Journal of Physics: Conference Series

Status and Perspectives of the INFN-LNS In-Flight Fragment Separator

To cite this article: P. Russotto *et al* 2018 *J. Phys.: Conf. Ser.* **1014** 012016

Status and Perspectives of the INFN-LNS In-Flight Fragment Separator

P. Russotto[1], L. Calabretta[1], G. Cardella[2], G. Cosentino[1], E. De Filippo[2], B. Gnoffo[2,3], M. La Cognata[1], N.S. Martorana[1,3], E.V. Pagano[1,3], R.G. Pizzone[1], L. Quattrocchi[2], S. Romano[1], A.D. Russo[1] and D. Santonocito[1]

[1]INFN-Laboratori Nazionali del Sud, Catania, Italy
[2]INFN-Sezione di Catania, Catania, Italy
[3]Dipartimento di Fisica e Astronomia Università, degli Studi di Catania, Catania, Italy

E-mail: russotto@lns.infn.it

Abstract. In the last 15 years the FRIBs@LNS facility has successfully produced Radioactive Ion Beams using the In-Flight technique. We report on the current status and future perspectives opened by FRAISE, a new fragment separator that will be build in connection with the upgrade of Superconducting Cyclotron of the INFN-LNS laboratories.

1. Introduction

In the last decades several facilities devoted to the production of Radioactive Ion Beams (RIBs) for experimental studies in nuclear physics have been developed worldwide [1–5] and many other are still under construction [6–9]. These facilities have been based on two main production techniques: the Isotope Separation On Line (ISOL) [10] and the In-Flight [11] production methods. Thanks to progress in producing RIBs with these methods, experiments employing short-lived isotopes have become feasible and widely used; therefore, many properties of unstable nuclei have been investigated [12–14]. However, there is still room for studies in this field, since the full perspectives opened by the use of RIBs are far from being fully exploited. In particular, coupling progress in production methods with advances in experimental techniques and detection devices can still open new interesting perspectives, allowing to carry out better or new experiments.

At the INFN-LNS [15] in Catania (Italy) a facility using the in-flight technique to produce RIBs has been operating for the last 15 years. Important results have been achieved as briefly discussed in the next section. The project of an upgrade of the LNS-INFN Superconducting Cyclotron, leading to an increase of the power of available primary beams, will open new perspectives for the production of RIBs. This will require the installation of a new Fragment Separator, whose main structure and principle of operation are briefly described in section 3. A variety of physics cases could then be investigated in the future, thanks to the performances of upgraded fragment separator and the detection devices already existing or in construction at the INFN-LNS. Few examples will be discussed in section 4.

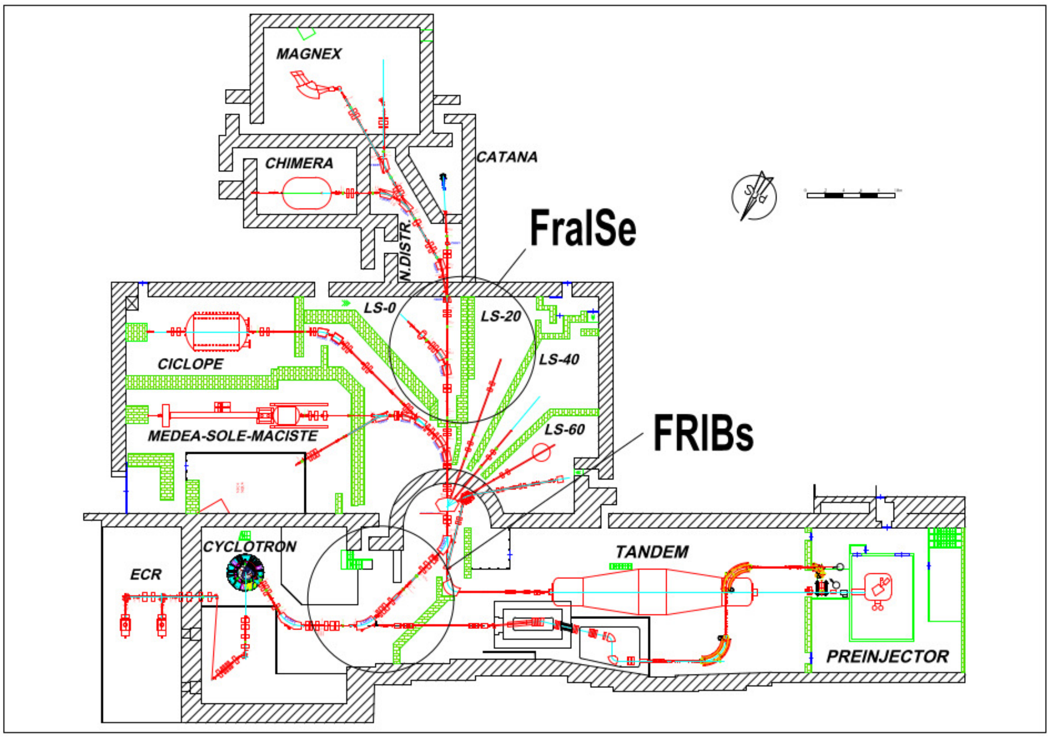

Figure 1. Schematic view of the INFN-LNS beam lines and halls. The position of the actual fragment separator, FRIBs, and of the new one, FraISe, are indicated by circles.

