EXPECTED PERFORMANCE OF THE STOCHASTIC COOLING AND RF SYSTEM IN THE COLLECTOR RING

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Abstract

The Collector Ring (CR) is designed for stochastic cooling of antiprotons and radioactive ions at the FAIR. Simulations of the cooling process in combination with required RF beam manipulations have been done taking into account the improved and recently fixed ion-optics. The measured RF properties of a first of series de-buncher system have been considered to evaluate the performance of the bunch rotation, de-bunching and re-bunching process within the planned CR operation cycle. In this paper, the expected beam parameters and matching at the extraction to the HESR storage ring are discussed. The latest hardware developments of the stochastic cooling system components are also presented.

INTRODUCTION

According to the Modularized Start Version (MSV) of the FAIR project, the accumulation of antiprotons will be done directly in the HESR. In this scenario, the moving barrier voltage and the HESR stochastic cooling system will be used to increase the beam intensity during 100 cycles with a typical cycle time of 10 s and 10^8 particles/shot from the CR. The injected antiproton beam has to meet the requirements given by the momentum acceptance of the HESR stochastic cooling system and the transverse acceptance of the machine. On the other hand, the HESR lattice has been also adopted for a future possibility to use radioactive ion beams or primary beams of stable heavy ions for nuclear and atomic physics experiments. In this case, a high beam quality is required for cooled radioactive beams from the CR which is dictated by the momentum and transverse acceptance of the HESR in the heavy ion beam operation mode. The stable heavy ions will typically have a much smaller momentum spread and transverse emittance as they will come to the CR after acceleration, i.e. no cooling at the CR is required, although they can be cooled if a high-quality beam is required for precise experiments in the HESR.

Within the planned typical cooling cycle of the CR, a short bunch of antiprotons or heavy ions will be rotated by a quarter of synchrotron oscillation period and then adiabatically de-bunched in order to match to the momentum acceptance of the CR stochastic cooling system. After cooling is completed, the coasting beam has to be re-bunched again before the extraction to the HESR. A comprehensive study of the beam dynamics including the required RF beam manipulations and the 3D cooling of antiprotons and heavy ions in the CR has been made during the last few years. The recently improved and fixed ion-optical design [1] of the machine has been considered for all the simulations presented in the following sections.

RF SYSTEM DEVELOPMENT

Five resonant cavities with the maximum available RF voltage of 40 kV/unit will be installed in the CR for the bunch rotation, adiabatic de-bunching and re-bunching. The first of series RF cavity is completed and successfully passed the site acceptance tests at GSI/FAIR in 2017. Specific features in the behavior of the RF voltage and phase within the CR operation cycle have been revealed during the tests [2]. The measured fall time of the RF voltage at the end of the pulsed mode after the bunch rotation is 10 µs as shown schematically in Fig. 1.

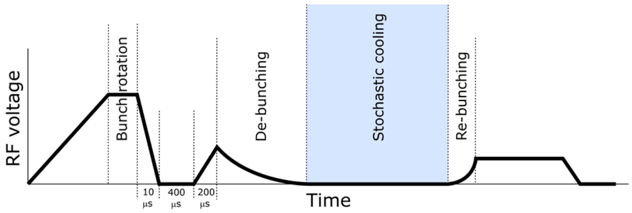

Figure 1: A schematic (not to scale) RF voltage pattern within the typical CR operation cycle.

The adiabatic de-bunching implies the operation of the RF cavities in the CW mode. The test measurements demonstrated that the transition time from the pulsed to the CW mode is around 400 µs, where the RF voltage is zero. The re-excitation from zero to a required voltage for the de-bunching in the CW mode takes approximately 200 µs. The phase difference between the reference signal generator and the RF voltage has the offset of 40-45° at the start of the de-bunching and is linearly decreased to zero during about 250 µs. The measured properties of the first of series RF cavity have been taken into account to examine the expected beam qualities prior to the stochastic cooling.

