EURISOL-DS Project

Deliverable (n°) D4/M3.1

Investigation on Ion Source Parameters

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Abstract

The EURISOL multi-mega-watt target station requires dedicated radioactive ion sources. Notably, they must be capable of operating under extremely hard radiations and with a larger fission target producing over 10^{14} fissions/s. The realisation of next-generation ion sources suitable for such operating conditions needs exhaustive studies and developments. In order to take up such a challenge, a review on radioactive ion sources was achieved and the investigation on ion source parameters was in particular focused on a plasma ion source through a R&D program.

1 Introduction

The Multi-MW (MMW) target station aims at producing the largest variety of neutron-rich-nuclear ion beams at intensities of a few orders of magnitude higher than ever produced. The radiation generated by the multiple interactions involved to generate over 10^{14} fissions/s is also accordingly higher. In addition the large size of the Uranium target out-gassing at temperatures beyond 2 000 °C must be close to the ion source. These conditions form a hostile environment for the operation of the ion source required to generate the beam made up by the nuclei released by the fission target. Consequently, the achievement of reliable and efficient ion sources relies on skilful studies and resourceful developments.

An exhaustive review was carried out to evaluate the capability of the ion-sources to operate under the irradiation conditions of the MMW target station. In addition, selectivity had to be taken into account to avoid the spread of unwanted radioactivity out of the target-ion-source system (TIS).

These studies led to determine the reference ion source for this target station to be the Resonance Ionisation Laser Ion Source (RILIS).

Furthermore, the developments required to meet MWW irradiation specifications were identified for this reference ion source. In parallel, R&D studies were initiated on the FEBIAD-type ion source [Kir03] in order to work out a high-performance prototype. Indeed, insofar as some needs will probably not be fulfilled by RILIS, such a R&D program is requested to meet the requirement of an additional ion source. The FEBIAD-type prototype developed has been named IRENA (Ionisation by Radial Electron Neat Adaptation) [Lau06, Che06, Lau08, Che08].

2 Ion source review for the MMW target station

To produce radioactive ions with the Isotope Separator On Line (ISOL) technique, four types of ion source have been operated: ECR (Electron Cyclotron Resonance) ion source, FEBIAD-type ion source, ion source based on surface ionisation and RILIS.

2.1 ECR ion source

ECR ion sources are most efficient for the ionisation of noble gases and volatile compounds. However, for radioactive beam production, the ECR ion source is the most constraining [Jar06]. Because of the level of radiation generated in the vicinity of the target, there is no possibility to use neither permanent magnet nor insulators made of organic material. In addition, RF injection is a delicate issue both for safety and efficient operation. Nevertheless, these days, important developments have been carried out on ECR ion sources in order to operate them at high power facilities [Lec08, Bri08].

2.2 FEBIAD ion source

FEBIAD type ion sources (Forced-Electron Beam for Ionisation by Arc Discharge) have been specifically developed for the production of radioactive nuclear beams. They are compact and supply stable arc discharges without the need for any feed gas. However, the ionisation efficiency drops when the incoming gas flow exceeds a few 10^{-3} mbar.l/s, due to an alteration of plasma confinement. Another weak point regarding the specifications for the MMW target station, is about the electrical insulators. In standard FEBIAD ion source, the ionisation chamber constitutes the anode. Since the cathode is electrically grounded, the electrical insulators must be in contact with the ionisation chamber. Having insulators so exposed to radiation and confined in a high temperature environment endangers the ion-source lifetime. Besides, the EBGP (Electron Beam Generated Plasma) which is a radial-type FEBIAD ion source shows attractive features for the development of a suitable prototype for the MMW target station.

