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NUCLEAR EXPERIMENTAL TECHNIQUE

Upgrading the Scanning Two-Dimensional Ionization Profile Monitor in Beam Transport Lines

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Abstract—The scanning two-dimensional ionization profile monitor (IPM) has been upgraded for the beam diagnostics in beam transport lines. The main parts of the monitor are an extractor, a scanner, and two analyzers with a slit at which residual-gas ionization products collected from a beam path as long as 50 mm arrive. The current amplifier based on microchannel plates and a current collector are placed in sequence behind the slit in order to increase the IPM sensitivity under high-vacuum conditions ($n \times 10^{-6}$ Pa). Two-dimensional beam profiles are obtained by scanning. A special electronic unit containing high-voltage supplies and collector-current meters has been created for the scanning and IPM control. Three upgraded IPMs have been placed between the accelerator and the physical facilities in each beamline of the DC-280 FLNR JINR cyclotron. Data processing and simultaneous display of experimental results from several IPMs are carried out by a program developed in the LabVIEW design environment. The minimum current of the ^{40}Ar ion beam with the energy of 5 MeV/nucleon at which the monitor is still operable is estimated to be several tens of picoamperes. The reliability of the upgraded IPM has been demonstrated by its operation.

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INTRODUCTION

The profile monitors of accelerated particle beams were created based on the collection of products of the residual gas ionization by a passing beam as early as in the 1960s [1, 2]. In the literature they are abbreviated as ionization profile monitors (IPMs). The use of such devices refers to noninvasive diagnostic methods. This method became widespread after microchannel plates (MCPs) were used in it for amplifying the current of collected ionization products. The application of MCPs has made it possible to create such fast and sensitive devices that they allowed observation of changes in profiles of each successive bunch in a beam at a synchrotron during particle acceleration. Therefore, MCPs have found the widest application in control systems for optimal tuning of the acceleration process in synchrotrons [3–5] or linear accelerators [6]. Along with the creation of new accelerators, IPMs are consistently improved by eliminating the shortcomings identified during operation. It was noted (e.g., in [7]) that IPMs suffered from the MCP aging effect, the MCP gain was not stable and decreased over time, and the aging rate increased with an increase both in the count rate and in the voltage applied to an MCP. The degradation is not uniform; the part of the MCP that is exposed to ionization products from the highest-intensity region of the beam undergoes the greatest aging. Special devices are set to monitor the degradation process; they are used to perform periodical calibration. The measured beam profile is then programmatically corrected for the degradation effect. A control grid was placed in front of an MCP to slow down its degradation in [8]. This grid periodically shut off the flow of ionization products, due to which the count rate was reduced and, therefore, the service life was increased.

The conditions for IPM operation in beam transport lines are milder. First, the vacuum in the transport lines is not as high as in accelerators; therefore, the number of beam-induced ionization products is proportionally larger, which means that a larger signal is generated. Second, the profile-measurement time is usually limited only by the speed of the operator's reaction when changes in the beam are observed [8]. In addition, conditions under which an MCP is not needed can often be created in beam transport lines. In this case, operation of an IPM is greatly simplified and the service life can be considered infinite. However, in some cases there is a need to use MCPs; therefore, problems associated with them inevitably arise. Unfortunately, although the operation conditions in transport lines are milder, nevertheless, the basic IPM design remains traditional, with the use of MCPs [9], with the same problems, and with the same high expenses.

IPMs in transport lines contain large MCPs to control a large area. Two methods are used to measure the beam profile. In one of these, electrons from the MCP output are collected onto a collector that is divided into numerous strips. A signal is read out of each strip using either multichannel electronics or switches if the signals have large amplitudes. In the other method, electrons from the MCP output are accelerated in an electric field and hit a phosphor screen. The resulting image is observed using radiation-resistant multipixel cameras, which are very expensive and degrade during operation under hard radiation conditions, especially in neutron fields.

It remains traditional that a simultaneous measurement of the distribution in two orthogonal coordinates is performed using two one-dimensional IPMs, which are separated by a certain gap to eliminate interference of electric fields. Such arrangement of the IPMs requires large free space in a transport line.

