MONTE CARLO SIMULATION MODEL OF INTERNAL PELLET TARGETS*

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Abstract

In this paper we present a numerical model of a pellet target, which can be used for simulations of the interaction with a circulating beam in a ring by a Monte Carlo method. Details of real geometry of the pellet target system and the beam are taken into account.

INTRODUCTION

The influence of interaction effects with target and intrabeam scattering on beam parameters grows for high intensity beams in storage rings with effective cooling. It is necessary to study the beam dynamics in storage rings taking into account_the_complex interference of IBS, internal target effects and electron cooling as the most effective cooling method here. Main target effects are Coulomb angle scattering (multiple scattering) and energy loss (energy straggling). The shape of the distribution tails of the energy loss in the target and large angle distribution as a result of Coulomb scattering on the atoms of the target is important to study beam dynamics. The pellet target is one of the new types of internal targets for the storage rings and the development of appropriate simulation models is desirable [1].

PELLET TARGET

Main Characteristics

The pellet target [2] is a variant of a micro-particle internal target and it permits using almost the full solid angle for detection without requiring differential pumping in the interaction region while providing larger thickness of the target compared to gas targets. Original target materials are hydrogen or deuterium, which were recently complemented by N_2, Ar, Kr, Xe [6]. The pellets are small spheres of frozen hydrogen with a typical mean diameter of about 30 μm containing about $6{\cdot}10^{14}$ hydrogen atoms. The pellets are vertically passed through the beam at a rate of about dozens kHz. The speed of the pellets is on the order of 50-100 m/s such that the pellets follow one another a few mm apart. The pellet beam has a small angular divergence (nearly ±0.04°) and covers about ±1 mm horizontally at the point of inter-section with the beam. The horizontal profile is a homogenously filled, round circle which can be approximated by a Gaussian [3].

Numerical Model of the Pellet Target

A developed program model is dedicated to the pellet target system, which basic characteristics are given in refs. [1,4]. The structure of the program module consists of two parts. The first part supplies the geometry of the pellet target system and parameters, which should be set. In the second part the energy loss according to the Urbán model and the angle scattering according to the "Plural Scattering" model [5] is calculated. The semidirect Monte Carlo simulation is applied. 2D geometry is used, i.e. transverse coordinates (*x* – horizontal, *y* - vertical) are accounted in the area of the target, and the longitudinal coordinate (along beam direction) is fixed. The real geometry of the pellet beam and the beam of accelerated particles is modelled. The pellets are generated from the injection nozzle with a specified period. The injection nozzle has an extension along the *x* coordinate. The shape of the pellet is assumed spherical. The diameter of this sphere and the range for random variation of the diameter can be set. The real local (not mean value) thickness of every pellet is taken into account. The beam of the pellets has a prescribed divergence and distribution on the length of the injection nozzle. The centre of the injection nozzle and the accelerated beam can be shifted relative to the fixed of the coordinate system (pipe of ion beam). A schematic of the algorithmic model for the program is in accordance to fig.1.

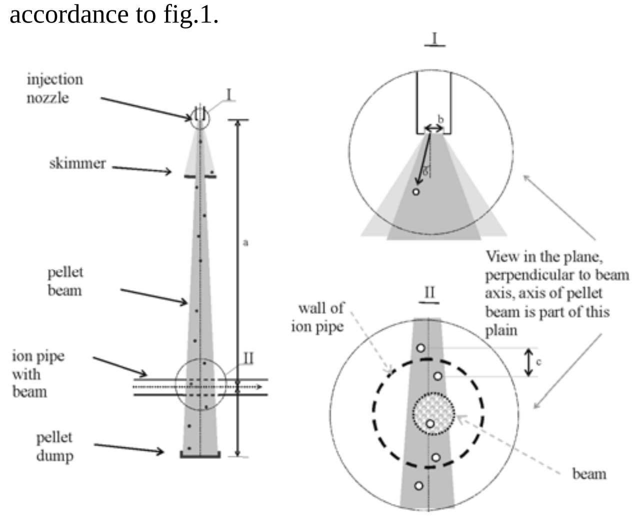

Figure 1: Schematic sketch of the pellet target set.

