RIBBON ELECTRON BEAM PROFILE MONITOR FOR BUNCHED BEAM TOMOGRAPHY*

V. Dudnikov#, Muons, Inc., Batavia, IL 60510, USA,
A. Aleksandrov, ORNL , Oak Ridge, TN 37831, USA

Abstract

Advanced beam diagnostics are essential for high performance accelerator beam production and for reliable accelerator operation. It is important to have noninvasive diagnostics which can be used continuously with intense beams of accelerated particles. Recently, an electron probe was successfully used to determine accelerated particle density distributions. However, the apparatus used for this diagnostic is large and complex which restricts its wider use for tomography of accelerated bunches.

In a novel proposed device for realization of electron probe tomography a strip cathode is used for ribbon electron beam formation instead of a scanning of pencil beam used in the previous electron probe bunch profile monitors. The apparatus with the strip cathode is smaller, has simpler design and less expensive manufacturing, can have better magnetic shielding, higher sensitivity, higher resolution, can have better measurement accuracy and better time resolution. With this device it is possible to develop almost ideal tomography diagnostics of bunches in linear accelerators and in circular accelerators and storage rings.

INTRODUCTION

Beam profile determination at high intensity ion accelerators requires the use of non-destructive methods. The basic physics and recent technical realizations of important non-intercepting profile diagnostics are summarized in Ref. [1]. Ionization Profile Monitors (IPM) and Beam Induced Fluorescence Monitors (BIFM) developed and used for the first time with intense proton beams by Dudnikov et al. [2, 3] are now routinely used in almost all proton accelerators. Some recent developments of IPM are presented in [1, 4].

A transverse electron beam scanners were realized recently for use in the SNS storage ring by Aleksandrov et al. [5, 6]. Other methods include laser beam scanners, which have been used at H^- LINACs, and Optical Transition Radiation screens and Synchrotron Radiation Monitors, which can be used for relativistic beams.

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. Additionally, minimally invasive diagnostics techniques are essential, due to the large beam power available, at modern hadrons accelerators. This beam power consideration excludes the use of intercepting methods like scintillation screens, SEM-grids or wire scanners due to the risk of melting when irradiated by the total beam intensity

Various methods for profile determination can be used to determine the properties of typical widths σ = 0.1 to >10 mm of not necessarily Gaussian shapes. The first class of technique is based on atomic collisions between the beam ions and the residual gas: the direct detection of ionized residual gas ions or electrons with an Ionization Profile Monitor (IPM) and the detection of single photons from excited levels of the residual gas by Beam Induced Fluorescence (BIF), can be used. In most synchrotrons and storage rings the transverse profile of the circulating beam is monitored via detecting the ionization products from the collision of hadrons with residual gas by an Ionization Profile Monitor [1-4]. The IPM, the most commonly used diagnostic, is complicated by the necessity to use large MCP plates with a limited lifetime.

PENCIL ELECTRON BEAM PROFILE MONITOR (EBPM) USED AT THE SNS

In the recently developed electron beam profile monitor (EBPM) developed at the SNS, a transverse beam profile is reconstructed from the deflection of electrons crossing the proton or ion beam after being influenced by the beam's space charge, as schematically shown in Fig. 1 [1]. A pencil electron probe similar to TV tube electron beam is formed by an electron gun and scanned through the proton beam by the electric field of deflectors as in an oscilloscope tube. The position of the scanning electron probe after crossing the proton beam is visualized by a fluorescent screen and the image is captured by a CCD camera for further processing. Assuming the electron beam has a much lower diameter than the proton or ion beam and the scan duration is much shorter than the ion bunch passage, the space charge field can be treated as constant.

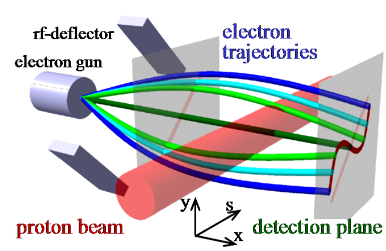

Figure 1: Schematic of an electron scanner for the vertical beam profile [1].

