ARC DISCHARGE ION SOURCE DEVELOPMENT AT CERN ISOLDE

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In cadrul unui proiect european desfăşurat la CERN, de tip Marie Curie Early Stage Training, a fost realizat un studiu detaliat (experimental, analitic şi numeric) al surselor de ioni de tip FEBIAD, folosite în mod curent la facilitatea experimentală ISOLDE. Un nou model analitic a putut fi dedus pentru comportamentul global al sursei, bazat pe datele experimentale acumulate. Acest model a fost deja implementat pentru realizarea a două prototipuride surse FEBIAD, care au îmbunătățit eficacitățile de ionizare 1+ ale gazelor nobile de 5 pana la 20 de ori (in functie de element). Modelul poate acum servi la optimizari viitoare ale surselor, pentru cerinte specifice ale diferitor tipuri de utilizatori sau ale diferitelor facilități experimentale din lume, în special pentru producerea de fascicule intense de ioni radioactivi.

Within a Marie Curie Early Stage Training project at CERN, a detailed study (experimental, analytical and numerical) of the standard ISOLDE FEBIAD ion sources has been done. A new theoretical model of the global source behavior could be inferred, based on the acquired experimental data. The source model already served to the development of two FEBIAD prototypes which improved the 1+ ionization efficiencies for the noble gases by 5 to 20 times (depending on element) This development can now serve to future ion source optimizations, for specific user or facility requirements around the world, especially for the production of high intensity radioactive beams.

Keywords: ion sources, arc discharge, modeling, plasma, CERN, ISOLDE.

1. Introduction

The ISOL method [1] consists in producing ion beams of radioactive isotopes, through the bombardment by particle beams of a thick target in which the reaction products are thermalized and diffuse out (through a specific transfer line) to an ion source for further acceleration and separation.

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ISOLDE [2][3] is the world-leading ISOL facility, dedicated to the production of a large variety of radioactive ion beams for a great number of different experiments (nuclear and atomic physics, solid-state physics, life sciences and material science), and is being operated by the ISOLDE Collaboration.

At ISOLDE, radioactive nuclides are produced in thick high-temperature targets via spallation, fission or fragmentation reactions. The targets are placed in the external proton beam of the CERN PSB, which has an energy of 1.0 or 1.4 GeV and an intensity of about 2μA. The target and ion source (coupled together in a compact unit) represent a small chemical factory for converting the nuclear reaction products into a radioactive ion beam. An electric field accelerates the ions, which are mass separated and steered to experiments. Until now, more than 600 isotopes of more than 60 elements (with Z ranging from 2 to 88) have been produced, with half-lives down to milliseconds and intensities up to 10^{11} ions/s.

The ion source development work done at ISOLDE is motivated not only by present demands (increased ionization efficiency and element selectivity, lower ionization time [4]), but also by the demands of future projects (HIE ISOLDE [5], EURISOL [6]) which will have to deal with increased gas pressures due to higher beam power impinging on the production target.

Within the Marie Curie “HIGHINT” project, a detailed study of the standard ISOLDE ion sources [7] (of FEBIAD type [8]) has been done. Through experimental, analytical and numerical investigations, several results have been obtained [9]:

- The detailed dependence of the FEBIAD performances on the operation parameters;
- The characterization of the FEBIAD plasma properties (composition, temperatures, densities, potential);
- The identification of the FEBIAD limitations, together with the corresponding theoretical justifications and solutions for their removal;
- An analytical model for the FEBIAD ionization efficiency, inferred from the experimental results and valid all over the investigated variation range of the operation parameters;
- The proposal of a customizable series of ion sources (VADIS), which can take advantage of the developed model to optimize the ion source design for the different chemical classes of produced isotopes.

This paper describes the general approach to ion source modeling with emphasis on the new FEBIAD model, together with the results obtained with the first prototypes based on the developed model (which are now the new standard ion sources in use at ISOLDE).

2. Ion source development. Modeling approaches.

The two main aspects to consider for any ion source development are the ion production and the ion extraction. Both of these can only be done after the validation of a reliable model of the investigated ion source, comprising all the phenomena dominant over the variation range of the operation conditions. We will present in this section the main approaches towards the modeling of the ion sources, depending on their type.