Standard doubly linked lists are used for the effective calculation of pellet coordinates in the case of a large distance between the injection nozzle and the beam. This approach provides the possibility to simulate locating the injection nozzle far from the beam without loss of calculation efficiency. The simulation of the real geometry and the path of particles through the pellets allows easily to build an event generator for simulation packages, taking into account beam dynamics and relative geometry of the pellet and an accelerated beam.

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Subprograms and auxiliary subroutines are written in FORTRAN 77 and C(C++) (equivalent variants) program languages.

Simulation Model of the Energy Loss

The energy loss $\Delta\varepsilon$ is determined by two contributions due to $\Delta\varepsilon_i$ ionization and $\Delta\varepsilon_e$ excitation processes in the pellet

$$\Delta\varepsilon=\Delta\varepsilon_e+\Delta\varepsilon_i\,, \qquad (1)$$

For the excitation process in case of the hydrogen pellets it is assumed that the atoms have only one energy level with the binding energy, which is equivalent to the ionization potential $I=16\cdot Z^{0.9}$. That means the energy loss due to excitation can be calculated as $\Delta\varepsilon_e=n_1 I$, where n_1 is the number of collisions. Due to a high local density of the pellets one assumes that there is a restricted number of collisions, which varies between 0 and 3 for ionization and follows the Poissonian distribution with a mean number $<n_i>$:

$$<n_i>=\sigma_i\,\Delta l, \qquad (2)$$

where σ_i is the macroscopic cross-section with index i=1 corresponding to the excitation and i=2 to the ionization process, Δl is the path length of the pellet. The macroscopic cross-section for excitations ($i=1$) is defined by

$$\sigma_1=\frac{d\varepsilon}{dx}\frac{1}{E_1}\frac{\ln(2m\beta^2\gamma^2/E_1)-\beta^2}{\ln(2m\beta^2\gamma^2/I)-\beta^2}(1-r)\,. \qquad (3)$$

β is the normalized speed of the incident beam, E_1 is the atomic energy level, $\gamma=(1-\beta^2)^{-0.5}$, m is the mass of the electron. The parameter r in Eq.(3) determines the relative contribution between the ionization and the excitation processes and can be chosen from 0 to 1. $d\varepsilon/dx$ is the mean energy loss that is proportional to the pellet density ρ_H (g/cm^3)

$$\frac{d\varepsilon}{dx}=0.3071\frac{\mathrm{MeV}\cdot\mathrm{cm}^2}{\mathrm{g}}\cdot\rho_H\frac{Z_t}{A_t}\frac{Z_i^2}{\beta^2}\left(\ln\left(\frac{2m_ec^2\gamma^2\beta^2}{I}\right)-\beta^2\right). \qquad (4)$$

Here A_t, Z_t are the atomic weight and number of the target material, Z_i is the atomic number of the incident particle. The macroscopic cross section of an ionization process is calculated according to

$$\sigma_2=\frac{d\varepsilon}{dx}\frac{\varepsilon_{\max}}{I(\varepsilon_{\max}+I)\ln\left(\frac{\varepsilon_{\max}+I}{I}\right)}r\,, \qquad (5)$$

where ε_{max} is the maximum possible energy transfer in a head-on collision with a target electron. The energy loss due to the ionization process is calculated by

$$\Delta\varepsilon_i=\sum_{j=1}^{n_2}\frac{I}{1-\frac{\eta_j\varepsilon_{\max}}{\varepsilon_{\max}+I}}\,. \qquad (6)$$

where η_j is a random number uniformly generated in the interval [0,1], n_2 is the number of collisions calculated by Eq.(2).

