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Results from the STAR TPC System Test

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Abstract

A system test of various components of the Solenoidal Tracker at RHIC (STAR) detector, operating in concert, has recently come on-line. Communication between a major sub-detector, a sector of the Time Projection Chamber (TPC), and the trigger, data acquisition and slow controls systems has been established, enabling data from cosmic ray muons to be collected. First results from an analysis of the TPC data are presented. These include measurements of system noise, electronic parameters such as amplifier gains and pedestal values, and tracking resolution for cosmic ray muons and laser induced ionization tracks. A discussion on the experience gained in integrating the different components for the system test is also given.

I. INTRODUCTION

The Solenoidal Tracker at RHIC (STAR) detector [1], currently under construction, is to be located at the Relativistic Heavy Ion Collider (RHIC) facility at Brookhaven National Laboratory. In the first phase of operation, scheduled for July 1999, the experiment will record and analyse the particles resulting from collisions between gold ions at a nucleus-nucleus center-of-mass energy of 40 TeV. The energy density created in the collisions is expected to be sufficiently large for the production of a quark gluon plasma, a new phase of matter. Owing to such large energy densities, unprecedented high particle multiplicities are expected, i.e. $\sim$ 5000 charged particles per event. Three dimensional imaging for track reconstruction is therefore required with excellent double-track resolution.

The main tracking device in STAR is a cylindrical Time Projection Chamber (TPC), 4.2 metres in length with inner and outer radii of 0.5 m and 2 m respectively [2]. Charged particles traversing the detector ionize the TPC gas. The primary ionization electrons drift towards two endcaps where the electron signal is amplified by anode wires and detected by an array of pads. Each endcap is divided azimuthally into 12 supersectors, each comprising an inner and outer sector module. The STAR system test brings together, for the first time, a TPC outer sector instrumented with readout electronics with prototype trigger, data acquisition and slow controls systems. The sector is temporarily mounted on a mini-field cage, limiting the maximum drift distance to about 10 cm. The primary objectives of the system test are to:

- test all aspects of the TPC electronics and measure system noise in a realistic environment;
- establish communication between the trigger, detector and data acquisition components and ensure these sub-systems work smoothly in unison for the collection of cosmic ray muons;
- use cosmic ray muons and laser induced ionization tracks to perform first measurements of cluster and track spatial resolutions;
- verify that the software for data acquisition, cluster finding, tracking and analysis works effectively with real TPC data;
- provide data for the tuning of the STAR simulation program to accurately reflect detector response;
- gain experience in long term running of the TPC sector and electronics.

II. STAR SYSTEM TEST COMPONENTS

The hardware and software configuration of the system test is described. The interconnection between components is illustrated in Figure 1.

