MONTE CARLO SIMULATIONS OF THIN INTERNAL TARGET SCATTERING IN CELSIUS

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Abstract

In the actual operation of the storage ring CELSIUS with the hydrogen pellet target, we sometimes observe a cooling phenomenon in the longitudinal phase space, that is, the circulating beam's rf phase width gets shrunk instead of blown up. This phenomenon occurs independently on the electron cooling. In this paper we intend to study and interpret this phenomenon as well as the beam lifetime in the presence of hydrogen pellet target with and without rf and with and without electron cooling by using Monte Carlo simulations [1].

INTRODUCTION

The consequence of using internal target in a storage ring is the growth of the beam phase space due to the small angle multiple Coulomb scattering and energy loss straggling. The target effects can be parametrized by two quantities, the mean square values of the small angle multiple scattering θ^2_{rms} and of the the relative momentum loss straggling δ^2_{rms} per target traversal. The beam lifetime is limited by the emittance growth. Various aspects of the emittance growth by internal target or stripper foil scattering in an ion storage ring have already been published in the literature [2][3]. The small angle multiple scattering distribution can be well represented by the theory of Molière. It is roughly Gaussian for small deflection angles, but at larger angles it behaves like Rutherford scattering with tails larger than Gaussian distribution. For our application it is sufficient to use a Gaussian approximation for the central 98% of the projected angular distribution, with a rms width θ_{rms} given by Molière's formula.

As for the energy loss straggling, the energy loss distribution of a particle traversing through a target layer is characterized by the s-called energy loss parameter

$$\kappa = \frac{\xi}{E_{\max}} \tag{1}$$

where $E_{\max}$ is the maximum possible energy transfer in a head-on collision with a target electron,, and

$$\xi = 0.1534 \frac{Z_p^2}{\beta^2} \frac{Z_t}{A_t} \rho\delta x \quad \text{[MeV]} \tag{2}$$

is related to the target thickness $\rho\delta x$ in g/cm^2, where β is the relativistic factor of the incident particle with charge number Z_p, A_t and Z_t are the charge number and the mass number of the projectile. The κ parameter distinguishes three regimes which occur in the description of energy loss distribution, i.e. $\kappa \le 0.01$, the Landau distribution is used; $0.01 < \kappa \le 10$, the Vavilov distribution is used; and $\kappa > 10$, the Gauss distribution is used.

An additional regime is defined by the contribution of collisions with low energy transfer which is estimated with the relation ξ / I_0, where I_0 is the mean ionization potential of the atom. Landau theory assumes that number of these collisions is high, i.e., Landau distribution has a restriction

$$\xi / I_0 >> 1. \tag{3}$$

Very thin target and high projectile energies are used in CELSIUS. For example, for hydrogen pellet target of 8×10^{-9} g /cm^2 effective thickness and proton beam of 400 MeV kinetic energy, one has $\kappa = 2.2\times10^{-9}$ and $\xi / I_0 = 1.1\times10^{-4}$. The Landau condition (3) is strongly violated and the energy loss distribution cannot be represented by the Landau function. Consequently, special model taking into account the atomic structure of the target is needed. In our present work, the Urbán model is applied in the simulations, and a subroutine GLANDZ from the GEANT is used to simulate the energy loss of a particle passing through the target.

SIMULATION PROGRAM

A computer program was written in standard Fortran to evaluate the time evolution of the beam's phase space and beam losses resulting from a target. The angle and energy straggling caused by the target is simulated with the Monte Carlo method. The tracking algorithm is like Accsim [4]. Each particle moving in the ring is described by the coordinates in the 6-dimentional phase spaces ($x, x', y, y', \varphi, \delta$). The simulations over one revolution can be summarized as follows:

- One thousand particles are randomly created at the middle of the injection section of the ring, with the initial coordinates following Gaussian or uniform distributions in the 6-D phase space in terms of the given beam emittances and the Twiss parameters at the starting location. The particles are then propagated in the ring in terms of the TRANSPORT matrix elements. Only the linear propagation is applied with no coupling in x and y.
- Each time a particle penetrates the internal target it loses a small amount of energy and is scattered by a small angle. There is, however, a peculiarity in the case of hydrogen pellet target. The rate of pellets reaching the interaction area is about 3 kHz and they travel at a speed of 50 m/s in the vacuum chamber. This implies that consecutive pellets are about 17

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mm (=50 m/s ÷ 3000 Hz) apart. Transversely, the pellet stream is 4 mm wide. The diameter of the pellets is at present 50 µm. In order to meet a pellet a circulating particle thus must hit a circle with a radius of 25 µm inside a rectangle of 4 mm wide and 17 mm high. The resulting probability is 3×10^{-5}. In the simulations we treat the pellet interaction by checking whether the particle is within ±2 mm of the central orbit and checking if a random number is smaller than 3×10^{-5}. If one of the conditions is not met, nothing happens to the circulating particle. Otherwise, the energy loss is calculated with the GLANDZ subroutine, and the transverse multiple angles are randomly generated from a Gaussian distribution with a rms planar scattering angle evaluated with Molière's formula. Then, the energy loss δT is subtracted from δ according to

$$\delta = \delta - \frac{\gamma}{\gamma+1}\frac{\delta T}{T} \qquad (4)$$

and the scattering angles θ_x and θ_y are added to x' and y' respectively: $x' = x' + \theta_x$, $y' = y' + \theta_y$.

