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	Contributors:	Alberto MONETTI, Julien GUILLOT, Maher CHEIKH MHAMED, Mattia MANZOLARO, Michele BALLAN, , Pierre DELAHAYE, Sebastian ROTHE
	Reviewed by:	K. Rusek, Univ Warsaw
	Approved by:	M.N. Harakeh, KVI Cart

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LIST OF ACRONYMS AND ABBREVIATIONS

ALTO	Accélérateur Linéaire et Tandem d'Orsay
Cs	Caesium
FEBIAD	Forced Electron Beam Ion Arc Discharge
FE	Front-End
GANIL	Grand Accélérateur National d'Ions Lourds
HIE-ISOLDE	High Intensity Energy ISOLDE
ISOL	Isotope Separation On Line
MM	Mass Marker technique
PARRNe	Production d'Atomes Radioactifs Riches en Neutrons
SIRa	Radioactive Ion Separator
SPES	Selective Production of Exotic Species
SPIRAL	Système de Production d'Ions Radioactifs Accélérés en Ligne
TISS	Target Ion Source System
TIS	Target Ion Source
UC_x	Uranium Carbide
UC_2	Uranium dicarbide
UO_2	Uranium dioxide
VADIS	Versatile Arc Discharge Ion Source

EXECUTIVE SUMMARY

The first exotic neutron-rich krypton isotope beams were produced by the ISOL method at the Niels Bohr Institute more than sixty years ago from an irradiated thick UO_2 target. Along the years, different primary beam drivers were developed and used across new facilities worldwide, and techniques for the production of radioactive ion beams -subject of the BeamLab Task-, associated to chemistry, physics and material science, were combined to make available an ever-increasing number of chemical elements and exotic radioisotopes. A particular challenge is the release and separation with appropriate efficiencies of refractory and chemically reactive beams such as transition metal, post transition metal and metalloids. The problems come from their generally high melting points, low volatility at operating temperatures up to 2200°C commonly used for the ISOL target operation, associated with eventual chemical reactivity with the structural material components. These difficulties can be addressed using appropriate target and structural materials, and exploiting the formation of more volatile and stable compounds with chemical reactants made available from impurities or from injection of traces. A new delivery method for ^{34}S chemical was developed at ISOLDE in the context of BeamLab, and the production of stable tin sulphide beams was tested off-line at ISOLDE, SPES and ALTO. This technique was validated on-line at ALTO with a new photofission target design. In particular, beams of $^{134}Sn^{34}S^{+}$ ions, separated at mass 168 were detected.
ISOL targets and ion sources operate at very high temperature levels (~2000°C). The thermal behaviour and the design shape are among the main parameters controlling the performances of the ionisation and the release efficiencies of isotopes. In this framework, many optimisation studies were achieved by ALTO, GANIL, ISOLDE and SPES for developing new reliable and efficient prototypes of targets and ion sources.

INTRODUCTION

Radioactive ion beams are exploited by a large community of physicists active in nuclear physics, astrophysics, atomic physics, material science and life science. One technique to produce radioactive ions is the isotope separation online ISOL technique [1], in which a target is combined with an ion source to maximise the secondary beam intensity and chemical element selectivity. Because of the use of thick targets, the efficiency of the ISOL technique strongly depends on the physicochemical properties of the nucleus of interest, as well as those of the TIS material. This sensitive dependence can be turned into an advantage by a clever combination of material and chemical products. Various approaches have already been tried and tested to extract selectively nuclei of a chemical species or to improve the beam purity. In particular, the use of a chemical vapour to form a volatile molecule containing the nuclei of interest has proved its feasibility. A particular challenge is the release and separation with appropriate efficiencies of refractory and chemically reactive beams, such as transition metal, post transition metal and metalloids. The problems come from their generally high melting points, low volatility at operating temperatures up to 2200°C commonly used for the ISOL target operation, associated with eventual chemical reactivity with the structural material components. Overcoming these difficulties would lead to the production of completely new nuclear beams in ISOL technique opening the way to unexplored fields and applications. To achieve these goals new target prototypes and new techniques for molecular beam production were developed at ALTO, GANIL, ISOLDE and SPES Facilities. A new uranium carbide target was successfully developed at ALTO using 3 times less uranium material but resulting in significantly increased production rates. A new customised thermocouple C type was successfully developed at SPES and it monitored reliably temperatures up to 2000°C. Moreover, the coupled field electrical-thermal numerical (Finite Element Method - FEM) model developed at SPES was validated and adopted for calculating the global target temperature taking into account the primary beam thermal load. A new fusion-evaporation target-ion-source assembly is under development in the framework of a collaborative work between GANIL and IPNO.
The successful development of a new oven concept for the provision of elemental ^{34}S and off-lines tests carried out at ISOLDE and SPES has triggered a beam time request for molecular tin beams at the ALTO facility. In a collaborative manner, the new concept was simultaneously tested and developed further both at SPES and at CERN, coordinated by ALTO. Radioactive SnS^{+} molecular Beams were reliably and successfully produced at the ALTO facility. Thanks to the sulfurization technique, $^{134}SnS^{34}$ was well observed during this online experiment.

SECTION 1 – NEW TARGETS

1.1. A HIGH TEMPERATURE TARGET DESIGN FOR THE SPES FACILITY

The SPES project at INFN-LNL aims at the production of neutron-rich Radioactive Ion Beams (RIBs) using the ISOL (Isotope Separation On-Line) technique. A 40 MeV 200 μA proton beam will directly impinge a uranium carbide target, generating approximately 10^{13} fissions per second. The target system is installed under vacuum inside a water-cooled chamber, and when it is required to produce and extract isotopes/elements characterised by low volatility, it needs to be operated at extremely high temperatures, between 2000 and 2200 °C. During operation the proton beam and a dedicated tubular oven (the target heater indicated in Figure 1) heated by Joule effect provide the heating power required to keep the target at the desired temperature level. In figure 1, a scaled version of the SPES target (capable to absorb a 40 MeV 20 μA proton beam) is represented with some details regarding its architecture: the UC_x disks, the graphite windows, dumpers and target vessel, the Ta target heater, the Ta heater wings and the Cu target clamps. This target was specifically optimised to operate stably at extremely high temperatures during the first stage of the SPES facility commissioning and operation at LNL, before installing the aforementioned full power target designed for 200 μA of protons at 40 MeV.

In order to have a reliable temperature monitoring during the target operation, a custom type C thermocouple was specifically designed, positioned and tested at Legnaro National Laboratories (LNL).

