# STORAGE RINGS FOR FAST COOLING OF ANTIPROTON AND RADIOACTIVE ION BEAMS

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*Abstract*

Production, fast cooling, and accumulation of intense secondary beams, antiprotons and rare isotopes, are key issues of the new accelerator facility proposed for GSI. Single primary bunches of $2\times10^{13}$ protons at 29 GeV and $1\times10^{12}$ $U^{28+}$-ions at 1 GeV/u shall be delivered from the new, fast-ramped 100 Tm-synchrotron SIS100. A large acceptance, reversible polarity collector ring CR is foreseen for fast RF debunching followed by fast stochastic pre-cooling in all phase planes. The envisaged total pre-cooling times are 4-5 s for 3 GeV antiprotons and 0.5-1 s for fully stripped RI at 740 MeV/u. Stochastic accumulation of antiprotons shall be made in a separate accumulator ring RESR. The RI beams are transferred to a New Experimental Storage Ring NESR, where electron cooling (EC) is applied simultaneously to internal target experiments. For experiments with antiprotons, a special 50 Tm storage ring HESR shall be equipped with internal target and EC up to 15 GeV, optionally also with stochastic cooling. The HESR design aims at a maximum luminosity of $2\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and at 100 keV energy resolution at lower luminosity. Basic design issues for the storage ring complex and results of numerical simulations of cooling rates and equilibrium beam properties are discussed.

## 1 OVERVIEW TO NEW FACILITY

The conceptual design report for an "International Accelerator Facility for Beams of Ions and Antiprotons" [1] on the GSI site was presented in autumn 2001. The proposal was evaluated in 2002 among other proposals for large-scale research instruments by the federal Research Council, which gave a fairly positive recommendation in favor of the GSI-proposal. In a press release of February 9, 2003, the federal research minister (BMBF) gave 'green light' for the preparation of the 675 M€ project a quarter of which has to be contributed by international partners.

The proposed accelerator complex (see fig. 1) may be characterized by following major scientific objectives:

- Nuclear structure physics with rare isotope beams (RI beams) at high mean intensities for external target experiments and high peak intensities for internal target experiments with cooled beams of short-lived nuclei.
- Nuclear collision experiments investigating compressed baryonic matter with heavy projectiles up to $^{238}U^{92+}$ at specific projectile energies up to 34 GeV/u.
- Internal target experiments with cooled antiproton beams at luminosities up to $2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for investigations of exotic hadronic states with high resolution.
- Atomic physics experiments with high-*Z* ions in a wide energy range up to relativistic energies.
- Plasma physics experiments investigating evolution and properties of hot, dense plasmas generated by means of intense heavy ion beam pulses.

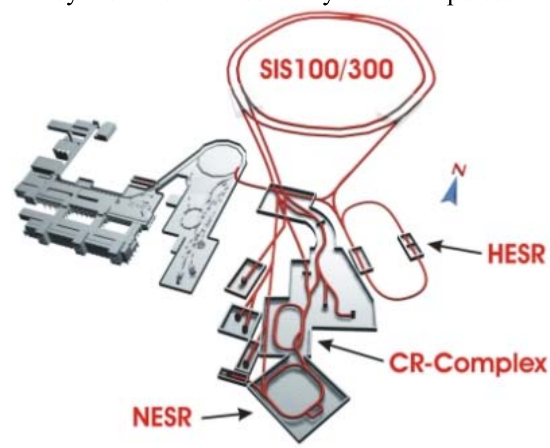



Figure 1: Preliminary layout of the proposed accelerator/storage ring facility at GSI (see text below).

The layout of the proposed accelerator/storage ring complex is shown in figure 1. The existing UNILAC-SIS18 accelerators (left side) shall serve as injectors, supplemented by a 50 MeV proton linac for antiproton production. The fast-cycling 100 Tm-synchrotron SIS100 [2], equipped with super-ferric 2 T-dipoles (ramp rate 4 T/s), will accelerate $1\times10^{12}$ $U^{28+}$-ions per cycle for RI production at 1-2.7 GeV/u and $2\times10^{13}$ protons per cycle for antiproton production at 29 GeV. The high beam intensities per SIS100 cycle are obtained by means of multi-turn filling the SIS18 up to the space charge limit at injection energy (11.5 MeV/u for heavy ions and 50 MeV for protons) and by accumulating 4 to 5 SIS18 cycles in the correspondingly larger SIS100 ring. The super-conducting 300 Tm-SIS300, installed in the same ring tunnel, will be used to accelerate about $1\times10^{10}$ $U^{92+}$-ions up to 34 GeV/u for nuclear collision experiments, but alternatively also as stretcher for SIS100-beams.

