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LUMINOSITY MONITORING AND BEAM-BEAM COUNTER PERFORMANCE

I. Introduction In the 1986-87 run the Beam-Beam Counters (BBC) were used for several purposes. They provided a fast Pbar-P vertex finder, complementary to the VTPC, the only measure of T_o (the interaction time), a minimum bias trigger, and the luminosity monitor. In this note we review the performance of the BBC in the recent run with respect to each of these functions.

II. Interaction Time and Vertex Finding As described in CDF-250, each of 64 BBC channels is equipped with both ADC and TDC readout. In addition, each of the two photomultipliers on a single counter are fed through a mean-timer to a Fastbus latch. A logic diagram is shown in Figure 1. The latch is gated twice, once at the time at which the incoming beams pass the counters, and once at the time at which the outgoing beams pass the counters. This timing is shown in Figure 2. The incoming gate, henceforth called 'beam-halo', is 100ns wide and closes 10ns before the crossing time (30ns before outgoing particles reach the counters). The outgoing gate, henceforth called 'beam-beam' is 15ns wide and is centered 20ns after the crossing at the time at which outgoing particles from an interaction reach the counters.

The interaction time and vertex finding are, in principle, straightforward. One simply averages the TDC values over all hit counters on a single side (east or west) and calculates the interaction vertex as

$$Z_{int} = c/2(T_W - T_E) \qquad (1a)$$

and the interaction time as

$$T_o = 1/2 \; (T_W + T_E) \qquad (1b)$$

where T_W and T_E are the mean times on the west and east sides, respectively. In practice, however, one must make corrections for pulse height slewing in order to obtain the best results.

The effect of pulse height slewing was corrected by fitting the three constants A,B and C of the function

$$T = \frac{A}{\sqrt{Q + B}} + C \qquad (2)$$

where T is the TDC value in ns (i.e. after D to E conversion) and Q is the ADC value in pC above pedestal (also after D to E). The constant B accounts for pedestal shifts, while C incorporates an arbitrary offset in the TDC start time as well as other, less well understood effects to be discussed below.

a) ADC and TDC performance

The TDCs employed were of the standard CAMAC variety, LeCroy model 2228A. These were read out through Fastbus with the help of a Struck Fastbus-CAMAC branch driver. These caused no problems other than an occasional dead channel. TDC calibrations were done at several points during the run and resulted in gains constant to a few percent and no significant pedestal (offset) shift. On the contrary, the ADCs did not perform so nicely. Again, calibrations were done at several points during the run and resulted in constant gains and pedestals. Figure 3 shows a pedestal distribution from the BBC accumulated during a level 1 query run. This clearly shows two peaks, characteristic of low frequency noise (eg. 60hz). The ADC resided in the Scaler crate in the trigger room. This crate has had repeated noise problems over the last two years, had very poor cooling, and should not be harboring a sensitive analog device such as the ADC. For the coming run, the ADC will be relocated in one of the trigger racks with 400hz linear supplies. It is hoped that this will eliminate the noise problems.

Prior to the run, each BBC channel was calibrated using cosmic rays. The high voltage for each channel was adjusted so that the Landau peak was roughly 300 counts above pedestal, about 15 pC. During the run no hint of minimum ionizing was seen in the ADCs. A typical ADC distribution taken from a minimum bias run is shown in Figure 4. This shows that the mean ADC value for this channel corresponds to roughly 10 minimum ionizing particles! It is likely that this effect is due to the fact that the counters are being hit with a high multiplicity (though not 10!) of non-minimum ionizing particles created by secondary interactions in the wealth of material in front of the counters (beam pipe, flanges...) and back-scattering off the lead of the forward electromagnetic shower counter. These effects degrade the timing performance of the BBC because multiple hits on a counter result in TDC times which are too small. Another possibility is that the ADC just wasn't working at all. This is clearly not the case as can be seen from Figure 5 which shows the expected relationship between TDC value and ADC pulse height. The procedure used to make this plot is discussed in section b below.

Despite these difficulties, we were able to obtain quite reasonable timing performance from the counters. This is because although the counters were hit quite hard, the PMT gains were set (intentionally) low and the ADC had sufficient range (15 bit) to prevent saturation, so that the TDC vs. ADC relationship followed the expected form.

b) TDC vs. ADC Fitting Procedure

Each BBC channel was fit separately to the function in equation (2). The ADC and TDC values used were in pC and nS respectively (i.e. after application of calibration constants). The need for the constant B in equation (2) is clear from Figure 3 where it can be seen that, although the main pedestal peak is centered at about -0.6 pC, amounting to only a 2% pedestal shift, there is a significant amount of data at considerably lower values.

The constants of equation (2) were fit using minimum bias data. The mean TDC value over an entire run was calculated in each of 42 ADC bins from -2 pC to 80 pC. Above 80 pC the mean value was fairly constant and inclusion of additional data above this value did not change the quality of the fit. In fitting to the function (2), each bin was weighted by a factor which depends on the bin center. This factor was the inherent rms width of the TDC values for that bin. In order to remove the dominant effect of the Pbar-P bunch widths, the rms was calculated from the distribution of $(T - T_o)$ where T_o is the interaction time which, in this case, was determined from all remaining channels using very hard cuts to obtain a good value without concern for acceptance. Figure 5 shows the results of this fit for a single channel. The error bars shown represent the rms deviation including the inherent width and the effects of bunch size. The functional fit is overlayed using a solid line.

One would hope that this fitting procedure could be done just once for each channel and that the constants A, B, C thereby obtained would be good for all runs. This however proved not to be the case, and the reason why is not well understood at this time. Typically, a set of constants would hold good for a period spanning one to two weeks after which channel to channel variations in the mean TDC values (after all corrections) would begin to be observed. One possible source of this effect is a change in the gains or pedestals in the ADC which were not well tracked during the run (although they did not appear to change when calibrations were done). This might be caused by the poor cooling in the Scaler crate, noise etc. The TDCs appeared to be very well behaved and it seems unlikely that they contributed to this problem. Once again it is hoped that moving the ADC to a quiet crate with linear supplies will solve this problem, and that doing more regular calibrations may identify the source.

The constant C of the fit gives the asymptotic value of the function, i.e. the TDC value for infinite pulse height. Several factors influence changes in this asymptotic value. Among these are changes in the timing of the Master Clock strobe (Beam-Beam Start) which sets the overall timing for the BBC (see Fig. 1), drifts in the NIM logic creating the TDC start signal, and a 'real' shift in the interaction time, T_o, associated with a shift in Z_{int}.

Because of these drifts, it is necessary to include the constant C in the TDC correction, so that the corrected TDC value, T' is given by

$$T' = T - \frac{A}{\sqrt{Q + B}} - C + 67.5$$

where the constant 67.5ns is an arbitrary offset added so that the corrected and uncorrected times appear at approximately the same place in a histogram (it is removed for calculating T_o). This has the undesirable effect of fixing the mean times on the east and west sides to be the same and therefore defining the mean T_o and Z_{int} both to be 0. One way around this problem is to adjust the constant C, after fitting, so that the mean value of Z_{int} for an entire run agrees with the mean value obtained by the VTPC.

A procedure was attempted in which the constants A,B and C were fit for a single run and the constant C adjusted for that run so that Z_{int} from the BBC and VTPC had the same mean value. For future runs, only the constants A and B were fit, leaving C fixed. This procedure resulted in fits which were systematically too low at low ADC values, where the variation of time with pulse height is greatest. Following this attempt, it was decided that all three constants would be fit for each minimum bias run and the constant C adjusted for agreement with the VTPC of the mean Z_{int}. Typical adjustments amount to a Z_{int} shift of about 10cm. It should be noted that this does not mean that the

VTPC and the BBC no longer give independent measures of Z_{int}. This is simply a method for removing all types of timing drifts without losing sensitivity for measuring Z_{int}. Only the mean value over the entire run has been adjusted, event to event values are still independent. It should also be noted that because of the arbitrary nature of the adjustment of the constant C, T_o values can no longer be compared from one run to another. T_o is now a relative, event to event, measure of the interaction time for a given run, but is subject to run to run offsets of as much as 1 ns. It is felt that, although this is clearly undesirable, it does not seriously affect the way in which T_o might be used by say, the tracking chambers. It is hoped that when the causes of the various drifts are fully understood a better method of removing them can be found.

c) Interaction Time and Vertex Algorithm The interaction time is found separately for the east and west sides. This is done with a clustering algorithm in which the corrected TDC values are arranged in decreasing order. All channels within a given time window (typically 8ns) are clustered together, beginning with the largest TDC value and proceeding downwards. If the corrected values of all hit channels are within 8ns of each other, then there is just one time cluster, otherwise there is more than one. The value of 8ns was chosen to allow for the dispersion of arrival times of light at the face of the phototubes due to variation of the position at which a particle hits a counter. This was necessary because the PMTs are being treated on a channel by channel basis, in order not to bias against counters with one malfunctioning channel, so that mean timing is not possible. Once the clustering is completed, the mean time of the cluster which includes the most channels is used as T_W or T_E and Z_{int} and T_o are calculated from equations (1a) and (1b) above.

Despite the various troubles, the overall performance of the BBC for interaction vertex and time determination was very good. Figure 6 shows a scatter plot where the abscissa is the VTPC vertex in cm and the ordinate is the BBC vertex in cm. Figure 7 shows the deviation $(Z_{BBC} - Z_{VTPC})$. The FWHM of this distribution is about 9cm, corresponding to a BBC time resolution of better than 125 pS (neglecting $\sigma_{VTPC}(Z)$ which is of order millimeters).

d) Offline code The offline code which performs the above T_o and Z_{int} analysis is contained in the BBCOFF module in C$TRS (dictionary file C$TRS:BBC_DIC.UIC). A document describing this code exists in C$TRS:BBCOFF.MEM.

III. Luminosity Monitor and Minimum Bias Trigger Since the minimum bias trigger and the luminosity monitor were one and the same during the '86-'87 run, with the luminosity monitor counting E·W coincidences and minimum bias data being triggered by them (in what follows, E·W will always refer to coincidences with at least one hit on each side), I will concentrate here on the performance of the BBC as a luminosity monitor since this is directly transferable to its performance as a minimum bias trigger.

a) BBC Cross Section The integrated luminosity is calculated as the number of BBC E·W coincidences divided by the part of the Pbar-P total cross section seen by the BBC. The average luminosity is just this number divided by the live time. The BBC cross section can be measured in the standard fashion outlined in the run plan by simultaneously measuring the BBC rate and the total Pbar-P cross section using the Forward Silicon. Unfortunately we were unable to make this measurement during the past run, so we must do our best to estimate the BBC cross section.

In order to estimate the BBC cross section, the total cross section must be broken up into its various components, elastic, diffractive and hard core (inelastic minus single and double diffractive), and the BBC acceptance for each determined. The acceptances used here are those determined from the simulation using the Rockefeller Monte Carlo (CDF-257). Level 1 Query scans, described below, lend at least some support to these values.

To estimate the total cross section at $\sqrt{s}$ = 1800 GeV, I have used all recent predictions from the literature. These predictions span a range of only 74 mb to 80 mb where both extremes come from a paper by Block and Cahn[1]. The smaller value is arrived at by extrapolating from lower energy data and assuming that the cross section is asymptotically constant at very high energies but locally proportional to $\log^2 s$, while the larger value results from assuming the cross section to continue to evolve proportionally to $\log^2 s$. Taking the mean of these two values I take the total cross section to be

$$\sigma_{tot} = (77 \pm 6) \text{ mb}$$

where the error is chosen simply to allow the value to comfortably span the entire range of the predictions.

Next I estimate the elastic cross section. UA4 has measured[2] the ratio σ_{el}/σ_{tot} at a center of mass energy of 546 GeV. They find σ_{el}/σ_{tot} = 0.215 ± 0.005. Taking the ratio of UA5 elastic and total cross sections[6] I get 0.194 at

200 GeV and 0.230 at 900 GeV. The prediction given by Goulianos[3] for $\sqrt{s}$ = 1800 GeV is σ_{el}/σ_{tot} = 0.229. This would appear to be inconsistent with the UA5 value at 900 GeV. However, this ratio should vary slowly, as is born out by the data in Figure 8, so the prediction of Goulianos is not so bad. Goulianos predicts a ratio of 0.221 at 900 GeV, so it seems conservative to associate an error of 0.01 with his prediction at 1800 GeV. This gives

$$\sigma_{el} = (17.6 \pm 1.6) \text{ mb}$$

where the error results from the uncertainty in the total cross section above, and the uncertainty in the ratio.

Given the above values for σ_{tot} and σ_{el}, the inelastic cross section is given by

$$\sigma_{in} = \sigma_{tot} - \sigma_{el} = (59.4 \pm 4.7) \text{ mb}$$

The inelastic cross section itself breaks up into three components, hard core, σ_o , and single and double diffractive, σ_{sd} and σ_{dd} respectively. Here I will make best estimates of σ_{sd} and σ_{dd} and then use σ_{in} above to calculate σ_o. UA5 has measured[4] the single diffractive cross section to be (7.8 ± 1.2) mb at 900 GeV (I use the convention here that the single diffractive cross section is the sum of the proton and anti-proton components, thus for comparison the values given by Goulianos, for instance, must be multiplied by two). The prediction of Goulianos for center of mass energy of 1800 GeV is 17.2 mb , and this value is given some support by the analysis of the BBC scalers done by Giokaris and Goulianos[5]. There is some controversy over the diffractive cross sections, but given that the BBC scaler analysis is the only experimental work of any kind at our energy, I use here a value somewhat larger than appears warranted from the data. From Figure 8 it can be seen that the predictions of Goulianos are systematically above the measured values. I use this as a measure of the uncertainty in the prediction and take

$$\sigma_{sd} = (15.0 \pm 5.0) \text{ mb}$$

There is even more uncertainty associated with the double diffractive cross section, however, its value is certainly small and the BBC acceptance is approximately 60%. Therefore it does not have a big effect on the overall BBC cross section. Guided by the literature I here assume

$$\sigma_{dd} = (4.2 \pm 1.0) \text{ mb}$$

where the error is assumed to be a conservative 25%.

Using these values, one arrives at

$$\sigma_o = \sigma_{in} - \sigma_{sd} - \sigma_{dd} = (40.2 \pm 6.9)$$

and, finally, using the Rockefeller Monte Carlo acceptances for the BBC we get

$$\sigma_{BBC} = 0.134\sigma_{sd} + 0.618\sigma_{dd} + 0.942\sigma_o = (42.5 \pm 6.0) \text{ mb}$$

b) Background The requirement of only a single counter hit on each side is necessary in order to make a reliable estimate of the cross section. However, this trigger also has the potential for admitting a substantial amount of background due to back scattering from beam-gas collisions. In order to determine the magnitude of the background accepted by the luminosity monitor, hand scans were done of 100 events from each of the minimum bias runs as well as from several of the minimum bias production tapes where pre-scaled minimum bias events were stripped off of high Pt runs. These scans spanned runs with average luminosities from $0.2 \times 10^{28}\ \text{cm}^{-2}\text{s}^{-1}$ to $6.7 \times 10^{28}\ \text{cm}^{-2}\text{s}^{-1}$.

The events scanned were separated into three categories, good beam-beam events, background events and events which, for one reason or another, could not be placed in either of the first two categories. Events in this third category, amounting to only a few percent of all events, were eventually removed from the sample. The first pass through the events used selection criteria which depended only on the VTPC. Events were called good beam-beam if either of two conditions were satisfied:

1) For events with a low multiplicity of VTPC tracks (<5) at least three tracks pointing at a vertex were required with at least one of the tracks opposing the others (in η).

2) For events with with five or more tracks in the VTPC at least two tracks were required to oppose the others pointing at a vertex. This was done to eliminate the background which typically consists of a single back scattered particle opposed by a large beam-gas spray in the forward direction.

The results of this initial scan are shown in Figure 9 as a function of the luminosity of the run. One might expect that the fractional background would decrease with increasing luminosity. The data does not contradict this hypothesis, however due to the limited statistics of the sample it is not distinguishable from a constant fraction of about 11%.

Following this initial scan, a second scan was done of rejected events in order to recover those beam-beam events which do not leave tracks in the VTPC (recall that the VTPC and the BBC have a very limited overlap). In order to do this, selection criteria based solely on the BBC latches and TDCs had to be established. This was done by separating rejected events into two categories, those events which were obvious background and those that were not. The different characters of the background events and events determined to be good beam-beam events by the VTPC selection were then used to establish the selection criteria.

An event with many VTPC hits but no tracks pointing at a vertex was called "obvious background". Figure 10a shows a distribution, for "obvious background" events, of the number of counters hit in the beam-beam gate on the side with the fewest counters hit in this gate. A very marked peak at a single counter is seen. Figure 10b shows the distribution of the number of time clusters (see IIc) on the side with the maximum number, for these same events. Figures 10c and 10d show these same distributions for a random selection of good beam-beam events. Based on these distributions "not obvious background" events were moved into the "good" category if:

1) There were more than 4 counters hit on each side in the beam-beam gate and

2) There was just one time cluster on each side.

The effect of lowering the multiplicity requirement in 1 was studied and it was found that reducing it to greater than two counters, rather than four, reduced the calculated background contribution by only 1%.

Figure 11 shows, as a function of luminosity, the fraction of good beam-beam events accepted by the BBC. It is seen again that this fraction has no obvious dependence on luminosity. One could fit the data to a function with some hypothesized form and parameterize the background fraction as a function of luminosity. However, the actual functional form is unknown and likely to be quite complicated, depending on many factors other than just the proton and anti-proton beam currents. Given this, it is felt that the most prudent thing to do is to assume a constant background fraction given by the mean of the data. In computing this mean the lowest point was eliminated and the mean calculated from the remaining points. The remaining 11 runs resulted in 988/1050 events scanned which passed the filter for a background fraction of (6 ± 0.7)% where the error quoted is a statistical error on the mean. By assuming a constant non-zero slope passing 1σ above the highest luminosity point in Figure 11, and consistent with the bulk of the points above 0.4 x 10^{28}, I estimate that a possible error of about ±3% is introduced by assuming a constant background fraction over this range of luminosities.

More work will be done in this area to improve the statistics in order to better understand the dependance of background fraction on luminosity.

c) <u>BBC Acceptance Check</u> In order to check the acceptances given by the Rockefeller Monte Carlo, a scan of Level 1 Query data was done. Raw data tapes from Level 1 Query runs with beam in the Tevatron were passed through a software filter which required at least five hits in the VTPC. All events which passed this filter were hand scanned. The same VTPC criteria as described above for the background study were used to define good beam-beam events. For all events declared as good beam-beam events, the BBC beam-beam latch bits were checked to determine if the event would have been counted as an E·W coincidence. 164/175 beam-beam events contained an E·W coincidence, giving a BBC acceptance of (93.7 ± 1.8) % .

