BEAM PROFILE MEASUREMENTS BASED ON BEAM INTERACTION WITH RESIDUAL GAS

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Traditional methods of beam profile measurements like wire scanners, harps, and screens have the disadvantage of intercepting the beam. Diagnostics of intense particle beams requires development of new non-intercepting beam monitoring methods. There are several kinds of diagnostic devices based on registration of products of accelerated beam particles interaction with atoms and molecules of residual gas in an accelerator vacuum chamber. Usually these devices are used as beam profile monitors, which register electrons or/and ions produced in collisions of beam particles with residual gas (residual gas ionization profile monitor). Some attempts were made in application of light radiation of excited atoms (gas scintillation profile monitor). The non-intercepting method of beam diagnostic based on light radiation of atoms excited by the beam particles has the advantage to be insensitive to external magnetic and electric fields and, as a consequence, to the beam space charge field. It allows to get higher spatial and time resolution. Measurements under different conditions at COSY-Juelich and in a cyclotron beamline at I'Themba LABS are presented and the pros and cons of the methods are discussed.

I. INTRODUCTION

The evaluation of the transverse beam position and profile is an essential issue for the optimization and successful operation of any accelerator facility. Concerning hadron linear accelerators the application of traditional intersecting methods like wire scanners and secondary electron emission (SEM) grids are restricted by the high beam current and the related problem of material heating and melting. The latter is for example a special problem in the case of superconducting cavities. At synchrotrons non-destructive methods are desirable to monitor the profile of the circulating beam. Several kinds of diagnostic devices based on the registration of products produced by the interaction between the beam particles and the residual gas atoms are under development or already in practical use. Usually these devices are used as beam profile monitors, which register electrons and / or ions (Ref. 1-5) as secondary particles. Some attempts have been already made to develop profile monitors which utilize the light emitted by beam excited residual gas atoms (Ref. 6-12). However, up to now, this promising approach in non-destructive beam diagnostics has neither been fully developed nor widely accepted so far. The non-destructive method of a beam diagnostic system, based on light emitted by atoms excited by the beam particles, has the advantage to be insensitive to external magnetic and electric fields, and, as a consequence, to the beam space charge field. Therefore it enables a higher spatial resolution and, in addition, a considerably higher time resolution to allow even single pulse measurements. However, the atomic excitation cross section for light emission is smaller by approximately three orders of magnitude compared to the ionization process. Practically this drawback does not limit the method application under specific conditions. The method can be applied to beams circulating in rings as well as to linear accelerators and beam transfer lines.

II. IONISATION BEAM PROFILE MONITOR

II.A. Method

A charged particle passing a beam transport system generates ion-electron pairs due to collisions with the atoms or molecules of the residual gas. The number of produced ion-electron pairs is directly proportional to the beam intensity. This fact allows nearly non-destructive beam profile measurements by collecting the ionization products on a position sensitive detector (Fig. 1). To separate the electron-ion pairs an external homogenous electric field is applied by metallic electrodes outside the beam path. In most cases a multi channel plate (MCP) is used as a preamplifier. In case of intense beams an external magnetic field in the same direction as the electric field is applied to overcome the space charge induced broadening effect of the profile, especially in case of registration of electrons. For the detection of the secondary electrons at the MCP output different types of anodes are used:

(i) harp detector behind the MCP, (ii) delay line anode - measuring time differences to localize the creation of single ions after signal amplification by the MCP, (iii) a phosphor screen directly behind the MCP and (vi) resistive anodes or wedge and strip anodes. For fast measurements in synchrotrons, a turn-by-turn read out mode will be implemented using an array of 100 photodiodes. Every photodiode is equipped with an amplifier-digitizer module providing a frame rate of about 10 MSamples/s (Ref. 4).
There are some differences in design of such monitors for linacs and transfer systems on the one hand, and devices provided for circular machines on the other hand.

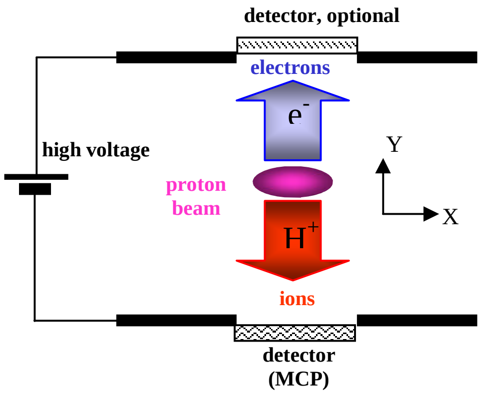


Fig. 1. Measurement principle of the ionization beam profile monitor (IPM).

