PARASITIC SLOW EXTRACTION OF EXTREMELY WEAK BEAM FROM A HIGH-INTENSITY PROTON RAPID CYCLING SYNCHROTRON

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Abstract

A new method to extract extremely weak beam from a high-intensity proton rapid cycling synchrotron (RCS) with the scattering foil in the parasitic mode is proposed in this paper. The method is made use of the foil, bump magnets, septum magnet and extraction magnet. It moves the beam closer to a scattering foil prior to the fast beam extraction by employing either a local orbit bump or momentum deviation, so that the halo part of the beam will be scattered. A part of the scattered particles will be extracted from the RCS and guided to the experimental area. Depending on how deep the scattering foil bites into the beam halo, the extracted beam intensity is very weak, which is up to 10^4 protons per cycle, and has a good time structure for many applications. Detailed studies including the scattering effect in the foil, the local orbit bump by the bump magnets and dispersive orbit bump by modifying the RF pattern, the multi-particle simulations by ORBIT and TURTLE codes, and some technical features for the extraction magnets are presented.

INTRODUCTION

Some proton applications such as detector tests and space radiation effects studies, ask for very weak beam intensity. In general, proton synchrotrons use third-order resonance extraction method to provide beams of large duty factor or even quasi-continuous wave beam, then defocusing systems to spread out the beams are used to reduce beam intensity to a very low level. It seems that no serious attempts have been made to provide very weak proton beam from a high-intensity rapid cycling proton synchrotron where the single-turn fast extraction should be used to keep up with the high repetition rate and the requirement on low beam loss during the extraction. In this paper, a new method is proposed to extract extremely weak proton beam from a high-power rapid cycling proton synchrotron in the parasitic mode when keeping the normal fast extraction. The concept is successfully applied to the rapid cycling synchrotron (RCS) of China Spallation Neutron Source (CSNS) with a more-or-less realistic design. CSNS is a large scientific facility under construction [1]. At the first CSNS phase, RCS is designed to accelerate beam from 80 MeV to 1.6 GeV in a repetition rate of 25 Hz, and the beam power at extraction is 100 kW. The main parameters of RCS are listed in Table 1.

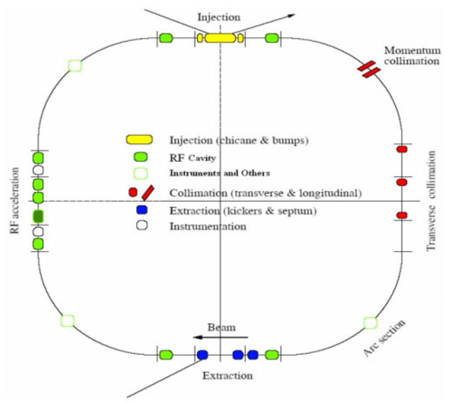

Figure 1: Layout of a quarter of CSNS RCS lattice and position of parasitic slow extraction system.

Table 1: Main Parameters of CSNS RCS

Circumference (m)	227.92
Injection energy (GeV)	0.08
Extraction energy (GeV)	1.6
Betatron tunes (h/v)	4.82/4.80
RF harmonics	2
Transverse acceptance (πmm.mrad)	540
Collimation acceptance (πmm.mrad)	~350

PARASITIC SLOW EXTRACTION METHOD

As a parasitic working mode, the proposed slow extraction method should have no or very little influence on the neutron applications. The principle of the method is as follows: a scattering foil is placed in a long straight section in a dispersive region of the RCS. Usually it does not interfere with the circulating beam, which has a large emittance, usually with a dense core and a sparse halo. In the normal acceleration period, the whole beam should be cleared from the foil to avoid beam losses. If a local orbit bump is created a few milliseconds before the fast extraction to moves the beam closer to the scattering foil, some halo particles will hit the foil and are scattered. Depending on how deep the scattering foil bites into the beam halo, a very small part of scattered particles enter the extraction channel and can be extracted. To limit the beam power of the lost particles by beam hitting on the scattering foil, those particles hitting the foil are controlled below 10 W. For a total beam power of 100 kW, this means that only 10^{-5} of the beam will be allowed

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to hit the foil. The schematic of the slow extraction system is depicted in Fig. 1 and Fig. 2. Major elements used in the slow extraction system are the scattering foil, four bump magnets which are symmetrically arranged and produce a purely local orbit bump, one septum magnet and one bending magnet. The scattering foil is preferred to have a design of fixed one, so the key limitation comes from the requirement on the bump magnets, which must be strong and perhaps fast ramping. Two solutions for the local orbit bump have been studied: one uses fast ramping magnets which producing an outward orbit bump and another uses fixed field bump magnets which produce an inward orbit bump decaying with beam rigidity. The scheme with the inward orbit bump is preferred and adopted here.