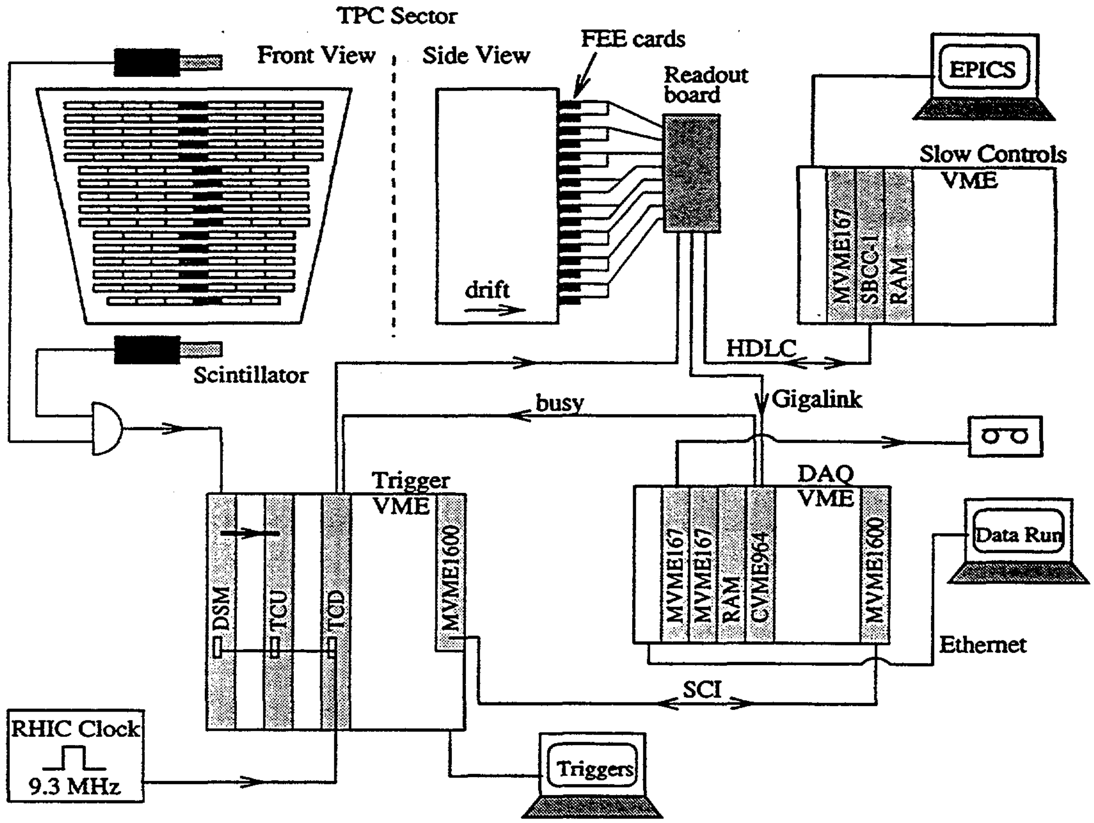

Fig. 1 The STAR TPC System Test for cosmic ray running.

A. TPC Sector and Front End Electronics

The 24 TPC supersectors contain a total of 136,600 pads arranged in 45 rows. The pads of the 13 inner sector rows measure 2.85 by 11.5 mm^2 while those of the 32 outer sector rows are 6.2 by 19.5 mm^2.

A TPC supersector is served by 6 readout boards each of which receives data from up to 36 Front End Electronic (FEE) cards mounted on the detector [3]. Each FEE card instruments 32 pads (or channels) with a low noise preamplifier and shaper - the STAR preAmplifier Shaper (SAS) - and a waveform digitizer which comprises a Switched Capacitor Array (SCA) and an ADC. The SCA/ADC records 512 time samples with 10-bit resolution at 12.3 MHz. The total number of space points within the entire TPC is thus close to 70 million.

At present, one TPC outer sector module has been instrumented with up to 16 FEE cards connected to one readout board. The FEE cards have been positioned in a vertical row for the detection of cosmic ray muons, as depicted in Figure 1. The TPC sector has been adjoined to a short extension fitted with a field cage, limiting the maximum drift distance to about 10 cm. (In the final system the ionization electrons will drift a maximum of 2.1 m.) The magnitude of the electric field is 130 V/cm. For a 90% argon - 10% methane gas mixture, this leads to a saturated electron drift velocity of 5.5 cm/μs.

B. Data Acquisition

The data acquisition system was designed specifically for use in the system test for the readout of a limited number of readout boards and is subsequently referred to as miniDAQ. It consists of:

- two Motorola VME167 modules with 68040 processors that run the miniDAQ software;
- one Cyclone VME964 module, housing an i960 processor, that holds the Rosie mezzanine card, a temporary data receiver for STAR;
- a Motorola VME1600-001 (Power PC) that acts as a trigger-miniDAQ interface;
- and an additional 32 megabyte memory board for interprocessor communication and event buffering.

Data from the readout board is transmitted to the miniDAQ Rosie board over a 1.5 Gbit/s optical fiber link, driven by a HP Gigalink serializer chip. These data are unpacked on the Rosie board into video ram (VRAM) which is accessible to the i960 processor bus. The Rosie card notifies the i960 processor when a complete event has been received. The miniDAQ software, having been notified by the trigger of an impending event, initiates the transfer of data from the Rosie VRAM to the shared memory extension in the miniDAQ VME crate. A busy signal is also distributed to the trigger to prevent further triggers.

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The software also includes processes for configuration, trigger distribution, event building, writing events to tape (an Exabyte tape is connected to one of the MVME167s) and supplying events to network sockets.

