IL NUOVO CIMENTO **45 C** (2022) 68
DOI 10.1393/ncc/i2022-22068-9

Communications: SIF Congress 2021

Simulation study of radioactive ion beams production at FRAISE (INFN-LNS)

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received 31 January 2022

Summary. — At INFN-Laboratori Nazionali del Sud, the new *FRAISE* (*FRA*gment *I*n-Flight *SE*parator) apparatus is reaching its final phase of construction. It will be able to operate with high power beams supplied by the Superconducting Cyclotron, also being upgraded in the same period. By means of the *in-flight* fragmentation method, FRAISE will be able to produce Radioactive Ion Beams (RIBs) with intensity about 20 times greater than the previous *FRIBs* apparatus. In this framework, the LISE++ simulation software has been used to analyze the production and optimization of several radioactive beams, making it possible to study interesting and innovative research topics in the field of nuclear physics.

1. – Introduction

One of the main challenges of current research in nuclear physics is the study of exotic structures not yet fully understood, particularly important for the understanding of the behaviour of nuclei far from the minimum of the stability valley.

Some neutron-rich radioactive nuclei, for example, can manifest *halo* exotic structures, in which the exceeding nucleons arrange themselves on potentially favored energy shells, far from the main core [1]. Many studies have also theorized the existence of exotic proton halos in radioactive proton-rich nuclei [2]. However, the presence of the Coulomb force decreases the probability of the formation of a proton halo, making this phenomenon even more difficult to be observed.

As the number of neutrons further increases, other exotic phenomena can emerge, such as the formation of neutron skins, structures of neutrons that cover an internal core with approximately the same number in protons and neutrons. Such phenomena lead to

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the presence of vibrational modes between the core and the skin, called Pygmy Dipole Resonances [3, 4], which can be connected to important astrophysical implications, as they influence the rate of (n, γ) reactions in stellar nucleosynthesis.

Another important topic concerns the presence of cluster structures of α-particles in exotic nuclei. The existence of cluster structures at certain excitation energies has already been known for some time even in stable nuclei, such as ^{12}C, ^{16}O or ^{20}Ne, containing n α-particles arranged in a more energetically stable cluster structure [5]. Recent studies have also highlighted the presence of such structures even in their neutron-rich isotopes, in which additional neutrons act as a bond between α-clusters, in a similar way to what happens in π and δ bonds of molecular orbitals. Two examples concern the structures of ^{10}Be and ^{16}C, in which two and three α-particles respectively can be arranged in linear structures (also triangular in the case of ^{16}C) linked together by valence neutrons [6, 7].

Phenomena involving unstable nuclei are also a powerful tool to investigate the properties of the Equation of State of nuclear matter. Therefore, the production of Radioactive Ion Beams (RIBs) is of crucial importance for the study of all these cutting-edge research thematics, so in recent times various methods have been developed for their production. One of these is the *in-flight* technique, in which a stable heavy ion beam is fragmented on a thin target, producing a multitude of beams as a reaction product. The beam thus produced, the so-called *cocktail beam*, containing many ion species among exotic nuclei of interest, is subsequently sent to a *fragment separator*, in which the beam of interest is selected and transported to the experimental room. In the following sections, the features of the INFN-LNS facility will be discussed, in particular by showing a simulation study of RIBs production by means of the future fragment separator *FRAISE*, currently under construction.

