The LIEBE high-power target: Offline commissioning results and prospects for the production of ^{100}Sn ISOL beams at HIE-ISOLDE

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Abstract

With the aim of increasing the primary beam intensity in the next generation Radioactive Ion Beam facilities, a major challenge is the production of targets capable of dissipating high beam power, particularly for molten targets. In that context, a direct molten loop target concept was proposed for short-lived isotopes for EURISOL. The circulation of molten metal enables the production of droplets enhancing the radioisotope diffusion. The concept also includes a heat exchanger ensuring thermal equilibrium under interaction with high proton beam power. A target prototype, named LIEBE, has been designed and assembled to validate this concept in the ISOLDE operation environment. The project is now in an offline commissioning phase in order to confirm the design specifications before tests under proton beam. Successful outcome of the project can lead to new beams with great interest in nuclear structure and physics studies. In particular, investigations fall short in the region around the double magic isotope ^{100}Sn at ISOL facilities because of the lack of a suitable primary beam driver and target-ion source unit for any of the present-day facilities. Achievable ^{100}Sn beam intensities and purities are calculated with ABRABLA and FLUKA considering the use of a high power molten lanthanum target combined with molecular tin formation and a FEBIAD ion source. The presented option takes into consideration upgrade scenarios of the primary beam at ISOLDE, going from a 1.4 GeV - 2 µA to a 2 GeV - 4 µA pulsed proton beam.

1. Introduction

Radioactive ion beam facilities constantly aim to enhance their key figures of merit, their beam intensity and purity, in order to cope with the increasing demands from experimental physics. Considering the factors influencing the radioisotope yield, i, described in equation.1 for ISOL facilities [1], a widespread approach is to increase the primary beam intensity, ϕ, and the isotope production cross section σ, eventually with a better choice of the primary beam energy. Folded with the number of target atoms intercepting the beam, N, the total isotope production is then reduced by efficiencies for diffusion-effusion of the species, their ionization and transport through a mass separator.

$$i = \phi \cdot \sigma \cdot N \cdot \epsilon_{target} \cdot \epsilon_{source} \cdot \epsilon_{sep} \cdot \epsilon_{transmission} \quad (1)$$

In that context, the new LINAC4 injector at CERN will allow the PSBooster to provide a 4 to 6.7 µA proton beam intensity [2], a two to three-fold increase compared to the 2.2 µA delivered with LINAC2 up to now. Along with the intensity increase, a proposal to increase the PSBooster energy from 1.4 GeV to 2 GeV was submitted to the CERN research board [3].

Although an upgraded primary beam will increase the production of radioisotopes in the target, no improvement will be achieved in the case of short-lived species if their release time is much longer than their half-life, which results in a low ϵ_{target}. Moreover, the increased power of the primary beam will induce higher thermomechanical stresses in the beam intercepting elements and will exceed the capacity of the present static target designs for power dissipation. The impact of a pulsed proton beam in liquid targets has been reported to create periodic stresses leading to damage of the container and beam window [4] [5] [6]. Consequently, new designs have to be implemented in order to fully exploit the possibilities offered by a high power primary beam. For that purpose, a concept of a molten target for direct beam production at 100kW cw 1GeV proton beam was proposed for EURISOL [7]. The concept consists in a loop of molten metal enhancing the radioisotope release by the formation of small droplets. The size and shape of the droplets greatly reduce the isotope diffusion time, improving the yield of short-lived isotopes [8]. In addition, the molten target material dissipates the excessive heat via an heat exchanger. LIEBE (Liquid Eutectic Lead Bismuth Loop Target for Eurisol) is a prototype target aiming to demonstrate that concept in the ISOLDE operation environment compatible with both a pulsed beam and several kW's of incoming beam power.

2. The LIEBE high power target

The prototype design [9], presented in Figure 1, circulates Lead-Bismuth Eutectic (LBE) in a loop at temperatures between 200 and 600 °C by the action of an external electromagnetic (EM) pump. The loop contains an irradiation chamber designed to cope with high power thermomechanical shocks from the PSBooster proton beam as well as a grid for liquid metal fragmentation into ⌀0.4 mm spherical droplets [10] [11]. Directly downstream, the droplets fall through a diffusion chamber where the radioisotopes are released and travel towards a VADIS ion source. Considering LBE at 600 °C the calculated release efficiency is a factor 5 higher for the exotic ^{177}Hg ($T_{1/2}$ = 127 ms) isotope compared to standard molten ISOLDE targets [9] [4].

