GENERATION OF SHORT INTENSE HEAVY-ION PULSES IN HIAF*

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Abstract

The HIAF is a new accelerator complex under design at IMP to provide intense primary and radioactive ion beams for nuclear physics, atomic physics, high energy density physics and other applications. As a key part of HIAF, the Booster Ring (BRing) is designed to accumulate and accelerate heavy ion beams provided by iLinac up to high intensity and energy. The high quality, well focused, strongly bunched intense Uranium beam (U^{34+}) with high energy and high intensity of 10^{11} will open a new area for the HED physics research in laboratory.

Based on the beam parameters of $^{238}U^{34+}$ proposed by the BRing, the two critical issues of producing short bunch with high beam intensity are studied. One is efficiency of adiabatic capture which can be a necessary prerequisite to ensure the beam intensity, and the other one is bunch compression in longitudinal which is an effective way of producing short pulse duration bunch. In this article, the analytical calculations and tracking simulations are described, the capture efficiency and possible bunch length under the action of planning RF system are presented.

Introduction

In China, the Heavy Ion Research Facility at Lanzhou (HIRFL) [1] is one major national research facility focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. A series of remarkable results have been obtained at HIRFL. Based on the developments and experience with heavy ion beam accelerators, a new project HIAF[2] was proposed by IMP in 2009. The facility is being designed to provide intense primary and radioactive ion beams for nuclear physics, atomic physics, application research sciences and so on. The schematic layout of HIAF project is shown in Fig.1.

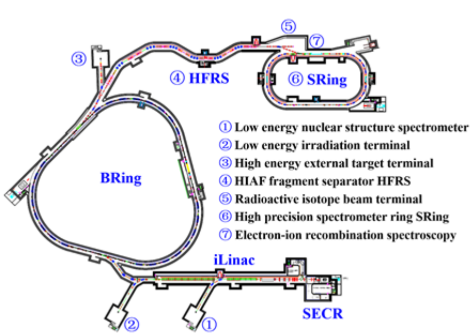

Figure 1: Layout of HIAF.

The HIAF project consists of ion sources, iLinac accelerator, synchrotrons and several experimental terminals. As a key part of the HIAF complex, BRing is a synchrotron being able to accumulate and accelerate full ion species with a circumference of 530 m and a maximum magnetic rigidity of 34 Tm，Table 1 shows the main configuration and parameters of the BRing.

Table 1: Main Parameters of BRing

Main parameters		
Circumference (m)	530	
Maximum magnetic rigidity (Tm)	34	
Momentum acceptance (Δp/p)	$\pm5.0\times10^{-3}$	
Injection beam parameters	$^{238}U^{34+}$	p
Injection energy (MeV/u)	17	48
Momentum spread (95%)	$\pm2\times10^{-3}$	$\pm2\times10^{-3}$
Particle number (ppp)	1.0×10^{11}	1.0×10^{12}

Capture and Acceleration

After two-plane painting injection and accumulation, the beam with the injection energy of 17 MeV/u is costing beam which will spread over 2π in rf phase and it has a momentum spread of $\Delta p/p = \pm 2 \times 10^{-3}$ (see Fig. 2.).

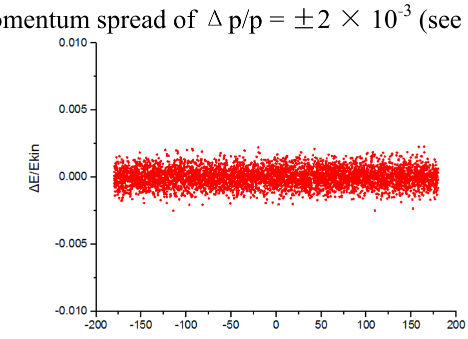

Figure 2: Initial distribution after accumulation.

The process of particle capture [3] in acceleration mode is one of the sources of the biggest particle losses, in order to increase the intensity of beams in an accelerator it is necessary to provide for the high efficiency of basic processes in the accelerator. so, the purpose of adiabatic capture is to optimize RF voltage settings and obtain the greatest efficiency of particle capture. The instabilities due to the space charge effects of intense beams will lead to beam loss seriously at the injection energy, so the beam must be captured and accumulated as soon as possible.

During the capture process, the capture voltage amplitude and the rf voltage ramping time are important parameters to be controlled. First we will start with the calculation of the required voltage which will provide enough stationary bucket area for safe beam capture. In order to avoid particle losses the bucket area generated by the capture voltage should be 1.5 times of phase-space area of the injected unbunched beam, and the required

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capture voltage should be 23kV, and then the rf voltage ramping time which should be as short as possible will be an important parameter to be studied. Figs. 3.1 - 3.6 show the longitudinal phase-space distribution at the end of the beam capture with different ramping time (10ms, 20ms, 30ms, 40ms, 50ms, 60ms), the longitudinal coordinates are azimuth – kinetic energy spread of the particles.