The arc discharge phenomena was well investigated since the beginning of the 20th century [10][11][12], but the general theory was developed for isolated mediums, where each phenomenon can be studied independently, while each ion source type represents a unique selection of dominant phenomena, with specific applicability ranges and saturation behavior. More than that, the requirement of extracting a beam from the generated plasma is strongly affecting the source design, making the plasma confinement designedly imperfect and often affecting the plasma density and energy distributions.

Therefore, for meaningful results, a separate model including the (possibly different) significant phenomena has to be developed for each type of ion source, and eventually refined for each implementation of the considered type.

The existing models for the overall behavior of an ion source are limited, due mostly to the limited diagnostic tools that can be employed on an operating source, for accessing its internal parameters. More than that, a model can only be developed (and usable) if the source performance is stable and reproducible for a given set of operation parameters, not only during different operation sessions but also for different units built after the same design.

For example, the ion source behavior can be affected by many parameters depending on the source manufacturing process or on the particular implementation of the plasma chamber to the ion source bench. The most important of these parameters are:

- The elementary composition of the employed materials;
- The vacuum conductance of the connections of the ion source unit to the separator or within the unit components;
- The stability and reproducibility of the critical input or output components (gas injection, power supplies generating the plasma or contributing to the beam extraction, cooling/heating system);
- The thermal properties of the systems connected to the plasma chamber, leading to a specific stabilization time and sensibility to perturbations.

Due to the different factors mentioned above, even for the same ion source design the plasma properties inside the source can be different for the same input parameters. In such a case, some of the processes affecting the ionization and/or beam extraction can reach limitations which will not be consistent for all the implementations. Therefore, the model usefulness is also conditioned by the specification of all the limits that can affect the model application, with the corresponding parameters that have to be considered.

The limitations described above led to different development solutions for different types of ion sources:

a) The ECR ion sources

They represent the most complex cocktail of phenomena. Their plasma is being generated through the injection into the plasma chamber of microwaves with a defined frequency, which will transfer their energy to the electrons having the same gyration frequency (due to the Lorentz forces) as the microwave frequency. These electrons will acquire sufficient energy for producing multiply charged (up to fully stripped) ions; the resulting plasma is confined by a magnetic field created through the superposition of a hexapole magnet (placed axially around the plasma chamber) and two (or three) solenoids, placed on the injection and on the extraction side (the eventual third one in the middle) of the plasma chamber.

The general behavior of these sources can be understood through the use of several “scaling rules” developed through extensive experimental investigations and linking the most important design parameters (i.e. the magnetic field configuration and/or the frequency and power of the microwave generator) to the ion currents generated by the source [13][14][15][16]. An exhaustive theory has been developed relatively recently [16], which treats each phenomena in detail but cannot fix all the floating parameters characterizing the global operation of a real source. The confirmed simulation tools are limited and only treating partially the source performance. More precisely, there are codes treating the ion extraction from a plasma with given parameters (KOBRA [18], IGUN [19], SCALA [20]), codes for electron dynamics in magnetic fields (TrapCAD [21]) and codes for treating the interactions within the plasma components (VORPAL [22]), but there’s no confirmed code for treating the global ion source behavior. Also, there are many codes developed in-house at various locations, for representing various punctual aspects of an ECR operation (RF heating of the electrons, time evolution of the charge state distributions inside the plasma, etc.).

b) The EBIS ion sources

They are employed for the multiple ionization of a wide range of elements. The ionization is provided by an intense electron beam, maintained focused by a strong axial magnetic field and accelerated by a complex system of successive electrodes (polarized at increasing potentials, corresponding respectively to the successive ionization potentials – from 1^+ to N^+ – of the atoms to be ionized). The radial ion confinement is provided by the negative space charge of the electron beam, while the axial confinement is provided by the electrostatic barrier produced by the electrodes situated on the two sides of the plasma chamber. This electrostatic barrier can also allow the operation of this type of ion source in the so called “trap mode”, when the generated ions can be kept confined (and eventually accumulated) in the plasma for a longer time before being extracted.