This contribution describes the concept of collection, fast cooling and accumulation of RI and antiproton beams in the 13 Tm-CR complex consisting of a large acceptance Collector Ring CR and an accumulator ring RESR. The pre-cooled beams are led to Experimental Storage Rings (xESR) equipped with internal target experiments and electron coolers: RI beams to the 13 Tm-NESR and antiproton beams via SIS100 to the 50 Tm-HESR.

## 2 SECONDARY BEAM PRODUCTION

### *2.1 Rare Isotope Beams*

Experimental data measured at the existing fragments separator FRS behind SIS18 confirmed that optimal yields of neutron-rich, i.e. most exotic, nuclei are obtained by induced fission of $^{238}$U-projectiles at energies up to 1.5 GeV/u. Therefore, $^{238}$U may be considered as reference nucleus for the formation of rare isotope ion beams at the proposed facility. The acceleration of $^{238}U^{28+}$ ions in the proposed SIS18-SIS100 accelerator combination will allow not only to attain a high primary beam intensity of $1\times10^{12}$ ions per cycle, but also to compress all projectiles into a single bunch of only 50 ns duration and 2% full momentum spread. The concept of time focusing minimizes the increase of the longitudinal emittance for the secondary beams and makes it possible to apply fast debunching (i.e. fast momentum spread reduction) after injection to the CR.

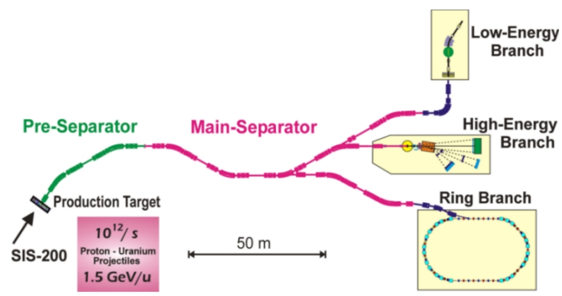



Figure 2: Layout of the Super-FRS [3], a magnetic separator equipped with super-ferric dipole and quadrupole magnets. The maximum bending power $B\times\rho_{max}$ is 20 Tm, the resolving power $M/\Delta M$ about 1500.

Table 1: A few examples of expected RI intensities per SIS100 cycle after Super-FRS and injection to the CR. The heavy species are produced by induced fission of $1\times10^{12}$ uranium projectiles per cycle at 1.5 GeV/u, the lighter ones by fragmentation of lighter projectiles (e.g. $^{55}$Ni from $^{58}$Ni) at lower specific energies. Decay times are given for nuclei at rest [3].

| Nucleus | Yield / cycle | Decay time $\tau_{1/2}$ [s] |
|---|---|---|
| $^{11}Be^{4+}$ | $6.0\times10^8$ | 13.8 |
| $^{46}Ar^{18+}$ | $3.2\times10^8$ | 7.8 |
| $^{55}Ni^{28+}$ | $3.9\times10^7$ | 0.2 |
| $^{71}Ni^{28+}$ | $6.7\times10^6$ | 2.6 |
| $^{91}Kr^{36+}$ | $4.2\times10^7$ | 8.6 |
| $^{104}Sn^{50+}$ | $5.0\times10^5$ | 20.8 |
| $^{132}Sn^{50+}$ | $4.0\times10^7$ | 39.7 |
| $^{133}Sn^{50+}$ | $4.0\times10^6$ | 1.4 |
| $^{187}Pb^{82+}$ | $1.0\times10^7$ | 15.0 |
| $^{207}Fr^{87+}$ | $3.2\times10^7$ | 14.8 |
| $^{227}U^{92+}$ | $1.6\times10^6$ | 66 |

It should be mentioned that, by each beam bunch, a rather large fraction (up to 30%) of the total beam energy of about 57 kJ at 1.5 GeV/u is deposited in a small volume of about 10 mm$^3$ in the (C, Al or Mg) production target of a few g cm$^{-2}$ thickness. The power loss of 340 GW averaged over 50 ns will destroy every kind of conventional (solid) target by immediate melting and shock waves [4]. Therefore, the development of targets that can be renewed after each beam bunch (every second or even faster) is crucial.