Since, by necessity, the VTPC was used in this study, there was little sensitivity to double diffractive events and virtually no sensitivity to single diffractive events. Thus, we should compare this value of the BBC acceptance to that given by the monte carlo for the hard core (σ_0) part of the cross section. The monte carlo predicts a BBC acceptance of 94.2% for σ_0, in excellent agreement with the value above.

d) <u>Luminosity Calculation</u> An offline module, LUMBBC (dictionary file C$TRS:LUMBBC.UIC), has been provided to perform luminosity calculation from the scaler banks, SCLD. This module is nearly identical to the online code in TRIGMON, and works as follows. At each event, the scaler banks are located and the livetime, the number of times at least one beam-beam hit occurred on the west and on the east, and the number of times an E·W coincidence occurred (with at least one hit on each side), is picked up. From these four quantities the luminosity is calculated according to the following formula:

$$\int Ldt = \frac{(E_t + W_t - BC) + \sqrt{(BC - E_t - W_t)^2 + 4(BC(WE)_t - E_tW_t)}}{2\sigma_{BBC}}$$

Where W_t and E_t count the OR of the beam-beam gate hits on the west and east sides, respectively, BC is the total number of live time beam crossings, $(WE)_t$ is the total number of E·W beam-beam coincidences, and σ_{BBC} is the BBC cross section from IIIa. This formula results from an algorithm which corrects the E·W coincidence rate for random coincidences between the east and west singles rates. It is correct only in the limit where the number of beam crossings is much greater than the number of collisions.[7] The calculation leading to this equation is done in Appendix A. Note that this correction applies only to accidental coincidences as opposed to the single beam events which cause correlated hits on both sides. This latter type of background is the dominant source of the events discussed above in IIIb. The correction had very little effect (typically 0.5%) during most of the run, but was important early on when the vacuum was bad (resulting in large singles rates) and the luminosity was low.

e) Stability of the BBC Luminosity Monitor Figure 12 shows the cross section for events passing a rather restrictive filter run on minimum bias events.[8] This cross section is calculated by dividing the integrated luminosity by the number of events passing the filter. The filter is restrictive enough that it passes essentially no background, although it does eliminate some fraction of real events as indicated by the fact that the cross section is lower than the BBC cross section of 42.5 mb. For the first three points on this plot, the events being counted by the luminosity monitor were not the same as those causing triggers. This is the reason for the step in the ratio of integrated luminosity to events passing the filter. Aside from this one feature, these data indicate that the luminosity monitor is stable to at least ±2%.

Another way to test the stability of the luminosity monitor is to compare the luminosity calculated from accelerator parameters to the luminosity given by the event rate seen by the BBC. Figure 13 shows a histogram of the ratio of the accelerator luminosity to the BBC luminosity.[9] This ratio has an rms deviation of 15%, considerably more than the 2% variation quoted above. All indications are that the BBC stability is much less than ±15%. This is evident not only from the data shown in Figure 12, but from hand scans of minimum bias data, trigger rates as a function of BBC luminosity and general features of the BBC system which make it hard to understand such a large run to run variation. Never the less, without an understanding of the precise cause of this disagreement, one cannot simply assume that this 15% deviation is due to accelerator uncertainties alone. Therefore, we take the conservative view here that the 15% deviation is due to equally weighted uncertainties in both the BBC and accelerator measurements. From this we arrive at a very conservative measure of the BBC run to run stability of ±11%.

f) Overall Uncertainty in the Luminosity

Finally, from the above discussion, we may estimate the overall uncertainty in the luminosity measurement given by the BBC. We have an 11% uncertainty in the event rate (this is given by the spread in the ratio of accelerator to BBC luminosities) and an 15% uncertainty in the BBC cross section. If we add these two in quadrature, we arrive at an overall uncertainty of ±19%. We note, however, that it is more proper to quote these errors separately, the first being an uncertainty do to fluctuations, while the latter is a systematic uncertainty.

Furthermore, it is important to note that in using the integrated luminosity to calculate physics quantities, we will in general be summing over a very large number of runs. In this case the uncertainty due to fluctuations (i.e. the 11% derived from Figure 13) will very quickly become negligible because it decreases as $1/\sqrt{N}$ where N is the number of runs being integrated over. In this case, and this will almost always be the case, the uncertainty in the integrated luminosity is entirely dominated by the 15% uncertainty in the cross section for triggering the Beam-Beam Counters.

III. Conclusion

We have reviewed the performance of the Beam-Beam Counters both offline and online. The BBC system has been shown to be capable of measuring the interaction time to better than 200 ps, and the interaction position to better than 6cm.

As a luminosity monitor, the BBC system has performed quite well. Indications from CDF data all point to an uncertainty in the luminosity measurement of ±15%, dominated entirely by the uncertainty in the cross section for triggering the BBC. These same data indicate that the run to run stability of the system is better than 2%. Unfortunately, the agreement with the luminosity given by accelerator parameters is not this good, and because this disagreement is not well understood on accelerator grounds, it must be assumed at this time that a BBC instability of some sort contributes. Given these facts, we have shown that the overall run to run uncertainty in the luminosity measurement of the BBC is approximately ±19% . When integrating over large numbers of runs, as we will always do in publishing physics, the run to run uncertainty becomes insignificant and the uncertainty in the integrated luminosity is dominated by the 15% uncertainty in the BBC cross section.

Acknowledgment I would like to thank Bellisario Esposito for help with much of the work on interaction time and vertex determination.

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7. I thank Mauro dell'Orso and Paola Gianetti for pointing this out. At a luminosity of 10^{29} with three bunches, the number of accidental coincidences is overestimated by 3%.

8. Figure 12 is courtesy of Aesook Byon. She used G.P. Yeh's filter ZVTFLT which required a good vertex in the VTPC (it has since been modified somewhat).

9. Figure 13 is courtesy of John Cooper. The accelerator luminosities (labelled T106) include all corrections known at this time. The TRIGMON luminosity includes no corrections. Changes since the time these data were produced include the 6% background correction (multiply by 0.94) and a small change in the BBC cross section from 40.0 to 42.5 (multiply by 40.0/42.5).

APPENDIX A

Luminosity calculation:

In the following equations, W_S and E_S are defined to be the number of ´singles' counts on the west and east sides, respectively, where a singles count is defined to be any hit not associated with a pbar-p interaction (i.e. neglecting other sources of correlated hits). P_{W_S} is the probability per crossing of having a singles count on the west and $A_{W_S \cdot E_s}$ is the number of accidental coincidences between west and east singles hits. The rest of the parameters are defined in section IIId.

$$W_S = W_T - (WE)_R$$

$$E_S = E_T - (WE)_R$$

$$P_{W_S} = W_S/BC$$

$$A_{W_S \cdot E_S} = \frac{E_S W_S}{BC}$$

$$(WE)_T = (WE)_R + \frac{E_S W_S}{BC}$$

$$BC(WE)_T = BC(WE)_R + (E_T - (WE)_R)(W_T - (WE)_R) =$$

$$BC(WE)_R + E_T W_T - E_T(WE)_R - W_T(WE)_R + (WE)_R^2 \longrightarrow$$

$$(WE)_R + (BC\ -^{2}E_T - W_T)(WE)_R - (BC(WE)_T - E_T W_T) = 0$$

$$(WE)_R = \frac{(E_T + W_T - BC) \pm \sqrt{(BC - E_T - W_T)^2 + 4(BC(WE)_T - E_T W_T)}}{2}$$

Finally, the integrated luminosity is given by $(WE)_R/\sigma_{BBC}$.

FIGURE CAPTIONS

Figure 1. A schematic diagram showing the Beam-Beam Counter logic for a typical counter. The box labelled 'Fastmac' TDC represents the CAMAC TDCs plus the Struck Fastbus - CAMAC branch driver.

Figure 2. A 'Minkowski' plot illustrating the timing of the BBC latch gates and TDCs. For reference, main proton and antiproton bunches as well as two satellites for each are shown.

Figure 3. An ADC pedestal distribution for a typical counter from a Level 1 Query run.

Figure 4. A pulse height distribution for a typical counter from a minimum bias run.

Figure 5. A plot of the dependence of the TDC value on the ADC pulse height. The abcissa gives the ADC value in pC above pedestal and the ordinate is the TDC value in nanoseconds.

Figure 6. A scatter plot with the interaction vertex position as found by the VTPC on the ordinate and that found by the BBC on the abcissa.

Figure 7. A histogram of the difference in vertex position between the VTPC and the BBC.

Figure 8. Measured and predicted cross sections at proton-antiproton colliders from 200 GeV to 1.8 TeV center of mass energy.

Figure 9. The fraction of minimum bias events passing beam-beam event selection criteria using the VTPC only.

Figure 10. Histograms of quantities used for selecting events based on BBC information. See section IIIb for a description.

Figure 11. The fraction of minimum bias events passing beam-beam event selection criteria using both the VTPC and the BBC.

Figure 12. Cross section for minimum bias events passing an event filter which eliminates backgrounds (and some real events). Courtesy A. Byon.

Figure 13. A histogram of the store by store ratio of the TRIGMON luminosity (i.e. the online BBC luminosity) to the luminosity calculated from machine parameters. All known corrections have been applied to the machine luminosity. Courtesy J. Cooper.

BEAM-BEAM COUNTER LOGIC

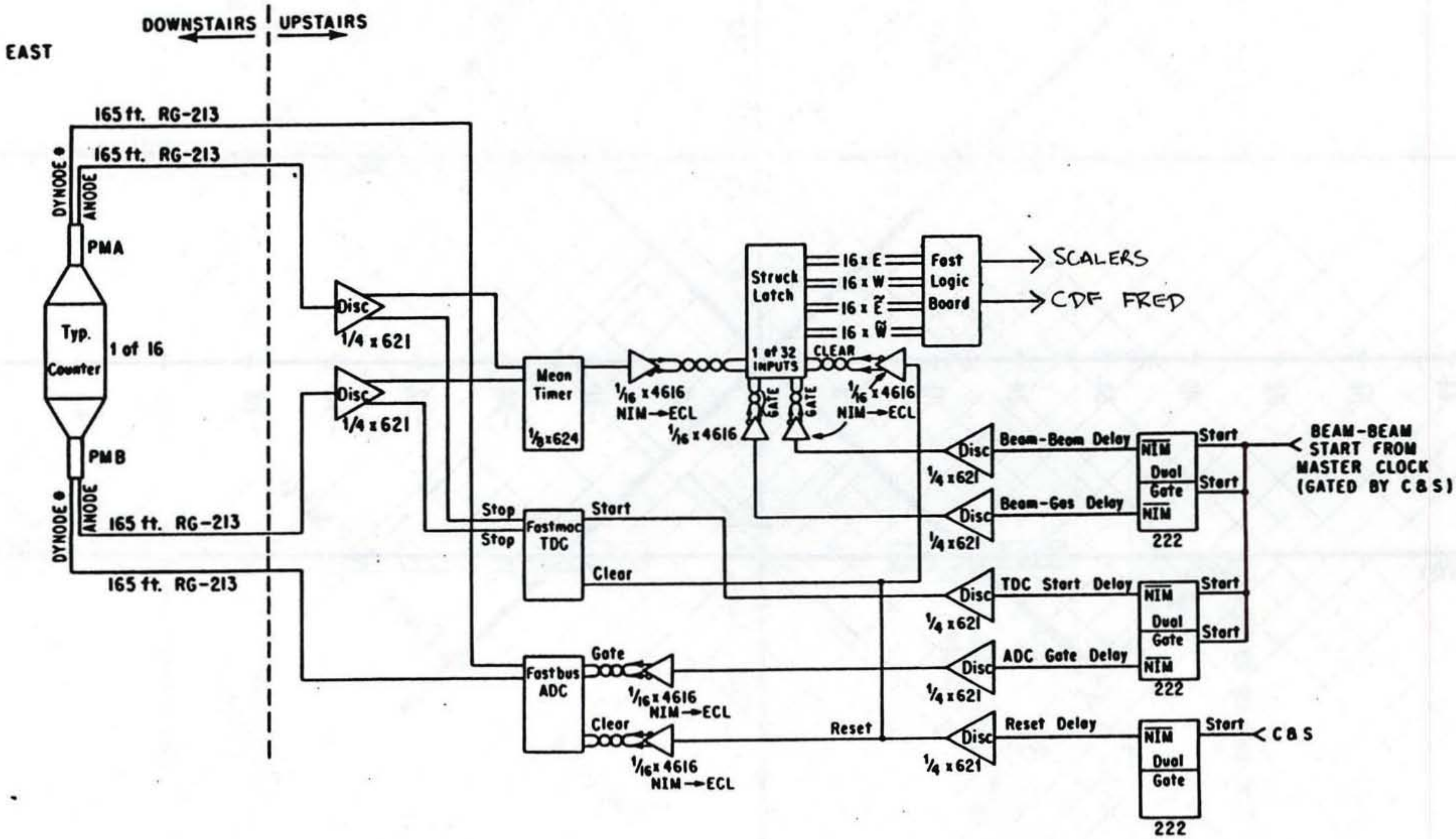
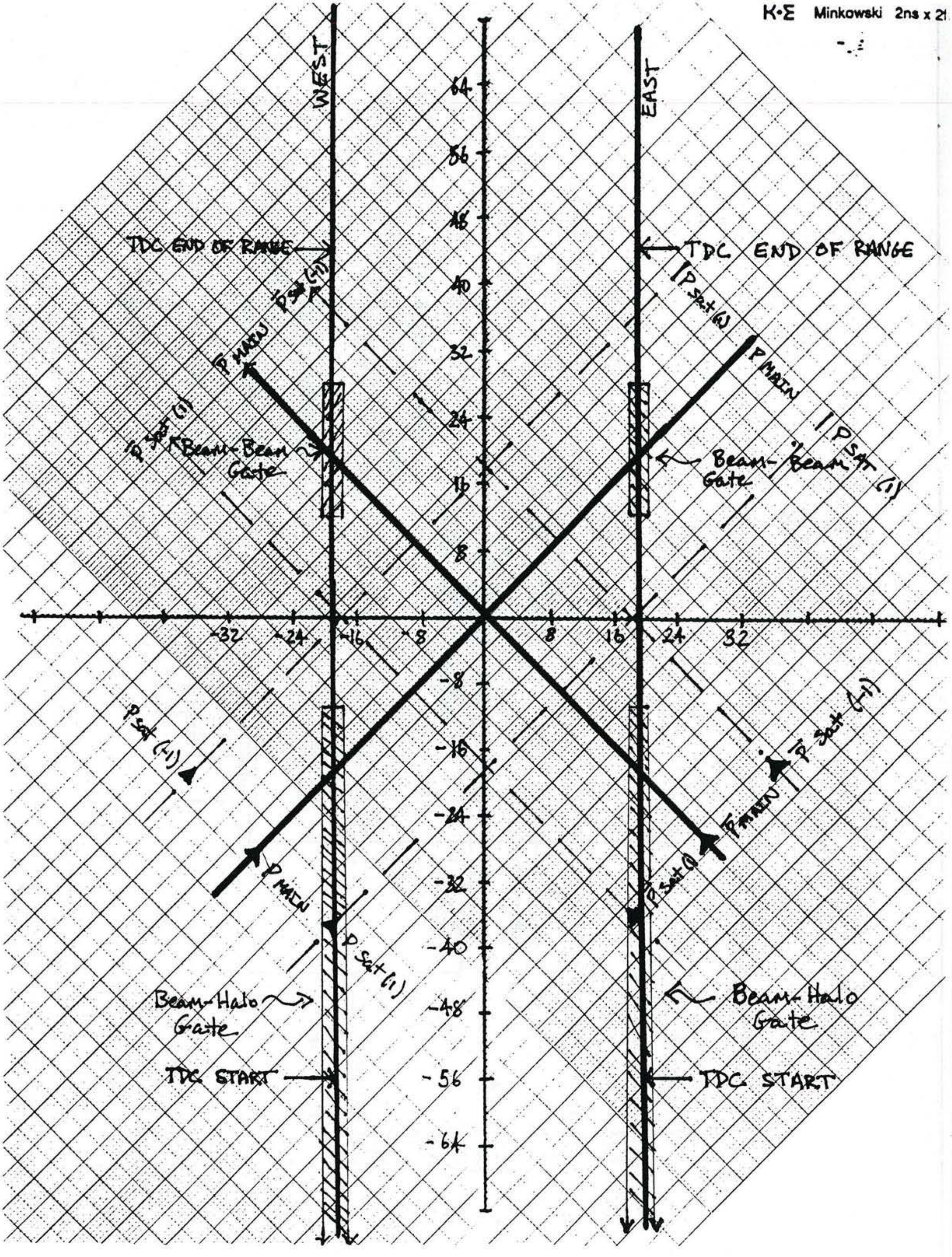


Fig. 1


WEST
EAST
64
56
48
40
32
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16
8
-32
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16
24
32
-8
-16
-24
-32
-40
-48
-56
-64
TDC END OF RANGE
TDC END OF RANGE
P MAIN
P MAIN
P MAIN
P MAIN
Beam-Beam Gate
Beam-Beam Gate
Beam-Halo Gate
Beam-Halo Gate
TDC START
TDC START

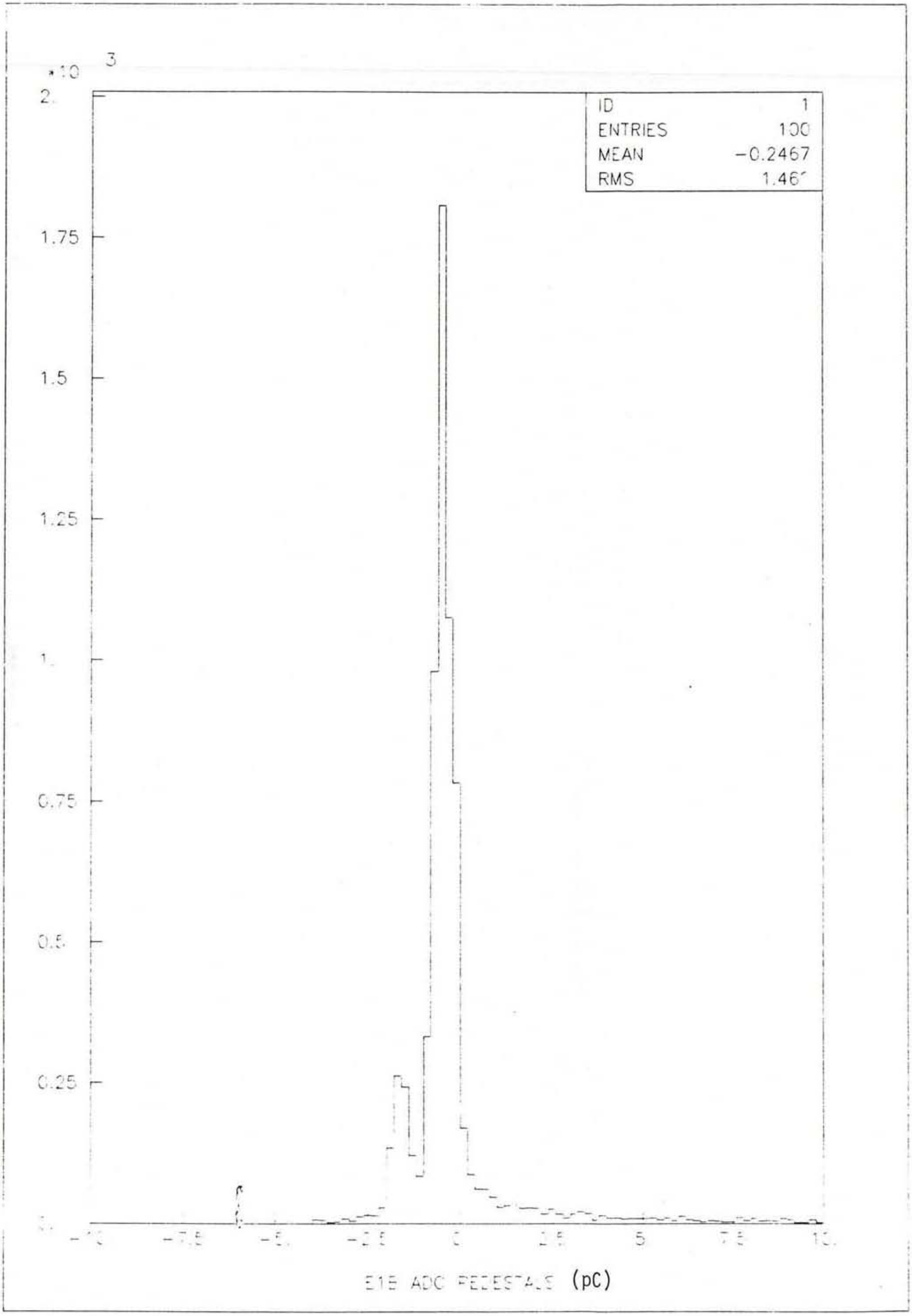

*10 3
ID 1
ENTRIES 100
MEAN -0.2467
RMS 1.46
2.
1.75
1.5
1.25
1.
0.75
0.5
0.25
5
(pC)