2. The FRIBs facility

The FRIBs@LNS (in Flight Radioactive Ion BeamS at LNS) facility [16], presently installed at the INFN-Laboratori Nazionali del Sud, allows one to carry out nuclear physics experiments investigating the properties of short-lived nuclear species. The RIBs are produced by using the so called in-flight technique, that is, the fragmentation of a fast projectile (the primary beam accelerated by the LNS Superconducting Cyclotron) on a usually thick Beryllium production target (placed near to the exit of the Superconducting Cyclotron). Since a multitude of (mainly stable) nuclei are produced in such a process, a magnetic analysis/selection is needed to single out RIBs of interest for the specific study. In FRIBs we use just two 45° dipoles of the standard transport line to perform the magnetic selection, trying to maximize the yield of the wanted unstable isotope and eliminate unwanted stable isotopes and the primary beam. In such a way, since 2001, following the pioneering work of G. Raciti and his collaborators, rare isotope from ^{6}He to ^{68}Ni have been produced and effectively used in several experiments. Produced RIBs were (or could be) delivered to many experimental halls, housing dedicated detectors like CHIMERA [17] and FARCOS [18], Magnex [19], Hodo-Ct [20] or to other multi-purpose scattering chambers. A schematic view of the INFN-LNS beam lines and halls is shown in Fig. 1; FRIBs is indicated by a circle.

Since a magnetic analysis cannot separate isotopes having the same m/q ratio (m/Z in case of fully stripped ions) and has always a finite dp/p acceptance ($\sim 1\%$ in the case of FRIBs) we obtain a cocktail beam, i.e. it contains several isotopes at the same time. In some cases, this can also be an advantage since a single experimental configuration allows to carry out a measurement with different RIBs at the same time. However, an event by event identification (tagging) of the ion arriving on the target point is needed in order to off-line select the wanted projectile.

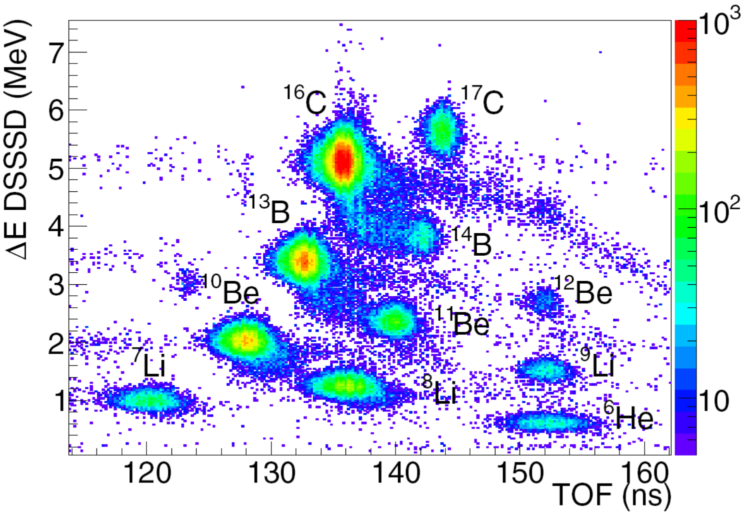

Figure 2. $\Delta E - ToF$ correlation plot, as given by the tagging system described in the text, for the cocktail beam produced by ^{18}O beam of 55 $AMeV$ on a 1500 μm thick ^{9}Be target. Extracted from Ref. [21].

For that, an advanced device [22] has been used in the CHIMERA beam line; it consists of a large-surface Micro Channel Plate detector placed about 13 meters before the entrance of the scattering chamber and producing the start of Time of Flight (ToF) measurement, and a thin (140 or 300 μm) Double Sided Silicon Strips Detector, with 32 (64×2 mm^2) strips on both horizontal and vertical planes, placed just before the entrance of the scattering chamber, delivering energy loss (ΔE), position and stop of ToF measurements. By combining the ΔE and ToF information, an event-by-event identification of arriving ion is then possible. As an example, the ΔE-ToF correlation plot for the cocktail beam obtained through the fragmentation of a primary ^{18}O beam of 55 $AMeV$ energy on a 1.5 mm thick ^{9}Be target is shown in Fig. 2. This was obtained with a magnetic rigidity selection of $B\rho \sim 2.8$ Tm. Since the magnetic rigidity is almost fixed, ions having the same m/q ratio have the same velocity and stay along a vertical line (constant ToF) in such a plot. In addition, also a Parallel Plate Avalanche Counter position sensitive detector, placed between the Silicon Strips Detector and the target station, has been used to get a trajectory measurement.

Typical intensities available with FRIBs, for nuclei not very far from stability valley (e.g. ^{10}Be,^{16}C,^{18}Ne,^{68}Ni) have been of about $10^{4-5}pps$; these intensities have been mainly limited by the maximum power (100 W) achievable with the actual Superconducting Cyclotron properties. Nevertheless, important physics cases have been investigated by using the RIBs delivered by FRIBs. As few examples, here we want to remind some important results. One was the discovery of an important diproton radioactivity contribution from ^{18}Ne excited states by G. Raciti and his collaborators [20]. It is worth mentioning also the investigation of the cluster structure of ^{10}Be by D. Dell'Aquila et al. [21], where, measuring the α+^{6}He break-up channel, the ^{10}Be excitation energy spectrum was reconstructed and the existence of a new 6^+ level around 13.5 MeV of excitation energy was found. Recently, also the Pigmy Dipole Resonance in radioactive neutron rich ^{68}Ni nuclei, excited by means of an iso-scalar ^{12}C probe, has been carefully studied [23], as reported in another contribution to this conference [24].

