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Detector Issues For Relativistic Heavy Ion Experimentation

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Several aspects of experiments using relativistic heavy ion beams are discussed. The problems that the current generation of light ion experiments would face in using gold beams are noted. A brief review of colliding beam experiments for heavy ion beams is contrasted with requirements for SSC detectors.

1. INTRODUCTION

The interest in relativistic heavy ion experiments has been growing as the series of fixed target experiments at the CERN SPS and the BNL AGS takes the floor. The hope of studying a totally new state of matter may be reached by the current round of experiments. A brief review of the typical experimental signatures is given. It may be that this round of light ion experiments does not find any anomalous behavior. Then the next step would be to accelerate a truly heavy beam, for example, gold ions. In the next section of this paper, some problems are discussed that the current experiments would have in this case. Another step would be to dramatically raise the energy density by building a relativistic heavy ion collider. In this type of collider a central rapidity plateau will be achieved which may be optimal for observing the phase transition. A short review is given of the type of experiments that can be designed for such a collider. The last section of this paper compares requirements for detectors for this type of collider with those needed at the Superconducting Super Collider (SSC).

2. BELLWETHER SIGNATURES OF A QUARK GLUON PLASMA

A bellwether is the sheep who leads the flock on whose neck the bell is hung. In the field of quark matter there are a number of signatures that

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have been mentioned over the years that may signal the occurrence of this new state. Eventually when real data is available to guide our thinking, some totally different signal may leap out. Fig. 1 lists these probes and divides them into 3 categories. First, there are the global event parameters. Here

SIGNAL	COMMENTS	
INCLUSIVE PARTICLE SPECTRA PARTICLE INTERFEROMETRY	INDICATORS OF TEMPERATURE, SIZE AND DENSITY	GLOBAL EVENT PARAMETERS
MULTI-PARTICLE CORRELATIONS IN RAPIDITY; ENERGY FLOW	LONG RANGE CORRELATIONS AND MACROSCOPIC FLUCTUATIONS CHARACTERISTIC OF FIRST-ORDER PHASE TRANSITION	
LOCAL CHARGE CORRELATIONS	COLOR SCREENING EFFECTS IN PLASMA DIFFERENT FROM NORMAL PAIR PRODUCTION BY VACUUM POLARIZATION	INDICATORS OF A PHASE TRANSITION
PARTICLE FLAVOR RATIOS	CHEMICAL EQUILIBRIUM IN HOT PLASMA GIVES A LARGE NUMBER OF STRANGE PARTICLES AND ENHANCED $\bar{\Lambda}/\bar{p}$ RATIO	
STABLE MULTIQUARK STATES	6-QUARK AND HIGHER CONFIGURATIONS READILY ASSEMBLED IN THE PLASMA	
DIRECT PHOTON PRODUCTION ($m_T = p_T$) LEPTON PAIR PRODUCTION (VIRTUAL PHOTON: $m_T^2 = m_{PAIR}^2 + p_T^2$)	$m_T \leq 50$ MeV: COHERENT EMISSION FROM LOCAL CHARGE FLUCTUATIONS $50 \leq m_T \leq 500$ MeV: HADRONIC DECAYS; SOME COHERENT EFFECTS $500 \leq m_T \leq 3$ GeV: DIRECT EMISSION FROM PLASMA $m_T \geq 3$ GeV: APPROACH TO EQUILIBRIUM; STRUCTURE FUNCTIONS OF QUARKS AND GLUONS CHANGE AND ARE COMPUTABLE IN PERTURBATIVE QCD	PENETRATING PROBES: DIRECT INFORMATION FROM THE PLASMA
HIGH-p_T JETS	MEASURES PROPAGATION OF QUARKS AND GLUONS THROUGH NUCLEAR MATTER; HADRONIZATION PROPERTIES REFLECT THE "REAL SEA" OF QUARK-GLUON PLASMA	

FIGURE 1. Experimental probes for new states of matter.

by measuring in a single event the inclusive single particle spectra or energy flow in a calorimeter, one may see indications of higher temperature and density than the ordinary event. Next, one looks for the phase transition into quark matter perhaps by, for example, measuring a large number of strange particles. Finally, one may try to measure the extent of the plasma by measuring particles that can penetrate the hadronic matter surrounding the quark matter such as direct or virtual photons. NA34 at the CERN SPS[1] shown in Fig. 2 has components that attempt to measure these three

