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IONIZATION BEAM PROFILE MONITOR FOR OPERATION UNDER HARD ENVIRONMENTAL CONDITIONS

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The design and the performance of the Ionization Beam Profile Monitor (IBPM) operating on the residual gas ionization principle are described. The main advantage of the constructed device is the non-contact measuring method. Operating under hard environmental conditions it delivers the information about the primary beam position, profile and intensity in “on-line” regime. It was tested under high gamma and neutron radiation conditions and changing vacuum using a range of low and intermediate energy beams at the beam current of a few nA to 15 μA. The diagnostic box was located in the vicinity of the accelerator, where the neutron flux was over 10^6 n/cm^{2}s. It was found out that the device is capable to operate in vacuum in the range of $10^{-6}\div10^{-3}$ mbar without the loss of the resolution power at the beam current as low as a few nA. The IBPM is prospective for beam profile monitoring due to long time. Emergency situations do not lead to decrease of its operability.

Keywords: ionization beam profile monitor, heavy ion beams, beam profile diagnostic, on-line beam monitoring, the U400M cyclotron of FLNR JINR, hard radiation conditions.

Introduction

In the last two decades a variety of beam diagnostic techniques and devices has been developed [1 - 15]. At the same time the beam intensity available at the present-day facilities has increased many times. The increasing beam intensity leads to a rise of neutrons and γ flux, accompanying the beam. Therefore, the problem of reliability of beam diagnostics devices operating under hard radiation conditions occurs, especially if the beam is to be monitored in the area close to the driver accelerator. Main factors influencing the reliability of the diagnostic device are due to an adverse impact of the beam on the diagnostics tools and vice versa. In emergency situations, the endurance of diagnostics tools to vacuum deterioration also becomes important.

The goal of this research was to build a reliable device which is able to determine the position and profile of the ion beam operating in a wide range of the beam intensities and resistant to adverse environmental conditions. A device satisfying these requirements seems to be the Ionization Beam Profile Monitor (IBPM) [1 - 8]. The minimum interaction with the ion beam is provided when no material is introduced into the beam. The ionization profilometer is a position-sensitive ionization chamber operating in a current mode. The residual gas is used as a buffer (working) gas. The residual gas pressure in the beam line is approximately 10^{-6} mbar, so the current density of collected ions is 10^{-13} - 10^{-11} A/mm^2. Usually, before collecting, the ionization current is amplified using microchannel plates (MCP). With the MCP as an in-situ ion current amplifier, a spatial resolution of 1 mm rms and temporal resolution of 1 ms have been achieved [2]. Using a microprocessor-based scanning ADC a sequence of ten profiles can be acquired in 100 ms.

Unfortunately, the MCP is a weak point of the IBPM, which does not deal with adverse conditions accompanying the ion beam. As the reliability of the profilometer has been assumed to be a dominating parameter, the MCP has been eliminated from the construction of IBPM. The speed of beam profile monitoring has been considered only for an operator convenience. The low level ionization current is amplified outside the ion collection region. The main function of the profilometer is reduced to measurement of the spatial distribution of the beam current. This is provided by measuring the ionization current of the ions originated in different parts of the monitored volume. The active volume is scanned by sequential directing of the positive ions moving from these parts of the volume to the ion collector. The development of such IBPM is described in [9, 10].

There are a number of other types of the beam profile measurement techniques representing the non contacting methods which base on the light emission detecting systems [11, 12], the laser beams [13], the IBPMs without a MCP [14], or micro-strip metal detectors [15]. Nevertheless the application of the developed IBPM seems to be the optimal for variable environmental conditions.

Principle of operation of the IBPM

The physical view of the IBPM and schematic layout are presented in Fig. 1, *a* and *b*, respectively. The IBPM consists of three main parts: the extractor, the scanner and the analyzer. Each of the parts operates like a couple of parallel conductive plates with high voltage applied between them. This results in the homogeneous electric field **E** perpendicular to the beam direction. The beam passes through the space between the electrodes of the extractor. Due to the collisions of the beam particles with the residual gas molecules, the latter get ionized. The operation principle of the IBPM is based on the collection of the ions with positive charge. Positive ions are accelerated in the direction of the electric field, gaining kinetic energy proportional to the distance passed in the extractor. Further they pass through the grid electrode at the bottom of the extractor and reach the scanner.

