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Submitted to Optical Engineering

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May 1987

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-22302

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This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

A Fast Megapixel CCD Image Acquisition and Analysis System for High Energy Nuclear Physics

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A two-camera system has been developed for photographing and analyzing images consisting of particle tracks from high energy collisions in a streamer chamber track detector. The CCD cameras view the collision region with typical images consisting of more than 100 tracks. Each camera consists of a 1024 × 1024 pixel CCD array. Up to 3 cameras can be read out simultaneously, at a rate of 5×10^5 pixels/second/camera digitized to 9-bits, through a custom-designed multiplexing interface into an integer array processor, computer and color display station. A software system has been developed which allows multiple asynchronous computer processes to record, analyze, and display the streamer chamber images. The system has been used in a high energy nuclear physics experiment for online analysis, digital data acquisition and storage of streamer chamber events, with subsequent offline image and physics analyses.

Contents

1 Introduction

1.1 Overview

This article describes an application of Charge-Coupled Device (CCD) technology to the field of high energy nuclear physics. A two camera system, the CCD Supervision System, has been developed for photographing and analyzing images from a Streamer Chamber (SC) particle track detector. These images consist of fluorescent tracks of charged particles and light nuclei created in high energy nucleus-nucleus collisions. The tracks curve and cross in space due to a strong magnetic field in the SC. A picture, taken with film, of a typical SC event is shown in Fig. 1. The three-dimensional trajectories and momenta of the particles can be obtained by stereoscopic reconstruction of the tracks from two or three camera views. The CCD Supervision System is designed to augment and ultimately replace the conventional approach of film photography followed by manual scanning and measuring. The analysis of pictures from SCs has been severely handicapped by the need to manually measure each track, resulting in small data samples. CCD photography and computer image processing could increase the speed of data analysis by orders of magnitude.

The CCD Supervision System is a hybrid of several commercial hardware and software products, a custom electronic interface between the cameras and the computer system, and software for system control. The system design was based on performance goals dictated by the physics needs of the latest generation of SC experiments. Other factors influencing system configuration were a 1.5 year time scale from conception to operation, a relatively modest equipment expenditure of $137,000 (1985 dollars), and a small team of two physicists, two graduate students, an undergraduate, and a part-time electronics engineer. The strategy for building the system was to use standard, widely supported products with existing software wherever possible. The system was constructed on time and with only a slight cost overrun. It was first used in November, 1986, in experiment NA35 at the Super Proton Synchrotron (SPS) accelerator at CERN, the Center for European Research in Nuclear Physics in Geneva, Switzerland. There the initial objectives of monitoring the SC and measuring simple physics observables online were accomplished. In 1987, the system will be enhanced, and used in several more experiments at CERN and at the Bevalac accelerator at the Lawrence Berkeley Laboratory (LBL) of the University of California in Berkeley, California.

All these experiments investigate extremely dense, high temperature phases of nuclear matter by colliding medium and heavy atomic nuclei at high energies. The colliding nuclei are compressed and heated into a fireball of nuclear dimensions ($\sim 10^{-15}$m), and the particles emitted can be analyzed to disclose details of the interaction. At the Bevalac, the beam energies range up to 2 GeV per nucleon (proton or neutron), twice the rest-mass energy of the incident nuclei. In Bevalac experiments[1] physicists study the equation of state of nuclear matter at three to four times normal density. Similar conditions are believed to occur in the interiors of collapsing stars in the initial milliseconds of a supernova explosion. At CERN, the beam energies can reach 200 GeV per nucleon, over two hundred times the nucleon rest-mass energies. In this regime the colliding nucleons are predicted to briefly dissolve into a plasma of quarks and gluons,[2,3] the elementary particles from which they are formed. This state is expected to quickly condense back into more familiar particles, leaving behind some signatures of its existence. A quark-gluon plasma state is believed to have existed for the earliest instants in the expansion of the Universe just after the Big Bang.

1.2 Streamer chambers

The SC is a successor to the bubble chamber. Bubble chambers, invented in the 1950's, were seminal devices for observing the physics of strongly interacting particles. SCs were invented in the mid-1960's and have since been developed and used throughout the world.[4] Both detectors provide very high quality tracking information about all fast charged particles in their volumes; both share the handicap of very laborious analysis of visual data. SCs are superior to bubble chambers in many applications because they can be triggered on a submicrosecond time scale, and can select an event of interest out of up to 10^5 beam particles per second.

Like most particle detectors, SCs work by collecting and amplifying the ionizational energy loss deposited in the detector by charged particles. In a SC, this energy is deposited in a gas, conventionally a mixture of He and Ne with some trace constituents, usually at standard temperature and pressure. After the passage of an ionizing particle, a trail of free electrons and ions remains in the gas from a few hundred nanoseconds to a few hundred microseconds, depending on the composition of the gas. This "memory time" allows external detectors in the experiment to decide whether to trigger on the event. For selected events a high voltage pulse of 500 kV and 15 nanosecond duration is applied to the chamber, creating glow discharges called streamers, which are several hundred microns to a few millimeters in diameter.

Particle tracks consist of streamers separated by gaps of up to 1 cm depending on the initial ionization. The streamers can be seen in Fig. 1 as the dots which define the tracks. Streamers generate light by recombination and atomic de-excitation; in HeNe gas this light has a characteristic orange color with wavelength around 6300 Å. The luminosity of the streamers depends strongly on the chamber voltage; with high enough voltage, the streamers are visible to the human eye. However, at lower voltage particle tracks are more precisely defined in space. Furthermore, lower voltage minimizes flares, which are caused when charged particles strike the electrified grids in the chamber. Flares cause CCD blooming and consequently poor picture quality. At lower voltages image intensifiers are employed to amplify the light for photography.

1.3 Design criteria

The lastest generation of nucleus-nucleus collision experiments at both the SPS at CERN and the Bevalac at LBL produce up to several hundred charged particle tracks in the SC. Because of the very high beam energy of the SPS, many of the reaction products are kinematically focussed within a narrow cone a few degrees from the beam axis. Both the large multiplicity and the high track density demand small streamer size and excellent localization – the chamber must be operated at low pulse voltage. The CCD Supervision System must have high resolution, high sensitivity to light, and a fast data rate in order to efficiently utilize expensive accelerator resources.

The most important criterion for acceptable system performance was the highest possible image resolution in the SC. This dictated the largest available CCD: the Texas Instruments 1024 × 1024 VPCCD. In order to read the CCDs into the computer system at a very fast rate, a custom camera-to-computer interface board was constructed. A high-speed integer array processor was required for buffering the CCD pixels into memory and for full frame image enhancement operations. The need to implement the system by Fall 1986 suggested a user-friendly, well defined, and widely compatible host computer environment. The last major criterion was a high quality image display at the full pixel resolution of the cameras.

The first goals for the CCD Supervision System were to provide a high resolution display of SC events in almost real time, quantitative measurements of event topology for trigger feedback, quantitative descriptors of chamber performance, and correlations of SC observables with data taken by other detectors. Both interactive queries and automatic background processing were desired, so a simple and flexible operator interface was needed which would permit operation either automatically or under explicit user control. Although an archive of standard parameters extracted from each picture would be recorded, it was not intended that many whole pictures would be stored digitally for offline analysis. After the NA35 run, the system had to be extendable for image recording at the Bevalac, which required the addition of a third CCD camera and a high speed, high capacity data recording system.

2 The CCD Supervision System hardware

This section describes the specifics of the five major hardware subsystems: the CCD cameras, the interface, the host computer, the array processor, and the high-resolution color display including a color hardcopy printer. A detailed schematic is presented in Fig. 2. The implementation is based on the VAXstation II computer, with the high-speed integer array processor, and the color display as peripherals. The image data enter the system from the CCD cameras through a custom interface into the array processor. The system hardware was chosen after intensive investigation into the commercial products for image acquisition, processing, and display available as of Fall 1985. This system offered superior hardware capabilities, a sound platform of vendor-supplied software, and a better development environment than any of the alternatives considered.

Two other schemes were investigated for the computer system: conventional image processors, and VME-bus/Motorola-68020 systems. Conventional image processors usually have a host computer, one or more video-rate (10 MHz) image data buses, several Mbytes of image memory, a fast pipeline processor, a display, a DMA link to the host, and a host-based library of standard image processing operations. These systems were expensive ($60,000 to $150,000), lacked sufficiently high resolution color displays, and were awkward to program. VME-bus/Motorola systems were appealing because of their high-bandwidth data bus, inexpensive memory, and high-performance, general-purpose 68020 microprocessors. Unfortunately, 68020 VME boards only became available at the end of 1985, interfacing the cameras into these systems was problematic, and neither a high-speed pipeline processor nor a high-resolution color display controller could be obtained. Furthermore, no image processing software was available and the issue of coordinating several microprocessors and the hardware from several different vendors was never resolved. This approach was too ambitious for the group to tackle with limited time, money, and experience.

