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An optimized plasma ion source for difficult ISOL beams

Maher Cheikh Mhamed*, Ailin Zhang

Institut de Physique Nucléaire d'Orsay, CNRS-IN2P3, Université Paris-Sud – Université Paris-Saclay, F-91406 Orsay Cedex, France

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ABSTRACT

The Ionization by Radial Electron Neat Adaptation (IRENA) ion source has been designed to operate under extreme radiation conditions. Based on the electron beam generated plasma concept, the ion source is specifically adapted for thick target exploitation under intense irradiation. A validation prototype has been already designed and tested offline. The design of a new optimized prototype for online difficult beams production with ISOL facilities will be presented and discussed. In particular, simulation activities for thermionic emission, ions confinement and extraction will be presented and results discussed.

1. Introduction

FEBIAD (Forced Electron Beam-Induced Arc Discharge) [1] type ion sources are among the most important ion sources for the production of radioactive ion beams. A new FEBIAD type ion source, named IRENA (Ionization by Radial Neat Adaptation) has been developed at IPN Orsay to operate efficiently and steadily under strong radiation conditions [2]. It has been designed with a radial configuration of the anode–cathode set to allow both efficient ionization and the confinement of the positive ions for efficient extraction. Operation without magnet is an important advantage since this particularly ensures the reliability and reduces substantially the ion source part of the radioactive waste. Furthermore using a radial cathode should enhance the lifetime of the ion source by preventing local wear as observed by post-irradiation analyses on planar cathodes [3,4]. To optimize the anode–cathode set and to improve the mechanical and electrical reliability, the second prototype was completely modeled with 3D-Lorentz simulation code [5]. To get a more flexible and efficient IRENA type ion source, a new prototype IRENA3 was designed at IPN Orsay.

We will present simulation works for the new prototype of IRENA3 ion source. The simulation work contains two parts. First part is dedicated for the optimization of the most important parameters for the ionization process. The second part is dedicated for the optimization for the geometrical parameters of the extraction system.

2. Simulation constructions and optimizations

The simulation work are done by *Lorentz-3E* [6] which is a suite of CAE programs providing sophisticated simulation and design tools customized for charged particle trajectory analysis in 2D and 3D. The simulation works are concentrated on the geometrical optimization for both ionization and extraction.

There are several ideal conditions assumption to make simulation successful: (1) all the boundaries in the IRENA ion source simulation are ideal, infinitely smooth. (2) The thermionic emission is independent of pressure but strongly depends on the temperature of the metal emitter. It can be obtained using the Richardson-Dushman equation [7]. (3) After traversing the anode grid, the electron motion is space charge-limited [8]. (4) Electron impacts and ionization are calculated by a simple cross section model [9]. (5) No magnet effect (only electric field) is involved in the simulation process.

The ionization process for this ion source depends strongly on the electron emission density from the cathode, anode grid structure and the space charge effect induced by electron negative charges. Indeed, the strong defocusing effect on the electron trajectories is the result of: the presence of the tangential component in the electron velocity at the emission point at the cathode surface, the defocusing effect the voltage distribution near the anode grid and the space charge effect induced by the presence of electron charges inside the ionization volume [8,10]. All these effects prevent electrons to reach the ion source axis and repel electrons towards the anode grid and cathode surface and thus electrons will be trapped in a space charge well. Due to the formation of first ions the electron space charge become less and less negative and thus makes electrons penetrating further towards the ion source axis and this increases the compensation the electron space charge and increases the ion yields [8].

* Corresponding author.

