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# Technical Proposal for the ILIMA Project

ILIMA
Isomeric Beams, Lifetimes and Masses
Collaboration
15th Dec 2005


**Abstract:**
Precision measurements of nuclear masses and lifetimes of stored exotic nuclei at relativistic energies and studies with isomeric beams are proposed. The planned experiments are a continuation of the successful experimental program at the present FRS-ESR facilities. The new Super-FRS-CR-RESR-NESR facility will yield access to interesting nuclei near and at the drip-lines which can not be accessed with the present facilities.

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# A Introduction and Overview

## 1. Research Objectives

Nuclear masses and lifetimes of exotic nuclei in ground and isomeric states are basic quantities which are essential for the understanding of nuclear structure and the creation of the elements in stars. Today the challenge is to measure the masses and lifetimes of exotic nuclei up to the limits of nuclear existence. From systematic precision measurements with the variation of proton (neutron) number along isotopic (isotonic) chains important information can be derived, like the location of the drip-lines, the development of shell closures, the changes in shapes and pairing. New experimental developments involving storage rings yield access to measurements of bare and few-electron ions in the laboratory, thus under conditions that prevail in hot stellar environments.
A great research potential is that not only ground state properties can be studied but also those of isomeric states, which are populated in projectile fragmentation and fission at relativistic energies. The experimental possibilities will expand with the availability of pure isomeric beams that can be used for secondary nuclear reactions, which will open novel ways to explore the nuclear structure.
The proposed investigations at the new facility as it was presented in the LoI will focus on:

1. mapping of large areas of the unknown mass surface:
   - near and at the drip-lines, e.g., investigate pairing for loosely bound nucleons;
   - $N \approx Z$ nuclei, e.g., investigate the role of the neutron-proton interaction;
   - in the region of shell closures, e.g., around the doubly magic nuclides $^{48}$Ni, $^{78}$Ni, $^{100}$Sn and $^{132}$Sn;
   - along selected chains of isotopes and isotones, e.g., explore predicted shell quenching far from stability;
   - at the pathways of nucleosynthesis in stars (r- and rp-process), in particular waiting points;
2. lifetimes of highly-charged ions, their decay modes and branching ratios;
3. mass-resolved isomeric states and related nuclear properties;
4. the production of and studies (e.g. decays and reactions) with pure isomeric beams.

## 2. Experimental Concept

Mass measurements of exotic nuclei are a challenge because of the low production cross sections and the inherent large emittance and longitudinal momentum spread of radioactive ion beams separated in flight. A further difficulty arises from the fact that the nuclei close to the drip-lines are short-lived and thus limit the preparation and observation times.
Two methods have been developed at GSI for accurate mass measurements of stored exotic nuclei at relativistic energies: *'Schottky Mass Spectrometry (SMS)'* for cooled beams of longer-lived isotopes [1], and *'Isochronous Mass Spectrometry (IMS)'* for hot beams of short-lived (down to microsecond range) fragments [2]. Both methods, well established in previous experiments, are based on precise measurements of the revolution frequency which unambiguously characterizes the mass-to-charge ratio of the circulating ions. In SMS the velocity spread of the relativistic hot fragment beams is presently reduced by stochastic and electron cooling. For IMS the ring optics is tuned to an isochronous mode such that the differences in velocities are compensated by different trajectories.
These two experimental methods are especially well-suited to measure effectively a large part of the mass surface in one run. In this way the systematic errors can be kept small if the reference masses for the calibration are reliable. The corresponding mass measurements in the Penning trap system of the Low-Energy Branch of the Super-FRS will yield complementary results and are predestinated to provide very accurate reference masses.
The lifetimes of stored nuclei can be obtained with two independent methods. The first one is to measure non-destructively the intensity changes of both the stored mother and daughter ions. These intensity changes are measured by applying Schottky spectrometry. The second is based on the fact

that daughter and mother nuclides differ by their magnetic rigidities. Thus, the resulting daughter nuclei can be recorded with particle detectors placed near the orbit of the mother nuclides, while the intensity of the mother nuclides is monitored by Schottky spectrometry. Both methods yield redundant information by simultaneous measurement of the decay of the mother and the population of the daughter nuclides.

Nuclei in isomeric states were already observed in previous campaigns for mass and life-time measurements [3,4,5,6] with the present FRS-ESR facility [7,8] due to the superb resolution obtained with stored and cooled beams. Using the Bρ-ΔE-Bρ separation method, isotopic pure beams can be injected and stored in the rings. Here, depending on the half-life and excitation energy of isomeric states a pure isomeric beam can be prepared. Then, the monoisomeric beam can be used in the NESR for reactions in the internal targets (see EXL project) or in measurements at the electron/antiproton colliders (see ELISe and AIC projects).

## 3. Competitiveness

The unique opportunities of the FAIR facility are:

- the production of radioactive nuclides which are very far off stability and are close or even at the drip-lines and which are of importance for nuclear physics and astrophysics;
- the combination of the in-flight separator Super-FRS and a system of storage rings CR-RESR-NESR which will be an ideal tool to provide short-lived exotic nuclides for precise measurements at relativistic energies;
- the precise mass measurements which can be performed by two established methods invented at GSI: Schottky Mass Spectrometry (SMS) and Isochronous Mass Spectrometry (IMS), both with sensitivity down to single ions.

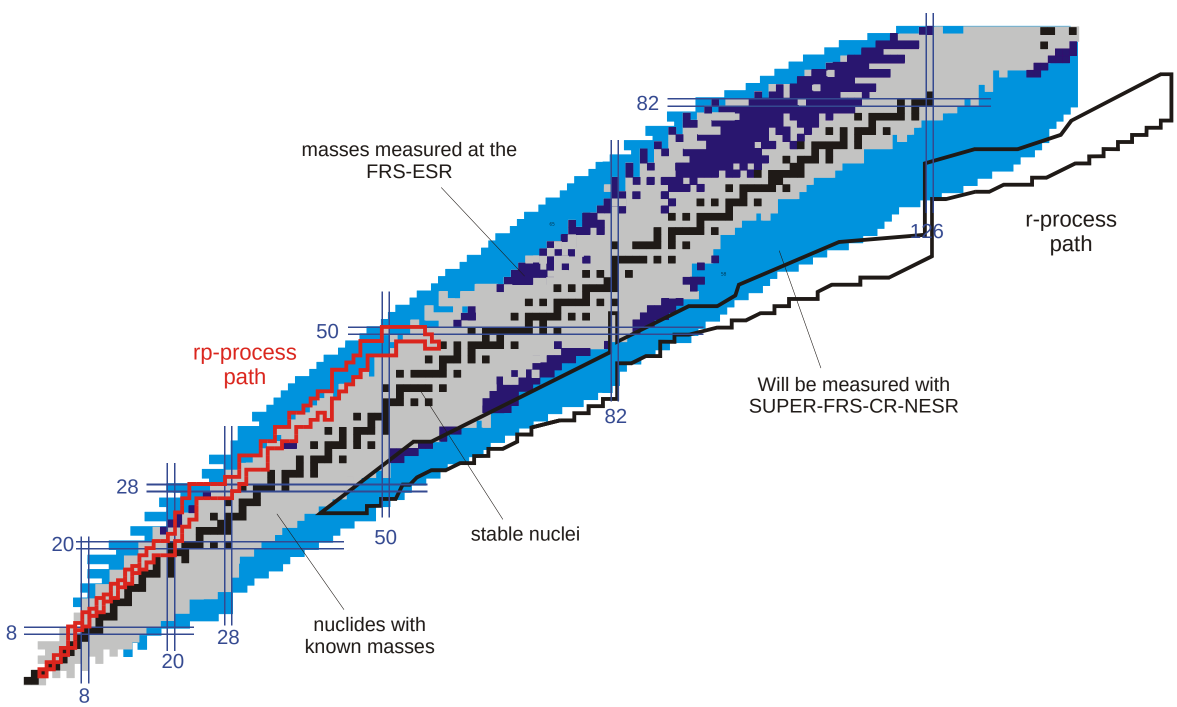


*Figure 1: The chart of nuclides with known and unknown masses. The range of the mass measurements performed presently in the storage ring ESR at GSI is marked as a dark-blue area. Nuclides with still unknown masses which will become accessible with the new facilities, the Super-FRS, the double-storage ring system of CR and NESR, are indicated by the light-blue area. Astrophysical paths for the r- and rp-processes are indicated as well.*

Thus, the combination of SIS-Super-FRS-CR-RESR-NESR of FAIR will provide unique possibility to produce relativistic exotic nuclides from presently unknown regions with rates of up to ~ $10^5$ times higher than existing at GSI nowadays, whereas SMS and IMS will be used to measure precisely the masses and half-lives.
The present status of the knowledge of atomic masses [9] and the large area of hitherto unknown masses, which will become accessible with the new facility, is illustrated in Figure 1. The light blue area covers those nuclides where direct mass measurements will be possible with the FAIR facility. The lifetimes can be measured simultaneously with mass measurements. Most of these nuclides can only be investigated with the new facility.
Another unique feature of the new facility is a possibility to produce pure monoisomeric beams for nuclear structure and reaction studies.

## B Systems

### 1. Experimental Setup

The combination of the Collector Ring (CR) and the New Experimental Storage Ring (NESR) is designed for research with exotic nuclei and will accept the full phase space of the projectile fragments delivered by the Super-FRS. The efficient storage of fission fragments will give access in particular to neutron-rich nuclei of medium mass. The goals for the mass resolving power and accuracy are about $10^6$ and 20–50 μu, respectively. We have already achieved these values for SMS in previous experiments [5,6], whereas for IMS still some improvements are required.
The experimental setup is schematically illustrated in Figure 2. Experiments involving nuclei with very short half-lives, down to the μs range, will be performed in the CR operated in the isochronous mode. The experimental equipment in the CR will include time-of-flight detectors and sensitive resonant Schottky probes, both enable precise revolution frequency measurements in a very short time. Longer-lived nuclides ($T_{1/2}$ longer than 1 s) will be stochastically pre-cooled in the CR and be transferred via the RESR to the NESR. Here, they will be cooled further by electron cooling and Schottky Mass Spectrometry will be applied. An independent measurement of the lifetimes will be performed by measuring the daughter nucleus in particle-identification detectors placed near the closed orbit of the stored beam in both rings.