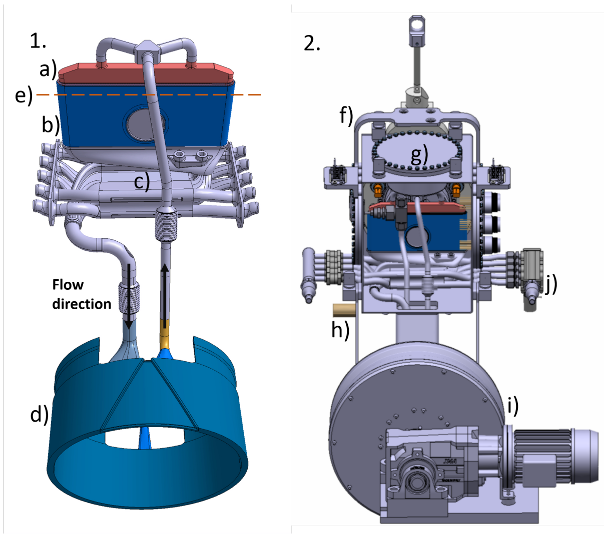

Figure 1: Schematic of the LIEBE prototype. 1. Liquid metal loop: a) irradiation chamber, b) diffusion chamber, c) heat exchanger (HEX), d) EM pump channel, e) proton beam path. 2. Second envelope f) robot handle, g) LBE tank, h) accelerometer, i) EM pump, j) water electrovalves.

Thermal control is achieved by 18 thermocouples coupled to heating elements around the loop. Excessive heat deposited by the proton beam can then be dissipated in a water-cooled heat exchanger designed with 5 different contact surfaces that one can separately actuate to tune the LBE temperature. The loop is enclosed by a second stainless steel envelope ensuring containment of the LBE in case of mechanical failure. Integrity of the cover is controlled by a pressure sensor monitoring a low pressure argon atmosphere inside the double envelope. In addition, the coupling of the loop target with the EM pump is guaranteed to be contact-less by checking the vibration level with an accelerometer, which also provides information about the flow conditions in the loop.

3. Offline commissioning

Following the finalization of the LIEBE prototype assembly, commissioning tests assessing the conformity of the designed features are presented hereafter.

Hydrodynamic characteristics. The breakup of a LBE jet exiting a nozzle under vacuum was previously studied in a dedicated setup [12]. The experimental results determined the minimum velocity of the LBE inducing the regime with the smallest droplet diameter, ⌀0.4 mm for a ⌀0.1 mm hole grid. Considering also the time the droplets travel through the diffusion chamber, a liquid metal flow of 0.13 L/s was identified as the optimal configuration for exotic mercury isotope release. Since the monitoring of the flow of LBE was not integrated in the prototype, due to vacuum and temperature requirements, tests in a loop replica were necessary to ensure that the optimal flow is achieved. In this way, a diagram of the flow function of the pump rotation speed could be drawn for different loop characteristics. The test setup design at IPUL laboratories is shown in Figure 2 .

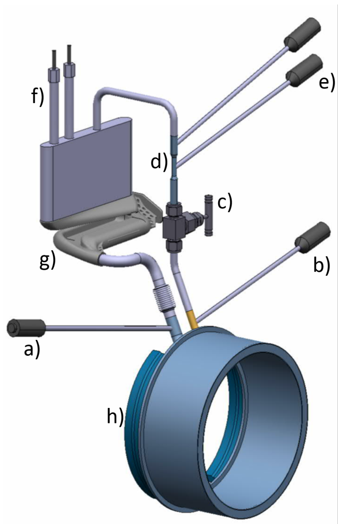

Figure 2: Schematic of the LIEBE loop replica designed and operated at IPUL laboratories. a) inlet manometer, b) outlet manometer, c) mechanical valve, d) Venturi tube, e) Venturi manometers, f) level meters, g) Heat Exchanger (HEX) replica, h) EM pump channel.

