EU contract number RII3-CT-2003-506395 CARE-Report-2007-029-HIPPI

Beam Profile Measurements Based On Light Radiation of Atoms Excited by the Particle Beam

J. Dietrich, Forschungszentrum Juelich, Germany
C. Boehme, T. Weis, University Dortmund, Germany
A.H. Botha, J.L. Conradie, P.F. Rohwer, iThemba LABS, South Africa

Abstract

Diagnostics of intense particle beams require the development of new non-destructive beam monitoring methods. The development of a profile monitor based on beam induced fluorescence is described in this paper. Beam profile measurements under various residual gas pressure conditions and particle energies performed at the synchrotron COSY-Juelich, Germany and at the cyclotron beam transfer line at iThemba LABS, South Africa are presented and the pros and cons of the applied method is discussed.

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 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 [1-4] as secondary particles. Some attempts have been already accomplished which utilize the light emitted by beam excited residual gas atoms [5-11]. However, up to now, this promising approach in non-disturbing beam diagnostics neither has 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 beam particles, has the advantage to be insensitive regarding 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. The atomic excitation cross section for light emission however 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.

Applied Method

The light emitted by the residual gas atoms is focused using a glass lens onto a position sensitive photomultiplier (PMT) array (see Fig. 1). 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) perpendicular to the beam axis. From the signals the beam position as well as the profile can be evaluated in one dimension.

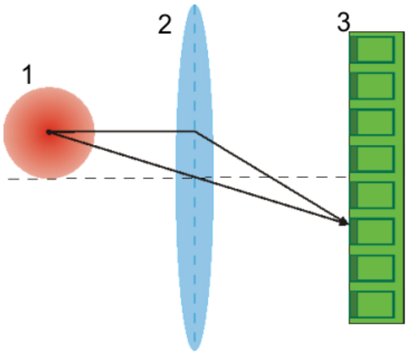

Figure 1: Measurement Principle (not to scale): The light from the beam (1) is focused with a glass lens (2) onto the multichannel photomultiplier (3).

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 crosses the chamber volume through 50 μm thin foils installed at the beam ports of the chamber. The exact setup is explained in [13], first results were reported in [12] and [14].

Profile Measurements

Profile Measurements at Short Beam Pulses

The first measurements with the setup were performed at an external beam transfer line at the COSY synchrotron at Juelich. A stored beam of $\sim 10^{10}$ protons at 1.35 GeV was extracted single turn from the synchrotron and transferred to the external beam line. The beam has 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 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 at 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. 2 shows the profile of the pulsed beam taken single pass and 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 the beam position has been shifted by about 10 mm being in very good agreement with the expected value.

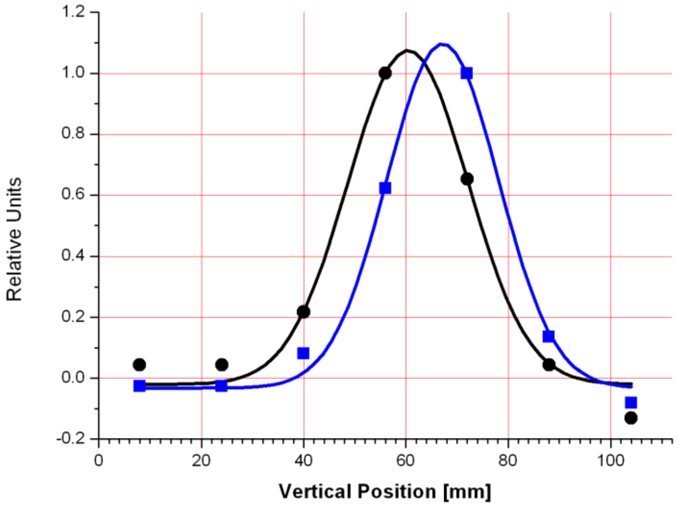

Figure 2: Singe pass beam profile of a pulsed (1.35 GeV, p=10 mbar) normal positioned (●) and shifted (■) beam (Gaussian fit to PMT data).