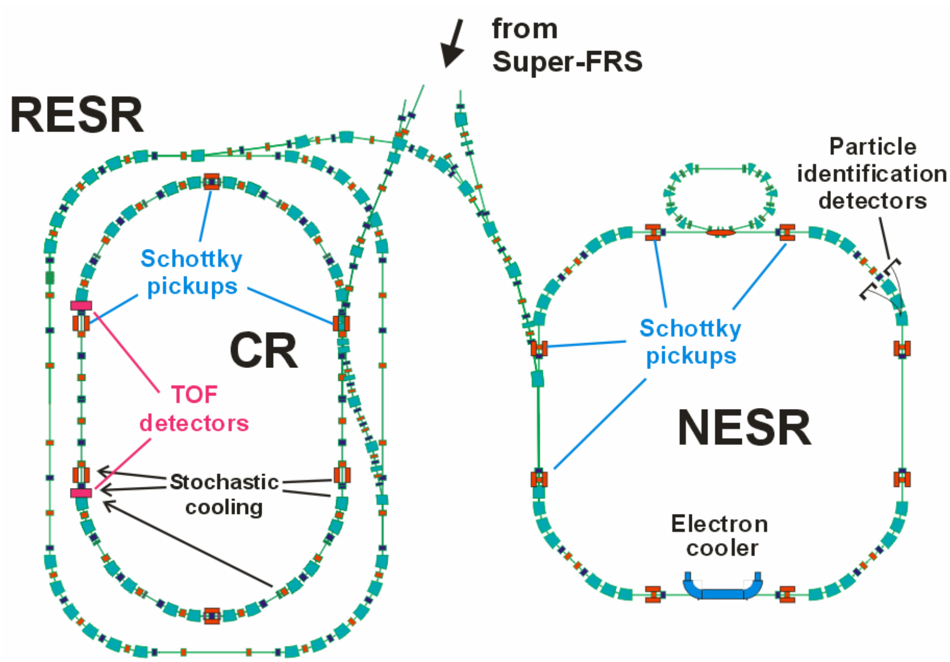


*Figure 2: Layout of the storage-ring facilities for direct mass and half-life measurements and studies with isomeric beams. Exotic nuclei separated in flight with the Super-FRS will be injected into the Collector Ring CR. Mass and half-life measurements of very short-lived nuclides (down to few tens μs) will be performed in the CR operated in isochronous mode. Longer-lived nuclides (longer than 1 s) will be stochastically pre-cooled in the CR and will be transferred via the RESR to the NESR. Here, they will be further cooled by electron cooling and Schottky Mass Spectrometry will be applied. Movable particle-identification detectors for independent half-life measurements will be installed behind one of the dipole magnets in the CR and the NESR. Some of the shown detector positions are optional.*

## 1.1 Sub project: Storage Rings and Beams

### 1.1.1 Rare Isotope Beams from Super-FRS Injected into CR and NESR

Nuclei produced in the Super-FRS target can be injected into the CR and then, via the RESR, into the NESR. It will be also possible to inject the ions into the NESR directly with a still rather broad acceptance ($\Delta p/p = \pm 1\%$). In this way experiments can be done when the CR and the RESR are used for other experiments like e.g. antiproton production.

For the mass and lifetime measurements a wide range of stored elements with similar mass to charge ratio is desired. This means no thick degraders are needed in the Super-FRS. Only very thin degraders may be used for reduction of the range of elements.

For production of certain isotopes and investigation of special decay branches, a good separation is required. For light and medium-mass projectile fragments the separation will be done by using thick degraders in the Super-FRS. For heavy nuclides and fission fragments a combination of this $B\rho$-$\Delta E$-$B\rho$ separation in the Super-FRS and the stochastic cooling in the CR, which is mass selective ($\Delta m/m \sim 10^{-3}$ [10]), will be necessary.

### 1.1.2 Cooling of Beams

An important feature of the new ring system is the short cooling time of about 1 s for all fragment species which is an ideal condition for SMS in the NESR. One task of the CR is the efficient collection and fast pre-cooling of secondary beams to a relative momentum spread of $5 \times 10^{-4}$ and to an emittance of less than $\varepsilon = 1$ mm mrad before the exotic nuclei are transferred to the NESR. This high beam quality is achieved by bunch rotation and subsequent stochastic cooling within 1s, for a typical fragment beam characterized by an initial momentum spread of $\pm 1.75\%$.

The fact that the beam has been pre-cooled in the CR will considerably reduce the time for electron cooling in the NESR. With this pre-cooling, it will be possible to reduce the emittance by electron cooling to $\varepsilon < 0.1$ mm mrad with a relative velocity spread of $\Delta v/v < 10^{-4}$ for an intensity of $10^8$ fully-stripped uranium ions within another 500 ms. For a low number of stored ions the spread will be below $\Delta v/v = 10^{-6}$.

Stochastic cooling in the CR is mass selective. This will be used to prepare isotopic pure beams to be injected into the NESR. Skipping the stochastic pre-cooling in the CR and injecting directly into the NESR will lead to longer electron cooling times in the NESR but avoids the mass selectivity and preserves the full mass spectrum for systematic broad-band scans. The electron cooling of an entire broad-band spectrum will be in the order of a minute but for the ions with initial velocities close to the electron velocity the cooling time will be within a few seconds only. It might be useful to reduce for this purpose the momentum acceptance in order to make cooling faster.

### 1.1.3 The Isochronous Mode of the CR

The isochronous mode of the CR is used to measure precise mass-to-charge ratios of ions despite of their velocity distribution. Same ions with different velocities and therefore also different magnetic rigidities follow different path lengths in the CR to enforce the same revolution times. For each storage ring there is a certain velocity for which this condition is fulfilled. This velocity is characterized by the transition point ($\gamma_t$) which should be equal to the Lorentz factor ($\gamma$) of the circulating ions. For the isochronous mode in the CR $\gamma_t$ is 1.84. The isochronous mode is achieved by a large dispersion function in the ring which reduces the momentum acceptance to $\pm 0.5\%$. The ion optics of the isochronous mode is illustrated by the beam envelopes in Figure 3.

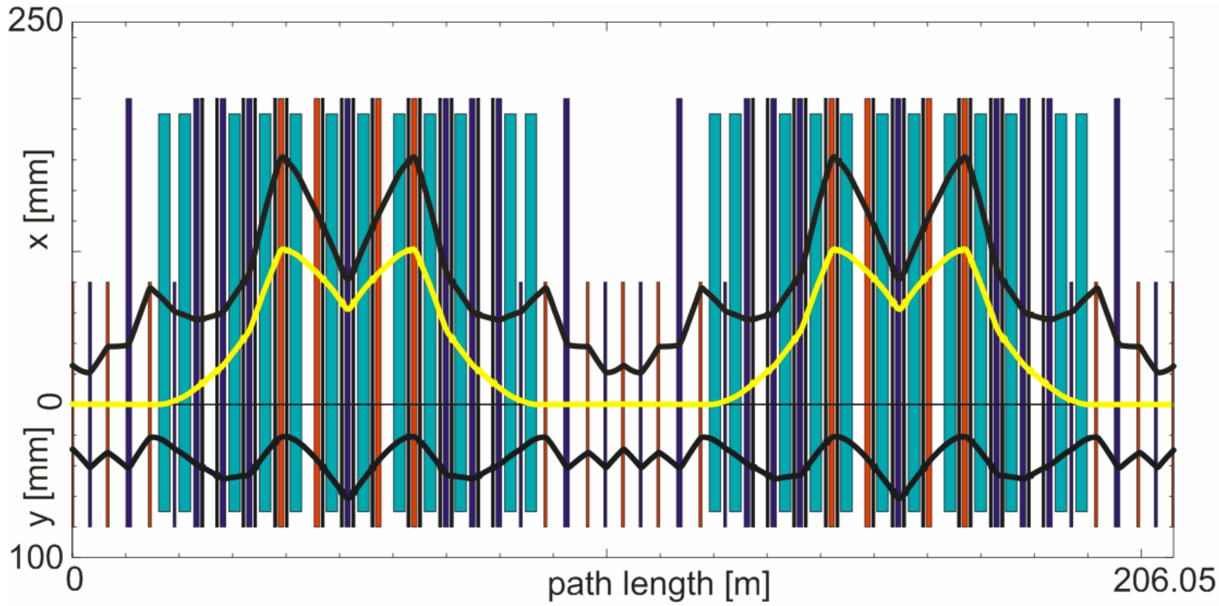


*Figure 3: Beam envelopes in the isochronous CR. The upper part shows the horizontal direction (x) including dispersion (black) and separately the dispersion curve only (yellow). The lower part represents the vertical direction (y). The envelopes are drawn for an emittance of 100 mm mrad in x and y and a momentum spread of ±0.5%. Red and blue rectangles mark the aperture of x and y focusing quadrupoles, respectively. The light blue rectangles represent the dipole apertures.*

**Simulations and verification in the experiment**

It is not sufficient to fulfill the condition $\gamma=\gamma_t$ to first order. At least the second order must be corrected with the hexapole magnets. For the iscochronous mode shown above, a full compensation of chromaticity and the second-order isochronicity was achieved in calculations. The induced 3$^{rd}$-order error in isochronicity is not negligible but can be corrected easily with one very weak octupole component in the center of the arc at the point of highest dispersion.

Still the optics has to be refined once the parameters of the magnets are known. It will be also investigated whether the relatively large beam diameter at the detector positions can be reduced.

A way to verify the isochronicity of the ion-optical setting must be developed. The experience with the present ESR showed that the isochronicity must be carefully checked in each experiment. This is done by changing the velocity of the stored primary beam and thus scanning the entire acceptance of the ESR. The precise velocity change is done by means of the electron-cooler voltages. As no cooler is foreseen in the CR, the electron-cooled ions can be injected from SIS18. This method is more complicated than at the ESR, but it has the advantage that the ions are injected exactly on the same orbit as later for the measurements.

Since the path-length acceptance of the ring is given by the magnetic rigidity and the isochronicity depends on the velocity, the CR cannot be isochronous for a broad range of mass-to-charge (m/q) ratios. This is illustrated in Figure 4 by an example from previous mass measurements [11]. A deviation in Bρ and m/q leads to non-isochronous motion.

At each revolution the ions must penetrate the carbon foil of the TOF-detector (see section 1.3.1), which slows them down due to atomic energy-loss and thus the ions travel over the entire range of magnetic-rigidities accepted by the ring. Since an ion can be also injected into the CR at any magnetic rigidity, the mass resolving power is dependent on the mass-to-charge ratio and is more reduced for less isochronous ions. This will be even more crucial in case of the CR as this new ring aims for higher acceptance than the present ESR. In order to improve the mass resolving power, additional information on the velocity or magnetic rigidity of the ions is needed. By measuring it for each ion, the results for mass measurements will be improved.