Fig. 3

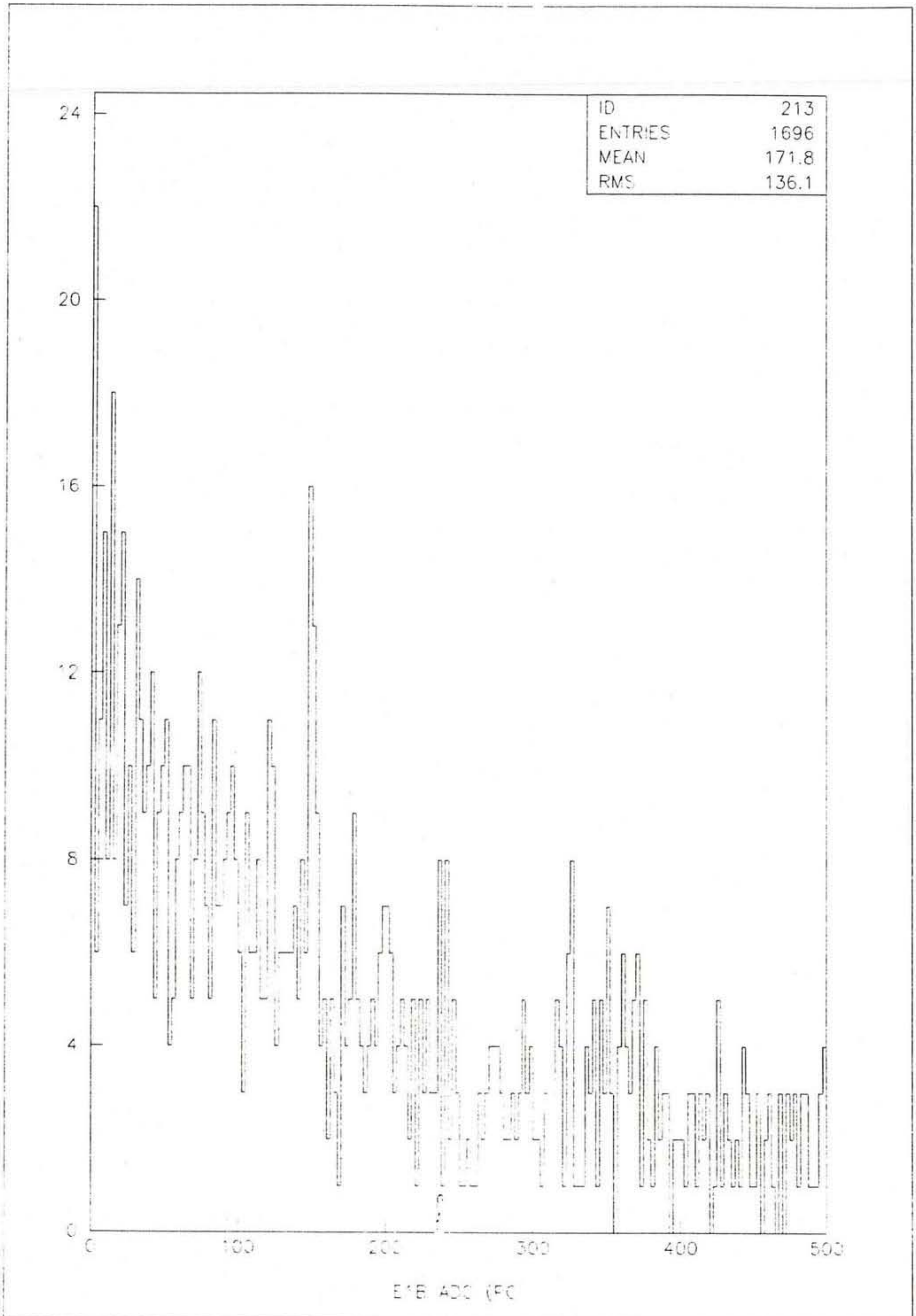

ID 213
ENTRIES 1696
MEAN 171.8
RMS 136.1
24
20
16
12
8
4
0
100
200
300
400
500

Fig. 4

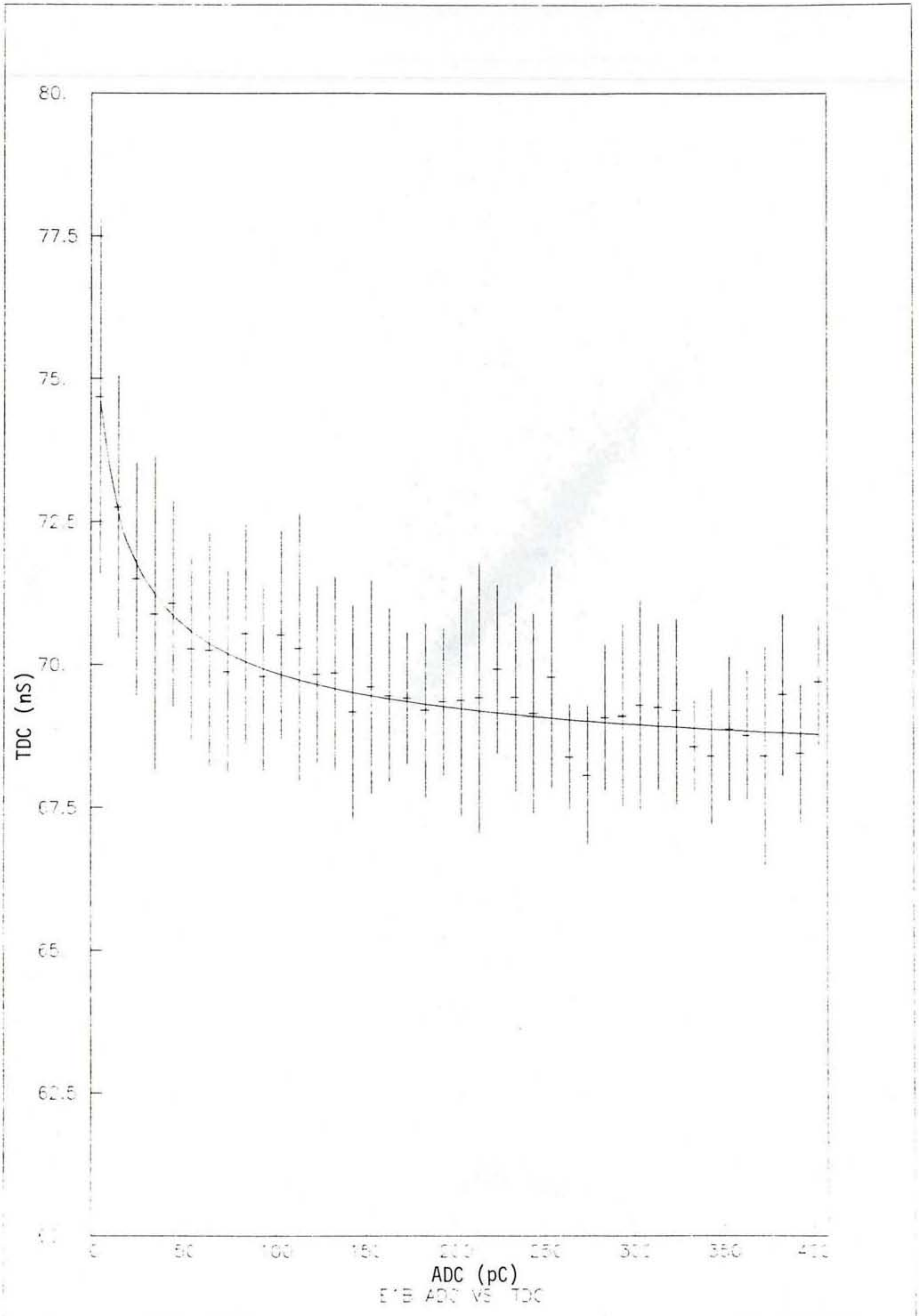


Fig. 5

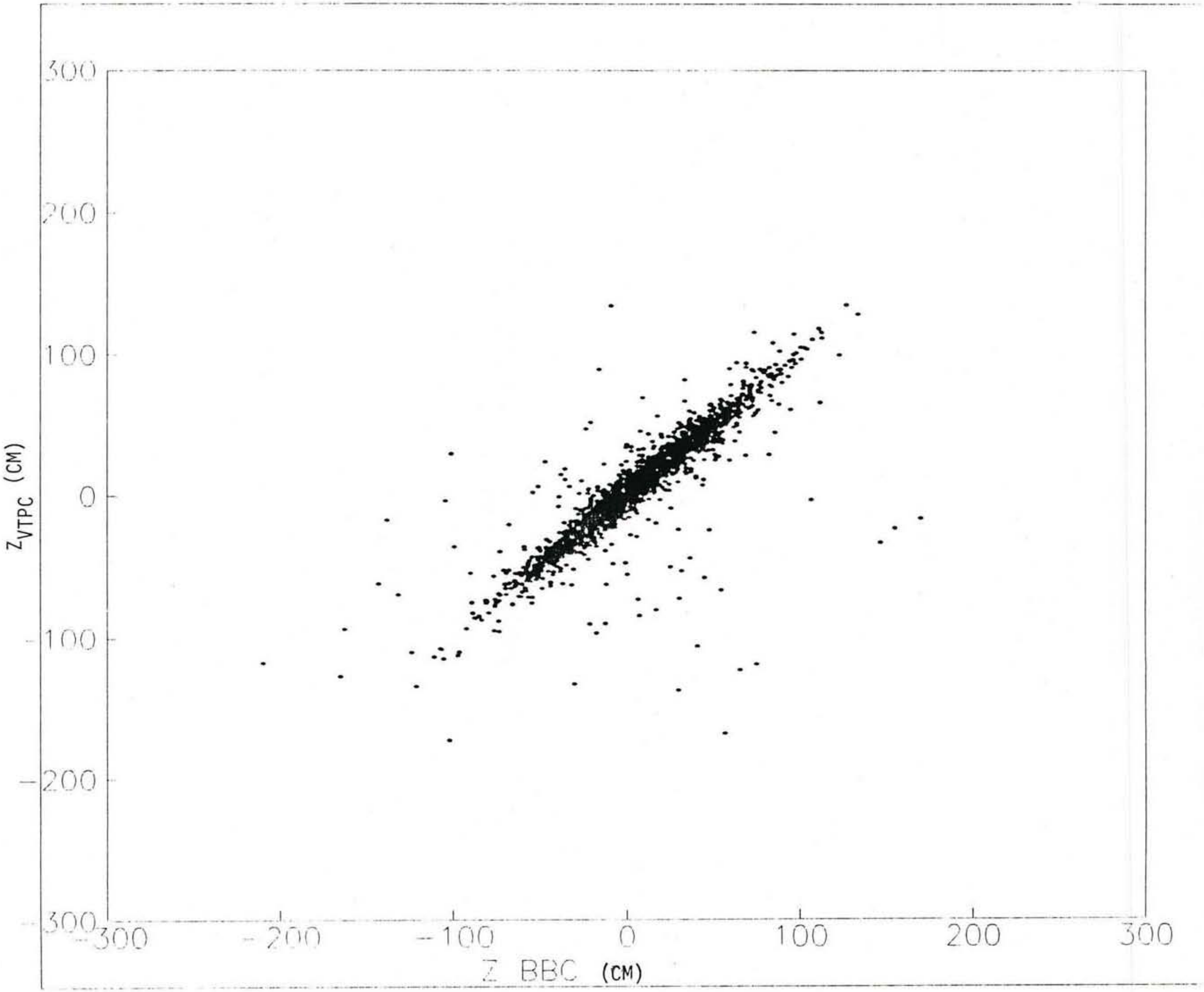

300
200
100
0
-100
-200
-300
Z_{VTPC} (CM)
-300
-200
-100
0
100
200
300
Z BBC (CM)

Fig. 6

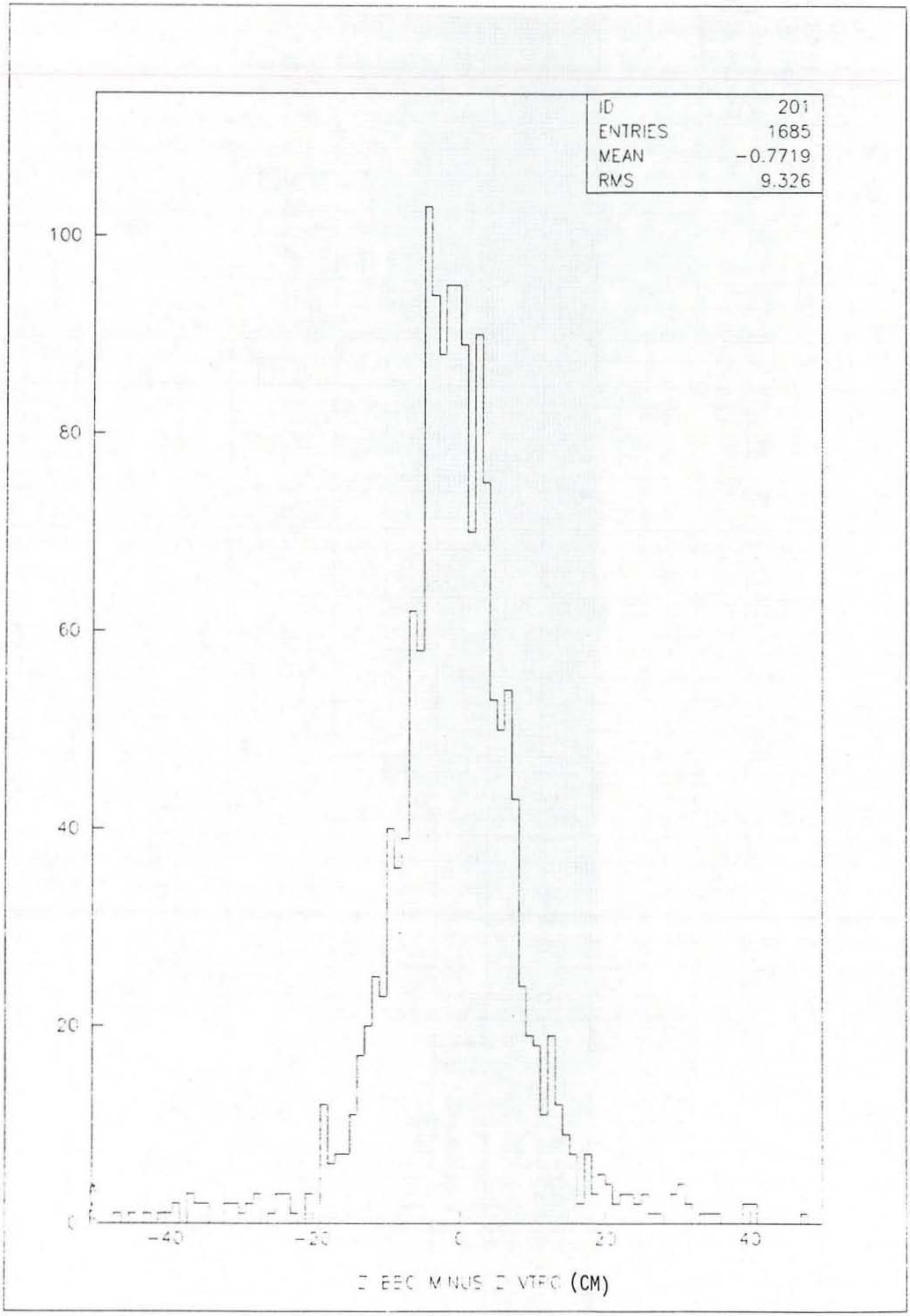

ID 201
ENTRIES 1685
MEAN -0.7719
RMS 9.326
100
80
60
40
20
0
-40
-20
0
20
40
(CM)

Fig. 7

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM. KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1513

