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A TEST OF PLANAR SPARK COUNTERS AT THE PEP STORAGE RING*

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Abstract

A test of planar spark counters (PSC's) at the PEP electron - positron storage ring showed the following. PSC's can be used under harsh experimental conditions without long term degradation of resolution. On line time-of-flight resolutions were below 200 psec, coordinate resolutions better than 4 mm, both limited to these values by the resistivity of the semi-conducting glass and the electronics used. The best single counter time resolution under realistic conditions at the storage ring was 76 psec. Pulse height was a good indicator of the number of particles striking a counter. Subsequent measurements using cosmic rays gave a single counter time resolution of 50 psec.

Introduction

Planar spark counters (PSC's)[1] are particle detecting devices designed mainly for very good time resolution. The basic principles of their operation can briefly be described as follows.

Two planar electrodes are mounted parallel with a gap width of typically 100 μm to 1 mm, which has to be uniform to a few percent. High voltage, V_{gap}, is applied to the gas gap, corresponding to fields of order $2 \cdot 10^5$ Volts/cm. The anode is made out of semi-conducting glass[2] with a volume resistance in the range 10^9 to 10^{10} Ω-cm. Gas under high pressure (10 atmospheres), comprised of argon or neon plus organic quenchers, flows through the gap. Ionizing particles which traverse the gap produce a localized discharge, between the electrodes. The high resistivity of the anode limits the discharge energy, while the ultraviolet absorptivity of the gas mixture stops the spark from spreading by photoionization. Therefore a spark desensitizes a region a few millimeters in size, depending on gap width, gap voltage and gas pressure. The recovery time is of the order of milliseconds, and depends on the dielectric constant and resistivity of the glass.

Conductive strips are affixed to the back of the anode and form a strip transmission line together with the cathode. The signals produced by the spark are typically of the order of Volts (into a load of 50 Ω), with a rise time less than 1 nsec and a length of some 5 nsec. The information from each hit strip thus consists of two times, t_+ and t_-, (one from each end of the strip at +y and -y), and one pulse height. Due to the strip line readout there is little variation in pulse height or time resolution over the active area of the counter. The mean time,

$t = (t_+ + t_-)/2$, is independent of the location of the spark along the strip, except for edge effects. The difference time is proportional to the location, y, of the spark along the strip: $y = v \cdot (t_- - t_+)/2$, where v is the signal velocity in the strip line, ≈15 cm/nsec.

The best time resolution measured[3] for a PSC is 24 psec, exceeding that of any other particle detecting device we know of. The spatial resolution[3] (≈200 μm) can also be quite good and is competitive with that of drift chambers. Most of the past experience in operating planar spark counters comes from laboratory tests using cosmic rays,[4] and from one experiment measuring the pion form factor at the VEP2M storage ring in Novosibirsk.[5] The purpose of the present test was to gain more experience using PSC's in a realistic experimental environment and to encounter, and find ways to overcome, the practical problems of this type of particle detector.

In the following we describe the counters themselves, including details of construction and operation, the setup of the experiment and the results of our measurements for both cosmic ray and storage ring operation.

<u>Counter components and construction</u>

Both electrode surfaces were prepared by repeated polishing with cerium oxide, using filtered deionized water on a laminar airflow clean table. We monitored the cleanliness of the electrode surfaces by observing how the final rinse water sheeted off the surface. The interference patterns in this very thin water wedge reveal imperfections or dirt of a size comparable to the wavelength of visible light. We required that no large points were present and that the water wedge did not tear, which would be indicative of the presence of oil. Finally the counter assembly was placed in an aluminum pressure vessel which could withstand pressures of over 12 atmospheres.

An exploded view of the PSC used in this experiment is shown in Fig. 1. The width of the spark gap, 185 µm, was set by indium plated brass washers between the electrodes. The cathode consisted of a 3 µm thick copper layer, vacuum deposited onto a substrate of float-cast window glass. A chromium layer of 10 nm thickness underlay the copper and provided for better adherence of the copper to the glass. The anode was made of a 9 x 9 cm^2 piece of semi-conducting glass, ground flat and polished.[6] On the back surface of the anode four copper strip lines were also vacuum deposited on top of chromium. The gap between strips was about 1 mm. The volume resistivity of the semi-conducting glass was $3 \cdot 10^{10}$ Ω-cm in one counter (PSC 1) and $6 \cdot 10^{10}$ Ω-cm in the other (PSC 2).

The anode was grounded via the strip lines and the cathode was connected to a high voltage power supply, producing a potential across the gap. The cathode extended beyond the anode at both ends to establish capacitive coupling to the ground of the strip lines. A brass block covered with 100 µm thick mylar tape served as a mount for the signal cables and as the ground coupler with a DC capacitance of ≈180 pF.

The gas used had two components. Some 70% was a noble gas (argon or neon) and the balance was a quencher, a mixture of organic gases, namely 16% isobutane, 3.3% ethylene, 3.3% 1,3 butadiene, 7.4% hydrogen and 1.5% diethyl ether.[7] The gas mixture flowed through the spark gap with a linear velocity of about 10 cm/sec and was recirculated by a metal bellows pump. A 0.3 µm filter just in front of the counter inlet was the only provision for keeping the gas clean.

Initial operation (burn-in)

Using a 250 µC ^{60}Co gamma source, we found the threshold voltage for sparks at $V_{gap} \approx 3$ kV. At threshold an increase in voltage of 1% is sufficient to double the source-induced counting rate. Very few signals ($<5\cdot10^{-4}$ Hz/cm^2) were observed for voltages below threshold.

Over a period of about one week the operating voltage was gradually raised. During this time the counters were exposed to the ^{60}Co source causing them to accumulate about 10^6 sparks/cm^2. The counting rates with source (2 Hz/cm^2) and without (no-source) were monitored during the burn-in period and the voltage was kept below that which gave a no-source counting rate in excess of .05 Hz/cm^2. One of the effects of this initial operation is to coat the electrodes with a film of polymerized gas, which, we believe, changes the work function of the electrode and helps localize the discharge.[3]

After the burn-in period the cosmic background (no-source) counting rate of the PSC's exhibited a long plateau in high voltage extending to about twice the threshold voltage (Fig. 2). At the top end of the plateau the counting rate increased rapidly with applied voltage. Observation of the pulses with an oscilloscope revealed multiple pulsing, with after-pulses separated from the first pulse by 20 to 300 nsec. It has been our experience that running counters in this voltage region leads to a steadily rising counting rate and eventually to a self-sustaining discharge in the spark gap.

Experimental setup

Fig. 3 shows the counters mounted on the front face of the luminosity monitor in the DELCO experiment at Interaction Region (IR)-8 of the PEP storage ring. The strip lines in the counters ran vertically, i.e. parallel to the y axis. The location of the counters at a small angle from the beam direction ensured that Bhabha scattering would be observed with a good counting rate. The two shower counters, L 1 and L 2, and their respective face counters, F 1 and F 2, provided the Bhabha trigger: L 1 · F 1 · L 2 · F 2 · X (Fig. 3). The beam crossing signal, X, defined the trigger timing and was derived from a capacitive pickup to one side of the interaction point. The five-fold coincidence rate was about 1 Hz, while the rates for the individual counters F 1, F 2, L 1, and L 2 were typically several kHz. This has to be compared with a beam crossing rate of 409 kHz. The overlap of the PSC and the shower counter amounted to 29% of the area of the shower counter and 75% of the area of the PSC. Ten percent of the Bhabha triggers had hits in both PSC's.

We note that the flux of particles entering the luminosity monitor is the highest of any counter in the DELCO experiment and rate dependent effects and limitations will be at their worst here. The PSC's experienced singles counting rates of 1-5 kHz, depending chiefly on stored beam currents and beam steering. The highest rates occured when the storage ring had current in excess of 40 mA (positrons plus electrons) and were the highest ever in the life of the counters, exceeding by over one order of magnitude those used during burn-in.