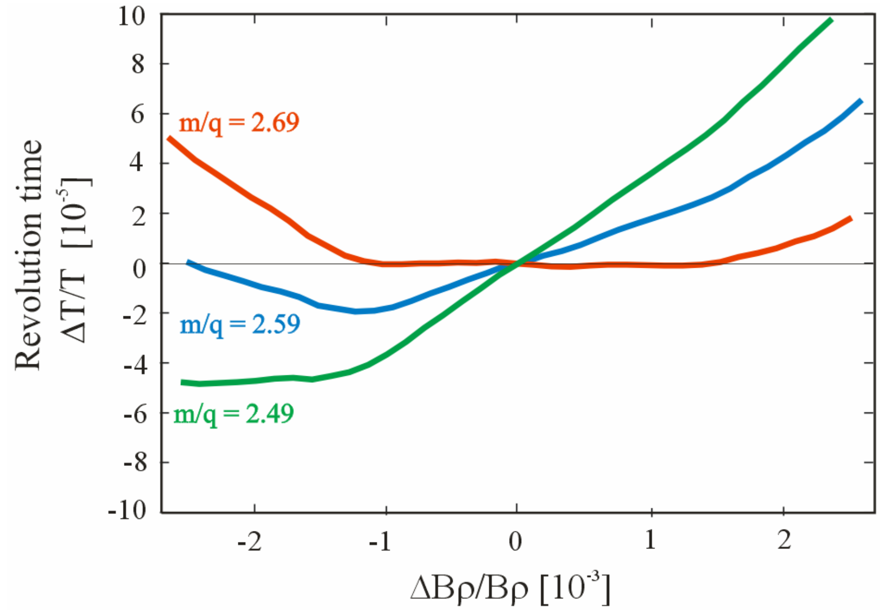


*Figure 4: Measured relative deviation in revolution time in the ESR as a function of magnetic rigidity from ref. [11]. The measured curve was transformed for different m/q ratios. Ions of different m/q have different average time-of-flight but were shifted for better comparison of the relative deviation ΔT/T. Note, only for one m/q ratio the ring can be exactly isochronous.*

The measured magnetic rigidity values do not need to be as precise as the mass resolution. A value of a few times $10^{-4}$ would be sufficient. There are three different methods suggested and will be investigated in detail:

- velocity measurement from the exit of the Super-FRS over the transfer beam line to the TOF detector in the CR. If only a few ions are injected, single ions can be detected with a segmented particle detector even on the short time scale of fast extracted beams (~100 ns);
- velocity measurement in the CR with two TOF detectors. (The same detector cannot be used twice as the ring is isochronous by intention). Two detectors with a distance of at least ~10m on a straight section are required;
- Bρ measurement in the CR with two foil detectors. One is the usual TOF detector and the other one would be placed in one of the dispersive arcs. The Bρ measured by position over just one revolution would not be precise as it also depends on the betatron oscillation of the beam. This contribution from betatron oscillations can be subtracted if the measurements are performed over many revolutions. Thus, only the constant dispersive contribution to the position can be extracted.

The most favored solution presently is a second time-of-flight detector. The two detectors need to be at positions in the ring between which the ring is not isochronous. Only then the velocity can be measured. At best, the detectors are located on two ends of a straight section. The distance in this case is about 30 m. The time-resolution of the present TOF detector was determined experimentally in the ESR and amounts to about $\Delta T$=50 ps [11]. This corresponds to a resolution of $\Delta v/v = 0.7\text{x}10^{-3}$, which is improved by observing an ion over many turns, e.g. to about $\Delta v/v = 3\text{x}10^{-5}$ after 50 revolutions taking into account the limited efficiency of the detector (see section 1.3.1). As the mass value from theory is usually known to about one order of magnitude better, the uncertainty in velocity determines the Bρ accuracy. At $\gamma$=1.84 the relative error of magnetic rigidity becomes $\Delta B\rho/B\rho = 1.0\text{x}10^{-4}$. It is noteworthy that the energy loss of $^{238}$U ions in two foils of 20 μg/cm$^2$ each leads only to a shift in Bρ of $1.4\text{x}10^{-4}$ over 50 turns. That means that also the energy loss in the foils could be traced.

The possibility to install a second TOF detector in the present ESR will also be investigated.

## 1.1.4 Production and Study of Pure Isomeric Beams

The combination of the Super-FRS with storage rings will provide access to pure isomeric beams. Already with the present FRS, the Bρ-ΔE-Bρ separation method provides monoisotopic beams in the storage ring ESR as illustrated in Figure 5 [12]. In the left panel of this figure a Schottky spectrum is shown for the case that the FRS is operated as a pure magnetic-rigidity analyzer. Applying the energy-loss separation with shaped degraders leads to a pure monoisotopic beam of $^{52}$Mn circulating in the ESR (right panel).

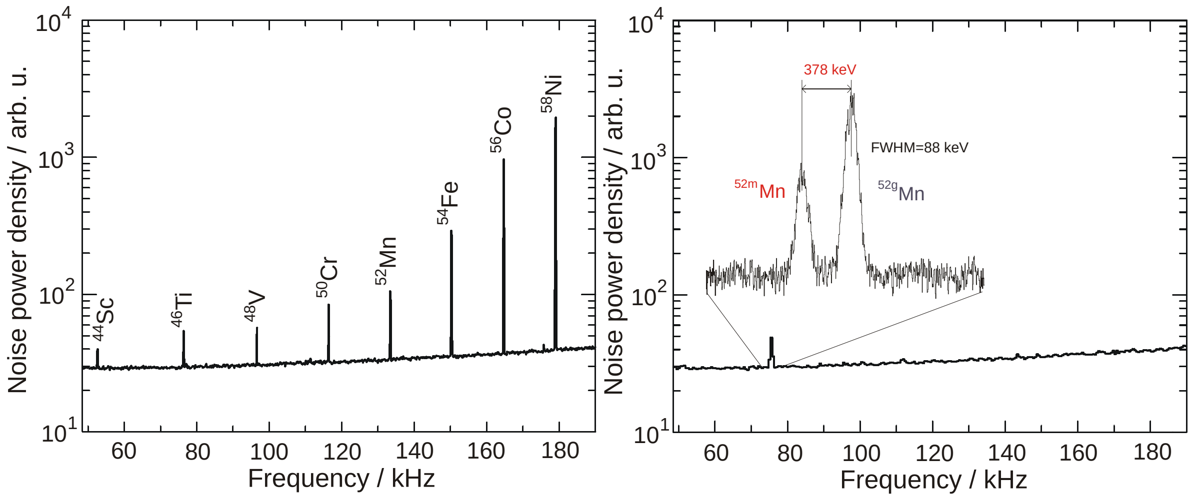


*Figure 5: Schottky spectra of stored and cooled fragments in the ESR. Left panel, the FRS is used as a magnetic-rigidity analyzer resulting in an isotope-cocktail beam in the storage ring whereas the Bρ-ΔE-Bρ separation method provides monoisotopic beams as demonstrated for $^{52}$Mn ions. The stored $^{52}$Mn ions consist of nuclei in the ground and isomeric states which are resolved by SMS, see zoomed part in the right panel [12].*

It is shown in Figure 5 that it is possible to observe ground and isomeric states. In the $^{52}$Mn case the excitation energy of the isomeric state is merely 378 keV.
Three methods can in principle be used to remove the ions in the ground state:

- first, one could try to use the mechanical scrapers installed inside the ring aperture to remove the ground state. This could be done at a dispersive plane in the NESR. Instead of using the scrapers mechanically also the beam energy can be moved with the help of the electron cooler. However, the separation of ground and isomeric states in space would be only 0.5 mm in case of an excitation energy of 10 MeV for mass number 100. The emittance of a high intensity beam of about 0.1 mm mrad and a corresponding beam diameter of 2 mm would not allow separation without intensity losses of the isomeric beam;
- a more promising variant is to use in addition a narrow HF resonant excitation of the motion of the ground state ions thus introducing a velocity shift. This would magnify the separation and would allow separation by scrapers. This has to be investigated in details. This method is still fast and the access to the pure isomeric beams could be achieved within a few seconds;
- thirdly, if the half-life of the isomeric state is significantly longer than the half-life of the ground state and, if it decays predominantly via beta channel, then the purification is easy to achieve by storing the beam till the ground state decays completely. Moreover, the charge-state selection of the incident ions can be used to influence their decay-properties [3,4].

The third way is straightforward and the most reliable. The scheme of production of pure isomeric beams starts with the Super-FRS whose specially configured degrader system allows to separate monoisotopic beams containing ground and isomeric states of specific nuclide. This mixed beam can be delivered to the CR and cooled there. The CR or RESR can operate as a purification trap

where the mixed beam will circulate until the short-lived component has completely decayed. Then this pure monoisomeric beam can be injected into the NESR, additionally cooled and used as monoenergetic relativistic pure isomeric beam for studies of nuclear reactions in the internal target or for investigations in the electron/antiproton heavy-ion colliders.
Indeed, at least a dozen of cases can be selected for which the beams of high-spin isomeric states can be purified relatively easily (see Table 1). A similar separation can be carried out for high-spin ground states (here the isomeric state must be rather short-lived). The mostly prominent candidates from Table 1 are $^{211m}$Po(25 s, 25/2) and $^{212m}$Po(45 s, 18). An even longer list could be produced for the lower heavy ion luminosities required for the antiproton heavy-ion collider.

*Table 1: List of nuclides and their half-lives, for which the isomeric state can be separated by waiting. The spin of the separated beam (I) is also given. The rate of produced nuclides is given at the exit of the production target per spill. The possible duty cycle is determined by the waiting time corresponding to $1x10^{-3}$ of the initial ground state intensity. A gain proportional to the lifetime of the isomeric state can be achieved by accumulating the beam in the NESR. Losses due to the thick degraders in the Super-FRS were taken into account and the luminosity refers to a $10^{14}$ atoms/cm$^2$ hydrogen target and an isomeric beam at 740 MeV/u. An initial isomeric ratio of 10% was assumed and a cut-off for the maximum intensity at $2x10^{28}$ cm$^{-2}$ s$^{-1}$ was introduced.*

| nuclide | $T_{1/2}$ isomeric state | $T_{1/2}$ ground state | I | prod. rate [1/spill] | luminosity [cm$^{-2}$ s$^{-1}$] |
|---|---|---|---|---|---|
| $^{42m}$Sc | 62 s | 0.6 s | 7 | $1x10^9$ | $1x10^{28}$ |
| $^{50m}$Mn | 1.7 min | 0.3 s | 5 | $1x10^9$ | $2x10^{28}$ |
| $^{54m}$Co | 1.5 min | 0.2 s | 7 | $7x10^8$ | $2x10^{28}$ |
| $^{82m}$Rb | 6.2 h | 72 s | 5 | $4x10^9$ | $1x10^{26}$ |
| $^{122m}$Cs | 4.5 min | 21 s | 8 | $6x10^8$ | $1x10^{25}$ |
| $^{140m}$Pm | 6 min | 9.2 s | 7 | $4x10^9$ | $8x10^{26}$ |
| $^{142m}$Eu | 1.2 min | 2.3 s | 8 | $1x10^9$ | $9x10^{26}$ |
| $^{211m}$Po | 25 s | 0.5 s | 25/2 | $1x10^7$ | $5x10^{25}$ |
| $^{212m}$Po | 45 s | 0.3 μs | 18 | $1x10^7$ | $2x10^{27}$ |

### 1.2 Sub Project: Schottky Pick-ups

At the ESR, the particle detection by means of Schottky-noise Fast-Fourier-Transform (FFT) frequency-measurements has been established as a versatile tool for non-destructive non-instantaneous mass and lifetime measurements. Some of the unique features of the method are:

- the detection is non-destructive. All detected ions circulate freely during the measurement;
- the detector itself cannot be destructed by the ions. The electronics is also shielded and, thus, radiation hard;
- the amplified signals are tiny and cannot be instantaneously distinguished from the noise of the electronics. The analysis of the noise by applying FFT allows one to extract the time-correlated harmonic contents into a frequency spectrum that exhibits the fundamental as well as the higher harmonics of the stored beam revolution frequencies;
- the dynamic range of the detected particle intensities is extremely high. Ion intensities as high as $2x10^8$ as well as low as a few particles can be detected by the same detector simultaneously;
- the method is very sensitive. Single fully ionized heavy ions with $Z > 30$ have been detected [5,6];
- the power-spectrum frequency peak area is proportional to the charge squared and to the number of stored ions. This allows for half-life measurements as well.
- A very broad band of magnetic rigidities can be detected simultaneously;

- The achieved resolving power of $2 \times 10^6$ [5,6] gives a very comfortable safety margin for future optimizations of the detection time versus frequency resolution.

