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Measurements of spatial variations in response of ionization chambers

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Measurements of the spatial variations in the response of three ionization chamber (IC) designs were tested as a function of chamber bias voltage, incident X-ray flux and fill gas. Two components of spatial variation are seen. When the ionization chambers are near saturation, spatial variations exist that are tied to the chamber geometry. While the response of some chambers is relatively flat, others show significant variation across the IC. These variations appear to be inherent in the response of each IC at saturation. When the chamber is far from saturation, large spatial variations in response are present when N_2 is used as a fill gas, but not when ambient air is used as a fill gas. These appear to be tied to space charge effects.

Keywords: ionization chambers; spatial variations.

1. Introduction

Ionization chambers (ICs) are commonly used instruments to measure the flux of ionizing radiation, including at synchrotron beamlines. In the typical parallel-plate design, the X-ray beam passes through gas between two charged plates with a large bias voltage between them. The X-ray beam causes ionization of the gas. These ions migrate due to the applied electric field, causing a small current proportional to the X-ray beam intensity to pass through the chamber. ICs enjoy several desirable features. The physical design and readout electronics of ICs is relatively simple. As gas is used to absorb X-rays, radiation damage is of relatively little concern compared with other beam intensity monitors. The design of ICs is also quite flexible. By altering the active length, fill gas and fill pressure of the ionization chamber, the chamber absorption can be tailored to either absorb most of the beam (for use as a primary detector) or only a small fraction of the beam (for use as a beam intensity monitor), while allowing most of the beam to pass through the IC.

ICs have been the subject of theoretical and experimental studies for over a century; as such, IC behavior is generally well characterized. While parallel-plate ICs appear to be quite simple, several effects can reduce the collection efficiency of ICs below their theoretical value (Knoll, 2000), typically by allowing ion pairs to recombine before they reach the IC plates. Initial recombination of ions occurs within the track of ions created by an absorbed X-ray photon. Previous work (Niatel, 1967; Nariyama, 2006) has shown that initial recombination scales as $1/E$, where E is the applied electric field. Volumetric recombination occurs outside of this region in the bulk of the IC fill gas. Niatel (1967) gives the decrement in IC current from the saturated value due to volume recombination as

$$\frac{I_{\rm s}-I}{I_{\rm s}}=\frac{\alpha}{2\pi ek\_k_{+}}\frac{I_{\rm s}}{DE^{2}}=\beta\frac{I_{\rm s}}{DE^{2}}. \qquad (1)$$

In (1), I is the measured IC current, $I_{\rm s}$ is the current at full saturation, D is the plate separation, α is the recombination coefficient, e is the elementary charge, and the k factors are the ion mobilities. Higher flux causes the volumetric recombination to increase, while initial recombination remains unaffected. Thus, for high-flux cases, volumetric recombination is often assumed to dominate over initial recombination. In addition to recombination, as the electric field induces movement and concentration of the charge carriers near the oppositely charged plate, diffusion processes can occur which enhance recombination. Space charge effects can act to alter the electric field in the chamber (Armstrong & Tate, 1965; Hajnal & Pane, 1978; Chabod, 2009; Boag & Wilson, 1952), though these effects are dismissed or ignored in many studies (Niatel, 1967; Bielajew, 1985; Nariyama, 2006; Chabod, 2008).

While many studies have examined IC saturation behavior with respect to applied electric field and incident X-ray flux, the authors are unaware of previous experimental studies examining variations in the IC response with changes in X-ray beam position in the IC, at least in current mode operation. [Such effects are well known for ICs in pulsed-mode operation, as discussed by Fulbright (1979).] Experimental measurements have generally used relatively large beams from laboratory tube sources (Niatel, 1967) or do not explicitly investigate beam positioning effects (Boag & Wilson, 1952; Nariyama, 2006). Much of the theoretical work on ICs

Table 1
Ionization chamber parameters.

