

Multisensor System for Monitoring Heavy-Ion Beams

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Received February 10, 2026; revised February 20, 2026; accepted February 25, 2026

Abstract—A multisensor system for monitoring beams from heavy-ion accelerators. The operating principle of the system is based on secondary electron emission resulting from the interaction of heavy ions with the material of the detector sensors. Using information about the distribution of signals from the sensors, a two-dimensional distribution of the $^{40}\text{Ar}^{8+}$ ion beam particles with an energy of 53 MeV at a given point in space was obtained online.

Keywords: charged particle beam diagnostics, heavy ions, secondary electron emission

DOI: 10.1134/S1062873826700590

INTRODUCTION

Today, accelerator technology is widely used in physical experiments to study the fundamental properties of matter, as well as for the production of radio-nuclides for nuclear medicine [1] and radiation therapy for cancer. The most important condition for the use of accelerator technology is its constant modernization, as well as the development and creation of new engineering and technological solutions in this field. Therefore, the main task is to improve the quality of charged particle beams, which is impossible to achieve without accurate and reliable diagnostic systems. There are many detector systems that can provide information about beam parameters such as beam current, emittance, and others. These systems can be divided into two categories: contact and noncontact ones. Noncontact systems include, for example, the beam position monitor (BPM) [2, 3], the signal from which is an electric charge induced by a beam moving in an ion guide. One example of a contact system is a pixel detector [4, 5], which has a high spatial resolution. For low-, medium-, and high-energy accelerators, a universal diagnostic tool is needed, not too complex like the BPM or too expensive like the pixel detector. Therefore, a simple solution for diagnosing beams of charged particles and heavy ions in a wide range of their energies and masses can be a grid detector (detecting sensors arranged in the vertical and horizontal planes to form a grid structure), the operating principle of which is based on secondary electron emission [6]. Despite the fact that such a detector belongs to the contact sensor type, its influence on the parameters and characteristics of beams of charged

particles or heavy ions extracted from the accelerator into an ion-optical system can be minimized. For this purpose, sensors are produced from thin wires made of refractory material. This detector has a very simple design made from inexpensive materials. The grid detector allows one to determine the profile of a beam of charged particles, and several such detectors located at a certain distance from one another provide information about the beam emittance. In addition, this type of detector can be used to study the processes of secondary electron emission of the materials from which the sensors of this device are made. Great potential is seen in the use of this detector on relativistic beams of heavy ions of the NICA accelerator—storage complex for conducting precision studies of ultra-dense nuclear matter. Therefore, this work focused on studying the properties of a multisensor system for monitoring low-energy heavy ion beams with subsequent use of the obtained data for applying this diagnostic system to high-energy beams (up to 4 GeV/nucleon) of the NICA accelerator systems.

BEAM DIAGNOSTIC SYSTEM

The operating principle of the multisensor system for monitoring beams of charged particles and heavy ions, developed at the Educational Laboratory of Nuclear Processes of the St. Petersburg State University [7], is based on secondary electron emission. The system consists of a grid sensor, an electronic data collection and processing system, and a software package.

The sensors are a grid that has 16 thin (25- μm -thick) insulated tungsten wires: 8 vertical and 8 hori-