The event size is 1.2 Mbytes which corresponds to the size of non-zero suppressed data from one readout board. The event rate is limited by the taping speed to 0.2 events per second.

C. Trigger

The triggering of interesting physics events within STAR is to be performed in dedicated processors running algorithms that analyse data from specific sub-detectors [1]. The trigger system is to comprise a low-level trigger that uses information from detector components with fast readout times (e.g. time-of-flight) and a high-level trigger that performs more sophisticated filtering based on complete event information. Presently, a prototype of the VME based low-level trigger hardware is in use. Its architecture is briefly outlined.

The Data Storage and Manipulation (DSM) board receives input signals for storage and a first analysis. Signals in coincidence with a master clock, replicating the RHIC strobe ($\sim$ 107 ns period), generate a 16 bit output word (level-0) that is passed to the Trigger Control Unit (TCU). The TCU uses a look-up-table to translate the DSM output word to a trigger word that is subsequently prescaled. A trigger command word is generated whenever the prescale condition for the particular trigger word is met. The TCU then assigns a 12 bit token to each generated command word which serves as an event tag to ensure data are not mixed during event building. The clock and trigger information (command word, token) is transmitted from a Trigger and Clock Distribution (TCD) board to the readout board over a bus at five times the RHIC crossing frequency.

The trigger level-1 Controller CPU (Power-PC) also extracts the trigger information from the TCU and the raw scintillator data from the DSM board. Level-1 CPUs can perform a more complex analysis producing a level-1 accept or reject. Trigger and DAQ words are also passed to miniDAQ over a Scalable Coherent Interface (SCI). The DAQ word is intended to allow the data acquisition and a proposed high-level trigger to respond differently to the different classes of level-0 triggers.

Slabs of scintillators, connected to photomultiplier tubes, are positioned above and below the sector to serve as a trigger for cosmic ray muons.

D. Slow Controls

The primary objective of the STAR slow controls system is to ensure that the entire detector is functioning correctly, thereby validating the data for physics analysis. A slow controls link to the TPC readout board has been been established using the High-level Data Link Control (HDLC) protocol (1 Mbit/s). HDLC was selected as it was able to meet with several requirements imposed by experimental constraints. These include the need for a large bandwidth over a distance of $\sim$ 30 metres, operation in a strong magnetic field, and a multidrop topology to minimize cabling. The VME master, a Radstone SBCC-1, features a 68360 processor and supports up to 4 HDLC channels. Each HDLC channel communicates with six readout board slave nodes over a multidrop RS-485 link. A slave node houses a 68302 microcontroller.

The HDLC link has been interfaced with the Experimental Physics and Industrial Control System (EPICS) software from which a number of control and monitoring tasks can be performed [4]. In addition, a memory test facility is provided to test the event buffer. Set bit patterns written to the readout board memory over the HDLC link are subsequently read back by miniDAQ and slow controls. A comparison of the output data with the original dataset examines the event memory buffer and further allows the integrity of the data acquisition and HDLC paths to be verified.

The slow controls software also incorporates processes for configuring the readout board and performing tests of pad aliveness. The event data can also be read out over the HDLC link upon request.

E. The State Manager

The miniDAQ, trigger and slow controls 'client' sub-systems have been interfaced to a prototype state manager 'server' whose primary function is to control the sequencing of states necessary for each sub-system, e.g. configure, initialize, run, pause, resume, terminate etc. In addition, a command state model provides for an asynchronous command interface between a sub-system and operator, while an alarm state model provides a synchronous error messaging interface between the sub-system and operator.

Currently a state manager 'server' is running on each local sub-system workstation, to which the appropriate sub-system 'client' connects. A prototype run control operator interface that centralizes control of all sub-system 'clients' is presently under development in the JAVA programming language.

III. Collection and Analysis of TPC Data

The data presented here were collected during October, 1996. Several different types of data taking runs were made in order to meet the system test objectives. Common to all data runs, however, is the creation of datasets consisting of tables which conform to the STAR Analysis Framework (STAF) [5]. STAF provides an architecture independent, high performance data format for the representation of complex datasets and a software-bus based framework for the easy integration of specialized FORTRAN, C and C++ analysis modules into a coherent process.

