HIGHLY-SENSITIVE IONIZATION DETECTORS OF ACCELERATED BEAM PARAMETERS FOR WIDE USE

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Abstract

Highly-sensitive non-destructive ionization detectors of accelerated beam cross-section were developed and are used. The image of the beam cross-section is formed on the screen of an image converter tube, recorded by a TV camera, and processed and represented on a computer. The detector designs for 1-100-MeV cilinder or ribbon beams were developed and investigated. A 20-30 keV beam detector has been prepared for testing. The applicability of the ionization detectors to observation of synchrotron radiation beams was considered. The distortions of the beam cross-section image under the action of external magnetic fields and the space charge field were estimated. The results of the first tests of the ionization detectors in controlling cyclotron beam current shape, duration and phase microbunches are presented. Such devices can be used for time-of-flight works and measurement of cyclotron beam energy too.

I. INTRODUCTION

Among the most important operations of controlling the parameters of a beam of accelerated particles are the measurement of its dimensions and position. Ionization profilometers are finding increasing use for this purpose [1-2]. This type of detectors id distinguished by their full transparence to a beam to be controlled, the absence of an additional radiation background, a weak dependence of their sensitivity on the type of accelerated particles and their energy, the simplicity of visualization of information, and their high potentialities. But the detectors of such a kind do not allow to observe a real beam density distribution in a beam cross-section.

This paper describes an ionization detector wich gives a possibility to cheek real beam cross-section, current value and some other beam parameters.

2. IONIZATION DETECTOR OF ACCELERATED BEAM CROSS-SECTION

The method and the design of an ionization detector for the operative observation of the real spatial density distribution of an accelerated beam over its cross-section were proposed in [3,4]. An operate of the detector was described in [5].

In accordance with Fig. 1 plane electric field used hiere for extracting and energy analyzing of ions of residuel gas. These ions distribution along the slit L after the slit corresponds to the beam intensity distribution in the direction of the slit. The energy distribution of the extracted ions corresponds to the distribution of the beam intensity along the other orthogonal coordinate. The analysis of this energy distribution is ensured by the electric field of the analyzing capacitor. As a result, a two-dimensional optical image of the extracted ion distribution in a plane passing through the exit slit of the extracting capacitor and perpendicular to its plane is generated on the image converter tube (ICT) screen. This image corresponds to the transverse distribution of the accelerated particles in the beam monitored.

The analyzing capacitor is set at an angle of 45° with the ion extraction direction and with the plane of the extracting electrode. This ensures a linear relation between

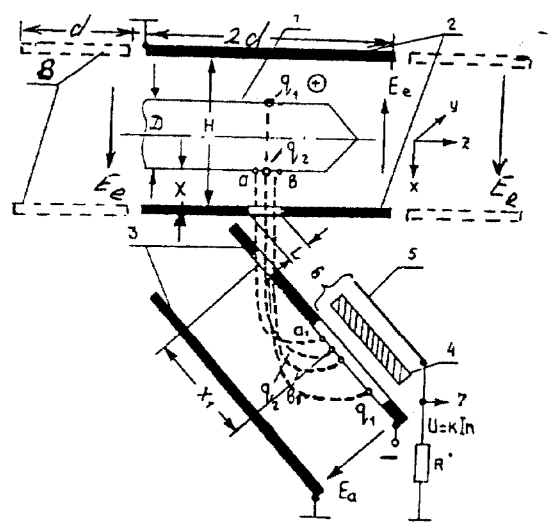

Fig.1. The basic elements of a beam cross-section detector: 1 - accelerated beam; 2 - extracting capacitor; 3 - analyzing capacitor; 4 - MCP; 5 - phosphor screen; 6 - ICT; 7 - output for monitoring the beam current; 8-corrective eltctrodes for low-energy beams.

the dimensions of the accelerated beam and its image. The image dimension X corresponds to the beam dimension X_1 in the extraction direction in accordance with the relationship $X_2 = 2X \cdot E_{ex}/E_a$, where E_{ex} and E_a are the extracting and analyzing field strength, respectively. The optical image of the accelerated beam cross-section is recorded from the ICT screen by an industrial TV camera for monitoring and computer processing. Fig. 2 illustrated the formation of a beam cross-section image.

