

STATUS AND COMPARISON OF WORLD-WIDE IN-FLIGHT FRAGMENT SEPARATORS

H. Simon*, M. Winkler, H. Weick
GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

Abstract

Generation of rare isotope beams by means of in-flight separation of nuclear fragments and fission products requires complex optical structures usually comprising multiple separator stages. Large aperture magnets providing maximum acceptance, radiation hard and superconducting are used to separate the reference isotope from the bulk of the primary and secondary heavy ion beam. The pre-separator stages are designed to dump a majority of the secondary beam in a controlled way and are therefore often a challenge for radioprotection, shielding and beam catchers. The complex optics of fragment separators makes use of energy degraders, intermediate focal- and image planes to minimize contamination of the desired isotopes. A comparison of optical designs and magnet technologies will be presented.

SECONDARY EXOTIC ISOTOPES

Since the pioneering experiments at the BEVALAC in Berkeley in order to study nuclei far from stability lines in the 1980ies, there has been developments all over the world in order to come up with different methods in order to get a handle on secondary beam production. The most common methods have been identified and described in Ref. [1] where production in targets and their extraction via the ISOL method is explained together with the at that time upcoming in-flight separation method being explored e. g. at the Lise spectrometer at GANIL in the Normandy, France, the A1200 at NSCL in Michigan, USA, the RIPS facility at RIKEN, Saitama, Japan, or at the FRS at GSI, Germany. Especially the latter, being coupled to a synchrotron driver are favorable when trying to perform experiments [2] at coupled storage rings. The current paper will capitalize on the upcoming instruments for in-flight production with energetic secondary beams. These are routinely explored at the aforementioned FRS and at second generation facilities where FRS will be extended to the Super-FRS [3] and the comparison with several similar upcoming or already running facilities will be performed.

USE CASE FOR SECONDARY BEAMS

Leaving the stability lines leads to sizable changes in nuclear structure. The Nuclear Physics Astrophysics and Reactions community formed and defining the requirement via viable physics program at the Super-FRS project developments at GSI/FAIR represents the current driving force for several secondary beam facilities. Astrophysics scenarios require precise data especially for unstable nuclei which also

needs to be predicted and interpreted with modern theory approaches. Reference [4] shows as an example that meanwhile computational power seconded with suitable methods in many-body theory and modeling based on realistic nucleon-nucleon forces reaches also heavy nuclei. Their production and separation are demanding, and require suitable methods for unambiguous identification for these heavier systems.

SEPARATION TECHNIQUES

A separation in-flight at sizeable primary beam energies of 0.1 GeV/nucleon to 1 GeV/nucleon is dominated by an interaction with the target leading to breakup reactions through fission and fragmentation. Energy loss and straggling in the target will be reduced with higher energies, allowing for the use of thick targets (i. e. thicknesses larger than 1 g/cm²). This is also the domain where the internal Fermi momentum of nuclei in the nucleus become smaller than the momentum of the incoming beam particles. This leads to kinematical focusing along the beam direction, so that higher beam energy leads to increased transmission of secondary beam products. The basic principle is a combination of magnetic separation via magnetic rigidity $B\rho$ which depends on the beam particle momentum over charge ratio. Different charge states (i.e. incomplete ionization of the ions) will lead to a different bending of the magnets and, thus, possible contaminants by unwanted side products that cannot be spatially separated. The charge can be identified by measurement of the specific energy loss in dedicated transmission detectors. Also here the different appearing charge states lead to tails in the energy loss distributions towards lower energy loss in the detectors. The magnetic separation system can be extended (as described in Ref. [3]) at dispersive planes with wedge-shaped degrader plates, that allow to make use of energy loss in the material depending on the squared ratio charge (state) over beta (the relative velocity to the velocity of light) of the particles. The dependence allows refocusing of beam particles in the next stages of the separator that come with certain charge states. At areas of the separator system where intensities are low enough to perform event-wise measurements with all beam particles detectors for energy loss measurements (ΔE , with a few percent relative resolution), time-of-flight (TOF - at a level of a few 10 ps resolution) and position with mm resolution, with particle rates of up to a few million particles-per-second (pps). The discussion of the dedicated instrumentation is outside the scope of this paper.

Typically, several magnet stages with degrader wedges at dispersive planes are combined into the full separator.