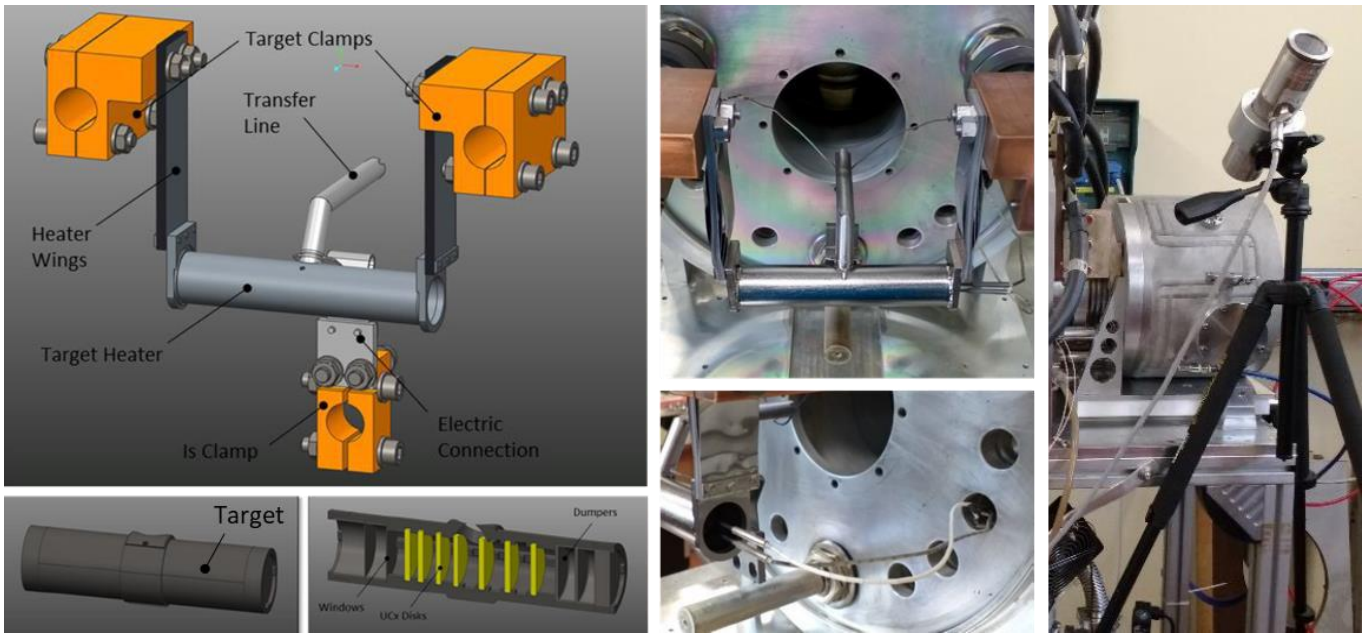

Figure 1: The scaled SPES target optimised for operation at very high temperatures: architecture and testing phase.

The results of the high temperature experimental tests performed at LNL are summarised in Figure 2. During these tests the target was heated making use exclusively of the target heater (Joule effect), with heating currents ranging between 400 and 1000 A. Thermocouples monitored reliably temperatures up to 2000°C and the target operated stably for some days without presenting any damage. Tests at higher temperatures started, showing the capability of the system to operate in the range of 2200 °C; a structured set of data will be collected within the first half of 2020. The coupled field electrical-thermal numerical (Finite Element Method - FEM) model developed to simulate the target thermal load effects proved to be capable of reproducing very closely the temperature data collected during the experimental tests. At this point, the numerical model was considered validated and ready to be adopted to estimate the target temperature fields taking into consideration also the proton beam thermal loads that were calculated making use of specific Monte Carlo codes.

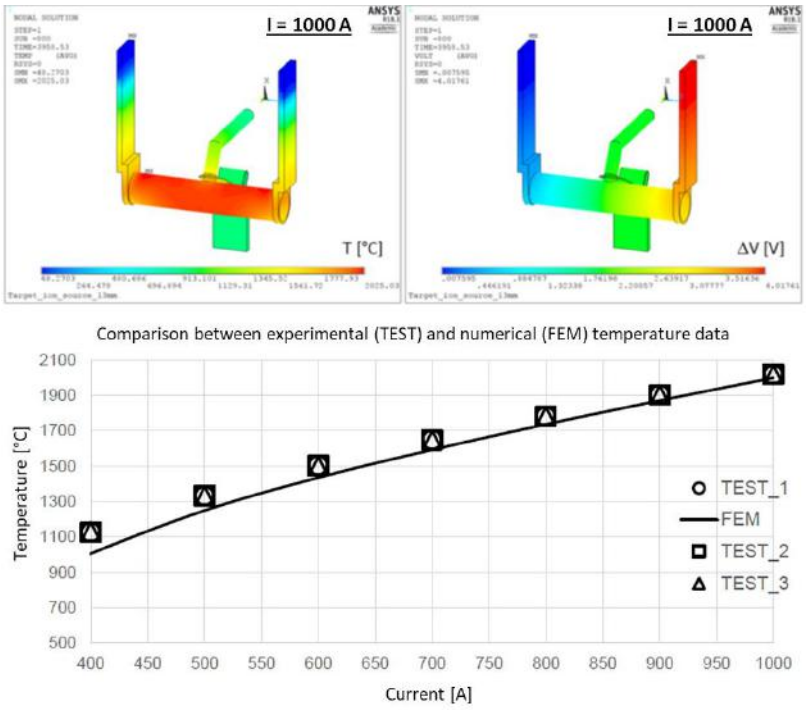

Figure 2: Target temperature and electric potential fields related to the maximum heating current value (1000 A) and temperature comparison between experimental tests (TEST_1, TEST_2, TEST_3) and the numerical model (FEM) for heating current values ranging from 400 to 1000 A.

Figure 3 reports both the average and the maximum temperatures as a function of the two thermal loads for the target, that are heater current (Joule effect) and primary beam intensity (protons). Isothermal lines in these plots allow defining all heater current and primary beam intensity combinations capable to reproduce the same target temperature. All these simulated data will be extremely useful during on-line operation at LNL.

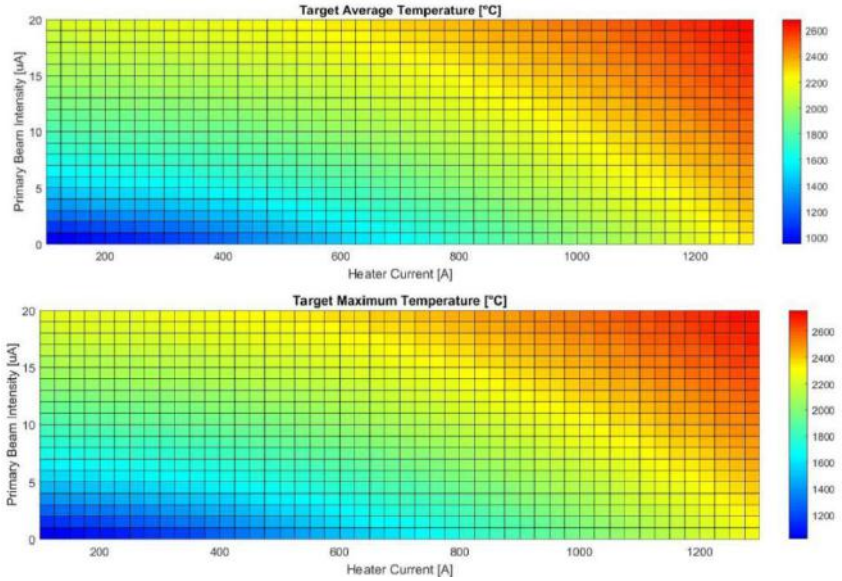

Figure 3: Target average temperature and target maximum temperature for different thermal load combinations (the two thermal load components are the Joule heating current and the primary beam intensity).

1.2. MATERIAL PROPERTIES INVESTIGATION AT GANIL

In the framework of the subtask 2 “material compatibility in reactive atmospheres”, GANIL has been investigating some of the properties of the material often used within the target and TISS design.

