RESIDUAL GAS BEAM PROFILE MONITORS FOR INTENSE BEAMS IN TRANSFER LINES

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Abstract

Muons, Inc. proposes to develop a Residual-Gas Beam Profile Monitor for Transfer Lines with pulse-to-pulse precision of better than 0.1 mm in position and size that will operate over a wide range of proton beam intensities including those needed for multi-MW beams of future facilities. Traditional solid-based beam intercepting instrumentation produces unallowable levels of radiation at high powers. Our alternative approach is to use a low mass residual-gas profile monitor, where ionization electrons are collected along extended magnetic field lines and the gas composition and pressure in the beam pipe are locally controlled to minimize unwanted radiation and to improve resolution. Beam Induced Fluorescence profile monitor with mirascope light collection is proposed.

INTRODUCTION

Intense (multi MW) proton beams pose a challenge for beam profile measurements. Solid-based beam intercepting instrumentation produces unallowable levels of radiation at these high powers. An alternative is to use a zero-or-low mass device such as a residual-gas profile monitor, either through collection of ionization or fluorescence. Challenges are to produce repeatable, pulse-by-pulse measurements of beam sizes and positions. Typical beam size is 1-2 mm rms, and the required pulse-to-pulse precision is 0.1 mm in position and size. The Long Baseline Neutrino Experiment (LBNE) target facility conceptual design anticipates a proton beam power of up to 2.3 MW at 60-120 GeV (1.6e14 protons per pulse, 1.5-3.5 mm sigma, 9.8 µs pulse length) on a solid target (graphite or beryllium). Beam profile determination at high intensity ion accelerators implies the use of non-destructive methods. The basic physics and recent technical realizations of important non-intercepting profile diagnostics are summarized in Ref. [1,2]. Residual gas Ionization Profile Monitors (IPM) and Beam Induced Fluorescence Monitors (BIFM) which were developed and first used with intense proton beams by Dudnikov [3,4,5,6,7,8,9] in 1965, are now routinely used in all proton accelerators. Some recent developments of IPM are presented in [1,10,11]. Modern BIFPM are described in [12]. Transverse electron beam scanners (TEBS) were realized recently for use in SNS storage ring by Aleksandrov, et al. [13,14,15,2]. Laser beam scanners are used at H^- LINACs, Optical Transition Radiation screens and Synchrotron Radiation Monitors for relativistic beams [1]. Non-destructive transverse profile measurements are preferred not only for single-path diagnostics at different locations in a transfer line, but also to enable time resolved observations of a stored beam within a synchrotron.

TECHNICAL APPROACH

A schematic of an ordinary residual gas beam profile monitor is shown in Fig. 1. Beam profile measurement is an important task for accelerator optimization and in general for accelerator experiments. The basic principle of an IPM is the beam ionizes the residual gas in the vacuum. An electric field is applied transverse to the beam direction to extract the ionized particles toward a position sensitive particle detector, e.g. a strip array or a phosphor. The electric field is created by high voltage electrodes. To increase the small number of ionized particles a micro-channel plate (MCP) multiplier is necessary. For each transverse plane of the beam a separate IPM is installed. An IPM utilizes the ions or electrons from ionization of the residual gas by the particle beam. The density of ionization is proportional to the beam intensity distribution. An external transverse electric field drifts the ions or electrons towards a microchannel plate.

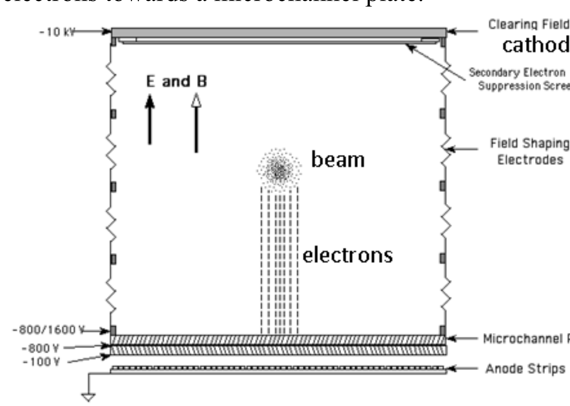

Figure 1: Residual gas beam profile monitor.

The incoming charges are amplified in the microchannel plate and deposited on approximately 200 collectors, each 0.25 mm wide x 10 cm long strips), which run parallel to the beam direction. The distribution of signal among the strips is representative of the transverse profile of the beam. These signals are further amplified and then digitized by the IPM electronics. The electronics can capture profiles on a turn by turn basis, for up to 20000 turns of data. Among the advantages of an IPM are that it is not invasive and can capture turn-by-turn transverse beam profiles.