### *2.2 Antiproton Beam*

The bunching procedure described above is applied also to the proton beam for the antiproton production. The concept – kinetic energy of 29 GeV and intensity of $2\times10^{13}$ primary protons, target and collection techniques, and acceptance of the CR (see Tab. 2) – is very similar to that of the former AAC-complex at CERN [5, 6]. However, because of the higher proton intensity and energy, we expect a somewhat higher antiproton yield of $5\times10^{-6}$ per incident proton at the desired energy of 3 GeV, i.e. about $1\times10^8$ per bunch.

## 3 FAST COOLING IN CR COMPLEX

The necessity of fast cooling and accumulation in the CR complex is determined by the consumption rates at the highest luminosities for the internal target experiments with the cooled secondary beams and, in the case of rare isotope beams, additionally by the decay time $\gamma\tau_{1/2}$ of the exotic nuclei in the laboratory system (see table 1).

Table 2: Selection of basic CR parameters.

| | | | |
|---|---|---|---|
| Bending power | 13 Tm | | |
| Circumference | 200.6 m | | |
| Super periodicity | 2 | | |
| Lattice type | FODO | | |
| Operation modes | Pbar cooling | RIB cooling | Isochr. mode |
| Maximum energy [GeV/u] | 3 | 0.79 | 0.79 |
| Betatron tunes $Q_h$ | 4.62 | 3.42 | 2.36 |
| $Q_v$ | 4.19 | 3.36 | 3.36 |
| Transition energy, $\gamma_{tr}$ | 4.3 | 2.88 | 1.84 |
| Horiz. acceptance [μm] | 240 | 200 | 70 |
| Vertical acceptance [μm] | 240 | 200 | 50 |
| Momentum acceptance | ±3% | ±1.75% | ±0.7% |
| Stoch. cooling at [GeV/u] | 3 | 0.74 | - |
| at $\beta$=v/c | 0.97 | 0.84 | - |
| at $\gamma$ | 4.2 | 1.8 | 1.84 |
| Revol. frequency [MHz] | 1.5 | 1.3 | 1.3 |
| Frequency slip factor $\eta$ | ≤0.07 | 0.17 | 0.0 |
| Rf peak amplitude [kV] | 400 | 400 | - |
| $\delta p/p$ after de-bunching | ±0.6% | ±0.35% | - |

### *3.1 CR Lattice*

The large acceptance Collector Ring CR (see table 2 and figure 3) is the first stage of the storage ring branch of the proposed facility [7]. Its maximum bending power of 13 Tm allows for the injection of rare isotope beams at 740 MeV/u and, reversing the polarity of all magnets, of antiproton beams at 3 GeV. Mainly due to the different particle velocities the ion optics has to be flexible in order to achieve optimal conditions for fast stochastic cooling for both species of beams (see table 2). In addition, the CR has to be operated in the isochronous mode ($\gamma=\gamma_t$) at a relatively low $\gamma_t$=1.84 for time-of-flight mass spectrometry of exotic nuclei.

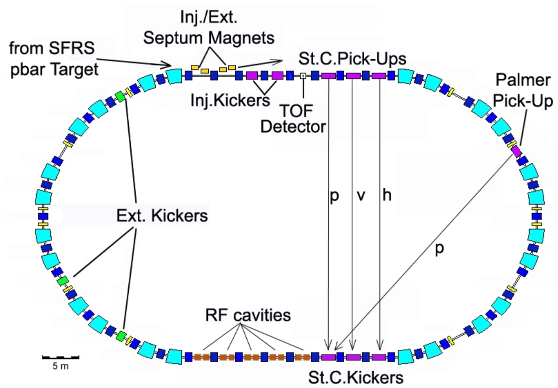



Figure 3: Layout of the Collector Ring CR. The ring will be equipped with superferric dipole magnets. The Palmer pickup is necessary only for rare isotope beams at the beginning of momentum cooling (too strong unwanted mixing).

