Sources for Production of Radioactive Ion-Beams

Helge L. Ravn, CERN-ISOLDE, Geneva 23, Switzerland

The possibility to accelerate unstable nuclei is presently considered to be one of the major opportunities of nuclear physics. Around the world a rising number of laboratories are engaged in the operation, construction or planning of accelerators dedicated to production of Radioactive Ion Beams (RIB) with energies above the coulomb barrier. This report reviews the special ion-source technique which is used to produce such secondary beams suitable for injection into an accelerating structure. A short introduction is given to the already well developed ion source and target technique in which on-line nuclear reactions are used continuously to produce and refine the unstable source feed material and convert it into a low energy singly charged DC beam. Emphasis is then given to a discussion of the techniques applied to fulfil the particular new requirements set to the radioactive ion sources in order efficiently match modern accelerators.

I. INTRODUCTION

Facilities that make use of Isotope Separators On-Line (ISOL) in which high intensity primary beams are used to produce low energy secondary beams of nuclei far from stability have now been operational for some decades. Systematic developments in that field now provide a large diversity of techniques for production of beams of unstable nuclei which now serve as a solid basis for further developments [1]. The many new projects and facilities dedicated to production of Radioactive Ion Beams (RIB) [2] with energies above the coulomb barrier which now emerge all make use of the on-line mass separator and its target and ion-source technology as injector or as starting point for new specific developments.

The interplay between the four involved issues: nuclear reactions, target, ion-source A and Z separation and post-acceleration has shown that the target and ion-source are the most crucial links of the chain and are so intimately linked that they usually are discussed together. The techniques used here distinguishes themselves in a number of ways from current accelerator ion-sources which are usually optimised for high current of stable species. This report starts with a brief introduction to the basic principles and particularities of the target and ion-sources for on-line mass separators followed by selected examples which illustrates the diversity of techniques used and the directions for future developments. Most of my examples are taken from the field I am familiar with where high energy protons are used as primary beam which allows to use thick targets and presently are giving the highest secondary beam intensities. A recent discussion of thin target catcher systems mainly used with ISOLs at heavy ion accelerators is found in ref. [3]. A more extensive overview of recent developments in the field may be found in the proceedings of the last EMIS conference [4.5].

II. THE PRINCIPLES OF ISOL ION-SOURCES

The essential point in developing ion sources for radioactive species is that the ion-source feed material has continuously to be produced and transferred from an adjacent nuclear target. Many different nuclear reactions may be used for production and with few exceptions they are very complex with many exit channels leading to a variety of short-lived and rare nuclei. Efficiency and speed are therefore the essential parameters. The processes which are needed to produce pure beams of radioactive nuclei are strongly dependent on the physical and chemical properties of the individual element and have to be developed specifically for each element or group of elements. Today the development of such systems has reached a stage that allows the production of low-energy beams of the radioactive isotopes of most elements in the periodic system. The principles of the individual systems vary only little with the chosen primary particles [1] used to produce the radioactivity. However, the variety and intensities of beams that may be obtained strongly depend on the primary beam as discussed in ref. [6].

A. Release and transfer of products to the ion source

The general problem is one of mass transfer, i.e. typically to separate the 10^{-1} to 10^{12} produced nuclei (per second) from the 10^{23} target atoms and to transfer them to the ion source. The different steps of this process and the losses from various effects are illustrated in Figure 1.

The separation of the products from the bulk of the target can be done by merely heating a target material with a low vapour pressure to a sufficiently high temperature so that the more volatile nuclei of interest, which are stopped in the target, are released by diffusion and desorption processes. In this way the flow of material can be kept sufficiently low to allow the ion source to perform optimally. A number of such materials have been found and their release properties studied [5].

The chemical affinity of the desired species to the walls of the target container, the transfer tube, and the ion source chamber determine the decay losses caused by the length of time the atoms are adsorbed. This phenomena may make apparently efficient ion sources useless for radioactive ions.

