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Enhanced microchannel plate performance at high particle fluxes by pulsed exposure mode of operation

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Operating a microchannel plate (MCP) in saturated mode provides a simple photon and particle counting detector. However, there is a finite recovery time after individual events during which individual microchannels no longer respond, reducing the overall sensitivity. At continuous high flux levels, the corrections from measured to true flux become increasingly large as the fraction of live microchannels rapidly decays to low values. Gating the flux arriving at the MCP greatly increases the proportion of live microchannels allowing periodic measurements to be made that accommodate high fluxes and associated low errors. Such improvements have been observed in a neutral particle analyzer on the Mega Ampere Spherical Tokamak. A simple analytical treatment accounts for the measured improvements. © *2004 American Institute of Physics.*

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I. INTRODUCTION

Detectors based on microchannel plates (MCPs) have proven to be extremely versatile for detecting a wide range of radiation and particles including UV and x-ray photons, ions, electrons and energetic neutrals. MCP detection efficiency ranges from a few percent for low energetic UV photons, rising up to 85% for energetic ions and electrons and approaching 100% for x-ray radiation.[1–3] However, this high sensitivity of the MCP detectors has a negative side, evident in the environment of high penetrative background radiation (x ray, neutrons) common in magnetic fusion research. When the detector is exposed to a high intensity particle flux (typically $>10^5$–10^6 cm^2 s^{-1} for electrons),[1,2] the presence of background radiation can be additionally complicated by detector saturation caused by MCP dead time effects. These effects result in lower average MCP gains and distortion of the pulse height distribution of the detector, a feature common to many of the high gain electron multiplier devices, such as photomultipliers. Thus, the incoming flux needs to be restricted to an acceptable value, normally by a collimator, with little or no control over the uncollimated and highly penetrative background radiation. As a result of these flux losses, both the signal/background ratio and statistics are degraded.

The main motivation behind our study was to extend the limits of operational space of the MCP based detector[10] of a neutral particle analyzer (NPA) allowing reliable MCP operation for high incoming particle fluxes in the presence of significant neutron background radiation.

There are many features that bear on the overall MCP performance requiring analytic treatment to be heavily dependent on often inaccessible measurements. Many factors affect MCP performance, including particle species and kinetic energy, bias voltage, flux intensity and distribution, MCP material and production technology, MCP accumulated counts (aging), etc. Analyses of these effects are available in the literature[1–3] and lie beyond the aims of this article. Here we concentrate on the development of a simple and robust experimental method aimed at accommodating high intensity fluxes in the presence of significant background radiation.

II. EXPERIMENTAL METHOD

A. MCP detector

A microchannel plate detector is an array of electron multipliers with a channel density of 10^4–10^6 cm^{-2}, oriented parallel to each other. It is normally used in either of two distinct modes determined by the bias voltage used in electron multiplier action. In the “analog” mode, at relatively low bias voltage, the MCP is exposed to a continuous low flux of particles, where the MCP remains unsaturated, and gives quantitative information about the spatial distribution and the fluxes of the incoming particles. This mode of operation is used in applications such as image intensifiers. In the “saturated” mode, the MCP is operated at high bias voltage and is used to detect individual particles. Each particle produces a large output charge pulse showing the arrival time with the spatial location of each event given by the activated anode. The pulse height, however, is insensitive to the actual energy of the incident particle, i.e., the MCP operates essentially as a counting device.