The fast electronics, high voltage supplies, and the gas recirculation station were located outside the radiation shielding wall of the IR. Therefore 60 m signal cables and gas lines were necessary to connect the counters. The signal cables from the PSC's were foam dielectric RG-8 cables and the gas connections were made with 1/4 inch (6 mm) diameter copper tubing. For the cosmic ray part of the experiment, the counters were mounted one atop the other in the IR, still with the same signal cables and gas connections. The trigger in this case was simply a coincidence between the two counters.

Data acquisition and analysis

The electronics used in this experiment were commercially available NIM and CAMAC units.[8] Each trigger generated a computer interrupt, a start signal for the time-to-digital converters (TDC's) and a gate for the analog-to-digital converters (ADC's).

Both ends of each strip line in the PSC's (four per counter) were connected to the inputs of discriminators with 30 mV thresholds. The pulses from the discriminators were used as the stop signals for the TDC's (two per strip). A discriminator output from one end of each strip also entered a scaler (one per strip). Before the discriminator, 20% of the signal from one end of each strip was diverted to an ADC unit (one channel per strip) by a resistive divider. The size of the pulses from the PSC's ranged from a few hundred mV to two Volts depending on the high voltage and the counting rate conditions in the counter. Fig. 4 shows a scatter plot of the pulse height from L 1 versus that from L 2. Bhabha events appear quite clearly as large correlated pulse heights in the shower counters.

In the analysis of the PSC's we select the strip with the largest pulse height to be the hit strip of the counter. The mean times, t_1 and t_2, and spark positions, y_1 and y_2, are those of the hit strip for PSC 1 and PSC 2, respectively. The pulse heights for the counters, q_1 and q_2, are the sums of pulse heights of all strips in PSC 1 and PSC 2, respectively. In both cosmic ray and storage ring data the difference of mean times is TOF = $t_1 - t_2$. In the case of storage ring data this represents the difference of flight times for the Bhabha electron and positron from their point of interaction to the spark counters.

For cosmic ray data TOF is the time of flight as shown in Fig. 5. The time resolution is obtained by fitting with a Gaussian curve. The width of the observed distribution is due to the combined resolutions of the two counters, hence single counter time resolution $\delta = \sigma_{TOF}/\sqrt{2}$. (We use δ to refer to a calculated resolution, while σ refers to a fitted Gaussian width). This assumes that the characteristics of the two counters are the same, which is true for data taken at low counting rate. A correction for pulse height slewing is made to the mean time amounting to at most a few percent reduction in σ_{TOF}.

Cosmic ray results

We took cosmic ray data in order to investigate the effects of gap voltage and counting rate on time resolution and pulse height. Fig. 6 presents the average pulse height, $\langle q \rangle$, and single counter time resolution, δ, as a function of V_{gap} for neon and argon gas mixtures: better time resolution and larger pulse height are obtained at higher gap voltage. We note that although one needs a higher V_{gap} for argon than for neon, the best time resolution achieved is approximately the same for both.

We also investigated high counting rate effects on the performance of the PSC's by placing a 250 μC ^{60}Co source close to the counters. We observed changes in both pulse height and time resolution with counting rate. In Fig. 7 the average pulse height, ⟨q⟩, and the time resolution, δ, of both counters is shown versus counting rate for a neon gas mixture with V_{gap} = 5.5 kV and for an argon gas mixture with V_{gap} = 7.0 kV. We observe a fall-off in average pulse height and a deterioration of time resolution with increasing counting rate which we ascribe to an effective lowering of the voltage across the spark gap. From Fig. 7 we conclude that PSC 2, with the more highly resistive glass, shows a larger counting rate effect than PSC 1 because its recovery time is longer.

This can be understood as follows: each spark discharges an area of about 0.25 cm^2. The recovery time for the affected area is proportional to the product of the volume resistance and the dielectric constant of the semi-conducting glass. For PSC 1 and PSC 2 the recovery times are 40 msec and 80 msec, respectively. The mean time between sparks within an area of 0.25 cm^2 at 1 kHz is about 320 msec corresponding to 8 and 4 recovery time constants for PSC 1 and PSC 2.

Multiplicity resolution

Fig. 8 shows pulse height distributions for PSC 1 and PSC 2 for Bhabha triggers in which both counters fired. The pulse height distribution for the luminosity counters L 1 and L 2 for these same events appears in Fig. 9a. In both PSC's we observed many events with pulse heights much greater than what a single spark would give. We interpret these events as Bhabha events which are originally outside the acceptence of the luminosity monitor, but which grazed the lead masks in front of the luminosity monitor thereby producing a spray of electrons into PSC, F, and L counters, and which did not deposit the full energy in the shower counters. In Fig. 9b we show the luminosity counter pulse heights for events with PSC pulse heights less than the cuts shown in Fig. 8, that is, consistent with a single spark. All but one of the spray events are eliminated.

Time resolution

The time distributions for PSC 1 and PSC 2 for Bhabha events in which both PSC's were hit are shown in Fig. 10a and 10b. The shaded areas are discussed later. The counters were operated at a gap voltage of 7 kV using the argon gas mixture. The singles rate into each PSC was ≃1.2 kHz. In Fig. 10c we show the distribution of TOF for these same events.

Using σ_1, σ_2 and σ_{TOF} we may infer the (intrinsic) single counter time resolutions δ_1 and δ_2. We have considered two additional factors: fluctuations in the start pulse for the TDC's due to the electronics, δ_{start}, and fluctuations due to the finite bunch length of the stored beam, σ_{beam}. All fluctuations are assumed to be independent. Since timing fluctuations in the TDC start pulse will effect t_1 and t_2 equally, they will not be present in the TOF distribution.

We use the following formulas to describe the widths of the various time distributions:

$$\sigma^2_{1,2} = \delta^2_{1,2} + \delta^2_{start} + \sigma^2_{beam}$$

and

$$\sigma^2_{TOF} = \delta^2_1 + \delta^2_2 + 2 \cdot \sigma^2_{beam}.$$

We have used the measured rms value of the bunch length,[9] 2 cm, to calculate the bunch length contribution, σ_{beam} = 68 psec. Using the measured values of σ_1 = 138 psec, σ_2 = 187 psec, and σ_{TOF} = 192 psec, we obtain the (intrinsic) single counter time resolutions of δ_1 = 76 psec and δ_2 = 148 psec and electronics fluctuations of δ_{start} = 93 psec.

The large inferred value of the start time jitter, δ_{start}, deserves comment. The contribution from the pick-up button, which we measured, was <10 psec. What we did not measure was the influence of power supply voltage ripple on discriminators. During the experiment we had indeed observed ripple in the power supply of one of these bins perhaps large enough to have been the cause of the large δ_{start} (the trigger electronics and the PSC electronics were in different NIM bins). The lesson to learn is that at the 100 psec level special care is necessary. The difference in intrinsic time resolution for the two PSC's then can be explained by the different resistivities of the semi-conductive glass in the two counters.

Albedo events

Bhabha scattered electrons and positrons which are originally outside, but close to, the acceptance of the PSC's, may still cause hits in either or both of the PSC's. A process which may cause such events is radiation coming back out of the shower counter (albedo). Such albedo events are difficult to eliminate or to correct for in luminosity monitors without tracking. They often constitute the largest error in luminosity measurements in colliding beam experiments.[10] To identify these effects we require that only one PSC register a good hit and that both shower counters, L 1 and L 2, have pulse heights consistent with good Bhabha events. The time distributions for the albedo events are indicated in Figs. 10a and 10b by the shaded areas. These time distributions show a time delay relative to the Bhabha event distributions and are much broader. This is because the albedo particles take a longer and more varied flight path into the PSC than does the incident positron or electron.

