CERN-INTC-2022-029 / INTC-P-635
13/05/2022

**EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

**Proposal to the ISOLDE and Neutron Time-of-Flight Committee**

# Determination of radioactive ion beam production yields using 1.4- and 1.7-GeV protons

May 13, 2022

Simon Stegemann[1], Jose-Luis Sanchez Alvarez[1], Mia Au[1,2], Elodie Aubert[1], Ana-Paula Bernardes[1], Cyril Bernerd[1], Edouard Grenier-Boley[1], Marco Calviani[1], Francesco Cerutti[1], Katerina Chrysalidis[1], Thomas Elias Cocolios[3], Gian Piero Di Giovanni[1], Alexandre Dorsival[1], Charlotte Duchemin, Sean Freeman[1,4], Matthew Fraser[1], Simone Gilardoni[1], Reinhard Heinke[1], Karl Johnston[1], Ulli Köster[5], Giuseppe Lerner[1], Bruce Marsh[1], Fabio Pozzi[1], Francesc Salvat Pujol[1], João Pedro Ramos[6], Edgar Reis[1], Jose Alberto Rodriguez Rodriguez[1], Ralf Erik Rossel[1], Sebastian Rothe[1], Jose Maria Martin Ruiz[1], Maximilian Schütt[1], Erwin Siesling[1], Piotr Krzysztof Skowronski[1], Thierry Stora[1], Joachim Vollaire[1]

[1] *CERN, Switzerland*
[2] *Johannes Gutenberg-Universität Mainz, Germany*
[3] *KU Leuven, Institute for Nuclear and Radiation Physics, Heverlee, Belgium*
[4] *The University of Manchester, Manchester, UK*
[5] *Institut Laue-Langevin, Grenoble, France*
[6] *Belgian Nuclear Research Centre, SCK CEN, Mol, Belgium*

**Spokesperson:** Simon STEGEMANN (simon.thomas.stegemann@cern.ch)
**Co-spokesperson:** Sebastian ROTHE (sebastian.rothe@cern.ch)
**Contact person:** Simon STEGEMANN (simon.thomas.stegemann@cern.ch)

**Abstract:** We propose to measure radioactive ion beam production yields of various isotopes from different target-ion source combinations, using protons at energies of 1.4 and 1.7 GeV. These measurements will allow us to validate physics expectations of increasing yield with proton energy and benchmark simulations at the higher proton energy.

**Requested shifts:** 28 shifts (split over several runs).

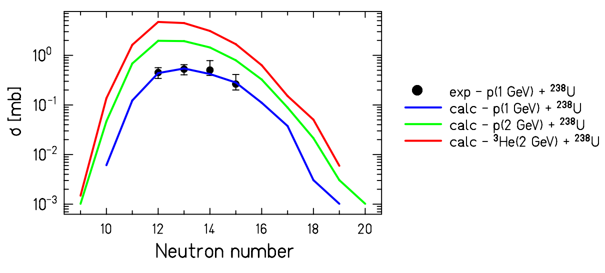
# 1 Introduction

ISOLDE is among the world-leading ISOL facilities providing radioactive-ion beams (RIBs) for research. ISOLDE's versatility is driven by the 1.4-GeV proton beam delivered by the Proton Synchrotron Booster (PSB) and its target and ion source repertoire. The high proton energy, unmatched by any other operating ISOL facility [1], and application of heavy-target materials (e.g. $UC_X$ and $ThC_X$) give access to a wide range of isotopes from the nuclear chart via fission, spallation and fragmentation reactions. However, user interest usually focuses on exotic RIBs that are challenging due to low production and/or low release efficiencies from the target-ion source system. As a result, target and ion source developments and facility upgrades for higher quality beams at ISOLDE are necessary to increase the capability of the facility.

