PARAMETER EVOLUTION OF AN ION BEAM INTERACTING WITH THE NUCLOTRON INTERNAL TARGETS

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Abstract

For beams of the Nuclotron (a specialized superconducting strong-focusing accelerator of nuclei at the Laboratory of High Energies, JINR) the nucleus-internal target interaction is theoretically investigated. Taking this interaction into account , analytical expressions for time evolution of such beam parameters as current, transverse and longitudinal emittances are obtained. Using these expressions, the corresponding graphical dependences are calculated for **d, C** and **Ar** nuclei with energies of 1 and 6 AGeV and different internal targets at the Nuclotron. The luminosities averaged over cycle time are estimated .

1 INTRODUCTION

Relativistic nuclear physics deals with the study of processes in which the constituents of nuclear matter move with relative velocities close to the velocity of light. The asymptotic character of such natural phenomena has played a decisive role in a constraction of the Nuclotron, a strong focusing superconducting accelarator of relativistic nuclei at the LHE of the Joint Institute for Nuclear Risearch in Dubna [1]. As the first experiments [2,3] showed, this accelerator provides good possibilities for internal target technique. Internal targets provide either an improved resolution and secondary particle identification for solid targets or vastly increased luminosity for materials of an intrinsically low density such as polarized gases. Serious drawbacks of the internal target technique are the reduction of the potential reaction yild by scattering of the beam particles out of the ring acceptance and formation of the beam halo. This scattering activate the ring structure and halo can produce background for detectors by recirculating incide the ring acceptance. This background is the result of interaction of the halo ions with the target frame which is usually much thicker than the target itself. Thus, the planning of internal target experiments requires a detailed knowledge of the ion-target interaction, beam lifetime and emittance growth.

2 BEAM-INTERNAL TARGET INTERACTION

Physics experiments with internal targets are usually realized in recirculation mode of synchrotron operation after beam injection and acceleration. It is important for this mode of operation that the mean energy loss of ions per target traversal is compensated by an appropriate synchrotron acceleration in the rf-cavity. If we suppose that ions traverse a homogeneous target every turn and residual gas effects are negligible, general analytical expressions for beam parameter evolution can be obtained.

Small angle scattering and energy loss straggling of ions lead to the growth of transverse and longitudinal beam emittances. For a sufficiently large number of target traversals it can be described by the following equations [4,5]

$$\epsilon_i^{(N)}(\eta) = \epsilon_i^{(0)} + 0.5N\beta_i\eta^2\overline{(\delta Y')^2} + \tag{1}$$
$$+0.5N\eta^2[\gamma_i D_i^2 + 2\alpha_i D_i D_i' + \beta_i (D_i')^2]\overline{\delta^2},$$

$$\epsilon_l^{(N)}(\eta) = \epsilon_l^{(0)} + 0.5N\beta_l\eta^2\overline{\delta^2}. \tag{2}$$

Here $\epsilon_i^{(0)}$, $\epsilon_i^{(N)}$ are the initial and after N target traversals horizontal (i=x) or vertical (i=z) transverse emittances corresponding to η standart deviations in the Gaussian distribution; $\epsilon_l^{(0)}$ and $\epsilon_l^{(N)}$ are analogous longitudinal emittances; $\beta_i, \alpha_i, D_i, D_i', \gamma_i = (1+\alpha_i^2)/\beta_i$ are the parameters of the accelerator at the target location; $\overline{(\delta Y')^2}$ and $\overline{\delta^2}$ are the mean square deviations in angle and relative momentum after target traversal; $\beta_l = (\omega_{rf}/\omega_s)\sqrt{(|\zeta|2\pi p\beta c)/(ZU cos\varphi_s)}$; ω_{rf} and ω_s are the frequences of rf-cavity and synchronous particle turn, respectively; $\zeta = \delta \cdot (\Delta\omega/\omega)$ is the longitudinal dispersion of the accelerator; U is the voltage amplitude of rf-cavity; φ_s is the phase of the synchronous particle; $p, \beta c$ and Z are the momentum, velocity and charge number of ions respectively. Using Moliere's approximation of the screened coulomb potential of the Thomas-Fermi atom and the Landau-like energy loss distribution, for relativistic nuclear-target interaction at the Nuclotron (γ= 1;6) we obtain

$$\overline{(\delta Y')^2} \approx 7 \cdot 10^{-8} t A_0^{-1} \left(\frac{ZZ_0}{A\gamma\beta^2}\right)^2 \cdot \tag{3}$$
$$\cdot \left(ln\left(\frac{\theta_{cm}}{\theta_m}\right) - 0.5\right) = t \cdot f_1(Z, A, Z_0, A_0, \beta),$$

$$\overline{\delta^2} \approx 2 \cdot 10^{-7} t \frac{Z_0}{A_0}\left(\frac{Z}{\beta^2 A}\right)^2 \left(1 - \frac{\beta^2}{2}\right) = \tag{4}$$
$$= t \cdot f_2(Z, A, Z_0, A_0, \beta).$$