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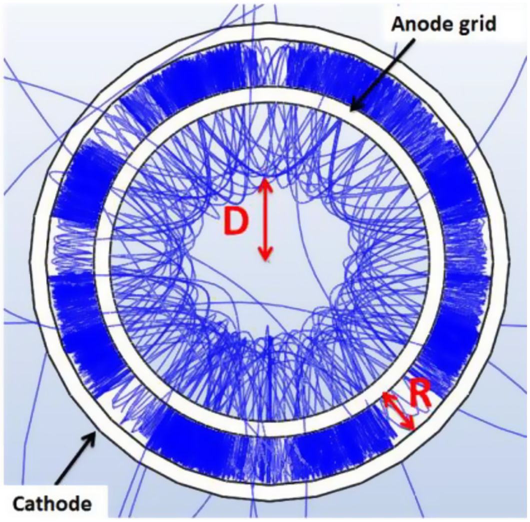

Fig. 1. A 3D electron trajectories simulation for IRENA3. (Right view according to Fig. 5 position, applied cathode voltage = 0 V, applied anode voltage = 50 V, R = 2 mm).

The aim of this simulation work is an attempt to find out the best geometrical configuration for the anode grid structure, the cathode-anode grid spacing and ion extraction geometry. The electron lifetime is also very important parameter for the ionization process. Longer lifetime for electron means more probability of electron-neutral atom interaction and thus a higher ionization probability. In order to simulate the space charge effect and the electron lifetime we have considered 7 steps for the life cycle of an electron from the emission point until the extinction point [7]. The 7 steps are:

(1) Electron production: electrons are produced by thermionic emission on cathode surface.
(2) Electron acceleration: electrons are accelerated by an applied voltage between cathode and anode.
(3) Reflector and secondary emitter: The cathode and anode are made of tantalum and this will provide a higher secondary electron emission coefficient [11].
(4) Electron decelerated by space charge. No magnet for electron confinement, space charge effect is extremely important for repelling electrons.
(5) Space charge and space charge compensation.
(6) Reflector and secondary emitter.
(7) Electron extinction.

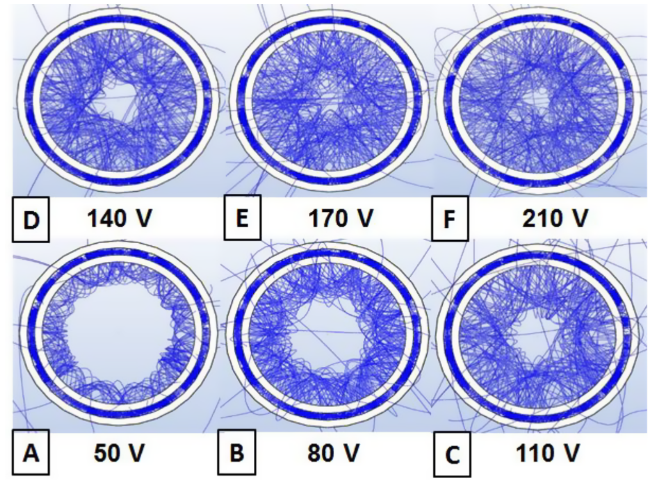

Fig. 3. Electron trajectories simulation results for different cases of anode voltage: case A (50 V), case B (80 V), case C (110 V), case D (140 V), case E (170 V), case F (210 V) (right view according to Fig. 5). R value was fixed at 1 mm.

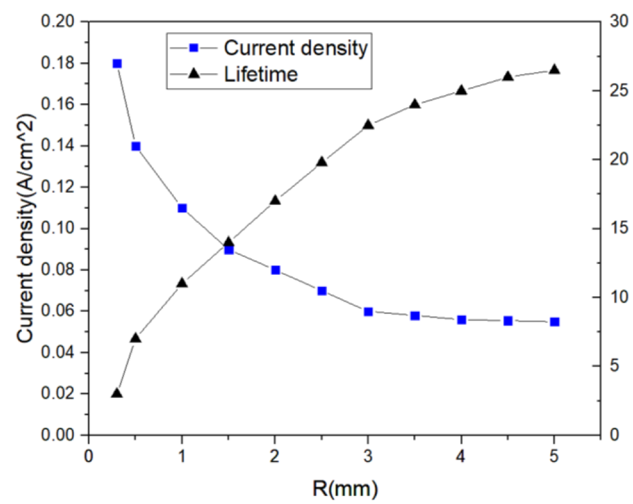

Fig. 4. Electron mean lifetime and current density of electrons according to R.