2.1 CCDs

The imaging devices for the system were chosen after consideration of several alternatives. Generally, scanned electron beam tubes like vidicons, saticons, and orthicons do not have adequate or linear resolution across the face of the device. The Kell factor[5] of interlaced scan lines also tends to reduce the effective resolution by a factor of roughly 0.7. In contrast, the resolution of CCDs is determined by the array size without positional variation or distortion. Devices with more than 1000 scan lines were not readily available for unclassified applications in 1985. Additionally, the relatively low quantum efficiency of the photocathodes of these tubes requires more image intensification. These factors motivated the choice of CCDs.

In comparison to film, CCDs have both advantages and disadvantages. The intrinsic resolution of film is limited by the size of its light-sensitive silver-halide grains, approximately 7 μm. This is superior to the 18 μm pixel dimension of the TI VPCCDs. Furthermore, images recorded on standard 35mm or 70mm film require less demagnification than comparable images recorded with CCDs. Film provides faster capture of high-resolution images than current CCD technology, and more compact data storage than magnetic media. The response of film to light is approximately logarithmic whereas CCDs have a linear response up to their full-well capacity. CCDs, because of their high quantum efficiency, are generally more sensitive than film. The main advantage of CCDs is that they provide directly digitized information.

At the beginning of the project in the summer of 1985, large format CCDs ($> 5 \times 10^5$ pixels) were only available from RCA and Texas Instruments. RCA discontinued commercial sale of their devices in late 1985. TI remained a good alternative with their 1024×1024 virtual phase array. Two of these CCDs were purchased, at a cost of $14,000 per chip. Subsequently, TI has withdrawn from the low-volume scientific CCD market.

The virtual phase technology was developed jointly by Jet Propulsion Laboratory and Texas Instruments, and has been used successfully in several different CCDs of various sizes.[6,7] These CCDs are front illuminated, have a charge transfer efficiency of >0.99995 at 1000 electrons per pixel, and have <50 electrons per pixel noise when cooled to -45 C. The full well capacity of these chips is about 2×10^5 electrons. Their quantum efficiency is between 30% and 50% in visible wavelengths. One of the CCDs in this system is essentially flawless, while the other has a single half-column defect about 50 pixels from one edge. These chips have delivered excellent performance in our application.

2.2 Cameras and controllers

The camera subsystems were made by Photometrics, Ltd. of Tucson, Arizona. Each consists of: a camera head with optics, CCD, and cooling system, a camera electronics box which regulates the CCD voltages, drives the CCD, and digitizes the pixels, and a Multibus camera controller board with an integral AM2901 12-bit bit-slice microprocessor to handle camera functions.

The camera heads provide the mechanical mounting of the CCDs, coupling the optics, cooling, and electronics. The CCDs are cooled to a temperature of -45 C by a combination thermoelectric (Peltier) and flowing water system. The camera heads include mounts for standard Pentax lenses. Electronically controlled mechanical shutters open and close in $\sim 10 - 40$

ms.

The camera drive electronics are housed in individual boxes which are located < 1 m from each camera head. The camera electronics boxes drive the CCDs clock phases at a rate of 5×10^5 pixels per second (500 kHz), or 2.0 μs per pixel. Once initiated, the CCDs are read out in a steady, non-interruptable stream of pixels, each digitized to 9 bits using successive approximation ADCs. The digitized pixel bits are transmitted serially over a 25 m cable from the SC experimental area to the experimenter's electronics room. Power and control signals share the same cable, and the drive voltages are regulated in the electronics boxes to minimize noise at the CCDs.

The camera functions are controlled by single-slot Multibus camera controller boards, which use standard Multibus protocol. The camera controllers supply the following functions: definition of CCD array subsections for individual readout, readout of the CCD array, continuous clearing of the CCD pixels, shutter operation including timed exposure, amplifier gain adjustment, and summation of pixels into lower resolution images.

Functions on the controller boards are specified by the 8-bit addresses of ROM-contained subroutines in the controller AM2901 microprocessor; these addresses are written as data over the Multibus after addressing the controller board. Some functions take one or more 12-bit parameters following the function command, such as array dimensions or gain factors. The digitized pixel data appear on an auxilliary connector at the front edge of each board; in this configuration the Multibus DMA bus-master control circuitry was disabled on each controller, so pixel streams from multiple controllers could be transfered in parallel to the interface board.

2.3 Image intensifiers

In order to register the low light output of the streamers an image intensification system is integrated into each camera setup. An imaging system including camera is displayed in Fig. 3. Each system consists of a mirror, primary lens, two-stage image intensifier assembly, and secondary lens. Tilting the mirror changes the field of view, while allowing the optical axis of the system to be fixed in space. The primary lens images the reflected view of the chamber onto the image intensifiers. Different lenses can be used to vary the field of view and demagnification.

The image intensifier assembly consists of a microchannel intensifier manufactured by AEG Inc., proximity-coupled to a Varo Inc. electrostatically-focussed first generation intensifier. Light from the output of the second intensifier stage is imaged onto the CCD via a macro lens with 50 mm focal length. The mirrors are attached to an iron shielding plate which reduces the magnetic field flux in the vicinity of the optics. In addition the cameras are encased in "mu-metal" shielding to eliminate any effect on the intensifiers of stray magnetic field.

The maximum luminous gain of the two-stage image intensifiers is approximately 3×10^6. The high gain is necessary because of the very low luminosity at low SC pulse voltage, and the 0.3% light collection efficiency of the secondary lens. See Table 1 for characteristics of the intensifiers. The limiting resolution of the optics system is 22 line-pairs/mm, dominated by physical pixel size on the CCD. For a 1.2×1.2 m^2 view of the SC, this corresponds to approximately 2.5 mm resolution in space.

2.4 Host computer

The host computer is a DEC VAXstation II (MicroVAX II), which includes a 1024×864 black-and-white display console with windowing and graphics capabilities. This computer is configured with 11 Mbytes RAM, a 71 Mbyte disk, a streaming cartridge tape, 4 terminal ports, and an ethernet link. It runs the VMS operating system. It was used for all program development for the system as well as its operation.

2.5 Array processor

The Mercury ZIP 3216 array processor is a five board set which resides on the Q-bus of the host computer and provides the system with data acquisition control, data buffering, and significant high-speed computing power for full-frame image processing operations. It is a fixed point processor, with 9 MIPS speed, two concurrent CPUs, and over 2 Mword internal data memory. Programs executing in the ZIP array processor control the cameras, fetch the pictures from its I/O ports, and buffer them in memory. The data are then transfered by DMA to the host computer at 1 Mbyte/second.

The array processor has a library of standard image processing algorithms, its own programming language, and a hardware simulator program on the VAX for the development of user-specific applications.

2.6 Custom interface

The interface in the system is a pair of Multibus boards which routes signals between the external apparatus and the computer system. These boards are a custom-built TTL logic-level board to send and receive signals from the experimental trigger, and another custom-built main interface board which multiplexes these signal sources into the Input/Output ports of the system array processor, the Mercury ZIP 3216.

The main interface board is a critical link in the data chain between the CCDs and the host computer. It is a single Multibus card which talks to the CCD camera controllers both via the Multibus and auxiliary data cables, and to the TTL logic board via the Multibus; it connects to the array processor I/O ports by a pair of cables. The primary job of the main board is to multiplex the streams of CCD data into the array processor in an interleaved fashion. The philosophy behind the design of this board was to make the interaction among the various system components as autonomous as possible. The data flow from the CCDs and the trigger signals drives the data acquisition cycle on an interrupt basis. There is no rigid sequencing built into the board to control the camera readout order or speed. It allows 1, 2, or 3 cameras to send pixels simultaneously, at different rates, and each array can be a different size.

The following critical time intervals determine the CCD data interleaving. Each CCD camera presents a 9-bit pixel every 2 μs (500 kHz.) The Mercury 3216 array processor executes 9 MIPS, and it is possible to grab a 16-bit word from the input port, and write it to memory in two 110 ns instructions. The main interface board uses a 64-deep, 15-bit wide, First-In-First-Out (FIFO) buffer for each camera's data stream. Pixels accumulate in the FIFO buffers, which issue a half-full flag at 32 pixels. The time to half-full is (32 pixels)$\times$(2 μs/pixel) $=$ 64 μs. The pixels are then burst-transfered to the array processor input port at its maximum rate: (32 pixels)$\times$(220 ns/pixel) $=$ 7 μs. The time to service all three half-full FIFO buffers, including an overhead of about 5 μs per camera, is 3$\times$(7 μs (burst)

+ 5 μs (overhead)) = 36 μs. This is roughly half the 32 pixel accumulation time of 64 μs, so in principle the array processor can spend almost half its time performing some background calculation during data acquisition.

