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Numerical simulations of space charge effects and plasma dynamics for FEBIAD ion sources

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Abstract

The FEBIAD ("forced electron beam induced arc discharge") ion sources are used for the production of radioactive ion beams for a wide range of chemical elements. Their small volume and high operating temperature provide good confinement times and ionization efficiencies.

The extracted ion current from a FEBIAD ion source depends on the parameters of the plasma created inside (density, temperature, potential), parameters which are themselves dependent on the input gas pressure and composition.

Within the framework of the HIGHINT Marie Curie and the EURISOL DS programs, investigations are ongoing for high power direct targets, which can accommodate up to 100 kW incoming proton beam power. For such systems, the quantity of impurities entering the ion source will increase, thus leading to a change of the plasma characteristics. The gas flow coming from the target will exceed the buffer gas flow, and the ionization of the trace elements will be controlled by the gas composition released from the target.

An insight on the complex phenomena taking place in the ion source can be achieved using a Particle-In-Cell code (VORPAL, "versatile, object-oriented, relativistic, plasma analysis code with lasers"), which can simulate the dynamics of neutral and charged particles inside the plasma: ionization, recombination and charge exchange phenomena, secondary emissions and sputtering.

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1. Introduction

The FEBIAD [1,2] ion sources are used in ISOL for the 1+ ionization of the refractory elements, being able to produce ion beams of elements having an adsorption enthalpy on the materials of the target-ion source unit of up to 6 eV, regardless of their ionization potentials.

They are the result of the development of the arc discharge ion sources towards smaller volume (down to a few cm^3), lower operating pressures (10^{-4} to 10^{-5} mbar, compared to 10^{-3} mbar for Nielsen source [3]) and consequently, lower extracted currents (from 1 to 100 mA/cm^2 down to 0.1 mA/cm^2). This was needed in order to reduce the operating pressures and extracted currents to values closer to those given by the radioactive products, and thus eliminating the need of handling unnecessary high intensity stable beams.

The pressure inside the source is the result of the buffer gas load (injected through a calibrated leak), of the radioactive products released from the target and of the residual gas given by the target evaporation and impurities.

Presently at ISOLDE, the buffer gas load is on the order of 10^{13} atoms/s, higher than the radioactive load (for a 2.6 kW proton beam, of less than 10^{11} atoms/s). The increase of the beam power to 100 kW would increase the radioactive gas load up to 10^{14} atoms/s [4], which will require a comparable buffer gas load.

The typical target vapor pressure is on the order of 10^{-6} mbar (which for SiC corresponds to an operating temperature of 1650 °C). Considering the current ISOLDE ratio between the target and ion source volumes

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($62.8\ cm^3/2.6\ cm^3$) the resulting pressure in the ion source given by the target evaporation can reach 10^{-4} mbar. The increase of the target volume (for the 100 kW EURISOL SiC target, a factor up to 5 was estimated [4]) will lead to a higher pressure, of 10^{-3} mbar or even more (as a too efficient impurity pumping would also reduce the time that the atoms of interest will stay in the ionizing electron beam and therefore reducing the ionization rate).

In these conditions, maintaining the same ionization efficiencies, the extracted current will have to be of 1–10 mA/cm^2, outside the operating domain of the FEBIADs [1]. This is again the domain of the original Nielsen source, characterized by lower ionization efficiencies, bigger confinement times and instabilities over a pressure variation.

A solution to these issues can be searched by using a commercially available plasma simulation code (VORPAL, [5]), for analyzing the effect of geometry, potential distribution, gas pressure and composition and by optimizing the particle flows inside the source.

The FEBIAD source is chosen as a starting point, for its highest operation stability amongst the presently available arc discharge ion sources and for its rather constant ionization efficiency over the operating pressure domain (this should minimize the code instabilities).

This paper presents the most important physical phenomena inside the source, the way they have been implemented in the code and the code validation of this approach with the first results for plasma dynamics.

