HIGH INTENSITY ASPECTS OF THE CSNS ACCELERATORS

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Abstract

China Spallation Neutron Source is a multi-disciplinary research platform under detailed technical design, which is based on a high power proton accelerator complex. Beam loss control is key in designing and operating the accelerator complex of high beam power. Major high intensity aspects of the accelerators that may result in beam losses are discussed in the paper. The emittance growth due to space charge effects in the linac and the rapid cycling synchrotron (RCS), the RF trapping and the injection/extraction in the RCS are the major loss sources. The measures to reduce the loss rate and the collimation methods in the accelerators are presented. Some beam loading effects to the RF systems in the linac and in the RCS, and the uniformization of the beam spot at the spallation target by non-linear magnets are also mentioned.

INTRODUCTION

CSNS (China Spallation Neutron Source) is a project under construction, which will be a unique facility in China for multi-disciplinary research using neutron scattering techniques. The CSNS accelerator complex, which consists of a medium-energy linac and a Rapid Cycling Synchrotron (RCS), is to deliver proton beams of 100 kW at Phase One, and progressively upgraded to 200 kW at Phase Two and 500 kW at Phase Three. The upgrading path in beam power is via the increase in linac energy and more accumulated particles in the RCS. The main parameters of the accelerators are shown in Table 1.

Table 1: Main Parameters of the CSNS Accelerators

	CSNS-I	CSNS-II	CSNS-III
Beam power (kW)	100	200	500
Repetition rate (Hz)	25	25	25
Average current (μA)	62.5	125	312.5
Proton energy (GeV)	1.6	1.6	1.6
Linac beam energy (MeV)	80	132	250
Linac peak current (mA)	15	30	40
Linac duty factor (%)	1.05	1.05	1.7
Linac cavities	4 DTL	+3 DTL	+SCL
RCS circumference (m)	228	228	228
RCS accumulated particles	1.6×10^{13}	3.1×10^{13}	7.8×10^{13}
RCS RF cavities (~20 kV/cavity)	8 (H=2)	+3 (H=4)	-

Note: "+" means added equipments from the previous phase.

SPACE CHARGE EFFECTS

Space charge effects play important roles in both the linac and the RCS, even in the beam transport line LRBT (Linac to RCS Beam Transport). They are the main causes of the emittance growth and beam loss.

Linac

Strong space charge effects have been found in high intensity linac including the CSNS linac (see Figure 1). They are the major causes for the emittance growth from the ion source to the DTL end.

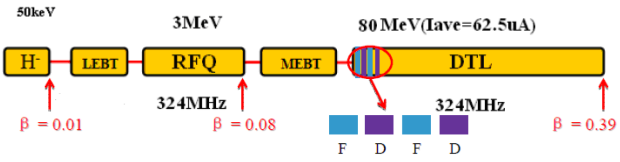


Figure 1: Schematic layout of CSNS-I linac.

In the LEBT, magnetic focusing by solenoids has been used to neutralize the space charge effect. A fast electrical chopper is placed just before the RFQ. The three solenoids can also produce symmetric emittance at the RFQ entrance for a non-symmetric beam from the Penning H^- ion source by using coupling effect [1]. However, quadrupoles are needed for a good matching when space charge is included even with a neutralization of 90% [2].

In RFQ, based on the experience of the ADS RFQ [3], the CSNS RFQ is expected to carry out high intensity beam up to 50 mA with good transmission efficiency.

In MEBT, a shorter MEBT without choppers has been designed following the successful test of the LEBT chopper. The transverse matching and longitudinal bunching are critical to control emittance growth during the structure transition from the RFQ to the DTL, since this is the most space charge dominant section in the linac. The matching should be adaptable to different peak currents in the CSNS phases.

On the one hand, linear space charge effect can be compensated by adjusting the transverse focusing and synchronous phase. The zero-current phase advance changes smoothly with beam energy to follow the tune depression change, as shown in Figure 2. On the other hand, non-linear space charge effect is difficult to be compensated and will result in betatron mismatch and filamentation. The coupling effect between the transverse and longitudinal phase planes induced by the space charge force will lead to the exchange of thermal energy or emittance between the two planes. This latter is also called equipartitioning, and was studied for the case of CSNS linac [4-5]. The selection of tunes is important to avoid the thermal energy transfer, as three different cases are compared in Figure 3 and 4. The focusing parameters of the linac have been selected based on the studies.