For this ion source category, the phenomena can be better put together in a global model, as there are fewer sources of plasma instabilities. Also, the electron energy and the loss currents from the plasma are better controlled. The global behavior of the ion source can be globally contained in a set of analytical equations [23] [24] [25], but the resulting system requires numerical solving.

c) The arc discharge ion sources

They are typically employed for the generation of 1+ ion beams, due to their simple design which is not allowing a sufficient ion trapping time (mandatory for N+ ionization).

Their operation principle relies on the generation of a plasma in the hot, gas-tight enclosure defined by a 2 or 3 electrode system: a cathode generating the primary electrons and one or two anodes providing the accelerating potential for the electrons and eventually serving to the plasma confinement (together with a solenoid-magnet field).

For these sources, the complexity is generally given by the small volume (making the plasma boundary effects dominant and maximizing the effect of non-uniformities) and by the extreme operation conditions (high temperature, complex gas composition, chemical reactions). Several efficient source types have been developed worldwide, but without a full model attached for justifying the good performances: the Nielsen source [26], the hollow cathode source [27], the Bernas-Nier source [28] (characterized by different configurations of ion extraction, performed respectively axially through a hole on anti-cathode side, cathode side, or radially through a slit in the anode), the FEBIAD source [8] (optimized Nielsen source, allowing stable operation for a wide range of operation pressures, due to the implementation of an electron accelerating grid in front of the cathode) and the EBGP source [29] (optimized hollow-cathode source, providing better performances through the implementation of a radial grid facing the internal side of the hollow cathode).

This led to the impossibility of implementing the same design to a different facility with the same ion source performances.

3. An original model for the ionization efficiency of the FEBIAD ion sources

An analytical model than can explain and predict the ion source behavior is very useful to the comprehension of the ion source performances and limitations, mandatory for any ion source development.

In particular, a model for the ionization efficiency requiring as input only the operation parameters that are set externally is presenting the additional advantage that it allows a better comprehension of the source response at the change of the operation conditions, while still permitting a quick and reliable diagnose of the source plasma.

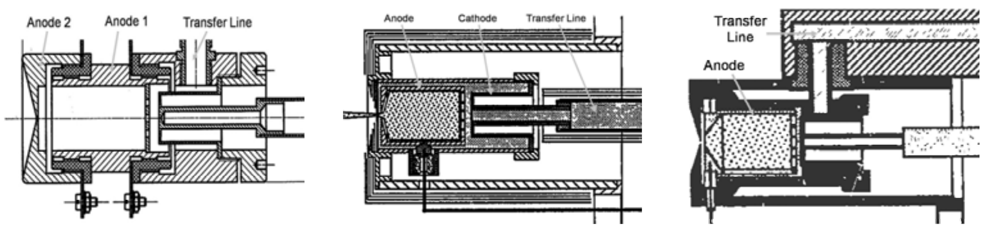

Figure 1. The FEBIAD ion source subtypes used at ISOLDE: MK3 (left), used for the ionization of metallic elements, MK5 (middle) used for the ionization of the refractory elements and MK7 (right) used for the ionization of the noble gases and of molecular compounds.

The ISOLDE FEBIAD ion sources are presented in figure 1. They are typically delivering total ion beam intensities in the range of 1 to 10 µA. The main components of a source are:

- A tantalum cathode, heated at around 2000°C for generating electron currents of up to 0.2A;
- The anode cylinder, serving as plasma chamber, polarized at potentials around 150 V;
- The accelerating grid, representing the anode side facing the cathode (opposed to the side with the ion extraction aperture); it typically has a geometrical transparence of about 50% and allows the acceleration of the electrons produced by the cathode;
- A solenoid, placed around the plasma chamber region, limiting the space charge expansion of the primary electron beam through the produced longitudinal magnetic field (with a strength on the order of some 10 mT).

The ions are generated by electron impact inside the plasma chamber and they are subject to recombination through different mechanisms [30] that can this way reduce the ionization efficiency. The support gas is injected through calibrated leaks close to the cathode, while the radioactive products are transported from the target container through a transfer line, as efficiently as possible.

