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PROGRESS REPORT
ON
THE STUDY OF HADRONIC MATTER AT THE HIGHEST DENSITY; THE SEARCH FOR THE DECONFINED QUARK-GLUON PHASE USING 2 TeV $\bar{p}$-p COLLISIONS ; and THE EXCLUSIVE STUDY OF NUCLEAR FRAGMENTATION USING THE LAWRENCE BERKELEY LABORATORY EOS-TPC

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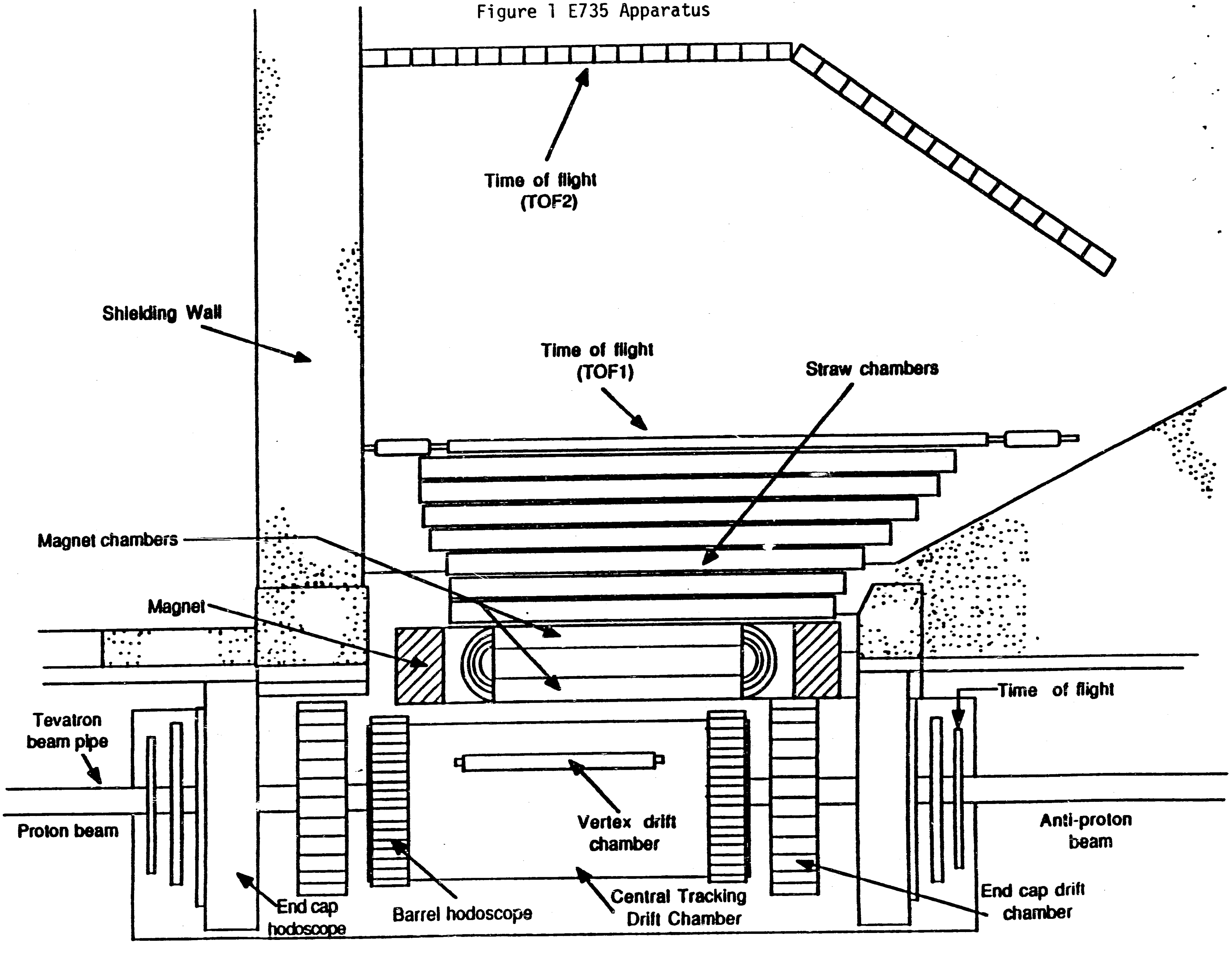
1. Fermilab Experiment 735. A Search for the Quark-Gluon Plasma.

1.1 Introduction

E735 was proposed in 1983 as a dedicated search for the quark-gluon plasma at the Fermilab Tevatron. The experiment was motivated by intriguing results from UA1 and UA5 as well as theoretical suggestions that one should be able to form states of energy density of about 10 times that of normal nuclear matter in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV. Lattice gauge calculations[1] suggested that the phase transition from confined quarks and gluons to the deconfined state was first order, involving a large latent heat and a change from few degrees of freedom in the hadronic phase to many degrees of freedom in the QGP phase. Van Hove[2] suggested that the correlation between average transverse momentum, $<p_t>$, and the charged particle multiplicity per unit pseudorapidity, $dN_c/d\eta$, be used to search for evidence of the phase transition. In his picture, a rise in $<p_t>$ vs $dN_c/d\eta$ followed by a plateau, followed by a second rise, would signify the hadronic, mixed, and quark-gluon phases of nuclear matter, respectively. E735 was designed to carry out this program as a function of particle type at the C0 collision region of the Tevatron. Charged particles were measured in two ways. A scintillator hodoscope, consisting of 240 elements gave coverage over 6.5 units of pseudorapidity. The hodoscope gave a fast first estimate of the event multiplicity and was used for event selection on-line. A central tracking chamber, CTC, was used to provide more precise tracking information off-line. It covered 3.2 units of pseudorapidity. The CTC was the responsibility of the Purdue High Energy Nuclear Physics group. The momentum of charged tracks was sampled by a small single arm spectrometer, consisting of tracking chambers and two time-of-flight arrays. Particle momenta from about .15 GeV/c to 3.0 GeV/c, depending on particle type, were measured. Typically, a few tracks per event entered the spectrometer. The apparatus is shown in Figure 1. A short 3 month test run was made during the spring of 1987. At this time, the CTC was still under construction. Final installation of the apparatus was made in May, 1988 followed by a year of running.