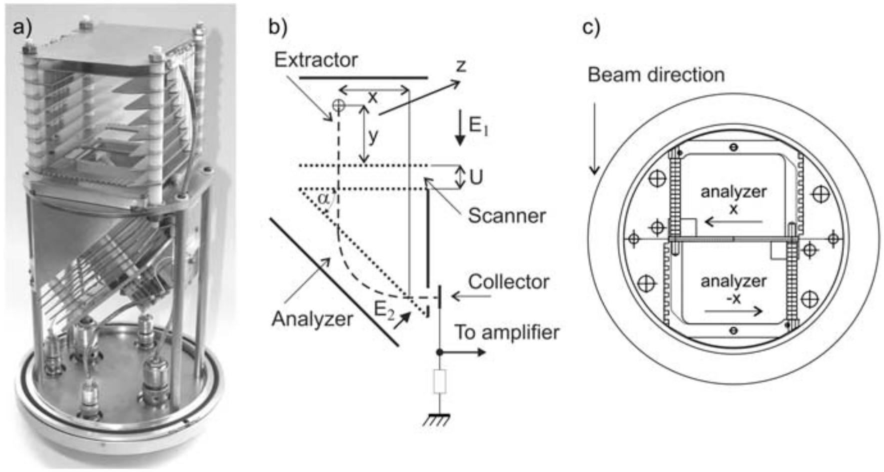

Fig. 1. a) The physical configuration of the IBPMs. The IBPM is adopted for mounting via ISO DN100 vacuum port. b) Schematic view of the IBPM: $\mathbf{E_1}$, $\mathbf{E_2}$ are the electric fields in the extractor and analyzer; U is the potential difference applied to the scanner; $(\pi - \alpha)$ is the angle between the $\mathbf{E_1}$ and $\mathbf{E_2}$ vectors; and x, y are the coordinates of the location of electron-ion pair production. c) Auto cad view of the bottom part of the IBPM. The layout window is set from the mounting flange projected along the beam axis. The location of two analyzer sections is visible. The function of each analyzer is to collect the ions deflected into two parallel directions; x and $-x$, perpendicular to the beam axis.

Passing the scanner, they gain an additional portion of energy, the same for all the ions, and leave it through the other grid electrode into the analyzer, where they are deflected by the constant electric field applied. The electrodes in the analyzer are rotated by α angle in relation to the electrodes in the scanner. The resolution of the IBPM is determined by the narrow slit installed in front of the collector. Only the ions that pass trough the slit are collected. The resolution of the IBPM of determines the size of slit. In our case the slit of 1mm was installed. More detailed description of the operation principle of the IBPM is given in Refs. [9, 10].

The analyzer part is used for collection of the ionization products along one selected direction. Obviously, to get the information about the beam current distribution in horizontal and vertical directions two independent analyzers are required. Therefore the IBPM is equipped with two analyzers fixed successively along the beam path. The second analyzer is turned by 180° in respect to the first analyzer as well the exit slit in the second analyzer is on the opposite side in relation to the slit in the first one. The schematic location of the analyzers along the beam path is presented in Fig. 1, *c*. The function of each analyzer is to assure scanning along x and y coordinates axes.

DC current amplifiers U5-11 are used to measure the ion current on the collectors. The electric fields inside the extractor and the analyzers are 200 and 282 V/cm, respectively, provided by DC high voltage power suppliers. The high voltage generator is used to generate saw-shaped scanning potential. The current module of high voltage generator provides us with the scanning voltage signal with a period of 2, 6 or 18 s. Within one scanning period, the analyzed volume in the extractor is scanned twice; on a rise and on a fall of a saw-shaped scanning pulses. The two ionization current signals and saw-shaped scanning voltage analog signals are digitalized by ADC and transferred to PC via the parallel port. Then all signals are processed and displayed on-line. Current amplifiers and DC high voltage suppliers have to be located in a distance more than 0.5 m from the diagnostic box depending on the radiation background. If the radiation background is on a high level, the electronic modules are located behind the radiation shield, or in a place more distantly located. The reason is the necessity to avoid the influence of high neutron and γ flux on them, resulting in their shortest life span.

In Fig. 2 an example of one and two dimensional beam profiles are presented. On the main panel of the data acquisition software, there are three sub panels; two, top-left and bottom-right displaying the beam current distribution along horizontal (top-left panel) and vertical (bottom-right) directions and the central panel displaying a two dimensional beam profile. In two first panels the dependence of ionization current as a function of scanning voltage is plotted.

