EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — ENGINEERING DEPARTMENT

CERN-EN-Note-2009-001 STI

Development of High Efficiency Versatile Arc Discharge Ion Source (VADIS) at CERN Isolde

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Abstract

We report here recent developments of Forced Electron Beam Impact Arc Discharge (FEBIAD) ion sources at CERN-ISOLDE. As a result of the propositions to improve the ionization efficiency, two FEBIAD prototypes have been produced and successfully tested in 2008.

Off-line studies showed that the 1+ ionization efficiencies for noble gases are 5 to 20 times larger than with the standard ISOLDE FEBIAD ion sources, and reach 60% for Radon, which allowed the identification at ISOLDE of ^{229}Rn, an isotope that had never previously been observed in the laboratory. A factor 3 increase is also expected for the ionization efficiency of the other elements.

The experimental and theoretical methodology is presented. The theoretical model which gives precise insights on the processes affecting the ionization is used to design optimal sources for the different chemical classes of the produced isotopes, as already demonstrated for noble gases.

Presented at: 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September, 2009

Geneva, Switzerland
November, 2009

Development of high efficiency Versatile Arc Discharge Ion Source (VADIS) at CERN ISOLDE [a)]

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We report here recent developments of Forced Electron Beam Impact Arc Discharge (FEBIAD) ion sources at CERN-ISOLDE. As a result of the propositions to improve the ionization efficiency, two FEBIAD prototypes have been produced and successfully tested in 2008.

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I. MOTIVATION

The evolution of the ISOL requirements for the ongoing and future projects worldwide[1] imposes an evolution of the 1+ ion sources.[2] In addition to the needs for efficiency, speed and selectivity, the future RIB sources will have to cope with higher gas loads and radiations, while maintaining good beam quality.

At ISOLDE, the design studies of increased beam intensities of up to 100kW 1GeV proton beam justified the investigation of the limitations of the presently used ion sources towards the significant increase of the radioactive gas loads. The extensive investigations (experimental, analytical and numerical) of the standard ISOLDE FEBIAD[3] ion sources done within the Marie Curie "HIGHINT" project produced several results:[4,5]

- The detailed dependence of the FEBIAD performances on the operation parameters and their limitations;
- The characterization of the FEBIAD plasma properties (composition, temperatures, densities, potential);
- An analytical model for the FEBIAD ionization efficiency, inferred from the experimental results 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 first results obtained with the VADIS series, together with the underlying experimental and theoretical studies.

II. ISOLDE FEBIAD CHARACTERISTICS

A. Experimental investigations

The evolution of the source performances was investigated for the broadest range of operation parameters, to identify all the significant phenomena affecting the ionization inside the source and thus the source limitations.

A beam energy analyzer developed in Jyväskylä[6] was adapted to the ISOLDE offline separator. The plasma potential of the ISOLDE FEBIAD sources could be precisely measured[5] and found to be dependent on the anode potential, ion source temperature and operation pressure; for the nominal operation conditions, it has the same value for all the 1+ extracted ions.

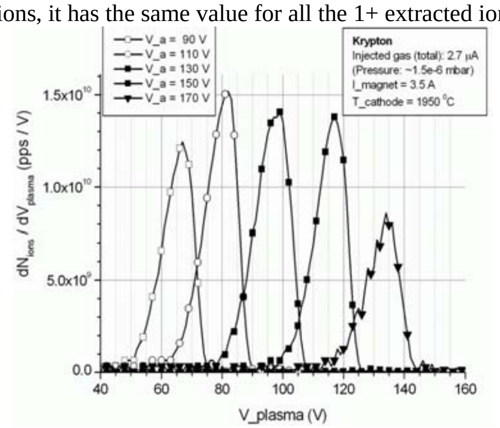

FIG. 1. Kr+ beam energy distribution for different anode potentials (V_a) in a MK5 FEBIAD source (0V is the ion source ground potential). The plasma potential (V_plasma) distribution is directly related to dN/dV.

For the nominal operation parameters (see legend in fig.1), the plasma potential is systematically lower than the anode (i.e. plasma chamber) potential, with measured differences of up to 40V (fig.1); the difference increases[5] with the decrease of the operation pressure, the increase of the anode potential or the increase of the source temperature.

This result pointed out that the ion extraction geometry has to be optimized for ions that will be repelled by the plasma chamber walls and also by the outlet plate, when it is set at the same potential.

Another experimental result leading to the development described in section III is the difference observed[5,7] between the ionization efficiencies of the different FEBIAD subtypes employed at ISOLDE. Namely, the ionization efficiency of the MK5 source (mounted with hot transfer lines) is systematically higher (with up to a factor 3) compared to the MK7 source (with cold transfer lines), for the same operation parameters.

B. Theoretical analysis

a) Contributed, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September, 2009.