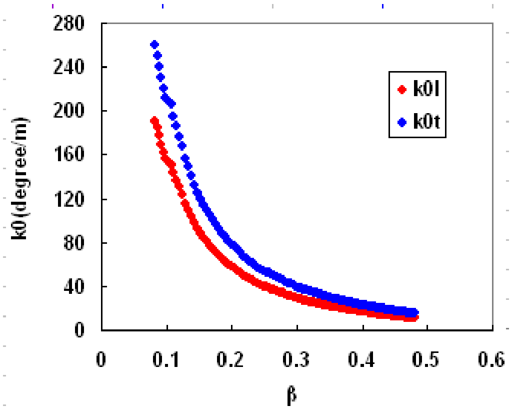


Figure 2: Zero-current phase advance per meter in CSNS DTL.

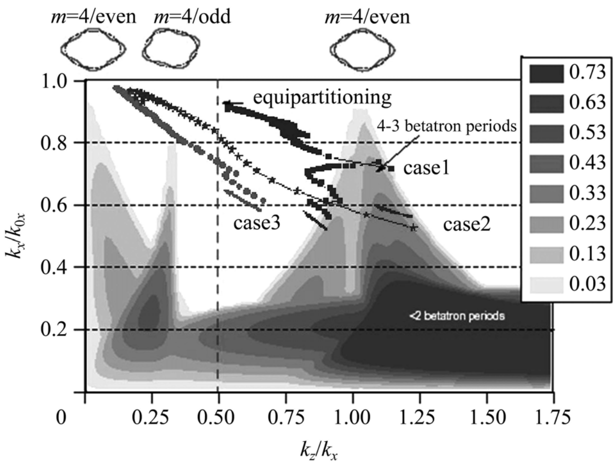
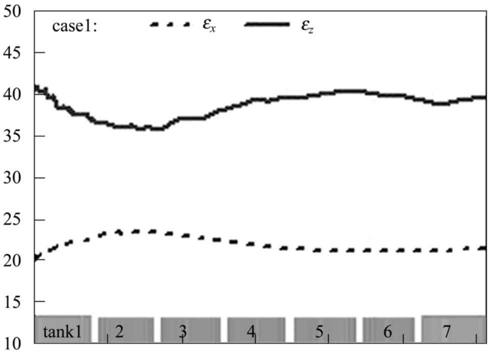


Figure 3: Stability chart for the CSNS DTL. Simulations are with nominal emittance ratio $\varepsilon_z/\varepsilon_{x,y}$=2 and for three different cases



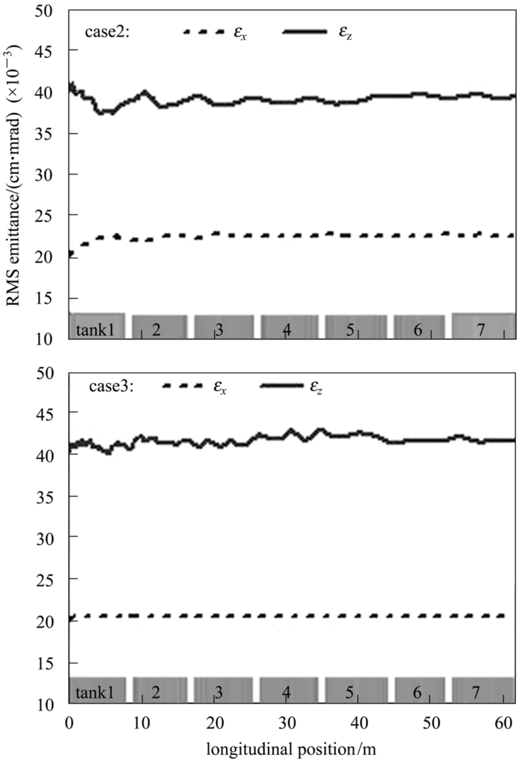


Figure 4: RMS emittance evolutions corresponding to the three cases in Figure 3.

LRBT

LRBT has been designed to have a long reserved space for the future linac upgrading, which is filled with periodic triplet cells. Space charge effects are found important especially in the entrance matching section and the bending section. However, it is still an emittance dominant beam line, and the linear space charge effect can be well compensated by adjusting the focusing elements including quadrupoles and a debuncher. The debuncher will suppress the momentum spread increase due to the longitudinal space charge to within ±0.1% that is required for the injection into the RCS. One interesting effect due to space charge is that the stripped protons by the foil scrapers are focused by the main H^- beam (see Figure 5).