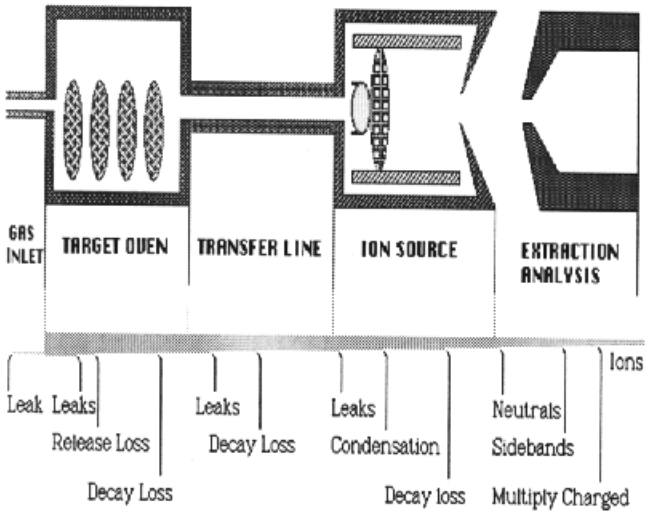

Figure 1: Layout of the ISOLDE concept of an ion-source connected via a short transfer line to a thick target. Also shown are the various mechanisms responsible for losses in the transfer of the reaction products from the target into the ion beam.

B. Overall efficiency

The obtainable beam intensities I are determined by Eq.(1)

$$I = \sigma \cdot \Phi \cdot N \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_3 \qquad (1)$$

where σ is the formation cross section, Φ is the primary-beam intensity, N the target thicknesses, ε_1 the release and transfer efficiency of the product from the target to the ion-source, ε_2 the ionisation efficiency and ε_3 the transfer efficiency determined by the radioactive decay losses during the transfer process. In favourable cases the release from the target and the transfer into the ion source ε_1 occurs with an efficiency of 90–100% and the ionisation efficiency ε_2 reaches 10-100%.

C. Time scale and structure

The time taken by the processes discussed in the previous sections resulting in the efficiency ε_3 caused by decay of the radioactive products can be theoretically described in terms of diffusion and desorption processes. A detailed discussion is found in Refs. [1] and [^{0}]. So far the fastest systems developed are based on solids in the form of foils, wires, and powders, kept at high temperature. The crucial parameter is a function p(t) which can be measured for the entire system but is often determined by the slowest step in the process. A simple description of this function is the delay half-time i.e. the time it takes for one half of the produced atoms to leave the target. For a powder target characterised by an average grain radius R and a product diffusion constant D, in the case where the delay is governed by the diffusion in the target grains, the delay time distribution which is the probability p(t) per unit time that an atom produced at time zero crosses the grain boundary at time t is:

$$p(t) = \frac{6D}{R^2} \sum_{n=1}^{\infty} \exp\left[\frac{-n^2\pi^2 Dt}{R^2}\right] \qquad (2)$$

Expressions of a similar type describe p(t) if the delay is governed by diffusion in target materials of other shapes, diffusion in the pores of the target material, or diffusion to and in the source. With reasonable assumptions for D and R, good fits to the experimentally observed release data can be obtained. For a product with mean lifetime T_m much shorter than the average delay time, the delay transfer efficiency is given by

$$\varepsilon_3 = \frac{3\sqrt{DT_m}}{R}. \qquad (3)$$

D. Charge state and emittance

A new requirement to the ISOL sources is production of high charge states ions and several groups are now developing ECR and EBIS technique for fast ionisation of radioactive species. The emittance of most the ISOL sources are around 25π mm mr or a few eV which may be further improved by cooling in traps as discussed below.

III. ION SOURCES

A. Surface ionisation sources.

The concept of surface ionisation has proven to be particularly successful for production of singly charged positive and negative radioactive ion-beams due to its simplicity, high efficiency and selectivity. As shown by the Langmuir equation ionisation efficiencies for positive ions of 50-100% may be obtained for elements with ionisation potential <5 eV and of negative ions for elements with electron affinity > 2 eV. For further details see ref. [8]. A typical example of this type of ion source developed at ISOLDE [9] for selective production of the halogens is seen in Figure 2. Here the vapour flow of mixed nuclear reaction products are allowed to impinge onto an LaB_6 surface. Due to its low work function (ϕ=2.6 eV) elements with high electron affinity like the halogens will be ionised with high selectivity. In fact ionisation efficiencies of 10-50% for the elements Cl Br I and At were obtained. Contrary to its positive

