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The new fragment in-flight separator at INFN-LNS

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Summary. — An upgrade project of the Superconducting Cyclotron has been underway at INFN-LNS since 2019. One of the goals of this project is to deliver RIBs (Radioactive Ion Beams) of high intensity. To reach this aim, a dedicated facility consisting of a new fragment separator FRAISE (FRAgment In-flight SEparator) is ongoing, exploiting primary beams with a power up to ≈2–3 kW. The high intensity achievable with FRAISE requires the use of suitable diagnostics and tagging systems, able to operate also in a strong radioactive environment. In this framework, an R&D program has been started to develop the FRAISE facility, the diagnostics system and the tagging device; the latter will be especially useful in the CHIMERA multidetector beam line. The present contribution discusses the status of the R&D program, with particular focus on the RIBs available thanks to the use of FRAISE.

1. – Introduction

At INFN-LNS, an upgrade project POTLNS is ongoing [1]. This project consists of an upgrade of existing and operating devices designed for the basic research in Nuclear Physics. The main upgrade concerns the Superconducting Cyclotron (CS); indeed, besides the current extraction system, based on an electrostatic deflector, there will be a

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new extraction system based on stripping. The stripping method will be efficient for ion beams in the Fermi energy range and with mass number up to $A \approx 40$ [2-4]. This CS upgrade offers outstanding opportunities also for the production of high intensity Radioactive Ion Beams (RIBs). To take full advantage of such possibilities, a dedicated apparatus consisting of a new fragment separator FRAISE (FRAgment In-flight SEparator) was designed and is currently in its final phase. FRAISE will exploit primary beams with a power up to $\approx$2–3 kW providing RIBs, by means of the in-flight fragmentation method, with intensity from $\approx 10^3$ pps, for nuclei further away from the stability valley, up to $\approx 10^7$ pps, for nuclei close to the stability valley. These intensities will permit to increase the yield by a factor of $\approx$20 with respect to the FRIBs facility [2, 4], operating at INFN-LNS from 2001 to 2019 for the production of unstable nuclei, using a primary beam power up to $\approx$100 W. As a consequence of this beam power constraint, the yield for RIBs far from the stability was not enough to conduct accurate measurements, allowing only addressing investigations concerned nuclei close to the stability. The improvement in intensity reachable with FRAISE will allow pursuing more precise studies on the latter, and will allow extending investigations to nuclei far from the stability valley. Presently, these investigations represent a challenge for nuclear physics, due to unusual and not well understood properties of unstable nuclei as well as their link with nuclear structure models, features of the nuclear force and nuclear astrophysics. Among the different research topics, by means of FRAISE the following could be possible: the study of nuclei with a neutron skin or a nuclear halo, interesting because both halos and skins determine a change in density, radii, dynamics and nuclear structure, comparing them with the stable ones [5]; the investigation of nuclei with neutron excess is also important due to the presence of an excitation mode, known as Pygmy Dipole Resonance, already studied at INFN-LNS using the FRIBs facility [6]. In addition, the study of the clustering structure of α particles in neutron-rich isotopes of Be, B, C, expected to have a molecular-like behavior, is a further interesting topic, with paramount impacts on the comprehension of the strong interaction [7,8]. Unstable nuclei also have a link with nuclear astrophysics because some stellar processes involve radioactive nuclei [9, 10]. Furthermore, FRAISE will be able to deliver neutron-rich and neutron-poor nuclei, as ^{46,34}Ar and ^{68}Ni, allowing extending the study of Isospin effects in Heavy-Ion reactions at Fermi energies, a topic that has been widely explored with the CHIMERA multidetector [11, 12]. Within this framework, the construction of the FRAISE facility offers a significant contribution in the panorama of nuclear physics.