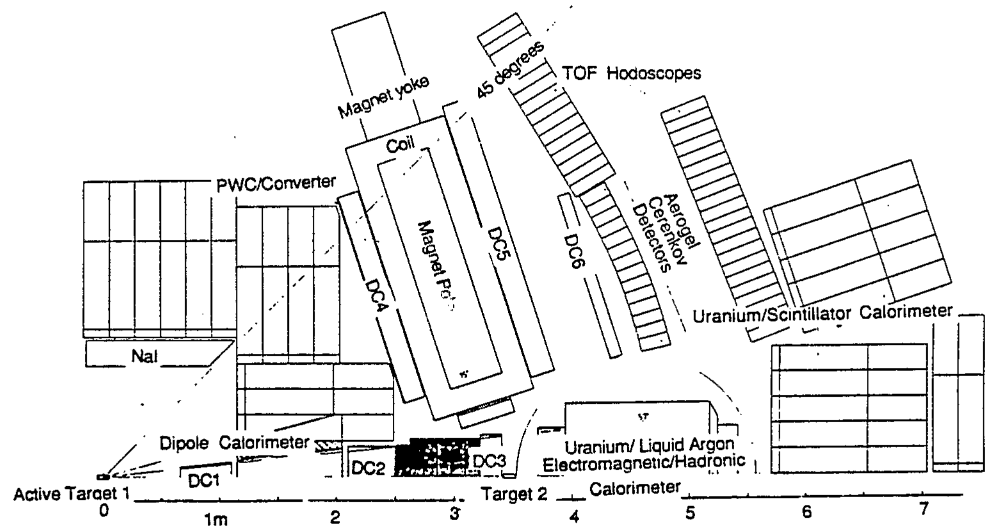

FIGURE 2. Experimental layout of NA34 - all but external spectrometer is reflected about the beam line.

apsects of the collisions. The uranium scintillator and uranium liquid argon calorimeters cover nearly the entire phase space to measure the energy flow. The external spectrometer with its time-of-flight (TOF) and Cerenkov counters can sample a small part of the phase space for strange particles in correlation with the energy flow. Finally, the electron pair spectrometer and muon spectrometer can measure the virtual photons which probe the plasma.

3. CAN PRESENT FIXED TARGET EXPERIMENTS USE GOLD BEAMS?

The main difference that occurs in going from an oxygen beam to a gold beam is the increase in the average multiplicity. One may expect this to increase like A^α. For α=1, $(197/16)^1 = 12$ while for α=1.3 $(197/16)^{1.3} = 26$. Of course this also means that the average energy in the calorimeter goes up by this corresponding amount.

For NA34 the external spectrometer was designed for an oxygen beam where the average multiplicity in it is one. Perhaps the drift chambers could still work with an order of magnitude increase of particles. However the particle identification system could not. The TOF has only ≈ 30 elements while the aerogel has only 4 elements. The silicon detectors do not work with the multiplicity of sulphur beams. The calorimeters can work provided the gain is lowered. On the scintillator devices this is easier since only the high voltage needs to be lowered. However, on the liquid argon device, the gains of the preamps must be lowered. Since some of the preamps are encased in hermetic containers normally residing in the liquid, this means replacement. The electron spectrometer would not work in this increased multiplicity. The muon spectrometer may work if the target is in the position just in front of the liquid argon calorimeter. In its normal position there would be too much background from π decays. In conclusion, more segmentation would help some aspects of NA34 cope with gold beams but probably this challenging possibility requires more thought.

The design philosophy for AGS experiment 802, Fig. 3, was to insure that with sulphur beams 95% of the elements would have no more than 1 double hit.[2]

