COLLIMATING TOUSCHEK PARTICLES IN AN ENERGY RECOVERY LINEAR ACCELERATOR*

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Abstract

The theories of beam loss and emittance growth by Touschek and intra-beam scattering formulated for beams in storage rings have recently been extended to linacs. In most linacs, these effects are not relevant, but they become important in Energy Recovery Linacs (ERLs) not only because of their large current, but also because the deceleration of the spent beam increases the relative energy deviation and transverse oscillation amplitude of the scattered particles. In this paper, we describe a methodology for designing a collimator scheme to control where scattered particles are lost. The methodology is based on Touschek particle generation and tracking simulations implemented in BMAD, Cornell's beam dynamics code. The simulations give the locations where scattering occurs and the locations where the scattered particles are lost. The simulations are used to determine the trajectory of the scattered particles, which are analyzed to determine optimal locations for collimators.

INTRODUCTION

Scattering amongst particles in a beam can share momentum between the transverse and longitudinal dimensions. Without relativistic effects, this sharing of momentum would usually be inconsequential to the trajectory of the particles through the accelerator. This is because the transverse momentum is typically of the same magnitude as the longitudinal momentum in the center of momentum frame. However, due to relativistic effects, transfers of momentum to the longitudinal frame are multiplied by a factor of γ when boosted into the lab frame. This boost makes the change to longitudinal momentum significant to the trajectory of scattered particles through the accelerator.

Scattering amongst particles in a beam is called intra-beam scattering (IBS). Touschek scattering refers specifically to those IBS events that result in one or both of the colliding particles being lost. IBS events that do not result in particle loss can blow up the beam dimensions. This paper focuses on Touschek scattering.

An accelerator with dispersion has an energy aperture that determines the largest deviation from the nominal beam energy that particles can have without colliding with the beam pipe. When a particle collides with the beam pipe it is lost, and it also generates Bremsstrahlung. In a linear accelerator, scattering does not lead to a large fraction of the beam being lost. However, the Bremsstrahlung can damage components in the accelerator tunnel and pose a radiation hazard in user regions. The latter concern is especially important in x-ray light sources, where scientists work in close proximity to the beam line.

In this paper we describe a methodology for placing collimators to efficiently collimate Touschek particles in a linear accelerator. A close study of Touschek losses is especially important in accelerators that perform energy recovery. Intra-beam scattering gives a relative energy change $\Delta E/E_0$ to the colliding particles. During the recovery phase of an energy recovery accelerator, E_0 can decrease by a few orders of magnitude, while ΔE stays the same. This increases the relative energy deviation. The amplitude of the trajectory of a scattered particle increases with its relative energy deviation, thus making it more likely to collide with the beam pipe.

The method we describe analyzes the trajectory of scattered particles through the accelerator to determine the most effective locations for collimator placement. It shows where a collimator of a given diameter would stop the most particles that would otherwise be lost in some designated region. It also provides the profile of current and power incident on the collimator, which is necessary information when designing the collimator and the shielding around it.

The methodology described in this paper builds upon on Touschek scattering and tracking simulations developed in BMAD. The simulations are described in detail in Refs. [1] and [2]. These simulations allow for a wealth of information to be collected about where in an accelerator IBS scattering occurs, and the trajectories of scattered particles through the accelerator. In this paper we describe how the information gathered from these simulations can be used to build an efficient collimator scheme. The scheme is efficient in that it provides the necessary collimation with a minimum number of collimators.

THEORY

A formula for the rate at which IBS scatters particles above a threshold energy change δ_m is derived in detail in reference [1]. This formula is a function of beam and Twiss parameters and can be evaluated at each element in an accelerator. Furthermore, the rate at which particles are scattered into an energy window $[\delta_E, \delta_E + \Delta\delta_E]$ is found by evaluating

$$R'\left[\delta_E\right] = \frac{R\left[\delta_E\right] - R\left[\delta_E + \Delta\delta_E\right]}{\Delta\delta_E}. \quad (1)$$

A particle whose momentum is changed by IBS has its J changed by,

$$J_n \approx \gamma_0 \mathcal{H}_0 \frac{\delta_E^2}{2}, \quad (2)$$

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where δ_E is the relative energy change imparted by the scattering event. The trajectory of the scattered particle can be estimated analytically using the new J, or for improved accuracy, we use non-linear tracking simulations.

The derivation in reference [1] is a more rigorous rework of the derivation of the Touschek scattering rate in reference [3]. The rework provides the orders in energy spread, divergence, and relativistic γ that the result is accurate to and additional insight into the effect.