However, due to limited maximum power delivered by the Superconducting Cyclotron, investigations have always been limited to nuclei not far away from stability valley, being the

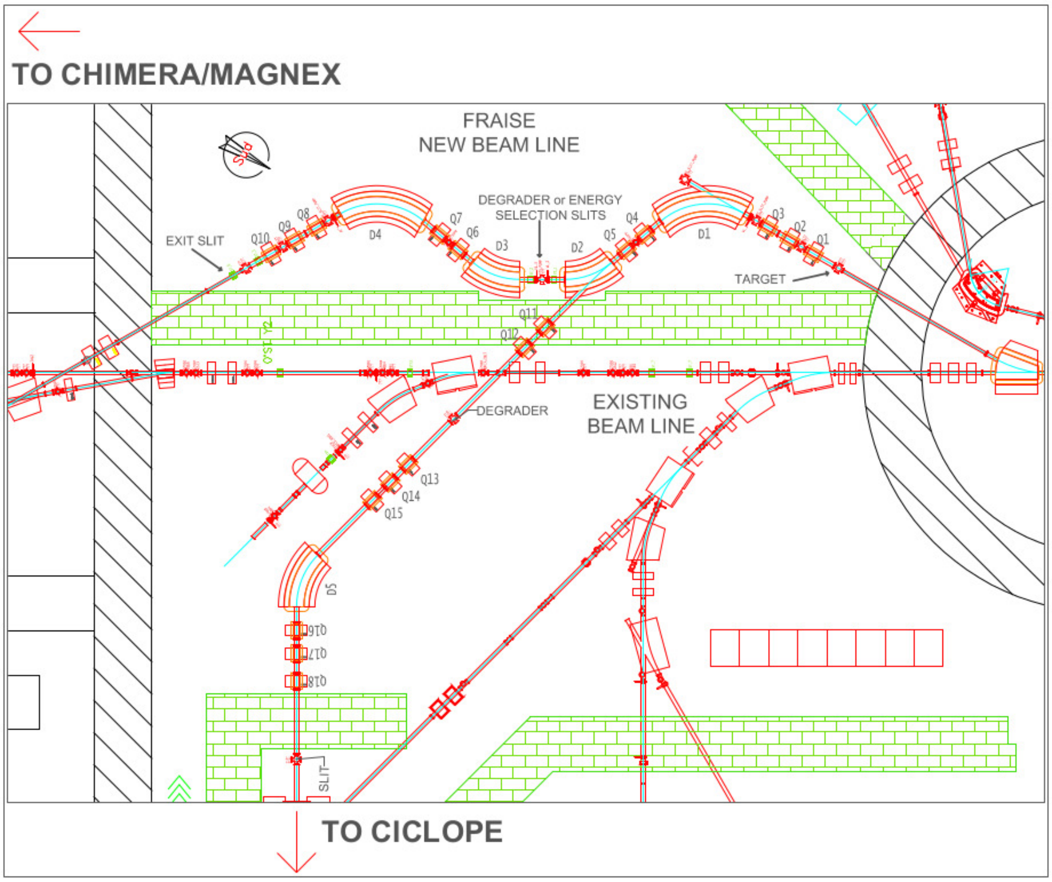

Figure 3. Schematic view of FRAISE the new fragment separator of the LNS.

yields for very exotic nuclei not sufficient for a realistic "time-limited" experiment.

3. FRAISE: the new FRAgment In-fligth SEparator of INFN-LNS

In the forthcoming years, the Superconducting Cyclotron of the INFN-LNS is going to be renewed and improved [25]. One of the main novelties will be the replacement of the actual extraction system, based on electrostatic deflector, with a new extraction system based on stripping. Extraction by stripping is based on the sudden change of the magnetic rigidity of the accelerated ion, when its charge state is suddenly increased crossing a thin carbon foil. This method will be highly efficient for light ions; indeed, ions with mass number $A < 20$ and energy higher than 15 $AMeV$ are fully stripped, q=Z, with probability $> 99\%$ when crossing a stripper foil with equilibrium thickness [26]. However, the new extraction method will be very efficient also for medium mass nuclei up to $A \sim 40$. Intensities of the order of 10^{13} pps will be reached for beams, from C to Ar, at energies of $30 - 70$ $AMeV$; typical beam power will be of ~ 5 kW. This upgrade project of the Superconducting Cyclotron opens new perspectives also for the production of fragmentation beams. The expected availability of higher power for primary beams can be used to produce very intense RIBs, allowing to obtain good intensities also for ions very far from stability valley. Due to the high intensity beams delivered by the upgraded Cyclotron, radio-protection issues impose to place the fragment separator in a position different from the present one, i.e. the accelerator vault, as shown in Fig. 1; in fact it is not possible to efficiently shield this area [27]. Therefore, we have started to study the design of a new fragment separator, named FRAISE (FRAgment In-flight SEparator), explicitly designed to profit of this intensity upgrade. Since the idea is to maintain the possibility to deliver the beam in the largest possible number of target positions, we decided to place the new fragment separator in the area in which are currently located the 20° and 40° LNS experimental halls; this area is shown as a circle in Fig. 1. According to performed simulations, up to 2 kW of primary beam power can be efficiently and safely used in this new configuration [27]. Detailed information about technical features and expected performance of FRAISE are available in Refs. [28].

A new production target, able to dissipate the heat absorbed, will be designed. After that, the first part of the fragment separator will be made up of two 70° and 40° dipoles (D1 and D2, respectively, in Fig. 3) and 1 triplet and 1 doublet (Q1-Q3 and Q4-Q5, respectively, in Fig. 3). The second part of the fragment separator will just be a mirror-copy of the first part. This is schematically shown in Fig. 3. This design ensures a full achromaticity of the fragment separator.