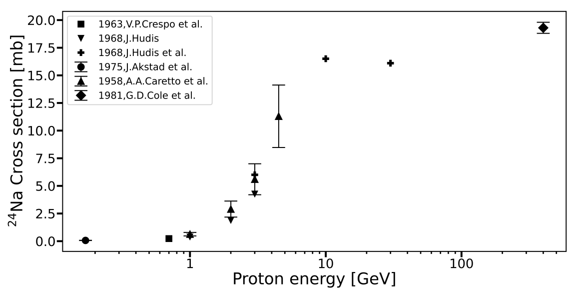
# 2 Motivation

Upgrades involving increased proton beam energy have been proposed in the past. For instance, the EURISOL project investigated 2-GeV protons, $^3$He and deuterons, to bridge gaps in terms of available beams from a baseline 1-GeV proton beam [2]. A proposal to increase the primary proton beam energy to 2 GeV at ISOLDE was made in 2012 [3]; the physics motivations presented then still remain strong now. These studies indicate higher production of low-Z nuclei for increased proton beam energies on a $UC_X$ target (see Fig. 1a). For example, this effect is remarkable for $^{24}$Na (Fig. 1b), where measured cross section show a rapid increase in the range from 1 to 10 GeV, indicating improved yields for light/medium mass fragmentation products.

Systematic isotope production data measured at GSI show significant increases when using higher energies of Pb beams on H. In particular, two regions show improved yields: deep spallation products, which were attributed to spallation evaporation reactions, and nuclei closer to stability with intermediate masses [2]. Light residues (Z $\lesssim$ 20) were not




(a)




(b)

Figure 1: (a) Calculated and measured production cross sections of Na-isotopes in a $^{238}$U target for different proton beam energies. Ref. [2]. The experimental values were measured at GSI with 1 GeV protons [4]. (b) Measured $^{nat}$U(p,X)$^{24}$Na production cross section. Note that the measured data from G. D. Cole et al. are cumulative cross sections.

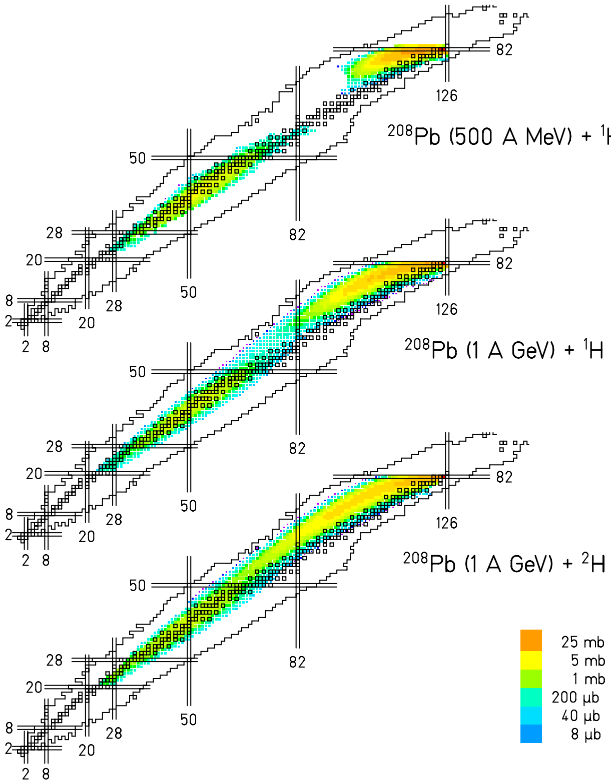



Figure 2: Spallation residues measured at GSI in inverse kinematics [5–8], resulting from $^{208}$Pb with 500-MeV protons, 1-GeV protons and 2-GeV deuterons. Ref. [2].

covered in this study, but the measured data shown in Fig. 1b indicate that increases in this region are likewise expected.

One can expect similar advantages for other target materials. Increases in cumulative yields of $^{131}$Ba and $^{117}$Te above proton energies of 0.5 and 1 GeV, respectively, were reported for tantalum [9]. For some less exotic, but still scientifically important isotopes, there is less improvement; cumulative yields of $^{155}$Tb in the same experiment saturated around 1 GeV [10]. This illustrates the importance of retaining flexibility in energies that can be delivered to ISOLDE by the PSB.