The hydraulic head was measured by level sensors on the inlet side of the pump replicating LIEBE conditions, 165 mm. The pressure developed by the pump was monitored with manometers at the entrance and exit of pump's region of interaction while the developed flow was measured with a Venturi tube. A mechanical valve was used to tune the pressure drop in the loop being able to determine the experimental data, pressure drop (ΔP) vs flow (Q), for different pump rotational frequencies plotted in Figure 3.

Different degrees of solidification of LBE in the loop caused high variance in the measurements. Despite that, linear fits systematically showed the expected hydraulic

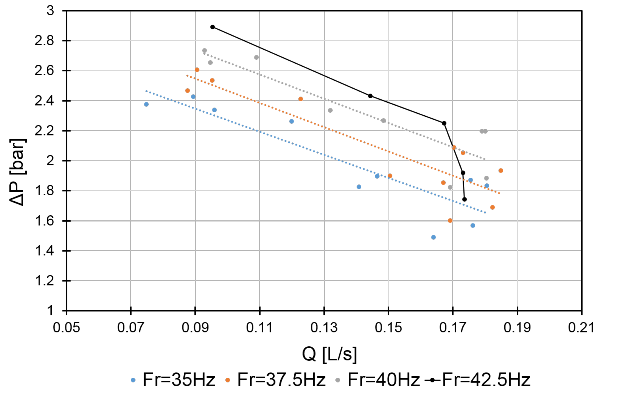

Figure 3: Pressure drop versus developed flow in LIEBE loop replica. Dotted lines are linear fits of the data for each frequency. The black line that link the datapoints of a single run at Fr=42.5 Hz shows the onset of cavitation and the maximum flow achieved in the loop.

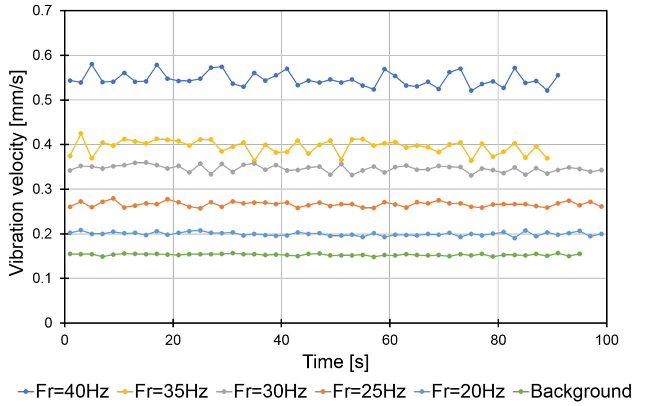

Figure 4: Vibration velocities detected on target without LBE flow.

power increases for higher rotational frequencies. As well, a flow limit of the loop was found at $[0.17 - 0.18]$ L/s with an onset of cavitation. The low liquid height and small pipe section at the Heat Exchanger (HEX) outlet impose a kinetic energy limitation of the flow. Considering the height of LBE from the HEX exit reference, $z = 47$ mm, the pipe diameter $\varnothing 16$ mm and the pressures losses through the HEX simulated with ANSYS CFD, $\Delta P_L = 0.008$ bar [9], the maximal flow is easily calculated with the energy balance:

$$\rho g z - \Delta P_L = \frac{\rho Q_{max}^2}{2S^2} \tag{2}$$

With ρ the LBE density at 200 °C and S the pipe section, the limiting flow is found at $Q_{max} = 0.176$ L/s agreeing with the experimental results (Figure 3) and ensuring that the optimal flow of 0.13 L/s for the droplet formation is well within the accessible loop operation parameters.

Electromagnetic pump mechanical stability. The mechanical stability of the coupling between the target and the EM pump its crucial for the safe operation of the target. If mechanical contact occurs, the magnetic wheel could transfer enough power to damage brittle elements of the ISOLDE target station (so-called front-end) such as the ceramics ensuring electrical insulation. Moreover, to ensure an efficient transmission of the force from the permanent magnet of the rotor to the flowing LBE, a maximum of 3.2 mm separates both elements in case of perfect alignment. The determination of the target vibration was therefore found of a principal safety system for LIEBE operation. The velocity vibration levels of the target for the different EM pump operating frequencies are plotted in Figure 4. The results comply with standard international norms for vibration evaluation on non rotary parts, ISO10816 [13], ensuring long-term operation for velocity values under 1.8 mm/s and for engines with driving power lower than 15 kW .

