BEAM EMITTANCE GROWTH BY INTERNAL TARGET EFFECTS IN COSY

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Abstract

The luminosity of a thin target experiment can be increased by many orders of magnitude using a recirculating beam in a storage ring. A limiting factor is the beam emittance growth. In the interesting range of target thicknesses ($< 10^{-6}$ radiation length) and proton energies (> 1 GeV) the usual multiple scattering approximations and the Landau energy loss distribution have to be modified. The resulting beam emittance growth is studied in a Monte Carlo simulation taking the lattice transfer matrices and synchrotron acceleration into account. The numerical results are compared with simple analytical estimates.

Introduction

Actually several light ion storage rings for nuclear and intermediate energy physics are planned, under construction or nearly completed. The cooler synchrotron COSY |1| which was recently approved to be built at KFA Jülich exhibits an especially high maximum energy (2.8 GeV kinetic energy for protons). The great attraction of all storage rings is the use of thin internal targets where the stored beam particles make on the order of a million passes per second through the target. This is in contrast to external experiments where the beam particles are dumped after one single target passage.

However a limiting factor of using internal targets is the beam emittance growth by small angle multiple scattering and energy loss straggling. Therefore, electron cooling as well as stochastic cooling is foreseen in most of the light ion storage ring projects. Unfortunately the maximum possible target thickness is limited by the cooling forces in such a way that self-supporting foils cannot be used in electron cooling nor in stochastic cooling experiments.

But there exists still the possibility to use self-supporting thin target foils in a recirculator mode without cooling. After beam injection and acceleration the synchrotron is operated in a storage mode. The beam is deflected to the internal target by a slight bump in the equilibrium orbit. An important point of the method is that the mean energy loss introduced by the target foil is compensated by an appropriate synchrotron acceleration. The useful beam lifetime depends very much on the emittance growth which is caused by the internal target. It is the aim of the present work to study this emittance growth due to self supporting thin target foils (thickness $\lesssim 1.10^{-6}$ radiation length) at proton kinetic energies $\gtrsim 1$ GeV.

Various aspects of the emittance growth by internal target effects in an ion storage ring have already been published in literature. Very useful formulas for analytical estimates of the transverse beam emittance growth can be found in the work of H. Bruck |2|. Using those formulas Cooper and Lawrence |3| studied the problem of charge exchange inflection into a proton storage ring through a 150 μg/cm² thick carbon foil at 800 MeV kinetic energy. Similar studies with respect to emittance growth and brightness gain were performed by Martin et al. |4|. Further computer simulations and analysis of charge exchange injections are reported in refs. |5-7|. H.O. Meyer |8| studied the interplay of internal target heating and electron cooling in a Monte Carlo computer simulation. He obtained numerical results for transverse and longitudinal equilibrium phase space distributions with the Indiana Cooler at 200 MeV proton energy and target thicknesses of the order of 100 ng/cm².

Since the emittance growth depends very much on the details of the small angle multiple scattering and energy loss probability distributions the predictions of those distributions are critically reviewed in sects 2 and 3. The Monte Carlo simulation program is sketched in sect. 4. Numerical calculations are performed using design parameters of COSY. Nevertheless, we believe that the results represent some general properties of the high-energy recirculator mode without cooling. The numerical example in sect. 5 refers to protons of 1500 MeV kinetic energy and a 10 μg/cm² thick carbon target.

The energy loss probability density distribution

In the presence of multiple scattering effects the probability density distribution $f(x,\Delta)$ of energy loss Δ by a layer of thickness x can be predicted by solving an appropriate transport equation. Landau |9| derived a probability density distribution for thin targets under the following two restrictions :

$$\xi / \Delta_{max} \ll 1 \qquad (1)$$
$$\xi / I \gg 1 \qquad (2)$$

Here, Δ_{max} is the maximum possible energy transfer in a head-on collision with a target electron and I is the mean atomic ionization potential. The scaling quantity ξ which is proportional to the target thickness x is given by :

$$\xi = 0.1535(\mathrm{MeV\ cm^2/g})(Z/A)(z/\beta^2)\rho\, x \qquad (3)$$

Here, Z is the charge number, A the mass number and ρx the areal density of the target, z the charge number and β the velocity of the projectile in units of light velocity c.