Materials used within the design of Target Ion Source Systems must fulfil constraints related to the hostile environment of high temperatures and high radiation dose rates. Characteristics available in the literature generally correspond to physical characteristics obtained under well-defined experimental conditions; in order to remove the influence of parameters unrelated to the material itself, as for example roughness of the material, which can strongly change the apparent emissivity. Within the framework of the TISS design, engineers need a database of material characteristics, which have been measured in experimental conditions close the working conditions of the TISS. Dedicated systematic measurements of electrical resistivity and thermal emissivity of materials provided by suppliers, and used as such, have been performed for different metals: carbon paper (Papyex), molybdenum, niobium, tantalum, nickel, titanium, vanadium, iron and cobalt.

The description of a specific setup, designed to measure the resistivity and the emissivity [2] gives the possibility to a potential user to appreciate the reliability of the method and of the results. The results have been extracted in the same experimental conditions. The values are affected by identical systematic errors, allowing a relative comparison easing the choice of the most suited material to a given application. Emissivities obtained for materials formerly mentioned are given in Figure 4.

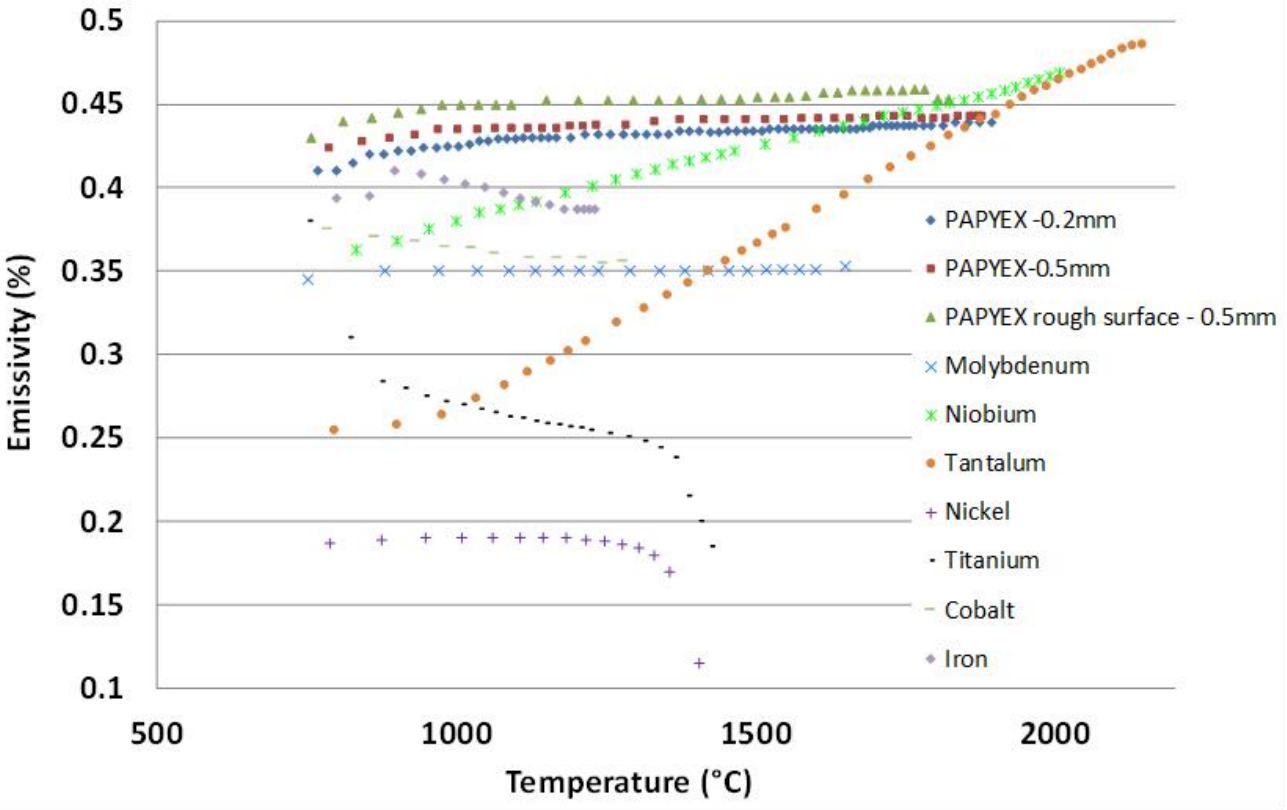

Figure 4: Emissivity as a function of temperature for different metallic samples. Estimated uncertainty: ± 5,3%

1.3. TARGET OPTIMISATION FOR PHOTOFISSION AT ALTO

The development of neutron-rich radioactive beams for the study of the structure of exotic nuclei is at the heart of the ALTO facility's research programme. To carry out this project, we produce ions using the ISOL technique (on-line isotope separation). For many years, the various facilities using this technique have been working to develop the most intense beams possible by increasing the number of nuclei present in the targets [3]. This approach generates heavy constraints on the target-ion source assemblies such as increasing the size of the target or dissipating the power of the primary beam deposited in the target.

An alternative approach is the optimisation of the existing parameters and in particular, the optimisation of the ratio of the number of uranium nuclei used to the number of fissions produced. This is the choice we made at the ALTO facility.

To carry out this study, the Monte Carlo code Fluka was used to simulate the fission production process in a uranium carbide target [4], [5]. In a previous study conducted at ALTO, it was observed that 90% of the fission products were produced in the first six centimetres of a 19.3 cm long target [6]. It was therefore decided to carry out modelling on both a so-called "long" target (193 mm) and a so-called "short" target (60 mm) for comparison.

The pellet structure was not modelled because it does not affect the production of fission products but rather their release. For the two simulated configurations i.e. short and long target, we have used a primary electron beam of 50 MeV of energy and 10 µA and a UCx target of 3.82 g/cm^3 of density. Figure 5 shows the electrons, photons and fission products distributions obtained for each of the two targets.

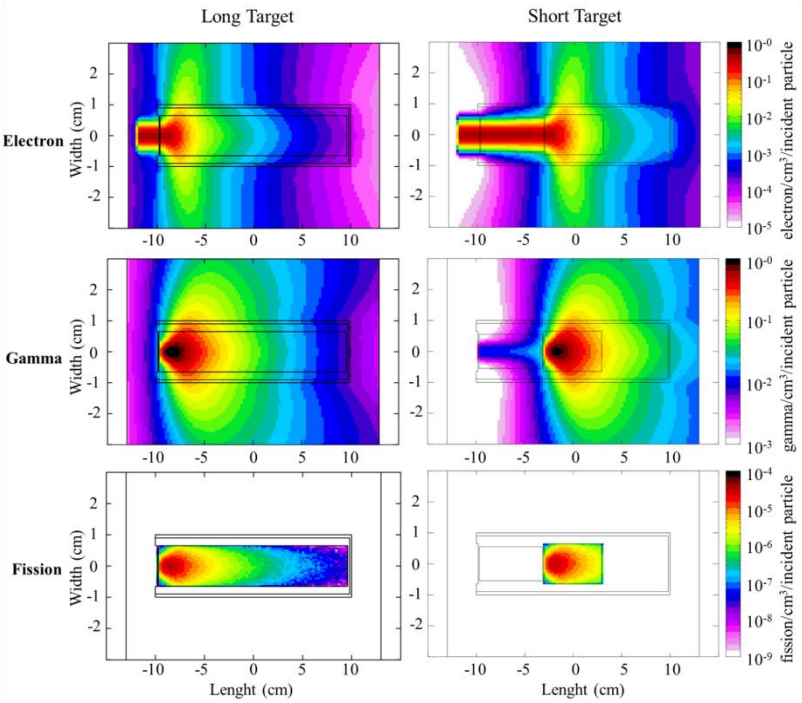

Figure 5: Electron, gamma and fission distributions obtained for long and short targets.