Qualification test at the Offline separator. Operation tests of the full LIEBE system were performed on the ISOLDE offline mass separator 1, as a commissioning stand prior to online operation on the ISOLDE GPS front-end. Beforehand, the LIEBE target remote handling operation was validated with robots at GPS, as well as with the test of the proper positioning of the pump with the help of a Telemax robot. The main objectives of the tests at the offline separator were to prove the thermal and mechanical stability of the prototype, and that the ion source could operate for stable beam production without interference caused by the vibrations or the fluctuating magnetic field induced by the pump. Figure 5 shows the stepped temperature increase during the outgassing sequence of the loop without LBE.

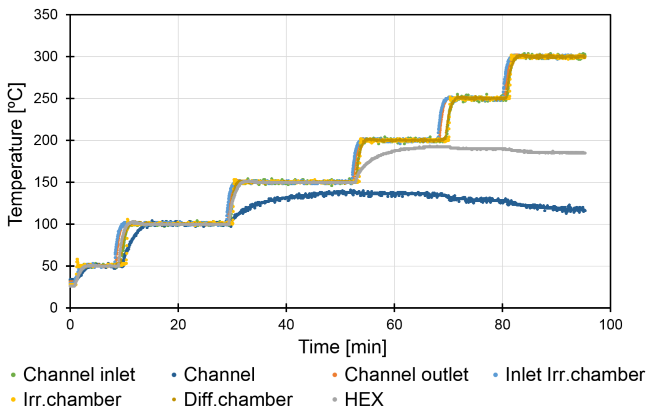

Figure 5: Temperature in different sectors of the loop during the out-gassing sequence.

The HEX and the pump channel sectors show temperatures of 180 and 120 °C respectively, too low considering a minimum of 200 °C to ensure that all the LBE is molten (Figure 5), $T_{LBE-fusion} = 125$ °C [14]. However, the missing heat in the loop was expected to be provided by the induced heating from the EM pump, calculated to be $P = 0.6$ kW at a pump rotor frequency $Fr = 30$ Hz

[9]. After melting of the LBE, the tests were interrupted by two issues: pressure peaks were caused from argon bubbles that remained trapped during the process of filling the LBE tank and triggered pressure interlocks stopping the heating in the target. In addition, three heating elements became non functional after a day.

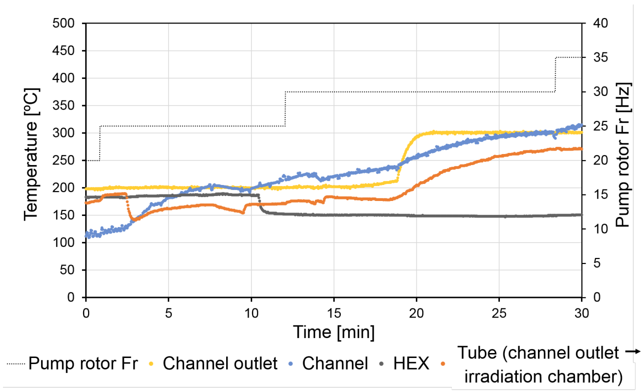

Figure 6: Temperature evolution during re-melting of the LBE in the loop. Channel temperature data has been averaged every 5 points (10s) to hide the parasitic currents created by the EM pump.

The interruption of the tests allowed to investigate the procedure for re-melting of the LBE under the loop thermal conditions shown in figure 5. This procedure has proven challenging since no complete melting could be achieved with the static heating elements alone. Once thermal equilibrium at 200 °C is reached in all possible sectors the EM pump needs to be used to provide the missing heat in the channel and start the flow of liquid metal. That way it can melt the remaining solid LBE in the HEX. Figure 6 shows the temperature evolution during the re-melting process. Sudden temperature drops are detected by the thermocouples in weakly heated sections indicating the onset of the flow. The moment at which LBE melts in the HEX can be identified as the drop in temperature after minute 10 . Accumulation of liquid metal in the diffusion chamber, since it cannot be evacuated through the HEX when the LBE is still solid, can eventually reach the transfer line towards the VADIS ion source, even in the presence of condensation baffles. In the present system such event is undetectable and would damage irreversibly the ion source and the GPS front-end. The insufficient heating system of the prototype does not allow for a safe re-melting process.