One of the disadvantages is that the radial electric field from the charge distribution of the beam itself is comparable to that of the external field. This causes a spreading

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of the ion or electron cloud, and necessitates a "correction" to the measured profile distribution. This correction depends upon the beam density. A modest external magnetic field (400-3000 Gauss dependent upon beam density) can confine the electrons (but not the ions) and eliminate the need for a theoretical correction. A secondary electron suppression grid prevents a secondary electron emission from the cathode plate. Electromagnetic crosstalk from the beam to the strips is reduced by shielding the MCP or by a grid. The applied magnetic field affects not only the residual gas particles but also the beam itself which is steered out of the original beam path. To compensate for this effect two corrector magnets are needed. The first corrector magnet steers the beam back to its center position while the second corrector magnet steers the beam back to the original beam direction. This magnet design increases the length because of the size of the magnets and the minimum distances between the magnets. To reduce the overall length to an acceptable value, a design with two main magnets and two corrector magnets can be used. During the measurement, only one main magnet per plane is used. The corrector magnets have four coils and can work in both planes while each of the main magnets work in one plane.

A luminescent screen can be used for visualization of the electron flux distribution with a digital camera. The electrons create light spots on a phosphor screen behind the MCP, which are monitored by a CCD camera. An overall resolution of typically 0.1 mm is achieved. This method is preferred for high energy synchrotrons, delivering low emittance beams, and in cooler rings. A typical time resolution is of the order of 1 to 10 ms, depending on the frame rate of the camera. To enable a μs time resolution, as required for a turn-by-turn readout, a multi-anode photomultiplier has to be installed as an additional fast readout system. Alternatively, an avalanche photo-diode array or the recently available Silicon Photomultipliers (SiPM)s could be used. The luminescent screen can deliver high spatial resolution (>0.1 mm), but temporal resolution is very limited by the screen properties and the digital camera.

A strip collector can have high temporal resolution (~0.1 μs) but has poor spatial resolution (~0.3 mm). An array of strips is mounted behind the MCP to collect the current of the amplified electrons. The spatial resolution is limited by the distance between the anode strips, having a pitch down to 0.25 mm. But it is possible to get a time resolution of 0.1 μs using sensitive broadband amplifiers or charge-sensitive amplifiers.

The spatial resolution can be improved by collecting electrons along extended magnetic field lines. To improve resolution to 0.1 mm it is necessary to extend the magnetic field up to 3 times. The corresponding magnet design is shown in Fig. 2. Notice that the area of the upper pole is smaller than the area of the lower pole.

After reaching a certain irradiation level, the MCP channels show an irrecoverable degradation of amplification caused by the amplified electrons at the exit side of the MCP. To perform a software correction of this local non-uniformity of MCP-amplification, a test device must be provided.

Opposite to the MCP an Electron Generator Plate (EGP, an MCP biased to yield electron field emission) can be mounted. Alternatively, the MCP can be homogeneously illuminated by a UV-lamp.

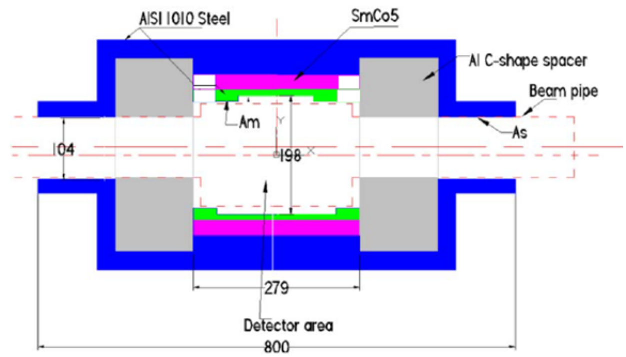

Figure 2: Design of collection magnet with extended magnetic field.

Since usually the vacuum pressure in a synchrotron is as low as 10^{-11} mbar, a controlled pressure bump might be necessary to increase the residual gas ionization events. For sufficient statistics within one bunch passage at least 100 ionization events have to be detected during a time of ~0.1 μs. To manage the count rate limit of MCPs, a time selected HV-switching is required. Contrary to synchrotrons the residual gas density in transfer lines is some orders of magnitude larger. In particular, at a transfer line the ionization rate can be large enough that **no** first stage MCP amplifier is required. A direct registration of the residual gas ionization electrons on a strip array followed by sensitive current-to-voltage amplifiers [3-7] is possible.

BEAM INDUCED FLUORESCENCE DETECTOR (BIFD)

Beam induced fluorescence (BIF) detectors are non-invasive and are able to measure the beam position and achieve transverse beam profiles within one beam pulse.

BIF detectors offer a reliable and robust measurement of beam position and transverse profiles of high current beams. For operation, the data analysis is done in the charge collecting mode as a projection of the raw image, which offers a highly dynamic response with sufficient accuracy, even without background subtraction. Hence, the event counting mode seems less practical and more complex for daily operation. Nitrogen seems to be the most appropriate residual gas, because of its spectral concentration between 390 and 430 nm. In addition, nitrogen shows the highest integral intensities. Especially the four times higher I_{gas} and Z makes it the right choice, if stopping power is an issue.