counterparts the negative ionising surface presents some drawbacks. The low work function materials are like the LaB_6 all chemical compounds which are prone to poisoning and decomposition at the high temperatures needed in order to obtain short delays. For this reason the LaB_6 source can only be operated at 1000°C for extended periods. This temperature is too low in order rapidly to desorb and efficiently ionise the number of other elements with interesting high electron affinities. In principle the problem can be solved by replacing the LaB_6 pellet by a flow of Ca vapours [10] which allows to rise the temperature while maintaining a low work function of the tubular ionising surface by constantly recovering it with a low work function layer. New developments in which high ionisation efficiencies of Cl^- and Na^- ions have been obtained from a tubular W-ionise kept at 2000°C and covered by Ba vapour have recently been reported [11].

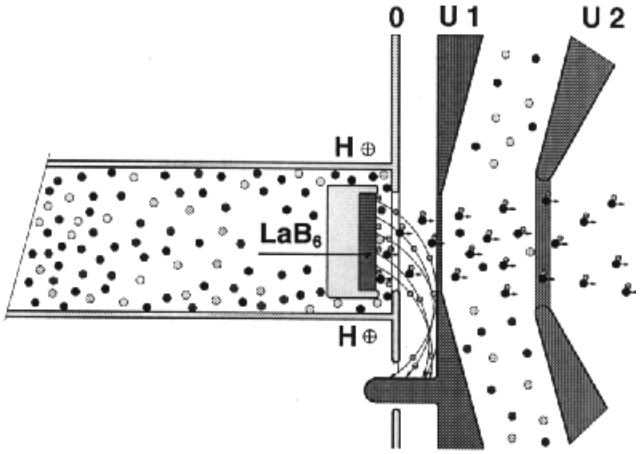

Figure 2: Surface ionisation source for production of negative ions. H magnetic field, U1 electron suppression electrode U2 extraction electrode.

B. High power density target for high energy protons

At ISOLDE 0.6-1 GeV protons with a maximum current of 4 μA has been used successfully in conjunction with thick targets of up to 100 g/cm^2. A Radioactive Ion Source Test (RIST) [10] aiming at the development of a target and ion source to produce higher intensity RIBs is presently being carried out at RAL where at the ISIS spallation neutron source 0.8 GeV proton currents of up to 200 mA are available. The RIST target will use the concept of the ISOLDE Tantalum foil target for simplicity equipped with a W-surface ioniser which will allow a test of the production of neutron rich Li, Na, K and proton rich Rare earth elements. This target material which operates at 2400 °C will be heated by the proton beam only and the crucial point is one of cooling since the ISIS proton beam will dissipate up to 30 KW of power in the target. Off line heating tests show that for a proton beam of up to 100 μA the cooling of such a target may still be achieved by means of simple radiation cooling provided the foil lay out is changed such that good thermal contact between the foils and the outer tube is obtained. This is achieved as shown in Figure 3 by welding discs and spacers together to form a cylindrical target with a tapered hole through the centre which assures a uniform beam power dissipation along the length of the target, helping temperature uniformity. At the same time the delay time is shortened due to the lower pumping impedance as compared to the usual ISOLDE targets which employs Ta powder or foil rolls.

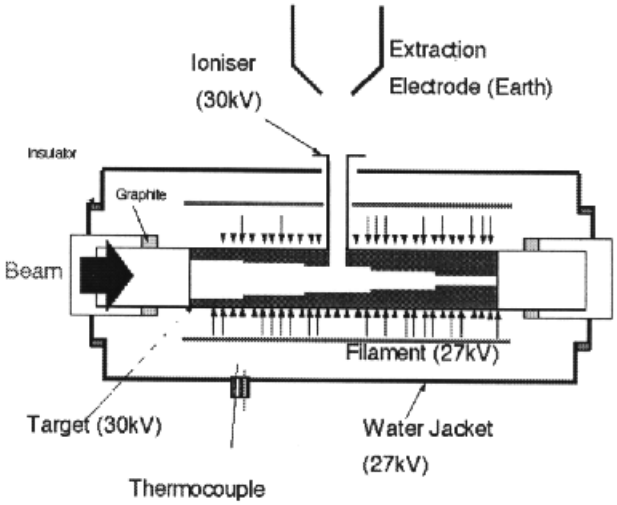

Figure 3. Details of the RIST Ta-disk target with a tubular W-surface ioniser. Electron beam heating is used to outgas the target or to keep it at operating temperature also at lower beam currents.