SIMULATION

Prior to tracking scattered particles through the lattice, an element-by-element energy aperture is determined by performing a binary search at each element for the maximum positive energy deviation δ_{m+} that can be introduced at that element before the particle is lost somewhere down the accelerator. The energy aperture is allowed to be non-symmetric, and the maximum negative energy deviation δ_{m-} is determined in a similar manner.

With the element-by-element energy aperture in hand, at the first element in the accelerator, Eq. 1 is used to produce a distribution of test particles which will be lost when tracked through the accelerator. These test particles are tracked to where they are lost using standard `BMAD` tracking routines, which take into account non-linearities. Where a test particle is lost, the current and power it represents are recorded. After all test particles have been tracked and recorded, the simulation moves on to the second element, third element, and so on to the end of the lattice. The results of this tracking are used to produce a profile of where scattered particles are lost in the accelerator.

The profile of lost particles is examined to determine where radiation hazards occur. In user regions, we wish to keep Touschek losses below 3 pA/m to minimize radiation exposure behind the shielding wall. Elsewhere in the accelerator, losses need to be minimized in regions with sensitive equipment.

To collimate particles being lost in a region, the simulation is set to record the trajectory of particles that are lost in that region. For each particle, the simulation looks for locations along the particle's trajectory where it would be stopped by a collimator of a given diameter. After the trajectories of all particles lost in the user region have been examined, a plot of current stopped versus collimator location is produced. The element where a placed collimator would stop the most current is deemed the most effective location for the collimator to be placed.

A collimator is inserted into the lattice at that location, and the simulation is ran again. The effectiveness of the collimator is judged by examining the new profile of particle loss. By the methodology of the simulation, the just placed collimator is guaranteed to reduce the current loss in the region being examined. However, it may take additional collimators to reduce the loss to acceptable levels. The trajectories of scattered particles are once again recorded, and again it is asked in what location would a collimator capture the most current.

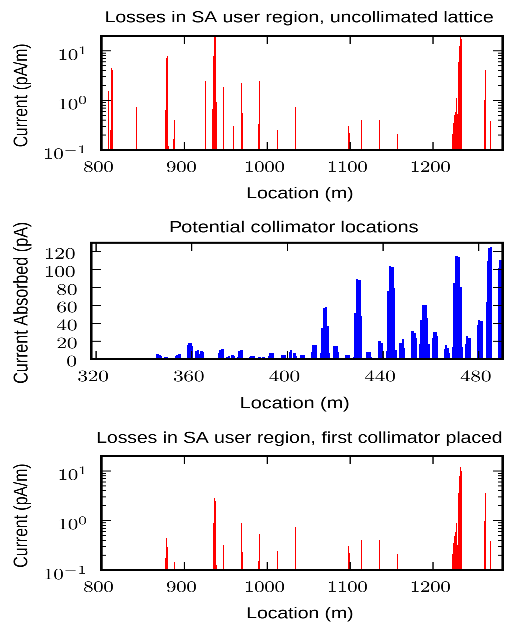

Figure 1: Collimation of south user region in CERL 3.0. (top) The current of IBS particles lost along chamber walls in the south user region. (middle) Potential collimator locations in the preceding turn-around. (bottom) Shows the current lost in the south user region after placing a collimator at 484.6 m.

The steps are repeated, adding one collimator at a time where it would stop the greatest number of scattered particles, until losses in the region under examination are reduced to acceptable levels.

Additionally, the simulations provide the distribution of particles incident on each collimator. Both the distribution of power and distribution of current are provided. This information is necessary to design effective shielding that surrounds the collimators in the accelerator tunnel.

Example Shown in Fig. 1 (top) is the profile of the current of scattered particles lost in the first user region of the uncollimated CERL 3.0 lattice. We would like to reduce the current lost in this region to less than 3 pA/m. Plotted versus location in Fig. 1 (middle) is how much of that current would be stopped if a 10 cm collimator were placed at that location. According to this figure, the most effective location to place the first collimator is 484.6 m down the linac. Placing a 10 cm collimator at this location would stop 124.5 pA that would otherwise be lost in the first user region. Figure 1 (bottom) is the profile of the current of scattered particles lost in the first user region after placing the first collimator. The presence of peaks higher than 3 pA/m indicates that further collimation is necessary.

Note that placing a second collimator at the second highest peak in Fig. 1 (middle) would be a mistake. To determine the best location for the second collimator, the first collimator must be inserted into the lattice and the simula-

Table 1: Location and current absorbed for a scheme of eight 10 mm diameter collimators that limits current deposited into user regions to below 3 pA/m. The beam passes through the TA collimators twice, once during the accelerating phase and once during the decelerating phase.