The architecture of the main interface board is illustrated in Fig. 4. Programs in the array processor control the interface by writing 16-bit words to the output port. The two most-significant-bits of the output word distinguish four possible modes: an interface command, a Multibus read address, a Multibus write address, or Multibus write data; the 14 least-significant-bits of the word are the output command, address, or data. Commands to the camera controllers and the TTL logic board are written to their Multibus addresses. Interrupts for input data conditions and errors are queued as 4-bit condition words in a 64-deep FIFO, the condition queue. The condition queue, the three possible pixel FIFOs, and a Multibus input data register comprise five channels in the interface available to the array processor input port. The channel to appear on the input is selected by an interface command.

The TTL logic board has four inputs and four outputs for sending and receiving logic signals. Input signals go via the Multibus into the condition queue as distinct interrupts. Each output and the input enable/disable functions are separate Multibus addresses.

2.7 Color display system

The high-resolution color display is a model One/75 made by Raster Technologies. It is interfaced to the VAXstation by a 16-bit two-way DMA DR11W board on the Q-bus. A 1024×1024 pixel image can be transferred to the screen in four seconds. The One/75 has a 1280×1024 byte (8-bits deep) video memory. The 19 inch diagonal screen is made by Sony, and can display the full 1280×1024 pixels, refreshed at 60 Hz noninterlaced rate. An application can choose up to 256 simultaneous colors from a palette of 16.7 million colors. An 8-bit in, 3×8-bit out lookup table translates pixel intensity values into pseudocolors. The model One/75 offers pan, up to 16-fold zoom, and a nondestructive cursor. These features can be controlled by an attached data tablet. A keyboard can be used to give graphic commands in local mode independent of VAX control. The vendor supplies a VMS software driver and a FORTRAN-callable subroutine library to control the display from the host.

Color hardcopies of pictures from the Raster screen are produced by a Seiko model CH-5301 thermal wax printer. The print resolution is 1280 × 1024 dots on an 8.5"×11" page of paper or clear plastic. The printer connects directly to the color video signals of the Raster model One/75 display, independent of the host computer.

2.8 Data cycle

The data acquisition program in the array processor starts by initializing the main interface board and the Multibus. It then writes Multibus commands to configure the read cycle for each CCD camera controller for the appropriate readout array size and enables the first interrupt to wait for the next accelerator beam spill. While idle, the CCDs are clocked to clear thermally generated charge; meanwhile the program selects the condition queue channel in the main interface board and waits for an interrupt. In response to a signal from the accelerator, through the TTL logic board, the program stops the clearing and opens the camera shutters. After a second signal from the external trigger logic of the experiment, the shutters are closed, and the CCD readouts are initiated.

The pixels are buffered in the small FIFOs in the interface board, which generate an interrupt when they accumulate 32 pixels. The software then chooses the FIFO channel and burst transfers 32 pixels through the input port into the array processor data memory. The end of the pixel data stream is signaled by a camera-done interrupt. After a maximum of two seconds, the readout is complete. The 9-bit pixels are then mapped into the range 0-239 by a lookup table, packed two pixels per 16-bit word, and DMA transfered into free memory buffers in the host, where concurrent processes can access the pictures for display, recording, and analysis. With the exception of recording entire pictures to tape, this sequence repeats once every cycle of the accelerator.

3 The software

The two major features of the software design are the utilization of asynchronous, concurrently executing computer processes, and the deployment of a large shared memory section for data, communication and control. The use of multiple specialized processes enhances run-time configurability and makes optimal use of the concurrent processing power available. It also simplifies the task of programming by dividing logically separate tasks into different programs. The shared memory (global section) allows several of the processes to read one copy of a picture without duplication, permits different, task-dependent, dynamic time scales for picture access, and is an efficient method for interprocess communication. The majority of the code was written in the C programming language.

3.1 Multiple processes

There are five concurrent computer processes (programs) that comprise the CCD Supervision System VAX software. They provide independent control of the user interface, the Mercury array processor, the Raster display, recording of data, and background calculations to extract physics information.

The user-interface process performs command parsing, distributes commands to the other processes, and calls additional utilities for configuration and debugging. It manages a set of screen windows which accept terminal input, show data buffer and process status, echo process error and message information, and offer online help. The other processes are viewed collectively as "background" processes. They run either automatically (auto mode) by taking their commands from command lists or manually (manual mode) by taking commands from the keyboard. They perform limited I/O to disk files, pop Workstation windows for special displays, exchange commands and information, and update screen displays maintained by the user-interface process.

The Mercury process controls the array processor, handles I/O from the CCD cameras and TTL Logic Board, and executes image processing tasks on the array processor. The Raster display process controls the color display and the digitizing tablet. Embedded in the display process are a lookup table utility which manipulates the pseudocolor representation of CCD images and a profiling utility which uses cursor-driven readback of video memory to plot intensity distributions and histogram intensity spectra. The recorder process reads or writes either whole or compressed pictures to or from disk or tape. The background process extracts physics information from the pictures, such as track intensity measures and track multiplicities, and maintains archive files of these data on disk.

3.2 Memory buffers

The global section is conceptually divided into two parts: a large data buffer for the pictures and their descriptive picture headers, and a smaller set of data structures for interprocess communication and buffer control.

Access to the picture buffers is controlled by distributed buffer management software which allocates space, coordinates data-sharing and arbitrates access conflicts. Each buffer can be accessed in two ways: exclusive write access, or shareable read access. When a process needs space to write a new picture or requests read access to an existing or anticipated picture, it calls buffer management routines. The request is either granted or placed in an appropriate queue until the resource becomes available. Synchronization is achieved by operating system flags and locks. Allocation of memory pool space and read access grants is completely dynamic; the background processes can function asynchronously, without additional communication about the state of the memory buffers.

3.3 Interprocess communication

The processes take their commands one at a time from the global section. Each process has its own message box where commands issued by an operator at the terminal accumulate for dispatching, and its own command list which is loaded during system configuration. In auto mode each process first looks in its message box, then its command list, and gets its next command. This permits the user to interrupt a process executing in auto mode. In manual mode each process looks in its message box only; if there is no current command it waits for user input.

4 The CCD Supervision System in the NA35 experiment at CERN

NA35 is a combination SC and calorimeter experiment. Calorimeters are electronic detectors which measure the total energy deposited in their volumes. They have a high event rate, provide directly digitized data, and are an excellent complement to a particle tracking detector like the SC.

4.1 Optics configuration

Two CCD cameras were used to simultaneously photograph events in the NA35 SC. The physical configuration of the SC, superconducting magnet, Marx generator and cameras in the NA35 experiment at CERN is shown in Fig. 5. The SC is 2.0 m along the beam axis, 1.2 m wide, and 0.72 m deep along the optical axis of the cameras. The cameras are located 3.4 m from the beam axis, and the optical axis is centered on the beam and almost orthogonal to it.

Fig. 6 presents a schematic description of the SC and optical setup at CERN. There are two semi-transparent fine-mesh electrode grids parallel to the beam and perpendicular to the optical axis, which conduct the high voltage pulses through the chamber. These are produced by a 22-stage double Marx generator which furnishes simultaneous pulses of positive and negative polarity of 15 nanosecond duration. This produces three regions of electric field in the chamber, of field strength approximately 20 kV/cm. There is a virtual ground plane at the center along the beam axis, the plus and minus high voltages at the grids ± 18 cm from the beam, and ground at the top and bottom walls of the chamber, ± 18 cm further from the grids. The magnetic field is homogenous, with the principal component parallel to both the electric field and the optical axis. The field bends charged particles in the plane orthogonal to the optical axis, and allows particle momenta to be determined. It also confines the electron avalanches during streamer formation to produce better track position resolution.

The film cameras, used to record the primary visual data in the experiment, photographed each event from three different angles simultaneously onto 70 mm fast film. The two CCD camera systems, each identical to that of Fig. 3, recorded one event simultaneously per beam spill. In the first configuration of the cameras listed in Table 1, a 50 mm focal length primary lens was used on one camera and a 135 mm focal length lens on the second. This enabled the first camera system to view a large area of the chamber with a demagnification of 65 and the second system a small area with higher spatial resolution at demagnification 23. Examples of each of these views are displayed in Figs. 7a and b for the same event. The lower demagnification in the second view enabled tracks in the central cone of high track density to be distinguished. In a second configuration the two camera systems each viewed the entire chamber by using 28 mm focal length primary lenses with demagnification 116. The characteristics of the various components of the imaging system can be found in Table 1.

High amplification of light was necessary to photograph streamers from particle tracks in the chamber at a distance of 3.4 m from its central plane. With an estimated average primary photon yield of 10^8 per streamer, only 338 photons per streamer reached the primary lens simply due to the geometrical solid angle of the lens (in this case a 50 mm focal length was used). The maximum luminous gain of the two stages of intensification is approximately 3×10^6. Again due to solid angle and the characteristics of the secondary lens only 0.3 % of the light from the output of the image intensifiers was transmitted to the CCD. For the 50 mm primary lens the average streamers were imaged onto a minimum of nine pixels of the CCD. The maxima of the streamer intensity distributions produced from 20K to 100K electrons per pixel in the CCD. Some blooming can be observed in the CCD images of Figs. 7a,b due to very bright flares in the chamber. Tuning the automatic gain control of the microchannel intensifiers suppressed most of the flares.