Position resolution

The electron and positron from a Bhabha event are collinear except for effects due to the emission of hard photons. Therefore Bhabha scattering can be used to investigate the coordinate resolution of the spark counters. In Fig. 11 we show the distribution of the location along the strip line, $y_{1,2}$, for each particle of a Bhabha event, determined from the difference of the times measured at each end of the hit strip. Events with the innermost strip hit for each counter were selected. Ideal distributions for y_1 and y_2 would be square and extend from -45 mm to +45 mm, the length of the striplines.

In this Figure we also show the distribution of the vertex position $\Delta y = y_1 + y_2$. Contributions to fluctuations in Δy are the bin width of the TDC's (50 psec least-count), δ_{bin}, the aforementioned radiative smearing of the tracks, σ_{rad}, and variations in the transverse position of the scattering vertex, σ_{trans}. Hence

$$\sigma^2_{\Delta y} = \delta^2_{bin} + \sigma^2_{rad} + \sigma^2_{trans}.$$

We suppose σ_{trans} to be neglible. Using a Monte Carlo calculation of Bhabha scattering including radiation[11] we estimate σ_{rad} = 2 mm. Our measured $\sigma_{\Delta y}$ is 3.3 mm. This gives δ_{bin} = 2.6 mm or 60 psec/$\sqrt{12}$, which is consistant with the TDC's bin width of 50 psec (the factor of $\sqrt{12}$ converts from the full width of a rectangular bin to the rms width of a Gaussian distribution).

PSC performance stability

The spark counters were operated for about 150 hours in the presence of stored beams, accumulating about 10^7 sparks/cm^2. The cosmic ray data presented here were collected after exposure in the the storage ring environment. The time resolution of the counters was found to be unchanged and has already been shown in Fig. 5. The high voltage plateau was also not markedly changed. The counters operated stably and reliably throughout the tests.

Conclusions

The results of the storage ring tests show that PSC's can be used in harsh experimental conditions. We consistently achieved on-line timing resolutions better than 200 psec and position resolutions smaller than 4 mm. The PSC's functioned reliably for the duration of the tests and afterwards exhibited no changes in their characteristics.

The best time resolutions under realistic beam conditions were 76 psec for PSC 1 and 148 psec for PSC 2. We conclude that the different time resolutions for these two counters were due to the different resistivities of the semi-conducting glass used. In addition, the measured value of the time resolution seems to be entirely limited by the choice of resistivity and might easily be improved by a factor of 3, as indicated by the cosmic ray results. The spatial resolution of the counters, 2.6 mm, was consistent with the bin width of the TDC's.

Pulse height proved to be a good indicator of the number of particles striking the counter, thus enabling us to get a clean Bhabha sample as demonstrated by the resulting shower counter pulse height distributions. Furthermore, the PSC time distributions for albedo events is different from that of non-albedo events, illustrating the possibility of using such counters to reduce this contribution to systematic uncertainty in luminosity measurements.

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FIGURE CAPTIONS

Fig. 1 An exploded view of a planar spark counter. From top to bottom is shown: the semi-conductive anode with the strip lines and the flat copper cathode. The four signal cables on each side are directly connected to the strip lines when assembled. The aluminum container at the bottom contains signal output connectors, HV feedthru, and gas inlet and outlet. Not shown is the cover to the container.

Fig. 2 Singles counting rate versus V_{gap} for a PSC after burn-in. Threshold occurs at $V_{gap} \simeq 4$ kV, followed by a long, slowly rising plateau. Above ≃6 kV the counting rate rises sharply with applied voltage. Data above 5 kV are cosmic ray (no-source) counting rates. Data below 5 kV are source-induced counting rates, normalized to the cosmic ray rates at the plateau.

Fig. 3 The schematic layout of the counters used in this experiment at IR-8 of the PEP storage ring. L 1 and L 2 are shower counters of lead-scintillator sandwich 16 radiation lengths thick, F 1 and F 2 are scintillation counters defining the aperture of the DELCO luminosity monitor. Longitudinal dimensions of the counters are not to scale. Trigger logic for Bhabha events required a coincidence of shower counters L 1 and L 2, face counters F 1 and F 2, and the beam crossing signal X, which was derived from a capacitive pickup on one side of the interaction point and which defined the trigger timing.

Fig. 4 Shower counter pulse heights q_{L1} versus q_{L2} for Bhabha triggers. The dense spot at the upper right corner are the Bhabha events. The many points with lower pulse height may be either due to Bhabha events which were originally outside the acceptance of the F counters, but which are scattered off the lead masks at 2.5 m from the interaction point, or showers from degraded beam particles which have hit the beam pipe and produce accidental coincidences.

Fig. 5 Distribution of TOF for cosmic ray triggers. Operating conditions were: neon gas mixture at V_{gap} = 6250 V. The solid curve is a Gaussian fit with $\sigma_{TOF}/\sqrt{2}$ = 49±4 psec.

Fig. 6 (a) and (b) average PSC pulse height, $\langle q \rangle$, and (c) and (d) single counter time resolution, δ, for cosmic ray data as a function of spark gap voltage, V_{gap}. Operating conditions were: (a) and (c) neon gas mixture, (b) and (d) argon gas mixture. Higher gap voltage yields simultaneously larger pulse height and better time resolution.

Fig. 7 (a) and (b) average PSC pulse height, $\langle q \rangle$, for cosmic ray data as a function of counting rate, and (c) and (d) single counter time of flight resolution, δ. Operating conditions were: (a) and (c) neon gas mixture at V_{gap} = 5.5 kV, (b) and (d) argon gas mixture at V_{gap} = 7 kV. Higher counting rate results in smaller pulse heights and poorer time resolution due to an effective lowering of the gap voltage.

Fig. 8 Pulse height distributions for (a) PSC 1 and (b) PSC 2 for Bhabha triggers. The cut value to select single hits is shown by the arrow.

Fig. 9 Shower counter pulse heights q_{L1} versus q_{L2} for the events of Fig. 8: (a) for a Bhabha trigger without a cut on the PSC pulseheights, and (b) for events consistent with a single hit only in each PSC as indicated in Fig. 8, i.e. $q_1 < 250$ and $q_2 < 200$.

Fig. 10 PSC single counter time distributions, (a) t_1 and (b) t_2, for Bhabha events (open histogram) and the albedo events (shaded histogram). The solid curves are Gaussian fits with (a) $\sigma_1 = 138 \pm 2$ psec and (b) $\sigma_2 = 187 \pm 3$ psec. (c) Distribution of TOF for Bhabha events. Curve is a Gaussian fit with $\sigma_{TOF} = 192 \pm 3$ psec.

Fig. 11 (a) Distribution of PSC hit position y_1 versus y_2 for events with innermost strip hit, with projections onto the y_1 and y_2 axes. In an idealized case the projections would be square distributions with a width of 90 mm, the length of the strip lines. (b) Distribution of $\Delta y = y_1 + y_2$ for the same events. The solid curve is a Gaussian fit with $\sigma_{\Delta y} = 3.3$ mm.

