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Exotic nuclei/Les noyaux exotiques

Fast unstable nuclear beam facilities: present and future

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Abstract

A review is given of the present and future facilities for the production and acceleration of unstable nuclear beams for exciting physics research at the limits of nuclear stability. The various methods for the production of unstable beams using in-flight and ISOL techniques with thick and thin targets are discussed, including their advantages and disadvantages. Some typical examples of facilities are shown. New concepts, future research developments and proposals for ambitious large facilities to meet the challenges of the future are described. ***To cite this article: A.C.C. Villari, J.R.J. Bennett, C. R. Physique 4 (2003).***

Résumé

Accélérateurs pour faisceaux d'ions instables : présent et futur. Un bilan est fait des installation présentes et futures pour la production et l'accélération de faisceaux d'ions instables visant la recherche à la limite de la stabilité. Les différentes méthodes pour la production de faisceaux instables, utilisant les techniques ISOL et en-vol, avec des cibles épaisses et minces, sont décrites avec leurs avantages et leurs inconvénients. Quelques exemples d'installations sont cités. De nouveaux concepts, des développements de recherche future et des propositions pour des installations de grande envergure qui permettraient de relever des défis du futur sont décrits. ***Pour citer cet article : A.C.C. Villari, J.R.J. Bennett, C. R. Physique 4 (2003).***

1. Introduction

The properties of stable nuclei and their reactions with one another have been studied for many years. It became clear that the study of nuclear physics was incomplete without the extension to unstable nuclei and, in particular, without the use of unstable beams. The conference held in Lysekil [1], Sweden, in 1966 may be considered to mark the beginning of this area of work. Theoretical estimates indicate that there may be up to 7000 nuclei lying between the proton and neutron drip lines [2]. The reader is referred to the many papers on the importance of unstable beams in physics; for examples, see references: [3–6]. At present, the main excitement and thrust of work with unstable beams are in:

- Nuclear astrophysics – the formation of the universe in the Big Bang and understanding the synthesis of elements [7] – understanding the r-process and rp-process;
- Shell structure far from stability – doubly magic nuclei;
- Drip line nuclei – neutron (and proton) halo and neutron skin – position of the drip lines;
- New nuclei beyond $Z = 112$;

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– Related scientific fields – beta decay and weak interactions – tests of parity violation – nuclear solid state physics – nuclear medicine.

Much of this work places the emphasis on the production of rare unstable beams of very short life times that are at the limits of present technical capabilities.

It is certainly possible to continuously produce short-lived radioactive particles in a target by bombarding it with a suitable stable beam. However, the number of unwanted reactions will produce a severe background for most experiments. On the other hand, the use of unstable beams gives a better reaction channel selectivity, enhancing the signal/noise ratio of an experiment.

In general, the method using radioactive targets is not as attractive as that using a radioactive beam, mainly due to the limited lifetime of the target.

2. The methods for producing fast unstable nuclear beams

Two major techniques used to produce fast unstable beams can be identified:

(a) The In-Flight Technique – projectile fragmentation and/or fission of relativistic beams – related to the use of a *thin target* followed by a mass separator;
(b) The ISOL Method with re-acceleration – related to the use of a *thick target* for unstable beam production and a post-accelerator.

Generally the production of a beam may be considered in several steps:

(A) The In-Flight Technique.
  (1) Production of the radioactive nucleus in a thin target in a fragmentation or fission reaction;
  (2) Release of the fragments from the target as an energetic ion beam;
  (3) Selection of the required isotope;
  (4) Formation into a beam;
  (5) Possible beam quality improvements;
  (6) Use directly in experiments;
(B) The ISOL Method – Isotope Separation On-Line.
  (1) Production and stopping of the radioactive nucleus in a thick target or gas catcher;
  (2) Release of the particle from the catcher and transport to the ioniser;
  (3) Ionisation;
  (4) Formation into a beam;
  (5) Selection of the required isotope;
  (6) Acceleration to the required energy and use in experiments.

Fig. 1, adapted from [8] and [9], illustrates schematically the In-Flight and ISOL techniques. The techniques are intertwined and the classification a little confusing.

In the in-flight method, the primary beam hits a relatively thin target so that the reaction products escape from the target with significant energies. Such fragmentation reactions are favourable when high-energy heavy ions hit a suitable target. The fragments, including any unstable species, are already ionised on emerging from the target and are directed forward in a reasonably narrow cone at considerable energy, but with a large momentum spread. Having a small primary beam spot on the target will help make the transverse emittance small. As much as possible of the beam is accepted into an analysing magnet and a particular isotope selected. Relatively complex beam lines are required to provide good isotopic purity, see for example the high resolution separator A1900 at NSCL, Michigan State University, [10]. Since most of the particles are fully stripped there are relatively few losses due to different charge states. The energy from the reaction is usually high enough for many nuclear physics experiments. Special methods are required to produce beams of good quality for acceleration.

At present there are several laboratories that can operate the thin target technique, GANIL (France), GSI (Germany), Dubna (Russia), RIKEN (Japan), NSCL (USA) and HIRFL (Lanzhou, China). General overviews can be found in papers by Sherrill [11] and Munzenberg [12] and recent information was given in EMIS-13 [5], EMIS-14 [6] and RNB 2000 [4]. More details will be given in Section 3.

In the ISOL Method, the primary beam hits a thick target. The unstable products remain at rest in the target material and diffuse out to the surface. Then they pass through (effuse) a transfer tube and eventually reach the ioniser and are extracted as an ion beam. The beam is mass analysed and the selected isotope transmitted to the experiment or to a post-accelerator. A variation