4.2 Supervision System online

The Supervision System was used in the NA35 experiment to obtain immediate feedback on chamber performance and the quality of the experiment's triggering system (types of events selected). It also provided a first look at the physics by analyzing events online and correlating SC observables with data taken online by the calorimeters. The beam spill was available once every 14.4 seconds for a duration of 4.2 to 7.4 seconds depending upon beam energy. This spill typically contained 10^5 beam particles. On the average one percent of these particles interacted in the target. From these 10^3 interactions, various triggers would select from 10 to 10^3 events for data recording. The calorimeters captured every event selected. The maximum SC event rate was one per second while the CCD Supervision System recorded one event per spill.

For each event recorded by the CCD cameras, information from another computer in the experiment was also recorded via the external terminal link shown in Fig. 2. This information consisted of roll and frame number for matching CCD, film and calorimeter data, and the energies deposited in the calorimeters. This CCD event was then immediately analyzed to determine the number of charged particles (multiplicity) and to evaluate several chamber performance measures, which examined the average light intensity per streamer in various regions of the chamber. An example of the multiplicity determination is depicted in Fig. 8. Pixel intensities are analyzed along contours in both views. A peak-finding algorithm is used to count the number of tracks crossing each contour. The two views are matched and the total number of particles crossing the contours is calculated. An online plotting facility was used for viewing trends in these data. This information was stored on disk event-by-event. Complete CCD frames of events in two views were recorded to magnetic tape. Due to the slow speed of the tape unit, only about one in every ten events was fully recorded. These events will be used for offline physics analysis and software development.

4.3 Offline analysis of data

For offline analysis, the available data can be divided into two categories: the full frame data stored on tape and the more compact event data stored on disk. The event data contain the results of the online analysis for each event. These data will be compiled to determine trends for the various triggers employed in the experiment and to give a cursory look at the physics results. This information will help to guide the analysis of the full frame CCD data and the film data. In particular the numbers of particles emitted into specific spatial regions will be determined and correlated with the energy information collected by the calorimeters.

The full frame data will be the focus of a much longer project. Software is still being developed to vector along tracks and to match tracks between the different views of an event. A detailed comparison will be made between digital information extracted from the CCD frames and operator scans and measurements of the same events recorded on film. Meanwhile, multiplicities and emission angles can easily be extracted from the full frame data for events where there is no magnetic field present in the SC. In such events the tracks are straight lines, thus simplifying the determination of the emission angle and tracking of particles into the calorimeters. For events where the magnetic field is switched on in the chamber, the multiplicity determination can certainly be made. Tracking becomes more complicated, as the particles traverse the chamber on helical paths.

5 Future prospects

The ultimate goal of this project is to implement a three camera system which will record the three views of one event onto fast, high volume digital media and perform offline stereoscopic reconstruction of particle trajectories in space. The third view will decrease the fraction of tracks which are not reconstructable because of obscuration and better constrain the fit in the stereoscopic reconstruction procedure. A third camera based on an identical 1024 × 1024 CCD chip will be incorporated into the system. The efficient handling of large volumes of data will be accomplished by employing a gigabyte optical disk.

Image analysis algorithms are being developed to identify the tracks in the pictures and follow them across the SC without confusion. After following a track, it can be described by fitting a curve in two dimensions along the maximum of its intensity distribution. Then track matching between views can be attempted with constraints provided by the position of the track in the chamber, its curvature, and its intensity structure. Once the tracks are parameterized and matched, they will be reconstructed using an existing three-view geometry program.

The intensity distribution along tracks will be studied. The brightness per unit length and the streamer spacing are closely related to the primary ionization of the charged particle and should permit determination of its charge and velocity which are very difficult to deduce from film. Independent knowledge of momentum, velocity, and charge provides unambiguous particle identification. Such complete information for a large fraction of the charged particles emitted in high energy nucleus-nucleus collisions could afford a much deeper insight into the underlying physics.

The CCD Supervision System has already provided online display and analysis of SC pictures in a high energy nuclear physics experiment. This is the first phase in a project to modernize SC methods by integrating electronic and digital techniques. In the future SC images will be photographed and recorded without film and measured with minimal operator assistance. Significant automation will provide an enormous increase in the data available from this detector. Quantitative intensity information from SC tracks will offer new opportunities for comprehensive analysis. These advances in technique are likely to be followed by further understanding of the fundamental physical processes in high energy nuclear collisions.

6 Acknowledgements

The authors are grateful to R. Stock and the entire NA35 Collaboration for their enthusiasm and encouragement, and to T.J.M. Symons for his consistent support of this project. The authors particularly thank M. Fahmie of the Bevatron Electronics Group for his help in the design and construction of the custom interface board, M. Wensveen for construction of the optics assembly, and H. Fessler, K. Geissler and J.P. Fabre for advice and assistance in the design and construction of the image intensifier optical assemblies. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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Equipment Vendors

AEG Aktiengesellschaft, Technische Roehren, Soeflinger Strasse 100, D-7900 Ulm, West Germany, telephone (0731)3991-1. (microchannel intensifiers).

Digital Equipment Corporation, 129 Parker Street PK03-1/90, Maynard MA 01754-2571 (617)897-5111.

Mercury Computer Systems, Wannalancit Technology Center, 600 Suffolk Street, Lowell, MA 01854 (617)458-3100.

Pentax Corporation, 35 Inverness Drive East, Englewood, Colorado 80112. (camera lenses).

Photometrics, Ltd., 2010 North Forbes Boulevard, Suite 103, Tucson, AZ 85745 (602)623-8961.

Raster Technologies, 2 Robbins Road, Westford, MA 01886 (617)692-7900.

Seiko Instruments USA, Inc., 1130 Ringwood Court, San Jose, CA 95131 (408)943-9100.

Texas Instruments, Inc., CCD Division, 13500 North Central Expressway, Post Office Box 225936, Dallas, TX 75265.

Varo Inc., Electron Devices Division, P.O. Box 401146, 2203 Walnut St., Garland, TX 75040 (214)272-3561. (image intensifiers).

Table 1. - Characteristics of the imaging systems

Characteristics	Camera 1	Camera 2
primary lens(1st configuration):		
distance to object	3354 mm	3400 mm
focal length (f)	50 mm	135 mm
f-stop	f/2.0-4.0	f/2.8-4.0
demagnification	65	23
primary lens(2nd configuration):		
distance to object	3354 mm	3354 mm
focal length (f)	28 mm	28 mm
f-stop	f/2.0	f/2.0
demagnification	116	116
microchannel intensifier:		
active diameter	25 mm	25 mm
maximum luminous gain	6×10^4	6×10^4
limiting resolution	34 lp/mm	34 lp/mm
2nd stage intensifier:		
active diameter	40 mm	40 mm
diameter used	25 mm	25 mm
maximum luminous gain	100	100
limiting resolution	56 lp/mm	49 lp/mm
secondary lens:		
focal length (f)	MACRO 50 mm	MACRO 50 mm
f-stop	f/2.8	f/2.8
demagnification	1	1

Figure captions

Fig.1. A film picture of a Streamer Chamber (SC) event from the NA35 experiment at CERN in Geneva, Switzerland. An incoming oxygen nucleus with total energy of 3200 GeV collides violently with a lead nucleus in the target, producing over 200 charged particles in the SC. These tracks curve in space due to a strong magnetic field. The individual streamer discharges are visible as small dots along the tracks. The tightly wound spirals are knock-on electrons.

Fig.2. A block diagram of the CCD Supervision System hardware. The major components are: the two CCD cameras; the Multibus including the camera controllers, the TTL logic board, and the main interface board; the Mercury array processor; the VAXstation host computer; and the color display system, including the screen and color printer.

Fig.3. A diagram of the CCD camera optical setup for the NA35 experiment. The SC is below and viewed by the mirror. Three primary lens sizes of 28 mm, 50 mm, and 135 mm were used during the experiment to view various portions of the chamber. The microchannel image intensifier is proximity coupled to the second stage electrostatic image intensifier, providing a maximum luminous gain of about 3×10^6. The secondary lens has a light collection efficiency of 0.3%. The shutter in the CCD camera allows selection of a single chamber pulse. The CCD is backed by a Peltier cooling system which keeps the chip temperature at -45 C to reduce noise. The overall system is sensitive to a few hundred photons per streamer from the chamber, and has a limiting resolution of 2.5 mm in the chamber.