CROSS SECTIONS AT PP̄ COLLIDERS

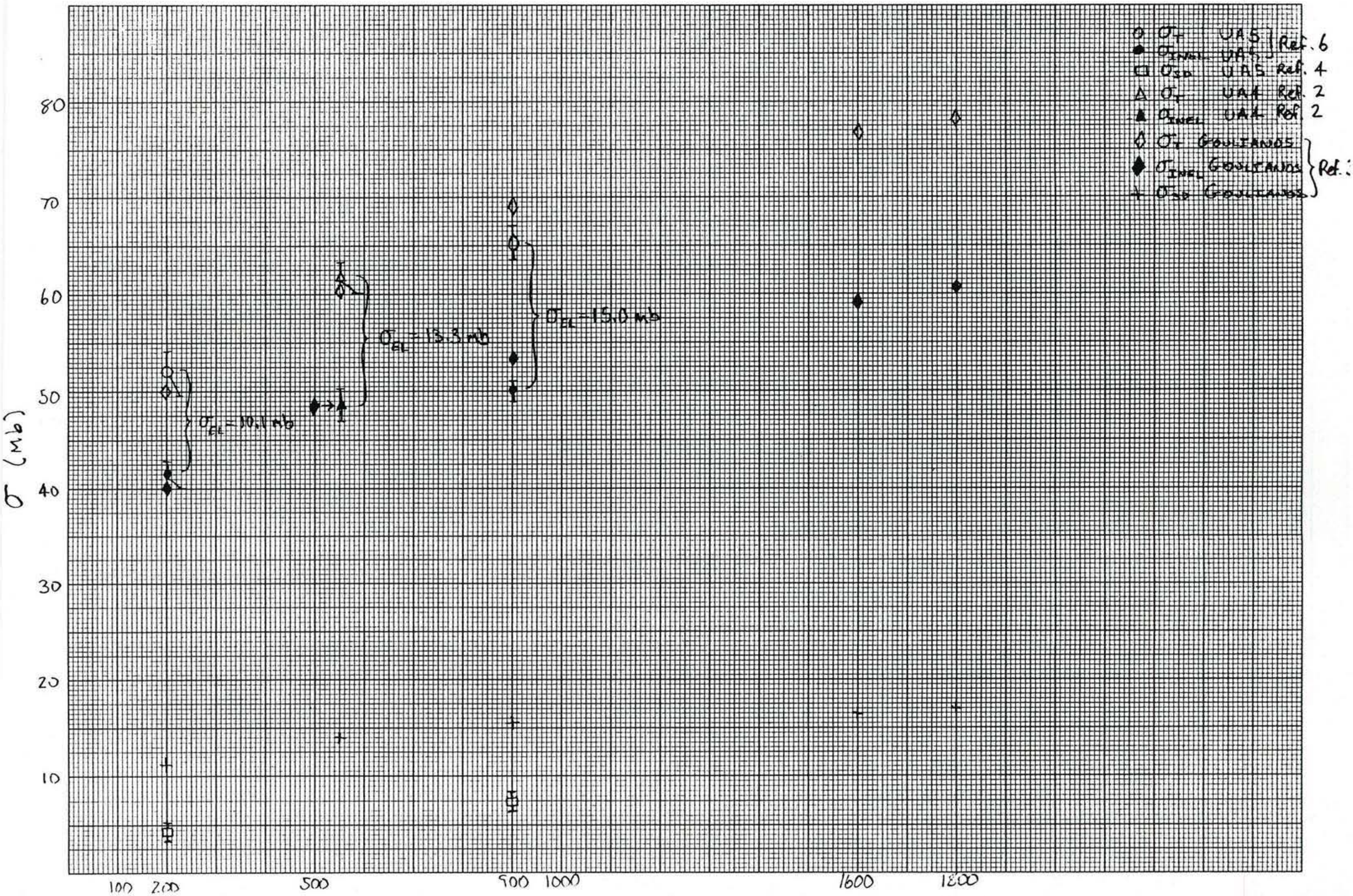


Fig. 8

FRACTION OF GOOD EVENTS _ VTPC ONLY SCAN

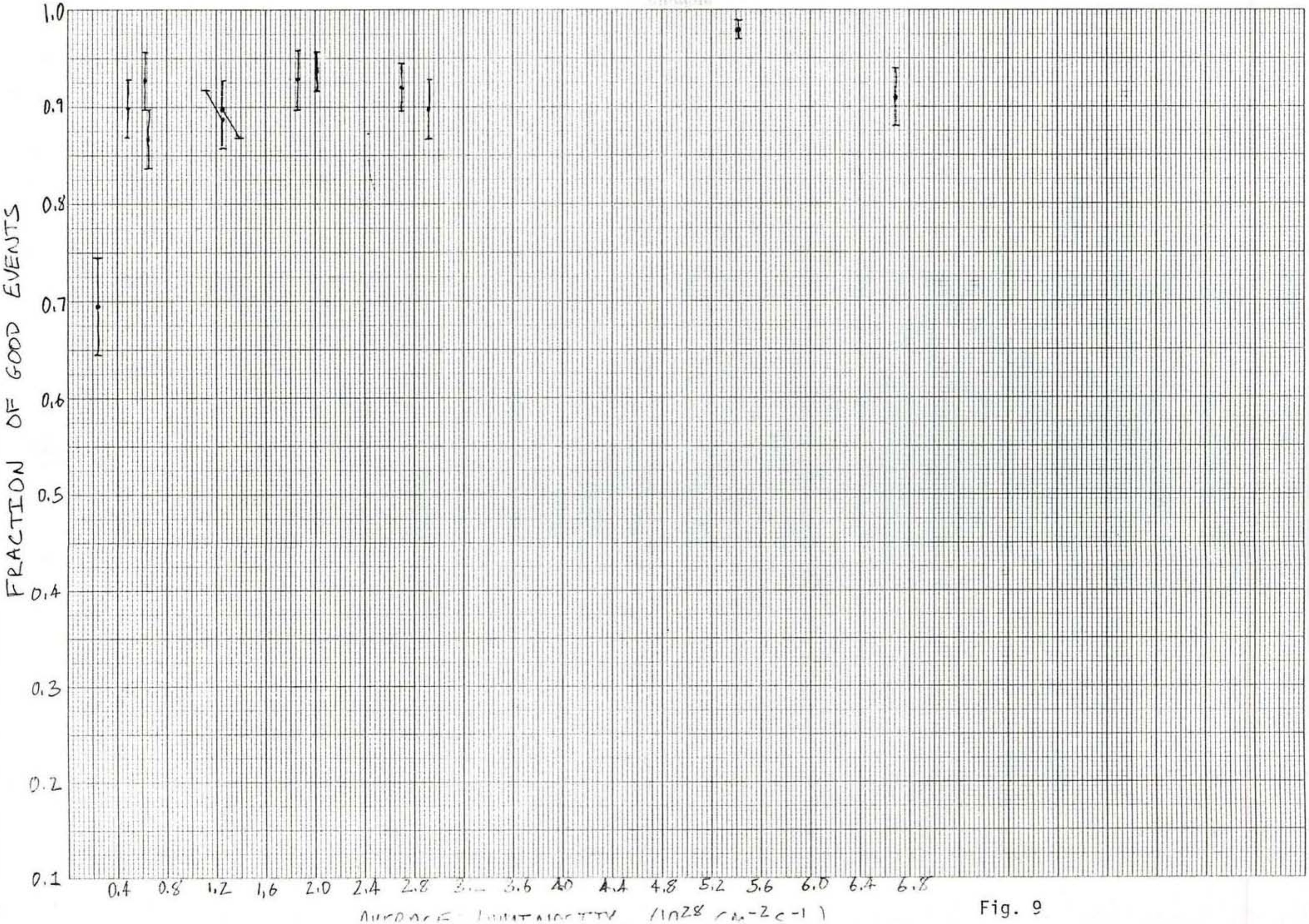


Fig. 9

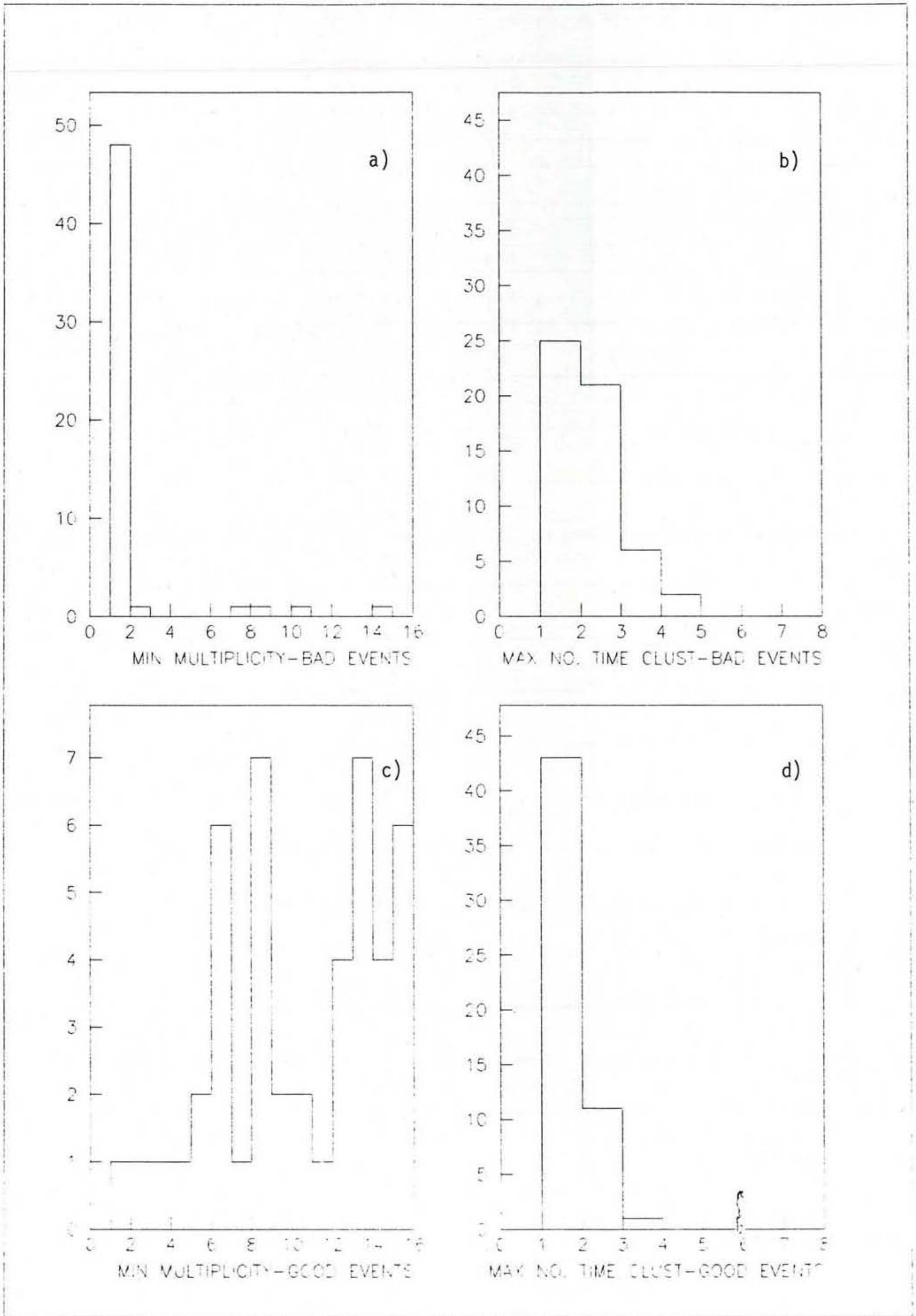

a)
b)
c)
d)
MIN MULTIPLICITY-BAD EVENTS
MAX NO. TIME CLUST-BAD EVENTS
MIN MULTIPLICITY-GOOD EVENTS
MAX NO. TIME CLUST-GOOD EVENTS

Fig. 10

K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM. KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1510

FRACTION OF GOOD EVENTS - VTPC + BBC SCAN

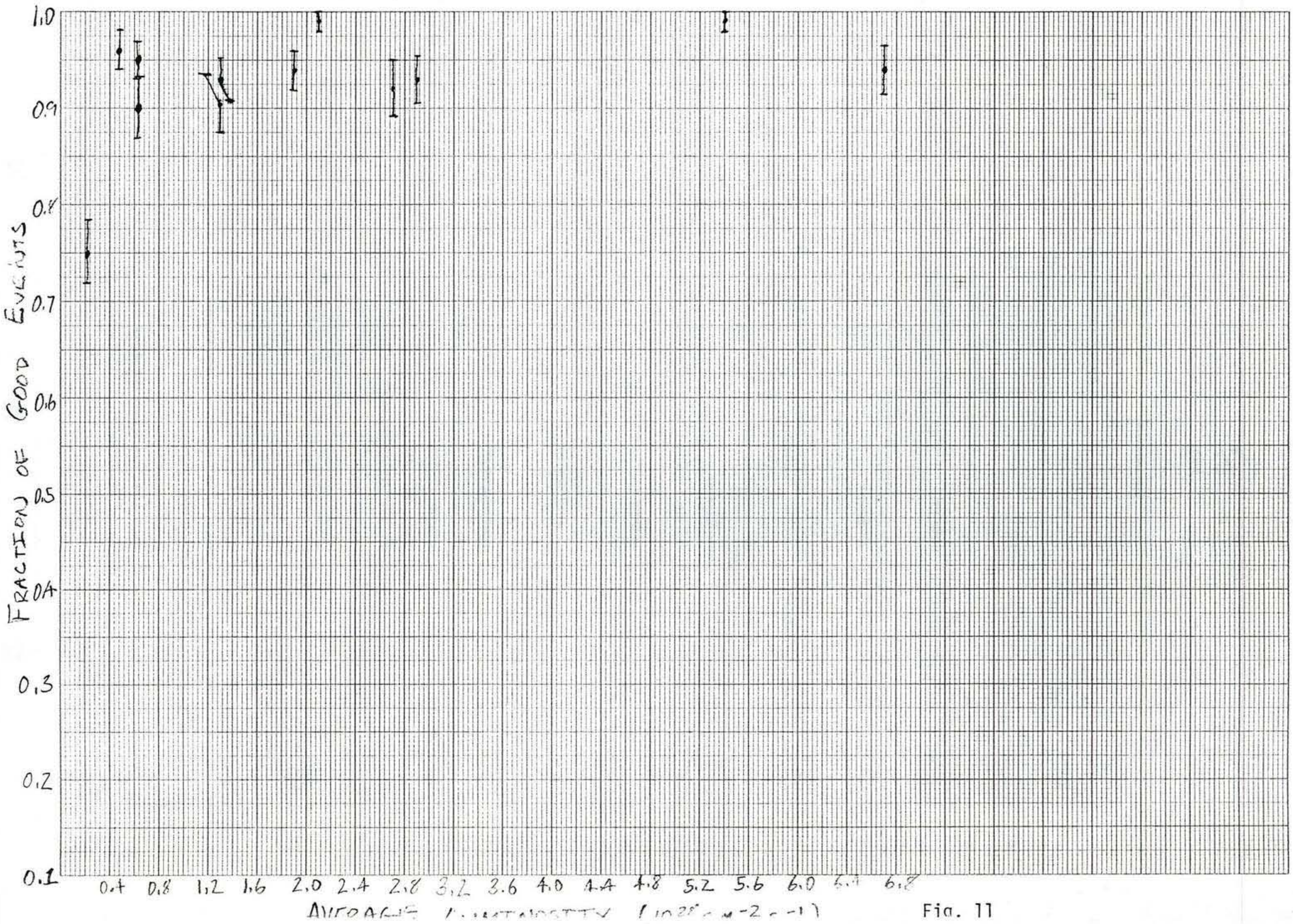
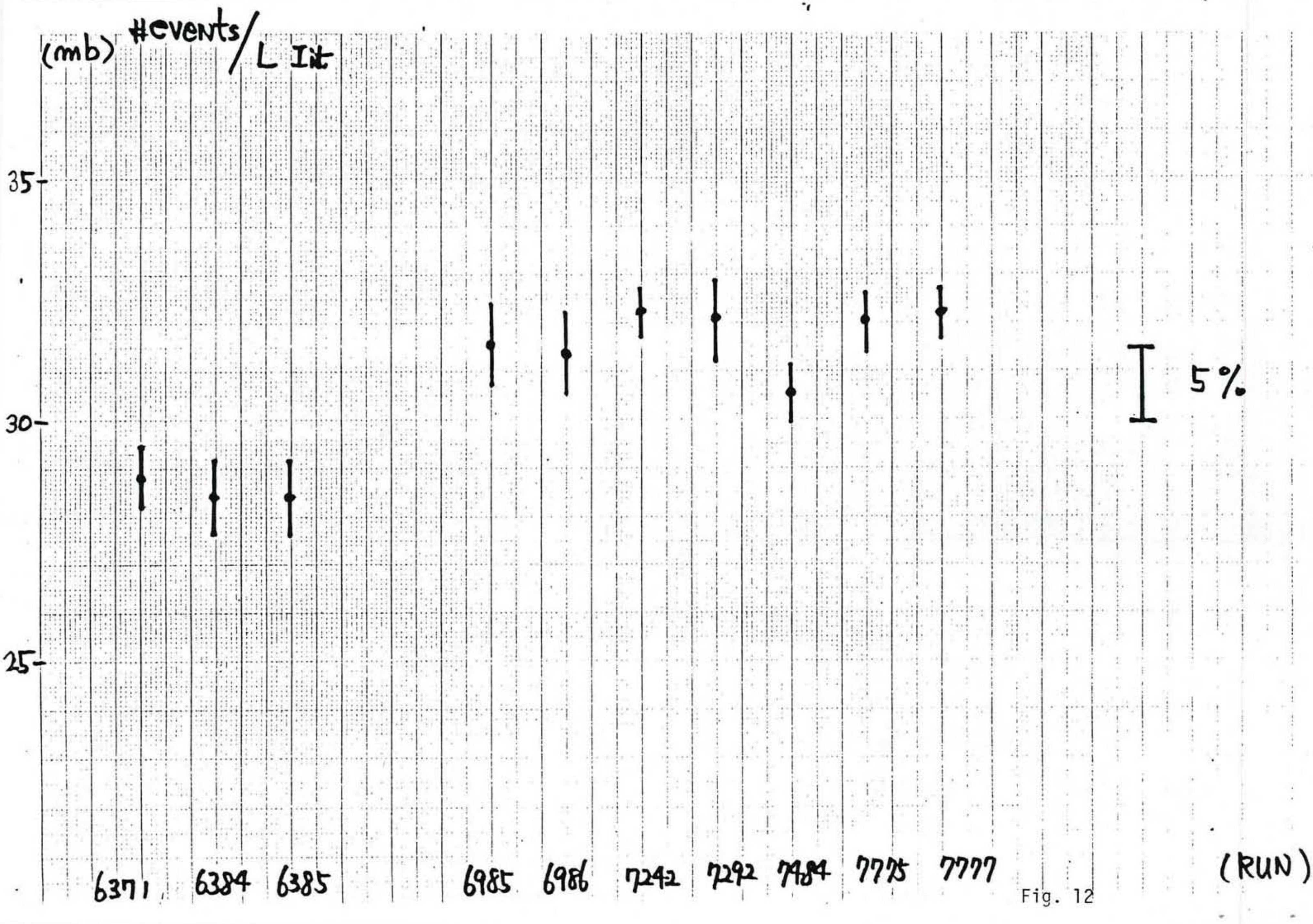


Fig. 11


(mb) #events/L Int
35
30
25
5%
6371
6384
6385
6985
6986
7242
7292
7484
7775
7777
(RUN)
Fig. 12

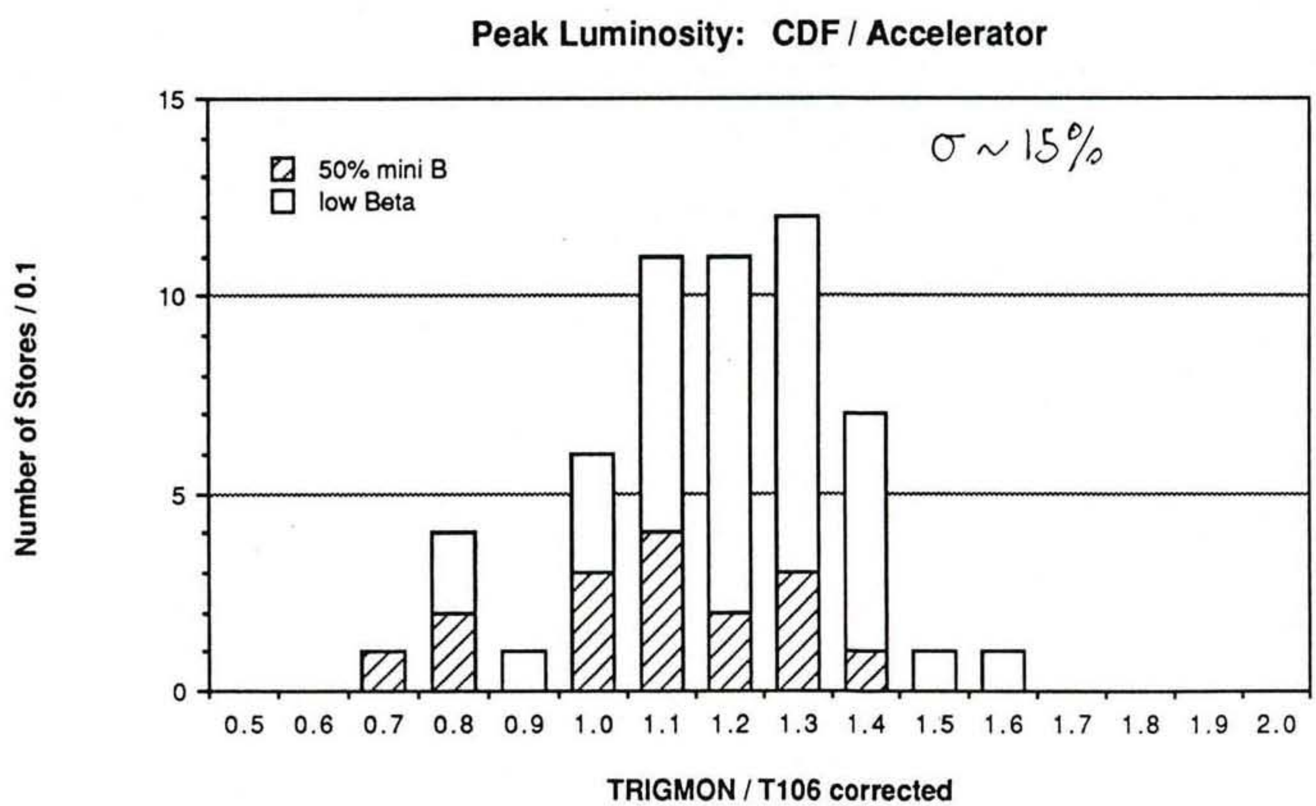

Peak Luminosity: CDF / Accelerator
15
10
5
0
50% mini B
low Beta
σ ~ 15%
Number of Stores / 0.1
0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
TRIGMON / T106 corrected

Fig. 13

CDF/COVER_NOTE/TO_REVISED_CDF_552/MILDLY_INTERESTING

Tony Liss

23-MAR-1988

This is a revised version of CDF-552 "Luminosity Monitoring and Beam-Beam Counter Performance" . Since the release of the original note, two things have happened which necessitated this revision.

First, I have put the correct BBC geometry into CDFSIM. Hovhannes Keutelian then ran the Rockefeller min-bias generator and CDFSIM to find the BBC acceptance for single and double diffractive and "hard core" events. The numbers I had used in the original CDF-552 came from CDF-257 where just the eta and phi values of the generated particles were used rather than CDFSIM. Hovhannes found that the original acceptances were somewhat low. The overall effect of the new acceptance values is to raise the BBC cross section from 42.5 to 44 mb.

