REVIEW OF ISOL-TYPE RADIOACTIVE BEAM FACILITIES

M. Lindroos, CERN, Geneva, Switzerland

Abstract

The ISOL technique was invented in Copenhagen over 50 years ago and eventually migrated to CERN where a suitable proton drive beam was available at the Syncho-Cyclotron. The quick spread of the technique to many other laboratories has resulted in a large user community, which has assured the continued development of the method, physics in the front-line of fundamental research and the application of the method to many applied sciences. The technique is today established as one of the main techniques for on-line isotope production of high intensity and high quality beams. The thick targets used allow the production of unmatched high intensity radioactive beams. The fact that the ions are produced at rest makes it ideally suitable for low energy experiments and for post acceleration using well established accelerator techniques. The many different versions of the technique will be discussed and the many facilities spread all over the world will be reviewed. The major developments at the existing facilities and the challenges encountered will be presented. Finally, the possibility of using the resulting high intensity beams for the production of intense neutrino beams will be briefly discussed.

INTRODUCTION

In a major review paper in the book, "Treatise on heavy ion science" [1], B. Allardyce and H. Ravn gives the following definition for Isotope Separation On-Line (ISOL): "Such an instrument is essentially a target, ion source and an electromagnetic mass analyzer coupled in series. The apparatus is said to be on-line when the material analyzed is directly the target of a nuclear bombardment, where reaction products of interest formed during the irradiation are slowed down and stopped in the system". Strictly speaking that puts all methods, including In-Flight production (IF) with stopping in a gas-cell, in which the radioactive ions are stopped before being re-accelerated, in the same category. However, classically the ISOL method has been associated with thick targets in which the reaction products are thermalised in the target itself and diffuse out to an ion source for further acceleration and separation. This paper will focus on the ISOL production in thick targets and other methods will just be mentioned for reference purposes.

THE ISOL TECHNIQUE

The great advantage of the thick targets is the large total cross-section available for production of ions. Three main reaction channels are responsible for the bulk production of ions: spallation, fragmentation and fission, Fig. 1. In ISOL

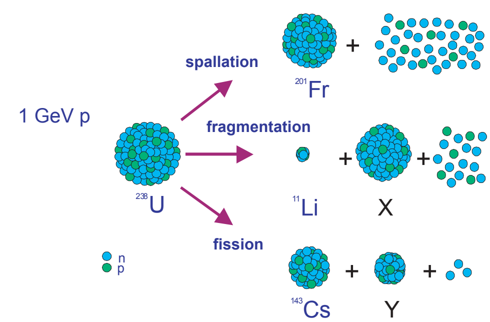

Figure 1: The three main reaction channels for ISOL production.

facilities with neutrons as the"driver beam" the two first channels are suppressed leading to a lower cross section but a higher beam purity. The disadvantage with ISOL production in general is the general difficulty to achieve high beam purity due to the many isobars of different elements produced simultaneously in the target. High beam purity can only be achieved with a combination of measures such as the right choice of target material, driver beam and ion source. Furthermore, refractory elements are in general difficult to produce due to the high temperatures required to make them volatile.

A schematic representation of the ISOL method and the major associated loss channels are shown in Fig. 2. An active target and ion source development programme is crucial for the success of any ISOL facility. The aim of such a program is to reduce the losses while maximize the production without further deterioration of beam purity.

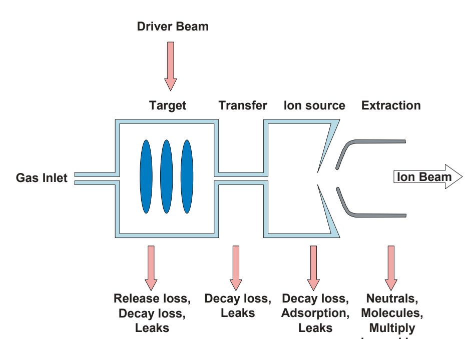

Figure 2: A schematic representation of the ISOL method and the major associated loss channels.