**This proposal:** With this beam time request, we intend to study RIB production yields using 1.4- and 1.7-GeV protons provided by the PSB to the GPS target station, to investigate the impact of stray radiation in different areas of ISOLDE, and to determine beam scattering through the ISOLDE target with increased proton energy.

Currently the PSB and ISOLDE-GPS are capable of handling increased beam energy for short-term investigations. Figure 3 shows the FLUKA simulated (CERN v. 4.2-2) ratio of in-target production yields using 1.7- and 1.4-GeV protons on a $UC_X$ target. Several regions are highlighted with noticeably increased production, similar to the experimental measurements discussed above. By measuring yields of a number of key isotopes using

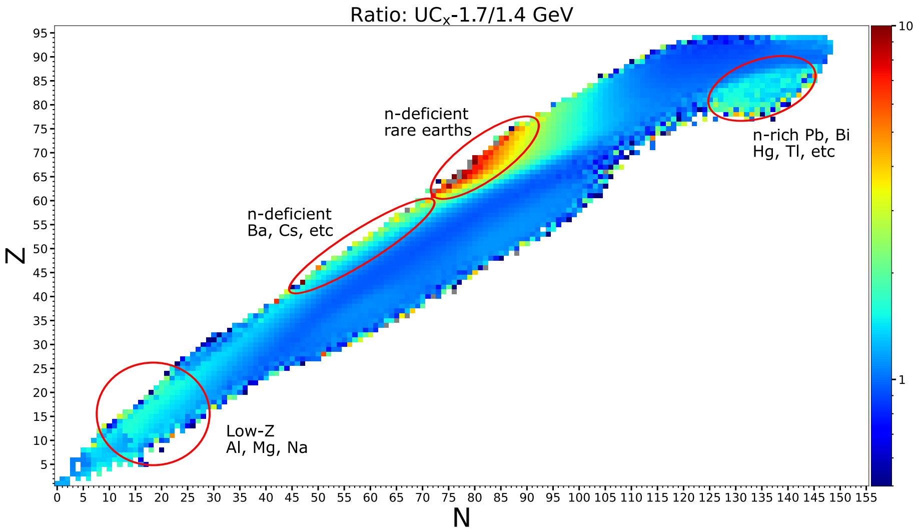



Figure 3: FLUKA simulated (CERN v. 4.2-2) ratio of in-target production yields between 1.7 and 1.4 GeV for a $UC_X$ target.

the ISOLDE Fast Tape Station (FTS), we will validate physics expectations of improved yields with increasing proton energy. The data will also be used to benchmark the yield simulations and therefore endorse their wider predictions.

# 3 Method

## 3.1 Tune of the proton beam from PSB to ISOLDE

An initial tune of the 1.7-GeV beam has already been prepared by the PSB team at the nominal intensity of $3 \cdot 10^{13}$ protons/pulse. This beam has been successfully transported to the PSB external dump. To transport protons to the GPS target station new optics calculations are needed in the BTY line that links the PSB and ISOLDE. Limitations in power converters prevent a simple scaling from 1.4 to 1.7 GeV, but the new optics calculations are expected to be completed in late June. The final setup and tune of the proton beam to ISOLDE requires a total of four shifts for tuning of the four PSB rings to the target, to record references for future use, to perform a subset of additional checks, e.g. kick-response, as well as taking references at different intensities and optics.

## 3.2 Yield measurements at different proton beam energies

To verify expected isotope production increases with energy, we will measure RIB yields with the $\beta$- and $\gamma$-detectors installed in the FTS. Ideally, to ease comparability, we will use both proton energies in the same PSB supercycle to measure yields back-to-back. We highlight five regions of the chart of nuclides, similar to those shown in Fig. 3, which promise considerable gains in yields. The request is summarized in Table 1. We wish to undertake a specific measurement campaign, initially with a surface ioniser (MK1) and $UC_X$ target. This will be followed by a more opportunistic approach using target-ion sources scheduled for the physics campaign; for this part there is flexibility over specific masses to measure (indicated by the use of X).