2. – RIBs facility at INFN-LNS

At INFN-Laboratori Nazionali del Sud, for the last 20 years, the production of radioactive beams has been possible thanks to the FRIBs (in-Flight Radioactive Ion BeamS) facility (fig. 1), by means of the in-flight technique [8]. The FRIBs facility has allowed produce exotic beams from ^{6}He to ^{68}Ni at intermediate energies, using primary stable beams accelerated by the Superconductive Cyclotron (CS) *K800* [9]. The RIBs are in fact produced by fragmenting such stable beams, with an optimal maximum power of 100 W, on a thin ^{9}Be target, whose thickness is adjusted for the desired production. Fragments produced in this way are then separated and focused through magnetic fields, also to clean the cocktail beam from undesired isotopes and from the unreacted primary beam. FRIBs is in particular made of two 45° dipoles of the beam line transporting beams from the CS to the various experimental halls of LNS, hosting detectors like CHIMERA [10], FARCOS [11] and MAGNEX [12]. A great variety of experiments have been carried out at LNS making use of FRIBs radioactive beams, as for example the evidence of the existence of a 6^+ state at 13.5 MeV of excitation for ^{10}Be [6], the existence of the Pygmy Dipole Resonance in the radioactive isotope ^{68}Ni [3, 4] or the production of highly pure ^{11}Be for the study of the β-delayed α emission [13].

Over the years, FRIBs has undergone upgrades and modifications, aimed in particular at improving the characteristics of the radioactive beam produced, as for example the possibility to produce purer beams. Magnetic fields, in fact, cannot separate ions with similar A/Z ratio, or magnetic rigidity $B\rho$, so different techniques can be employed to improve the quality of the final radioactive beam. For example, one of these uses a material on the beam line, namely a *degrader*, with the purpose of slowing down the ions

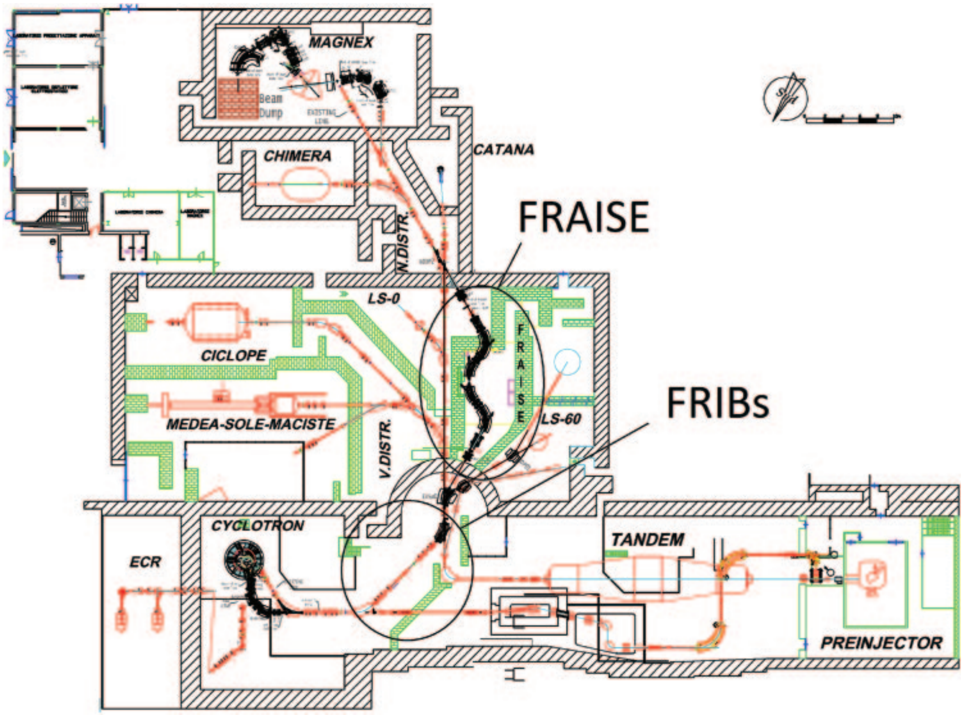

Fig. 1. – Map of the INFN-LNS. Both the position of the previous FRIBs fragment separator and the location of the new future FRAISE spectrometer are shown [9]. Courtesy of A. D. Russo.

of the cocktail beam. The energy loss of a ion inside matter is in fact roughly proportional to AZ^2, and different ions lose different values of kinetic energy inside the same material. This leads to a spread in velocity for different ions in the radioactive beam, hence to a corresponding spread in magnetic rigidity, after passing through the degrader. This allows separating nuclei with the same A/Z value just by setting the magnetic rigidity of the dipoles of the second branch of the separator, for instance after the degrader, to the right value of the specific isotope to produce the beam. The employment of such a technique, however, introduces straggling effects, due to the energy loss of ions in the degrader, causing a decrease in energy resolution, nevertheless with the advantage of producing purer beams. During the OTPC@LNS experiment, for example, an aluminum degrader 1000 μm-thick has been placed in the center of the fragment separator, between the two dipoles, to produce a 95% pure ^{11}Be beam [13, 14].

