EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ISOLDE and Neutron Time-of-Flight Committee

Motivations to receive a 2 GeV proton beam at ISOLDE / HIE-ISOLDE: Impact on radioisotope beam availability and physics program

03rd Oct 2012

M. Borge[1], M. Kowalska[1], T. Stora[2]

[1] CERN, PH-SME-IS
[2] CERN, EN-STI-RBS

Abstract

The figure of merit of a given radioactive ion beam facility results from the combination of the following factors:

1.- Diversity of available beams.

2.- Beam intensity (referred as ion or isotope yield when the intensity is normalized for a given primary proton beam intensity, namely ions/μC).

3.- Beam quality, for instance purity (i.e. presence of other ion components for a given isotope beam) and emittance.

4.- Yearly availability of the facility.

5.- For an ISOL-type facility (Isotope mass-Separation OnLine), (Non) degradation of beam intensity over time, related to ageing of the production target or ion source that experience the harsh environment in the primary irradiation zone at the target station location.

This document describes the motivation to receive a 2GeV proton beam at ISOLDE for the ongoing and future physics program. It shows how the 2GeV proton energy option will reinforce the leading position of ISOLDE/HIE-ISOLDE in the world map of the facilities delivering radioactive ion beams. It will notably improve the first two figures of merits for our facility. The document is also accompanied with a short description of the technical issues to be considered along the way.

1.- INTRODUCTION

The ISOLDE facility presently produces about 1000 different isotopes beams for over 70 different chemical elements. This is by far the largest offer in present ISOL-type facilities in the world. The ISOL method is based on a moderate- to high-energy light ion beam that impinges onto a thick target maintained at extremely high temperatures. The recoil products come at rest in the target materials, before being ionized and later separated in a mass spectrometer. This approach is complementary to the second method of isotope beam production, the so-called in-flight fragmentation, in which a heavy ion beam impinges onto a thin target and the fast recoil fragments are separated in a series of large acceptance dipoles [1]. At ISOLDE, the beams are subsequently injected and accelerated in a LINAC in the REX-ISOLDE post-accelerator. HIE-ISOLDE foresees the upgrade of the post-accelerator, and a design study is ongoing to cope with the increased proton beam intensity which will become available with the start-up of Linac 4.

The unique position of ISOLDE in the map of the worldwide facilities results from its long-standing R&D program on target and ion sources which leads to new intense beams on the one hand, and from the primary proton beam characteristics received from the Proton Synchroton Booster on the other hand. Thus, the pulsed 1 or 1.4GeV proton beam combined with a wide range of thick targets allows accessing several nuclear reaction channels. This in turn makes ISOLDE the only facility that can provide beams in some specific regions of the nuclide chart, when compared to the other facilities in operation or in the planning phase. Examples of the future requested isotope beams (especially the post-accelerated ones) can be found in the Letters of Intent and Proposals for the upcoming physics program at HIE-ISOLDE, submitted to the INTC in June 2010 and October 2012, respectively [2a, 2b]. The presently available beams and those requested for HIE-ISOLDE LOIs are shown in Fig. 1, and give a good representation of the variety of the beam requests which fully exploit the diversity of ISOLDE beams.

