A New Method of Ion Beam Diagnostics

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Abstract

In the considered method of ion beam diagnostics, information on beam parameters is taken out via fast neutral particles produced in definite quantum states in a specially shaped target before the bending transport line area. The target is formed so that these particles follow the ion velocity in magnitude and in direction with accuracies required for measurements. The beam parameters are determined in a convenient area outside the transport line by means of a compact magnetic analyzer and electrons produced from selective photoionization of the used quantum state of the fast neutral particles. The realization of such diagnostics in the area of charge-exchange $H^- \to P$ injection of meson factory storage ring is considered.

1. INTRODUCTION

A charge-exchange method of particle flux control in the modern accelerators and the storage rings is broadly used. By using negative ions at the beginning of a beam transport line and forming charge-exchange targets at various transport line areas a convenient separation of high energy beams can be realized. A charge-exchange process in a target always leads to some flux of fast neutral particles (A^o) which follow the ion velocity in magnitude (in relative units) and in direction (in rad) with high accuracies. At present various methods of nonperturbative diagnostics on high-energy H^- beams, where information on the beam parameters is taken out via the fast H^o atoms, are proposed [1-5]. The disadvantages of these methods are a long drift distance in time-of-flight measurements of the energy spectrum [2] or the large mass and size characteristics of the magnetic analyzers when the H^o detachment to protons is used in the measurements [1,4]. A new method of ion beam diagnostics proposed by the author [6] and considered in this paper allows to avoid these difficulties.

2. METHOD

For ion beam diagnostics based on the fast neutral particles A^o a compact apparatus can be created if information on the ion energy spectrum then is passed to electrons. A maximum accuracy of this transformation can be realized for the neutral particles in a definite quantum state in an optimum shaped photon target. A quantum state, photon polarization and their frequency ω in the particle rest frame are chosen so as to achieve a necessary accuracy of the information transfer to the electrons and a required ratio of photoionization probabilities of the used and other quantum states. A kinematic analysis of an electron detachment after the photon absorption by the fast neutral particle $A^o(n)$ in the quantum state "n" (photoionization) shows that, depending on the photon polarization, the created electron follows the particle energy (in relative units) and momentum direction with accuracies:

$$\Delta E_e/E_e \leq \frac{2\beta\gamma}{(\gamma-1)C}\cdot\sqrt{2(\omega-\varepsilon_n)},$$

$$\Delta\theta_e[rad] \leq 2\cdot\frac{\sqrt{2(\omega-\varepsilon_n)}}{\gamma\beta C}, \qquad (1)$$

where we use the atomic units ($e = m_e = \hbar = 1$), $E_e = E_o/M_o$; β and γ are relativistic beam parameters, M_o and E_o are the mass and energy of the neutral particle, $\omega = \omega_o\gamma(1-\beta\cdot cos\eta)$, ω_o is the photon energy in the laboratory frame, η is the lab. angle between the particle and photon momenta, C is the speed of light, ε_n is the photoionization threshold of the quantum state "n". Taking into account a maximum cross section of a photoionization near the threshold ε_n, the best accuracy of an information transfer on ion beam parameters to the electrons is achieved for

$$(\omega-\varepsilon_n)_{min} \approx \gamma\omega_o\{\mid \Delta\beta\cdot[\beta(1-\beta cos\eta)\gamma^2 - -cos\eta] \mid +\beta sin\eta\cdot \mid \Delta\theta_i \mid\}, \qquad (2)$$

where $\Delta\beta$, $\Delta\theta_i$ are the spreads of the particle (ion) velocities in value and direction, respectively.

As an example, we estimate potentialities of such diagnostics for the H^- beam in the area of the charge-exchange injection at meson factories. Usually, for a high ($\approx$ 99%) efficiency of the $H^- \to P$ transformation carbon foils are used. As a result of the H^- destruction the H^o atoms ($\approx$ 1%) in various quantum states are produced. A relative number of the H^o atoms in the quantum state "n" ($\delta_{on}, n = 1,2,\ldots$) depends on the H^- ion energy, thickness and material of the stripping target [7,8]. A flux

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of the fast H^o atoms leaves the ion beam after the stripping foil in a transport line area with a bending magnet. Except a charge separation in the magnetic field a destruction of some quantum states of the H^o atoms takes place. Taking into account the $H^o(n)$ -photoionization cross sections (see for example [9]), for a transfer of the information on beam parameters from the fast H^o atoms to the electrons conveniently to use quantum states "$1s$" and "$2s$" which dominate in the H^0 flux. Conditions of an optimum photoionization of the $1s$- and $2s$-quantum states are obtained as a result of the Monte Carlo simulation of the elementary acts of the electron creation from the ns-quantum state of the A^o. The correspondent probability distributions of the electrons in the spaces of transverse momenta ($P_x/P_o, P_y/P_o$, where $P_o = \sqrt{2(\omega - \varepsilon_n)}$) and energy ($E_e$) in the laboratory frame (the own distributions) are obtained. The results of the simulation show that for a transfer of information on the transverse beam emittance, for example in the (X, X')-plane, to electrons with a maximum accuracy, the photon target must be polarized in the (Y, Z)-plane of the Cartesian coordinate system (X, Y, Z) with the Z-axis in the direction of the A^o flux. $X' = dX/dZ$ is the ion trajectory slope proportional to the transverse momentum P_x. The corresponding own distribution of electrons $f(P_x, P_y)$ at $\eta = \pi/4$ and $3\pi/4$ is shown in Fig.1. For other angles η similar distributions