Satisfactory results can also be obtained without the use of pure RIBs: in some cases, a beam containing different isotopic species can in fact allow several experiments to be carried out with a single measurement. To do this, it is necessary to use a diagnostics system in order to identify, or to *tag*, the ions of the radioactive beam produced, and to select the species of interest off-line. The tagging system used at LNS for the FRIBs facility is made of a Micro Channel Plate detector, detecting the start of the Time of Flight of the ions of the cocktail beam, and a Double Sided Silicon Strips Detector (DSSSD) with a grid of 32×32 strips vertical front and horizontal back, about $\approx$12.9 meters apart [15]. In this way, by combining the energy loss and time of flight data obtained for each ion into a two-dimensional graph, it is possible to construct a $\Delta E - ToF$ matrix and to identify the ions of the cocktail beam. From here, by means of graphical cuts on both ΔE and ToF, it is possible to off-line select only the ions of interest. At LNS, it is also possible to acquire the measurement in time of flight using the radio-frequency of the CS accelerator as a time reference, with a period of the order of tens of ns [9].

3. – FRAISE: new fragment separator at LNS

From June 2020, LNS has started plans for the upgrading of its machines and infrastructures, in particular concerning the upgrade of the Superconducting Cyclotron and the construction of a new beam line hosting the new fragment separator FRAISE (FRAgment In-flight SEparator) [9, 14, 16, 17]. The main upgrade of the CS will concern the replacement of the extraction system to greatly improve the available power of the produced beams. This will in fact be based on stripping, allowing accelerating ions from C to Ar at energies between 30–70 MeV/u, with an intensity up to 10 kW, much higher that the previous 100 W. The improvement of the outgoing beam power will hence open new research possibilities, since in this way it will be possible to produce intense RIBs not only for the ones previously produced with FRIBs, but also for ions even further from the stability valley, that will be produced with higher intensities. However, by increasing intensities, FRIBs will no longer be able to sustain adequate radiation protection measures, making it no longer usable as a fragment separator. For this reason, the new FRAISE spectrometer, specifically designed to withstand such high energy outputs, will be built in a new location, in the present experimental rooms LS-20 and LS-40, modified to have appropriate radiation shielding, mainly to avoid contamination of neutrons and γ rays, unaffected by the separator magnetic fields (fig. 2). FRAISE will be made of a total of four magnetic dipoles, arranged in a symmetric configuration with respect to a central axis. A chamber with the fragmentation target will be placed at the beginning of the FRAISE beam line. This in particular will be a CLIM rotating target [18] of beryllium discs to increase the active area of the target itself, improving its energy deposition and avoiding issues due to the target overheating. Two duplets of quadrupoles are placed ahead and behind the target chamber, to improve the focusing of the entering stable beam and outgoing cocktail beam.

The fragment separator itself consists of two symmetric branches, to ensure optimal achromatic conditions of the apparatus. The two branches are made of two dipoles, respectively 70° and 40°, and a focusing quadrupole and sextupole interposed between them. Moreover, two chambers have been placed on the beam line, the first one in correspondence with the plane of symmetry between the two branches, in which there is the greatest energy dispersion of the produced cocktail beam, the second one at the exit of the fragment separator. A slit on the symmetry plane can be used to vary the acceptance $\Delta p/p$ of the fragment separator, in order to reduce the energetic dispersion of the outgoing components. A second slit can be used to reduce and remove unwanted isotopes from the cocktail beam, improving the quality and purity of the produced beams.

An aluminum degrader can be introduced near the symmetry plane, just after the central slit, to separate species with a similar A/Z ratio. However, the usage of a degrader can worsen the final quality of the beam, although improving its purity.