The first run of E735 has provided the world with some tantalizing views of the physics at $\sqrt{s} = 1.8$ TeV. By correlating $<p_t>$ with $dN_c/d\eta$ (Fig. 2), we have seen behavior consistent with a first order phase transition.[3] Furthermore, the increase

Figure 1 E735 Apparatus



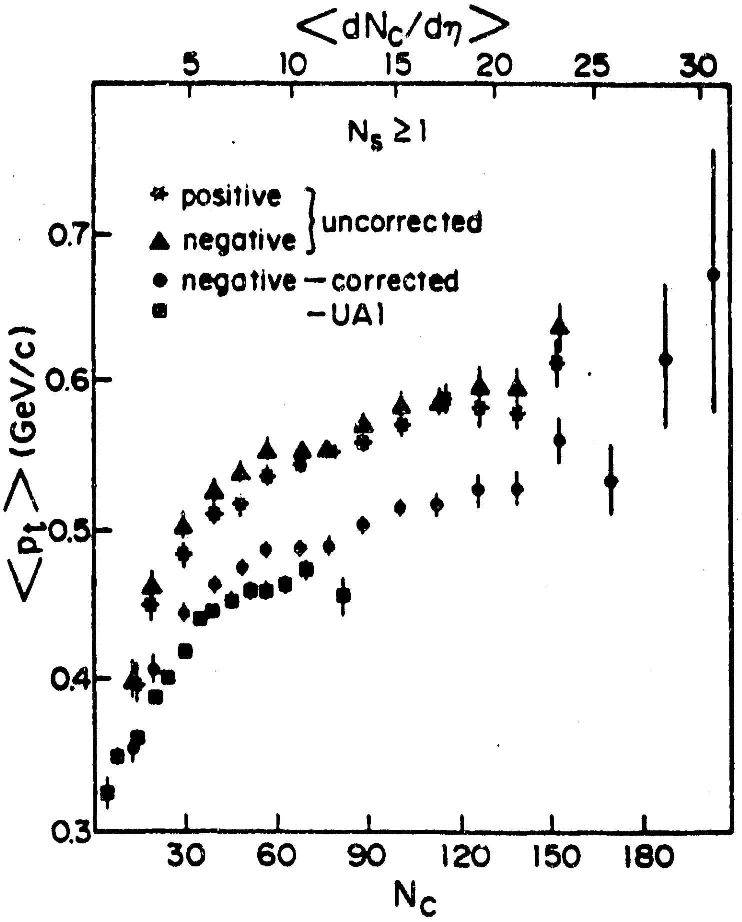


FIG. 2 $\langle p_t \rangle$ as a function of N_c and $\langle dN_c/d\eta \rangle$ for all positive tracks and all negative tracks averaged over the interval 0.15 GeV/c $< p_t <$ 3.0 GeV/c. The corrected $\langle p_t \rangle$ of negative particles includes unobserved particles with $p_t <$ 0.15 GeV/c (see text). The last few uncorrected data points are omitted for clarity. The UA1 data (Ref. 5) are from $\sqrt{s}$ =540 GeV/c.

of $<p_t>$ vs $dN_c/d\eta$ is more dramatic for the heavier species (Fig. 3)[4] The antiprotons show a rise, a plateau, followed by a second rise at the values of $dN_c/d\eta$ expected on the basis of simple estimates of the energy density required to make the QGP.[5]

One of the possible signatures of the formation of a QGP is the enhanced production of strange particles, such as kaons and lambdas.[6] This enhancement would occur if chemical equilibrium were achieved in the QGP. It is not attained in normal hadronic matter. Recently, enhanced K/π ratios have been observed in relativistic heavy ion collisions.[7] It is possible, however, to explain these by dynamical effects, without resorting to the formation of a QGP.[8] Nonetheless, such signals may be consistent with the formation of a QGP and should be viewed in the larger context of multiple signals. In Figure 4 we show the K/π and $\bar{p}/\pi$ ratios vs multiplicity from our 1987 data.[4] The two ratios show markedly different behavior, with the former increasing about 40% over the multiplicity range studied, while the latter may rise and then decrease as the multiplicity increase. A preliminary analysis of the 1989 data shows that the λ/p ratio remains constant at about 35% (Fig. 5).

An analysis effort is underway to determine the size of the hadronizing system using the Hanbury-Brown and Twiss intensity interferometry technique[9] applied to hadrons.[10] Like-signed pions entering the spectrometer can be used to determine the system size as a function of the event multiplicity. Preliminary results shown in Fig. 6, indicate that the hadronization volume is an increasing function of multiplicity. This indicates a larger initial energy density as $dN_c/d\eta$ increases.