In the case of the "long" target, the electrons penetrate shallowly into the target. In fact, about 90% of the electrons interact in the first 6 centimetres of this target. Interestingly, when a "short" target is used, the electron distribution profile is the same in the target. Thus, decreasing the size of the target does not impact the Bremsstrahlung effect at the beginning of the target. As a conclusion, by reducing the length of the target to 6 cm, the number of fissions produced remains almost the same. Indeed, the total number of fissions produced in the long target is 2.22×10^{10}

compared to 1.97×10^{10} in the short target (Figure 6). The reduction in the volume of the target has made it possible to optimise the fission to volume ratio of uranium used. This has the direct consequence of generating three times less radioactive waste. In addition, with a smaller target size but centred in the oven, fission products are created closer to the opening leading to the transfer tube prior to ionisation and in a smaller volume than before, which will improve effusion efficiency.

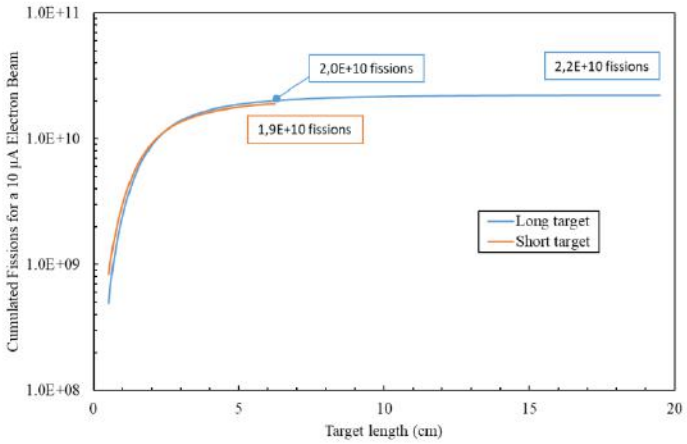

Figure 6: Cumulative fissions obtained for a "long" (blue curve) or "short" (orange curve) target for a 50 MeV electron beam at an intensity of 10 µA.

As a result of the simulations, the "short" target geometry was adopted at the ALTO facility. A graphic container dedicated to this new target was designed. During the radioactive ion campaign conducted at ALTO in June 2019, a short target was tested and production measurements were carried out on Caesium nuclei of mass 139 to 148.

For this experiment, the UC_x target was synthesised by following the conventional protocol used at ALTO [7], which consists of mixing ground uranium dioxide (UO_2) powder with excess graphite and then pressing this mixture into pellets 13 mm in diameter and 1 mm thick. These pellets are placed in a graphite container and then heated to 2000°C to produce uranium carbide (Figure 7). The container is then installed in the target-ion-source system to be irradiated.

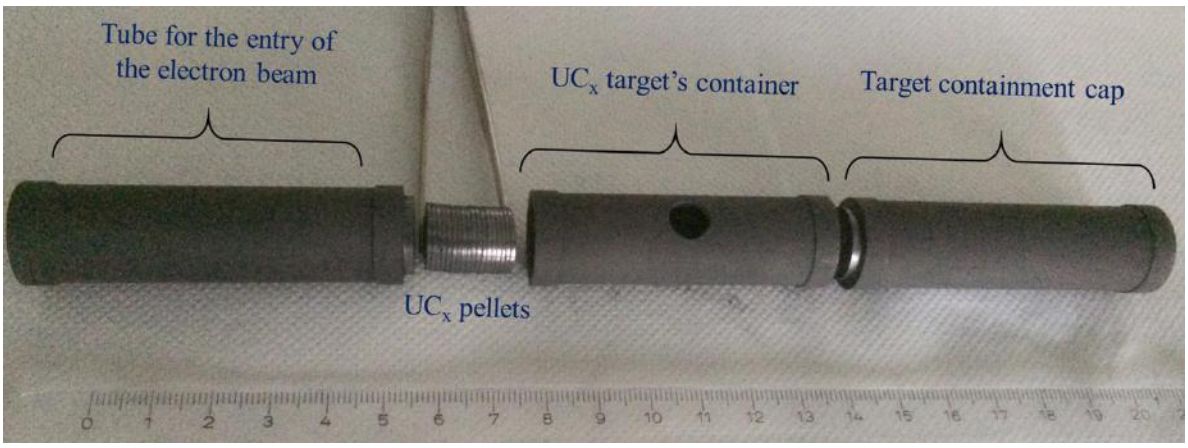

Figure 7: Short target configuration in its graphite container irradiated at ALTO in June 2019.

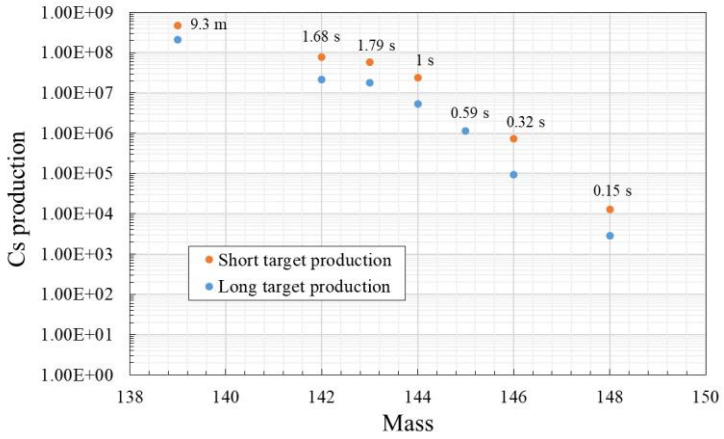

Figure 8: Caesium production obtained with a short target during the radioactive ion campaign conducted at ALTO in June 2019; comparison with previous results.

The obtained Caesium production rates are presented in Figure 8. The reduction in target size resulted in production rates that were 2-4 times higher for Caesium ions with masses between 138 and 146 and 5-8 times higher for those between 146 and 148. Thus, this strategy has not only reduced the quantity of radioactive material used but has also significantly increased production rates. The reduced size of the target and its confinement under the source has made it possible to reduce the path of the particle from its exit from the UC_x target to its ionisation volume. The other advantage of this approach is to drastically reduce the amount of radioactive waste generated during on-line experiments. Thus 70% of material compared to long targets could be saved.

1.4. TARGET DEVELOPMENTS FOR FUSION-EVAPORATION REACTION WITH ISOL TECHNIQUE

A thin (4µm) nickel target is under development to produce neutron-deficient short-lived isotopes by fusion-evaporation reactions at the ALTO and GANIL facilities. Its dimensions are relatively large (-40 mm in diameter) to limit the primary beam power deposited per cm^2. The expected working temperature is 1300°C at maximum, and the target should last 2 weeks at minimum.

During the first tests, the nickel foil tore in regions where the temperature was the highest (Figure 9). An analysis showed that the microscopic structure changed during the heating process. Crystals formed, leading to shrinking and finally to breaking the foil (Figure 10).

