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SIMULATION STUDY OF HEAVY ION BEAM INJECTION AND ACCELERATION IN THE HESR FOR INTERNAL TARGET EXPERIMENTS WITH COOLING

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Abstract

Heavy ion stochastic momentum cooling is investigated under the constraint of the present concept of the High Energy Storage Ring (HESR). A bare uranium beam is injected from the collector ring (CR) into the HESR at *740 MeV/u* and a beam preparation for an internal target experiment is outlined. Further the acceleration of the ion beam to *4.5 GeV/u* is considered and an internal target experiment is studied. The simulations include the beam-target interaction due to a Hydrogen target. The capability of momentum filter cooling is envisaged and at lower energies where the revolution harmonics begin to overlap the possibility of Time-Of-Flight (TOF) momentum cooling is examined. The simulation studies make use of a Fokker-Planck and a two-dimensional symplectic tracking code in longitudinal phase space including cooling and the synchrotron motion induced by the electric fields of the rf-cavities.

INTRODUCTION

The HESR [1] has been originally designed for storage and acceleration of up to 10^{11} anti-protons for internal target experiments with high momentum resolution up to $\approx 1\cdot 10^{-5}$ in the momentum range *1.5 GeV/c to 15 GeV/c*. Since in the modularized start version the storage rings RESR and NESR are postponed the accumulation of the beam delivered by the CR has to be accomplished in the HESR itself. The well-established stochastic stacking method [2] is however not applicable. Instead a different method using moving barriers and stochastic filter momentum cooling is established [3] to accumulate 10^{10} anti-protons within *1000 s*. Recently, proposals were tabled to also prove the feasibility of the HESR storage ring for the application of heavy ion beams with the special emphasis on the experimental program of the SPARC collaboration at FAIR. The magnetic rigidity range $5\text{Tm} \le B\rho \le 50\text{Tm}$ allows the storage of $^{132}Sn^{50+}$ and $^{238}U^{92+}$ ions in the kinetic energy range *740 MeV/u* up to $\approx$ *5 GeV/u*. In this study a bare $^{238}U^{92+}$ beam with $N = 10^8$ ions and a kinetic energy *740 MeV/u* is kicked injected from the collector ring (CR) [4] into the HESR. To transfer the beam from CR to the HESR it is essential to provide a gap of *318 ns* for the CR's extraction kicker. Therefore, an adiabatic capture of the DC-beam is employed. The initial rms-relative momentum spread, $1.5\cdot 10^{-4}$, of the DC-beam in the CR will increase to $\sigma_p = 3.3\cdot 10^{-4}$ (rms) while the beam becomes bunched with an rms-bunch length of *110 ns*. A nearly Gaussian shaped ion beam is then kicked injected into the HESR. The horizontal as well as vertical emitttance is ε_{rms} = *0.125 mm mrad*. The HESR lattice with zero dispersion in the straights has been optimized for internal target experiments and stochastic cooling with γ_{tr} = 6.23. The lattice can however be adjusted for transition gamma values between *6* and *25* [5]. A hydrogen target with density $N_T = 4\cdot 10^{15}\,\text{cm}^{-2}$ is used for internal target experiments. The barrier bucket (BB) cavity of the HESR is utilized to compensate the strong mean energy loss induced by the beam-target interaction [6].

COOLING AT 740 MeV/u

For an internal target experiment at *740 MeV/u* two scenarios have been investigated. One which makes use of the bunch-into-bucket transfer has already been outlined in [7]. The other scenario described here devotes the resources of moving barriers and momentum cooling for beam injection and preparation of an internal target experiment. The CR beam is kicked injected into the stable area of two barriers *1.1 μs* apart and with the maximum available barrier peak voltage *2 kV* as shown in the longitudinal phase space Figure 1. There is enough space for the HESR injection kicker rise/fall time.