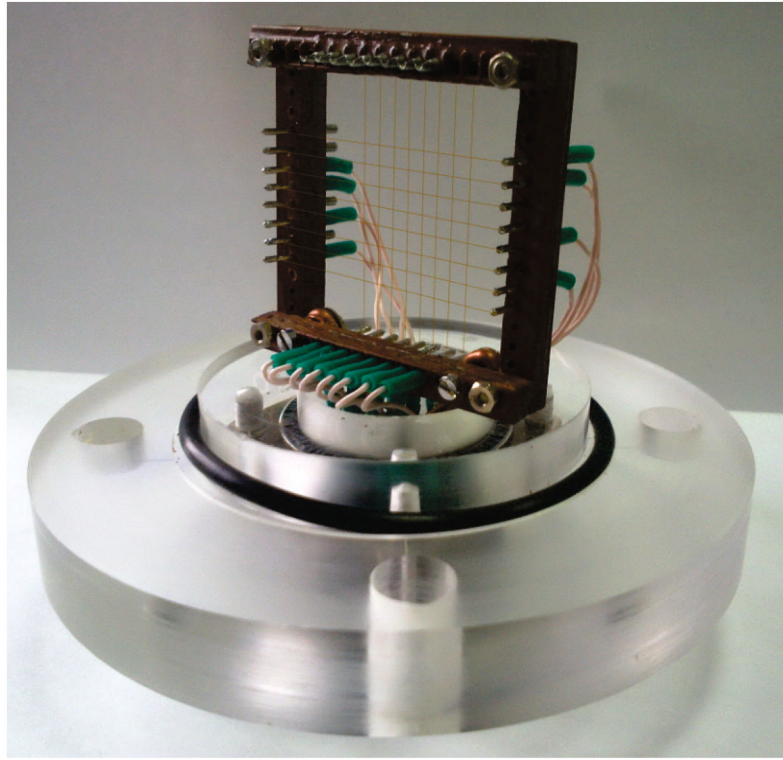


Fig. 1. Sensor grid of the system of monitoring beams of charged particles and heavy ions [7].

zontal ones. The sensors are located in a plane perpendicular to the beam direction at a distance of 2.5 mm from each other. The sensor grid is mounted on a special frame (Fig. 1) which is placed in the ion guide of the accelerator complex. As a result, each sensor wire can be considered as a generator of a current, which is proportional to the number of secondary electrons knocked out of this sensor wire by the beam particles [7].

Figure 2 shows the diagram of the electronic system for collecting and processing signals from sensors. A modulator (M), which is part of the high-frequency system of the accelerator, generates a trigger signal. This signal is sent to a binary counter (BC) and then to an analog multiplexer (AM). The charge from sensors of a beam monitoring system (grid sensors, GS) is integrated using a 16-channel low-noise amplifier (AIS-16). The amplified signals from the AIS-16 are fed to the AM and then to an analog-to-digital converter (ADC), which digitizes these signals and transmits the information to a personal computer (PC). The binary counter BC synchronizes both the AM and the ADC. During one beam pass, one amplification channel is read, and then the binary counter switches the next channel for further digitalization. As a result, the digitized signal is a discrete set of voltage amplitude values from each sensor. Figure 3 presents an example of a signal from one of the sensors, obtained by their irradiation with argon ions at an energy of

53 MeV at the Unique Scientific Facility (USF) "Cyclotron of the Ioffe Institute, type U-120."

After processing and digitizing the signals, using the software package, we obtain a two-dimensional distribution of the beam profile. In this way, the beam is continuously monitored in real time. The use of this system makes it possible to determine the profile of beams of charged particles and heavy ions based on signals from sensors of the system.

The amplitude of the signal of an individual sensor (wire) can be represented as a convolution of the pulse function and the current function [8]:

$$V(t) = \int_0^t h(t-s) I(s) ds, \quad (1)$$

where $I(s)$ is the time dependence of the electrode current; $h(s)$ is the pulse function of the amplifying system,

$$h(t) = \frac{K}{C_f} \exp\left(-\frac{t}{\tau}\right), \quad (2)$$

K is the amplification factor; C_f is the capacitance of the capacitor in the amplifier circuit, and τ is the RC time constant equal to 200 μ s.

Equation (1) shows that, using the inverse convolution of the output signal $V(t)$ and pulse function $h(t)$, one can get the time dependence $I(t)$ of the current on