A new tagging system has been studied and designed for the new apparatus. The tagging detectors currently used for FRIBS, based on Silicon strips, can no longer be used for FRAISE, as they would be unsuitable to withstand the high intensities that

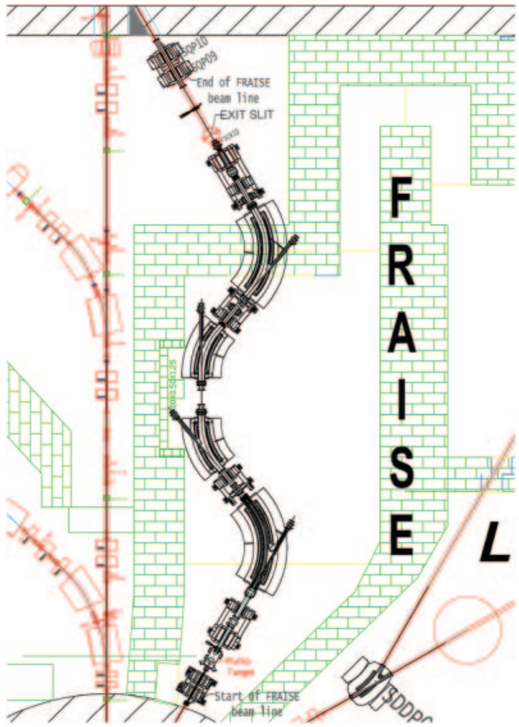

Fig. 2. – Schematic plan of the new FRAISE fragment separator at LNS [17]. Courtesy of A. D. Russo.

can be reached with the new Superconducting Cyclotron. For this reason, new detectors based on Silicon Carbide (SiC), a radiation hard material, have been designed, carried out by the SiCILiA project [19]. The new detectors will consist of single pads of size $5\,\mathrm{mm} \times 5\,\mathrm{mm}$, and $100\,\mu\mathrm{m}$ thickness, organized in an array of $6\,\mathrm{cm} \times 3\,\mathrm{cm}$ total active area. In this way, thanks to such an extended area, it will also be possible to tag ions in the lateral points of greater dispersion, while the intensity on the whole detector surface will be of the order of 10^7 pps.

4. – Procedure of optimization of a RIB with LISE++

To obtain beams with a good compromise between purity and intensity, simulations have been performed using the *LISE++* code, a software conceived specifically for RIBs production simulation by means of the in-flight method, calculating transmissions and yields of the produced fragments collected in a spectrometer.

As the specific cases of RIB produced may vary, the optimal parameters of FRAISE are each time calculated, as for example the magnetic rigidity $B\rho$ of the magnetic dipoles, the thickness of the beryllium fragmentation target, the opening width of the slits, and the thickness of an aluminum degrader at the center of the spectrometer, used to further improve the purity of the beam. However, it is worth noting that the use of an aluminum degrader can also be counterproductive in some cases, by slightly improving the purity of the beam , yet drastically decreasing its energy resolution. For this reason, the production of each specific beam of interest must be studied and analyzed individually.

Moreover, for the purpose of the simulations, a maximum intensity of 2 kW has been used since the first magnetic dipole would produce high and potentially harmful doses of γ radiations and neutrons, despite the presence of adequate shielding for high radiation doses. For this reason, it was decided to downgrade the power of the cyclotron to about 2–3 kW for the production of radioactive beams. Moreover, two silicon carbide detectors are placed on the beam line for diagnostic and tagging purposes. The first one, in particular, will be placed at the center of the fragment separator, on the symmetry plane of the two spectrometer arms. This will be of particular importance as it will act not only as a detector, but also as an *active* degrader, varying the characteristics of the outgoing cocktail beam. For this reason, the first test was devoted to study the impact of the presence of this detector at the center of the separator. The second SiC detector has been placed at the end of the second separator branch, after the exit slit. Performances of the separator have been studied by means of beam profile simulations on the tagging detectors and by simulating $\Delta E - ToF$ plots; to build these, the passage of ions at the center of the fragment separator is assumed as the start signal of the time-of-flight, while the stop and the energy loss are provided from the SiC detector at the spectrometer exit, for a total flight base of ≈9 m