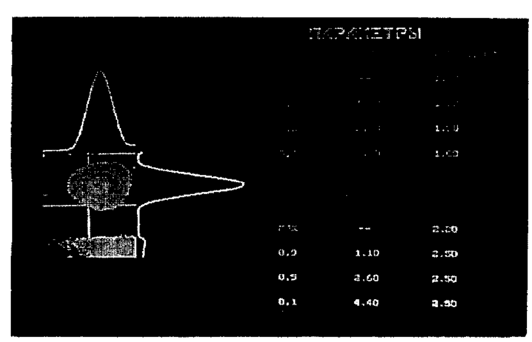

Fig.2. The characteristic image of a beam cross-section on a computer display.

It should be noted that the output current of the ICT at a stable vacuum represents the value of the accelerated beam current. Such detectors can be successfully used to record beams of any ionizing radiation, such as SR beams or accelerated beams of neutral particles.

3. SENSITIVITY AND RESOLUTION

The sensitivity of the detector depends, first of all, on the ionization losses of the accelerated beam energy $d\epsilon/dx$ ($MeVcm^2/g$) in residual gas. The stopping power of air under normal conditions versus the kinetic energy of various particles is shown in Fig. 3 [6].

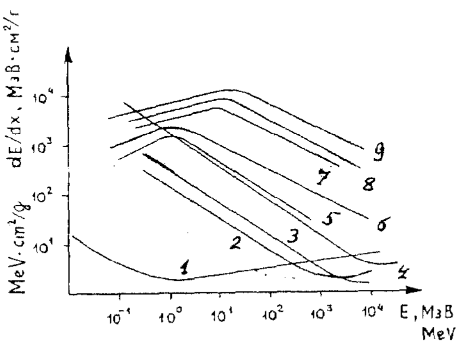

Fig. 3. The ionization losses of various particles versus their energy: 1 - electrons; 2 - protons; 3 - deuterons; 4 - α-particles; 5 - ${}^{7}_{3}Li$; 6 -${}^{9}_{4}Be$; 7 -${}^{12}_{6}C$; 8 -${}^{14}_{7}N$; 9 -${}^{16}_{8}O$.

The current of ionized particles to the collector Ic is related to the accelerated beam current Ib and the width of the extraction slit in the current collector L and determined by the expression

$$I_c = K_{col} \cdot L \cdot \frac{p}{ep_o} \cdot \frac{d\epsilon}{dx} \cdot \rho. \qquad (1)$$

Here $K_{col} \approx 1$ is the ionized particle stacking coefficient; p is the working pressure in the ion guide; p_o is the normal atmospheric pressure; e is the particle energy loss due to production of an electron-ion pair ($e \approx 30$ eV); ρ is the air density ($\rho = 1.3 \cdot 10^{-3}\ g/cm^3$). For example, for a 30-MeV proton beam $d\epsilon/dx = 18\ MeV \cdot cm^2/g$. At typical pressures of about 10^{-6} torr and a beam current of 10^{-6} A the collector current $I_c = 3 \cdot 10^{-13}$ for a slit width $L = 1mm$.

The threshold sensitivity of the detector based on standard MCPs and phosphors and combined with an industrial TV camera was estimated experimentally. The experiments showed that the signal-to-noise ratio > 3 is ensured at an ICT phosphor current density of about $10^{-9}\ A/mm^2$. This corresponds to a mean current of residual gas ions of $\approx 10^{-16}\ A/mm^2$ or 600-700 particle/$mm^2 \cdot s$ when two MCPs with a gain of $\approx 10^7$ are used. This level is essentially higher than the level of the MCP internal noise. the threshold sensitivity can be considerably increased by the known means.

The usefulness of such detectors in observing and monitoring synchrotron radiation (SR) beams in present-day electron and proton storage accelerators is considered. The present paper estimates the following two cases: (1) an SR channel directly connected with the accelerator vacuum system-so-called vacuum ultraviolet (VUV) channel and (2) an X-ray SR channel separated from the accelerator vacuum system by a thin beryllium foil.

