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Production of RIB: methods and applications

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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 for the future are described.

Keywords: Radioactive beams; particles sources and targets; particle accelerators.

Se discuten las ventajas y desventajas de varios métodos para la producción de haces inestables con técnicas en vuelo e ISOL para blancos gruesos y delgados. Se muestran algunos ejemplos típicos de aceleradores. Se describen conceptos novedosos, desarrollos de proyectos de investigación y propuestas para aceleradores ambiciosos para enfrentar los retos del futuro.

Descriptores: Haces radioactivos; fuentes y blancos de partículas; aceleradores de partículas.

PACS: 29.25.-t; 29.27.-a

1. Introduction

Several are the frontiers of modern nuclear physics and these can be studied via decay and reactions involving stable and unstable nuclei. Theoretical estimates indicate that there may be up to 7000 nuclei lying between the proton and neutron drip lines [1]. Presently evaluated nuclei number according to the latest NUBASE is 2830 [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 = 118.
- 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.

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 - related to the use of a thin target followed by a mass separator.

B) The ISOL Method with re-acceleration ï¿½related to the use of a thick target for unstable beam production and a post-accelerator.

Figure 1 [8, 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 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-14 [5] and RNB 2000 [4]. More details

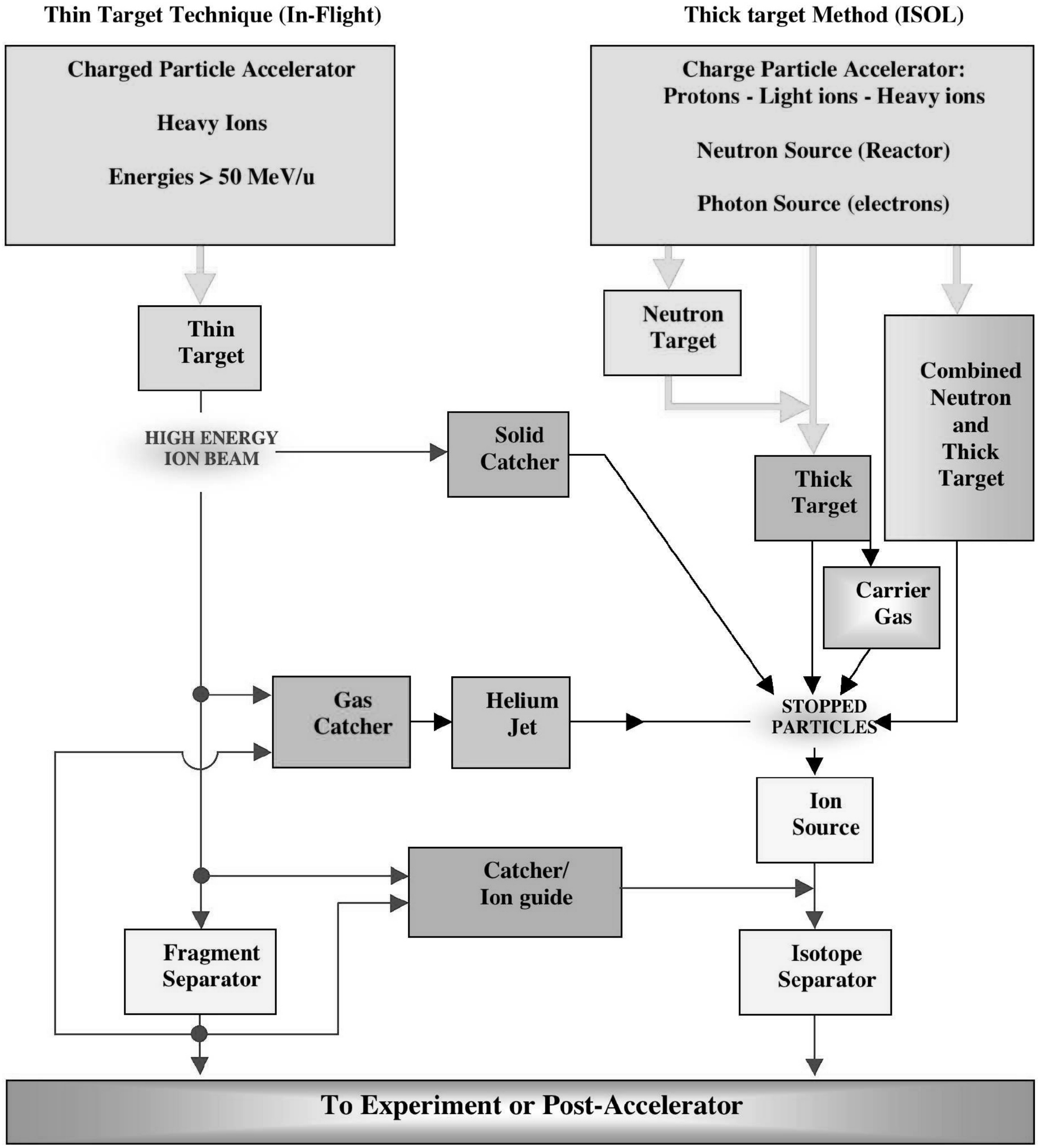

FIGURE 1. Schematic diagram of the Thin-Target (In-Flight) and Thick-Target (ISOL) Methods.

will be given in chapter 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 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 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 (larger than 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. 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, like nickel [22]. The beam on the target needs to be small to minimise the size of the particle source and hence it production 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 Solenoides Supraconducteurs Intenses) at GANIL [23]. 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 +/- 5 . The product of the beam spot and the divergence of the secondary beam gives an emittance of the order of 40 mm mrad, compatible with the admittance of the lpha-shapedspectrograph situated immediately downstream of the target. 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 [24].