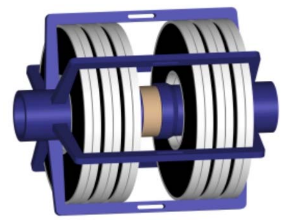
So far, two different lattice structures have been studied carefully: a lattice with identical ion optical settings in $180^0$-arcs and a so-called split ring lattice with strongly reduced frequency slip factor $\eta$ in the arc between stochastic cooling pickups and kickers, which had been already proposed about 10 years ago for the Super-LEAR lattice [8]. The results of the studies for the split ring lattice in comparison with the symmetric lattice may be summarized as following:

- the number of quadrupole families is increased by nearly a factor of 2,
- chromaticity and higher order field corrections are much more complicated, and
- the dynamic apertures seem to be considerably smaller (if not too small) compared to the physical apertures.

Before the final decision about the choice of the CR lattice, numerical calculations of transverse cooling rates for all phases of the cooling process have to be completed.

## 3.2 Bunch Rotation

As explained above the injected secondary beam particles are concentrated in a single, 50 ns long beam bunch. This permits, immediately after injection, fast momentum spread reduction by a factor of approximately 5 by means of bunch rotation followed by adiabatic debunching. The first harmonic RF cavities have to be tuned to 1.3 MHz for RI beams and to 1.5 MHz for antiprotons. A rather high total RF voltage of 400 $kV_{pp}$ is necessary in the case of RI bunches, for which a compromise between enough horizontal acceptance and sufficiently small frequency slip factor $\eta$=0.17 is much harder to find.



| | |
|---|---|
| Load material | MA |
| Reson. RF for RI | 1.3 MHz |
| Reson. RF for pbar | 1.5 MHz |
| Voltage | 40 $kV_{pp}$ |
| Shunt impedance | 929 Ω |
| Power | 862 kW |
| Length | 1 m |

Figure 4: Preliminary layout and parameters of the CR bunch rotation cavity. 10 cavities are required.

## 3.3 Stochastic Cooling

The starting conditions for stochastic cooling are determined by large transverse emittances and by the momentum spread after bunch rotation and adiabatic debunching. Because of the stronger (unwanted) mixing the momentum cooling of rare isotope beams starts with the so-called Palmer method until the momentum spread is below the mixing limit for notch filter cooling ($\delta p/p \approx \pm 0.1\%$). The Palmer pickup is installed at a position, where the dispersion amplitude is large compared to the betatron amplitude. The momentum deviation is deduced from the difference between signals from inner and outer electrodes of the pickup system. As the Schottky power is proportional to the square of the ionic charge $Z$, the high charge states of rare isotopes ($Z \geq 25$) guarantee an excellent signal to (thermal) noise ratio.

Table 3: Parameters for stochastic cooling at CR

| | | Pbar cooling | RI cooling |
|---|---|---|---|
| After injection | Horiz. emittance [μm] | 240 | 200 |
| | Vertical emittance [μm] | 240 | 200 |
| | Momentum spread [%] | ±3 | ±1.75 |
| After debunching | Horiz. emittance [μm] | 240 | 200 |
| | Vertical emittance [μm] | 240 | 200 |
| | Momentum spread [%] | ±0.5 | ±0.35 |
| After cooling | Horiz. emittance [μm] | 0.5 | 5 |
| | Vertical emittance [μm] | 0.5 | 5 |
| | Momentum spread [%] | ±0.1 | ±0.05 |
| Total cooling time [s] | | 5.0 | 0.5-1 |

Transverse cooling of antiprotons and rare isotopes will be switched on when the unwanted mixing between pickups and kickers has reached tolerable values and the wanted mixing between kickers and pickups is still strong enough. This is the case at a momentum spread of approximately ±0.3%. This preliminary estimate has to be confirmed by numerical simulation of the cooling process. The corresponding computer code based on the Fokker-Planck approach is in preparation and should be available by the end of this year.

The preliminary technical layout of the stochastic cooling system at the CR is based on power-amplifiers for two or three bands in the frequency range 1 to 4 GHz. The 50 Ω-kickers will be equipped with a total power of about 8 kW. Mainly for the antiproton cooling it is crucial to aim at optimal signal to noise ratio at the pickup side. Cooling of pickup terminators with liquid-$N_2$ and application of low noise head amplifiers are envisaged. In addition, the mechanical distance between pickup electrodes is planned to be reduced synchronously to the progress of transverse cooling, in order to yield an optimal Schottky signal.