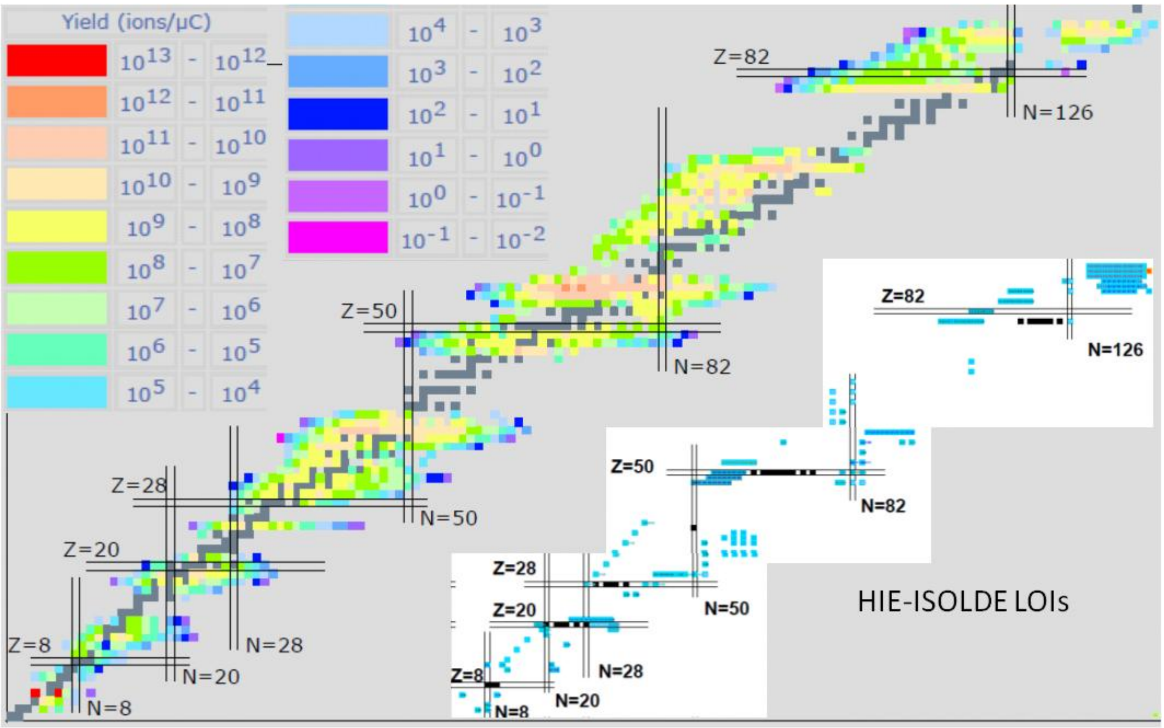

Figure 1: Available radioactive ion beams at ISOLDE (ISOLDE yield database, www.cern.ch/isolde, Oct 2012). Inset: Requested radioactive ion beams (blue squares) collected from the HIE-ISOLDE Letters of Intent submitted in 2010 to INTC. Vertical scale: Proton number Z. Horizontal scale: Neutron number N.

Three main nuclear reaction channels can be triggered upon interaction of the 1/1.4GeV protons from PSB with the target nuclei: spallation, fission and fragmentation, and the resulting total cross sections across the nuclear chart are shown in Fig. 2 [3]. The contribution of the three channels in the total cross section depends on the target nuclei and on the specific isotope to be produced, as illustrated in Fig. 2 for a 238-U target. Such 238-U based targets deliver about 70% of the scheduled beam time at ISOLDE.

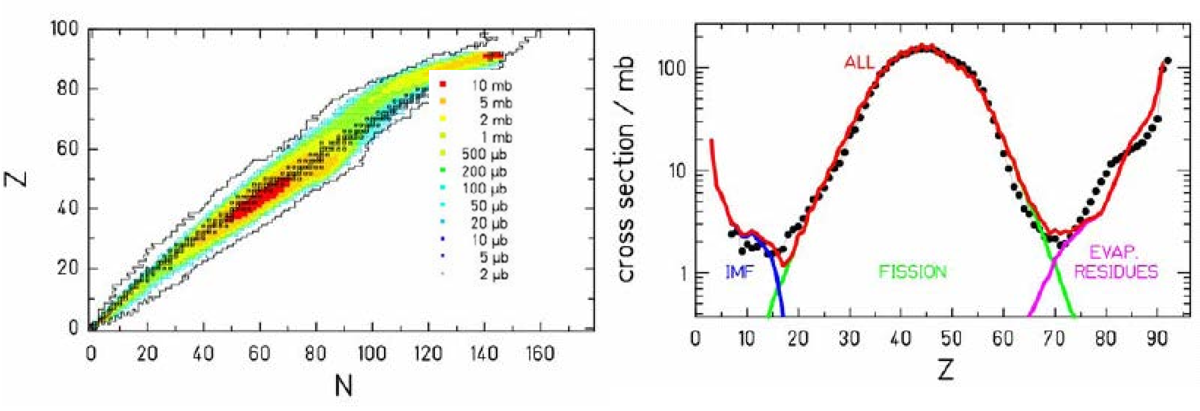

Figure 2: Reproduced from ref. [3]. **Left**: Calculated production cross-sections of various nuclides using 1 GeV protons on 238-U target. **Right**: Contribution of fragmentation (blue, IMF), fission (green), and spallation (pink, Evap. Residues) in the numerical simulations and comparison with experimental data (black dots).

