleration:

- the former starts at the meniscus where negative particles are extracted from the plasma chamber thanks to the electric field imposed between EG and PG. A strong transverse magnetic field (peak value 110mT) bends the electron trajectories towards the EG in order to separate them from the main beam

- the latter takes places between EG and PA; this is a region where the initial kinetic energy of the incoming ions is further increased at the expense of the imposed electric field.

It is only remembered here that the two-species model with non-zero initial energy allows to address these experimental conditions [5]. A C-L model is found to agree with the experimental data only for moderate extraction voltages, so that a further modification to the Child-Langmuir law is given in the following, aimed at reproducing the experimental data by including the effect of limited source production capability, analogous to hot cathode emission [5].

ANALYSIS OF EXPERIMENTAL DATA

Several characteristic curves of the measured beam current as a function of the extraction voltage (V_{EG}) have been collected in different experimental conditions. In Figure 1, data for different RF powers, at constant acceleration voltage and pressure, are displayed. It can be easily recognised that the data exhibit a common trend for low extraction voltages, whereas they follow different characteristic curves at high voltages; this result has already been found experimentally [6]. It was verified that data lying on the black curve can be described by a C-L-law like function; as the extraction voltage increases, the dearth of charged particles makes the hypothesis on which the former law is based no longer valid, thus causing the trend change.

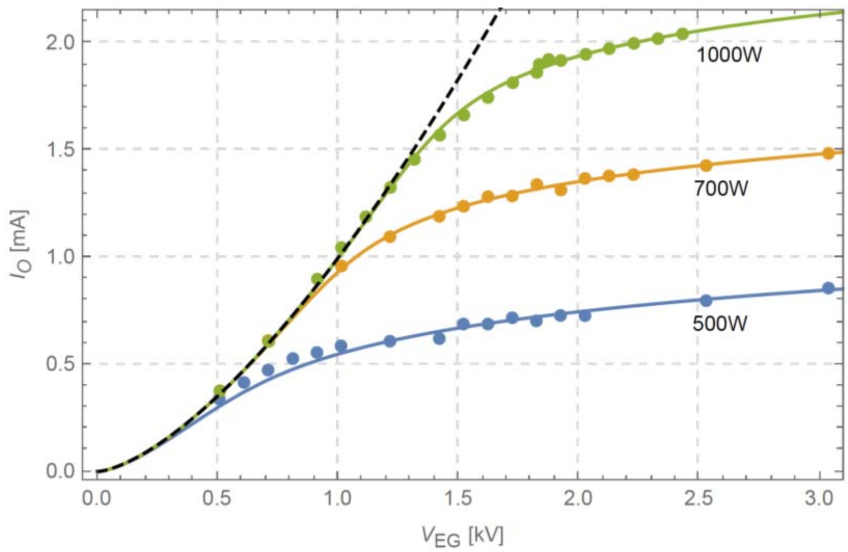

FIGURE 1. Negative oxygen current as a function of extraction voltage with different RF powers; source pressure 0.35Pa; V_{acc}=15kV. The black dashed line correspond to the usual Child-Langmuir law; the fitting lines are .

As in thermionics the smallest between C-L and Richardson laws determine the current limit, in NIO1 and many other ion sources the V-I characteristic shows saturation at sufficiently high extraction voltages. This phenomenon was studied at different RF power, P_{RF}, leading to the definition of the perveance factor as a function of P_{RF}.

A non-linear model was empirically found to fit the data by introducing two parameters:

- I_{sat} linked to the value of the extracted current at which the Child-Langmuir law predicts saturation

- k_i the coefficient that influences the steepness of the saturation phenomenon.
The final formula reads as follows:

$$V_{EG} = I\left(1 + \exp\left(\left(I - I_{sat}\right)/k_i\right)\right)^{2/3}$$

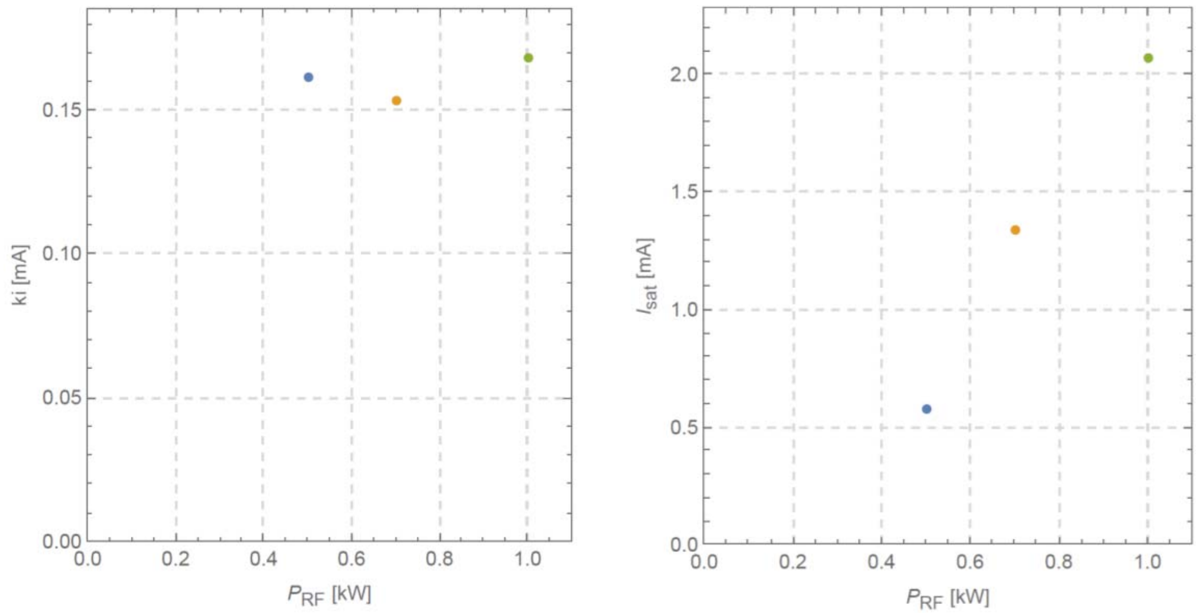

FIGURE 2. Parameters of the fitting curve as functions of the RF power.

In fig. 2 the fit parameters are shown as functions of the RF power: it can be noticed that I_{sat} grows as P_{RF} increases corresponding to the increased negative ion production; k_i depends weakly on P_{RF}; it might be influenced by the beam optics.

CONCLUSIONS

The present paper presents a phenomenological interpretative model for the current extracted and accelerated from an ion source; the model reduces to the usual Child-Langmuir law at low voltages, whereas at high voltage it reproduces the saturation observed in experiments. The saturation seems to depend on the source parameters and can be interpreted as the limited amount of particles, inside the source, available for extraction.

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