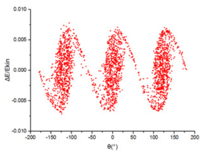
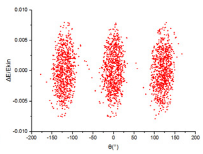
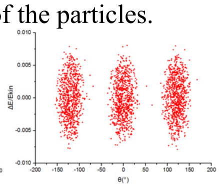

Figure 3.1: 10ms. Figure 3.2: 20ms. Figure 3.3: 30ms.

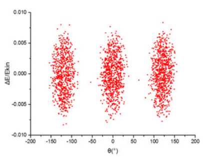
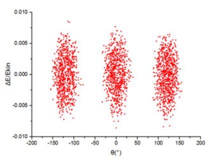
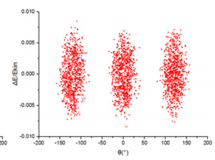

Figure 3.4: 40ms. Figure 3.5: 50ms. Figure 3.6: 60ms.

As it can be seen from these Fig. 3.1, the longitudinal phase-space distribution at the end of capture will become quite non-uniform if the rf voltage ramping is very rapid and significant particle loss of nearly 17% is accompanied, in other words, short capture time will lead to filamentation and great beam loss, as the capture time becomes longer, the beam distribution in phase space becomes more uniform(see Figs. 3.3 - 3.6) and beam loss (see Fig. 4.) is gradually reduced, the capture efficiency will exceed 95% if the capture time is more than 40ms. From Fig. 5, we can know than the momentum spread will have a big increase with the sudden jump of the rf voltage. Taking into account the above factors, we obtained the RF voltage curve during the whole capture process, as shown in Fig. 6.

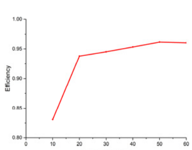
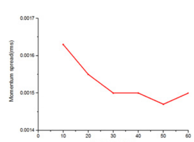
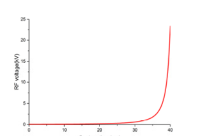

Figure 4: Capture efficiency. Figure 5: Momentum spread. Figure 6: Voltage curve.

After the capture is completed, we should transform stationary buckets into moving ones, which the beam acceleration will be started. Since the ionization cross sections decrease with beam energy, high ramp rates are significantly contributing to the minimization of ionization beam loss and the stabilization of the dynamic residual gas pressure, so, the acceleration will be conducted in two steps, the first step is fast acceleration of

U^{34+} beam with 12 T/s up to 0.7 T which the beam energy range is from injection energy of 17MeV/u to 200 MeV/u, and the second step is normal acceleration which the energy range is from 200MeV/u to the extraction energy. During the first step acceleration period, a voltage of 240kV is required to keep the synchronous particle on its ideal orbit. And the corresponding revolution frequency range is from 0.106~0.320MHz, the lower limit of frequency exceeds the working range of the cavity, so the RF cavity will work in a harmonic number 3, the rf frequency modulation range will extend from 0.319~0.961MHz. During the second step acceleration period, the required RF voltage is 31kV,the RF cavity will work in a harmonic number 1, and the rf frequency range will be from 0.320~0.476MHz, the detailed parameters is in Table 2.

Table 2: Basic Beam and RF Parameters

Ion species	**Ion species**	$^{238}U^{34+}$
Fast acceleration	energy(MeV/u)	17~200
	frev(MHz)	0.106~0.320
	Bdot(T/s)	12
	Voltage(kV)	240
	h	3
	frf(MHz)	0.319~0.961
Normal acceleration	Energy(MeV/u)	200~800
	h	1
	frev(MHz)=Frf(MHz)	0.320~0.476
	Bdot(T/s)	1
	Voltage(kV)	31

Debunch

Due to the first step acceleration is performed in a harmonic number 3, so the debunching will be used to change the number of bunches from 3 to 1 at the end of first step acceleration. During the debunch process, RF voltage is decreased from 240kV to initial voltage of 0.05kV, Figs. 7.1 - 7.6 shows the beam distribution in phase space at the end of debunch with different RF voltage decreasing time.

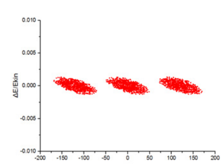
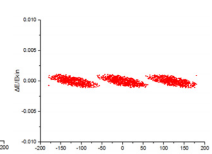
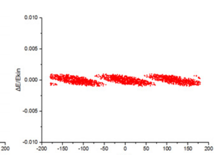

Figure 7.1: 10ms. Figure 7.2: 20ms. Figure 7.3: 30ms.

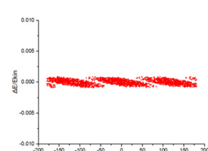
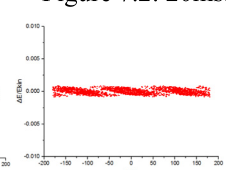
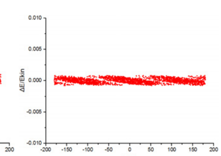

Figure 7.4: 40ms. Figure 7.5: 50ms. Figure 7.6: 60ms.

From these figures, we can see that, if the debunching time is not enough, the beam will not be continuous at the end of debunching, and the momentum spread (see Fig.8) will be larger if the RF voltage amplitude is increased in the second step acceleration. Taking into many factors,

ISBN 978-3-95450-182-3

such as momentum spread, operational cycle, the debunching time of 40ms is decided.