Here the simulation of the production of ^{15}C will be reported, produced by fragmenting a ^{18}O primary beam at 55 MeV/u on a ^{9}Be fragmentation target 1250 μm-thick. Although the target thickness has been optimized for the production of this isotope, fragmentation of the primary beam produces a rich cocktail of reaction products. Figure 3 shows the horizontal distribution of all the ions of the cocktail beam produced without any degrader or SiC detector at the symmetry center. In this case, many ions of the beam produced still pass through, even if the ^{15}C component is still predominant with a purity of ≈65%, arriving on the SiC detector at the exit of the fragment separator.

The composition of the output beam changes considerably by introducing the 100 μm-thick SiC detector on the symmetry plane. By setting a magnetic rigidity for the dipoles of the second arm following the degrader, consistently for the transport of ^{15}C which has been slowed down inside the material, the majority of the ions in the beam undergo such a decrease in velocity that they are discarded from the cocktail beam. As it can be seen from fig. 4, the resulting beam of ^{15}C obtained at the output of the spectrometer is then

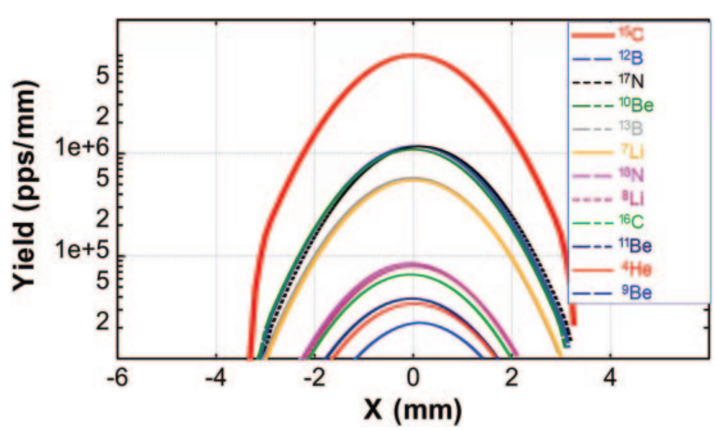

Fig. 3. – Horizontal distribution of the ions of the cocktail beam obtained for the production of ^{15}C [20].

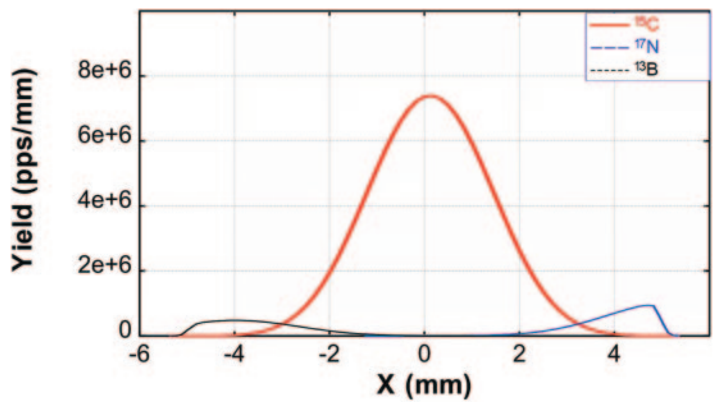

Fig. 4. – Effects of the presence of the SiC detector at the center of the fragment separator: the beam is much cleaner with respect to that shown in fig. 3 [20].

much purer, reaching values in the order of 90%, with impurities of ^{17}N and ^{13}B, having magnetic rigidity $B\rho$ similar to that of the desired ion. Furthermore, a small horizontal widening of the beam can be noticed, due to the presence of the detector on the beam line, causing straggling and slightly decreasing the resolution of the beam by ^{15}C, from 2.05% to 2.16%.

