A NOVEL FIELD CAGE DESIGN FOR THE CPS IPM AND SYSTEMATIC ERRORS IN BEAM SIZE AND EMITTANCE

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Abstract
An ionization profile monitor has been recently installed in the CERN proton synchrotron. We present the design for a novel and simplified field cage structure that suppresses the secondary electrons that are induced by the ionized ions. We discuss the field cage design and the beam size and emittance systematic error considering the non-uniformity of the fields, the space-charge effect of the beam, and the lattice parameter errors.

INTRODUCTION
A new ionization profile monitor (IPM) has been developed and installed in the CERN proton-synchrotron (CPS) which includes a number of novel features, in particular: an electron imaging detector comprising multi-pixel silicon detectors that are bonded on Timepix3 readout chips [1]; a novel field cage to provide an electric field ($E_x$) to accelerate the ionized electrons onto the imaging detector that also suppresses the creation of background secondary electrons; a 3-pole self-compensating magnet to provide a 0.2 T magnetic field ($B_y$) to guide the electrons onto the imaging detector against a strong space charge electric field ($E_x$) and a novel 3-D particle-tracking code to simulate the profile to estimate the IPM-performance.

The new type of electron imaging detector has been previously reported [2, 3], and the general design of the IPM has also been reported [4]. The existing simulation codes that are used for an IPM are summarized in [5]. The first performance report of this IPM system was recently published [3], and the measured beam size was observed to be in good agreement (1% error) with the value that was measured using a wire-scanner monitor in the CPS.

The IPM was installed in the CPS at SS82 ($s = 510 - 511$ m) to measure the horizontal profile. The twiss-parameters at this location are $\beta_x = 12$ m, $\beta_y = 22$ m, and $D_x = 2.4$ m, $D_y = 0$ m. The horizontal and vertical beam size was calculated as follows:

$$\sigma_{x,y} = \sqrt{ \frac{\varepsilon_{x,y} \beta_{x,y}^2 + D_x^2 \delta_x^2}{\beta_y} }$$

$$\sigma_{y} = D_y \delta_y$$

The normalized emittance $\varepsilon_x$ and $\varepsilon_y$ is typically 1.5 and 1.6 $\mu$m, respectively. The contribution of a momentum dispersion ($\delta$) to a beam size is dominant in case of an extraction beam. $\delta$ is typically $0.9 \cdot 10^{-3}$ for an injection beam and $1.5 \cdot 10^{-3}$ for an extraction beam. For an injection beam with the total kinetic energy (TKE) of 1.4 GeV ($\beta y = 2.3$), the horizontal size is 3.4 mm, which is 1.4 times larger than the beam size with the momentum dispersion. However, for an extraction beam with the TKE of 25 GeV ($\beta y = 28$), the beam size is 3.7 mm, which is 4.1 times larger. Consequently, the beam sizes at the injection and the extraction are observed to be similar. However, the vertical beam size decreases to 1/3.5 as $\beta y$ increases.

FIELD CAGE DESIGN

The IPM field cage is depicted in Fig. 1, which is a simple structure that uses no side electrodes between the anode cathode that are generally used to improve the homogeneity of the field. The detector is mounted in a Faraday cage to shield the detector system from beam induced RF interferences. The anode with a honeycomb-structured RF shield is placed above the detector and forms part of the Faraday cage. The cathode is biased at a maximum voltage of $\sim 20$ kV.

The IPM should only detect ionized electrons, which contain only about a hundred electrons per beam bunch [6]. The real signal is contaminated with: secondary electrons generated by the ionized ions that collide on the cathode; signals induced by primary and secondary beam losses; electrons from electron clouds and flash-over discharge. The second case can be avoided by precisely tuning the accelerator. If the latter two cases are observed to occur a significant number of electrons would be generated: some of these would be mixed into the real signals. Simulating such a situation requires detailed particle-tracking calculations for $E_x$ and $E_y$. To reduce the secondary electrons that are generated by particle collisions, part of the cage structure is covered with titanium and carbon coating.