2. – RIBs available with the FRAISE facility at INFN-LNS

In the following, we discuss about some of the RIBs available with FRAISE. Such results have been obtained through simulations using the LISE++ software [13], considering the FRAISE configuration described in refs. [2-4] and displayed in fig. 1 (left). As it can be noted, two slits, respectively located in the dispersive plane and at the exit of the separator, will be present. The latter one will allow reducing the presence of undesired nuclei in the cocktail beam, while the one placed in the dispersive plane will permit reducing the $\Delta p/p$ from a typical value of $\approx$1.2% to lower values. An aluminum wedge/degrader, located after the central slit (fig. 1 (left)), will also be used for the purpose of separating ions with the same A/Z, obtaining beams with high purity, as described in refs. [2, 4]. The high beam intensity achievable with FRAISE requires the use of diagnostics and tagging systems able to operate also in a strong radioactive environment and to sustain several experiments per year. In this respect, a detection system

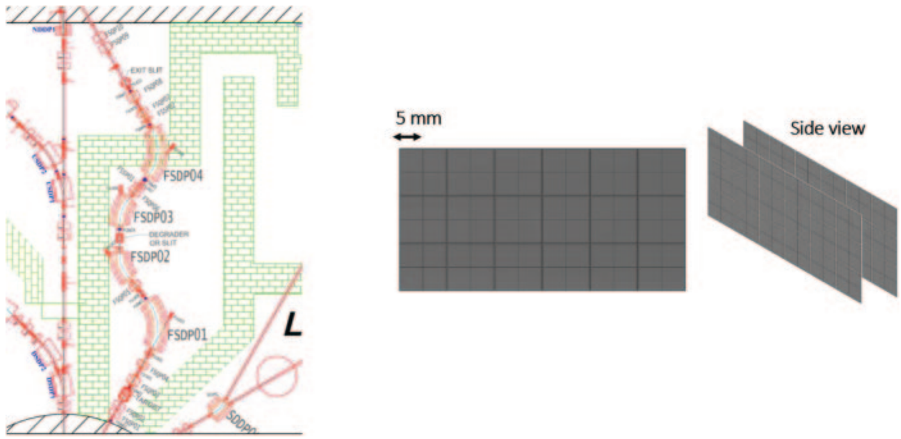

Fig. 1. – Left: view of the FRAISE apparatus [2-4]. Right: scheme of the SiC detection system in development for the diagnostics and tagging systems of the FRAISE facility.

based on the SiC technology is in development [14]. In detail, the system will consist of two arrays, each one made of single detection pads with a surface of $5 \times 5\,\mathrm{mm}^2$ and a thickness of $100\,\mu\mathrm{m}$, arranged to cover an area of $\approx 60 \times 30\,\mathrm{mm}^2$. The two SiC arrays, with the same features, will be located at a distance of few cm, in order to reduce the dead area and to obtain a reconstruction of the trajectory, as schematically displayed in fig. 1 (right). Such a segmentation will allow for a maximum value of $\approx 10^7$ pps over the whole array. The diagnostics system will provide information about isotopic identification, intensity, energy, position and to some extent trajectory of beams. In particular, the RIBs composition will be determined by measuring the ΔE energy loss of ions and the time of flight (ToF) between two detection systems, or with respect to a time signal synchronous with the primary beam, arrival on production target, as the CS Radiofrequency signal. The same device could be used not only as a diagnostics element, but also as a tagging one in the final set-up of the CHIMERA multidetector beam line; in this case, it will be necessary to have an event-by-event tagging of cocktail beams, using the ΔE-ToF method and the trajectory measurement. A feasibility study has been started during these years at INFN-LNS, performing simulations and preliminary tests to investigate the use of SiC detectors, as discussed in ref. [4]. Additionally, in order to sustain the expected rates, also fast integrated electronics is under development. In the performed simulations, we included a SiC detector, with a thickness of $100\,\mu\mathrm{m}$, placed at the exit of the fragment separator and an aluminum $100\,\mu\mathrm{m}$ homogenous wedge located on the symmetry plane, see fig. 1 (left). As a first step, we used as inputs for simulations primary beams whose extraction by stripping in the upgraded CS has been studied in details. These primary beams are indicated in table I, together with the energy and the beam power used as the input for the simulations. Regarding the energy used as the input for each simulation, we point out that these primary beams can be accelerated also at lower energies, allowing extending the studies at RIBs with lower energy with respect to the ones obtained in the simulations. However, the primary beam energy has to be enough to make the fragmentation reaction fruitful and to obtain a totally stripped beam. For each simulation we used a ^{9}Be production target with optimized thickness to produce the isotope of interest. Following fig. 2, fig. 3 shows the results