The sensitivity of the detectors to SR (VUV and X-rays) was estimated by the well-known expression for the spectral density from [7]. Data on the absorption cross-sections ere taken from [8]. The integration over the SR spectrum was performed numerically from the ionization threshold of respective gas. The elementary cross-section of the SR beam was taken at the center of the vertical distribution. The initial data for calculations and the results obtained are presented in Table 1.

Table 1. .

Channel type	Current I_e, mA	Gas in a channel	Pressure torr	Intermed. absorber	Ions per sec
VUV	100	N_2	10^{-8}	no	≈ 500
X-ray	1	Xe	10^{-6}	Be, 200μm	≈ 300

Here VUV is the channel for vacuum ultraviolet; Ie is the electron current in the storage accelerator. in both cases the thickness of a gas target was taken equal to 0.1 mm, the distance from the radiation exit point 5m, the SR beam area 1 x 1 mm.

It is seen that the intensity of ion production in residual gas is sufficiently high and, therefore, the brightness of the image generated allows its recording by available apparatus. in the calculation allowance was made for VUV-caused ionization of residual gas. It has been suggested to use xenon to record X-rays. Xenon is conveniently introduced into the box enclosing the detector between two beryllium foils cutting off VUV radiation. The absorption of the SR beam in Xe at a pressure of 10^{-6} torr is negligible.

The resolution of the diagnostic system as a whole is determined by the detector design and parameters, the resolution of the ICT and the TV system, and the parameters of the beam under investigation. The resolution of the ICT and the TV camera proves as a rule better than 30 line/mm. the slit width L influences directly the energy resolution of the analyzer. it is seen from Fig.1 that the peripheral particles "a" and "b" determine the broadening of the beam by 0.5 L/D, where D is the vertical dimension of the beam. At a permissible scatter of 5% for $D = 10$ mm the permissible value of L is 1 mm. As shown in [8], the most of the ions from residual gas have an energy of about 0.02 eV for 0.01-100-MeV beams. The displacement of the ions recorded due to their own velocities can be ignored at a field strength $E = 1 - 2$ kV in the detector.

4. IMAGE DISTORTIONS

The deformation of the beam cross-section images under the action of external magnetic fields and the beam space charge were studied with the use of a program for calculation of particle dynamics. The program performs the numerical integration of the equations of particle motion in the Cartesian coordinates in applied electric and magnetic fields

$$\ddot{\mathbf{r}} = \frac{q}{m}(\mathbf{E} + [\mathbf{vB}]) \qquad (2)$$

The integration was made sequentially in three regions of the detector (Fig.1); the extracting capacitor, the region between the extracting and the analyzing capacitors, and the analyzing capacitor. The distortion of the beam cross-section image means in this paper the value of $\Delta D_{max}/D$, where D_{max} is the maximum deviation of an image point from its initial position by the action of some disturbing factor; D is the characteristic dimension (diameter) of the cross-section of the undisturbed beam image.

Assuming that the 10% changes in the linear dimensions of the image are permissible, one can find the permissible external magnetic fields on the axes shown in Fig. 1: $B_{xmax} = 0.05\ T, B_{y_{max}} = 0.01\ T$, and $B_{zmax} = 0.04\ T$. Here the field strength in the deflector was taken to be 2 kV/cm. To estimate the distortion of the beam cross-section image by the volume charge field in the framework of the model considered the dynamics of $^{14}_{1}N$ secondary ions was calculated using the above program. At a 10% permissible image distortion the limiting value for the beam current is 2 mA for a 20-30 keV primary beam of protons or α-particles ($A/z > 1-2$) with a radius of 1 cm and a field strength of 2 kV/cm in the extracting capacitor and reduces down to 1 mA for a beam of $^{6}_{1}Li$ ions ($A/z = 6$) with the same parameters. For the beams with an energy of tens-hundreds of MeV the limiting current attains tens of milliamperes.