The IRENA3 design structure is presented in Fig. 5. All ionization chamber elements are made of tantalum. The 3D simulations of electron trajectories used to estimate the mean lifetime value is presented in Fig. 1.

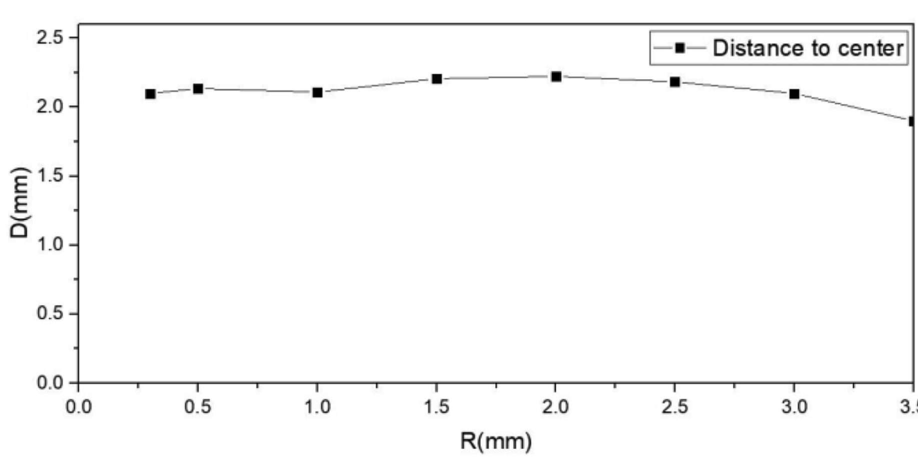

Fig. 2. Simulation results of D parameter according to R parameter.

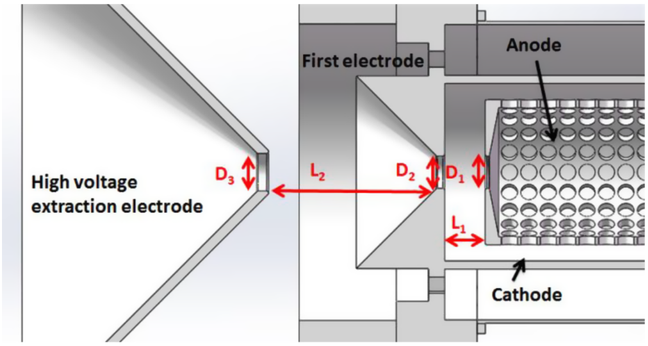

Fig. 5. Design structure of IRENA3 and Optimized extraction parameters. D1: diameter of extraction hole on the anode, D2: diameter of extraction hole of the first electrode, D3: diameter of extraction hole of high voltage electrode, L1: distance between anode and first electrode and L2 is the distance between first electrode and high voltage electrode.

To get enough space charge effect and to maximize the mean lifetime for electrons, simulation efforts have to be focused on the optimization of the geometrical parameters. However, due to mechanical constraints, the geometrical anode grid transparency was fixed at ~77% and the inner anode radius was fixed at 4 mm. Only the distance between anode and cathode can be optimized. Moreover, the applied voltage on anode and cathode can be studied and optimized.

As it is shown in Fig. 1, the R means the distance between anode and cathode, the D means the distance from the anode axis at which the electron are repelled towards the anode grid and the cathode. The D parameter distance defines the location of the virtual cathode [8] and represents the strength of the space charge effect. According to the simulation results presented in Fig. 2, it's clear that the R values have a very little influence on the D parameter. For a fixed value of R = 1 mm and with the variation of the applied anode cathode voltage, we can deduce from Fig. 3 that the optimal voltage range extends from 110 V to 170 V.