In the present work extremely thin targets and high proton energies are considered. For instance, for a carbon target of 10 μg/cm² thickness and 1500 MeV proton kinetic energy one has $\xi = 0.9$ eV, I = 80.8 eV and $\Delta_{max} = 5.87$ MeV. Thus the Landau condition (2) is strongly violated and the probability density distribution cannot be represented by the Landau function.

Considering the limit of extremely thin targets the probability of multiple scattering tends towards zero and $f(x,\Delta) \to x\, w(\Delta)$ for $\Delta > 0$ where $w(\Delta)$ is the macroscopic single scattering cross-section. The high energy loss part of $w(\Delta)$ is well described by the Bhabha formula for energetic knock-on electrons (see page 44 of ref. 10). In order to obtain a model description of the low-energy loss part of $w(\Delta)$ in the region of atomic binding effects we follow closely a method developed by Ispirian et al. |11|. The resulting probability distribution, i.e. the integral over the probability density distribution, is shown in Fig. 1.

The small angle multiple scattering distribution

For very thin targets the most recent and widely accepted theory of small angle multiple scattering is due to Sigmund and Winterbon |12|. For an appropriate scaling Sigmund and Winterbon define the following dimensionless variables τ (for the target thickness x) and $\tilde{\alpha}$ (for the scattering angle α)

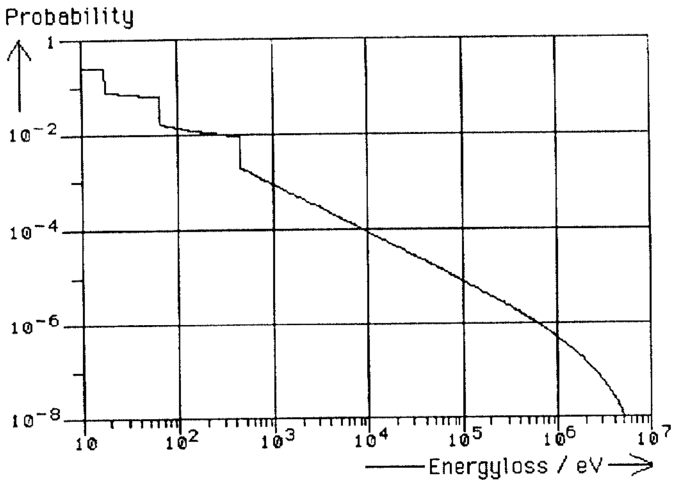

Fig.1 Energy loss probability distribution, protons on carbon (2250 MeV/c, 10 $\mu g/cm^2$)

$$\tau = \pi a^2 Nx \tag{4a}$$

$$\tilde{\alpha} = \frac{a\, p\beta c}{4zZe^2}\,\alpha \tag{4b}$$

Here, a is the screening radius, Nx the number of target atoms/unit area, e the elementary charge, p the momentum and βc the velocity of the projectile. The small angle scattering approximation ($\alpha = \sin\alpha$) is used.

The probability density distribution for scattering into the spatial angle interval $d\tilde{\alpha}$ is given by the product $\tilde{\alpha}\, f_1(\tau,\tilde{\alpha})$. The tabulated function $f_1(\tau,\tilde{\alpha})$ for screened ion-atom potentials of the Thomas-Fermi type |12| is incorporated into the simulation program in such a form that smooth interpolations are possible.

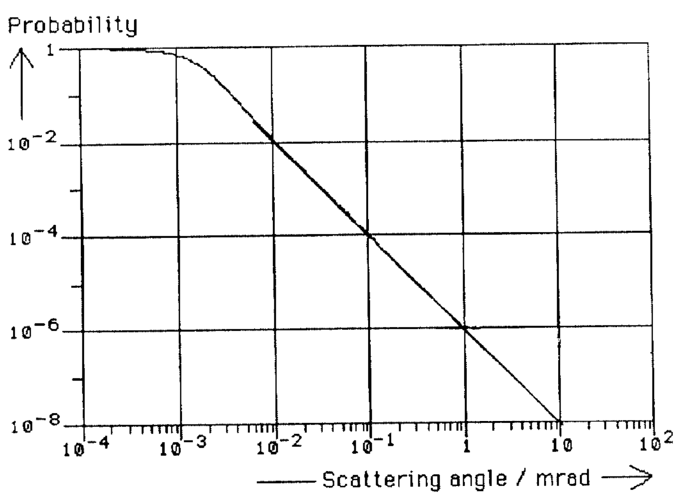

Fig.2 Small-angle scattering probability distribution, protons on carbon (2250 MeV/c, 10 $\mu g/cm^2$)