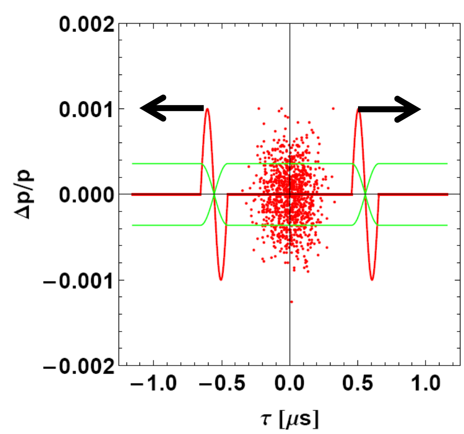

Figure 1: Phase space portrait of the injected beam bunch (red points). The two barrier pulses (red) are *1.1 μs* apart. The separatrix of the BB is drawn in green. After injection the barriers are moved as indicated with arrows.

It is visible that the momentum spread of the incoming beam bunch (red points) with $3\sigma_p \approx 1\cdot 10^{-3}$ significantly exceeds the bucket height, $(\Delta p/p)_{bucket} = \pm 4\cdot 10^{-4}$, for the available BB cavity operating at a frequency $f_{BB} = 5\,\text{MHz}$. After injection the barriers are moved adiabatically within *500 ms* in the direction as indicated in

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the figure. A symplectic particle tracking code taking into account the synchrotron motion in the rf fields of the barriers including stochastic cooling, internal target operation and intra beam scattering has been developed to map the ions in the longitudinal phase space with coordinates $(\tau, \Delta p/p)$ where $\tau \in [0, \pm T_0/2]$ is the time in the bunch. The revolution period is $T_0 = 2.31\,\mu s$. The final position of the barriers after *500 ms* is shown in Figure 2. It can be seen that the momentum spread of the ions inside the separatrix is adiabatically reduced while those outside the separatrix only debunch and stay outside the separatrix. They are not lost since the momentum acceptance of the HESR is larger than $\pm 2.5 \cdot 10^{-3}$.

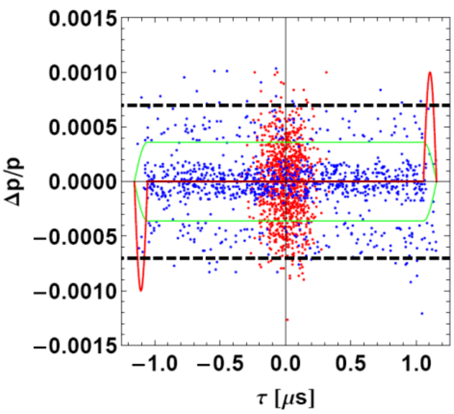

Figure 2: Phase space portrait of the beam (blue points) after *500 ms*. For comparison the injected beam (red points) is shown. The dotted lines indicate the TOF cooling acceptance.

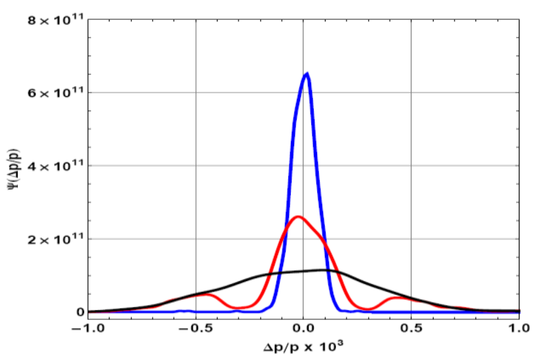

Figure 3: The initial beam distribution is shown in black. The beam distribution at *t = 0.5 s* (red) exhibits two bumps at $\pm 0.5 \cdot 10^{-3}$ corresponding to the particles outside the separatrix in Figure 2. Cooling moves these particles into the separatrix, blue curve.

Stochastic TOF momentum cooling with a cooling acceptance of $\Delta p/p = \pm 7 \cdot 10^{-4}$ and strong cooling capability of the tails in the momentum distribution is now invoked. The internal target is switched on *3 s* after injection. The tracking simulations predict an equilibrium after *6 s* and that the particles outside the separatrix are well cooled into the separatrix. The equilibrium momentum distribution (blue) is depicted in Figure 3. It is clearly apparent that the mean energy loss due to the thick Hydrogen target is effectively compensated with cooling assisted by the barrier cavity. More than *70 %* of the uranium ions inside the separatrix have a fractional momentum spread less than $5 \cdot 10^{-5}$ during the internal target experiment. The particles which are initially outside the cooling acceptance are lost (*3 %*).

