SIMULATION OF BEAM CAPTURE PROCESS IN HIRFL-CSRM

LI Peng[1], YUAN You-Jin[1], YANG Jian-Cheng[1], JIANG Pei-Yong[1, 2], XIA Jia-Wen[1]
[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

In this paper, beam capture process is simulated in the main cooler-storage ring (CSRm) with the real RF cavity curves. By now, CSRm can accelerate all ions from protons up to the heaviest element, uranium, with variable energies and different efficiency. During the beam capture process, the capture voltage and capture time must be coincided to the beam momentum spread to avoid the beam loss. Moreover, the mismatching between the actual beam energy with the setting beam energy circle also causes the low beam capture efficiency. The evolution of longitudinal phase space during the capture process is presented in this simulation.

INTRODUCTION

The HIRFL-CSR facility consists of the main cooler-storage ring (CSRm), RIB production and transfer line two (RIBLL2), experimental storage ring (CSRe) and experimental terminals [1]. The layout of HIRFL-CSR is shown in Fig. 1.

CSRm can accelerate all ions from protons up to the heaviest element, uranium, with variable energies and different efficiency. After accumulated and e-cooled in the CSRm, the beam is captured adiabatically with fixed capture time and the setting RF voltage. Because of the RF cavity frequency limitation, the RF harmonic number sometimes needs to be changed for the second capture during the acceleration cycle. Then the beam is accelerated to the extraction energy for different experiments. During the beam capture process, the capture voltage, capture time, beam momentum and the setting of the energy circle affect the capture efficiency. A new particle longitudinal motion code with real RF cavity curve was developed to simulate those mentioned effects.

LONGITUDINAL EQUATION OF MOTION

An extended synchrotron mapping equation is adopted to track the beam trajectory in this simulation. The special equation is:

$$\phi_{n+1} = \phi_n + 2\pi h \eta \delta_n + \Delta\varphi(\theta)$$

$$\delta_{n+1} = \delta_n + \frac{eV}{\beta^2 E}(\sin\phi_{n+1} - \sin\phi_s) + \frac{\Delta U}{\beta^2 E} - \lambda\delta_n \qquad (1)$$

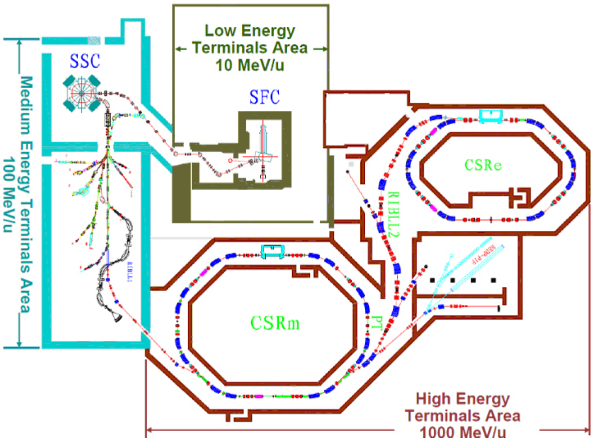

Figure 1: The layout of HIRFL-CSR.

Where the ϕ_s, h, η, β, V, E are the respectively synchronous phase angle, harmonic number, phase-slip factor, velocity factor, beam energy. The ϕ_n, ϕ_{n+1} are the particle nth and n+1th phase angle. The δ_n, δ_{n+1} are the particle nth and n+1the off-momentum. In Eq. (1), RF phase modulation is expressed by the quantity $\Delta\varphi(\theta)$ that is the difference in RF phase error between successive turns in the accelerator [2]. The quantity λ is the phase-space damping parameter related to electron cooling. The quantity ΔU is space charge force [3].

CSRM CIRCLE

The execution sequence for the beam parameters of CSRm is as follows: injection, accumulation, capture, acceleration, harmonic change for second capture, next acceleration and slow or fast extraction.

RF PARAMETERS CALCULATION

During the acceleration, the magnetic curve consists of parabola ramping, linear ramping and parabola ramping. The two parabola ramping are completed in the period 256 milli-second. The capture process is calculated in this section within 64 milli-second.

The voltage data is calculated according to the following steps [4]:

1. Setting the RF voltage for the Injection flat-top, this voltage is the RF voltage at the end of the first parabola ramping. At the end of the first parabolic ramping, the phase is calculated by the formula:

$$V_{inj}\sin(\phi_1) = 2\pi R\rho\dot{B} \qquad (2)$$

Where the $\dot{B}$ (BdotMax) and ϕ_1 is the magnetic field variation and phase at the end of the first parabola ramping. The bucket area is constant during the 256 milli-second parabola ramping. The bucket area is calculated by the formula:

---

*Work supported by HIRFL-CSR project
#lipeng@impcas.ac.cn

$$A = \frac{8R}{hc}\sqrt{2\frac{Z}{M}\frac{V_{inj}E_0}{\pi h|\eta|}}\alpha(\phi_1) \qquad (3)$$

2. During the RF capture process, the synchronous phase ϕ_s is equal to zero (below transition) for a Stationary Bucket. The RF voltage ramps to the capture voltage within 64 ms. According to the ϕ_1 and the voltage V_{inj}, the capture voltage V_{cap} is obtained by the $V_{cap} = V_{inj}\alpha(\phi_1)^2$.