	Chamber A	Chamber B	Chamber C
Total L (mm)	162	95	20
Active L (mm)	150	60	12
Guard ring L (mm)	4	13	2
Active W (mm)	63	50	18
Plate separation D (mm)	14	11	10

assumes that the entire fill volume of the IC is illuminated with radiation (Boag & Wilson, 1952; Armstrong & Tate, 1965; Hajnal & Pane, 1978; Bielajew, 1985). Chabod (2008, 2009) has provided expressions for IC saturation behavior for a spatially varying illumination, including the effects of space charge. However, the perturbation analysis by Chabod has a limited domain where the series solution converges, especially in cases far from saturation or with high Langevin factors (Chabod, 2009). While spatial variations in IC response should ideally be quite minor, the authors have anecdotally encountered significant variations in IC output with beam position for certain IC designs. This finding has motivated the current measurements.

The current study focuses on measuring variations in the response of ICs to changes in beam position with respect to the chamber plates for parallel-plate ICs in current mode operation. A range of bias voltages, incident fluxes and IC designs has been examined. The influence of fill gas has also been investigated.

2. Experimental set-up

Three commercially available ICs were examined in this work, as described in Table 1. They represent a wide range in size and cost, and have specifications typical of those found in ICs in use at synchrotron beamlines. The baseline chamber is denoted as Chamber A, a relatively long IC design capable of operating with pressurized gas. While the plate separation for this chamber is 14 mm, the windows of the chamber are only 10 mm in height. As such, unlike with the other two chambers in this study, the beam cannot probe the region near the plates of this IC. Chamber B is a moderate-length general-purpose design commonly used at the Advanced Photon Source (APS). Chamber C is a small IC design used as a relatively non-intrusive beam intensity monitor. Unlike Chambers A and B, which have metal bodies, the body of Chamber C is made of a polymer. All of these ICs used polyimide windows to separate the IC volume from the ambient air, and all used guard rings of equal length (in the beam direction) both upstream and downstream of the collection plate maintained at electrical ground.

The measurements in this work were performed at the 7BM beamline of the APS, Argonne National Laboratory (Kastengren *et al.*, 2012). Unfocused monochromatic X-rays at 8 keV from the beamline's double-multilayer monochromator passed through a set of adjustable slits 35.5 m from the X-ray source. As unfocused bending-magnet radiation was used in this study, the beam intensity within the beam profile can be considered uniform. Each ionization chamber was placed approximately 1.2 m downstream of the slits on a motorized translation stage. For all experiments the chamber plates were placed above and below the beam; as discussed by Nariyama (2004), the IC response is somewhat lower when the plates are placed to the sides of the beam. The beam was centered in the chamber horizontally, and the IC was translated vertically to probe the dependence of IC response on beam position relative to the collection plates. The IC was carefully leveled with respect to the beam to ensure the beam was parallel to the collection plates at each measurement location. The X-ray flux passing through the chamber was monitored independently using a silicon PIN diode; the response of this diode is known to be linear with flux for the range of flux used in this experiment and almost uniform spatially. Moreover, the response of the diode has been calibrated using an independently calibrated diode. The output of the ionization chamber and PIN diode were integrated for 1 s at each measurement location. The variations in IC response across the height of the ICs was examined by varying the chamber bias voltage, incoming flux and fill gas, as will be discussed in the next section.

To vary the incident X-ray flux on the IC, both slit size and attenuating foils were used. For the lowest flux measurements the beam size at the slits was 4 mm $\times$ 0.1 mm (H $\times$ V). Attenuating foils (aluminium and polyimide) were used to attenuate the beam by approximately a factor of five. To create a more moderate flux, the attenuating foils were removed. For the highest flux case, the slit size was increased to 4 mm $\times$ 1 mm (H $\times$ V). In all cases the beam height is relatively small compared with the chamber height. Limited tests of the influence of beam size on IC response were performed, but no dependence of IC response on beam shape at a given level of flux was seen.

3. Results

The voltage required to cause saturation in the chamber has a significant dependence on the incident flux on the IC and the chamber gas, as has been described in the literature. However, the voltage required for saturation also depends strongly on the spatial location of the X-ray beam in the chamber and the detailed chamber geometry; this dependence has not to the authors' knowledge been previously documented. Fig. 1 shows the spatial response of Chamber A as a function of X-ray beam position for several applied voltages with N_2 as the fill gas. The incident flux in these measurements is approximately 1.5×10^{10} photons s^{-1}. Distance y is measured from the IC centerline, with the positive direction pointing toward the plate at the bias voltage and away from the plate at electrical ground. In addition, the ratio of IC to PIN current assuming complete charge collection in the IC is shown on the figure, assuming 35 eV per ion pair is required for ionization (Knoll, 2000).