In summary, we see that the 1987 data contain several features (as a function of the multiplicity) which are consistent with the formation of a QGP.

- enhanced K/π ratios.
- $<p_t>$ dependence of the antiproton spectra.
- Enhanced $\bar{p}/\pi$ ratio in the $5 \leq dN_c/d\eta \leq 12$ region.
- Increase of the hadronization volume proportional to dn_c/dy. The 1989 data should substantially reduce the statistical uncertainties associated with the signals which are listed above.

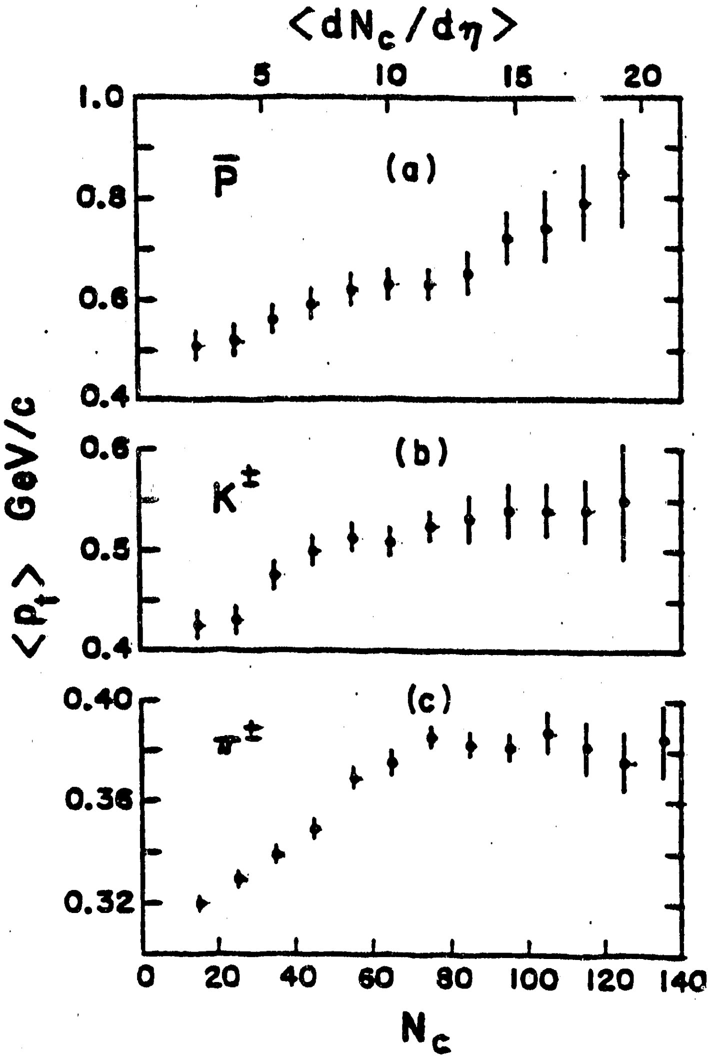


FIG. 3 (a)–(c) Plots of $\langle p_t \rangle$ vs $dN_c/d\eta$ (or N_c) for $\bar{p}$, kaons, and pions, respectively, for particles with $p_t < 1.5$ GeV/c.

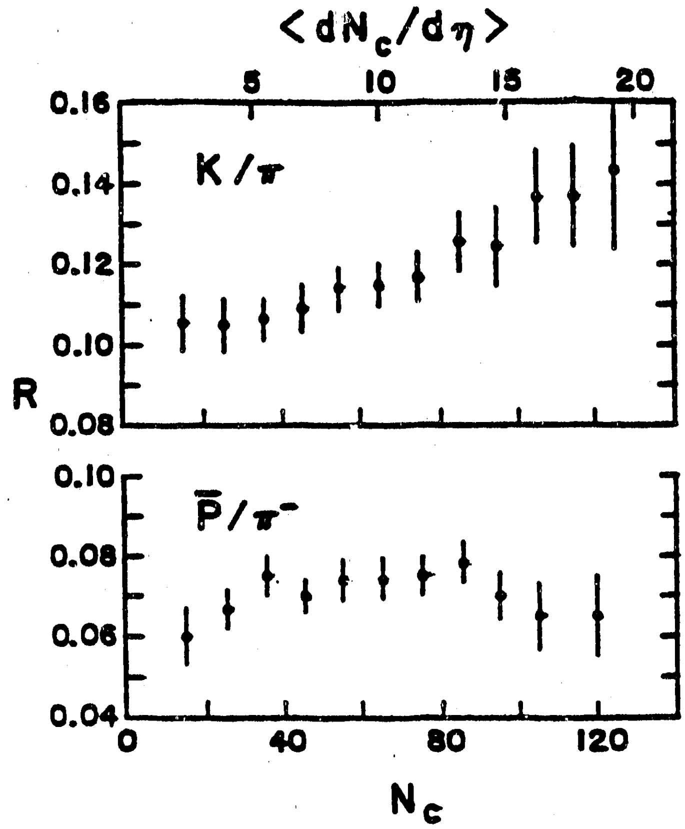


FIG. 4 Ratios of K/π and $\bar{p}/\pi^-$ as a function of charged multiplicity N_c. The ratios are calculated for equal rapidity intervals.