INJECTION AND ACCELERATION

The ion beam from the CR is kicked injected into the standing bucket of the *h = 1* cavity with *2 kV*. The maximum achievable energy gain per nucleon per turn of an bare uranium ion is $dT = 0.165$ keV/u/turn since the maximum magnetic field ramp rate in the HESR is limited to $dB/dt = 25$ mT/s and the maximum *h = 1* cavity peak voltage is *2 kV*. The magnetic field ramp for acceleration to *4.5 GeV/u* consists of a quadratic transition (*0.2 s*) to increase the acceleration phase linearly from zero to *12.3* degrees from injection energy to the linear ramp with constant energy gain and a quadratic transition (*0.2 s*) to an intermediate flat top at *3 GeV/u*. After adiabatic reduction of the cavity voltage from *2 kV* to *100 V* (*0.6 s*) and debunching to a DC beam at *3 GeV/u* the lattice optics is changed to $\gamma_{tr} = 14.6$ to avoid a too small ring frequency slip factor. The beam is then re-captured by rising the voltage adiabatically from *10 V* to *2 kV* in *0.6 s*. The lower voltage *10 V* was chosen to avoid a beam filamentation which causes an increase in the bunch area. The beam is then accelerated to the final flat top energy which is reached after *50 s*, see Figure 4.

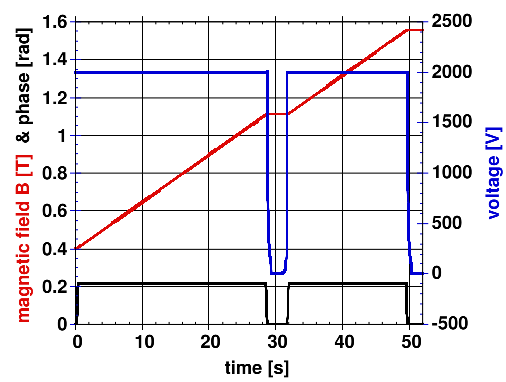

Figure 4: Magnetic field ramp (red) to accelerate the uranium beam from *740 MeV/u* to *4.5 GeV/u*. The intermediate flat top at *3 GeV/u* has a duration of *3 s*. During acceleration the cavity voltage is constant *2 kV*.

The kinetic energy per nucleon and the ring frequency slip factor $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ during acceleration is shown in Figure 5. Figure 6 shows the time evolution of the fractional momentum spread and the bunch length during tracking of the ions in the synchrotron phase space to the flat top energy. The figure shows at the beginning a decrease of the momentum spread and an increase of the bunch length during the quadratic transition when acceleration starts. Both quantities decrease during acceleration as expected.

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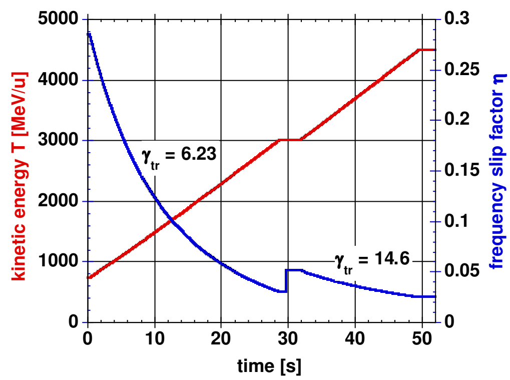

Figure 5: Kinetic energy and frequency slip factor versus time. Transition gamma is changed at *t = 29.7 s*.

