FRS000: Proposal for beam tests at the Fragment Separator FRS

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Summary

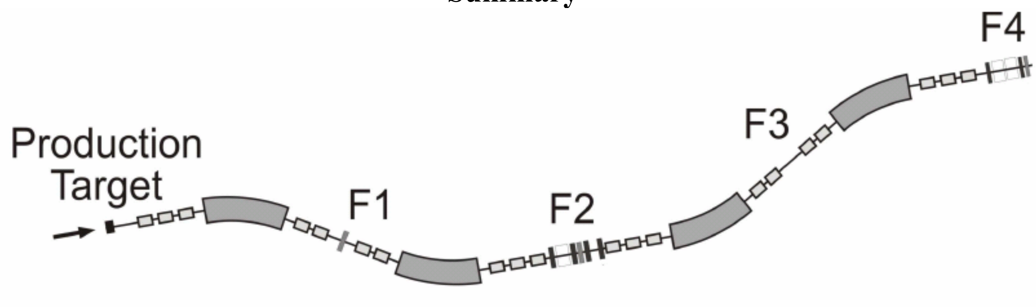

Fig. 1. Schematic drawing of the FRS; the focal planes are indicated and named F1-F4.

The Fragment Separator FRS, in operation since more than 20 years, is one of the most versatile in-flight separators designed for the production of relativistic radioactive beams and used in research studies with exotic nuclei. Due to its flexible design various types of equipment and detecting systems can be integrated at the different focal planes opening the perspective to very different type of experiments with heavy ions. This has been assured by dedicated testing and commissioning runs within FRS000. To continue this successful scheme towards the Super-FRS and to improve it further we ask for a renewal of FRS000 with dedicated beam time as main user at the beginning or at the end of the beam blocks to test new components and prototypes needed in the future at the Super-FRS. In some cases, depending on the required experimental conditions, e.g. beam quality and intensity, we can also share 1:1 with other main experiments.

Motivation

The FRS [1] is a very versatile ion-optical device consisting of conventional magnetic elements combined with layers of matter placed at different focal planes to achieve isotopic separation (Bρ-ΔE-Bρ) or simply to match the phase-space of the heavy ion beam to special experimental conditions. The magnetic elements (dipole, multipole magnets) are sketched in Fig. 1 together with the focal planes F1-F4.

Differently shaped degraders at dispersive focal planes, for example F2 in Fig. 1, are routinely used to preserve the ion-optical achromatic condition of the overall system. In this way the best spatial separation of fragments can be achieved. Monoenergetic degraders are used to bunch the energy distribution of the fragment beam to reach a narrow range straggling [2]. In both cases it is necessary that the beam spot on the degraders is strictly determined by the ion-optical focus condition. From these statements it follows directly that the classical ion-optical elements and in addition the combination with energy degraders must reach a high performance to achieve the experimental goals of isotopic separation with a small contamination up to the heaviest fragments. In contrast to cyclic accelerators and storage rings all FRS magnets are equipped with individual power supplies which is the base for the very versatile operational modes, optimized for each experiment. However, this also provides a delicate source of severe performance losses if already only one of the quadrupole magnets is tuned to a field differing from the calculated values.

The Super-FRS [3] at FAIR is completely based on experiences from the present FRS, and taking additionally into account the consequences arising from the expected higher primary beam intensities (up to a factor of 10-100). The latter enhancement requires a two stage separator concept, i.e., a pre-separator followed by a main-separator. The separation principle of the Super-FRS is almost identical compared to the FRS, i.e., the spatial separation is based on the Bρ-ΔE-Bρ method. The Super-FRS has a much larger momentum and angular acceptance than the FRS, e.g., for the most exotic projectile fragments and specially fission fragments the achievable gain is roughly a factor 10. The consequence is that larger degrader dimensions have to be used and thus their prototypes need to be tested in the present FRS. The much larger apertures of the Super-FRS will also induce larger image aberrations. In turn, this means that these image aberrations of the present ion-optical system including degraders have to be fully understood. This provides not only maximized performance for the present experiments, but enables to apply this experience for the design and operation of the Super-FRS.