The parameters set externally are: the anode potential, the cathode temperature, the internal magnetic field (generated by a solenoid) and the operation gas pressure and composition.

Based on the analysis of all the phenomena characterizing the FEBIAD operation [30] and on extensive experimental investigations [9], the ionization efficiency was deduced [9] to be given by the expression:

$$\varepsilon = 2.33 \cdot 10^4 \cdot f \cdot V_{source} \cdot A \cdot \exp\left[\frac{-W}{kT}\right] \cdot l \cdot \frac{\ln\left(\frac{U}{V_{ioniz}}\right)}{U \cdot V_{ioniz}} \cdot \frac{\sqrt{M_i}\sqrt{T}}{S_{out}} \qquad (1)$$

In formula (1), the most important parameter for ion source development is the ion extraction factor, f, which serves as a quality factor for the ion source. It is defined as the average probability for an ion to be extracted before losing its charge through any of the phenomena competing with the ionization. The geometrical interpretation of f (see fig. 2) is that it corresponds to the active volume of the source, where the favorable distribution of the electrical field leads to the successful extraction of the ions produced therein. Considering that all the ions are having the same energy (which is the thermal energy of the neutral atoms, as the residence time is insufficient for any ion heating), the f factor should be identical for all the elements, opposite to the ionization efficiency itself, which is element specific.

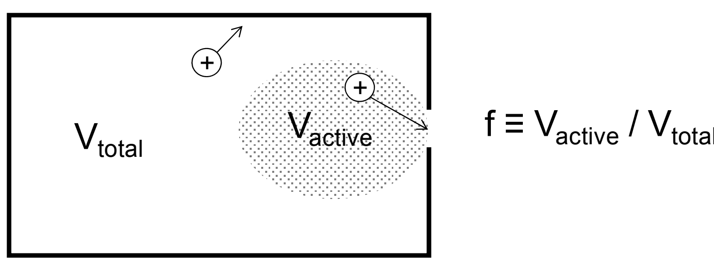

Fig. 2. The geometrical interpretation of the f factor.

The ionization efficiency for a given element can be directly measured, being defined as the ratio between the input neutral gas current (injected into the source through a calibrated leak) and the extracted ion current for the analyzed element:

$$\varepsilon = \frac{I_{n\_E}}{I_{i\_E}} \qquad (2)$$

By replacing the experimental value of the ionization efficiency obtained through the formula (2) into the formula (1), the f factor can be obtained for a given set of operation parameters. The knowledge of the f factor for a single point (the nominal set of operation parameters) can serve to the understanding of the current ion source performance, but for the comprehension of the limiting factors acting on the ionization efficiency (a requirement for the ion source development), all the operation parameters have to be varied independently, for identifying the points of inflexion in the variation curve of f.

This complete analysis has been done in [9]; we will only present here the application of this method for the main parameter defining the ionization rate inside the source, which is the operation temperature. This parameter has a strong effect on the properties of the plasma created inside the ion source, as it defines the density of the primary electrons emitted by the cathode.

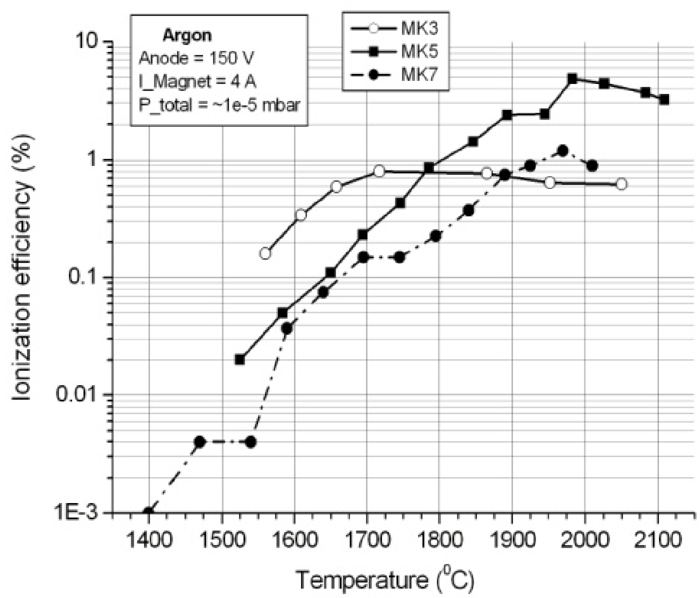

Fig. 3. The temperature dependence of the Argon ionization efficiency, for all the FEBIAD subtypes used at ISOLDE.