A. Geometry Events

Geometry events are triggered whenever a new configuration of FEE cards and readout boards is established. They allow a geographical mapping of the FEE card locations on every readout board. The FEE card addresses are etched into the TPC pad plane, while a unique readout board network and node identifier is encoded in connectors attached to the board mounting. The readout of these addresses through miniDAQ is initiated by a special trigger. The resulting configuration is used in subsequent data analyses that can also test for any cabling errors.

B. Pedestal Events

One hundred events were typically taken for any given pedestal determination run. Normal data taking conditions were used throughout with the exception of the anode wire voltage which was turned off to avoid contamination from cosmic rays. The average ADC count was evaluated for each time bucket of every channel, amounting to a total of 589,000 pedestals for a fully instrumented readout board. The RMS of each distribution provided a measure of the noise level. The pedestal calculations were performed off-line, but are now to be done in the i960 processor of the Cyclone board.

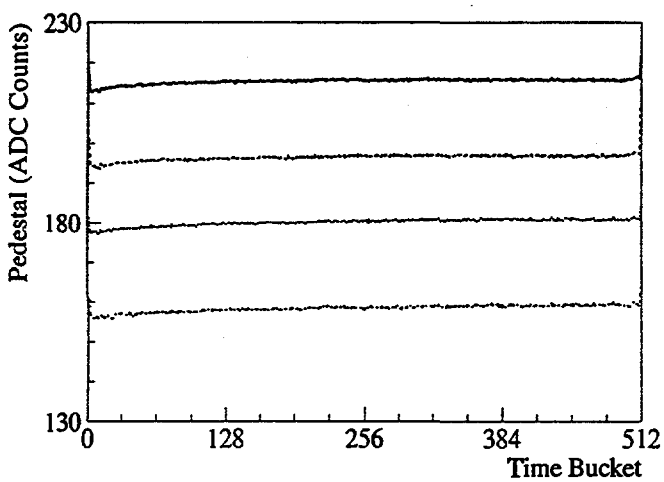

Fig. 2 Pedestal values as a function of time bucket for four channels.

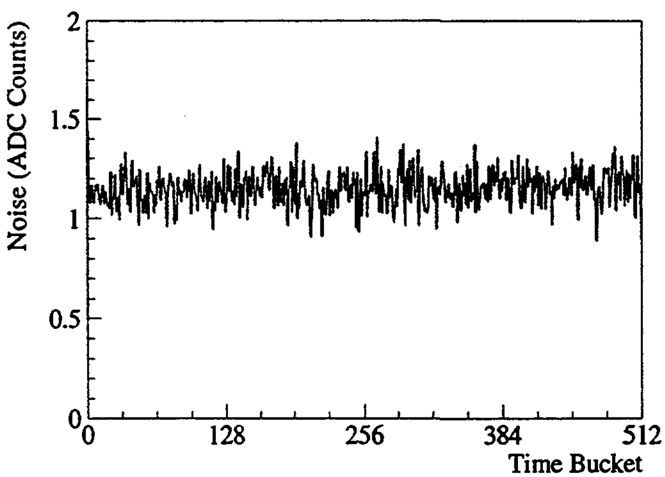

Fig. 3 Noise as a function of time bucket for a typical channel.

Figure 2 displays the evaluated pedestals for all time buckets for a sample of four channels. Separate pedestals are required for each time bin because of leakage and charge injection variations. The structure apparent in the early time buckets is linked to the integrator reset switch within the SAS. Figure 3 shows the corresponding noise level. It is equivalent to approximately 1000 electrons, in accordance with expectations from contributions from the SAS, SCA and TPC pad. The noise amounts to about 5% of the signal due to a minimum ionizing particle leading to a signal to noise ratio that reaches the detector resolution limit.

