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Authors

Engelage, J.
Baumgartner, M.E.
Beleal, E.

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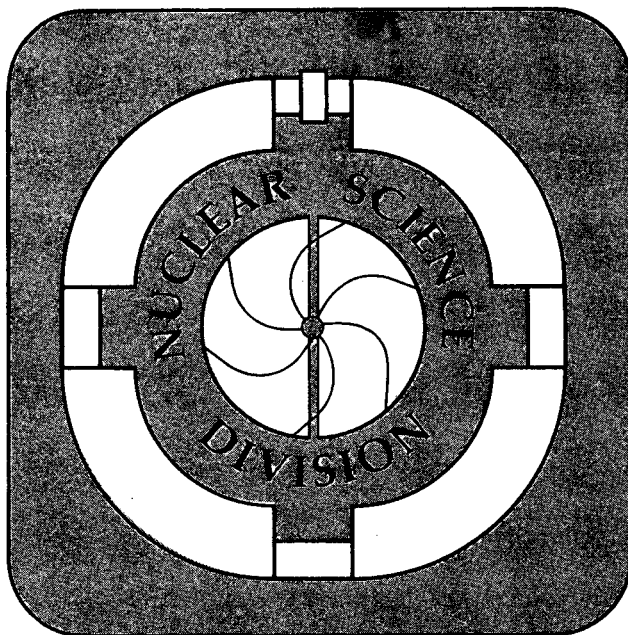
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Nuclear Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720
USA

DESIGN OF THE BEVALAC HEAVY ION SPECTROMETER SYSTEM AND ITS PERFORMANCE IN STUDYING ^{12}C FRAGMENTATION

J.Engelage^{a 1}, M.E. Baumgartner^{b 2}, E. Beale^b, B.L.
Berman^{c 3}, F. Bieser^b, F.P. Brady^d, M. Bronson^{b 4}, J.B.
Carroll^e, H.J. Crawford^a, I. Flores^{a 5}, D.E. Greiner^b, L.
Greiner^{b 6}, O. Hashimoto^f, G. Igo^e, S.
Kadota^f, P.N.Kirk^g, P.J. Lindstrom^b, C. McParland^b, S.
Nagamiya^{f 7}, D.L. Olson^{c 8}, J. Porter^{b 9}, J.L. Romero^d, C.L.
Ruiz^{g 10}, T.J.M. Symons^b, I. Tanihata^f, R. Wada^{b 11}, M.L.
Webb^{d 1}, J. Yamada^b, H. Yee^b

^a U.C. Space Sciences Laboratory

^b Lawrence Berkeley Laboratory

^c Lawrence Livermore National Laboratory

^d University of California - Davis

^e University of California - Los Angeles

^f Institute for Nuclear Study, University of Tokyo

^g Louisiana State University

ABSTRACT

A description is given of the design and operation of the Heavy Ion Spectrometer System (HISS) at the Lawrence Berkeley Laboratory Bevalac. The general characteristics of the apparatus, which include a large superconducting magnet with drift chambers before and after for precise angle and momentum analysis of high multiplicity events and a large scintillation array for charge and velocity measurements, are explained. The performance of each part as measured in a ^{12}C fragmentation experiment is discussed in detail. The main features of the data-acquisition and apparatus-monitoring systems and of the off-line event reconstruction are given.

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 - 3.2 Calibration and Resolution of the Scintillation Counters
 - 3.3 Calibration and Resolution of the Drift Chambers
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- 5 Bibliography

Appendix 1

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- 1 Present address: Lawrence Livermore National Laboratory, Livermore, California
 - 2 Present address: Hoffman-LaRoche, Basel, Switzerland
 - 3 Present address: George Washington University, Washington D.C
 - 4 Present address: Aeon Inc., Santa Fe, New Mexico
 - 5 Present address: Lawrence Berkeley Laboratory, 1 Cyclotron Rd, Berkeley, CA
 - 6 Present address: U.C. Space Sciences Laboratory, Berkeley, California
 - 7 Present address: Columbia University, New York, New York
 - 8 Present address: University of California, Riverside, California
 - 9 Present address: Arco Solar Inc., Fairfield, California
 - 10 Present address: Sandia National Laboratory, Albuquerque, New Mexico
 - 11 Present address: Texas A & M University, College Station, Texas

1.0 INTRODUCTION

Until recently, most experimental studies in relativistic heavy-ion physics have been measurements of either single particle inclusive cross sections or two particle correlations¹. Such experiments have provided a wealth of information on the general features of nucleus-nucleus collisions. Unfortunately, inclusive experiments involve an integration over many degrees of freedom, and this integration results in a significant loss of information. It obscures the dynamics of the reaction and masks any collective effects that might be present¹.

Some of the missing information concerning the multiplicity and topology of a nuclear collision has been supplied by emulsion and streamer chamber studies. However, these experiments are limited by low statistics and an inability to distinguish clearly the isotopic signature of the reaction products². The result has been the proposal of several inherently different theoretical models to describe the reaction mechanism involved in high energy heavy-ion collisions³. It is clear from both experimental and theoretical studies that detailed information on the interaction process and collective effects can only be provided by experiments that are exclusive in some region of rapidity. The Heavy Ion Spectrometer System (HISS) at Lawrence Berkeley Laboratory was constructed to achieve this goal. HISS was designed to provide precise measurements of the charges, masses, and momenta of many nuclei originating in individual nuclear interactions and to function efficiently at the rates necessary to accumulate high statistics. For these reasons we believe that HISS is of interest to the community of nuclear physicists as a whole and that this system can serve as a model for future detectors at other heavy ion accelerators.

2.0 DESCRIPTION OF THE APPARATUS

2.1 General Design Considerations

HISS was designed to meet the needs of a broad range of multiparticle correlation experiments. Specific attention was paid to the need for large solid angle, high spatial resolution, and high momentum resolution. The inherent flexibility of the HISS facility permits a wide variety of possible experiments. The most important features of the facility are:

- [1] A large volume superconducting dipole magnet of high dispersion
- [2] Several drift chambers with large aperture and the ability to resolve multiple tracks
- [3] Arrays of segmented scintillation counters for measuring both the charges and the velocities of each of the reaction products.
- [4] A computer system with several CPUs for control of both the experiment and the spectrometer, the acquisition of data, and the on-line analysis.

The characteristics of each component of the system will be presented in subsequent sections of this paper. To aid in the discussion of the description and performance of HISS, a brief description of one of the first experiments to be carried out on HISS, the dissociation of ^{12}C , is presented⁴⁻⁷.

2.2 The ^{12}C Dissociation Experiment

The ^{12}C dissociation experiment was performed specifically to address the questions concerning reaction dynamics in peripheral collisions between relativistic heavy-ions. The configuration of the HISS facility for this experiment is shown in figure 1. The specific objectives of the experiment were to measure

the energy and momentum transferred to the excited projectile. The experiment was performed in an energy regime where the hypotheses of limiting fragmentation and factorization have been extensively tested in single particle inclusive measurements^{5,8}. The role of the target nuclei in the observed reaction was simply as a means of injecting energy into the ^{12}C projectile. Thus the character of the reaction mechanism should be revealed through a measurement of only the projectile fragments.

Excitation energies from a few MeV to several hundred MeV were observed in reactions of ^{12}C at 2.1 GeV/nucleon with C and CH_2 targets. After the ^{12}C projectiles interacted in the target, the projectile fragments were separated from the target fragments by the field of the HISS magnet. The experimental setup shown in figure 1 included beam definition scintillators for defining an event trigger, drift chambers for determining particle trajectories and a time of flight scintillation array. The event trigger of the experiment required a single ^{12}C projectile to strike the target and no uninteracted ^{12}C nucleus to be seen exiting the spectrometer^{6,7}. The rigidity, $\vec{R} = \frac{\vec{P}}{Z}$, of each projectile fragment was determined from the position information obtained with the drift chambers and by tracing the trajectory through the mapped magnetic field. The scintillation array was used to measure the velocity and the charge of the fast ions. The mass of each projectile fragment was calculated from the measured values for rigidity, velocity and charge. The HISS system was ideal for this experiment because of the need to resolve the charge, the mass, and the momentum for all projectile particles in an individual interaction.

2.3 The Bevalac

The Bevalac delivered a beam of fully stripped ^{12}C ions of total kinetic energy 25.2 GeV to the experimental area at the rate of ten pulses per minute. Beam intensity during data collection was 10^3 – 10^4 ions per pulse. Beam flux was limited because of the relaxation time of the downstream drift chambers. The transport line into the experimental area, beam 42 of external particle beam (EPB) channel II, contained three dipole magnets and seven quadrupoles⁹. A final focus was produced on the veto scintillator, *DS*, downstream of the HISS dipole by a series of three quadrupoles located five meters upstream of the magnet.

2.4 The Superconducting Magnet

A 625 ton superconducting dipole forms the heart of the HISS system. As shown in table 1, the HISS magnet has pole tips with a diameter of 2.1 meters, a gap of 1 meter, a maximum central field of 30 kilogauss, and a maximum $\int B \cdot dl = 75 \text{ kG} \cdot \text{m}$. A window frame steel yoke limits the stray field¹⁰. A 40 ton stainless steel vacuum tank with a $1 \times 3 \text{ meter}^2$ exit window resting between the pole tips serves to reduce background interactions¹¹. Inside the vacuum chamber was a target wheel with eight positions that was operated by remote control.

The dipole is equipped with a 400 watt helium refrigerator from Cryogenic Consultants Inc. and a Sullair screw type compressor. The refrigerator is a Claude cycle, liquid nitrogen precooled, twin series expander (20° K and 5° K expansion) device using wire wound heat exchangers and piston expanders¹². The cryogenic system is controlled by a Digital Equipment Corporation LSI 11/23 microprocessor with a touch screen input.

Electrical, mechanical and cryogenic systems were monitored once each second by more than 100 sensors. These sensors include 32 strain gauges to monitor the mechanical integrity of the support cylinders, 19 thermistors to measure the temperatures of the coil and the helium gas, 30 solid state pressure and liquid level sensors to gauge the pressure and level of the liquid helium, 8 isolation amplifiers to track various voltages when the magnet was energized, and 48 channels of relay input registers to scan the power supply and quench protection chains. The quench detectors turn off the power supply if a resistive voltage in the coils is registered and cause the magnet to discharge through a 1800 kg., 0.22 ohm, iron dump resistor that is hard wired to the coil¹⁰. A PDP 11/34 computer reads the sensor data via CAMAC and provides several pictorial displays for immediate analysis. The data is subsequently filed on the VAX 11/780 for future analysis, as shown in figure 2¹³.

2.5 Beam Defining Scintillators

As shown in figure 1, the first two of five beam defining scintillators used in the experiment were the time of flight start scintillator, *TOF 1*, and the total scintillator, *TOT*. The scintillator *TOF 1* was used as the start for the time to digital converters (TDC). The scintillator *TOT* was run at maximum gain and with the lowest threshold setting possible on the accompanying discriminator to register all particles entering the spectrometer. The information from the *TOT* scintillator was used to reject events which could have resulted from multiple beam particles. The *TOT* scintillator was also used to trigger an updating one-shot, *UDOS*, set to a 1 μ s width. This signal was used to define a clear time window around each good beam particle. As shown in figure 3, the updating one-shot afforded maximum protection from beam structure and pile-up. Both *TOF 1* and *TOT* scintillators were located at the

last focus before the superconducting magnet. The energy or E scintillator and the hole scintillator, HS , were positioned 10 meters downstream of TOF 1 and TOT . The scintillator E was 0.5 mm thick and was used to identify single beam particles. The output of the E scintillator was passed through a window discriminator. The upper threshold on this discriminator was set to eliminate all multiple hits within the response time of the photomultiplier tube. The lower threshold was set to veto all charged particles except Carbon projectiles. The scintillator HS was 6.3 mm thick with a 50 mm hole in its center. The HS scintillator was used to veto beam particles with greater than a 4 mrad divergence. The coincidences between TOF 1 and TOT which did not fire HS and were "not preceded" ($\overline{PRE}$) measured the number of particles which entered the system in the correct geometry ($INGEO$) or phase space. The number of single ^{12}C particles ($BEAM$) that were incident on the target was provided by the number of $INGEO$ particles that passed the energy criteria set by the window discriminator of the E scintillator. The remaining beam scintillator, DS , was placed 8 meters "downstream" of the center of the dipole to veto any beam particles which did not interact. The output of the DS scintillator was used as a veto in combination with the incoming $BEAM$ particles to form the interaction trigger

$$INT = TOF\ 1 \cdot TOT \cdot \overline{PRE} \cdot \overline{HS} \cdot E_{lo} \cdot \overline{E_{hi}} \cdot \overline{DS} = BEAM \cdot \overline{DS}$$

As defined, the trigger guaranteed that all events began as only a single, good beam particle hitting the target and that no uninteracted beam particle was left within the beam envelope after the TOF scintillation array. Thus the trigger served to eliminate beam halo, upstream fragmentation and multiple hits within the response time of the TOT scintillator. When an interaction trigger was received, the system $BUSY$ signal was generated to lock out any

further triggers until the present event was processed. Thus $INT \cdot \overline{BUSY}$ constituted the event trigger for the experiment.

