INTERNAL TARGETS IN THE NUCLOTRON*

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The potentialities of investigation of nucleus-nucleus collisions on internal beams of the Nuclotron (a specialized superconducting strong-focusing accelerator of nuclei at the LHE) are discussed. Emphasis is made on the importance of the change of beam parameters as a result of ion-internal target interaction. Analytical expressions for the evolution of beam parameters are obtained. The target station, which was used in a first experiment at the Nuclotron, is described. The time change of the ion flux interacting with an internal target, which was controlled by means of target radiation, agrees with theoretical estimations.

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1. Introduction

At present we have a clear notion of the general picture of nucleus-nucleus collisions over a wide energy range that makes it possible to plan confidently the development of accelerator facilities and to form installations on nuclear beams. 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 detailed construction plan and cost estimate of the Nuclotron, a specialized superconducting accelerator of relativistic nuclei at the LHE of the Joint Institute for Nuclear Research in Dubna [1]. This accelerator provides new possibilities for internal target technique. Taking into account a small vacuum chamber of the strong focusing machine, one can place detectors closer to the target and

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construct a setup with a solid angle approaching to 4π. Choosing the internal target thickness, one can detect various products of the fragmentation of colliding nuclei and obtain information on them without deterioration of average beam luminosity (see below). This feature is important to record complete information on nucleus-nucleus collision.

2. Internal target effects

As a result of nucleus-internal target interaction, new particles are created and beam parameters are evaluated. Using the Courant-Snyder formalism [2] for transverse phase ellipses and taking initially the Gaussian distribution of (Y_i, Y_i')-coordinates over ions in a beam, the following correlation can be obtained

$$\left\langle (\widehat{Y}_i)^2 \right\rangle = \frac{2\beta_i \epsilon_i^{(0)}(\eta)}{\eta^2} . \tag{1}$$

Here $\langle\rangle$ is the mean value over the all ions in a beam, $Y_i = X, Z$ are, the horizontal (radial) and vertical (axial) displacements from the equilibrium orbit, respectively; $(\widehat{Y}_i)^2 = Y_i^2 + (\alpha_i Y_i + \beta_i Y_i')^2$; $\pi\epsilon_i^{(0)}(\eta)$ are the emittance areas before ion-internal target interaction corresponding to η standard deviations in the distributions, and enclosing a ξ part of all ions in the beam ($\eta = 1 \rightarrow \xi = 0.384$, $\eta = 2 \rightarrow \xi = 0.865$, $\eta = 3 \rightarrow \xi = 0.989$); $\beta_i, \alpha_i, D_i, D_i', \gamma_i = (1 + \alpha_i^2)/\beta_i$ (see below) are the parameters of the accelerator at the target location. When a fast ion is nondestructible after the j-traversal of the internal target, the change $\delta Y_{i,j}'$ of the trajectory slope and the relative momentum deviation $\delta_j = \Delta p_j/p$ take place. The deviation $\delta Y_{i,j}$ behind the target can be usually neglected. Assuming the number of betatron oscillations per turn $Q_i = m_i/n_i$ (m_i and n_i are the whole numbers), $\mu_i = 2\pi Q_i$, and using Twiss' transport matrices (see, for example, [3]), we obtain the deviations

$$\begin{aligned} \delta Y_i\,(n_i) = {}& \beta_i \sum_{j=1}^{n_i} (\sin j\mu_i)\,\delta Y_{i,j}' + D_i \sum_{j=0}^{n_i-1} \left[\cos j\mu_i + \alpha \sin j\mu_i\right] \delta_{j+1} \\ & + D_i'\beta_i \sum_{j=1}^{n_i-1} (\sin j\mu_i)\,\delta_j\,, \end{aligned} \tag{2}$$

$$\begin{aligned} \delta Y_i'\,(n_i) = {}& \sum_{j=1}^{n_i} (\cos j\mu_i - \alpha \sin j\mu_i)\,\delta Y_{i,j}' \\ & + \sum_{j=0}^{n_i-1} \left[D_i'(\cos j\mu_i - \alpha \sin j\mu_i) - \gamma_i D_i \sin j\mu_i\right] \delta_{j+1}\,, \end{aligned} \tag{3}$$