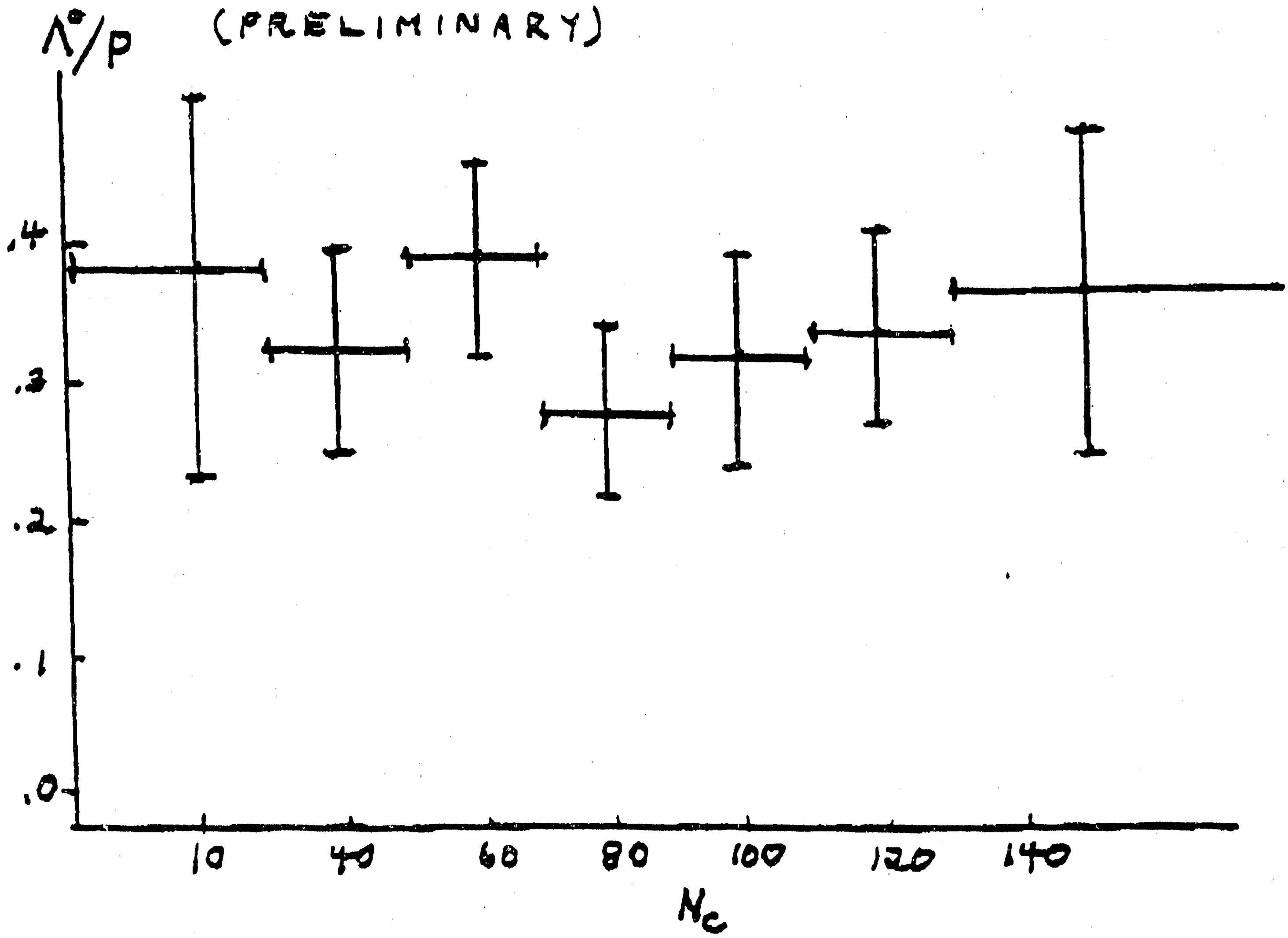


Figure 5

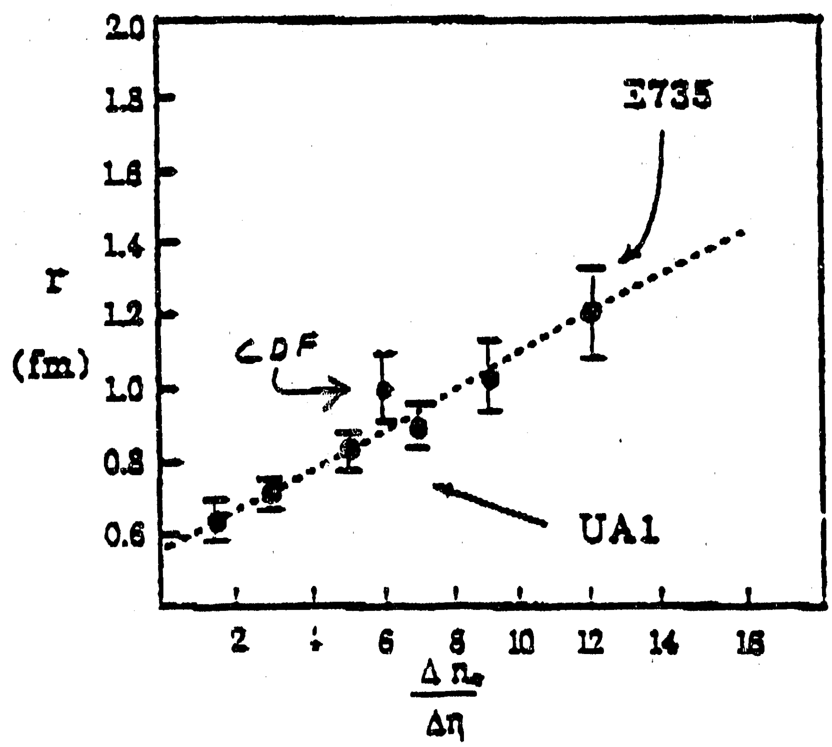


Figure 6

1.2 Milestones set in 1990.

During the past year, approximately 2500 raw data tapes (9 track) were reduced to about 40 8 mm data summary tapes (DST). This task was performed on the Fermilab Amdahl computer and was overseen by our graduate student, Philip Cole, who is in residence at Fermilab. The entire process took about three months. These DSTs have subsequently been distributed to all members of the E735 collaboration. The DST's contain approximately 15 million events compared to about 5 million taken during the 1987-1988 three month running period. Most of the 1988 running period was devoted to acquiring high multiplicity events. Analysis of these data has begun at each of the participating institutions.

The Purdue High Energy Nuclear Physics group has the primary responsibility for analyzing the Central Tracking Chamber (CTC) data. Our long-term objectives are to determine the multiplicity distribution and the pseudorapidity distribution within the CTC acceptance. In addition, we will perform an intermittency analysis. In order to accomplish these goals, we have developed a detailed GEANT simulation of the E735 apparatus. This simulation was developed and tested at Purdue and then distributed to all members of the E735 collaboration.

At present, we are conducting detailed comparisons between the simulation and the CTC data. This comparison involves several steps. An event generator, such as the one developed by UA5, is used to generate the primary particles following a proton-antiproton collision. These particles serve as input to the GEANT simulation where they are tracked through the experimental apparatus. The space points of charged tracks which fall within the CTC are then further processed into Flash Analog to Digital Converter (FADC) spectra. This effectively maps the GEANT space points into the time and amplitude dimension, simulating the effects of drift time and charge division in the CTC. These FADC spectra are then processed using the same codes employed in analyzing the actual data. The spectra are converted to hits, which serve as input to the tracking routines. Finally, tracks are formed which can be compared to the GEANT input tracks. In Fig. 1 we show the ratio of hits used in fitting tracks to all "good" hits found by the hit finding algorithm versus the number of good hits for both simulation and data. Fig. 2 shows the impact parameter distribution of tracks in the xy plane for both simulation and data. A cut on impact parameter is central to the definition of what we call a "primary" track, i.e. a track coming from the event vertex. By using the simulation, we can compare the number of primaries found after the cut to the