C. Hot cathode discharge ion sources

Although the special version of the surface ion-source the thermoionising cavities allows quite efficient ionisation of elements with ionisation potentials up to ~7 eV [13] electron impact ionisation in various types of plasma discharge ion sources are generally used for ionisation of elements with ionisation potentials >6 eV. Due to the distribution of electron and ion energies in the plasma these ion sources have low chemical selectivity and ionises quite efficiently all elements that can be kept predominantly in the gas phase.

The main type of such sources especially developed for ISOL applications is the FEBIAD-source [14] of which the ISOLDE version [15] is shown in Figure 4. The advantage of this source is that it avoids the arc threshold pressure and associated instabilities by extracting the primary electrons by means of a grid. This allows the source to ionise many elements heavier than

Ne with efficiencies of 20-70% and widely independent of pressure.

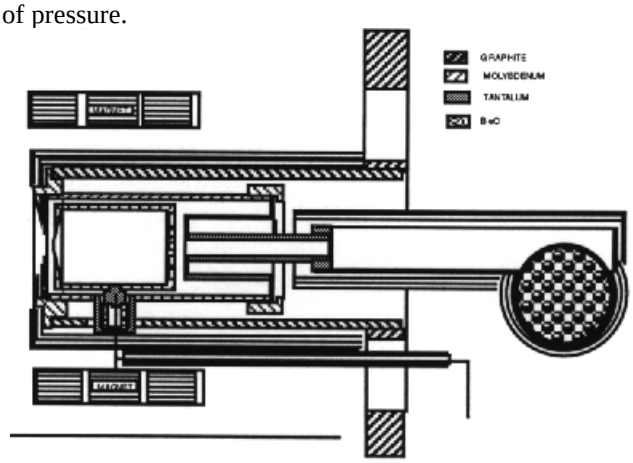

Figure 4: FEBIAD target and ion source unit with ohmic loss heated cathode and body which allows to operate at 1800-2000 ˚C.

D. Electron-Cyclotron Resonance (ECR) ion sources

One would think that the ECR ion source is the obvious accelerator source also for high-charge-state radioactive ions. In fact it has already been introduced at ISOL because of its very high efficiency for production of singly charged ions of the light gaseous elements [16, 17, 18, 19]. In particular the absence of the hot cathode avoids the very high losses due to adsorption of the elements C, N and O on hot metallic surfaces. For ionisation of less volatile metallic elements the cold enclosure may cause unacceptable delays despite its attractive efficiency of around 1% for a given high charge state metallic ion. Presently this source type receives much attention in order to solve this problem as well as its quite high emittance. The present status is illustrated in Figure 5 which shows the NANOGAN ECR-source coupled to a GANIL target for which on-line efficiencies of $^{18}Ne^{5+}$ have been measured to be 20% [20, 21].

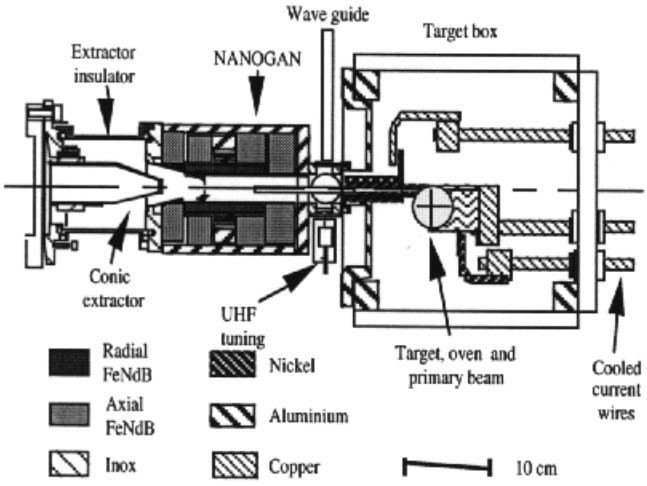

Figure 5: ECR ion source with permanent magnets combined with a porous carbon target at high temperature.