The Schottky pick-ups will be installed in the CR and the NESR rings. Since, the nuclides with the shortest half-life will be studied in the CR, the corresponding pick-ups have to be as fast as possible. In the ESR experiments presently, 10 s of measurement time is needed to identify a single stored medium-Z ion. Thus, the improvements of a single pick-up design as well as the multiple-pick-up operation will be investigated to reduce the measurement time. These improvements are described below.

**Multiple pick-up operation**

The method is not instantaneous, and the time needed to gather one record is given by the Fourier relation, i.e. two frequencies can be distinguished after a time proportional to the inverse of their difference. An average of *n* records (with *n* being an integer greater than zero) improves the signal-to-noise ratio by a square root of *n* if the signals occur in all *n* records with the same strength. Presently at ESR, 10 seconds were needed to accumulate and average 100 records of about 0.1 seconds each (i.e. one FFT data point corresponds to about 10 Hz) in order to detect a single medium-Z particle with a signal-to-noise ratio of about 4 to 1.

For short-lived nuclides, the time needed for one record can be reduced not only by lowering the frequency resolution, but also by working at even higher harmonics of the revolution frequency ($\Delta f/f$ = const) and/or by operating several Schottky pick-ups with correlated readouts. This correlated readout of ***N*** pick-ups (presently suggested are 4 pick-ups in the CR and 8 pick-ups in the NESR) will either improve the signal-to-noise ratio by a factor of $\sqrt{N}$ (or $\sqrt{4}$ and $\sqrt{8}$, respectively) or it will shorten the time needed to detect a particle by the same factors. Additionally, the correlated readout is mandatory for very high harmonics, where the spread in the revolution frequencies of particles filling the NESR aperture is larger than the frequency difference between neighboring harmonics. In such a case, one pick-up will work at a lower harmonic, where the aforementioned frequency overlap does not take place. The correlated readout of the low harmonics pick-up with the high harmonics would lead to an unambiguous assignment of the frequencies.

**Resonant Schottky pick-ups**

The aim of the resonant pickups is to increase the sensitivity and by this to reduce the measurement time. For the CR in the isochronous mode, the ring is operated with ions at $\gamma = \gamma_t = 1.84$, and the relation between frequencies and masses is (assuming the required mass accuracy of about $\Delta m/m \approx 5 \cdot 10^{-7}$)

$$\frac{\delta f}{f_0} = \frac{1}{\gamma_t^2}\frac{\delta m}{m} \approx 1.5 \cdot 10^{-7} .$$

Due to the Nyquist theorem, the minimum measurement time needed to reach this resolution is approximately

$$\delta t \approx \frac{2.5}{\delta f} \approx \frac{1.7 \cdot 10^{7}}{f_0} .$$

In order to make the measurement time as short as possible, it is therefore desirable to choose the operating frequency $f_0$ as large as possible. A good choice of the operating frequency seems to be a frequency which is lower than the cut-off frequency of the vacuum chamber by a certain safety margin. Frequencies of roughly 400 MHz should therefore be chosen, leading to $\delta t \approx 42$ ms. This would allow the measurement of nuclear masses with lifetimes of the same duration.

It should be noted that in the NESR the measurement time would be larger by a factor of about 10, as the NESR is operated at $\gamma_t = 5.79$. However, this is not very disturbing, as the time needed to measure masses in the NESR is mainly determined by the time for stochastic pre-cooling and subsequent electron cooling, which is of the order of a second.

Prior to the actual cavity design a comprehensive signal analysis as well as detailed field calculations of the quality factor and the shunt impedance are indispensable.

**Design**

The pick-up can be built in the form of a resonator, e.g. as a pillbox cavity. The cavity should be loaded critically, such that the loaded quality factor (*Q)* should be one half of the unloaded *Q*. Cavity resonators of this type with copper as a conducting surface can attain *Q* values of 1000 or larger.

The range of nuclear masses (spectrum bandwidth) which can be observed simultaneously is determined by the loaded *Q* value and the $\gamma_t$ value, as well:

$$\frac{\Delta m}{m} \approx \frac{\gamma_t^2}{Q_{loaded}} .$$

Hence the final choice of the loaded *Q* depends on a critical evaluation of the pros and cons of a high signal-to-noise ratio and the simultaneously observable mass range.

In order to maximize the signal-to-noise ratio, it will be examined whether cryogenic temperatures are needed to operate the device. Cooling of the pickups would reduce the noise level. The equivalent noise temperature of the first preamplifier must not exceed this value. This would require a nitrogen distribution system. How this is possible inside the CR (NESR) beam pipe will be investigated. Basically, the cryogenic installations are available for the superconducting magnets.

Another boundary condition (at least in the NESR) is due to the fact, that a resonant cavity is equivalent to a strong beam impedance, which can lead to instabilities for cooled high-intensity beams. The resonator must therefore be 'hidden' to the beam during other experiments when the Schottky pick-ups are not in use. Mechanical cavity closings will be used for this purpose.

The position and the geometry of the Schottky pick-ups cannot be defined before the details for ion optical elements of the CR and the NESR are known. Presently, the plans are to investigate both a resonant pick-up with a very high quality factor as well as multiple pick-ups, positioned at the entrance of the dipole magnets in the NESR, where they would not hamper other experiments. The smaller vertical aperture—70 mm—is of advantage since it leads to shorter and more sensitive pickups. The pickups can be subdivided in four horizontal parts which—when furnished with individual readouts—will allow for some spatial resolution as well. For optimization, a close collaboration with the NESR project group was established.

**Costs**

The costs for the Schottky pick-ups are listed below in Table 2.

*Table 2: Costs for Schottky pick-up detectors.*

| Item | costs per item / k€ | number | costs / k€ |
|---|---|---|---|
| Schottky pick-ups in the CR | 25 | 4 | 100 |
| Schottky pick-ups in the NESR | 25 | 8 | 200 |
| Cavity coupling | 10 | 12 | 120 |
| Cavity closings (mechanical) | 15 | 12 | 180 |
| Low-noise, broad-band amplifiers | 25 | 12 | 300 |
| | | Sum: | 900 |

During the design and construction phase of the resonant pick-ups one year FTE of a physicist or an electrical engineer and one year FTE of a construction engineer are required before placing an order to an external company.

### 1.3 Sub Project: Particle Detectors

#### 1.3.1 Time-of-Flight Detector

A special TOF detector will be designed to measure the revolution times within a few hundred microseconds for ions stored in the CR. For these measurements, the CR will be operated in the isochronous mode. Thus, nuclides with half-lives down to the microsecond range can be accessed, complementary to measurements of longer-lived nuclides with Schottky pick-ups. The design of the TOF detector will be based on the detector that is currently successfully used for IMS in the ESR. In this type of detector [13,14,15], ions pass through a thin foil and release secondary electrons on both sides of the foil. The electrons are transported isochronously by crossed electric and magnetic fields to two microchannel-plate (MCP) detectors. Since the energy loss of the ions in the foil of 50 to 100 keV is small compared to their kinetic energy of several 100 A MeV, it is possible to observe more than a few thousands revolutions of the ions before the ions leave the acceptance of the ring. The detector is sensitive to single particles. The signals created by the present detector are characterized by a rise-time of about 800 ps and a FWHM of about 1.5 ns. The time resolution of time-determination is about 50 ps and the detection efficiency ranges from 10% to almost 100%, depending on particle type and its energy.

**Simulations**

Simulations have been performed [16] to characterize the performance of the detector system, in particular to quantify limitations on the time resolution of the detector. It was found that the initial energy spread of the electrons released from the foil leads to a spread in arrival times at the MCP detectors of about 20 ps. A shift in the position of the MCP detector plane relative to the plane of the foil, which is required for proper operation of the detector system, also causes a spread in arrival times of 20 ps. This accounts for a part of the uncertainty of the time determination. Further simulations are required to investigate the effect of inhomogeneities in the electric and magnetic fields on the arrival time distribution of the secondary electrons and on the efficiency of electron transport.

**Radiation Hardness**

The TOF detector is operated with a very low number of particles in the ring (<100). In all other cases it is removed into a separated vacuum chamber. Therefore radiation hardness is not an issue.

**Design**

A scheme of the TOF detector, currently used in ESR-IMS measurements, is shown in Figure 6. A CsI-coated carbon foil (27 $\mu g/cm^2$) with a diameter of 40 mm is used to create the secondary electrons. The homogenous electric field is formed by a stack of potential plates. The magnetic field of about 0.01 T is created by an external dipole magnet. Two MCPs in chevron arrangement with an active diameter of 40 mm detect the secondary electrons.

Further developments are planned for the TOF measurements to improve the timing characteristics of the detector and its detection efficiency, to reduce the energy loss of the ions in the detector foil and to allow for an independent measurement of the velocity of the ions.

Improvements of the time resolution of the MCP detectors can be performed by optimization of the detector geometry and voltages, as well as by using MCPs with smaller channel sizes. MCP detectors with significantly smaller peak widths (FWHM of 600 ps) have already been built [17]. An increase in the MCP detector efficiency can be obtained if the burst of ions in the beginning of a new bunch is suppressed for a short time till the ions are lost which only make a few turns and do not reach stable orbits. Here, the detector foil could be pulsed by a positive potential during the first turns, which would prevent the secondary electrons from reaching the MCP detectors and causing saturation.