Second, the analysis of the 630 GeV min-bias data has been completed and it was necessary to assign a BBC cross section at the lower energy. This work was done by the min-bias group, and it seemed reasonable to include the value here. Appendix B has been added and contains the BBC acceptances and the cross sections assumed at 630 GeV.

T.M. LISS
20-MAR-1988
Rev. 1

LUMINOSITY MONITORING AND BEAM-BEAM COUNTER PERFORMANCE

I. Introduction In the 1986-87 run the Beam-Beam Counters (BBC) were used for several purposes. They provided a fast Pbar-P vertex finder, complementary to the VTPC, the only measure of T_o (the interaction time), a minimum bias trigger, and the luminosity monitor. In this note we review the performance of the BBC in the recent run with respect to each of these functions.

II. Interaction Time and Vertex Finding As described in CDF-250, each of 64 BBC channels is equipped with both ADC and TDC readout. In addition, each of the two photomultipliers on a single counter are fed through a mean-timer to a Fastbus latch. A logic diagram is shown in Figure 1. The latch is gated twice, once at the time at which the incoming beams pass the counters, and once at the time at which the outgoing beams pass the counters. This timing is shown in Figure 2. The incoming gate, henceforth called 'beam-halo', is 100ns wide and closes 10ns before the crossing time (30ns before outgoing particles reach the counters). The outgoing gate, henceforth called 'beam-beam' is 15ns wide and is centered 20ns after the crossing at the time at which outgoing particles from an interaction reach the counters.

The interaction time and vertex finding are, in principle, straightforward. One simply averages the TDC values over all hit counters on a single side (east or west) and calculates the interaction vertex as

$$Z_{int} = c/2(T_W - T_E) \tag{1a}$$

and the interaction time as

$$T_o = 1/2 (T_W + T_E) \tag{1b}$$

where T_W and T_E are the mean times on the west and east sides, respectively. In practice, however, one must make corrections for pulse height slewing in order to obtain the best results.

The effect of pulse height slewing was corrected by fitting the three constants A,B and C of the function

$$T = \frac{A}{\sqrt{Q + B}} + C \tag{2}$$

where T is the TDC value in ns (i.e. after D to E conversion) and Q is the ADC value in pC above pedestal (also after D to E). The constant B accounts for pedestal shifts, while C incorporates an arbitrary offset in the TDC start time as well as other, less well understood effects to be discussed below.

a) ADC and TDC performance

The TDCs employed were of the standard CAMAC variety, LeCroy model 2228A. These were read out through Fastbus with the help of a Struck Fastbus-CAMAC branch driver. These caused no problems other than an occasional dead channel. TDC calibrations were done at several points during the run and resulted in gains constant to a few percent and no significant pedestal (offset) shift. On the contrary, the ADCs did not perform so nicely. Again, calibrations were done at several points during the run and resulted in constant gains and pedestals. Figure 3 shows a pedestal distribution from the BBC accumulated during a level 1 query run. This clearly shows two peaks, characteristic of low frequency noise (eg. 60hz). The ADC resided in the Scaler crate in the trigger room. This crate has had repeated noise problems over the last two years, had very poor cooling, and should not be harboring a sensitive analog device such as the ADC. For the coming run, the ADC will be relocated in one of the trigger racks with 400hz linear supplies. It is hoped that this will eliminate the noise problems.

Prior to the run, each BBC channel was calibrated using cosmic rays. The high voltage for each channel was adjusted so that the Landau peak was roughly 300 counts above pedestal, about 15 pC. During the run no hint of minimum ionizing was seen in the ADCs. A typical ADC distribution taken from a minimum bias run is shown in Figure 4. This shows that the mean ADC value for this channel corresponds to roughly 10 minimum ionizing particles! It is likely that this effect is due to the fact that the counters are being hit with a high multiplicity (though not 10!) of non-minimum ionizing particles created by secondary interactions in the wealth of material in front of the counters (beam pipe, flanges...) and back-scattering off the lead of the forward electromagnetic shower counter. These effects degrade the timing performance of the BBC because multiple hits on a counter result in TDC times which are too small. Another possibility is that the ADC just wasn't working at all. This is clearly not the case as can be seen from Figure 5 which shows the expected relationship between TDC value and ADC pulse height. The procedure used to make this plot is discussed in section b below.

Despite these difficulties, we were able to obtain quite reasonable timing performance from the counters. This is because although the counters were hit quite hard, the PMT gains were set (intentionally) low and the ADC had sufficient range (15 bit) to prevent saturation, so that the TDC vs. ADC relationship followed the expected form.

b) TDC vs. ADC Fitting Procedure

Each BBC channel was fit separately to the function in equation (2). The ADC and TDC values used were in pC and nS respectively (i.e. after application of calibration constants). The need for the constant B in equation (2) is clear from Figure 3 where it can be seen that, although the main pedestal peak is centered at about -0.6 pC, amounting to only a 2% pedestal shift, there is a significant amount of data at considerably lower values.

The constants of equation (2) were fit using minimum bias data. The mean TDC value over an entire run was calculated in each of 42 ADC bins from -2 pC to 80 pC. Above 80 pC the mean value was fairly constant and inclusion of additional data above this value did not change the quality of the fit. In fitting to the function (2), each bin was weighted by a factor which depends on the bin center. This factor was the inherent rms width of the TDC values for that bin. In order to remove the dominant effect of the Pbar-P bunch widths, the rms was calculated from the distribution of $(T - T_o)$ where T_o is the interaction time which, in this case, was determined from all remaining channels using very hard cuts to obtain a good value without concern for acceptance. Figure 5 shows the results of this fit for a single channel. The error bars shown represent the rms deviation including the inherent width and the effects of bunch size. The functional fit is overlayed using a solid line.

One would hope that this fitting procedure could be done just once for each channel and that the constants A, B, C thereby obtained would be good for all runs. This however proved not to be the case, and the reason why is not well understood at this time. Typically, a set of constants would hold good for a period spanning one to two weeks after which channel to channel variations in the mean TDC values (after all corrections) would begin to be observed. One possible source of this effect is a change in the gains or pedestals in the ADC which were not well tracked during the run (although they did not appear to change when calibrations were done). This might be caused by the poor cooling in the Scaler crate, noise etc. The TDCs appeared to be very well behaved and it seems unlikely that they contributed to this problem. Once again it is hoped that moving the ADC to a quiet crate with linear supplies will solve this problem, and that doing more regular calibrations may identify the source.

The constant C of the fit gives the asymptotic value of the function, i.e. the TDC value for infinite pulse height. Several factors influence changes in this asymptotic value. Among these are changes in the timing of the Master Clock strobe (Beam-Beam Start) which sets the overall timing for the BBC (see Fig. 1), drifts in the NIM logic creating the TDC start signal, and a 'real' shift in the interaction time, T_o, associated with a shift in Z_{int}.

Because of these drifts, it is necessary to include the constant C in the TDC correction, so that the corrected TDC value, T' is given by

$$T' = T - \frac{A}{\sqrt{Q + B}} - C + 67.5$$

where the constant 67.5ns is an arbitrary offset added so that the corrected and uncorrected times appear at approximately the same place in a histogram (it is removed for calculating T_o). This has the undesirable effect of fixing the mean times on the east and west sides to be the same and therefore defining the mean T_o and Z_{int} both to be 0. One way around this problem is to adjust the constant C, after fitting, so that the mean value of Z_{int} for an entire run agrees with the mean value obtained by the VTPC.

A procedure was attempted in which the constants A,B and C were fit for a single run and the constant C adjusted for that run so that Z_{int} from the BBC and VTPC had the same mean value. For future runs, only the constants A and B were fit, leaving C fixed. This procedure resulted in fits which were systematically too low at low ADC values, where the variation of time with pulse height is greatest. Following this attempt, it was decided that all three constants would be fit for each minimum bias run and the constant C adjusted for agreement with the VTPC of the mean Z_{int}. Typical adjustments amount to a Z_{int} shift of about 10cm. It should be noted that this does not mean that the

VTPC and the BBC no longer give independent measures of Z_{int}. This is simply a method for removing all types of timing drifts without losing sensitivity for measuring Z_{int}. Only the mean value over the entire run has been adjusted, event to event values are still independent. It should also be noted that because of the arbitrary nature of the adjustment of the constant C, T_o values can no longer be compared from one run to another. T_o is now a relative, event to event, measure of the interaction time for a given run, but is subject to run to run offsets of as much as 1 ns. It is felt that, although this is clearly undesirable, it does not seriously affect the way in which T_o might be used by say, the tracking chambers. It is hoped that when the causes of the various drifts are fully understood a better method of removing them can be found.

c) Interaction Time and Vertex Algorithm The interaction time is found separately for the east and west sides. This is done with a clustering algorithm in which the corrected TDC values are arranged in decreasing order. All channels within a given time window (typically 8ns) are clustered together, beginning with the largest TDC value and proceeding downwards. If the corrected values of all hit channels are within 8ns of each other, then there is just one time cluster, otherwise there is more than one. The value of 8ns was chosen to allow for the dispersion of arrival times of light at the face of the phototubes due to variation of the position at which a particle hits a counter. This was necessary because the PMTs are being treated on a channel by channel basis, in order not to bias against counters with one malfunctioning channel, so that mean timing is not possible. Once the clustering is completed, the mean time of the cluster which includes the most channels is used as T_W or T_E and Z_{int} and T_o are calculated from equations (1a) and (1b) above.

Despite the various troubles, the overall performance of the BBC for interaction vertex and time determination was very good. Figure 6 shows a scatter plot where the abscissa is the VTPC vertex in cm and the ordinate is the BBC vertex in cm. Figure 7 shows the deviation (Z_{BBC} - Z_{VTPC}). The FWHM of this distribution is about 9cm, corresponding to a BBC time resolution of better than 125 pS (neglecting $\sigma_{VTPC}(Z)$ which is of order millimeters).

d) Offline code The offline code which performs the above T_o and Z_{int} analysis is contained in the BBCOFF module in C$TRS (dictionary file C$TRS:BBC_DIC.UIC). A document describing this code exists in C$TRS:BBCOFF.MEM.

III. Luminosity Monitor and Minimum Bias Trigger Since the minimum bias trigger and the luminosity monitor were one and the same during the '86-'87 run, with the luminosity monitor counting E·W coincidences and minimum bias data being triggered by them (in what follows, E·W will always refer to coincidences with at least one hit on each side). I will concentrate here on the performance of the BBC as a luminosity monitor since this is directly transferable to its performance as a minimum bias trigger.

a) BBC Cross Section The integrated luminosity is calculated as the number of BBC E·W coincidences divided by the part of the Pbar-P total cross section seen by the BBC. The average luminosity is just this number divided by the live time. The BBC cross section can be measured in the standard fashion outlined in the run plan by simultaneously measuring the BBC rate and the total Pbar-P cross section using the Forward Silicon. Unfortunately we were unable to make this measurement during the past run, so we must do our best to estimate the BBC cross section.

In order to estimate the BBC cross section, the total cross section must be broken up into its various components, elastic, diffractive and hard core (inelastic minus single and double diffractive), and the BBC acceptance for each determined. The acceptances used here are those determined by Hovhannes Keutelian using CDFSIM and the Rockefeller minimum bias generator, MBR. Level 1 Query scans, described below, lend at least some support to these values.

To estimate the total cross section at $\sqrt{s}$ = 1800 GeV, I have used all recent predictions from the literature. These predictions span a range of only 74 mb to 80 mb where both extremes come from a paper by Block and Cahn[1]. The smaller value is arrived at by extrapolating from lower energy data and assuming that the cross section is asymptotically constant at very high energies but locally proportional to $\log^2 s$, while the larger value results from assuming the cross section to continue to evolve proportionally to $\log^2 s$. Taking the mean of these two values I take the total cross section to be

$$\sigma_{tot} = (77 \pm 6) \text{ mb}$$

where the error is chosen simply to allow the value to comfortably span the entire range of the predictions.

Next I estimate the elastic cross section. UA4 has measured[2] the ratio σ_{el}/σ_{tot} at a center of mass energy of 546 GeV. They find σ_{el}/σ_{tot} = 0.215 ± 0.005. Taking the ratio of UA5 elastic and total cross sections[6] I get 0.194 at

200 GeV and 0.230 at 900 GeV. The prediction given by Goulianos[3] for $\sqrt{s}$ = 1800 GeV is σ_{el}/σ_{tot} = 0.229. This would appear to be inconsistent with the UA5 value at 900 GeV. However, this ratio should vary slowly, as is born out by the data in Figure 8, so the prediction of Goulianos is not so bad. Goulianos predicts a ratio of 0.221 at 900 GeV, so it seems conservative to associate an error of 0.01 with his prediction at 1800 GeV. This gives

$$\sigma_{el} = (17.6 \pm 1.6) \text{ mb}$$

where the error results from the uncertainty in the total cross section above, and the uncertainty in the ratio.

Given the above values for σ_{tot} and σ_{el}, the inelastic cross section is given by

$$\sigma_{in} = \sigma_{tot} - \sigma_{el} = (59.4 \pm 4.7) \text{ mb}$$

The inelastic cross section itself breaks up into three components, hard core, σ_o , and single and double diffractive, σ_{sd} and σ_{dd} respectively. Here I will make best estimates of σ_{sd} and σ_{dd} and then use σ_{in} above to calculate σ_o. UA5 has measured[4] the single diffractive cross section to be (7.8 ± 1.2) mb at 900 GeV (I use the convention here that the single diffractive cross section is the sum of the proton and anti-proton components, thus for comparison the values given by Goulianos, for instance, must be multiplied by two). The prediction of Goulianos for center of mass energy of 1800 GeV is 17.2 mb , and this value is given some support by the analysis of the BBC scalers done by Giokaris and Goulianos[5]. There is some controversy over the diffractive cross sections, but given that the BBC scaler analysis is the only experimental work of any kind at our energy, I use here a value somewhat larger than appears warranted from the data. From Figure 8 it can be seen that the predictions of Goulianos are systematically above the measured values. I use this as a measure of the uncertainty in the prediction and take

$$\sigma_{sd} = (15.0 \pm 5.0) \text{ mb}$$

There is even more uncertainty associated with the double diffractive cross section, however, its value is certainly small and the BBC acceptance is approximately 60%. Therefore it does not have a big effect on the overall BBC cross section. Guided by the literature I here assume

$$\sigma_{dd} = (4.2 \pm 1.0) \text{ mb}$$

where the error is assumed to be a conservative 25%.

Using these values, one arrives at

$$\sigma_o = \sigma_{in} - \sigma_{sd} - \sigma_{dd} = (40.2 \pm 6.9)$$

and, finally, using the Rockefeller Monte Carlo acceptances for the BBC we get

$$\sigma_{BBC} = 0.17\sigma_{sd} + 0.71\sigma_{dd} + 0.96\sigma_o = (44 \pm 6) \text{ mb}$$

b) Background The requirement of only a single counter hit on each side is necessary in order to make a reliable estimate of the cross section. However, this trigger also has the potential for admitting a substantial amount of background due to back scattering from beam-gas collisions. In order to determine the magnitude of the background accepted by the luminosity monitor, hand scans were done of 100 events from each of the minimum bias runs as well as from several of the minimum bias production tapes where pre-scaled minimum bias events were stripped off of high Pt runs. These scans spanned runs with average luminosities from 0.2×10^{28} $cm^{-2}s^{-1}$ to 6.7×10^{28} $cm^{-2}s^{-1}$.

The events scanned were separated into three categories, good beam-beam events, background events and events which, for one reason or another, could not be placed in either of the first two categories. Events in this third category, amounting to only a few percent of all events, were eventually removed from the sample. The first pass through the events used selection criteria which depended only on the VTPC. Events were called good beam-beam if either of two conditions were satisfied:

1) For events with a low multiplicity of VTPC tracks (<5) at least three tracks pointing at a vertex were required with at least one of the tracks opposing the others (in η).

2) For events with with five or more tracks in the VTPC at least two tracks were required to oppose the others pointing at a vertex. This was done to eliminate the background which typically consists of a single back scattered particle opposed by a large beam-gas spray in the forward direction.

The results of this initial scan are shown in Figure 9 as a function of the luminosity of the run. One might expect that the fractional background would decrease with increasing luminosity. The data does not contradict this hypothesis, however due to the limited statistics of the sample it is not distinguishable from a constant fraction of about 11%.

Following this initial scan, a second scan was done of rejected events in order to recover those beam-beam events which do not leave tracks in the VTPC (recall that the VTPC and the BBC have a very limited overlap). In order to do this, selection criteria based solely on the BBC latches and TDCs had to be established. This was done by separating rejected events into two categories, those events which were obvious background and those that were not. The different characters of the background events and events determined to be good beam-beam events by the VTPC selection were then used to establish the selection criteria.

An event with many VTPC hits but no tracks pointing at a vertex was called "obvious background". Figure 10a shows a distribution, for "obvious background" events, of the number of counters hit in the beam-beam gate on the side with the fewest counters hit in this gate. A very marked peak at a single counter is seen. Figure 10b shows the distribution of the number of time clusters (see IIc) on the side with the maximum number, for these same events. Figures 10c and 10d show these same distributions for a random selection of good beam-beam events. Based on these distributions "not obvious background" events were moved into the "good" category if:

1) There were more than 4 counters hit on each side in the beam-beam gate and

2) There was just one time cluster on each side.

The effect of lowering the multiplicity requirement in 1 was studied and it was found that reducing it to greater than two counters, rather than four, reduced the calculated background contribution by only 1%.

Figure 11 shows, as a function of luminosity, the fraction of good beam-beam events accepted by the BBC. It is seen again that this fraction has no obvious dependence on luminosity. One could fit the data to a function with some hypothesized form and parameterize the background fraction as a function of luminosity. However, the actual functional form is unknown and likely to be quite complicated, depending on many factors other than just the proton and anti-proton beam currents. Given this, it is felt that the most prudent thing to do is to assume a constant background fraction given by the mean of the data. In computing this mean the lowest point was eliminated and the mean calculated from the remaining points. The remaining 11 runs resulted in 988/1050 events scanned which passed the filter for a background fraction of (6 ± 0.7)% where the error quoted is a statistical error on the mean. By assuming a constant non-zero slope passing 1σ above the highest luminosity point in Figure 11, and consistent with the bulk of the points above 0.4 x 10^{28}, I estimate that a possible error of about ±3% is introduced by assuming a constant background fraction over this range of luminosities.

More work will be done in this area to improve the statistics in order to better understand the dependance of background fraction on luminosity.

c) BBC Acceptance Check In order to check the acceptances given by the Rockefeller Monte Carlo, a scan of Level 1 Query data was done. Raw data tapes from Level 1 Query runs with beam in the Tevatron were passed through a software filter which required at least five hits in the VTPC. All events which passed this filter were hand scanned. The same VTPC criteria as described above for the background study were used to define good beam-beam events. For all events declared as good beam-beam events, the BBC beam-beam latch bits were checked to determine if the event would have been counted as an E·W coincidence. 164/175 beam-beam events contained an E·W coincidence, giving a BBC acceptance of (93.7 ± 1.8) % .