During the last four years, it turned out to be very useful to have a so called FRS000 beam time for testing new equipments at the FRS. As a result of the FRS000 beam time the target ladder for the second target position of the FRS and the related beam optics could be commissioned. A new beam profile detector for high intense fast-extracted beams [4], the Isomer TAGger detector (ITAG) [5] and other devices were successfully tested [6]. Many of the scheduled experiments have already benefited from the progress achieved during the FRS000 beam time. The new isomeric tagger station routinely in use at the last focal plane (F4, see figure 1) for example provides now a quicker and more reliable particle identification of the radioactive beams being produced. In the last years new TPC detectors with C-pads, new electronics and improved characteristics were developed by the Bratislava–GSI collaboration [7].

However, during these beam times we were always strongly limited in our planned program by being treated generally as a parasite experiment.

Our plan for the FRS000 beam time in the next two years (2011-2012) includes:

1. ***Ion-optical measurements***
2. ***Test of high-rate capable detectors for the Super-FRS***
3. ***Test of the Super-FRS target wheel***
4. ***Developing readout, controls, and fail-safe operation concepts.***

Some of these tests are an essential prerequisite for developing the technical expertise and technologies necessary for the Super-FRS. As such, they will contribute to a timely completion of the Super-FRS project within the context of FAIR.

Technical requirements

We give the specific technical requirements for each of the four previous points.

1. Ion-optical measurements

The proposed ion-optical measurements will be done with homogeneous high-resolution tracking detectors (TPCs) placed at all focal planes. In F2 and F4 we have to place two TPCs to measure position and angles and their correlations in coincidence with selected momenta. At the entrance of the FRS a full determination of the incident phase-space of the beam is needed as well. It would be necessary to measure the ion-optical matrix elements in first and higher-order. In case calculations and measurements differ significantly, the fields will be empirically adjusted to end up with a more reliable model which is then the base for the future field settings in experiments. Different ion-optical modes will be tested, like the energy-bunching with the last dipole stage only (F3 to F4).

After the classical optical elements have been measured and verified, an investigation of the combination with degraders and special targets is to be done. Target and degrader properties can be precisely measured via energy-straggling studies [8] with a heavy ion projectile beam (e.g. Pb, U). In turn for these investigations the high-momentum resolution of the FRS is a prerequisite. After the material characterization via energy-loss measurements we will test the sum of all these contributions by the isotopic separation of U projectile fragments close to the Z of the beam. The different atomic charge states represent for the ion-optical measurements a unique calibration and on the other hand the highest performance for the fragments is needed in this case.

For ion-optical measurements we ask 2 days per year, day time only, of high-quality SIS beam, preferable slow-extracted U beam at energies ranging from 100-1000 MeV/u, sharing not less than 1:1.

2. Test of high-rate capable detectors for the Super-FRS

a1. Tracking detector: GEM-TPC detectors: With the increasing primary beam intensity of the SIS18 (and later on SIS100) and thus also secondary beam intensities new developments are required for future tracking and particle identification. For this reason we plan to test the GEM-TPC (Gaseous Electron Multiplier-Time Projection Chamber) detector prototypes. It has been designed and constructed by the Helsinki-Bratislava collaboration as a tracking detector for the Super-FRS [9].

A total of 12 GEM foils with dimensions of (256x56) mm^2 were used to assembly three triple-GEM stacks. The foils passed leakage current tests; the current was kept below 0.5 nA at 500 V for 30 minutes. The foils glued were scanned with a digital camera in order to identify possible defects and no-uniformity of the holes diameter. The GEM-stack was powered by resistive voltage divider in a way that the amplification of each GEM foils will be the same and at the same time maintain the transfer field very high. The active detector volume of the prototype is (250x50x100) mm^3. The uniform electric field of the drift volume is done by high-voltage cathode plane and Mylar strips around the field cage walls. The prototype is equipped with a Chevron cathode connected to the delay line for the readout and with parallel strips split in half and connected to charge sensitive preamplifiers.