2.3 Ion source based on surface ionisation

The surface ionisation source and the thermo-ionisation source consist of a tube or cavity maintained at high temperature. Surface ionisation is mainly efficient for elements with low ionisation energy. With the proper tube material, the surface ionisation source appears to be an efficient and selective ion source for producing alkali-metal beams. Because of their simplicity, such ion sources are the most reliable for operating under MMW irradiation conditions. However, as the ionisation efficiency depends on the tube material, the surface state of the tube during operation is an important parameter. Indeed, it can be altered by a strong out-gassing from the target system. For UC_X targets, the carbon vapour creates carbide compounds with many materials. The design of the transfer tube between the fission target and the ion source must take this aspect into account.

2.4 RILIS

By choosing properly the wavelengths of two or three different laser pulses, the photo-ionisation induced allows a pure element-selective ionisation. The power of existing lasers allows to reach most competitive ionisation efficiencies. In addition, the state of the art already allows to cover about 80% of the elements. Furthermore all the sensitive parts of the laser system are away from the irradiated fission target. Based on these major advantages, the RILIS was chosen as the reference ion source for the MMW target station. The main developments required for operation at the future target station are concerned with laser transmission to the ionisation cavity and plasma confinement in this cavity. The issue on laser transmission deals mainly with safety. The issue on plasma confinement occurs if the pressure in the hot ionisation cavity is high. Then non-resonant ionized metals even those with higher ionization potential than the element of interest may create enough ions to deteriorate the plasma conditions in the cavity. In addition, the lack of electron emission from the cavity at high temperature will further degrade the plasma confinement. IPNO laboratory took in charge the general study on RILIS for the MMW target station.

Studies and developments on these types of ion sources have to be all the more skilful and creative as technical tests are difficult to carry out under conditions similar to the MMW target station. Extrapolations are delicate because of the lack of accuracy on a few related parameters. In this context, IPNO laboratory focused on the investigation of parameters for the development of a FEBIAD-type ion source: IRENA prototyping.

3 Research and Development on IRENA ion source

Currently, no radioactive ion source fulfils the fundamental operation specifications of the MMW target station. The level of radiation considered exceeds by far those of today's ISOL facilities. Furthermore, the vapour flow from the fission target is potentially troublesome for all ion sources. Indeed, compared to ISOLDE-CERN standard UC_X target, the total surface of the fission target is a factor of three larger and the amount of Uranium is larger than a factor of ten. In contrast, Nielsen or Nier-Bernas ion sources can deliver steadily a few mA with an emittance of 20 π.mm.mrad at 40 kV for an incoming gas flow beyond a few 10^{-3} mbar.l/s. However, producing an intense arc discharge in that vapour pressure leads to a quick wearing of the cathode. So it has been decided to establish a R&D program focused on a FEBIAD-type ion source capable of operating under hard radiation and with a larger fission-target system.

These criteria lead us to consider the EBGP (Electron Beam Generated Plasma [Nit85]) ion source, a radial-type FEBIAD ion source. This ion source shows attractive features for high power facilities: the insulators are delocalised away from the ionisation chamber, the source works without any magnet and the configuration gives the possibility to reach high ionisation efficiency (>30% measured for ^{40}Ar). In particular, the insulator delocalisation allows heating the cathode up to 2500 °C and thus the production of non volatile ions. 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 enhances the lifetime of the ion source by preventing local wear as observed by post-irradiation analyses on planar cathodes.

Nevertheless, using the EBGP ion source with a thick target for on-line separation also requires modifications. In particular, the confinement by the cathode structure of the transfer line ending with the anode strongly favours short-circuit hazards.

Based on the EBGP ion source, a prototype has been worked out: IRENA (Ionisation by Radial Electrons Neat Adaptation). A validation prototype was designed and assembled (fig. 3.1) at the ALTO facility. The assembly was achieved in collaboration with NIPNE.