However, on the symmetry-dispersive plane we plan to have a mechanical control of beam profile by means of a mechanichal slits system, and the possibility to insert, just after the slits system, a wedge (degrader) for performing a better rejection of unwanted ions. In fact, a magnetic spectrometer cannot separate ions having the same A/q ratio (A/Z in case of fully stripped ions); one solution is then to use a degrader, i.e. a piece of matter inserted at the dispersive focal plane between the two sections of the fragment separator. Because the atomic slowing down of the ions is roughly proportional to Z^2/v^2, different isotopes, depending mainly on their atomic number, will have different velocities after passing through the degrader. This change in velocity causes the isotopes with the same A/Z ratio to be separated in the second dispersive stage. Detailed calculations [29] show that this second selections is roughly sensitive to A^3/Z^2. This method has been described elsewhere [1] and requires that the material is shaped as a wedge or with thickness increasing properly in order to preserve the achromaticity of the separator. This can be simply understood qualitatively since for a given fragment different positions in the dispersive focal plane correspond to different velocities, and then the energy loss must be adjusted accordingly by varying the thickness: a thicker degrader is needed at the higher velocity side and a thinner one at the lower velocities. A degrader that is shaped accordingly is called an "achromatic" degrader. Because the degrader slows all particles down, including the selected isotope, the $B\rho$ setting of the magnetic elements following the degrader have to be accordingly adjusted. In particular, when a degrader is used, the optical settings of the two dispersive sections of the fragment separator are not mirror of each other anymore, and the magnetic rigidity of the second dipole has to be decreased. In other cases, it can be desirable that the shape of the wedge preserves another parameter of the beam such as, for instance, its velocity. In that case, the wedge is called "monochromatic" and is shaped in order to narrow the energy spread of the selected particles. This feature can be used in experiments where the incident energy of the RIBs must be well known as, for example, in spectroscopy experiments. It should be noted that using a wedge always reduces the rate of the produced RIBs. At the exit of the fragment separator, a second slits system will allow a further selection/control of the beam profile. This section of the FRAISE will be then able to deliver RIBs toward the CHIMERA and MAGNEX halls.

Since we want to maintain the possibility to deliver the RIBs in other target positions, we plan to build also a second arm of FRAISE towards the already existing CICLOPE large area multi-purpose scattering chamber. This solution is achieved operating the second dipole D2 to bent the beam at $-5°$ instead of the 40° of the previous configuration; an additional 45° (D5) dipole will drive the beam towards CICLOPE. Also in this case we foresee to have a slits system on the intermediate plane, followed by a wedge and a second slits system at the exit. Also one doublet (Q11-Q12) and two triplets (Q13-Q15 and Q16-Q18) need to be added. The possibility of placing the SOLE superconducting solenoid [30] before the CICLOPE chamber has been taken

into account; SOLE could act as a beam focusing element on the CICLOPE target station, but could also be used as a stand-alone device operated in a configuration similar to the one of the HELIOS spectrometer at Argonne [31, 32], as discussed below.
Also a revision and improvement of the diagnostic systems [33, 34] will be needed to measure the intensity and the profile of the RIBs cocktail along the lines, in order to perform an optimal transport towards the target stations.
This new design is expected to be able to transport a larger fraction of produced beams, having a larger and selectable momentum acceptance up to a $\Delta p/p \sim 4\%$, to be compared with the old solution having a fixed $\Delta p/p \sim 1\%$. With an efficient rejection of the unwanted species from the cocktail beam, by proper using the slits systems and the wedge, RIBs produced will have an higher purity. In many cases, it will be possible to get higher intensities for the wanted isotope, with respect to FRIBs, still keeping the total rate low enough to allow the use of the present tagging system. Expected intensities, calculated by using the LISE simulation code [35], are listed in table 1.
In order to efficiently exploit the projectile fragmentation mechanism primary beams of 40-60 AMeV of incident energy are commonly used; it follows that RIBs at 20-45 AMeV (after the wedge and tagging steps) will be produced. However, as shown in that table, we are also taking into accounts the possibility to use very thick tagging detectors or additional degrader foils, to get RIBs at few AMeV; this energy regime is interesting for nuclear astrophysics studies, as discussed below; in these cases, a proper refocusing of the RIBs after the degrading could also be required.

Table 1. Expected yield with the new fragment separator FRAISE

main product	primary beam/energy (AMeV)	thickness Be target (μm)	wedge thickness (μm)	primary intensity (kW)	expected yield (kHz)	purity (%)	energy after tagging (AMeV)
^{14}Be	$^{18}O/55$	1500	0	2	2.6	2	46
^{14}Be	$^{18}O/55$	1500	1000	2	2.2	70	43
^{13}N	$^{16}O/40$	700	600	2	1230	54	4
^{14}O	$^{16}O/40$	700	600	2	807	36	4
^{18}Ne	$^{20}Ne/60$	1000	0	2	16700	16	43
^{18}Ne	$^{20}Ne/60$	1000	1000	2	3120	47	24
^{17}F	$^{20}Ne/60$	1000	1000	2	3300	49	23
^{34}Si	$^{36}S/40$	500	500	2	980	81	11
^{38}S	$^{40}Ar/40$	500	300	2	1840	66	17
^{34}Ar	$^{36}Ar/50$	250	0	2	2800	4	41
^{34}Ar	$^{36}Ar/50$	250	500	2	426	12	4
^{68}Ni	$^{70}Zn/50$	250	200	1	490	50	18

4. Some FRAISE physics cases

4.1. Isospin physics

The study of Isospin effects in Heavy-Ion reactions at Fermi energies has been an important field of research of LNS laboratory in the last 15 years [17, 36]. As a relevant example, thanks to the