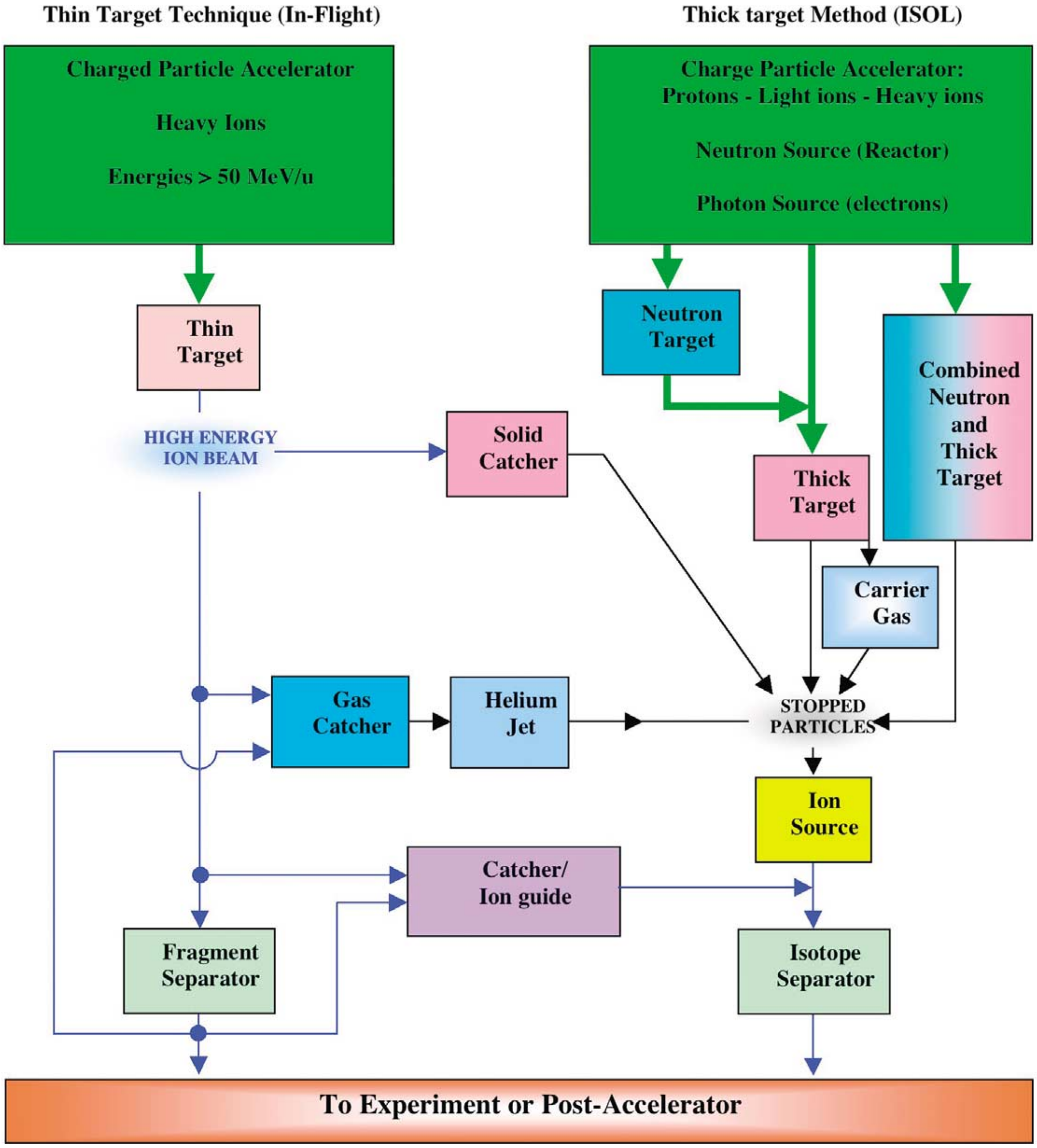

Fig. 1. Schematic diagram of the thin-target (In-Flight) and thick-target (ISOL) methods. Primary beams are shown in green, ion beams in blue and neutral beams in black.

of the ISOL target is to fire protons or deuterons into a converter target to supply copious amounts of neutrons, which interact with a thick production target. The converter and the production targets can be united into one target. Considerable ingenuity is displayed in the methods used to transport the particles from the target to the ion source. In most cases the particles effuse through the low pressure connecting tube, but in some cases it is necessary to sweep the particles along in a flow of gas or attach the particles to an aerosol in a carrier gas.

The thin-target and thick-target methods can be combined; the particles from the thin fragmentation target are stopped in a solid catcher and then pass into the rest of the ISOL. Alternatively the particles can be stopped in a gas catcher and passed into the ion source via a helium gas jet. Another variation is to stop the energetic particles in a gas and then have a helium gas ion guide system or IGISOL. The particles emerge from the IGISOL as singly charged ions, so avoiding the need for a separate ioniser.

A great advantage of the use of a thin target is that all the particles are released instantaneously, whereas in the thick-target technique, where all the particles are stopped, there can be considerable delay in the release. This is due to the slow diffusion out of the target and effusion through the connecting tube to the ioniser [13]. In addition, many particles physically or chemically stick to the surfaces, which can slow the effusion to such an extent that all the unstable particles decay before they reach the ioniser.

A disadvantage with the thin targets is that the particles emerge from the target as an energetic beam with a poor beam quality – a large energy spread and a wide-angle beam. This will usually require a spectrometer with a large momentum and angular acceptance for isotope selection. In addition, for further acceleration, there will need to be some form of cooling to produce a beam of suitable energy spread and emittance; this could be absorbers to virtually stop the beam and a gas ion guidance system. Several laboratories are looking at this method. The particles from the thin target are passed through a wide acceptance fragment separator and a particular isotope selected. The beam is passed through absorbers and then into a gas catcher and ion guidance system. The particles emerge from this as a good quality low-energy beam, which can then be passed through a mass separator and accelerated to high energy.

In the thick target, the beam quality is a function of the ion source and, in general, both energy spread and emittance are small. Clearly, the beam energy obtainable is variable from almost zero upwards.

In general, the difficulty of production and the resultant scarcity of the beams give a demand for the largest possible quantity or yield of radioactive ions for experiments. This point should be considered when comparing the efficiencies of the various parts of the production process by different methods; finally the yield is usually more important than efficiency.

However, efficiency can be an important consideration for access and disposal because of the radioactivity formed in the target and in other parts of the system. In general the activity from the beams does not present major problems because of the low intensities. However, the targets, neighbouring parts of the system and the mass separator become highly active; contamination is also a problem. As a result, maintenance and disposal has to be carefully considered. In addition, the primary beam will usually constitute a major radiation hazard. This will result in heavy shielding around the target area and sophisticated remote handling of the target, its environment and separators, independently of the technique chosen.

3. Thin target facilities

Important progress in the study of the fundamental properties of nuclei came about when intense heavy-ion beams became available and the first results of experiments using fast unstable ion beams appeared. Perhaps the best example is the measurements of the interaction cross sections of light nuclei, first made at the BEVALAC, USA by I. Tanihata and collaborators [14], which provided the evidence for the existence of an unexpected halo for the nucleus ^{11}Li. Since these experiments in 1985, projectile fragmentation has also been used at GANIL – France [15], GSI – Germany [16], MSU – USA [17], FLNR – Russia [18], HIRFL – China [19] and RIKEN – Japan [20] to produce and study reactions induced by radioactive beams. Separators have been built at these centres in order to maximise the beam production and purity. All these facilities have in common the fact that the unstable beams are produced by projectile fragmentation at energies between 40A and 2000A MeV. It turns out from the principle of production and separation using a spectrograph that the optimum efficiency of the process is reached when the unstable beam has a velocity similar to that of the primary beam [21]. Therefore these are facilities devoted to efficiently produce intermediate-high energy ($>40A$ MeV) unstable beams.