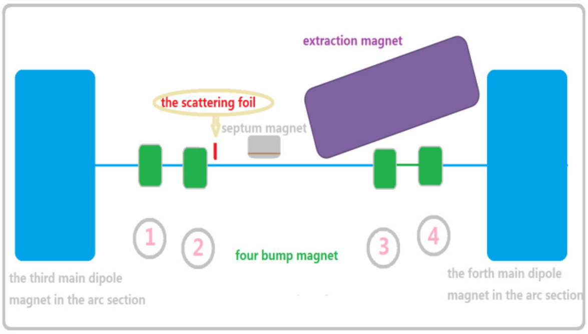

Figure 2: Schematic for the parasitic slow extraction system (blue: RCS dipole magnets, green: bump magnets, gray: septum magnet, purple: extraction bending magnet, red: scattering foil).

A design scheme is as follows: it is wished to maintain the original acceptance of 540 πmm mrad at the foil at 80 MeV and about 350 πmm mrad at 1.6 GeV without applying momentum deviation. With an inward bump decaying from the initial 23.2 mm at 80 MeV to 3.8 mm at 1.6 GeV, and the shrinking beam halo emittance from 350 πmm mrad to 150 πmm mrad also due to acceleration, and the additional orbit bump is 23.8 mm by 0.8% momentum deviation, one can move the beam halo to scrape the foil which is 48.3 mm. The bump magnets are aligned according to the shifted orbit to save apertures. The maximum momentum deviation for the reference particle is limited to 0.8% to have a maximum momentum deviation including the momentum spread still within 1%.

If one modifies the RF frequency pattern to create a momentum deviation from the nominal one for the centre particle, one can produce additional orbit bump at the scattering foil which are located in the high dispersion region. In the normal operation mode, the RF frequency changes in synchronization with the ramping magnetic field during acceleration. In real machines, the synchronization is assured by readjusting the frequency curve with the measured close-orbit errors in different dispersive locations. One can intentionally create a small desynchronization to obtain momentum deviation that produces the required orbit bump at the foil. For producing an outward orbit bump, one should increase the RF frequency slightly.

The scattering foil is the key component for this method. The beam-material interaction contains multiple Coulomb scattering, Rutherford scattering, elastic nuclear scattering and inelastic nuclear scattering. For the particles that can be extracted must have a large scattering angle, so only Rutherford scattering and elastic nuclear scattering take into accounted. From Fig. 3, we can see that for material of higher atomic number, the scattering probability is smaller. Therefore, the Carbon foil is chosen as the scattering foil.

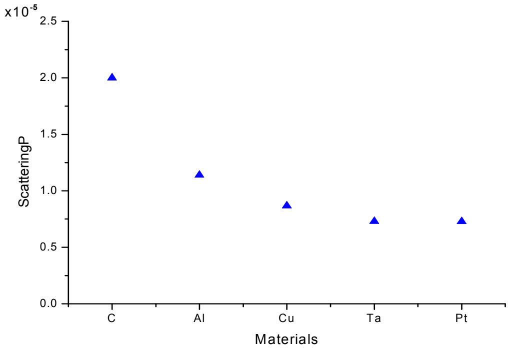

Figure 3: The scattering probability for different foils with the same equivalent thickness by FLUKA.

SIMULATION RESULTS

In this part, it is shown how the method works. In order to study the whole process of the parasitic slow extraction, an artificial beam distribution is assumed [2]: the distribution has a beam core with the emittance of 60 πmm.mrad and 97% of particles, and a sparse beam halo with the emittance of 150 πmm.mrad and 3% of particles. Both the beam core and beam halo distributions are Gaussian distributions truncated to ±3σ. Simulation shows that only a small part of the beam halo particles (about 1/300) that have large emittance may have the chance to hit the foil. To simplify the simulation process, only an emittance ring that contains 1/300 of the beam halo particles with the largest emittance is used for the study. For this situation, a self-made FORTRAN program ('HOLLOW BEAM') is developed to generate the ring type beam distribution in the horizontal phase plane.