3. After the first parabolic ramping, the magnetic field deviation will be constant at the linear ramping period. The voltage which calculated by the Eq. (2) will rise linearly. The bucket area is calculated by the Eq. (3) and the bucket height is calculated by the formula:

$$BucketH = \frac{1}{\beta}\sqrt{\frac{2Z}{M}\frac{V}{\pi h\eta E_0}}\sqrt{2\cos(\phi)-(\pi-2\phi)\sin(\phi_s)} \quad (4).$$

Where the V and ϕ is the voltage and phase value during the linear acceleration.

4. During the second parabolic ramping, the bucket area will be kept at constant again. The magnetic deviation Bdot will be decreased from the BdotMin to zero. The voltage will be rise to the setting voltage V_{mid} at the middle top. The bucket area and bucket height is calculated by the Eq. (2) and Eq. (3).

5. The voltage is zero at the middle energy flattop; meanwhile, the beam is becoming the coasting beam again.

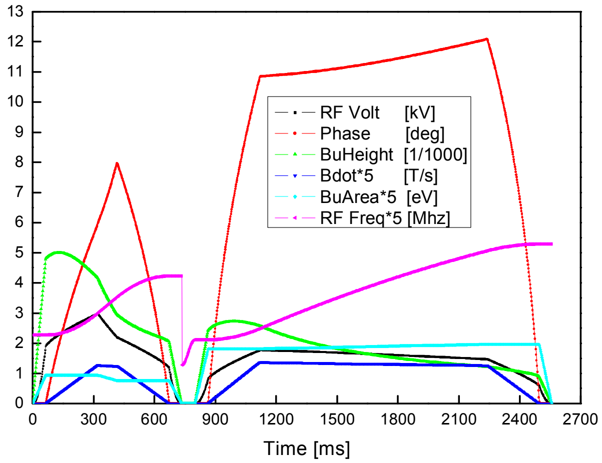

Figure 2: RF parameters during the acceleration.

6. After the harmonic number changed (n=2→1), the coasting beam will be captured again after 192 milli-second and again accelerated to the extraction energy. Therefore, the RF voltage calculation method is the same as the previously mentioned steps. The RF parameters cycle that according to the table 1 during the acceleration is shown in the Fig. 2 [5].

Table 1: Parameters of the Simulation

Parameters	Ion: $^{6+}C^{12}$		
Segment	Accumulation	Middle layer	Extraction
Energy (MeV)	7	25	200
Horizontal Tune	3.62	3.62	3.619
Vertical Tune	2.61	2.61	2.61
RF Voltage (kV)	3	2.2→1.8	1.5
Harmonic number	2	2→1	1
Tips	Circumference: 161.0014 m The middle layer is used to change the RF harmonic number.		

SIMULATION RESULT AND DISCUSSIO

Particle Distributions

The initial particle distribution for the simulation is that of completely unbunched beam. Because the electron cooling is not taken into account in the simulation, the initial momentum deviation is setting to the ±2‰ and the initial phase width is 2π [5]. In the simulation program, there are two model beam distribution which are uniform and Gaussian distribution.

Standard Capture Simulation

Using the Eq. 1, the capture procedure of the carbon beams in the CSRm was simulated. The RF voltage curve and RF parameters including bucket area, bucket height and phase value curve are loaded into the simulation program. During the capture period, any particle falls out of the bucket are viewed as lost. In order to make the accordance of the variable, the coordinate $(\phi, \Delta\delta/\delta_s)$ is transformed to $(\phi, \Delta E/E_s)$. The longitudinal phase space at the end of the capture period is shown in Fig. 3.

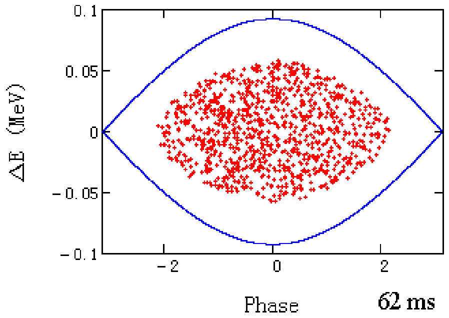

Figure 3: Phase space at the end of the capture period.