The energy and intensity of the primary beam is an important parameter, not only for cost considerations, but also for optimising the yield of the unstable beam. As an exercise, let us consider only projectile fragmentation as being the principal production process and use the EPAX model [22] for estimating the yield of ^{18}O, ^{31}Ar, ^{45}Ar and ^{74}Rb. In this calculation the optimum primary beam is used in each case, i.e., ^{18}O, ^{36}Ar, ^{48}Ca and ^{84}Sr, and a fragment separator similar to MSU-A1900, corresponding to an angular acceptance of 40 mrad and a moment acceptance of $\pm 4\%$. The production yield was calculated as a function of the bombarding energy and is plotted in Fig. 2 as the ratio to the yield at 100A MeV. In all calculations the optimum target thickness was taken into account, corresponding to maximising the selected secondary beam. The thick pink line indicates the range ratio $R(E)/R(100A\ \mathrm{MeV})$ for ^{12}C beam. It shows that the primary beam range dominates the yield behaviour; the higher energy corresponding to larger range and higher secondary beam yields. On the other hand, for example, an enhancement of a factor 30 of the primary beam intensity of ^{18}O at 100A MeV would completely compensate the production of ^{14}Be at 1000A MeV (green curve).

It should be noted that the yield curves in Fig. 2 are valid in the case where a single charge dominates the charge state distribution of the secondary beam at the exit of the target. This is true only for light ions at intermediate energies. Heavier ions have a wide charge state distribution at intermediate energies, which would distribute the yields in a correspondingly wider magnetic rigidity range. Therefore, the enhancement of the yield by primary beam intensity at lower energies is much more important. However, the technical demands on the ion source to produce sufficient primary beam current, particularly for the heavier ions, are considerable.

Simplifying the arguments and only considering the secondary beam intensities, the real question is whether it is more convenient to have higher primary beam energies or higher intensities. The answer is strictly related to the technical capabilities

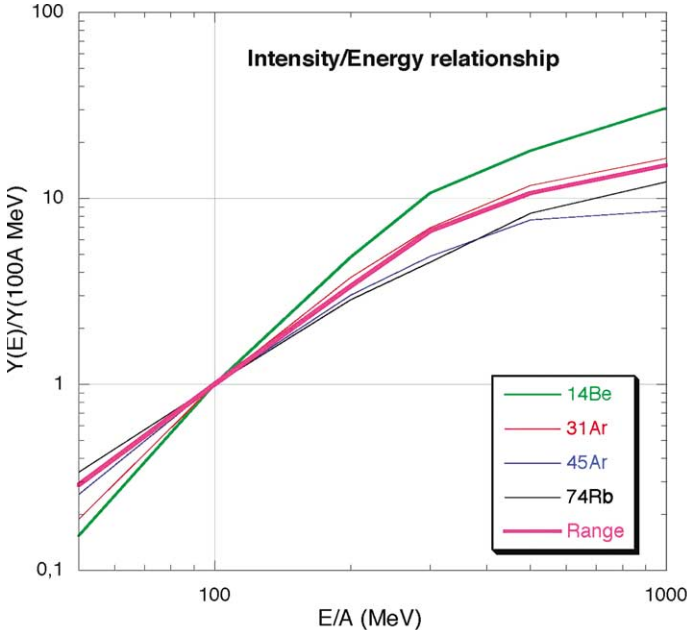

Fig. 2. Yield ratio of a selected set of secondary beam isotopes as a function of the primary beam energy. See text.

and costs of accelerating high currents and high energies. It is dependent on the accelerator technology, i.e., cyclotrons, linacs or synchrotrons and the availability of high currents from the ion sources. It is also clear that the answer to this question is continuously in evolution.

In the following two sections, intermediate and relativistic energy facilities are described briefly. An attempt to answer the latter question is also given in the following sub-sections.

3.1. *Intermediate energy facilities*

3.1.1. *The driver*

The facilities considered in this section are GANIL, MSU, FLNR, RIKEN and HIRFL. All of these facilities have the capability to deliver unstable beams produced via the thin target method in the energy range of 40–200*A* MeV. All these facilities have cyclotrons as driver accelerators. Cyclotrons are proved to be well suited for producing heavy ion beams in the intermediate energy domain with reasonable intensities, up to several particle micro-amperes (pμA). The accelerated beam power corresponds to values not exceeding 6 kW. The GANIL Facility is currently able to deliver the highest beam power from a heavy ion cyclotron; 5.2 kW of ^{36}Ar extracted (although not used in an experiment) at 95A MeV [23].

The primary beam intensity is of course dependent on the ion source intensity. The above facilities use electron cyclotron resonance (ECR) ion sources [24] to produce multicharged ions to maximise the energy reached in acceleration and to improve the beam versatility. Moreover, at GANIL, MSU and RIKEN, two or three accelerators are used in series, with or without electron stripping stages in between, to further increase the energy.

While the cyclotrons at MSU are based on superconducting technology, at GANIL, FLNR and HIRFL room temperature coils are used for creating the magnetic field. At RIKEN, the present cyclotrons use room temperature coils while the new Ring cyclotron being built for the RIB Factory is superconducting [25].

A compilation of beam energies and intensities delivered by these facilities is a hard task. Moreover, it should be noted that a very fast evolution of these values makes this task already more difficult. Therefore, Table 1 gives the present maximum energy and intensity of already accelerated (and used in experiments) beams for each facility. It should be noted that in almost all cases, ions could vary from protons to uranium.