For 10-100 keV beams allowance must be made for their displacement by the field of the detector. The geometry of a compensator shown in Fig. 1 ensures the return of particles at the detector outlet to the axial line of the beamline. The maximum deviation of the beam occurs in the middle of the extracting capacitor to be

$$h_{max} = 2h_1 = Ed^2/2\epsilon. \qquad (3)$$

For example, at the typical parameters $\epsilon = 20\ keV$, $H = 4\ cm, D = 1\ cm, d = 4\ cm$, and $E = 2\ kV/cm$ the beam displacement $h_{max} = 0.8\ cm$.

5. PARAMETERS OF THE DETECTORS

Several designs of the detectors of the considered type have been developed and tested by now at Russian Research Centre "Kurchatov Institute".

Dtectors have 2 MCP, a total amplification reach 10^7. Working pressure in the beamline is better than 10^{-5} Torr. Spatial resolution in visual control is not more than 1 x 1 mm. Field of view in the beam cross-section from 30 x 30 up to 300 x 50 mm for difference constructions . Dimensions of the hole for the base flanges are $D = 100\ mm$, $D = 160\ mm$ and 350 x 120 mm. The threshold sensitivity was meagured for 30 MeV beam protons and for 15 MeV beam ions $^{16}_{4}O$ in scanning beam 300 x 40 mm. Results are less than 10 nA/cm^2 and less than 1 nA/cm^2 accordingly.

A detector of cyclotron beam current microbunch form and current was developed on the basis of the ionization beam cross-section detector. The developed detector records ionization electrons, because they have essentially less time of flight in the detector. Provision was made to reduce the scatter in electron time of flight. The processing and accumulation of the ICT output current signals from each microbunch allow one to obtain an integral form of microbunch. The first experiments with the detector of such a type showed its efficiency and an appropriate resolution. Fig. 4 illustrates the potentialities of the diagnostic described. Its further development will permit operative time-of-flight measurements of the beam energy.

6. CONCLUSION

The detectors for high-energy beams have been successfully used to date in some cyclotrons and electrostatic accelerators in few acceleration laboratories. A low-energy beam detector has been prepared for testing on a multy-charged ion source. A detector for ribbon beams with field of view 300 x 50 mm was successfully tested in a PEI tandem generator (Obninsk).

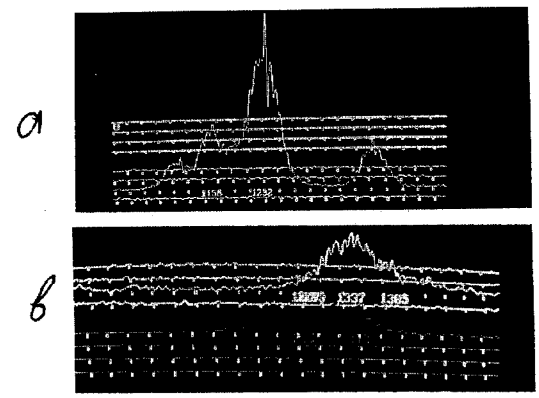

Fig. 4. a - A microbunch image with multy-turn extraction of the beam ($f = 18.5\ MHz$, time-marks - 1 ns). b - Microbunch images from two detectors for energy measurements with one-turn extraction ($f = 9.5\ MHz$, time-marks - 1 ns).

The non-interrupted detectors ensure the operative control of the dimensions of a particle beam over its cross-section, its density a position and displacement of the beam cross-section, its center of gravity in the beamline, as well as the value of the beam current. The computer processing of the TV signals allows the quantitative processing of the basic parameters of the beam cross-section, aids the creation of a library of images. The color image of the beam cross-section on the computer monitor makes easier its visual control and . The estimates allow one to expect that the ionization detectors will be successfully used for controlling SR. Work is under way on preparing the detector of this type to tests in the VUV channel of the Kurchatov Synchrotron Radiation Source. Detectors of beam microbunches were investigated at RRC KI cyclotron successfully.

The experience of work with the ionization detectors of accelerated beam cross-section revealed their rich potentialities, sensitivity and sufficiently highreliability. Clearly, they can be used on various accelerators operating in both the permanent and the pulsed modes of acceleration of various particles in the wide energy range.

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