RADIOACTIVE NUCLEAR BEAMS (RNB)

The future challenges for nuclear physics will require radioactive beams and not only isotopes at rest. After pioneering work at Louvain-la-Neuve in the 1990s [2] the technology for the post acceleration of radioactive ions has recently started in earnest and several facilities are now becoming operational. The major challenges encountered are the adaption of the time structure of the beam, the need to increase the charge state for economic accelerating systems and the low intensities compared to similar systems for stable beams.

FIRST GENERATION ISOL FACILITIES

Existing facilities

There are a number of first-generation ISOL facilities in Europe and elsewhere in the world (see Fig. 3), and their main characteristics are listed in Tab. 1. They have rejuvenated Nuclear Physics by giving rise to many unexpected, exciting and important scientific discoveries, but the in-flight facilities developed from existing stable-beam machines have limitations, and the ISOL complexes generally deliver weak intensities and have modest post-accelerating capability. The advancement of the related science will soon be hindered without new and vigorous investment. It is necessary to improve by orders of magnitude the intensities of the currently available ions, and to offer a vast range of new beams further away from stability as well as more efficient instrumentation.

Intermediate facilities

The main limiting factors for carrying out cutting-edge research at the present ISOL facilities are threefold: (i) the driver beam intensity, (ii) the target and ion-source technology and safety related issues and (iii) the energy of the post-accelerated beams. The first two limit the intensity and 'exoticity' of the available beams, while the third limits the scope of the research methods that can be utilized. Major advances in these three areas will give access to new and unique research opportunities, as detailed in, the EURISOL RTD report [3]. This preliminary feasibility study also demonstrated that the technical advances necessary before the construction stage can be envisaged are numerous and challenging. Therefore the European nuclear science community has established a detailed roadmap for reaching the ultimate ISOL facility. This road map encompasses three requirements: (1) optimal exploitation and upgrading of the current European ISOL facilities indicated in Tab. 1, in particular REX-ISOLDE [8] and SPIRAL; (2) construction of intermediate facilities such as SPES [4], SPIRAL II [6], and MAFF [7], shown in Tab. 2; and (3) detailed feasibility studies and technical preparatory work of the most challenging components for the ultimate ISOL facility, to be carried out in the framework of design studies.

The continued vigorous scientific exploitation of the current facilities will enhance the science case, further build and coalesce the user base and train the young scientists needed for the future exploitation of future RNB facilities. The breadth of the scientific opportunities offered and the diversity and difficulty of the technical challenges to be overcome have led the European community to propose building a network of complementary, mid-term or "intermediate-generation" facilities along the path towards the European ultimate facility, EURISOL. SPES, at the Laboratori Nazionali di Legnaro in Italy, will mainly concentrate on the technical challenges associated with a high-intensity proton driver. SPIRAL II, at GANIL in France, dedicated to the production of intense beams of fission fragments, will need to overcome limitations due to target technology, as well as to find solutions for a superconducting heavy-ion linear accelerator, which could be applied to the EURISOL post-accelerator. MAFF, at the reactor in Munich in Germany, will produce unequaled amounts of fission fragments from thermal neutrons and become a unique testing ground for target and ion-source technology as well as environmental issues concerning safety and radiation protection. The continuous upgrading of REX-ISOLDE at CERN will certainly advance our capabilities in target technology, ion sources and beam preparation (multiply charged ions, element and isotope separation, etc.). The pioneering work at TRIUMF in Canada on a high power ISOL facility is of great importance. The ISAC-2 [9] project will push the linac technology and advance the charge multiplication technique with an ECR breeder for high intensity radioactive beams.

The next five year plan at TRIUMF includes the construction of two new target stations for target development. One of the target stations will operate close to the limit of the ISOL technique applying a 100 kW of protons to the target. Such an investment will not only be highly profitable for the ISAC [10] facility but also for the world wide ISOL community, and will attract many new experiments with a resulting increase in the user community of TRIUMF. An example of recent spearheading development work at ISAC is the high power target [11] capable of handling up to 17 kW of stopped beam power in the target unit itself, Fig. 4.