* h.simon@gsi.de

At the first stage of all next-generation spectrometers a separation stage with two dipole stages interspersed with a wedge degrader system ($B\rho - \Delta E - B\rho$) is used to clean up the secondary beam at prohibitively high rates for detection of individual particles.

Typically, the next stage is then a so-called main separator with several additional separation stages, comprising of magnet stages ($B\rho$). Here also the specific energy loss (ΔE) in a further degrader station is used for further refinement of the beam. In the possible presence of detectors, energy loss, TOF, and positions, can also be measured, and necessary corrections being applied. In summary the $B\rho - \Delta E - B\rho + B\rho - \Delta E - \text{TOF}$ scheme is adapted in the next generation facilities, described in this paper.

PERFORMANCE CONSIDERATIONS

Looking at the achievable selectivity for particular isotopes or ranges of isotopes for experiments [4] it becomes clear that heavier nuclei are harder to separate with the previously explained separation techniques than lighter nuclei. Especially the background contributions arising from different charge states have a big impact on the overall separation performance. Meanwhile the resolution [5] is achieved with several efforts, especially on instrumentation and analysis side, but for several cases the background nuclei will prevent running at reasonable data rates as they will unavoidably cross the detector systems for separation. Operating the separators at higher energies reduces the amount of charge states drastically and allows for an unambiguous and optimized use of secondary beams in the experiments with heavy nuclei. As the cross sections for ion production drop as a rule of thumb by an order of magnitude for every step further away from the stability line the availability of very intense primary beams with a suitable reaction path to the wanted species, i. e., the availability of various ion sources for producing primary beams, is a key ingredient for running the secondary beam facilities.

Going from the GSI to the FAIR facility [6] one of the major ingredients is the GSI injector chain with various ions being developed as primary beams, with the SIS18 synchrotron, running at lower energies with lower charge states at the space charge limit, injecting into the SIS100 synchrotron to reach highest intensities with 100 Tm beams. These will be extracted to the Super-FRS [7] production target. The gain in primary intensity is matched with a similar separator performance in order to form an optimized system.

EXPERIMENTAL AIMS & REQUIREMENTS

The advent of secondary beams was accompanied by several discoveries, especially in the light nuclei region. The evolution of shell structure from the line of stability to the outskirts of the nuclear landscape has been intensively studied. One major discovery here at the intensity frontier, over-arched by an ^{48}Ca beam at a beam energy of 345 MeV-

per-nucleon with the SRC cyclotron using the Big-RIPS separator at the RIBF facility in Japan, is the measurement of the ^{28}O doubly magic nucleus [8].

In several facilities the Nuclear Astrophysics communities has formed strong bounds to the Nuclear Structure Physics and Reaction studies (e. g. NUSTAR at GSI/FAIR). Star evolution with fusion reactions into the iron region and subsequent explosive scenarios to populate even heavier nuclei (e. g. Pb, Pt, Au, Ag) go along reaction corridors far away from the nuclear stability line. The properties of key nuclei or along altered shell closures are key ingredients in understanding the reaction dynamics that is directly reflected in the abundance patterns of the elements. On the other hand, theory predictions (compare e. g. Ref. [9]) allow to reach in this region with calculations done with nucleon nucleon forces as input and many body approaches in order to understand complex nuclei from first principles. Heavier Nuclei are, thus, becoming more and more attractive for nuclear structure studies.

NOVEL FACILITIES

The section is organized with brief descriptions of the facilities together with special focus on their features and primary beam parameters (Fig. 1) at the respective facilities.

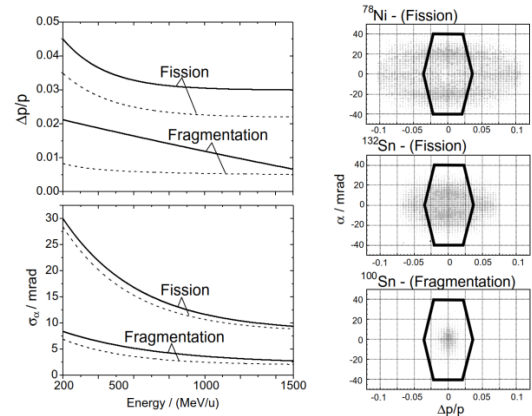


Figure 1: General feature for the transmission through limited apertures following the secondary beam production. The relative momentum spread $\Delta p/p$ and the angular spread σ_α are displayed. Left panels show the restriction (thick black lines) and a density plot for the particles entering the separator due to the acceptance of the separator (for the Super-FRS).