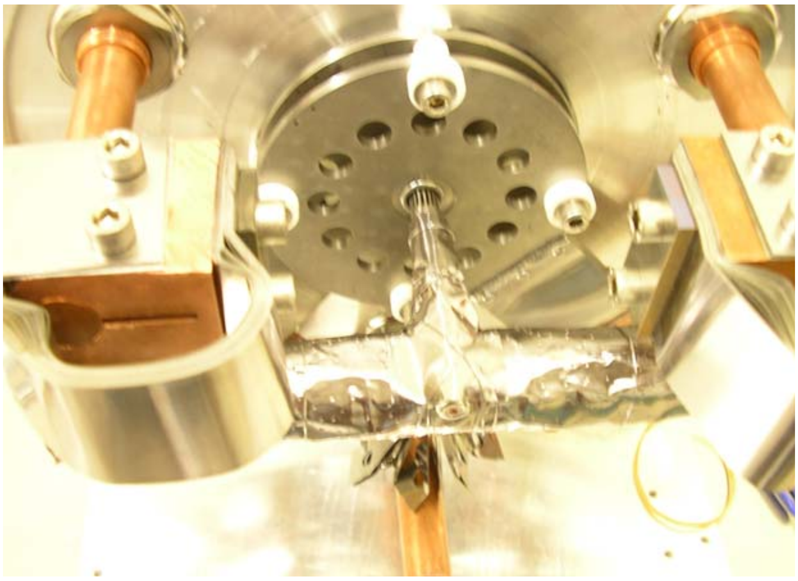

Figure 3.1: The feasibility prototype of IRENA ion source.

The IRENA feasibility prototype was tested off-line. Various stable beams were produced (fig. 3.2) and a study of the total stable beam intensity as a function of the cathode temperature was achieved (fig. 3.3). These systematic tests allowed us to check the expected behaviour of the first IRENA prototype. The results obtained were used to start calculations using IES Lorentz-EM codes. Nevertheless, the tests have to be extended to determine the optimal operation conditions.

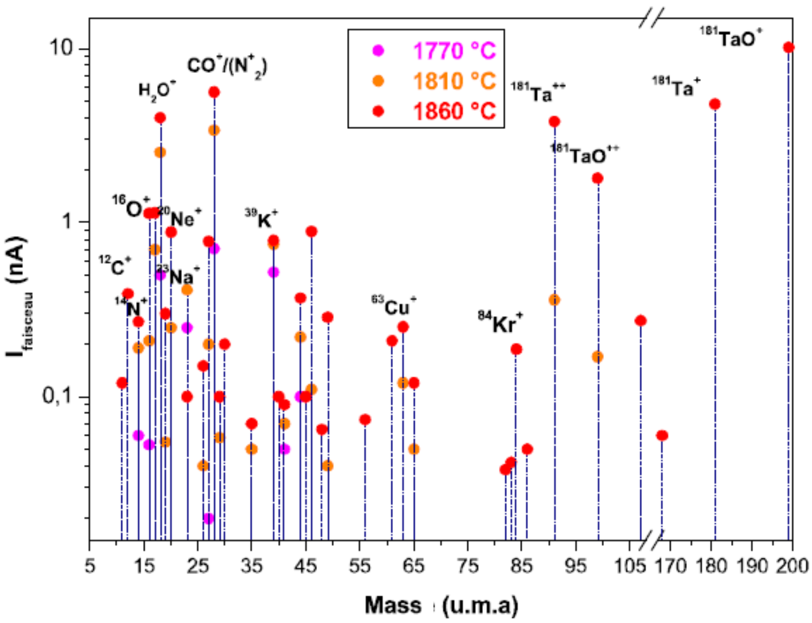

Figure 3.2: Mass spectrum of beams extracted from the IRENA feasibility prototype at the off-line mass separator of the ALTO facility; arc voltage 100 V, pressure in the vicinity of the extraction electrode about 10^{-5} mbar.