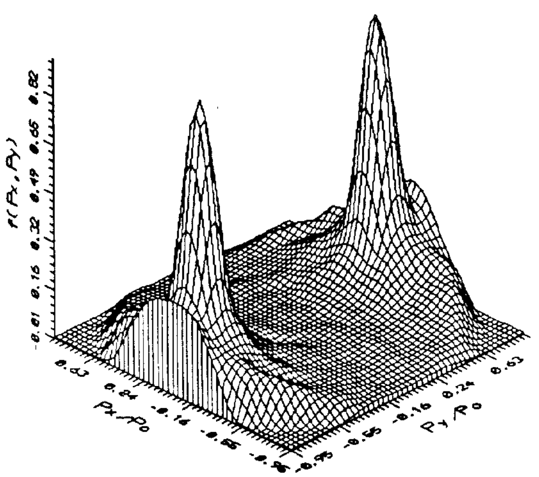

Figure 1: The own distributions of electrons in the (P_x, P_y)-space for the $A^o(ns)$-atom photoionization ($\eta = \pi/4, 3\pi/4$, optimum photon polarization).

but with a various distance between the maxima along the P_y-axis are obtained. The measurement accuracy of X' in the considered diagnostic method determined by the half-width of the distribution $\varphi(P_x) = \int f(P_x, P_y)dP_x$ is independent of η and equals

$$\Delta X'_{[rad]} \approx \frac{\sqrt{2(\omega - \varepsilon_n)}}{4\gamma\beta C}, \quad (3)$$

The measuring apparatus is supposed to integrate the electron distribution along the P_y-axis not perturbing information in the (X, X')-plane. Unlike the above-mentioned condition, a maximum accuracy of the information transfer on the longitudinal beam emittance and the ion energy spectrum to electrons is achieved when the planes of the photon polarization and the $A^o(ns)$-photon interaction are mutually perpendicular. The corresponding own energy distribution of electrons in dimensionless units $XS = [E_e - (\gamma - 1)C^2]/(0.1\gamma\beta CP_o)$ is shown in Fig.2 and independent of η. It is easy to see that the

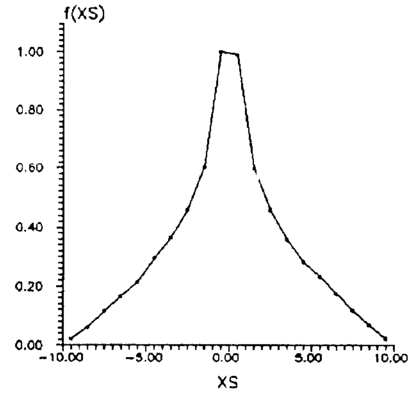

Figure 2: The own energy distribution of electrons for the $A^o(ns)$-atom photoionization (optimum photon polarization).

accuracy in determining the ion energy by electrons in relative units is equal to

$$\Delta E_e/E_e \approx \frac{0.4\beta\gamma}{(\gamma - 1)C} \cdot \sqrt{2(\omega - \varepsilon_n)}. \quad (4)$$

The photon targets necessary for the diagnostics of the H^- beams with various energies are simply realized when the information on the beam parameters is received through the H^o atoms in the $2s$-quantum state (ε_2=3.395 eV). In this case, e.g. forming the optimum photon target by means of N_2-laser (ω_o=3.678 eV) at $\eta = 58^o$, the accuracies of measurements $\approx 10^{-2}\%$ in energy and $\approx 3 \cdot 10^{-5}$ rad in X' can be obtained for the H^- beam with E_i=600 MeV, $\Delta\beta/\beta \approx \pm 10^{-3}$ end $\Delta\theta_i \approx \pm 10^{-3}$ rad at the Moscow Meson Factory Linac (MMFL). For the more energetic ions with $E_i \geq 800$ MeV (LAMPF), the information on the beam can be obtained from the intense flux of the H^o atoms in the $1s$-quantum state ($\delta_{01} \approx 50\delta_{02}, \varepsilon_1 = 13.599$ eV). For this, the optimum photon target is simply realized by means of a fourth-harmonic radiation of a Nd:YAG-laser (ω_o =4.6595 eV). But in this case the accuracies of the measurements of the beam parameters are about twice worse than in the above-considered case.