The BigRips separator [10] at the RIBF facility in RIKEN, Wakoshi, Japan, shown in Fig. 2 is the first next generation system, including a pre-separation stage, and is running since 2007. The system is characterized by a large acceptance of $\sigma_x = \pm 40$ mrad and $\sigma_y = \pm 50$ mrad, and a corresponding momentum acceptance of $\Delta p/p = \pm 2.5\%$ (see Fig. 1, and the Super-FRS paragraph). The facility is driven by a powerful cyclotron (SRC) providing beams up to 345 MeV/nucleon for a variety of beams from He up to Uranium. The facility provides routinely high intensities (e. g. ^{48}Ca with 500 pA,

^{238}U with 70 pA). The former can be used to populate light exotic elements in the chart of nuclei in very high rates. The related physics program capitalizes on several studies in this region including the recently achieved landmarks which is the study of ^{28}O [8] the heaviest known and presumed to be doubly magic Oxygen isotope. The separation scheme is shown in Fig. 2 and follows the previously described methods.

BigRIPS Separator

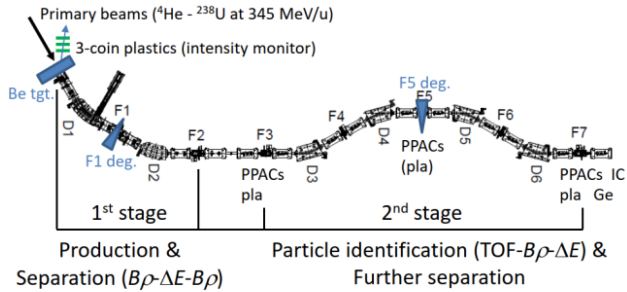


Figure 2: BigRips at the RIBF facility, RIKEN, Japan. The separator runs at a magnetic rigidity in the high $B\rho$ mode up to 9.9 Tm. (courtesy: Shin'ichiro Michimasa)

Figure 3 shows the ARIS spectrometer [11–13] at the FRIB facility, at Michigan State University in the US. Here the pre-separation stage is set up in vertical direction from a hot area for the production target. The ARIS aims at handling a beam power of up to 400 kW i.e. 42 μA or 2.6×10^{14} $^{48}\text{Ca/s}$ which sets a landmark in the intensity frontier. Since the startup in May 2022 several experiments in the light and mid-mass region have been carried out and a beam power of 20 kW has been reached. A ramp up to 30 kW is planned for the Year 2026. The primary beam energy from is at the low end of the assessment in Fig 1. The maximum energy from the sc RF LINAC is limited to 200 MeV/nucleon.

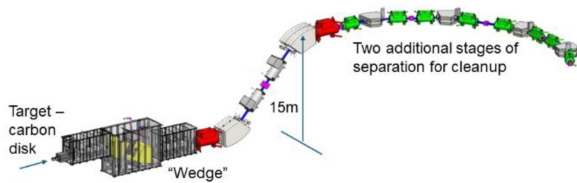


Figure 3: ARIS at the FRIB facility, MSU, Michigan, USA. The separator runs at a magnetic rigidity up to about 7.5 Tm. (courtesy: Georg Bollen)

The HIAF facility is based on a set of synchrotrons and is designed to work with high intensities, e.g. 100 pA U^{92+} at 800 MeV/nucleon. The HFRS separator (see Fig. 4 in Ref. [14]) is characterized by a large acceptance of $\sigma_x = \pm 30$ mrad and $\sigma_y = \pm 25$ mrad, and a corresponding momentum acceptance of $\Delta p/p = 4\%$. The separator currently runs at a maximum rigidity of 15 Tm and will be ramped up in a second stage to 25 Tm.

HIAF and the HRS have recently commissioned with a $^{209}\text{Bi}^{31+}$ beam at 633.86 MeV/nucleon where an intensity 1×10^{10} particles/s has been achieved. A successful experiment has been reported at the attached storage ring (SRING)

on 13.4.2026. The comprises several implementations of advanced digital twins e.g. also for the initial commissioning with beam that could be finalized very efficiently.