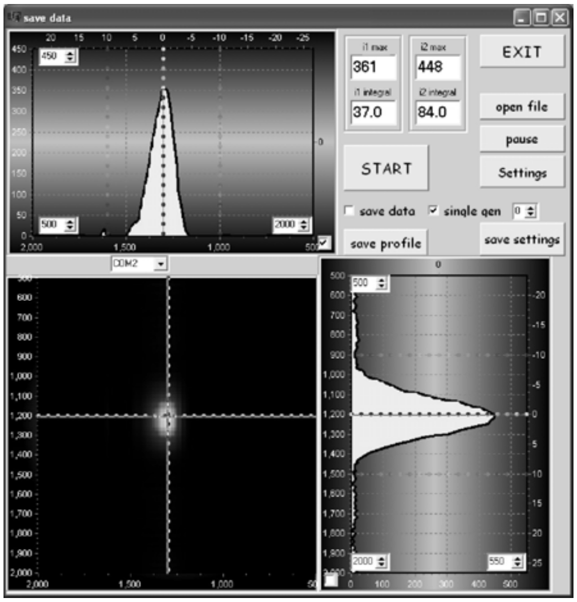

Fig. 2. An example of the ^{11}B beam profile is displayed by the data acquisition software. The beam energy was 33 AMeV, beam intensity was 1 μA, measured under the pressure of $2 \cdot 10^{-5}$ mbar. In the top-left and the bottom-right panels the dependences of $I_1(U_1)$ and $I_2(U_1)$ are displayed, respectively. In the bottom-left (central) panel 2D beam profile is shown.

The x axis of all the panels relates to the beam coordinates inside the extractor. The two-dimensional beam profile is generated by the projection of one dimensional distribution into two dimensional matrix. The refresh time depends on the half-period of the scanning voltage. During the half-period of 1 s more than 60 values of ion current are measured. The number of measurements increases with the increase of scanning voltage period. After one half-period time, the value of start/stop signal changes and the stored data stream is displayed. As soon as the beam profile is generated, a new measurement cycle starts from the last stored data.

Although the scanning method along two mutually perpendicular directions does not offer a detailed beam profile image, monitoring of the dynamical evolution of the artificially generated profile is sufficient to focus the primary ion beam to the optimum size and to tune up the beam spot in/at the center of the target.

Operation of the diagnostic system under hard environmental conditions

IBPM was tested using a wide range of primary beams, in a few different location places at various radiation and vacuum conditions. It was used to monitor ^{7}Li, ^{11}B, ^{32}S beams in the energy range of 30 ÷ 50 AMeV delivered form the U400M cyclotron to in flight separators ACCULINNA and COMBAS. Other testes were performed at ^{20}Ne, ^{40}Ar, ^{86}Kr, ^{132}Xe beams at 4 ÷ 5 AMeV in the U400 cyclotron. The IBPM was tested at the beam current in the range from a few nA up to 15 μA. The linearity of the beam current measurements at constant vacuum is presented in Fig. 3, *a*. The IBPM were mounted in a few different diagnostic boxes (located a few meters from the cyclotron or in front of the production target of the separators) and tested under hard radiation conditions (neutron flux ~10^6 neutron/cm^2 · s). The location of the IBPM in front of the production target of the ACCULINNA separator is shown in Fig. 3, *b*. In the case of low energy beams, the IBPM was installed in a low-background experimental hall, distant from the cyclotron for routine monitoring the beam parameters during the irradiation process of polymer foils. In all test measurements with listed beams IBPM was checked under a hard radiation conditions and variable vacuum conditions. The operating time of a continuous beam monitoring was up to one month. No effects on the IBPM operability have been found. The only effect influencing the measured beam profile was due to secondary electrons emission while a material was put on the beam axis in a small distance from the IBPM. The interaction of the secondary electrons with positive ions in the extractor volume leads to the distortions of the measured beam profile. This effect is independent on radiation and ambient pressure in the IBPM operability range.

Each time in a new location of the IBPM, before routine measurements, it has to be calibrated. An example beam profiles measured during the calibration process at ACCULINNA separator are shown in Fig. 4, *a* and *b*. At first the ^{11}B was centered on the beam optical axis measuring the beam transmission and a setup of collimators. An example of the beam profile is shown in Fig. 4, *a*. Then the beam was aligned using a dipole magnet on the border of the calibration frame, with square hole of 35.5×35.5 mm^2, which was installed at the entrance of the diagnostic box. The beam profile at the border of the frame is shown in Fig. 4, *b*. Such operation delivers us the second calibration point in millimeters, which is equal to a half width of the square hole in the frame (~ 17 mm). The effect of the increasing intensity of the same intensity beam is due to secondary electrons.