- The electron cooling is usually on during an internal target experiment in CELSIUS. So, each time a particle passes through the cooler's interaction region, it is reduced with its angles and momentum difference $\frac{\delta\theta_j}{\delta s} = \frac{F_j}{M_p c^2 \cdot \beta^2 \gamma}$, where F_j ($j = x, y, s$) denotes the cooling force, $\theta_x = \frac{dx}{ds}$ and $\theta_y = \frac{dy}{ds}$ denote angles of the ion, and $\theta_s = \frac{\Delta p}{p_0}$ denotes its relative momentum difference. At the exit of the interaction region, the ion's angles and momentum difference become $\theta_j + \delta\theta_j$ respectively.
- Each time a particle runs through the rf cavity its fractional momentum difference is changed according to its actual rf phase φ, i.e. $\delta = \delta + \frac{\gamma}{\gamma+1}\frac{Z_p U_a \sin\varphi}{T}$, where U_a is the rf peak voltage.
- Wherever a particle's position exceeds the available aperture limitation, it is tagged lost and removed out of the tracking. The horizontal and vertical acceptances of the machine are restricted to 40 and 30π mm-mrad in the simulations.

NUMERICAL RESULTS AND DISCUSSIONS

Cooling Effect in Longitudinal Phase Space

Interestingly, simulation can exhibit the cooling phenomenon in the longitudinal phase space that we observed several times in the practical operation of the machine. This phenomenon happens when the electron cooling is off. Fig. 1 shows the history of the distribution of 1000 particles in the momentum space in the case of rf turned off, where the target stream is within (-1,+3)mm of the central orbit.

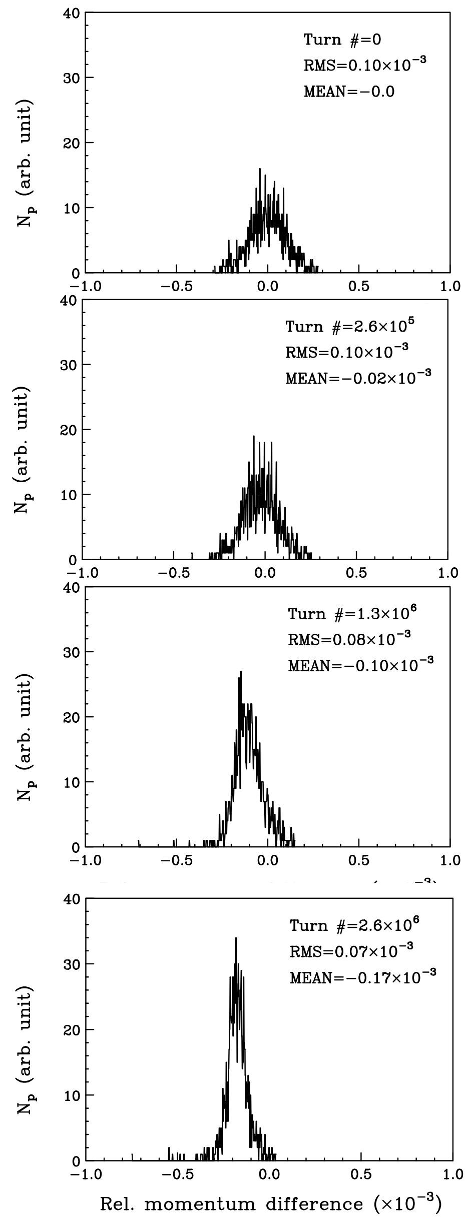

Figure 1: Simulation result showing the history of particles' distribution in the momentum space. The turn number, the rms and mean values of the relative momentum difference are indicated. The target stream is assumed to be within (-1,+3)mm of the central orbit.

We can see that more and more number of particles shrink into the momentum core with the increase of the turn number, and this effect actually becomes more pronounced when the target stream is outward displaced from the central orbit. This can be interpreted as follows: particles with large momenta have more chances to hit on the target because the dispersion function is positive at the target location. As a result, these particles have more chance to lose energies. As shown in Fig. 1, the rms relative momentum difference of the beam is decreased to 6.5×10^{-5} from the initial value 1.0×10^{-4} after 2.6×10^{6} turns. Similarly, when rf is on, simulation can show a shrinkage of the beam width in the rf phase angle.