2. Physical phenomena in an arc discharge ion source

Neutral feed of the ion source: The measured variation of the radioactive ion-beam intensity as a function of time after the proton impact was fitted [6] using the empirical expression below:

$$R(t) = C \cdot (1 - \exp(t/\tau_r)) \cdot (\alpha \cdot \exp(-t/\tau_f) + (1-\alpha) \cdot \exp(-t/\tau_s)) \quad (1)$$

This release function is a result of all the physical processes involved in the transport of radioactive atoms from their production place inside the target to their detection on the tape station: diffusion from the target material, desorption from the material surface, effusion to the ion source, eventual chemical reactions all along the high temperature target-ion source unit, radioactive decay, ionization, extraction from the ion source and beam transport. Therefore, the constants C, α, τ_r, τ_f, τ_s are dependent on the analyzed element, the target, the ion source parameters and on the associated temperatures.

In our first approach, we consider that the effect of ionization and ion extraction from the ion source does not influence the shape of the release function and therefore we assume that the radioactive load in the ion source follows the relation (1).

The other two components of the ion source neutral load (presented in Table 1) are not time-dependent.

Table 1
Composition of the gas input of a ISOL FEBIAD

Gas input	Present day (ISOLDE)	Future (100 kW target)
Buffer gas	$\sim 10^{13}$ at/s	$>10^{14}$ at/s
Radioactive products	$<10^{11}$ at/s	$\sim 10^{14}$ at/s
Target evaporation; impurities	$\sim 10^{-4}$ mbar	$\sim 10^{-3}$ mbar

Electron emission: The characteristic construction element of the FEBIAD ion sources is the accelerating grid placed in front of the cathode, which eliminates the space-charge limitation of the cathode electronic emission. Therefore, the emitted electron current is not affected by the gas pressure or the ion production rate, and can be obtained using the Richardson–Dushman equation:

$$j_{cath} = A \cdot T^2 \cdot \exp(-W/kT)\ [\mathrm{mA/mm^2}] \quad (2)$$

where A is Dushman's constant ($\approx 120\ \mathrm{mA/mm^2\ K^2}$) and W [eV] is the work function of the cathode material.

On the contrary, because of the direct contact with the plasma, the electron emission from the anode walls is space-charge limited; therefore, it is estimated by the Child–Langmuir relation:

$$j_{th} = (4/9) \cdot \varepsilon_0 \cdot (2e/m) \cdot (1/2) \cdot (V^{3/2}/d^2)\ [\mathrm{mA/mm^2}] \quad (3)$$

where V is the potential difference between the plasma and the anode walls and d is the plasma sheath dimension (on the order of a few Debye lengths).

Electron impact ionization: The electron beam produced by the accelerating grid will oscillate inside the anode body, confined by the applied potentials and magnetic field. The impact ionization cross section is estimated by using the Lotz semi-empirical formula [7]:

$$\sigma_{q\to q+1} \approx 4.5 \times 10^{-14} \cdot \sum_{nl} [\ln(E_e/E_{q+1,nl})/(E_e \cdot E_{q+1,nl})](\mathrm{cm^2}) \quad (4)$$

where E_e [eV] is the electron energy, nl are the quantum numbers defining the electrons to be stripped and $E_{q+1,\ nl}$ [eV] is their binding energy.

The generated ion current density inside the ion source, n_{ioniz}, is then calculated by taking into account the accelerated electron flux and the gas parameters inside the ion source.

The ionization probability for the maximum beam ionization ("beam ionization" limit) is given by

$$p_e = 1 - \exp(-n_e \sigma_{q\to q+1} \tau_0) \quad (5)$$

where n_e is the electron beam density [el/cm^2 s] and τ_0 is the time that the neutral atom remains in the beam.

The *charge exchange* cross-section between different particle species is estimated by using the Muller and Salzborn formula [8]:

$$\sigma_{q\to q-1} = 1.43 \times 10^{-12} \cdot Z_q^{1.17}/E_i^{2.76}(\mathrm{cm^2}) \quad (6)$$

where Z_q is the ion charge state and E_i [eV] is the ionization potential of the neutral atom.