SIMULATIONS OF LONGITUDINAL PHASE SPACE PAINTING FOR THE CSNS RCS INJECTION

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Abstract

China Spallation Neutron Source (CSNS) is a high power proton accelerator-based facility. Uncontrolled beam loss is a major concern in designing the high power proton accelerators to control the radio-activation level. For the Rapid Cycling Synchrotron (RCS) of the CSNS, the repetition frequency is too high for the longitudinal motion to be fully adiabatic. Significant beam loss happens during the RF capture and initial acceleration. To reduce the longitudinal beam loss, phase space painting is used in the RCS injection. This paper presents detailed simulation studies on the longitudinal motion in the RCS by using the ORBIT code, which include different beam chopping factors, momentum offsets, injection times and RF voltage patterns. With a trade-off between the longitudinal beam loss and transverse incoherent tune shift that will also result in beam losses, optimized longitudinal painting schemes are obtained.

INTRODUCTION

China Spallation Neutron Source (CSNS) project was proposed to provide a multidisciplinary platform for scientific research and applications based on neutron scattering techniques [1, 2]. It is an accelerator-based facility with a proton beam power of 100 kW and a repetition rate of 25 Hz. The high beam power proton accelerator complex consists of an 80 MeV linac as the injector and a 1.6 GeV rapid cycling synchrotron (RCS) as the main accelerator.

One of the primary concerns in designing high power proton facilities such as the CSNS is the radio-activation caused by uncontrolled beam loss that can limit the machine's availability and maintainability. Proton synchrotrons usually have beam loss as high as several tens of percent, mostly occurring during the injection, initial RF capture, and at the time of transition-energy crossing [3]. The design of the CSNS RCS injection system has been attempting to reduce the beam loss by increasing the beam emmittance and beam uniformity to alleviate the transverse space charge effects [4, 5]. This study is devoted to the longitudinal motion in the RCS. The beam loss due to the RF capture, acceleration and the bunch factor is the primary factor to determine the longitudinal injection mode and the RF pattern in the RCS.

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RF CAPTURE AND ACCELERATION IN THE RCS

In the RCS, the RF cycle can be divided into four periods (Fig.1): injection, RF capture, acceleration and switched-off after extraction. Significant beam loss usually occurs during the RF capture (before the first critical point in Fig.1). The second critical point is at the mid-acceleration when the phase space acceptance decreases due to large synchronous phases that are needed for the fast acceleration. With a maximum RF voltage of 168 kV, the synchronous phase will reach to about 45^{o}.

The RF capture process is adiabatic if its duration is long enough compared with the synchrotron period T_s, which is usually true in slow cycling synchrotrons. With an adiabatic capture, the capture efficiency is high and the dilution in the longitudinal emittance due to the filamentation effect is small. However, in a rapid cycling synchrotron such as the CSNS RCS, the adiabatic condition does not hold really and a large emittance dilution will happen if the initial beam is a coasting one. The high repetition frequency of the RCS leaves little time for the RF capture to be fully adiabatic. As the magnetic field ramps very gently near its minimum value, the short interval before the minimum magnetic field is suitable for the beam injection to increase time for adiabatic capture. The voltage amplitude of the ring RF system must be programmed according to the increasing synchronous phase to ensure a sufficiently large RF bucket area to minimize particle losses at the same time to keep the acceleration pace synchronized with the magnetic field throughout the RF cycle. Other methods, e.g. a chopped beam injection, are helpful to reduce the beam loss during the RF capture. Both continuous and chopped beam injections are studied in an effort to search the appropriate schemes. However, the chopped beam injection usually reduces the bunch factor. The painting by momentum offset is used to cure the problem.

SIMULATIONS WITH ORBIT

Due to the nature that the longitudinal motion is independent of the transverse motion in proton synchrotrons, here we carry out simulations only on the longitudinal motion. However, the longitudinal motion has an impact on the transverse motion by the transverse incoherent tune shift. Therefore, the longitudinal studies also cover the impact before we take full-3D simulations. The code ORBIT [6] has been used for the beam dynamics simulations including the space charge effect in the RCS. It can perform simulations either on the 1D longitudinal motion or on the 2D transverse motion or on the 3D motion. The transversal simulations of CSNS have presented optimized transversal painting schemes [4, 5].