STOCHASTIC COOLING SYSTEM DEVELOPMENT

The 1-2 GHz stochastic cooling system of the CR consists of two slot-line pick-ups, the Palmer pick-up based on the Faltin structure and two slot-line kickers. The electrode plunging by means of linear motor drives on the slot-line pick-up tanks will be implemented to increase the shunt impedance during the cooling. The engineering concept is shown in Fig. 2. The drives are designed to synchronously move the electrode modules from ± 80 mm to ± 10 mm towards the beam axis following the shrinking beam size. The linear drive is ready and has been successfully tested at GSI/FAIR for all required directions [3].

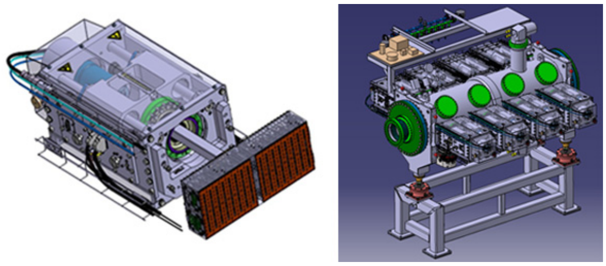

Figure 2: 3D model of the assembly of one electrode module mounted to the linear drive (left) and the horizontal pick-up tank with four drives at each side (right).

The detailed coupling impedance measurements of the designed slot-line structure have been done which gives the relative sensitivity of the pick-up as a function of frequency and the distance between the plates of the structure [4]. The dedicated simulation of the pick-up longitudinal shunt impedance at the mid band frequency with the HFSS code [5] has been employed to obtain the absolute values of the longitudinal and transverse impedances shown in Fig. 3.

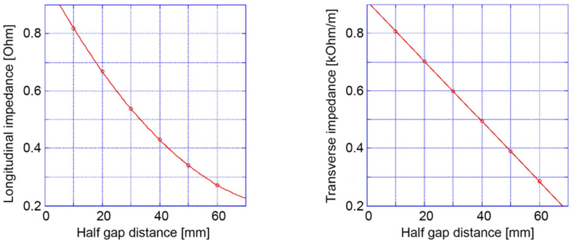

Figure 3: The longitudinal (left) and transverse (right) coupling impedance of the slot-line structure as a function of the half gap distance between the electrode plates.

ANTIPROTON BEAM DYNAMICS

The analysis of the energy spectrum of 3 GeV antiprotons after the production and separation shows that the momentum spread of the beam is uniform with the width of ± 3%. The injected bunch will typically have the full length of about 50 ns as given by the expected time structure of the proton beam. The particle tracking simulation of the bunch rotation process implies setting of the RF voltage to 100 kV during 1310 turns followed by the linear decrease to zero with the falling time of 10 µs.

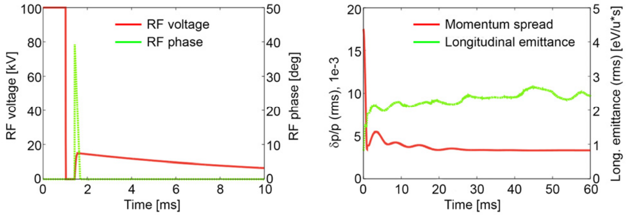

Figure 4: The RF voltage and phase pattern (left) and evolution of the antiproton beam parameters during the bunch rotation and de-bunching (right).

After 400 µs, the voltage is re-excited to 15 kV within 120 µs and then exponentially decreased to zero. The decay time constant of the RF voltage during the de-bunching period is 10 ms. The momentum slipping factor of the ring for the antiproton optics is 0.014. It is dynamically varied as a function of particle momentum deviation. In Fig. 4 the RF voltage and phase pattern as well as the evolution of the momentum spread and longitudinal emittance are shown.

