The FRIBs upgrade at LNS

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Abstract. The FRIBs facility at the Laboratori Nazionali del Sud produces, since 2001, Radioactive Ion Beams (RIBs) at intermediate energies by projectile fragmentation. Using such beams nuclear physics experiments of international relevance have been accomplished so far. The fragments of interest are selected along the extraction line of the superconducting cyclotron, configured as a fragment separator. RIBs rates up to 10^5 ion/sec on target have been successfully achieved by a cyclotron primary current up to 600 enA. However a possible upgrade of the production and selection system has been studied and it is going to be realized in the next months. Features of the upgrade and the expected improvements in RIBs production yields and transmission are reported.

1. Introduction
Production of radioactive isotopes beams (RIBs) by means of an in-flight separation scheme provide unique opportunities to study reactions and properties of unstable nuclei far from stability. This possibility is available at LNS where the FRIBs facility delivers, since 2001, radioactive ion beams at intermediate energies by projectile fragmentation and in-flight separation [1, 2]. The facility makes use of the present extraction line of the LNS Superconducting Cyclotron, configured as a Fragment Separator, to select the products of projectile fragmentation. In order to cope with the lack of purity of the produced secondary beams, the leading idea of the project was the application of the tagging technique. It consists on the identification, event-by-event, of each nucleus of the secondary beam, before it interacts with the secondary target, i.e. the reaction target, with a proper detection system which modify as less as possible the characteristics of the secondary ions. This tagging technique has been proved to be very useful to discriminate the contributions of the contaminants present in a secondary beam. In particular the facility demonstrates to be very competitive in reaching the proton-rich side of nuclear chart allowing the study of the two-proton decay of ^18Ne [3].

In the aim to produce more exotic nuclei with intensities useful for experiments, an upgrade of the facility has been studied in recent years and it is going to be realized at the end of 2010. The upgrade will concern the production and selection systems of the FRIBs facility and will allow to gain a maximum factor of 30 in the RIBs rate on reaction target.
2. The FRIBs facility

![Figure 1. Layout of the LNS facility. The Fragment Separator (inside the oval shape) connects the SC to the switching hall.](image)

The production of RIBs at intermediate energies at LNS was achieved by the In-Flight method, using $^{12}\text{C}$, $^{20}\text{Ne}$, $^{40}\text{Ar}$ and $^{58}\text{Ni}$ projectiles, accelerated by the Superconductive Cyclotron (SC) at energies between 62 and 40 MeV/u. Production targets have been set in a rotating holder just at the exit of the SC whose extraction line was used as an achromatic fragment separator (FRS) (Fig. 1). The present version of the separator consists on two bending dipole magnets, a quadrupole in front of the first dipole and four quadrupoles among the dipoles. A possible degrader could be placed at the intermediate focus but it was not used in our experiments.

Different neutron- and proton-rich nuclei have been produced (Fig. 2) by using $^{12}\text{C}$, $^{20}\text{Ne}$, $^{40}\text{Ar}$, $^{58}\text{Ni}$ and, recently, $^{13}\text{C}$, $^{16}\text{O}$ and $^{18}\text{O}$ projectiles and individual rates on target up to $10^5$ ions/sec were measured for primary beam currents up to 600 enA. The rate on target of the best studied case are reported in table 1. The production and the optical transport of these nuclei have been well optimized and the nuclei have been used in experiments [3, 4].

| Reaction | Ion     | Rate  | Reaction | Ion     | Rate  |
|----------|---------|-------|----------|---------|-------|
| $^{20}\text{Ne}+^{9}\text{Be}$ | $^{18}\text{Ne}$ | $9\times10^4$ | $^{13}\text{C}+^{9}\text{Be}$ | $^{11}\text{Be}$ | $2\times10^4$ |
| $^{17}\text{F}$ | $3\times10^4$ | $^{12}\text{B}$ | $8\times10^4$ |

Table 1. RIBs rates, measured in ions/sec on the secondary target. The rates are measured for a primary beam current of 600 enA.
2.1. The tagging method

Several different isotopes are transmitted through the fragment separator. The purity could be improved by placing a degrader at the intermediate focus of the fragment separator but this option turned out to be poorly useful at the energies and mass domain of the primary beams delivered by the LNS Superconducting Cyclotron. In order to discriminate the number of nuclei at the exit of the fragment separator, the leading idea of the FRIBs project was then to apply the tagging technique: namely, the identification, on an event-by-event basis, of each nucleus of the secondary beam cocktail, before it impinges on the secondary target. Obviously, the tagging detector must not stop the incoming ions and should modify as less as possible their characteristics. Therefore, we applied the $\Delta$E-ToF method to identify each incident fragment using the $\Delta$E signal from a silicon detector and the time of flight measured from the same signal generated by the silicon detector with respect to the radio-frequency signal supplied by the accelerator (Fig. 3). The use of the RF signal meets the requirement to maintain as minimal as possible the amount of material the secondary beams have to passed through. On the other hand the periodic nature of the RF signal causes the inversion in the isotope sequence observed in Fig 3, top panel, with consequent mixing of the neighbour species. The setup of a specific start counter for the measurement of the "true" time-of-flight is planned.

Here again we would like to point out the uniqueness of the tagging method, i.e. the possibility to simultaneously carry out a variety of experiments with different exotic nuclei, by selecting offline the isotope of interest before it impinges on the interaction target.

