On the Use of Thin Scrapers for Momentum Collimation *

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Abstract

In transverse collimation systems, thin scrapers are used as primary collimators to interact with the beam halo and increase its impact parameter on the secondary collimators or absorbers. In the same way, placing the primary collimator in a dispersion region is used for momentum collimation. However, the use of scrapers for momentum collimation presents an additional disadvantage when handling medium-low energy beams. The energy lost by ionization is non negligible and the proton can be kicked out of the RF bucket. The material and thickness of the scraper have to be carefully adjusted according to the position of secondary collimators and momentum aperture of the machine. We derive simple analytical expressions for a generic case. The same calculations have been applied to the case of the SNS accumulator ring. After careful considerations, the use of scrapers for momentum collimation was ruled out in favor of a beam in gap kicker system.

1 INTRODUCTION

Momentum collimation is typically performed by placing the primary collimator in a dispersion region [1, 2]. On the other hand, thin scrapers are used as primary collimator in low and medium energy machines to enhance the divergence of the halo partcicles and drive them into the collimator without absorbing them.

A natural extension of this method is to place a thin scraper in a maximum dispersion location as primary collimator. Secondary collimators are located downstream generally at locations where the dispersion is smaller. There are two main problems, first, the energy lost by ionization is non-negligible and the proton can be kicked out of the RF bucket or even the momentum aperture of the ring preventing the proton from reaching the secondary collimator. Second, the betatron oscillation of particles with negative momentum deviation may be reduced after the interaction with the scraper.

In this paper we follow a single particle approach to calculate under which conditions momentum collimation using a primary scraper is acceptable. Section 2 contains the derivation of the constrains on thickness and optics. In section 3 we apply these criteria to the specific case of the SNS accumulator ring and the RCS study for the SNS.

2 MOMENTUM COLLIMATION USING THIN SCRAPPERS

The transverse coordinate of a particle in a dispersion region with dispersion D is given by Eq. (1).

$$x = \sqrt{\epsilon\beta}\cos(\phi) + D\delta, \tag{1}$$

where $\delta = \delta p/p_0$ is the relative momentum deviation and $D\delta$ is the closed orbit deviation for off momentum particles. Assuming a slow emittance growth in the transverse and longitudinal planes, the particle hits the scraper at maximum betatron elongation and with an angle close to zero [1]. Particles with positive momentum deviation reach the scraper when $cos(\phi) = +1$ while for $\delta < 0$, $\cos(\phi) = -1$.

After traversing a primary scraper with an aperture X_1 located at $s = s_1$ where the Twiss functions are D and β (see Fig. 1), the particle coordinates, now denoted by primes, are changed in the following way:

$$\begin{array}{rcl} x : X_1 & \longrightarrow & X_1 \\ x' : 0 & \longrightarrow & x' = \theta_{scat} \\ \delta : \delta & \longrightarrow & \delta' = \delta - p_{loss}/p_0 \\ \phi : n\pi & \longrightarrow & \phi' \end{array} \tag{2}$$

Here, θ_{scat} is the angular kick produced in the scraper, mainly due to multiple Coulomb scattering, p_{loss} is the momentum lost by the particle by ionization given by the Bethe-Bloch equation;

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta_r^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta_r^2\gamma^2T_{max}}{I^2} - \beta_r^2\right] \tag{3}$$

$$p_{loss} = \delta p = \frac{dp}{dx}\delta x = \frac{1}{\beta_r}\frac{dE}{dx}\delta x.$$

with δx the thickness of the scraper and dE/dx the ionization energy loss which depends on the material and beam energy. In the last equation β_r is the relativistic factor.

After the passage of the particle trough the scraper, the position x of the proton remains unchanged but its momentum deviation changes and so does the closed orbit around which it was oscillating. As a result the betatron oscillation amplitude $\sqrt{\epsilon\beta}$ also changes. We assume that the emittance of the particle is increased mostly by the energy loss change an not by $theta_{scat}$ and Coulomb scattering. We

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[1] Note that this is not necessary true for one-pass systems such as transfer lines and linacs.