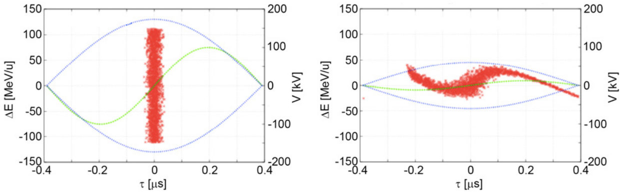

Figure 5: Phase space plot before (left) and after (right) of the bunch rotation. Blue line is the separatrix. Green line is the RF voltage.

The initial bunch length of 12.5 ns (rms) with the Gaussian distribution truncated at $\pm 3\sigma$ is considered in this simulation. A small fraction of the particles in the tail of the distribution cannot be trapped by the separatrix within the quarter of the oscillation period of 1.5 ms as shown in Fig. 5. The beam becomes coasting after the adiabatic debunching which takes about 100 ms. The final momentum spread is $3.28\cdot10^{-3}$ (rms) for the Gaussian distribution truncated at $\pm 3\sigma$. We have examined the beam qualities depending on the antiproton bunch length at injection. As an example, the final momentum spread is $3.76\cdot10^{-3}$ if the initial bunch length is 25 ns (rms).

The longitudinal cooling process is studied by solving the Fokker-Planck equation. The cooling and diffusion terms are derived as a function of energy and time using the stochastic cooling model. The optimal system gain in 147 dB corresponding to the engineering required microwave power of 1.5 kW and is kept constant during the cooling process. The available microwave power is designed as totally 8 kW which should be shared with the longitudinal and transverse cooling. The electrode plunging of the pick-ups can be optionally included in the simulation by using the calculated variation of the coupling impedances of the slot-line structure. The initial momentum spread is $2.7\cdot10^{-3}$ (rms) as a reference case. The momentum spread of $1.9\cdot10^{-4}$ is reached after 10 s as shown in Fig. 6. The plunging helps to reach the equilibrium value earlier, i.e. after 7-8 s of the cooling. Before the extraction to the HESR the beam has to be re-bunched which is performed with the RF voltage increase from 30 V to 400 V during 0.7 s. Finally, the antiproton bunch has the length of 80 ns (rms) and the momentum spread of $6.4\cdot10^{-4}$. In this case, there is no margin between the momentum spread of the injected bunch and the acceptance of the stochastic cooling system at the HESR which is $6\cdot10^{-4}$. Simulations show that the cooling efficiency can be increased by the dynamical variation of the momentum slipping factor during the cooling. Then the final momentum spread after the re-bunching is $3.9\cdot10^{-4}$. The quadrupole power supplies are designed to provide the required ramping rate for the optics variation.

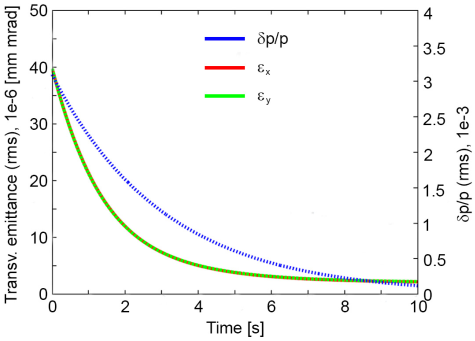

Figure 6: The evolution of the momentum spread and transverse emittance during the simultaneous 6D cooling of the antiproton beam.

The transverse cooling simulation including the beam feedback effects is performed by numerical solution of the emittance rate equation. The initial emittance of the antiproton beam is 40 π mm mrad (rms) in both planes. The system gain is varied from 150 dB to 143 dB to obtain the optimal cooling performance. The corresponding required engineering microwave power is 2.8 kW for each plane. After 10 s of cooling, the horizontal and vertical emittance is reduced to 2.1 π mm mrad which is within the estimated HESR acceptance of 2.6 π mm mrad.