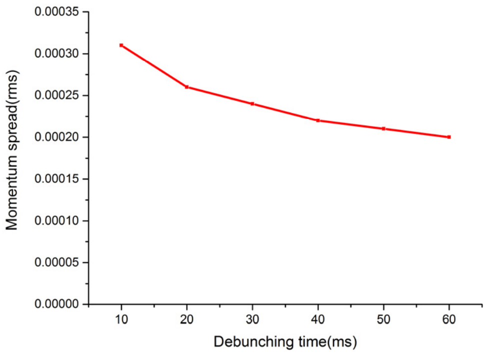

Figure 8: Momentum spread dependence of debunch time.

Compression

Short bunch can be gotten through non-adiabatic compression [4 - 8] and it is implemented by fast rotation in the longitudinal phase space, and the phase space rotation is initiated by a fast jump of RF voltage amplitude. We can know from the contents mentioned above, the RF voltage amplitude in two different acceleration stages are 240kV and 31kV respectively, so the bunch compression can be performed immediately after the second acceleration stage, we investigate the effect of three different initial voltage(the voltage will be in a range of nearly 0kV to 31kV at the moment of the beam energy reaches the required) on the bunch length and beam power of $^{238}U^{34+}$ at the energy of 400MeV/u , the beam distribution in phase space are shown in Figs. 9.1 - 9.4, the beam loss is detected, and the result is shown in Fig.10, the bunch length and beam power results are shown in Fig.11.

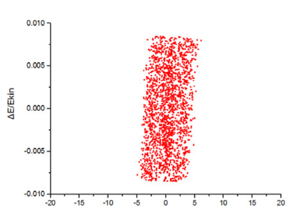

Figure 9.1: 1kV.

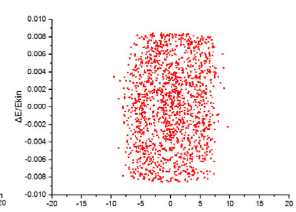

Figure 9.2: 10kV.

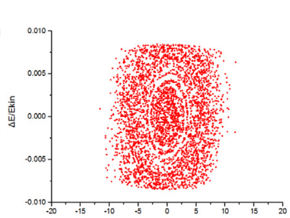

Figure 9.3: 20kV.

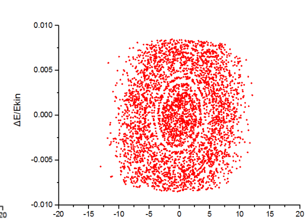

Figure 9.4: 30kV.

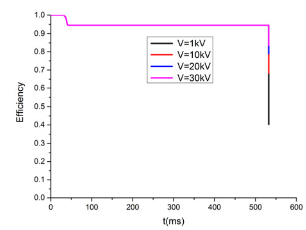

Figure 10: Beam loss.

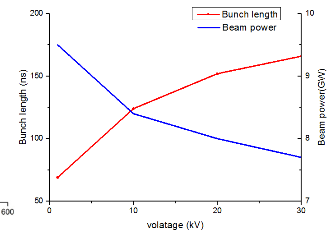

Figure 11: Bunch length and beam power.

From the results, we can see that, if the initial voltage is too small, there will have a large beam loss at the end of beam compression, in this case, the beam length of 69ns can be expected, and the beam power is 9.5GW, the voltage program during the whole process is shown in Fig. 12. With the initial voltage increase, the beam loss is decreased, but the bunch length is increased, and the beam power is decreased. If the initial voltage is 30kV, the beam length is 166ns, and the beam power is 7.7GW.

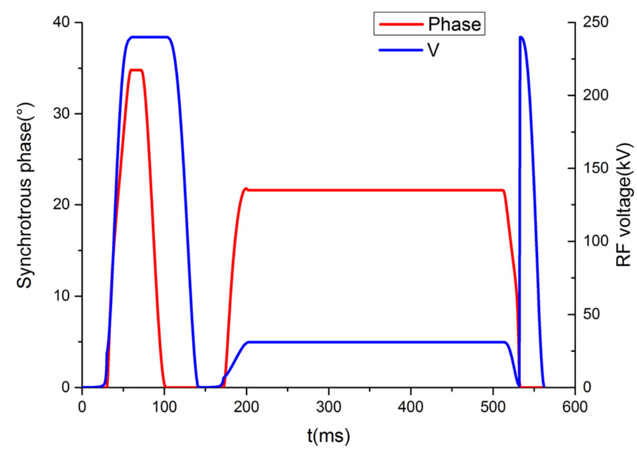

Figure 12: Voltage program during the whole process.

CONCLUSION

The short beam length of less than 100ns and high beam power of more than 9GW can be expected through bunch compression using a set of RF system in BRing at HIAF, which will greatly reduce the cost of high frequency system, but a big challenge is the construction and cooling of the Cavity due to the high duty factor.

The beam transmission efficiency during the beam capture and bunch compression need to be further optimized.

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ISBN 978-3-95450-182-3