**(a) Neutron-rich isotopes of very light elements**
$^{8,9}$Li and $^{11}$Be are best produced from heavy, neutron-rich targets such as Ta or $UC_X$. These nuclides are all short-lived, hence only few experimental data exist. Measurements at the BNL Cosmotron using 1.0- and 2.8-GeV protons showed cross section increases of $\times 4.4$ to $\times 8.7$ for $^{9}$Li, $^{16}$C and $^{17}$N from W and U targets respectively [11]. Experimental data at intermediate energies will define the excitation curve more accurately and validate predictions in this mass range.

**(b) Very neutron-rich isotopes of light elements**
A particularly strong energy dependence has been observed for Na from $UC_X$ (see Fig. 1). While $^{24}$Na has a suitable half-life for activation measurements, the more neutron-rich require on-line techniques.

The sodium isotopes $^{27-35}$Na were discovered from Ta, Ir and U targets, using an on-line separator with 10- to 24-GeV protons from the CERN Proton Synchrotron [12–15]. Up to A = 33 sodium yields measured at ISOLDE-PSB at 1.4 GeV are all higher compared to 0.6-GeV protons at the SC. However, differences in used target structures make conclusions about the underlying production rates difficult to reach. We propose measurements here using the same target-ion source unit to remove ambiguities of features such as different release characteristics.

**(c) Heavy neutron-rich nuclides**
The region south and southeast of $^{238}$U and $^{232}$Th is particularly interesting in terms of nuclear structure and potential astrophysical impact, but clear experimental data on the best choice of target and the influence of incident proton energy are lacking. The Rn isotopes $^{226-228}$Rn had been discovered at ISOLDE-SC with 600-MeV protons [16–18]. Later $^{229}$Rn was discovered at ISOLDE-PSB with 1.4-GeV protons [19]. The francium isotopes $^{224-226,229-231}$Fr were discovered at ISOLDE-SC [16, 20, 21], $^{227,228}$Fr were first produced with 10-GeV protons at the PS [14] and $^{232}$Fr with 1-GeV protons on $UC_X$ targets at the IRIS separator at PNPI. [22]. However, again differences in target and ion sources used make it difficult to evaluate underlying production rates satisfactory. In a dedicated comparison at ISOLDE increased yields for Fr isotopes produced from $UC_X$ were determined when increasing the proton energy from 1.0 to 1.4 GeV [23]. We wish to study the expected further gain up to 1.7 GeV.

**(d) Neutron-deficient nuclides close to N=50**
Excellent beams of neutron-deficient Cd isotopes with 600-MeV protons on molten Sn at the CERN-SC enabled discovery of $^{97-100}$Cd [16, 24, 25]. However, neighboring elements are not efficiently released. Only much heavier target materials (e.g. La, Ce) would assure fast release, but production is hampered since the required emission of 40 or more nucleons via spallation is disfavored at lower proton energies ($< 600$ MeV). Using $LaC_X$

targets with 1.4-GeV protons at the PSB eventually enabled successful experiments with neutron-deficient beams in this region, because of rising deep spallation cross sections with increasing proton energy. A further rise of yields is expected with 1.7-GeV protons and should be quantified. Ta or $UC_X$, which offer higher operation temperatures, may also be used for very short-lived isotopes of this area (e.g. towards $^{100}$Sn). Proton energies of 1.7 or 2 GeV assure population of this region, where 80 or over 100 nucleons have to be abraded from the target nucleus.

**(e) Isomeric ratios**
While certain types of experiments (laser spectroscopy, mass measurements,. . . ) can cope with a relatively wide range of isomeric ratios, many HIE-ISOLDE experiments (Coulex, transfer reactions) prefer or require beams where one isomer dominates. Where available, selection can be achieved via pronounced hyperfine structure splitting. For others, target and energy selection can influence isomeric state population such that we propose to measure how isomeric ratios of medium mass nuclides vary with the proton energy.