The GEM-TPC test can be performed by using different slow-extracted beams (e.g. C, Kr, U) at energies ranging from 100-1000 MeV/u. The site for a in-beam test can be F2 (allowing higher intensities due to shielding) or F4 where the air-mounted chamber can be operated up to an intensity of 1 MHz. Ion trajectory reconstructions and tracking have to be performed at different beam intensities. For comparison Time Projection Chambers detectors will be also used. A suitable period for this test will be the second half of 2011.

During 2012 we foresee to equip the detector with a different electronics like for instance N-XYTER [10] and AFTER [11] enabling single channel readout and thus increasing furthermore the rate capability. In addition to that, high granularity of the readout will provide valuable information needed for the optimization of the readout electrode geometry and gas gain.

For the GEM-TPC test we ask 3 successive days of beam time per year, day time only, to have the GSI infrastructure and the individual experts available. Each test period needs in addition about 4 hours to set up the beam at the FRS with a beam, sharing not less than 1:1.

a2. Tracking and Timing: diamond detectors: For radioactive beams at velocity $\beta \sim 0.85$ a time resolution of about 40-20 ps (FWHM) is necessary in order to resolve mass numbers A>150. By using standard FRS plastic scintillators between F2 and F4 (distance of 36m) the resolution achieved is about 100 ps. Between F1 and F2 it becomes difficult to have a clear identification for A>150 due to the higher particle rates and shorter distance.

This scenario will be similar at the middle focal plane of the Super-FRS were the maximum intensity foreseen can reach even $\approx 10^8$ particles/spill. A possibility to operate at the high counting rate is to use segmented scintillator strip detectors. Another possibility is to use diamond detectors.

Nowadays, many semiconductor detectors are used in particle and nuclear experiments as trigger or tracking detectors. Among them, diamond has some brilliant features for use in severe environments. First, diamond has a relatively wide bandgap energy of E_g=5.47 eV, higher than that of silicon with E_g=1.13 eV. Therefore it does not need pn-junctions and refrigeration as well (it also can be used even in high-temperature environments). Secondly, the carrier mobility of diamond is large and because of its high breakdown voltage one can apply stronger electric field to have carrier drift faster. Charged particles that traverse diamond film lose their energy on creation of electron-hole pairs. Then electrons and holes are separated and drift into the electrodes by the electric field applied, which can be measured as a current. Typical rise-time of a pulse created by a single heavy ion passing a thin diamond detector is the order of 100 ps. Finally, diamond is a radiation-hard material [12] which allows the use it in high-radiation environments such as high-intensity ion beam lines.

We plan to test diamond films, synthesized through the chemical vapor deposition (CVD) method, to make tracking and timing at the Super-FRS. The location of this test can be F1 or F2. Single channel or strip diamond detectors can be used.

The design for the in-beam diamond detectors is very close to an ideal tracking device, providing all 4 spatial coordinates (x,y,z,t) with sufficient resolution in a single layer of detector material. Detailed studies on small samples have already been performed by the RD42 collaboration at CERN [13] for minimum ionizing particles produced at LHC. Small detectors have been also successfully used by the HADES collaboration, where a good timing resolution and radiation hardness was shown in a number of experiments.

Despite the performance of single crystal diamond material is superior with nearly spectroscopic performance, it is only available in sizes smaller than 100 mm^2. In order to cover the quite large areas at the focal planes of the FRS and Super-FRS with a homogeneous layer of detector material, polycrystalline diamond produced by chemical vapor deposition (PCCVD) has to be used. This is meanwhile routinely available on larger sizes of (50x50) mm^2 with a good charge collection efficiency of 20-30% at a layer thickness of 100–200 μm.

In the framework of the Joint Research Activity RHIB of the EURONS integrated infrastructure initiative of the 6 EU framework new high rate diamond detectors from polycrystalline material for tracking and TOF had been developed, e.g. for the R3B experiments. While the tracking capabilities at high rates could have been shown already in first test experiments [14] a good time of flight performance still has to be proven for large area segmented detectors. Especially the larger capacities of individual channels, signal crosstalk of neighbouring segments and a compact design of many channels do not allow a simple extrapolation of the results obtained using small size detectors.