The main ionization process for IRENA ion source is the ionization by electron impact. Indeed, the low energy "plasma electrons" created during the ionization process will leave the plasma volume very quickly and will be stopped on the anode body [8]. In addition, the large ratio of primary to "plasma" electrons is typically greater than 10^6 [8] and this makes plasma electrons contribution negligible in the global ionization process. The electron current density was calculated according to a reference surface of ~360 mm^2. We note that the typical electron current density of IRENA ion source (~10^3 A/m^2) is very close to the mentioned value on reference 9 (~4×10^3 A/m^2) [8]. The electron lifetime and electron current density are two effective parameters in the ionization process. In order to increase the ionization probability and to achieve the best ionization efficiency, we should find out a compromise proposal for these two parameters. The corresponding R value at the cross point between the two curves is the optimum value. We deduce that 1.5 mm is the best value of R (see Fig. 4).

3. Extraction simulations

Once we got the ions in the ionization chamber, the next step is to extract them. Special attention should be given to the electrode design in order to minimize the beam divergence angle, electric field on the electrode surface, beam emittance and the spark risks. The most important parameters in the extraction system design are the angle and the radius of the extraction apertures of the electrode system and the distance between the high voltage electrode and the first electrode (see Fig. 5). The simulations of ions extraction for IRENA3 are based on the discussed ion source design above.

Several designs of electrode system are simulated for IRENA3. From the simulation results, the proposed design in Fig. 5 is the best design giving the highest ion extracted current and the lowest beam emittance.