At this level of flux the chamber is nearly saturated starting at -250 V bias. The IC response is nearly equal to the ideal

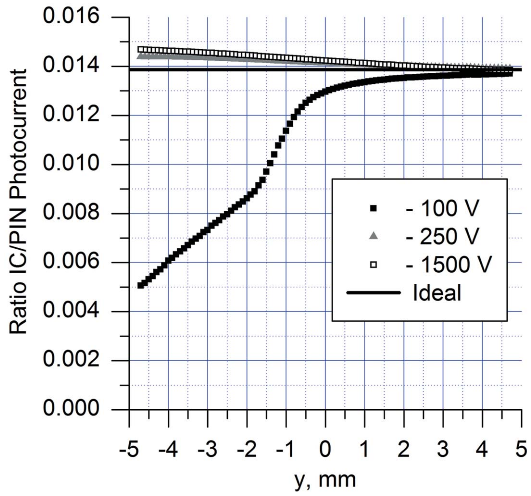

Figure 1
Response of Chamber A *versus* beam position at various voltage levels. Incident flux = 1.5×10^{10} photons s^{-1}, N_2 fill gas.

response assuming total charge collection, as well as nearly equal to the response for higher voltage values. At -100 V bias, however, the chamber is clearly not in saturation. However, the degree to which the chamber is not saturated varies significantly across the chamber. Near the negative plate (*i.e.* large y values) of the IC, the response is nearly equal to the ideal response, as well as the response at higher voltages. Near the center of the IC, the response is only slightly less than the saturated value. However, near the positive plate (small y values), the IC response is only 35% of that seen at -1500 V bias. Clearly, strong gradients in response exist inside the IC.

These variations in response become far more pronounced at higher levels of flux. Fig. 2 shows the response of Chamber A at a flux level of 6.5×10^{11} photons s^{-1}. The degree of saturation in the chamber is clearly much lower for a given voltage than at the lower levels of flux used for Fig. 1. The spatial variations seen at lower flux levels are still evident.

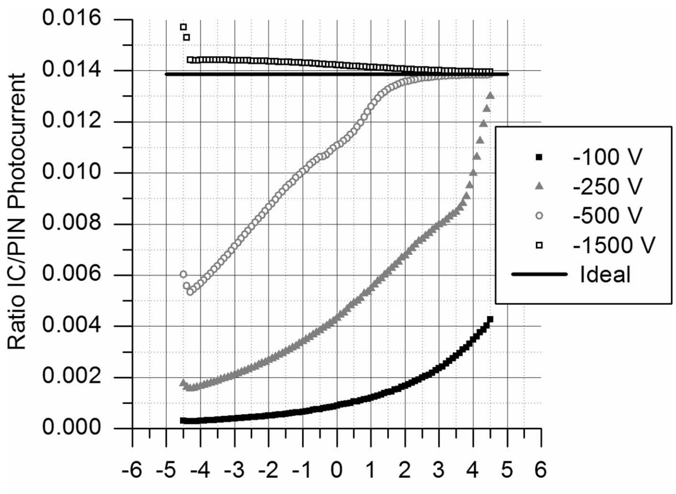

Figure 2
Response of Chamber A *versus* beam position at various negative voltage levels. Incident flux = 6.5×10^{11} photons s^{-1}, N_2 fill gas.

There appear to be two components to the spatial variations in IC response. The first component is seen at lower voltage levels: the chamber tends to have much lower response near the positive plate than near the negative plate, unless the voltage is sufficiently high to saturate the chamber. The second component of spatial variations is more subtle. Even at the highest voltages tested and at relatively low flux (conditions that ensure the chamber is saturated), the IC response tends to be slightly higher near the plate at electrical ground (the positive plate in Figs. 1 and 2) than the plate at the bias voltage (the negative plate in Fig. 1 and 2). This variation between the edges of the IC is approximately 6% of the average response (an average change in response of 0.7% per mm change in beam position). While not large, this variation in response may be mistaken for subtle variations in beam intensity if the beam position through the IC varied.