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. Due to the low photon yield (basic background pressure 10^{-7} mbar with internal gas target) a data taking 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. Fig. 3 illustrates such a beam profile taken at the COSY ring and shows that the applied method can even be successfully used in a synchrotron.

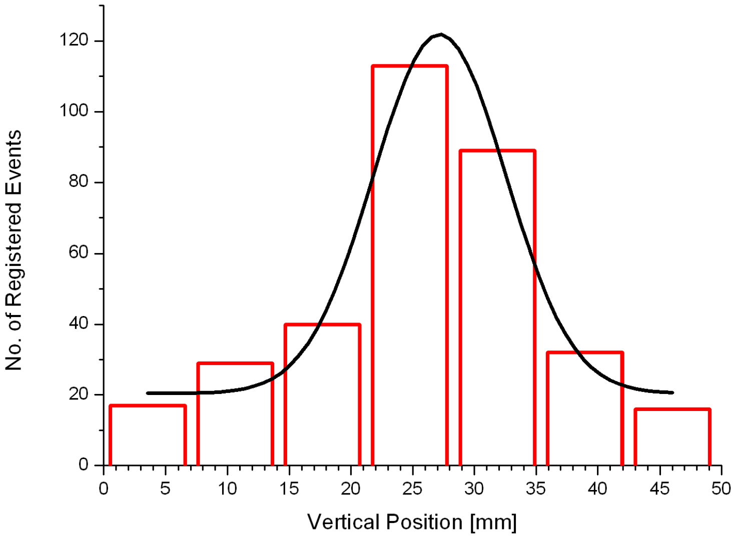

Figure 3: Beam profile measured at 10^{-7} mbar pressure in the COSY ring (Gaussian fit to channel data). Events have been summed up for 4 seconds. Beam data: 1 GeV, $\sim 5 \cdot 10^9$protons.

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 has been available at residual gas pressures of approximately 10^{-5} mbar. The 32 individual PMT pixels were divided into 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) has been available a couple of cm downstream 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 strength is shown in Fig. 4. 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.

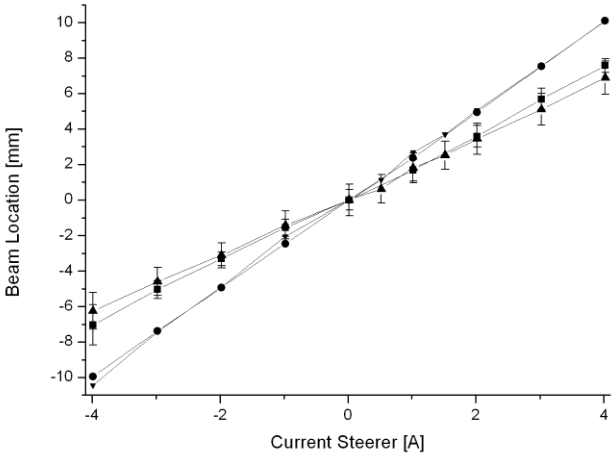

Figure 4: Beam position versus steerer strength measured with our optical beam profile monitor (▲ and ■) and a BPM (●) located downstream.

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. 5 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 optical unlinearities.

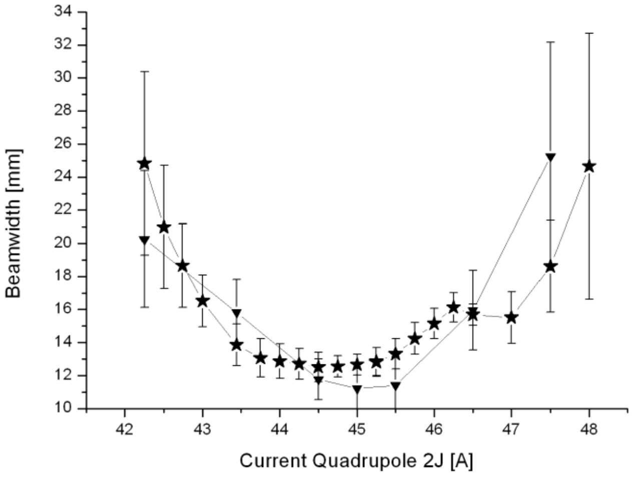

Figure 5: Horizontal σ-beam widths versus quadrupole strength for a 3.14 MeV proton beam.

