COMBINED MOMENTUM COLLIMATION METHOD IN HIGH-INTENSITY RAPID CYCLING PROTON SYNCHROTRONS*

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Abstract

A new momentum collimation method – so-called combined momentum collimation method in high-intensity synchrotrons is proposed and studied here, which makes use two-stage collimation in both the longitudinal and the transverse phase planes. The primary collimator is placed at a high-dispersion location of an arc, and the longitudinal and transverse secondary collimators are in the same arc and in the down-stream dispersion-free long straight section, respectively. The particles with positive momentum deviations will be scattered and degraded by a carbon scraper and then cleaned mainly by the transverse collimators, whereas the particles with negative momentum deviations will be scattered by a tantalum scraper and mainly cleaned by the longitudinal secondary collimators in the successive turns. Numerical simulation results using TURTLE and ORBIT codes show that this method gives high collimation efficiency for medium-energy synchrotrons. The studies have also shown two interesting effects: one is that the momentum collimation is strongly dependent on the transverse beam correlation; the other is that the material for the primary collimator plays an important role in the method.

INTRODUCTION

Momentum collimation in a high-intensity proton rapid cycling synchrotron (RCS) is a very important issue. In this paper, the emphasis is on the momentum collimation for a high-intensity compact rapid cycling proton synchrotron. For large synchrotrons such as LHC at CERN and main injector in FERMILAB, there are sufficient spaces to allocate a full two-stage momentum collimation system in one of the arcs. However, for compact synchrotrons, the straight sections in arcs are much limited. Thus, simplified momentum collimation method is employed for the latter case. The two reference methods are: the ISIS method by using two-stage massive collimators; the J-PARC method by using a standard two-stage collimation but with the secondary collimators in the downstream dispersion-free straight section. The former has the two collimators within the same long dispersive straight section, and the latter has the primary collimator in one of the arc sections and shares the secondary collimators with the transverse collimation system. The new momentum collimation method proposed here will be a combined collimation method: it will be a full two-stage collimation method, but with secondary collimators in one arc straight sections and one dispersion-free straight section. We take the CSNS/RCS as the example to study the collimation mechanism, but the method is general and applicable to other similar machines.

The China Spallation Neutron Source (CSNS) of several hundreds kW is a short-pulse accelerator facility mainly consisting of an H$^-$ linac and a proton rapid cycling synchrotron (RCS) [1].

MOMENTUM COLLIMATION SCHEME

Combined Method for Momentum Collimation

The CSNS/RCS lattice of four-fold and all-triplet cells has been designed to provide good conditions to place momentum collimators. Figure 1 shows the lattice functions and the momentum collimation scheme.

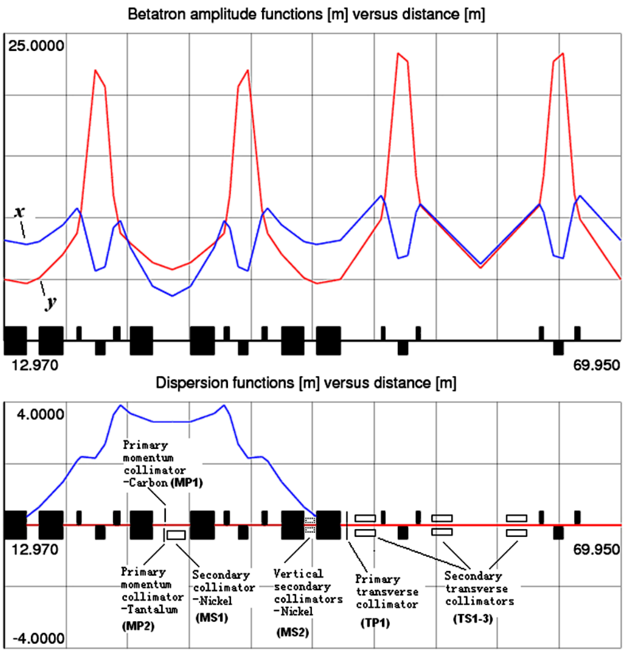

Figure 1: Triplet lattice and the momentum collimation scheme for CSNS/RCS.

The combined momentum collimation scheme is detailed here [2]:1) Combining two separate two-stage collimation systems and a single-stage collimation system. The primary momentum collimator is placed at a location of high normalized dispersion. The whole transverse collimation system will be employed as the secondary collimators. The second two-stage collimation is composed of the primary momentum collimator and a secondary momentum collimator closely adjacent to the former, but the collection of the scattering particles is executed in successive turns. The single-stage collimation

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*This work was supported by the National Natural Science Foundation of China (10975150, 10775153).

