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A NEW METHOD OF ION BEAM DIAGNOSTICS

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Новый метод диагностики пучка ионов

В рассматриваемом методе диагностики пучка ионов информация о параметрах пучка выводится с помощью быстрых нейтральных частиц, образующихся в определенных квантовых состояниях на специальным образом сформированной мишени перед поворотным участком канала транспортировки пучка. Мишень формируется таким образом, чтобы данные частицы повторяли скорость ионов по величине и направлению с требуемыми для измерений точностями. Параметры пучка определяются в удобном месте за пределами канала транспортировки с помощью компактного магнитного анализатора и электронов, образующихся в результате избирательной фотоионизации используемого квантового состояния быстрых нейтральных частиц. Рассмотрена реализация такой диагностики на участке перезарядной $H^- \to P$ инжекции в накопительное кольцо мезонных фабрик. Если информация о параметрах пучка ионов H^- выводится с помощью быстрых атомов H^0 в метастабильном $2s$-квантовом состоянии, то для пучка H^- с энергией ионов $E_i \geq 600$ МэВ может быть достигнута точность соответствия распределений электронов и ионов по энергии $\leq 10^{-2}\%$ и по угловой координате $\leq 3 \cdot 10^{-5}$ рад.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Artiomov A.S. **E9-92-501**

A New Method of Ion Beam Diagnostics

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. If information on the H^- beam parameters is taken out via fast H^0 atoms in the metastable $2s$-quantum state, the accuracies of correspondence between electron and ion distributions of $\leq 10^{-2}\%$ in energy and $\leq 3 \cdot 10^{-5}$ rad in angular coordinate can be obtained for the H^- beam with the ion energy of $E_i \geq 600$ MeV.

The investigation has been performed at the Laboratory of High Energies, JINR.

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Introduction

A charge-exchange method of particle flux control in the modern accelerators and the storage rings is broadly used [1]. 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°) in various quantum states. These particles can be used for the ion beam diagnostics if a target is formed so that the particles follow the ion velocity in magnitude (in relative units) and in direction (in rad) with accuracies required for the measurements. In the elementary acts of particle creation these accuracies can be estimated by $\leqslant (\mu_o \cdot I_o / M_i \cdot E_i)^{0.5}$ where μ_o is the reduced mass of the neutral particle and the remaining part of the ion in its destruction or the ion and electrons in their recombination, I_o is the affinity energy, M_i and E_i are the mass and energy of the ion, respectively. 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° atoms, are proposed [2-6]. The disadvantages of these methods are a long drift distance in time-of-flight measurements of the energy spectrum [3] or the large mass and size characteristics of the magnetic analyzers when the H° detachment to protons is used in the measurements [2,5]. A new method of ion beam diagnostics proposed by the author [7] and considered in this paper allows to avoid these difficulties.

Method

For ion beam diagnostics based on the fast neutral particles A° 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 $A^\circ(n)$ 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:

$$\Delta E_e/E_e \leqslant \frac{2\cdot\beta\cdot\gamma}{(\gamma-1)\cdot C}\cdot\sqrt{2\cdot(\omega-\varepsilon_n)}\ , \qquad \Delta\theta_e^{(rad)} \leqslant 2\cdot\frac{\sqrt{2\cdot(\omega-\varepsilon_n)}}{\gamma\cdot\beta\cdot C}, \qquad (1)$$

where we use the atomic units ($e=m_e=\hbar=1$), $E_e= E_o/M_o$; β and γ are relativistic beam parameters, $\beta= V_o/C$; V_o, M_o and E_o are the velocity, mass and energy of the neutral particle, $\omega = \omega_o\cdot\gamma\cdot(1-\beta\cdot\cos\eta)$, 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

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

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 $H^- \rightarrow P$ injection at meson factories. Usually, for a high (≈ 99%) efficiency of the $H^- \rightarrow P$ transformation carbon foils are used. As a result of the H^- destruction the H° atoms (≈ 1%) in various quantum states which follow the ion energy and momentum direction with a high accuracy are also produced. A relative number of the H° atoms in the quantum state "n" (δ_{on}, n = 1,2,...) depends on the H^- ion energy, thickness and material of the stripping target [8,9]. For a target with a minimum thickness, a value δ_{on} is equal to $\sigma_{-1n}/\sigma_{-1o}$ (σ_{-1n}, σ_{-1o} are the partial and total cross sections of the single-electron H^- detachment) and decreases when the target thickness and the value "n" increase. A flux of the fast H° 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° atoms takes place. Taking into account the $H^\circ(n)$-photoionization cross sections (see Fig 1), for a transfer of the information on beam parameters from the fast H° atoms to the electrons conveniently to use quantum states "1s" and "2s" which dominate in the H° 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. 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 simulation is based on an angular distribution of the electrons in the rest frame of the ionized A° atoms, which was theoretically obtained by Cooper and Zare [11]