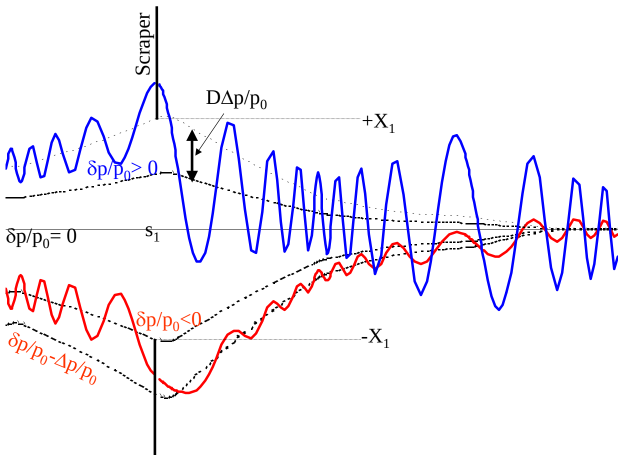

Figure 1: Schematic view of the use of thin scrapers for momentum collimation. After the traversal of the scraper, the closed orbit decreases a factor p_{loss}/p_0. The betatron oscillation around the closed orbit is enhanced for $\delta > 0$ while for $\delta < 0$ we have cooling.

deduce the new emittance by identifying Eq. (1) before and after the scraper.

$$\sqrt{\epsilon\beta}\cos(\phi) + D\delta = \sqrt{\epsilon'\beta}\cos(\phi') + D\delta'$$

Introducing Eq. (2) and $\cos(\phi) = \pm 1$, we get

$$\sqrt{\epsilon'}\cos(\phi') = \pm\sqrt{\epsilon} - D\frac{p_{loss}}{p_0\sqrt{\beta}}. \qquad (4)$$

Or equivalently,

$$\sqrt{\epsilon'} = \frac{\pm\sqrt{\epsilon} + \frac{Dp_{loss}}{p_0\sqrt{\beta}}}{\cos(\phi')}.$$

While the dispersion usually vanishes on the straight sections of the ring, the betatron oscillation does not. A big betatron oscillation allows to catch the protons safely in a secondary collimator located at the straight section. We impose thus the condition $\sqrt{\epsilon'} - \sqrt{\epsilon} > 0$ which may be rewritten from Eq. (4) as

$$\frac{\pm\sqrt{\epsilon} + \Delta - \sqrt{\epsilon}\cos(\phi')}{\cos(\phi')} > 0,$$

where we have introduced the constant quantity

$$\Delta = Dp_{loss}/(p_0\sqrt{\beta}).$$

The product of numerator and denominator has to be positive. We also take $\sqrt{\epsilon}$ common factor and we are left with

$$[\sqrt{\epsilon}(\pm 1 - \cos(\phi')) + \Delta]\cos(\phi') > 0. \qquad (5)$$

This condition must be fulfiled to have an increase in emittance when traversing the scraper.

Case 1 $\cos(\phi') > 0$ In this case, Eq. (5) is reduced to

$$\Delta > -\sqrt{\epsilon}(\pm 1 - \cos(\phi')).$$

For particles with positive momentum the quantity $(1 - \cos(\phi))$ is always positive and the second term is a negative quantity. From the definition of energy loss, Δ is always positive. Thus, for particles with positive momentum deviation this is always true and the betatron oscillation is enhanced by the energy loss.

In the case of particles with negative momentum deviation, for the last inequation to hold, Δ has to be larger than the maximum of the second term of the inequality. As we imposed $\cos(\phi' > 0)$, we obtain the final condition:

$$\Delta = \frac{Dp_{loss}}{p_0\sqrt{\beta}} \geq 2\sqrt{\epsilon} \qquad (6)$$

Case 2 $\cos(\phi') < 0$ For negative $\cos(\phi)$, Eq. (5) implies

$$\Delta(-\sqrt{\epsilon}(\pm 1 - \cos(\phi'))) < 0.$$

For particles with $\delta > 0$, $cos(\phi)$ is never negative. This is easily understood from Fig. 1. The new orbit of the particle after loosing momentum lays under the old one, and the phase never becomes negative.

For $\delta < 0$ we have

$$\Delta < \sqrt{\epsilon}(-1 - \cos(\phi))).$$

As $(-1 - \cos(\phi))$ is a negative number between -1 and 0 and $\Delta > 0$, this condition is never fulfilled.

Scraper thickness We are left then with Eq. (6) as the necessary condition to increse the betatron oscillation of the particle. Introducing Eq. (1) in Eq. (6), we have

$$\frac{p_{loss}}{p_0} \geq 2(\delta - \frac{X_1}{D}). \qquad (7)$$

That means, introducing a momentum loss large enough to make the closed orbit jump more than twice its initial amplitude, we can increase the emittance of the particle. This is sketched in Fig. 2.

Eq. (7) together with (3) gives a fair approximation of the length of the scraper necessary to increase the particle emittance. However, the added closed orbit deviation due to the large loss in momentum is non negligible. In practice, this is a very strong condition as the final excursion of the particle just after the scraper is very large and the aperture at the elements before the dispersion vanishes is very demanding. Also, the minimum thickness of the scraper becomes energy dependent.