2.- IMPACT OF A 2GEV PRIMARY PROTON BEAM FOR ISOLDE/HIE-ISOLDE: TECHNICAL ASPECTS

2.1 Gains in yields with 2GeV proton beam

The beam intensities available at ISOLDE, or at any given ISOL-type facility, result in a first approach, from the folding of four parameters:

- The primary proton beam intensity **I** (expressed as μA or μC)

- The target thickness **X** (in g/cm^2), which provides the number of target nuclei with which the proton beam interacts

- The production cross-section σ (mb), which is the probability that a given nuclear product is formed

- Different efficiencies ε_{rel} ε_{ion} ε_{sep} ε_{transp} (release, ionization, mass-separation, transport), which depend on the type of the beam, ion source, or parameters during operation.

The yields **Y** (radioactive ion beam intensities, often normalized for I=1p.μA of primary proton beam) can be then computed from eq. [1]:

$$\mathbf{Y = I\,X\,\sigma\varepsilon_{rel}\,\varepsilon_{ion}\,\varepsilon_{sep}\,\varepsilon_{transp}} \qquad \text{eq. [1]}$$

Obviously, the yield **Y** for various isotope beams directly impacts the figure of merit for a given facility such as (HIE)-ISOLDE, as defined at the beginning of this document.

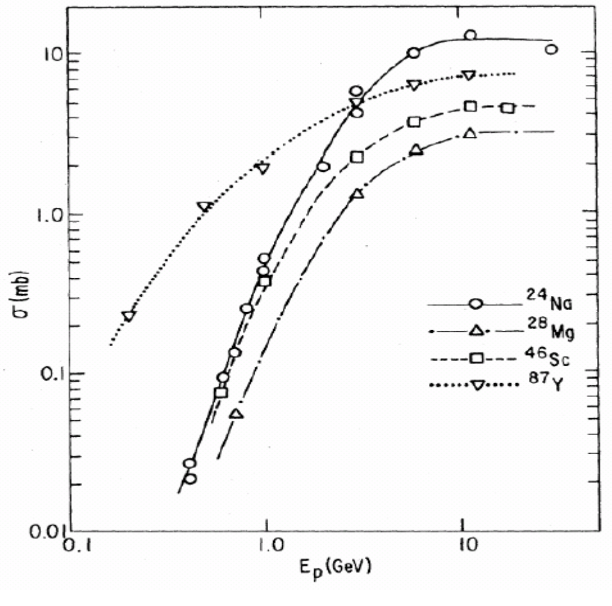

Figure 3: Measured experimental cross-section σ for different elements by interaction of protons of 200 MeV to 30 GeV energies with 197-Au ([4] and references therein). It is clearly seen that cross-section increases up to 10 GeV proton energy.

The production cross-section σ in proton-induced nuclear reactions depends on the proton energy, as shown in Fig. 3 (see [4] and references therein). This linearly scales with the yields Y for a given proton beam intensity, as seen in eq. [1]. The proton beam presently delivered to ISOLDE by PSB can be set to 1 or 1.4GeV energy, as a result of the last upgrade of the proton accelerator in 1999 [5]. Experimental investigations were performed to verify that the isotope production with protons at 1.4GeV was higher for diverse relevant ISOLDE beams and targets [6]. In Figs. 4a,b,c the yield increase when raising the proton energy is further illustrated on representative beams for the three production channels, namely fragmentation, fission and spallation. As can be seen, gains are obtained for the three cases, although at different levels. Increasing the proton energy from 1.4 to 2GeV will lead to the following gains:

- Isotopes produced from fission reactions gain x1.4 on average;
- Fragmentation products gain x2 to x5;
- Spallation products gain of more than x6 for exotic isotopes [6].

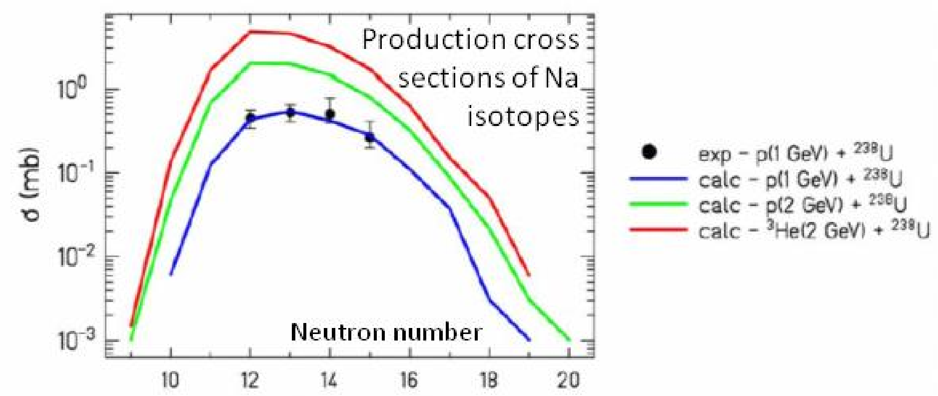

Figure 4a: Cross section gains for fragmentation residues measured at 1GeV at ISOLDE and expected gain at 2GeV. From ref. [6].