In fig. 3 it can be seen that the general trend for the FEBIAD sources is to have an increasing ionization efficiency towards the high operation temperatures. The maximum values of the ionization efficiencies are consistent with the standard values published for Argon [31].

The saturation occurring around 2000°C is an effect of the increasing background pressure inside the source due to material evaporation (details in [9]). A surprising information obtained through this investigation was that there is a consistent difference between the different sub-types (MK3, MK5 and MK7), which could not be explained before. It was found [9] that this difference is generated by different electrical field distributions inside the different sources, which lead to the extraction of different ion fractions from the ion source. This result was implemented in one of the prototypes presented in section 5.

The figure 4 is presenting the corresponding f factors for the measurements presented in figure 2. The goal for a highly efficient arc discharge ion source is to achieve a high f factor (as close to 1 as possible) and to maintain it up to the highest possible operation temperatures (corresponding to intense electron beams and therefore to the ionization of a high fraction of the injected amount of gas).

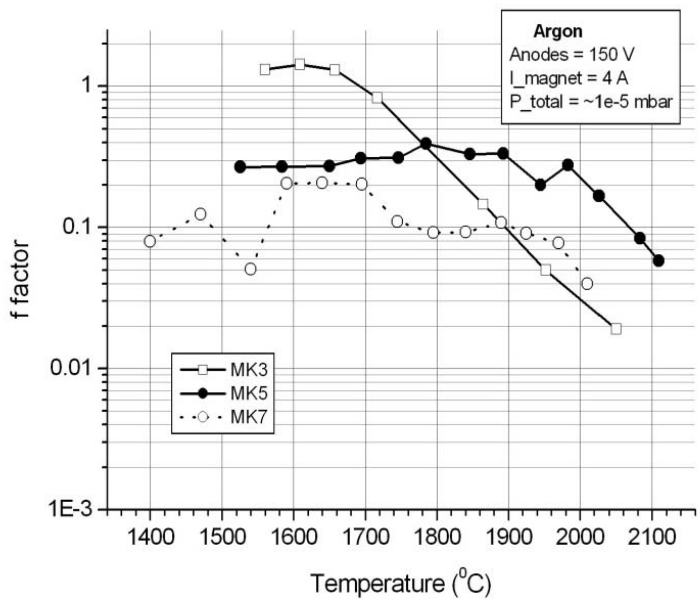

Fig. 4. The ion extraction factor, calculated using the formula (1) for the measurements presented in figure 1.

It can be seen that the source with the best performances is the MK5, which is characterized by an f factor close to 0.3 up to ~2000°C. The MK7 source, having an f factor close to 0.1, is more affected by instabilities due to a smaller active volume. The MK3 ion source presents an excellent f factor at low temperatures, but this is not leading to high ionization efficiencies due to the fast decrease towards the high temperatures. The temperature where the f factor is dropping is the same for the MK5 and MK7 sources, but it is significantly smaller for the MK3 type, due to the rise of the background pressure at different temperatures for the different employed materials (graphite for the MK3, Molybdenum for MK5 and MK7). The limitation mechanisms leading to the decrease of the ionization efficiency are extensively analyzed in [9].

4. Ion source designs based on the proposed ion source model

The analytical model presented in section 3 could fit the behavior of all the ISOLDE FEBIAD sources at the variation of all the operation parameters within a wide variation range [9]. The extensive experimental results obtained in the process served to the understanding of the limitations acting on the ionization efficiency of ion sources in use at ISOLDE. Two ion source prototypes have been proposed, built and successfully tested in 2008.