2.6 Drift Chambers

Two meters upstream of the scintillators E and HS was the first of four drift chambers used in the experiment. The second upstream chamber, $DC\ 3$, was positioned 223 cm downstream of $DC\ 4$. Both $DC\ 4$ and $DC\ 3$ had six sense planes each with a 40 cm by 30 cm active area. The positions measured by $DC\ 4$ and $DC\ 3$ were used to establish the incident angle and position of each beam particle at the target. These beam definition chambers were identical in mechanical construction and electronic instrumentation to the big chambers which were located 250 cm and 345 cm downstream of the center of the dipole. As shown in figure 4, the two large chambers, $DC\ 1$ and $DC\ 2$, also contained six sense planes and eight high voltage foil planes.

The chambers $DC\ 1$ and $DC\ 2$ differ from $DC\ 3$ and $DC\ 4$ in that the 100 cm by 200 cm active area of $DC\ 1$ and $DC\ 2$ required a 2.5 cm thick aluminum frame for support. The foil planes were constructed of aluminized mylar which consisted of 1000 angstroms of aluminum deposited on 6.4μ of mylar. The foils were stretched across epoxy-fiberglass windows made of NEMA-G10. The sense planes were made of printed circuit board and epoxy-fiberglass plates. Both high voltage and sense wires were 75μ Beryllium-Copper. As shown in figure 4, wires were oriented at 0° , $+60^\circ$, and -60° with respect to their fiberglass frames. The wires were spaced 1.0 cm apart and glued to the fiberglass frames.

As shown in figure 4 each sense wire was separated from the adjacent high voltage wire by a distance of 1.0 cm. Planes of similar wire orientation were aligned so that the high voltage wires of one plane were shadowed by the

sense wires of the other plane. This alignment made it possible to determine whether a particle passed to the left or to the right of a sense wire. Each chamber provided a measurement for each of the three orientations 0° , $+60^\circ$, -60° . This redundancy coupled with position information obtained from the TOF scintillation array, was used to calculate the position and vector direction of each fragment.

The signals from each of the sense wires were processed by the front-end electronics shown in figure 5. This front-end electronics supplied information concerning the position of each passing ion. The front-end electronics also provided some protection from spurious tracks produced by knock-on electrons, or delta rays, which are a major nemesis of gaseous detectors in heavy ion experiments. This suppression of delta rays was accomplished by splitting the incoming signal and delaying one-half of it while allowing the other half to set a dynamic threshold. As shown in figure 5, the core ionization of the track was then readily discernible from delta ray radiation.

All sense wires were connected to a Le Croy 4290 TDC system. As shown in figure 3, the start pulse to the system was provided by the logic pulse from the *TOF* 1 scintillation counter.

2.7 Time of Flight (TOF) Scintillation Array

The TOF array mentioned previously consisted of seventy (70) scintillation counters divided into four (4) sections or hodoscopes. Two hodoscopes contained twenty (20) counters of dimensions $2.5 \times 10 \times 300 \text{ cm}^3$, and two hodoscopes contained fifteen (15) counters of dimensions $2.5 \times 10 \times 200 \text{ cm}^3$. Each scintillator was individually wrapped and was viewed at both ends by an Amperex XP2230 photomultiplier tube. Each tube was connected to a base that was modified to operate over a large dynamic range while exhibiting only

a small distortion in pulse shape. As shown in figure 6, this modification involved the addition of a Darlington pair to each of the last five stages. This type of emitter-follower circuit increases the power level available to the dynode while maintaining the voltage gain as set by the resistor chain. Each hodoscope was powered by a Le Croy HV4032A high voltage supply that was controlled by computer. The high voltage was set initially so that each tube delivered a 300 mV pulse when irradiated with a ^{90}Sr source. The bases of the tubes were equipped with two anode outputs, one of which was connected to a Le Croy 2280 ADC system, as shown in figure 7. The second anode signal supplied the stop for the individual channels in a Le Croy 2228A TDC system. The Le Croy 2228A TDC system was activated by a *TOF* 1 logic pulse, as shown in figure 3.

2.8 Computing Facilities

Incoming data were read from seven CAMAC crates through a microprogrammable branch driver (MBD) and into a PDP 11/45. The data were subsequently written both to magnetic tape and to a shared 80-megabyte disk. As illustrated in figure 2, the data on the disk were stored in a circular buffer to permit access from two additional PDP 11s and a VAX 11/780 which were also part of the HISS computing facility. Using a circular buffer allowed access to the most recent data thereby enabling us to make real time comparisons between current and past data sets. Consequently, only one set of programs was used for both on-line and off-line analysis reduction^{14,15}.

The monitoring of the experiment was greatly enhanced by the number and complexity of the programs that could be run on the VAX 11/780. Those programs fell into two categories; those set to watch the apparatus, and those designed to watch the incoming data. The software developed to monitor the

equipment included graphic displays of the temperature and pressure at various places in the magnet as well as the voltage and current values for the photomultiplier tubes in the scintillation arrays. These displays were augmented by more precise values recorded in tabular form which could also be easily displayed. The remainder of the equipment monitoring package consisted of "watch dog" programs running in the background which would trigger various alarms when adverse changes occurred. The second package designed to monitor the incoming data included a graphic display of the hit pattern in all four drift chambers, the scintillation counters that were struck, and the current status of the data buffer in the MBD. The values of the various scalars and important ratios were also displayed and were compared with corresponding visual scalars. The scalar values were also compared to the values read off-line by one of the off-line analysis programs.

As shown in figure 8, there were eight programs running under the analysis shell program, LULU¹⁵. The LULU analysis shell is essentially an executive program which contains sophisticated sorting and plotting packages. This analysis shell provided an environment in which data and results could be easily passed between the different analysis programs.

3.0 PERFORMANCE OF APPARATUS UNDER EXPERIMENTAL CONDITIONS

3.1 Aperture of HISS

The aperture of the HISS system was calculated using a Monte Carlo program and the field map of the HISS magnet. The results of the calculations were that the aperture of the spectrometer remains constant at 173 msr for particles with rigidities between 1000 MV/c and 11000 MV/c. This is

sufficient to contain all of the projectile fragments of mass 2 or greater and all protons near beam velocity. The aperture was limited by *DC 2* in the plane perpendicular to the bending plane of the dipole. The aperture was limited at low velocity by *DC 2* and the region of phase space covered by the Chebychev coefficients used for momentum reconstruction. As can be seen in figure 9, the acceptance for rigidities perpendicular to the bending plane of the dipole was symmetric about zero, while the acceptance in the bending plane had a much more complex shape.

3.2 Calibration and Resolution of the Scintillation Counters

All information pertaining to the charge of the ions was obtained from the scintillation counters in the TOF array. These counters were calibrated using beams of protons and fully stripped ^{12}C ions. These beams were chosen to fine tune the high voltage for each photomultiplier tube and to maximize the dynamic range of the ADC's of the scintillation counters. Both beams were swept across each scintillator of the TOF array by ramping the current in the HISS magnet. The charge, Z , was calculated using the following relationship.

$$Z = \frac{c_1}{Q} + c_2 + c_3 \cdot Q + c_4 \cdot Q^2 + c_5 \cdot Q^3$$

The constants, c_i , were independently determined for each scintillator. Q , the square root of the product of the ADC outputs from the two photomultipliers attached to each counter was used rather than the sum in order to minimize the position dependence resulting from the light attenuation within the scintillators. There was substantial attenuation of the light within these counters because of their length. In figure 10, we show the function relating the charge and ADC product. As is shown in figure 11, the standard deviation

for the distribution of pulses produced by ions of charge Z is approximately 0.1 charge units, independent of Z .

The scintillation counters were also used to measure the time of flight of the fragments over a flight path of approximately 7.6 meters. The time of flight for an individual fragment was calculated by averaging the outputs from the two tubes attached to each counter according to the following equation:

$$t_{TOF} = g \cdot \left[\frac{TDC\ 1 + TDC\ 2}{2} \right] - t_o - t(Z)$$

where t_{TOF} is the time of flight in picoseconds, g is the conversion factor between channel number and picoseconds, $TDC\ 1$ and $TDC\ 2$ are the digitized channel numbers for the two tubes attached to each counter, t_o is the correction for the non-zero offset of the time-to-digital converter, and $t(Z)$ is the correction for the time dependence on pulse height. As shown in figure 12, the standard deviations for the timing distributions ranged from about 170 ps for ^{11}B to about 250 ps for protons⁷.

3.3 Calibration and Resolution of the Drift Chambers

The trajectories of incoming beam particles were determined using the twelve (12) TDC values in $DC\ 3$ and $DC\ 4$. The calculated trajectories were subsequently used to determine the transverse coordinates at which the beam particle hit the target. The coordinates from these chambers were also used to identify projectiles in the beam halo and to eliminate from the data sample all events in which the projectile interacted in the material upstream of the target. In the data sample 20% of the primary beam tracks were so flagged.

There were two ways in which unacceptable primary beam tracks were flagged. First, events in which the incoming beam particle was incident outside the active area of the target were removed. These events were easily

identified because their coordinates in *DC 3* or *DC 4*, or both, lay outside acceptable limits. Next, events in which the projectile suffered a small elastic collision between chambers *DC 3* and *DC 4* were removed. As shown in figure 13, a linear correlation existed between the like coordinates in *DC 3* and *DC 4*. This linear correlation graphically displays the envelope of the beam. Tight cuts on the beam envelope were used as another criteria for defining acceptable beam particles.

Downstream tracks for primary fragments, or uninteracted beam particles which missed the *DS* veto, were generated from their **X** and **Y** coordinates in *DC 1* and *DC 2*. Each spatial coordinate was grossly determined by drawing an imaginary line between the predicted coordinates of the interaction in the target and the coordinates of each primary fragment in the TOF array. The **X**-position of a primary fragment at the TOF array was roughly determined by the **X**-position of scintillator that was fired. The **Y**-position of a primary fragment at the TOF array was roughly determined by using the TDC signals from the scintillator that was fired, as follows

$$\mathbf{Y}_{TOF} = \left[\frac{L}{\tau} \right] \left[TDC\ 1 - TDC\ 2 - TDC_0 \right]$$

TDC_0 is the TDC value for a particle which strikes the center, $\mathbf{Y}_{TOF}$, of the scintillator under examination and the quantity $\frac{L}{\tau}$ is the TDC channel to length conversion factor. The line was constructed only for primary fragments with a charge greater than 0.6 which hit somewhere between scintillators 8 and 54, the range of the drift chambers. Any scintillator in the TOF array that was fired was required to have output signals for both TDCs and both ADCs to meet the above requirements. Further, the sum of the outputs from the TDCs could not be greater than 10 ns (200 channels). No tracks were found if there was no matching hit in the TOF array. At this point, the

expected X and Y positions in $DC\ 1$ and $DC\ 2$ were determined from the intersection of the chambers and the imaginary line, discussed above.

For the next iteration of those spatial coordinates the closest combination of wires in $DC\ 1$ and $DC\ 2$, within a ten (10) centimeter radius of the coordinates predicted, was located. The final positions were obtained using the output TDC values of the wires that were located. The outputs from the TDCs were converted to a distance in microns on a channel by channel basis using a look up table. A separate table for each pair of planes (S, T and U) was developed for each chamber. Figure 14 is a plot of distance versus channel number for the S planes of $DC\ 1$, and it exemplifies the non-linear time to distance functions encountered. As shown in figure 15, the spatial resolution of a single cell in the drift chambers was typically $\sigma = 150\mu$, while σ for a single chamber was approximately 220μ .

The reason for taking three steps to find the track for each fragment was the large number of wires that were fired per particle in $DC\ 1$ and $DC\ 2$. As shown in figure 16, the production of delta rays effectively doubled the number of wires that were fired in $DC\ 1$ and $DC\ 2$. The vast number of wires that fired made it difficult to distinguish the wires fired by the primary fragment from the wires fired by either delta rays or cross-talk in the electronics. The problem was successfully overcome by the introduction of "darkness", a non-least squares fitting procedure using gaussian weights. A detailed discussion of "darkness" and how it is calculated can be found in Appendix 1.

As shown in figure 17, the efficiencies for $DC\ 1$ and $DC\ 2$ ranged from 76% for particles of charge 1 to 98% or greater for particles with charge greater than 3. The efficiencies of the drift chambers were determined by taking a large sample of particles registered in the TOF array, and fitting the resulting darkness distribution of each chamber to a binomial probability

distribution. The efficiencies were calculated as a function of charge because the average number of electrons produced in the P-10 gas used in the chambers was charge dependent. The method was checked with ^{12}C particles from a data file that was taken with the beam veto scintillator, *DS*, removed from the trigger. This sample was then restricted to events which registered a charge of six (6) in both the *DS* scintillator and either scintillator 15 or 16 of the TOF array. The efficiency of the chambers was then calculated by determining the percentage of these particles with good tracks. A good track being defined as one which

- (1) pointed back to the target in the **Y** direction to within ± 1 mm
- (2) yielded the correct mass for $^{12}\text{C} \pm 0.5 \frac{\text{GeV}}{c^2}$
- (3) had a darkness greater than three, meaning that at least three (3) planes in both *DC 1* and *DC 2* returned reasonable values.