Tests will be performed in 2020 to better understand the microstructure evolution of the nickel and if possible to fix this issue before using the foil as a reaction target.

Figure 9: Image of the nickel foil installed on its graphite frame before (left) and after (right) the heating period.

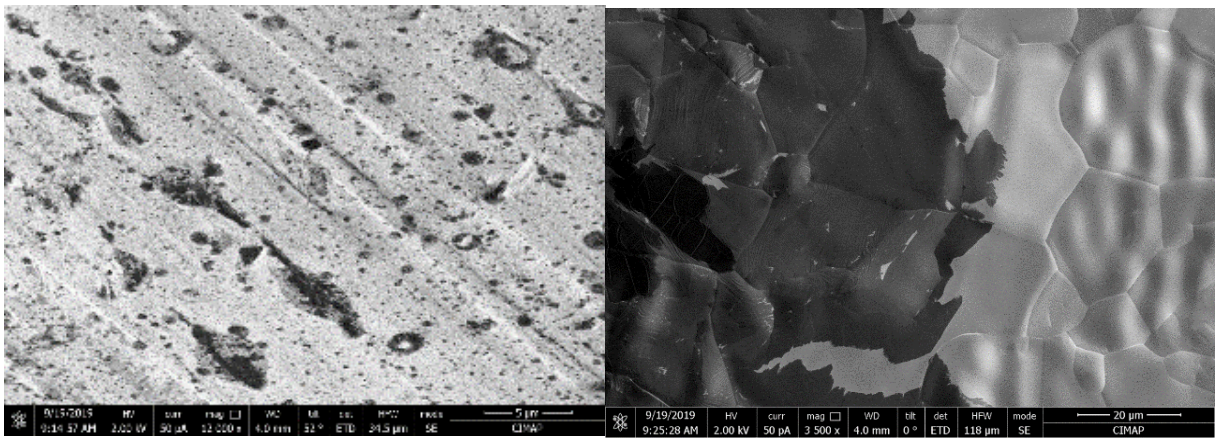

Figure 10: Microscopic Image of the nickel structure before (left) and after (right) the heating period. Full width of left image: 34.5 µm. Full width of right image: 118µm.

SECTION 2 – ION SOURCES FOR DIFFICULT ISOL BEAMS

At GANIL, in 2018 and 2019, the SPIRAL 1 upgrade has been commissioned on-line with the VADIS [8] ion source coupled to the standard SPIRAL 1 targets. Such a target – ion source system (TISS) is new for the SPIRAL 1 facility. Fig. 1 summarises the development phases of the new TISS. It presents the evolution of yields for some of the new beams delivered by the TISS since its very early development phase. In 2011, a test at low power was undertaken on the SIRa test bench. Figure 11 shows a projection of the measured yields for a nominal power (1200W). In 2013, a very short test was undertaken at full power at SPIRAL 1 [9]. Many isotopes of elements such as Na, Mg, Al, P, and Cl were observed with intensities ranging from a few 100 pps to 10^8 pps. From 2014 to 2017, the facility was temporarily stopped, to undertake infrastructure work required to include a charge breeder. The charge breeder enables the post-acceleration of the beams produced by the new TISS by the cyclotron CIME. One of the main aims of the on-line commissioning was to reproduce the yields measured in 2013. In 2018, a difficult start-up of the TISS prevented the measurement of reliable yields [10]. A modification to fix a weakness issue with the insulators of the FEBIAD was undertaken. In 2019, the new and modified TISS was successfully used to produce a beam of ^{38m}K for a Coulomb-excitation experiment. Such a beam could be accelerated to the required rate ($7{\cdot}10^5$ -5.10^7 –pps), by using the FEBIAD ion source in surface – ionisation mode. Finally, the intensities obtained in 2013 could be nominally reproduced within a factor of 2, except for ^{33}Cl, for which a lower intensity was measured. The yields re-measured in 2019 with the consolidated version of the TISS are encouraging for future experiments at SPIRAL 1. These include beams such as Al or Cl, which are traditionally difficult to produce with the ISOL method. The new TISS enables the formation of molecular beams. First attempts to test this method at SPIRAL 1 for optimising the yields of short-lived Al beam were undertaken during the tests of 2019. A SF6 gas was injected as a support gas in the FEBIAD TISS, while a ^{36}Ar beam was impinging on the graphite target. While the leak rate was experimentally difficult to control, the measured yields for these beams after the injection of SF6 was visibly increased. The measured rates were improved by a factor of about 10 for ^{25}Al (see Figure 11), and 3 for ^{26m}Al. The reason for the determination of different enhancements for these 2 isotopes of comparable half-life has still not been identified. Further studies for enhancing the yields of these beams by forming AlF molecules are scheduled in 2020.

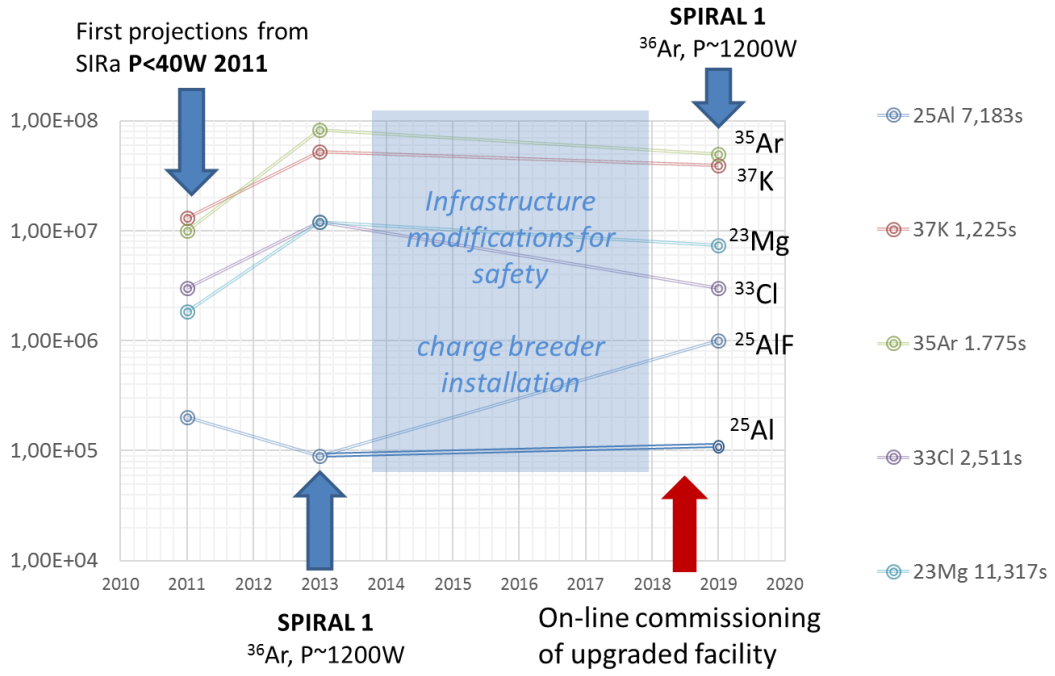

Figure 11: Evolution of some yields from first tests at low power in 2011, at nominal power in 2013, and finally at the on-line commissioning of the facility in 2019. From 2014 to 2017, the facility was shut down for infrastructure work.