Traces of LBE reaching the ion source were identified with mass scans during the target operation. High contamination levels of Pb^+ and Bi^+ ions from LBE up to 0.8 μA can be seen in Figure 7 (peak near the 190 amu due to a slight miss-calibration of the magnet). It was also confirmed with a visual inspection after the tests. Despite this issue, the tests confirmed that the present prototype design allows the production and separation of an ion beam with ISOLDE mass separator.

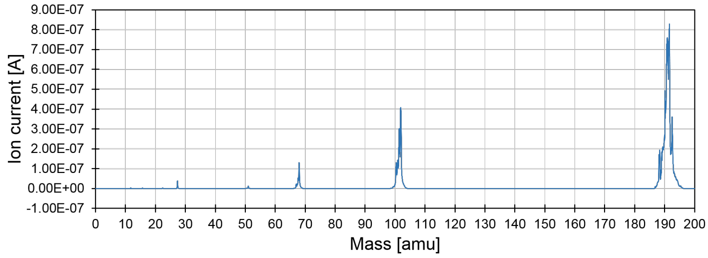

Figure 7: Mass scan with the full loop at 200 °C, except for the HEX at 150 °C, and LBE circulating with the EM pump rotor at $Fr = 25$Hz.

Monitoring systems commissioning. The LIEBE loop has been designed and a review made to propose a set of monitoring systems for its safe operation in the ISOLDE environment. The integrity of the double envelope to confine LBE is monitored through a partial pressure of Ar. The thermocouples provided appropriate temperature profiles, while a LBE level sensor under test could not provide reliable figures. The accelerometer could be tested when the EM pump was used to re-melt the LBE once it is solidified in the loop. The vibration levels of the target with a restricted flow could be recorded. Figure 8 shows the vibration velocity during a different re-melting process in LIEBE. Higher average values of vibration are found per pump rotor frequency, compared to Figure 4, as well as higher amplitude of variations. Reduced values can be seen after minute 40 indicating an improvement in the flow conditions in the loop. The accelerometer proved to be a valid sensor to evaluate the flow in LIEBE.

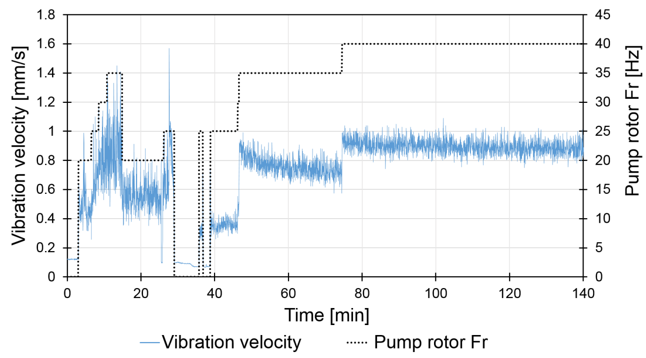

Figure 8: Vibration velocities detected on the target during re-melting of LBE in the loop.

The offline commissioning tests revealed issues that must be addressed to proceed with online operation. The thermal system must be upgraded with more reliable and powerful elements to allow for remelting of the LBE without the need to operate the EM pump. In addition, the pressure developed by the EM pump under a critical situation of blockage in the loop must be investigated to avoid any spilling of the liquid metal through the ion source.

4. Prospects for the production of ^{100}Sn beams

The region of the nuclide chart around ^{100}Sn has been a focal point of interest for nuclear physics for long, and remains a region of high interest as reported in the last NuPECC Long Range Plan [15]. While the LIEBE target has been designed to demonstrate the release of volatile and produce elemental isotope beams such as At, Hg or Xe from LBE, other compositions of molten metal or salts could be considered. A large range of molten materials have already been safely operated at ISOLDE both under cw and pulsed beam conditions at the Syncrocyclotron and at the PS-Booster. In this section, we investigate the possibility to use lanthanum-based eutectics in an adapted version of the LIEBE prototype, to provide ISOL beams in the ^{100}Sn vicinity, eventually promoting their release with molecular formation. The most exotic ISOL beams of neutron deficient Sn were produced as 3 ions/min $^{101}SnS^+$ by fusion-evaporation at ISOL-GSI combined with a FEBIAD ion source [16] and at ISOLDE as 10 ions/s ^{103}Sn and 2.10^3 ions/s ^{104}Sn by spallation on thick solid LaC_x targets combined with a tantalum tubular cavity and RILIS [17]. The recently developed fusion-evaporation target and ion source unit by V. Kuchi et al. at GANIL is another candidate to produce interesting rates in that region [18]. In Table 1, we list a range of parameters required for the validation of the LIEBE target in such a configuration.