The agreement was within the statistics of both calculations.

3.4 Analysis

At this point in the analysis, the information obtained from the TOF array and the information from the drift chambers were sewn together for each primary fragment. As shown in figure 8, passing information between the different analysis programs was greatly simplified by having those programs run under the LULU analysis shell. Events were examined for cases in which two tracks pointed to the same scintillator in the TOF array. Each event was also examined for primary fragments in which no track was found. The agreement between the value of the charge logged for each fragment in the front and the back TOF hodoscope was recorded. This was only significant for fragments in the range of scintillators 9 through 19, since only those fragments

would have struck the back TOF array. Flags were set for events in which not all the particles had tracks, for events in which some trajectories did not point back to the target, and for events in which adjacent scintillators had fired. The **X** coordinates of the primary fragments at the TOF array were calculated from their trajectories and the distances from the center of the scintillators were determined. The above information along with charge, time of flight, and the **X** and **Y** coordinates from all detectors was then used to calculate the rigidities of the primary fragments with tracks.

The vector momentum of the particles passing through the spectrometer was obtained using a Chebychev momentum reconstruction procedure developed by H. Wind at CERN¹⁶. This approach was selected over a more cumbersome ray tracing technique for its speed. A set of Chebychev coefficients was obtained by numerically integrating a large number of sample trajectories through the field of the HISS magnet. The field of the HISS magnet was obtained by mapping the surface of a rectangular solid containing the central field of the HISS magnet to an accuracy of 0.4% at five (5) centimeter intervals. It was converted to a volume map using La Place's equation and the VAX 11/780 computer. The generation of the Chebychev coefficients was such that the error was insignificant when compared to an uncertainty of 50μ in the position of a particle in the drift chambers. The interaction position at the target and the **X** and **Y** coordinates in *DC 1* and *DC 2* were coupled with this set of Chebychev coefficients to give the rigidity, momentum vector at the target, and length of the flight path from the target to the TOF array for each fragment. When combined with the position uncertainty of the drift chambers, a resulting resolution in rigidity of $\frac{\Delta R}{R} = 0.0042$ for beam particles was obtained.

The rigidity was used with the value of the charge as measured in the TOF array to determine the momentum of each fragment. The velocity for each fragment was obtained by dividing the calculated path lengths by the adjusted time of flight values. The mass, M , of each fragment was then determined using the following formula

$$M = \frac{R \cdot Z \cdot c}{L} \times \left[t_{TOF}^2 - \left(\frac{L}{c} \right)^2 \right]^{\frac{1}{2}}$$

where R was the rigidity of the fragment, Z was the charge of the fragment, L was the path length, and t_{TOF} was the adjusted time of flight. The mass distribution for particles with charge $Z = 1$ is shown in figure 18. Mass resolutions in this experiment ranged from $80 \frac{\text{MeV}}{c^2}$ for protons to $170 \frac{\text{MeV}}{c^2}$ for ^{11}B particles⁷. Masses corresponding to unreal particles were flagged while those corresponding to real particles were adjusted to known values. Finally the energy of those particles with real mass values was calculated using the appropriate masses and momenta.

4.0 CONCLUSIONS - Status and Prospects

In conclusion, the design goals of the HISS detection facility have been met or exceeded. Of the problems discussed, most have been subsequently solved or solutions are currently being implemented. The aperture of the spectrometer has been effectively increased by the addition of a large area drift chamber to replace the smaller *DC 1* and *DC 2* drift chambers¹⁷. A finely segmented scintillation array has been constructed to augment the current TOF system. The new array has been designed to increase the systems ability to resolve events with multiple fragments of similar rigidities by at least two orders of magnitude.

The facility continues to grow and mature as new and better detectors are developed to investigate the high charge and mass fragments produced in heavy-ion collisions. A 25×100 cm Cerenkov array has been added to the common detector system which has allowed excellent identification of isotopes up to mass 90 in the 1.5 to 1.7 GeV/nucleon range¹⁸. Currently a three segment, multiple sampling ionization chamber (MUSIC) for charge and trajectory identification of fragments from carbon up to and including uranium, is being tested. A prototype of MUSIC was developed and successfully tested at the HISS facility three years ago¹⁹. Plans are currently under consideration for detectors to outfit both the target²⁰ and mid-rapidity regions making the investigation of exclusive heavy-ion collisions a reality at HISS.

The HISS facility has been in full operation since 1982. Since that time several experiments have been staged at the facility including a study of collective effects near the kinematic limit²¹, the use of $2\pi^-$ and $3\pi^-$ correlations to provide a detailed determination of the pion source in central nuclear collisions²², and an investigation of the giant resonances in ^{16}O decay²³. Three experiments, using different setups, were staged within a six week period⁴. Such a diversity and frequency is testimony to the flexibility and value of the HISS facility.

We wish to thank Jose Alonso, Robert Force and the Bevatron Operations staff for their efforts in providing the auxiliary services needed to make this facility and experiment a success.

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Appendix 1

DARKNESS: a technique to minimize the effect of secondary electrons

One of the major technical problems in determining the trajectories of heavy ions at relativistic energies is the presences of secondary electrons or delta rays²⁴. These secondary electrons emanate from interactions between heavy ions and the electrons of any slowing medium (e.g. the material of which the detector is composed). For example, the probability that a fully stripped ^{12}C ion with kinetic energy 2.1 GeV per nucleon will create a delta ray with kinetic energy greater than 1 MeV within the volume of one of the drift chambers is almost 10%. A 1 MeV electron generated in the vacuum window or in the front of DC1 will completely traverse both downstream chambers and still have sufficient energy upon reaching the TOF hodoscope to be indistinguishable from a proton of beam velocity. On the average a delta ray with a kinetic energy of only 100 KeV will traverse the entire thickness of both DC1 and DC2. The probability that a ^{12}C ion with a kinetic energy of 2.1 GeV/nucleon will create such a delta ray within the first millimeter of DC1 or DC2 is essentially 50%. Thus the chambers, being efficient detectors of charged particles, registered the passage of the delta rays as well as the parent ions, resulting in many events with multiple hits. The magnitude of the problem is shown in figure 16. Shown in this figure is the response of DC1 to ^{12}C projectiles. A perfect event would be characterized by exactly six hits, but one sees that as many as twelve wires fire 40% of the time. Clearly, if one is interested in detecting particles with charge one and particles with charges much greater than one simultaneously, the effects of secondary electrons cannot be neglected.

For the drift chambers described, the simplest procedure for track fitting would have been to minimize the sum of the differences squared from all 12 drift chamber planes. However, this least squares fit does not work well since it uses all differences and heavily weights the largest differences. In the average track there were several spurious differences due to delta ray contamination. Thus a method was needed that would heavily weight the small differences and ignore large differences. The method chosen was to maximize the "darkness" for a series of test tracks within a 10 cm radius of the predicted track.

The first step in calculating the darkness for a test track was to calculate the predicted hit locations, $\bar{\xi}_n$, for each plane, n . This was accomplished using the technique discussed in section 3.3. The second step was to find the difference between the predicted location, $\bar{\xi}_n$, obtained from the test track, and the actual location, ξ_n , for each plane, n . The actual location for each plane was determined by the number of the wire that fired and the drift time of the TDC on that wire. Next the projection of each of those differences on a gaussian distribution with a standard deviation, σ , of one (1) millimeter was calculated. Finally the darkness of a chamber was obtained by summing the projections over all the planes in that chamber. Thus darkness can be defined mathematically as

$$\text{Darkness} = \sum_{n=1}^6 \text{EXP} \left[\frac{-(\bar{\xi}_n - \xi_n)^2}{2\sigma^2} \right]$$

To illustrate the effect of this "darkness" maximization consider the case of the first two planes of a downstream drift chamber. Let the passage of a beam particle or accompanying delta ray electrons be registered in the S_1 and S_2 planes as x_1 and x_2 respectively. The difference between these values and the predicted value, $\bar{x}$, is $|\bar{x} - x_1|$ and

$|\bar{x} - x_2|$ or Δx_1 and Δx_2 . Letting $D = |\Delta x_1 - \Delta x_2|$, then for $D < 2\sigma$, darkness is maximized at a new $\bar{x}' = \frac{x_1 + x_2}{2}$ or $\Delta x_1' = \Delta x_2' = \frac{D}{2}$, and both data points are used. If, however, $D > 2\sigma$ then only one of the data points is used and darkness will be maximized at either $\Delta x_1 \approx 0$ or $\Delta x_2 \approx 0$, depending upon which data point is closest to the projected value (i.e. whether $|\bar{x} - x_1| < |\bar{x} - x_2|$ or $|\bar{x} - x_1| > |\bar{x} - x_2|$). Thus the parameter σ determines whether a difference is small enough to be included in the average or is rejected. In this experiment the darkness calculation was insensitive to the width of the gaussian chosen from the single plane resolution of 150μ to a value of $1mm$. The larger value was chosen to increase the granularity of the track finding routine and thereby reduce the CPU time expended in searching for tracks.

This ability to identify and reject spurious data points makes the technique of darkness maximization superior to a least squares fit of the data. Hits produced by the passage of the primary fragment typically lie close to the predicted position. Spurious hits from knock-on electrons are usually much further away from the predicted position. Thus darkness is maximally weighted by true, not spurious, hits.

As shown in figure 19, charge two particles having tracks with darkness less than three (3) failed to reproduce the clean charge distribution present for charge two particles with tracks of darkness greater than three (3). These observations when linked with the high efficiencies of *DC 1* and *DC 2*, indicate that malfunctions of the chambers were not the major contributor to tracks with low darkness. This implied that many of the tracks with darkness less than three (3) were the product of so called "zoo" events. A zoo event being an event of questionable origin. An example of a zoo event would be one that contained low momentum fragments from a secondary interaction that took

place downstream of *DC 1*.

The large number of events with unacceptable primary beam tracks, 20%, and zoo events, 13%, made it necessary to preview an event before the reconstruction of any tracks was attempted. This preview served to eliminate bad events from the reconstruction routine, and this made more efficient use of the available computing time. The events eliminated were those in which the event was flagged as bad upstream, the projectile had interacted downstream of *DC 1*, or the fragments were masked by equipment malfunctions. A more detailed description of the cuts is given in table 2. To verify that good events were not being lost in the preview, a random sampling of one hundred (100) eliminated events was examined event by event. The results of that survey are given in table 3. The survey technique was chosen over the Monte Carlo method because of the difficulty in generating a realistic sampling of events.

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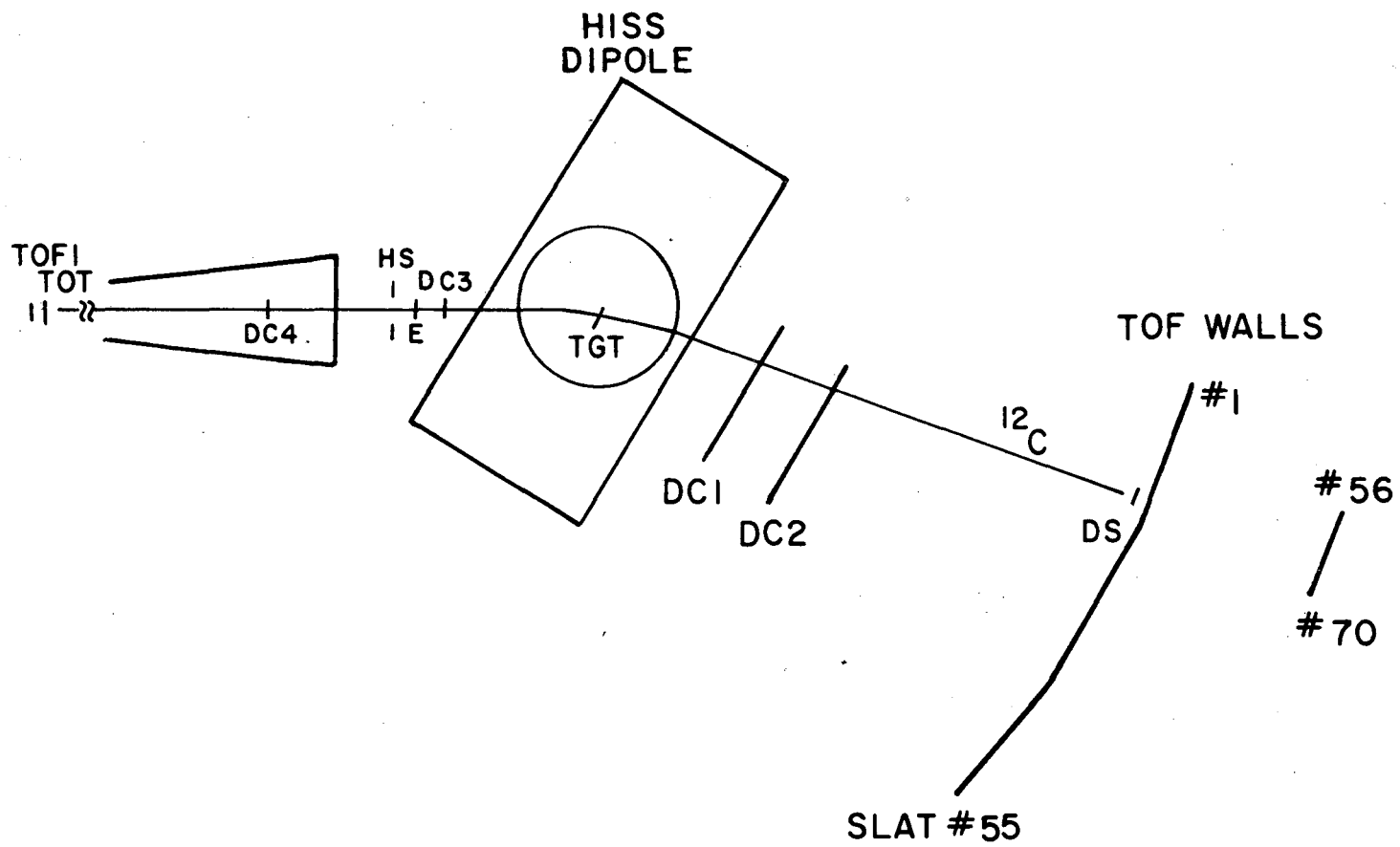
showing charge agreement in both front and back TOF arrays which were contained in events in which at least one fragment pointed back to the target. Although error bars include both statistical error and small differences in efficiencies between chambers, the dominant error is caused by changing the initial requirements on the data sample given above (see Crawford et al.²⁶).