Figure 1 21/08/90 14.03

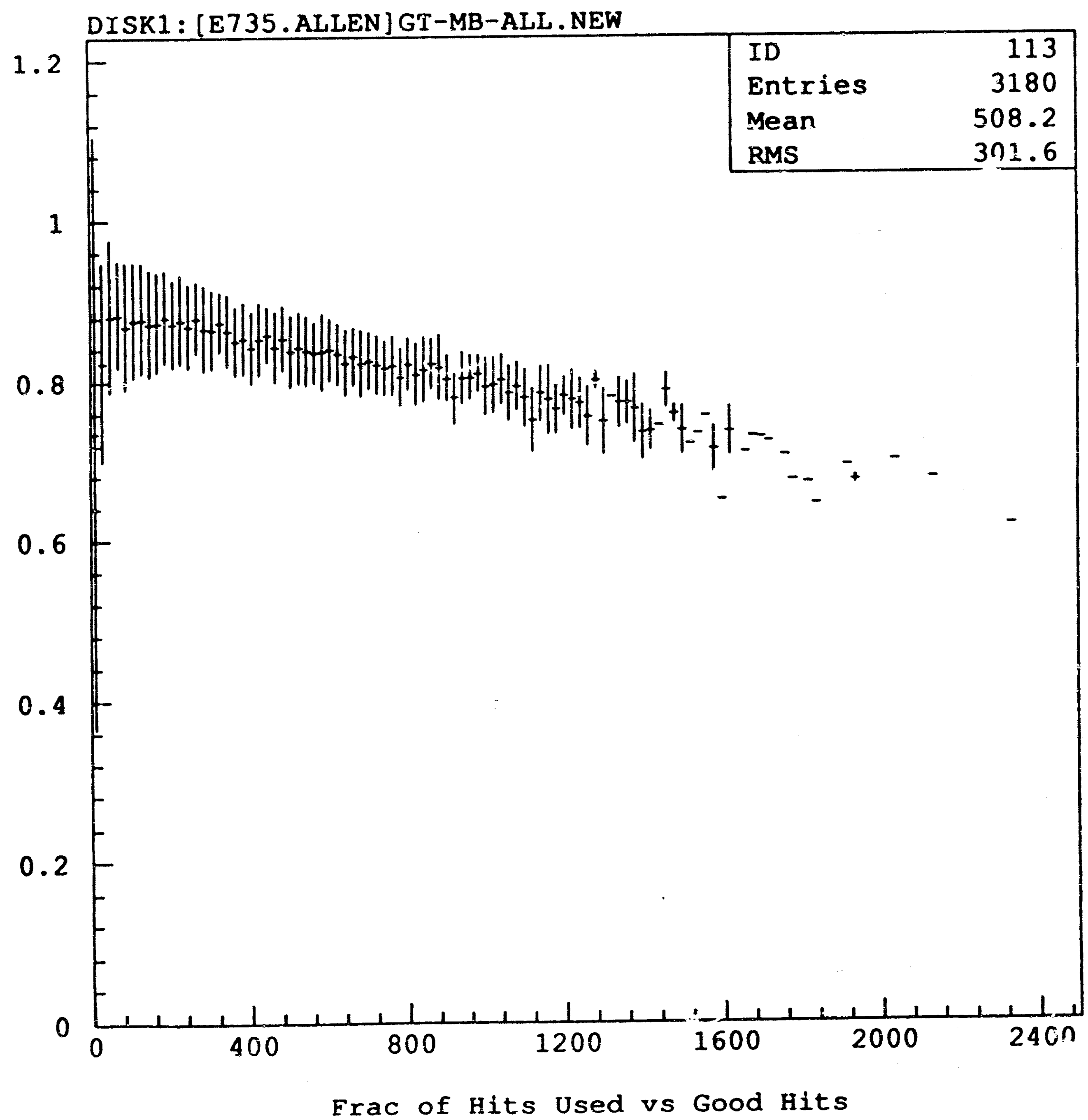


Figure 2

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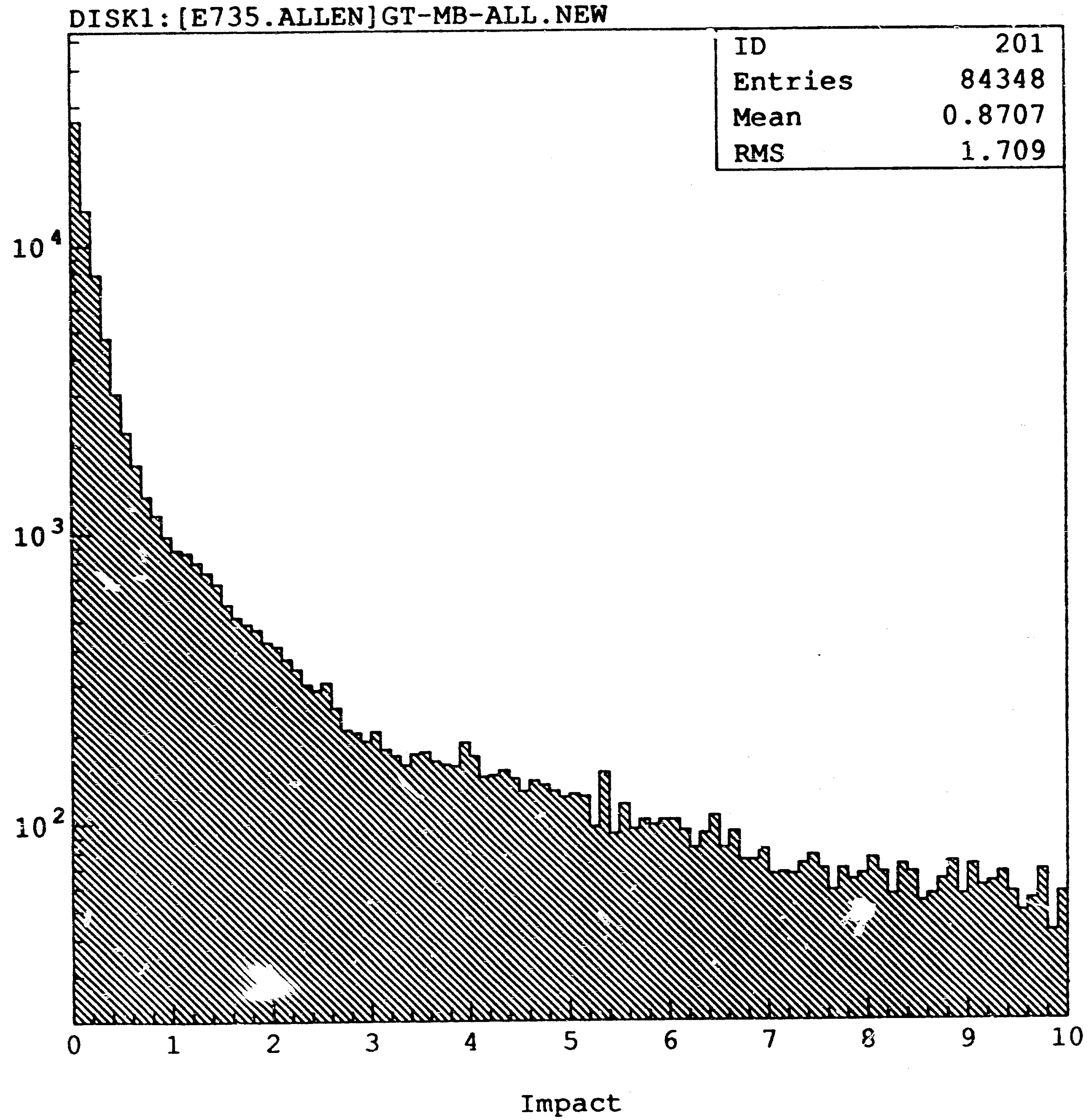

actual number which served as input to the simulation. After some degree of tuning both the simulation and the tracking algorithms, we will proceed with the above plan of study. This work is being performed primarily by our graduate student, Charles Allen, with assistance from our senior research scientist, Young-il Choi.

We have also begun analyzing spectrometer arm data. This program is being carried out both at Purdue and at Fermilab. The objective is to determine the average transverse momentum as a function of multiplicity for pions, kaons, and antiprotons. These data must be corrected for various effects, including, the spectrometer acceptance as a function of event vertex position, momentum of the track, multiplicity of the event. etc. These corrections are calculated using a GEANT simulation run on the Fermilab Amdahl computer. This work is being done by Philip Cole and supervised by senior scientists at both Purdue and Fermilab.