IOP Conf. Series: Journal of Physics: Conf. Series **1014** (2018) 012016 doi:10.1088/1742-6596/1014/1/012016

capabilities of the CHIMERA multi-detectors [17] careful studies of the reaction mechanisms have been pursued.
In the Limiting experiment, the competition between incomplete fusion and binary reactions in central collisions of medium mass nuclei (^{40}Ca+^{40}Ca,^{46}Ti,^{48}Ca and ^{48}Ca+^{48}Ca) at 25 $AMeV$ was investigated [37–39]. It resulted that the incomplete fusion was more probable, against the binary reactions, for the neutron rich-systems. By using the CoMD-II dynamical model [40], it was demonstrated that the observed effect depends on the stiffness of the symmetry energy and, by comparing the obtained mass spectra with prediction of the model, an effective constrain for the symmetry energy was obtained. These systems were also used for a careful study of the Isospin equilibration phenomena [38, 39], studying the isobaric $^{7}Li/^{7}Be$ and $^{3}H/^{3}He$ ratio); by analyzing the crossed systems ($^{48}Ca +^{40} Ca$ and viceversa) it was there found that complete equilibration does not take place at these energies. The ^{40}Ca+^{40}Ca ($N/Z = 1$) and ^{48}Ca+^{48}Ca ($N/Z = 1.4$) represent a couple of systems with very large Isospin difference, an ideal case for investigating Isospin and symmetry energy effects. However, the new FRAISE will be able to offer better cases. In fact, in this mass region, neutron rich-poor $^{46,34}Ar$ of about 10^6 pps will be produced by using primary ^{48}Ca and ^{36}Ar beams, respectively. This will allow to further extend the Isospin differences ($N/Z = 1.56$ for ^{34}Ar and 0.89 for ^{34}Ar) and to study above mentioned effects in very exotic conditions.
In the region of heavier projectile-target, the Intermediate Mass Fragments production was carefully studied in $^{124}Sn+^{64}Ni$, $^{112}Sn+^{58}Ni$, $^{124}Xe+^{64}Ni(Zn)$ at 35 AMeV semi-peripheral collisions [41, 42]. There it was shed light on the mechanisms of dynamical fragment production, proposing the scenario of the fast fragmentation-rupture of the neck, connecting projectile and target like fragments at the beginning of their re-separation, as mechanism of lighter IMF emission. Other dynamical mechanisms were evidenced in the break-up of the excited PLF*, as evidenced by the observation of non-isotropic angular distributions for the emission direction of break-up products [41]. By looking at systems with different Isospin content, an higher probability of occurrence of the dynamical emission was found for the neutron rich systems, thus envisaging a role of the Isospin content on triggering the conditions leading to the dynamical emission mechanisms. These reactions have also been used to investigate the density dependence of the symmetry energy at densities smaller than the saturation one, by studying the neutron enrichment of the neck emitted fragments [43].
In these cases, the use of very neutron rich projectile as the ^{68}Ni, already produced with the old FRIBs, will allow to reach higher Isospin content for the entrance reaction channel. Moreover, it is now possible to greatly enhance the energy and angular resolutions of such studies by coupling CHIMERA with the new FARCOS [18] device.
It follows that the FRAISE RIBs, in these regions of medium mass nuclei, will represent an important opportunity for extending studies, already performed at LNS, toward high Isospin asymmetries. We remind here that in these studies, symmetry energy effects depends on the square of the Isospin asymmetry; higher Isospin asymmetries allows then to enhance the effects and to separate these from those related to the properties of symmetric matter. This is of some importance in order to get observation that, through comparison with transport model [40, 44], can shed light on the properties of the effective in-medium nucleon nucleon interaction.

4.2. Cluster physics
In the recent years the study of cluster structures of nuclei has become one of the main topic of nuclear physics [45]. Cluster structures have been well evidenced in stable light nuclei, especially for the alpha-conjugate nuclei as well described in the Ikeda theory-diagram [46]. One important issue is to study how the cluster structure evolves when valence particles (either protons or neutrons) are added [47]. In this instance there exists the possibility that the valence particles - most typically neutrons - may be exchanged between the alpha-particle cores [47]. This type

of exchange process is completely analogous to the exchange of electrons in atomic molecules. This leads to the concept of nuclear molecules, with alpha particles playing the role of core structure and neutrons acting as covalent bonding between them. This is well described in the modified Ikeda theory-diagram [46]. In this framework, nuclei arranged as nuclear molecules are expected to have very deformed configurations, characterized by high angular momentum and strong rotational band structure in the excitation energy spectrum. This has been already studied in several Be isotope [48], including the case of ^{10}Be [21] discussed in sect. 2. Another interesting case is the one of C isotopes; possibly the best case for the linear arrangement of cluster, from a theoretical perspective, is ^{16}C [49], though in this instance experimental data is very sparse. As an example the break-up of ^{16}C in $^{6}He+^{6}He+^{4}He$ has been already investigate with FRIBs, in the same experiments studying the ^{10}Be case [21]. The collected statistic was enough to extract the ^{16}C excitation energy spectrum and to speculate on new levels, but still not enough for a quantitative assignment. With FRAISE the yield of ^{16}C will increase by a factor $\sim$ 20; this kind of measurements will become then easily feasible. Many others unstable light nuclei, expected to have molecular or halo structure, will be produced and made available for effective experiments. Also in this case, the use of FARCOS array coupled with CHIMERA multi-detector will allow to get very high energy and angular resolutions, high efficiency and excellent identification capabilities.