Loc. (m)	Region	Current Absorbed (pA)
470.1/2676.7	TA1/2	1949
484.6/2691.1	TA1/2	984
1147.0	SA	26
1756.9	CE	56
1852.6	CE	154
1871.9	CE	617
2041.9	NA	108
2134.7	NA	18

tion ran again. The results will show the best location to collimate particles that are not collimated by the first collimator.

The beam in this example is the CERL high current mode where $I = 100$ mA, $\epsilon_{xn} = \epsilon_{yn} = 0.3 \times 10^{-6}$ m, and the bunch repetition rate is 1.3 GHz. The CERL beam is 5 GeV.

Intra-beam scattering leading to Touschek losses occurs primarily in regions with finite dispersion [1]. For the CERL, the finite dispersion regions preceding the first user region are the first turn-around and the first user region itself. We find that shielding the first user region requires two collimators in the first turn-around and one collimator in the user region itself. The collimator placed in the user region itself is necessary to protect the later parts of the user region from particles scattered in the earlier parts.

RESULTS

Figure 2 shows the current of scattered particles striking the beam pipe along the full length of version 3.0 of the CERL lattice before any collimators are added. Figure 3 shows the results of the same simulation ran on the lattice after collimating the user regions by the method described in this paper. The user regions are 808 m through 1284 m, and 1889 m through 2207 m. The scheme consists of eight 10 mm diameter collimators and reduces the current lost in the user regions to below 3 pA/m. The current incident on each collimator is shown in Table 1. Note that the TA collimators are traversed twice: once during the accelerating phase and once during the decelerating phase.

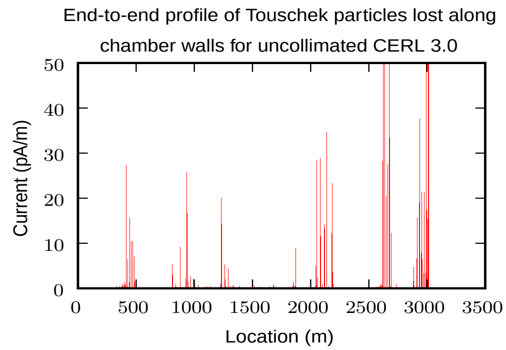

Figure 2: Touschek losses along chamber walls for uncollimated CERL 3.0 lattice. User regions extend from 808 m through 1284 m, and 1889 m through 2207 m.

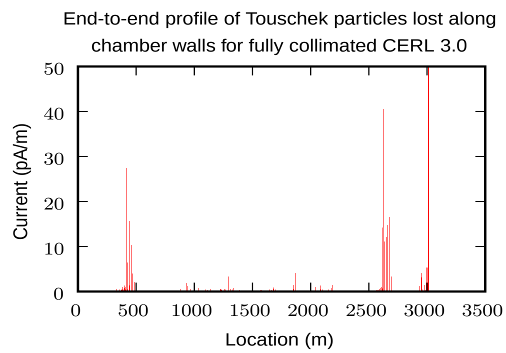

Figure 3: Touschek losses along chamber walls for fully collimated CERL 3.0 lattice. Losses in user regions have been limited to below 3 pA/m.

CONCLUSION

A methodology for designing an efficient collimator scheme based on data taken from IBS particle generation and tracking simulations has been presented. This methodology analyzes where scattered particles are generated and their trajectory through the accelerator to determine the most effective locations for collimators to be placed. Additionally, the simulations provide the distribution of particles incident on each collimator.

This methodology has been applied to design an efficient collimation scheme for the Cornell Energy Recovery Linac and limits particle loss to below 3 pA/m in the user regions. The collimators and shielding in this scheme need to handle currents up to 2 nA.

Collimators are effective at eliminating the radiation hazard caused by scattered particles, but their presence in the beam pipe generates wake fields which can degrade beam quality and limit current. The effect of wake fields due to collimator placement will be the subject of future work.

REFERENCES

[1] M. Ehrlichman and G. Hoffstaetter, “Touschek Scattering in Linear Accelerators,” In preparation (2009).

[2] G. Hoffstaetter, M. Ehrlichman, A. Temnykh, “Intra Beam Scattering in Linear Accelerators, Especially ERLs,” EPAC’08, TUPP040, (2008).

[3] A. Piwinski, ”The Touschek Effect in Strong Focusing Storage Rings” (1998)