There is another problem that has not been noted in the literature. An MCP is located in monitors with a conventional design close to the trajectory of the beam and is exposed, especially during the adjustment, to the halo of scattered particles, which has a very detrimental effect on it. By placing the MCP near the beam, it is possible to attain the highest spatial and time resolutions. However, such resolution is far from always required in transport lines, where beams have dimensions of approximately 1 cm. As an example, a spatial resolution of 1 mm was achieved in [10, 11] when ionization products hit MCPs, which were protected from the beam halo, as early as after their passing through an analyzing capacitor that was proposed by the authors as an additional IPM component. It was proposed to use the property of ionization products collected in an electric field, which consists in the fact that while they move they acquire energy proportional to the traveled distance, i.e., the coordinate. Ionization products and ions in particular enter the analyzing capacitor through a 1-mm-wide slit that is perpendicular to the beam axis; they hit the MCP after separation according to the acquired energies and, therefore, to the orthogonal coordinate. As a result, a two-dimensional image of the beam profile is obtained using a single IPM. The disadvantage of this method is the lower sensitivity, since ionization products are collected from the beam path that is equal to the slit width (i.e., 1 mm) in order to attain a high resolution, whereas this path in traditional IPMs is as large as 50 mm. In addition, the problem of nonuniform MCP degradation has not also been resolved.

The idea of using an analyzing capacitor [10] in an IPM was used in [12]. Ionization products are collected on it from a beam path as large as 50 mm in order to increase the IPM sensitivity while keeping its resolution at a fixed level; some of them then fly to the collector through a 1-mm-wide slit with the same length, which is oriented in parallel to the beam axis. A two-dimensional profile image is obtained by scanning, during which ionization products from different areas of the beam transport line are successively incident on the slit. This device was selected as a prototype for creating a high-sensitivity low-cost IPM suitable for operation in beam transport lines.

THE PRINCIPLE OF OPERATION AND THE DESIGN OF THE SCANNING TWO-DIMENSIONAL IONIZATION PROFILE MONITOR

The IPM consists of three main parts: an extractor, a scanner, and an analyzer (Fig. 1). Each part operates as a pair of parallel conductive plates with a uniform electric field between them. The tested beam passes through the space between the electrodes of the extractor. As a result of the interaction between beam particles and residual-gas molecules, the latter are ionized. The ionization products are accelerated in the direction of the electric field, and the energy that they acquire is proportional to the traveled distance. Accelerated positive ions pass through the grid electrode of the extractor and enter the scanner, in which all ions acquire additional equal energies. Ions leave the scanner through the other grid electrode and hit the analyzer, whose electrodes make angle α with the electrodes of the scanner. The ions are deflected in a constant electric field of the analyzer, and some of these pass through a narrow exit slit. The condition of the energy balance for ions that have passed the exit slit of the analyzer can be represented by the linear equation with respect to the coordinates:

$$(E_1 y + U)\cos 2\alpha = E_2 x / 4\sin\alpha, \tag{1}$$

where E_1 and E_2 are the electric field strengths between the plates of the extractor and the analyzer, respectively; U is the potential difference between the scanner electrodes; α is the angle at which the analyzer electrodes are rotated with respect to the scanner electrodes; $(\pi - \alpha)$ is the angle between the electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$; x and y are the coordinates of the point of electron-ion pair production in a plane that is perpendicular to the beam axis.

Among all of the ions generated in the extractor, only those ions penetrate in the exit slit that are produced in a thin flat layer with a width determined by the slit width. The location of this region in the extractor can be changed by scanning the potential-difference value U. If the electric field strengths between the plates of the extractor and the analyzer are constant, the width of the layer and its inclination in the (x, y) plane remain unchanged at any U value.

The fact that the beam profile can be simultaneously measured in two mutually perpendicular directions is an additional conclusion drawn from the analysis of linear equation (1). To do this, one must determine the sign of the parameter near variable x in Eq. (1) and, in the simplest case, transform Eq. (1) to the form $E_2 = E_1 2\sin2\alpha\cos\alpha$. This condition is satisfied if the angle $\alpha = 45°$. Physically, this means that a monitor equipped with a single common extractor and a single common scanner may have two analyzers arranged in sequence downstream of the beam. In order to change the sign of variable x, the second analyzer must be turned through 180° with respect to the first, so that its exit slit is on the opposite side. Thus, using a single IPM, it is possible to simultaneously measure the two-dimensional beam profile and save space for placing detectors in the transport line.