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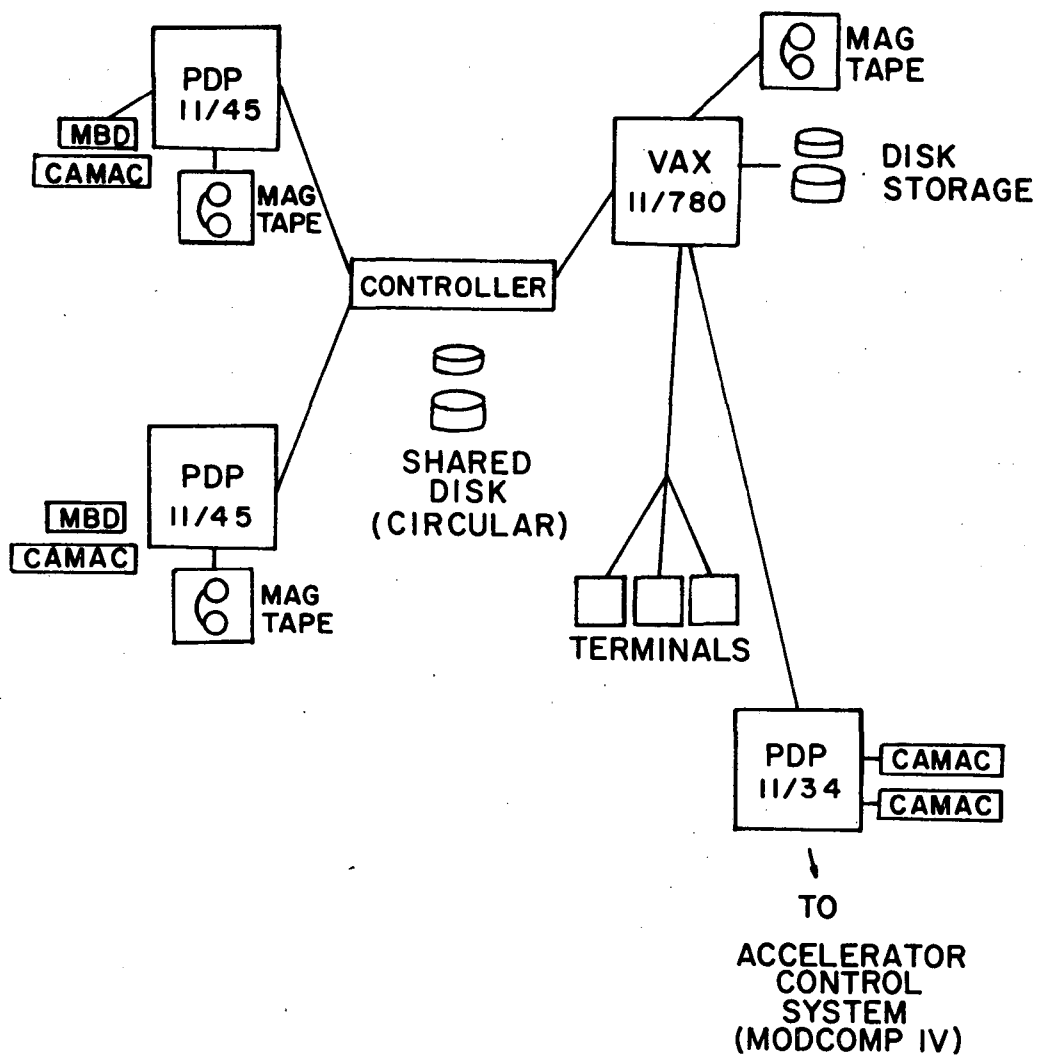
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XBL 8311-4605 A

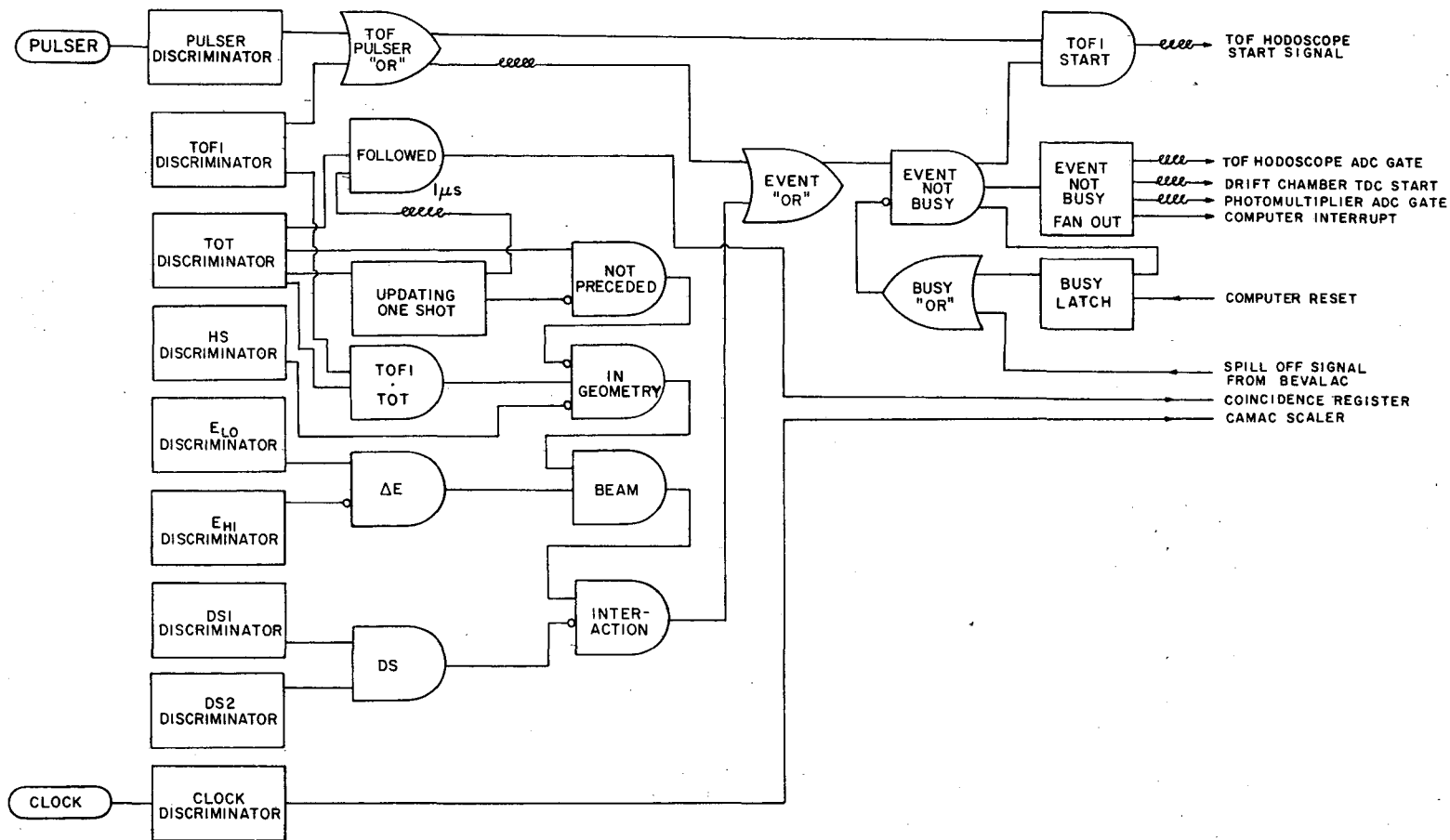
Fig. 1



HISS COMPUTER SYSTEM

XBL 887-2673

Fig. 2



TRIGGER LOGIC

XBL 887-2690

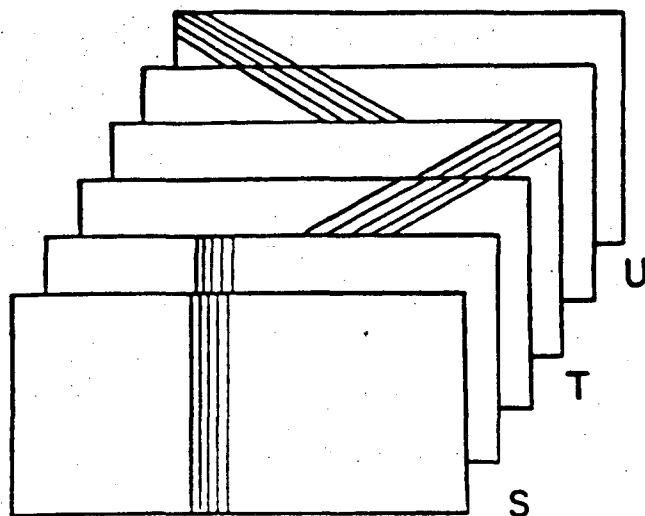
Fig. 3

HISS DRIFT CHAMBER

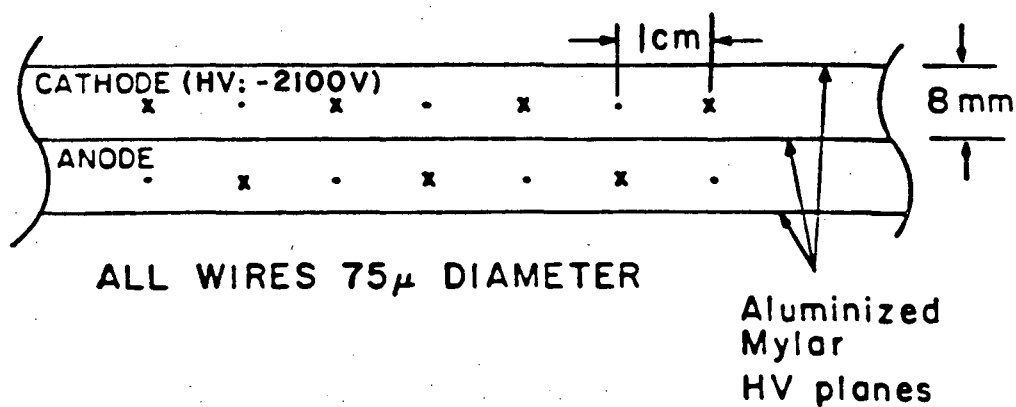
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GAIN: 2×10^4