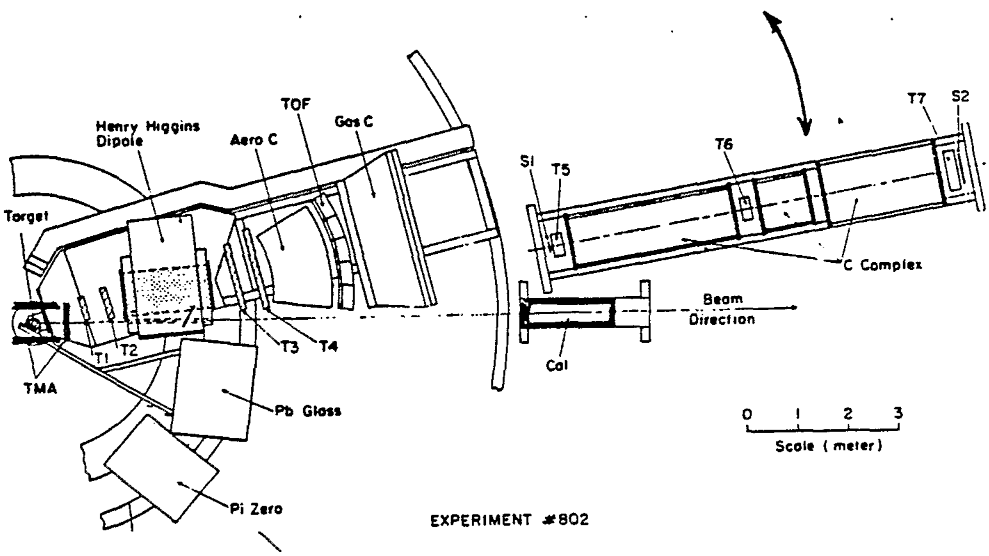

FIGURE 3. Experimental layout of AGS 802.

Basically, the segmentation must be larger than the square of the average multiplicity, $\bar{n}$. For example, the target multiplicity counter has 5000 pads. One particle fires on the average 2 pads. At $\bar{n}$=50 the 95% requirement is met. By going to gold the multiplicity increases by $(197/32)^{\alpha} \approx 6\text{-}11$. So the number of pads in target multiplicity counter would have to increase by $\approx (6\text{-}11)^2 \approx 100$. The wire chambers in the spectrometer, T1-4, are each made up of 5x2 planes x,y,u,v,w,x',y',u',v' and w'. For $\bar{n}$=20 hits, the tracks are unambiguously found in 99% of the cases. However the performance decreases exponentially. Only doubling the average multiplicity makes the track finding impossible. There are 15 particles expected from a sulphur beam in the TOF implying a theoretical segmentation of 225. Actually there are 166 actual strips of scintillator. These strips are of a minimum size to get enough photons out to measure the timing accurately. Therefore it would take a new concept to make such a measurement. Similarly the Cerenkov counters have a limited number of elements, 100 in the aerogel and 32 in the gas section. The lead glass calorimeter has 256 + 64 pieces. Although at low multiplicity one would hope to measure individual π°'s, even at the highest multiplicities the neutral energy flow could be well measured.

The AGS 810 experiment, Fig. 4, uses a CCD array surrounding the target and in phase 1 a time projection chamber (TPC) downstream. The track to

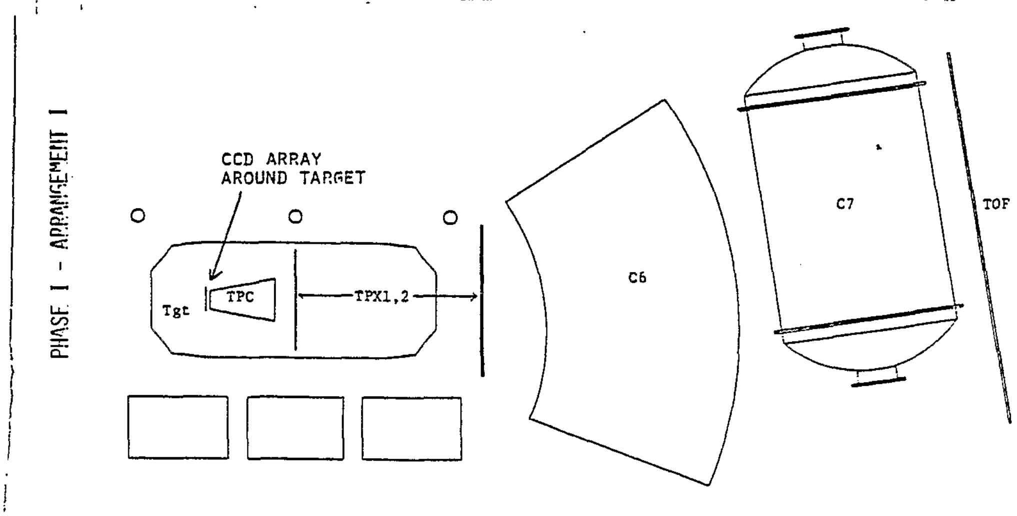

FIGURE 4. Experimental layout of AGS 810.

pixel density for a sulphur beam is 1:100 where the pixel size is 3x4 mm^2. There have been Monte Carlo studies[3] which show that pattern recognition may be possible if this ratio deteriorates to 1:10 or even 1:4. Even if this density becomes prohibitive, the TPC can be moved downstream to decrease the number of hits per pixel.