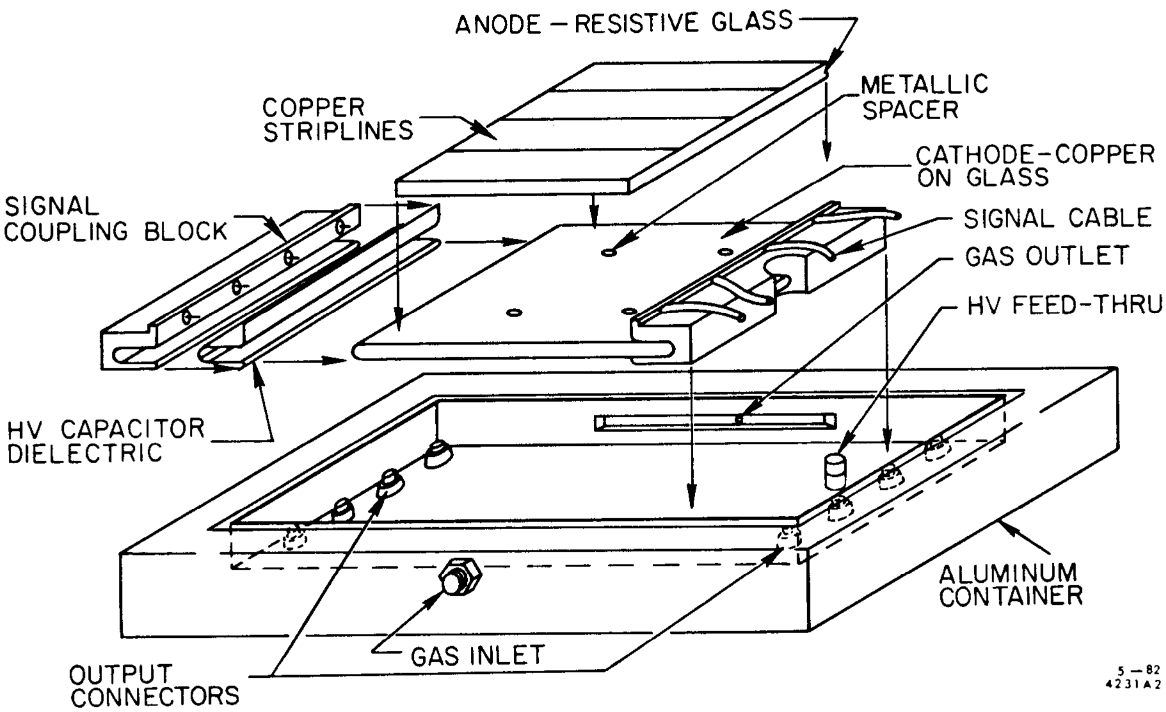
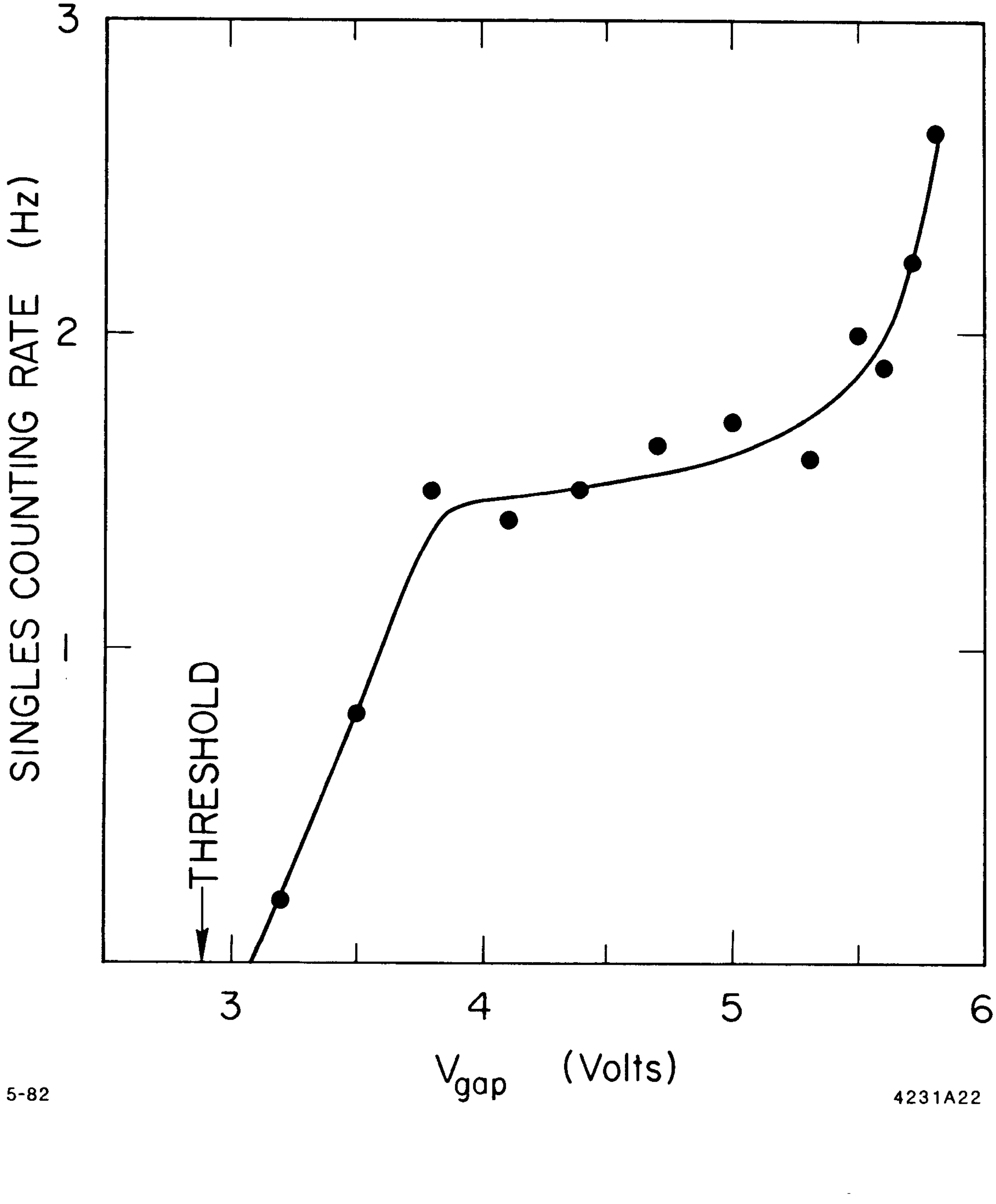

ANODE – RESISTIVE GLASS
COPPER
STRIPLINES
METALLIC
SPACER
CATHODE-COPPER
ON GLASS
SIGNAL
COUPLING BLOCK
SIGNAL CABLE
GAS OUTLET
HV FEED-THRU
HV CAPACITOR
DIELECTRIC
ALUMINUM
CONTAINER
GAS INLET
OUTPUT
CONNECTORS
5 – 82
4231A2