The spatial variation in IC response cannot be easily explained with the extant theoretical works in the literature. Chabod (2008, 2009) provides one of the few theoretical treatments that can account for nonuniform illumination of the IC. However, the first term of the perturbation analysis by Chabod (2008) is unchanged whether the IC is uniformly illuminated or illuminated only over a portion of the IC's height. There are a few possible explanations for the variations in spatial response across the ion chamber. Some possible explanations are tied to differences in the behavior of the negative and positive charge carriers. It should be noted that, as electrons are the negative charge carriers with N_2 as the fill gas, the mobilities of the positive and negative charge carriers are much different (Knoll, 2000). As discussed by Knoll (2000) and Nariyama (2004), diffusion processes can become important when electrons are the negative charge carriers. As discussed by Chabod (2009), as well as Boag & Wilson (1952), space charge effects can also become particularly important when electrons are the negative charge carriers. It is also possible that photoelectrons, whose range in air and N_2 is on the order of a few mm at 8 keV energy (Berger, 1993), may strike the positive plate before fully depositing their energy into the chamber gas, lowering the response of the ion chamber; this possibility is discussed by Boag & Wilson (1952) and Nariyama (2004). Moreover, the electric field inside the IC may be distorted (for example, by end effects), allowing more of the charge to be collected when the beam is near one plate than when it is near the other.

In order to investigate the nature of these variations, the chamber polarity was reversed. If charge carrier behavior led to the spatial variations, a reversal of the bias voltage would reverse the direction of these variations. On the other hand, if the spatial variations were due to the geometric design of the IC, reversing the polarity of the bias would have no effect. Fig. 3 shows data for the same conditions as in Fig. 2, but with positive, rather than negative, bias on the IC. The large variations in response when the chamber is far from saturation are present to a similar extent as was seen with negative chamber bias, but in the opposite direction. It is again near the positive plate that the highest voltages are needed to achieve saturation. This suggests that the spatial variations at

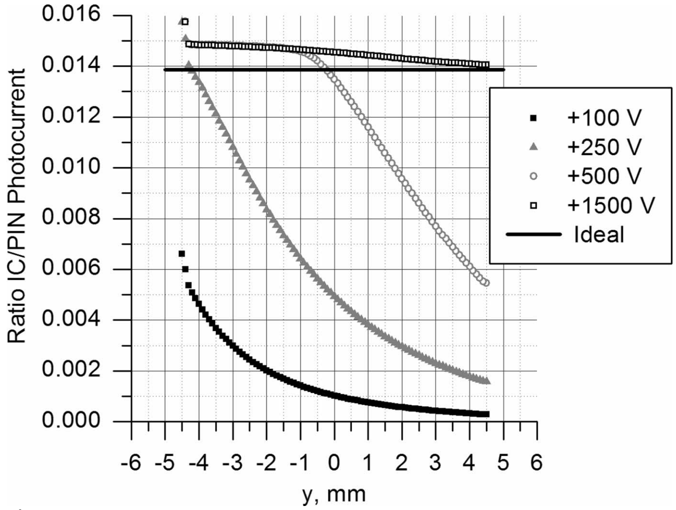

Figure 3
Response of Chamber A *versus* beam position at various positive voltage levels. Incident flux = 6.5 × 10^{11} photons s^{-1}, N_2 fill gas.

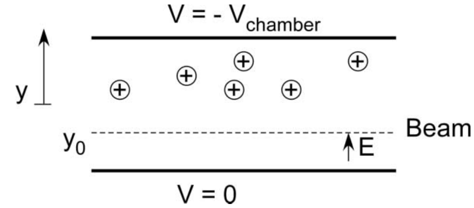

Figure 5
Schematic of the model geometry.

moderate voltages are due to charge carrier behavior. On the other hand, the subtle variations in response at saturation retain the same sense as was seen at negative bias; the chamber response is highest at the plate near electrical ground. This suggests that these variations are due to the IC geometry and design.