3. The extraction beam line: Present and Future

The present version of the separator has a geometrical acceptance of 0.1 msr and the maximum magnetic rigidity is limited to 2.7 Tm due to limitations of the present quadrupoles. Both solid angle and magnetic rigidity can be upgraded, to 4 msr and 4 Tm respectively, by adding two new quadrupoles in front of the first dipole, by replacing the four quadrupoles with six new ones of larger diameter, and by optimizing the quadrupoles position according to the setup shown in Fig. 4 [5]. Moreover two sextupoles $S_4$, $S_9$ near the quadrupoles $Q_4$, $Q_9$, not shown in Fig. 4, are necessary to reduce the chromatic effects. In table 2, the acceptances of the present and upgraded Fragment Separator are reported. By applying the described changes, we estimate a remarkable factor 40 in the RIBs intensities at the final focus.

However, in order to take into account the transmission along the beam line up to the experimental caves, the calculated beam acceptances for the upgraded Fragment Separator have
Figure 3. $\Delta E$-ToF identification from the Si-Strip detector.

| Acceptance $\times$ $3 = 9\pi$ | Acceptance $\times$ $2 \times 7.5 = 15\pi$ | Momentum Acceptance $\times 0.5\%$ |
|---------------------------------|---------------------------------|-----------------------------------|
| Existing line                   | Upgraded line                   | Gained Factor                     |
| $3 \times 3 = 9\pi$             | $2 \times 7.5 = 15\pi$          | $0.5\%$                           |
| $3 \times 16 = 48\pi$           | $2 \times 30 = 60\pi$           | $1\%$                             |
| $5 \times 4 = 20\pi$            | $4 \times 5 = 20\pi$            | $2\%$                             |

Table 2. Horizontal angular acceptance, vertical angular acceptance and momentum acceptance of the existing and upgraded FRIBs line. Both the angular acceptance are calculated for a beam spot on the production target of $x = 3\text{mm}$ and $y = 2\text{mm}$.

| Acceptance $\times 3 = 9\pi$ | Acceptance $\times 5 \times 4 = 20\pi$ | Momentum Acceptance $\times 0.5\%$ |
|--------------------------------|---------------------------------|-----------------------------------|
| Ciclope-Medea beam lines       | Chimera beam line               | $20^\circ$ line                   |
| $3 \times 3 = 9\pi$            | $10 \times 4 = 40\pi$           | $3 \times 10 = 30\pi$            |
|                                | $5 \times 4 = 20\pi$            | $2 \times 20 = 40\pi$            |
|                                | $0.8\%$                         | $0.7\%$                           |

Table 3. Acceptance in transverse space and in momentum of the beam lines of the LNS up to the main experimental caves.

to be compared with the corresponding acceptances of the beam lines. In table 3 the angular and momentum acceptances of some of the beam lines present at LNS are reported. By matching the acceptances both in angle and momentum, we can easily deduce that the factor 40 in RIBs intensities at the final focus is reduced to a factor of about 12 on the secondary target.

3.1. Beam spot on target

This factor can be increased by acting on the primary beam spot on the production target. Indeed, the secondary beam emittance could be reduced, without reducing the angular
acceptances, by reducing the size of the beam spot. For example a shrinkage of the beam spot to a size of 1 mm in diameter will allow the production of beams with emittances 1/3 the one reported in table 2. This reduction will result in a better match between the Fragment Separator and the transport beam lines emittances with a consequent gain of a factor about 30 in the transmitted RIBs intensities with respect to the present configuration.

Beam spots of 1 mm are not usually produced with Cyclotrons. In this respect the focusing condition of the Superconducting Cyclotron have to be well studied to understand to which extend the required reduction of the spot size could be achieved while preserving a small primary beam emittance.

On the other hand, when the beam is focused on such a small spot, a large amount of power is dissipated on a small volume of the production target. A rotating target will probably be a solution to handle the high power.

4. Conclusions

Since 2001 the FRIIBs facility of LNS produces RIBs at intermediate energy by the in-flight technique. The facility operates in an innovative way: instead of trying to select a specific ion as RIB, the RIBs mixture collected at the exit of the fragment separator is tagged on an event-by-event basis, before it interacts on a secondary target. Different experiments have been already performed using the RIBs produced by the facility among them the DIPROTON experiment on two-proton radioactivity [3]. Some improvements are planned on the facility with the aim of increasing the secondary beam intensities. A new configuration of the Fragment Separator will give a gain in the transmission through the device of a factor about 40 at the final focus of the Fragment Separator and of a factor about 30 on the secondary target. The last will be achieved by keeping the size of the beam spot on target around 1 mm, consequently obtaining a better match between the selection and transport beam lines.

Of course, when the primary beam is focused on such a small beam spot a lot of power (around
100W) is dissipated in a small volume of the target. A rotating production target could meet this requirement.

With the availability of more intense radioactive beams the use the degrader for cleaning up the secondary beams will be reconsidered.

Meanwhile the beam lines will be equipped with diagnostic devices to improve the phase of tuning of the magnetic elements of both the fragment separator and the beam lines, in order to better optimize the optical transport. Up to now the optical transport was optimized using the pilot beam procedure, i.e. by using a beam having the same magnetic rigidity of the secondary beam of interest. The new diagnostic devices will allow to directly perform the optical tuning with the secondary beam, making the entire procedure quicker and much more accurate.

References

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