Bunch compression study using the envelope model in CSRm*

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Abstract: The feasibility of attaining a short-pulse-duration heavy ion beam with a nanosecond pulse length is studied in the main ring of the Heavy Ion Research Facility in Lanzhou (HIRFL). Such a heavy ion beam can be produced by non-adiabatic compression, and it is implemented by fast rotation in the longitudinal phase space. In this paper, the possible beam parameters during longitudinal bunch compression are studied by using the envelope model. The result shows that a shortest heavy ion bunch $^{238}U^{28+}$ of 29 ns with energy of 200 MeV/u can be obtained, which can satisfy high energy density physics research.

Key words: CSRm, longitudinal compression, phase space rotation, HEDP

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1 Introduction

Heating matter by heavy ion beams plays an important role in the field of high energy density physics (HEDP) [1, 2]. HEDP and warm dense matter (WDM) studies are currently interesting in the fields of laser-plasma interactions, high-energy density astrophysics, equation-of-state sciences, high current discharges, etc. To produce WDM and HEDP by using ion beams, the beam energy should be focused in a local area of the target at a very short duration to create a higher energy density. That means a much higher beam power is needed.

In order to maximize the energy deposition of the heavy ion beam, the total number of particles has to be concentrate in a single bunch with a length that is as short as possible. A very efficient way to achieve a short heavy ion bunch is through strong longitudinal bunch compression [3, 4]. The CSRm [5] accelerator facility offers a unique possibility to generate such heavy ion beams with short pulse duration. In this paper, the possible beam dynamics parameters are estimated by using the envelope model. A simulation of longitudinal bunch compression in a heavy ion ring will be carried out as a part of the feasibility study for generating intense beams in the CSRm facility.

2 Beam dynamics simulation for bunch compression in CSRm

CSRm is the main ring of the ion cooling storage ring system at the Institute of Modern Physics in Lanzhou, China. Table 1 shows the parameters of CSRm. The heavy ion beams are injected first into the CSRm for the accumulation with e-cooling [6] and then are accelerated. The accelerated beam can be compressed longitudinally.

In order to achieve the greatest possible number of particles, the CSRm can be operated with a medium-charge state instead of highly charged ions. For the typical heavy ion beam $^{238}U^{28+}$, however, the bunch pulse length is about 500 ns at 200 MeV/u, which is longer than the required length of 50 ns for optimal target heating to generate high energy density plasma. So the ion pulse length has to be shortened by a factor of 10 or more.

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Table 1. CSRm parameters.

parameter	value
circumference/m	161
horizontal,vertical tunes	3.64,2.61
Max. magnetic rigity/Tm	12.05
Max. horizontal beta function/m	15.3
Max. vertical beta function/m	30.5
Max. dispersion function/m	5.4
transition gamma	5.418

A more efficient way to produce short bunches is through fast bunch compression with a 90° rotation of the longitudinal phase space ellipse. The phase space rotation is initiated by a fast jump of RF voltage amplitude. If the RF voltage jumps from $V_{\rm i}$ to $V_{\rm f}$ with the initial momentum $\Delta p/p$, the final bunch length $l_{\rm f}$ becomes

$$l_{\rm f} \propto \sqrt{A/q\cdot(V_{\rm i}/V_{\rm f})}\cdot\Delta p/p\,, \qquad (1)$$

where A is the mass number, q is the charge state. In contrast to the adiabatic capture process, where the voltage rise time has to be several times the synchrotron period, at fast compression the final voltage has to be reached as fast as possible, and the bunch compression ratio is decided by

$$r = l_{\rm f}/l_{\rm i} = \sqrt{V_{\rm i}/V_{\rm f}}\,, \qquad (2)$$

where $l_{\rm f}$ is the final bunch length, and $l_{\rm i}$ is the initial bunch length. The final bunch length depends on the ratio of the initial $V_{\rm i}$ and the final $V_{\rm f}$ voltages. From the above formulas, it can be concluded that if the initial momentum spread is small enough, and the final voltage is large enough, the bunch length will be shortened effectively after longitudinal rotation in phase space.

The longitudinal compression dynamics is calculated with the envelope equation [7]. The initial beam parameters are assumed in Table 2. Fig. 1 to 3 show the longitudinal dynamics during the bunch compression in CSRm.