ORBIT and TURTLE codes are used to study the details. For ORBIT [3] codes could not simulate two lines at the same time, only the bump magnets and the scattering foil are set in ORBIT codes and the extraction lattice is designed in TURTLE codes. A blackbody is set in ORBIT codes at the position of the entrance of the septum magnet with the same size of the septum's good field to record the particles' position and momentum that hit it that are input to TURTLE codes. The simulation results in ORBIT codes are shown in Fig. 4. The extraction efficiency with the thickness of the foil is shown in Fig. 5.

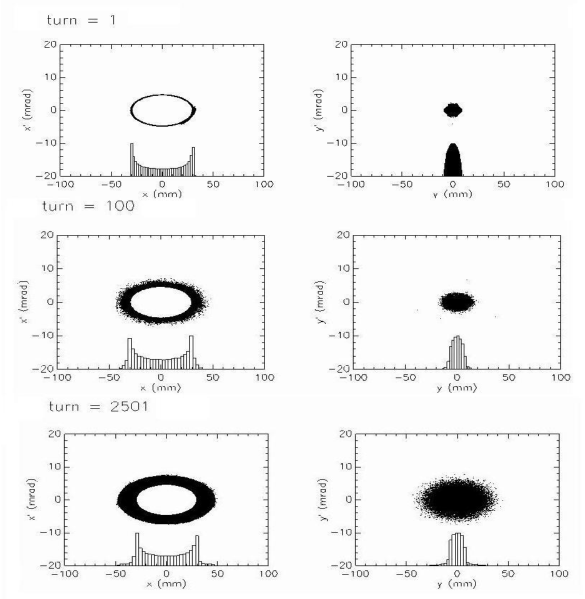

Figure 4: Beam distributions in ORBIT codes at the middle point of the dispersion-free long straight section at different turns during the scattering foil at 1.6GeV. (0.2% energy dispersion, 10^6simulation particles, 2500turns).

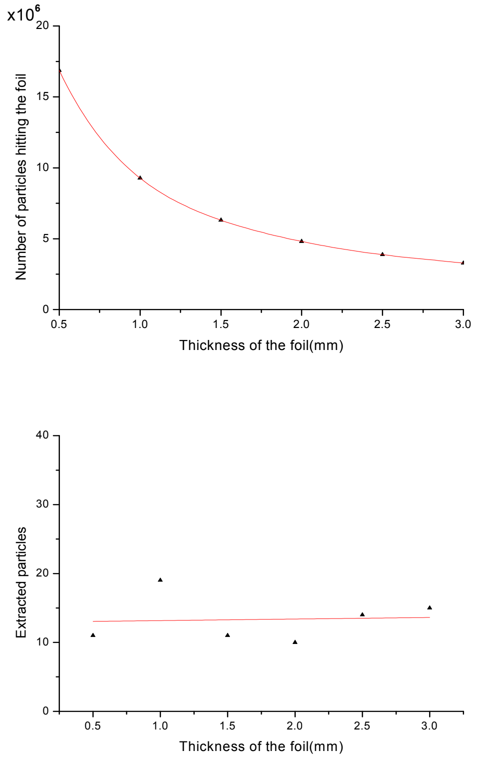

Figure 5: Number of extracted particles with different thickness of the foil.(upper: number of particles that hit the foil, lower: number of extracted particles).

With 10^6 simulation particles, about 15 particles can be extracted. There are 1.56×10^{13} particles in reality and 1/10000 of the total particles are beam halo particles. We use 10^6 particles to take the place of 1.56×10^9 particles, so the real particles that can be extracted is 23400 in 2500 turns. About 10 particles can be extracted per turn which can meet the demands. From Fig. 5, we can see that the extracted efficiency has no reference to the thickness of the scattering foil.

MAGNETS PARAMETERS

This part is just to show that the magnets that are used for parasitic slow extraction are still normal magnets. The key magnets parameters are shown in table 2.

Table 2: The Key Magnets Parameters

Parameters	Bump magnet	Septum magnet	Extraction magnet
Field(T)	0.38	1.19	1.9
Good field (mm)($H\times V$)	180×120	30×20	80×60
Uniformity (%)	0.13	0.2	0.7
Power loss (kW)	12.4	12.7	94.8
Temp. rise (°C)	14.7	19.5	14.9

CONCLUSIONS

The simulation studies with coasting ring-type beams show that the parasitic slow extraction method is an effective method in compact synchrotrons of medium-energy and high-intensity. A small desynchronization is created to obtain momentum deviation that produces the required orbit bump at the foil. Although the studies have been carried out with the CSNS parameters, the method should be applicable to other compact high-intensity synchrotrons with available space at large dispersion region. An alternative design using the same principle but employing the fast extraction channel in the straight section was reported in Ref. [4].

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