Space charge saturation, occurring at high MCP gain, results in a change of the pulse height distribution (PHD) from a negative exponential to a peaked quasi-Gaussian shape, allowing a discriminator to be set for event counting, so that measured rates are relatively insensitive to the MCP gain shifts. Stacking of two or three MCPs is normally used to achieve the high gain required for saturation. In this case,

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peaking of PHD occurs as a saturated effect caused by space charge limitation of the secondary electron yield in a number of channels in the last plate, centered at the exit of the unsaturated channel in the first plate. In further discussions here, we consider the MCP chevron detector as a stack of two MCPs unless otherwise stated. For random stacking of two MCPs, the number of saturated channels depends on the number of electrons leaving the first plate as well as the bias voltage and interplate distance, yielding the average number of $n_0 \sim 6.5$ channels in the second plate.[4] Since the first MCP operates in unsaturated mode, the second MCP is responsible for the effective detector dead time when an individual microchannel detects a particle. The MCP channel recovery time from the maximum charge density pulse depends on the particular detector material, technology, aging as well as other factors.[1,2,5] Calculations based on single strip current, lumped or distributed capacitance, and number of experimental measurements are available in the literature typically yielding dead times of several milliseconds.[5]

B. Dead time losses

Full modeling of the MCP count losses and recovery is a complex task and beyond the scope of this article. Here we use a simple analytical model describing the gross behavior of the MCP count loss in saturated mode for different methods of operation.

Modern MCP chevron detectors consist of an array of densely packed miniature electron multipliers (microchannels) and function with an input flux of up to 10^6 cm^{-2} s^{-1}. Therefore, the MCP count rate is an accumulated measurement from a large number of microchannels, each subjected to a relatively low particle flux of up to tens per second. The performance of a MCP is best understood by appreciating the role of individual microchannels. In the “saturated mode,” when a microchannel detects an incident particle, it is insensitive to subsequent particles until there is recovery of the electron emission in the dead time. In the case of the chevron MCP detector, recovery actually takes place in the second MCP and specifically in those microchannels whose charges have been depleted detecting particles.

In the following, we assume an isotropic distribution of the incoming flux incident upon the MCP surface and thus we can consider a counting loss rate in a single microchannel before extending the results to the whole MCP. We use the following definitions: τ_{dead} is the detector system dead time assumed to follow each detector count, m is the recorded count rate and n is the true particle incident rate in each microchannel.

In the simple case of steady state emission, and assuming the dead time τ_{dead} is shorter than the average time between event pulses, the dead time losses can be estimated from several models. We also assume that the true events occurring any time in the dead period are lost. In this case, a nonparalyzable model[6] is applicable where the fraction of time a microchannel is dead is given by $m\ \tau_{\mathrm{dead}}$. Therefore, the rate at which true events is lost is simply the product $mn\ \tau_{\mathrm{dead}}$, such that

$$m = \frac{n}{1 + n\tau_{\mathrm{dead}}}. \tag{1}$$

For the MCP detector with a channel packing density ρ (number of MCP channels per unit area), and with the assumption of isotropic distribution of incoming flux, Eq. (1) transforms to

$$M = \frac{N\rho}{\rho + N\tau_{\mathrm{dead}}}, \tag{2}$$

where M is the recorded MCP flux and N is the true flux.

At high counting rates, the model predicts a rapid rise in dead time losses. These losses can become severe, requiring the flux of incoming particles to be limited to values corresponding to a given dead time.

This simple analysis assumes that the detector is exposed to a constant flux of particles. We now consider the case where the source of particles to the MCP is not continuous but consists of a number of short MCP exposures, i.e., the incoming flux is gated. Similar techniques but for slightly different reasons are sometimes used in other devices incorporating electron multipliers, for example, in nuclear physics, e.g., Ref. 7 and Thomson scattering.[8] The measurement cycle for each microchannel then consists of a short exposure time, followed by a subsequent channel recovery period. We assume that the intervals between MCP exposures are longer than the detector channel dead time and that the exposure time, τ_{gate}, is shorter than the dead time. In addition, both τ_{gate} and τ_{dead} are much longer than the response time of a few nanoseconds of the MCP. Under these conditions, each microchannel will have recovered by the start of the next detector exposure. Also as $\tau_{\mathrm{dead}} > \tau_{\mathrm{gate}}$, only one count per microchannel can be detected, irrespective of how many events succeeding the first occur during the exposure gate time.