3 SNS RAPID CYCLING SYNCHROTRON

During the design period, a rapid cycling synchrotron for the Spallation Neutron Source project at Oak Ridge was

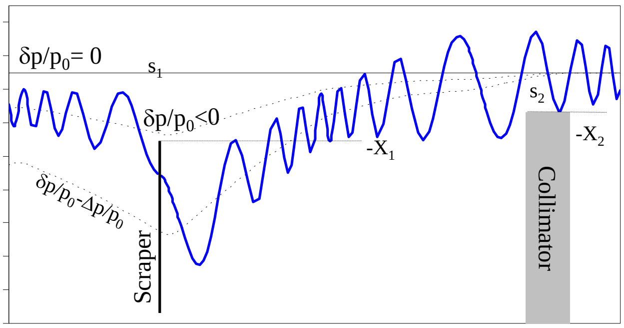

Figure 2: Absorption of the momentum halo by a secondary absorber after interaction with the striper.

under study. As with any synchrotron, the main contribution to losses is in the longitudinal space during the initial part of the ramping. This problem is especially important for rapid synchrotrons as the RF capture and first stages of acceleration are non-adiabatic. A high efficiency longitudinal collimation system is an essential ingredient in the design of such machine.

The SNS synchrotron ring is 300 meters of circumference with four 32 m long arcs and injection energy of 400 MeV [3]. The maximum dispersion occurs in the middle of the arc with D_{max} = 4.4 m and β_x = 16 m in what becomes the point of minimum momentum acceptance. The RF bucket acceptance is $\delta p/p_0|_{RF}$ = 1%. The beam emittance at 99% is $\epsilon_{99\%}$ = 260 πmm·mrad. The ring momentum acceptance is given by the dipole aperture at D_{max} and is $\delta p/p_0|_{ring}$ = 3.8% for protons at zero emittance.

We would like to install a momentum collimation in such a ways to cut any particle with $\delta p/p_0 \geq 3.8$ and do not intercept the beam in the bucket. Fig. 3 shows the acceptance in emittance-momentum space produced by such collimators. For a collimator ideally located at maximum dispersion $D_max = 4.4$ m,

$$X_1 = \sqrt{\epsilon_{99\%}\beta} + D\delta p/p_0|_{RF} = 108.5mm.$$

From Eq. (7) we find that $\Delta p/p_0$ = 0.029. That momentum loss may be achieved with a scraper of Tungsten 1.2 cm thick or 2.2 cm for copper. The aperture required just downstream in the next dispersion minima is 144 mm. Some of the quadrupoles should have increased aperture. Also, these protons are now completely outside of the ring momentum aperture. They would be lost in the next arc if they are not captured by long secondary collimators in the straight section.

Unfortunately, in the location of maximum dispersion there is no space available to locate the scraper. The next space available is at a relative dispersion maximum with $D = 2.2$ m and $\beta = 6.5$ m. For these values, X_1 = 80 mm and $\Delta p/p_0$ = 0.053. A scraper made of Tungsten 2 cm thick of Copper 4 cm should be used. The dipole half aperture must be kept over 120 mm. Even if feasible, the added

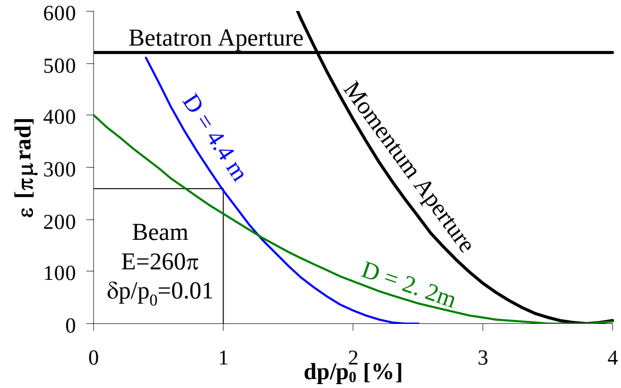

Figure 3: Emittance-momentum deviation diagram for the SNS rapid cycling synchrotron. The acceptance of the ring in momentum and betatron amplitude is shown together with the expected extent of the beam. Momentum collimators would be located at D=4.4 m or D=2.2 m.

cost of increasing the magnets aperture has to be taken into account. It is also necessary to perform further studies on the energy dependence, the heat load in the scraper

4 CONCLUSIONS

Some basic formulas have been derived to establish the main parameters of a momentum collimation system using scrapers.

Special care has to be taking into account when estimating the effects of the passage of the beam through the scraper. When performing simulations, an accurate six dimensional analysis is necessary to estimate the cleaning efficiency of the system.

5 AKNOWDLEGEMENTS

I would like to thank G. Franchetti, Y.Y.Lee, Y. Papaphilippou and J.Wei for useful discussions and carefully reading the manuscript.

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