The feasibility prototype has been designed for a standard thick target. Dimensions of the ionisation chamber are close to those of the EBGP ion source to have a comparison basis with existing measurements [Lau06]. Contrary to the EBGP, the cathode is ohmically heated to get reliable operation and to assure a negligible magnetic field inside. The electrical power required to heat a 1 mm thick Ta cathode to 2000 °C is about 5 KW. To better understand the effect of the differences between these two ion sources, and also to prepare the design of the upgraded IRENA prototype, the feasibility prototype has been modelled using Lorentz codes [Che08].

Figure 3.3 shows the evolution of the ion extracted beam current as a function of the cathode temperature, measured with a Faraday cup inserted at the object point of the mass separator. These measurements have been performed with the arc voltage set at 100 V. The ion beam current starts to increase very significantly when the cathode temperature approaches 2000 °C. It has a similar evolution as the electron bombardment current.

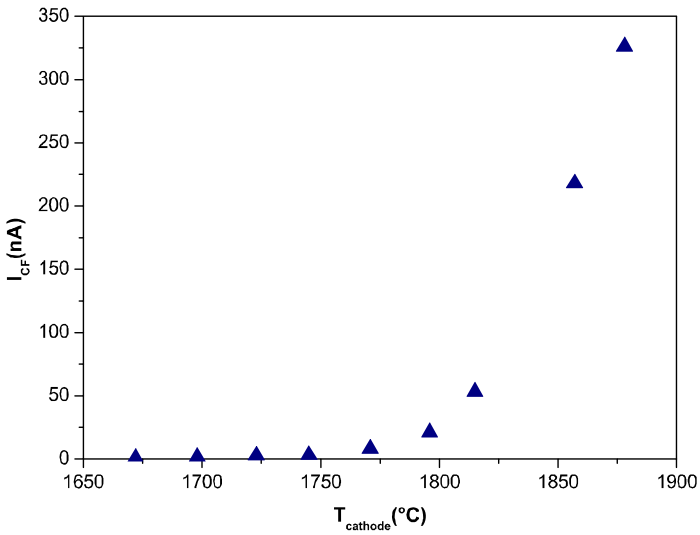

Figure 3.3: Evolution of the total ion beam current extracted from the IRENA feasibility prototype as a function of the cathode temperature. The ion beam current was measured with a Faraday cup inserted at the object point of the mass separator. The arc voltage applied is 100 V.

The first prototype of the IRENA ion source was modelled in 2D using the LORENTZ-EM code. In all the simulations, the arc discharge voltage was fixed at 100 V as it was during all the experimental tests mentioned previously and the space charge effect is taken into account. The effects due to the anode grid structure and to the out spacing between cathode and anode were studied for different emission current densities.

The results show that the anode grid structure causes a strong distortion of the equipotential lines which induces a defocusing effect on the electron trajectories (fig. 3.4). In addition, we have deduced an effective transparency of the anode grid of 27 % (half the value of the EBGP transparency).

The effects of increasing the spacing between the cathode and the anode grid were investigated by simulating electron trajectories. The results show that the larger the cathode-anode spacing, the further the electrons penetrate towards the ionisation chamber axis (fig. 3.5).