In conclusion, the use of gold beams leads to higher multiplicity which demands more segmentation in detectors other than calorimeters. In some cases this can be achieved in the context of an experiment designed for a lower multiplicity, but in most cases, this requires a new design.

4. DETECTOR DESIGNS FOR RELATIVISTIC HEAVY-ION COLLISIONS

Recently there was a workshop at Brookhaven[4] to explore the designs for such experiments and estimate the cost of these detectors. Here there will be only an extremely tiny part of all the interesting contributions to that workshop covered, so the interested reader is encouraged to consult the quite readable proceedings directly. Fig. 5 shows a generic detector for fixed target. This same arrangement can be used in a collider as shown in Fig. 6.

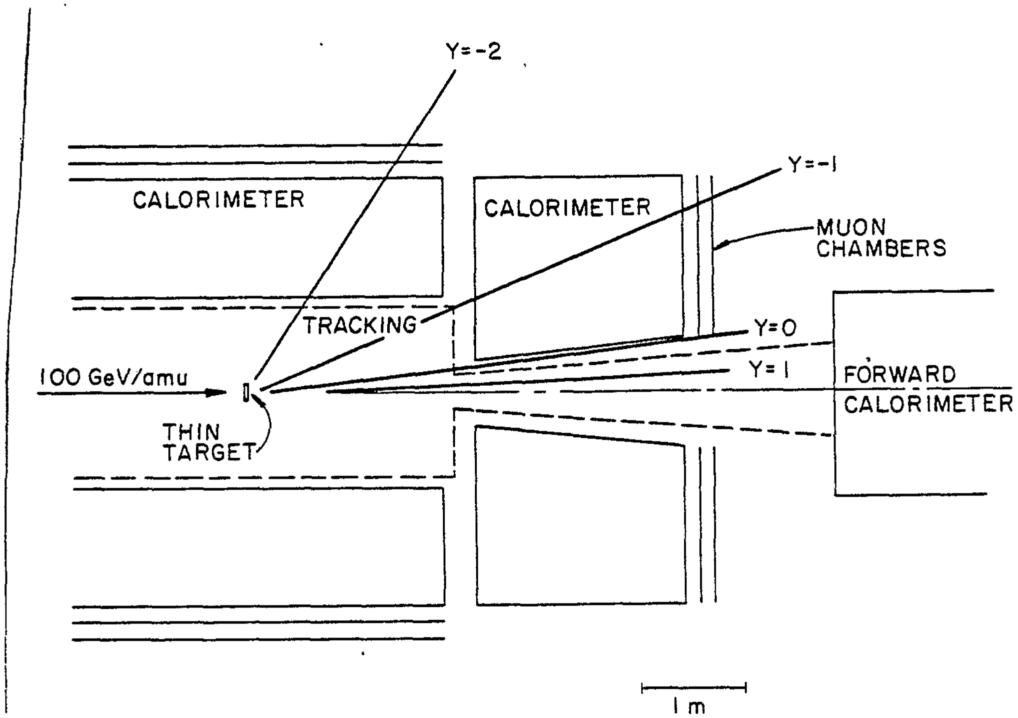

FIGURE 5. A generic fixed target experiment showing tracking and calorimetry.

Basically the central rapidity region (y=0) which is quite forward in the fixed target environment is transformed to 90° when the laboratory frame becomes the center of mass frame.

One group in the workshop designed a calorimeter based experiment shown in Fig. 6.[5] A detector to measure the multiplicity could be made using a drift chamber or streamer tube technique. There is a calorimeter which covers the pseudo rapidity (η) interval $|\eta| < 2$. It has a rather coarse granularity ($\Delta\eta$, $\Delta\phi \approx 0.2$). Also it does not need to be very deep in terms of nuclear absorption lengths. The authors point out that since there are so