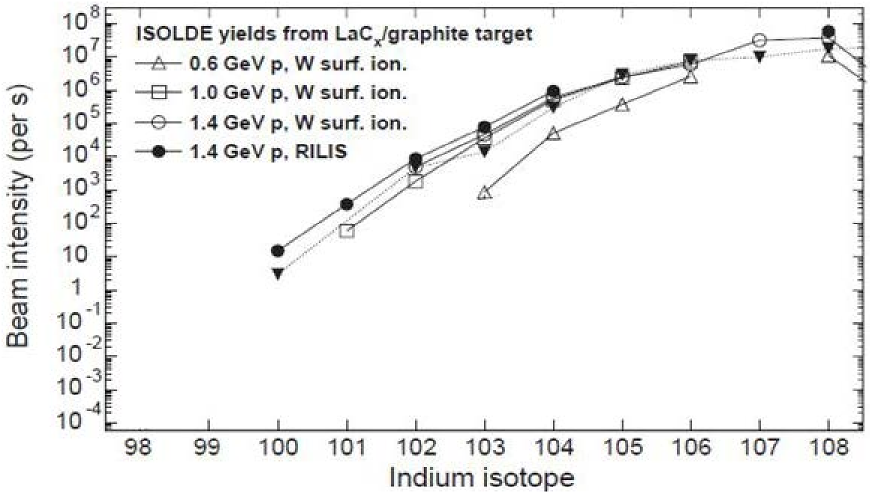

Figure 4b: Observed gains on spallation products at ISOLDE increasing the proton energy from 600MeV, 1GeV and later to 1.4GeV. Further gains are predicted when going from 1.4 to 2GeV. Adapted from ref. [4].

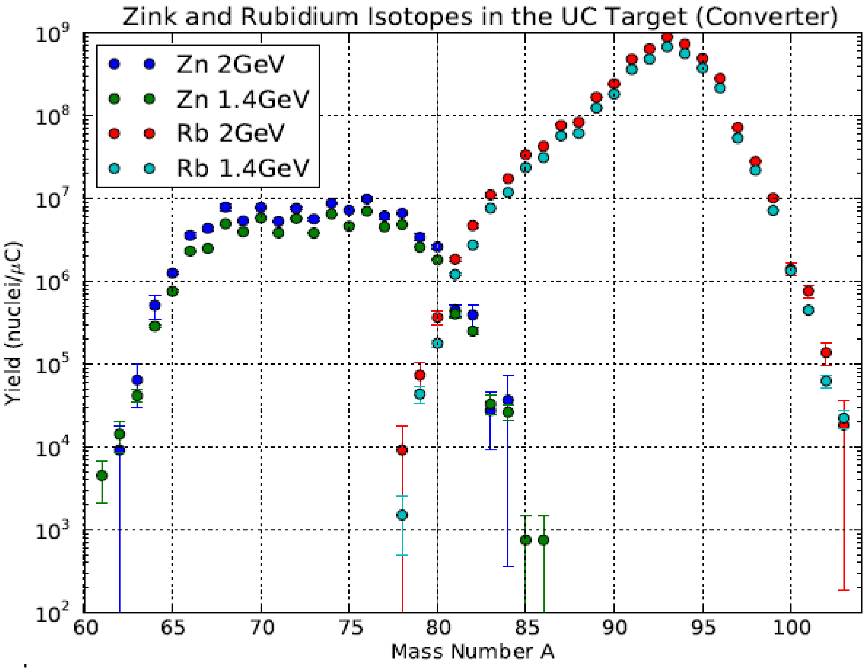

Figure 4c: Predicted gains for fissions products when going from 1.4 to 2GeV protons. Other advantages for the production of fission products with 2GeV proton beams are described in Ref. [7].