Simulation Model of the Scattering Angles

Collisions of the beam particles with the target nuclei result in single and plural Coulomb scattering. Following Moliere's treatment of a screened Coulomb potential, one finds the average number of scattering events per particle and passage of the pellet

$$\langle n_t\rangle=6702.33\rho_H Z_s'\exp\left(\frac{Z_E'-Z_x'}{Z_S'}\right)Z_i^2\frac{\Delta l}{\beta^2}\,, \qquad (7)$$

for material with one type of atoms:

$$Z_S'=\frac{Z_t(Z_t+1)}{A_t}\,,\; Z_x'=Z_S'\ln\left(1+3.34\left(\frac{Z_tZ_i}{137\beta}\right)^2\right),$$

Δl is the local path length in the pellet. According to "Plural Scattering" model, the number of scatters at a given passage is sampled from a Poisson distribution with mean 1.167$\langle n_t\rangle$. The individual scattering angles are calculated by sampling them from the following distribution:

$$\frac{dN}{d\theta}=\vartheta_\alpha^2\frac{2\theta}{\left(\theta^2+\vartheta_\alpha^2\right)^2} \qquad (8)$$

ϑ_α is so-called screening angle:

$$\vartheta_\alpha=\left(4.52\times10^{-3}MeV\right)\frac{\left(\beta^2+1.78\times10^{-4}Z_i^2Z_t^2\right)^{\frac{1}{2}}Z_t^{\frac{1}{3}}}{m\beta^2\gamma} \qquad (9)$$

For every scattering event an angle $\Delta\theta$ is calculated by

$$\Delta\theta=\vartheta_\alpha\sqrt{\frac{1}{\eta_1}-1}\,, \qquad (10)$$

where η_1 is a random number uniformly distributed in the interval [0,1]. The transverse particle coordinates are then modified according to $\Delta\theta_x=\Delta\theta\cos(2\pi\eta_2)$, $\Delta\theta_y=\Delta\theta\sin(2\pi\eta_2)$ with η_2 another random number in the interval [0,1].

SIMULATION PROGRAM PACKAGE PETAG01

A computer program package (called PETAG01) has been written to evaluate the pellet target characteristics in real time. This package can be included in any user program, where the time evolution of the beam's phase space and beam energy losses resulting from a pellet target are studied. The PETAG01 package consists of a number of subroutines, which should be called in a certain order. There are three subroutines which a user must call: (i) the initialization routines ARRINI, (ii) PETAG01INI and (iii) the routine, which calculates the parameters of the incident particle, PETAG01. All these routines call other subroutines in the package. The documentation head of the program source code includes a complete list of the subroutines in the package. Communication between the user's program and the PETAG01 package is done by one array DATAINP. The array is used to store the initial parameters of the pellet target system. The sequence of a call of the subroutines has following steps. Step 1 is the initialization of array DATAINP, Step 2 sets default parameters of the pellet target, Step 3 places the required values of the pellet target into array DATAINP (here all or some parameters of the pellet target can be redefined by the user if it is necessary), Step 4 calls PETAG01INI to give an initialization of the target system parameters, Step 5 calls PETAG01 to calculate parameters of the incident particle.

The incident particle is described in a Cartesian coordinate frame with transverse axes *x* (horizontal), *y* (vertical). Five independent variables characterize the particle before and after the target passage, which is associated with the call routine PETAG01. These variables are namely x, θ_x, y, θ_y and the relative momentum deviation $\delta p/p$. The call of the PETAG01 causes a variation only in three variables: θ_x, θ_y, $\delta p/p$. That means at a certain time ($t=t_0$) the input variables into PETAG01 have the values $x = x_0$, $\theta_x = \theta_{x0}$, $y = y_0$, $\theta_y = \theta_{y0}$, $\delta p/p = \delta p/p_0$ and output variables are treated as $x = x_0$, $\theta_x = \theta_{x0} \pm \Delta\theta_x$, $y = y_0$, $\theta_y = \theta_{y0} \pm \Delta\theta_y$, $\delta p/p = \delta p/p_0 - \Delta p/p$. The quantities $\Delta\theta_x$, $\Delta\theta_y$, $\Delta p/p$ are calculated according to the theory given in the previous sections and they depend on the current time *t* and the current particle coordinates *x, y*.