The range of $f_1(\tau,\tilde{\alpha})$ is extended beyond the tabulated range |12| using the Rutherford single scattering cross section ($f_1 \rightarrow \tau/2\tilde{\alpha}^4$). This extension is necessary since we are interested in the beam distortions resulting from $\sim 10^6$ target traversals. Therefore, scattering processes occuring with a probability of $\sim 10^{-3}$ and less must also be taken into account. This is especially important in view of the fact that the mean square of a scattering distribution depends strongly on the tails of the distribution. The resulting probability distribution is shown in fig. 2.

The Monte Carlo simulation program

The transport of a particle is described in first order approximation using the transport matrix |13| R. Several steps are performed for one revolution : (i) transport from target to the cavity (ii) momentum change in the cavity according to the actual phase lag (iii) transport from the cavity to the target (iv) random change of the angle deviations in the horizontal and vertical plane and the momentum deviation. The number of steps per revolution can be changed according to special requirements. For instance, beam scrapers, cavities and internal targets can be inserted at several positions. For the start the coordinates of a certain number of particles can be defined randomly according to a six dimensional gaussian phase space ellipsoid distribution. There exists also the possibility to start with a sharp δ-like pencil beam, i.e. all particles start at the coordinate of the reference particle. The phase space conservation requires det R = 1. This condition is guaranteed by a special constraint in order to avoid the accumulation of many small numerical errors.

Numerical results and discussion

The resulting growth of the transversal emittance the survival probability and the relative momentum deviation as a function of the turn number are shown in figs. 3 and 4. The emittances ε are defined using the variances and covariances of the distributions e.g. $\varepsilon_x = (\sigma_1\sigma_2 - \sigma_{12}^2)^{1/2}$. The calculations are performed for the internal target position TP2 using an achromatic mode of operation. The β-values at TP2 are $\beta_x = 1.93$ m and $\beta_z = 4.52$ m. The synchrotron acceleration voltage amplitude is $U_0 = 3$ kV, the harmonic number h = 1 and the transition energy $\gamma_{tr} = 2.458$. The bucket size $\Delta E = 15.1$ MeV is much larger than the maximum energy loss of 5.87 MeV so that the particles remain stable within the separatrix.

In order to record the emittance growth from the beginning we start with a pencil beam of 100 particles. The transversal beam emittances are limited by x - and z - beam scrapers of ± 6 mm slit width which are located for numerical simplicity at the target position TP2. Particle losses start at about 120 000 turns and amount about 30 % after 300 000 turns (see fig. 3). They are exclusively due to the axial beam scraper which represents a more stringent emittance limit than the radial beam scraper because of the larger β-value. The resulting limitation of the axial beam emittance can be seen in fig. 3.

The periodic structures in fig. 4 reflect the effect of the synchrotron oscillation which can be seen because of the low statistics. The rms width of the relative momentum deviation is on the order of 3 10^{-4} after 300 000 turns. The history of a selected single particle in the longitudinal phase space is shown in fig. 5. The trajectory of the particle is characterized by concentric ellipses reflecting the well known synchrotron oscillations. One sees that from time to time the particle suffers larger energy losses yielding big changes of the synchrotron amplitude .

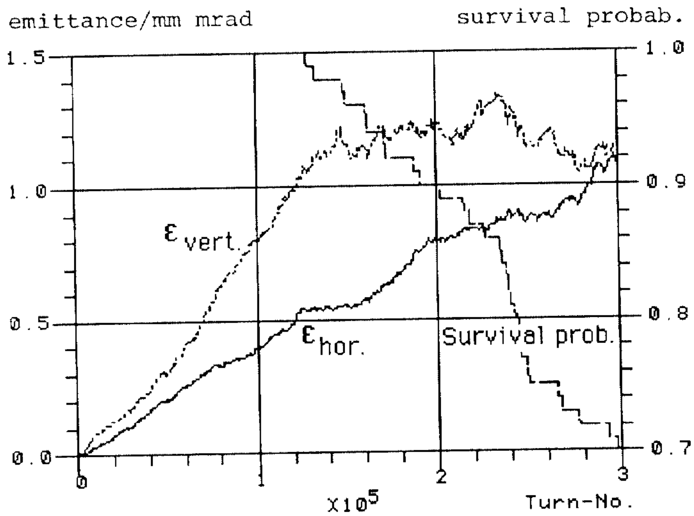

Fig.3 Emittance (left ordinate in mm mrad) and survival probability (right ordinate) vs. turn number