To compare these issues smaller single channel detectors as well as large area strip diamond detectors will be tested at the same time. Due to the special properties of PCCVD diamond, reasonable tests can only be performed using high energy heavy ions (A>50) with a large specific energy loss penetrating several layer of these detectors and additional scintillators at the same time. Due to extended tests of different hardware and electronics the test should be performed in smaller blocks of several hours distributed over a few days. As high beam intensities could be simulated by shorter extraction times, the location of this test can be F2 or F4 which are easier to access in a test phase.

For the diamond detector test we ask for 3 successive days per year, day time only, to have the GSI infrastructure and the individual experts available. Each test period needs in addition about 4 hours to set up the beam at the FRS with a beam, sharing not less than 1:1.

b. Beam Profile monitor: Within the task NUSTAR 3 of the FP6 EU Design Study, Beam Chamber (BC) [4] detectors for fast-extracted ion beams have been proposed and designed by the Bratislava group for future experiments at the Super-FRS.

For beams with a spill length as short as 50 ns a single ion tracking is not achievable anymore, but only measurements of the bunch profile can be performed. This problem arises from the large amount of charge (up to several nC) which is deposited in the detector. The use of a gas detector leads to a long integration time which is needed for charge collection (≈μs). This causes a spreading of the charge and thus strongly affects the measurement of the beam profile. For this reason the use of fast electronics and lower gas pressure (around 1 mbar) has been proposed.

A prototype was tested in 2007 at the FRS with Carbon beams at intensity of few 10^9/spill. Online measurement showed stability of the response with still considerable stability for higher intensity. The detector has a modular design with basic module size of (100x100) mm^2. It contains 3x50 wires. Each wire with 2 mm pitch was directly connected to three integrated passive delay lines for x and y position measurements. The digitalization of the fast signal was obtained by using a Flash ADC SIS3301.

The low pressure Beam Chamber can be tested in F1 area with fast extracted beams at intensities of 10^9-10^{11}/spill in 2012. The test can be performed in parallel to part of the test of the Super-FRS target using the same fast-extracted beams.

3. Test of the Super-FRS target wheel

a. Characterization of Target: The first version of the Super-FRS graphite target wheel is already available (see Fig. 2). At present it undergoes a longer test procedure of testing the stability of the mechanical motion under vacuum conditions. After this a characterization of the target properties with an ion beam is planned. The wheel itself has been measured, but due to the type of material and the layout with steps of different target thickness some questions remain:

a1. Absolute target thickness: It is planned to measure the target thickness with a heavy ion beam at different positions of rotation. A heavy ion beam is one of the most sensitive tools when combined with the FRS as a high resolution spectrometer to measure the energy loss of the ions. This technique has been applied in the past to establish a precise knowledge of stopping powers of heavy ions at relativistic energies [15].

a2. Homogeneity: The choice of graphite as the target material was made for good shock absorption and operation at high temperature. A disadvantage is the non-homogeneity of the material due to its macroscopic grain structure. A strong enlargement of the variation of energy loss of heavy ions has been observed in the past [16]. However, it also varied with different grades of the material. The resulting energy spread should still be small compared that from the nuclear fragmentation reactions which must be verified. The energy spread due to microscale inhomogeneity should be also tested for carbon-carbon composite which has been shown to have a better response to proton beam-induced pressure waves. In this case the cylindrical sample should be placed on the actual target ladder. Again the FRS as spectrometer is the best tool to measure the resulting energy spread as has been done for basic investigations of energy-loss straggling [17].