THE TEST RUNS

As an example, in this section we show results of test simulations, where the parameters of the incident beam are evaluated depending on some parameters of the pellet target. The energy loss and angle straggling caused only by the target is simulated with the Monte Carlo method. Each particle moving is described by the coordinates in 5-dimensional phase space (x, x', y, y', δp/p). In our test simulations one million particles (Ai = 1 and Zi = 1) are randomly created with initial coordinates following a uniform distribution. All particles have uniform energy of 1 GeV. Each time all particles penetrate the pellet with a diameter of d=30 µm. After passing the pellet for each particle there are losses of the energy and scattering by a small angle. The parameter r (in formulas 3, 5) is set to 0.4.

Fig. 2 shows the comparison of the energy loss distributions for cases of different treatment of the pellet geometry. One can see that the spectrum width is much larger if the pellet is represented as a sphere, where the path length inside the pellet varied depending on the distance from the centre. This case is closer to the real shape of the pellets obtained in such type of targets [2].

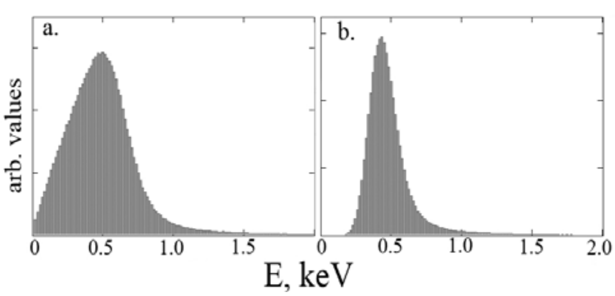

Figure 2: The energy loss distributions caused by the pellet if it has a) sphere geometry; b) disk with uniform passage Δl=2/3d. Number of hits is 1.

The behavior of the energy distribution in the cases, where the number of hits with pellets is 3 or 100, is shown in Fig. 3. These results are compared with distributions calculated analytically with Landau's theory, which assumes that the number of collisions in the target must be high (approximately more then 10).

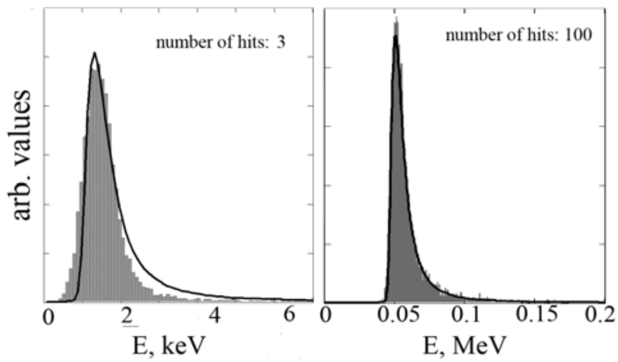

Figure 3: The energy loss distributions. The histogram corresponds to the Monte Carlo calculation using PETAG01 package; the solid line is calculated according to Landau’s theory.

Fig. 4 shows calculated scattering angle distributions for 1 and 100 hits of the pellet. These distributions are characterised by sufficiently large scattering angles. The cause for these large scattering angles is a small impact parameter or a close fly-by of the beam-proton at the pellet-proton.

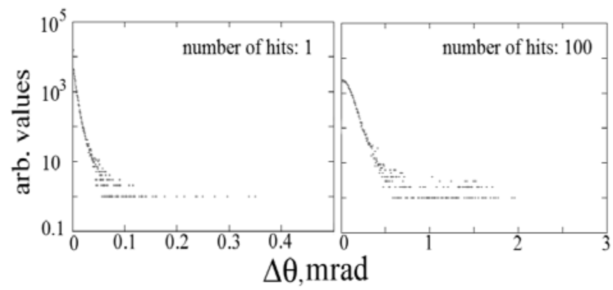

Figure 4: Scattering angle distributions.

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