MIRASCOPE RESIDUAL-GAS LUMINESCENT BEAM PROFILE MONITORS

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Abstract

Advanced beam diagnostics are essential for high-performance accelerator beam production and for reliable accelerator operation. Traditional solid-based beam-intercepting beam profile monitors produce unallowable levels of radiation expected multi-MW beams at future facilities. Residual-gas beam profile monitors, however, introduce negligible additional material in the beam and can operate over a wide range of proton beam intensities including those needed for multi-MW beams at future facilities, particularly in beam transfer lines. Two types of residual-gas beam monitors are presented, one which detects the ionization produced in the gas, and another which detects the beam-induced fluorescence light emitted by the gas molecules, with improved light collection provided by a mirascope.

INTRODUCTION

Non-invasive diagnostics can be used continuously with intense beams, while invasive techniques interfere with the beams and distort the beam profiles. In addition, traditional solid-based beam monitoring instrumentation produces unacceptable levels of radiation operating in high power beam environments. Non-invasive determination of accelerated particle distributions and profiles is the most difficult task of bunch diagnostics.

To be non-invasive, a beam profile monitor should be a zero-or-low mass device that uses the existing residual gas in the beam pipe or by injecting a small amount of gas into the beam pipe by means of a controlled leak. Beams passing through gas produce ionization and fluorescence, either of which can be collected to produce a beam profile. We discuss both the collection of ionization and the collection of beam induced fluorescence light. In the latter case the light collection efficiency can be improved by utilizing a mirascope, as described below.

BACKGROUND

The basic physics and recent technical realizations of important non-intercepting profile diagnostics are summarized in [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 [3-9] in 1965, are now routinely used in all proton accelerators. Some recent developments of IPM are presented in [1,10,11]. Modern BIFMs are described in [12]. Transverse electron beam scanners (TEBS) were realized recently for use in the SNS storage ring by Aleksandrov et al. [13-15,2]. 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. Pulse-to-pulse precision of better than 0.1 mm in position can be achieved. A beam induced fluorescence profile monitor with mirascope light collection is described here.

BEAM INDUCED FLUORESCENCE MONITOR (BIFM)

Beam induced fluorescence monitors are non-invasive and are able to measure the beam position and achieve transverse beam profiles within one beam pulse. The BIF principle and the detailed setup (hardware, optics, readout and control) of the system is described in [16].

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 appears 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 not a good 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.

To observe the fluorescence of the 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 monitor is shown in Fig. 1.

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

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occurs. A background is calculated from 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.

A schematic representation of a BIFM that employs an image intensifier and a mirascope light collector is shown in Fig. 1. Light rays emerging from inside are reflected and form an image above the opening and pass into the optics to the image intensifier.

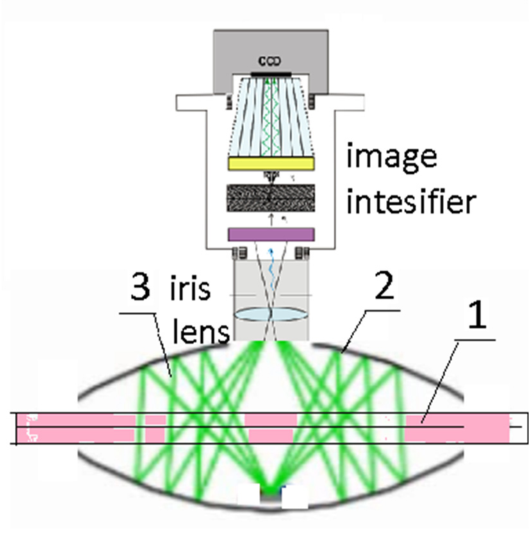

Figure 1: Schematic of a BIFM with a mirascope light collector. The beam is labelled 1, the paraboloidal mirror is labelled 2, and light rays are labelled 3. The two mirrors are joined together, and two holes permit the beam top pass through.

By placing the lens near the image, nearly 100% of the emitted light can be transported to the image intensifier, which is ~5 times better than in conventional BIFMs. The operational parameters for BIF signal strength and quality are the N_2 gas pressure, the iris opening and the MCP high voltage. The CCD in the image intensifier can operate in an event counting (EC) mode or in a charge collection (CC) mode. In the CC mode the image of the beam profile can be captured by a camera. In the EC mode the coordinates of the active pixels are aggregated to record the image.

MIRASCOPE LIGHT COLLECTOR

The light collection from beam induced fluorescence can be improved by using a mirascope, a device invented in the 16th century by Giovanni Battista Della Porta, the inventor of the telescope [17]. A mirascope consists of 2 paraboloidal mirrors with an opening at the top, connected as shown in Fig. 2. Light rays emerging from an object form a three-dimensional image above the opening.