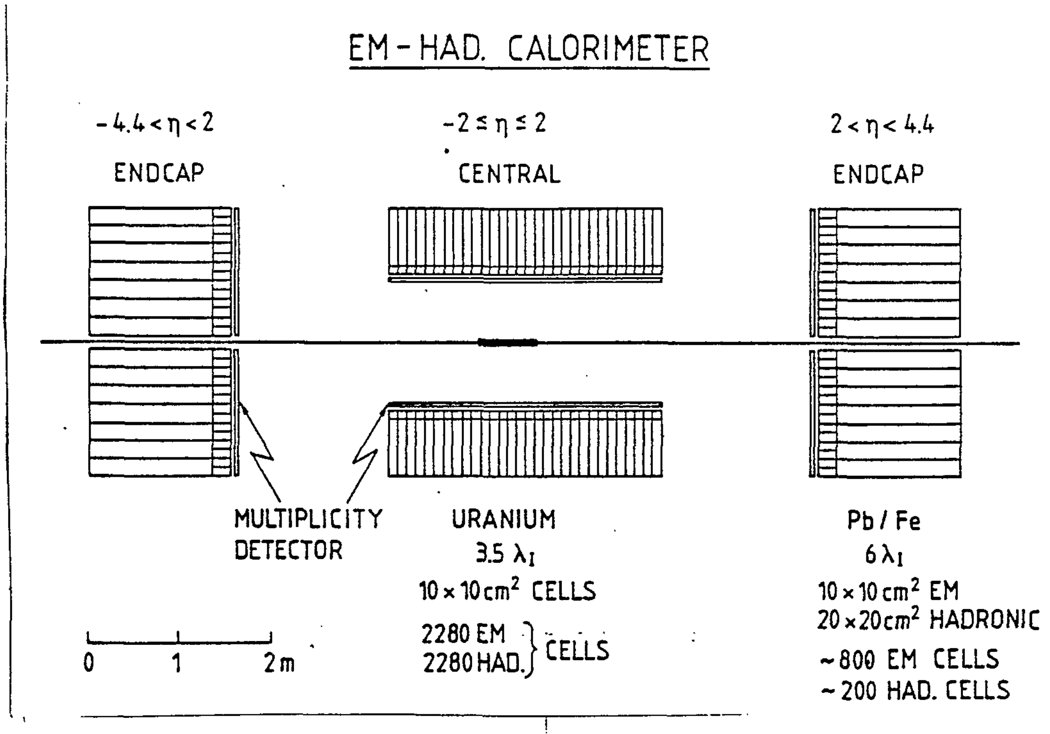

FIGURE 6. Sketch of calorimeter based experiment for colliding heavy ion beams.

many particles mainly of low momentum, the fluctuations on the transverse energy is small even if some of the energy of a few particles leaks out. This is in contrast to the requirements for a particle physics calorimeter which is measuring the fragmentation of a quark or gluon. In that case the leading particle of the fragmentation can have a large fraction of the energy and therefore it would be serious if its energy were not fully measured. An open question was whether the albedo from the calorimeter would destroy the multiplicity measurement.

Now the events can be categorized with respect to their multiplicity and energy flow characteristics and then to probe for a signature of the quark gluon plasma the concept of a small port was introduced much like the external spectrometer in NA34. An example of such a spectrometer is shown in Fig. 7. Magnetic analysis of charged particles is provided by the small magnet. Inside the field region may be a TPC which measures both the trajectory of the track as well as dE/dx to help identify the particle. Later there can be a TOF counter and perhaps a ring imaging Cerenkov particle (RICH). Finally a small calorimeter may pick up the energy lost in the port

