On the Use of Predeflectors for Improved Beam Loss Concentration

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Abstract

Loss concentration has become an ever more important issue in high-current machines for spallation sources, hadron facilities etc. A major problem in the design of the collimators is outscattering, i.e. the fact that particles hitting the face of the collimator at shallow depth have a high probability of being back-scattered into the machine aperture and lost somewhere else. As most loss mechanisms generate unfavourably shallow impact depths, computed collimator efficiencies are generally unsatisfactory. This paper shows how predeflectors of varying complexity (from a simple scatter foil to an electrostatic mini-wire-septum) can increase the average hitting depth, and thereby improve collection efficiency. The latter is further enhanced if the predeflection principle is combined with a premagnetised collector. Both methods were studied by the computer tracking code ACCSIM [1]. Application to the CERN PS Booster and the TRIUMF KAON Accumulator Ring is discussed.

1 INTRODUCTION

The advent of medium-energy, high-intensity accelerators like spallation neutron sources, hadron factories etc. featuring proton currents of hundreds of μA, confronts machine designers with the problem of efficient control of beam loss. Even if loss can largely be reduced by appropriate design, there remain processes like charge exchange injection or RF capture which are inherently lossy. These residual losses, typically of the order of one per cent, need imperatively to be concentrated onto specially designed, generally shielded, absorbers. Regardless of how massive they may be, their efficiency is limited by a substantial fraction of primary particles back-scattered into the machine acceptance, which in turn is due to the relative slowness of most loss mechanisms leading to shallow and grazing incidence of lost particles onto the absorbers.

2 OUTSCATTERING FROM COLLIMATORS

If one investigates processes leading to beam loss, like transverse growth by instabilities or on stopbands, foil scattering in charge exchange injection, particles lost from the accelerating bucket and spiralling to the walls, etc., it turns out that the particles approach the collimator with a 'transverse drift speed' less than 50 m/s for practically all processes, with the exception of the last mechanism quoted: In very fast-cycling machines non-accelerated particles may spiral inwards at a few mm/μs, if the local lattice dispersion is made large. Apart from this situation, one will have to deal with impact parameters from zero through a couple of times 50μm, as the revolution periods are of the order of 1 μs. This is to be related to the outscattering rates and angles as found by the established Monte-Carlo codes used for detector design. Table 1 presents results from GEANT3 [2] for 1 GeV protons, a representative energy for the class of machines considered.

Table 1: Outscattering of 1 GeV Protons from Iron (unmagnetized / with transverse magnetic field B)

Impact Para-meter	B = 0		B = 1.8 T	
	Out-scatter	Average Exit Angle	Out-scatter	Average Exit Angle
mm	%	mrad	%	mrad
0.01	67.6	10.5	36.6	9.0
0.05	58.4	17.3	24.2	16.1
0.1	53.4	17.6	20.4	26.6
0.5	36.6	30.9	8.4	60
1.0	30.0	41.9	7.6	68.3
2.0	21.6	57.2	4.5	84.1
5.0	11.4	73.8	2.4	101
10.0	5.4	150	1.6	198

The normalised phase space plot of Fig. 1a illustrates the limits of a massive collimator : Due to outscattering, a large fraction of primary particles emerges and continues to turn on larger circles eventually hitting other aperture limits. To prevent this, one places a second absorber downstream at a suitable betatron angle. As outscattered particles have lost too much energy to survive one more turn, those that miss the second collimator finish less than a betatron wavelength downstream.

3 IMPROVEMENT BY PREDEFLECTORS

3.1 Effect of a Predeflector

Contrary to a thick collimator, all protons hitting a thin foil or degrader will pass, be scattered symmetrically and continue to turn, although on a different closed-orbit as they have lost some energy. Fig. 1b shows how the main collimator, located some tens of degrees downstream, intercepts one (now deeper penetrating) tail of the distribution and, eventually, the other one after a number of turns. In between, the remaining cloud hits the foil again causing

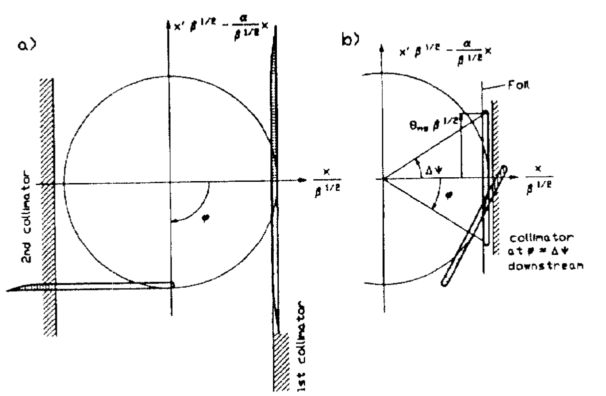

Figure 1: Multiple scattering out of a collimator (a) and by a scatter foil (b)