The deflection angle is maximal at the beam edge and decreases during the scan towards the beam centre; no deflection occurs when passing the centre. The electron trace in the detector plane is recorded. The diagonal

*Work supported by Contract DE-AC05-00OR22725 and by STTR grant DE-SC0007559
#Vadim@muonsinc.com

deflection makes sure that the profile information is extracted from the derivative of this trace with respect to the beam direction. This method was considered for high energy synchrotrons [5] and recently commissioned at the SNS [6]. Using a scanning ion beam instead of electrons, the method was analyzed and tested at CERN [7]. The corresponding mathematical formalism for profile reconstruction is given in Ref. [5, 7].

The setup at the SNS-Ring [5] as shown in Fig. 2 consists of an electron gun (1) providing a pencil electron beam up to 70 keV and a current of up to 1 mA for 1 μs pulses with a 5 Hz repetition rate. The beam passes an electric deflector (2), for a diagonal sweep with 20 ns duration, and two quadrupoles (4) to enlarge the spatial range and parallelize the beam during scanning. After crossing the ion beam (5), where the deflection occurs, the electrons are visualized by a phosphor screen (6) and recorded with a camera. To achieve a reasonable deflection, the electron beam energy has to be matched to the ion beam current. The advantage is the possibility of sliced profile measurements with high time resolution as given by the short sweep duration of only 20 ns. The transverse profile is derived from the angle of deflection of the electron beam according to the following formula, see also [7]:

$$\frac{d\theta}{dx} = \int_L \frac{e}{mv^2} \cdot \frac{\delta(x,y)}{\varepsilon_0} dy$$

where *e, m* are the electron charge and mass, respectively, v is the velocity, $\delta(x,y)$ is the ion beam density distribution, and θ is the electron beam deflection angle. This assumes that the path of the electrons is approximately straight, the net energy change to the electrons by the proton beam is close to zero, and the effect of the ion magnetic field can be neglected.

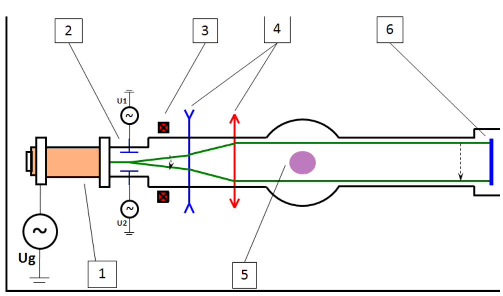

Figure 2: Diagram of electron scanner from [6].

The first quadrupole extends the range of the deflection while the second quadrupole focuses the electron beam such that the electron beam is parallel. The electron gun is pulsed once a second, but faster rep rates of up to 5 Hz are possible. One vertical and one horizontal scanner are installed in the SNS ring tunnel. GigE_Vision CMOS cameras acquire the images from the fluorescent screens. Because the scanners are located in a straight section of the ring, the radiation levels are low enough to not damage the cameras. A single PXI-based computer running LabVIEW controls the cameras, timing, pulse generators, and power supplies of the electron scanner.

As shown in Figs. 1, 2 a significant part of the scanner is used for the extension of the scanning e-beam. Large quadrupole magnets also complicate the magnetic shielding of this version of scanner. For these reasons, electron beam profile monitors (EBPM) with electron beams formed by the deflection of pencil e-beams are very long, bulky, and complex.

More practical e-beam profile monitors that are more suitable for proton beam tomography can be developed using a strip cathode for formation of a ribbon beam as discussed below in the technical objectives section. The analysis of the data for beam bunch transverse profiles for the system that we are proposing will be very similar to what has been developed for the EBPM as described below.