The energy loss of the ions due to the carbon foil could be reduced by the use of thinner carbon foils (strong laser ablated carbon foils down to 4 $\mu g/cm^2$ are available). Preliminary off-line tests with thinner carbon foils have yielded efficiencies in the range of 30% - 70% for 5.5 MeV alpha particles. For the placement of two TOF detectors in the CR (as outlined in 1.1.3) it would be advantageous to increase the active area of the detector from a circle with the diameter of 40 mm to an area of 40 mm x 100 mm. The overall size of the detector would increase proportionally. Developments will be made with the goal to implement such an increase in active area without significant loss in the timing performance. Additional measurement of $B\rho$ could be made using a position sensitive TOF detector. The electrons are already imaged to the channel plate. The anode must be adapted to provide the position distribution of the electrons.

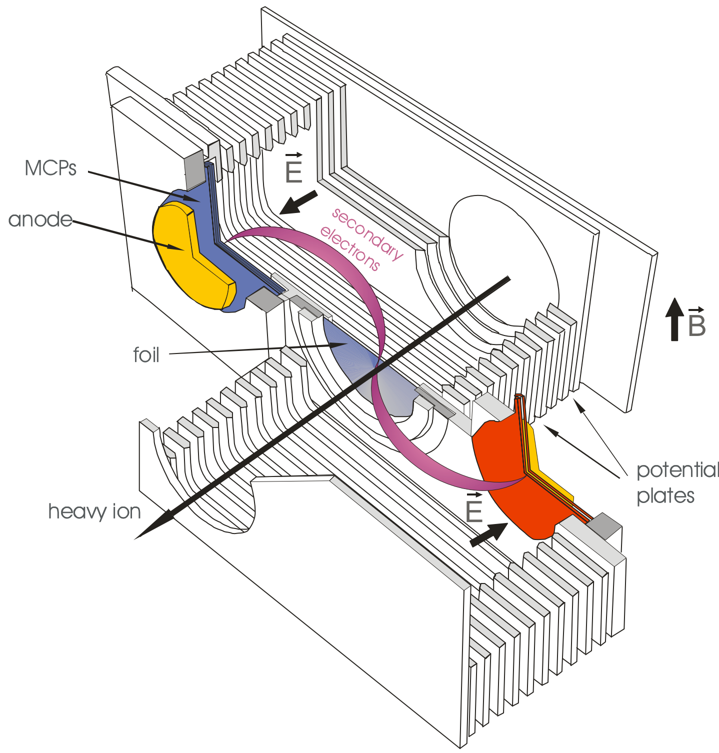


*Figure 6: Scheme of the TOF detector. Electrons released on both sides of the detector foil are isochronously transported to the two MCP detectors. The branch of the detector for detection of the electrons released in direction of the ion velocity is shown only partially.*

**Construction**

The construction of the TOF detector must be suitable for ultra-high vacuum. Stainless steel, aluminum based ceramics, and glass are suitable materials. The detector is bakeable up to 400 $^{0}$C. The dimensions of the current detector itself without connections and magnet are 350 mm x 170 mm x 90 mm. The dipole magnet is formed by two coils, which are located above and below the vacuum chamber. The voltages for the potential plates and the current for the coils are provided by computer-controlled power supplies. These construction characteristics will also be used for the TOF detectors in the CR.

**Costs**

The following cost estimate assumes that vacuum pumps and two magnets from the existing TOF detector in the ESR can be reused in the CR.

*Table 3: Costs for TOF detectors.*

| Item | costs per item / k€ | number | costs / k€ |
|---|---|---|---|
| Vacuum chamber, baking | 60 | 1 | 60 |
| Partially reused vacuum chamber | 20 | 1 | 20 |
| Magnets | 5 | 2 | 10 |
| Vacuum pumps, valves controllers | 90 | 1 | 90 |
| Detector, MCP | 25 | 2 | 50 |
| Electronics, power supplies | 25 | 2 | 50 |
| Slow control of HV and step motor | 2 | 2 | 4 |
| Scaffolding with adjustment | 2 | 2 | 4 |
| Cables for signals and control | 2 | 1 | 2 |
| | | sum: | 290 |

During the design and construction phase of the TOF detectors three year FTE of a physicist is required.

### 1.3.2 Decay Detectors

Already in the ESR particle detectors were used in coincidence with reaction studies in a gas jet. These detectors were placed behind dispersive magnetic fields to trace the ions which have changed their magnetic rigidity due to reactions in the internal target. Previously mainly atomic charge-exchange was investigated. An example in Figure 7 shows the separation and detection of uranium charge states [18] detected with a multi-wire proportional chamber (MWPC) after a charge-exchange reaction.

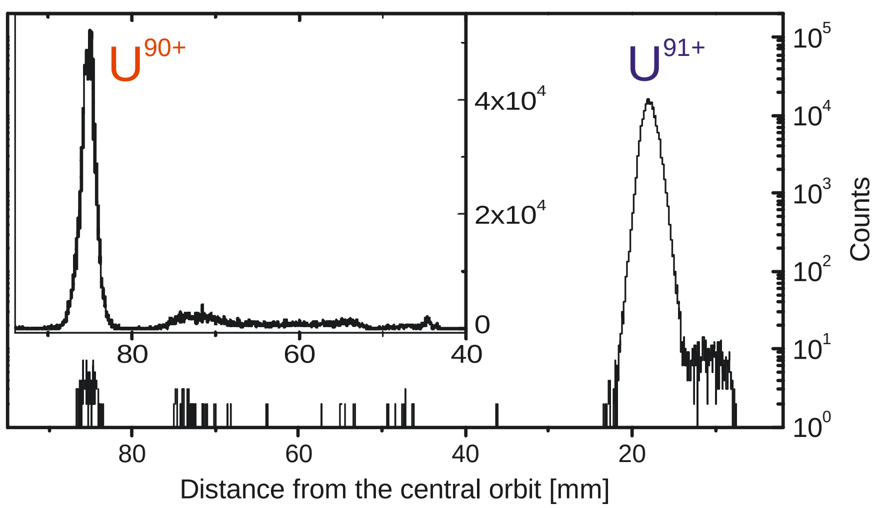


*Figure 7: Different Uranium charge states detected with a MWPC placed behind a dipole magnet of the ESR [18]. The main intensity was in the $91^+$ charge state. After some time operating the gas jet, the detector was moved and only the $90^+$ was detected, shown in the upper-left corner.*

The detection of the heavy ions can be used to investigate decay modes of the ions stored in the CR or NESR. The mass and charge after the reaction can be determined. Since the emittance of the cooled beam is practically not increased by beta decay and only little increased by alpha decay, the resolution can be quite high even though there is no dedicated spectrometer imaging. The properties and the setting of "the spectrometer" are defined by the ring parameters for stored ions. A simulation of the resolution was performed using the ion-optical code GICO [19] and the Monte-Carlo code MOCADI [20].

**Position of detectors**

The ions can decay anywhere on the straight section in front of the dipole magnet or even in the arc. Good separation can only be achieved for ions decaying on the straight section. As can be seen from the calculated trajectories in Figure 8, the full magnetic rigidity spread cannot pass through the whole arc of the NESR. Large Bρ deviations like charge change of a Ca beam, which changes the magnetic rigidity by 5%, must be detected earlier. Only ions with change in Δ(Bρ)/Bρ of less than 1.75% may pass the following quadrupoles.

As one can see from Figure 8 in principle many detector positions are necessary to cover the range of $\Delta Z = \pm 1$ for all elements. There are four arcs in the NESR where the detectors could be placed. However, it will not be possible to cover all of them with particle detectors. Other NUSTAR experiments plan similar detection (AIC, EXL and ELISe proposals). This means that the detector pockets after the gas target and after the electron/antiproton colliding zones can be used in common and even, to a large extent, the same detectors. Only the ILIMA project aims presently for the use of such detectors in the CR. For cost reasons the number of these detectors will be first restricted to two only.

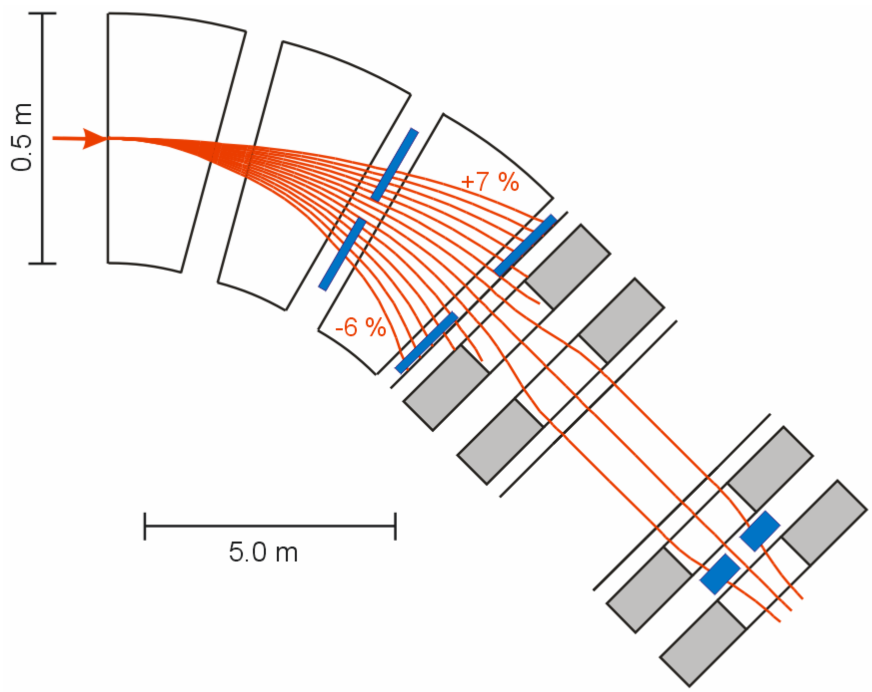


*Figure 8: Ions with different magnetic rigidities in the first half of the arc. Trajectories are shown in steps of 1% relative difference. In blue the positions of detectors are indicated.*

**Types of detectors (Si counters)**

The MWPC counters from the ESR could be reused in combination with detectors capable of particle identification. The momentum-to-charge determination by a position measurement alone does not allow background-free measurements as some fraction of the stored ions will decay not on the straight section but inside the dipoles and will be differently deflected and thus cause background.

This will be overcome by using Si counters and measuring energy deposition. The detector in a pocket may even be replaced by a stack of silicon counters at a position in between the dipoles. The pocket will be separated from the UHV region of the storage ring by a thin foil. As an example the detector stack for the ESR [21] is shown in Figure 9.