FUTURE FACILITIES

Concurrently with the building of these intermediate facilities, the on-going studies of RIA [12] and EURISOL will cover aspects specific to the design and implementation of the next-generation facility, which is expected to encompass the combined advances of the mid-term realizations, while pushing them to a qualitatively higher level. This original strategy would provide Nuclear Physicists with radioactive ion beams of unmatched intensity, variety and quality. These would be a major component of the worldwide supply of RIBs, as indicated in Tab. 3. The EURISOL facility will include the development of a liquid

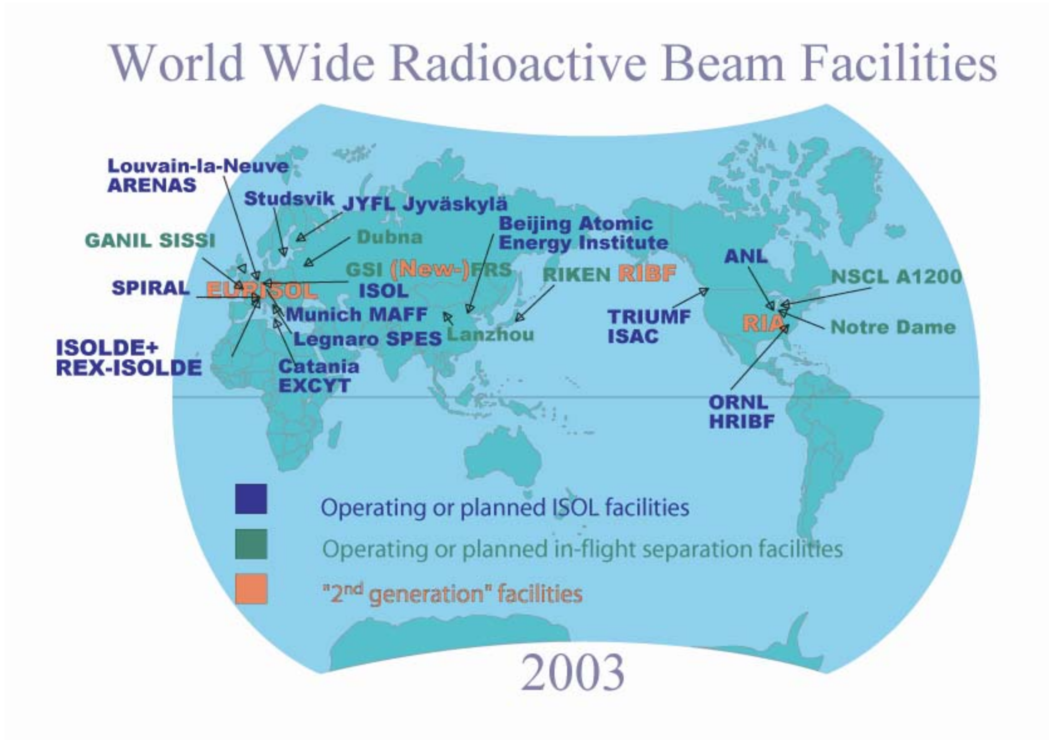

Figure 3: A map of existing and planned ISOL and In-Flight facilities in the world

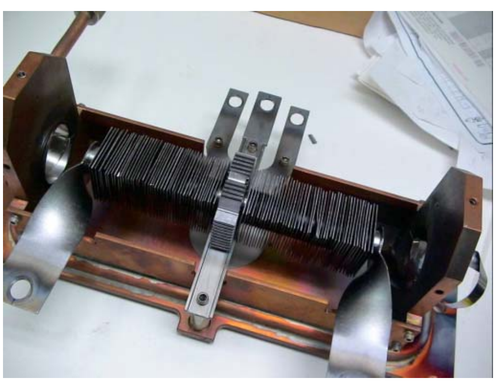

Figure 4: An ISAC target unit capable of handling up to 17 kW of stopped primary beam power.

metal neutron converter which will push this technology to its ultimate with an estimated maximum of 5 MW of primary beam power.

THE BETA-BEAM

The beta-beam facility [13, 14], see Fig. 5, could provide the neutrino physicist with electron (anti-) neutrino beams of unmatched intensity making it possible to probe issues such as CP violation in the weak sector [15]. The study of a beta-beam facility figures as an integral part of the proposed EURISOL design study and is described elsewhere in these proceedings [16].