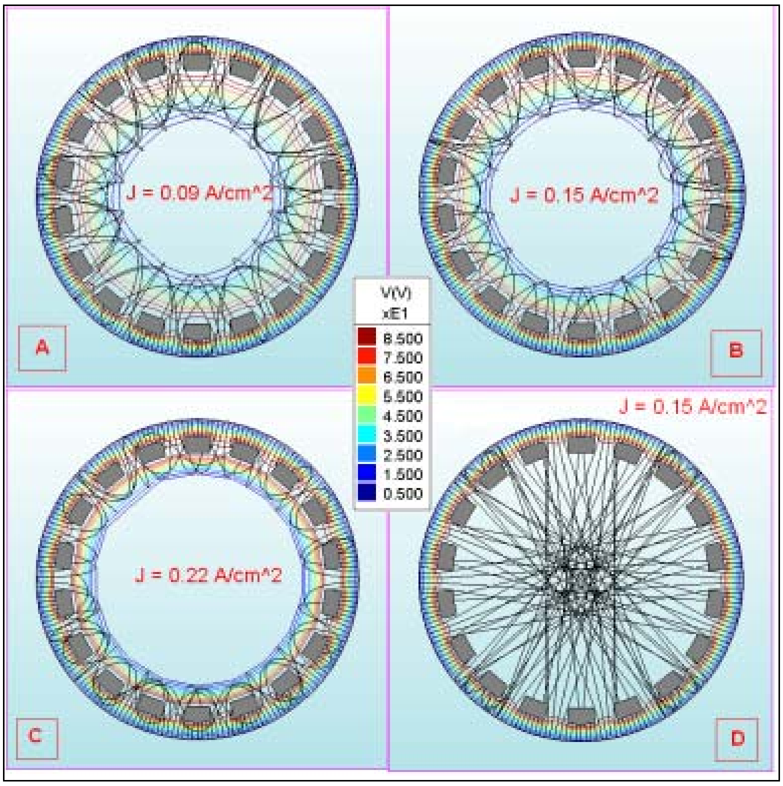

Figure 3.4: Simulation results of electron trajectories in the IRENA ion source, taking into account the space charge effect for different cathode emission current densities (J). The full negative space charge compensation is illustrated in case D.

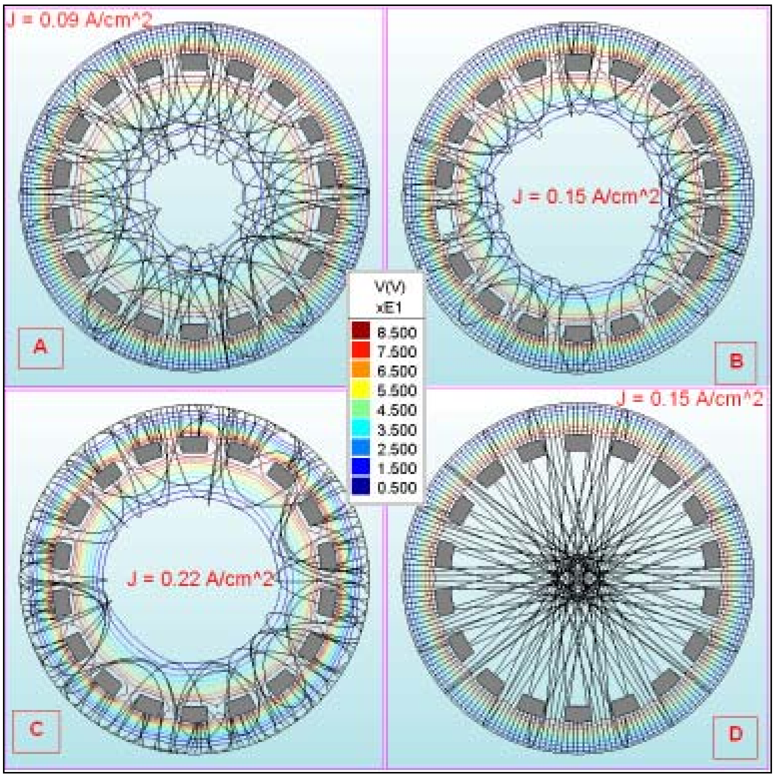

Figure 3.5: The effect of increasing the spacing between the cathode and the anode grid in IRENA ion source, taking into account the space charge effect for different cathode emission current densities (J). The full negative space charge compensation is illustrated in case D.

4 Selectivity

In addition to the fundamental operation specifications exposed, an essential exploitation specification has to be integrated: selectivity, i.e. nuclear beam purity. The purity of nuclear beams delivered by next generation facilities is a major concern in various aspects. First, a substantial part of the nuclei of interest has very low production cross-sections, up to a few orders of magnitude lower than nuclei closed to the stability valley. The exploitation of such beams of interest can only be considered in absence of contamination by more commonly produced isotopes. Although beam purification can be carried out along the radioactive beam lines, e.g. by a high-resolution mass separator, it is of prime importance to be able to get the highest selectivity in the TIS itself. Such a high selectivity allows to keep confined in the TIS the main part of unwanted generated radio nuclei, and to reduce the activation of the successive beam-line elements of the facility.