Lanthanum based liquid loop req.	
Lanthanum eutectic characterization	· Melting Point · Vapor pressure · EM pump induction · Viscosity
Material compatibility	· Corrosion
Hydro-dynamic properties	· Droplet formation · Cavitation
MCl_x compounds	· Formation temperature · Effusion transport · Ionization
Monitoring systems and full loop operation	

Table 1: Requirements to be fulfilled to validate a lanthanum based liquid loop target.

ISOL static targets made of molten metals have been developed and used already a long time ago. More specifically, pure metals such as Ge, La, Pb, eutectics such as LBE as used for LIEBE, lanthanum-based eutectics and salts such as NaF-LiF and TeO_2-K_2Cl_2-Li_2Cl_2 ($TeCl_4$) were used to produce ISOL beams as shown in Table 2. We introduce here, in addition, lanthanum-based eutectics with low melting points compatible with the present LIEBE prototype operating temperature range, developed for up to 600 °C. While the structural material used for lanthanum-based static targets has been tantalum, as shown in Figure 9, this is not a practical solution for a full loop manufacturing, and more appropriate alloys should be used

Molten targets operated online		
Material	Operation temp.[°C]	Beams
Ge	1100	Zn
Sn	1100	Cd
Pb	700	Hg
Bi		
Pb-Bi	600	Kr/Xe/I/Cd/Hg/At
NaF-LiF	700	CO/Ne
$TeCl_4$	420	SbCl/SnCl
Sc-La	1300	Ca/K/Ar
Y-La	1300	Sr/Rb/Kr
La	1400	Ba/Cs/Xe
Th-La	1400	Ra/Fr/Rn
Gd-La	1400	Eu/Sm
Lu-La	1400	Yb/Tm
Prospective eutectics for beams in the ^{100}Sn region		
Ag-La	518 *	Cd/MCl_x(M=In,Sn,Sb)
Au-La	561 *	Cd/MCl_x
Ni-La	532 *	Cd/MCl_x

Table 2: Molten metal targets; Operated molten metal targets with a focus on lanthanum eutectics targets are shown on the first two sections. The last part shows low melting point (*) lanthanum eutectics considered for operation in a LIEBE loop target. [19] [8]

if chemical compatibility and corrosion issues are found with the employed stainless steel 316L. The production

Figure 9: Tantalum container used at ISOLDE for a static molten lanthanum target. The external diameter is 21 mm. A tantalum ring for reinforcement at the beam window in case of shocks induced by the pulsed PSB beam can be seen on the right, while baffles to prevent release of metal from the target into the ion source through the chimney are seen in front

rate in the vicinity of ^{100}Sn was simulated with ABRABLA [20] and FLUKA [21] [22] Monte Carlo Codes for nominal density with future beam parameters of 2 GeV, 4 µA under discussion for HIE-ISOLDE. None of the codes have provided sufficient statistics with reasonable computing time to give direct data on ^{100}Sn, and extrapolation from the isotope chain was performed, as shown on Figure 11. The extrapolated figures provide an in-target production rate of 52 and 3020 pps for the FLUKA and ABRABLA codes respectively. ABRABLA provides higher predicted rates for all Sn isotopes in the range A=103-112. In the case of FLUKA, full transport of primary and secondary particles is taken into account, and in the case of ABRABLA the rate is deduced from cross section computation, folded with the primary beam intensity and target thickness. Without experimental benchmarking at this energy for spallation with thick lanthanum targets, we cannot obtain here more precise estimates. In both cases, with the present proton beam parameters of 1.4 GeV 2 µA, a significant reduction is seen for the ^{103}Sn production rates, and likely even larger differences could be expected for ^{100}Sn. Furthermore, the present static molten targets operated at ISOLDE can barely operate with more than 1 µA. The production and release of Sn isotopes has been achieved in elemental form at high temperatures, and as molecular ion at much lower temperatures. While more recently Sn molecular ions were produced as sulfide SnS^+, former studies indicate the possibility to release Sn as chloride ions. Indeed high volatility for Sn release can be gained with these molecules, while the reaction of lanthanum with chlorine leads to the formation of $LaCl_3$ with a melting point of 850 °C. On figure 10 , the volatility of SbCl, SnCl molecules is shown along with those formed from the components of the target. In our case, due to their high melting points, both the lanthanum eutectics components as well as $LaCl_3$ are expected to display low volatility of less than 10^{-4} mbar at operating temperatures of 600 °C, compatible with transfer lines and ion sources used at ISOLDE for the differential isotope release. For instance, release and ionization of Boron as BF_x ions has been achieved with 1.5% efficiency using SF_6 reactive gas injection, a cooled transfer line and a VADIS ion source [23]. Stable tin isotopes have been separated with Calutrons at ORNL in the form of $SnCl_4^+$ ions at 9 % separation efficiencies [24]. To meet these figures in a LIEBE loop environment, a proper investigation and design of the transfer line, and proper operating conditions of the ion sources will be required. Based on other collected data for molecular ion transport and formation, we propose to define a targeted figure of merit for the development and operation of a LIEBE target loop operated with a lanthanum eutectics, a VADIS ion source and reactive gas injection to be of 1%. In these conditions, the LIEBE target aims at producing a rate of 0.5-30 $^{100}Sn^+/s$.