The lower limit of ionization current sensitivity is a multi parameter function of the ambient pressure, beam intensity and its charge state. One has to keep

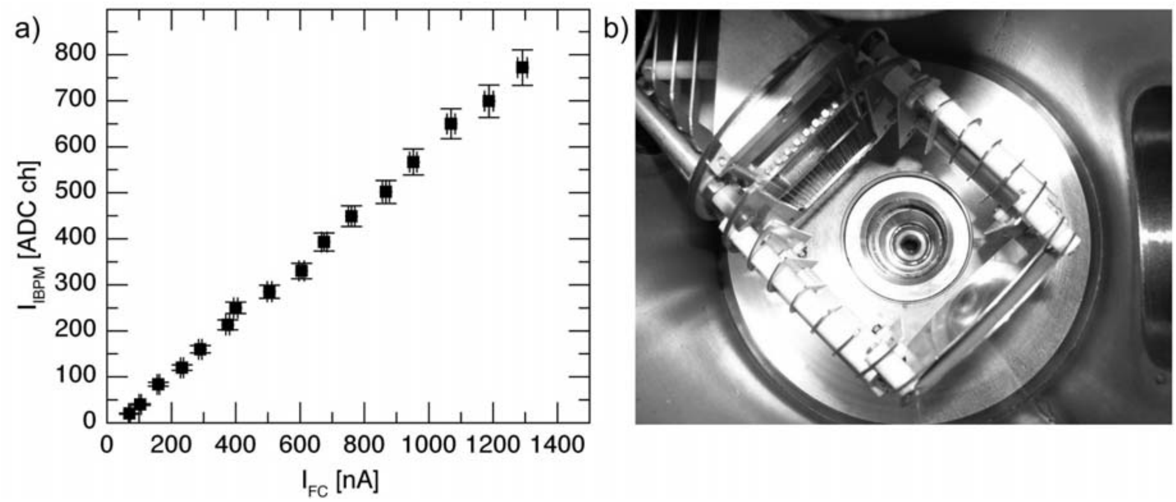

Fig. 3. a) Dependence of the ionization current I_{IBPM}, (vertical axis) on the beam current measured by Faraday cup (horizontal axis). b) The location of the IBPM in front of the production target of the ACCULINNA separator. The round dark circle in the center of the picture is the target material.

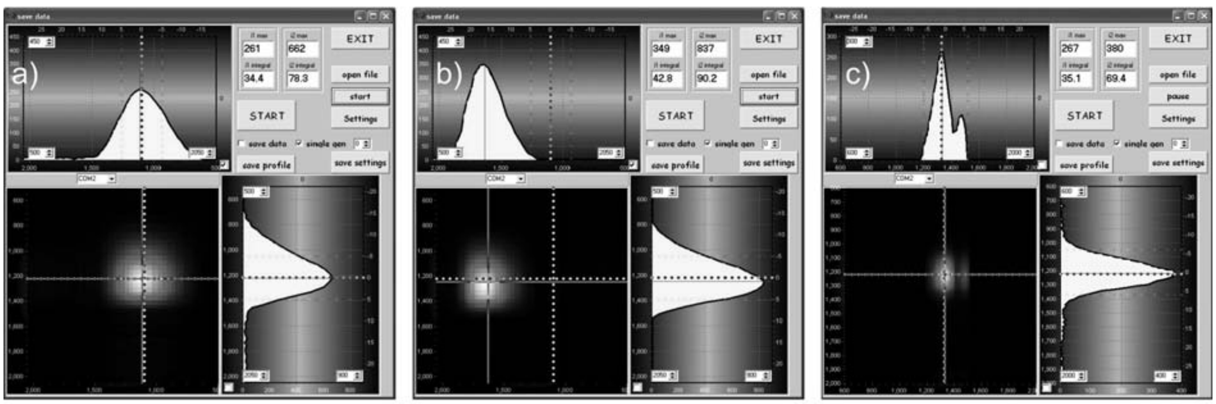

Fig. 4. a) ^{11}B centered on the beam optical axis. b) The beam aligned on the border of the calibration frame, installed at the entrance of the diagnostic box, corresponding to a half width of the square hole in the frame (~ 17 mm). c) Example of the two beams profile for the different beam energies. Main peak corresponds to the nominal energy; the small peak corresponds to the beam coming at lower energy.

in mind that there is no exact lower limit set generally, as it is a multi parameter function. The upper limit of the residual gas pressure is determined by the mean free path of a single ion under such pressure. If the mean free path is shorter than the distance from ionization place to the collector the beam profile is distorted.

