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CORRELATION METHOD OF MEASUREMENTS
OF ION BEAM PARAMETERS

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Introduction

For high-brightness ion accelerators it is important to obtain information on beam parameters not affecting them appreciably during measurements (nonperturbative diagnostics). For this purpose in a bending transport line area fast neutral particles can be used. These particles are produced as a result of ion destruction or the charge-exchange process in a specially shaped target which is practically transparent for a beam (for H\(^+\) beams see [1–5]). The target is formed so that these information-carrier neutral particles (IN-particles) follow the ion velocity in magnitude (in relative units) and in direction (in rad) with accuracies required for measurements. These accuracies can be estimated by \( \delta \approx (\mu_n \cdot I_n / M \cdot \xi) \)\(^{0.5} \) where \( \mu_n \) 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, \( I_n \) is the affinity energy, \( M \) and \( \xi \) are the ion mass and energy, respectively. In sources, for example of negative ions, the probability of IN-particle generation (\( \eta \)) in residual gas can be quite considerable (\( \eta \approx 0.2 \pm 0.4 \)). In this case, using the well known methods [1–5] for any density of a probing target, it is impossible to separate directly information on beam parameters from a flux of background IN-particles on a detector. The correlation method of nonperturbative measurements of ion beam parameters considered in this paper allows one to overcome these difficulties.

Method

The correlation method of nonperturbative measurements of the ion energy spectrum has been previously proposed [6,7]. It is based on the use of test IN-particles produced in a target, pseudorandomly modulated in time, and detected at distance \( L \). To measure the transverse beam emittance, for example in the \( (Y,Y') \)-plane (see Figure), one or a few thread-type targets parallel to the \( (X,Z) \)-plane can be formed in front of a bending transport line area. If the ion beam current is invariable during
measurements, the spatial X-dimension of the target must be
required for reproducing target time modulation by the flux \( \phi_{pn} \) of
test IN-particles

\[
\phi_{pn}(t) = \text{const}_{m} \cdot I_{n}^T(t),
\]

(1)

where \( I_{n}^T \) is the flux of photons or particles in the \( n \)-target. The
targets are fixed in space and separated from each other along the
Y-axis. When one target is used, it moves in parallel along the
Y-axis. Taking into account (1), the autocorrelation function of
the flux of test IN-particles on a \( m \)-detector is equal to

\[
R_{nm}^{pp}(\tau) = \int_{-\infty}^{\infty} \phi_{pn}(t) \cdot \phi_{pn}^*(t-\tau) \cdot dt = \sum_{\kappa=0}^{\infty} \delta(t-k \cdot \tau).
\]

(2)

The pulsed characteristic \( h_{nm}(t) \) of the drift distance from the
\( n \)-target to the \( m \)-band-type detector (\( Y' = \text{fix} \)) is related to the
velocity \( V \) distribution of IN-particles (\( t = L/V \)) in the \( n-m \)
direction and, hence, to the energy spectrum of ions. The fluxes of
IN-particles in the \( n \)-target area (\( \phi_{np}^* \)) and on the \( m \)-detector
(\( \phi_{nm}^* \)) are related by the convolution

\[
f_{nm}(t) = \int_{0}^{\infty} h_{nm}(\tau) \cdot \phi_{np}^*(t-\tau) \cdot dt , \quad \sum_{m} \phi_{nm} = 1,
\]

(3)

where \( \phi_{nm}^* = \phi_{np}^* + \phi_{nm}^* \), \( \phi_{np}^* \) is the flux of background IN-particles
produced in the residual gas. Taking into account the independence
of \( \phi_{nm}^* \) and \( \phi_{np}^* \) and measuring the cross-correlation function
between the fluxes of target particles or photons and IN-particles
on the detector

\[
R_{nm}^{pp}(\tau) = \int_{-\infty}^{\infty} I_{n}^T(t) \cdot f_{nm}(t-\tau) \cdot dt = B_{nm} \int_{0}^{\infty} h_{nm}(t) \cdot R_{nm}^{pp}(t+\tau) \cdot dt = \]

\[
= B_{nm} \sum_{\kappa=0}^{\infty} h_{nm}(\tau-k \cdot \tau),
\]

(4)

we obtain the pulsed characteristic of the drift distance in the
\( n-m \) direction \( (I_{nm}^T = I_{n}^T) \). Using normalization \( \int h_{nm}(\tau) dt = 1 \), we
get from the \( B_{nm} \)-matrix information on the ion distribution in the
\((Y, Y')\)-plane and thus on the beam Y-profile and transverse
eittance.