3.1.2. *The production system and separator*

The nature of the target is important for improving the production yields mainly in the intermediate energy domain. It is preferable to use light elements, like beryllium or carbon. However, heavier targets are preferred for the production of neutron deficient unstable isotopes, such as nickel [26]. The beam on the target needs to be small to minimise the size of the particle

Table 1
Maximum beam energies and currents available at intermediate energy facilities: selected cases already used in experiments

Facility	Maximum beam energy/nucleon (A MeV)	Maximum present HI beam intensity (pnA)	Corresponding power (W)
GANIL	95	1570 (^{20}Ne)	3000
RIKEN	135	550 (^{16}O)	1180
MSU	150	100 (^{16}O)	240
FLNR	47	320 (^{7}Li)	105
HIRFL	69	3 (^{36}Ar)	3.3

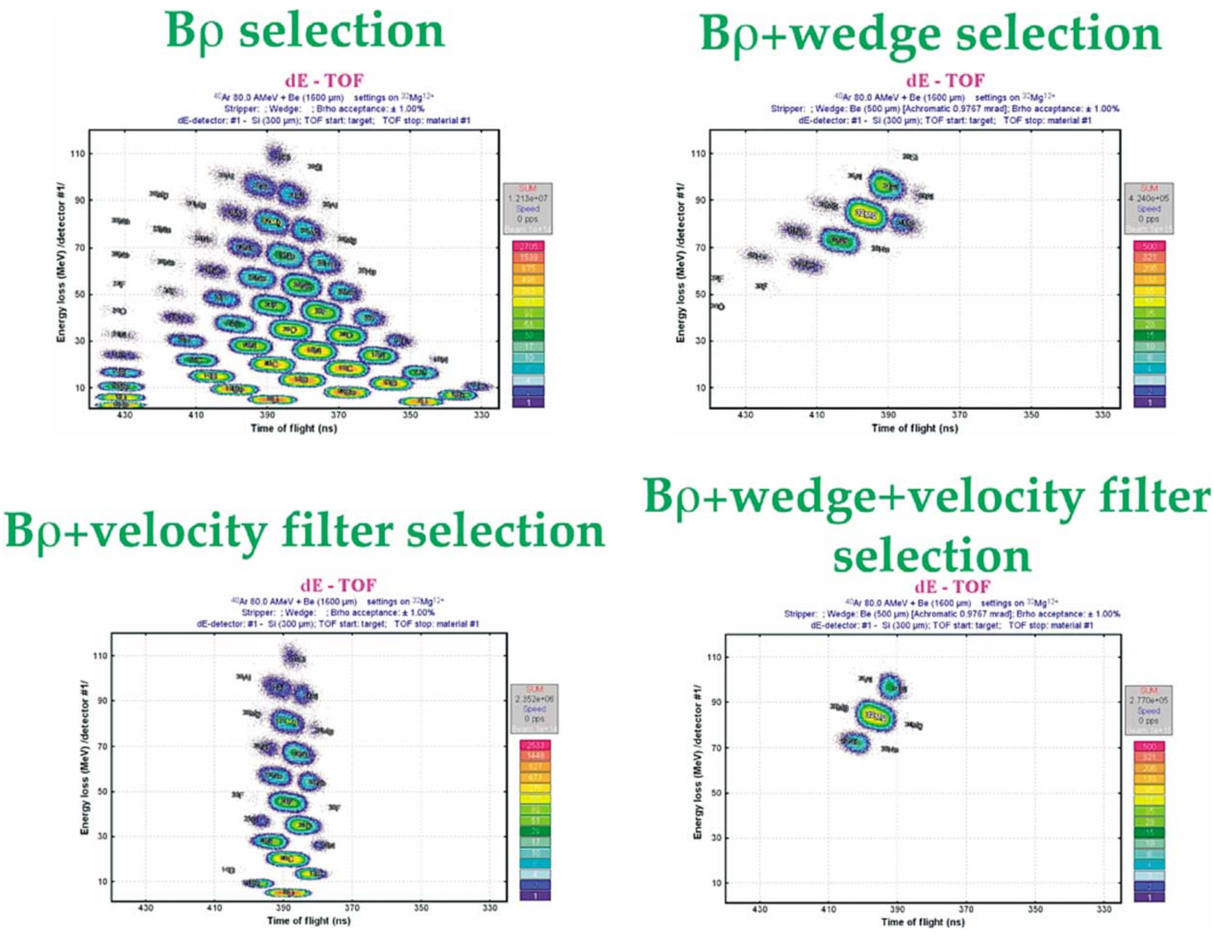

Fig. 3. Identification matrix (energy loss in a particle detector as a function of time of flight) for fragments produced by projectile fragmentation of ^{40}Ar on a beryllium target. The different frames show the usefulness of the different selections used. The pictures were calculated with the code LISE [29] using the LISE-3 parameters.

source and hence it's beam emittance for acceptance into the separator that follows. Thus the target must withstand not only high intensities, but also very high power densities.

The state of art example for a complete production ensemble is SISSI ('Source d'Ions à Solénoïdes Supraconducteurs Intenses') at GANIL [27]. It is composed of two superconducting solenoids surrounding a production target. The first solenoid concentrates the primary beam in a spot of 0.4 mm diameter on the rotating target (2000 rpm) of 15 mm diameter. The second solenoid, placed just behind the target allows an angular acceptance of the fragments of $\pm 5°$. The product of the beam spot and the divergence of the secondary beam gives an emittance of the order of 40π mm mrad, compatible with the admittance of the 'alpha-shaped' spectrograph situated immediately downstream of the target.