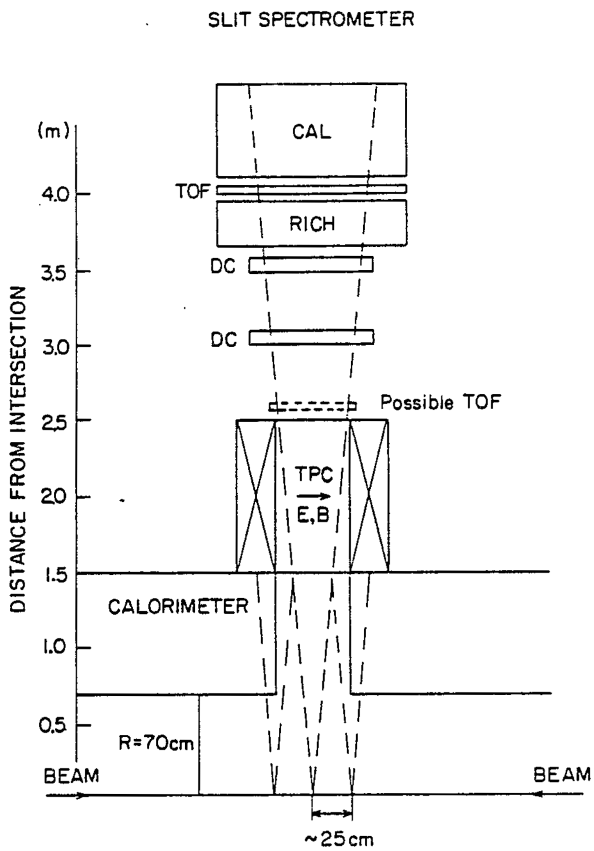

FIGURE 7. Typical "port" spectrometer for experiment in Fig. 6, covering 10° in θ and ϕ at y = 0.

measured before they decay. Such a port may have many locations in phase space as listed below:

	Average Charged Multiplicity for Au + Au Collisions	Δϕ	θ	Special Characteristics
1.	0.2	0.2	2°-8°	
2.	0.5	0.5	8°-20°	
3.	0.8	20°	30±0.5°	
4.	8.4	90° 2°	90°±1° 90°±45°	"Mills cross" for interferometry.
5.	1.5	10°	90±5°	Single particle plus multiparticle correlations.
6.	2.2	1°	90°±70°	Search for rapidity fluctuations.

Another group designed a detector specifically for the detection of dimuons.[6] There are two main problems with the separation of muons from pions. First at low momenta π's decay and give real muons. At higher momenta, pions punchthrough large amounts of absorber to mimic muons. This group realized these characteristics and optimized a detector which tries to overcome both of these problems, although differently, in two kinematic domains. At 90°, see Fig. 8, there is a special 1 cm beam pipe so the absorber can start very close to the collisions. Outside of the absorber which also is a calorimeter to measure the energy flow, are magnetized iron toroids. Thus a muon to be identified at large angles must penetrate a large amount of absorber. This reduces to a minimum the π decay background. In the forward

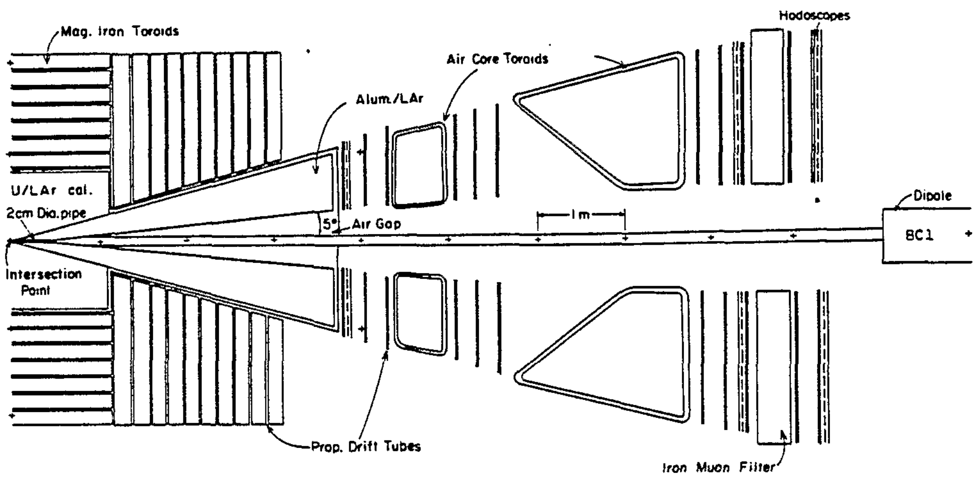

FIGURE 8. Dimuon experiment for colliding heavy ion beams.

direction there is a long low Z(Al) absorber/calorimeter so that the multiple scattering does not overly degrade the angle measurement that follows in an air core toroid. The group estimated $\approx$ 70 $\mu^+\mu^-$ events/hour for gold and gold collisions at $L = 3 \times 10^{26}$ cm^{-2} sec^{-1} at 100 GeV/nucleon. The mass resolution as a function of the rapidity of the muon pair is displayed in Fig. 9. $m_{\mu\mu} \propto E_1 E_2 \theta_{12}{}^2$. Near $y_{\mu\mu} = 0$ where the energy resolution of the muons dominates, the area of good acceptance is for $m_{\mu\mu} \gtrsim 3.5$ GeV. For $|y_{\mu\mu}| \gtrsim 2$, there is a region of good resolution near the J/ψ (m = 3.1 GeV) but the ϕ probably would be hard to see. In this region $\theta \propto \sqrt{L}/x_0$ where L is the length of the track measured and x_0 is the total number of radiation lengths that the muon must travel through.