Since, by necessity, the VTPC was used in this study, there was little sensitivity to double diffractive events and virtually no sensitivity to single diffractive events. Thus, we should compare this value of the BBC acceptance to that given by the monte carlo for the hard core (σ_0) part of the cross section. The monte carlo predicts a BBC acceptance of 96% for σ_0, in excellent agreement with the value above.

d) Luminosity Calculation An offline module, LUMBBC (dictionary file C$TRS:LUMBBC.UIC), has been provided to perform luminosity calculation from the scaler banks, SCLD. This module is nearly identical to the online code in TRIGMON, and works as follows. At each event, the scaler banks are located and the livetime, the number of times at least one beam-beam hit occurred on the west and on the east, and the number of times an E·W coincidence occurred (with at least one hit on each side), is picked up. From these four quantities the luminosity is calculated according to the following formula:

$$\int L dt = \frac{(E_t + W_t - BC) + \sqrt{(BC - E_t - W_t)^2 + 4(BC(WE)_t - E_t W_t)}}{2\sigma_{BBC}}$$

Where W_t and E_t count the OR of the beam-beam gate hits on the west and east sides, respectively, BC is the total number of live time beam crossings, $(WE)_t$ is the total number of E·W beam-beam coincidences, and σ_{BBC} is the BBC cross section from IIIa. This formula results from an algorithm which corrects the E·W coincidence rate for random coincidences between the east and west singles rates. It is correct only in the limit where the number of beam crossings is much greater than the number of collisions.[7] The calculation leading to this equation is done in Appendix A. Note that this correction applies only to accidental coincidences as opposed to the single beam events which cause correlated hits on both sides. This latter type of background is the dominant source of the events discussed above in IIIb. The correction had very little effect (typically 0.5%) during most of the run, but was important early on when the vacuum was bad (resulting in large singles rates) and the luminosity was low.

e) Stability of the BBC Luminosity Monitor Figure 12 shows the cross section for events passing a rather restrictive filter run on minimum bias events.[8] This cross section is calculated by dividing the integrated luminosity by the number of events passing the filter. The filter is restrictive enough that it passes essentially no background, although it does eliminate some fraction of real events as indicated by the fact that the cross section is lower than the BBC cross section of 42.5 mb. For the first three points on this plot, the events being counted by the luminosity monitor were not the same as those causing triggers. This is the reason for the step in the ratio of integrated luminosity to events passing the filter. Aside from this one feature, these data indicate that the luminosity monitor is stable to at least ±2%.

Another way to test the stability of the luminosity monitor is to compare the luminosity calculated from accelerator parameters to the luminosity given by the event rate seen by the BBC. Figure 13 shows a histogram of the ratio of the accelerator luminosity to the BBC luminosity.[9] This ratio has an rms deviation of 15%, considerably more than the 2% variation quoted above. All indications are that the BBC stability is much less than ±15%. This is evident not only from the data shown in Figure 12, but from hand scans of minimum bias data, trigger rates as a function of BBC luminosity and general features of the BBC system which make it hard to understand such a large run to run variation. Never the less, without an understanding of the precise cause of this disagreement, one cannot simply assume that this 15% deviation is due to accelerator uncertainties alone. Therefore, we take the conservative view here that the 15% deviation is due to equally weighted uncertainties in both the BBC and accelerator measurements. From this we arrive at a very conservative measure of the BBC run to run stability of ±11%.

f) Overall Uncertainty in the Luminosity

Finally, from the above discussion, we may estimate the overall uncertainty in the luminosity measurement given by the BBC. We have an 11% uncertainty in the event rate (this is given by the spread in the ratio of accelerator to BBC luminosities) and an 15% uncertainty in the BBC cross section. If we add these two in quadrature, we arrive at an overall uncertainty of ±19%. We note, however, that it is more proper to quote these errors separately, the first being an uncertainty do to fluctuations, while the latter is a systematic uncertainty.

Furthermore, it is important to note that in using the integrated luminosity to calculate physics quantities, we will in general be summing over a very large number of runs. In this case the uncertainty due to fluctuations (i.e. the 11% derived from Figure 13) will very quickly become negligible because it decreases as $1/\sqrt{N}$ where N is the number of runs being integrated over. In this case, and this will almost always be the case, the uncertainty in the integrated luminosity is entirely dominated by the 15% uncertainty in the cross section for triggering the Beam-Beam Counters.

III. Conclusion

We have reviewed the performance of the Beam-Beam Counters both offline and online. The BBC system has been shown to be capable of measuring the interaction time to better than 200 ps, and the interaction position to better than 6cm.

As a luminosity monitor, the BBC system has performed quite well. Indications from CDF data all point to an uncertainty in the luminosity measurement of ±15%, dominated entirely by the uncertainty in the cross section for triggering the BBC. These same data indicate that the run to run stability of the system is better than 2%. Unfortunately, the agreement with the luminosity given by accelerator parameters is not this good, and because this disagreement is not well understood on accelerator grounds, it must be assumed at this time that a BBC instability of some sort contributes. Given these facts, we have shown that the overall run to run uncertainty in the luminosity measurement of the BBC is approximately ±19% . When integrating over large numbers of runs, as we will always do in publishing physics, the run to run uncertainty becomes insignificant and the uncertainty in the integrated luminosity is dominated by the 15% uncertainty in the BBC cross section.

Acknowledgment I would like to thank Bellisario Esposito for help with much of the work on interaction time and vertex determination.

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4. R. E. Ansorge et al., Z. Phys. C, 33, 175 (1986)
5. N. Giokaris and K. Goulianos, Private communication.
6. G. J. Alner et al., Z. Phys. C, 32, 153 (1986)
7. I thank Mauro dell'Orso and Paola Gianetti for pointing this out. At a luminosity of 10^{29} with three bunches, the number of accidental coincidences is overestimated by 3%.
8. Figure 12 is courtesy of Aesook Byon. She used G.P. Yeh's filter ZVTFLT which required a good vertex in the VTPC (it has since been modified somewhat).
9. Figure 13 is courtesy of John Cooper. The accelerator luminosities (labelled T106) include all corrections known at this time. The TRIGMON luminosity includes no corrections. Changes since the time these data were produced include the 6% background correction (multiply by 0.94) and a small change in the BBC cross section from 40.0 to 42.5 (multiply by 40.0/42.5).

APPENDIX A

Luminosity calculation:

In the following equations, W_S and E_S are defined to be the number of 'singles' counts on the west and east sides, respectively, where a singles count is defined to be any hit not associated with a pbar-p interaction (i.e. neglecting other sources of correlated hits). P_W is the probability per crossing of having a singles count on the west and $A_{W \cdot E}$ is the number of accidental coincidences between west and east singles hits. The rest of the parameters are defined in section IIId.

$$W_S = W_T - (WE)_R$$

$$E_S = E_T - (WE)_R$$

$$P_{W_S} = W_S/BC$$

$$A_{W_S \cdot E_S} = \frac{E_S W_S}{BC}$$

$$(WE)_T = (WE)_R + \frac{E_S W_S}{BC}$$

$$BC(WE)_T = BC(WE)_R + (E_T - (WE)_R)(W_T - (WE)_R) =$$

$$BC(WE)_R + E_T W_T - E_T(WE)_R - W_T(WE)_R + (WE)_R^2 \longrightarrow$$

$$(WE)_R + (BC\ -^2 E_T - W_T)(WE)_R - (BC(WE)_T - E_T W_T) = 0$$

$$(WE)_R = \frac{(E_T + W_T - BC) \pm \sqrt{(BC - E_T - W_T)^2 + 4(BC(WE)_T - E_T W_T)}}{2}$$

Finally, the integrated luminosity is given by $(WE)_R/\sigma_{BBC}$.

APPENDIX B

The following values, taken from the latest results of the UA experiments at CERN are used to find the BBC cross section at $\sqrt{s} = 630$ GeV :

$$\sigma_{tot} = 59.1 \text{ mb}$$
$$\sigma_{el} = 0.215 \cdot \sigma_{tot} \text{ mb}$$
$$\sigma_{sd} = 10.0 \text{ mb}$$
$$\sigma_{dd} = 2.5 \text{ mb}$$

Using

$$\sigma_{BBC} = .116\sigma_{sd} + .750\sigma_{dd} + .938\sigma_{o}$$

gives a BBC cross section at $\sqrt{s} = 630$ GeV of

$$\sigma_{BBC} = (34.8 \pm 3.5) \text{ mb}$$

where the error is a conservatively assigned 10% .

FIGURE CAPTIONS

Figure 1. A schematic diagram showing the Beam-Beam Counter logic for a typical counter. The box labelled 'Fastmac' TDC represents the CAMAC TDCs plus the Struck Fastbus - CAMAC branch driver.

Figure 2. A 'Minkowski' plot illustrating the timing of the BBC latch gates and TDCs. For reference, main proton and antiproton bunches as well as two satellites for each are shown.

Figure 3. An ADC pedestal distribution for a typical counter from a Level 1 Query run.

Figure 4. A pulse height distribution for a typical counter from a minimum bias run.

Figure 5. A plot of the dependence of the TDC value on the ADC pulse height. The abcissa gives the ADC value in pC above pedestal and the ordinate is the TDC value in nanoseconds.

Figure 6. A scatter plot with the interaction vertex position as found by the VTPC on the ordinate and that found by the BBC on the abcissa.

Figure 7. A histogram of the difference in vertex position between the VTPC and the BBC.

Figure 8. Measured and predicted cross sections at proton-antiproton colliders from 200 GeV to 1.8 TeV center of mass energy.

Figure 9. The fraction of minimum bias events passing beam-beam event selection criteria using the VTPC only.

Figure 10. Histograms of quantities used for selecting events based on BBC information. See section IIIb for a description.

Figure 11. The fraction of minimum bias events passing beam-beam event selection criteria using both the VTPC and the BBC.

Figure 12. Cross section for minimum bias events passing an event filter which eliminates backgrounds (and some real events). Courtesy A. Byon.

Figure 13. A histogram of the store by store ratio of the TRIGMON luminosity (i.e. the online BBC luminosity) to the luminosity calculated from machine parameters. All known corrections have been applied to the machine luminosity. Courtesy J. Cooper.

BEAM-BEAM COUNTER LOGIC

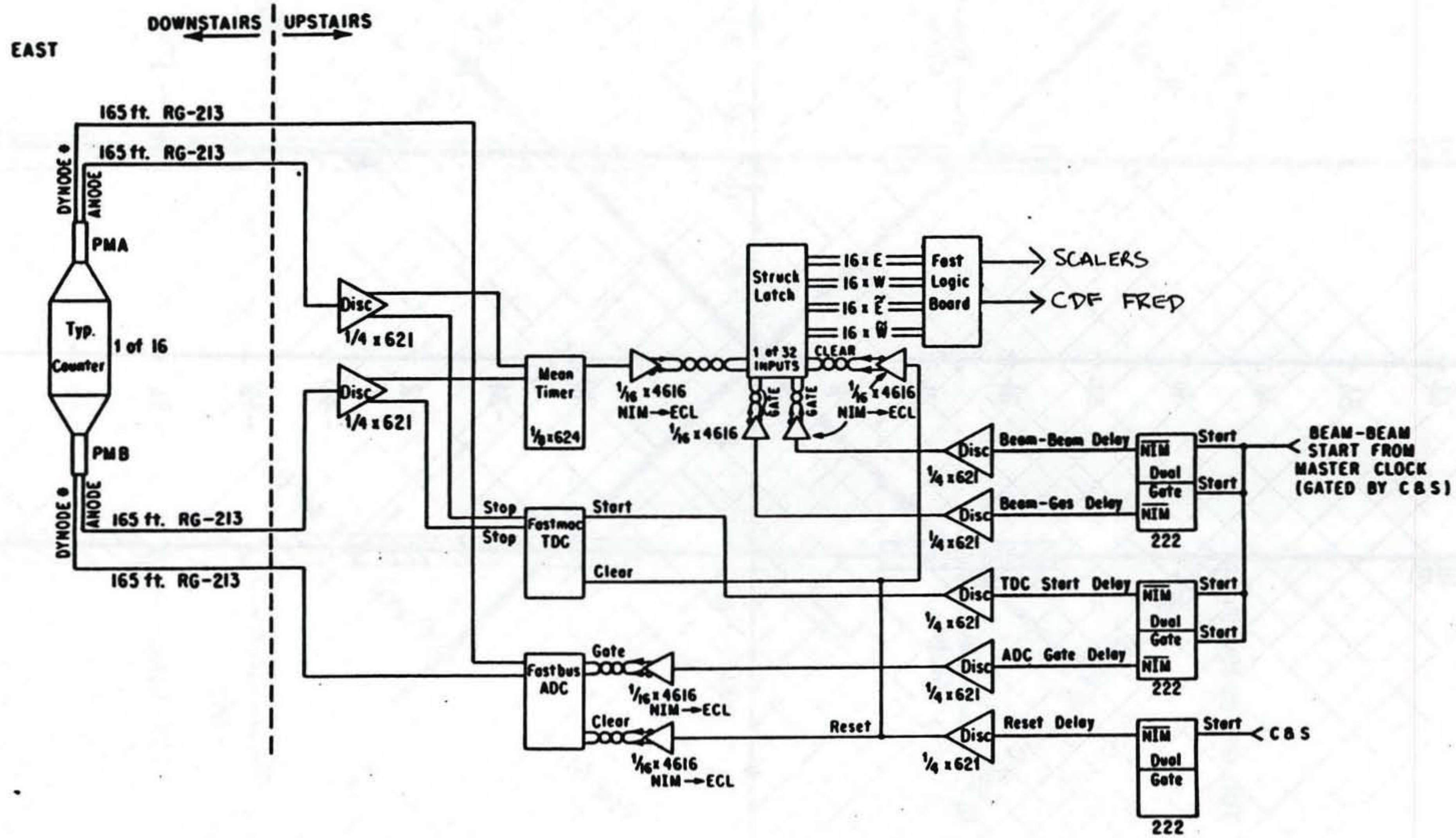
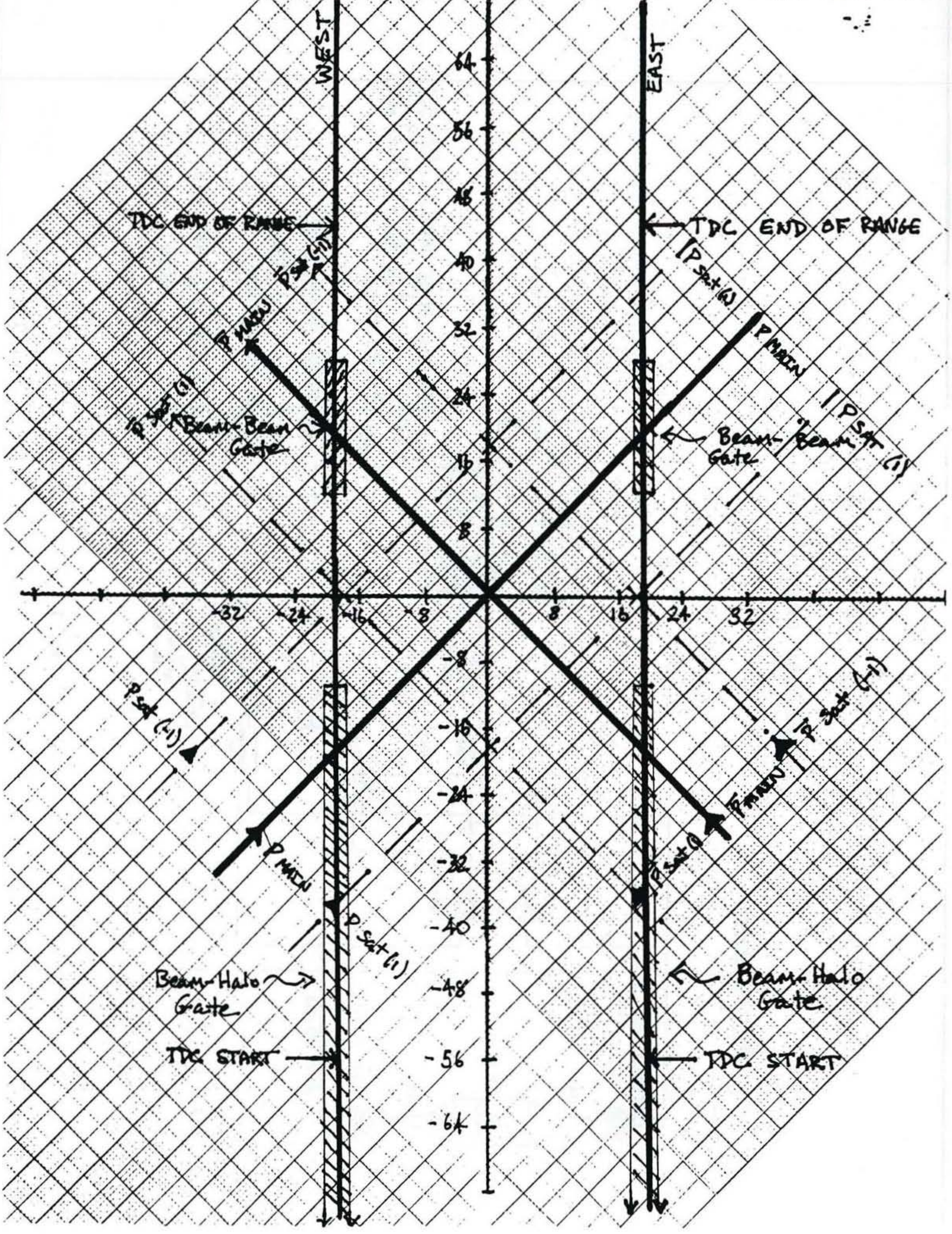


Fig. 1

K•Σ Minkowski 2ns x 2



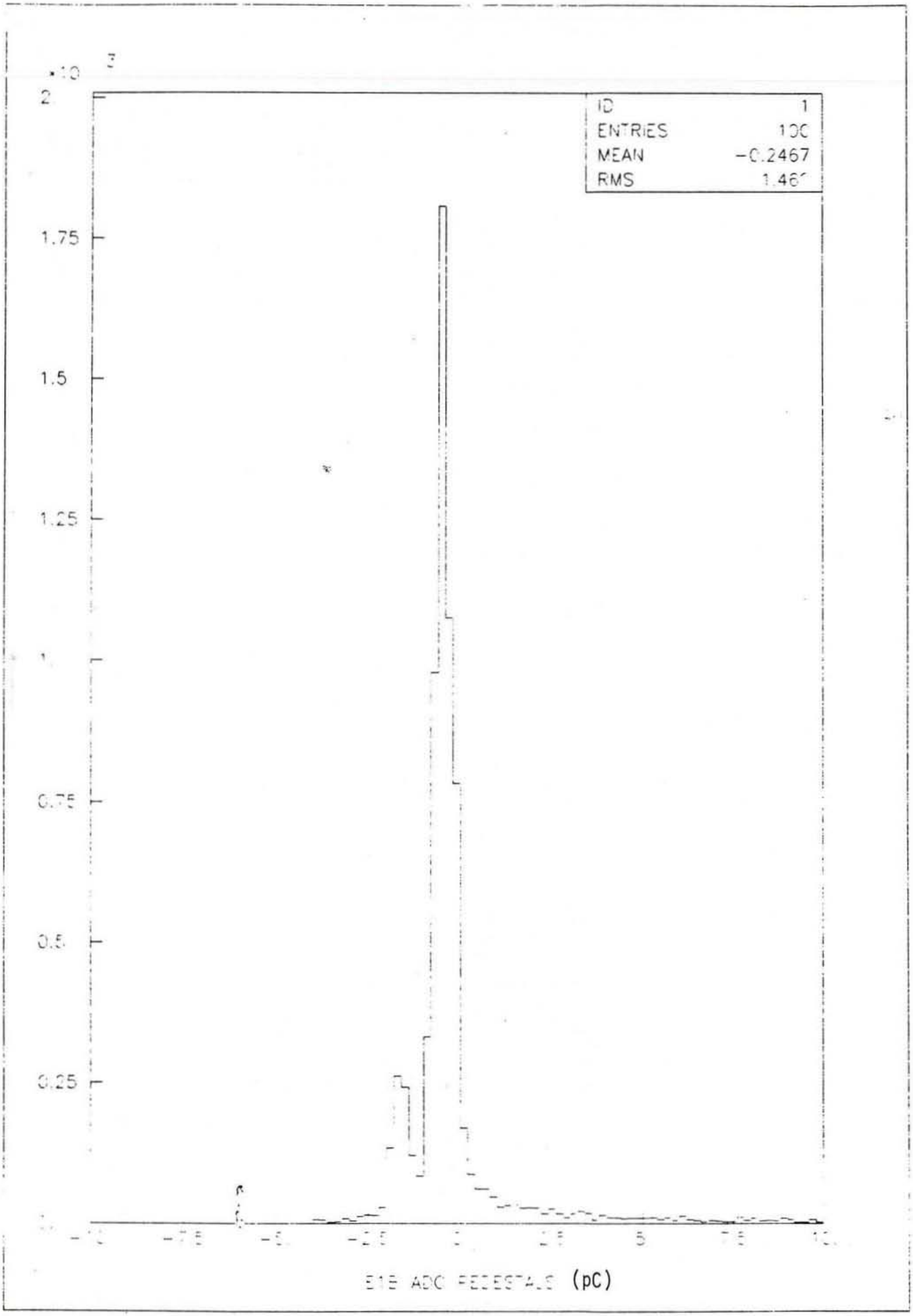

×10 3
ID 1
ENTRIES 100
MEAN −0.2467
RMS 1.46
2
1.75
1.5
1.25
1
0.75
0.5
0.25
5
7.5
(pC)