There are investigations to determine the radial ion beam profile from the measured energy spectrum of the residual gas ions accelerated in the space charge beam potential. It was demonstrated that with one-dimensional radial symmetry the radial distribution of the primary beam ions density and space charge potential can be determined from the energy distribution of the residual gas ions radially leaving the beam tube (Ref. 13).

II.B. Ionization Beam Profile Monitor of COSY-Juelich

II.B.1. Design

For beam profile measurements, a residual gas ionization beam profile monitor using a micro channel plate (MCP) and a position sensitive detector was developed and installed at the cooler synchrotron and storage ring COSY (Ref. 14, 15). Since COSY operates with beam intensities up to 10^{11} protons/deuterons and a vacuum of 10^{-11} - 10^{-9} mbar, there is a high risk of detector damage. Different detector protection mechanisms such as moveable (pneumatic driven) protection screen and MCP high voltage triggering were implemented to improve detector lifetime and performance. Profile measurements with electron cooled beams are reported. Between two electrodes a parallel ion drift field is maintained. Residual gas ions are drifted onto the MCP chevron assembly that provides an electron multiplication factor up to 10^7 (Ref. 16). The secondary charge produced from each ion is collected by a wedge and strip anode (see Fig. 2) (Ref. 17).

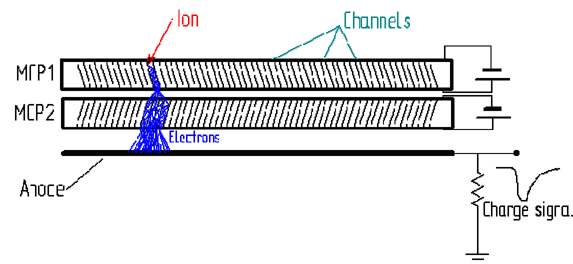


Fig. 2. Position sensitive detector.

The charge signals from each electrode are first converted into time signals which are then digitized. A PC running CoboldPC software (Ref. 18) is used for data readout, analysis and visualization. The detector and the readout method used allow the measurement of the position of separate residual gas ions and is especially suitable for low and medium intensity beams. The images of higher contrast compared to the phosphor screen approach are achievable (Ref. 18). A position sensitive wedge-and-strip anode is placed on a 2 mm thick ceramic substrate of 65 mm outer diameter with germanium layer on the opposite side (see Fig. 3). The anode consists of three electrodes called by their geometry wedge, strip, and meander.

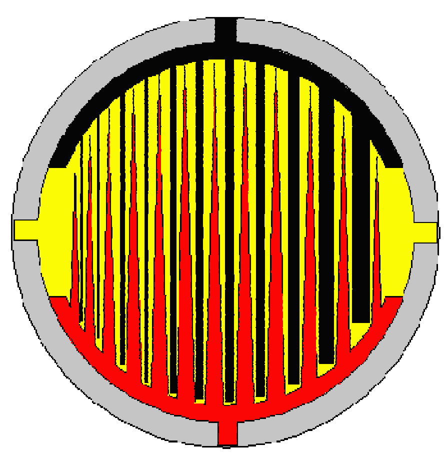


Fig. 3. Wedge-and-Strip Anode.

Since this is a charge coupled device, secondary electrons leaving the MCP assembly hit the germanium layer and induce a signal on the anode structure (see Fig. 2) (Ref. 19). The charge of secondary electron cloud is distributed over all electrodes. To determine the position of the cloud's centre of mass i.e. the residual gas ion coordinates one needs to measure the charge on each electrode independently and compute *x* and *y* values using the formulae:

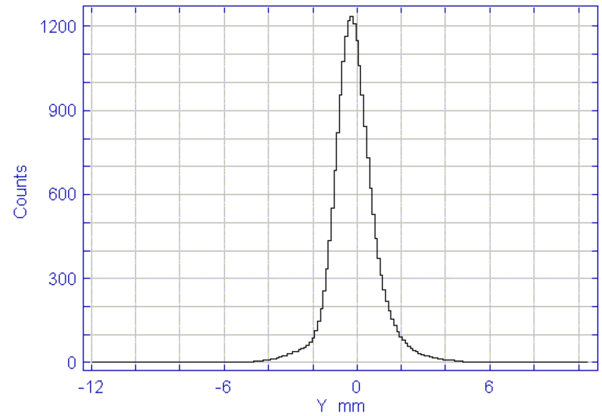
$$x = \frac{Q_s}{Q_s + Q_w + Q_m}$$

$$y = \frac{Q_w}{Q_s + Q_w + Q_m}$$

where Q_s, Q_w and Q_m are measured charges on strip, wedge, and meander respectively. As one can see in Fig. 3 the equations are derived just from the geometry of the anode structure. The charge-to-time converter is based on the LeCroy's MQT 300AL chip (Ref. 15, 20) which utilizes a Wilkinson dual slope converter. The time signals are transported to the control room where a time-to-digital converter (TDC) and a PC are installed. The TDC is connected to the computer via an internal ISA card (Ref. 18, 21). As mentioned above CoboldPC program (Ref. 18) is used for data acquisition, analysis and visualization. The program has a modular structure and can be easily adopted for different hardware and data analysis algorithms i.e. other detector types.

II.B.2. Profile Measurements of an Electron-cooled and Uncooled Proton Beam at COSY

Vertical profiles of electron-cooled and uncooled proton beams have been measured (see Fig. 4). At the moment of data acquisition about $1.3 \cdot 10^9$ protons at 45 MeV were stored in the ring. Residual gas pressure was measured to be 10^{-9} mbar. As one can see the density of the electron cooled beam is higher compared to the uncooled one (see Fig. 5). The profile of the cooled beam meets the expectation and agrees well with the H^0 profile measured simultaneously. However the width of the uncooled beam seems to be too small. Unexpected aperture limitations could be the reason for this discrepancy (Ref. 22). The lifetime of the micro channel plates and the ionization event rate are crucial issues for the profile measurement of intense proton beams. Regular monitoring of MCP condition, e.g. gain distribution and detection efficiency is necessary to provide reliable beam



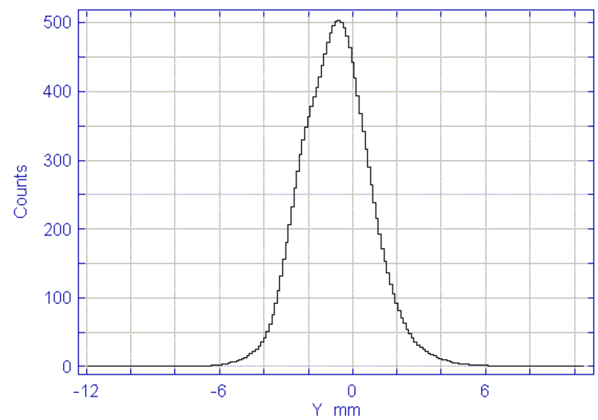


Fig. 4. Profile of a cooled (upper trace) and an uncooled (lower trace) proton beam.

profile measurements. Despite we used Long-Life™ MCPs aging effects, such as an inhomogeneous distribution of the gain over the surface, have been observed. For monitoring and online calibration purposes an α-source has been installed on the flange opposite to the detector. So the detector can be illuminated with α-particles. Different detector protection mechanisms such as a moveable (pneumatic driven) protection screen and MCP high voltage triggering were implemented to improve detector lifetime and performance. MCPs with inhomogeneous gain distribution have been investigated by means of scanning electron microscopy and energy dispersive x-ray microanalysis (EDX) (Ref. 23). Small damaged regions on the MCP surface faced to the anode were found. Elementary composition on these regions was determined using EDX. We still do not properly understand the interrelation between the inhomogeneous gain distribution and damaged regions also the origin of Chlorine on the surface.