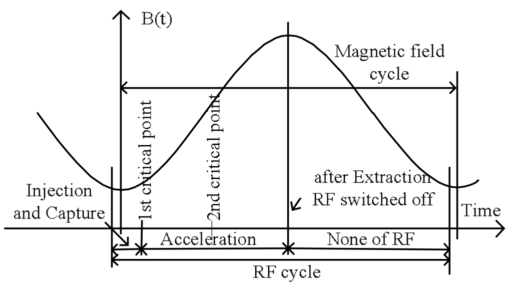

Figure 1: Magnetic field and RF cycle.

RF Voltage Pattern

In a synchrotron, the energy gain per revolution is linked to the ramping speed of the magnetic field $\dot{B}$ in dipole magnets by

$$V \sin\varphi_s = 2\pi R\rho\dot{B}, \qquad (1)$$

where R is the mean radius of the ring, ρ is the radius of curvature in dipole magnets.

In a rapid cycling synchrotron, a cosine-like magnetic field with respect to time has to be used as a White circuit power supply system is necessary to save the energy and alleviate the impact of very sharp load to the electricity network [1]. To keep the acceleration in pace with the ramping magnetic field, the RF voltage and the synchronous phase should vary according to Eq.(1). The choosing of the maximum RF voltage and the largest excursion φ_s is a compromise between the cost of the RF system with a higher voltage and the beam loss increase with a large φ_s. In the preliminary design, the maximum RF voltage of 168 kV and the maximum synchronous phase of 45° have been chosen. However, the detailed RF voltage and synchronous phase patterns, together with a good longitudinal injection scheme, are still very important to minimize the beam loss.

On the other hand, the RCS RF system design concerns not only the maximum RF voltage but also the RF voltage limitation, say about 100 kV in the first milliseconds due to the disfavored frequency range for the ferrite-loaded cavities. Therefore, all the studies on the longitudinal motion are based on these conditions.

Chopped Beam Injection

As mentioned above, the continuous beam injection scheme has relatively low RF capture efficiency, thus the injection with a chopped beam has also been studied. The purpose of chopping the beam is to create a macro-time structure in the linac beam by a chopper in the linac front-end so that the macro pulse can fit properly into the RF buckets in the RCS. Herein, the chopping factors of 100%, 90%, 83%, 75%, 60% and 50% are used for simulations, where the chopping factor is defined as the ratio of macro bunch full length to RCS RF voltage wave length at the injection, i.e. smaller chopping factor means more beam is chopped. Figure 2 shows the simulation results of the beam loss and the transverse tune shift dependent on the chopping factor. More particles are lost as the chopping factor increases. However, beam chopping does increase the transverse tune shift, especially in the injection period. The transverse tune shift Δν can be calculated by the following formula [7]:

$$\Delta\nu = -\frac{r_p n_t}{2\pi\beta^2\gamma^2\varepsilon B_f} \qquad (2)$$

here r_p =1.53×10^{-18}m is the classical radius of proton, n_t the accumulated particles in the RCS, β and γ the Lorentz's relativistic factors, ε the transverse emittance and B_f the bunch factor.

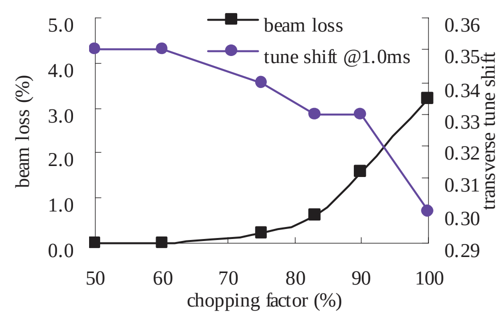

Figure 2: Longitudinal beam loss and transverse tune shift vs. chopping factor (1.0 ms is the time after the minimum magnetic field).