The cathode contains an ion trap to reduce the secondary electrons generated by the ion collisions; the ion trap structure is described in the following section.

Noble Ion-Trap Structure

Secondary electrons are generated when ions collide with the cathode. These electrons are then reaccelerated to the anode and the detector where these signals are mixed with the real signals. The position distortion of ions due to the $E_x$ on the cathode is larger than that of the ionized electrons on the anode. This difference is due to the gyro-

Figure 1: Field cage of the CPS IPM.
tion motion with $B_\parallel$. Since the Larmor radius is a linear function of the ionic masses, the radius of ions is 1,800 times greater than the radius of an electron. Therefore, mixed signals exhibit the following two components: a real beam profile and a broad-structured distribution that is observed to originate from the ion-induced secondary electrons.

To repel the secondary electrons from the cathode a grid mesh is typically placed in front of the cathode, and a gap voltage is applied between the grid and the cathode. However, this method cannot eliminate the secondary electrons generated at the grid wire caused by the ion-bombardment process (as shown in Fig. 2).

**Figure 2: Secondary electrons from a grid.**

A window on the cathode acts as an ion trap. The ions pass through the ion trap and are then accelerated again onto the backside of the cathode or the inside wall of the ion-trap window. In this calculation, only three particles out of 70 are observed to return to the inside surface of the cathode. However, the generated secondary electrons that originate from these ions cannot reach the detector. Figure 4-(b) depicts the trajectories of the secondary electrons generated at the inside wall of the ion trap emitted with the TKE of 10 eV. The emitted electrons return to a point near the emission point by a gyration motion with the $B_\parallel$ of 0.2 T with the radius of about 50 μm, and some of the emitted electrons are accelerated to the chamber wall and collide with it.

**Figure 4: Particle trajectory calculations. (a) Ions to the ion-trap and (b) secondary electrons from the inside wall of the ion-trap accelerated to the chamber wall.**

**SYSTEMATIC ERROR OF BEAM SIZE**

The influence of field distortion on the measured beam size was monitored using the 3D-particle-tracking code, IPMsim3D [5, 8], which was developed for this project. Details of the code will be published in a forthcoming publication. This code uses 3D fields of the $E_x$ and $B_\parallel$ that were estimated using an external code, whereas $E_x$ was estimated internally. $E_x$ was calculated using CST Studio. $B_\parallel$ was assumed to have a uniform distribution of 0.2 T. A point-spread function (PSF) was calculated analogously to the optical design. The electron source that is defined in this study is not a point but a line with a length of 14 mm, which covers the longitudinal extent of the detector. The trajectory of electrons emitted at different positions on the line was estimated.

One standard deviation on a histogram of electrons that were hitting the detector is chosen to be the measure of point spread. An $E_z$ field along the $z$ axis creates point spread because the $E_z \times B_\parallel$ drift makes a horizontal-position shift. By varying the line position, a 2D map of the PSF was obtained. Similar calculations were conducted using CST. These results were observed to be consistent (Fig. 5). Figure 5 shows the point spread at different positions of $y$ when $x = 0$; it also depicts that the point spread near the anode is less than 1 μm. In contrast, the point spread becomes larger from $y = 9$ mm as it approaches to the window. At 10 mm there is a local minimum of approximately 1 μm, which is smaller than the value that is calculated for the case of no window. The $E_z$
vectors originated from the cathode edge (at \( z = \pm 100 \text{ mm} \)) and from the window exhibit opposite directions; moreover these fields are offset at this point.

In the main region of interest (\(-15 < x < 15 \text{ mm} \) and \(-15 < y < 15 \text{ mm} \)) the point spread is less than 10 \( \mu \text{m} \). Assuming the PSF to be a Gaussian function and a constant PSF value of 10 \( \mu \text{m} \), the systematic error on the beam size is estimated to be approximately 6E-4%.