Section 3 – Molecular Beams

3.1. *Development for new molecular beams at the SPES offline Front-end*

At the SPES off-line facility, a development programme for new molecular beams was carried out, dedicated to the efforts in production of tin molecular beams, due to the growing physics interest. As demonstrated in [11], sulphur could react with Sn, creating a molecular SnS^+ ion beam. In order to achieve this, it is essential to supply sufficient S atoms to the target and ion source system.

Due to the lack of availability of isotopically enriched S-based gases, in the case of sulphide beams, it is desired to introduce isotopically pure ^{34}S in elemental form. However, experiments led at ISOLDE showed that, when using the standard Mass Marker technique (MM), it is concluded that all sulphur is released already during the initial conditioning and calibration of the target. Indeed, the heating power transferred by conduction and by radiation from the hot target can increase significantly the temperature of the mass marker capillary. Measurements with thermocouples have shown that the coldest point in the mass marker capillary still exceeds the boiling point of sulphur of 444 °C.

The first test at the SPES offline FE was performed with the standard mass marker technique: the Sn metallic foil was bonded with the natural sulphur powder (not enriched) and inserted inside the capillary tantalum tube, as shown in Figure 12.

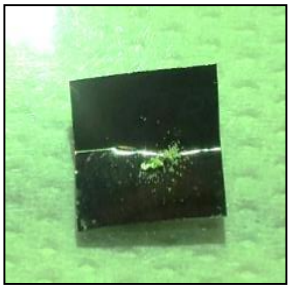

Figure 12: Sn metallic foil with S powder.

In order to obtain the temperature profiles of the mass-marker capillary for different heating currents, numerical calculations were performed and the results are presented in Figure 13. The dotted red line represents the position where the Sn metallic foil was positioned.

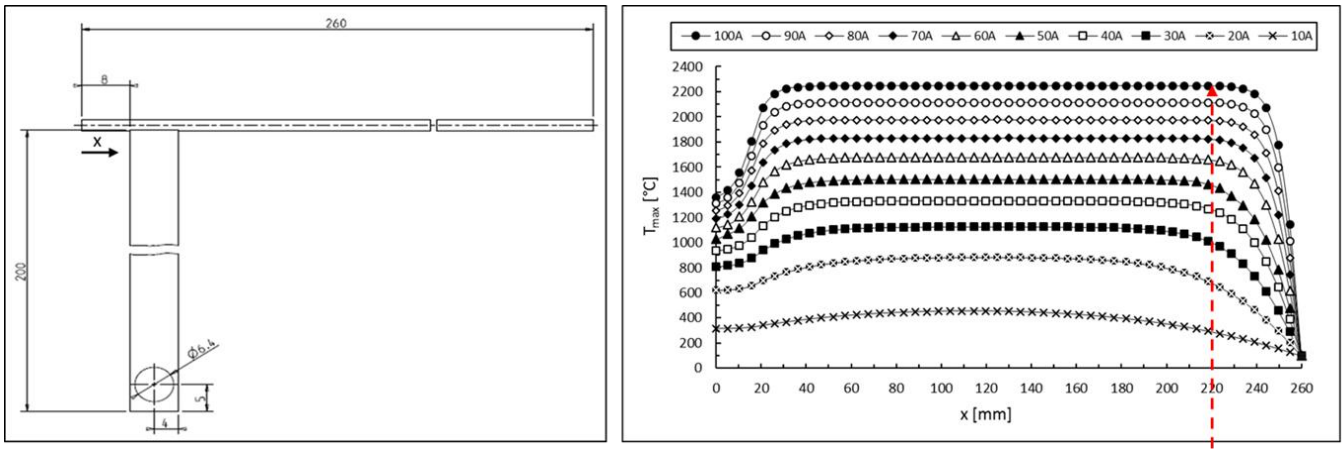

Figure 13: Assembly of the S delivery system for the first tests with the temperature profile.

Previous tests with only Sn foil showed that Sn beams started to be visible for oven temperatures close to approximately 1350°C. On the other hand, when the sulphur was added to the Sn foil, SnS, Sn and S beams started to be visible with an oven current of 30 A, corresponding to oven temperatures of approximately 1000°C. At an oven current of 50 A (about 1450°C of temperature), the interesting SnS beams were the dominant part, as presented in Figure 14.

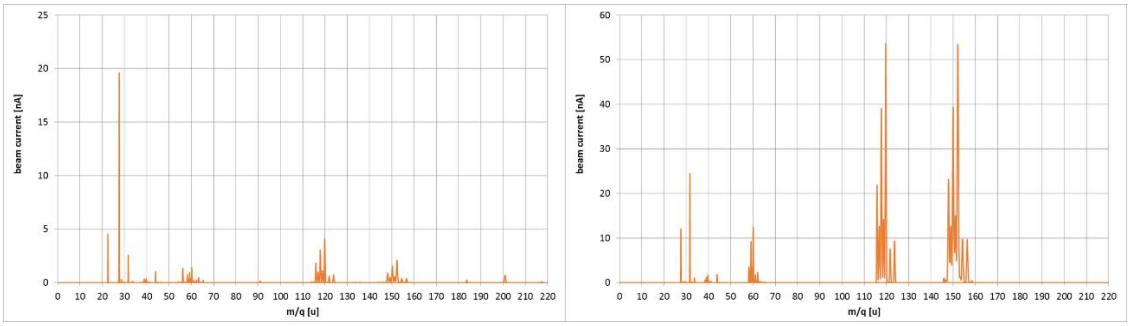

Figure 14: Beam current for various masses currents: 30 A - 1000°C (left); 50 A - 1450°C (right)

In addition, the Sn beams present at low temperature were probably due to the dissociation of the SnS molecules in the plasma chamber. These tests clearly demonstrate the higher volatility of the SnS molecule with respect to elemental Sn: a faster transport of Sn is expected to translate immediately to a yield increase for very short-lived Sn isotopes. Moreover, the use of SnS molecules will allow for obtaining beams of isobarically pure neutron-rich Sn isotopes. In fact, Sb and Te isotopes are the main contaminants of the Sn beams, but sulphides of Sb and Te do not form or are not released from the target. In this way, the SnS beams will result to be essentially pure because masses are out of the fission production range of SPES.

On the other hand, these tests showed the importance of a controlled and slow release of the sulphur. During the online experiment, the sulphur cannot be refilled and the risk of uncontrolled injection of rather large quantities of sulphur is quite high. In order to be able to control the release of sulphur, at ISOLDE a new concept for the MM was proposed. According to this solution, the sulphur sample is placed within a cartridge made of Boron Nitride (BN) heated by a 1 mm diameter tantalum wire, as shown in figure 15. In addition, the cartridge is placed in the water-cooled aluminium flange of the target unit assembly at a location that is less affected by the thermal radiation coming from the hot target and ion source. Once vaporised, the sulphur diffuses through a standard mass-marker tantalum capillary to the target and ion source volume.