This simulation is of particular importance because it allows us to point out how the presence of the single SiC detector acts as an *active* degrader, allowing to improve the conditions of the produced beam by ^{15}C, by increasing the purity of the beam radioactive product, leaving its production rate unchanged and just slightly reducing its energy resolution.

Moreover, a passive aluminum degrader can be added on the beam line after the central slit, in correspondence with the first tagging detector, to further increase the purity of the resulting ^{15}C beam. In this case, using a thickness of 200 μm of aluminum, the components of the beam are then further separated horizontally, so that by intervening on the exit slit it is possible to almost completely remove the polluting side components and to produce a beam of ^{15}C with a level 99% purity (fig. 5).

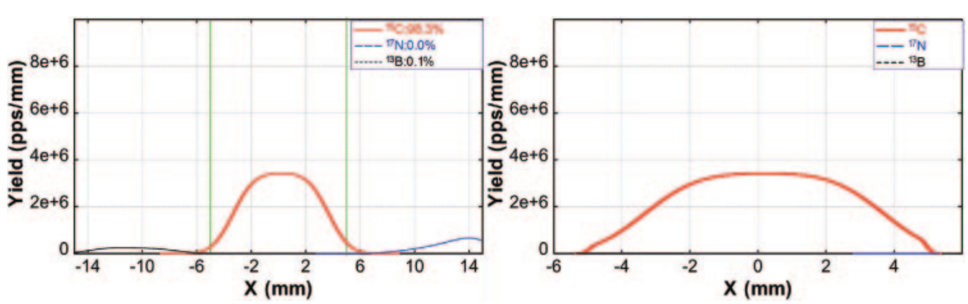

Fig. 5. – Horizontal distribution of the cocktail beam components related to the production of ^{15}C, using the configuration with SiC tagging detectors and a 200 μm-thick aluminum degrader. The purification effect can be seen as the final beam (right) appears to be composed almost exclusively of ^{15}C [20].

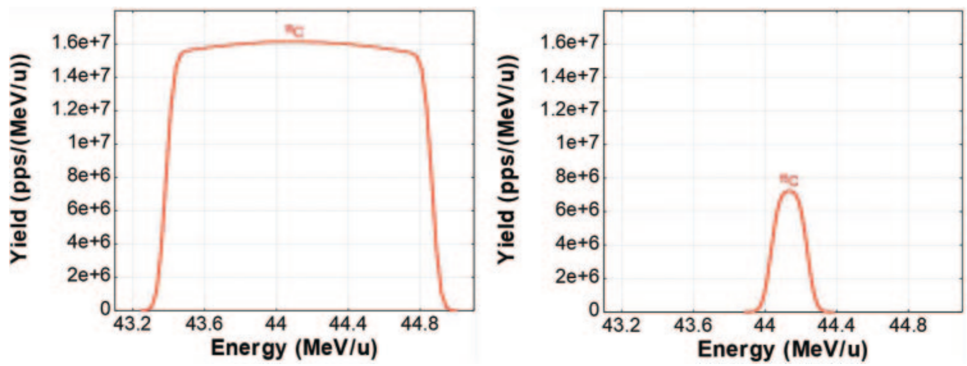

Fig. 6. – Energy distribution of ^{15}C in the two simulations, with $\Delta p/p \approx 1.32$ (left) and $\Delta p/p \approx 0.08$ (right) [20].

Further tests have been performed to increase the energy resolution of the desired beam, by acting on the central slit of the fragment separator and varying its impulse acceptance. Considering that different positions on the horizontal plane at the center of the separator correspond to different magnetic rigidities for a single ion, and therefore different emission energies, by closing the central slit it is possible to greatly increase the energy resolution, selecting only a small variation of energy. In this way, however, all the components of the beam with different energy are discarded from the outgoing beam, thus greatly reducing the yield production rate of the ion of interest. The example in fig. 6 shows the case of the previous beam of ^{15}C ($\Delta E \approx 2.28\%$), for which the central slit was closed until a $\Delta p/p \approx 0.08\%$ impulse acceptance was obtained, reaching energy resolution $\Delta E \approx 0.37\%$. However, much of the yield production has been removed, reducing the intensity of the outgoing beam by 93%.