after an "elementary act" of ion-internal target interaction in the absence of oscillation damping (effect of n_i target traversals and following turns). Here and below we suppose that ion traverse a homogeneous target every turn and residual gas effects are negligible. When the mean energy loss per target traversal is compensated by an appropriate synchrotron acceleration in the rf-cavity (recirculation mode of accelerator operation), the $\delta Y_i(n_i)$ and $\delta Y_i'(n_i)$ distributions with the mean values of $\overline{\delta Y_i(n_i)} = \overline{\delta Y_i'(n_i)} = 0$ and their mean square deviations are independent of the "elementary act" number. Thus, from the fundamental limit theorem of probability theory, we can assume that the resulting (Y_i, Y_i')-distributions after many "elementary acts" of ion-internal target interaction will be also Gaussian. From this, and using correlation (1), the following expression on the evolution of transverse beam emittances $\epsilon^{(N)}(\eta)$ can be obtained

$$\epsilon_i^{(N)}(\eta) = \epsilon_i^{(0)} + 0.5N\beta_i\eta^2\overline{(\delta Y')^2} + 0.5N\eta^2\left[\gamma_i D_i^2 + 2\alpha_i D_i D_i' + \beta_i (D_i')^2\right]\overline{\delta^2}\,, \tag{4}$$

where N is the number of target traversals, $\overline{(\delta Y')^2}$ and $\overline{\delta^2}$ are the mean square deviations in angle and relative momentum after the target traversal.

For small synchrotron oscillation amplitudes with Gaussian distribution in longitudinal $(\Delta\varphi, \delta)$-phase space ($\Delta\varphi$ is the rf-phase lag with respect to the φ_s-phase of the synchronous particle), and from formal analogy between upright longitudinal and similar transverse ($\alpha_i = 0$) phase ellipses, one can obtain the following equation for the evolution of longitudinal emittance:

$$\epsilon_l^{(N)}(\eta) = \epsilon_l^{(0)} + 0.5N\beta_l\eta^2\overline{\delta^2}\,. \tag{5}$$

Here $\epsilon_l^{(0)}$ is the initial longitudinal emittance,

$$\beta_l = h\sqrt{(|\zeta|2\pi p\beta c)/(ZU\cos\varphi_s)}\,, \quad h = \omega_{\rm rf}/\omega_s\,,$$

is the harmonic number of rf-cavity; ω_s is the frequency of the synchronous particle turn, $\zeta = \delta(\Delta\omega/\omega)$ is the longitudinal dispersion of the accelerator, U is the voltage amplitude of rf-cavity, p, βc and Z are the momentum, velocity and charge number of the ions, respectively. For $\eta = 1$ and $\alpha_i = 0$ Eqs (4), (5) coincide with the result of Ref. [4].

For high energy ions Coulomb scattering, elastic (diffraction) and inelastic nuclear scattering in the target take place (see, for example, [5]). Therefore the resulting $\delta Y_{i,j}'$ and δ_j distributions have a complex form and depend strongly on the target thickness. The total cross sections of above--mentioned interactions can be estimated by $\sigma_c \approx 10^{-20}(Z/\beta)^2 Z_0^{4/3}$ [cm^2], $\sigma_d \approx \sigma_{in}$, and $\sigma_{in} \approx 6\cdot 10^{-26}(A^{1/3} + A_0^{1/3})$ [cm^2], respectively. Here A is the mass number of the ions, Z_0 and A_0 are the charge and mass numbers of the target, β_c is the ion velocity. Because of the large Coulomb differential cross section for small angles this scattering defines evolution of transverse and longitudinal beam emittances. For thin targets the values $\overline{(\delta Y')^2}$ and $\overline{\delta^2}$ in Eqs (4), (5) can be obtained taking into account only single Rutherford scattering from a screened potential and the results of Ref. [6]:

$$\overline{(\delta Y')^2} \approx 5 \cdot 10^{-8} t A_0^{-3} \left(\frac{Z Z_0}{\gamma \beta^2}\right)^2 \left(\ln \frac{\theta_{\text{cm}}}{\sqrt{2}\theta_{\min}} - 0.25\right), \tag{6}$$

$$\overline{\delta^2} \approx 2 \cdot 10^{-5} t \frac{Z^2 Z_0^{5/3}}{\beta^3 A A_0^2}. \tag{7}$$

Here:

$\gamma = (1-\beta^2)^{-0.5}$, t is the target thickness [g/cm^2],

$\theta_{\min} \approx 2.8 \cdot 10^{-6} Z_0^{1/3}/(\beta\gamma A_0)$ is the atomic screening angle of the target,

$\theta_{\text{cm}} \approx 2.3 \cdot 10^{-3} Z Z_0/[\beta^2 \gamma A (A^{1/3} + A_0^{1/3})]$ is the maximum angle of the Rutherford scattering determined by nuclear radii of an ion and a target.