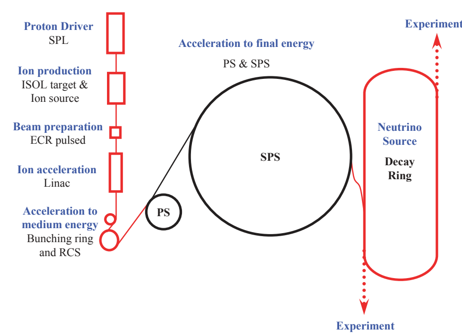

Figure 5: A possible layout of a beta-beam facility at CERN

CONCLUSIONS

The world wide quest for intense radioactive beams for nuclear physics and its applications is driving the development of a new generation of radioactive beam facilities in the world. A number of intermediate facilities will serve as test benches for the technology to be deployed in the future facilities. The beta-beam option is an interesting synergy

Table 1: First generation ISOL RNB facilities

Location	RIB starting date	Driver	Post-accelerator
Louvain-la-Neuve Belgium	1989	Cyclotron p, 30 MeV, 200 A	Cyclotrons K = 110, 44
SPIRAL: GANIL Caen, France	2001	2 cyclotrons heavy ions up to 95 A MeV, 6 kW	cyclotron, CIME K = 265, 225 A MeV
REX ISOLDE: CERN Geneva, Switzerland	2001	PS booster p, 1.4 GeV, 2 A	Linac up to 3.1 A MeV 0.8-3.1 A MeV
EXCYT Catania, Italy	2004	K=800 cyclotron heavy ions	15-MV tandem 0.28 A MeV
HRIBF Oak Ridge, USA	1997	Cyclotron p, d, a, 50-100 MeV, 10-20 A	25-MV tandem
ISAC-I: TRIUMF Vancouver, Canada	2000	Cyclotron p, 500 MeV, 100 A	Linac up to 1.5 A MeV

Table 2: Intermediate ISOL RNB facilities

Location	RIB Starting Date	Driver	Post-accelerator
SPIRAL-II: GANIL Caen, France	2008	SC linear accelerator LINAG deuterons up to 40 MeV heavy ions up to 15 A MeV	cyclotron CIME K = 265, 225 A MeV
MAFF Munich, Germany	2008	Reactor 10^{14} $\mathrm{n/cm^2\ sec}$	Linac up to 7 A MeV
SPES Legnaro, Italy	2008 (Initial phase)	SC proton linac	ALPI linac
ISOLDE upgrade CERN	2008	PS booster p, 1.4 GeV, 10 A	Linac up to 5 A MeV
ISAC-II: TRIUMF Vancouver, Canada	2006	Cyclotron p, 500 MeV, 100 A	Linac up to 6.5 A MeV

with the high energy physics world and could also result in unprecedented intensities of high energy radioactive beams suitable for IF production of even more exotic radioactive beams.

ACKNOWLEDGMENTS

The author wants to thank all colleagues in the world wide ISOL community which have provided valuable input for this paper. A special thanks to the colleagues in the EURISOL design study proposal writing group, Yorick Blumenfeld, Peter Butler, John Cornell and Graziano Fortuna for key input.

REFERENCES

[1] H.R. Ravn and B.W. Allardyce, “On-Line Mass Separators”, in Treatise on Heavy-Ion Science, Edt. D. A. Bromley, Plenum Press, New York, 1989, ISBN 0-306-42949-7

[2] M. Gaelens, M. Cogneau, M. Loiselet and G. Ryckewaert,“Post-acceleration of 7Be at the Louvain-la-Neuve radioactive ion beam facility”, Nucl. Instr. Meth. B 204(2003)48-52

[3] “The EURISOL report”, Edt. J. Cornell, GANIL, Caen, 2003, European commission contract No. HPRI-CT-1999-500001

[4] “Project of a Next-generation ISOL Facility for Exotic Beams at LNL”,EPAC, Vienna, 2000 http://www.lnl.infn.it/