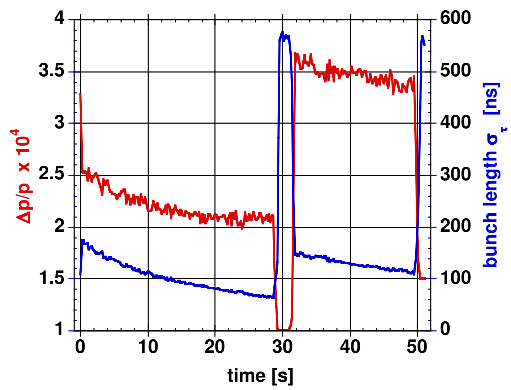

Figure 6: Rms fractional momentum spread times *10^4* (red) and rms bunch length during acceleration to *4.5 GeV/u*.

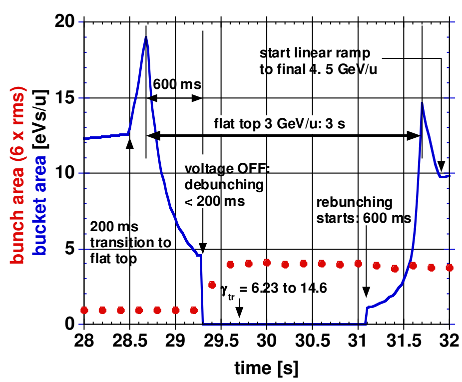

Figure 7: Bunch area (6 times rms, red) and bucket area (blue) in the intermediate flat top region. Transition gamma is changed from *6.23 to 14.6* when the beam is completely debunched (*29.7 s*).

The rms bunch area in the synchrotron phase space $(\phi, \Delta E/\omega_0)$ is constant at 0.17 eVs/u (Figure 7). At the intermediate flat top the rms fractional momentum spread decreases to $1 \cdot 10^{-4}$, Figure 6, due to the adiabatic voltage reduction while the bunch length increases. The bunch area is conserved, Figure 7. After turning off the voltage the momentum spread stays constant and the beam completely debunches. The bunch area is increased by a factor of four, Figure 7. In the following adiabatic recapture and acceleration of the beam to the final energy the rms bunch area 0.68 eVs/u is conserved. At flat top energy *4.5 GeV/u* the voltage is reduced adiabatically. The resulting DC beam with an rms fractional momentum spread $1.5 \cdot 10^{-4}$ is then used in an internal target experiment with momentum filter cooling assisted by the barrier bucket cavity of the HESR to compensate the mean energy loss. A solution of the Fokker-Planck equation predicts the time evolution of the momentum distribution during the experiment, Figure 8. An equilibrium is attained after *10 s* with an rms fractional momentum spread $2 \cdot 10^{-5}$.

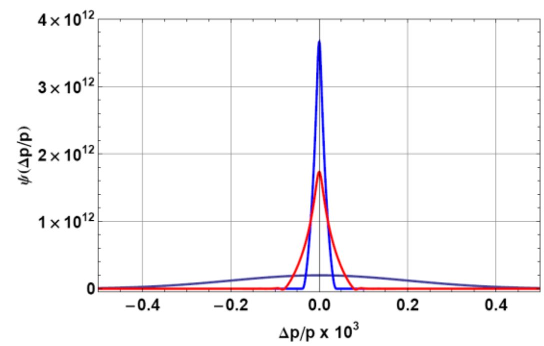

Figure 8: Momentum distributions (black: initial, red: *5 s*, blue *10 s*) during cooling with target at *4.5 GeV/u*.

SUMMARY

The present investigation reveals that the available cavity voltages in the HESR are sufficient for capture, preparation and acceleration of a bare uranium ion beam bunch delivered by the CR. The beam can either be prepared with TOF stochastic cooling for an internal target experiment at *740 MeV/u* or it can be accelerated to *4.5 GeV/u* within *50 s* with the maximum available magnetic ramp rate. Fast stochastic filter momentum cooling can then be applied assisted by the BB cavity for an internal experiment. The present and recent [7] investigations reveals that the size of the incoming ion CR beam bunch should not increase to avoid significant particle losses at injection. Already now safety margins are exhausted.

Thorough theoretical and experimental investigations of high energy stochastic cooling assisted by barrier cavities and internal target operation will be performed at COSY to explore the bunching effects observed in the recent simulations at *2 GeV/u* [7].

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