## 3.3 Beam scattering at 1.7 GeV

The PSB beam energy increase is expected to impact both the neutron yield and spectrum, as well as the scattering of primary and secondary protons, and light ions [26]. Since exact fluence and geometry influences the facility (e.g. neutron converter design and target station operation), we propose to determine the scattered beam profile at 1.7 GeV with dose-reactive foils and activation foil monitors such as Al and Ta. One shift is requested for these measurements.

# 4 Summary of requested shifts:

In total we request 28 shifts. Four are used for proton beam tuning from PSB to the GPS target, one is used to measure stray radiation in different areas of ISOLDE and one is used to determine the beam scattering through ISOLDE targets. Table 1 summarizes the shift request, which covers multiple target and ion source configurations. Dedicated scheduling is difficult, with the exception of the $UC_X$+MK1 combination, which we request as a dedicated run. For the remaining species, flexible scheduling is requested by allocating time on suitable targets when they are in place for other ISOLDE experiments.

The specific requests associated with Sections (a) to (e) are summarized in Table 1.

Table 1: Breakdown of shift request. Where an X is used, there is some flexibility in the specific mass measured. These measurements will form part of the opportunistic measurements made when suitable targets are in place for other experiments. The specific setup at the time will then determine the isotopes measured.

| | | | | |
|---|---|---|---|---|
| | Proton beam tuning PSB-GPS | | | 4 Shifts |
| | Stray radiation measurements | | | 1 Shift |
| | Beam scattering measurements | | | 1 Shift |
| | Isotopes | Target | Ion source | Shifts |
| (a) | $^{6,8}$He | $UC_X$/Ta | VD7 | 1 |
| | $^{8,9}$Li | $UC_X$/Ta | MK1 | 1 |
| | $^{11}$Be | $UC_X$/Ta | RILIS | 0.5 |
| (b) | $^{X}$Ne | $UC_X$ | VD7 | 1 |
| | $^{X}$Na | $UC_X$ | MK1 | 1 |
| | $^{X}$Mg | $UC_X$ | RILIS | 1 |
| | $^{X}$Al | $UC_X$ | RILIS | 1 |
| (c) | $^{230}$Fr, $^{231}$Ra | $ThC_X$ | MK1 | 0.5 |
| | $^{X}$Fr, $^{X}$Ra | $UC_X$ + $ThC_X$ | MK1 | 4 |
| | $^{X}$Rn | $UC_X$ + $ThC_X$ | VD7 | 2 |
| (d)/(e) | $^{X}$Xe | $UC_X$ + $CeO_X$ or $LaC_X$ | VD7 | 2 |
| | $^{X}$Cs, $^{X}$Ba | $UC_X$ + $CeO_X$ or $LaC_X$ | MK1 | 3 |
| | $^{X}$Ag,$^{X}$Cd, $^{X}$In, $^{X}$Sn | $UC_X$ + $CeO_X$ or $LaC_X$ | RILIS | 4 |
| **Total** | | | | **28** |

# References


[1] Y. Blumenfeld, T. Nilsson, and P. Van Duppen. Physica Scripta **T152** (2013), 014023. DOI: 10.1088/0031-8949/2013/T152/014023.

[2] K. H. Schmidt, A. Kelić, S. Lukić, M. V. Ricciardi, and M. Veselsky. Physical Review Special Topics - Accelerators and Beams **10** (2007), 014701. DOI: 10.1103/PhysRevSTAB.10.014701.

[3] M. Borge, M. Kowalska, and T. Stora. Tech. rep. CERN, 2012.

[4] M. V. Ricciardi, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, S. Czajkowski, et al. Physical Review C - Nuclear Physics **73** (2006), 014607. DOI: 10.1103/PhysRevC.73.014607.

[5] B. Fernández-Domínguez, P. Armbruster, L. Audouin, J. Benlliure, M. Bernas, A. Boudard, et al. Nuclear Physics A **747** (2005), 227–267. DOI: 10.1016/j.nuclphysa.2004.10.013.

[6] L. Audouin, L. Tassan-Got, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, et al. Nuclear Physics A **768** (2006), 1–21. DOI: 10.1016/j.nuclphysa.2006.01.006.