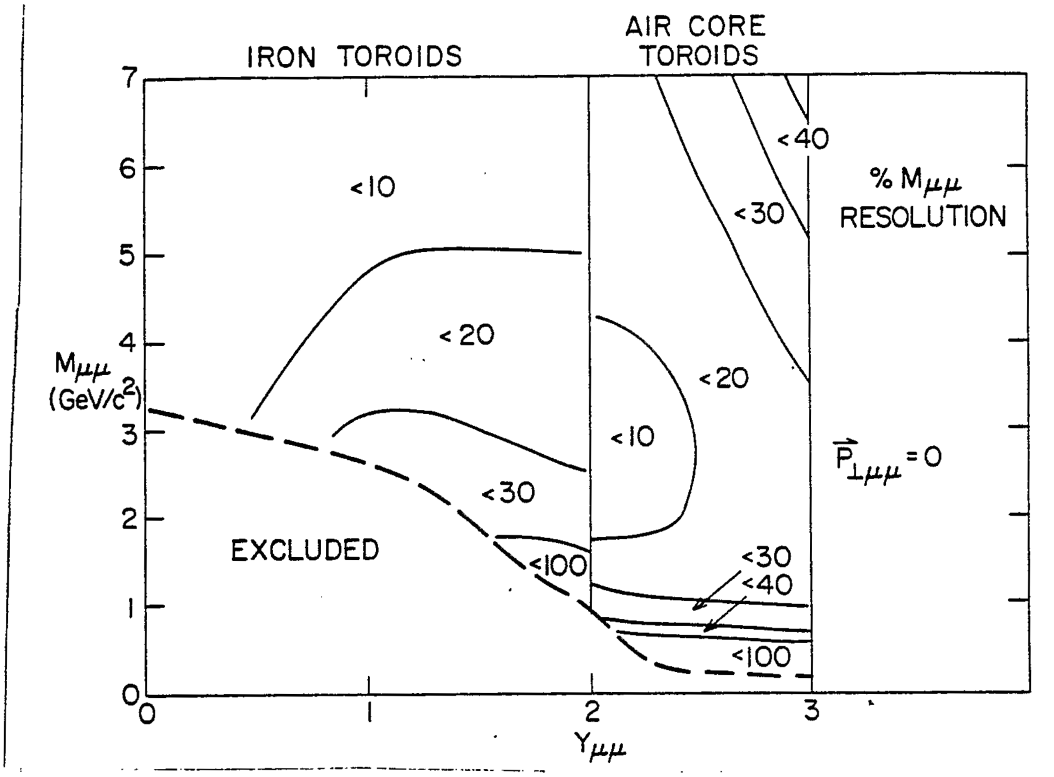

FIGURE 9. Mass resolution at $P_T = 0$ for dimuon spectrometer of Fig. 8. Contours of equal percentage $m_{\mu\mu}$ resolution are plotted versus dimuon rapidity and mass.

The initial complement of detectors for RHIC looked like it could be built with essentially current state of the art technology at a cost of ≈ \$55,000,000.

5. COMPARISONS WITH SSC DETECTOR REQUIREMENTS

There may be some area of overlap in detector technology between heavy ion collider detectors and SSC detectors. The physics of the SSC is quite different:

Physics Topic	Signature
High mass Z', W'	High P_T leptons
Supersymmetric particles	Jets & missing P_T with no leptons
New generations of heavy quarks	Jets & missing P_T with leptons
Leptoquarks	Jets & leptons with no missing P_T
Compositeness	High P_T jets

A typical detector was sketched, Fig. 10, at the Snowmass workshop in 1984.[7] It features a central tracking and electron identifier, a deep calorimeter, and muon tracking chambers in magnetized iron sheets. Here is a table of comparison of requirements for detectors-the SSC versus heavy ion collisions.