[5] Antonio C. C. Villari and the SPIRAL group, “First results at SPIRAL-GANIL”, Nucl. Instr. Meth. B 204(2003)31-41

[6] “SPIRAL PHASE-II”, European RTT, Final Report, (GANIL R 01 03) and http://www.ganil.fr/

[7] D. Habs, M. Gro, W. Assmann, F. Ames, H. Bongers, S. Emhofer, S. Heinz, S. Henry, O. Kester, J. Neumayr, F. Ospald, P. Reiter, T. Sieber, J. Szerypo, P. G. Thirolf, V. Varentsov, T. Wilfart, T. Faestermann, R. Krcken, P. Maier-Komor,“The Munich accelerator for fission fragments MAFF”, Nucl. Instr. and Meth. B 204 (2003)739-745 and http://www.ha.physik.uni-muenchen.de/maff/

[8] O. Kester, T. Sieber, S. Emhofer, F. Ames, K. Reisinger, P. Reiter, P. G. Thirolf, R. Lutter, D. Habs, B. H. Wolf, G. Huber, P. Schmidt, A. N. Ostrowski, R. von Hahn, R. Repnow, J. Fitting, M. Lauer, H. Scheit, D. Schwalm, H. Podlech, A. Schempp, U. Ratzinger, O. Forstner, F. Wenander, J. Cederkaell, T. Nilsson, M. Lindroos, H. Fynbo, S. Franchoo, U. Bergmann, M. Oinonen, J. Aeystoe, P. Van Den Bergh, P. Van Duppen, M. Huyse, N. Warr, D. Weisshaar, J. Eberth, B. Jonson, G. Nyman, M. Pantea, H. Simon, G. Shrieder, A. Richter, O. Tengblad, T. Davinson, P. J. Woods, G. Bollen,

Table 3: Future ISOL RNB facilities

Location	Driver	Post-accelerator	Type of facility
Europe: GSI Germany	synchrotron heavy ions: 1.5 A GeV	-	In-Flight
Europe: EURISOL	CW linac, protons 1 GeV, 1-5 MW	CW Linac up to 100 A MeV	ISOL
USA: RIA Rare Isotope Accelerator	900 MeV protons heavy ions: 400 A MeV, 100 kW	Linac up to 815 A MeV	ISOL, In-Flight
JAPAN: RIKEN RIB Factory	Ring-cyclotrons up to 400 A MeV (light ions) up to 150 A MeV (heavy ions)	- storage and cooler rings	In-Flight

L. Weissmann, L. Liljeby, K. G. Rensfelt and the ISOLDE Collaboration, “Accelerated radioactive beams from REX-ISOLDE”, Nucl. Instr. and Meth. B 204(2003)20-30

[9] Alan Shotter, “Advances at ISOL facilities”, Nucl. Instr. Meth., B 204(2003)17-19 and http://www.triumf.ca

[10] http://www.triumf.ca

[11] P. Bricault, M. Dombsky, A. Dowling and M. Lane, “High power target developments at ISAC”, Nucl. Instr. Meth. B 204(2003)319-324

[12] Bradley M. Sherrill,“Overview of the Rare Isotope Accelerator project”, Nucl. Instr. Meth. B 204(2003)765-770, http://www.phy.anl.gov/ria/index.html and http://www.nscl.msu.edu/ria/index.php

[13] P. Zucchelli, “A novel concept for a $\nu_e\nu_e$ neutrino factory : the beta-beam”, Phys. Lett., B532(2002)166

[14] B. Autin, M. Benedikt,S. Hancock, H. Haseroth, A. Jansson, U. Koester, M. Lindroos, S. Russenschuck,F. Wenander, M. Grieser, “The acceleration and storage of radioactive ions for a neutrino factory”, J. Phys., G 29(2003)1785-1796

[15] J. Bouchez, M. Lindroos, M. Mezzetto, “Beta-Beams: present design and expected performances”,5th International Workshop on Neutrino Factories and Superbeams NuFact 03 , New York, NY, USA , 2003

[16] M. Benedikt, S. Hancock and M. Lindroos, see these proceedings