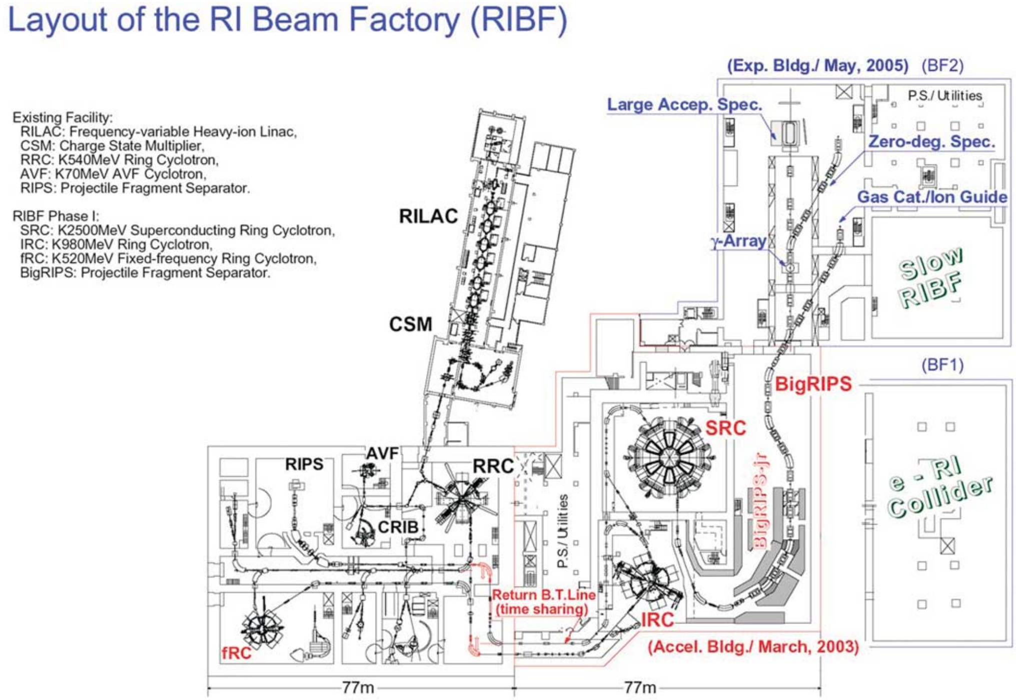

Fig. 4. Layout of the planned unstable beam factory at RIKEN. (Courtesy of RIKEN.)

The A1900 superconducting fragment separator [10] at MSU is currently pre-eminent in its category, with the highest angular/moment acceptance presently available. Each laboratory has its own separator, with characteristics varying as a function of the momentum and mass of the unstable elements to be selected. Nevertheless, the techniques are usually the same to achieve good mass separation and involves an achromatic optical system with degrader [28]. The magnetic deviation allows a separation of the fragments – as a function of the position in the focal plane of the separator – in the A/Z ratio. The function of the degrader is shown in Fig. 3. It is usually placed between the two main dipoles of the separator, in the intermediate dispersive focus of the system, allowing an extra filtering in the A^3/Z^2 ratio. As the energy loss in the degrader – usually a thin foil of beryllium or Mylar – for different elements (Z) are different, it allows an improvement in the separation after the second magnetic deviation. Extra filtering, involving the velocity of the fragments, is also possible in the LISE-3 spectrometer at GANIL. This feature can be fundamental when searching for very rare phenomena.

3.1.3. The RIKEN-F factory

In the intermediate energy domain, the RIKEN-RIB factory [25], presently in construction near Tokyo, will provide very high primary intensities in the highest energy domain. The cascade of three or four cyclotrons, also alternatively augmented by the linear accelerator – RILAC – will allow beams to be accelerated from protons to uranium up to $\sim 400A$ MeV. Moreover, the intensities of these beams could reach hundreds of microamperes. The accelerator has the configuration shown in Fig. 4. The accelerator is composed of a superconducting ring cyclotron (SRC) and an intermediate energy ring cyclotron (IRC). Light nuclei are accelerated to $500A$ MeV and the heaviest nuclei are accelerated to $400A$ MeV with very high intensities. The heavy ion beams obtained from the SRC will be converted into unstable beams by the RIPS II separator. The separated beams (as well as the primary beam) are sent to the various new experimental facilities. An upgrade of this facility is already planned, involving a double collider (MUSES) and an electron linac for electron-unstable nuclei collision studies.

3.2. The relativistic energy facility at GSI

High secondary beam intensities can also be efficiently produced by the fragmentation of relativistic heavy ions. At GSI, the use of the synchrotron SIS, capable to accelerate heavy ions to energies of around $1.0A$ GeV is well suited to this task. Although having an injection efficiency of only 1%, the very high energy of the primary beams compensates largely for the lower intensities of the primary beams inside SIS. The advantage of high intensities is particularly striking when considering the fragmentation and fission of very heavy ions, like lead and uranium. This is due to the fact that the charge state distribution

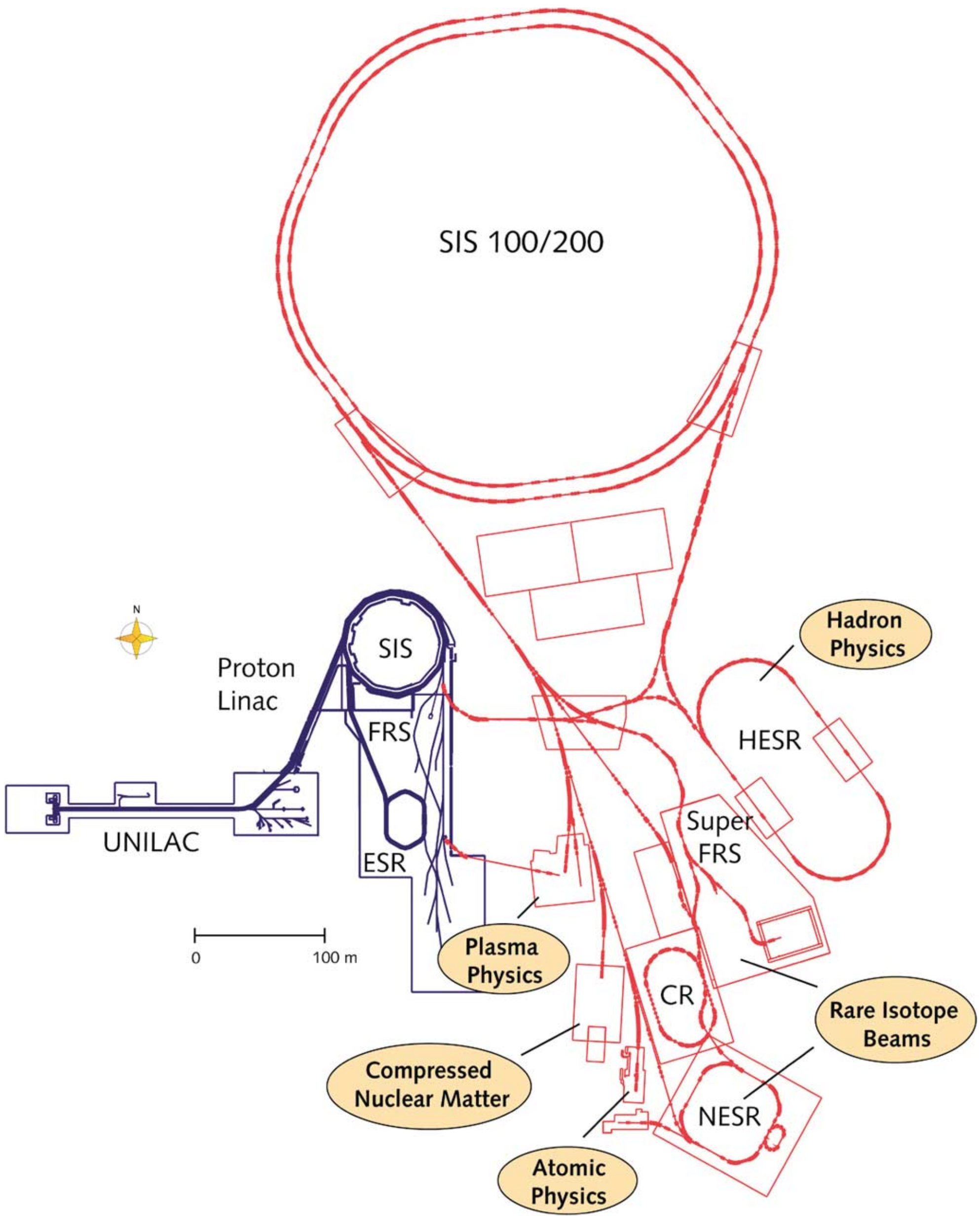

Fig. 5. The new project at GSI.