HV: -2000V



WIRE ORIENTATION

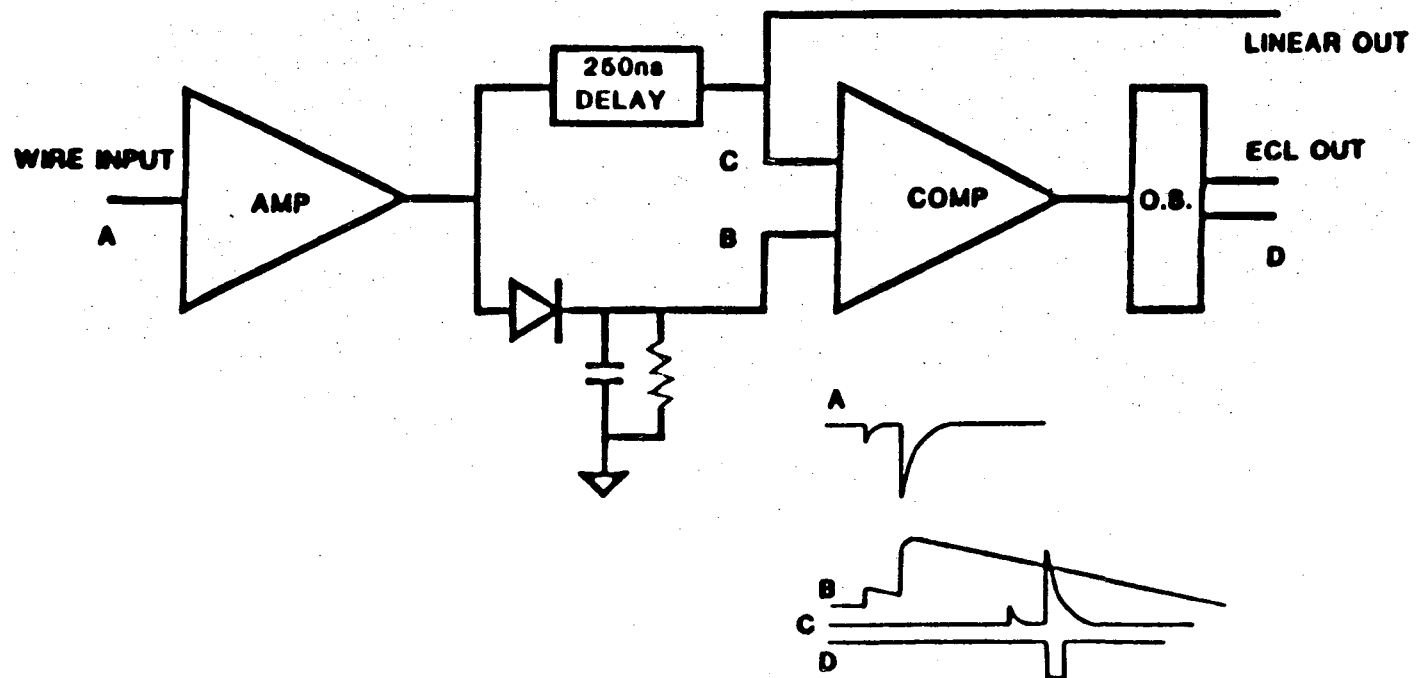


TYPICAL CROSS SECTION

XBL 887-2674

Fig. 4

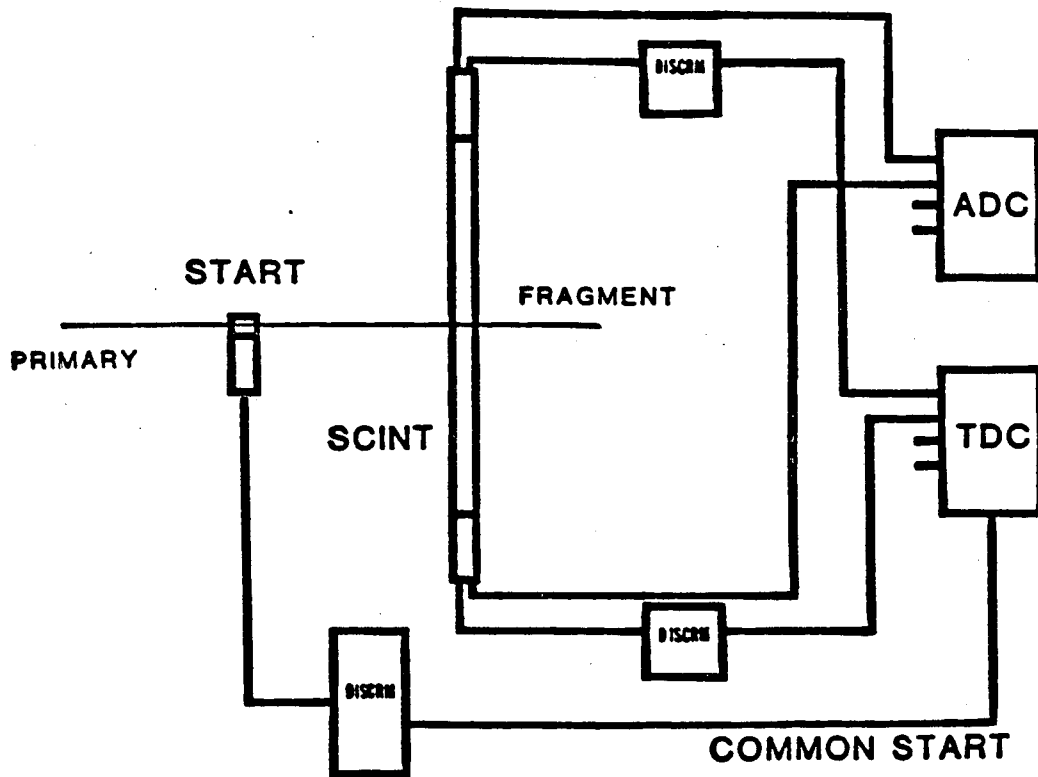
HEAVY ION DRIFT CHAMBER FRONT END



XBL 887-2675

Fig. 5

TOF ELECTRONICS

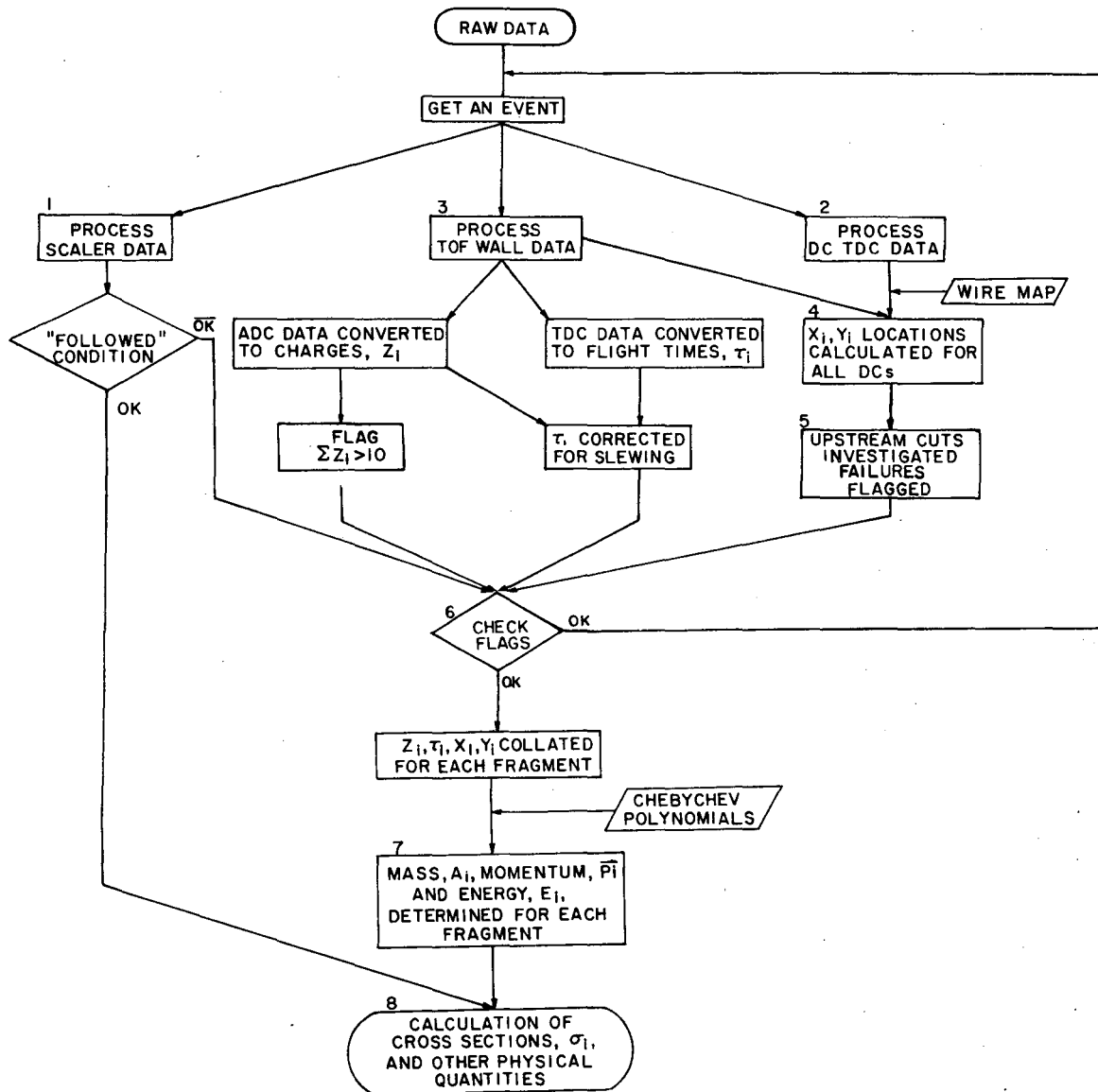


**LE CROY 2280 ADC SYSTEM
LE CROY 2228A TDCS
LE CROY 620D DISCRIMINATORS**

XBL 887-2686

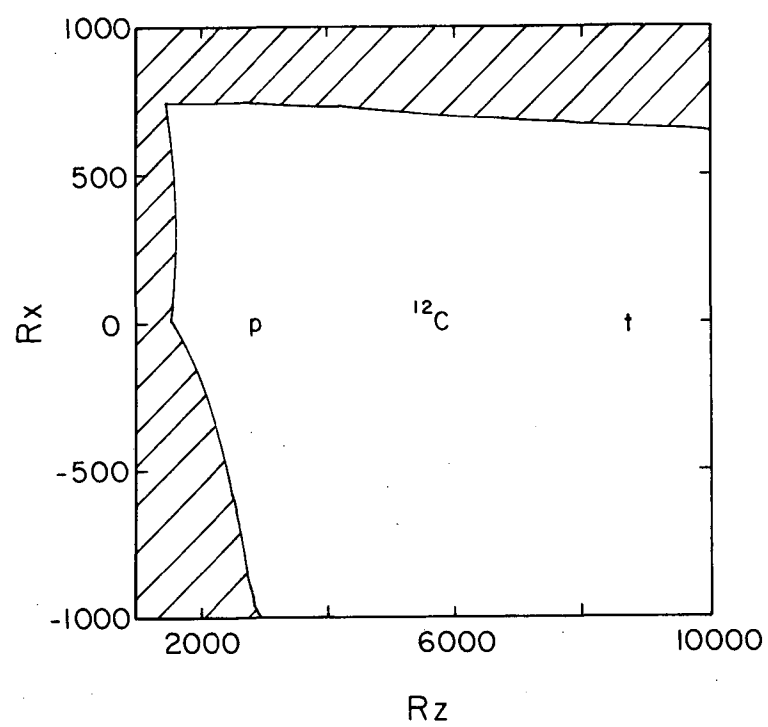
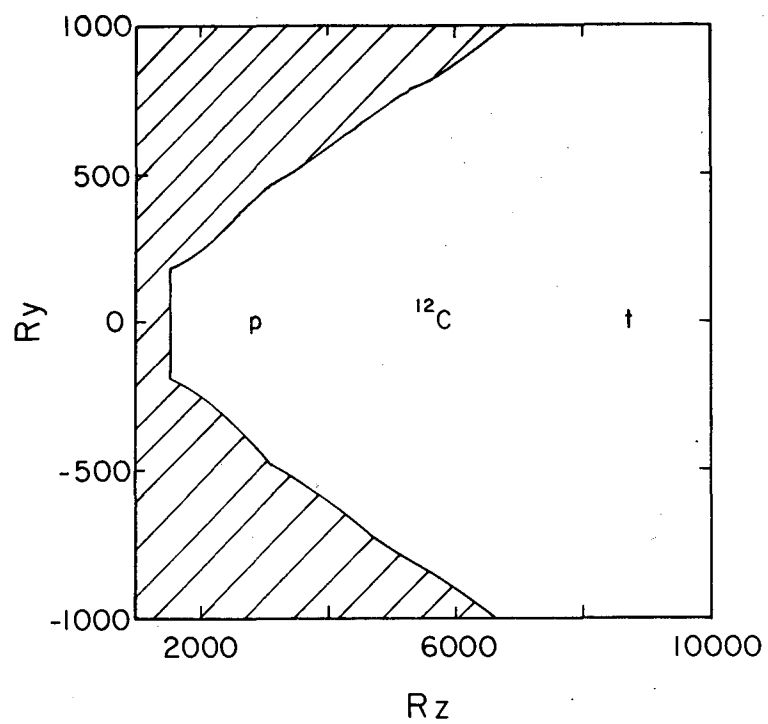
Fig. 7