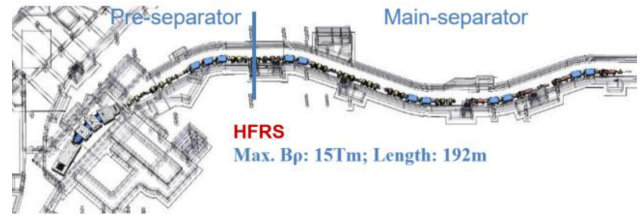


Figure 4: HFRS at the HIAF facility, IMP, Huizhou, Guangdong, China. Phase 2 comprises a 25 Tm option for the separator. (courtesy: Yiangcheng Jang)

The SuperFRS will be installed in the course of 2026/27 [15], and is planned to be able to accept first beam by the end of 2027. The Super-FRS separator (see Fig. 5) is characterized by a large acceptance of $\sigma_x = \pm 40$ mrad and $\sigma_y = \pm 20$ mrad, and a corresponding momentum acceptance of $\Delta p/p = 5\%$. Currently the system shown in Fig. 5 is set up to two experimental areas at the beginning and the end of the high-energy branch, that is the current scope of implementation. The Low energy branch is planned for a later stage and the Early and first science program will be started in this configuration. A stagewise implementation of first the Low energy branch with an additional spectrometer for reaction products of the secondary beams – with the feature to be able slow them down to rest for trap and laser spectroscopy experiments, is foreseen. With the advent of the planned rings a dedicated ring branch will be additionally set up and provided for the users.

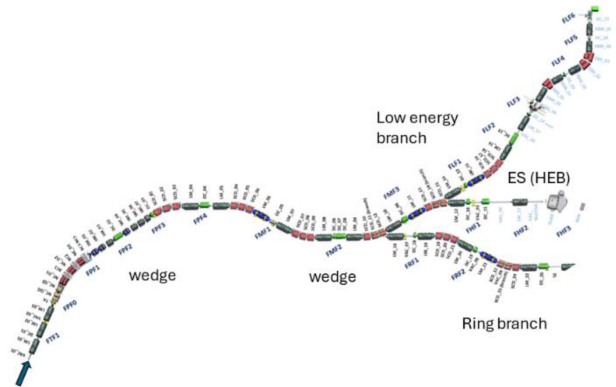


Figure 5: Super-FRS at the FAIR facility, Darmstadt, Germany. The length from target to the Early Science experiment (ES) at the High energy branch HEB is 18 m. The separator runs to a magnetic rigidity up to 20 Tm. Two more branches can be implemented in the future: the low energy branch with a dedicated spectrometer, and the Ring branch serving the planned storage rings for the full implementation of the FAIR facility.

The next facility to ramp up in Korea is the IF separator at the IRIS facility (RAON), Daejeon, Korea. The separator is built for magnetic rigidities up to 7.5 Tm.

The IF separator (see Fig. 6 in Ref. [16]) is characterized by a large acceptance of $\sigma_x = \pm 40$ mrad and $\sigma_y = \pm 50$ mrad,

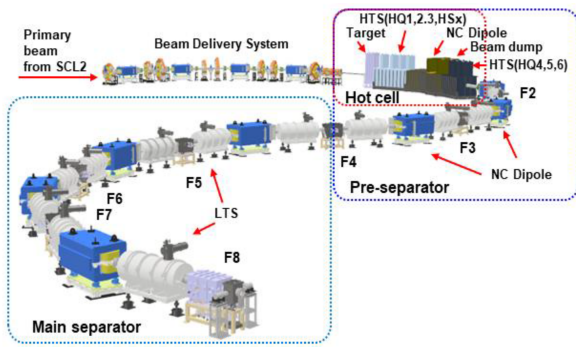


Figure 6: IF at the IRIS facility (RAON), Daejeon, Korea. The separator is built for magnetic rigidities up to 7.5 Tm. (courtesy: Jang Youl Kim)

and a corresponding momentum acceptance of $\Delta p/p = 6\%$. The separator is completed since 2022 but the sc driver Linac to 200 MeV/nucleon is still missing but expected to be built in the upcoming years. Currently the facility operates successfully a low energy separator KOBRA [16] which is coupled to the LINAC at somewhat lower energies (15 MeV/nucleon).

CONCLUSION

The paper summarizes the status and features of the currently advancing next generation fragment separators. Several boundaries for the achievable performance and usability for experiments are given. We expect an ecosystem of several facilities ramping up where the new HIAF and FAIR separators will be able to run at highest beam rigidities which is favourable for experiments with heavy beams whereas FRIB is capitalizing on highest beam intensities. The synchrotron driven devices are perfectly suited to serve storage rings.