Receiving a proton beam at 2GeV will lead to further gains in yields of most of the nuclides requested at HIE-ISOLDE and produced by all above mechanisms. A small drop in beam intensities at 2GeV may be expected for close-by spallation products when compared to the present proton beam. However this could clearly be circumvented keeping the option of delivering protons at 1.4GeV.

Furthermore, a 2GeV proton driver is believed to be better suited for EURISOL, the next generation ISOL radioactive beam facility in Europe [1,9,10].

2.2 Delivery of 1.4/2GeV protons to (HIE)-ISOLDE

Quite interestingly ISOLDE can receive since 1999 proton beams at 1 and 1.4GeV energy. For the past years, the physics program was done at more than 95% with 1.4GeV protons, and for 2012, it will be not less than 100% of the delivered beams. From this observation, we can clearly understand the benefit to receive 2GeV over 1.4 for the future HIE-ISOLDE facility, in the same way as today 1.4GeV energy has shown to provide a clear advantage versus the 1GeV option in the present ISOLDE facility.

A short survey of the drivers' characteristics of the present or planned facilities delivering radioactive ion beams with the ISOL method in Europe and elsewhere also shows that the leading position of ISOLDE would be reinforced this way. Indeed, the two complementary next generation ISOL-type facilities in Europe, SPIRAL II in France and SPES in Italy, are based on low energy drivers: SPIRAL II in GANIL foresees a 40MeV, 200kW deuteron Linac, and the production of fissions fragments with a neutron converter. The SPES facility at INFN is based on a 40MeV, 8kW proton beam which will mainly induce fission fragments by direct proton beam impact. Elsewhere, the related facility ISAC 2 at TRIUMF, Canada, is based on a 500MeV, 50kW proton cyclotron, and exploits spallation, fragmentation and fission reactions with different targets. In terms of proton driver characteristics, this is a higher power version similar to the former ISOLDE-SC, when located at the SC with 600MeV protons up to 1988.

Preliminary investigations have been initiated to check how the BTY proton transfer line from PSB to ISOLDE could accommodate a 1.4/2GeV proton beam instead of the present 1/1.4GeV [8]. Indeed some modifications of the steering and focusing elements will be required, along with the suitable power converters.

2.3 Additional technical aspects

Accommodating a 2GeV proton beam will require additional investigations related to the beam production technologies. In the following we introduce the most important ones.

Heat deposition in the target units:

The increased heat deposition in the target is moderate, and less than the increase of the incoming beam power (2/1.4= 1.43) keeping the same average beam intensity (2 to 6 μA, depending on the different intensity upgrade scenarios presently under investigation). This is consistent with a reduced dE/dX in the different target materials when going from 1.4 to 2GeV proton beam energy.

Beam dump dimensioning:

The beam dumps will have to handle an increased range and some additional beam power to be dissipated. Indeed the present beam dumps were compatible with the last proton energy upgrade to 1.4GeV. This will unlikely be met when going to 2GeV and to about 10kW average beam power.

Shielding and air activation:

Additional shielding for the target stations, and treatment of air activation will need to be also addressed. These different aspects are for instance already treated in the intensity upgrade of the HIE-ISOLDE Design study.

3.- IMPACT OF A 2GEV PRIMARY PROTON BEAM FOR ISOLDE/HIE-ISOLDE: PHYSICS INTEREST

Based on the above simulations we can expect a several-fold increase in yields of radionuclides when using 2GeV protons (see Fig. 4a,b,c,). This has a double impact on the physics at ISOLDE. First, beams already accessible at ISOLDE can be investigated in a shorter time interval to produce the same or better physics output and thus more runs can be scheduled. Second, it gives access to more exotic and thus low-intensity beams, which were not at all accessible at ISOLDE, or which could not be investigated by some of the experimental techniques. In this case, more physics proposals are to be expected.

The above points are specifically relevant for very exotic beams, where a single isotope is often investigated during two weeks or longer (e.g. 11,12-Be, 44-Ar, 72-Kr, 78-Zn), i.e. during a period probes the limits of target's lifetime. In the 30 HIE-ISOLDE LOIs [2a] and recent 30 proposals [2b] (the latter only for physics around 5MeV/A and not for low-energy studies) this trend is well visible: the average beamtime request is 30 shifts, with some reaching 40 shifts for one isotope and ideally during one run. The submitted HIE-ISOLDE proposals amount to 800 8-h shifts which do not include the backlog from low-energy experiments. And only 500-600 shifts can be scheduled within a running year. Thus, a 2-5 increase in beam intensity will immediately mean a decrease in the required shifts, making the shift backlog easier to handle and letting more users profit from the unique capabilities of the ISOLDE facility.