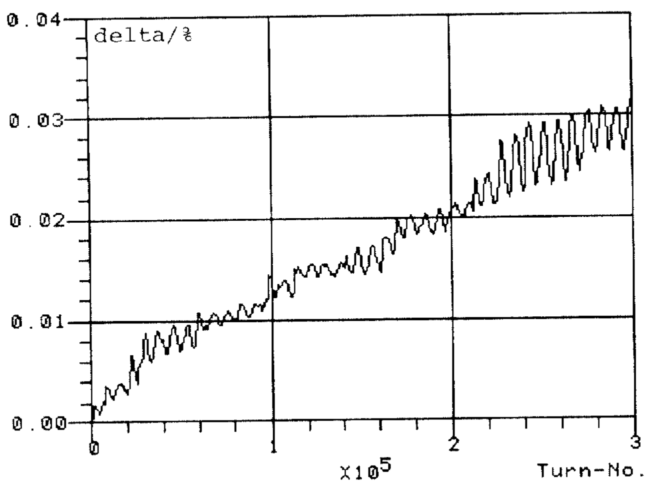

Fig.4 Relative rms momentum spread in % vs. turn number

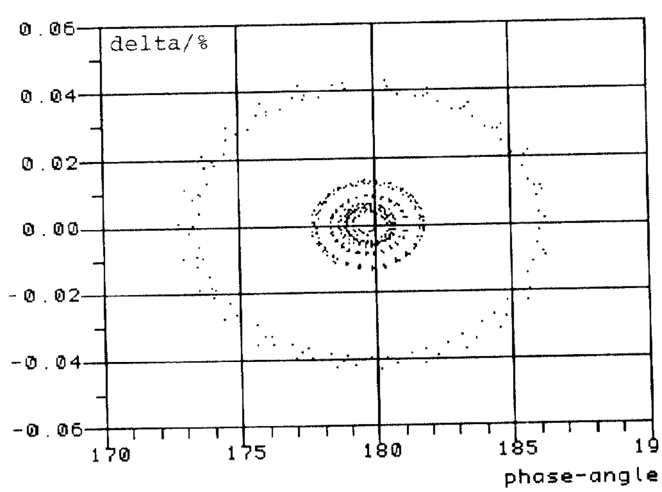

Fig.5 History of one single particle in longitudinal phase space (relative momentum deviation in % vs. phase angle in deg)

According to refs. 2,3 the transversal emittance growth can approximately be described by the following simple expression :

$$\varepsilon = 1/2\ N\ \beta\ \theta^2_{rms} \qquad (5)$$

Here, N is the number of turns, β the value of the betatron amplitude function at the target location and θ_{rms} the rms width of the plane projected scattering angle in a single target traversal. Thus, one expects a linear emittance growth with turn number as long as particle losses by beam scrapers are negligible. Neglecting the statistical fluctuations the numerical results are in accordance with this prediction (fig. 3). Comparing ε_x and ε_z one can also see that the emittance growth is proportional to the β-values. An upper limit estimate of θ_{rms} can be obtained using the Particle Data Group Formula without the logarithmic term $\theta_{rms} = (14.1\ \mathrm{MeV}/p\beta c)\ (x/x_{rad})^{1/2}$ where x_{rad} is the radiation length (= 42.7 g/cm² for carbon). This yields $\theta_{rms} = 3\ 10^{-6}$ rad and $\varepsilon_x = 2.6$ mm mrad after 300 000 turns which is a factor 2.4 larger than the calculated values. Thus for a rough estimate of the emittance growth one can use those formulas.

The numerical results demonstrate the feasibility of an internal target experiment with self-supporting foils in COSY. Only 30 % of particles are lost after 300 000 turns. Increasing the scraper widths or decreasing the β-values at the target location by a factor 2 yields the same survival probability of 70 % for 1.2 10^6 turns. The resulting emittances scale according to eq. 5, i.e. they increase either by a factor 4 or 2.

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