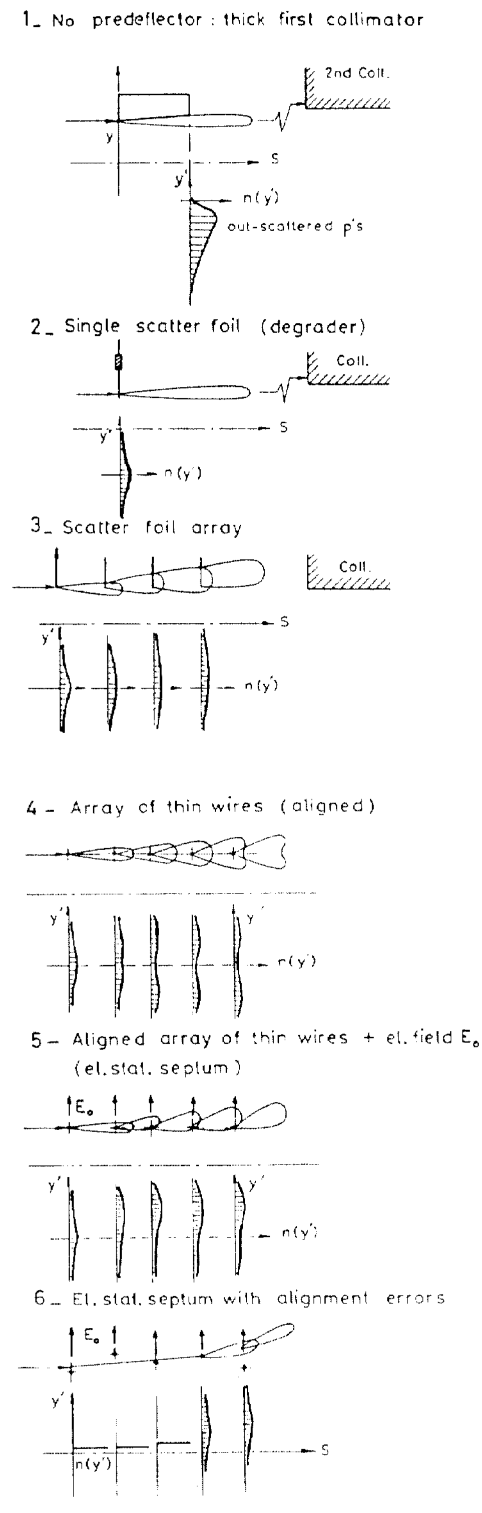

Figure 2: Evolution of predeflectors towards increasing efficiency and complexity

further scattering and enhanced amplitude growth. This latter is another component of the mechanism.

One sees from Fig. 1b, that a positive deflection θ decreases the betatron phase by $\Delta\psi = \arctan(\theta\beta/x)$, and the optimum distance of the collimator is just at a phase advance $\phi = \Delta\psi$. For this case the increment in betatron amplitude at the collimator is given by $\Delta x_a = \frac{\theta^2}{2}\frac{\beta_a\beta}{x_a}$, which is the potential hitting depth. Thin predeflectors have proved their efficiency in the CERN ISR [3]. Also, scatter foils mounted rigidly on the exit faces of the septum magnets are foreseen in the future protection system [4] of the extraction septa of the CERN PS Booster. In simulations, however, they do not remove *all* particles lost.

In order to improve the efficiency of the collimator system, one may envisage more sophisticated predeflectors: Fig. 2 shows a number of concepts evolving from the simple foil. As a first step, one imagines that an array of foils, progressively retracted from the beam envelope (Fig. 2-2), promises an enhancemenmt of the outward wing of the scattering angle distribution $n(y')$. An aligned array of thin wires does essentially the same job and appears easier to realise in practice. Positioned parallel to the beam envelope (Fig. 2-4) it depletes the forward peak and enhances the tails of $n(y')$. From there it is only a logical step to apply an electric field to the outside of the wire plane which becomes a mini-wire-septum (Fig. 2-5). To assure a net beneficial effect, the analysis shows that one needs ultra-thin wires as proposed for pre-septa in advanced slow-extraction concepts [5] . These septa are designed with a symmetric potential where forces from both sides cancel, which would not make sense in the present application. It is nevertheless possible to operate a one-sided low-density septum if one relaxes on alignment tolerances or, in other words, tensioning forces, allowing larger deflections of the wires. This is the concept of the wire septum with tolerated alignment errors (Fig. 2-6). In simulation it appears superior to the perfect one.