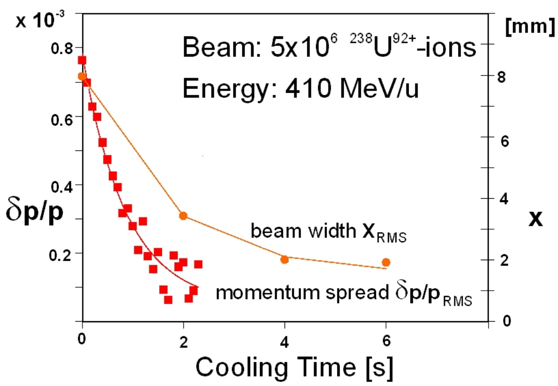



Figure 5: Results of stochastic cooling experiment at ESR (see text).

The requirement of a total cooling time of 5 s for antiprotons is considered to be feasible if the "state of the art" achieved at CERN and FNAL is applied adequately to the technical design of the CR cooling system. For rare isotope cooling, the total cooling time of 0.5 s seems to be rather challenging, though the signal to noise ratio for highly charged ions is excellent. Fortunately, the results of cooling experiments at the ESR with artificially heated fully stripped uranium ions at 410 MeV/u are quite promising (see fig. 5). Cooling time constants of less than 1 s for momentum cooling and 2 s for horizontal emittance cooling were obtained with about 500 W total power at 50 Ω-kickers in the frequency band 0.9-1.65 GHz.

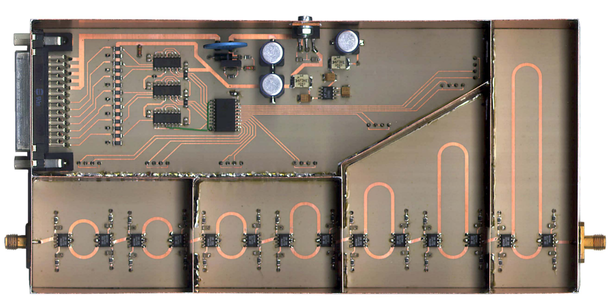


Figure 6: Prototype of a 1.27 ns-delay electronically switched in steps of 10 ps.

So far, we believe that the same pickup and kicker electrodes can be employed for both the RI and the antiproton stochastic cooling. Novel planar electrodes (slit couplers) suitable for the relativistic parameter $\gamma$ of the beam particles, 1.8 for RI and 4.2 for antiprotons, are under development. The 15% difference in the particle velocities has to be taken into account for the signal combination as well for the electrical length adjustment of transmission lines and notch filters. Suitable electronically switched delay units are under development. A prototype is seen in Figure 6.

## 4 BEAM ACCUMULATION

### 4.1 Rare Isotope Accumulation

Pre-cooled rare isotope bunches can be transferred either directly or after deceleration in the RESR to a lower specific energy to the NESR. If allowed by the lifetime of nuclei, the rare isotope beams may be accumulated in the NESR by means of RF stacking and electron cooling. This method has been applied successfully for many years at the existing ESR. Achievable stacking factors are proportional to the beam lifetime divided by the time between two subsequent injections. If the latter is assumed to be about 1 s, we may expect stacking factors that are approximately equal to the nuclear decay time of the exotic ions in the laboratory system (see table 1). Hence, e.g. for $^{132}$Sn, one could accumulate up to $2.4\times10^9$ nuclei within one minute. With an internal target of $4\times10^{13}$ atoms/cm$^2$ and 1 MHz revolution frequency a luminosity of about $1\times10^{29}$ cm$^{-2}$s$^{-1}$ would be available for experiments.

### 4.2 Antiproton Accumulation

After pre-cooling in the CR, single bunches of up to $1\times10^8$ antiprotons are transferred every 5 s to the accumulator ring RESR, where RF stacking will be combined with stochastic accumulation. The injected bunch is captured into a first harmonic RF bucket, moved towards the tail of the stack and de-bunched there. The momentum cooling into the stack core is made by two or three separate pickup and kicker systems. In addition, the core of the stack has to be cooled all the time in all phase planes. About $7\times10^{10}$ antiprotons per hour shall be accumulated this way. The accumulated antiproton beam is transferred to SIS100, where it is accelerated to the energy required for the internal target experiment at the HESR. The design of the RESR, recently added to the storage ring complex, is in a very early stage. The main motivation was, to have a ring especially optimized for the fast accumulation of antiprotons. The lattice is under investigation and the conceptual design of the stochastic accumulation system has just begun. We hope to get, at least, some advise from experts at FNAL and CERN, where similar requirements have been fulfilled many years ago.