b. Background measurement

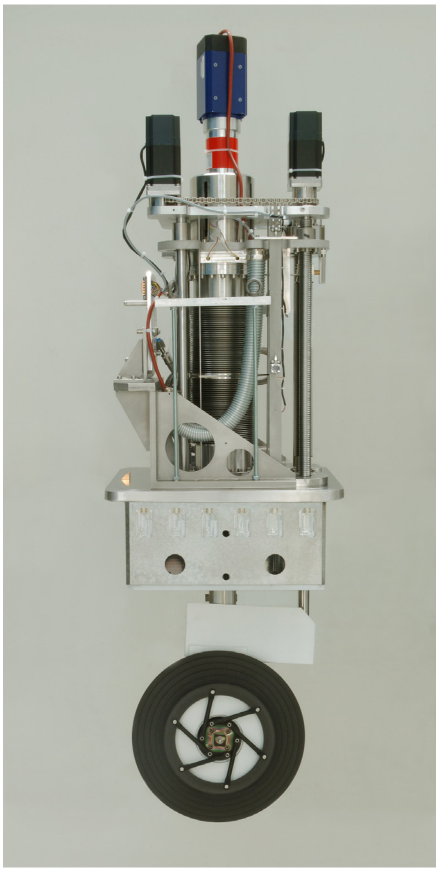

Fig. 2. The target wheel of 450 mm outer diameter with its drive mechanism. Steps of different thickness can be selected by moving the wheel.

The Super-FRS aims for more extreme ratios in rates of exotic nuclei to primary beam than today at the FRS. This also means that possible sources of background must be avoided more carefully as they may even dominate the count rate. One such source is primary beam hitting the neighboring step in target thickness on the wheel. In this case the primary beam or fragments of high production cross section may pass through the separator.

In principle this requires a careful investigation with sensitive particle detectors in the hostile environment near the target to measure the exact beam profile including a possible tiny beam halo. Another way is to use the fragment separator and to look at fragments of quite different production cross sections. In this case nuclides with orders of magnitude higher production cross section will be transmitted for ions hitting the wrong step, while the beam hitting the right target thickness is much suppressed. This method corresponds to the real background problem and therefore presents a very realistic test case. In recent FRS experiments ratios of intensities differing by six orders of magnitude could be observed in similar sources of background. Such a dynamic range cannot be achieved with any direct particle detector.

During the measurement it is planned to move the beam slightly to explore the limits. The beam properties are the ones of SIS-18, but they are expected to be similar to SIS-100 and in one FAIR operation mode also beam from SIS-18 is foreseen to go directly to the Super-FRS.

c. Irradiation Test: Another disadvantage of the graphite material compared to metal targets are the larger material modifications after strong irradiation. Presently it is very difficult to obtain doses like at the FAIR facility. Nevertheless, first effects on the limits can be seen also for heavy ions beams at high velocity. At lower velocities with UNILAC beams strong effect have already been observed [18]. Especially the reduction of thermal conductivity can be critical as well as the hardening of the material as it reduces the shock absorption qualities.

At GSI there are only two experimental area with enough shielding to make full use of the available $^{238}U^{28+}$ beam intensity up to 193 MeV/u with intensities of up to 2 10^{10}/spill and of 1000 MeV/u with up to 3 10^{9} /spill $^{238}U^{73+}$. They are at the FRS target stations and at the HHD beam dump position behind the first FRS dipole. The HHD beam dump lacks proper focusing equipment and beam spot sizes are in the order of Centimeters. Millimeter spot sizes and corresponding higher local doses can be achieved on the FRS target.

It is planned to place graphite samples on a separate target ladder for easier handling and not to disturb the other experimental program at the FRS. We aim at irradiating the samples with doses of 10^{15} ions/cm^2. This number is motivated by the observed effects at UNILAC energies with doses of 10^{13}/cm^2. At the higher velocities a much weaker effect is expected from the lower energy deposition dE/dx. For example the track creation yield can be reduced by three orders of magnitude [19]. However, the velocity effect is not clear and these numbers are mainly based on experience with lower dE/dx by lighter ions. It is the goal to establish a better velocity scaling in the relevant energy range for Super-FRS and FAIR. Having 10^{10} ions per second on an area of (5x5) mm^2 it requires 7 hours for the dose of 10^{15}/cm^2. At the higher energy for the same dose 2 days are required. We aim for 5 samples 3 at lower and two at higher energy.

For the Super-FRS target wheel test we ask in total 10 days of beam time, day only, in particular 7 days in 2011 and 3 days in 2012.