E Resonant laser ionisation sources

The most selective ion source principle is based on resonance excitation of atoms. Laser ion-sources where 2 to 3 beams of intense laser light which is at least resonant in one step followed by transitions which lead into auto-ionising- or Rydberg states have been used both at ISOL [22] and for trace analysis [23] to ionise a number of metallic elements with efficiencies of 20-30%. Presently only low duty cycle pulsed lasers (10kHz) are used to saturate the transitions. In order to overcome the losses the photo ions are stored between laser pulses in the potential trough of a gas cell [24] or a hot cavity [25] as shown in Figure 6. The consequently bunched ion-beam structure may be useful for post acceleration. By combining this principle with laser ablation more freedom in the timing of the bunching may be obtained [26].

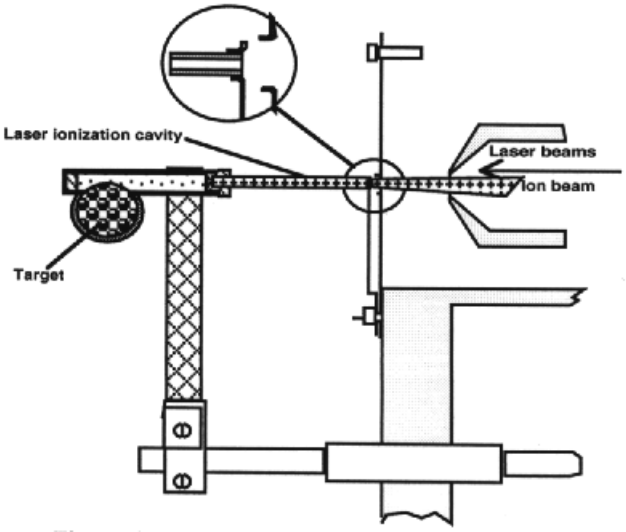

Figure 6: Layout of the ISOLDE laser ion source

F. Penning trap and EBIS as charge breeder

An alternative solution to obtain the needed high charge states directly, is to divide the mass transfer process into the following separate steps: release and singly charge ionisation, transfer of the singly charged ions away from the hostile target region to a first magnetic analysis stage, bunch and cool the singly charged ions in an electromagnetic trap [27] and transfer them to an Electron Beam Ion Source (EBIS) acting as a charge breeder before final acceleration. Such a novel and highly efficient acceleration scheme has recently been proposed by the ISOLDE collaboration [28, 29].

The singly charged radioactive ions presently being delivered by the ISOLDE on-line mass separators are continuously injected into a large Penning trap where they are stopped by collisions with the atoms of a buffer gas accumulated and finally extracted in pulses. That this scheme allows to accumulate and eject 10^7-10^8 ions/bunch with an efficiency that approaches 100% and an emittance < 10 π mm mrad has recently been demonstrated [30, 31].

Due to the low emittance the bunches from the Penning trap can now without losses be transferred to the EBIS structure [32] as shown in Figure 7. Here the ions are captured in the radial potential well of an intense electron beam where they undergo stepwise electron impact ionisation until the desired charge state is reached. The advantages of this scheme are the more narrow charge state distribution compared to the ECR sources and its independence of the chemical properties of the elements. The total efficiency of external ion injection into the CRYSIS of the Manne Siegbahn Laboratory and the subsequent ejection was measured to be 14.5% and independent of ion confinement times up to 200 ms [33]. Similar measurements performed at DIONE at Saclay [34] showed total efficiencies for N^{1+} and Ar^{1+} of 59% and 52% respectively and after a confinement time of 40 ms an efficiency of 30% for N^{7+} and 9.4% for Ar^{14+} .