UPGRADING THE IONIZATION PROFILE MONITOR

In order to significantly increase the IPM sensitivity, a current amplifier is placed between the slit and the collector. It consists of a narrow and long MCP or two MCPs in the form of a chevron, depending on the requirements for the amplification. A narrow secondary-electron multiplier can also be used. Naturally, in this case, the polarity of the collector current is negative. Electrons are collected at the cathode when an MCP is used and ions are collected at the cathode in the prototype. A narrow collector is much easier to shield from interference noise relative to a wide collector consisting of narrow strips, which is used in traditional monitors. By shielding the narrow collector, one can easily obtain a noise level below 1 pA and, hence, attain the necessary sensitivity at a lower MCP voltage and reduce the aging effect. It should be noted that in order to achieve almost 100% efficiency in detecting ionization products with different energies the negative voltage applied to the input MCP plane should be greater than 1.9 kV [13].

In the scanning mode, both the high-intensity flux of ionization products from the beam region and the weak flux from the periphery are periodically incident on the MCP. As a result, the problem of nonuniform MCP degradation is eliminated and the aging time is significantly increased. For the monitoring of the MCP degradation, it is sufficient that a Faraday cup be periodically introduced into the beam at a fixed vacuum level and its readings be compared to the profile-integral value of IPM readings. The loss of the gain during MCP aging can be easily compensated by increasing the voltage.

The accelerators at LNR JINR include beam transport lines with inner diameters of 100 and 70 mm. The transport lines are equipped with diagnostic units along their lengths for placing equipment through the of DU-160 and DU-100 holes, respectively. Therefore, designs of IPMs have been developed for the two sizes and the required number of such IPMs has been manufactured. Each IPM in both designs has two MCP assemblies and a collector, which are fixed in place by two screws and can be quickly replaced if their degradation becomes unacceptable. Figure 2 shows the appearance of the IPM for placing in the diagnostic unit through DU-100.

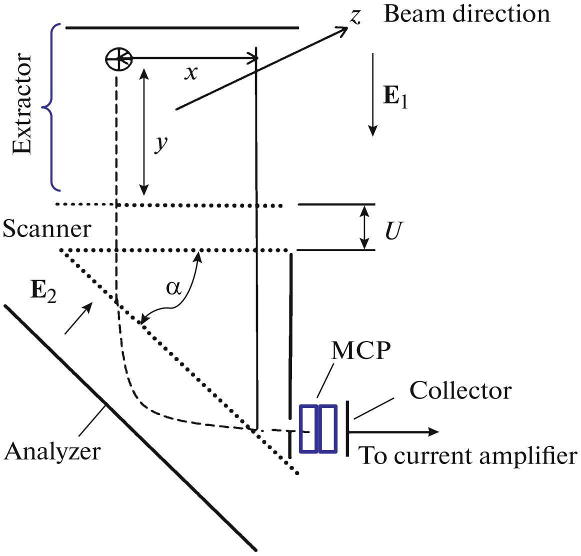


Fig. 1. The schematic diagram of the scanning two-dimensional ionization profile monitor: ($\mathbf{E}_1$, $\mathbf{E}_2$) vectors of the electric field strength between the plates of the extractor and the analyzer, respectively; (U) potential difference between the scanner electrodes; α is the angle at which the analyzer electrodes are rotated with respect to the scanner electrodes; ($\pi - \alpha$) angle between the electric field vectors $\mathbf{E}_1$ and $\mathbf{E}_2$; and (x, y) coordinates of the point of electron—ion pair production on a plane that is perpendicular to the beam axis.

THE CONTROL SYSTEM AND THE TECHNOLOGY FOR DATA READOUT

It is sufficient to use only two electronics channels for data acquisition during scanning. This fact greatly simplifies and cuts the cost of the production and operation of the described IPM. A special PRFL-01 module, whose appearance is shown in Fig. 3, has been developed for work with the IPM. The module is enclosed in a single housing and consists of several parts: a microprocessor, a high-voltage power supply, and software.