of the fragments is squeezed at relativistic energies, enhancing the acceptance of the following separator. Moreover, the angular distribution of the fragments is also more forward focussed than in the intermediate case, due to kinematics of the reaction. This facilitates the design of the fragment separator.

The present GSI facility is particularly well adapted for the production of fast fission fragments, unlike the intermediate energy facilities.

In the European scenario, GSI and GANIL are quite complementary, GANIL is more suited for the production of light heavy ions ($A < 120$) at intermediate energies and GSI of heavier ions at relativistic energies.

3.2.1. The GSI project [30]

Following the need to improve the unstable secondary beam intensity, the new project at GSI uses the present GSI accelerators to inject heavy ion beams of higher intensities into a new 100/200 Tm double-ring synchrotron SIS100/200 (see

Fig. 5). The most important advances are the possibility to substantially enhance the beam intensity in the synchrotron ring through faster cycling and, for heavy ions, to lower the charge state in the accelerator, which enters quadratically into the space charge limit. These two major improvements of the new SIS200 synchrotron ring allows 1.5*A* GeV heavy ion beams to be achieved at an intensity of 10^{12} particles per second. Together with a new fragment separator – Super FRS – the intensity of the primary beams will be enhanced by a factor of 100 and up to a factor of 10 000 in secondary beam intensities.

A new storage ring system, with a collector ring CR and the new experimental storage ring NESR, for storage, accumulation and cooling of the secondary beams will allow internal target experiments to be performed with light nuclei such as hydrogen and helium. Another possibility is to intercept the NESR ring with a small electron storage ring allowing the study of electron–nucleus collisions, probing the charge distributions and form factors of very exotic nuclei.

4. Thick target facilities

The most serious limitation of the thin target method is the poor quality of the secondary beam, which results in losses in beam transmission and isotope selection. The problem become increasingly important if the beam is slowed down. From this point of view, the study of secondary beam reactions at low energies using intense radioactive ion beams requires a different production method. The coupling of the ISOL technique with a post-accelerator provides for production and separation of intense radioactive beams at variable energy with little intensity loss and the opportunity to study nuclear reactions with these beams at lower energies, in particular near the coulomb barrier.

The first accelerated unstable ion beam produced with the ISOL technique was at CRC-UCL, Louvain-La-Neuve, Belgium [31]. The radioactive beam of ^{13}N was obtained from the reaction $^{13}C(p,n)^{13}N$ by impinging protons of 30 MeV from the CYCLONE-30 Cyclotron on to a powder ^{13}C target. The radioactive ^{13}N was transferred into an ECR ion source through a long transfer tube. Then the atoms were ionised, extracted and injected in the cyclotron CYCLONE. The first results obtained by the Louvain-la-Neuve group quoted 10^6 pps of radioactive ^{13}N after acceleration. At the present time, this number has been significantly enhanced ($\sim 10^9$ pps) [32] and ^6He, ^7Be, ^{10}C, ^{11}C, ^{15}O, ^{18}F, ^{18}Ne, ^{19}Ne, ^{35}Ar ion beams are also available.

4.1. Present facilities

The facilities based on the accelerated ISOL technique are: SPIRAL/GANIL – France [33], ISAC/TRIUMF – Canada [34], HRIBF/ORNL – USA [35], REX-ISOLDE – CERN [36] and CRC-UCL – Belgium. The energy and element domains are quite complementary.

In the classic ISOL technique a proton or a light-ion beam is accelerated to a high energy and bombards a thick target, producing radioactive nuclei by spallation, transfer reactions, fragmentation of the target and/or induced fission. This is the method used in the latter facilities, with the exception of SPIRAL, where a heavy ion bombards a thick light target. Another exception to be mentioned is the Holifield Radioactive Ion Beam Facility at ORNL, where a tandem Van de Graaf accelerates a negative ion beam. The EXCYT/LNS facility in Italy [37] also uses a tandem as post-accelerator and will be commissioned in 2004.

The high current of 500 MeV protons – 100 μA presently limited to 20 μA – available at TRIUMF in Vancouver makes the ISAC facility capable of delivering the highest available unstable beams intensities at an energy of up to 1.5*A* MeV. This intensity is likely to increase significantly over the coming years.

4.2. SPIRAL

At SPIRAL in Caen, projectile fragmentation of heavy ion beams is the production mechanism process of most importance. In all cases, the fragments are stopped in the target, which is heated to a high temperature to facilitate the migration of the radioactive atoms to the surface. Usually the target is located at a short distance from the ion source and the radioactive atoms effuse via a transfer tube to the plasma region where they are ionised and then accelerated. As the atoms are ionised and accelerated in a manner identical to that for stable beams, the resulting radioactive beams have good dynamical and optical characteristics when compared with projectile fragmentation, as well as a precisely adjustable energy. The originality of the SPIRAL project lies in the use of an extended range of heavy ions, up to the maximum available energies. Such an approach differs from the proton (or light-ion) beam technique in that the projectile rather than the target is varied in order to produce the different radioactive species, thereby allowing the use of the most resilient and efficient production target for most cases.

For SPIRAL, the high-energy beam delivered by the present GANIL cyclotrons interacts with a thick target, where all the reaction products are stopped. The target is thereby heated by the primary beam up to 2200 °C. Such a temperature is a challenge for the target in terms of reliability and duration. A numerical code has been developed to simulate the temperature distribution

Fig. 6. SPIRAL conical target (a) and the special design for He production (b). Both targets were built to work at 2 kW maximum primary beam power.

inside the target and is described in [38]. It can be shown with this code that convenient temperatures (<2400 K) can be achieved with high primary beam powers if the target presents a conical shape (Fig. 6). In the case of a low power primary beam, extra ohmic heating can be added through the axis of the target to maintain the diffusion of the exotic ion beam.