Further support of the hypothesis that the large spatial variations in response far from saturation are due to charge carrier behavior comes from examining the IC behavior with air, rather than N_2, as the fill gas. As discussed by Knoll (2000), the oxygen in air readily forms negative ions from the electrons created in the ionization process, while N_2 does not. As such, the positive and negative charge carriers have similar mobilities, in stark contrast to the mobilities in N_2. Fig. 4 shows the spatial response for the same conditions as Fig. 2, but with ambient air as the IC fill gas. Note that the ideal IC response is somewhat higher than in Figs. 1–3 owing to the higher absorption of X-rays in air compared with N_2. The spatial variations at lower voltage levels, where the chamber is clearly not saturated, are much lower than was seen with N_2 as the fill gas. The response tends to be slightly lower near the positive plate in these data, as was seen in Figs. 1–3. The change in negative charge carrier behavior appears to fundamentally alter the spatial variation in IC response when the chamber is far from saturation.

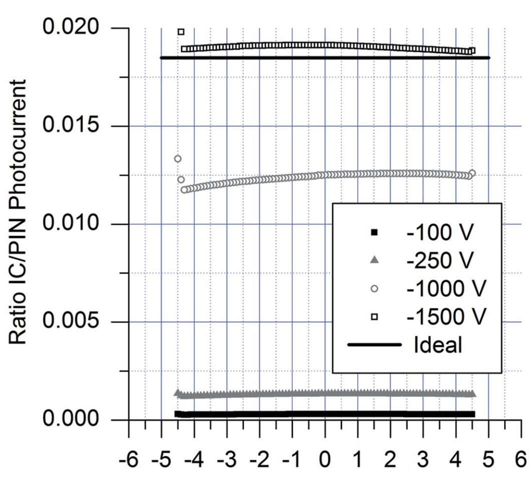

Figure 4
Response of Chamber A *versus* beam position at various voltage levels. Incident flux = 6.5 × 10^{11} photons s^{-1}, air fill gas.

The most promising explanation for the spatial variations in IC response below saturation is space charge effects. Boag & Wilson (1952) provide a detailed explanation and one-dimensional model of the space charge effects for a uniformly illuminated IC. In this work we will develop a similar one-dimensional model for a chamber filled with N_2 illuminated with an infinitesimally thin beam. Fig. 5 shows a schematic of the model geometry, which assumes negative bias on the chamber (as used in Figs. 1 and 2). Since the electron mobility is orders of magnitude greater than the positive ion mobility, space charge effects due to electrons are ignored. The electric field E can be modeled as

$$\frac{\mathrm{d}E}{\mathrm{d}y} = \begin{cases} 0, & y \le y_0, \\ i/(k_+ \varepsilon_0 E) = f_+/E, & y \ge y_0, \end{cases} \tag{2}$$

where i is the current density (in A m^{-2}) moving through the IC. This equation can be solved for E,

$$E = \begin{cases} 2\big[f_+(y_0 + C)\big]^{1/2}, & y \le y_0, \\ 2\big[f_+(y + C)\big]^{1/2}, & y \ge y_0. \end{cases} \tag{3}$$

An iterative solution can be used to determine C, using the condition that the integral of E across the chamber must equal the applied voltage.

Model calculations were performed to match the conditions of the measurements in Fig. 2 using tabulated values of the positive ion mobility (Viehland & Mason, 1995), a current density matching that found in the measurements shown in Fig. 2, and −1500 V applied voltage. The electric field for different beam positions y_0 is shown in Fig. 6. As the beam moves closer to the positive plate, the voltage present at the beam position declines dramatically. Indeed, for $y_0 < -1$ mm the model given in (3) becomes undefined. At this point the space charge from the positive ions has overwhelmed the applied chamber voltage. In reality, as the effective E at the beam location decreases, recombination will increase, causing the chamber to appear unsaturated and reducing the space charge effects. This behavior qualitatively matches the behavior seen in Figs. 1 and 2. Moreover, the quantitative agreement is also reasonably good; for example, at −1500 V bias the

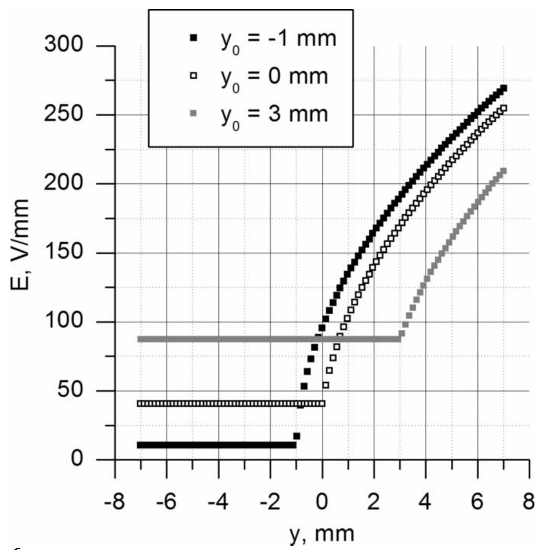

Figure 6
Spatial variations in IC electric field owing to space charge effects. Applied voltage = −1500 V, d = 14 mm, current density = 4 mA m^{-2}.