The Microprocessor Section

An Atmel ATmega1281 microcontroller is the basis of the PRFL-01 module. Interaction with external circuits is performed via the Ethernet communication channel. The TCP/IP settings and data exchange are carried out using the HTML protocol. The module

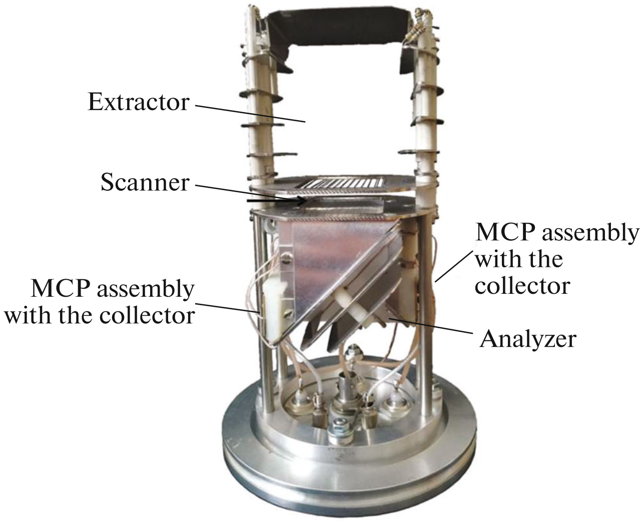


Fig. 2. The external appearance of the IPM for placing in the diagnostic unit through a DU-100 hole.

has its own WEB interface for the configuration and control.

The signals from the IPM collectors are fed to two analog inputs that are isolated from the general circuit. The current-to-voltage converter embodies the classical scheme on a mezzanine board. The conversion factor is 1 V/nA. The signals are then digitized by a 16-bit analog-to-digital converter. The measurements are synchronized with the formation of a scanning voltage with a triangular waveform. The profile is measured twice per period: first, during the increase in the scanning voltage and then during the decrease in it. The period of the scanning voltage is 2 s and 400 samples are taken over one period. The data are formed as a simple HTML table with three columns and are updated every second. The first column contains the values of the scanning voltage; the second and the third are the intensity data for x and y coordinates, respectively.

The High-Voltage Section

The high-voltage section is assembled on two boards and is separated from the microprocessor section by a shield. The power supply of the high-voltage section is controllable. The power is turned on or off by an operator's command, but the power turns off automatically at shutdown of the control program on the computer. The high voltage is generated by EMCO converters; an external feedback circuit with an operational amplifier is used to stabilize the voltage. In contrast to the use of a generator of triangular high-voltage pulses U for scanning in [12], the voltage is now generated by a microcontroller using a digital-to-analog converter. As a result, it is possible to programmatically change the scanning time, the voltage value, and the number of samples (i.e., the resolution).

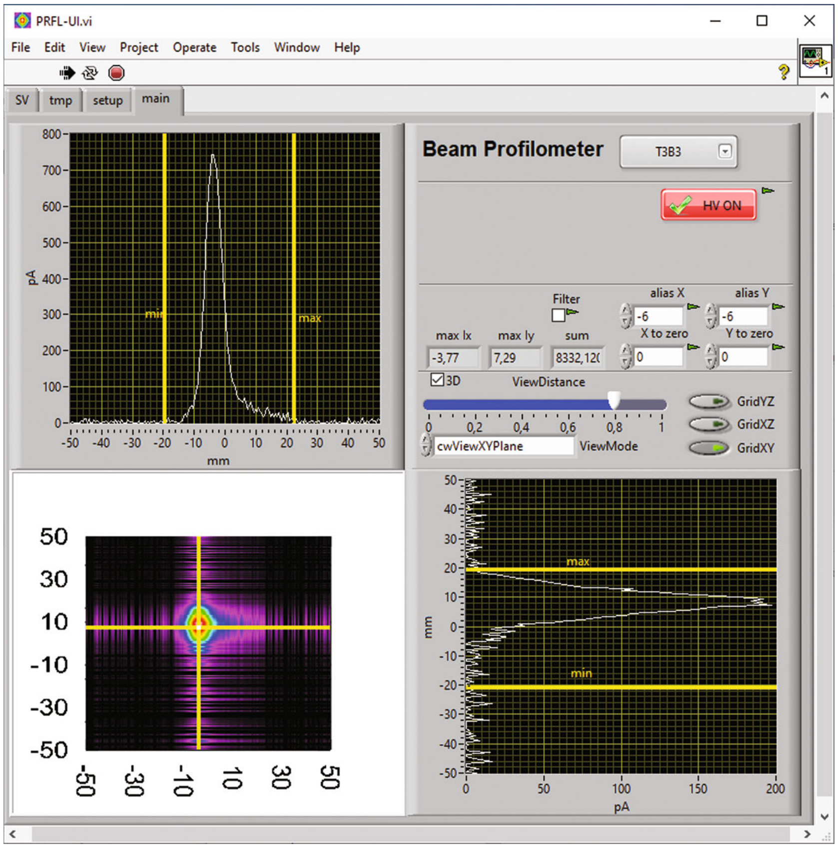
Fig. 3. The PRFL-01 module for the IPM.