Since there can be, at most, a single count per microchannel, the probability of an observed count per exposure is given by $m\tau_{\mathrm{gate}}$. The average number of true events per exposure gate of a duration τ_{gate} is by definition equal $\overline{\eta} = n\tau_{\mathrm{gate}}$. We can apply Poisson statistics to predict the probability that at least one true event occurs in a given microchannel during the exposure (gate) time

$$\boldsymbol{\Psi} = 1 - e^{-\overline{\eta}} = 1 - e^{-n\tau_{gate}}. \tag{3}$$

Since only one count can be recorded, the above expression is also the probability of recording a count during τ_{gate}. Equating the two expressions for this probability, we obtain

$$m = \frac{1}{\tau_{\mathrm{gate}}}(1 - e^{-n\tau_{\mathrm{gate}}}). \tag{4}$$

Similarly to the steady state case, this equation can be extended to a MCP giving an expressions for flux

$$M = \frac{\rho}{\tau_{\mathrm{gate}}}(1 - e^{-N/\rho\ \tau_{\mathrm{gate}}}). \tag{5}$$

The main benefit of the gating technique, compared with the constant particle source, is that dead time losses can be greatly reduced by decreasing the duration of the detector exposure. In the limit of $\tau_{\mathrm{gate}} \to 0$, we would expect $M \Rightarrow N$, i.e.,

$$\lim_{\tau_{\mathrm{gate}} \to 0} M = \lim_{\tau_{\mathrm{gate}} \to 0} \left[\frac{\rho}{\tau_{\mathrm{gate}}} (1 - e^{-N/\rho\ \tau_{\mathrm{gate}}}) \right] = N. \qquad (6)$$

In many experimental circumstances, the temporary losses of information between exposure pulses are well compensated by obtaining measurements at much higher counting rates. In addition, neither the duration of the dead time nor its detailed behavior has any influence on the counting losses. Since no more than a single count per channel can be recorded in a gate time, the maximum observable flux is $\rho/\tau_{\mathrm{gate}}$ in contrast to $\rho/\tau_{\mathrm{dead}}$ in the steady state case. Because of the similarity of these results, τ_{gate} can be viewed as the effective dead time of the MCP detector operated in the gated mode and can be much smaller then the detector dead time.

In the chevron MCP detector, the last MCP is responsible for the dead time effects. So in this case, the effective density of MCP channels is downgraded by the additional factor of $n_0(\rho_{\mathrm{eff}} \approx \rho/n_0)$.

A continuous presence of the background radiation affects the available number of the MCP channels throughout both the MCP exposures and the "off" periods. For constant background radiation, the effective channel density ρ_{eff}, available during the detector exposure time, is approximated by $\rho_{\mathrm{eff}} \approx \rho - M_{\mathrm{back}}\tau_{\mathrm{gate}}$, where M_{back} is the recorded background radiation flux.

III. APPLICATION OF THE METHOD

We now apply the analysis to the situation of interest here, where a detector is used to monitor a high intensity neutral particle flux in the presence of a background of a high neutron flux and x rays. Simply collimating the particle flux does not affect the highly penetrative background radiation. It also has a number of disadvantages such as a decrease of the useful statistics and lower signal/background ratio of the measurements. We have therefore found that gating of the MCP greatly extends its useful operational space. The conventional way to gate the detector is via the bias voltage. Alternatively, the source flux can be gated which offers additional benefits such as faster response and more effective background subtraction. Flux gating can be achieved by different means. The application of one of these techniques to our experimental setup is presented in the next chapter. The analytical model described above is used in interpreting results and in estimating MCP dead time losses comparing steady state with gated modes of operation.