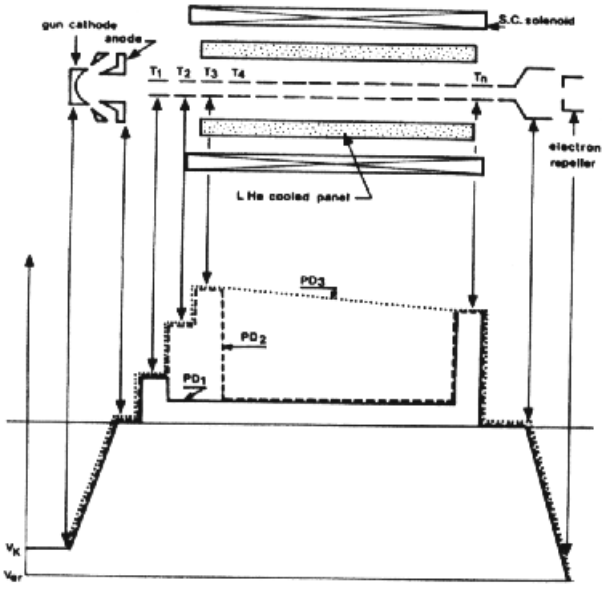

Figure 7: Layout of a typical EBIS ion source

IV. CONCLUSION

Space did not allow to make a complete review of the field of ion-sources for RIB accelerators. Instead references were given to the field of ISOL ion-sources which forms the basis for the new developments. By means of a few examples it is demonstrated that the field is rapidly developing. In particular recent development of elegant ion handling techniques by means Penning traps, EBIS, ECR- and Laser ion sources holds much promise for new and exciting physics with RIB in the coming years.

VI. REFERENCES

[1] H. L. Ravn and B. W. Allardyce, in Treatise on Heavy Ion Science, Ed. D. A. Bromley (Plenum, New York, 1989), Vol. 8, p. 363.

[2] D. K. Olsen, Proocedings of this conference.

[3] P. Van Duppen, et. al., Rev. Sci. Instrum. 63(1992)2381.

[4] Nucl. Instrum. and Meth. B70(1992)1.

[5] H. L. Ravn, ibid B70(1992)107.

[6] H. L. Ravn et. al., ibid B88(1994)441.

[7] H. L. Ravn, Phys. Rep. 54(1979)201.

[8] R. Kirchner, Nucl. Instrum. and Meth. 186(9981)275.

[9] B. Vosicki et. al., ibid 186(1981)307.

[10] R. Mueller et. al., ibid 127(1975).

[11] T. Kozlowski, Private communication.

[12] J. R. J. Bennett, et. al., RAL Report RAL-94-095, p. 11.

[13] R. Kirchner, Nucl. Instrum. and Meth. A292(1990)203.

[14] R. Kirchner et. al., ibid 133(1976)187 and B70(1992)56.

[15] S. Sundell et. al., ibid B70(1992)160.

[16] V. Bechtold et. al., Proc. 7th. Workshop on ECR ion-sources, Jülich, 1986 p. 248.

[17] P. Decrock et. al., Nucl. Instrum. and Meth. B58(1992)252.

[18] L. Buchmann et. al., ibid B63(1992)521.

[19] G. Gimmond et. al., ibid B70(1992)118.

[20] P. Sortais,et. al., XIth Workshop on ECRIS, Groningen 5-7/5/93, KVI Report 996 p. 97

[21] P. Sortais, 7th. Int. Conf. on Physics of Highly Charged Ions, 19-23/9/94, Wien, Nucl. Instrum. and Meth.B To be published.

[22] G.D.E. Alkhazov, et. al., Nucl. Instrum. Meth. A280(1989)141.

[23] F. Ames et. al., Appl. Phys. B51(1990)200.

[24] L. Vermeeren et. al., Phys Rev. Lett. 73(1994)1935.

[25] V. I. Mishin, et. al., Nucl. Instrum. Meth. B73(1993)550.

[26] H. L. Ravn, ibid B70(1992)107.

[27] R. B. Moore et. al., J. Mod. Opt. 39(1992)361.

[28] H. Haas et. al. Proc. Int. Conf. On Radioactive Nuclear beams Berkeley, CA 1989, Eds. W. D. Meyers,

T. M. Nitchke and E. B. Norman World Scientific Singapore 1990, p 59

[29] Proposal To The ISOLDE Committee: ISC/P68, CERN/ISC 94-25, 14.11.1994.

[30] G. Bollen, Proc. Nobel Symposium 91, Lysekiel, Sweden, 1994, Physica Scripta , To be published

[31] J. Stein, diploma thesis University of Mainz and G. Bollen Private communication.

[32] E. D. Donets, Rev. Sci. Instrum. 61(1990)225.

[33] E. Beebe, et. al., Nucl. Instrum. and Meth. B93(1994)378.

[34] J. Faure, et. al., ibid 219(1984)449.