Fig.4. A block diagram of the custom main interface board. This board interfaces the two (or three) CCD camera controllers and the TTL logic board on the Multibus to the Mercury array processor I/O ports. The pixels are buffered in 64 entry First-In-First-Out buffers until they are read out. Various interrupt and error conditions generated are queued in the Condition Queue. The four possible kinds of data from the Mercury are a

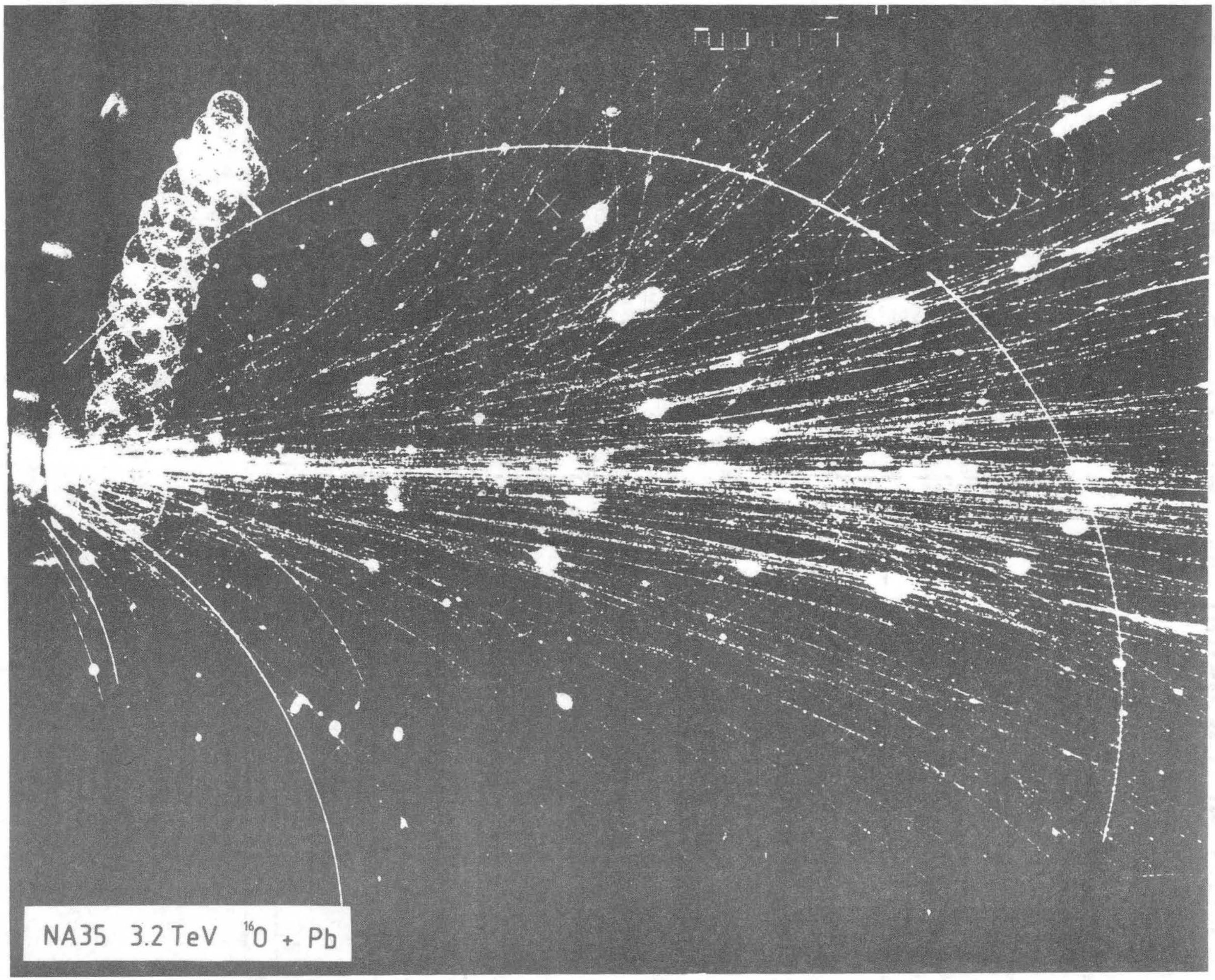
Multibus Read Address and request, a Multibus Write Address, Multibus Data such as camera instructions, and interface commands. Among the interface commands, data to be read can be selected from any of the pixel FIFO Channels, the Condition Queue, or the Multibus Read Data. Conditions in the Condition Queue drive the interrupt service routines in the array processor.

Fig.5. A view of the NA35 SC in the superconducting magnet at CERN. The Marx generator supplies high voltage pulses to the SC. The camera dome houses three 70 mm film cameras and two CCD cameras. Downstream of the chamber (unshown) are calorimeters for triggering and energy measurement.

Fig.6. A schematic diagram of the SC and optical setup at CERN. The SC is a rectangular box $2.0 \times 1.2 \times 0.72$ m^3. Simultaneous positive and negative pulses of approximately 500 kV and 15 ns duration are conducted from the Marx Generator into the chamber via the grids. Both the resulting electric field and the external DC magnetic field are parallel to the optical axis (vertical). The particle tracks originate from the target, and curve in the plane perpendicular to the optical axis. The chamber is viewed through a magnetic shielding plate at a distance of 3.4 m by the image intensified CCD cameras.

Fig.7. Two CCD pictures of the same event taken with the Supervision System, in the configuration where a) the first camera has a 50 mm primary lens viewing a large area of the chamber and b) the second camera a 135 mm lens viewing the downstream end of the chamber with high magnification. This particular event is presented since its features, namely the bright tracks originating from the secondary interaction vertex in the middle of view a), allow easy identification of the overlap between the two views. Compare these pictures to the film picture in Fig. 1. The bright jagged spots in the pictures are due to bright flares which overflow the CCD pixels (blooming).

Fig.8. An example of the online background analysis performed by the background process during the NA35 experiment. The CCD picture has been cut by a preselected contour, and the intensity along this profile is plotted at the right. A peak-finding algorithm recognizes and counts the tracks crossing this profile, providing a simple estimate of the track multiplicity (count).