RCS

The RCS lattice is designed to be four-fold, all triplet cells and have separate-function long straights as shown in Figure 6. Space charge effects in the RCS have been studying by using ORBIT and SIMPSONS codes [6]. This includes both transverse and longitudinal space charge effects in the injection painting process, RF capture and acceleration. The working point, injection painting scheme and RF voltage pattern have been selected based on the simulations. The longitudinal painting by using off-momentum injection helps reducing the tune shift/spread. The maximum Laslett tune shift at

CSNS-I is about -0.3. The transverse emittance growth due to the space charge is the most important source of beam losses. Both correlated and anti-correlated painting schemes have been studied for controlling of the emittance growth [7].

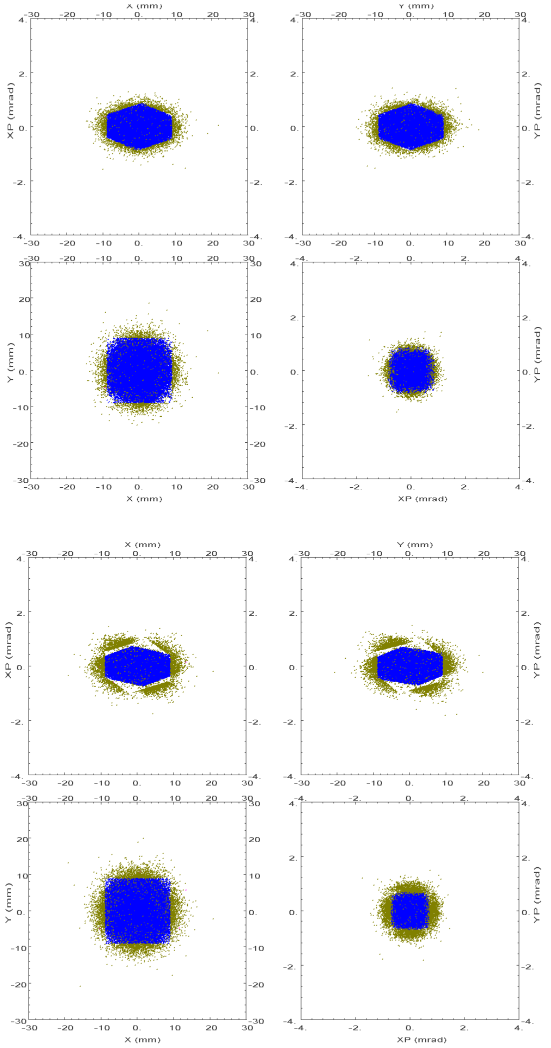


Figure 5: Beam distributions in phase spaces at the third foil scraper (left: without space charge; right: with space charge. Blue for H⁻ particles, cyan for protons).

In order to reduce the tune excursion, higher order harmonic RF cavities will be added in the upgrading phases [8]. A dual harmonic RF system composed of eight second-harmonic (H2) cavities and three fourth-harmonic (H4) cavities at CSNS-II can limit the Laslett tune shift within -0.2 (see Figure 7). At CSNS-I, the dual harmonic RF working mode by transforming one of the eight H2 cavities into H4 in the first milliseconds and then returning to H2 is also under study.

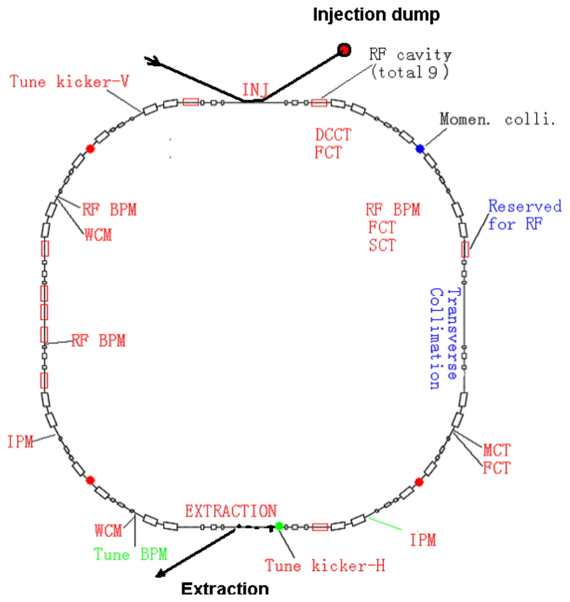


Figure 6: Functional layout of the RCS.