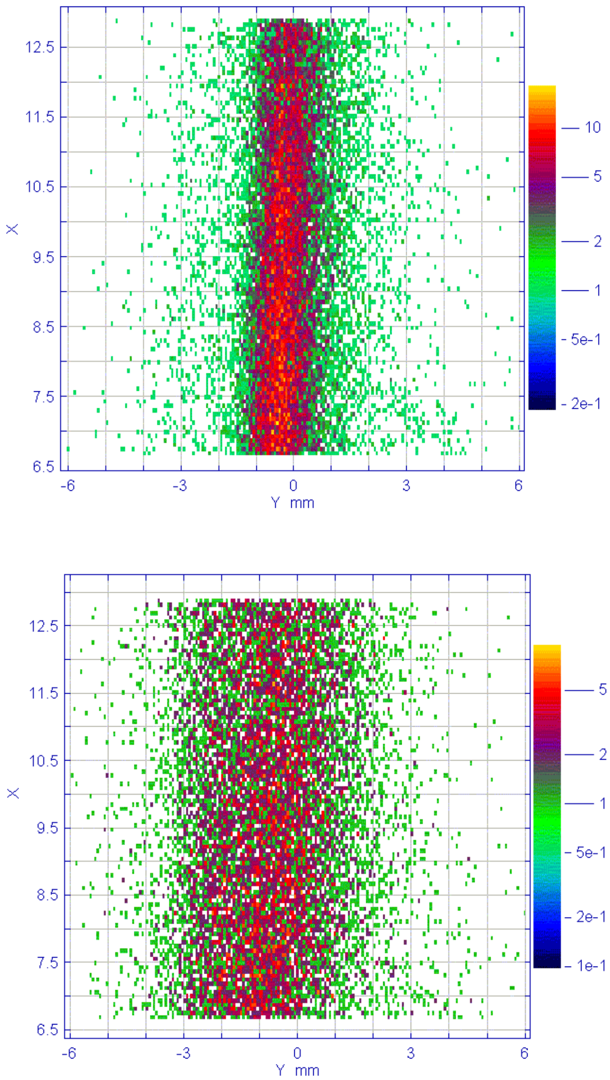


Fig. 5. 2D image of a cooled (upper image) and an uncooled (lower image) proton beam.

III. RESIDUAL GAS FLUORESCENCE MONITOR

III.A. Method

Gas molecules in the beam pipe from either residual or injected gas are excited by the passing particle beam. The molecules are not only ionized, but also electrons are promoted to excited states. When the electrons fall to lower energy levels, photons are emitted. In particular, the excitation of N_2 results in two transition bands in the optical region (decay of N_2^+ levels generate light in the wavelength range 390 nm < λ < 470 nm and decay of N_2 in the range of 337 nm < λ < 380 nm). The lifetime is in the range of 60 ns (Ref. 8). If the molecules have not traveled to far from the interaction point with the particle beam the photons can be collected to produce an accurate measure of the beam profile. This is really a completely non-destructive method of beam profile monitoring. If the emission lines are in the visible spectrum, glass lenses can be used to focus the light onto detectors.

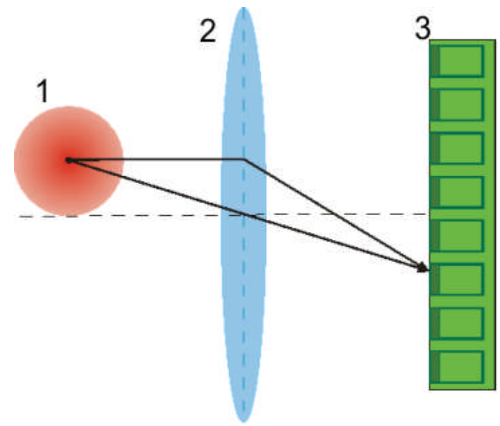


Fig. 6. Measurement Principle (not to scale): The light from the beam (1) is focused with a glass lens (2) onto the linear array multi-anode photomultiplier (3).

The light yield can be enhanced by defined injection of a gas (or a gas jet) into the beam pipe (Ref. 24). The perfect gas will have large cross sections in the visible range and short excited-state lifetimes. The gas should also be easily pumped by the vacuum system. Therefore Nitrogen gas is commonly used in this case. As detectors image intensifiers consisting of a photo-cathode, a MPC, and a phosphor screen are in use (Ref. 25). The light pattern generated is observed with a CCD camera which is coupled to the image intensifier via a tapered light guiding system. Or the light is focused directly on a photomultiplier tube. The advantage of the method is that nothing has to be installed inside the vacuum pipe and the commercially available CCD data acquisition can be used. Sometimes this method is referred to as beam induced fluorescence (BIF).