FLOW CHART FOR DATA ANALYSIS



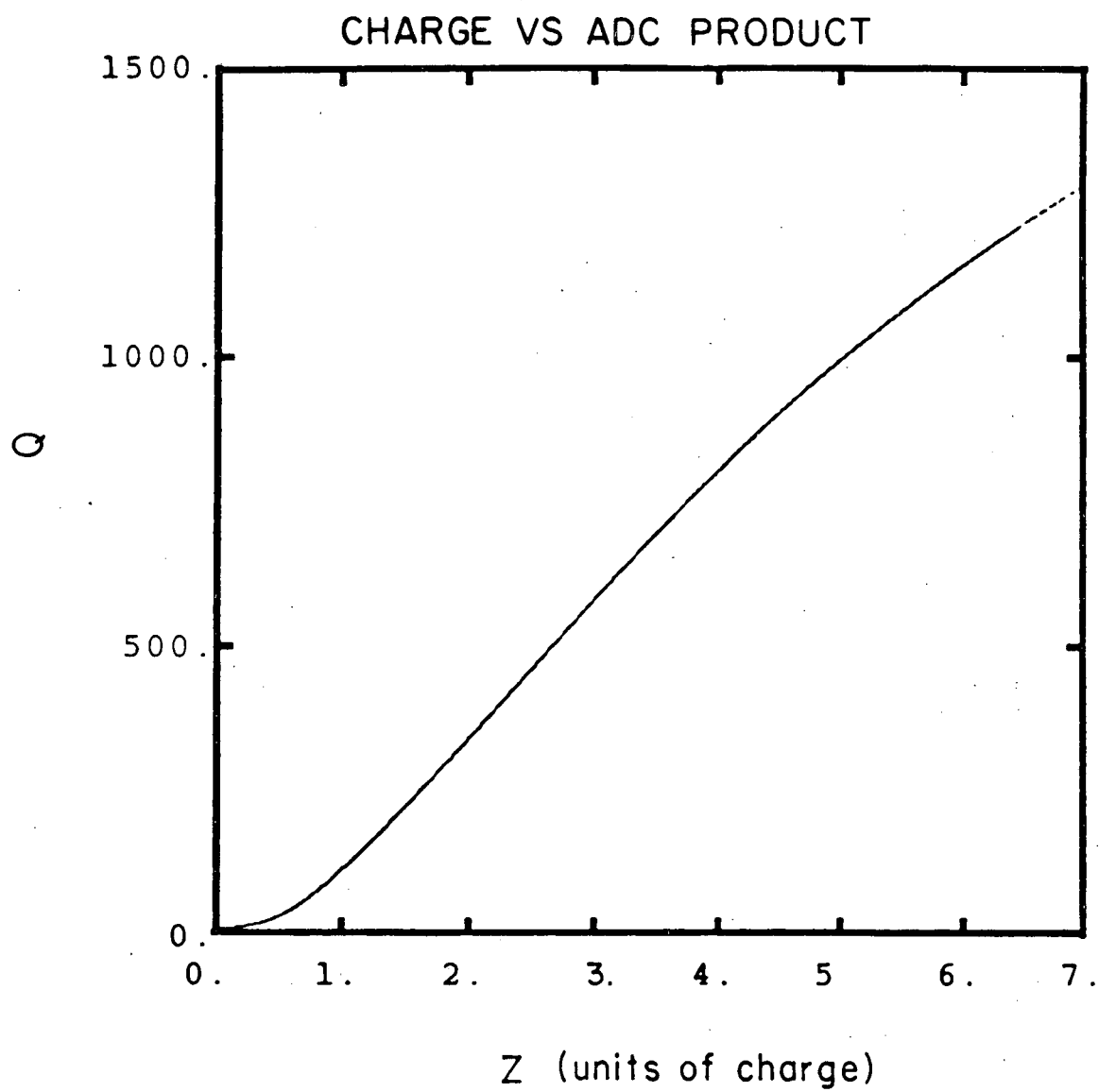
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Fig. 8



XBL 887-2688

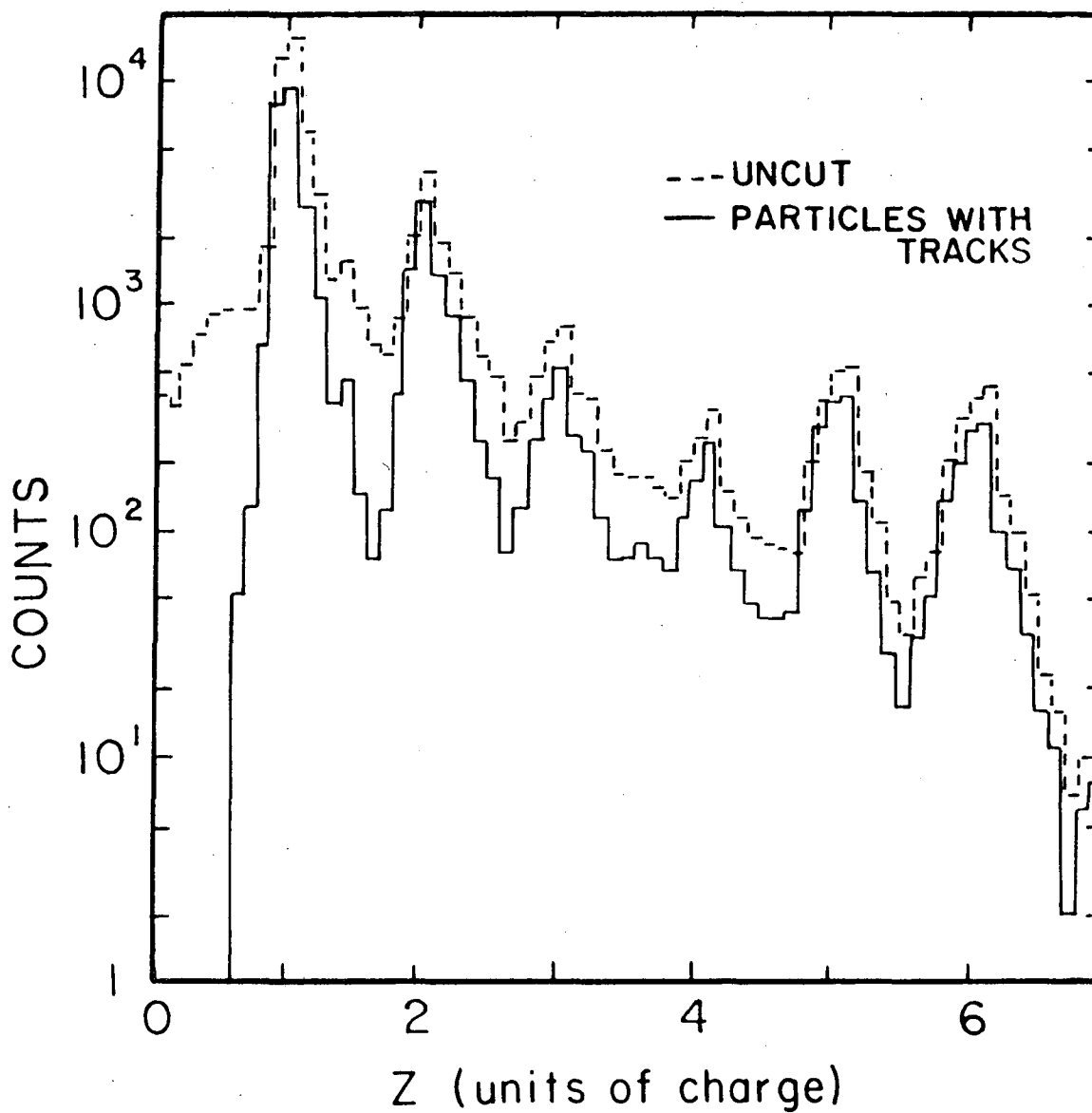
Fig. 9a,b



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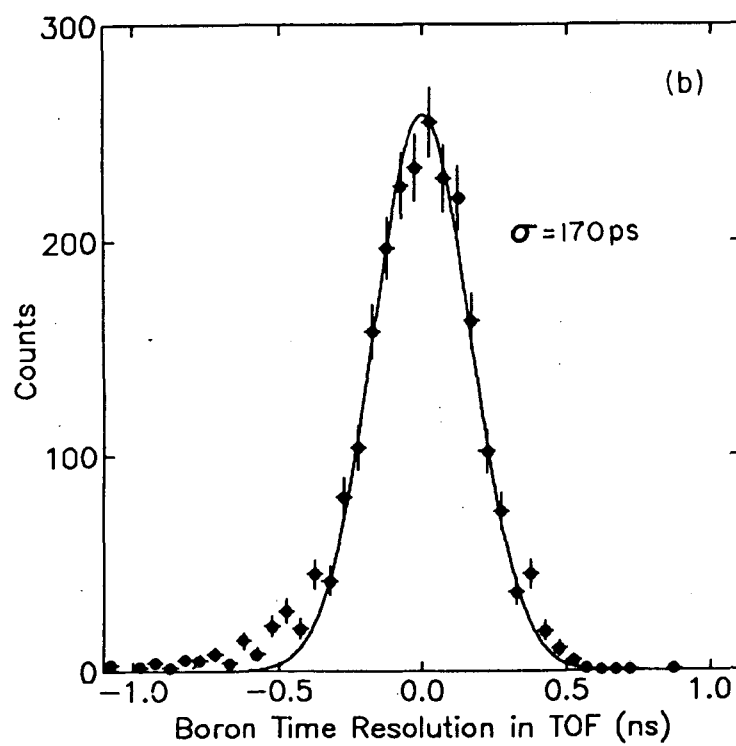
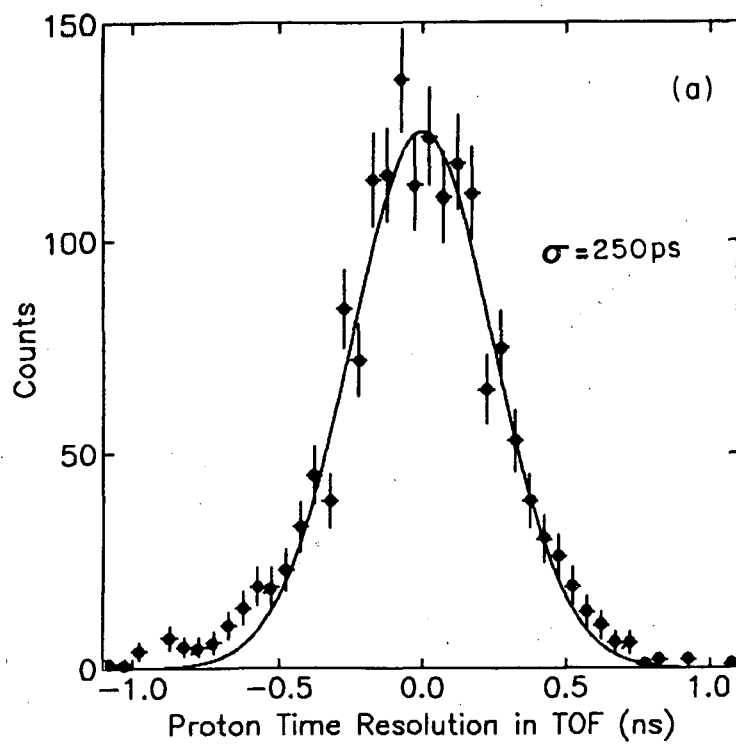
Fig. 10