Fig. 3

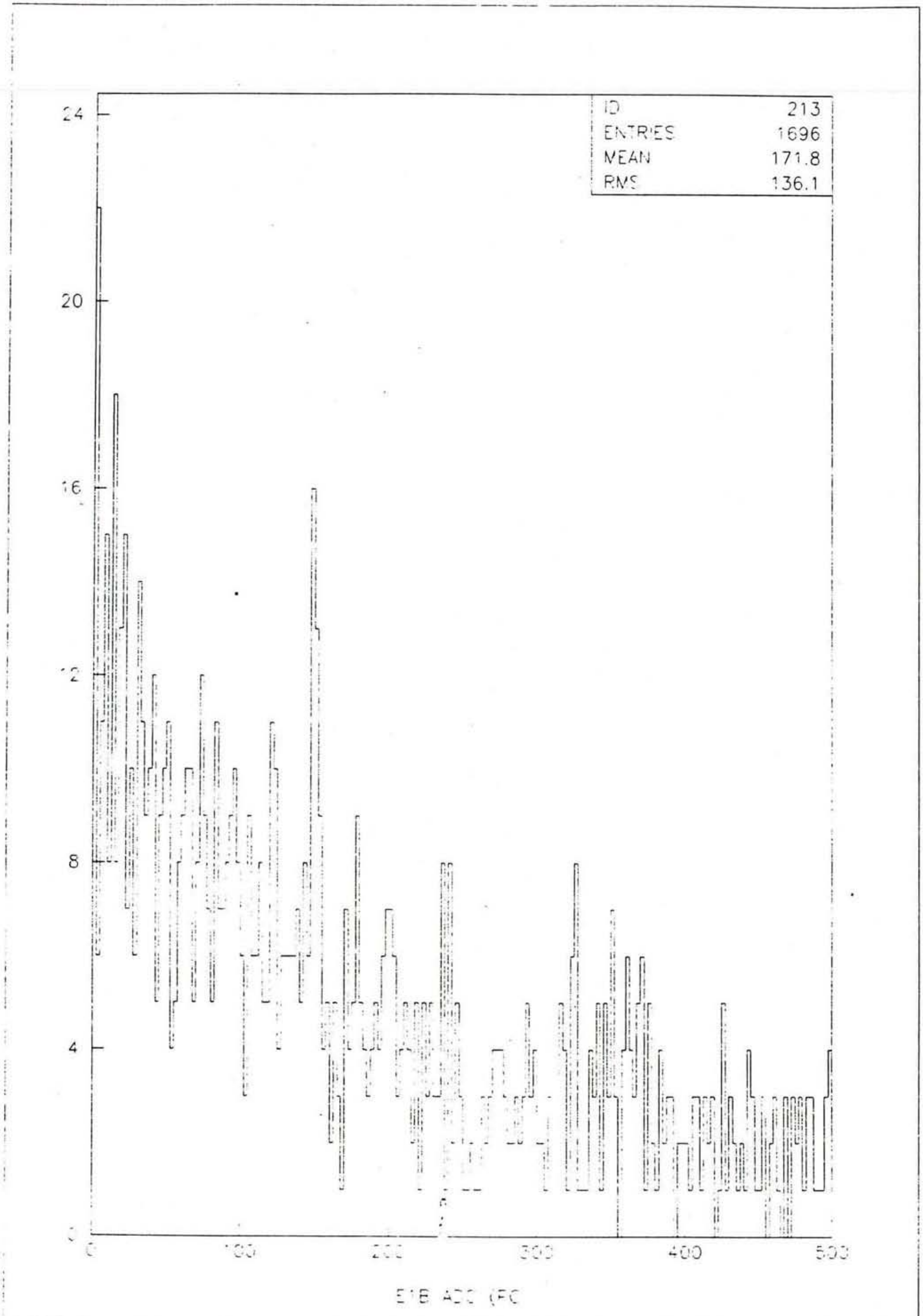

ID 213
ENTRIES 1696
MEAN 171.8
RMS 136.1
24
20
16
12
8
4
0
0
100
200
300
400
500

Fig. 4

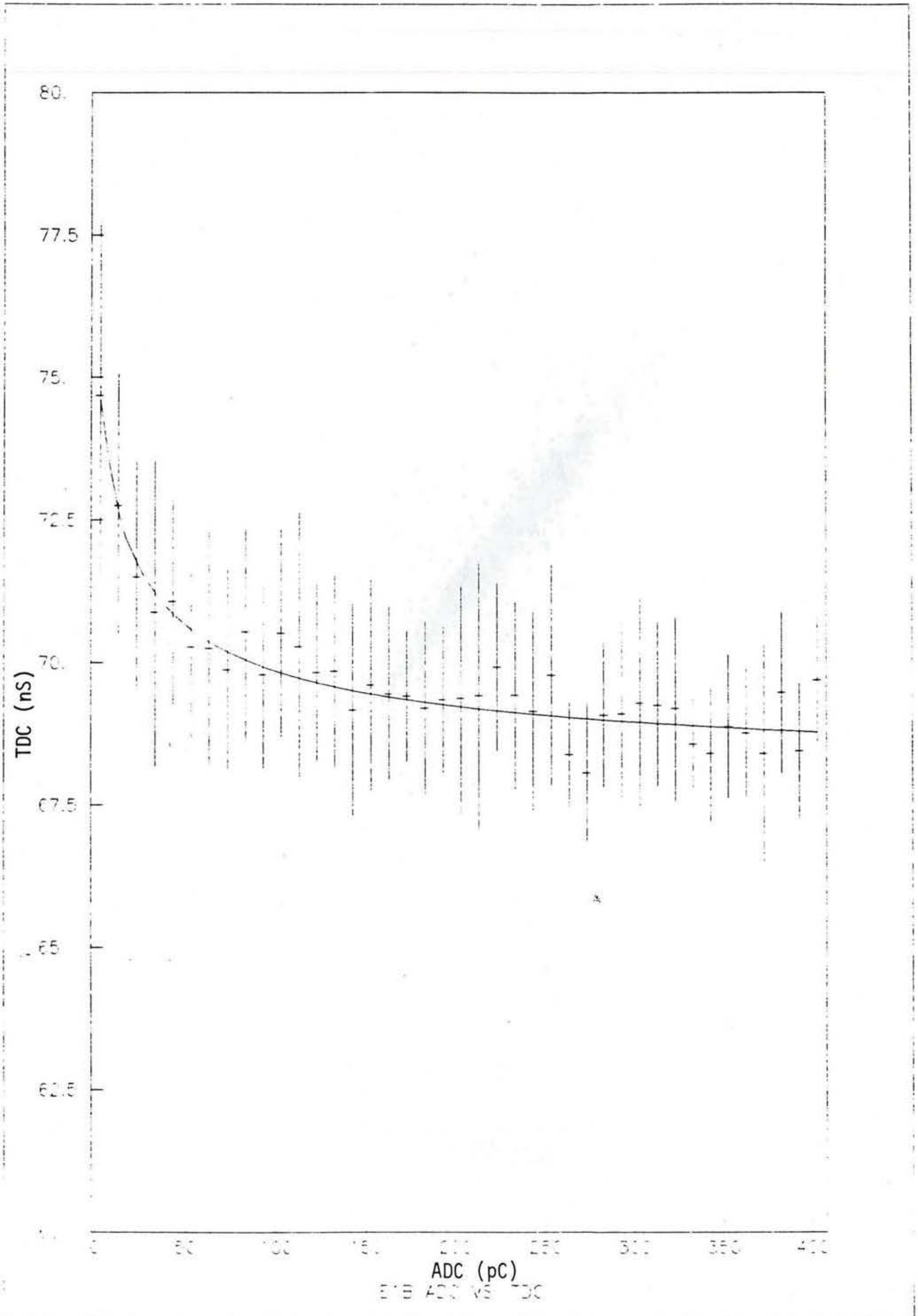


Fig. 5

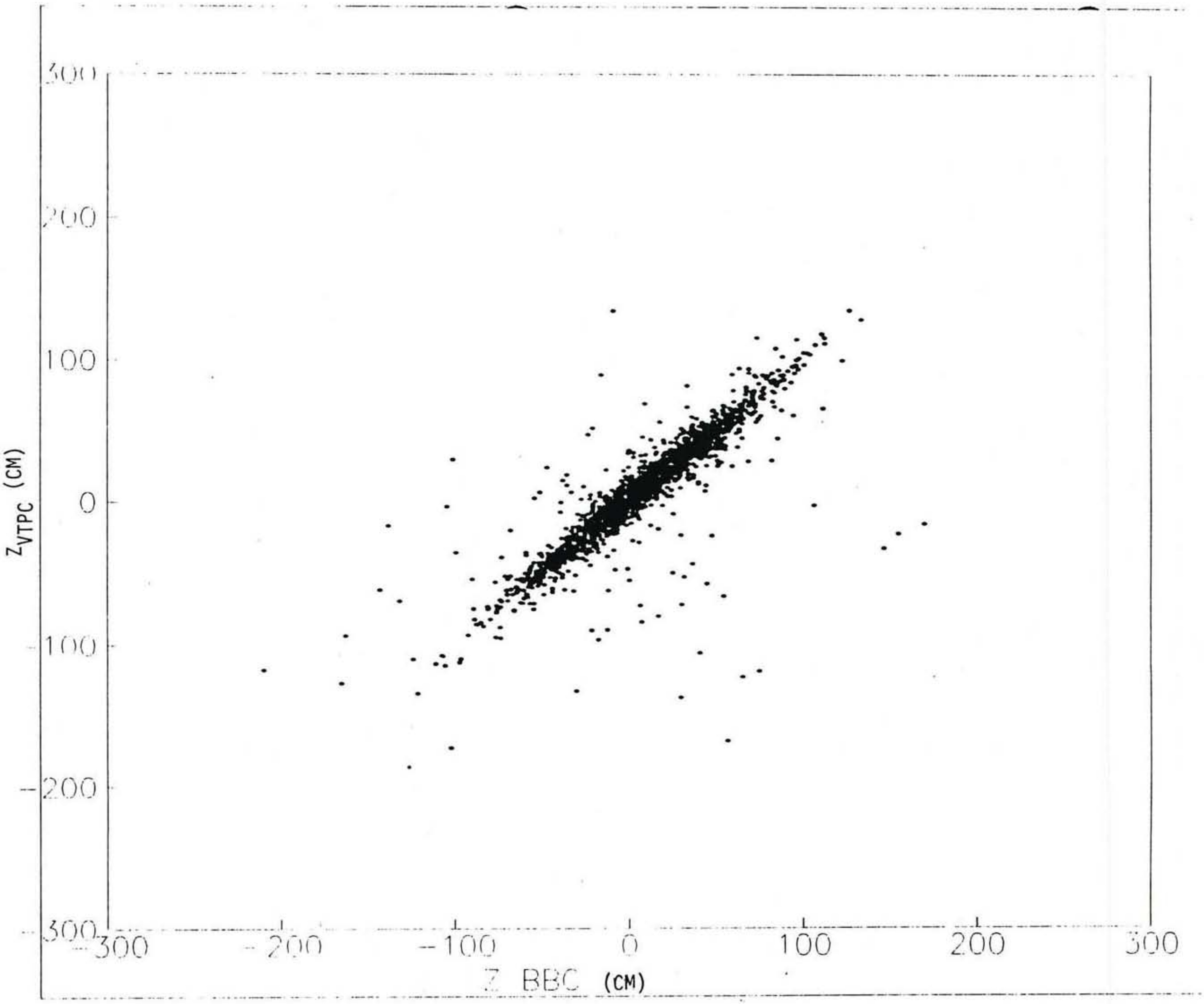

300
200
100
0
-100
-200
-300
Z_{VTPC} (CM)
-300
-200
-100
0
100
200
300
Z BBC (CM)

Fig. 6

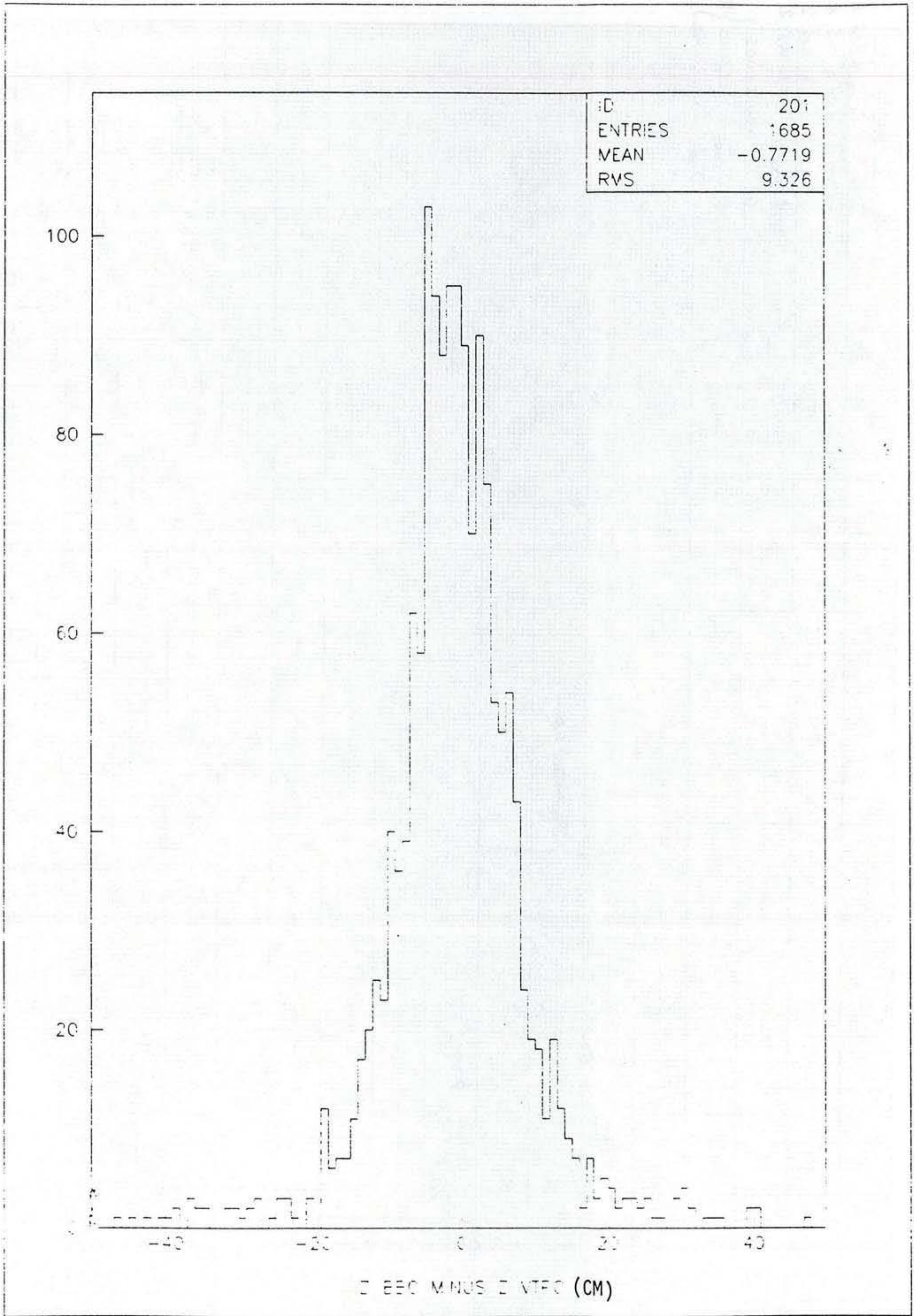
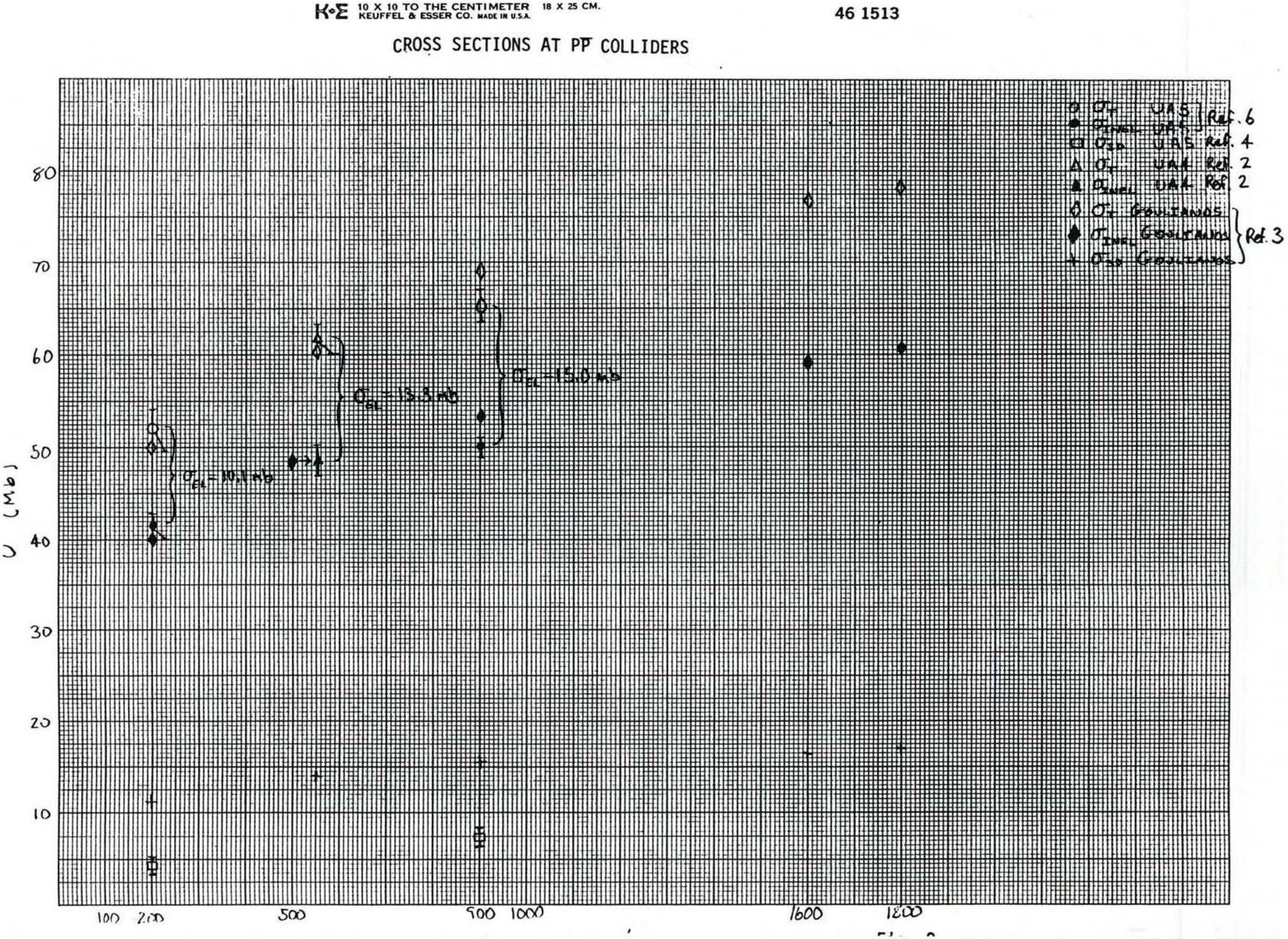