TABLE I. – *Primary beams, whose extraction by stripping has been studied in detail, with relative energy and power used as the input for the simulations.*

Ion	Energy (MeV/A)	Power (kW)
$^{12}C^{6+}$	60	2
$^{18}O^{8+}$	70	2
$^{20}Ne^{10+}$	60	2
$^{40}Ar^{18+}$	60	2

of RIBs simulations. At the top of each figure, the primary beam, the energy and the beam power used in the simulation are indicated, while the values reported in each pad, under the isotopes, represent the expected yield (pps) and the energy after the exit slit (MeV/A). For the sake of clarity, we emphasize that figures show only RIBs where the isotope of interest is well separated in the 2D-ΔE-ToF simulated plot and with enough purity. The ΔE-ToF plot was simulated using, as plot options, the energy loss in the SiC detector and the time of flight difference between the RF signal and the SiC detector. The simulations performed using, as inputs, primary beams whose extraction by stripping has been carefully studied showed the possibilities to cover a wide range of mass number with high intensity. However, with the aim to cover wider mass number and intensity ranges it is of paramount importance also to consider the achievable RIBs with further primary beams, whose extraction by stripping in the upgraded CS is not yet studied in detail. As an example, ^{13}C at 55 MeV/A and 2 kW of beam power could allow producing ^{9}Li with 10^{6} pps, and ^{12}B with 1.2 10^{8} pps, permitting to have an improvement in intensity with respect to the one obtained using ^{12}C (see fig. 2 (left)).

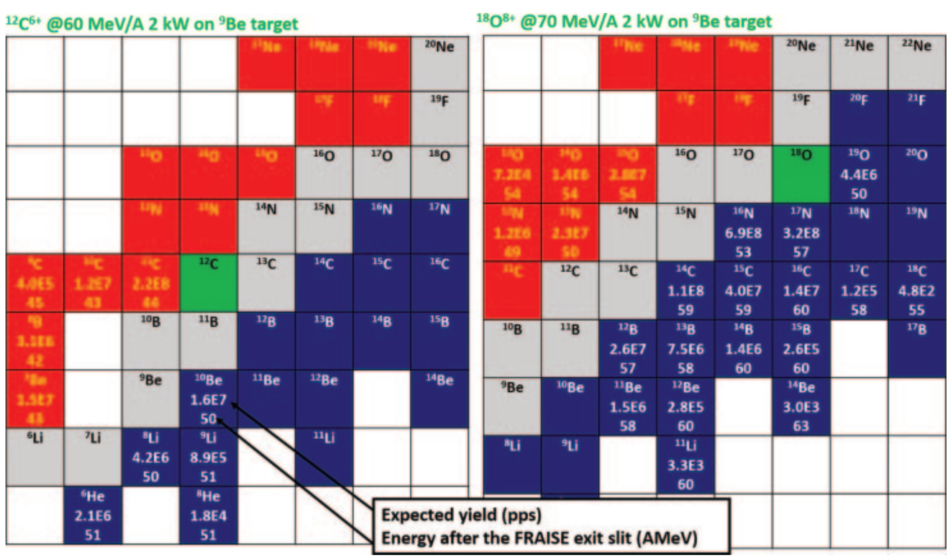

Fig. 2. – Left: simulation of RIBs achievable with FRAISE, using ^{12}C as the primary beam. Right: simulation of RIBs achievable with FRAISE, using ^{18}O as the primary beam. See text for details.