5. Conclusions

The LIEBE prototype has been fully assembled and has operated on the offline separator. The commissioning phase has identified several features for operating at the optimal flow and has confirmed a complying mechanical stability of the coupling between the EM pump and the target. However, several points related to the thermal design and control of the prototype have been found to prevent the safe operation of the target. A re-design and replacement of the heating elements of the loop and further experimental testing must prove that the thermal control of the target prevents any risk of LBE solidification during operation. In case of solidification due to a technical stop, an appropriate remelting procedure of the liquid metal must be elaborated. Upon validation of these steps and online operation, this high power molten target could be tested with lanthanum-based eutectics, with the potential to produce interesting yields in the ^{100}Sn region.

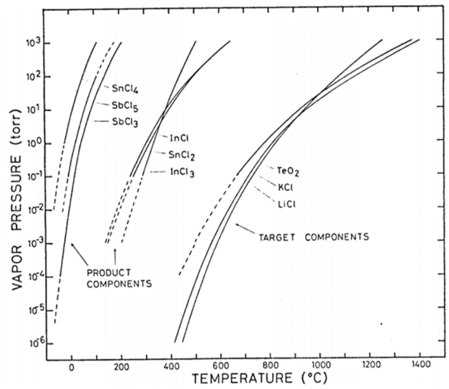

Figure 10: Volatility of $SnCl_x$ and other molecules; reprinted from ref [25]; lanthanum-based eutectics under consideration in table 1 are also expected to display low volatility in the LIEBE temperature range.

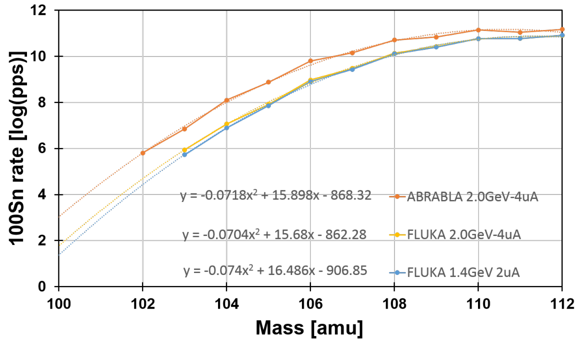

Figure 11: In-target production rate of the neutron deficient tin isotopes up to ^{100}Sn from Monte-Carlo simulations. Extrapolation with second order polynomial function is used to obtain estimates for ^{100}Sn. See text for details.

References

[1] U. Koster, Intense radioactive-ion beam produced with the isol method, The European Physical Journal A 15 (2002) 255–263.

[2] R.Catherall, et al., The isolde facility, Journal of Physics G: Nuclear and Particle Physics 44 (9).

[3] M.Borge, et al., Motivations to receive a 2 GeV proton beam at ISOLDE / HIE-ISOLDE: Impact on radioisotope beam availability and physics program, CERN-INTC-2012-069. URL `https://cds.cern.ch/record/1482729/?ln=de`

[4] J.Lettry, et al., Release from isolde molten metal targets under pulsed proton beam conditions, Nuclear Instruments and Methods in Physics Research B 126 (1997) 170–175. doi:10.1016/S0168-583X(96)01088-9.