One of the important issues to settle is whether or not the rise in $<p_t>$ with $dN_c/d\eta$ is due to minijets or is a result of the QGP phase transition. We intend to address this question by comparing our data with a simulation containing minijets, for example Pythia. It will be used to simulate both CTC and spectrometer data.

1.3 Publications from E735 in 1990.

The E735 collaboration published a Physical Review Letter detailing the average transverse momentum of pions, kaons and antiproton.[4] The analysis presented in this paper was performed on the data acquired during the 1987-1988 running period. A 60% increase in mean transverse momentum for antiprotons was observed as $dN_c/d\eta$ increased from its minimum bias value of 3 to about 18. The mean transverse momentum for charged pions increased about 25%. For further details, see reference 3.

The E735 collaboration was invited to make a contribution to a conference on collider physics. Our post doctoral research assistant, Norman Morgan, was selected to make the presentation for the collaboration. His talk summarized recent results from the Tevatron.[11]

The Central Tracking Chamber was described in detail in a paper published in Nuclear Instruments and Methods.[12] The construction method, using low mass composite materials was emphasized.

2. An Exclusive Study of Nuclear Fragmentation using the EOS-TPC

2.1 The search for critical phenomena using the EOS-TPC.

The Purdue High Energy Nuclear Physics group has initiated an experimental program to study multifragmentation at the Lawrence Berkeley Laboratory Bevalac. Heavy projectile beams at 1 GeV/nucleon will bombard light targets. The resulting projectile fragments will be detected in a Time Projection Chamber (TPC).and other ancillary detectors, permitting the determination of the charge and momentum of all of the reaction products on an event-by-event basis. The unique features of this experiment are:

- the use of reverse kinematics, ie a heavy projectile incident on a light target. All of the reaction products have essentially the same velocity and are carried forward into the TPC.

- the development of a new detector, the Equation Of State (EOS) TPC. This device is being built by the Relativistic Nuclear Physics group at LBL.

- the characterization on an event-by-event basis of the nature of the reaction. This last point is detailed below.

The Purdue High Energy Nuclear Physics group has a long history of working in the field of nuclear fragmentation. Our previous <u>inclusive</u> studies have led us to suggest the analogy between nuclear fragmentation and a liquid-gas phase transition occurring in a van der Waals gas.[13] Recently, Campi has analyzed 400 exclusive gold-emulsion events and concluded that nuclear fragmentation has the characteristics of a critical phenomenon.[14] The experiment we will conduct at the Bevalac will allow us to extract the critical exponents describing the phase transition. Using the EOS-TPC and a Multiple Sampling Ionization Chamber (MUSIC), the momentum and charge of each projectile fragment will be determined. Events can then be characterized as being subcritical, critical, or supercritical. Further physics details can be found in the accompanying proposal submitted to LBL.

Our experiment is part of a larger program of the EOS-TPC group, of which the Purdue High Energy Nuclear Physics group is a part. In fact, we are participating in two additional experiments, both of which concentrate on flow effects in nuclear matter at Bevalac energies. All of these experiments will begin running in the latter half of 1991. At present we have two graduate students, Mark Gilkes and Penny Warren who will obtain Ph. D. theses from the fragmentation experiment. In addition, Eric Hjort, a post doctoral research assistant is stationed at LBL to participate in the hardware and software development of the EOS-TPC system.

The primary responsibilities of the Purdue High Energy Nuclear Physics group are:

- design, testing, and installation of the beam line between the last quadrupole magnet and the TPC entrance. This includes beam-locating scintillation detectors and a gas ionization detector to distinguish beam particles from multifragmentation reaction products. The beam line will be used in all of the TPC experiments. This work is being done both at Purdue and at LBL.

- simulations for calculating track reconstruction efficiencies. The

- development of analysis techniques for extracting the critical indices from the data.

- participating in the other two (at present) TPC experiments. This will include running shifts, maintaining detectors, and analyzing data.

The three TPC proposals were accepted by the PAC at LBL in June. The experiments will begin running in the second half of 1991.

3. A proposal to the Relativistic Heavy Ion Collider

3.1 A study of the central rapidity region at RHIC using a TPC.

We have proposed an experiment to study particle and jet production in the central rapidity region, $|\eta| \leq 1$. Other members of the collaboration are U. C. - Davis, U. C. L. A., U. Frankfurt, Johns Hopkins, Kent State, Lawrence Berkeley Lab, Texas A&M, Washington, and Zagreb-Boskovic Institute. The proposal was presented at the RHIC workshop held at Brookhaven National Laboratory, July 2-7, 1990. A letter of intent will be submitted to BNL in September, 1990.

The experiment aims to study two aspects of hadron production that are fundamentally new at RHIC. Because of the high charged particle multiplicity in a central collision, one can study correlations between global observables on an event-by-event basis. For example, speckle interferometry may permit the determination of the hadronization volume[15] Pion spectra can be studied on an event-by-event basis as well, allowing the determination of the slope parameter of the spectrum. Particle ratios, ie, antiproton to pion, kaon to pion, can also be studied on the same basis. One signature of a phase transition occurring at the critical point might be violent fluctuations in these ratios.

A second aspect of the proposed experiment is a study of the hard scattering of partons as a probe of the properties of nuclear matter at high energy density. The observation of jets, whose E_T>40 GeV, may provide a signature of quark-gluon plasma formation. It is estimated that jet attenuation is reduced by a factor of approximately 10 in the QGP as opposed to in hadronic matter.