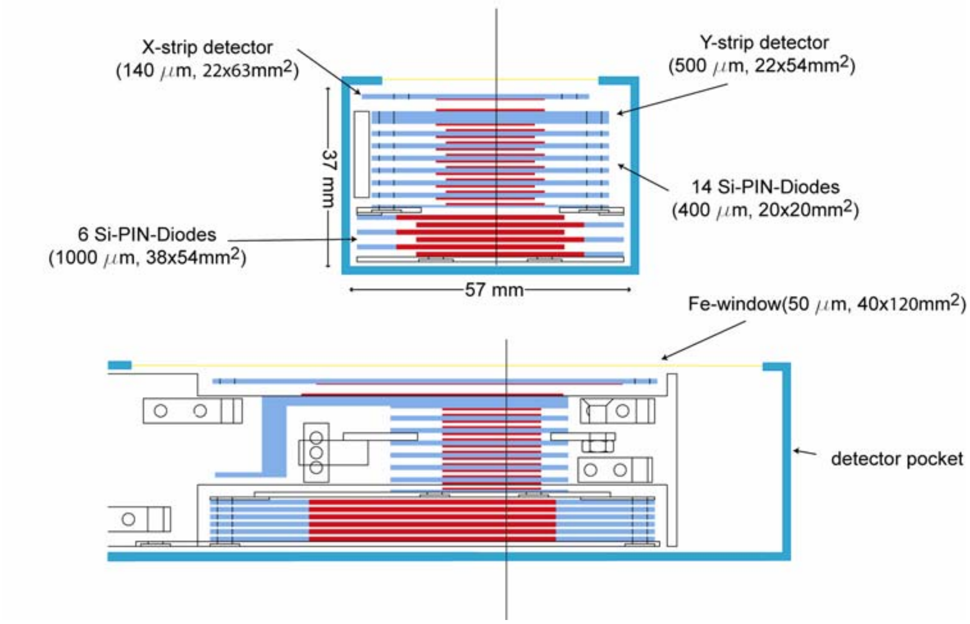


*Figure 9: Heavy ion detector developed for the ESR. Identification of heavy-ion reaction products is done via energy loss, and momentum determination. The latter is derived from the position measurement.*

The total range in Si of 740 MeV/u heavy ions is still small enough to fit such a detector into a narrow pocket. For example the range of 740 MeV/u $^{132}$Sn is 57 mm, in the case of $^{72}$Ni it would be 101 mm. Since this value is still large reducing the ion energy with a passive absorber will allow to measure the energy deposition at the end of the range without covering the whole track with Si detectors. This will yield unambiguous identification as shown in Figure 10 for $^{58}$Ni ions and some lighter isotopes and isotones at 740 MeV/u. A degrader of 21 g/cm$^2$ Fe was used to bring the ions close to the end of their range. The degrader will be composed of two movable wedges and thus can easily be varied in thickness.

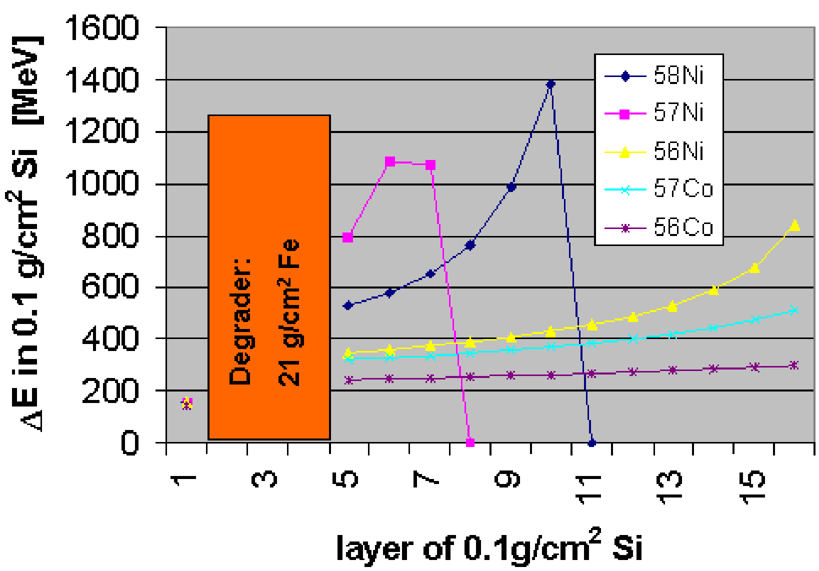


*Figure 10: Calculated energy deposition profiles as a function of the silicon layer. Energy losses of $^{58}$Ni ions and some lighter isotopes and isotones of 740·MeV/u in front and behind of a 21 g/cm$^2$ Fe degrader. The thickness of one Si layer corresponds to about 0.4 g/cm$^2$.*

A stack of several Si detectors (about 0.4 g/cm$^2$) would be sufficient to identify the ions and to determine their position. About 30% of the ions will be lost in the degrader due to secondary reactions. Therefore, a measurement of the energy loss before the degrader is also required, which will yield the identification of the nuclear charge Z of the ion.

**Rates, rate capability**

The rates on a certain detector depend on the number of injected particles. Behind the cooler they can be very high as atomic electron capture occurs at a much higher rate compared to nuclear decay. Detectors should therefore be placed only in the three other arcs. The resulting count rates are rather low, just sufficient to allow a good observation of decay characteristics. This would result in count rates of $10^4$/s at maximum.

**Costs**

The cost estimate below accounts for a scenario with 4 vacuum pockets alternatively used by 2 silicon detectors.

*Table 4: Costs for the decay detectors.*

| Item | costs per item / k€ | number | costs / k€ |
|---|---|---|---|
| Vacuum pockets with step motor | 20 | 4 | 80 |
| Si detectors with indiv. readout | 54 | 2 | 108 |
| | | sum: | 188 |

## 2. Data Acquisition and Analysis

### 2.1 Data Acquisition

The data acquisition systems for Schottky pick-ups in the CR and NESR can be designed based on the present experience. It must provide fast continuous sampling of the raw data and store them on-line. It is important to record the measured raw data without adding noise. Presently, the 30$^{th}$ harmonics with frequencies around 60 MHz are mixed with the fixed frequency of the local oscillator and shifted to the frequency range between zero and 300 kHz. This practically covers the momentum acceptance of the ESR. A 16-bit ADC samples the data with the double frequency. Thus, a data stream of 1.2 MB/s has to be handled. This leads to more than one TB ($10^{12}$ bytes) of data per 10 days of measurements. Presently, the system can work at the double sampling rate as well, and is, therefore, well suited for the CR and the NESR. The technical developments of the computing and storage power in the recent years allowed us to have an affordable system capable of handling and storing such an amount of raw data. It is safe to assume that the software and hardware capabilities of the electronics and computers in the near future will be even better, and that the correlated readout of multiple pick-ups (see section 1.2) will be affordable as well. The continuous recording of the raw data is an important step towards a versatile off-line data analysis that can be tailored to the lifetimes, to the envisaged precision, to the required sensitivity, and to a dedicated search of weak signals obscured by strong background peaks. The hardware and software improvements are subject of an R&D project that was recently initiated in close collaboration with the Division for Computing and Experimental Electronics at GSI. The list of possible improvements is given below:

- choice of the sampling frequency (10 MHz presently, 80 MHz are possible) of the ADCs, their dynamic range, and their local FIFOs. Feasibility of the detection and of the analysis with a set of less expensive linear ADCs by compensating the lower dynamics with higher sampling rates;

- timing & synchronization: (i) the GSI-Gerätebus as a time stamp distributor, (ii) commercially available GPS controlled modules, (iii) Timing standards, e.g. IRIG II, (iv) implementation of the planned Campus Standard System Time (CSST);
- choice of the frequency mixers, of the intermediate frequencies, and of the local frequency generators in order to improve the quality of the measurements and the quality of transmitted signals as well;
- the choice of the decimations, of the center frequencies, and of the digital filters depends strongly on the aforementioned parameters;
- the FFT of multiple arguments, phases, and phase shifts will be studied via modeling, simulations as well as via prototyping;
- the off-line data analysis will be refined not only with respect to the multitude of pick-ups. The digital frequency windowing in one of the pick-ups—e.g. FFT and $FFT^{-1}$ window conditions—has to be developed and studied as well;
- measurements of Schottky frequencies of small numbers of nuclei without cooling has to be developed as a new experimental method for measuring cross sections and momentum distributions (see e.g. the AIC proposal).

The data stream from the TOF detector is presently collected by a commercial digital oscilloscope (Tektronix TDS 7404) which has an analog bandwidth of 4 GHz, sampling rate of 20 GSamples/s (8 bit) and allows for a continuous measurement of up to about 2 ms. Data storage is done with a raid system. Future developments will certainly allow a higher data rate and more storage depth.

The count rate of the particle detectors is low and the data acquisition can be done using standard VME electronics.

## Costs

*Table 5: Costs for data acquisition systems.*

| Item | costs per item / k€ | number | costs / k€ |
|---|---|---|---|
| Data acquision for Schottky Pick-Ups | | | |
| Amplifiers | 1 | 12 | 12 |
| Remotely controlled tunable mixers | 10 | 12 | 120 |
| Remotely controlled frequency generators | 10 | 12 | 120 |
| Data acquisition, VME crate | 10 | 2 | 20 |
| ADCs | 1 | 72 | 72 |
| Cables, connectors, and such | 5 | 2 | 10 |
| Data storage | 15 | 1 | 15 |
| Data acquision for TOF detectors | | | |
| Data acquisition (Digital Oscilloscopes) | 60 | 2 | 120 |
| Data storage | 15 | 1 | 15 |
| Data acquision for decay detectors | | | |
| Data acquisition (VME crate, electronics) | 20 | 1 | 20 |

Sum: 524

## 2.2 Data Analysis and Evaluation

Special software has been developed for off-line Fourier transformation and particle identification of the recorded time stamps from the Schottky detectors. This software has to be extended for multiple pick-ups. Considering the large amount of data, automatic peak finding has to be established as a reliable method.
The software for IMS measurements has to be extended to account for the second TOF detector.

**Mass evaluation**

In each previous experiment on mass measurements with the present FRS-ESR a large area on the chart of nuclides was measured with high precision. Even larger areas are expected to be covered within the ILIMA project.
Each mass from the vast number of measured nuclides can be correlated to the masses of all the other nuclides. This is effectively done by the correlation matrix analysis [1,22]. Each mass value in this approach is automatically determined from all other masses present in the data set. The reliability of the analysis is increased with the increased number of included correlations. Reference masses in different charge states are used for the calibration. Since the reference mass values with their statistical and systematical uncertainties enter the correlation matrix, their values are not only corroborated but their errors might be reduced as well. The measured regions of the chart of nuclides usually overlap or will be linked by the new measurements. This means that the measured frequency (revolution time) relations can be combined thus improving the accuracy. This is a unique situation since nearly the entire chart of nuclides can be measured precisely with the two presently developed techniques.
Therefore, a mass evaluation system should be built up. This system must include all the measured frequency (revolution time) relations connected in the correlation matrix. Highly accurate reference masses will be extracted from the most recent Atomic Mass Evaluation (e.g. AME 2003 [9]) table. On the long run, the present AME evaluation procedure should be modified in such a way that the correlations from the ILIMA mass measurements are an integral part of the mass evaluation.