The PSF from other error sources, including: the non-uniformity of \( B_y \), the initial momentum of the ionized electrons, and \( E_x \) were also checked using the code. The magnet is designed to ensure that \( B_y \) and \( B_z \) remained less than the order of \( O(-3) \) of \( B_y \). The \( B_x \) were assumed to have a linear function of \( z \), which is \( B_{x,x} = 10^{-3} B_y z \) within the longitudinal extent of the detector. The initial momentum of the electrons was calculated assuming that the residual gas in the IPM is pure hydrogen gas. The code calculates the double-differential cross section and estimates the initial momentum of electrons obtained by the ionization. The PSFs are also depicted in Fig. 5 for these additional error sources. The estimated total PSF, including all error sources, was approximately 30 \( \mu \text{m} \). The effect of this PSF is a 3E-3% systematic error of the beam size measurements.

The profile distortion due to \( E_x \) was previously reported in [4]. The systematic error on the measured beam size is 3E-2% when \( B_y = 0.2 \text{ T} \). The error is less than the required error of 0.5%. There is an error originating from the pixel size of the detector, which is 55 \( \mu \text{m} \). The spatial resolution is thus 55/sqrt(12) \( \mu \text{m} \) and the resulting systematic error is approximately 9.2E-4%.

**SYSTEMATIC ERROR OF EMITTANCE**

The systematic error for emittance that is discussed in this study is in a similar manner as that in [9, 10]. The required systematic error is 10% [11]. The horizontal beam emittance can be calculated using the slip factor, \( \eta \), as in Eq. (2), where \( T_s \) is the revolution period of the synchronized particle and \( \sigma_t \) is the longitudinal beam size. The factor \( A \) is defined as \( A = D_x / \eta \). The error components on each factor are exhibited in Eq. (3). The values for \( \sigma_x \) and \( \delta \) are assumed to be as 3.6 mm and 0.9E-3 for injection and 3.7 mm and 1.5E-3 for extraction. The contributions of longitudinal motions dominate for the extraction beam. The error is 10 to 30 times greater than that observed in the injection beam because there is only a singular point at which a beam satisfies the condition \( \sigma_x = \sigma_t \). Each systematic error is summarized in Table 1.

\[
\text{err} = \frac{\partial \sigma_x}{\partial \sigma_t} \left( \frac{\sigma_x}{\eta} \right)^2 = \frac{\partial \sigma_x}{\partial \sigma_t} - A^2 \left( \frac{\sigma_t}{\eta} \right)^2
\]

The factor \( A \) is the revolution period of the electron to eliminate the secondary electrons that are otherwise formed by the collision of ions on the cathode or grid-wires. The field non-uniformity of the field cage was 3.6/3.7 mm and \( 0.034/0.18% \), respectively, as depicted in Fig. 5 for these additional error sources. The estimated statistical error on the phase slip factor, \( \eta \), can be expressed using Eq. (4). The relativistic Lorenz factor at the transition energy, \( \gamma_T \), was observed to be \( 6.01 \pm 0.005 \) [12]. The systematic errors of the slip factor were further observed to be \( 0.034% \) and 0.18%, and the errors of factor, \( A \), for injection and extraction beam were 1.0% and 1.2%, respectively. During longitudinal profile measurement, the system yields a beam width of \( \sqrt{\sigma_T^2 + \Delta t^2} \) if the measurement system exhibits a time resolution of \( \Delta t \), which is a Gaussian-function-type response. The step response of the wall current monitor for the CPS [13] is 206 ps for a 10-90% rise time; thus, it is reasonable to consider 40 ps to be the value of \( \Delta t \).

The simple sum of these absolute values is observed to limit the systematic error. The estimated statistical error for the injection beam is 2.2%; however, it is observed to be approximately 50% for the extraction beam. The main contribution for the extraction beam is sourced from factor \( A \).

**SUMMARY**

A novel ion-trap structure was developed for the ionization profile monitor (IPM) for the CERN proton synchrotron to eliminate the secondary electrons that are otherwise formed by the collision of ions on the cathode or grid-wires. The field non-uniformity of the field cage was calculated, and the point-spread function was obtained. The expected systematic error for the beam size is 3E-3%, whereas the errors for emittance are 2.2% for the injection beam and 50% for the extraction beams.
REFERENCES