Fig. 1



SINGLES COUNTING RATE (Hz)
3
2
1
THRESHOLD
3
4
5
6
V_{gap} (Volts)
5-82
4231A22

Fig. 2

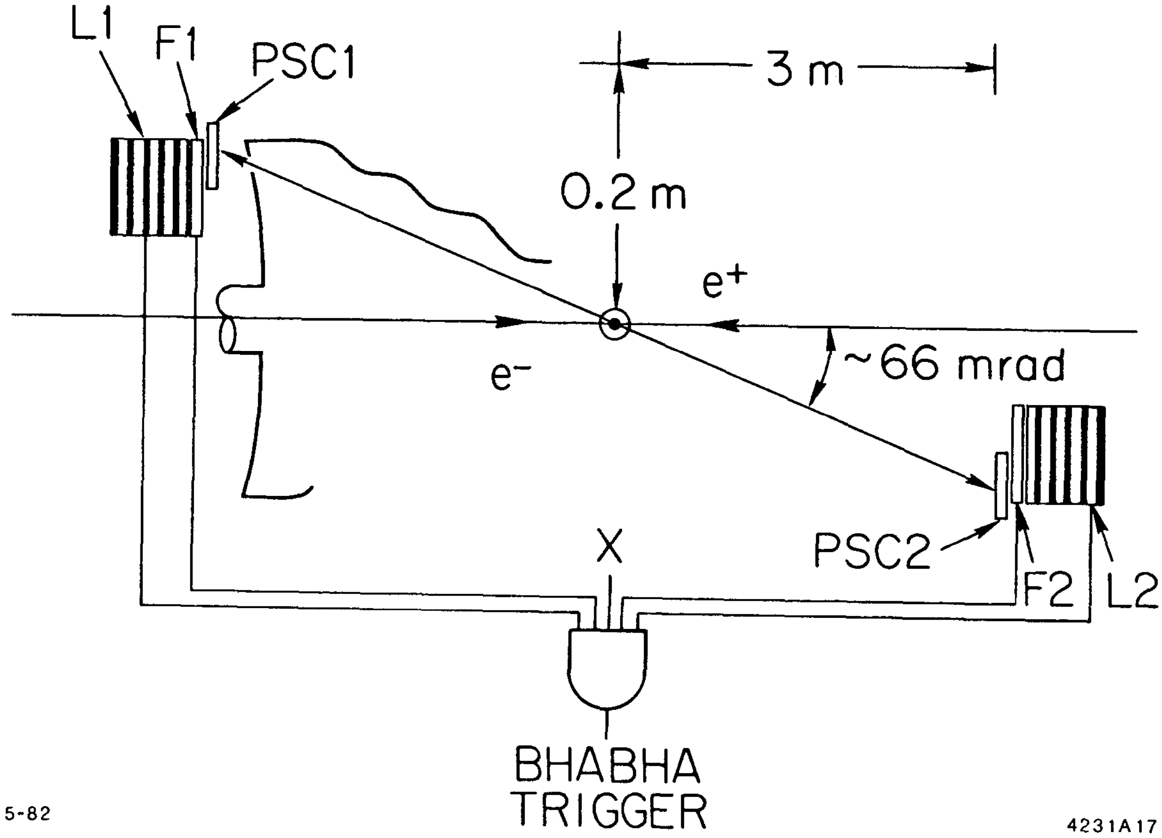
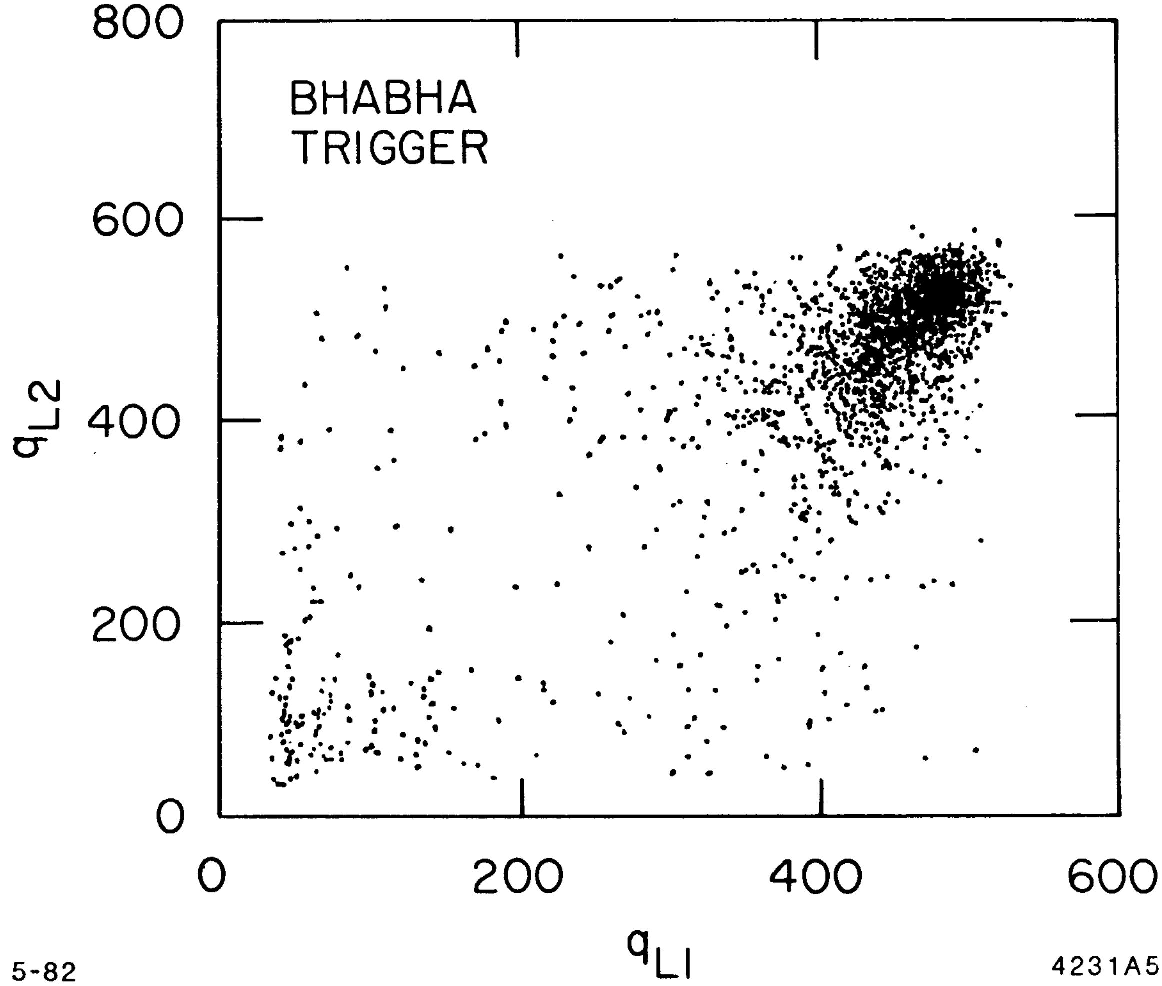

L1
F1
PSC1
3 m
0.2 m
e+
e−
~66 mrad
PSC2
F2
L2
X
BHABHA
TRIGGER
5-82
4231A17

Fig. 3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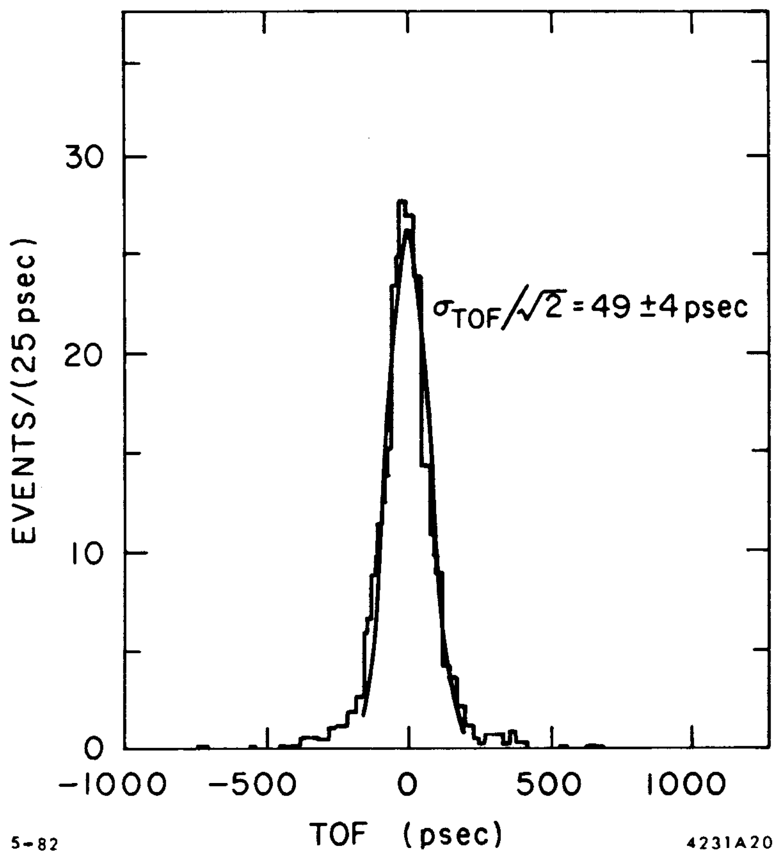
200
0
0
200
400
600
q_{L2}
q_{L1}
5-82
4231A5