An example illustrating potential benefits of the gating mode is shown in Fig. 1. The MCP detector, with an effective channel density of $\rho_{\mathrm{eff}} \sim 3 \times 10^4$ cm^{-2} and dead time of $\tau_{\mathrm{dead}} \sim 8 \times 10^{-3}$ s, is subjected to $\sim 10^7$ cm^{-2} s^{-1} particle flux. In addition, there is a $\sim 5 \times 10^5$ cm^{-2} s^{-1} background flux of neutrons x rays giving an intrinsic noise level of just 5%. In order to avoid dead time losses the steady state true count rate of a MCP should not exceed $\sim 10^6$ cm^{-2} s^{-1}. Since the background rate cannot be adjusted, the primary flux needs to be restricted to $\sim 5 \times 10^5$ cm^{-2} s^{-1} resulting in signal/background ratio of 100%, 20 times less than that theoretically available from the experimental conditions.

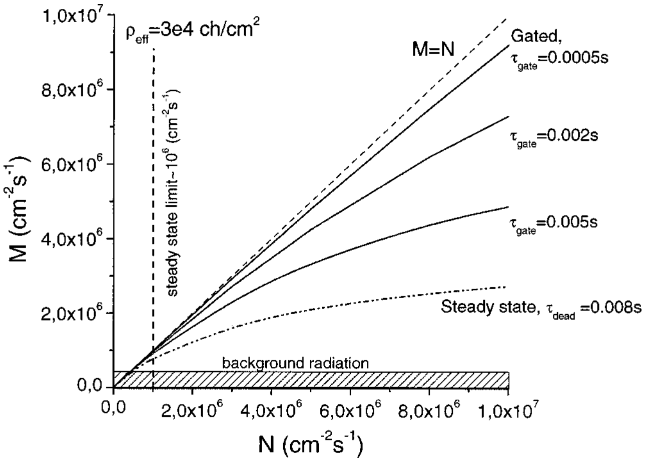

FIG. 1. Estimates of the recorded count rate for the exposures of duration 5, 2, and 0.5 ms. The steady state curve for dead time τ_{dead}=8 ms is also shown together with a typical level of the neutron background rate.

The recorded count rate in the case of steady state MCP irradiation and a dead time $\tau_{\mathrm{dead}} \sim 8$ ms together with a typical level of the neutron background rate and MCP steady state operational limit are shown in Fig. 1. In the case of a gated MCP, the dead time losses can be all but eliminated by reducing the exposure time. Estimates of the recorded count rate for the exposures of duration 5, 2, and 0.5 ms are also shown in Fig. 1. Using the MCP gating technique and cycling a relatively short detector exposure to the original high intensity, the dead time losses are minimized and the original signal/background ratio of ~ 20 is restored.

A simple universal curve estimating the relationship between the true rate of events N and the recorded rate M is shown in Fig. 2. When $M\tau_{\mathrm{gate}}/\rho_{\mathrm{eff}} \sim 1$, essentially all available MCP channels have been depleted of charge, imposing a limitation on gate exposure time. For a given event rate N,

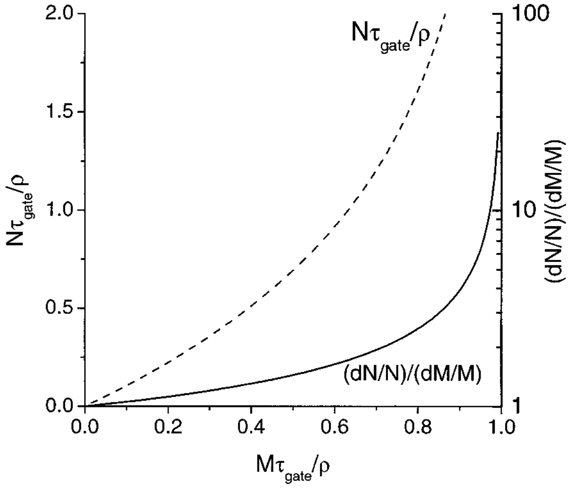

FIG. 2. Normalized plots relating true and recorded rates N and M, respectively. Here ρ_{eff} is the effective number of available MCP channels and τ_{gate} is the detector exposure time. Also plotted is the factor relating the associated error in N and M.