The experimental apparatus is shown in Fig. 1. It consists of a cylindrical TPC which covers about $\pm$ 2 units of pseudorapidity centered about η=0. The inner (outer) radius of the TPC is 50 cm (200 cm). A magnetic field is coaxial with the beam. Each TPC half has 75,000 channels. Surrounding the TPC is a 2 m radius time of flight (TOF) cylinder. For 2% occupancy and 2000 charged particles in the central region, 10^5 pixels of 6 cm^2 each are required. Beyond the TOF is a calorimeter. Further details can be found the accompanying three year proposal.

The Purdue High Energy Nuclear Physics group is intent in pursuing the study of nuclear matter at the highest energies at RHIC. We believe that we are uniquely suited to this endeavor, having had considerable experience at the Fermilab Tevatron (E735). In addition, our experience in the nuclear fragmentation field gives us a unique perspective on the physics of phase transitions.

We will be submitting a letter of intent to Brookhaven National Laboratory this September, detailing the proposed experiment. As part of this effort, we will be submitting a request for R&D funds which will be used to address several of the technical issues which must be solved before such a detector can be built. In

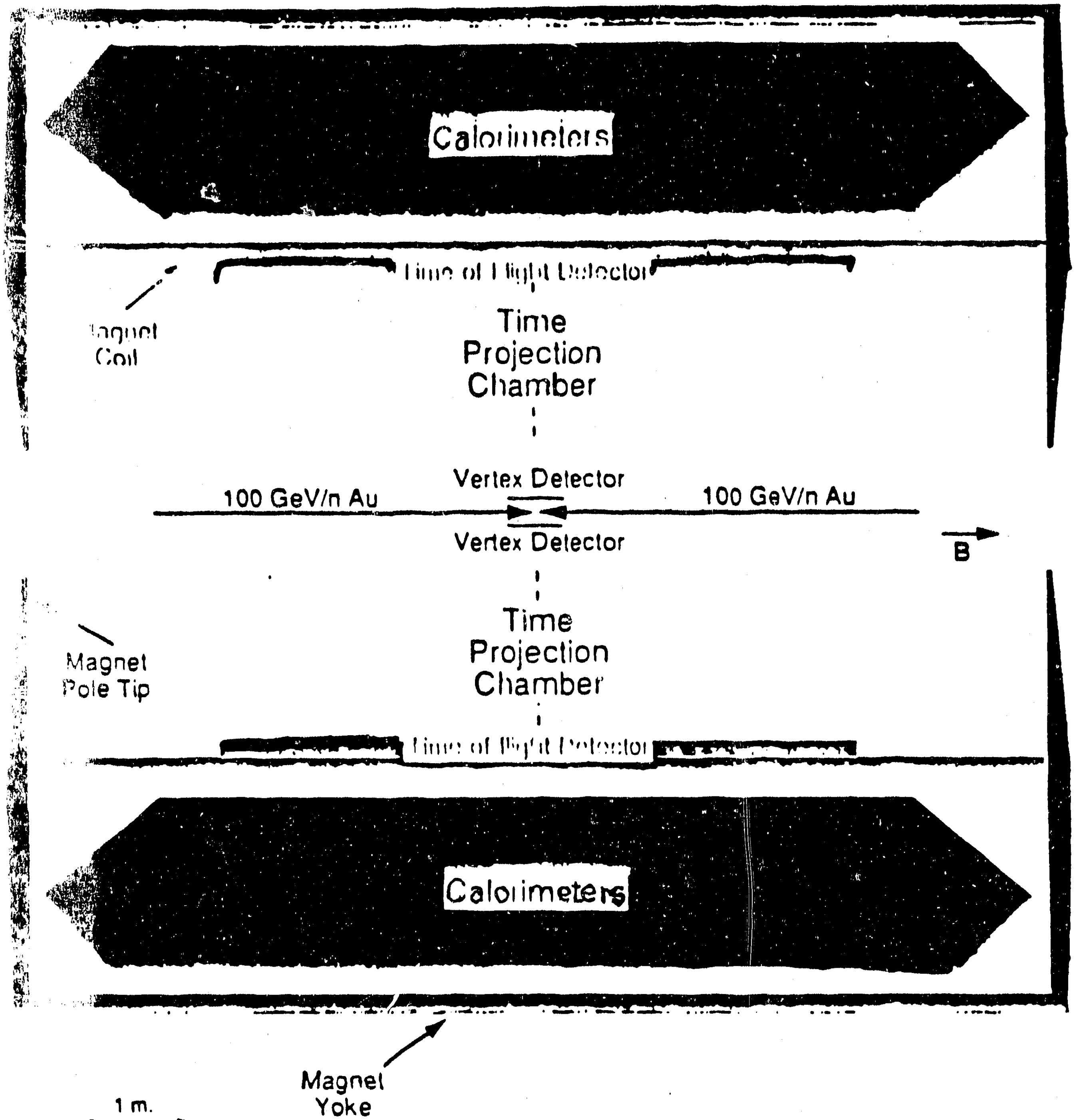

Figure 1. Sketch of apparatus for RHIC experiment.

particular, the Purdue group will be investigating new techniques in time-of-flight using silicon avalanche diodes. Further details can be found in our three year proposal.

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1. Fermilab Experiment 735. A Search for the Quark-Gluon Plasma.

1.1 Introduction

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