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The theoretical model takes into account the different physical processes[4] affecting the ionization in the plasma chamber (size in Fig.3), as inferred from the experimental data.[5]

The previous models used to estimate the ionization efficiencies assumed either a thermalized plasma with an average electron temperature of ~3eV,[8] either the recirculation of the primary electrons inside the source volume,[9,10] producing several ionizations until their energy drops below the ionization potential of the atoms present in the plasma.

In our model, the ionization efficiency is described by eq.1, and the experimental results can be reproduced over a broad variation range of operation parameters by considering only one passage of the primary electrons and no ion trapping (assumptions justified by the absence of any confinement).[5] The electrons will therefore maintain their initial acceleration energy (typically 150 eV) and the ions the thermal energy of the neutral atoms (~0.2 eV at 2000 °C).

$$\varepsilon = f \times R_{ioniz} / n_{n\_in}$$
$$\Rightarrow \varepsilon = f \times V \times \left(n_e \times n_n \times \sigma_{ioniz} \times v_{rel} / n_{n\_in}\right) \qquad (1)$$

where $\mathbf{R_{ioniz}}$ is the ionization rate inside the ion source volume; $\mathbf{n_{n\_in}}$ is the gas flux injected into the ion source; **V** is the source volume; $\mathbf{n_e}$ is the electron density; $\mathbf{n_n}$ is the neutral gas density; $\boldsymbol{\sigma_{ioniz}}$ is the electron impact ionization cross section; $\mathbf{v_{rel}}$ is the relative velocity between the electrons and the neutral atoms; **f** is the fraction of the produced ions that are successfully extracted before losing their charge on the ion source walls (identified[5] as the main source of ion losses) or before being pumped out from the source volume, as neutrals.

The f factor can therefore serve as a quality factor for an efficient design and operation of the ion source. It is found[5] to be between 0.1 and 0.3 for the standard ISOLDE sources and with the development shown in section III, it could be improved up to ~1, over a temperature range from 1600°C to 2300°C.

An important limitation of the performance (leading to a reduced f factor in eq. 1) was observed in a dedicated experiment,[5] where the source was operated with pure Ar (fig.2).

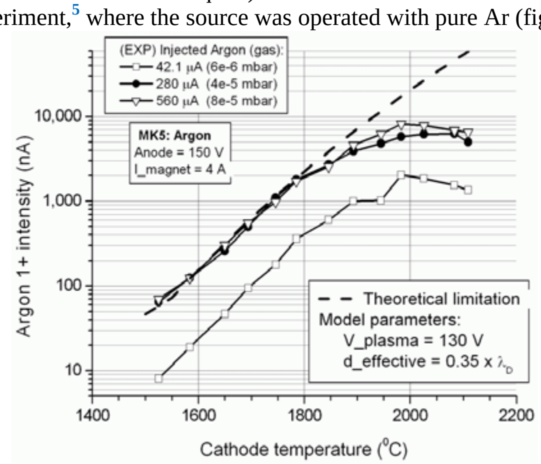

FIG. 2. Saturation of the extracted ion current at the successive increase of the injected gas amount (see text).

By increasing successively the injected amount of gas, the Ar^{1+} current reached a saturated value depending only on the source temperature.

This saturation can be described using the Child-Langmuir relation for the total current that can be extracted from the source volume at the space charge limit (dashed curve in figure 2). The potential drop is taken as $\Delta V = V_{plasma} = 130$ V (because the central part of the outlet plate is grounded) and the effective accelerating gap is a free fitting parameter and taken to be $0.35 \times \lambda_D$ (the Debye length being temperature dependent, through n_e).

The fit is only accurate below 1800°C, where the Ar^{1+} represents the full extracted beam. Above this temperature other beam components are appearing, due to the increase of the impurity partial pressures inside the source. Also, above 2000°C the intensity of the primary electron beam reaches space charge saturation at the accelerating grid (see section IV).

C. Computer simulation

The simulation code CPO[11] was employed to map the internal electrical field distribution and to better illustrate the origin of f in equation 1.

The active volume is defined as the fraction of the ion source volume where the generated ions are extracted from, due to the favorable field distribution. The active volume is therefore connected to f through eq.2:

$$V_{active} \cong f \times V \qquad (2)$$

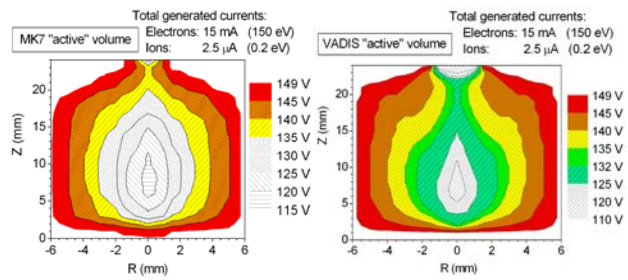

FIG. 3. (Color online). Potential contours inside MK7 (left) and MK5/VADIS (right) that can serve to estimate the active volumes and to justify the beam energy distributions (see text).