Here $\gamma = (1-\beta^2)^{-0.5}$; t is the target thickness $[g/cm^2]$; A, Z_0 and A_0 are the nuclear mass number, charge and mass number of the target respectively; $\theta_m \approx 3 \cdot 10^{-6} Z_0^{1/3}\sqrt{1 + 1.77 \cdot 10^{-4}(ZZ_0/\beta)^2}/(\beta\gamma A)$

is Moliere's screening angle; $\theta_{cm} \approx 0.15(1 + 1.53 \cdot 10^{-2} Z Z_0/\beta)/[\beta\gamma A(A^{1/3} + A_0^{1/3})]$ is the maximum angle of the Rutherford scattering determined by the nuclear radii of target and projectile. The growth of beam emittances, inelastic nuclear scattering and large angle elastic scattering in a single projectile passage through the target lead to beam losses. If we take into account only the first channel, the time evolution for circulating beam intensity (in relative units) can be obtained from the Fokker-Planck model of projectile diffusion in the (Y_i', Y_i)-phase spaces [6]. As the longitudinal emittance growth can be influenced by the rf-cavity voltage (see eq.(2)), we suppose that particle losses in the longitudinal phase space can be made negligible. Using the results of ref.[7], the probability of projectile loss because of diffusion in a beam after N target traversals is estimated by $P(N) = \prod_{i=x,z} P_i(\epsilon_i^{(N)})$, where calculated $P_i(\epsilon_i^{(N)})$-function is shown in fig.1.

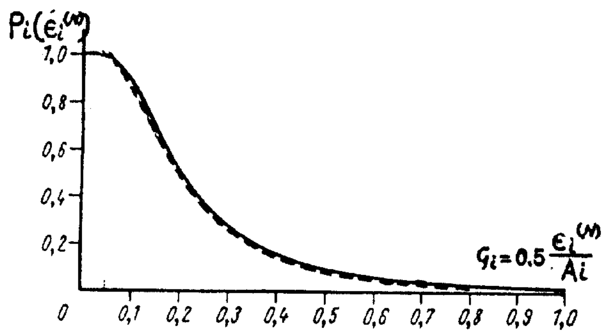

Fig.1. The probability of diffusion particle loss in (Y_i', Y_i)-phase spase for the beam with transverse emittance $\epsilon_i^{(N)}$, the dashed line shows the $exp[-5.36(\varsigma_i - 0.06)]$ approximation.

Approximating this function by $exp[-5.36(\varsigma_i - 0.06)]$, the effective cross section σ_i of particle loss after start time τ_i can be obtained as

$$\sigma_i \approx 4.5 \cdot 10^{-31} \frac{\eta^2}{A_i} \left[0.35\beta_i \left(\frac{Z_0 Z}{A\gamma\beta^2} \right)^2 \cdot \right. \tag{5}$$

$$\cdot \left(ln\left(\frac{\theta_{cm}}{\theta_m}\right) - 0.5 \right) + Z_0 \left(\frac{Z}{\beta^2 A} \right)^2 \left(1 - \frac{\beta^2}{2} \right) \cdot$$

$$\left. \cdot \left(\gamma_i D_i^2 + 2\alpha_i D_i D_i' + \beta_i (D_i')^2 \right) \right],$$

$$\tau_i \approx \frac{2S\left(0.12A_i - \epsilon_i^{(0)}\right)}{t\eta^2\beta c} \cdot \tag{6}$$

$$\cdot \left[\beta_i f_1 + \quad f_2 \left(\gamma_i D_i^2 + 2\alpha_i D_i D_i' + \beta_i (D_i')^2 \right) \right]^{-1},$$

where S, A_i are the ring circumference and acceptance.

Inelastic nuclear interaction and large angle elastic scattering lead to the projectile loss in every passage through the target with the cross section

$$\sigma_t = 0.5\sigma_c \left(\theta_{xa}^{-2} + \theta_{za}^{-2} - 2\theta_{cm}^{-2} \right) + \tag{7}$$
$$+ 0.5\sigma_{in}[4 - erf(\theta_{xa}/2\theta_d) - erf(\theta_{za}/2\theta_d)].$$

Here $\theta_{ia}^2 \approx A_i/(\beta_i\eta^2)$ (i=x,z), $\theta_d \approx 0.15[A(\gamma^2 - 1)^{0.5}(A^{1/3} + A_0^{1/3})]^{-1}$, $\sigma_{in} \approx 6 \cdot 10^{-26}(A^{1/3} + A_o^{1/3})^2$, $\sigma_c \approx 3 \cdot 10^{-31}[Z_o Z/(\beta^2\gamma A)]^2$ and Gaussian approximation of a central maximum of plane diffractional nuclear scattering is used. In eq.(7) we should assume $\theta_{ia} = \theta_{cm}$ when $\theta_{ia} > \theta_{cm}$. Depending on the collision energy and the type of colliding nuclei, different terms dominate in σ_t. The average beam lifetime (T_b) and cross section of the projectile loss (σ_{loss}) can be estimated as

$$T_b \approx \frac{a + \sum_i \tau_i \cdot \sigma_i \cdot b_i}{\sigma_t + \sum_i b_i \cdot \sigma_i}, (i = x, z) \tag{8}$$

$$\sigma_{loss} = \sigma_t + \sigma_{ef} = a/T_b, \tag{9}$$

where $a = A_0 S/(6 \cdot 10^{23} t\beta c)$, $b_i = 1$ if $\tau_i < T = a/\sigma_t$ and $b_i = 0$ otherwise, σ_{ef} is the effective cross section of the diffusion projectile loss.