4.3. Nuclear Structure

Nuclear structure studies in nuclei far from stability valley usually requires both high efficiency detector array and high cross sections reactions. Direct reactions represent the tool of choice as they allow to infer basic properties of investigated nuclei: elastic scattering can probe protons and neutrons density distributions, inelastic scattering can probe collective aspects, and transfer reactions allow to get information on single particle states and couple-correlation. The necessity to use inverse kinematic, in the case of RIBs, introduces some experimental problems both in the identification of low energy particles emitted in such kind of reactions and in the angular resolution, since the strong focusing of products in a limited angular region tends to reduce the achievable separation among the excited states. An approach allowing to overcome such difficulties is to use an array of segmented detectors placed in a homogeneous magnetic field generated by a solenoid, following the scheme already used by the Helios spectrometer at Argonne [31, 32]. The basic idea is to place the target inside the solenoid along the magnetic axis, and focus the charged particles from the two-body reaction on an array of silicon detectors placed along the same magnetic axis of the solenoid. Measuring energy, time of flight and the impact point, it is then possible to identify the emitted particle and reconstruct the emission angle. In fact the Helios spectrometer has used this new approach for the measurement of light charged particle and has been successfully used in several experiments, proving the validity of this method and the advantages in terms of resolution and detection efficiencies. An R&D study on possibility to build a Helios-like spectrometer at the LNS, using the already existing SOLE solenoid [30], presently placed after the MEDEA detector [50], has already been started. Such kind of spectrometer represents an ideal instruments for measuring direct reactions induced by the RIBS produced with FRAISE. As a relevant example, we just discuss briefly the case study of elastic and inelastic scattering of ^{8}B on protons. ^{8}B is a proton rich nucleus, candidate for being a proton-halo nucleus with a proton separation energy of 137 keV. Experimental evidences of the proton halo structure are not straightforward [51–54] and comparison of experimental data and simulations leads to controversial conclusion. The ^{8}B isotope can be produced using a primary ^{12}C beam at 55 $AMeV$ on a thick 1500 μm ^{9}Be target. Assuming a primary beam intensity of 2 kW, a 1000 μm thick Al wedge, and a selective slits setting of $\Delta p/p \sim 2\%$, we expect to be able to deliver $1.9\times10^{5}pps$ of ^{8}B, over a total cocktail beam rate of 3.3×10^{5}, with a purity of $\sim$ 60% with only ^{7}Be as strong contaminant. The expected $\Delta E - ToF$ correlation, using a tagging

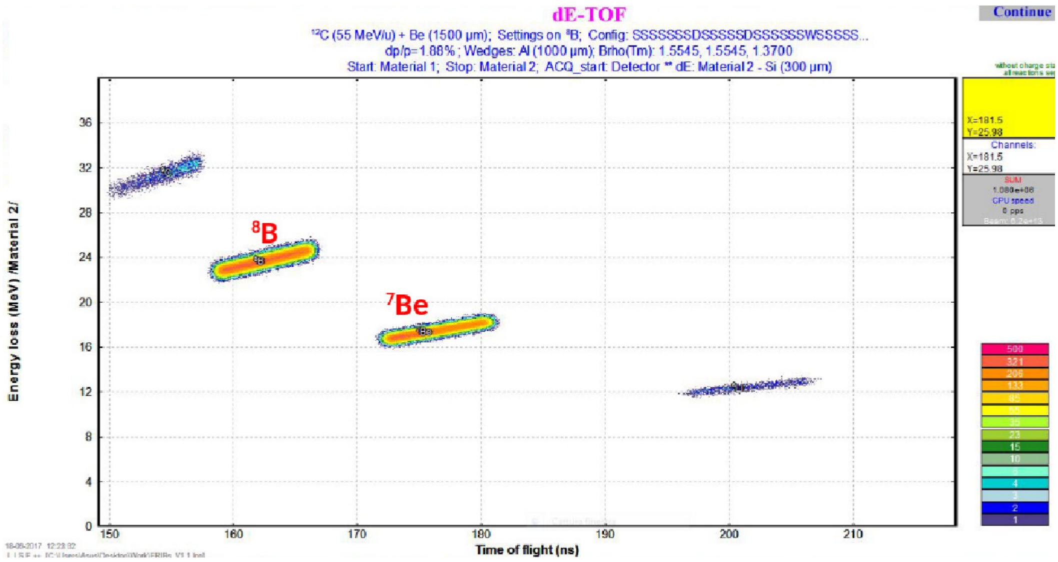

Figure 4. expected $\Delta E - TOF$ tagging of the cocktail beams produced by ^{12}C of 55 $AMeV$ energy on ^{9}Be target.

system similar to the one now in operation, is shown in Fig. 4. A clear separation between the species is obtained. This will make feasible a (p,p') scattering measurement. Moreover, by using a Helios-like spectrometer it would be possible to reach, with respect to previous measurement, a higher efficiency for measuring the angular distributions and a better resolution of the excited states.

Another interesting case is the study of the scattering of ^{11}Be on protons. ^{11}Be has received particular interest because of the inversion between $p_{1/2}$ and $s_{1/2}$ orbitals [55] and has a neutron-halo structure, with resonances above the particle emission threshold. Also in this case we expect to reach about $1.5 \times 10^5 pps$ with FRAISE. Studies of (p,p') elastic and inelastic scattering at MSU allowed to populate excited states up to about 8 MeV [56]. However, due to the very small separation between ground and first excited state (320 keV), energy level have not been separated. Moreover, the excitation energy spectrum shows several not resolved resonances and, up to now, the angular distributions have been studied for energy bins containing several levels. Comparison with theoretical calculations do not reproduce the inelastic angular distributions [56]; a possible cause could be connected to the ^{10}Be core excitation contribution. A Helios-like spectrometer would make the separation of these excited states possible allowing for a deeper understanding of the ^{11}Be structure.

4.4. Nuclear Astrophysics

With FRAISE we foresee also to extend the use of RIBs towards the low energy domain, in order to exploit the possibility of indirect measurements having astrophysical interest. In fact, many interesting projectiles could be delivered, allowing to estimate reaction rates of great interest for explosive nucleo−synthesis calculations. Explosive nucleo−synthesis takes place in some of the most spectacular and peculiar scenarios of the cosmos. The main feature of such phenomena, from the nuclear astrophysics point of view, is the fact that the nucleo−synthesis takes place through the realm of exotic nuclides at energies which are sensitively below the Coulomb barrier. In such environments, in fact, the average time for a reaction to take place is much shorter than the decay time of the involved isotopes. Among such explosive scenarios, Type I X-ray bursts [57–59,62] are observed as sudden, intense emissions of X-rays. These bursts are very interesting phenomena especially because they might turn out to be also very useful probes of our cosmos [58, 59] and a very useful tool to constrain neutron star models. With this respect, we want to highlight the importance of the studies in those fields mentioning the recent discoveries of a binary neutron−star coalescence through gravitational waves [60] and of heavy elements production in the same sites [61]. Of course, this might be possible only if an exhaustive understanding of the development of the burst is achieved. But, up to now, most of the reaction rates adopted in nucleo−synthesis calculations rely on theoretical estimates using statistical models and, therefore, may be subject to significant uncertainties since levels densities are not large enough to allow for their application .