III.B. Residual Gas Fluorescence Profile Monitor of COSY-Juelich

III.B.1. Design

The light emitted by the residual gas atoms is focused using a glass lens onto a position sensitive photomultiplier (PMT) array (see Fig. 6). In the presented setup a Hamamatsu PMT array has been used (32 pixels, 7 x 0.8 mm^2 size each, 1 mm pitch, sensitive between 200 nm and 600 nm with the maximum between 300 nm and 450 nm).

From the signals the beam position as well as the profile can be determined in one dimension. To allow beam diagnostics also at higher residual gas pressures a gas test chamber has been used in addition at one of the external beam transfer lines of the COSY accelerator. This chamber could be filled with an arbitrary gas up to atmospheric pressure. The single pass beam enters and exits the chamber volume through 50 µm thin foils installed at the beam ports of the chamber. The exact setup is explained in (Ref. 27), first results were reported in (Ref. 26-29).

III.B.2. Profile Measurements at Short Beam Pulses

The first measurements with the setup were performed.with a stored beam of ~10^{10} protons at 1.35 GeV which was single turn extracted from the COSY synchrotron and transferred to the external beam line. The beam had a pulse length of ~100 ns and a diameter at the monitor of ~40 mm. The gas target was filled with N_2 at a pressure ranging from 10^{-1} to 10^{+3} mbar. The image of the beam was projected onto the described PMT array located at a distance of 0.5 m from the beam (focal length of lens 100 mm). The 32 pixels of the PMT array were divided

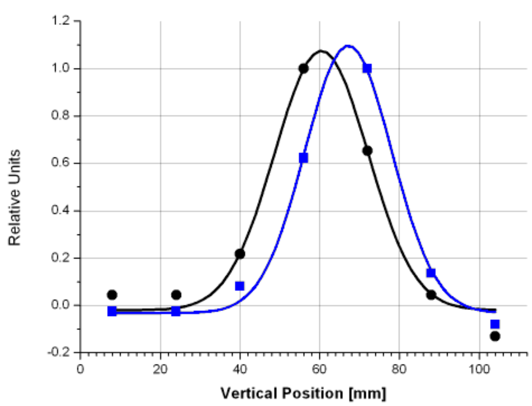


Fig. 7. Singe pass beam profile of a pulsed (1.35 GeV, p=10 mbar) normal positioned (●) and shifted (■) beam (Gaussian fit to PMT data).

into 8 groups with respectively 4 neighboring pixels combined. The output signals of these 8 groups were amplified by current to voltage preamplifiers located nearby the PMT and registered by oscilloscopes with a bandwidth of 500 MHz as a function of time. Based on the measured voltage signal the relative intensity of light at each channel could be calculated. Fig. 7 shows the profile of the single pass beam pulse obtained from the PMT signals as described above. Along with that, a beam profile was taken with a photo plate inserted in the beamline showing a consistent result of the beam width. Also a profile of the beam shifted by 10 mm was obtained showing a very good agreement with the expected value.

III.B.3. Profile Measurements of a Coasting Beam in the Synchrotron COSY

In order to find out if the optical method could also be applied to the synchrotron with its low residual gas pressure, for a series of measurements the monitor has been set up at the COSY ring for a series of measurements. Due to the low photon yield (basic background pressure 10^{-7} mbar with internal gas target) a profile measurement within a single turn is not possible. During the experiments with short beam pulses the residual gas has been N_2, while in the synchrotron vacuum system the main contribution comes from H_2. The fluorescence cross section within the sensitivity of the used PMT for H_2 is an order of magnitude lower compared to N_2 and further reduces the photon yield. To allow a reasonable signal statistic the events have to be summed up for several seconds giving a maximum of a few hundred events per channel.

III.B.4. Profile Measurements in the Cyclotron Beamline at Low Energies

The latest experiments were performed at iThemba LABS, Somerset West, South Africa. The fluorescence beam monitor was installed at the SPC1 beam transfer line. Here a 3.14 MeV proton beam with typical beam currents of several 100 µA was available. The residual gas pressure was approximately 10^{-5} mbar. The 32 individual PMT pixels were divided into 8 groups of respectively 2 neighboring pixels combined. Seven of these groups, located at the center of the array, were used for readout. One additional group located at the side was shielded from visible light by a thin, black paper in order to measure the background. A standard capacitive beam position monitor (BPM) was available a couple of cm downstream of the PMT device. In a first series of experiments the beam position at the location of the PMT-monitor was changed using an upstream steering magnet. The displacement of the beam center was simultaneously measured with our optical beam profile monitor and the BPM. The displacement as a function of the steering magnet current is shown in Fig. 8. The location of the BPM further downstream gives a steeper slope of the curve. Taking the longitudinal BPM monitor offset into account, the results of both monitors are in good agreement.