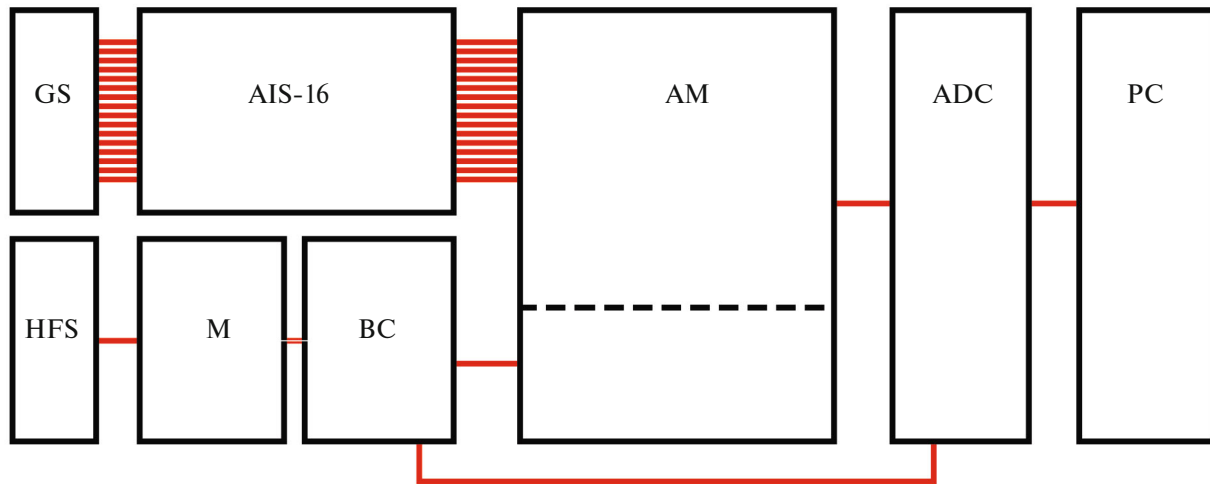


Fig. 2. Schematic diagram of the electronic data collection and processing system of the multisensor system of monitoring beams of charged particles and heavy ions [7].

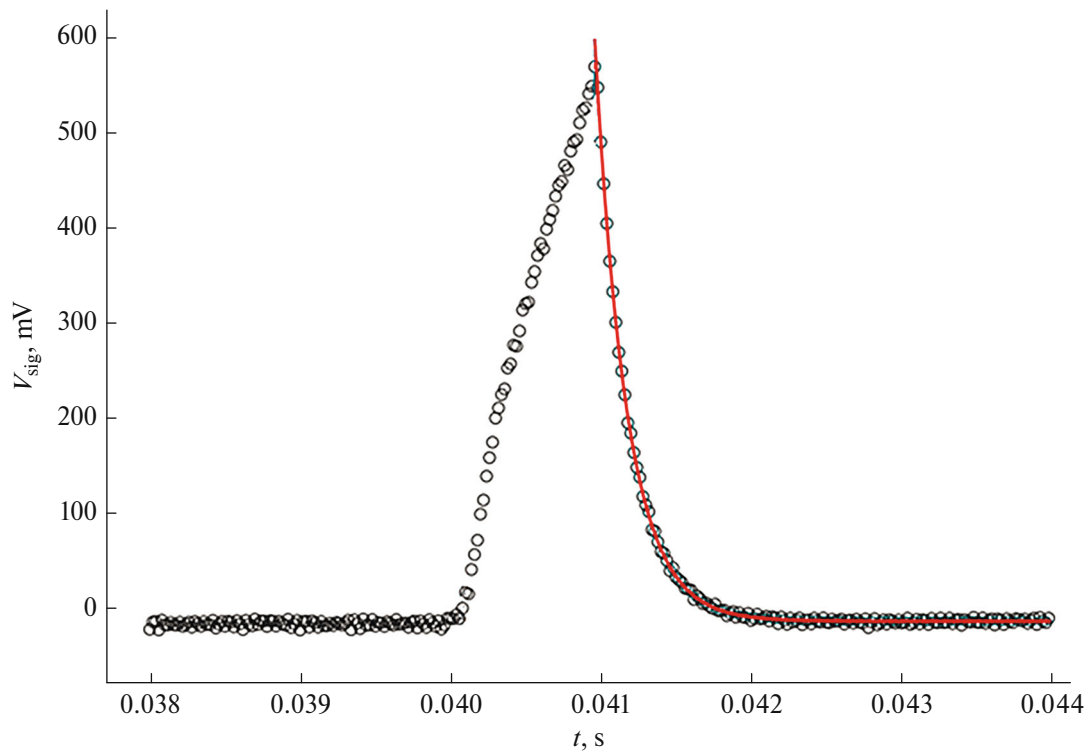


Fig. 3. An example of the signal of a single channel (sensor), recorded during irradiation of the sensors with $^{40}\text{Ar}^{8+}$ ions at 53 MeV. The red exponential curve shows the signal decay.

the sensor. By integrating this dependence over time, it is possible to obtain the value of the charge of secondary electrons, the emission of which is caused by the beam particles falling on the sensor and, accordingly, determine the number of secondary electrons (N_{sec}).

The inverse problem, namely, the calculation of the transverse distribution of the beam particle density, can be solved similarly. The solution to this problem is based on the assumption of independence of one-dimensional (horizontal and vertical) distributions.