$$d\sigma/d\Omega = \sigma_{tot}\cdot[1+\beta_o\cdot P_2(\cos\theta)]/4\pi\ , \qquad (3)$$

where $P_2(\cos\theta)= 0.5\cdot(3\cdot\cos^2\theta-1)$, σ_{tot} is the photoionization cross section, θ is the angle between the electron momentum and the photon polarization vector, β_o is the asymmetry parameter which for the ns-quantum states is equal to 2. 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° 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.2. For other angles η similar distributions 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 $\varphi(P_x)= \int f(P_x,P_y)dP_y$ is independent

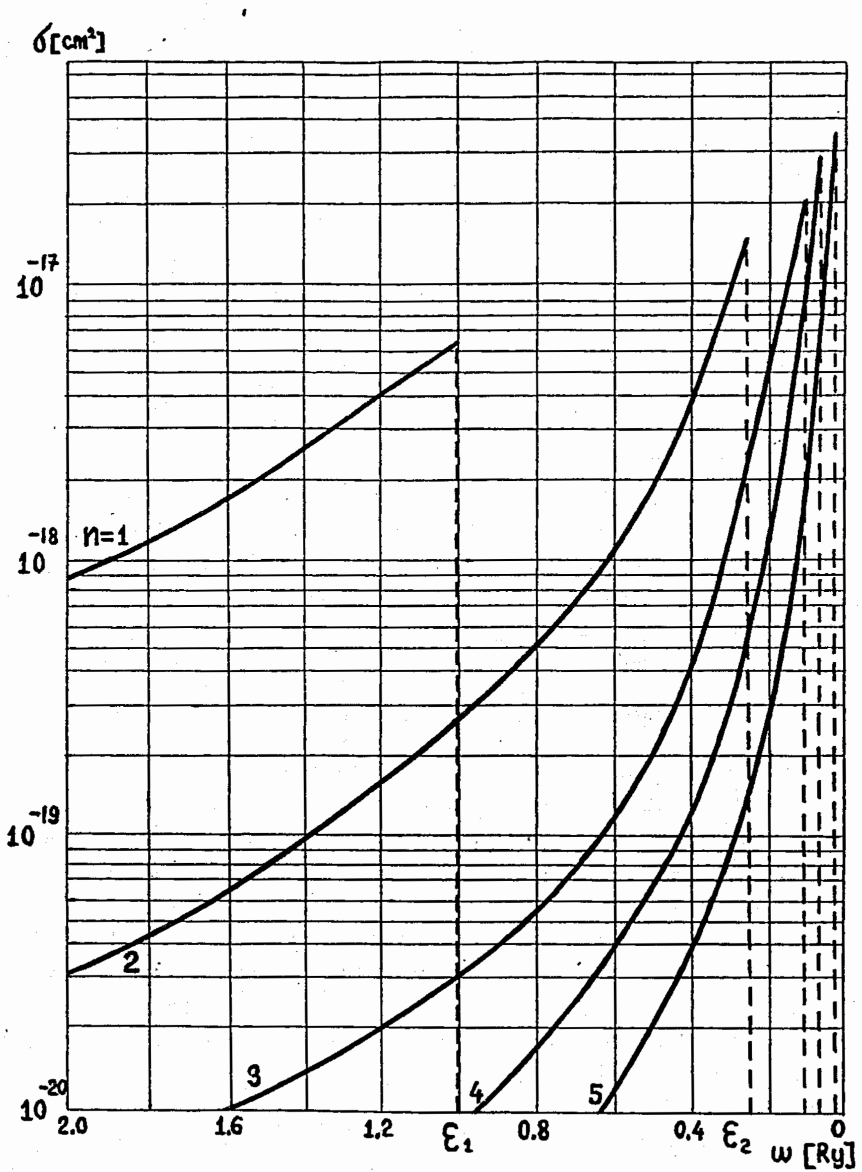

Fig. 1. The cross sections of H°(n) photoionization [10].