As a rule of thumb the yield drops by about one order of magnitude when going one isotope further from stability. Thus, one can estimate that for most chemical elements produced at ISOLDE we will be able to extend our studies by one isotope on each side of stability. This gives access to dozens of new, often very interesting isotopes (semi- or doubly-magic, halo-like, unbound, or very deformed, to name but a few properties). For example, on the neutron-deficient side the doubly magic 100-Sn and on the neutron-rich the halo-nucleus 14-Be will be now accessible. In addition, we will be able to extend the Ca chain, presently reaching 54-Ca, which remains to be a challenge from the theoretical point of view.

A good overview of the planned ISOLDE physics in the HIE-ISOLDE era is shown in the right side of Fig. 1 (the proposals [2b] cover almost the same nuclides). The scientific interest lies on the studies of isospin symmetry, close the magic numbers and on very heavy nuclides beyond Z=82 and N=126, where a good gain in yield can be expected. For details of the physics interest, see [2a,2b].

4.- SUMMARY

Going to 2GeV will lead to a several-fold increase in yields of most ISOLDE beams which will open up new possibilities for the addressed physics questions will allow for a more efficient use of beamtime. Furthermore, a 2GeV proton driver is believed to be better suited for EURISOL, the next generation ISOL radioactive beam facility in Europe [1,9,10]. In this way, ISOLDE will enjoy and even higher edge, compared to other ISOL-facilities, and will strengthen its worldwide uniqueness.

5.- REFERENCES

[1] Nupecc Long Range Plan 2010 – Recommendations and Roadmap, http://www.nupecc.org/index.php?display=roadmaps/roadmaps, March 2011.

[2a] LOIs: (i) Document search: http://cdsweb.cern.ch/search?op1=a&op2=a&cc=INTC+Public+Documents&as=1&d1m=5&d2y=2010&p1=intc-i&jrec=28&ln=en&d1y=2010&so=a&d1d=1&m1=a&m3=a&m2=a&d2m=7&d2d=1; (ii) Minutes of the 37th INTC, Letters of Intent for HIE-ISOLDE CERN-INTC-2010-20 to CERN-INTC-2010-58 http://committees.web.cern.ch/committees/intc/minutes/intc37.pdf, March 2011.

[2b] Proposals: (i) Document search: http://cdsweb.cern.ch/search?ln=en&as=1&cc=INTC+Public+Documents&m1=a&p1=intc-p&f1=&op1=a&m2=a&p2=&f2=&op2=a&m3=a&p3=&f3=&action_search=Search&c=INTC+Public+Documents&c=&dt=&d1d=01&d1m=09&d1y=2012&d2d=10&d2m=10&d2y=2012&sf=&so=a&rm=&rg=10&sc=0&of=hb

[3] Light nuclides produced in the proton-induced spallation of 238U at 1GeV, MV Ricciardi et al., Phys Rev C73, 014607 (2006)

[4] Intense radioactive ion beams produced with the ISOL method, U. Koester, Eur. Phys. J. A15, 255 (2002); Cross-section measurements of nuclides formed by reactin of 0.2-6.0 GeV protons with 197Au, S. B. Kaufman and E. P. Steinberg, Phys. Rev. C 22(1), 167 (1980).

[5] 40 years anniversary of PSB. https://indico.cern.ch/conferenceDisplay.py?confId=194629, Oct 2012

[6] Isotope production comparison at ISOLDE with 1 and 1.4 GeV protons, U Georg et al., Nucl. Phys. A701, 137c (2002)

[7] Optimization studies of the CERN-ISOLDE neutron coverter and fission target system, R. Luis et al., EPJA 48(6), 90 (2012).

[8] BTY line at 2GeV, D. Voulot, S. Pittet, A. Newborough, EDMS #1178703.

[9] M. Veselsky, S. Lukić, A. Kelić, M. V. Ricciardi, K.-H. Schmidt, www-w2k.gsi.de/eurisol-t11/deliverables/D1/Preliminary%20Report.pdf, Oct 2012.

[10] M. Felcini, A. Ferrari, CERN-AB-Note-2006-006, EURISOL-05-25-2006-0001 (2006).