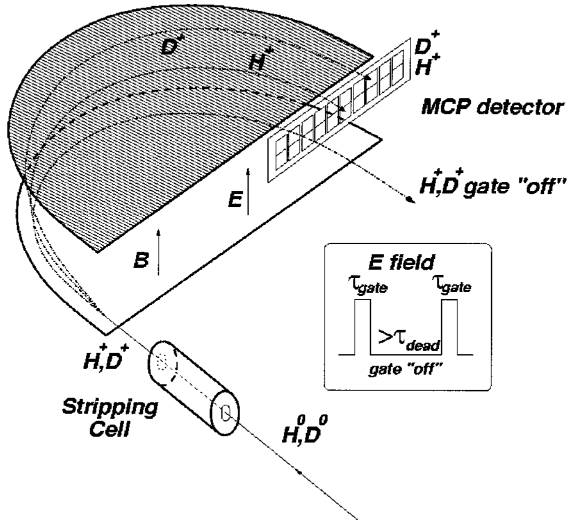

FIG. 3. Schematic of the $E\|B$ NPA apparatus. When switching off the electric field the D^+ and H^+ ions miss the MCP (gate off).

and a MCP channel density ρ, the choice of duration for the exposure time is normally a compromise between available statistics and acceptable dead time losses.

The corresponding fractional errors dN/N can also be calculated by a differentiation of Eq. (5) and expressed as a function of dimensionless ratio $M\tau_{\text{gate}}/\rho_{\text{eff}}$

$$\frac{dN}{N} = \frac{dM}{M}\left|\frac{M\tau_{\text{gate}}/\rho_{\text{eff}}}{\ln(1-M\tau_{\text{gate}}/\rho_{\text{eff}})(1-M\tau_{\text{gate}}/\rho_{\text{eff}})}\right|. \tag{7}$$

The resulting fractional error curve is shown in Fig. 2, demonstrating a rapid error accumulation with increased ratio of $M\tau_{\text{gate}}/\rho_{\text{eff}}$.

A. Experimental apparatus

We show experimental results from both the gated and nongated MCP detector used in the neutral particle analyzer (NPA) employed on the Mega-Amp Spherical Tokamak (MAST) experiment.[9] Two co-injected deuterium neutral beam injectors (NBI) are used to heat the plasma, each delivering up to 2.5 MW of 40–70 keV neutral hydrogen beams. During deuterium beams to deuterium plasma operation (D-D) on MAST, relatively high levels ($\sim 4\times 10^{13}$ s^{-1}) of 2.45 MeV neutron and neutron-induced gamma ray fluxes are produced affecting the neutral particle analyzer. This 78 channel $E\|B$ dual mass NPA diagnostic instrument[10] measures charge-exchanged neutral particle flux emitted by the plasma and is used to study the ion heating and the energy distribution of the thermal and fast ions $[0.5 < \mathrm{A(Amu)}E(\mathrm{keV}) < 600]$. In the NPA, the charge-exchanged neutrals from the plasma are ionized in the stripping cell and are then dispersed according to their mass and energy in the parallel electric and magnetic fields produced by a D-shaped magnet and electrostatic deflection systems as shown in Fig. 3.

The NPA detector is based on three large area double MCP chevrons, mounted in tandem and fabricated by Galileo Electro-Optics Corp.[10] The 4.6×13 cm plates are cut with a 8° bias angle with respect to a bore of 25-μm-diameter and 32-μm-center-to-center spacing. The multi anode collector is comprised of 50 independent anodes of area 0.4 cm^2 each (0.4×1 cm) which are arranged in two 25 anode rows. The MCP chevron has a gain of $\sim 5\times 10^6$ electrons/pulse and is operated in pulse counting or saturated mode. The signal processing electronics for each anode consists of a charge sensitive impedance matching buffer and a 100× gain and a 1 MHz bandpass preamplifier/discriminator (Le Croy MVL 100). Monitoring of the neutron and x-ray induced noise background is facilitated by using "masked" areas of MCP, insensitive to the bombardment by charged particles.[10] Neutron detection efficiencies of 1.7×10^{-3} counts/neutron for 2.45 MeV D-D neutrons have been detected.[10]