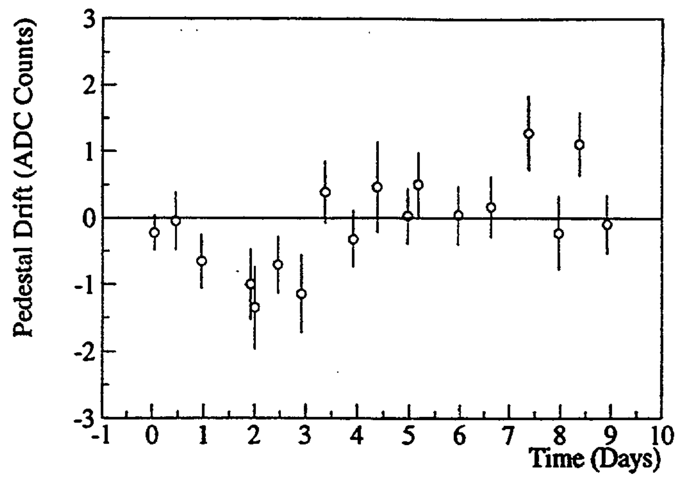

Fig. 4 Pedestal stability. The shift in the mean pedestal value averaged over all channels and time buckets, relative to the first measurement. The error bars give the one sigma standard deviation.

Frequent pedestal event runs enabled the stability of the pedestals to be monitored over a period of several days. The mean pedestal value averaged over all channels and time buckets, is plotted as a function of time in Figure 4. Small shifts in the pedestal values are evident. These, however, are correlated with variations in temperature and, to a lesser extent, humidity, which are not representative of the conditions under which STAR will operate. Since, in STAR, temperatures will be controlled and the humidity kept at a steady level, the observed shifts can be regarded as an upper limit to expected performance in STAR.

C. Pulser Events

For pulser events, a current pulse is applied to the TPC ground plane inducing a charge signal on the pad plane. A subsequent analysis of the ADC counts provides information on the the relative gain of each channel. Periodic pulser events then allow the stability of the gain to be monitored. Figure 5 is a demonstration of how the gain of several typical channels varied over a period of days. While some shifts are expected from temperature variations and an improvement to the readout board grounding during data taking, the mean of the gain was nevertheless seen to be stable to within ± 0.6% of the mid-value.

Absolute electronic gain measurements are also performed using an on-chip calibration system. The typical gain of the SAS is 16 mV/fC resulting in a 50 mV output signal for a minimum ionizing particle.

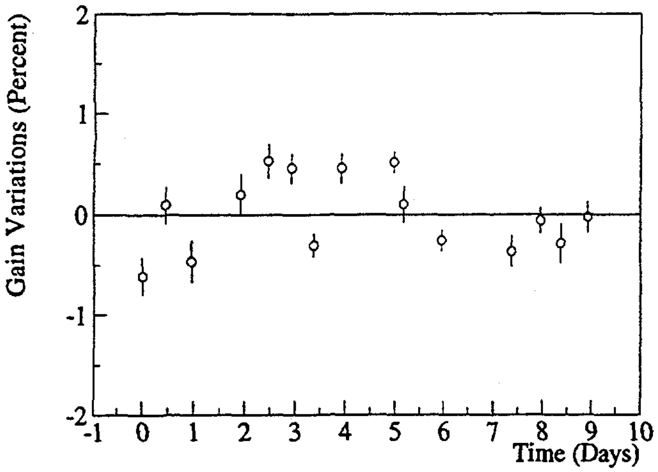

Fig. 5 Gain stability. The percentage change in the gain averaged over several channels, relative to the gain averaged over the entire 9-day running period. The error bars give the one sigma standard deviation.

D. Cosmic Ray Muon Events

Events triggered by cosmic ray muons allowed the track reconstruction software to be applied to real TPC data for the first time. An important parameter to determine is the hit (or cluster) resolution. The hit resolution determines the accuracy with which the position of a charged track can be measured, which in turn directly influences the particle momentum resolution. Initial measurements from tracks fitted to hits from cosmic ray muons (with pedestals subtracted and gain corrections applied) yielded hit resolutions of $\sigma_{xy} \sim 390\ \mu$m in the azimuthal direction and $\sigma_z \sim 780\ \mu$m in the drift direction[1], as demonstrated in Figure 6. The resolutions achieved are as expected from Monte Carlo simulations. In the azimuthal direction they are mainly determined by charge sharing among adjacent pads, and in the drift direction by diffusion and electron statistics. The drift resolution corresponds to $\sim 20\%$ of one time bucket. It is noted that these measurements were performed in the absence of a magnetic field and are thus expected to improve under normal running conditions, wherein the TPC will be located inside a solenoidal coil that produces a uniform 5 kG magnetic field.