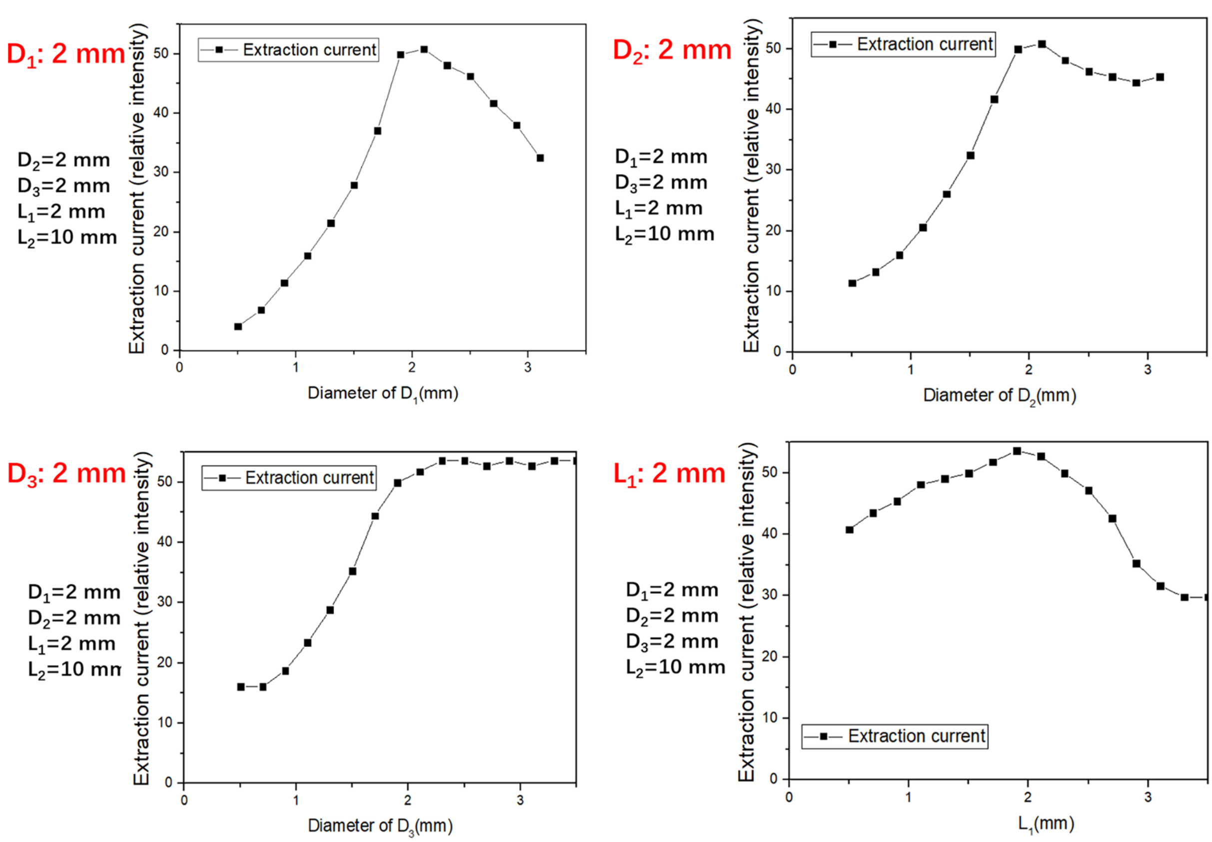

Fig. 6. Simulation results for the electrode geometrical parameters.

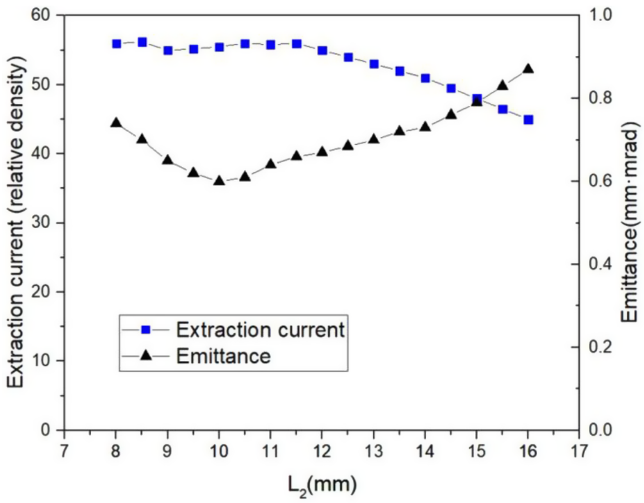

Fig. 7. Extraction current and emittance according to L_2. The emittances are RMS emittance and calculated by the simulation results.

There are five geometrical parameters which have to be optimized. Simulation results are shown in Fig. 6. L_1 is the distance between anode and cathode, L_2 is the distance between extraction hole and extraction electrode and D_1, D_2 and D_3 are the 3 extraction hole diameters.

Previous experimental tests [12] with the second prototype of IRENA (IRENA2) showed that when L_1 value exceeds 2 mm the extracted ion current drops drastically. On the other hand, due to mechanical reliability constraints we limit the minimum value of L_1 at 2 mm. D_1, D_2, D_3 values were set initially at 2 mm and we deduce from Fig. 6 that this value remains optimal except for D3 which is the minimum optimal accepted value. Also from Fig. 6, we confirm that 2 mm is an optimal value for L_1 gap of this new prototype.

The applied extraction potential is 30 kV. The extraction simulation results are shown in Fig. 7. The maximum extracted ion current and the lowest emittance were obtained for $L_2 \sim 10$ mm.

4. Conclusion and outlook

The main geometrical optimizations for IRENA3 ion source were achieved through this simulation work and space charge effect has been taken into account. The geometrical parameters of the ionization chamber were optimized according to the electron mean lifetime, electron current density in the ionization volume. These two parameters are effective in the ionization process. The best geometry parameters of the extraction system were calculated at 10 mm from the extraction hole.

Before the mechanical design of the IRENA3 prototype, thermal simulation work will be the next step. After that, first off-line tests will be carried out for IRENA3.

Declaration of Competing Interest

There is no conflict of interest for this paper.

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