The field distributions in figure 3 are obtained through the superposition of the electrical fields generated by the source electrodes and by the electrical charges (electrons and ions) generated inside, with the specified energies and densities (no dynamics included). The distributions are systematically different for the two source types due to the different geometry of the outlet plates.[3] The active volume is delimited by the potential surfaces of 149.8 V (V_{anode}-E_{ion}/e) and the lowest potential surface anchored on the extraction aperture (~133 V for the MK7 and ~131V for the MK5). The difference between these active volumes can justify the higher values of the f factor (and consequently of ε) for the MK5 source compared to the MK7.

III. THE "VADIS" SERIES

Based on these learning, two prototypes have been proposed and tested online at CERN ISOLDE in 2008 (fig.4).

FIG. 4. The modified pieces for the two prototypes: accelerating grid (left), anode body (center) and outlet plates (right).

The first one successfully improved the MK7 ionization efficiencies to the level of the MK5 source, due to the increase of the active volume (and consequently of the f factor) through the adaptation of the source extraction geometry.

The second one further improved the efficiencies of both MK5 and MK7 types, by the reduction of the CO impurity that was taking a major fraction of the extracted current, reaching this way the space charge limit (fig.2) and reducing the f factor at high temperatures. This was done through the elimination of the graphite from the source materials (accelerating grid and outer ring of outlet plates). This design is now implemented at ISOLDE in the new VD series (including until now the subtypes VD5 and VD7), replacing the MK series.

IV. EXPERIMENTAL RESULTS

The two prototypes have been tested with noble gases on the ISOLDE offline and online separators and were employed to produce Argon, Krypton, Xenon and Radon RIBs.

The measured efficiencies for the noble gas series are presented in figure 5. The irregularities observed below 1900°C (compared to the typical exponential dependence reported in fig.2) are linked to the irregular variation of the cathode emitted current (dotted line), generated by an imperfect thermal shielding of the unit. The saturation above 2000°C is given by the saturation of the electron current drawn from the cathode by the accelerating grid (as marked by the dashed curve, representing the Child Langmuir space charge limited e-current, considering no charge compensation from the ions).

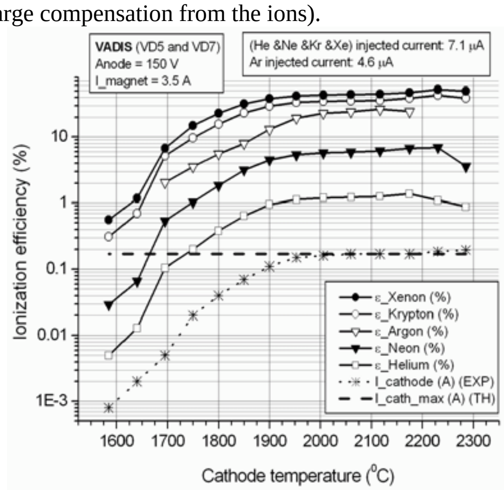

FIG. 5. Noble gas efficiencies (offline and online) for the second prototype. The temperature dependence and saturation are linked to the cathode current (dotted), reaching the space charge limit at the accelerating grid at high temperatures (dashed).

Table 1 provides the best ionization efficiencies measured for these prototypes, compared to previous recorded figures.[12] The Radon efficiency is estimated through extrapolation from the stable noble gas series, using eq.1.

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).

TABLE 1. Improvement of the ionization efficiencies

FEBIAD Ion Source	Ionization Efficiency (%)					
	He	Ne	Ar	Kr	Xe	Rn
Standard MK7[12]	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)					

As any increase of the ionization efficiency acts directly on the total RIB yield, the yields are expected to directly scale with the efficiency gain. The first results are in line with this expectation (table 2).

TABLE 2. RIB yields measured at CERN ISOLDE (with the corresponding target materials and element half-lives).

YIELDS	^{31}Ar *(15 ms)*	^{72}Kr *(17 s)*	^{73}Kr *(26 s)*	^{138}Xe *(14.1m)*	^{229}Rn *(~12s)*
Measured (at/μC)	5[13] *(CaO)*	1.1e4 *(Nb)*	1.2e6 *(Nb)*	2.4e9 *(UC_x)*	200[14] *(UC_x)*
Database (at/μC)	1.5 *(CaO)*	2.0e3 (Nb)	7.4e4 *(Nb)*	5.7e8 *(UC_x)*	-

The second prototype allowed the determination of the masses of $^{223-229}$Rn by precision mass spectrometry at ISOLTRAP; the isotope ^{229}Rn was identified for the first time in a laboratory and its half-life could be measured.[14]

V. CONCLUSIONS

The on-line operation of these prototypes confirmed the proposed ion source model and lead to the introduction at ISOLDE of the VADIS series, consisting of sources optimized for the different chemical classes of produced isotopes.

The prototype results have been confirmed by the present production units (VD5, the "hot plasma" version and VD7, the version with water-cooled transfer line).

Future models optimized for lower operation temperatures and for higher gas loads can be obtained on the basis of the same developed source model.[5]

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