A relevant example is the $^{14}O(\alpha,p)^{17}F$: this reaction could be the onset of a possible route that breaks out from the HCNO cycles, leading to the build-up of new elements. It follows that the knowledge of this reaction cross section is of fundamental importance to estimate the rate of heavy element production. But, even with a high rate RIBs, cross section at the relevant energies, between 1-2 MeV in the center of mass, will be hard to measure. In fact, such energies are quite smaller than the Coulomb barrier (4.5 MeV, in the case of the $^{14}O(\alpha,p)^{17}F$): since nuclear reactions take place through tunneling of this barrier, cross sections are very small and the signal-to-noise ratio approaches zero. This is even more critical in the case of RIBs, as beam intensities hardly exceed 10^6 pps, several orders of magnitude less than typical stable beams. It follows that cross sections at astrophysical energies are extrapolated from higher energies where data are available. However, systematic uncertainties due to extrapolation might jeopardize model predictions. Moreover, in the case of direct measurements, the ejected proton (or/and ^{17}F) has to be detected: this has to face many problems (small counting rate, low statistics, large background, energy and angular resolution).

Indirect methods, such as the Trojan Horse Method (THM), developed by the LNS nuclear astrophysics group [63, 64], have then been devised to bypass these shortcomings. The basic idea underlying indirect methods is the use of nuclear reaction theory to link the cross section of astrophysical importance to the one of a different process, easier to study with present-day facilities. The THM has proved its effectiveness in the extraction of cross sections of reactions having charged particles or neutrons in the exit channel, allowing to achieve astrophysical energies with no need of extrapolation. In the THM approach, the low-energy cross section of a $A(x,b)B$ reaction is obtained by extracting the so called quasi-free contribution to a suitable $A(a,bB)s$ reaction. Therefore, a careful analysis of the reaction dynamics and of the role of clusters is necessary before applying the method. The application of the recent developments of the THM formalism to reactions induced by RIBs would open a new frontier in nuclear astrophysics and in nuclear structure studies. The method itself has been already successfully applied to exotic beams [65–67] and the possibility of having low-energy exotic beams at LNS could give a unique opportunity for the nuclear astrophysics community. Targets containing ^6Li such as ^6LiH or ^6LiF can be used as a source of virtual α-particles, coming from ^6Li direct break-up. A great advantage of this project is the possibility to use beam energies larger than the ones needed for direct measurements, as prescribed by THM. Silicon strip detector array could be used to detect the emitted particles, guaranteeing excellent energy and position resolution. The region relevant for astrophysics, located below about 1.5 MeV, can be fully covered as well as the region at about 2 MeV where direct data are often available for comparison and method validation. Besides particle identification, e.g., by means of the standard DE-E technique, the channel of interest can be singled out by the coincidence measurement of the outgoing particles and the extraction of the reaction Q-value spectrum.

Other interesting reactions, that could be studied with similar methods and experimental apparata are the $^{18}Ne(\alpha,p)^{21}Na$, another important route toward heavy elements nucleo−synthesis, the $^{34}Ar(\alpha,p)^{37}K$ reaction, since ^{34}Ar is a waiting point in X-ray bursts

nucleo−synthesis [68, 69] and the $^{13}N(\alpha,p)^{16}O$ reaction, since in asymptotic giant branch stars this reaction might be an additional n-source for heavy element production through slow neutron capture (s-process); the ^{13}C supply might be reduced if ^{13}N is burnt to ^{16}O before it decays thus influencing the s-process.
Thus, the possibility to measure RIBs induced reaction cross sections at low energies with the THM will represent a step forward in the physics programs of the INFN-LNS.

5. Acknowledgments
The authors wish to thank the NewCHIM collaboration, for the continuous work and support to the FRIBs facility, and the ASFIN2 and LNSSTREAM2 collaborations for their contribution to the discussion of physics cases for the new Fragment Separator.