In reality, we must form such targets when convolution (4) of
\( h_{nm} \) and \( R_{nm}^{pp} \) does not change the supposed \( h_{nm}(t) \)-function. In
accordance with (8), this condition means that a periodically
reproducing element of the autocorrelation function of the \( I_{n}^T \) flux
must have a sufficiently narrow shape in time with width \( \Delta < \tau_{\text{max}} \),
where \( h_m(t) = 0 \) for \( |t| > \tau_{\text{max}} \), and its period \( T \) must meet the
condition \( T > 2 \cdot \tau_{\text{max}} \). Correlation methods measure a useful signal
with a background which is several orders of magnitude more than the
signal. Thus, measuring \( R_{nm}(t) \) by "n-m" correlometers, the
energy spectrum and distribution of ions in the \((Y,Y')\)-plane can be
controlled without perturbation of beam parameters.

**Apparatus**

Nonperturbative measurements of ion beam parameters, for example
in a source of \(^7\)H\(^-\) ions, can be realized according to the scheme
shown in Figure. It is analogous to the previously proposed one
[7], but it contains "n" identical photon targets \( (I_n^p) \) and photon
detectors \( (D_n^p) \), "n-m" correlometers \( (C_{nm}) \) and band-type detectors
\( (B_{nm}) \) of fast \(^7\)H\(^-\) atoms. When probing targets are formed by
diaphragming radiation with an optimum polarization and a
wavelength of \( \lambda = 10600 \) Å from the Nd:YAG laser with synchronised
modes (see Fig.a,b), the test \(^7\)H\(^-\) atoms follow the \(^7\)H\(^-\) velocity in
magnitude (in relative units) and in direction (in rad) with
accuracies of \( \sim 4 \cdot 10^{-3} \cdot \left( E_{\text{kin}} \right)^{-0.5} \). The series duration of
pseudorandom radiation pulses is \( T_p = 100 \) ns and the width of the
autocorrelation function is \( \Delta \approx 50 \) ps [9]. Thus, such photon
targets due to \(^7\)H\(^-\) photodetachment can efficiently generate test
IN-particles \( (H^+) \) and allow one to measure pulsed characteristics
of the drift distance \( h_m(t) \) which are fairly short in time. At
present, potentialities of the above diagnostics are mainly
limited by the fast action of correlometers.

The cross-correlation function \( R_{nm}(t) \) between the photon flux
\( I_{nm}^p \) from a partly reflecting \( M_{nm} \)-mirror and current \( I_{nm}^c \) from
the \( D_{nm} \)-detector can be measured by means of a time-integrated
\( C_{nm} \)-correlometer based on charge-coupled (CC) linear structures
[7,10]. As a result of the waveguide propagation of photons
through GaAs-CC-linear structure 1 (see Fig. c), the \( I_{nm}^c \)-current
modulates the flux \( I_{nm}^p \) by the photoelectric absorption effect
within a \( \sim 100\% \) dynamical range of modulation. An instantaneous
spatial distribution of charges over the pixels of this structure
corresponds to the discrete-in-time representation of the shape of
Fig. Schematic of measurement apparatus.
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Correlation Method of Measurements of Ion Beam Parameters

A correlation method of nonperturbative control on the ion energy spectrum, beam profile and transverse emittance in a bending transport line area, is suggested. The method is based on measurements of the cross-correlation function between a flux of photons or particles from a probing target pseudorandomly modulated in time, and that of fast neutral particles produced in the target and recorded at a drift distance. Characteristics of the apparatus used to realize the proposed diagnostic method by means of time-integrated correlometers based on charge-coupled devices, are considered for a source of $H^-$ ions.

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