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is that for some particles only the secondary momentum collimator at arc takes the effect. 2) Using a thin foil (MP2 in Figure1) of higher atomic number at negative X (X as horizontal) as one part of the primary momentum collimator to produce significant scattering but with little energy loss, this can help minimizing the decrease in I_x (Courant-Snyder invariant) due to the longitudinal-horizontal coupling effect, so it facilitates the collection of the particles by the transverse collimators. 3) Using a thin carbon foil (MP1 in Figure1) at positive X to produce significant increase in I_x while keeping a modest scattering. This will help the collection of the scattered particles by the transverse collimation system. 4) Using a thick high-Z jaw (MS1 in Figure1) as a secondary momentum collimator along with the thin high-Z foil at the negative X position of 0.5-1.0 mm further from the reference orbit. The betatron motion in successive turns can make the collimator effective in collecting the scattered particles having a small I_x but a large momentum deviation. These particles are difficult to be collected by the transverse collimators. At the same time, this collimator also acts as a single-stage collimator. 5) A second thick collimator (MS2 in Figure1) located in the downstream arc section to localize some of the lost particles due to large angle scattering in the primary momentum collimator. Parameters of the collimation system in the CSNS RCS are given in Table 1.

Table 1：Parameters of the Collimators in the CSNS RCS at energy level of 80 MeV

Collimators	Primary		Secondary	
Material	Ta foil	C foil	1st W block	2nd W block
Longi. Pos. (m)	28.465	28.465	28.515	40.910
Thickness (mm)	0.0013	0.05	30	30
Shape	Erect	Erect	Erect	Erect
Trans. Pos.	$-X$	$+X$	$-X$	$\pm Y$
Off X-axis (mm)	-71.08	+71.08	-71.58	±45.79

Longitudinal-transverse Coupling Effect and material choice for momentum collimators

As mentioned in Ref. [3-4], the energy loss in a thin primary collimator at dispersive locations with positive momentum deviation will increase I_x in betatron motion, which is helpful for the collimation of those particles in the dispersion-free straight. In the contrary, it will decrease I_x if the momentum deviation is negative and thus is not favoured.

Material choice for the primary momentum scraper is important here. We can find that different materials have different effect in energy loss and scattering angle. For different materials but the same rms scattering angle, the relative change in momentum due to the passing thru the foil is different. For material of higher atomic number, the relative change in momentum is smaller. For example, the relative momentum loss is only one seventh in Tantalum than in carbon, e.g. 1.0×10^{-4} and 7.3×10^{-4} at 80 MeV, respectively, and this rule holds for different beam energy. Therefore, a tantalum foil is chosen at negative X and a carbon foil is chosen at positive X for the primary collimators to play the corresponding roles.

For the thick collimators in the arc, a material with a short stopping range and a small scattering angle per unit length is favoured to obtain high collimation efficiency. In theory, a material of large density and low-Z is helpful. The elements or their alloys in Column VIII in the Periodic Table of the Elements look to be good candidates, e.g. nickel or tungsten.

Beam correlation and collimation

One can fill the beam emittance in an RCS by correlated or anti-correlated injection painting. When the particles with larger momentum deviation pass through a primary momentum collimator placed at larger X position, the correlation will play an important role in the vertical plane. If the beam is anti-correlated, when the inner particles in the horizontal emittance with a large negative momentum deviation are to be collimated, they have a large I_y. This means that the scattering is perhaps too strong in the vertical plane and results in significant beam loss in the rest of arc. The similar situation happens at collimating the particles with large I_x and I_y when the beam is correlated. As shown at next section, the anti-correlated beam is preferred for the combined collimation method.

SIMULATION RESULTS

To analyze the correlation effect, hollow beams in phase spaces are produced by using a self-made FORTRAN program to represent either correlated or anti-correlated or non-correlated beams. This will also make the simulations much more efficiently with relatively less particles.

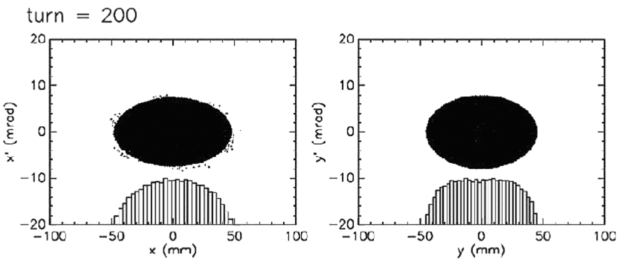

Figure 2: Distributions in the phase spaces with one-turn injection and after 200 turns at the injection point with an anti-correlated beam. The injection energy is 80 MeV.