3.2 The Mini-Wire-Septum

It is useful to know the technological limits before discussing the function of the septum. We adopt typical parameters from the study [6],[7] of the pre-septum of the projected TRIUMF KAON Extender Ring:

Electric field $E_0 = 5$ MeV/m, d = 33 μm diameter carbon wires operating at 0.05 N tensioning force T, which corresponds to 1/10 of their measured breaking force. A length of l = 0.5m, i.e. N = 200 wires h = 50 mm long at a = 2.5 mm distance yields a deflection angle $\theta_s = (eE_0l)/(p\beta c) = 2.5\,\text{MeV}/(p\beta c)$.

The force on each wire is then $F_x = \frac{1}{2}\epsilon_0 a h E_0^2 = 0.014$ N and the maximum deflection $x_B = hF_x/(8T) = 1.73$ mm. Obvously such a bulging would be prohibitive for a slow-extraction septum but seems acceptable in the present context; another salient distinction is that only a small aperture, comparable to a, is required; this limits the potentials of the electrodes and permits keeping the wires at a positive potential $V_W = \frac{1}{2\pi}E_0 a \ln(\frac{a}{d\pi}) = 6.3$kV such that the field in the main aperture is zero and clearing electrodes are not required. The cathode would then be at $-V_W$ at a distance of about 2.6 mm.

The strong bulging entails significant alignment errors of the wires. If we describe them by a Gaussian of standard deviation σ, the deflection angle $\theta_s(x) = \theta_s F(x/\sigma)$ as well as the rms angle $\theta_W(x)$ of multiple scattering by the wires depend on the impact parameter x of the incident particle w.r.t. the ideal plane of the wires. From [8] we compute $\theta_W(x) = [13.6\text{MeV}/(p\beta c)][Nd^2\pi p(x/\sigma)/(4\sigma X_0)]^{\frac{1}{2}}$ with the radiation length X_0=188 mm for carbon and $p(x)$ denoting the normalised Gaussian and $F(x)$ its integral. Inserting our septum parameters and assuming σ=0.4 mm one obtains θ_W=0.65MeV$/(p\beta c)\sqrt{p(x/\sigma)}$. This is to be compared to the value for the perfect septum θ_W=13.6MeV$/(p\beta c)[Nd\pi/(4X_0)]^{\frac{1}{2}}$=2.25MeV$/(p\beta c)$, i.e. $\theta_W \simeq \theta_s$. As it is very likely that a primary hits the wires of the aligned septum once, the total deflection fluctuates between zero and $\simeq \theta_s$ and will transform at the collimator entrance into a wide zone of possible impact parameters .

A particle approaching an imperfect septum experiencies some scattering already at $x < -\sigma$ causing emittance growth that drives the particle, by ever-increasing steps, across the septum, attaining kicks comparable to those of the perfect septum beyond the mid-plane. Altogether the transformed impact parameters cover roughly the same zone as those of the ideal septum. It turns out that the humble imperfect septum does as well as a perfect one which would be technologically out of reach. Here we deal with energies of (i) 1 GeV (CERN PS Booster), and (ii) 450 MeV (TRIUMF KAON Accumulator) for which we obtain θ_s=1.7 (i) and 3.3mrad (ii). For β's$\simeq$6 m and x_a = 30 mm, say, maximum impact parameters of Δx_a = 2 (i) and 8 mm (ii) can be expected.

4 THE MAGNETIZED COLLIMATOR

It is evident that transverse magnetisation of the collimator bends trajectories away from its inner face, however the effect is small (bending radius 3 m for 1 GeV protons and a field of 1.8 T). An estimate for the case of Table 1 predicts a significant effect only for impact parameters greater than 0.4 mm, which is essentially confirmed by the table.

5 SIMULATION RESULTS AND CONCLUSIONS

In order to evaluate the efficiency of predeflectors, an annulus in phase space is driven into them by the relevant loss mechanism (rising injection bump in scenario (i), scattering at the stripper foil in (ii), respectively). Results as displayed in Table 2 below show that in case (i) each scatter foil and collimator magnetisation improve the efficiency significantly while the effect of both combined is rather marginal, in case (ii) however, magnetisation combined with a scatter foil reduces uncontrolled loss by a factor three. The ideal septum, if slightly misaligned (thereby simulating the imperfect one), yields even larger impact parameters than an aligned one, rendering magnetic collimators superfluous in all instances.

Table 2: ACCSIM simulations of the effect of predeflectors on loss concentration in the CERN PS Booster and the TRIUMF KAON Accumulator

(i) Septum Protection at the PSB (1 GeV)			
Predeflector Type	Av. Impact Param. [mm]	Coll. Efficiency [%] B = 0	B = 1.8 T
None	0.02	46.5	67.7
Foil W 7μm	0.82	70.0	80.9
Foil W 22μm	1.35	75.0	82.7
(ii) TRIUMF KAON Accumulator (450 MeV)			
Foil Cu 0.05mm	1.3	77.6	92.5
Ideal Septum	7.9	100	100
idem, +0.5mrad	9.4	100	100

6 ACKNOWLEDGEMENTS

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