4. Developing readout, controls, and fail-safe operation concepts

Controls requirements at the Super-FRS are an important issue. For this reason a large scale time and trigger distribution is foreseen for the Super-FRS within the FAIR accelerator control system. A new generation timing system prototype called BuTiS (Bunchphase Timing System) available at GSI since 2007 can be readily tested now for applications at the FRS. It provides a time reference with an absolute accuracy of 100 ps/km and a timing jitter well below of 10 ps [20]. In its final stage the system is to be accomplished with a real-time messaging system called white rabbit [21]. Both systems are integral part of the foreseen accelerator controls for FAIR. The state of all subsystems forming a system can be gathered and analyzed, as well as distributed to all control units in the system, within a guaranteed latency on an absolute time scale. Thanks to these properties the time distribution system will be also of interest for data acquisition applications of the instrumentation of the Super-FRS, i.e. the coupling of several stations at distant locations to a combined system with a common time base, and subsequent data transfer to central data storage and online analysis. Such foreseen system allows for time of flight measurements to a few 10 ps precision and an accuracy complying with the requirements for particle identification (PID) throughout the Super-FRS branches [22]. Eventually, this enables to flexibly set up PID measurements being used for tuning secondary beams, without being forced to cross connect all stations with signal cables, thus minimizing the cabling efforts for the new installations.

The BuTiS clock distribution has been tested with a precision timing electronics called Tacquila [23] in the laboratory and a very good channel to distant channel uncertainty of 23 ps (r.m.s.) has been achieved under realistic conditions. The necessary fiber distribution and receiver systems for BuTiS are thus currently being ordered to be setup at the FRS focal planes F2 and F4, as well as in S8 and Cave-C, where the R^3B precursor experiment is situated, within this year (2010). We want to test the system by determining the achievable quality of PID measurements under real conditions using this novel approach.

The white rabbit messaging system, a development driven by CERN and GSI/FAIR as major players [21,24], is working in principle but lacks client implementations to be used in the field. First switches will be installed at GSI in the first half of 2011. Here, we are involved in the ongoing developments. As soon as the system becomes available it will be set up using conventional fiber or cupper based network cabling and tested. Using this system the BuTiS based precision clock pulse distribution evolves into an absolute time stamp system, facilitating event synchronization and allows testing the real time messaging for control applications in particular while interacting with accelerator controls.

We apply for beam tests in parallel to the tests using slow extracted beams and performing particle identification measurements with BuTiS in 2011/12, so that eventually the system can be used routinely for experiments. The white rabbit will then be used to provide absolute time stamps and event separation. In 2012 we will use the white rabbit receivers to set up and test real time messaging between the accelerator controls and the FRS.

Beam time request

	2011	**Primary Beam**	**2012**	**Primary Beam**
1.	4 shifts	Pb or U	4 shifts	Pb or U
2. a1 a2 b	2 shifts 6 shifts 4 shifts shared (3)	setup C, Kr, U A>50	2 shifts 6 shifts 4 shifts shared (3)	setup C, Kr, U A>50
3.	2 shifts 4 shifts (U^{28+}) 14 shifts (U^{73+})	setup $U^{28+/73+}$ $10^{10}/2\ 10^{9}$	70%/30% shared 2011/12	
4.	shared (2a,b)	slow extract.	shared (2a,b)	slow extract.
	Total 8 days, (16 shifts only day time) share not less than 1:1		**Total** 8 days, (16 sh. only day time+ 20 sh. {3.}) share not less than 1:1	

Table 1. Distribution of the FRS000 beam time in 2011 and 2012.

We ask for 8 days of beam time each in year 2011 and 2012 to perform ion optics studies, detector, controls and data acquisition tests. Target tests require in total 10 days of beam time. A proposed share would be 70% in 2011 and 30% in 2012. In order to perform these tests in the most effective manner, we'd like to restrict ourselves to 2 shifts per day during daytime, so that all experts and technicians from accelerator division, electronics division, detector and target laboratories, and our own group will be most time available.

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