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

400A MeV. Moreover, the intensities of these beams could reach hundreds of microamperes. 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.

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 of accelerating 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 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.

Following the need to improve the unstable secondary beam intensity, the new project at GSI [26] (FAIR) 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. 2). 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 1.5A GeV heavy ion beams to be achieveed at an intensity of 1012 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.

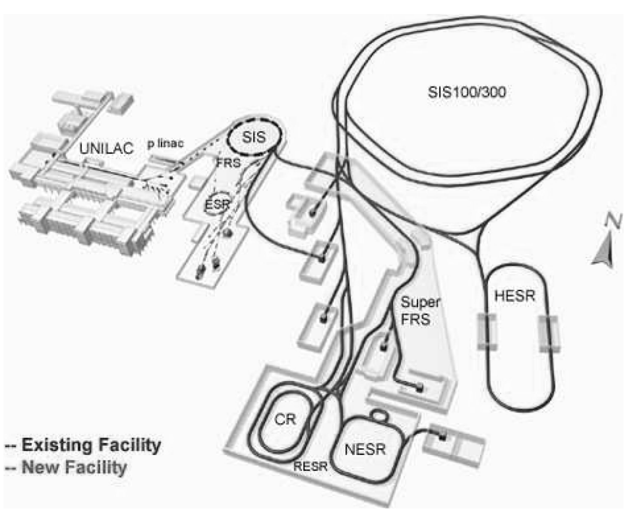

FIGURE 2. Present and future GSI facilities.

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 [27]. The radioactive beam of 13N 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 (10^9 pps) [28] and ^6He, ^7Be, ^{10}C, ^{11}C, ^{15}O, ^{18}F, ^{18}Ne, ^{19}Ne, ^{35}Ar ion beams are also available.

The facilities based on the accelerated ISOL technique are: SPIRAL/GANIL France [29], ISAC/TRIUMF Canada [30], HRIBF/ORNL USA [31], REX-ISOLDE CERN [32] 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 [33] also uses a tandem as post-accelerator and will be commissioned in 2004. The high current of 500 MeV protons with 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 1.5A MeV. This intensity is likely to increase significantly over the coming years.

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 2200C. 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 inside the target and is described in [34]. It can be shown with this code that convenient temperatures (2400K) 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 [35] 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 25A MeV. The first exotic beam from SPIRAL was delivered to an experiment at the end of September 2002 [36]. The isotope ^{18}Ne (half-live of 1.67s) was produced by projectile fragmentation of the primary beam, ^{20}Ne, at 95A MeV on a carbon target. At present, beams of ^{6,8}He at 15.4A MeV and 3.5A MeV and ^{74,76}Kr at 7.3A MeV have also been delivered for experiments. The intensities achieved using a primary beam power of respectively 1.4kW and 500W are in perfect agreement with the expected ones. The intensities of ^{8}He at 15.4A MeV and 3.5A 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. Nowadays, new beams of oxygen and nitrogen are also available, as well as primary beam intensities up to 3 kW on the various targets.

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 [37] 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 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 to accelerate 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: 1) stopped beams, 2) 1A MeV post accelerated beams, 3) 10A MeV post accelerated beams, 4) 400A MeV in-flight fragments. Figure 7 shows the facility schematically.

5.2. The LINAG/SPIRAL2 project

The LINAG project [38] 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 to accelerate 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, 3He or 4He, and fusion-evaporation reactions involving heavy ions of 14.5A MeV. This first phase (called SPIRAL2, Figure 3) 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 100. SPIRAL2 can be coupled to the present experimental area of GANIL, which accommodates the high acceptance spectrometer VAMOS [39], the gamma spectrometer EXOGAM [40] and other key equipment as well as SPEG [41] and LISE. Several domains of research in nuclear physics at the limits of the stability will be covered by this project, 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 design study

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 design study is thoroughly investigating the scientific and technical challenges posed by such a facility and establishing a cost-estimate of capital investment and running costs. Possible synergies with other European installations and projects are also being considered.

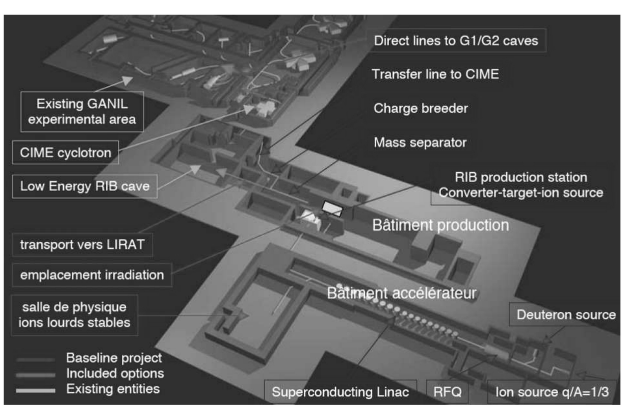

FIGURE 3. The LINAG/SPIRAL2 project.

6. 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 (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.

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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