RIBBON ELECTRON BEAM PROFILE MONITOR (REBPM)

The ribbon electron probe beam profile monitor (REBPM) using a strip cathode is proposed as shown in Fig. 3. The electron ribbon (6) is generated by the strip cathode (1) with extractor (2). The transverse dimensions of the ribbon are defined by the collimator with two slits (3) and (5). The width or duration of the ribbon electron probe (6) is formed by the deflection of the ribbon electron beam across slit (5) by a pulsed voltage on the deflecting plates (4). Electrons of the ribbon electron probe after deflection by electric field of the proton bunch are visualized on the luminescent screen (7) and recorded by a fast CCD camera for further processing by the corresponding software discussed above.

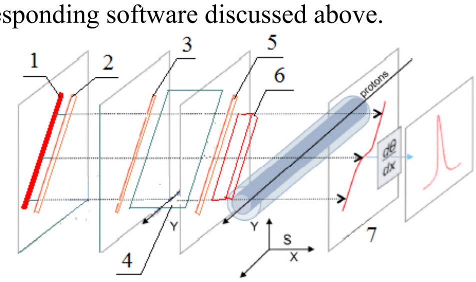

Figure 3: Electron probe beam profile monitor with a strip cathode.

This version of the REBPM is smaller, with easier fabrication, operation, and magnetic shielding compared with other options. Several similar systems can be integrated for production of tomographic 3-D images of proton bunches. The proposed tomographic system is more compact, easier for operation and less expensive than the residual gas ionization profile monitors (IPM) discussed above.

A simplified diagram of REBPM is shown in Fig. 4. The ribbon electron beam (3) is formed by a strip cathode (6) and crosses a proton bunch (7). Electrons are deflected by electric and magnetic fields of the bunch (7). This deflection is reflected by the position of electrons imaged in the luminescent screen (5) and recorded by a CCD camera (8). Electron multiplication with a micro channel

ISBN 978-3-95450-115-1

plate (MCP) (4) can be used for synchronization and for brightness amplification. A pulsed high voltage (~150 kV) power supply (1) is used for electron beam acceleration (extraction). The electron source and cathode are supported by the high voltage insulator (2).

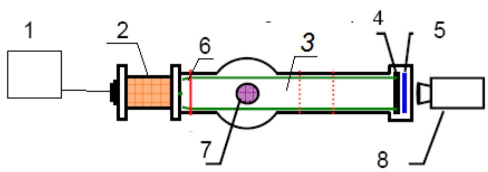

Figure 4: A simplified diagram of REBPM. 1-high voltage pulser; 2-high voltage insulator of electron gun; 3-ribbon slice of electron probe; 4-MCP; 5-luminescent screen; 6-strip electron source; 7-proton bunch; 8-CCD camera.

It is possible to use a field emission cathode formed by a brush of nanotubes for pulsed (~10 ns) electron beam production. A beam intensity ~ 1 mA/cm of cathode is necessary (cathode is ~15 cm long) for good visibility of the electron trace on screen (5) without the MCP.

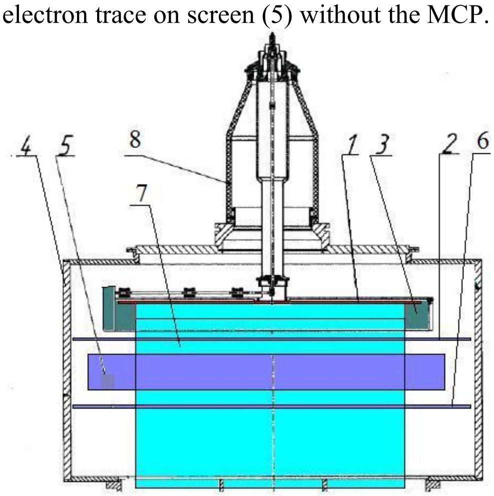

Figure 5: Design of a strip cathode electron gun for ribbon beam formation.