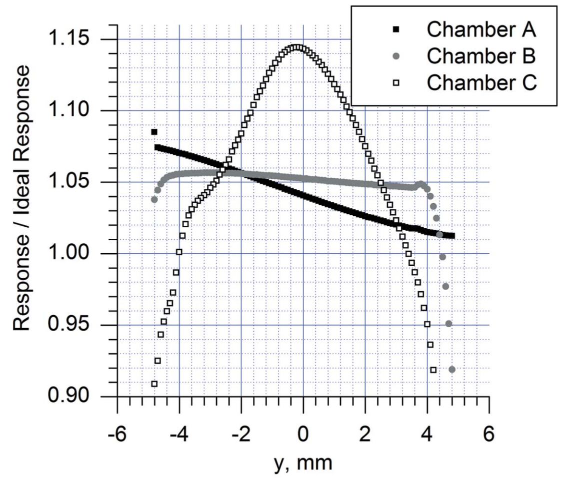

Figure 8
Comparison of response of different ion chamber designs. Bias voltage = −1500 V, N_2 fill gas, 6–8 × 10^{10} photons s^{-1} incident flux.

region around $y = -4$ mm in Fig. 2 appears to be slightly lower than in Fig. 1, indicating that some additional recombination may be occurring in this region at −1500 V applied voltage.

This model can also be used to examine the effect of changing flux and chamber voltage. Fig. 7 shows the model results when the current density (flux) is reduced by a factor of ten and when the chamber voltage is reduced. Lowering the flux substantially reduces the influence of space charge, providing far less opportunity for recombination. Reducing the applied voltage at constant current density substantially reduces E at the beam location, which will prompt additional ion recombination. These behaviors all match the qualitative behaviors seen in Figs. 1–3: lower bias results in lower IC response, and higher flux results in an IC response closer to saturated behavior.

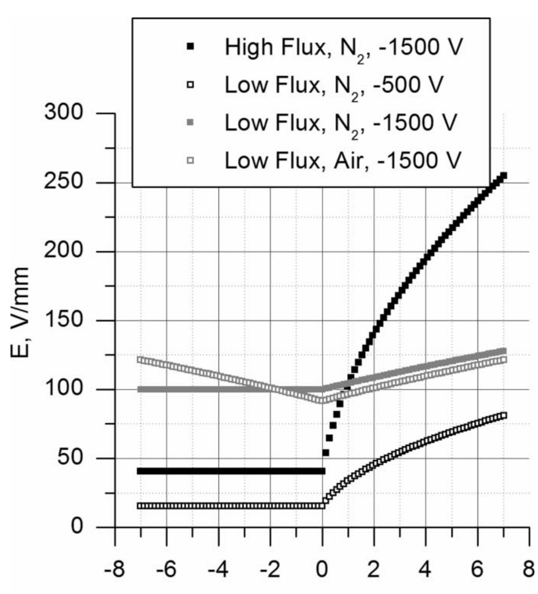

Figure 7
Spatial variations in IC electric field owing to space charge effects. Current density = 0.4 and 4 mA m^{-2}, d = 14 mm.

This model can be further extended to examine space charge when the negative charge carriers have similar mobility to the positive charge carriers; this corresponds to the use of air as the fill gas; a sample of the results is shown in Fig. 7. While space charge effects can still be significant in this case, E at the beam location is relatively insensitive to the beam location in the chamber. As such, this simple one-dimensional model captures all of the qualitative behavior seen in the variations in IC response below saturation. It should be noted that, as the beam occupies only a small portion of the width of the IC in these measurements, the results of this one-dimensional model should be considered only an approximation of the charge and E distribution in the chambers studied in this work.