Even if FEBIAD-type ion sources are considered as non-selective [Kir92], a proper design of the transfer line including selective trapping can make such sources as selective as any ECR or EBIS. In addition, chemical processes can be applied to extract some specific non-volatile elements.

5 IRENA modelling in 3D by Lorentz-3EM

Based on 2D simulations results, we started the investigation of a series of design configurations by means of 3D simulations. These design configurations required full 3D modelling.

Experimental results obtained and published have been used to start simulation calculations. These calculations have been developed to focus on the design of an optimized plasma ion source for high-intensity irradiation. Indeed the MMW target station appears clearly to be the most critical case for ion source operation.

Based on various 2D/3D simulations (fig. 5.1a), the first optimized prototype was fully designed in September 2008. The cylindrical anode with uniformly distributed holes replaces the anode grid (fig. 5.2). The spacing between the cathode and the anode-grid was optimized as a function of the applied arc-discharge voltage in order to get the best electron confinement in the ionization volume (fig. 5.1b).

Furthermore, the electrical connections along with the insulating components and the water cooling system were totally reviewed in order to achieve the best reliability of the ion source (fig. 5.3).

a) b)

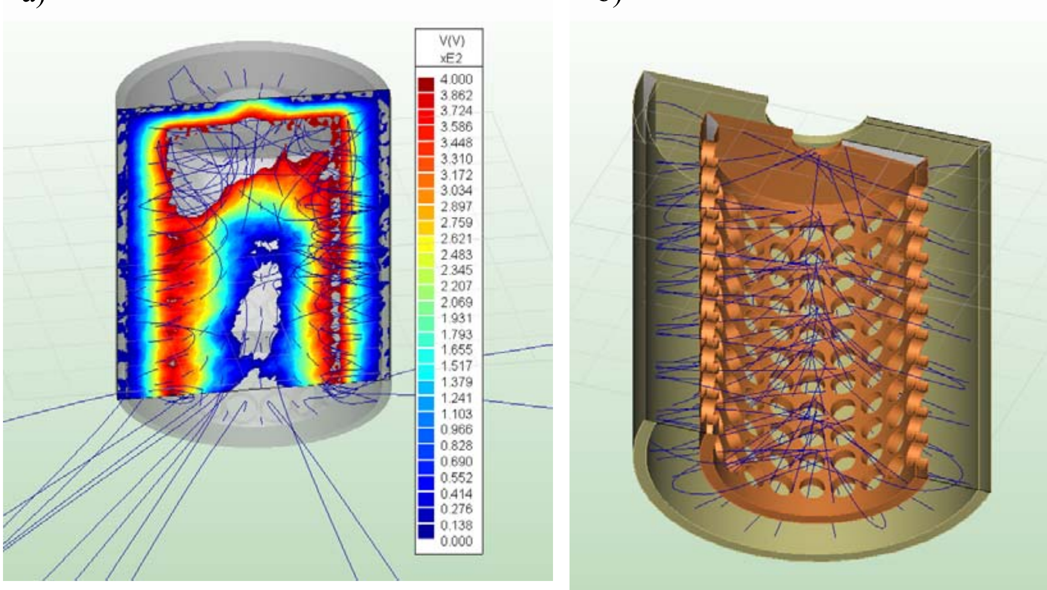

Figure 5.1: a) Electron trajectories with 400 V arc discharge taking into account the space charge effect. b) Electron trajectories with totally compensated space charge (an ideal operating mode of the IRENA ion source) show a good electron confinement in the ionization volume.