References
[1] Anne R *et al* 1987 *Nucl. Instr. Meth.* A **257** 215
[2] Geissel H *et al* 1992 *Nucl. Instr. Meth.* B **70** 286
[3] Kugler E *et al* 1992 *Nucl. Instr. Meth.* B **70** 41
[4] Kubo T *et al* 1992 *Nucl. Instr. Meth.* B **70** 309
[5] GANIL/SPIRAL 2001-2007 Achievemnets, Highlights and Perspectives http://hal.in2p3.fr/in2p3-00336915/
[6] see http://www.fair-center.eu/
[7] see http://frib.msu.edu/about/index.html
[8] Prete G 2010 The LNL radioactive beam facility *Scholarpedia* **5(5)** 9751
[9] see http://pro.ganil-spiral2.eu/spiral2
[10] Van Duppen P 2006 Isotope Separation On Line and Post Acceleration *Lect. Notes Phys.* **700** 37-77
[11] Blumenfeld Y, Nilsson T and Van Duppen P 2013 *Phys. Scr,* **T152** 014023
[12] Tanihata I 1995 *Prog. Part. Nucl. Phys* 33 505-573
[13] Casten R F and Sherrill B M 2000 *Prog. Part. Nucl. Phys* **45** 171-233
[14] Hagino K 2012 Exotic nuclei far from the stability line *Preprint* http://arxiv.org/abs/1208.1583v2
[15] www.lns.infn.it
[16] Raciti G *et al* 2008 *Nucl. Instr. and Meth.* B **266** 4632
[17] Pagano A 2012 *Nucl. Phys. News* **22** 28 and refs. therein
[18] Pagano E V *et al* 2016 *Eur. Phys. J. Web of Conf.* **117** 10008
[19] Cappuzzello F, Agodi C, Carbone D and Cavallaro M 2016 *Eur. Phys. J.* A **52** 167
[20] Raciti G *et al* 2008 *Phys. Rev. Lett.* **100** 192503
[21] Dell'Aquila D *et al* 2016 *Phys. Rev.* C **93** 024611
[22] Lombardo I *et al* 2011 *Nucl. Instr. and Meth. (Proc. Suppl.)* B **215** 272
[23] Martorana N S *et al* 2018 *submitted to Phys. Lett.* B
[24] Martorana N S *et al* 2017 *see contribution to this workshop*
[25] Calabretta L *et al* 2017 *Mod. Phys. Lett.* A **32** 1740009
[26] Kunihiro S *et al* 1992 *Atomic Data and Nucl. Data Tables* **51** 173-241
[27] Russo S. (INFN-LNS) 2017 private communications
[28] Russo A D, Calabretta L, Cardella G and Russotto P 2017 *Preliminary design of the new FRagment Ions SEparator at INFN-LNS* contr. at *40th European Cyclotron Progress Meeting*, Sept. 2017 INFN-LNL Legnaro (Italy); Russo A D *et al* 2018 *LNS Activity Report 2015-2016* in press
[29] Dufour J P *et al* 1986 *Nucl. Instr. and Meth.* A **248** 267
[30] Bellia G *et al* 1996 *IEEE Trans. on Nucl. Sc.* **43** 1737
[31] Wuosmaa AH *et al* 2004 *Nucl. Phys.* A **746** 267c
[32] Wuosmaa A H *et al* 2007 *Nucl. Instr. and Meth.* A **580** 1290
[33] Amato A *et al* 2009 *LNS Activity Report 2009* 160
[34] Pagano E V *et al* 2018 *LNS Activity Report 2015-2016* in press
[35] Tarasov O B and Bazin D 2016 *Nucl. Instr. and Meth.* B **376** 185
[36] De Filippo E and Pagano A 2014 *Eur. Phys. J* A **50** 32 and refs therein
[37] Amorini F *et al* 2009 *Phys. Rev. Lett.* **102** 112701
[38] Cardella G 2012 *et al Phys. Rev.* C **85** 064609
[39] Lombardo I *et al* 2012 Jour. of Phys.: Conf. Ser. **381** 012093; Lombardo I *et al* 2013 Jour. of Phys.: Conf. Ser. **420** 012094.
[40] Papa M *et al* 2007 *Phys. Rev.* C **75** 054616 and refs therein
[41] De Filippo E *et al* 2016 *Il Nuovo Cimento* C **39** 404

[42] Russotto *et al* 2015 *Phys. Rev* C **91** 014610
[43] De Filippo E *et al* 2012 *Phys. Rev.* C **86** 014610
[44] Baran V, Colonna M, Greco V and Di Toro M 2005 *Phys. Rep.* **335** 410
[45] Freer M 2007 *Reports on Progress in Physics* **70** 2149
[46] Ikeda K, Tagikawa N and Horiuchi H 1968 *Prog. Theo. Phys. Suppl. extra number* **464**
[47] Freer M 2010 Clusters in nuclei *Scholarpedia* **5(6)** 9652
[48] von Oertzen W 1996 *Z. Phys.* A **354** 37.
[49] Itagaki N *et al* 2001 *Phys. Rev.* C **64** 014301
[50] Migneco E *et al* 1992 *Nucl. Instr. and Meth.* A **314** 31
[51] Minamisono T *et al* 1992 *Phys. Rev Lett.* **69** 2058
[52] Warner R E *et al* 1995 *Phys. Rev* C **52** R1166
[53] Schwab W *et al* 1995 *Z. Phys.* A **350** 283
[54] Kelley J H *et al* 1996 *Phys. Rev. Lett.* **77** 5020
[55] Talmi I and Unna I 1960 *Phys Rev. Lett* **4** 469
[56] Shrivastava A *et al* 2004 *Phys. Lett.* B **596** 54
[57] Galloway D K *et al* 2008 *Astrophys. J. Suppl.* **179** 360
[58] Galloway D K *et al* 2003 *Astrophys. J.* **590** 999
[59] Galloway D K *et al* 2006 *Astrophys. J.* **639** 1039
[60] Abbott B P *et al* 2017 *Phys. Rev. Lett.* 119 **161101**
[61] Abbott B P *et al* 2017 *Astrophy. J. Lett.* 848 **2**
[62] Strohmayer T E and Bildsten L 2006 *Compact Stellar X-Ray Sources* (Cambridge, UK: Cambridge Univ. Press)
[63] Spitaleri C *et al* 2016 *Eur. Phys. J.* A **52** 77
[64] Tribble R E *et al* 2014 *Rep. Prog. Phys.* **77** 106901
[65] Cherubini S *et al* 2015 *Phys. Rev.* C **92** 015805
[66] Pizzone R G *et al* 2016 *Eur. Phys. J.* A **52** 24
[67] La Cognata M *et al* 2017 *Astrophys. J.* **846** 65
[68] Parikh A *et al* 2008 *Astrophys. J. Suppl.* **178** 110
[69] Iliadis C 2007 *Nuclear Physics of Stars* (Wenheim, Germany: Wiley-VCH Verlag)