The Software

The program for control, data processing, and displaying of measurement results was developed in the LabVIEW design environment. Unprocessed data are available in the form of graphs on the *tmp* tab. The *main* tab displays the main window for visualizing the beam profile (Fig. 4). The data on the x and y coordinates, the formed beam profile with the intensity marked with colors, the trend of the total intensity, and the beam cross-sectional area are available there. Turning the high voltage on/off, filtering signals from interference noise, calibrating the beam position, writing the profile to a file, and reconstructing the beam profile from a saved file are possible using the controls.

THE EXPERIENCE FROM USING IPMs IN TRANSPORT LINES

The need for increasing the IPM sensitivity, which was described in [12], arose when the IPM was used in beam transport lines at the high-current DC-280 cyclotron of FLNR JINR [14]. Special measures were taken to reduce the beam losses during transfer; in particular, the vacuum in the lines was significantly improved to a level of $n \times 10^{-6}$ Pa. The IPM continued its successful operation without the MCP in the pilot mode at a beam current as high as 100 μA and at a specified vacuum. However, such a monitor does not allow tuning of the accelerator, which is usually performed at low beam currents, so as not to worsen the radiation environment. In this regard, three upgraded IPMs were placed in each line and a program was created with which it was possible to simultaneously observe the passage of the beam along the beamline from the accelerator to the user's target. High-voltage sources with the remote control via an Ethernet communication line were used to supply and adjust the MCP voltage. Figure 4 shows the image of the beam profile in one of the transport lines from the DC-280 cyclotron, which was measured during the tuning. When the beam intensity reaches the pilot mode, the voltage



T3B3

Filter ☐

alias X -6

alias Y -6

max Ix -3,77

max Iy 7,29

sum 8332,12(

X to zero 0

Y to zero 0

☑ 3D

ViewDistance 0 0,2 0,4 0,6 0,8 1

ViewMode cwViewXYPlane

Fig. 4. The main window of the software for the visualization and IPM control. The presented image of the beam profile in one of the transport lines from the DC-280 cyclotron was obtained during the tuning.

supplied to the MCP must be lowered significantly, even to a level below 1.9 kV.

The monitor-electronics units and the voltage sources for the MCPs are located in rooms that are shielded from radiation and are located as far as 15 m away from the IPMs installed in the transport lines.

An attempt was made to determine the minimum sensitivity threshold of the upgraded IPMs on the beam of accelerated ^{40}Ar ions with an energy of 5 MeV/nucleon. The beam current was measured using a Faraday cup placed on the beamline in the diagnostic unit immediately past the IPM. The minimum current that could be measured using the Faraday cup was 1 nA. It was noted that the beam profile could be reliably measured at this current. An approximate estimate based on the signal-to-background ratio showed that the beam profile could be measured even at a current of several tens of picoamperes.

The high sensitivity and operational safety of the upgraded IPM were demonstrated during its operation. It can also find application in the production of isotopes using proton beams or in biological and material science research.

CONCLUSIONS

The scanning two-dimensional ionization profile monitor was upgraded for diagnostics in beam transport lines. The monitor consists of the following main parts: an extractor, a scanner, and two analyzers with a slit onto which the products of ionization of the residual gas are collected from a beam path as long as 50 mm. A current amplifier based on microchannel plates and a current collector are sequentially placed behind the slit of each analyzer in order to increase the IPM sensitivity under high-vacuum conditions ($n \times 10^{-6}$ Pa). A two-dimensional image of the beam profile is obtained by scanning. An electronic unit containing high-voltage sources and collector-current meters was created for scanning and controlling the IPM operation. Three upgraded IPMs are located in each beamline of the DC-280 FLNR JINR cyclotron on the path from the accelerator to physical facilities. Data processing and display of measurement results from several IPMs simultaneously is carried out using the program developed in the LabVIEW design environment. The estimated minimum beam current of ^{40}Ar ions with an energy of 5 MeV/nucleon, at which the monitor is still operable, is several tens of picoamperes. The reliability of the upgraded IPM has been demonstrated during its operation.

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