Also, we notice from Fig.1 that the target interaction in the absence of rf develops a low energy tail in the momentum distribution and causes the peak of the profile shift downward. This peak roughly corresponds to the mean energy of the beam. However, when rf is on, the low energy tail and the shift of the peak are disappeared. As a comparison, Fig.2 shows the mean value and the rms value of the relative momentum difference versus the number of turns for both rf on and rf off cases. This implies that the mean energy loss can be compensated by the rf for the present thickness of the target used in CELSIUS.

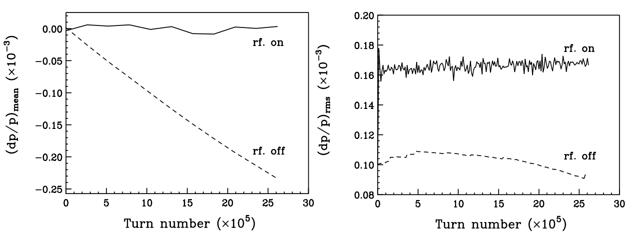

Figure 2: Simulation results showing the mean value (left) and rms value (right) of the relative momentum difference vs the turn number for both rf on and rf off.

Another interesting result is that a synchrotron oscillation of two bunches inside the stationary bucket starts to show up when the rf is switched on some time later than the target on. As an example, Fig. 3 shows the profile of particles in the rf phase angle after the target interaction has been ongoing for about 3.66×10^{6} revolutions (~1.4 sec). This behavious is due to the fact that, after interacting with the target from some time, the beam suffers a mean energy loss as a whole and develops a low energy tail (see Fig. 1).

Beam Lifetime

We simulated the lifetime of the 400MeV proton beam. The effective thickness of the hydrogen pellet target was 7.8×10^{-9} g/cm^2. The simulated result of the beam current vs time is shown in Fig. 4, together with the results measured in practise, where the beam current at start is scaled to one. In this simulation, we assumed that the pellet stream fills the full transverse aperture to account for the gas pressure in the vicinity of the target station which appears to be of the same order of magnitude thickness as the pellets. The simulation can correctly predict that the best lifetime is obtained when both rf and electron cooling are present, whereas the worst lifetime appears with electrn cooling on only. However, the simulations overestimate the beam lifetime. This could be because the target thickness is underestimated, and the horizontal aperture that was used in the simulation is bigger than the actual one. The single scatering of larger angle was not included in the simulations, but an estimation shows that the loss rate of the single scattering with angles exceeding the machine's acceptance angle is negligible.

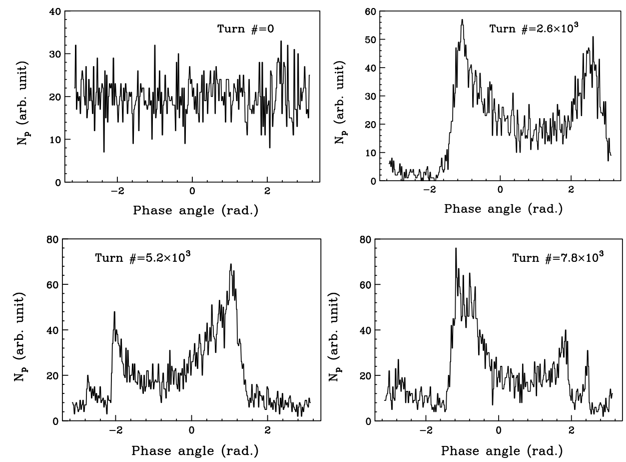

Figure 3: Simulation results showing the synchrotron oscillation of two bunches in the stationary bucket, which occurs when the rf comes on after the target interaction has been ongoing for 3.66×10^{6} turns.

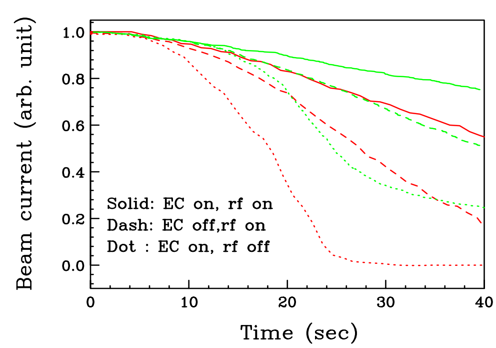

Figure 4: Comparison of lifetime that is simulated (in green) and measured (in red) for 400 MeV proton interacting with hydrogen pellet target of effective thickness of 7.8×10^{-9} g/cm^2.

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