RF Voltage

During the beam capture process, RF voltage is needed to set a suitable value to capture the beam adiabatically to maintain high capture efficiency. The particles will loss if the RF capture voltage isn't large enough to match the beam momentum spread. In this simulation, different RF capture voltages with the same capture time are selected to obtain the optimal value. The figure 4 show the simulation result when the RF capture voltage is selected to 1 kV. From the result, we can see that much particle would locate outside the bucket if the RF capture voltage isn't large enough to match the beam momentum spread. The capture efficiency of the figure 4 simulation is only 65%.

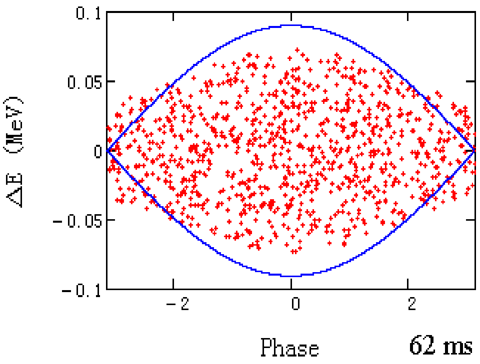

Figure 4: Phase Space under the unsuitable voltage

Capture Time

The capture time is usually defined as the time which the RF voltage increases from the zero to the capture voltage. According to the reference [6], the adiabatic capture criteria can be fulfilled if the capture time is much larger than the phase oscillation period. In the paper, the optimum capture time is choosing on the basis of the simulation results. Figure 5 illustrates the evolution of the longitudinal phase space within one millisecond capture time. In this simulation, only 50% particles were captured in the phase space area. During the operation of HIRFL-CSR, capture time is set to 64 milliseconds.

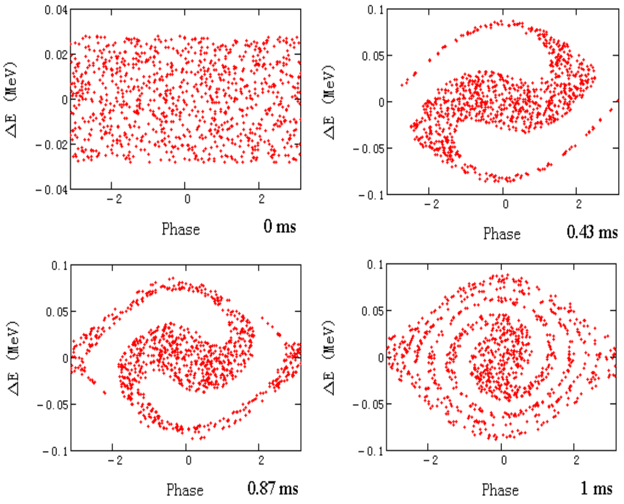

Figure 5: Evolution of longitudinal phase space with the one millisecond capture time.

Energy Deviation

If the beam actual energy isn't coinciding with the RF cycle, the capture efficiency would be low during the capture period. In the simulation, different beam energy is set to simulate the beam capture efficiency. Figure 6 shows the different capture efficiency under three beam acceptance. In the accelerator operation, the RF capture voltage must be matched with the momentum of injection beam.

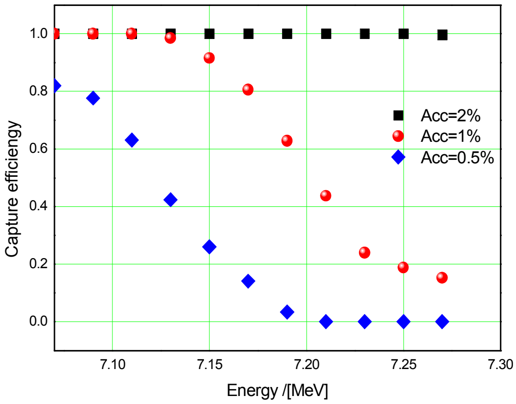

Figure 6: Capture efficiency under different setting energy circles.

CONCLUSIONS

In order to capture the costing beam to very high efficiency, the RF voltage and capture time should be set correctly. The beam actual energy must coincide with the real RF cavity cycle.

REFERENCES

[1] J.W. Xia, W.L. Zhan, B.W. Wei, et al., Nuclear Instruments and Methods A 488 (2002) 11.

[2] S.Y. Lee, Accelerator Physics Second ed., Shang Hai, 2006.

[3] K.Y. Ng, SPACE-CHARGE effect on bunch rotation, In: FERMILAB-FN-0702 August 2001.

[4] Peng Li, Y.J. Yuan, J.C. Yang, J.W. Xia, et al. Nuclear Instruments and Methods A 697 (2013) 17.

[5] L.J Mao, Simulation and Experiments of Electron Cooling in HIRFL-CSRm, Ph.D. thesis, Graduate University of Chinese Academy of Sciences, July 2008.

[6] W.T Weng, Fundaments Longitudinal Motion, BNL Report, Now. 7, 1988