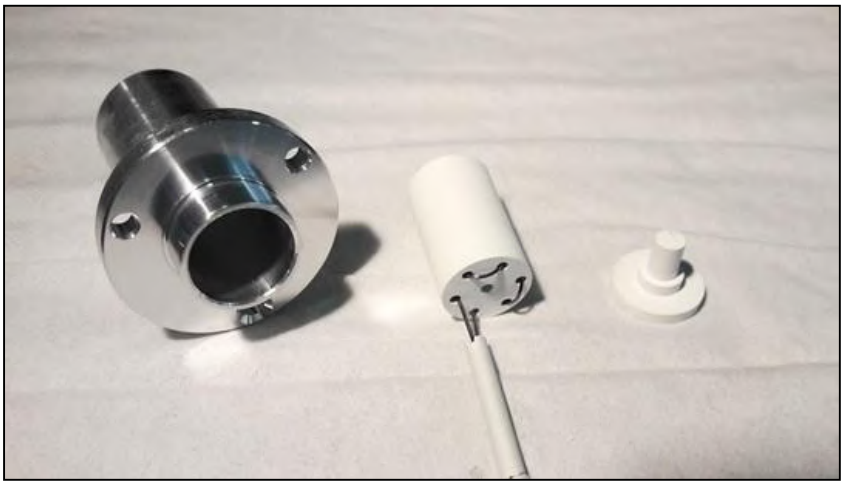

Figure 15: Heater assembly for reactants with low boiling point (CERN). From left to right: Aluminium case, heating cartridge: boron nitride insulating the tantalum heating wires and containing the sulphur powder, plug.

Tests with this prototype were performed at SPES offline Front-End (FE). Since for such test a TIS unit including only the SPES Plasma Ion Source (PIS) without the target heater was employed, it was not necessary to assemble a longer Ta oven with a thermal radiation shield, as suggested by the ISOLDE team. A photograph of the assembly is presented in Figure 16. It was indeed possible to verify that, when the ion source was heated by a 400 A current, less than 1 nA S current was detected.

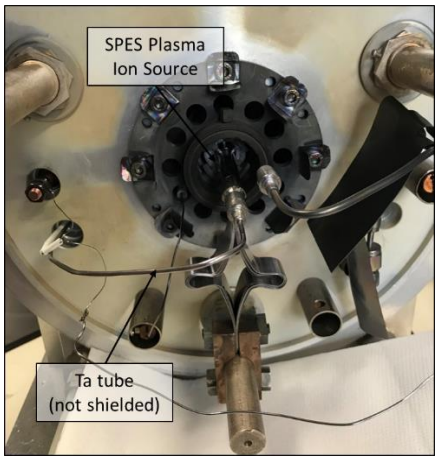

Figure 16: Final assembly of the S delivery system. Its heating circuit was connected to the oven feedthroughs.

During the tests, a controlled release of the sulphur was verified and the following observations and conclusions were made:

- The oven current should be regulated in much smaller steps with respect to the SPES standard 1 A step increase
- In collaboration with the CERN team it was suggested to increase the tantalum heating wire diameter to decrease heating power
- The release of the sulphur increased for consecutive tests performed on the same assembly

The last point is very important because this effect might be attributed to the Ta surfaces of the capillary tube that react with the first load of S, forming a thin layer of TaS_2. Such layer might act as passivation for the material, reducing the likelihood of additional chemical reactions between the Ta substrate and the incoming S and letting the sulphur travel undisturbed to the ion source. This is probably why the power required to release sulphur was lower for the latter tests respect to the first one, as shown in Figure 17. Moreover, these tests showed that the total amount of sulphur needed to perform a full experiment is certainly higher due to the reaction between Ta and sulphur.

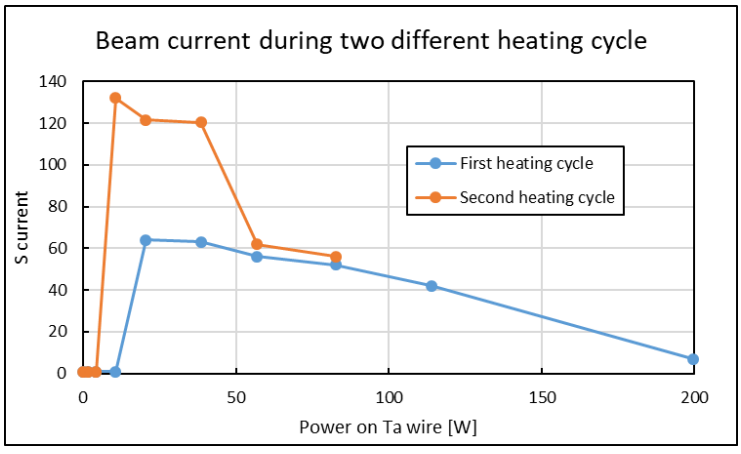

Figure 17: Sulphur beam current (nA) for power on the S oven during two consecutive tests.

3.2. MOLECULAR TIN BEAM DEVELOPMENT FOR ON-LINE EXPERIMENTS AT ALTO

As presented in the previous paragraph, a design change was suggested by CERN towards even better controllability of the temperature of the sulphur cartridge. This improved delivery system will enable fine control for the supply of sulphur as chemical reactant required for the formation of radioactive molecules. The number of windings was reduced to one loop only, and the wire thickness was increased. This has improved the working range of the system while maintaining the relatively coarse controls of the respective current supply. The final heating cartridge is shown in Figure 18.

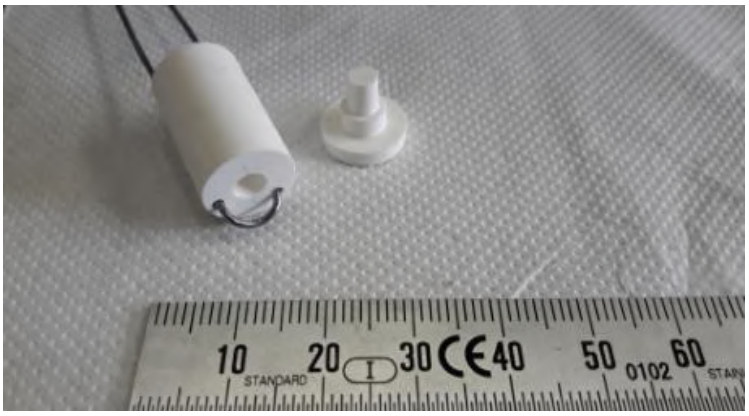

Figure 18: New sulphur heating cartridge. Only one loop is required and the cross section of the wire has been increased.

At CERN a two-week off-line campaign was scheduled, investigating the robustness of the delivery system as well as the ionisation efficiency of SnS in combination with standard target and ion source configuration – chosen to be as close to the ALTO on-line experiment as possible.

The main result from the off-line campaign is the successful measurement of the overall efficiency for SnS delivery, which includes the formation of the molecule Sn + S -> SnS, the survival of the molecule while transported to the ion source, the ionisation process itself, and finally the mass separation. Two consecutive ionisation efficiency measurements were performed, yielding 4.9% and 7.9% respectively. This result is very promising for on-line application for this molecule. Other key findings resulting from the tests are the requirement of a transport capillary made from molybdenum – tantalum has been found to react too well with sulphur, leading to embrittlement of the capillary. The use of a sample of ~100mg enriched sulphur has been found sufficient for a typical on-line operation period of 10 days. Larger sample sizes require an increase of the boron nitride cartridge inner volume, which should be feasible if a bigger quantity should become necessary. Furthermore, we have operated the ion source for 14 days with sulphur atmosphere potentially reacting with the material of the source. The krypton ionisation efficiency was monitored throughout the campaign and was found to be rather stable. Additionally, the approximately 5 heating and cooling cycles did not affect the performance of the ion source. In conclusion, the sulphur delivery system was found to be rather reliable and robust.