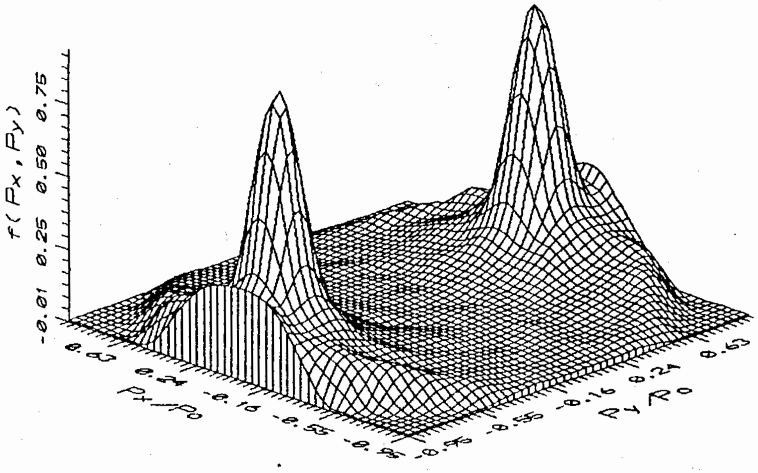

Fig.2. The own distributions of electrons in the (P_x,P_y)-space for the A°(ns)-atom photoionization (η= π/4,3π/4 , optimum photon polarization).

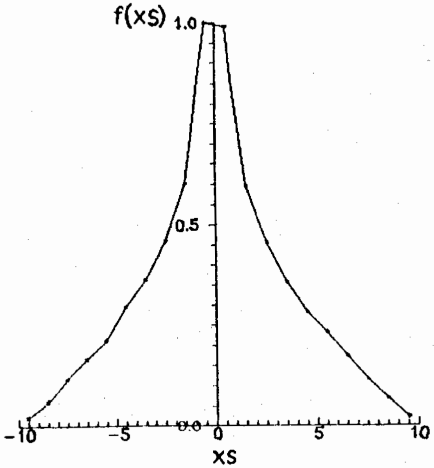

Fig.3. The own energy distribution of electrons for the A°(ns)-atom photoionization (optimum photon polarization).

of η and equals

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

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 photon-A°(ns) interaction are mutually perpendicular. The corresponding own energy distribution of electrons in dimensionless units $XS = [E_e-(\gamma-1)\cdot C^2]/(0.1\cdot\gamma\cdot\beta\cdot C\cdot P_o)$ is shown in Fig.3 and independent of η. It is easy to see that the accuracy in determining the ion energy by electrons in relative units is equal to

$$\Delta E_e/E_e \approx \frac{0.4\cdot\beta\cdot\gamma\cdot\sqrt{2\cdot(\omega-\varepsilon_n)}}{(\gamma-1)\cdot C} . \qquad (5)$$

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° atoms in the 2s-quantum state (ε_2= 3.395 eV). In this case, e.g. forming the optimum photon target by means of a N_2-laser (ω_o= 3.678 eV) at η= 58°, 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, $\Delta\beta/\beta \approx \pm 10^{-3}$ and $\Delta\theta_i \approx \pm 10^{-3}$rad at the Moscow Meson Factory Linac (MMFL). For the more energetic ions with $E_i \geqslant$ 800 MeV (LAMPF, SSC), the information on the beam can be obtained from the intense flux of the H° atoms in the 1s-quantum state ($\delta_{o1} \approx 50\cdot\delta_{o2}$, ε_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.

Apparatus

For measuring the electron flux parameters and determining through them the corresponding ion beam parameters a compact multifunctional apparatus which is proposed in [12] can be used. The ion beam parameters are determined taking into account a drift distance of the fast neutral particles from the charge-exchange target to the photon one. The apparatus based on a dipole magnet (MA) with a homogeneous field and interpolar distance D_m sufficient to pass unhindered all the electrons produced from a photoionization of the fast neutral particles (see Fig.4).

The ion energy spectrum and longitudinal beam emittance measurements are performed according to a scheme (Fig.4a) 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 [13]. The reproduction accuracy of the phase structure of the flux of neutral particles by the electron flux is mainly defined by the projection ΔZ_m of the target area (where the electrons are collected from) onto the Z-axis and by the difference of the electron trajectory lengths in the magnetic analyzer due to the electron angular spread.