The first prototype could reproduce the higher efficiencies of the MK5 source (figure 3) also for the MK7 source, thus increasing the noble gas efficiencies for ISOLDE experiments by up to a factor 4 (see table 1). The principle behind the development was the increase of the MK7 f factor through the optimization of the distribution of the electrical field extracting the ions from the plasma [9][32].

The second prototype could further increase the efficiencies of both MK5 and MK7 types, by another factor ≤4 (depending on the element). The principle behind this development was the decrease of the background pressure inside the ion source at temperatures above 2000°C, which allowed maintaining a high f factor up to higher temperatures compared to those in figure 4 [9]. It was also employed on-line and allowed the identification at ISOLDE of ^{229}Rn [33], an isotope that had never previously been observed in the laboratory.

Table 1

The achieved improvement of the ionization efficiencies

FEBIAD Ion Source	Ionization Efficiency					
	He	*Ne*	*Ar*	*Kr*	*Xe*	*Rn*
Standard MK7 [31]	0.14	0.36	2.0	4.3	11	-
1st Prototype (and MK5)	0.37		7.8	11	19	
2nd Prototype (and VD5&7)	1.4	6.7	26	38	47	62
Multiplication factor (noble gases)	10	18.6	13	8.8	4.3	
Multiplication factor (all other elements)*	~3 (expected)					

The production of noble gases RIBs profits from both developments, therefore the quoted multiplication factors are representing the ratio between the efficiencies of the 2nd prototype and of the standard MK7 sources. The other (condensable) elements will profit only of the second development, therefore the multiplication factor represents the ratio between the efficiencies of the 2nd prototype and of the standard MK5 sources (identical as for the 1st prototype).

The success of these prototypes led to the introduction of the new designs as the new standard ion sources at ISOLDE (starting from 2009), the “MK” series being replaced by the “VD” series.

All the multiplication factors listed in table 1 for the ionization efficiencies are translating directly into the increase of the available intensities of radioactive ion beams, which is an important requirement for many ISOLDE users.

5. Conclusions

The extensive collection of experimental measurements brought by the present work cleared up many of the saturation phenomena limiting the ionization efficiency of the FEBIAD ion sources. This already served to establish an analytical model of the ion source operation and consequently of its ionization efficiency. The excellent results of the ion source designs based on this learning made them now the new standard ion sources in use at ISOLDE. The extrapolation of the ion source operation conditions using the developed model will allow the development of other ion source designs, optimized for the ionization of specific chemical classes of the isotopes produced through the ISOL method. Also, the extensive characterization of the FEBIAD ion sources validated them as a candidate for the future facilities dealing with increased gas loads.

SYMBOL LIST

ISOLDE – acronym for Isotope Separator On Line
RIB – Radioactive Ion Beam
PSB – Proton-Synchrotron Booster (CERN)
FEBIAD – Forced Electron Beam Induced Arc Discharge (ion source type);
ECR – Electron Cyclotron Resonance (ion source type);
EBIS – Electron Beam Ion Source (ion source type);
EBGP – Electron Beam Generated Plasma (ion source type);
KOBRA, IGUN, SCALA, TrapCAD, VORPAL – names of commercially available programs for plasma related simulations;
MK3, MK5, MK7 – acronyms used for the FEBIAD subtypes used at ISOLDE before the present development;
VD3, VD5, VD7 – new acronyms used for the ISOLDE FEBIAD subtypes, employing the presented development;
ε - ion source ionization efficiency;
f – ion extraction factor, defined as the average probability for an ion to be extracted;
V_{active} – the volume inside the source where the ions are extracted from;
V_{source} – the volume of the ion source ;
A – Richardson-Dushmann constant for thermoelectronic emission;
W – the work function of the cathode material ;
k – Boltzmann's constant;
T – the temperature of the ion source;
l – number of electrons in the valence shell of the atom with a given I_p;
U – the kinetic energy of the ionizing electrons;
V_{ioniz} – the ionization potential of the investigated element;

M_i – the mass of the investigated ion ;
S_{out} – the surface of the ion source extraction aperture.
I_{n_E} – neutral gas current (of the element E) injected into the ion source;
I_{i_E} – ion current (of the element E) extracted from the ion source.

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