The growth of beam emittances, inelastic nuclear scattering and large angle elastic scattering in a single ion passage through the target lead to the beam losses. If we take into account only first channel, the following expression of the time evolution for the circulating beam intensity (in relative units) can be obtained:

$$I_1(\tau) = \prod_i I_{1i} = \prod_i \left(\frac{erf\left(\frac{\eta}{\sqrt{\xi_i}}\right)}{erf(\eta)}\right)^2, \tag{8}$$

where $\xi_i = \epsilon_i^{(N)}(\eta)/A_i \geq 1$, $I_{1i}(\tau) = 1$ otherwise, $\tau = NP/\beta c$, A_i is the ring acceptance in X or Z directions, $erf(x)$ is the error function and P is the ring circumference. This result agrees with the more complex expressions in Refs [3, 4], where the Fokker–Planck method is used. Taking into account only angular scattering, the total cross section, which leads to the loss of the ion in a single passage through the target, is obtained as

$$\begin{aligned}\sigma_t = \sigma_{in} + 0.5\sigma_c \left(\theta_{xa}^{-2} + \theta_{za}^{-2} - 2\theta_{\text{cm}}^{-2}\right) \\ +0.5\sigma_{in}\left(2 - erf\left(\frac{\theta_{xa}}{2\theta_d}\right) - erf\left(\frac{\theta_{za}}{2\theta_d}\right)\right).\end{aligned} \tag{9}$$

Here $\theta_{ia}^2 \approx A_i/\pi\beta_i$ $(i = x, z)$, $\theta_d \approx 0.15[A(\gamma^2-1)^{0.5}(A^{1/3}+A_0^{1/3})]^{-1}$ and Gaussian approximation of the central maximum of the plane diffractional nuclear scattering is used. In Eq. (9), we must assume $\theta_{ia} = \theta_{\rm cm}$ when $\theta_{ia} > \theta_{\rm cm}$. Depending on the collision energy and the type of colliding nuclei, in Eq. (9) the different terms dominate. The combination of Eqs (8), (9) yields the following expression of the time evolution of the circulating beam intensity

$$I(\tau) = I_1(\tau)\exp\left(\frac{-\tau}{T}\right), \tag{10}$$

where $T = PA_0/(6\cdot 10^{23}t\beta c\sigma_t)$. For estimation of the beam lifetime ($T_{\rm b}$) the expression $I_1(\tau)$ can be approximated by $\exp(-\tau/T_{ef})$, starting from the minimum time τ_i corresponding to $\xi_i = 1$. Thus one can assume

$$T_{\rm b} \approx \begin{cases} \frac{T}{1+T/T_{ef}} & \text{if } \min\tau_i < T; \\ T & \text{otherwise;} \end{cases} \tag{11}$$

where $T/T_{ef} = \sigma_{ef}/\sigma_t$, σ_{ef} is the effective cross section of the ion loss depending on the beam emittances and the accelerator parameters (see Eqs (4)–(8)). The luminosity is the product of a beam current and a target thickness averaged over time. Taking into account Eq. (11), the luminosity $L_{\rm c}$ averaged over the cycle time $T_{\rm c}$ of the accelerator ($T_{\rm c} > T_{\rm b}$) is equal to

$$L_{\rm c} = \frac{N_0}{T_{\rm c}\left(\sigma_t + \sigma_{ef}\right)}, \tag{12}$$

and independent of the target thickness. Here N_0 is the number of the storage ions before ion-internal target interaction, $\sigma_{ef} = 0$ or $\neq 0$ according to the condition in Eq. (11). The equivalent target thickness for an external beam is defined as

$$t_{eq}\ [\mathrm{g/cm^2}] = \frac{A_0}{6\cdot 10^{23}(\sigma_t + \sigma_{ef})}. \tag{13}$$