ACKNOWLEDGEMENTS

The author wants to thank all colleagues in the Early-Science-Task-Force [18]. We are grateful to our collaborators: CEA Saclay, France, CERN, Geneva, Switzerland, Chalmers University, Gothenburg, Sweden, CMERI, Durgapur, India, HIP, Helsinki, Finland, IFJ-PAN, Cracow, Poland, JLU Gießen, Germany, Lund University, Sweden, TU-Darmstadt, Germany, WUST, Wroclaw, Poland, University of Groningen, Netherlands, VECC, Kolkata, India.

REFERENCES

- [1] H. Geissel, G. Münzenberg, and K. Riisager, “Secondary Exotic Nuclear Beams”, *Ann. Rev. Nucl. Sci.*, vol. 45, p. 163, 1995. doi:10.1146/annurev.ns.45.120195.001115
- [2] T. Suda and H. Simon, “Prospects for electron scattering on unstable, exotic nuclei”, *Prog. Part. Nucl. Phys.*, vol. 96, p. 1, 2017. doi:10.1016/j.pnpnp.2017.04.002
- [3] H. Geissel, H. Weick, M. Winkler, *et al.*, “The Super-FRS project at GSI”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 204, pp. 71–85, May 2003. doi:10.1016/S0168-583X(02)01893-1
- [4] T. Onishi *et al.*, *J. Phys. Soc. Jpn.*, vol. 77, pp. 083201, 2008.
- [5] N. Fukuda *et al.*, “Identification and separation of radioactive isotope beams by the BigRIPS separator at the RIKEN RI Beam Factory”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 317, pp. 323, 2013. doi:10.1016/j.nimb.2013.08.048
- [6] J. Blaurock, H. Simon, O. Boine-Frankenheim, and P. Spiller, “FAIR completion of construction works, towards commissioning and first science”, in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3923–3927. doi:10.18429/JACoW-IPAC2023-THYD1
- [7] H. Geissel, M. Winkler, H. Weick, *et al.*, Technical Design Report, 2009, <https://repository.gsi.de/record/54552/files/GSI-2013-05264.pdf>
- [8] Y. Kondo *et al.*, “First observation of 280 ”, *Nature Phys.*, vol. 620, pp 965–970, 2023. doi:10.1038/s41586-023-06352-6
- [9] B. Hu *et al.*, “Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces”, *Nature Phys.*, vol. 18, pp. 1196-1200, 2022. doi:10.1038/s41567-022-01715-8
- [10] T. Kubo, “In-flight RI beam separator BigRIPS at RIKEN and elsewhere in Japan”, *Nucl. Instrum. Methods Phys. Res. B*, pp. 97-113, vol. 204, pp. 97, 2003. doi:10.1016/S0168-583X(02)01896-7
- [11] L. Bandura *et al.*, “Fragment separator momentum compression schemes”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 645, pp. 182 -186, 2011. doi:10.1016/j.nima.2010.12.015
- [12] M. Hausmann *et al.*, “Design of the Advanced Rare Isotope Separator ARIS at FRIB”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 317, pp. 349-353, 2013. doi:10.1016/J.NIMB.2013.06.042
- [13] M. Portillo *et al.*, “Commissioning of the advanced rare isotope separator ARIS at FRIB”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 540, pp. 151–157, 2023. doi:10.1016/j.nimb.2023.04.025
- [14] Y. Jang *et al.*, “Heavy ion accelerator facility front end design and commissioning”, *Phys. Rev. Acc. Beams*, vol. 22, pp. 110101, 2019. doi:10.1103/PhysRevAccelBeams.22.110101
- [15] J. Schmidt, “Update on the FAIR machine installation status”, talk presented at IPAC'26, Deauville, France, May 2026, paper THO4M01, this conference.
- [16] D.G. Kim *et al.*, “Beam commissioning of the KoBRA in-flight fragment separator at RAON”, *Nucl. Instrum. Methods Phys. Res. B*, vol. 573, p. 166043, 2026. doi:10.1007/s40042-025-01435-1
- [17] S. Choi *et al.*, “The RAON facility: an overview”, *J. Korean Phys. Soc.*, vol. 87, pp. 447-454, 2025. doi:10.1007/s40042-025-01435-1
- [18] Early-Science-Task-Force, https://www.gsi.de/work/gesamtprojektleitung_fair/super_frs/people_behind_the_project/task-force-early-science