Figure 5.2: The new anode-grid structure designed for tests at IPN Orsay. Its dimensions are 12 mm in length, 9 mm in diameter and 0.5 mm in thickness. The diameter of the grid holes is 1 mm.

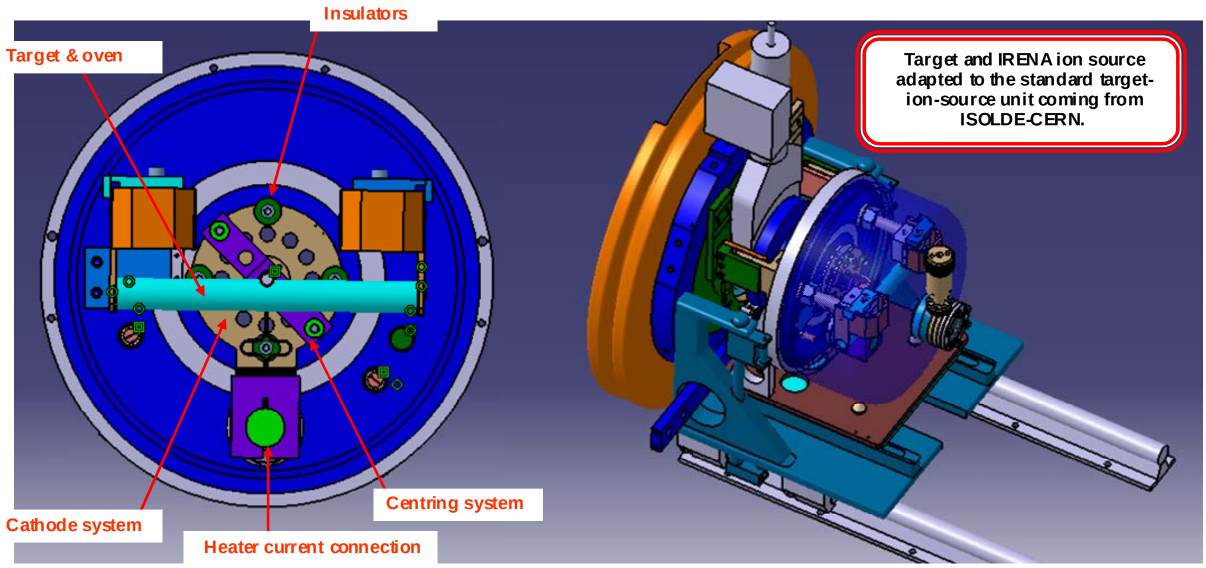

Figure 5.3: Conceptual design of the new optimized prototype of IRENA ion source. All parts have been manufactured and delivered at IPN Orsay for tests in 2009.

6 Integration to the MMW target station

The investigation on the IRENA ion-source parameters has been achieved through the multiple design configurations in 3D using Lorentz simulation codes. An optimized version of IRENA has been fully designed. The prototype has been built in 2009 for further tests.

In collaboration with NIPNE, the coupling of IRENA to the target unit has been designed. Taking into account the key parameters for both selectivity and fast release, different versions have been considered depending on the isotopes of interest. Figure 6.1 shows an example.