The luminosity is the product of beam current and target thickness averaged over time. In recirculation mode of the accelerator run the luminosity L_c averaged over the cycle time T_c has the maximum value of $L_c = N_0/(T_c\sigma_{loss})$ (N_0 is the number of the circulating particles before beam-target interaction)which is independent of target thickness when $t_{g/cm^2} \geq t_c = A_0 S/(6 \cdot 10^{23} T_c \beta c \sigma_{loss})$.

3 INTERNAL TARGET EFFECTS AT THE NUCLOTRON

Using the above results, the numerical calculations of internal target effects for **d**, **C** and **Ar** nuclei with energies of 1 and 6 AGeV are obtained at the Nuclotron ($A_i \approx 40\pi$ mm·mrad, $\epsilon_i^{(0)} \approx 2\pi$ mm·mrad, $\beta_i \approx 780$ cm, $|\alpha_i| \approx 1.3$, $D_i \approx 220$ cm, $D_i' \approx 0.3$ at the target location). Fig.2 shows the curves characterizing the transverse emittance growth of the nucleus beam for different internal targets.

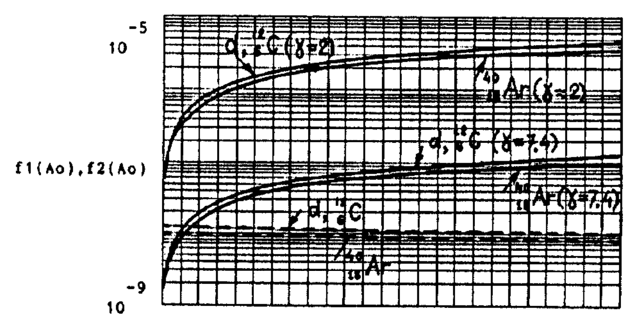

Fig.2. The f_1 (solid line) and f_2 (dashed line) functions vs target mass number A_0 for different projectiles.

σ_t and σ_i as a function of the target mass number A_0 are shown in fig.3. When the initial beam emittances ($\epsilon_i^{(0)}$) are known, the corresponding values of T, τ_i and T_b can be

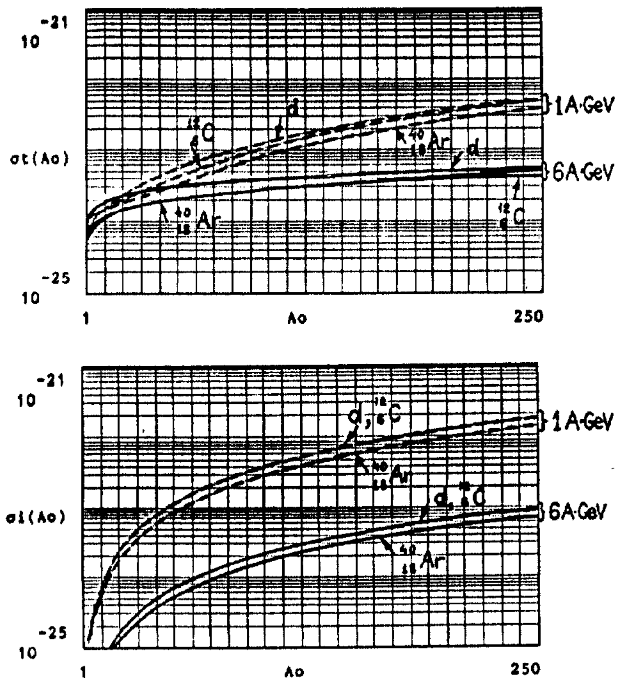

Fig.3. The σ_t and σ_i cross sections of the loss of relativistic **d, C** and **Ar** nuclei at the Nuclotron vs target mass number A_0.

obtained from fig.3 and eqs.(6),(8). The maximum values of luminosities averaged over cycle time at the first stage of Nuclotron run (T_c= 10 s) are plotted in fig.4

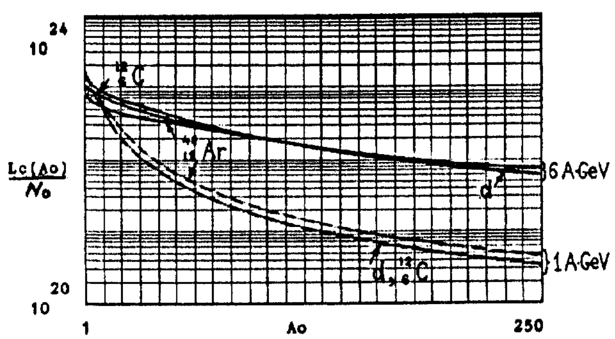

Fig.4. The maximum values of luminosities averaged over cycle time for different internal targets and **d, C** and **Ar** beams at the Nuclotron (T_c= 10 s).

4 REFERENCES

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