ID 201
ENTRIES 1685
MEAN -0.7719
RMS 9.326
100
80
60
40
20
-40
-20
0
20
40
Z BBC MINUS Z VTPC (CM)

Fig. 7

CROSS SECTIONS AT $P\bar{P}$ COLLIDERS



K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM. KEUFFEL & ESSER CO. MADE IN U.S.A. 46 1510

FRACTION OF GOOD EVENTS _ VTPC ONLY SCAN

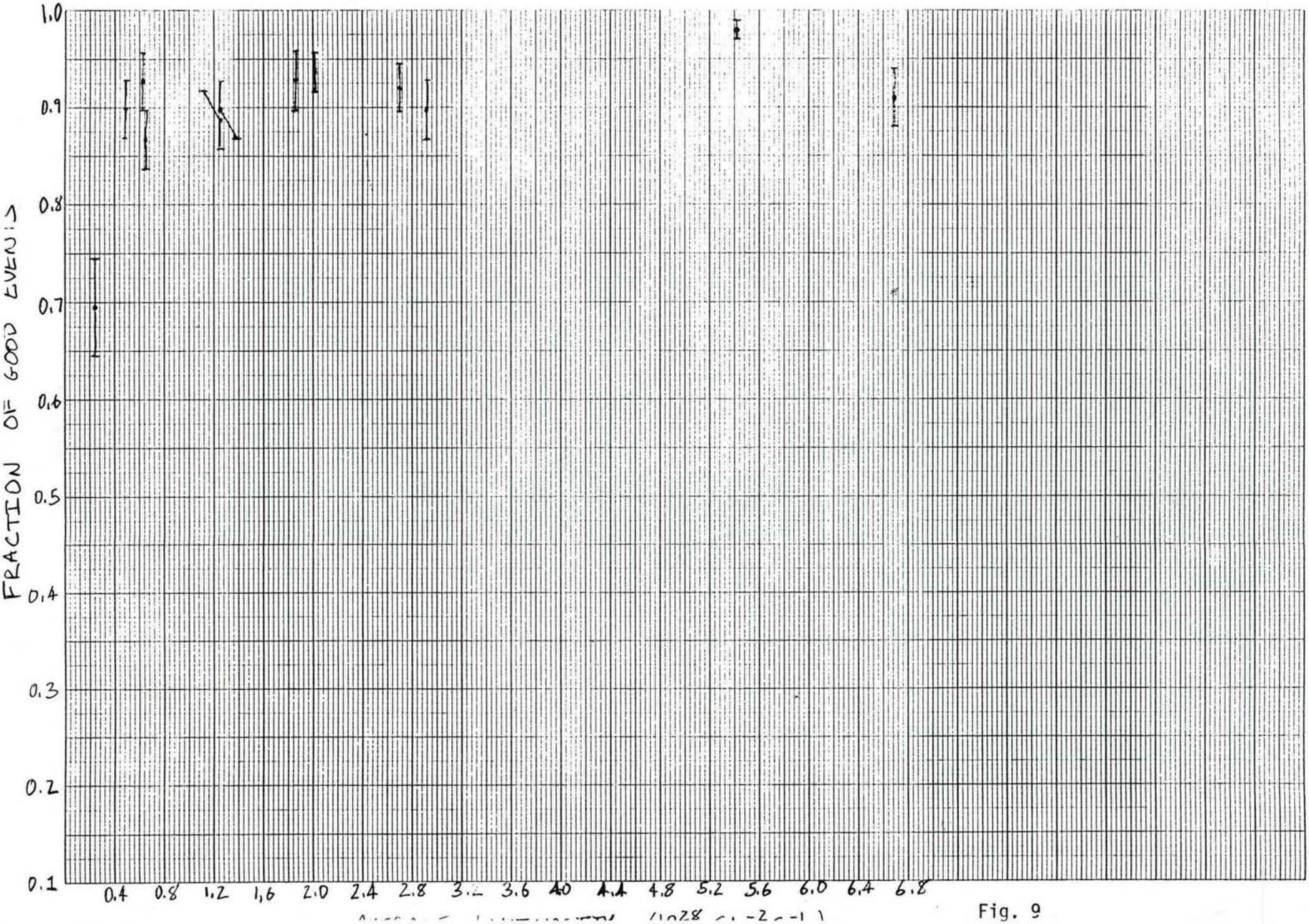


Fig. 9

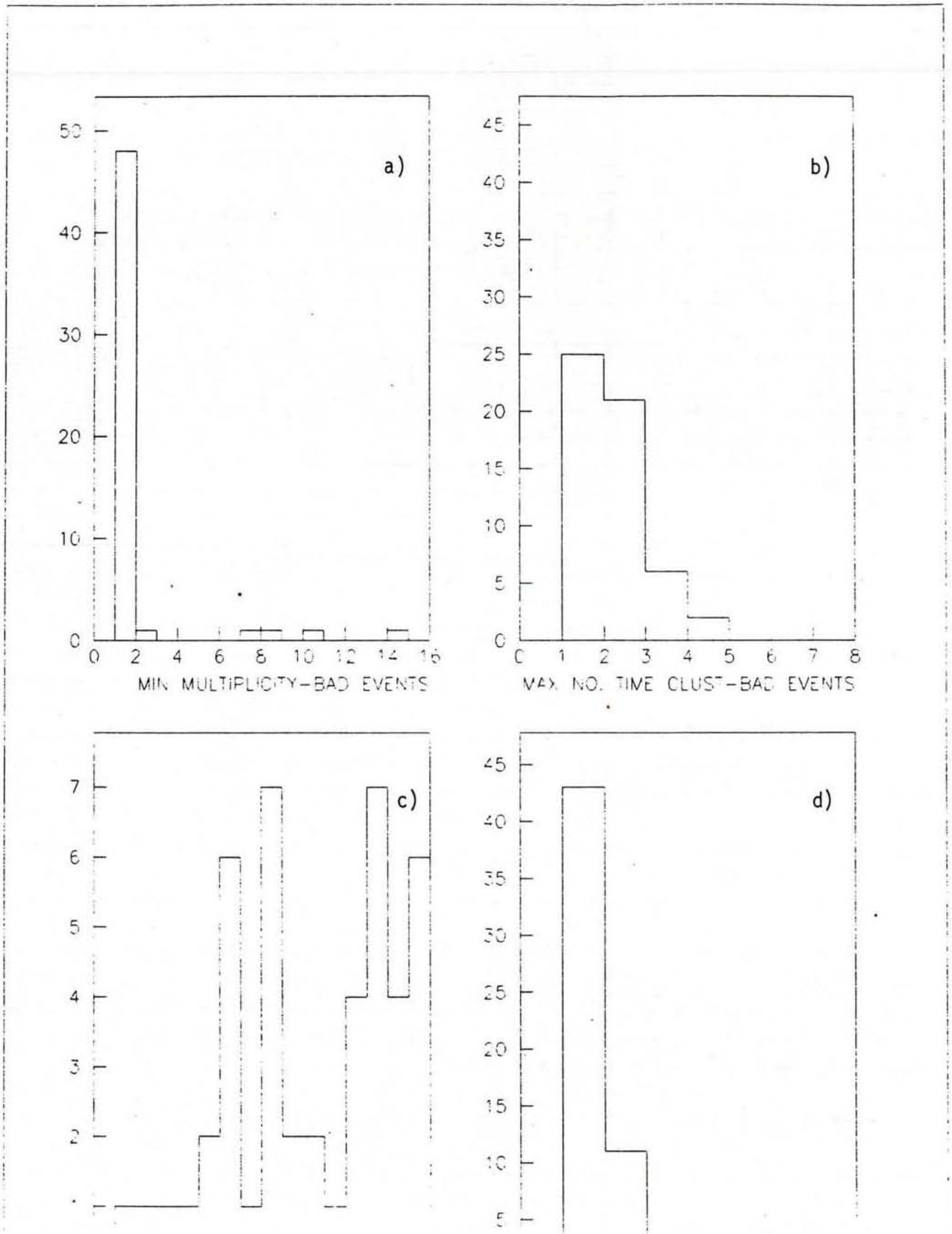

a)
b)
c)
d)
MIN MULTIPLICITY-BAD EVENTS
MAX NO. TIME CLUST-BAD EVENTS
MIN MULTIPLICITY-GOOD EVENTS
MAX NO. TIME CLUST-GOOD EVENTS

Fig. 10

FRACTION OF GOOD EVENTS - VTPC + BBC SCAN

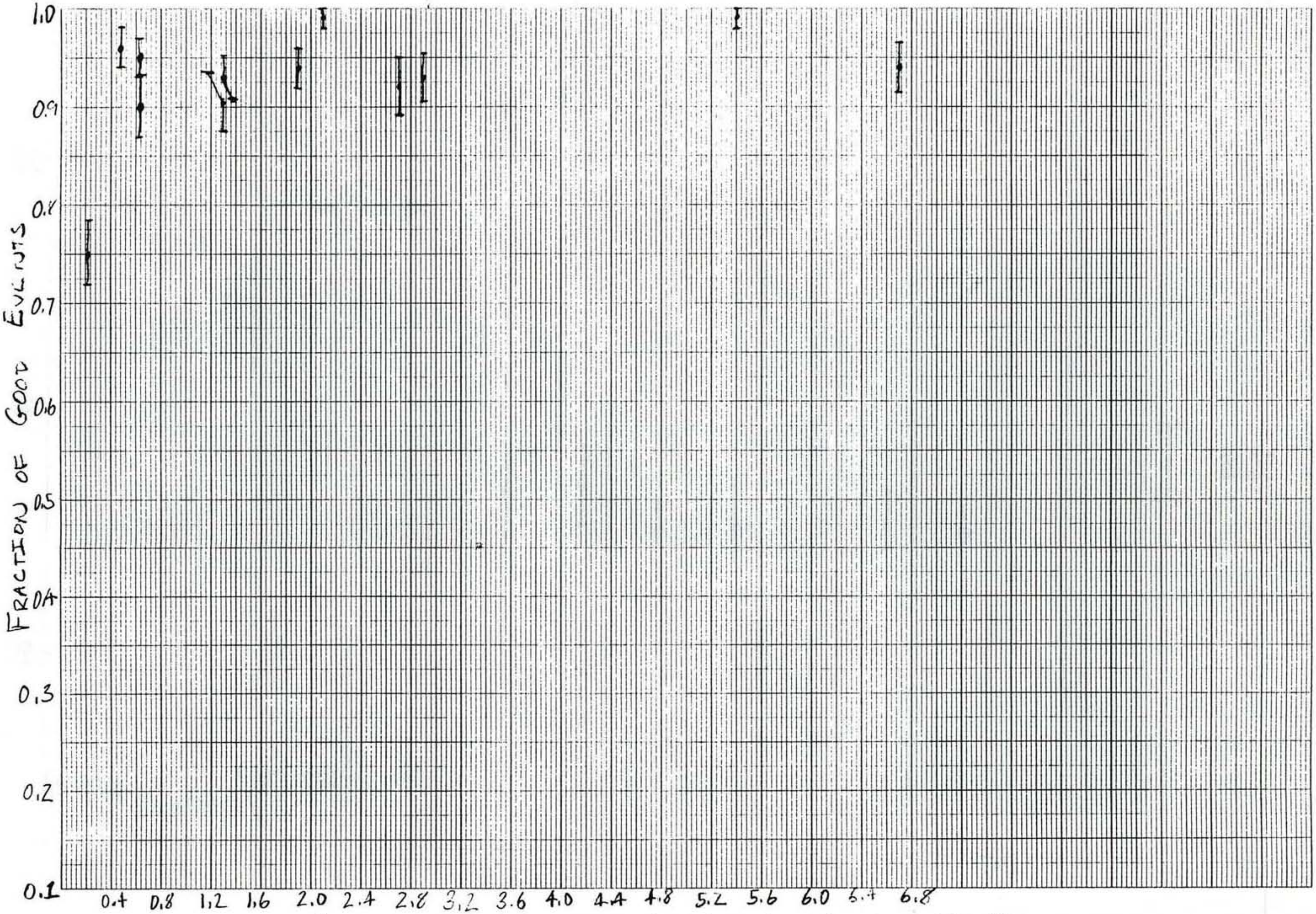
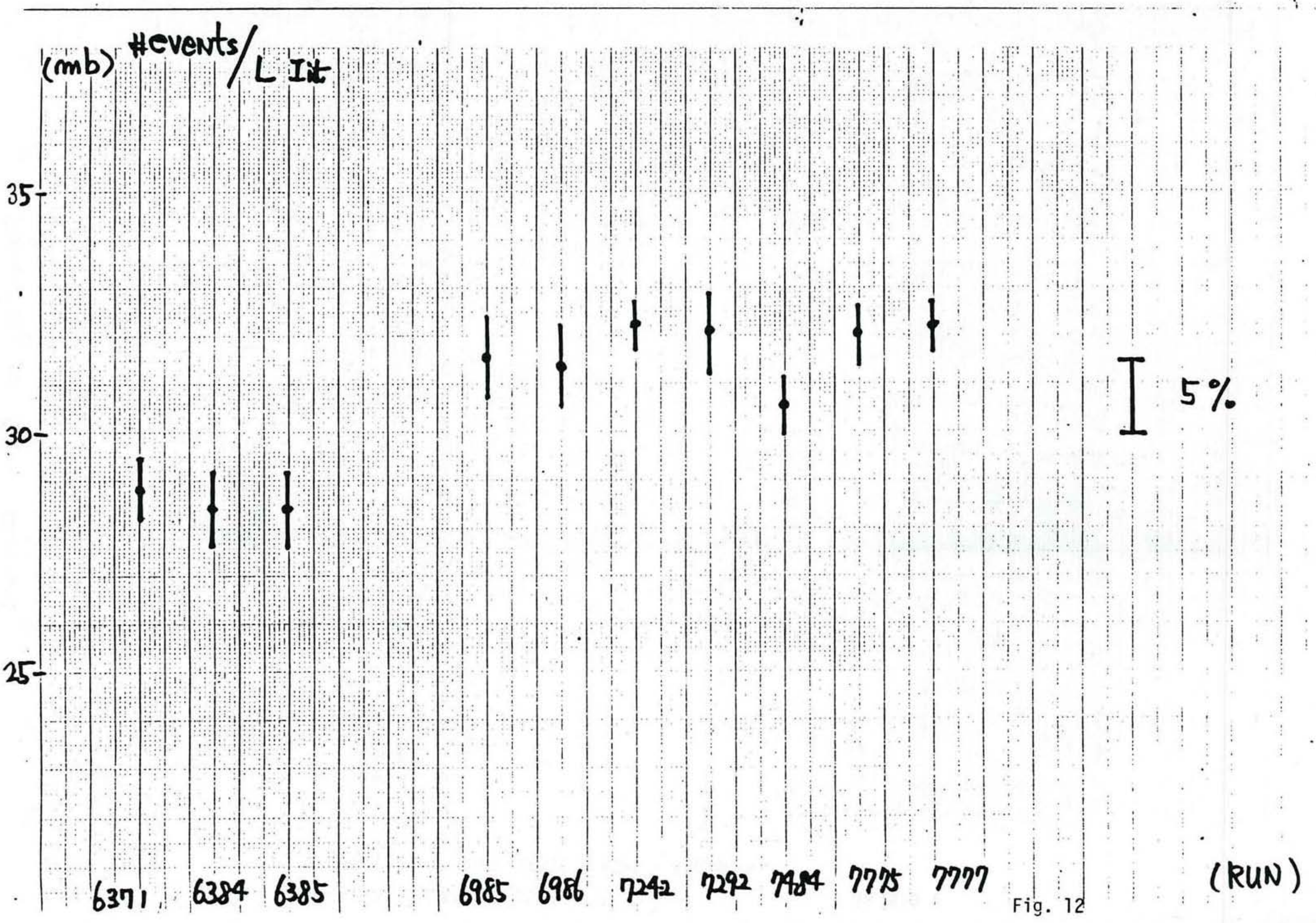


Fig. 11


(mb) #events/L Int
35
30
25
5%
6371
6384
6385
6985
6986
7242
7292
7484
7775
7777
(RUN)
Fig. 12

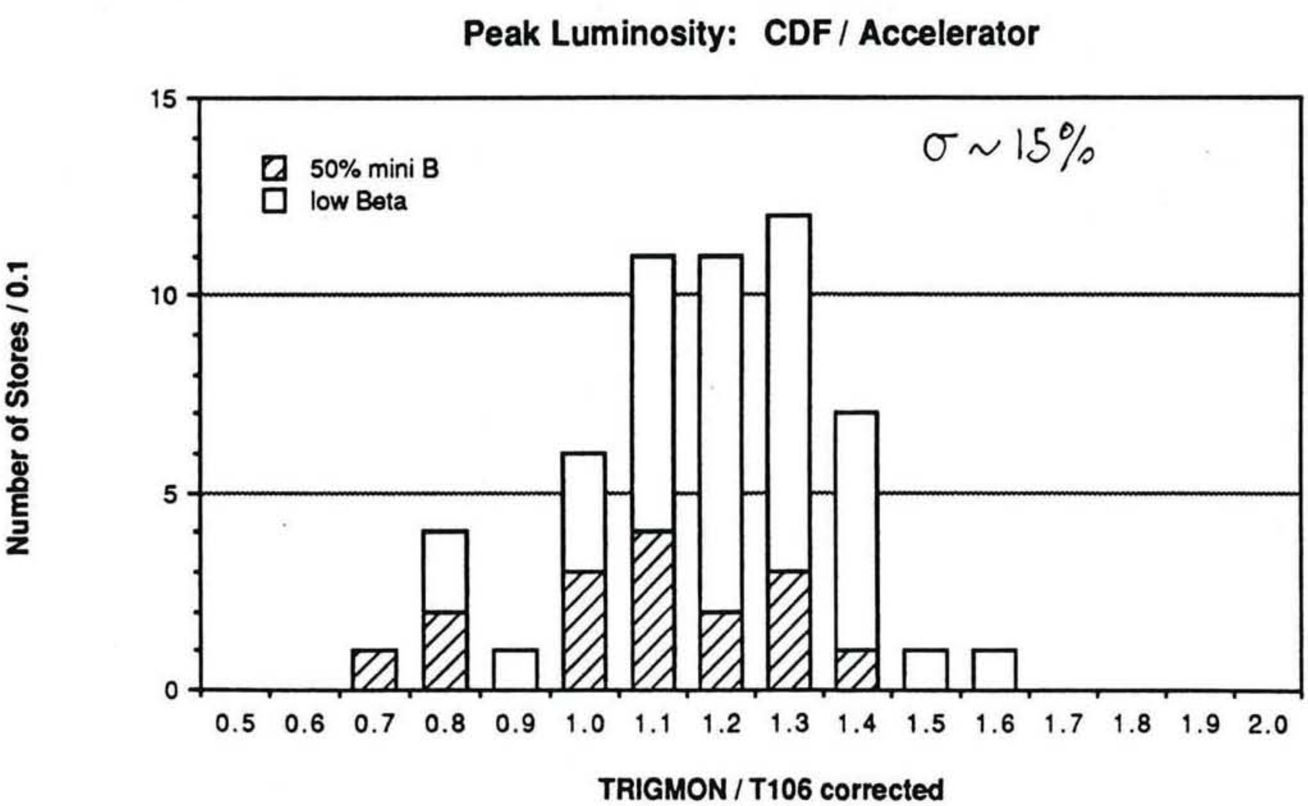

Peak Luminosity: CDF / Accelerator
σ ~ 15%
50% mini B
low Beta
Number of Stores / 0.1
15
10
5
0
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
TRIGMON / T106 corrected

Fig. 13