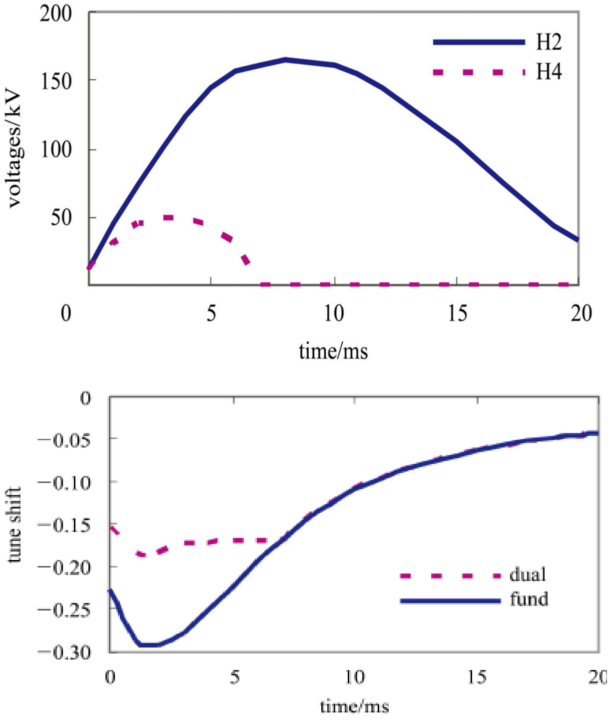


Figure 7: Dual harmonic acceleration at CSNS-II. Upper: voltage patterns for the two harmonics; lower: Laslett tune shifts with and without dual harmonic acceleration.

BEAM LOSSES AND COLLIMATION

Although total beam loss power in high intensity accelerators is very important, the uncontrolled beam is more important for hands-on maintenance. At CSNS, the beam loss rate regulation of 1 W/m is also obeyed as in other similar facilities. Therefore, efforts have been paid to reduce the total beam loss and localize the lost particles by collimators.

Beam Loss Control in the Linac

Emittance growth due to beam chopping in LEBT will result in larger beam loss in the RFQ. Certainly, beam loss is more important in the DTL tanks where the energy is higher. Although the geometrical rms emittance decreases with beam energy and the apertures of the drift tubes increase with higher β, the emittance growth due to the space charge effect and all kinds of errors can still lead to possible beam losses in the DTL tanks. Therefore, careful tuning of the linac is necessary.

Collimation in the LRBT

In order to reduce beam losses at the injection, e.g. H^- particles missing the stripping foil, and obtain better painting results, the H^- beam is well collimated to be within 4 πmm·mrad by foil scrapers in the LRBT [9-10]. Three groups of four foil strippers are combined together with triplet focusing cells of a phase advance of 60° in both the transverse planes, and this will produce ideal emittance of hexagonal shape in the two planes (see Figure 5). The converted protons are transported along with the main H^- beam until the downstream switch magnet where the protons are directed to the experimental area for medium-energy proton applications, whereas the H^- beam is injected into the RCS. The thickness of the scraping foils is optimized as a trade-off between the beam loss due to partially-stripped H0 particles and the multiple scattering effect in the foils.

Beam Loss and Collimation in the RCS

The beam loss mechanisms in the RCS have been studied. The main loss sources are: 1) loss at the injection stripping foil due to nuclear scattering and multiple scattering, and non-stripped H^- particles; 2) RF capture loss; 3) transverse emittance growth due to space charge and nonlinear resonance crossing; 4) loss at the extraction septum due to the misfiring of the kickers; 5) accidental total beam loss. Fortunately, most particle losses happen at low energy or close to the injection energy. This means that the loss power is relatively lower on the one hand and that the collimation is easier on the other hand. The total beam loss rate in the RCS is estimated to be within 5% at CSNS-I, 2% at CSNS-II and 1% at CSNS-III, and this means a total beam loss power less than 1 kW in the RCS.

A good collimation system with the collimation efficiency higher than 90% is designed. Both transverse collimation and momentum collimation are considered. A dispersion-free long straight section provides the required space and phase advances for designing a two-stage transverse collimation system, which is made of a primary collimator to scatter the halo particles and two to four secondary collimators to collect the scattered particles [11] (see Figure 8). The lattice has been designed to provide high normalized dispersion at the middle points of the arcs, where is ideal to place a primary momentum collimator. A combined momentum collimation system has been studied by employing both the transverse secondary collimators and dedicated secondary momentum collimators at the arcs [12].