ORBIT code [5] is employed to carry out the collimation in multi-turn mode including acceleration. Both hollow and filled beams are used in the simulations; beam distribution of the later is shown in Figure 2. To simplify the study, the transverse collimators are presented by a single black-body absorber but with a collimation efficiency of about 100% or 95%. Table 2 gives the collimation efficiencies and the swiftness of different collimation mechanism with hollow beams. From the simulation results, it can be seen that the collimation efficiency with an anti-correlated beam is much higher than that with a correlated beam, except for the innermost particles with very small I_x.

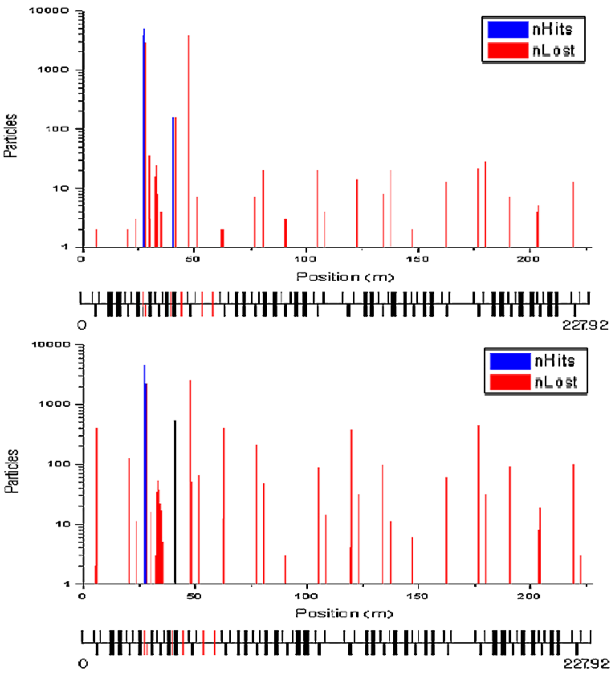

Figure 3: Distribution of the lost particles along the ring and the hitting particles at the collimators in the CSNS RCS. nHits denotes the number of particles hitting on the collimators and nLost denotes the number of the absorbed particles. A total of 50000 particles are injected. The simulations cover the energy range of 80–90 MeV corresponding to CSNS-I phase. Upper: anti-correlated beam; lower: correlated beam.

Table 2: Collimation efficiencies and turns to collimate all the particles hitting the primary momentum collimator at the energy of 80 MeV, with the transverse collimation efficiency taken as 100%.

C-S invariant (πmm.mrad) /off-moment.	Anti-correlated Collim. efficiency	Turns	Correlated Collim. efficiency	Turns
I_x=333, δ= 1.03%	98.4%	80	61.9%	70
I_x=333, δ= -1.03%	94.1%	250	58.8%	130
I_x=18, δ= -1.85%	94.3%	80	96.2%	100

Consistent to the studies with ring-type distributions, the overall simulations with more or less realistic longitudinal motion show good momentum collimation efficiency with an anti-correlated distribution but much worse with a correlated distribution, as shown in Table 3. It also shows the simulation results with higher injection energies of 130 and 250 MeV. After the thicknesses of the primary and the secondary collimators adjusted to the beam energy, we can obtain almost similar momentum collimation efficiency with an anti-correlated beam, perhaps slightly worse with higher energy; If a tertiary collimator in nickel or tungsten with a length of 0.5m and a rectangular shape is placed in the same long drift of the middle arc, the collimation efficiency at 250 MeV can be maintained almost the same as at 80 MeV. Figure 3 shows the distribution of the lost particles along the ring and the hitting particles at the collimators.

Table 3: Overall collimation efficiencies of the momentum collimation system at the CSNS RCS

Correlation	Anti-correlated			Correlated		
Energy (MeV)	80-90	130-140	250-260	80-90	130-140	250-260
Efficiency (%,η_t=100%)	95.4	96.8	92.5	63.9	49.4	36.0
Efficiency (%, η_t =95%)	92.6	93.9	89.3	62.4	48.2	34.9
Efficiency (%,η_t =95%, with a tertiary collimator)	-	-	91.8	-	-	35.0

CONCLUSIONS

The simulation studies show that the combined momentum collimation method is an effective method in compact synchrotrons of medium energy and high intensity. The particles with large positive off-momentum pass through a thin carbon foil, and will be removed effectively by the transverse collimation system. The particles with large negative momentum deviations pass through a thin tantalum foil, and can be mainly collimated by the combination of the whole transverse collimators and a nickel block at the proximity of the primary momentum collimator. The studies also show that the momentum collimation efficiency is much higher for an anti-correlated beam than for a correlated beam; and the material of the collimators plays an important role in the collimation. Without the generality, the method is applicable to other compact high intensity synchrotrons.

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