[7] T. Enqvist, W. Wlazło, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, et al. Nuclear Physics A **686** (2001), 481–524. DOI: 10.1016/S0375-9474(00)00563-7.

[8] T. Enqvist, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, S. Czajkowski, et al. Nuclear Physics A **703** (2002), 435–465. DOI: 10.1016/S0375-9474(01)01340-9.

[9] C. Duchemin, T. E. Cocolios, K. Dockx, G. J. Farooq-Smith, O. Felden, R. Formento-Cavaier, et al. Applied Radiation and Isotopes **178** (2021). DOI: 10.1016/j.apradiso.2021.109983.

[10] C. Duchemin, T. E. Cocolios, K. Dockx, G. J. Farooq-Smith, O. Felden, R. Formento-Cavaier, et al. Front. Med. **8** (2021), 1–11. DOI: 10.3389/fmed.2021.625561.

[11] I. Dostrovsky, R. Davis, JR, A. M. Poskanzer, and P. L. Reeder. Phys. Rev. **139** (1965), B1513.

[12] R. Klapisch, C. Philippe, J. Suchorzewska, C. Detraz, and R. Bernas. Phys. Rev. Lett. **20** (14 1968), 740–742. DOI: 10.1103/PhysRevLett.20.740.

[13] R. Klapisch, C. Thibault-Philippe, C. Detraz, J. Chaumont, R. Bernas, and E. Beck. Phys. Rev. Lett. **23** (1969), 652.

[14] R. Klapisch, T. C, A. M. Poskanzer, R. Prieels, C. Rigaud, and E. Roeckl. Phys. Rev. Lett. **29** (1972), 1254.

[15] M. Langevin, C. Détraz, D. Guillemaud-Mueller, A. Mueller, C. Thibault, F. Touchard, et al. Phys. Lett. B **125** (1983), 116.

[16] P. G. Hansen, P. Hornshoj, H. L. Nielsen, K. Wilsky, H. Kugler, M. Alpsten, et al. Phys. Lett. **28B** (1969), 415–419.

[17] M. J. G. Borge, D. G. Burke, F. Calaprice, O. C. Jonsson, G. Lovhoiden, R. A. Naumann, et al. Zeitschrift für Phys. A At. Nucl. **325** (1986), 429–434.

[18] M. J. G. Borge, D. G. Burke, H. Gabelmann, P. Hill, O. C. Jonsson, N. Kaffrell, et al. Zeitschrift für Phys. A At. Nucl. **333** (1989), 109–110.

[19] D. Neidherr, G. Audi, D. Beck, K. Blaum, C. Böhm, M. Breitenfeldt, et al. Phys. Rev. Lett. **102** (2009), 112501. DOI: 10.1103/PhysRevLett.102.112501.

[20] W. Kurcewicz, E. Ruchowska, P. Hill, N. Kaffrell, G. Nyman, and T. I. Collaboration. Nucl. Physics, Sect. A **464** (1987), 1–8. DOI: 10.1016/0375-9474(87)90418-0.

[21] P. Hill, N. Kaffrell, W. Kurcewicz, and G. Nyman. Zeitschrift für Phys. A At. Nucl. **320** (1985), 531–532. DOI: 10.1016/b978-0-7236-0778-6.50006-9.

[22] K. A. Mezilev, Y. N. Novikov, A. V. Popov, Y. Y. Sergeev, and V. I. Tikhonov. Zeitschrift für Phys. A At. Nucl. **337** (1990), 109. DOI: 10.1007/BF01283942.

[23] K. Peräjärvi, J. Cerny, L. M. Fraile, A. Jokinen, A. Kankainen, U. Köster, et al. Eur. Phys. J. A **21** (2004), 7–10. DOI: 10.1140/epja/i2004-10038-4.

[24] T. Elmroth, E. Hagberg, P. G. Hansen, J. C. Hardy, B. Jonson, H. L. Ravn, et al. Nucl. Phys. A **304** (1978), 493–502.

[25] D. J. Hnatowich, E. Hagebo, A. Kjelberg, R. Mohr, and P. Patzelt. J. Inorg. Nucl. Chem. **32** (1970), 3137–3148.