E. Laser Induced Ionization Events

The ability to distinguish between two close tracks is of particular importance given the high multiplicity yield in high energy heavy ion collisions. The two-track resolution is extracted from an analysis of laser induced ionization tracks.

A laser beam directed from the inner to outer radius of the TPC sector, is reflected back by a mirror at a small angle relative to the incident beam. Two tracks in close spatial proximity result, as show in Figure 7. Several such events were recorded at various opening angles. Initial studies reveal that hits from two tracks merge into one cluster whenever the track separation

[1]The coordinate system is defined such that the z axis follows the drift direction and the $x - y$ plane is perpendicular to it with the x axis parallel to the sector pad rows

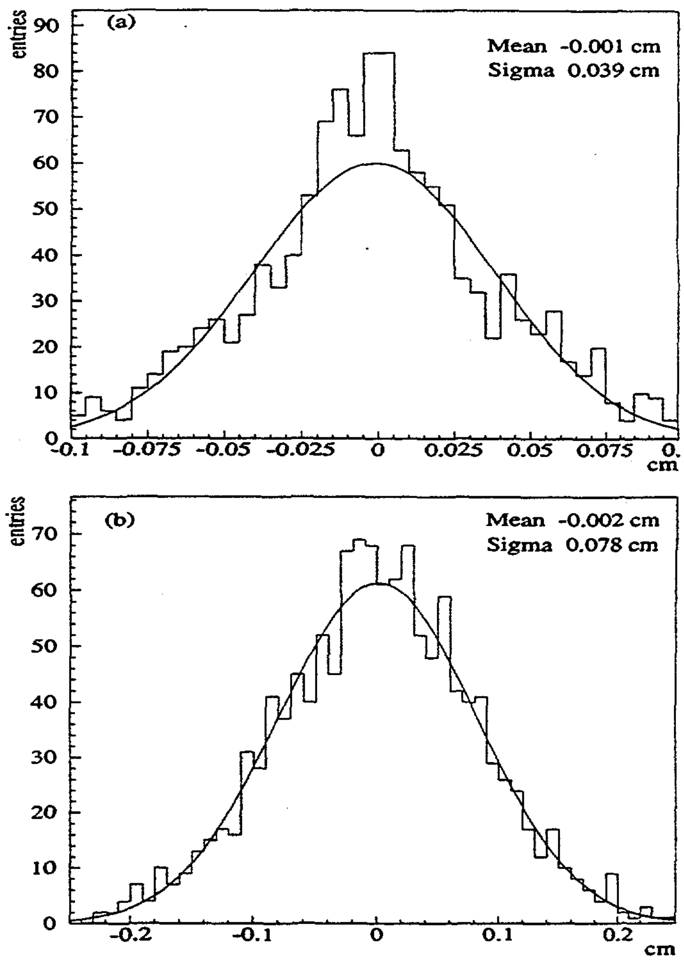

Fig. 6 Particle hit residuals in the (a) azimuthal and (b) drift direction.

in the $x - y$ plane is less than ~ 1 cm, as demonstrated in Figure 8. In momentum space, this translates to two separable tracks whenever their relative momentum difference is greater than 1%, which is within the specification for Hanbury-Brown Twiss interferometry analyses that determine the source size of the interacting medium.

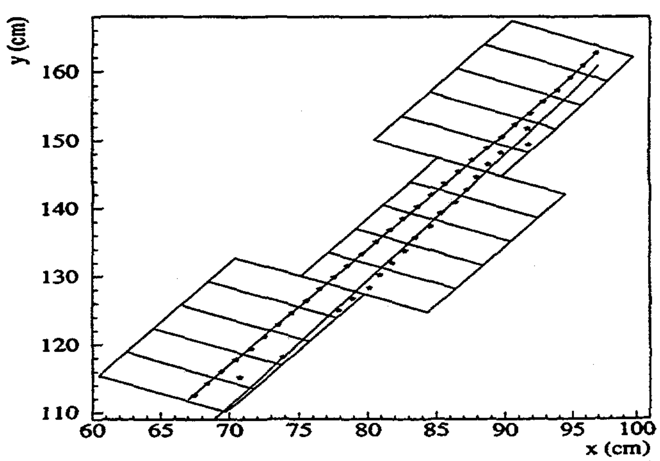

Fig. 7 Laser induced tracks in the TPC outer sector. The area instrumented with electronics is also shown.