Let $\rho(x)$ and $\rho(y)$ are one-dimensional distributions of beam particles. They are called independent if

$$\rho(x, y) = \rho(x)\rho(y). \quad (3)$$

This simplification is explained by the fact that the ion beams are guided to the sensors using correctors changing the beam position only in the vertical or horizontal plane, as well as using quadrupole lenses focusing the beam. Using this assumption, the transverse distribution of the beam particle density can be obtained as follows. The signals of the multisensory system (Fig. 3) are the integrals

$$\begin{aligned} V_{iX} &= A \int_{\varepsilon_1}^{\varepsilon_2} dx \int_{y_{\min}}^{y_{\max}} \rho(x, y) dy \\ &\equiv A(\varepsilon_2 - \varepsilon_1) \int_{y_{\min}}^{y_{\max}} \rho(X, y) dy, \end{aligned} \quad (4)$$

$$\begin{aligned} V_{jY} &= K \int_{\zeta_1}^{\zeta_2} dy \int_{x_{\min}}^{x_{\max}} \rho(x, y) dx \\ &\equiv K(\zeta_2 - \zeta_1) \int_{x_{\min}}^{x_{\max}} \rho(x, Y) dx, \end{aligned} \quad (5)$$

where V_{iX} and V_{jY} are the values of the maximum peaks of signals of vertical and horizontal sensors, respectively; A and K are normalization constants; ε_2 and ε_1 are the coordinate of the boundaries of the i th vertical sensor; ζ_2 and ζ_1 are the coordinate of the boundaries of the j th horizontal sensor; $x_{\min}$, $x_{\max}$, $y_{\min}$, and $y_{\max}$ are the boundaries of the sensor grid of the beam monitoring system; X and Y are the coordinates of the mid-points of the i th and j th vertical and horizontal sensors, respectively.

From here, one can obtain the signals of the i th and j th sensors:

$$\frac{V_{iX}}{(\varepsilon_2 - \varepsilon_1)} = A \int_{y_{\min}}^{y_{\max}} \rho(X, y) dy, \quad (6)$$

$$\frac{V_{jY}}{(\zeta_2 - \zeta_1)} = K \int_{x_{\min}}^{x_{\max}} \rho(x, Y) dx. \quad (7)$$

Applying interpolation to these values (separately for vertical and horizontal sensors) we obtain the interpolation functions $F(x)$ and $G(y)$. Then, by multiplying the obtained interpolation dependences and normalizing them to the number of particles in the beam, which is determined from the value of the current of the beam of ions extracted from the accelerator,

$$C \int_{x_{\min}}^{x_{\max}} \int_{y_{\min}}^{y_{\max}} F(x)G(y) dx dy = N_{\text{particles in beam}}, \quad (8)$$

one can obtain a two-dimensional distribution function of the beam particles,

$$\rho(x, y) = C \cdot F(x)G(y), \quad (9)$$

according to the values of which the beam profiles are constructed (Fig. 5).

It is important to note that the correctness of the normalization to the number of beam particles directly depends on both the accuracy of determining the beam current and the size of the beam itself. If the beam width (in the vertical or horizontal direction) exceeds the width of the grid area of the multisensory beam monitoring system, the final integral (8) will be normalized to the entire beam current, while only a part of it will fall into the grid area. For the task of determining the region of greatest beam intensity, this will not lead to an increase in the errors of the results obtained.

To calculate the functions $F(x)$ and $G(y)$, the Shape-Preserving Piecewise Cubic Interpolation (PHIP) method [9] was chosen because it does not create fluctuations at the boundaries of the data section. Assuming that the beam structure is uniform, one can also use ordinary linear interpolation. A comparison of the results of interpolation using the PHIP method and the simple linear method showed that the values of the integrals along the interpolation curves have close values for both methods. The PHIP method was chosen as more informative in terms of data visualization.

Thus, an apparatus was developed that made it possible to visualize the profiles of beams of charged particles and heavy ions.

EXPERIMENTS USING THE MULTISENSOR SYSTEM FOR MONITORING BEAMS OF CHARGED PARTICLES AND HEAVY IONS

The multisensory system for monitoring beams of charged particles and heavy ions was used in a series of experiments with $^{40}\text{Ar}^{8+}$ ion beams with an energy of 53 MeV at the Unique Scientific Facility (USF) “Cyclotron of the Ioffe Institute, type U-120, with the capability of accelerating ions over a wide energy range.”

The experimental setup consisted of the multisensory system mounted on one of the output channels of the cyclotron. The grid sensor was placed inside the ion guide, and the electronic system for collecting and processing data from the sensors was installed outside (Fig. 4). The beam was guided and focused onto the sensors using quadrupole lenses and corresponding electromagnetic correctors. Figure 5 shows examples of the distribution of particles of the $^{40}\text{Ar}^{8+}$ ion beam with an energy of 53 MeV, obtained in the experiments conducted. The visualization of the heavy ion beam profile together with the use of correctors and quadrupole lenses of the ion-optical system of the cyclotron,



Fig. 4. Multisensor system for monitoring beams of charged particles and heavy ions, mounted on the ion guide of the U-120 Cyclotron of the Ioffe Institute.