We used the NPA electrostatic deflection system (see Fig. 3) to control the MCP exposure to the flux of charged ions, effectively gating the MCP. This approach gives fast on/off times due to the quick time response of the electrostatic system and allows effective neutron noise subtraction for each channel using the data recorded during MCP "rest" time (between gated pulses), when the detector is exposed only to the relatively low intensity background flux.

A fast push–pull high voltage transistor switch, fabricated by Behlke Electronic, controls the voltage gate on the electrostatic deflection. The switch consists of two identical solid-state metal-oxide-semiconductor field effect transistor (MOSFET) switches controlled by a TTL input signal, and each alternately operational with response time of ~120 ns (~100 ns turn-on delay and ~9 ns turn on/off rise time).

B. Experimental results

To avoid dead time effects, the average flux in the first plate of the MCP chevron must not exceed a critical threshold. A multichannel pulse height analyzer has been used to estimate this limit on the MCP performance and to study the PHD of the detector using mono-energetic Li^+, and K^+ ion beams and continuous exposure of the MCP to the incoming flux of ions. The rate of 5–8 10^4 Hz defines the upper limit before gain deterioration, accompanied by the distortion of the PHD, and occurs provided the beam is defocused. We also found that a MCP rest time of 3–8 ms is sufficient for full detector recovery, consistent with theoretical predictions and experimental results of others.[1,2,5] A number of complications caused by dead time losses arise during the high intensity flux measurements. Results from one of the MAST NPA detector channels are shown in Fig. 4. In this example, the incoming flux was collimated and the detector count rate stayed below a safe limit of 5×10^4 Hz. The results show relatively high statistical variations with neutron noise exceeding 4×10^4 Hz with an unacceptably low signal/noise ratio of ~1 in the latter part of the discharge during the NBI heating.

The proposed gating technique is assessed in a set of almost identical NBI heated MAST discharges. In these discharges two deuterium beams were injected with a total power of ~1.6 MW boosting both the neutron rate and the NPA statistics as the NPA views across both neutral beams which increase the charge exchange rate.

The duration of the MCP exposure has been optimized for maximum statistics while avoiding significant dead time saturation losses. The results of this investigation are shown

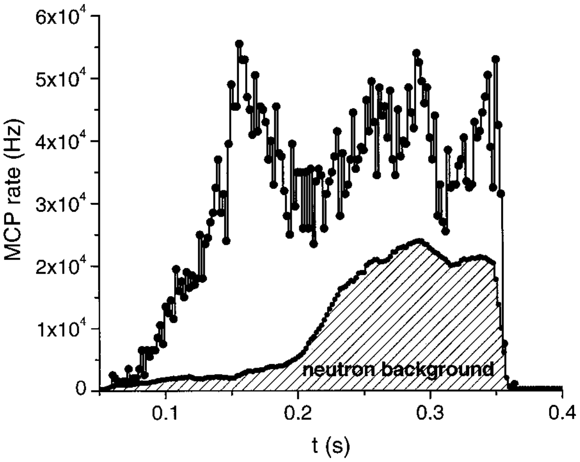

FIG. 4. Count rate and neutron noise for one of the MCP channels. The incoming flux has been collimated to be below $\sim 5 \times 10^4$ Hz.

in Fig. 5. Here the count rate measured during exposures of various duration is plotted against the MCP exposure time (gate duration). Calculations from the analytical model are also shown for two cases, (i) assuming no background and (ii) using a constant neutron background rate of 2×10^4 Hz throughout the plasma discharge. A better agreement between the analytical model and the experimental measurements is achieved when the background radiation is taken into account. A slight variation between model and experimental data for MCP exposures longer than $\sim 10^{-3}$ s probably arises from some MCP channels recovering in the gate period where the simple analytical model is not fully applicable. Variations in the flux of incoming plasma particles are considered to be negligible as all the data have been taken during almost identical plasma discharges. Results suggest acceptable dead time losses for the MCP exposures of up to 5×10^{-4} s followed by the exponential decay for the exposures of longer duration. The large error bars for the shorter gate periods are due to the low count statistics and impose a practical lower limit on the gate duration.