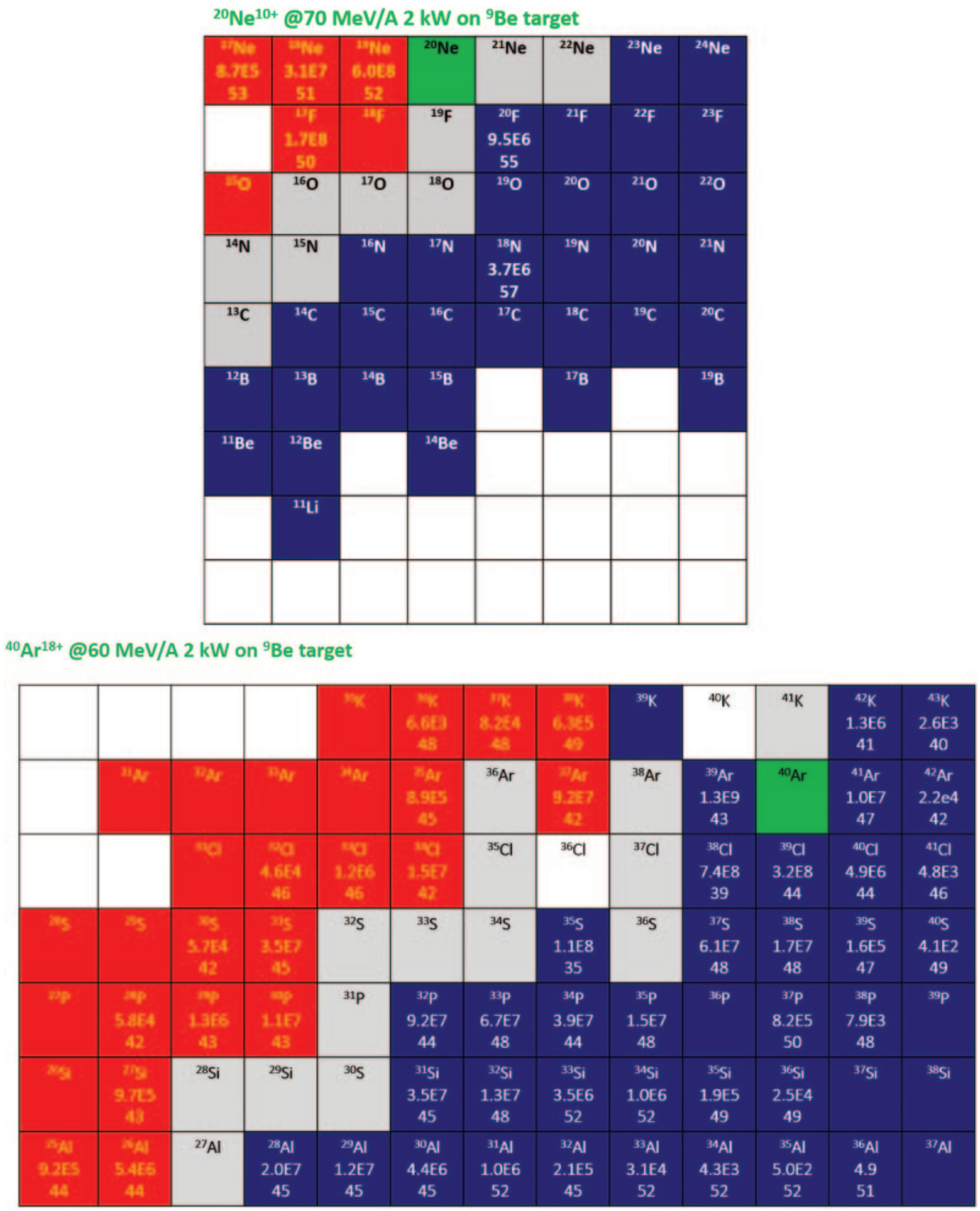

Fig. 3. – Top: simulation of RIBs achievable with FRAISE, using ^{20}Ne as the primary beam. Bottom: simulation of RIBs achievable with FRAISE, using ^{40}Ar as the primary beam. See text for details.