After production and diffusion, the radioactive atoms effuse to the ion source through a cold transfer tube that makes a chemical selection, as the main part of the non-gaseous elements sticks on the walls of the tube. The atoms then enter into the ECR (Electron Cyclotron Resonance) ion source Nanogan-3 [39] where they are ionised and extracted to form the radioactive ion beam. The beam is finally accelerated by the CIME cyclotron up to energies of 25*A* MeV.

The first exotic beam from SPIRAL was delivered to an experiment at the end of September 2002. The isotope ^{18}Ne (half-live of 1.67 s) was produced by projectile fragmentation of the primary beam, ^{20}Ne, at 95*A* MeV on a carbon target. At present, beams of ^{6,8}He at 15.4*A* MeV and 3.5*A* MeV and ^{74,76}Kr at 7.3*A* MeV have also been delivered for experiments. The intensities achieved using a primary beam power of respectively 1.4 kW and 500 W are in perfect agreement with the expected ones. The intensities of ^{8}He at 15.4*A* MeV and 3.5*A* MeV, corresponding to the charge states of $2+$ and $1+$, were of 1.4×10^4 pps and 4×10^4 pps, respectively, while for ^{76}Kr, the intensity was 1×10^6 pps.

5. New concepts and the future

The versatility of the production system is of paramount importance when considering the evolution of methods for producing unstable nuclei. The mixing of the thin and thick target techniques and the development of new production methods, aiming to optimise the extraction, ionisation and eventually the acceleration of the secondary beam is mandatory. The versatility and adaptability is even more important than the primary beam intensity, simply because the efficiency of the production system can vary by several orders of magnitude depending on the technique used.

This ingredient defines the choice of the driver for future projects as being a multi-beam accelerator, which can be better adapted to optimise the production conditions; two examples are the RIA and the LINAG projects.

5.1. The RIA project

The ambitious RIA facility [40] proposed in the USA embodies both the ISOL and fragmentation techniques to produce intense radioactive beams over a very wide spectrum of isotopes. A superconducting heavy ion linac, capable of accelerating

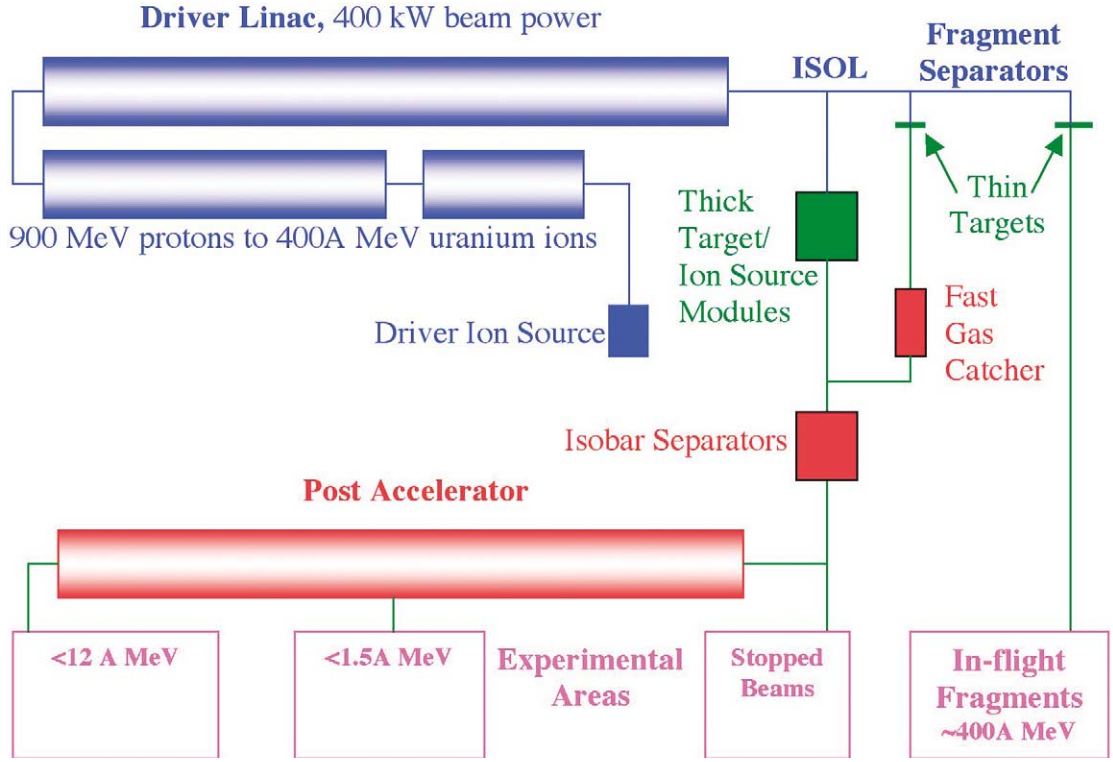

Fig. 7. Shematic Layout of the RIA facility.

intense beams of protons to 900 MeV and heavier ions, up to uranium, to 400A MeV, is used to bombard both thick and thin targets, respectively. The linac is able of accelerating several charge states simultaneously, thereby increasing the heavy ion intensity. Flowing lithium liquid is proposed for the thin fragmentation targets to withstand the high power dissipation. The fast gas catcher must deal with relatively large currents of radioactive ions; it is a crucial part of the scheme and has yet to be proved to work successfully. A linear post accelerator produces ions of up to 12A MeV. The radioactive ion beams can be used in four experimental areas: (i) stopped beams, (ii) $\sim 1A$ MeV post accelerated beams, (iii) $\sim 10A$ MeV post accelerated beams, (iv) $\sim 400A$ MeV in-flight fragments. Fig. 7 shows the facility schematically.

5.2. The LINAG project

The LINAG project [41] in France at GANIL proposes a multi-beam driver in order to allow both fragmentation and ISOL techniques to produce radioactive beams. A superconducting light-heavy ion linac capable of accelerating 1 mA protons, deuterons and heavy ions up to a 100A MeV is used to bombard both thick and thin targets. The most important difference between LINAG and RIA is the mass domain of the driver. The superconducting linac is optimised to $A/Q = 3$, better adapted to light masses ($A < 100$) and adapted to the evolution of the ECR ion sources. This choice is a compromise between the minimisation of the beam losses during acceleration (no stripping is used during acceleration) and the length of the machine.