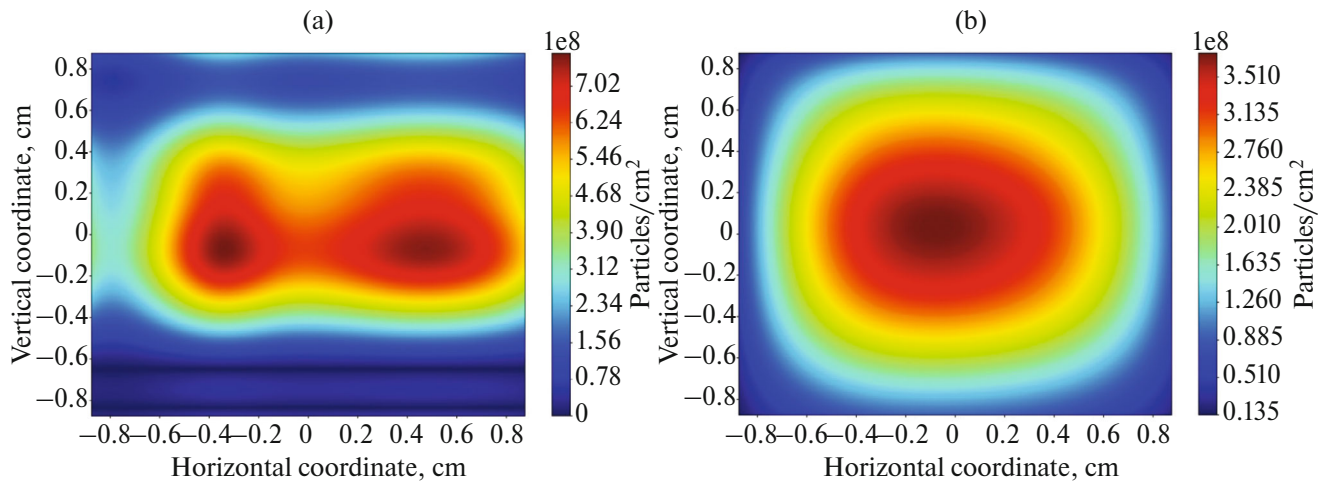


Fig. 5. Distribution of particles in the beam of $^{40}\text{Ar}^{8+}$ ions with an energy of 53 MeV (a) before and (b) after correction of its shape.

made it possible to quickly correct the beam shape in real time.

The presented distributions demonstrate that the beams have a complex shape. The width of the beams obtained in the experiment in some cases exceeds the width of the grid of the multisensor system. Despite this, it was possible to determine the position and transverse density distribution of particles in each beam. Further analysis of the obtained distributions

and signals from the sensors showed the versatility of this beam diagnostic system and provided information on its applicability to heavy ion beams of both medium and high energies.

CONCLUSIONS

Thus, we presented the results of the application of a multisensor system for monitoring beams of charged

particles and heavy ions in experiments on $^{40}\text{Ar}^{8+}$ ion beams with an energy of 53 MeV. The results of the experiments demonstrated the possibility of using a multiwire system to visualize the profiles of heavy ion beams and determine their transverse density distribution. At present, work continues on analyzing the signals obtained during the experiments in the context of the tasks of determining the secondary electron emission coefficients of $^{40}\text{Ar}^{8+}$ ions with an energy of 53 MeV when they interact with tungsten (the sensor material). The obtained data will provide an opportunity to test the applicability of the theory of secondary electron emission for heavy ions in a wide energy range.

ACKNOWLEDGMENTS

We thank the staff of the Ioffe Institute for assistance in conducting the experiments, as well as the St. Petersburg State University Science Park for infrastructural support.

AUTHOR CONTRIBUTION

E.O. Zemlin—research concept, theoretical study of the possibility of visualizing the profile of a heavy-ion beam, processing experimental data, writing and editing the manuscript; V.I. Zherebchevskii—general management of the study, editing the manuscript; M.F. Kudoyarov—conducting experimental sessions, editing the manuscript; N.A. Mal'tsev—design and manufacture of the experimental stand; V.V. Petrov—experimental data processing, editing the manuscript.

FUNDING

This work was supported by the Russian Science Foundation (grant no. 23-12-00042, <https://rscf.ru/project/23-12-00042/>).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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