Fig. 4



EVENTS/(25 psec)
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20
10
0
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−500
0
500
1000
TOF (psec)
5-82
4231A20

Fig. 5

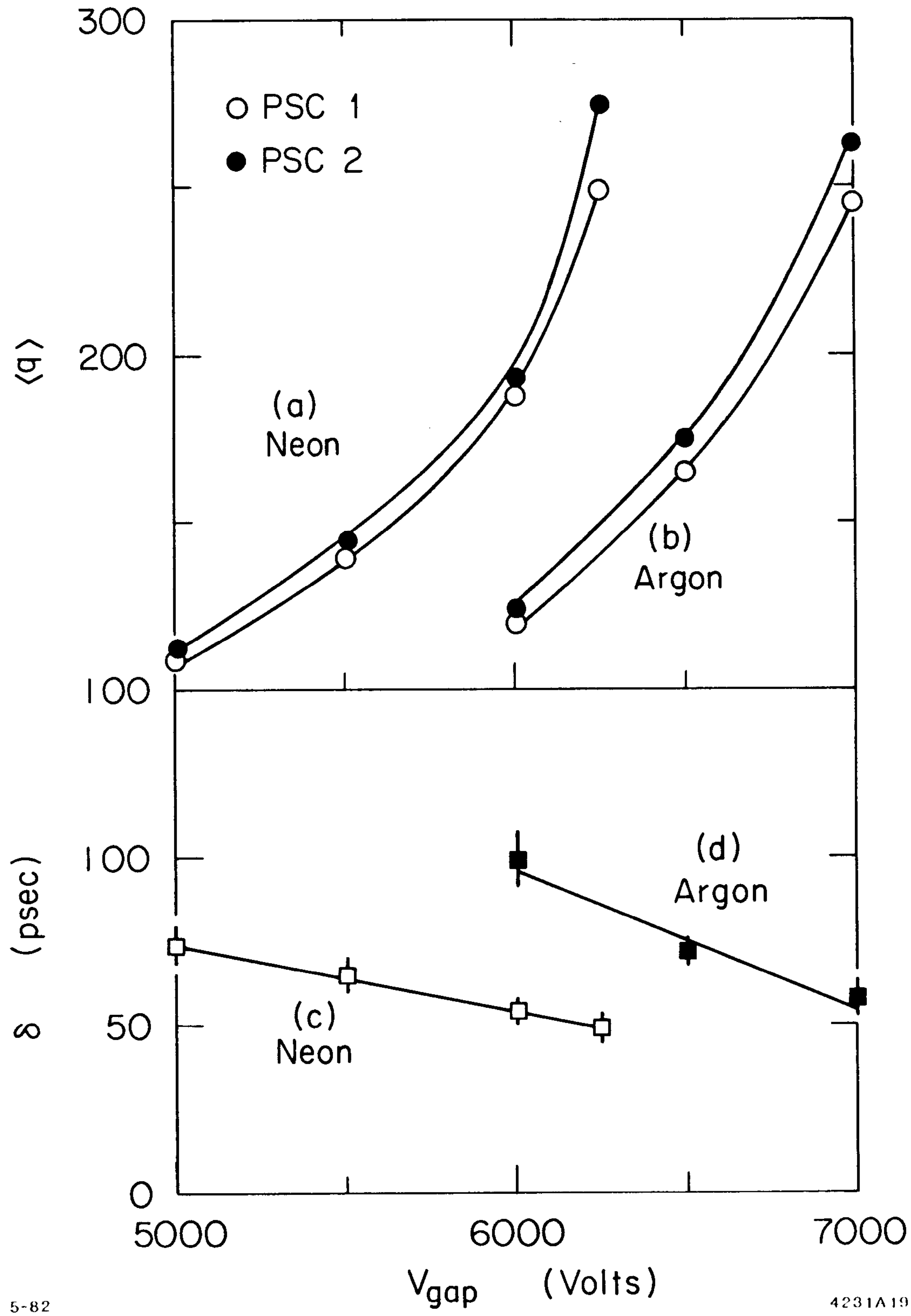
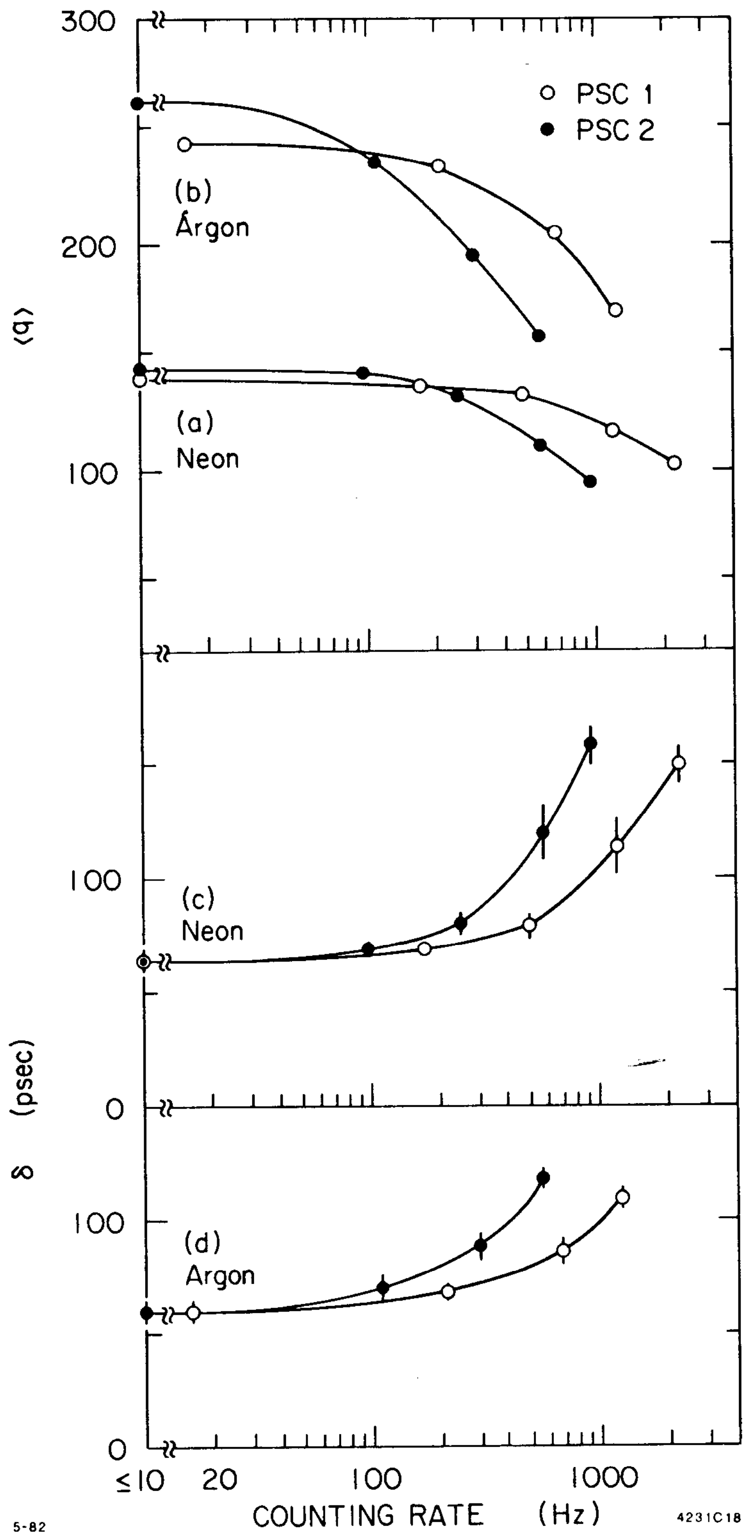