Therefore, one might focus on different selection criteria such as larger molecule masses and shorter transition-lifetimes, provided by rare gases like Xe and Kr. Helium is no alternative due to its wrong profile image in the considered pressure range. However, for most beam parameters N_2 is the optimal choice because of its high light yield. Moreover, it was shown that all nitrogen profiles show the same profile width. Once a residual gas is selected, optical components can be further optimized.

The BIF principle and the detailed setup (hardware, optics, readout and control) of the system is described in Ref. [16]. To observe the fluorescence of the ion beam interaction with the nitrogen gas molecules at lowest gas pressures, image intensified camera systems (ICCD) are required, preferably with a 2-stage micro-channel plate (MCP) amplification to enable single photon counting. An image intensifier that can be used is the Hamamatsu V4183U. An example of a BIF detector is shown in Fig. 3.

Thus, the relay-lens coupled camera systems are preferred for permanent installations in the future. All images of the CCD cameras are recorded in 8-bit format.

Operational parameters for BIF to gain signal strength and quality are the N_2 gas pressure, the iris opening and the MCP high voltage. By setting MCP and iris in a proper way, systems can be used for profile measurements in:

Charge collection (CC) mode: The intensifier gain is adjusted to avoid camera saturation at the expense of some detection efficiency. Here, the overlap of detected events is not a problem as long as no saturation occurs. A background is calculated by the outer region of the image and subtracted from each pixel. The total light yield N_{CC} is obtained by integration over the CCD matrix after background subtraction. Profiles are projections of the matrix in the vertical plane.

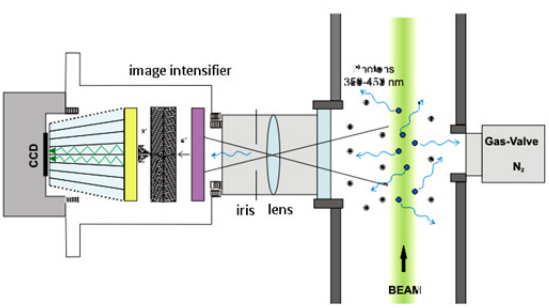

Figure 3: Schematic of BIFD.

It is possible to use light collected from beam induced fluorescence by using a mirascope [17], a device invented in the 16th century by the inventor of the telescope. A modern mirascope consists of 2 paraboloids, connected as shown in Fig. 4.

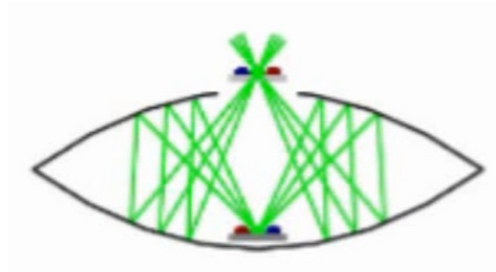

Figure 4: Schematic of mirascope light collection.

For imaging the light collected, a model of a mirascope of 6” with drilled holes for beam was used. For beam imaging, a luminescent tube was used. A photograph of the image is shown in Fig. 5.

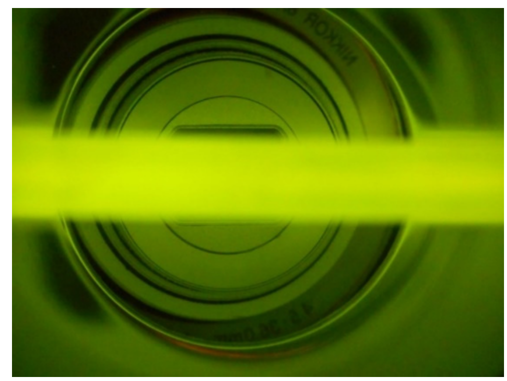

Figure 5: A photograph of the image of a beam as created by the mirascope.

Light emitted by the beam is collected by the paraboloids and creates a beam image, shifted from original. By placing a lens near the image, it is possible to collect almost 100% of the emitted light. The luminescent tube can be used for geometrical calibration of the BIF.

CONTROLLED LEAK

A calibrated nitrogen leak and differential pumping is used to create a local pressure bump. The leak chamber is located on a separate chamber, featuring its own ion pump and gauges, which is then connected to the beam line vacuum system by a remote-controlled gate valve, which could be pulsed [18]. Since the trapped gas volume in the leak shut off valve is enough to bring the leak chamber pressure out of the ion pump operating range, the leak is permanently left on while the ion pump actively keeps the pressure in the desired range. As a passive safety measure, a small orifice connects to a titanium sublimation pump to keep the pressure down and avoid the need for a tunnel access in case of a power failure.

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