## 5 ELECTRON COOLING CONCEPT

### 5.1 RI beams in NESR

Because of the short lifetime of exotic nuclei one has to optimize stochastic pre-cooling in the CR and final electron cooling in the NESR. Stochastic cooling rates decrease strongly when the beam temperatures approach a certain lower limit, where the (wanted) mixing is so slow and the signal to noise ratio so small that the cooling process is stopped. Electron cooling rates show the opposite behavior. They reach optimal values as soon as the longitudinal and transverse beam temperatures are small enough, i.e. the relative velocities between cooling electrons and ions are comparable to the mean electron velocity spread. The envisaged final beam parameters after precooling in the CR (see table 3) may be considered as optimal parameters for the subsequent electron cooling in the NESR, where electron cooling rates between 1 and 10 $s^{-1}$ are required.

Main applications for electron cooling at the NESR are

- fast accumulation of RI beams,
- compensation for beam heating and mean energy loss in the internal target in proton scattering experiments, and
- formation of short ion bunches for the collision with electron bunches for electron scattering experiments, including the compensation for phase space dilution by beam-beam effects.

Main parameters of the NESR electron cooler are:

- 10-450 keV variable electron energy corresponding to electron cooling in the ion energy range 20 to 800 MeV/u,
- up to 2 A electron current at a beam diameter of 25 mm,
- $\leq$ 0.2 eV transverse electron temperature,
- about 0.2 T solenoid field in the cooling section with a straightness of $B_\perp/B_\parallel \leq 5\times10^{-5}$, and
- effective cooler length of 4 m.

The rather tight tolerance for the straightness of the magnetic field in the cooling section is absolutely necessary to attain the envisaged cooling rates $\geq$10 $s^{-1}$, especially at high cooling energies. Numerical simulations using different codes have confirmed this. Another result of the simulations is the necessity of sufficiently high magnetic field strength, in order to achieve the so-called magnetized cooling delivering much higher cooling rates compared to non-magnetized cooling at lower fields. The simulation results are in fairly good agreement with experimental cooling results at the ESR in a wide range of ion energy up to 450 MeV/u.

## *5.2 Antiprotons in HESR*

Very similar to the situation in the NESR, beam quality and luminosity in the HESR will be determined by the capability to counteract beam heating caused by antiproton-target interactions and by intra-beam scattering. The realization of the technical requirements that can be derived from the experimental experience with electron cooling at lower energies is quite challenging. As mentioned above and confirmed by recently performed numerical simulations strong cooling can be achieved only by magnetized cooling requiring a strong longitudinal magnetic field ($B_\parallel \geq 0.5$ T) that guides the electron beam along the entire interaction region of up to 30 m length. It is evident that the requirements concerning the parallelism of the magnetic field ($B_\perp/B_\parallel \leq 1\times10^{-5}$) are even more stringent than for the NESR electron cooler and absolutely mandatory for reasonably high cooling rates (0.1 to 0.01 $s^{-1}$), especially at the highest antiproton energies between 10 and 14 GeV.

The generation of a cold electron beam at energies up to 8 MeV (corresponding to an antiproton energy of 14 GeV) with an electron current of up to 1 A is another technical challenge. If magnetized cooling with a maximum energy of 8 MeV is required, two possible solutions for the acceleration of the electrons are conceivable: electrostatic acceleration or linear RF accelerator. Electrostatic acceleration certainly has the advantage of small energy spread in the electron beam compared to the acceleration by an RF linac. Moreover, it provides a continuous electron beam without any time structure, which would be best suited for the cooling of a coasting antiproton beam in the HESR.

The acceleration of electron beams in commercially available electrostatic accelerators might be feasible if the electron beam current can be recuperated with high efficiency. An electron current loss below 100 μA seems to be acceptable in this type of accelerator. First experiments in the framework of a similar research program at FNAL/USA are promising [9], but, so far, the project is not focused to achieve the considerably higher cooling rates by means of magnetized cooling. The technical feasibility of magnetized cooling in the full energy range of the HESR is presently being studied in close cooperation with BINP in Novosibirsk.

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