300
200
100
100
50
0
⟨q⟩
δ (psec)
○ PSC 1
● PSC 2
(a)
Neon
(b)
Argon
(c)
Neon
(d)
Argon
5000
6000
7000
Vgap (Volts)
5-82
4231A19

Fig. 6



300
200
100
100
0
100
0
⟨q⟩
δ (psec)
○ PSC 1
● PSC 2
(b)
Argon
(a)
Neon
(c)
Neon
(d)
Argon
≤10
20
100
1000
COUNTING RATE (Hz)
5-82
4231C18

Fig. 7

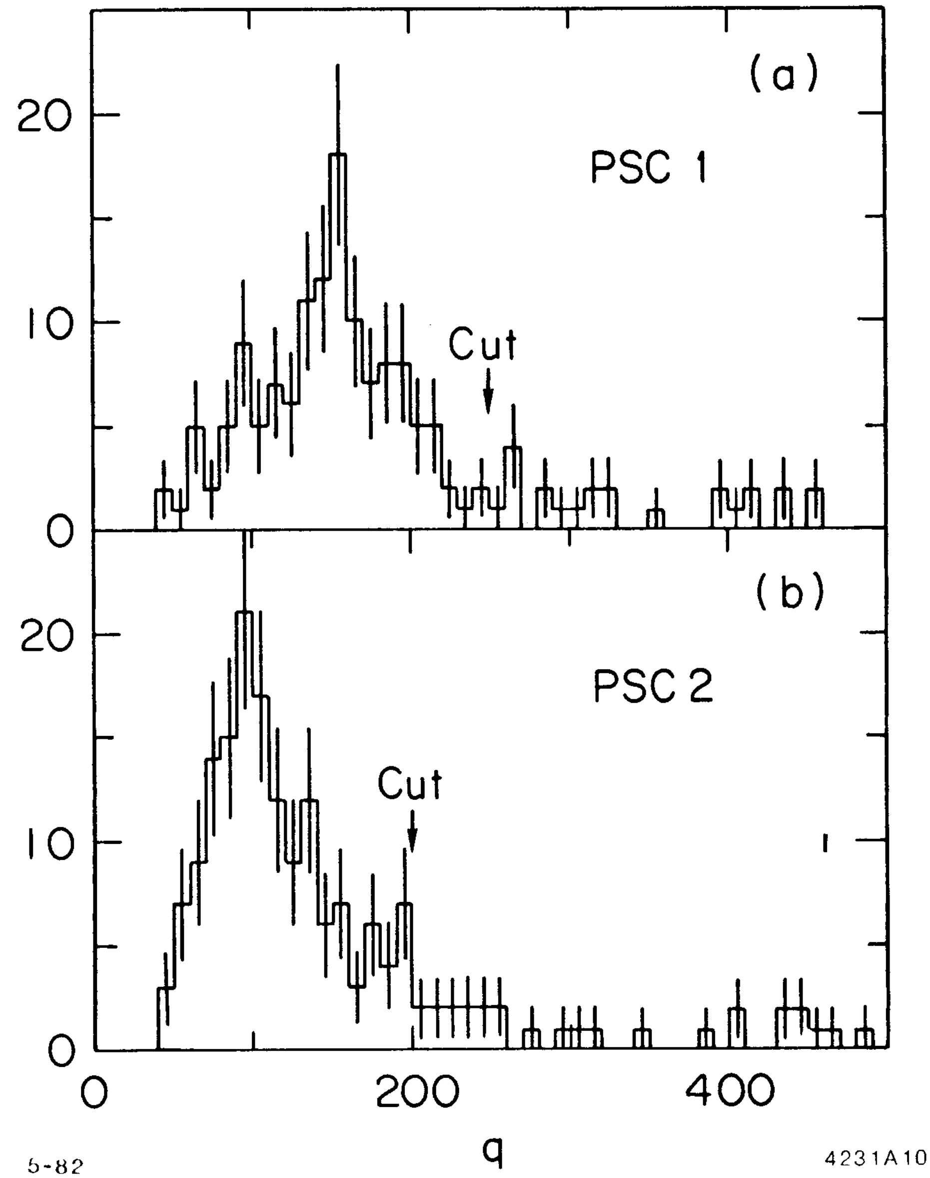


Fig. 8

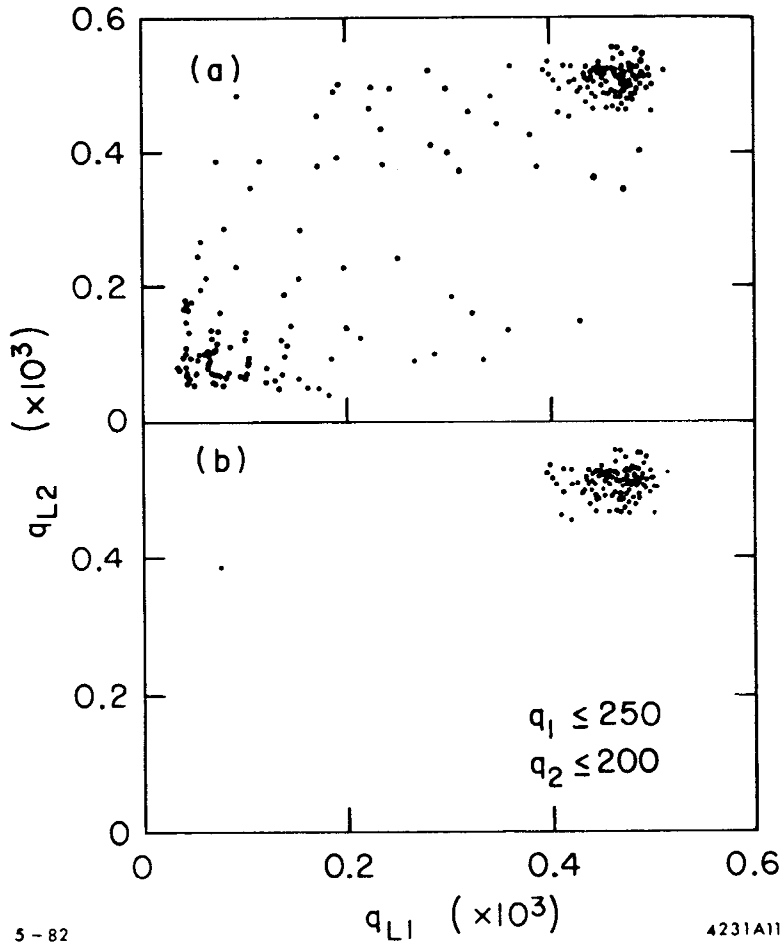
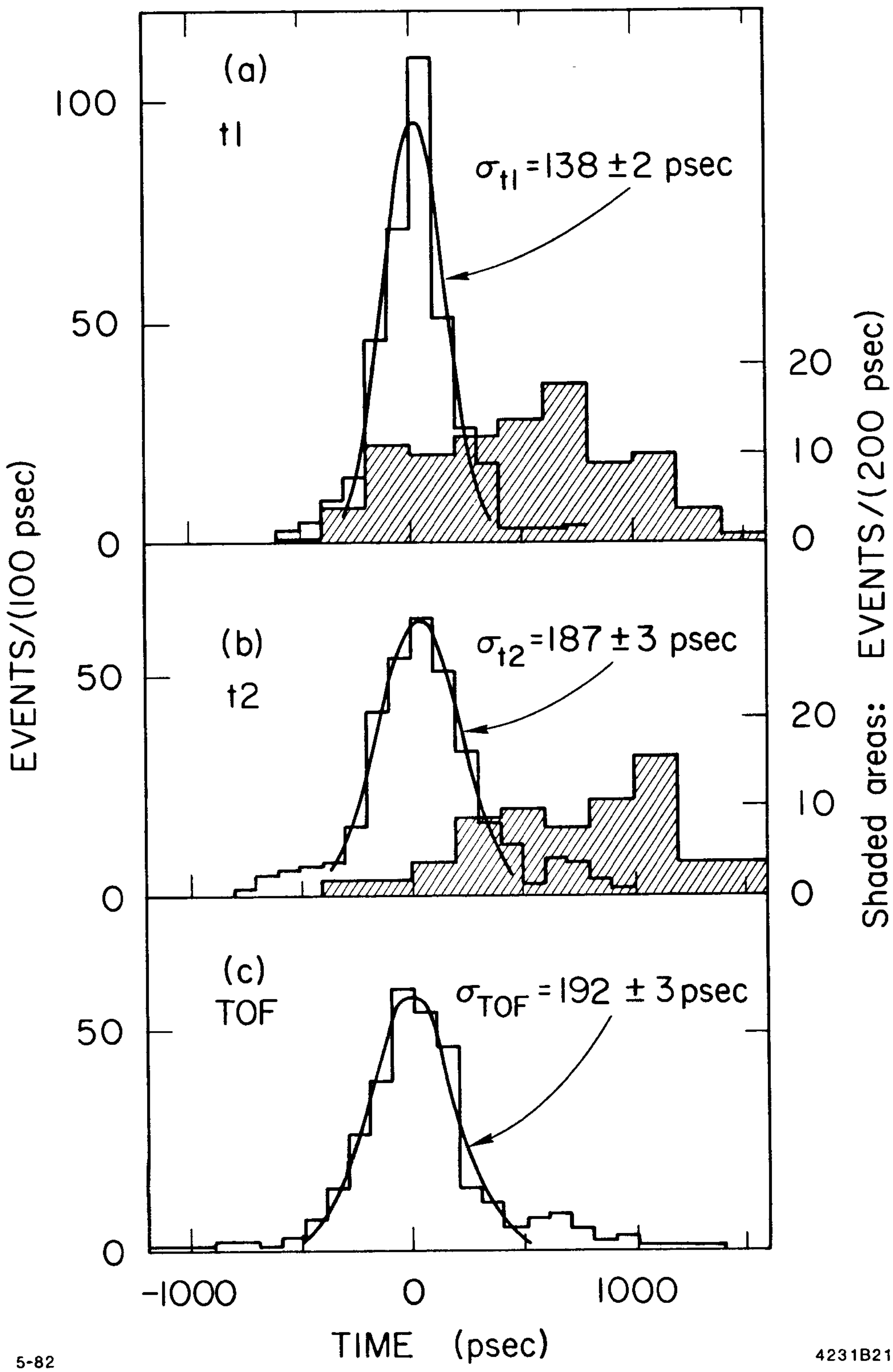
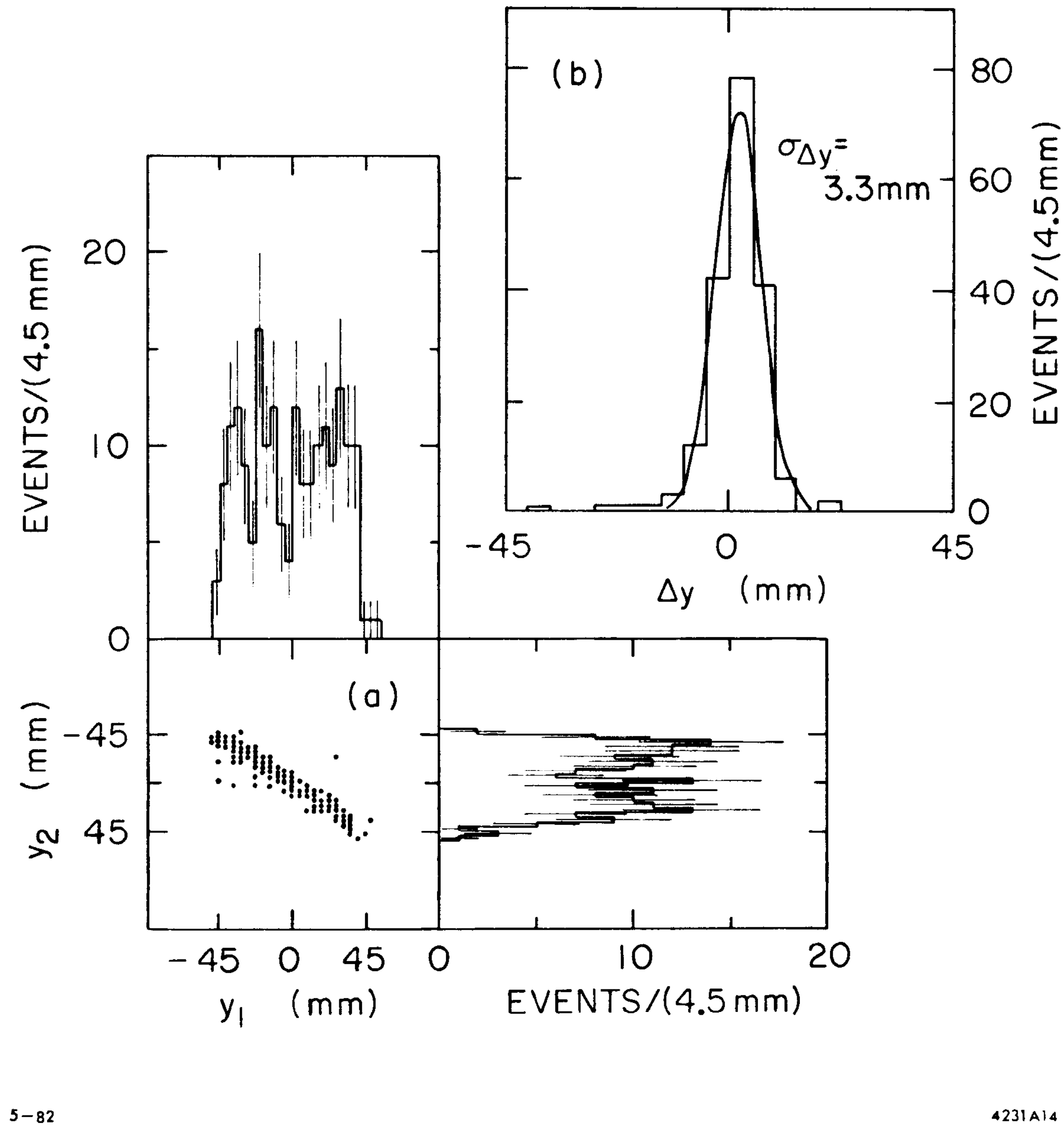

(a)
(b)
0.6
0.4
0.2
0
q_{L2} ($\times 10^3$)
$q_1 \leq 250$
$q_2 \leq 200$
0
0.2
0.4
0.6
q_{L1} ($\times 10^3$)
5 - 82
4231A11

Fig. 9



(a)
t1
σ_{t1} = 138 ± 2 psec
(b)
t2
σ_{t2} = 187 ± 3 psec
(c)
TOF
σ_{TOF} = 192 ± 3 psec
100
50
0
20
10
EVENTS/(100 psec)
Shaded areas: EVENTS/(200 psec)
-1000
1000
TIME (psec)
5-82
4231B21

Fig. 10



(a)
(b)
$\sigma_{\Delta y}$=
3.3mm
EVENTS/(4.5 mm)
y_2 (mm)
y_1 (mm)
Δy (mm)
-45
0
45
10
20
40
60
80
5-82
4231A14

Fig. 11