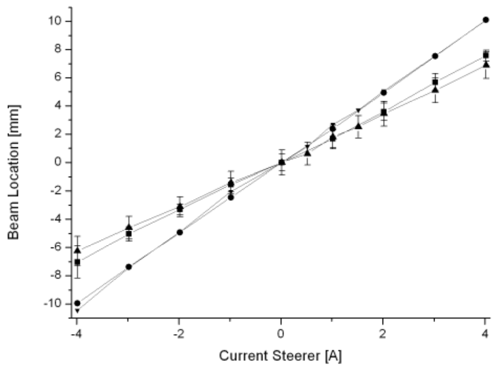


Fig. 8. Beam position versus steering magnet current measured with our optical beam profile monitor (▲ and ■) and a BPM (●) located downstream.

In a second series of experiments a quadrupole magnet located in front of the monitor was used to change the beam width. The σ-beam widths determined from the beam profile versus quadrupole strength is shown in Fig. 9 for two slightly different beam transfer line settings. For small variations in the neighborhood of the horizontal focus the beam widths show the expected behavior. Deviations seen for larger beam diameters are expected to be caused by partial beam loss or beam optics nonlinearities.

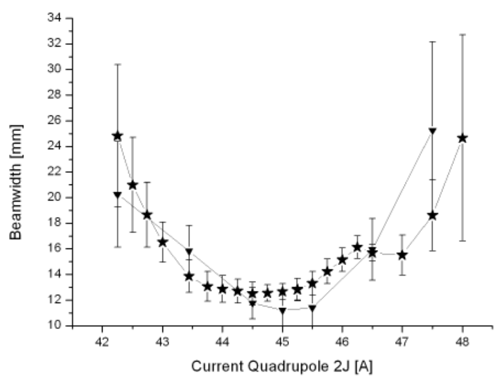


Fig. 9. Horizontal σ-beam widths versus quadrupole strength for a 3.14 MeV proton beam.

In addition the beam profile and the light production has been measured at different pressures between 10^{-5} and $5 \cdot 10^{-4}$ mbar. The cross section for optical emission within the sensitivity of the PMT has been calculated. From the experiments we deduced cross sections which are apparently almost one (1.35 GeV / COSY) or even two orders of magnitude (3.1 MeV / iThemba) larger than presented in (Ref. 10). The reason for the discrepancy is subject to further investigations.

IV. CONCLUSIONS

Beam induced fluorescence and ionization of the residual gas rely on beam particle energy loss to create photons and ions. The cross section for light production is about three orders of magnitude smaller than for ionization. Gas ionization monitors (IPM) are therefore times more efficient. The ions or electrons are collected in a solid angle of about 4π. As a consequence the signal strength is higher. A high resolution down to 100 µm, limited by the MCP, is possible. Disadvantages are the complexity of the vacuum installation, the need of a compact magnet with large homogeneity in special cases, aging of the MCP and there is no commercial hardware and data acquisition system available. Due to the collecting electric field considerable deflection of the primary beam at low energies has to be taken into account. The IPMs are mainly used in synchrotrons.

The beam induced fluorescence monitor (BIF) is really a completely non-destructive method of beam profile monitoring if there is no additional pressure bump necessary. The advantages are the simple mechanics (nothing installed in the vacuum), high resolution is possible, limited by the optic system, commercial hardware and data acquisition system is available, and this method is insensitive to the magnetic and electric fields, and, as a consequence, to the beam space charge field. The method is well suited for profile measurements in a radiation environment with high dose levels like in front of the target of a neutron spallation source. The light can be transported by an optical system out of the target area, where no electronics could be installed. The disadvantages are the low signal strength due to the lower cross section and the smaller solid angle $\Delta\Omega \approx 10^{-4}$ and 10 % detection efficiency. The signal strength could be improved with a local pressure bump. The BIF monitors are mainly used in linacs and transport beamlines.

The developed profile monitor based on light radiation of atoms excited by the beam particles has been successfully tested in proton beam experiments at low (3.1 MeV) and high (1.35 GeV) energies. The intrinsically very high time resolution could be demonstrated by resolving the beam profile of a single pulse. Even in synchrotrons the monitor has shown its capability to measure beam profile and position.