3. APPARATUS

For measuring the electron flux parameters and determining through them the corresponding ion beam parameters a compact multifunctional apparatus which is proposed in [10] can be used. The apparatus based on a dipole magnet (MA) with a homogeneous field and interpolar distance D_m sufficient to pass unhindered all the

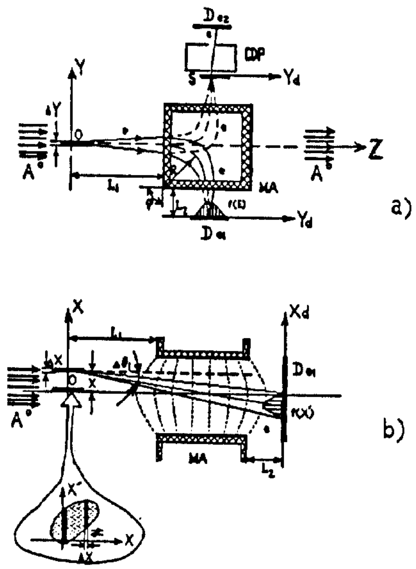

Figure 3: Schematic of measurement apparatus.

electrons produced from a photoionization of the fast neutral particles (see Fig.3).

The ion energy spectrum and longitudinal beam emittance measurements are performed according to a scheme (Fig.3a) well known for magnetic analyzers where, instead of a diaphragming slit of the analyzer, a band-type photon target (O) is formed. The energy spectrum of the ions is determined according to the spatial distribution of the electron flux density along the Y_d-axis on the detector D_{e1}. Electrons with momenta needed for the phase analysis are operatively separated by means of the diaphragm S, when a sign and value of the analyzer magnetic field are changed. The longitudinal emittance of the ion beam is determined according to a combination of the spatial distributions of the selected electrons on the detector D_{e2} after the cavity dispersed in phase (CDP), e.g. with a circularly polarized rf-field [11].

For measuring the transverse emittance in the (X, X')-plane and the X-profile of the neutral particle flux (and through them of the ion beam in the charge-exchange target area), the band-type photon target is localized within the (Y, Z)-plane and moves in parallel along the X-axis (Fig.3b). A computer simulation of the influence of boundary fields, inaccuracies in adjusting and manufacturing of the magnetic dipole shows that electron distributions on the detector D_{e1} along the X_d-axis are described by the expression

$$X_d = a \cdot X + b \cdot X', \quad (5)$$

where "a" and "b" are determined only by parameters of the analyzer chosen and can be defined in control experiments by means of a testing electron beam. The ion distribution in the (X, X')-plane can be reconstructed according to the X_d-distributions of the electrons on the detector for controllable characteristics of the photon target (defining a probability of an electron generating) and its position in the space (X). At the same time the functional dependence of the integral electron flux on the detector upon the target position defines the beam profile along the X-axis. For a short time interval (e.g. during a laser pulse) a certain information on the ion distribution over the (X, X')-plane can be obtained by means of several band-type photon targets fixed in space, created and separated from each other along the X-axis by diaphragming a laser radiation. The distance between them (δX) is defined by a condition of the electron distributions overlapping on the detector along the X_d-axis.

The required diagnostics of the above considered H^- beam at the MMFL can be realized during a time of $\tau_m \approx$ 1 s by means of the $H^o(2s)$ atoms, pulsed photon target ($\approx$ 300 kW/pulse, N_2-laser) synchronized with the beam and apparatus (see Fig.3) with $\varphi = \pi$, R= 200 mm, $L_1 = L_2 = 0$, D_m= 40 mm, spatial resolution of the detectors $\Delta d \approx \Delta Y \approx \Delta X \approx 0.1$ mm, $\delta X \approx 1.3$ mm and projection of the target area (where the electrons are collected from) onto the Z-axis $\Delta Z_t \leq 20$ mm (energy spectrum, profile, transverse emittance) or $\Delta Z_t \leq 1$ mm (phase analysis, longitudinal emittance). A value of magnetic field of such an electron analyzer is H= 110 Oe. For a precise operation of the apparatus spatial position of the band-type photon target should be controlled with accuracies of $\delta(X) \approx \delta(Y) \leq 0.1$ mm, $\alpha(X) \approx \alpha(Y) \leq$ 3 mrad. Moreover, the background magnetic fields H_b should be well shielded off, as well as required accuracy of the magnetic field magnitude H in the analyzer $(H_b \approx \delta H \leq 3 \cdot 10^{-4} H)$. In a charge-exchange area at the LAMPF (E_i= 800 MeV) the above considered apparatus allows to realize more operative diagnostics of the beam (through the intensive flux of $H^o(1s)$ atoms) and without detriment to the measurement accuracy.

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