Momentum Offset Painting

If the beam from linac is injected into just the center of the RF bucket, the charge intensity at the bucket center becomes fairly high, and the transverse tune shift or spread becomes very large. Injection with a momentum offset can avoid such problem. With a momentum offset, the longitudinal painting will form a hollow beam and the charge intensity along the bunch length will become flattened. Figure 3 shows the simulation results of the beam loss and transverse tune shift with momentum offsets. Here, the chopping factor is 83%. A larger momentum offset will result in a larger beam loss but will efficiently decrease the transverse tune shift.

Starting Time of Injection

The time of adiabatic capture is extended when the beam is injected during a short interval before the minimum magnetic field. Figure 4 shows the beam loss and transverse tune shift with different injection starting times. The earlier starting time corresponds to the lower beam loss and the larger turn shift.

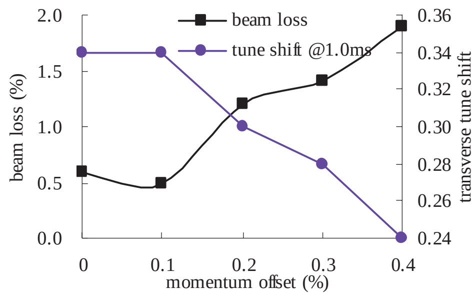

Figure 3: Longitudinal beam loss and transverse tune shift vs. momentum offset with the chopping factor of 83%.

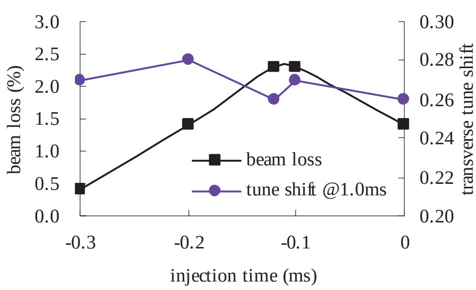

Figure 4: Longitudinal beam loss and transverse tune shift vs. injection time with the chopping factor of 83% and momentum offset of 0.25%.

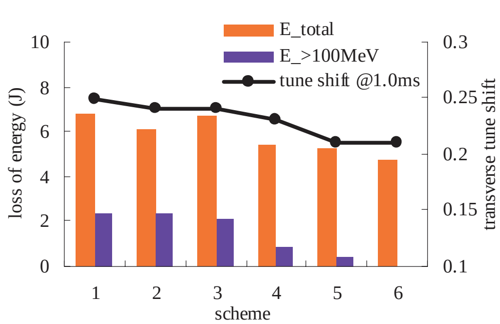

Figure 5: Longitudinal loss of energy and transverse tune shift vs. injection schemes (1 - 100% 0.49% -0.3ms; 2 - 90% 0.50% -0.3ms; 3 - 83% 0.52% -0.3ms; 4 - 75% 0.50% -0.3ms; 5 - 60% 0.63% 0.0ms; 6 - 50% 0.73% 0.0ms).

Optimized Schemes

The simulation results show that beam chopping, momentum offset painting and injection time all have the contradictory effects on the longitudinal beam loss and the transverse tune shift. This indicates an optimized longitudinal injection scheme should be a compromise between the longitudinal beam loss and the transverse tune shift. Provided the maximum longitudinal beam loss is limited by 2%, the maximum momentum offsets are obtained relative to every chopping factor and injection time. The schemes with minimum transverse tune shifts for difference chopping factors are showed in figure 5. The losses in the total beam energy and in the beam energy above 100 MeV are illustrated together. It is obvious that the schemes with smaller chopping factor and larger momentum offset look promising longitudinal painting schemes. Finally, it will depend on the 3D studies and the proton hit on the stripping foil to choose the longitudinal scheme.

CONCLUSION

The RF capture and acceleration processes in the CSNS RCS are simulated by using the ORBIT code. The optimized longitudinal painting schemes are given to control the longitudinal beam loss and reduce the transverse tune shift. The present study only focuses on the longitudinal motion. Future work will be fully three-dimensional by involving transverse phase space painting and the correlativity between the transverse and longitudinal motions.

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