In a third series of experiments we made the attempt to measure the beam profile downstream a beam collimator. In the case of only small beam losses (σ-widths in the order of collimator width) we clearly could determine the beam dimension with respect to the collimator setting. With increasing losses however we believe that the measured beam profile is dramatically spoiled by the light emitted from scattered particles and there is no evidence seen yet for a reliable profile measurement.

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 and is given in Fig. 6 together with data obtained at COSY. 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 expected from [9], the reason for the discrepancy is subject to further investigations.

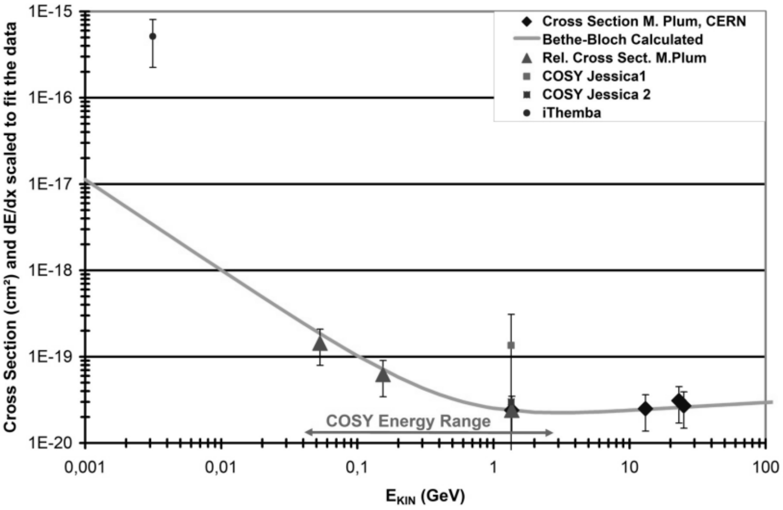

Figure 6: Cross section for light production for N_2 versus proton energy. The graph shown is based on the Bethe Bloch formula fitted to reference values from [9].

Summary

The non-destructive beam diagnostic system based on light radiation of atoms excited by the beam particles has been successfully tested in first 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 bright light as well as beam and secondary particles than microchannel plates (MCP), which are applied 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.

Acknowledgements

We like to thank I. Meshkov and A. Parfenov from JINR Dubna, Russia as well as I. Mohos from FZJ Jülich, Germany for the cooperation in earlier experiments with our optical beam profile monitor. We also like to thank the operators at the iThemba LABS and COSY-Juelich for operating the machines during our experiments.

We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395) and of the BMBF and NRF, Project-code SUA 06/003.

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] R.G. Bikmatov, L.G. Boriskin, V.I. Kudelaynen, I.N.Meshkov, V.V. Parkhomchuk, Atomnaya Energia, vol. 24, № 1, 1967.

[6] L.Rezzonico, in Proc. of the 11th Conf. on Cyclotrons and their Applications, Tokyo, Oct. 1986.

[7] D.P.Sandoval et al., BIW, Santa Fe, AIP Conf.Proc. 319, p.273, (1993).

[8] 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.

[9] M.A. Plum et al., Nucl. Instr. Meth. A492 (2002), p.74.

[10] M.A. Plum, 11th ICFA International Mini-Workshop on Diagnostics for High-Intensity Hadron Machines, Oak Ridge, Oct. 21.-23., 2002.

[11] F. Becker et al.,proc. DIPAC 2007, Venice, to be published.

[12] J. Dietrich et al., 33rd ICFA Adv. Beam Dynamics Workshop, Bensheim, 2004, AIP Conf. Proc. 773, pp. 184-187.

[13] J. Dietrich et al., IKP Annual Report 2004, Jül-4168.

[14] C.Böhme et al., 26. Arbeitsbericht der Arbeitsgruppe Energiereiche Atomare Stöße, Dresden, 2005.