XBB 874-3086

Fig. 1

CCD Supervision System Block Diagram

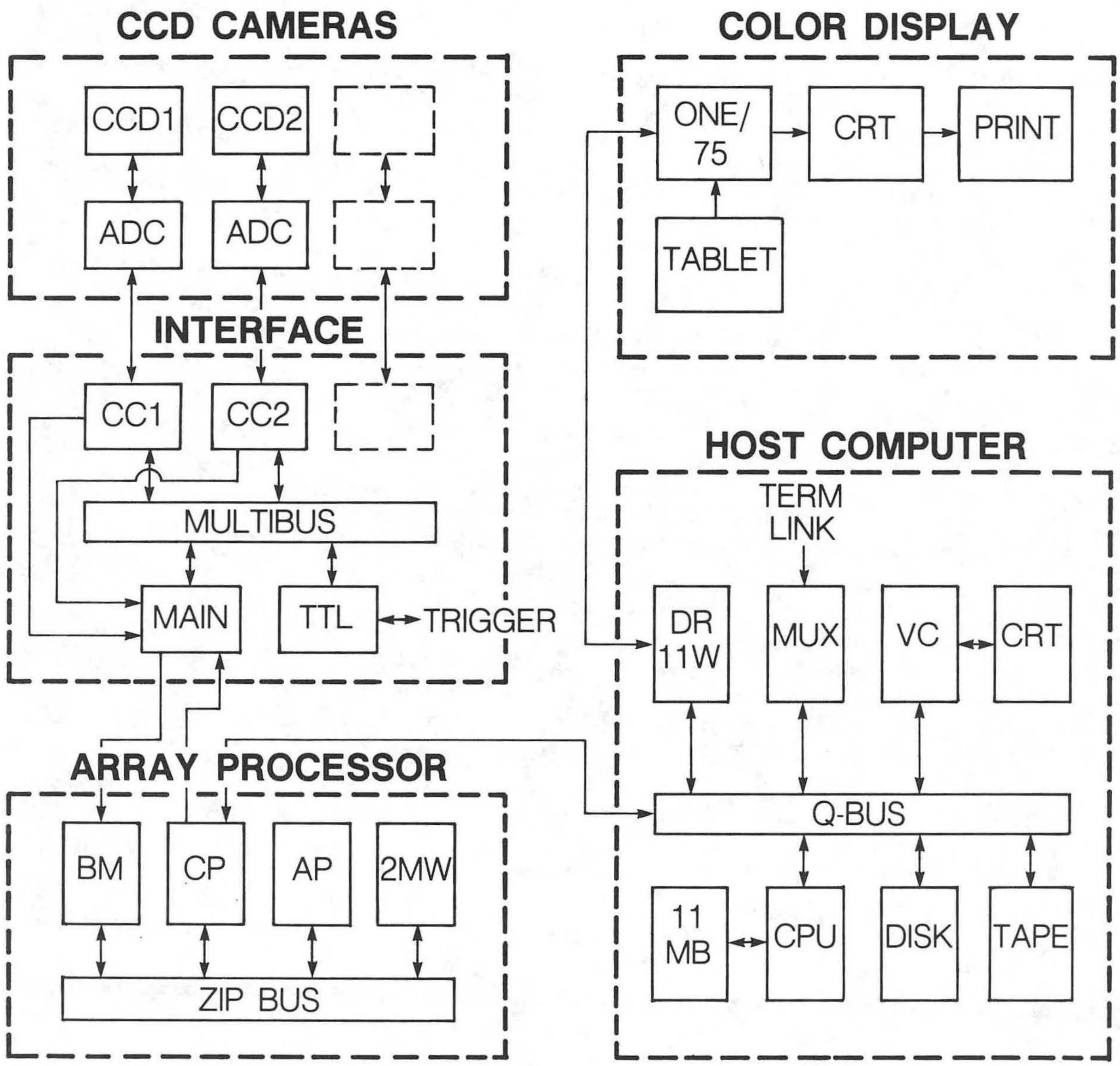
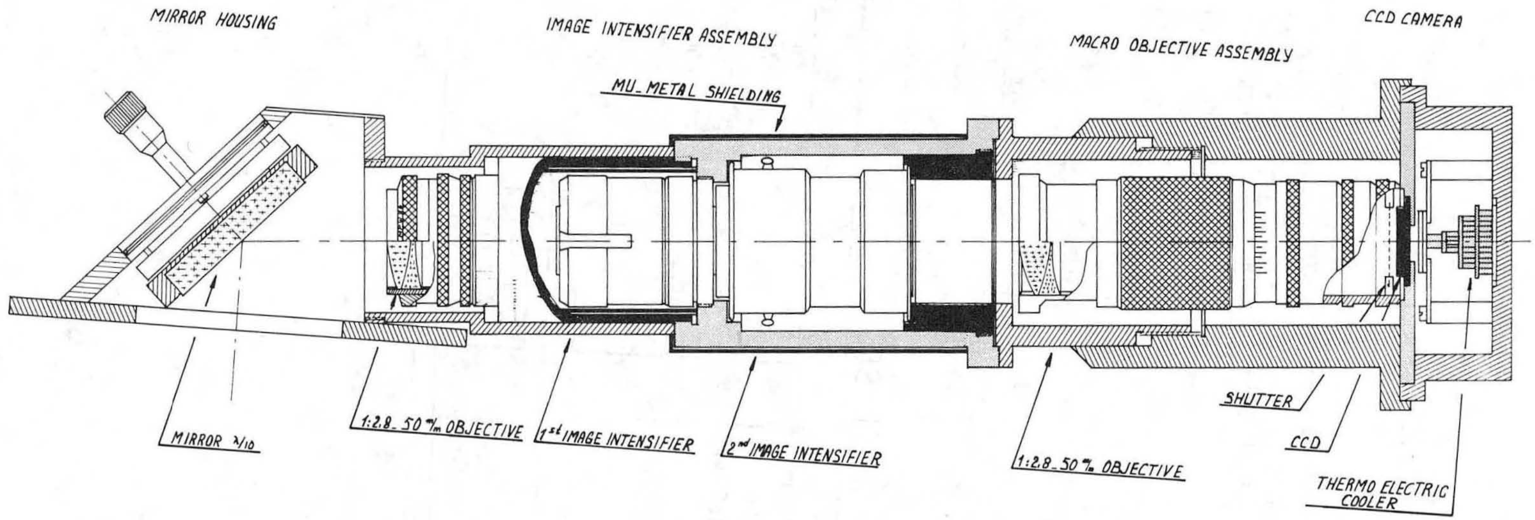