Further support that chamber geometry plays a significant role in the variations in IC response at saturation can be seen by examining the behavior of the other two ion chambers. Fig. 8 shows the response of Chambers A, B and C at 6–8 × 10^{10} photons s^{-1} flux at −1500 V bias, all with N_2 as the fill gas. Under these conditions all of the chambers are at saturation across the width of the ICs. There are significant differences between the ICs in their response *versus* beam position in the chamber. As discussed previously, Chamber A shows a nearly linear increase in response as one moves toward the grounded plate. Chamber B, aside from some more significant variations very near the plates, has a relatively flat response with spatial position. Chamber C, on the other hand, shows large variations in response with beam position. The response when the beam is in the center of the chamber is quite high. However, near the plates the response is more than 10% lower. To reiterate, these trends occur when the chamber bias voltage is sufficient to reach saturation, and are otherwise insensitive to incident flux, fill gas or chamber polarity. As such, they seem to be directly tied to the design of the ICs themselves.

These variations may be understood in terms of the geometry of these ICs. A schematic of the generic chamber geometry used in this work is shown in Fig. 9. Chamber A has long wide collection plates; as such, one would expect the

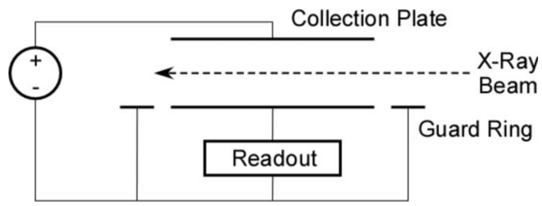

Figure 9
Schematic of the generic IC geometry.

electric field over most of the IC volume to be highly uniform and the end effects to be relatively minor. The guard rings used on this IC, however, are quite narrow. Chamber B has significantly shorter collection plates. On the other hand, the guard rings of this design are quite large relative to the collection plate size. Given that Chamber B has less spatial variation than Chamber A at saturation, this suggests that the additional area devoted to guard rings in this chamber improves the electric field distribution in the chamber and hence the uniformity of the chamber response, potentially by minimizing end effects. In Chamber C the collection plates are both narrow transverse to the electric field and are quite short in the beam direction compared with the plate separation. As such, it is perhaps not surprising that the response of this IC shows significant variations with beam position.

The influences of fill gas, incident flux and bias voltage have been probed with Chambers B and C as well. The results of these measurements confirm the trends seen in Chamber A. At low levels of bias the IC response is quite low near the positively charged plate. As the incident flux increases, this effect becomes more pronounced, and higher bias voltages are needed to reach a given level of saturation. The use of air, rather than N_2, as a fill gas virtually eliminates the large spatial variations seen far from saturation.

4. Discussion

There are two major conclusions from this work. The first is that, under conditions representative of those found at synchrotron beamlines, ICs can demonstrate significant spatial variations in response, especially in gases where electrons are the negative charge carriers. A simple one-dimensional model of space charge effects in these chambers shows that the space charge effects can qualitatively explain the spatial variations seen in these experiments, and furthermore gives reasonable quantitative agreement considering the simplicity of the model. It seems clear that space charge effects must be accounted for to adequately describe the saturation behavior of ICs under the high-flux narrow-beam conditions seen at synchrotron beamlines.

The second major conclusion of this work is that residual variations in IC response exist even when the IC is saturated. It appears that these spatial variations in response at saturation are not easily eliminated; they cannot be remedied by increasing the electric field, attenuating the beam or changing the fill gas. Given the current results, it seems warranted that, if an IC will be used as an absolute intensity monitor, the IC should be positioned carefully, and the spatial variations in IC response must be first measured and understood. Otherwise, spatial variations in IC response may be erroneously attributed to variations in beam intensity.

5. Conclusions

The spatial variation of three ionization chamber designs was measured as a function of incident X-ray flux, bias voltage and fill gas. When N_2 is used as a fill gas and the bias voltage is insufficient to drive the chamber to saturation, large spatial variations in the IC response are evident. These variations appear to be tied to space charge effects, as a simple model of space charge effects can account for the observations seen in this work. Other variations in IC response exist when at saturation and appear to be tied to the geometry of the IC. While these variations at saturation generally seem subtle, for certain chamber geometries these spatial variations can be quite pronounced. These variations at saturation are also insensitive to chamber electric field, fill gas and incoming beam intensity, and as such not easily remedied.

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