[5] J.Lettry, et al., Effects of thermal shocks on the release of radioisotopes and on molten metal target vessels, Nuclear Instruments and Methods in Physics Research B: Beam Interactions with materials and Atoms 204 (2003) 251–256. doi:10.1016/S0168-583X(02)01919-5.

[6] E.Noah, L.Bruno, R.Catherall, J.Lettry, T.Stora, Hydrodynamics of isolde liquid metal targets, Beam interactions with Materials and Atoms 266 (2008) 4303–4307.
[7] Y.Blumenfeld, P.Butler, et al., EURISOL design study: towards an ultimate ISOL facility for europe, International Journal of Modern Physics E 18 (2009) 1960–1964.
[8] T. M. Mendonca, High power molten targets for radioactive ion beam production: from particle physics to medical applications, in: IPAC2014: Proceedings of the 5th International Particle Accelerator Conference, 2014, pp. 2143–2145. doi:10.18429/JACoW-IPAC2014-WEPRO080.
[9] M.Delonca, Development of new target concepts for proton beams at cern/isolde, Ph.D. thesis, Universite de Technologie Belfort-Montbeliard (2015).
URL https://cds.cern.ch/record/2230047
[10] D.Houngbo, et al., CFD analysis and optimization of a liquid leadbismuth loop target for ISOL facilities, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 777 (2015) 202–210. doi:10.10166/j.nima.2014.12.056.
[11] D.Houngbo, et al., Development of a liquid pb-bi target for high-power isol facilities, Nuclear Instruments and Methods in Physics Research B: Beam Interactions with Materials and Atoms 376 (2015) 57–59. doi:10.1016/j.nimb.2016.01.021.
[12] M.Delonca, et al., Shower formation in a liquid LBE target. an experimental and numerical study of the jetting and dripping regimes, unpublished (to be submitted).
[13] ISO 10816. mechanical vibration: Evaluation of machine vibration by measurements on non-rotating parts (2014).
[14] OECD (Ed.), Handbook on Lead Bismuth Eutectic Alloy and Lead properties, Materials compatibility, Thermal-hydraulics and Technologies, Natural Science, 2015.
[15] E. S. Foundation (Ed.), NuPECC Long Range Plan 2017 Perspectives in Nuclear Physics, 2017.
[16] R. Schneider, et al., Identification and halflife measurement of 100Sn and neighbouring nuclei, Phys. Scr T56 (1995) 67–70.
[17] S. Rothe, priv. comm. (2018).
[18] V. Kuchi, Development of an innovative isol system for the production of short lived neutron-deficient ions, Ph.D. thesis, Universite Caen-Normandie (2018).
[19] H. Ravn, et al., New molten-metal targets for ISOLDE, in: Proceedings of the 8th international EMIS conference, 1973, pp. 432–444.
[20] A. Kelic, M. V. Ricciardi, K.-H. Schmidt, Abla07 - towards a complete description of the decay channels of a nuclear system from spontaneous fission to multifragmentation, Proceedings of the Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, ICTP Trieste, Italy, 4-8 February 2008.
[21] A. Ferrari, A. Fassò, P. R. Sala, J. Ranft, Fluka: A multi-particle transport code (program version 2005), Tech. rep., CERN, cERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773 (2005). doi:10.5170/cern-2005-010.
URL https://cds.cern.ch/record/898301?
[22] T. Böhlen, F. Cerutti, M. Chin, A. Fassò, A. Ferrari, P. Ortega, A. Mairani, P. Sala, G. Smirnov, V. Vlachoudis, The FLUKA code: Developments and challenges for high energy and medical applications, Nuclear Data Sheets 120 (2014) 211–214. doi:10.1016/j.nds.2014.07.049.
[23] C. Seiffert, Production of radioactive molecular beams for cern-isolde, Ph.D. thesis, Technische Unveristat Darmstadt (2014).
[24] L. O. Love, Process efficiencies in calutron separations, in: Proceedings of the 8th international EMIS conference, 1973, pp. 128–136.
[25] O. Glomset, et al., A liquid salt target for selective production of neutron deficient antimony isotopes at ISOLDE, Yellow Report 10.5170/CERN-1981-009.