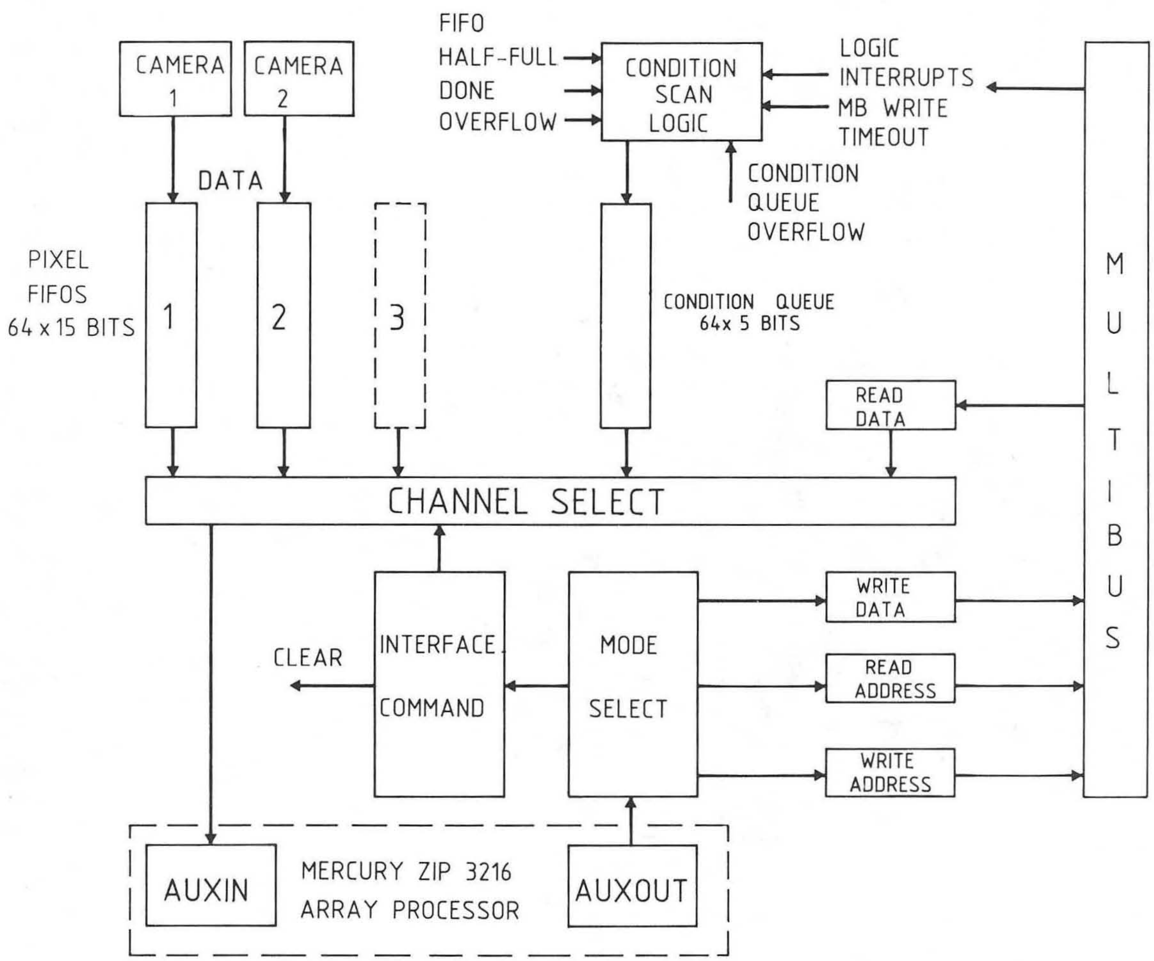
Fig. 2



XBL 874-1751

Fig. 3

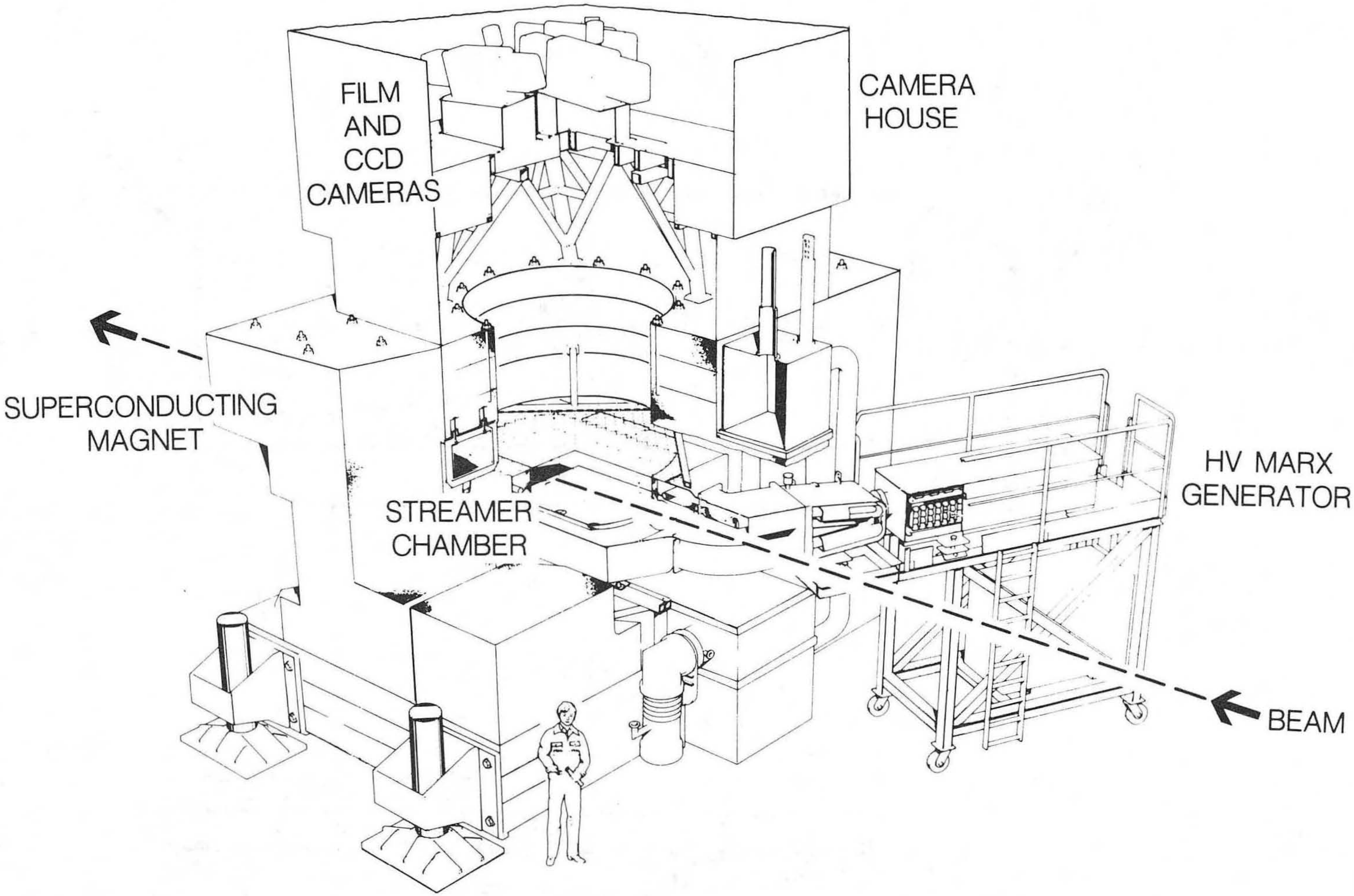
CCD CAMERA-COMPUTER INTERFACE BOARD BLOCK DIAGRAM



XBL 874-1750

Fig. 4

NA35 STREAMER CHAMBER



XBL 8974-9252

Fig. 5

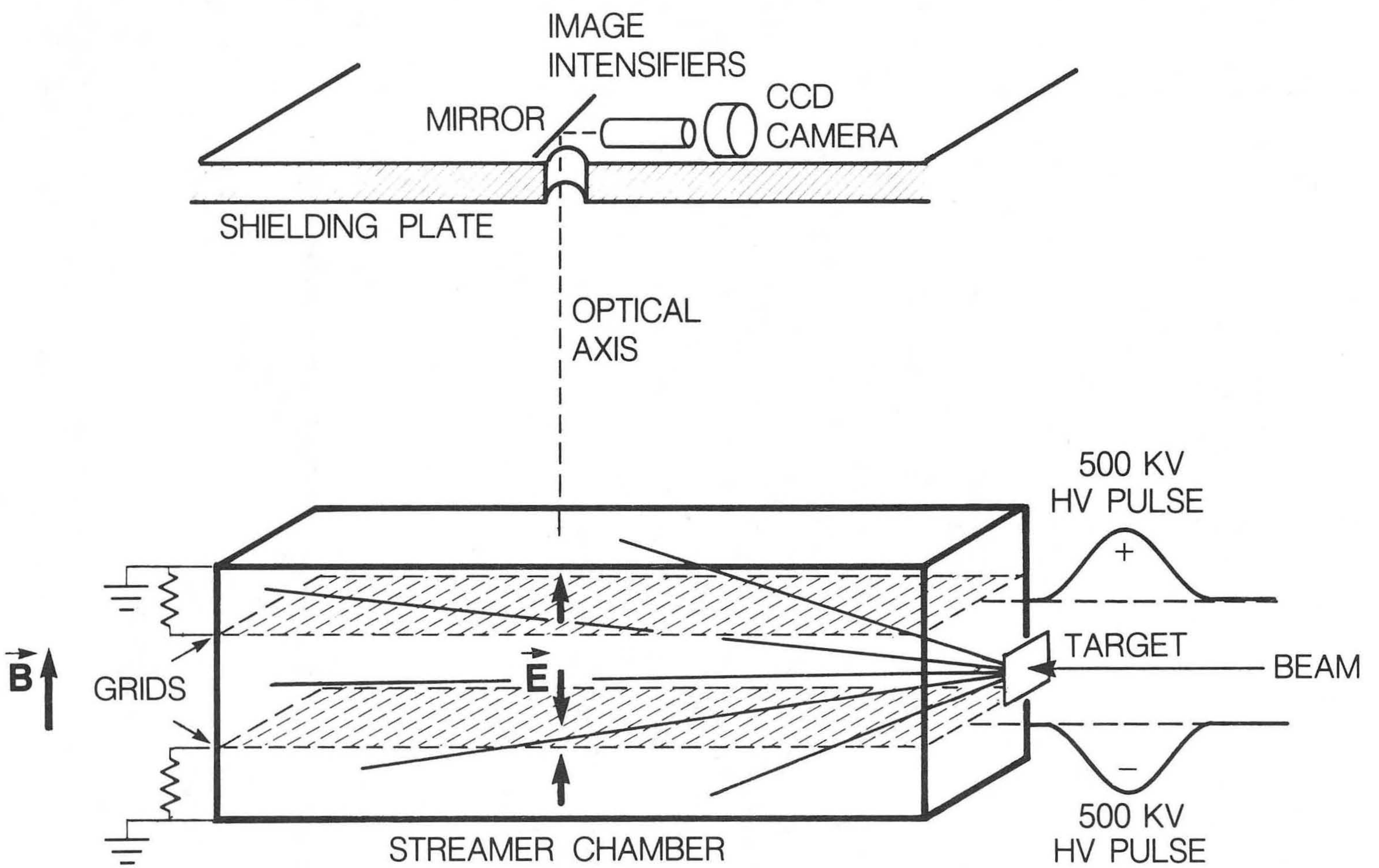
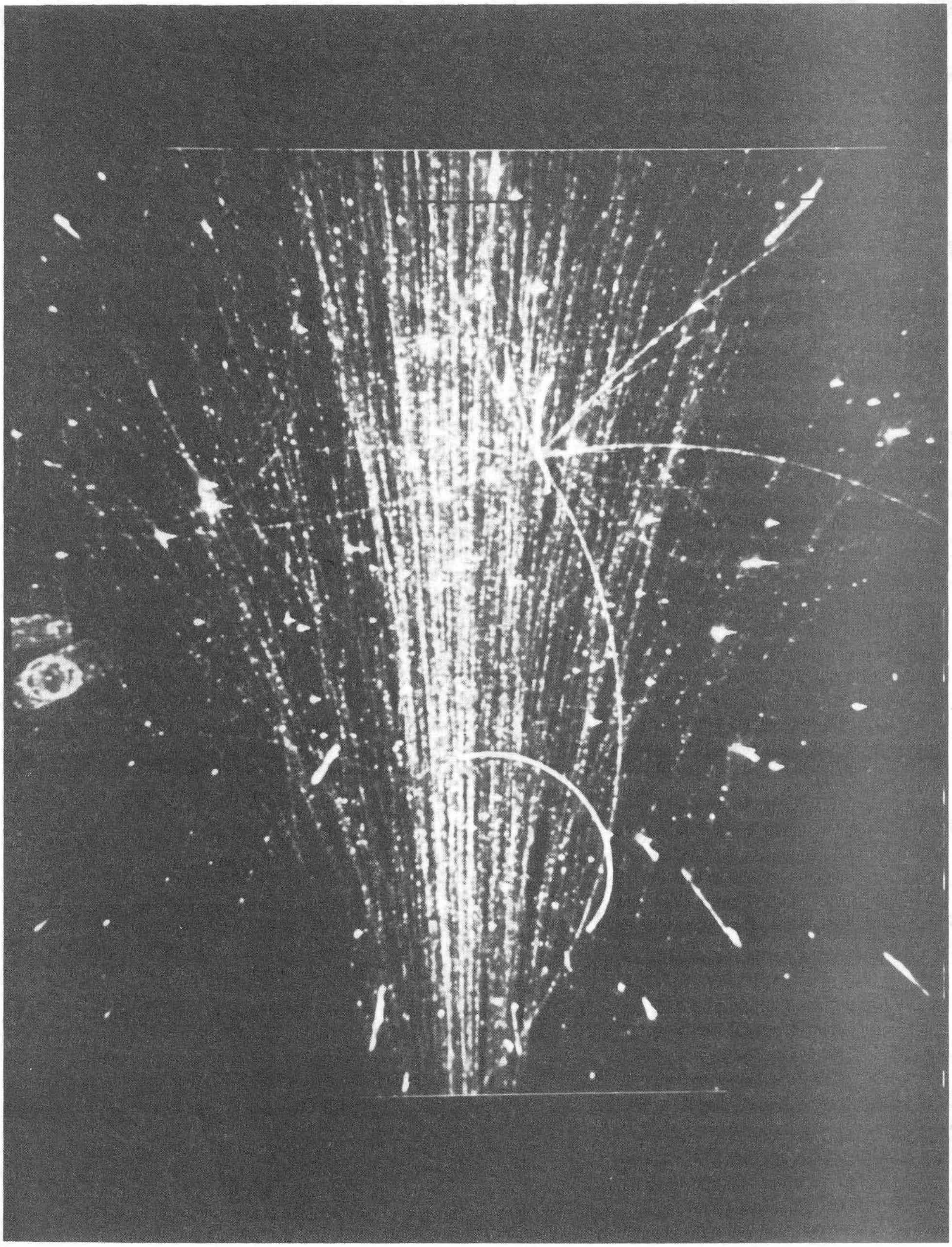