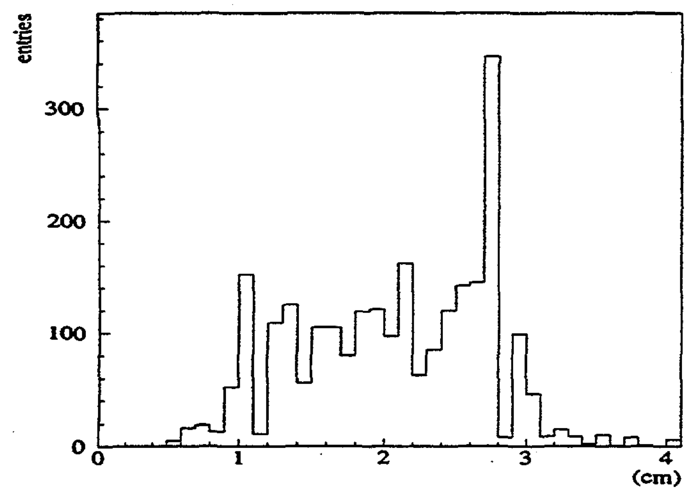

Fig. 8 Two-track hit separation from laser induced ionization events. While tracks are created with up to 3 cm separation, they are seen to merge below a separation of ~ 1 cm.

IV. Experience Gained and Future Plans

The integration of the various components of the system test helped identify certain sub-system specific details that required modifications to software packages and in some cases, suggested a minor redesign of the hardware, primarily for debugging purposes. Nevertheless, handshaking interfaces between the TPC readout board, and the miniDAQ, trigger and slow controls systems were quickly established. The use of datasets conforming to the STAR Analysis Framework (STAF), at the level of miniDAQ, trigger and slow controls greatly facilitated the data analysis. The prototype state manager further allowed easy control of the sequencing of states necessary for data-taking to occur.

The system test will continue to operate in the years preceding installation of the detector, allowing operators to gain experience in the running of the TPC and electronics and providing a realistic test bed for the track reconstruction software. A cosmic ray test involving the entire TPC detector, with two partially instrumented TPC supersectors, is scheduled for the period between May and July, 1997 at Lawrence Berkeley National Laboratory. The data acquisition system will be equipped with 6 Rosie cards mounted on 3 Cyclone VME964 modules enabling data from 6 readout boards to be read out over 6 fiber links. The test will further incorporate the TPC gas system, the laser system and the central trigger barrel detector. Both cosmic rays and laser induced tracks will be used to study resolutions as a function of angle and position providing for the fine-tuning of the Monte Carlo simulation programs over an entire area of a supersector. Continued system test running will further allow finer details of the TPC to be probed, such as a study of the edges of the TPC where possible distortions to the electric field may be apparent.

V. Conclusions

Essential hardware and software components of the STAR detector have been brought together for the first time. Communication has been established between a sector of the STAR TPC, instrumented with one readout board housing final versions of the FEE cards, and a temporary data acquisition system, a trigger prototype and the slow controls system. The combined system has operated effectively in concert, enabling TPC data to be collected from several different types of triggered data acquisition runs. The subsequent data analysis has allowed several properties of the STAR TPC to be determined, and has provided for a realistic test of the track reconstruction software and the fine-tuning of the Monte Carlo simulation programs. An analysis of cosmic ray muons enabled first measurements of the TPC outer sector hit resolution to be made. The results yielded resolutions of $\sigma_{xy} \sim 390$ um in the azimuthal direction and $\sigma_z \sim 780$ um in the drift direction. An analysis of laser induced tracks yielded a two-track separation resolution of ~ 1 cm. The resolutions obtained under the presented conditions (limited drift distance and the absence of a magnetic field) indicate that the resolutions to be realized under STAR operating conditions will meet with the specifications in the STAR Conceptual Design Report [1].

VI. Acknowledgments

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