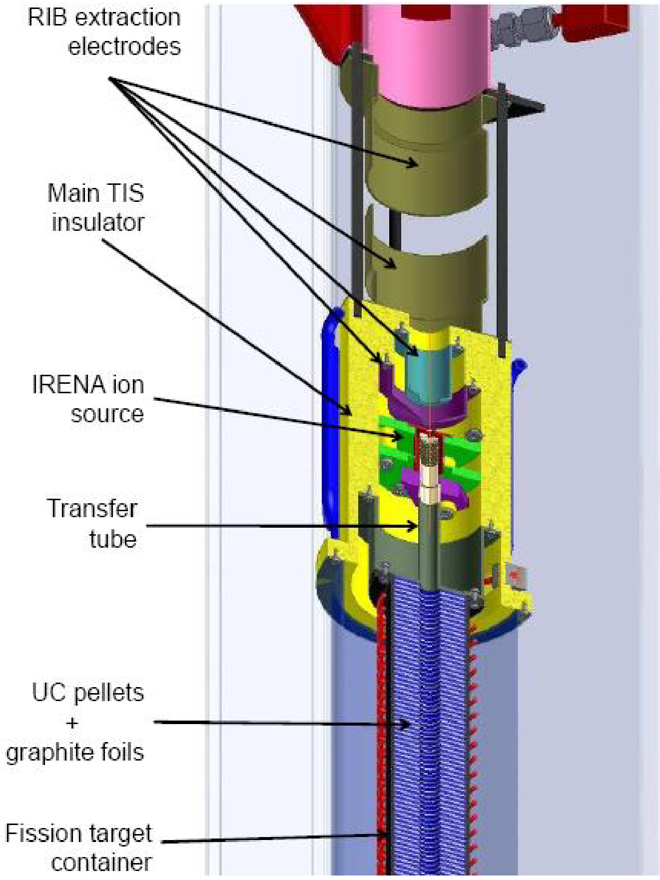

Figure 6.1: A version of the IRENA coupling to the target unit.

The coupling of RILIS to the target unit has been designed also in the collaboration with NIPNE. Similarly to the IRENA coupling, different versions have also been considered (fig. 6.2). The optimisation of the coupling depends on the characteristics of the ionisation cavity to be developed, and on the element of interest.

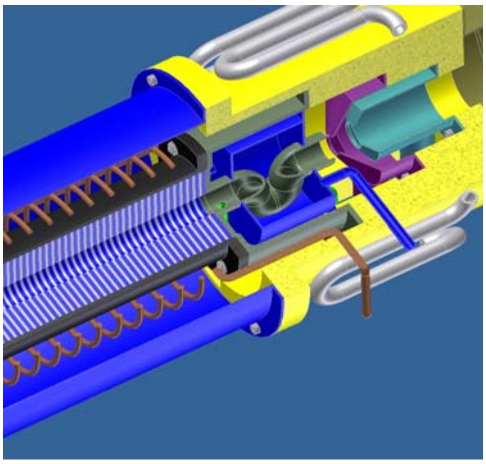

Figure 6.2: A version of the RILIS coupling to the target unit which includes a cooling system adapted to the environment of the MMW target station.

7 R&D Perspectives

A large number of tests and calculations are still required to work out the final IRENA prototype, the effective and operational one at the MMW target station. The R&D program established during EURISOL-DS project is promising insofar as the IRENA device already shows advantageous features. Its configuration is very close to the RILIS hot cavity or thermo-ionisation source. This makes IRENA a very adaptable complementary ion source. Furthermore, some IRENA developments should benefit both RILIS and thermo-ionisation source developments. For instance, to prevent plasma deterioration in the RILIS ionisation cavity at high pressure operation, a remedy could consists in using the IRENA radial structure and applying a low arc voltage to generate lots of radial electrons at low energy just to confine the plasma. Tests are planned in a second step to determine the best conditions to provide such a confinement without inducing ionisation so as to keep selectivity at maximum.

The IRENA configuration represents also one of the most minimal configurations of discharge ion source, without magnetic confinement, so one of the most reliable candidates for operating in strong-radiation environment.

By developing a transfer tube with adjustable cooling and heating, IRENA would gain in selectivity with, in addition, the option of functioning in a thermo-ionisation mode.

In this way, this ion source gives the possibility of accessing at once to a large variety of nuclear beams without the constraint of changing ion source.

8 Acknowledgement

We acknowledge the financial support of the European Community under the FP6 "Research Infrastructure Action-Structuring the European Research Area" EURISOL DS Project contract no 515768 RIDS. The EC is not liable for the use that can be made of the information contained herein.

9 References

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