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.4b). 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

$$X_d = a\cdot X + b\cdot X' , \qquad (6)$$

where "a" and "b" are determined only by parameters of the

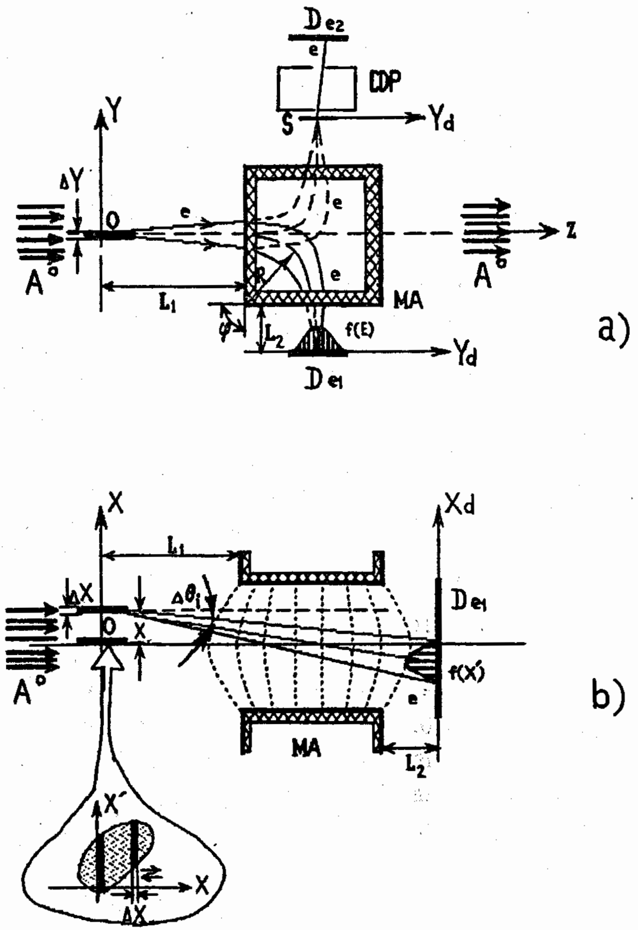

Fig.4. Schematic of measurement apparatus.

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 pulse of the ion beam) 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.

A computer simulation of functioning of the apparatus allows to estimate its characteristics, for which a sufficient accuracy of measurements of the ion beam parameters is provided. For example, nonperturbative diagnostics of the above considered H^- beam at the MMFL can be realized by means of the apparatus (see Fig.4) 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, $\Delta Z_m \leqslant 20$ mm (energy spectrum, profile, transverse emittance) or $\Delta Z_m \leqslant 1$ 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 $\delta(X) \approx \delta(Y) \leqslant 0.1$ mm, $\alpha(X) \approx \alpha(Y) \leqslant 3$ 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 ($H_b \approx \delta H \leqslant 3 \cdot 10^{-4} \cdot H$). A number of H(2s) atoms passing through the photon target during a pulse of the ion beam ($\tau_i \approx 100$ μs) is estimated of $\approx 3 \cdot 10^7$. For such a flux of information carriers, a frequency of the beam pulses f= 100 Hz and by forming the pulsed ($\tau_l \approx 10$ ns, N_2-laser) photon target, synchronized with the beam, with a power of ≈ 300 kW/pulse the measurements of the ion beam parameters during a time of $\tau_m \approx 1$s can be realized. 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° atoms in 1s-quantum state) and without detriment to the measurement accuracy.

Conclusion

The peculiarity of the considered diagnostic method is that the information on the beam parameters is taken out via fast neutral particles and then is passed to the electrons in a convenient area outside the beam transport line. The maximum accuracy of this diagnostics can be achieved when electrons are mainly generated as a result of near-threshold photoionization of some quantum state of the neutral particles in a specially shaped photon target. An employment of the electrons at a last stage of an information reception on an ion beam allows one to realize the diagnostics by means of a compact multifunctional apparatus. The proposed diagnostic method is most convenient in bending areas of a beam transport line with a charge-exchange control over fluxes of high energy particles. In this paper we considered the simple apparatus based on the magnetic analyzer which allows one to realize nonperturbative control of various beam parameters with a sufficient accuracy in the charge-exchange $H^{-} \rightarrow P$ injection area of meson factory storage rings. This was not our purpose to find a type of electron analyzer and its parameters for realization of the maximum possibilities of the considered diagnostic method. The results of the computer experiments allow one to optimize the photon target for an information transfer on ion beams to electrons through a flux of fast atoms in the ns-quantum state (n= 1,2,...) with maximum accuracy. The considered apparatus can be also used in areas of high-energy H^{-} linacs with intermediate extraction of a part of the beam into a separate transport line of protons or H° atoms. For a small energy or more heavy ions a diagnostic apparatus based on electrostatic analyzers of electrons can be preferable.

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