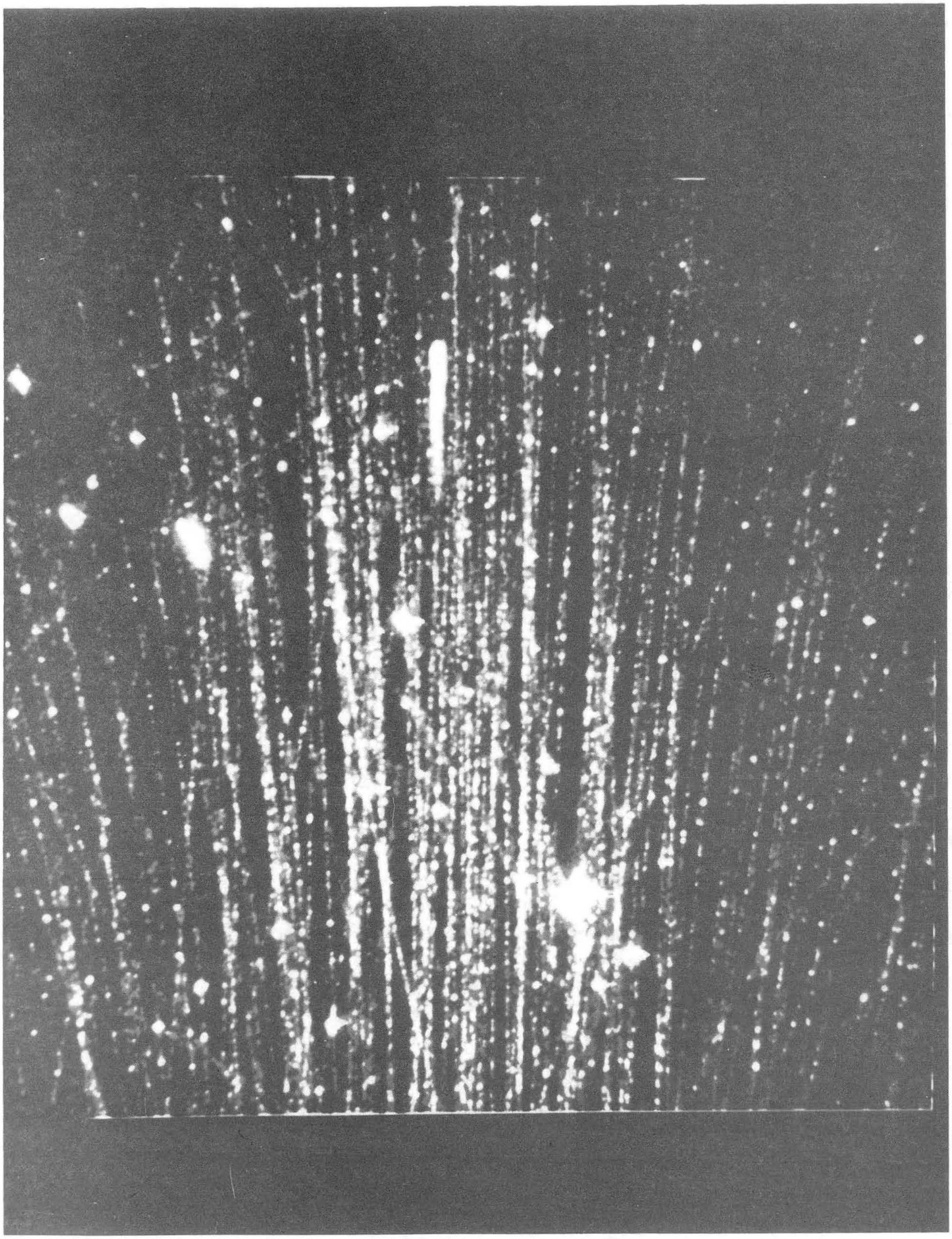
IMAGE
INTENSIFIERS
CCD
CAMERA
MIRROR
SHIELDING PLATE
OPTICAL
AXIS
500 KV
HV PULSE
+
TARGET
BEAM
−
500 KV
HV PULSE
B
GRIDS
E
STREAMER CHAMBER
XBL 874-9251

Fig. 6



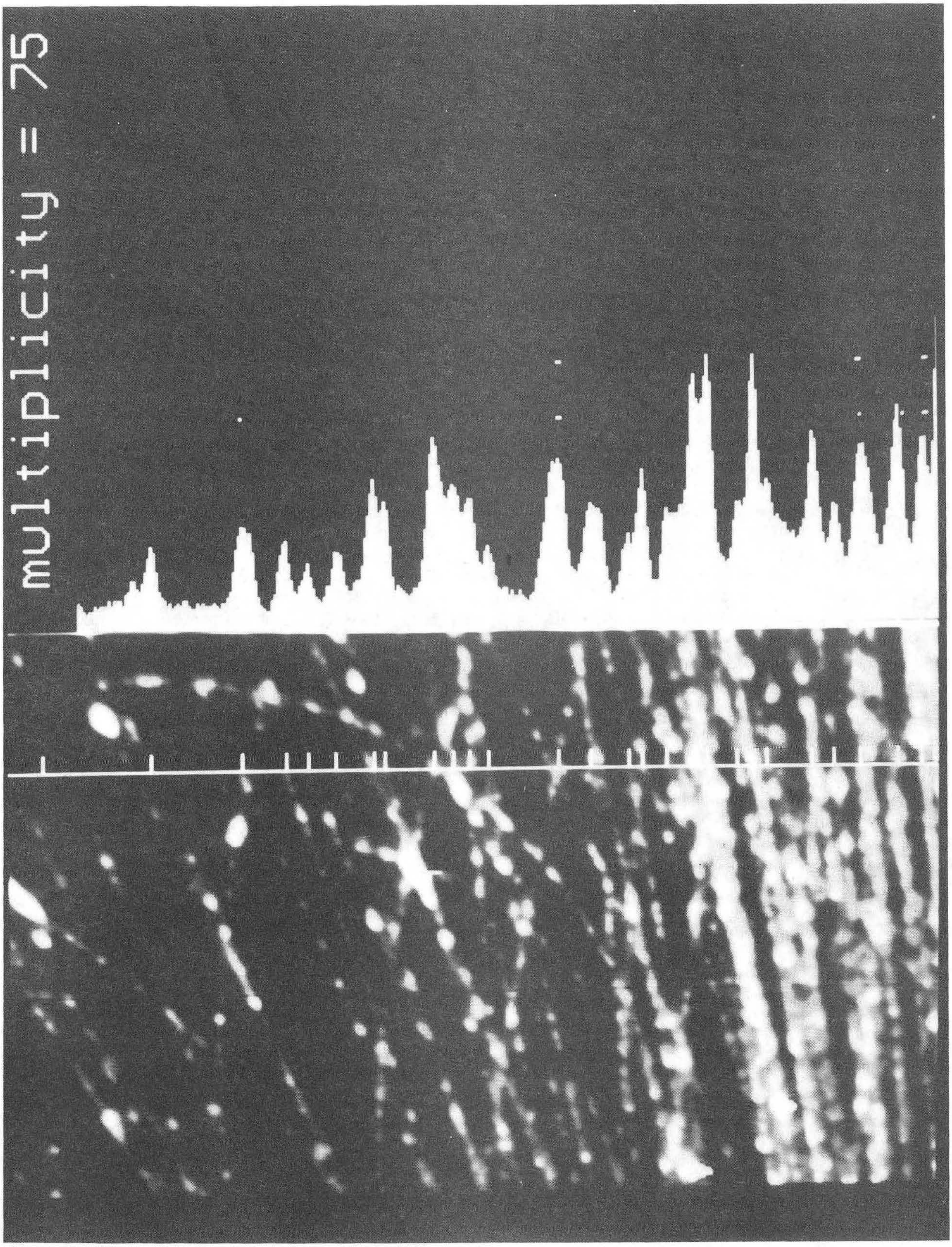
XBB 874-3085

Fig. 7



XBB 874-3084

Fig. 8



XBB 874-3083

Fig. 9

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