The first experience with the multi-channel photomultipliers have shown that they are appreciably more resistive against injurious exposures to the beam and secondary particles than microchannel plates (MCP), which are used usually for electron and ion registration.

N_2 can be considered as possible scintillation substance, but also in environments with H_2 as main residual gas the presented method can be used to monitor the beam profile.

It should be mentioned that in both methods a calibration and regular checking of the MCP and PMT is necessary.

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REFERENCES

1. B. G. Budker, Ya. Derbenev, I. Meshkov et al., Atomnaya Energia, v. 40, № 1, 1975; Particle Accel., vol. 7, 1976.
2. V. Mikhailov, V. Rezvov et al, Proc. of the 13th Int. Conf. Cyclotrons and their Application, Vancouver Canada, 1992, p.473.
3. V. Kamerdzhiev and J. Dietrich, IKP Annual Report 2001, Jül-3978.
4. T. Giacomini et al., BIW 2004, Knoxville, AIP Conf. Proc. 732, New York: Am. Inst. of Physics, 2004, pp. 286-293.
5. K. Wittenburg, Strahlprofilmonitore für den HERA-Protonenring, DESY HERA 1986-06.
6. R.G. Bikmatov, L.G. Boriskin, V.I. Kudelaynen, I.N. Meshkov, V.V. Parkhomchuk, Atomnaya Energia, vol. 24, № 1, 1967.
7. L. Rezzonico, in Proc. of the 11th Conf. on Cyclotrons and their Applications, Tokyo, Oct. 1986.
8. D.P. Sandoval et al., BIW, Santa Fe, AIP Conf.Proc. 319, p.273, (1993).
9. O.I. Brovko et al., Proc. of the International Workshop Relativistic Nuclear Physics: from hundreds of MeV to TeV. (Varna, Bulgaria, September 10-16, 2001), published by JINR, Dubna, 2001. vol. 1, pp.89-94.
10. M.A. Plum et al., Nucl. Instr. Meth. A492 (2002), p.74.
11. M.A. Plum, 11th ICFA International Mini-Workshop on Diagnostics for High-Intensity Hadron Machines, Oak Ridge, Oct. 21.-23., 2002.
12. F. Becker et al., Proc. DIPAC 2007, Venice, to be published.
13. R. Dölling, Proc. DIPAC 1999, Daresbury, p.47.
14. M. Schulz-Rojahn, Messung von Strahlprofilen am internen COSY-Protonenstrahl mittels Restgasionisation, Doctor's thesis, Bonn, 1998.
15. V. Kamerdzhiev, Diploma thesis, FZ Jülich, 2000.
16. J.L. Wiza, Microchannel Plate Detectors, Nucl. Instr. and Meth. 162 (1979) 587-601.
17. O. Jagutzki, J.S. Lapington, L.B.C. Worth, U. Spillmann, V.Mergel, H. Schmidt-Böcking, Position sensitive anodes for MCP read-out using induced charge measurement Nucl. Instr. and Meth. A 477 (2002) 256-261.
18. http://www.roentdek.com/.
19. J.S. Lapington et al., Spatial resolution limitations of microchannel plate/conductive charge division readout devices, Nucl. Instr. and Meth. A 273 (1988) 663-666.
20. LeCroy MQT 300A datasheet.
21. http://www.acam.de/.
22. H.J. Stein, private communication.
23. R. Schneider, Prüfbericht Institut Fresenius, Dresden, 2002.
24. Y. Hashimoto et al., Proc. EPAC 2002, Paris, pp.1900-1902.
25. P. Forck and A. Peters, 33rd ICFA Adv. Beam Dynamics Workshop, Bensheim, 2004, AIP Conf. Proc. 773, pp. 179-183.
26. J. Dietrich et al., 33rd ICFA Adv. Beam Dynamics Workshop, Bensheim, 2004, AIP Conf. Proc. 773, pp. 184-187.
27. J. Dietrich et al., IKP Annual Report 2004, Jül-4168.
28. C. Böhme et al., 26. Arbeitsbericht der Arbeitsgruppe Energiereiche Atomare Stöße, Dresden, 2005.
29. J.Dietrich et al., Proc. PAC 2007, Albuquerque.