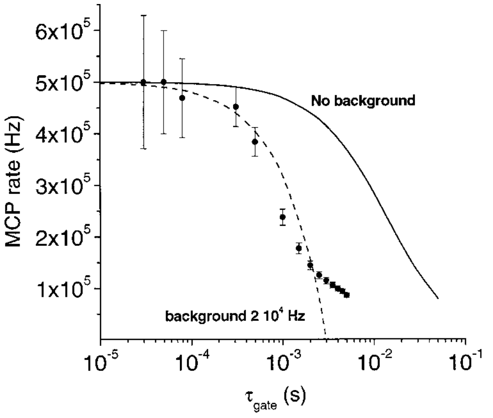

FIG. 5. Count rates obtained using a range of MCP exposures. The results of the analytical model are also shown for two cases, in the absence and presence of background (2×10^4 Hz count rate).

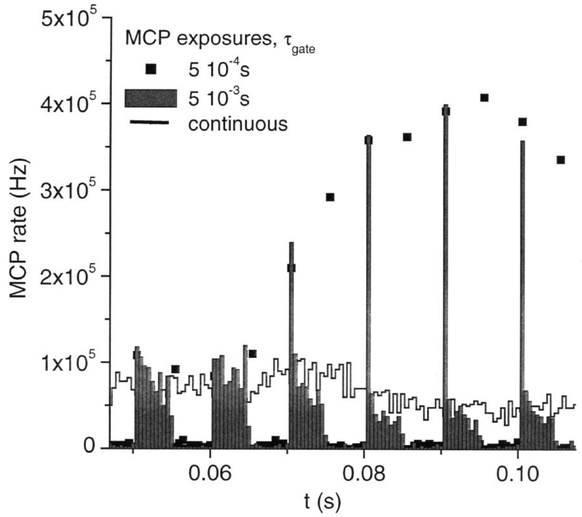

FIG. 6. Observed count rates for the MCP detector operated in continuous exposure and gated using 5×10^{-4} and 5×10^{-3} s exposures with 5×10^{-3} and 1×10^{-2} s cycle times, respectively.

Measurements are consistent with calculations as shown in Fig. 6, where the detector count rates for a MCP in three different operational modes are compared. In the first discharge the MCP detector was conventionally operated, i.e., open to continuous exposure of the high intensity particle flux (solid line). In two subsequent discharges the detector exposure was gated using the NPA electrostatic deflection system. Gated MCP exposures of 5×10^{-3} s (histogram) and 5×10^{-4} s (squares) were used followed by 5×10^{-3} s MCP rest period in both cases, where the incoming neutral particle flux converted to ions was deflected away from the MCP. A 2 kHz digitization rate was used making the 5×10^{-4} s MCP gating practically identical to the first time slice in 5×10^{-3} s MCP exposure gate. All three cases presented in Fig. 6 exhibit a very similar behavior for the low density, low count part at the beginning of the discharge. As expected from the pulse height distribution analysis, at this low count rate a conventionally run MCP shows very similar rate values to both gated periods of 5×10^{-4} and 5×10^{-3} s. The rise in the plasma density and plasma current is accompanied by an expected large increase in counting rates for the pulsed run detectors but saturates the conventionally run MCP due to dead time losses, thus demonstrating the clear advantages of the MCP gating technique. During exposure to the higher intensity fluxes in a latter part of the discharge, two gated cases also behave differently. At the start of a relatively long 5×10^{-3} s MCP exposure the recorded count rate is similar to the high values obtained during the much shorter 5×10^{-4} s exposures, but in line with results presented in Fig. 5, it was followed by an exponential decay towards the saturated values of the conventionally run MCP.