To reduce the beam loss at the extraction, a method using slow bumps at both the transverse collimation and the extraction regions has been proposed to remove some halo particles at low energy and is under detailed study [13].

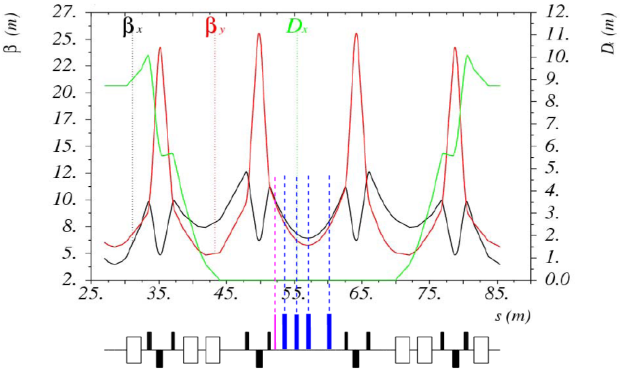


Figure 8: Transverse collimators along with a ring superperiod. The primary (pink) & secondary (blue) collimators are shown with betatron functions.

BEAM SPOT UNIFORMIZATION AT THE SPALLATION TARGET

In order to prolong the lifetimes of the spallation target and the proton beam window and decrease the direct irradiation of the proton beam to the moderators, special non-linear magnets – step-like field magnets (SFM) have been designed in the RTBT [14]. Two pairs of SFMs can transform the irregular distribution of the extracted beam from the RCS into a uniform-like distribution at the target, and reduce the halo part outside of the target. From CSNS-I to CSNS-III, the core emittance of the extracted beam from the RCS increases and the spot size also increases to control current density at the target, as shown in Figure 9 and in Table 3. The distribution transformation system has been designed to adapt the changes. Another option using octupoles is also under study.

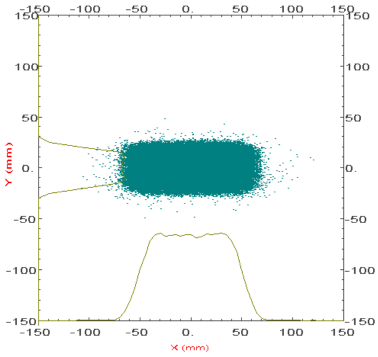


Figure 9: Transformed beam distribution at the CSNS-III target.

Table 2: Beam Characteristics at the Target

	w/o SFM	with SFM
Particles out of footprint	2.2%	2.0%
Particle out of target	0.64%	0.16%
Peak density (10^{-2} A/m^2)	5.51	2.52

OTHER HIGH INTENSITY ASPECTS IN THE CSNS UPGRADING PHASES

Beam loading effect: The beam injection into the RCS at CSNS-I can work with non-chopped beam or chopped beam. In the first case, the RF voltage should start from very low value, e.g. about 10 kV, to obtain quasi-adiabatic RF capture. However, a low RF voltage also means strong beam loading effect in the RF system. Sophisticated LLRF system including feed-forward loop is under developing to address this issue. At CSNS-II or CSNS-III, only chopped beam will be used so that higher RF voltage is used to allow the painting in the longitudinal phase plane, but beam loading effect is still important as the circulating beam current will increases.

The injection stripping foil becomes an important issue at CSNS-III, although it is considered a relatively easy problem. With more accumulated particles in the RCS, the foil lifetime due to temperature rise becomes a concern. Preliminary study shows that it is still less critical than that at SNS. Relatively thick foils are used at CSNS to have a good stripping efficiency, as the CSNS injection system is designed to have a low power beam dump at injection and only H0 particles are sent to the dump after being stripped by the second stripping foil [15].

CONCLUSIONS

CSNS has been designed to tackle a high-intensity beam that will be increased to 200 kW and 500 kW in the upgrading phases from 100 kW in the first phase. Linac energy will be increased to alleviate the space charge effects with more accumulated particles in the RCS in the upgrading phases, and a dual-harmonic RF system will be built for the same purpose. Beam loss control and collimation system are key in operating the accelerator complex at high beam power, and they have been studied with great cares. Other high-intensity aspects such as beam uniformization at the spallation target and beam loading effect have also been studied.

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