SIGNAL DISTRIBUTION IN SCINTILLATION ARRAY



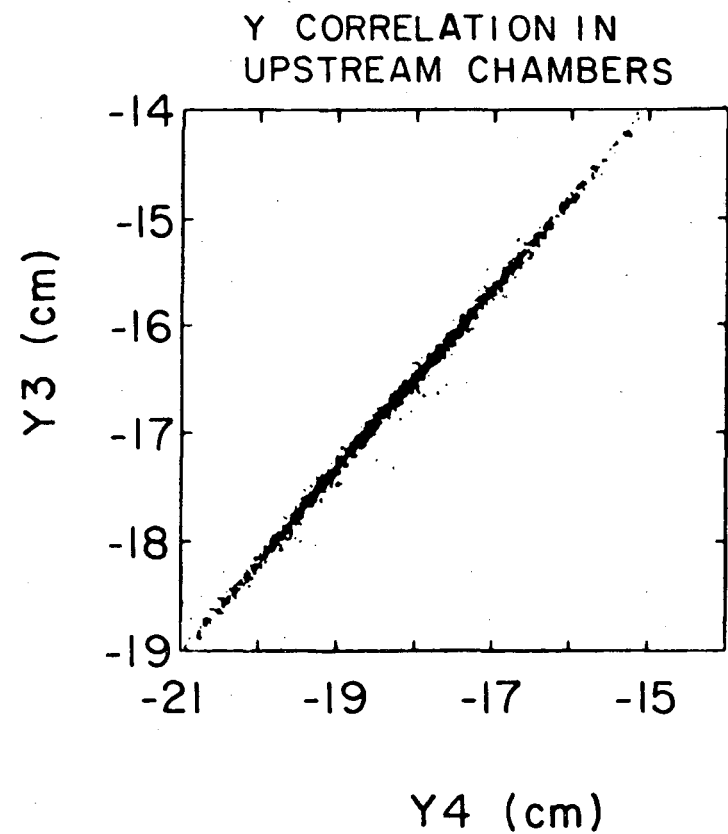
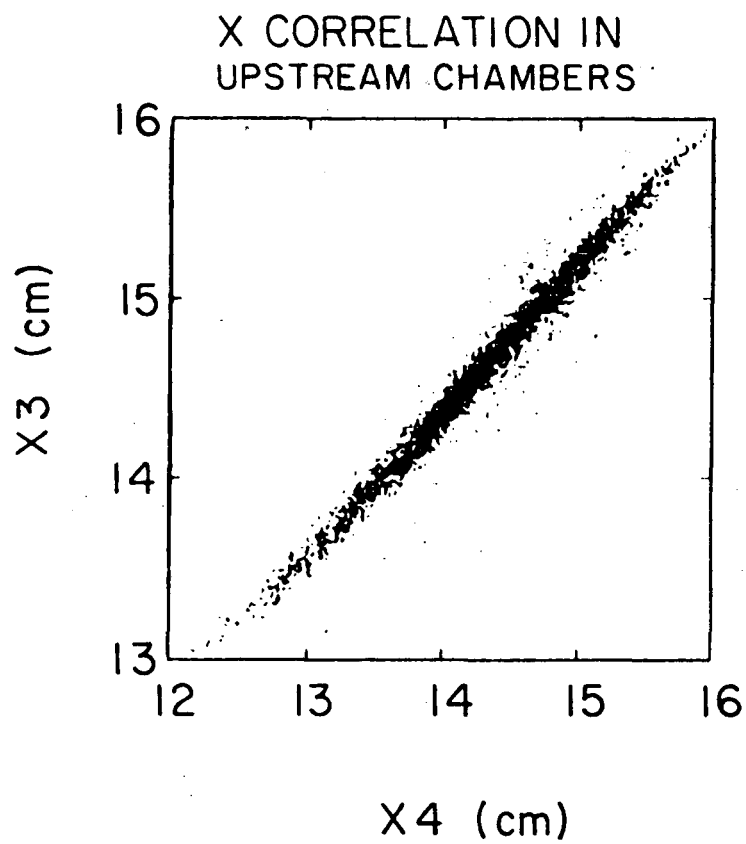
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Fig. 11



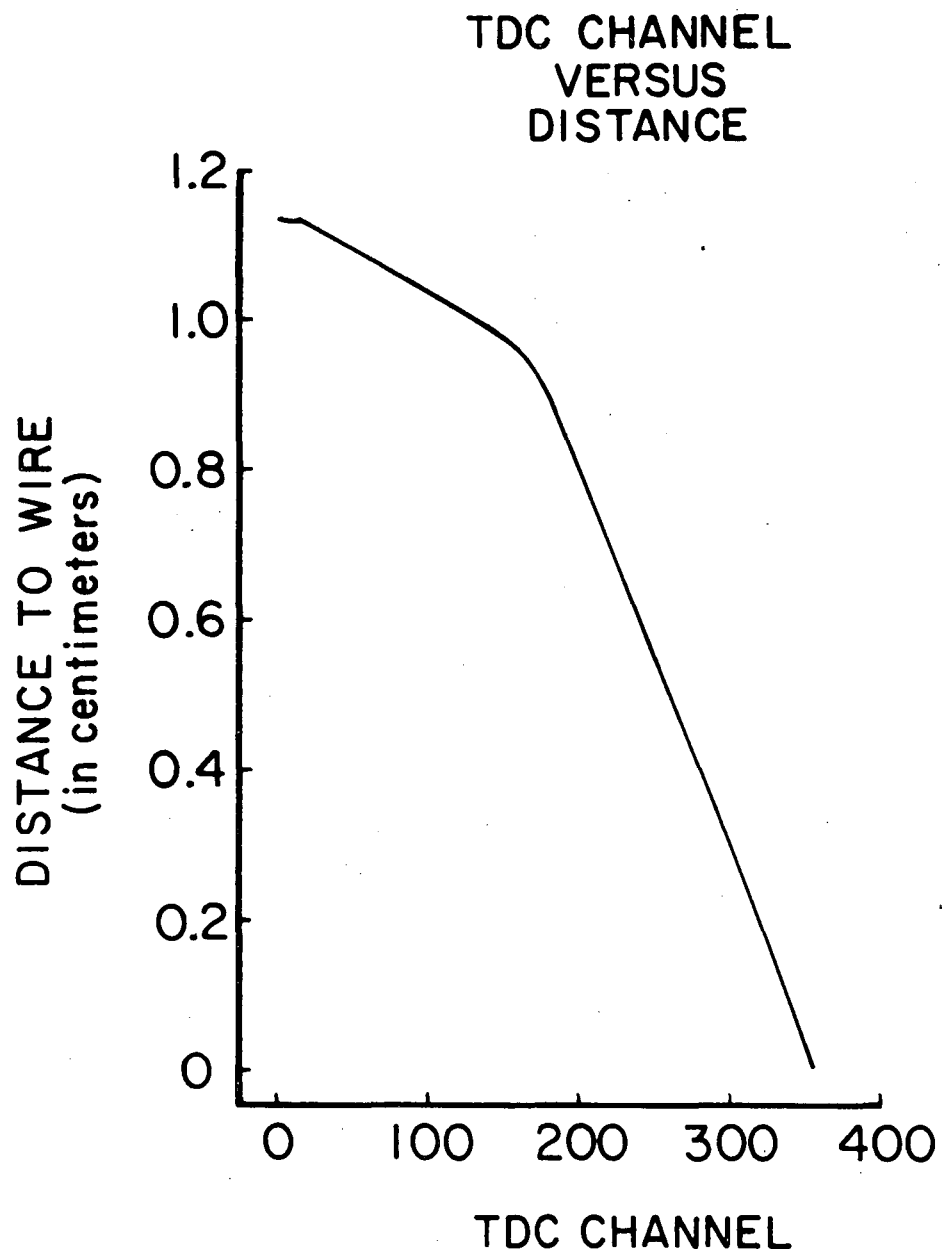
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Fig. 12a,b



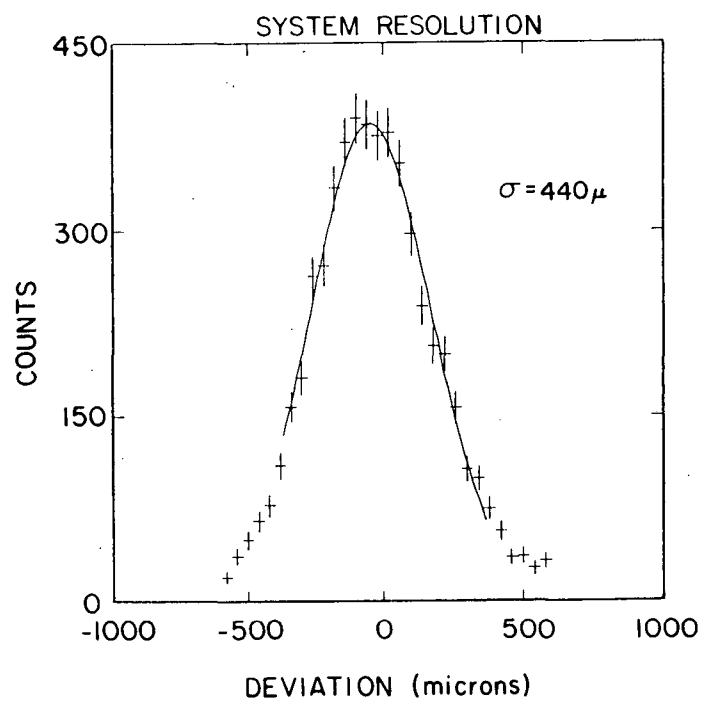
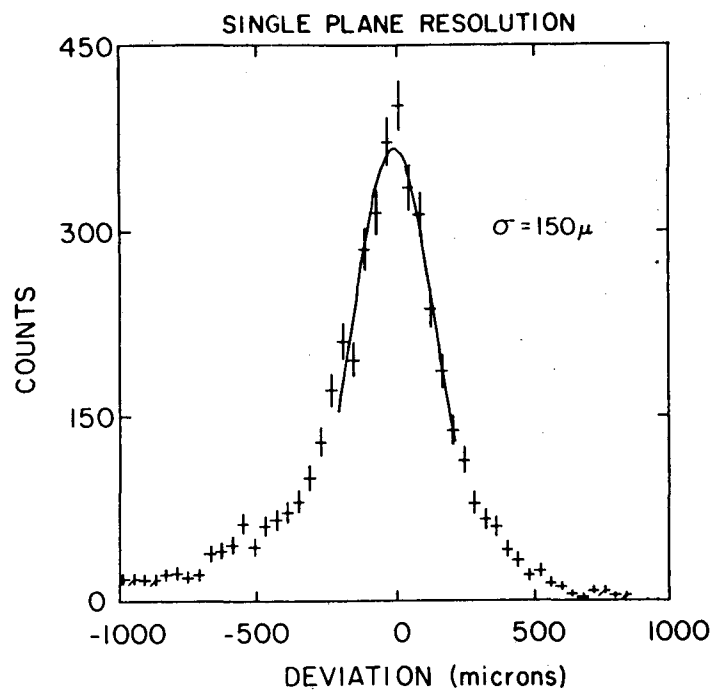
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Fig. 13a,b



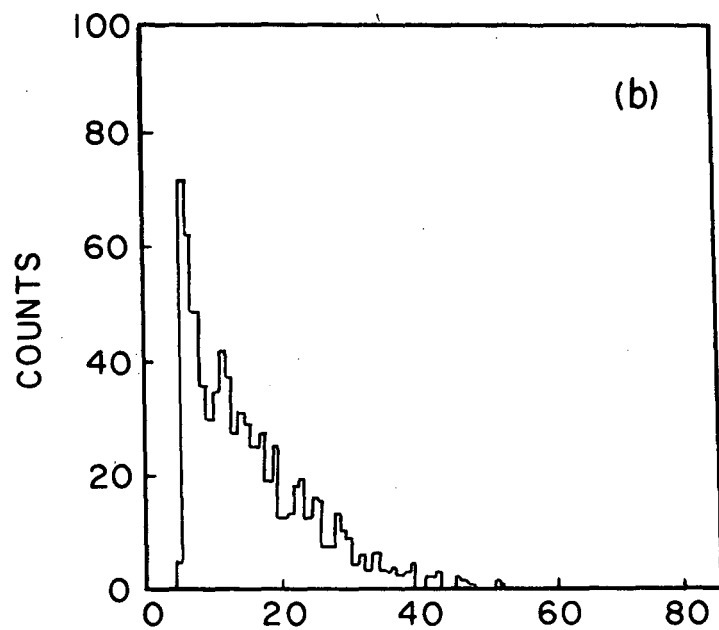
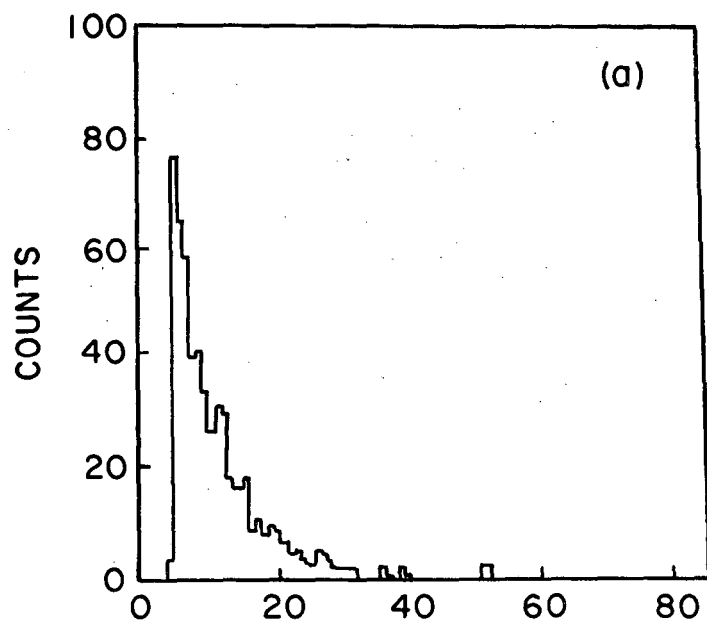
XBL 887-2687