The project, as outlined here, can be constructed in various phases, starting at low energy. It would cover a broad range of possibilities of primary and secondary beams. These beams could be used for the production of intense secondary beams by all reaction mechanisms (fusion, fission, fragmentation, spallation, etc.) and technical methods (recoil spectrometers, ISOL, IGISOL, etc.). Thus, the most advantageous method for a given problem of physics could be chosen. In the first phase, this corresponds to an acceleration potential of about 40 MV, with fission induced by neutrons from a converter, or by direct beams such as d, ^{3}He or ^{4}He, and fusion-evaporation reactions involving heavy ions of 14.5A MeV. This first phase (called SPIRAL2, Fig. 8) expands the range of unstable beams available at GANIL to heavier ones.

The post acceleration in the SPIRAL2 phase is by the cyclotron CIME, which is well adapted to produce beams in the range of 10A MeV for masses $A \sim 100$. SPIRAL2 can be coupled to the present experimental area of GANIL, which accommodates the high acceptance spectrometer VAMOS [42], the gamma spectrometer EXOGAM [43] and other key equipment as well as SPEG [44] and LISE. Several domains of research in nuclear physics at the limits of stability will be covered by this project,

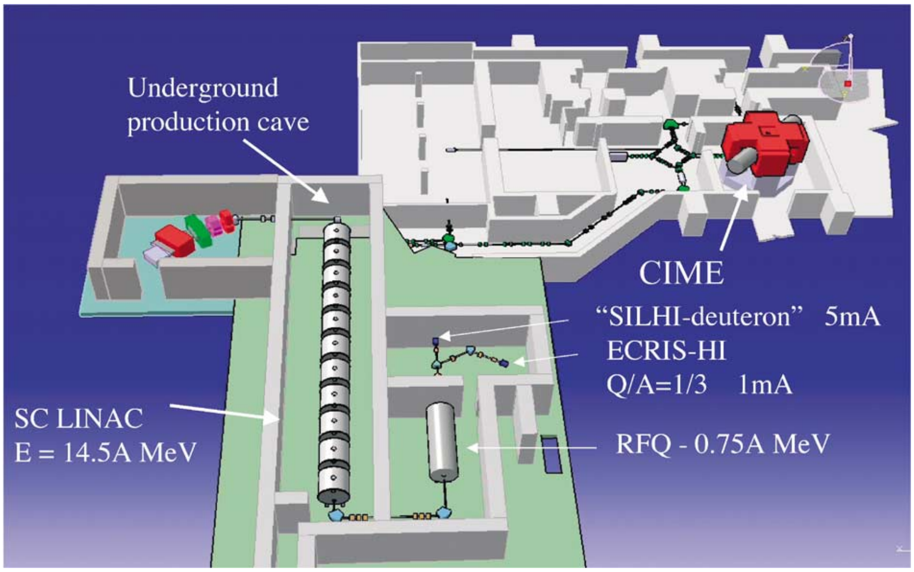

Fig. 8. Layout of the SPIRAL2 facility at GANIL.

including the study of the rp-process, magicity close to $N = 82$ and $N = Z = 50$ and the study of very heavy and superheavy nuclei.

5.3. *EURISOL RTD*

In the European scenario, an ultra high intensity ISOL-based facility delivering high intensities of all kinds of unstable beams is being considered as a goal in 10 or 15 years time. This 3-year study is thoroughly investigating the scientific and technical challenges posed by such a facility, identifying the R&D required before a full engineering design could be undertaken, and establishing a cost-estimate of capital investment and running costs. Possible synergies with other European installations and projects are also being considered.

5.4. *The thrust for the FUTURE*

The thrust for the future is for the new generation of accelerated radioactive ion beam facilities to yield higher intensities of all possible isotopes at energies of at least $100A$ MeV.

The challenges are to produce:

(1) The intensity;
(2) The full range of isotopes;
(3) Very highly charged ion beams – ideally fully stripped;
(4) Simple, long life targets that can withstand high primary beam powers;
(5) Targets, transport systems and ionisers, which provide overall particle transmission that is fast compared to the decay times;
(6) High selectivity.

Thus, the main areas of developments are in:

(1) Gas catchers and ion guides for thin fragmentation targets. This is because the community sees a strong advantage with no chemical limitations of element from thin fragmentation targets. Coupled to a suitable gas catcher and efficient high current ion guide with short delay times it would provide a powerful technique for future accelerated beam facilities. The target can probably be simpler than the relatively complicated thick targets that have to operate at high temperatures and be designed for fast diffusion and effusion;
(2) ECR ion sources and charge amplifiers for multiply charged ions and hence smaller, less expensive post accelerators;
(3) Laser ion sources for high selectivity;

(4) Alternative neutron converter-targets. This is seen as a possibly better method to overcome the power dissipation in thick targets and separates the power dissipation and other properties from the converter target and the production target;
(5) Cooling thin targets for fragmentation at high power density, particularly for the lower mass primary beams that require reasonably heavy targets, where liquid lithium is inappropriate.

However, the thick target technique has been shown to be competitive in both short delay times and, with suitable chemistry, the production of ions of chemically challenging elements.

An important feature is multi-user operation. In most radioactive ion beam facilities only one user can receive beam. Yet the target produces a wide range of isotopes. It is more efficient if several beams and experiments can run in parallel. This is possible at low energy but would require more than one accelerator for high-energy beams, although it is possible to obtain intermediate energies for simultaneous experiments. It is worthwhile to be able to operate a number of low energy ($\sim$100 kV) beams and a high-energy beam; this is incorporated into the proposals.

And a word of warning; as the primary beam currents become larger and fissionable materials like uranium are used more, the problems of radiation safety, shielding, activity, remote handling, maintenance and disposal increase, along with the associated costs. Already some facilities are experiencing difficulties in obtaining the necessary authorisation under the safety regulations and it is likely to become even more difficult in the future.

Currently there are a number of EU projects either funded or proposed that cover most of the areas needing development that are listed above:

(1) Ion Sources as part of the EURISOL RTD project;
(2) TARGISOL, a proposal to study target diffusion and effusion;
(3) A proposal to study ion catchers and guides – ION CATCHER;
(4) SAFERIB, a proposal to consider safety aspects of facilities;
(5) CHARGE BREEDER, for studying the breeding times and efficiency.

The technological development which will be accomplished in the following years, will guide the research to reach the limits of the nuclear stability.

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