3. Target station arrangement

The linear area of the Nuclotron with an internal target station is the installation with its own independent vacuum pumps. It can operate both as a part of the beam transport line of the Nuclotron and independently of it when the accelerator is off. The independent vacuum pumping and dismountable design of the station allow one to change functional possibilities of this installation operatively and without an influence on the vacuum and cryogenic systems of the other Nuclotron areas. We can realize the mounting of the next batch of internal targets or elements for following irradiation on the internal beam of the Nuclotron and also the total replacement of the station for another experiment. Thus, at this installation one can use various types of internal targets (foils, thread-like, jets, beams *etc.*), test new methods of beam diagnostics and realize certain experiments analogous to those with a solid angle approaching to 4π on an external beam. Taking into account the supposed beam intensities in a first stage of operation (see [1]), emittances and parameters of the Nuclotron (see [7]), one can expect the following mean luminosities [$cm^{-2}s^{-1}$]:

$$
\begin{aligned}
&L_c(d \to 1 \text{ AGeV} \approx 4\cdot 10^{33}(\text{C}, \text{CH}_2), && 7\cdot 10^{32}(\text{Cu}), && 10^{32}(\text{Au});\\
&L_c(d \to 6 \text{ AGeV} \approx 4\cdot 10^{33}(\text{C}, \text{CH}_2), && 2\cdot 10^{33}(\text{Cu}), && 10^{33}(\text{Au});\\
&L_c(^{12}\text{C} \to 1 \text{ AGeV} \approx 4\cdot 10^{32}(\text{C}, \text{CH}_2), && 10^{32}(\text{Cu}), && 2\cdot 10^{31}(\text{Au});\\
&L_c(^{12}\text{C} \to 6 \text{ AGeV} \approx 6\cdot 10^{32}(\text{C}, \text{CH}_2), && 3\cdot 10^{32}(\text{Cu}), && 2\cdot 10^{32}(\text{Au});\\
&L_c(^{40}\text{Ar} \to 1 \text{ AGeV} \approx 2\cdot 10^{30}(\text{C}, \text{CH}_2), && 6\cdot 10^{29}(\text{Cu}), && 10^{29}(\text{Au});\\
&L_c(^{40}\text{Ar} \to 6 \text{ AGeV} \approx 2\cdot 10^{30}(\text{C}, \text{CH}_2), && 10^{30}(\text{Cu}), && 6\cdot 10^{29}(\text{Au}).
\end{aligned}
$$

In the first run we used the target station made of two crossing cylinders of the beam transport line and a larger diameter cylinder with three internal targets. The dimensions and wall thickness (0.5 mm) of the station are optimized to detect second particles by external detectors with a maximum solid angle and minimum losses. The foil targets of CH_2 (1.6 μm thickness), Cu (0.55 μm) and Au (1.7 μm) are hanged up by 9 μm diameter quartz fibres in the C-shaped frames mounted vertically on the table rotating by means of a step motor with a high precision. Extraction of all frames with the targets from the beam transport line, choice of a necessary target for experiment, and control of its spatial position relative to the transport line axis are realized by means of an electro-optical device connected with the rotation axis of the table and the distant control system of the step motor. This allows to introduce the target by a remote control into the beam on a controllable depth and time exposition distantly and at a determined time moment relative to the beginning of an ion acceleration cycle. The upper dismountable flange of the station is used to change the frames with the targets. It has a window for visual control of the targets in adjusting and two branch pipes for placing detectors in vacuum.

In a first experiment at the Nuclotron with a deuteron beam, several $\Delta E - E$ scintillation telescopes are used to detect secondary protons and deuterons. To control the intensity and lifetime of a part of the deuteron beam interacting with the target, the radiation of the target material is used. The radiation is detected through the window by a photomultiplier tube and by a tandem-microchannel-plate detector in vacuum. The obtained oscillograms indicate the time structure of the coasting beam, and a decrease of intensity in time agrees with theoretical estimations for the used targets and deuteron energy (200 MeV). While adjusting the acceleration mode at the Nuclotron (the absence of targets in the beam transport line), radiation signals corresponding to the bombardment of the station wall by a part of the deuteron beam were episodically observed.

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