HEAVY ION BEAM DYNAMICS

We have considered $^{132}\mathrm{Sn}^{50+}$ beam with the energy of 740 MeV/u in the simulations. The calculated momentum spread at injection into the CR is $1.25\cdot10^{-2}$ (rms) of the Gaussian distribution truncated at $\pm 1.2\sigma$. The momentum slipping factor of the ring for the radioactive ion optics is 0.178. The bunch rotation is performed by applying the RF voltage of 200 kV within 210-220 turns. The re-excited RF voltage for the adiabatic de-bunching is 5-10 kV depending on the initial bunch length which is assumed as 12.5-25 ns (rms) for the Gaussian distribution truncated at $\pm 3\sigma$. The corresponding final momentum spread is $1.36\cdot10^{-3}$-$1.53\cdot10^{-3}$ after the bunch rotation and de-bunching which totally takes 5 ms.

The stochastic cooling of the radioactive ion beam can be performed by the Palmer, TOF (time of flight) or filter method [1]. In Fig. 7, the coherent term for each of the methods is shown. The Palmer cooling method has the full momentum acceptance of $\pm 6.99\cdot10^{-3}$. The acceptance of the filter method is $\pm 1.37\cdot10^{-3}$. The TOF method has the largest acceptance of $\pm 1.39\cdot10^{-2}$. Assuming that the coasting beam has the momentum spread of $2\cdot10^{-3}$ (rms) of the Gaussian distribution truncated at $\pm 3\sigma$ after the de-bunching, only the Palmer or TOF method can be used at the start of the cooling. After the momentum spread becomes less than the acceptance of the filter method, the system can be switched to the filter cooling which provides a larger cooling force and can therefore efficiently cool the beam to the required qualities. As an example, the Palmer method can pre-cool 10^8 ions during 3.5 s. With the following hand-over to the Filter method, the beam is cooled to the momentum spread of $7\cdot10^{-5}$ after 5 s of cooling as shown in Fig. 8.

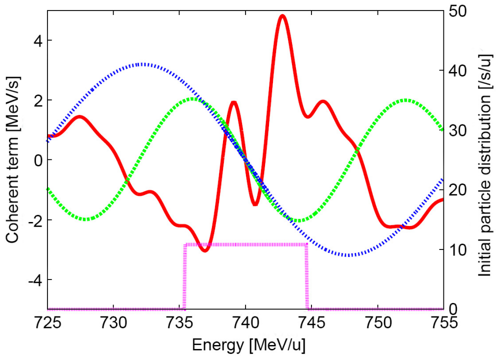

Figure 7: The coherent term of the Palmer (green), TOF (blue) and filter (red) cooling method. The initial beam distribution is given with pink line.

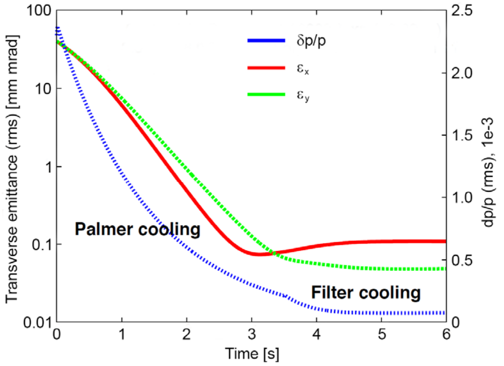

Figure 8: The evolution of the momentum spread and transverse emittance during the simultaneous 6D cooling of the radioactive ion beam. The particle number is 10^8. The hand-over from the Palmer to filter method is at 3.5 s.

Within the same cooling scenario, the beam of 10^6 ions can be cooled to the momentum spread of $1.3\cdot10^{-5}$ after 2 s. The momentum spread of the ion beam is increased by a factor of 3 during the re-bunching process. The final momentum spread is therefore within the HESR acceptance of $7\cdot10^{-4}$. The Palmer system has to be equipped with the maximal power of 1000 W while for the filter system 60 W has to be provided to attain the cooling time of 4-5 s. The horizontal and vertical emittance can be decreased to 0.1 mm mrad during 3-4 s of cooling while the estimated transverse acceptance of the HESR is 2.6 π mm mrad. In this case, the required microwave power is 1000 W for each plane.

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