The use of ^{16}O could permit to have ^{15}O with 2.7 10^8 pps, ^{14}O with 1.4 10^7 pps, and ^{13}O with 4.2 10^5 pps, allowing performing experiments in the oxygen chain with a higher intensity with respect to the one obtained with ^{18}O (see fig. 2 (right)). The following

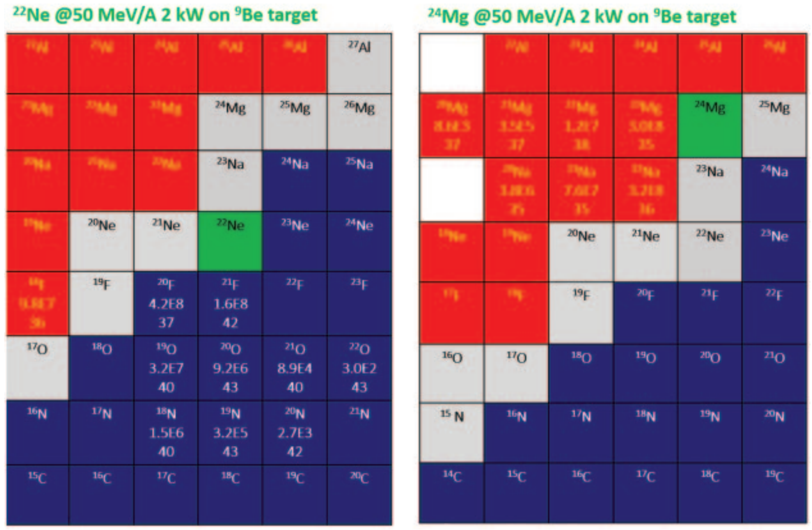

Fig. 4. – Left: simulation of RIBs achievable with FRAISE, using ^{22}Ne as the primary beam. Right: simulation of RIBs achievable with FRAISE, using ^{24}Mg as the primary beam. See text for details.

figs. 4, 5 have been obtained by using the same conditions of the figures shown above, but using as inputs for simulations primary beams whose extraction by stripping in the upgraded cyclotron needs to be studied and confirmed in detail. These primary beams are indicated in table II, together with the energy and the beam power used as the input for the simulations. We stress that such results represent just a preliminary idea about the RIBs available at INFN-LNS thanks to the FRAISE apparatus.

Fig. 5. – Left: simulation of RIBs achievable with FRAISE, using ^{27}Al as the primary beam. Right: simulation of RIBs achievable with FRAISE, using ^{32}S as the primary beam. See text for details.

Table II. – *Primary beams, whose extraction by stripping has to be studied and confirmed in detail, with the relative energy and power used as inputs for the simulations.*

Ion	Energy (MeV/A)	Power (kW)
$^{22}Ne^{10+}$	50	2
$^{24}Mg^{12+}$	50	2
$^{27}Al^{13+}$	50	2
$^{32}S^{16+}$	50	2

3. – Conclusions

This contribution focused on the RIBs obtainable thanks to the use of the FRAISE facility. Such results have been obtained by performing LISE++ simulations. We carried out the simulations using as inputs both primary beams whose extraction by stripping has been carefully studied, and primary beams whose extraction by stripping has not yet been studied in detail. Regarding the latter, we point out that the obtained results represent a preliminary investigation that needs to be confirmed by further studies. In the R&D program, further steps will concern the characterization of the SiC arrays coupled to fast integrated electronics, and the validation of the whole system, using radioactive sources, stable beams and, finally, RIBs.

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