## 3. Beam/Target Requirements

The proposed experiments will require the Super-FRS, CR, RESR and NESR facilities. Fast extracted beams from the synchrotrons will be necessary in order to efficiently inject into the ring system. For experiments on mass and half-life measurements in the CR, we can accept beam pulses each few hundred milliseconds. These experiments can partially be done in parallel with an independent program in the NESR.
Experiments in the NESR will require beams to be delivered every few seconds or every few minutes dependent on the case and nuclei investigated.

## 4. Physics Performance

The physics performance can be estimated from the present experience.
In the SMS experiments a single stored ion is sufficient to determine its mass value with an accuracy of about $5x10^{-7}$, provided there exist reliable calibration masses. The corresponding number of ions for the IMS measurements amounts presently to about 100. This number will be improved after the implementation of the improvements of the TOF detector.
Although, the life-time of a single stored ion can be determined, the accuracy of the half-life determination depends on the total number of measured ions.
The obtained new mass and half-life values will provide new physics results on the locations of the drip-lines, the pathways of the astrophysical nucleosynthesis processes, etc.
The application of the three types of detectors for direct mass and lifetime measurements in the NESR and CR rings is summarized in Table 6. For the studies with pure isomeric beams the

detectors built for the in-ring reaction and scattering studies (see EXL, ELISE and AIC proposals) will be used in addition to the equipment listed.

*Table 6: Detectors needed for measurements of masses and lifetimes in the CR and NESR.*

| Detector | CR | | NESR | |
|---|---|---|---|---|
| | masses | lifetimes | masses | lifetimes |
| Time-of-flight | X | X | | |
| Schottky pick-ups | X | X | X | X |
| Decay detectors | | X | | X |

# C Implementation and Installation

## 1. Cave and Annex Facilities

Room for electronics of approximately 10 $m^2$ is needed inside the CR and NESR near to the detectors. For example a TOF detector requires one standard rack. Additional space is required to place a PC for instrument control. The overall control will be done from a control room where also the storage rings can be operated. The TOF detector itself and the separated vacuum chamber to remove the time-of-flight detector from the ring require an area of 2x4 $m^2$.
The data acquisition system for SMS will be placed outside the ring. Space for approximately two racks is needed.
The decay detectors in the vacuum pockets just require a possibility to access the beam line at these points for the mounting.
It is obvious that all new detector developments can be performed and tested with the present FRS-ESR facilities.

## 2. Detector –Machine Interface

### Vacuum and beam pipe

The ring itself must be operated under UHV. The NESR should reach pressures of $10^{-11}$mbar. The requirements are not so stringent for ILIMA experiments but still all components in vacuum must be bakeable at 400 °C.
The TOF detector will be mounted in a separate vacuum chamber connected to the CR, where it can be tested off-line. For on-line experiments, it can be moved to its position in the ring. The valve in between must be opened only after having reached good UHV conditions. The movement must be remote-controlled. The whole set-up occupies an area of 4 x 2 $m^2$ including space for maintenance. It will be bakeable and pumped by turbo-molecular and ion pumps. A similar solution for the placement of the TOF detector is being used successfully for IMS measurements in the ESR. The present scheme is shown in Figure 11. Critical for implementation is the space needed in the ring beam line. The detector itself requires only 20 cm in the beam direction but the surrounding magnet requires about 0.5 m. To fit two such detectors in the CR, probably no separate vacuum chamber can be used. It must be combined with other instrumentation in order to save space.
The decay detectors are placed inside the pockets and are separated from the UHV by a window of 25 μm titanium. This means that the pockets can be baked and the detectors can be inserted later. This technique is also used at the ESR.
The Schottky pick-ups are installed permanently in UHV. The resonant cavities will be equipped with closings to avoid their influence on the stored beams when they are not in operation.

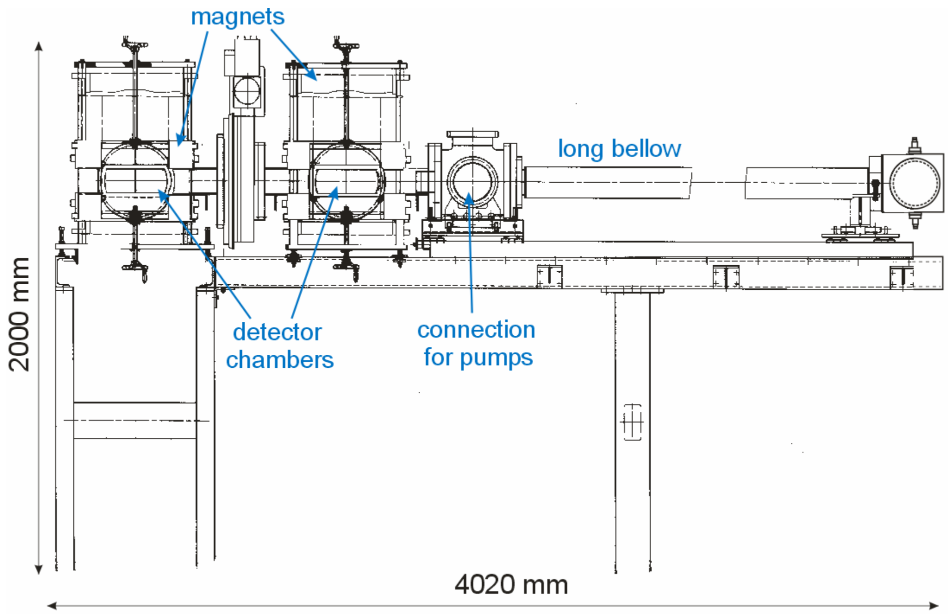


*Figure 11: Setup for the TOF detector in the ESR. The left detector chamber is in the ring beam-line and the right one is used for off-line testing. Therefore, also two magnets are used. To a third chamber a turbo and an ion-getter pump are connected. For moving the detector in and out of the beam line a long bellow is needed.*

**Target, in-beam monitors, in-beam detectors**

For tuning the beam in the ring, beam diagnostics such as profile grids and position probes are necessary in the same way as it is required by other experiments. Also slits inside the ring (scrapers) have proven to be helpful for separation of unwanted species and collimation in front of detectors. The standard beam transformers will measure the current of the stored beam.

**Timing**

Timing is a very important issue for the planned ILIMA experiments. Precise synchronization of the many detectors is essential. Our needs require a new development as described above for the case of the operation with multiple Schottky pick-ups.

**Radiation environment and shielding**

The radiation on the detectors during ILIMA experiments is very low. The intensity on the particle counters is anyway limited by the count rate and Schottky detectors are not beam destructive. Sensitive detectors will be removed from the beam to a shielded position during other experiments.

### 3. Assembly and Installation

The TOF detector will be assembled and tested off-line in Justus-Liebig University of Giessen, and will then be transported to the FAIR facility. Here it can be tested again in a separated chamber off-line with LASER pulses and alpha sources.

The Schottky detectors, vacuum chamber for the TOF detector and vacuum pockets will be installed during the construction of the storage rings. The pockets themselves can be filled later.

The decay implantation detectors may be tested with radioactive beams at the existing fragment separator (FRS).

## D Commissioning

Alignment of the detectors has to be done during construction of the storage rings and may be checked later like for the other parts of the ring beam-line. However, the requirements are not so stringent, as e.g. for the storage-ring magnets.

A major effort will be the commissioning of the isochronous mode of the CR. The revolution frequency for ions with different initial momenta and angles has to be investigated and the higher order optical elements will have to be adjusted.

## E Operation

ILIMA experiments use the radioactive ion beams provided by the Super-FRS. Already the planning of experiments requires a detailed knowledge about the operation of the Super-FRS. This will be even more the case during experiments. The same holds for the operation of storage rings. In the past the operation of the FRS-ESR was achieved by having the FRS and ESR experts as an integral part of the experimental collaboration. The ILIMA collaboration is organized in the same way.
The difference, however, will be that the experiments in future will be more complex and there are also more facilities to be operated. As a consequence it will be necessary to form a research team with the accelerator specialists for all experiments.

The power consumption for ILIMA experiments is completely dominated by the power needed for Super-FRS and CR/NESR operation. The experiment itself requires only normal 230V, 16A connections. Whether cooling by liquid nitrogen will be applied is still an open issue.

## F Safety

The general safety considerations are the same as for any operation of the CR or NESR.
No inflamable gases will be used in detectors.
High voltage of several kV will be necessary.
The radiation cannot exceed the level of $10^9$ uranium per second which is foreseen as an upper limit for radiation shielding to the outside. For most of the experiments much lower intensities are required and only the production of isomeric beams might run with up to $10^8$ ions per second.

## G Organization and Responsibilities, Planning

### 1. Organization

The organizational structure of the ILIMA collaboration was approved at the meeting on September 2, 2004. The working-group structure, the working packages, tasks and responsibilities have been introduced in this meeting. The organigram of ILIMA was made such that it fits to the general structure of NUSTAR.

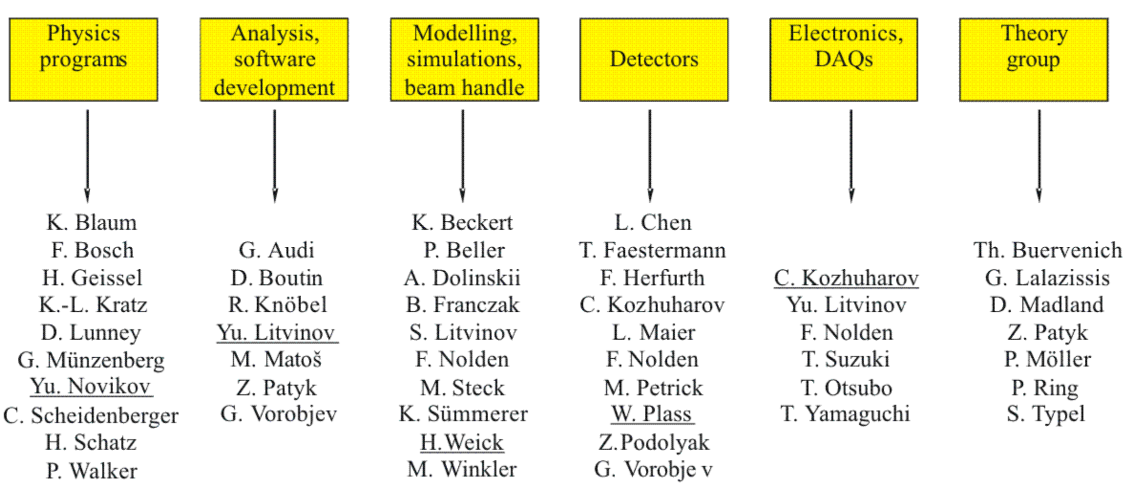


*Figure 12: Work packages defined in the ILIMA project and the members of the working groups.*

The working groups are shown in Figure 12. Some of them ("modeling etc.", "detectors", "electronics, DAQs," "software development") join the common NUSTAR groups. The groups of "physics program" and "theory" are responsible for the development of the scientific program of the investigations. The contact persons of the groups underlined will represent the ILIMA in the corresponding NUSTAR working groups. A writing group was defined and is responsible for preparation and presentation of this technical proposal. This group consists of: H. Weick, H. Geissel, C. Kozhuharov, Yu. Litvinov, F. Nolden, Yu. Novikov and W. Plass.