The IBPM was tested on ^{11}B beam at 33 AMeV for routine beam profile measurements performed at different vacuum conditions. At starting conditions the ambient pressure was on the level of $4 \times \times 10^{-6}$ mbar. The diagnostics box has been located at a large distance from the accelerator, where it was possible to work under changing vacuum conditions. It was possible to observe profiles of ^{11}B ion beam at 33 AMeV with the beam current of 5 nA under the residual gas pressure up to $4 \cdot 10^{-6}$ mbar. At the pressure of 10^{-3} mbar IBPM was still operating, although the spatial resolution was deteriorated. At higher pressure (forevacuum) it was not operable because of a glow discharge between the electrodes. With further increase of the pressure up to the atmospheric magnitude, the discharge disappeared. As soon as vacuum conditions had been restored, the IBPM was operable again. It was established that, the sensitivity of the IBPM increases proportionally to the increase of the residual gas pressure.

Conclusions

Experimental tests of the IBPM demonstrated that is resistant to influence of adverse conditions accompanying the beam. The IBPM was tested at beam intensities ranging from ~ 5 nA to 15 μA. The lower threshold on the beam current during the scanning period which was conventionally given for the existing IBPM and its electronics modules is one second. That value can be improved by application of faster and more sensitive current amplifier. A new improved data acquisition line is already being constructed. The upper limit is not the operation limit of the IBPM, but the maximum beam intensity at the tests. The device operates in vacuum in the range of $10^{-6}\div10^{-3}$ mbar without the loss of the resolution power and it is stable against unexpected vacuum loss or oil vapors with short recovery time. The maximum operating pressure is 10^{-3} mbar. The physical dimension of the IBPM can be easily modified to match a desired scanning volume. The cross section of monitored area is restricted by the size of mounting flange. After two months of testing on the several heavy ion beams, under different environmental conditions no remarks concerning the operability of the IBPM have been found.

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МОНІТОР ПРОФІЛЮ ПУЧКА ДЛЯ РОБОТИ В СКЛАДНИХ УМОВАХ

Ю. Г. Тєтєрєв, Г. Камінські, Фі Тан Хуонг, Є. Козік

Описано принцип дії та конструктивне виконання профілометра пучка, що базується на іонізації залишкового газу. Основна перевага такого пристрою полягає в тому. що вимірювання профілю здійснюється безконтактним способом. Інформація про позиції пучка, його профіль та інтенсивності може бути одержана в режимі онлайн навіть за дуже жорстких умов експлуатації. Профілометр було випробувано в умовах високих рівнів нейтронного і гамма-випромінювання та при різних тисках вакууму на пучках іонів низьких та проміжних енергій із струмом від декількох нА до 15 мкА. Його було встановлено в діагностичний блок поблизу прискорювача, де густина потоку перевищувала 10^6 нейтрон/(см^2 · с). Пристрій здатний працювати у вакуумі $10^{-6} \div 10^{-3}$ мбар з постійною просторовою роздільною здатністю. Він застосовний для неперервного моніторування профілю пучка протягом тривалого часу. Аварійні ситуації не призводять до погіршення його роботи.

Ключові слова: іонізаційний профілометр пучка, пучки важких іонів, діагностика профілю пучка, онлайн моніторування, циклотрон У400М ЛЯР, жорсткі радіаційні умови.

МОНИТОР ПРОФИЛЯ ПУЧКА ДЛЯ РАБОТЫ В СЛОЖНЫХ УСЛОВИЯХ

Ю. Г. Тетерев, Г. Камински, Фи Тан Хуонг, Е. Козик

Описаны принцип действия и конструктивное выполнение профилометра пучка, основанного на ионизации остаточного газа. Главное достоинство такого устройства заключается в том, что измерение профиля осуществляется бесконтактным способом. Информация о позиции пучка, его профиле и интенсивности может быть получена в режиме онлайн даже в жестких условиях эксплуатации. Профилометр был испытан в условиях высоких уровней нейтронного и гамма-излучения и при разных давлениях вакуума на пучках ионов низкой и промежуточной энергии с током от нескольких нА до 15 мкА. Он был установлен в диагностический блок вблизи ускорителя, где плотность потока превышала 10^6 нейтрон/(см^2 · с). Устройство способно работать в вакууме $10^{-6} \div 10^{-3}$ мбар с постоянным пространственным разрешением. Оно пригодно для непрерывного мониторирования профиля пучка в течение длительного времени. Аварийные ситуации не приводят к ухудшению работоспособности.

Ключевые слова: ионизационный профилометр пучка, пучки тяжелых ионов, диагностика профиля пучка, онлайн мониторирование, циклотрон У400М ЛЯР, жесткие радиационные условия.

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