5. – New study objectives with FRAISE

The new FRAISE fragment separator will allow producing RIBs of good intensity even for ions with extreme isospin values far from the stability line, which cannot be produced with the FRIBs separator. Through these isotopes, it will be possible to investigate many cutting-edge topics in heavy ion physics. Table I shows a series of radioactive beams for which this simulation study was carried out, in particular reporting the configuration parameters for the most performing production of the desired isotope. Few examples: the study of exotic clusters in medium-light nuclei (^{14}Be or ^{16}C); the study of direct reactions in inverse kinematics with light medium nuclei (^{8}B, ^{11}Be) for the research of nuclei in which the existence of halo of neutrons or protons has been hypothesized; the competition between reaction mechanisms as a function of the isospin of the projectile (^{34}Ar, ^{46}Ar), using for example neutron-poor or neutron-rich isotopes of the same element; the study of nuclear resonances, such as pygmy dipole resonance and isospin effects in collision between heavy ions (^{20}O, ^{38}S, ^{68}Ni); the investigation of reactions of astrophysical interest for medium-light ions (^{13}N and ^{14}O).

TABLE I. – *Preliminary simulations of the production of different RIBs, interesting for many research topics.*

Primary beam/ energy (MeV/u) / intensity (kW)	Primary Product	Target Thickness (μm)	Wedge Thickness (μm)	Expected Yield (kHz)	Purity (%)	Exit Energy (MeV/u)	ΔE (%)
^{18}O/55/2	^{15}C	1250	200	21600	100	44	2.27
^{18}O/55/2	^{16}C	1250	0	6800	99	46	2.1
^{18}O/55/2	^{14}Be	1250	200	1.59	100	47	2.13
^{12}C/62/2	^{8}B	2250	0	2400	58	47	2.1
^{13}C/55/2	^{11}Be	1500	0	5830	97	47	2.06
^{36}Ar/50/2	^{34}Ar	500	0	7360	61	33	2.8
^{48}Ca/45/2	^{46}Ar	500	0	1650	93	30	2.2
^{24}Mg/50/2	^{20}O	750	0	191	97	40	2.3
^{40}Ar/40/2	^{38}S	250	100	4320	93	29	2.5
^{70}Zn/50/1	^{68}Ni	250	0	753	78	36	2.1

6. – Conclusions

In this paper, the recent and future developments on the production of Radioactive Ion Beams at INFN-Laboratori Nazionali del Sud (LNS) were reported. In particular, the present LNS upgrade program was discussed, which will involve an upgrade of the current Superconducting Cyclotron (CS) and the construction of the new FRAISE fragment separator (FRAgment In-Flight SEparator). With the new systems it will be possible to produce beams of radioactive isotopes far from the stability valley, not achievable with the current FRIBs@LNS facility, due to too low intensities of the primary beams, even with excellent purity and intensity.

As for the FRAISE fragment separator, the production and optimization of various RIBs of interest for the study of cutting-edge research topics in heavy ion physics has been studied by performing simulations on LISE++. In particular, preliminary results have been obtained for many different beams, calculating the characteristics of the spectrometer in order to obtain the best compromise between purity and intensity for the produced beam. Moreover, the effect of the presence of two 100 μm-thick silicon carbide (SiC) detectors on the beam line was studied, used for ion tagging and diagnostics of the cocktail beam produced after the target. It has also been shown that by adding a further aluminum degrader and adjusting the width of slits placed in the center and at the exit of the separator, it is possible to eliminate the polluting components of the cocktail beam and vary its energy resolution, allowing to produce more energetically resolute beams. The results of this work constitute a starting point for all users of INFN-Laboratori Nazionali del Sud, who intend to use FRAISE for their experiments in the future.

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The author wishes to thank the CHIRONE Collaboration for the support to this work. Furthermore, thanks are due to A. D. Russo for the fruitful discussions and the use of the most recent pictures of the FRAISE fragment separator.

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