An example of the imaging by a commercial mirascope is shown in Fig. 2, in which a red ball located inside the mirascope at the bottom produces a three-dimensional image above the opening.

Figure 2: Mirascope with red ball inside at bottom and its image formed above the opening

Figure 3 shows a representation of an image of a beam passing through a mirascope, simulated by placing a luminescent tube inside the mirascope.

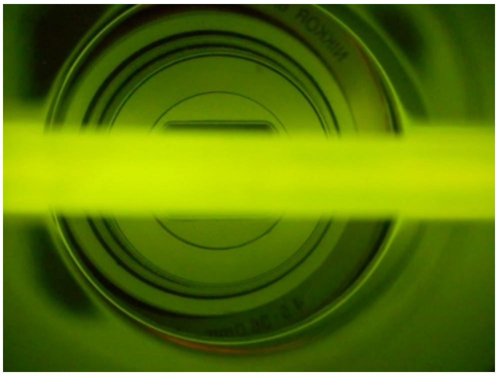

Figure 3: A photograph of the image of a beam as created by the mirascope.

Light emitted by the luminescent tube is collected by the paraboloids and creates an image, shifted from the original. 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.

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 than in the accelerator. 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.

COMPARISON WITH IPM

In an IPM, electrons (or ions) produced by ionization of the residual gas (or in controlled leak gas) drift downward in a parallel E and B field region and impinge on the anode as shown in Figure 4 (ions drift upward). Typically, the signal is multiplied by a microchannel plate read out by anode strips arranged parallel to the beam. Field shaping electrodes and the magnetic field add complexity and cost. Furthermore, the radial electric field of the beam is comparable to that of the applied electric field, which necessitates corrections to the recorded profile distributions, and the applied electric field and the magnetic field cause steering of the beam.

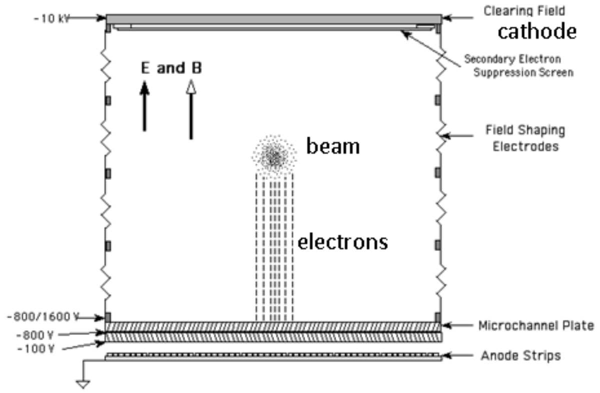

Figure 4: Schematic of a residual gas Ionization beam Profile Monitor (IPM).

The gas composition and pressure in the beam pipe are locally controlled to minimize unwanted radiation and to improve resolution. Ionization cross sections vary with energy and beam type, as shown in Figure 5, for hydrogen. Ionization yields and fluorescence yields scale with energy deposited in the gas by the beam, and depend on the charge Z of the beam particle as Z^2, according to Bethe-Bloch, so that applications to ion beams produce higher yields than proton beams. Fluorescence cross sections in nitrogen are about 10 times greater than ionization cross sections in hydrogen, and have similar energy dependence. Typically ionization yields are greater than fluorescence photon yields [12]. Typical photon collection efficiencies are about 10^{-2} for conventional optics, however the use of a mirascope improves photon collection efficiency to near 100%.

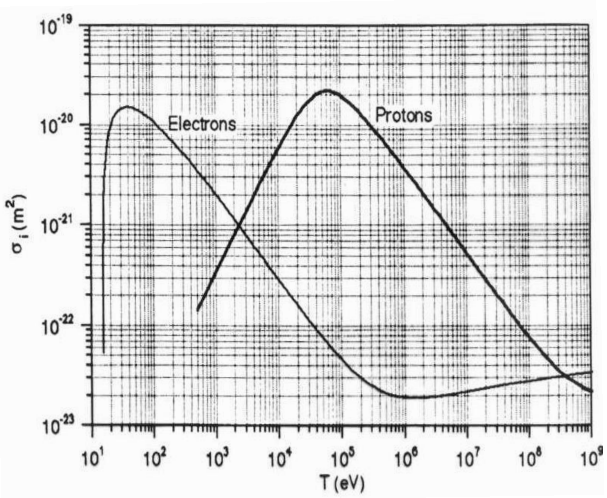

Figure 5: Ionization cross section of hydrogen for electron and proton beams as a function of beam energy [19]. Cross sections in nitrogen are ~6 times greater than in hydrogen.

CONCLUSION

BIFMs are simpler and less expensive than IPMs, and are less invasive. BIFMs have been developed and improved, and have operated in a number of beam energies and types, particularly in heavy ion beam transfer lines. Use of Mirascope light collectors can further improve the performance of BIFMs.

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