A more detailed list of the tasks for the implementation of the proposed program is given in Table 7.

*Table 7: Tasks and responsibilities.*

| Task | Group | Contacts |
|---|---|---|
| Key experiments:<br>- mass measurements<br>- life-time measurements<br>- isomeric beams | St. Petersburg NPI<br>GSI<br>JLU Giessen<br>MSU<br>JGU Mainz<br>TU München<br>Uni. Surrey<br>CSNSM Orsay | Yu.N. Novikov<br>Yu.A. Litvinov, H. Geissel<br>W. Plaß<br>H. Schatz<br>K.-L. Kratz<br>T. Faestermann, P. Kienle<br>P.M. Walker<br>D. Lunney |
| Coupling of the Super-FRS with the CR and NESR | GSI | H. Weick, A. Dolinski, P. Beller, S.A. Litvinov |
| Stochastic cooling in CR | GSI | F. Nolden |
| Electron cooling in NESR | GSI | M. Steck |
| Time-Of-Flight detectors | JLU Giessen<br>St. Petersburg NPI | W. Plaß<br>G.K. Vorobjev |
| Decay detectors | TU München<br>St. Petersburg NPI | T. Faestermann<br>D.M. Seliverstov |
| Resonant Schottky pick-ups | GSI<br><br>JLU Giessen | C. Kozhuharov, Yu.A. Litvinov, F.Nolden<br>L. Chen |
| Software development | GSI<br>St. Petersburg NPI<br>SINS Warsaw<br>Uni. Saitama<br>Uni. Niigata | C. Kozhuharov, Yu.A. Litvinov<br>G.K. Vorobjev<br>Z. Patyk<br>T. Yamaguchi<br>T. Ohtsubo |
| DAQ systems for Schottky pick-ups and data storage | GSI<br>JLU Giessen | C. Kozhuharov, Yu.A. Litvinov<br>L. Chen |
| DAQ systems for TOF detectors and data storage | JLU Giessen<br>GSI | W. Plaß<br>C. Kozhuharov |
| Theory:<br>- Interpretation of data<br>- New predictions<br>- Improvement of theoretical models | GSI<br>MPI Heidelberg<br>Los Alamos NL<br>SINS Warsaw<br>TU München<br>Uni. Thessaloniki | S. Typel<br>Th. Bürvenich<br>D. Madland<br>Z. Patyk<br>P. Ring<br>G.A. Lalazissis |
| Mass evaluation | CSNSM Orsay | G. Audi |

It was suggested that the ILIMA collaboration makes use of the present FRS-ESR facilities to develop the tools for the future scientific program. This is important to ensure that technical developments will be done in the coming few years despite of a dense experimental schedule at the

ESR. It also provides the possibility for students to work on the technical developments of the new project and still obtain new physical results.

The ILIMA spokesperson and the ILIMA project manager were elected and their responsibilities were defined:

**The spokes person** is responsible for the coordination of:

- the general development of the project;
- the research program;
- the transition of the current developments into the future;
- the money expenses within the framework of the project;
- the activities of different working groups;
- the contacts with other FAIR projects;
- the collaboration meetings.

**The project manager** is responsible for the coordination of:

- the current activities of the working technical groups;
- the preparation of technical documents;
- the money expenses for the technical parts of the project.

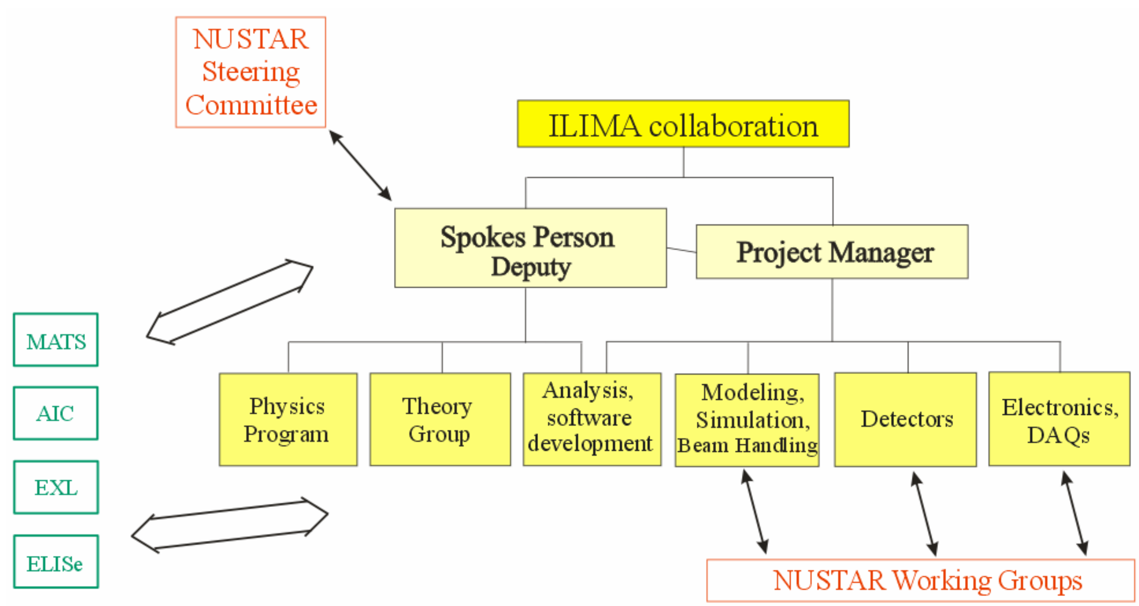


*Figure 13: Organigram illustrating the structure of organization.*

## 2. Planning and Cost Estimations

**Costs**

The breakdown of the costs was presented in the sections on the individual sub-projects. A summary is given below:

*Table 8: Costs for the sub projects.*

| Task/Milestone | Cost estimate / k€ | FTE required |
|---|---|---|
| Adjustment of the ion-optical parameters of the CR for the isochronous mode | | 1.5 |
| Technical Design Report | | |
| Schottky pick-ups | 900 | 3.25 |
| Time-of-flight detectors | 290 | 3 |
| Decay detectors | 188 | 1.75 |
| Data acquisition systems | 524 | 2 |
| Software development | | 1 |
| | Total: 1902 k€ | 12.5 FTE years |

**Time schedule**

We plan to extend the possibilities of the present detectors. This requires some years of research and development. In principle, the time until the construction of the storage rings should be sufficient. Certain parameters need to be fixed sooner as the ion-optical design of the CR and NESR has to be frozen by the end of 2006. Other ring parameters have to be decided in the technical design report by the end of 2007. At that time still some research on the ILIMA detectors will be in progress as they cannot be finalized years before the first usage. The time span for the individual tasks is shown in Figure 14. Nevertheless, the detectors will be designed and assembled before the building of the new storage rings. Moreover, they will be tested in the existing ESR. The detectors are small in size and will be mounted inside the new rings during their construction.

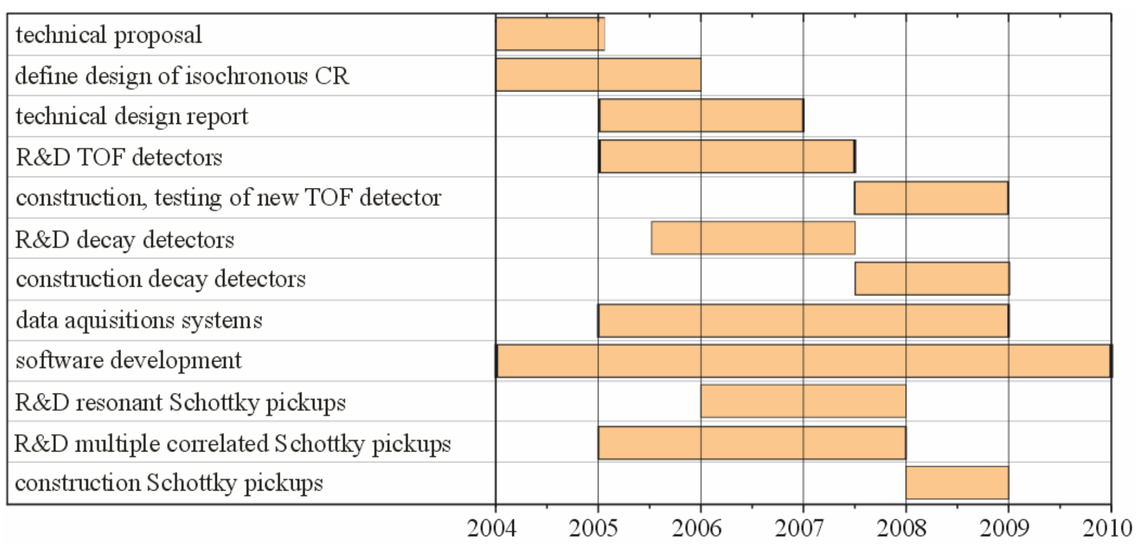


*Figure 14: Time schedule for the ILIMA sub projects.*

The advantage of the ILIMA project is the possibility to perform all main experiments already in full scale in Phase I of the FAIR project. The measurements with short-lived nuclides will be possible with IMS directly after the commissioning of the CR and the Super-FRS. In Phase II with increasing projectile intensity, we will stepwise proceed towards the drip-lines.

## H Relation to other Projects

The program of the ILIMA project has close relations to other NUSTAR projects: MATS, EXL, AIC and ELISe.

The MATS project is dedicated to mass measurements of exotic nuclides with precision which can exceed the IMS and SMS precision. However, the areas on the chart of the nuclides which can be covered by this installation will be smaller than the vast areas accessible to ILIMA with a couple of Super-FRS and storage rings settings. The accurate MATS measurements can be used as excellent reference values for the calibration of the ILIMA frequency and TOF spectra.

The EXL and ELISe projects can favorably consider the use of the pure isomeric, high-spin beams that can be produced with ILIMA. These unique monoenergetic relativistic intensive beams can be used for reactions on the internal targets at the NESR within the framework of the EXL program and for scattering experiments of the ELISe project at the electron collider or AIC for antiproton collisions.

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