Two VADIS ion sources and sulphur delivery systems have been produced at CERN and were shipped to ALTO to be used for the off-line and the on-line experiments.

3.3. ON-LINE RADIOACTIVE MOLECULAR TIN BEAMS PRODUCTION AT ALTO

The successful developments at SPES and ISOLDE have triggered the beam time request for molecular tin beams at the ALTO facility. In a collaborative manner, the new concept was simultaneously tested and developed further both at SPES and at CERN, coordinated by ALTO. In October 2019, with the participation of ALTO, SPES, GANIL and ISOLDE teams, an off-line test was carried out at ALTO for the production of SnS stable beams using pure ^{34}S as a reactant and using a transport capillary made from molybdenum.

The main goal of this offline test was to find out the optimum parameters for operating the TIS for the on-line experiment at ALTO. The new sulphur delivery system was coupled to a VADIS ion source and the standard target configuration at ALTO. Also, in the SPES and ISOLDE off-line tests the sulphur vapour was injected directly in the transfer tube towards the ionisation volume, while in the ALTO configuration, it was decided to inject the sulphur vapour directly in the target volume through a special hole drilled on the axis of the tantalum target oven. It was also decided to use the new short target configuration in this experiment (presented in §1.3) and the short graphite container was filled with graphite pellets simulating the presence of the UCx pellets in the on-line configuration. In these tests, the target was heated up to 2000 °C and the ion source and the transfer line up to 1950 °C. We note that the maximum temperature reached for the target at the ISOLDE tests was 1850 °C. Figure 19A shows the TIS configuration for the off-line tests at ALTO. The main outputs of this test are:

- Stable SnS molecules are already formed, extracted and identified on the PARRNe mass separator.
- The sulphur system delivery connection seems to be reliable.
- At 2000 °C of target heating, sulfur vapour is emitted very quickly and it was very hard to control the evaporation reaction.

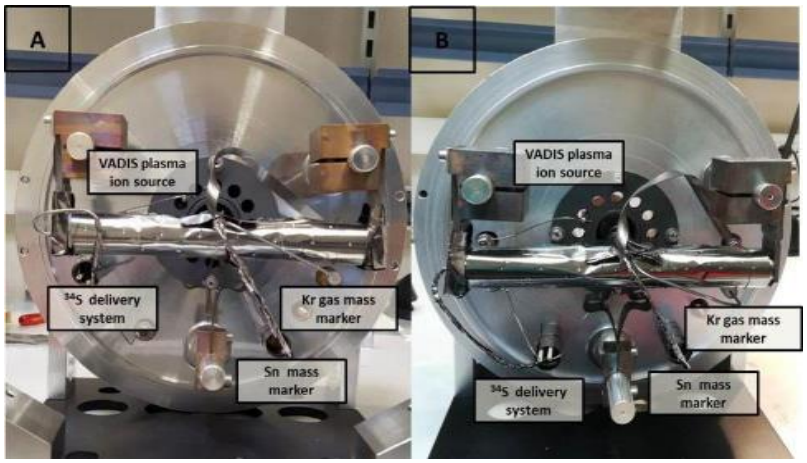

Figure 19: A: Final assembly of the S delivery system in the off-line configuration. B: Final assembly of the S delivery system in the on-line configuration.

As a main conclusion, it was decided, for the on-line configuration, to move the sulphur delivery system further away from the target container and to improve the heating protocol of the sulphur evaporation system in order to better control the evaporation process. Figure 19B shows the TIS configuration for the on-line tests at ALTO.

The on-line radioactive SnS Beam production experiment took place in November 2019 with the participation of ISOLDE, SPES and ALTO teams over two weeks. The starting phase was the production of SnS stable beams in the real operation conditions. After optimisation of the target and ion source parameters and the heating power of the sulphur cartridge, we have measured the overall molecular production efficiency ($I_{SnS}/(I_{SnS} + I_{Sn})$) which was 75%.

For this experiment, a VADIS ion source was coupled to the new short UCx target and the sulphur delivery system connected as described above. The UC_x target was impinged by an electron beam of 50 MeV of energy and 10 µA

of intensity and the PARRNe tape station was used as the implantation setup of the radioactive isotopes for measuring production yields of elemental Sn and SnS isotopes. The main results of this experiment are radioactive SnS molecules are well formed and released from the UCx target volume in a stable way and with stable intensities over the time. ^{132}Sn and ^{133}Sn was produced but ^{132}Sn^{34}S and ^{133}Sn^{34}S were much more released. Moreover, ^{34}Sn isotopes have not been detected in elemental form but were observed in ^{134}Sn^{34}S form. The major observation is the purification of the tin beams by sulfurization. We note the antimony, main isobaric contaminant of tin isotopes, was suppressed and we got very pure SnS beams. Figure 20 illustrates the purification effect of the sulfurization process in the case of ^{133}Sn^{34}S production.

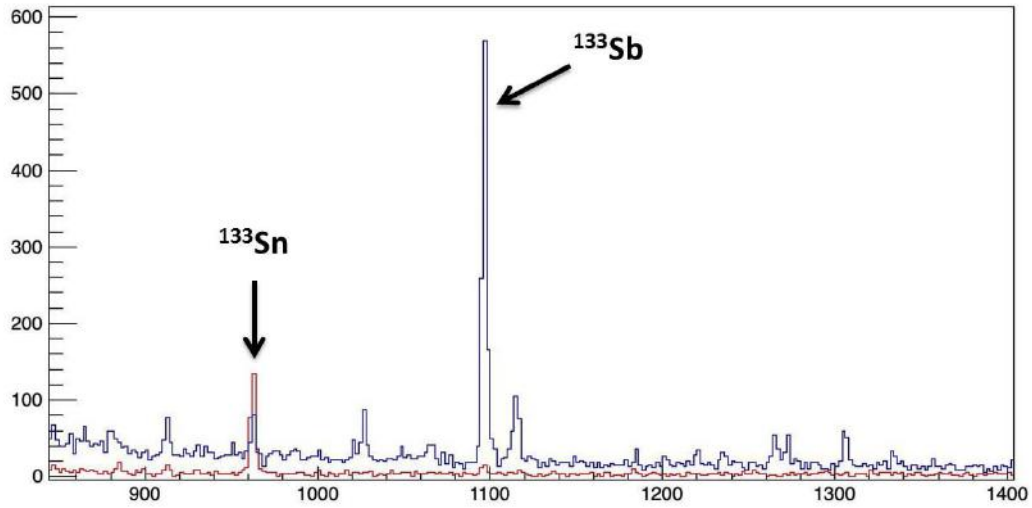

Figure 20: Blue curve: gamma spectrum for mass 133 obtained with standard release technique, red curve: gamma spectrum for mass 167 (133+34) obtained with sulfurization release process. A clear increase of ^{133}Sn yield is obtained by the sulfurization process.

CONCLUSION

A valuable collaborative work has been carried out in the framework of the Beamlab task. The most critical parameters for targets and ion sources were studied which led to the development of new optimised prototypes of targets and ion sources. The results obtained will be benefit for worldwide ISOL-type facilities.

The success of the new technique of sulfurization developed in the frame of the Beamlab task will also immediately benefit the ALTO and ISOLDE facilities for addressing the increasing demand for difficult exotic beams.