The benefits of the presented technique are naturally limited by applications where the MCP detector is saturated by a high intensity flux of particles in the presence of highly penetrative background radiation such as neutrons and x rays. These conditions are common in magnetic fusion research and are typical for the NPA detector during the high power NBI injection in MAST. An example from MAST is presented in Fig. 7. Here the count rate in one of the NBI heated discharges is shown together with the neutron noise for one of the NPA channels. In this discharge the MCP exposure

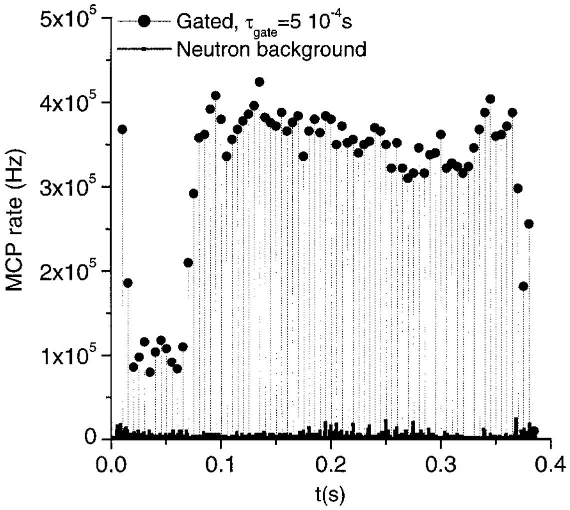

FIG. 7. Count rate of the MCP detector using 5×10^{-4} s exposures at a cycle time of 5×10^{-3} s. The results are shown together with neutron background noise and experimental conditions similar to discharge presented in Fig. 3.

was limited to 5×10^{-4} s followed by 5×10^{-3} s detector rest time. The MAST plasma conditions were very similar to those presented in Fig. 4 where the incoming flux of particles was collimated to avoid MCP saturation effects. MCP saturation is avoided by gating the incident flux and the signal to noise ratio increase by about an order of magnitude to acceptable values of ~30. The gating technique described here, where the MCP exposure is controlled by gating of the NPA electrostatic deflection system, rather then the detector bias voltage, provides an effective and accurate method for background subtraction. This is important for future MAST operations where the neutron yield is expected to be an order of magnitude higher.

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[1] J. L. Wiza, Nucl. Instrum. Methods **162**, 587 (1979).
[2] M. Hellsing, L. Karlsson, H. O. Andren, and H. Norden, J. Phys. E **18**, 920 (1985).
[3] H. C. Straub, M. A. Mangan, B. G. Lindsay, K. A. Smith, and R. F. Stebbings, Rev. Sci. Instrum. **70**, 4238 (1999).
[4] J. L. Wisa, P. R. Henkel, and R. L. Roy, Rev. Sci. Instrum. **48**, 1217 (1977).
[5] A. J. Peurrung and J. Fajans, Rev. Sci. Instrum. **64**, 52 (1993).
[6] G. F. Knoll, *Radiation Detection and Measurement*, 3rd ed. (Wiley, New York, 2000), Chap. 4 p. 121.
[7] U. Farinelli and R. Malvano, Rev. Sci. Instrum. **29**, 699 (1958).
[8] N. J. Peacock, D. C. Robinson, M. J. Forrest, P. D. Wilckock, and V. V. Sannikov, Nature (London) **224**, 448 (1969).
[9] A. C. Darke *et al.*, Proceedings of the 18th Symposium on Fusion Technology, Karlsrhue, Germany, 1994, p. 799 (unpublished).
[10] S. S. Medley and A. L. Roquemore, Rev. Sci. Instrum. **69**, 2651 (1998).