[26] R. Luis, J. G. Marques, T. Stora, P. Vaz, and L. Zanini. *Optimization studies of the CERN-ISOLDE neutron converter and fission target system.* The European Physical Journal A **48** (June 2012). DOI: 10.1140/epja/i2012-12090-9.

# Appendix

**DESCRIPTION OF THE PROPOSED EXPERIMENT**

The experimental setup comprises: Fast TapeStation

| Part of the | Availability | Design and manufacturing |
|---|---|---|
| Fast tape station | ☒ Existing | ☒ To be used without any modification<br>☐ To be modified |
| | ☐ New | |
| Part 1 of experiment/ equipment | ☐ Existing | ☐ To be used without any modification<br>☐ To be modified |
| | ☐ New | ☐ Standard equipment supplied by a manufacturer<br>☐ CERN/collaboration responsible for the design and/or manufacturing |

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

| Hazards | | RILIS | GLM |
|---|---|---|---|
| **Thermodynamic and fluidic** | | | |
| Pressure | [pressure][Bar], [volume][l] | | |
| Vacuum | | | |
| Temperature | [temperature] [K] | | |
| Heat transfer | | | |
| Thermal properties of materials | | | |
| Cryogenic fluid | [fluid], [pressure][Bar], [volume][l] | | |
| **Electrical and electromagnetic** | | | |
| Electricity | [voltage] [V], [current][A] | | |
| Static electricity | | | |
| Magnetic field | [magnetic field] [T] | | |
| Batteries | ☐ | | |
| Capacitors | ☐ | | |
| **Ionizing radiation** | | | |

| | | | |
|---|---|---|---|
| Target material [material] | | $UC_x$, $ThC_X$, Ta, $LaC_X$, $CeO_X$ | |
| Beam particle type (e, p, ions, etc) | | $p^+$ | |
| Beam intensity | | 2 $\mu$A | |
| Beam energy | | 1.4, 1.7 GeV | |
| Cooling liquids | [liquid] | | |
| Gases | [gas] | | |
| Calibration sources: | ☐ | | |
| • Open source | ☐ | | |
| • Sealed source | ☐ [ISO standard] | | |
| • Isotope | | | |
| • Activity | | | |
| Use of activated material: | | | |
| • Description | ☐ | | |
| • Dose rate on contact and in 10 cm distance | [dose][mSV] | | |
| • Isotope | | | |
| • Activity | | | |
| **Non-ionizing radiation** | | | |
| Laser | | ☒ | |
| UV light | | | |
| Microwaves (300MHz-30 GHz) | | | |
| Radiofrequency (1-300 MHz) | | | |
| **Chemical** | | | |
| Toxic | [chemical agent], [quantity] | | |
| Harmful | [chem. agent], [quant.] | | |
| CMR (carcinogens, mutagens and substances toxic to reproduction) | [chem. agent], [quant.] | | |
| Corrosive | [chem. agent], [quant.] | | |
| Irritant | [chem. agent], [quant.] | | |
| Flammable | [chem. agent], [quant.] | | |
| Oxidizing | [chem. agent], [quant.] | | |
| Explosiveness | [chem. agent], [quant.] | | |
| Asphyxiant | [chem. agent], [quant.] | | |
| Dangerous for the environment | [chem. agent], [quant.] | | |
| **Mechanical** | | | |

| | | | |
|---|---|---|---|
| Physical impact or mechanical energy (moving parts) | [location] | | |
| Mechanical properties (Sharp, rough, slippery) | [location] | | |
| Vibration | [location] | | |
| Vehicles and Means of Transport | [location] | | |
| **Noise** | | | |
| Frequency | [frequency],[Hz] | | |
| Intensity | | | |
| **Physical** | | | |
| Confined spaces | [location] | | |
| High workplaces | [location] | | |
| Access to high workplaces | [location] | | |
| Obstructions in passageways | [location] | | |
| Manual handling | [location] | | |
| Poor ergonomics | [location] | | |

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]