The design of the electron gun with a strip cathode for ribbon electron beam formation is shown in Fig. 5. The ribbon electron beam (7) is emitted by a strip cathode (1). Some low temperature emitters discussed in [8, 9] are attractive cathode candidates since they survive in atmosphere for easy fabrication and maintenance. There are several practical strip emitters to choose from such as impregnated cathodes with tungsten with lanthanum admixture, iridium with cerium, or tantalum coated by lanthanum hexaboride. For reliable visualization of the ribbon electron beam on the phosphor screen it is enough to have about 5 mA emission for 1 cm strip cathode. A low emission temperature is important for long-term geometric stability of the emission system (it can be heated for a short time for activation).

The ribbon electron beam (7) is accelerated by the pulsed high voltage between the emitter (1) and the anode (2) with the narrow slit as shown in Figs. 1,5. The initial ribbon beam divergence is controlled by a beam forming electrode (3). The narrow ribbon beam is formed by a collimator comprised of two narrow slits in the electrodes, (2) and (6). Two deflecting plates (5) are used to quickly scan the ribbon beam through the slit in the electrode (6) to form a short slice of ribbon beam synchronized with proton beam bunch. The vacuum vessel (4) must be well demagnetized and must have good magnetic shielding to prevent any deflection of the electron beam by external fields. A high voltage insulator (8) is used for support of the electron beam emitter.

The pulse transformer has a modular design. It contains a set of identical modules that are connected in series to form the secondary winding. Each module contains a ring shaped ferromagnetic core, insulating rings and secondary winding made by two wires used for cathode heating. The ferromagnetic core is wound with 20-micron metglass (amorphous alloy) tape, with varnish insulation between the layers. The primary winding of the transformer is a straight conductor on the axis of the grounded tank wall.

The transformer is connected to the electron gun by a short coaxial feeder with voltage and beam current sensors inside.

REFERENCES

[1] Peter Forck, "Minimal Invasive Beam Profile Monitors For High Intense Hadron Beams", IPAC 2010, Kyoto, Japan, 2010.

[2] G. Budker, G. Dimov, and V. Dudnikov, in Proceedings of the International Symposiumon Electron and Positron Storage Rings, Saclay, France, 1966 (Saclay, Paris, 1966), Article No. VIII-6-1; (V.Dudnikov, Ph.D Thesis, INP, Novosibirsk, 1966); G. Budker, G. Dimov, and V. Dudnikov, Sov. Atomic. Energy 22, 384 (1967); V. Dudnikov, in Proceedings of the Particle Accelerator Conference, Chicago, 2001 (IEEE,Piscataway, NJ, 2001); www.cad.bnl.gov/icfa/presentations/Friday_AM/Dudnikov.ppt

[3] G. Dimov, V. Dudnikov, "Determination of Circulating Proton Current and Current Density Distribution (Residual Gas Ionization Profile Monitor)", Instrum. Experimental Techniques, 5, 15 (1967).

[4] G. Ferioli et al., DIPAC'03, p. 116 (2003) and C. Fischer et al., BIW'04, p. 133 (2004).

[5] A. Aleksandrov et al, "Feasibility Study of Using an Electron Beam for Profile Measurements in the SNS Accumulator Ring", PAC 2005, p. 2586-2588.

[6] W. Blokland, et al.,"Electron Scanner For SNS Ring Profile Measurements", Proceedings of DIPAC09, TUOA03, Basel, Switzerland, 2009.

[7] J. Bosser et al., Nucl. Instrum. Meth. A 484, p. 1 (2002).

[8] V.G. Dudnikov, J.H. Whealton, Physics and Technology of Ion and Electron Sources, Encyclopedia of Applied Physics, Vol.14, p.1-36, VCH Publishers, Inc.,1996.

[9] G. Kuznetsov, Nuclear Instruments and Methods in Physics Research Section A: Volume 340, Issue 1, 1994, p. 204-208.

[10] Niels de Jonge, et al., "High Brightness Electron Beam From A Multi-Walled Carbon Nanotube", Nature 420, p.393-395 (2002).