Fig. 14



XBL 887-2685

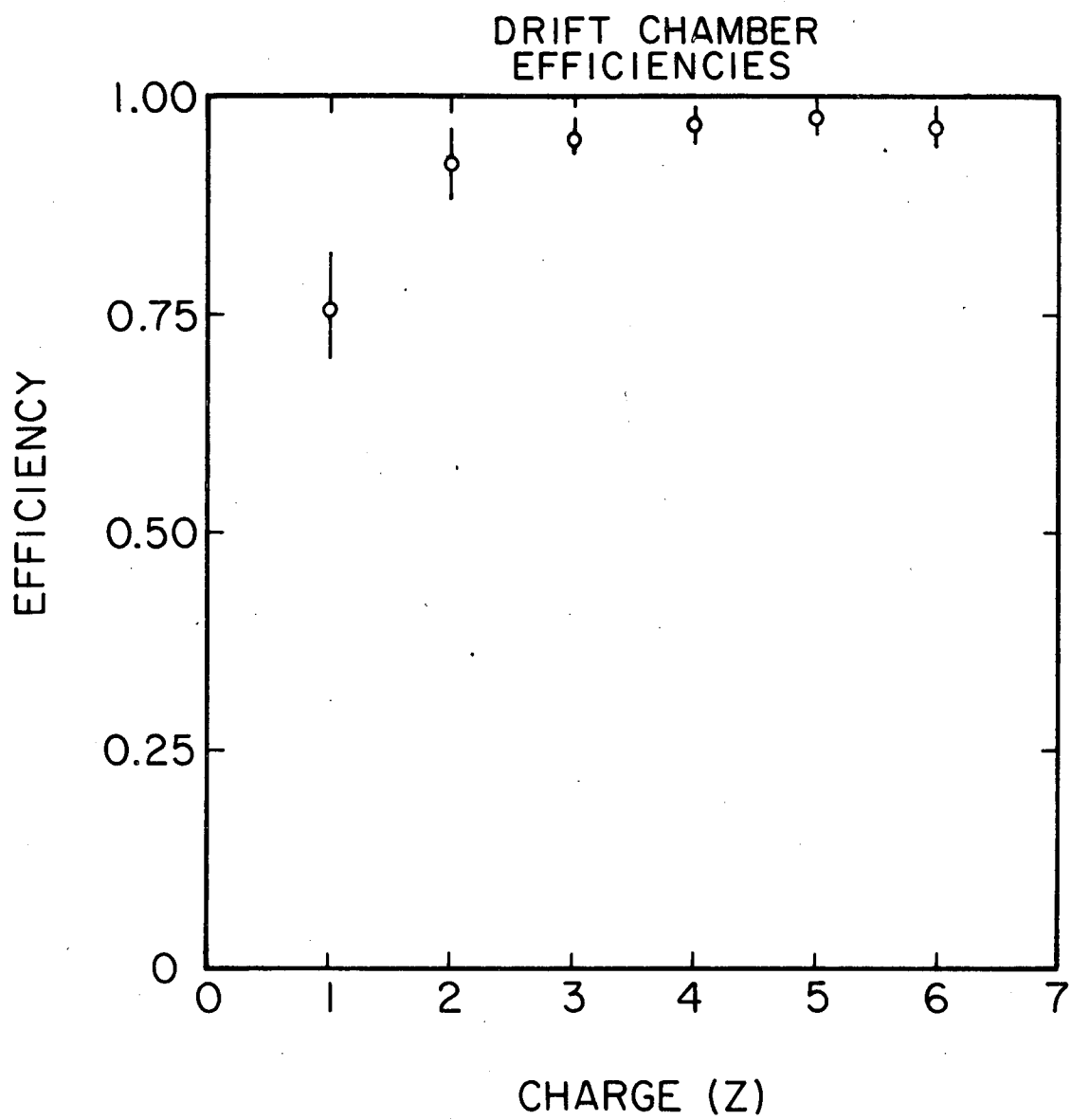
Fig. 15a,b



NUMBER OF WIRES

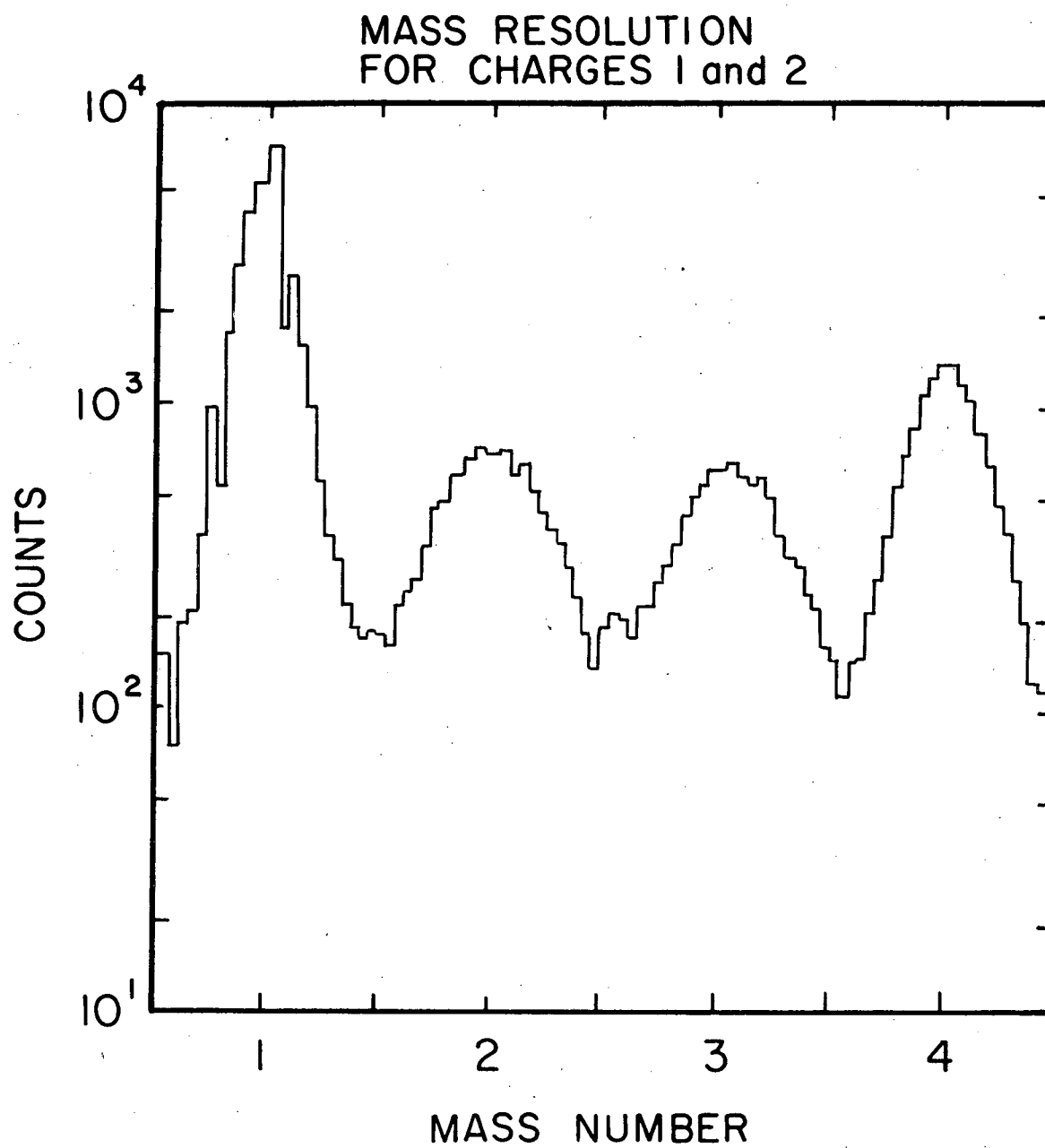
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Fig. 16a,b



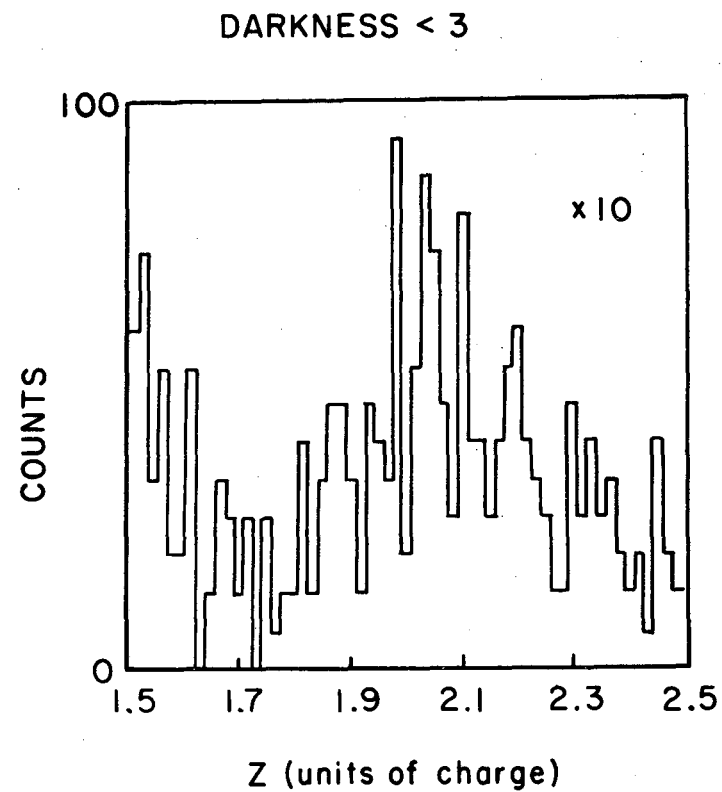
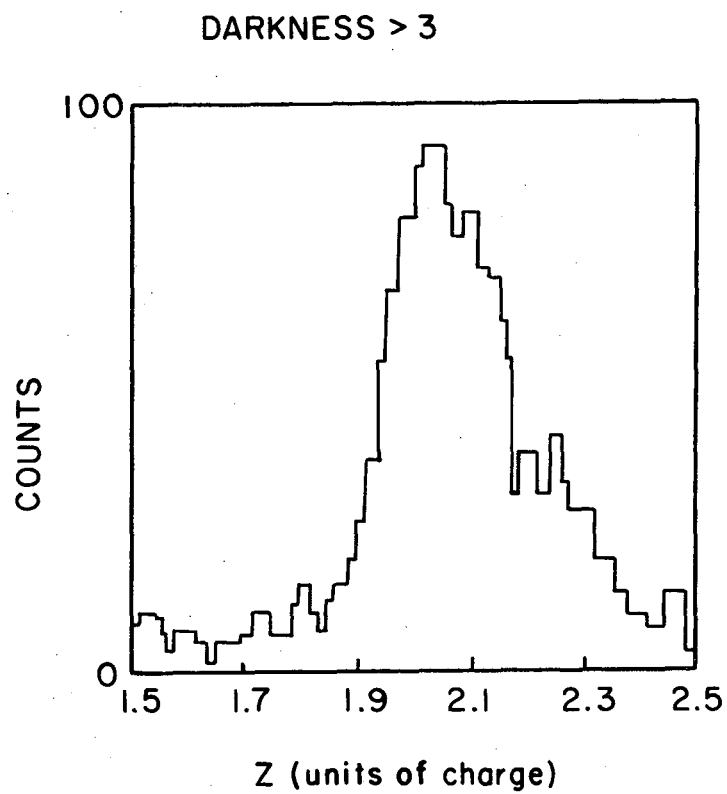
XBL 887-2682

Fig. 17



XBL 887-2683

Fig. 18



XBL 887-2684

Fig. 19a,b

TABLE 1

HISS Magnet Parameters

Central field	3 Tesla
Field on conductor	4.6 Tesla maximum
Superconducting coil	Nb-Ti in Cu matrix in liquid He
Conductor cross section	1.19 cm $\times$ 0.4 cm
Copper/Superconductor ratio	19:1
Ampere turns	5.12×10^6
Current	2200 A
Conductor current density	5000 A/cm ²
Magnetic energy	55.2 MJ
Yoke: Window frame type	5.13×10^5 Kg
Pole diameter	2.1 m (83 inches)
Magnet gap	1.0 m (40 inches)
Unobstructed azimuthal angle	110° at front and back
Mounting	Rotatable base
Magnet total mass	5.67×10^5 Kg

TABLE 2

CUTS MADE IN DRIFT PROGRAM

CUT #	REASON
1	Total charge in the TOF wall is greater than ten (10). The event looks like there was an interaction downstream and high charge shows up because target fragments make it into the TOF wall.
2	Beam particle breaks up downstream of DC1. These events are distinguished by having only one track in DC1 and several hits in the TOF wall. The cut is made on the following basis --less than eight (8) wires in DC1, less than the number of wires "needed" for two tracks --multiplicity in TOF greater than three (3).
4	More than 200 dalitz conditions per chamber. This number is selected because events with higher numbers of dalitz conditions are hard to analyze correctly due to the number of random matches.
6	Event failed to pass upstream chamber cuts.
10	More than 150 wires fired in the chambers. This is the limit in which one is still able to find solid tracks.
20	No wires were passed from program that processed the drift chambers.

TABLE 3

SURVEY OF EVENTS ELIMINATED IN THE
TRACK RECONSTRUCTION PROGRAM

CUT #	DESCRIPTION	COUNT
1	Total charge greater than ten	15
2	Beam split up downstream of DC1	4
3	Both cuts 1 and 2 apply	5
4	Too many dalitz conditions	8
6	Bad upstream flag set	59
7	Both cuts 1 and 6 apply	6
8	Both cuts 2 and 6 apply	2
9	Cuts 1, 2 and 6 all apply	1
Total (300 triggers)		100

*LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720*