Table 2. The initial beam parameters for bunch compression in CSRm.

ion species	$^{238}U^{28+}$
particle energh/(MeV/u)	200
number of beam ions	2×10^9
horizontal emittance/πmm·mrad	10
vertical emittance/πmm·mrad	10
momentum spread	1×10^{-3}

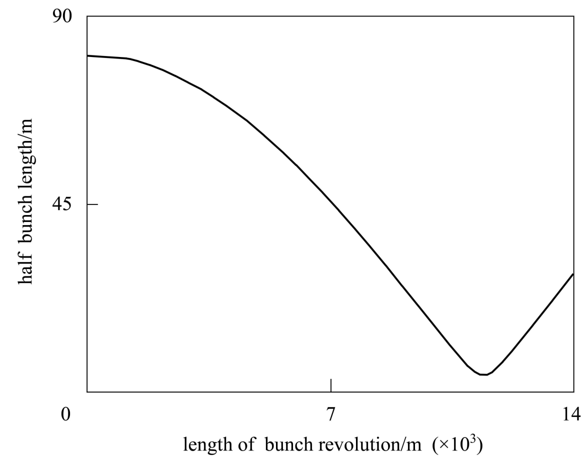

Fig. 1. Half-bunch length as a function of the revolution length.

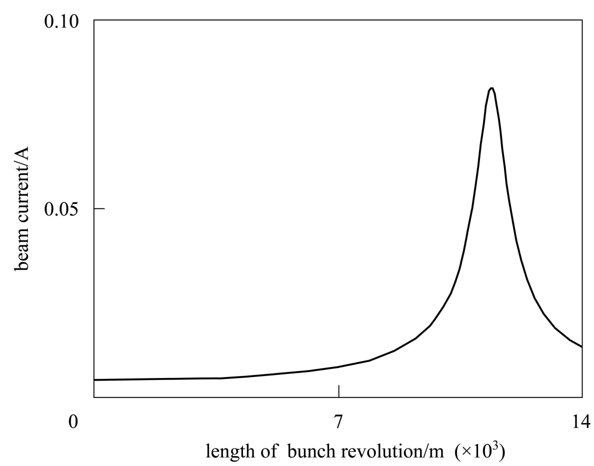

Fig. 2. Momentum spread as a function of the revolution length.

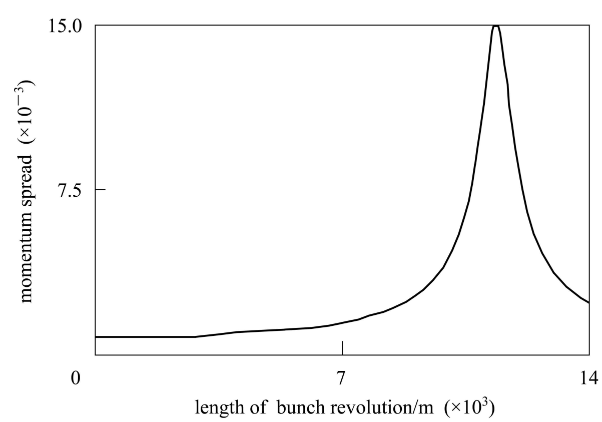

Fig. 3. Beam current as a function of the revolution length.

In this case, the initial voltage is 1 kV, and a final voltage of 380 kV is applied. During the bunch compression, the bunch length becomes smaller while the momentum spread becomes larger. From the above figures, it is known that the half bunch length is decreased from 80.5 m to 4.66 m. In other words, the bunch pulse length is decreased from 500 ns to 29 ns. The momentum spread is increased from 1×10^{-3} to 1.5×10^{-2} which is the limit of the momentum spread, and the peak current is increased from 0.005 A to 0.082 A. The compression corresponds to a 90° rotation of the initial phase space ellipse and takes place in 70.58 revolution laps. Similar compression physics is also under development at RIKEN [4] and SIS18 [7].

3 Conclusion

Bunch compression in the CSRm using the fast rotation scheme was investigated by using the envelope model. The initial beam parameters were restricted by the magnetic rigidity and space-charge tune shift. The momentum acceptance of the CSRm is 1.5%, so that the bunch can be compressed to the limitation of momentum spread. The calculation results indicate that a beam with a pulse duration of about 50ns can be expected from bunch compression in CSRm.

Transverse and longitudinal space-charge forces will be induced during the bunch compression. Future work will address the physics of the space-charge dominated beam.

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