	SSC	Heavy Ion Collider (central collisions)
Rate	10^8 interactions/sec 1.6 interactions/crossing radiation damage is a concern	10^3/sec S+S 10^2/sec Au+Au
Particle Density	10^3/sr in jets	10^3/sr all over. The average multiplicity with a 5% occupancy requires more than 10^5 elements.
Calorimetry	Missing P_T requires a deep calorimeter with no cracks, high accuracy and large dynamic range $\Delta\eta$, $\Delta\phi \approx 0.03 \rightarrow$ number of elements $\approx$ 200,000	Energy flow requires only a shallow coarse calorimeter number of elements $\approx 10^4$.
Leptons	Multi TeV ℓ^+,ℓ^-	Low mass $\ell^+\ell^-$
γ	All	Low P_T γ
Particle Identification	μ,e in TeV range	Low P_T e,μ,$K^\pm$,p,$\bar{p}$
Trigger and Data Acquisition	$\approx 10^8$ trigger rejection needed on line - Large amount of data/event Big offline load	Large amount of data/event Big offline load
Dead Material	Tenths of radiation length allowed	Try to minimize material to minimize conversions, scatters, etc.
Physics	Striking signatures hoped for	Interpretation difficult
Cost	$\approx$ \$250 million for 1	$\approx$ \$55 million for 4

Since the maximum particle density is similar in the two cases, one may ask whether approaches that have been suggested for the SSC environment may have application in the heavy ion collider. For example, V. Radeka[8] has suggested a way to improve the number of independent readouts in a tradition bicycle wheel drift chamber, see Fig. 11. Normally each axial wire is read

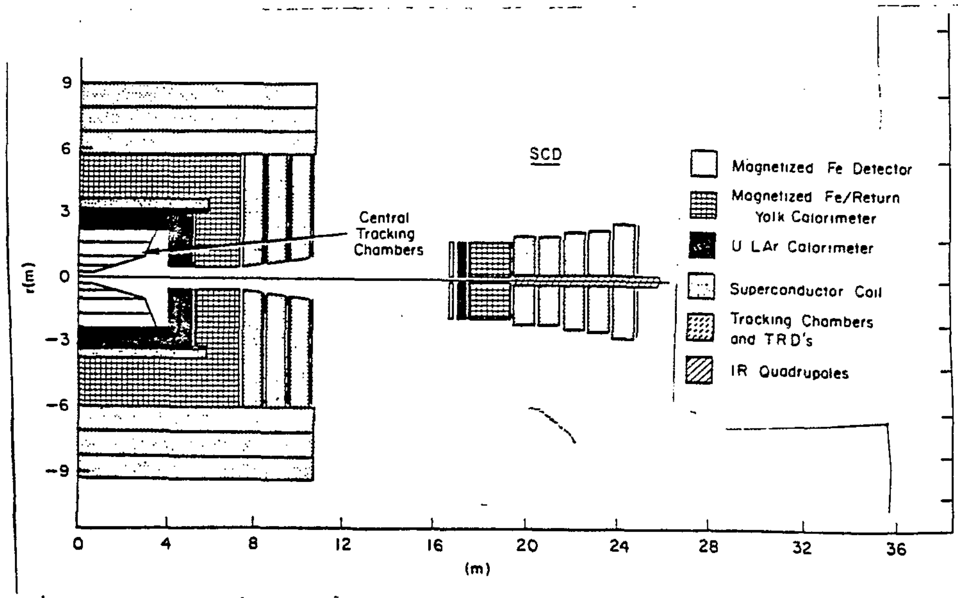

FIGURE 10. Typical detector for the SSC.

out separately perhaps with charge division to measure the coordinate along the wire. With proper electric field and pulse shaping, the electronics can measure multiple hits in time as several tracks arrive at the wire. However, the second coordinate would normally not separate the multiple tracks. With the multiple cathode strips sketched in Fig. 11, the wire is broken up into many separate pieces to improve the effective segmentation. The pads are resistively coupled so that the number of separate amplifiers can be tuned to the optimum. Although this has not been implemented on a large scale, the idea deserves attention.

H. Walenta et al.[9] have proposed the induction drift chamber for a high rate environment like the SSC as well as for good spatial resolution which would help resolve the high track density of heavy ion collisions. This idea is outlined in Fig. 12 together with the readout technique. The spatial accuracy comes from measuring both the anode signal and the difference of the signals from the two nearest potential wires. The first measurements from a prototype chamber have given a position resolution σ = 25 μm with some hope that it can even be improved by a factor of up to 2.5 by using different gases.

Finally an alternative to the successful soda straw tube chambers[10] was recently constructed by R. Bouclier et al.[11] using the idea of a small cell size. It has 128 separate anodes each 80 cm long and each surrounded by a hexagonal array of 6 cathode wires. The position resolution achieved was

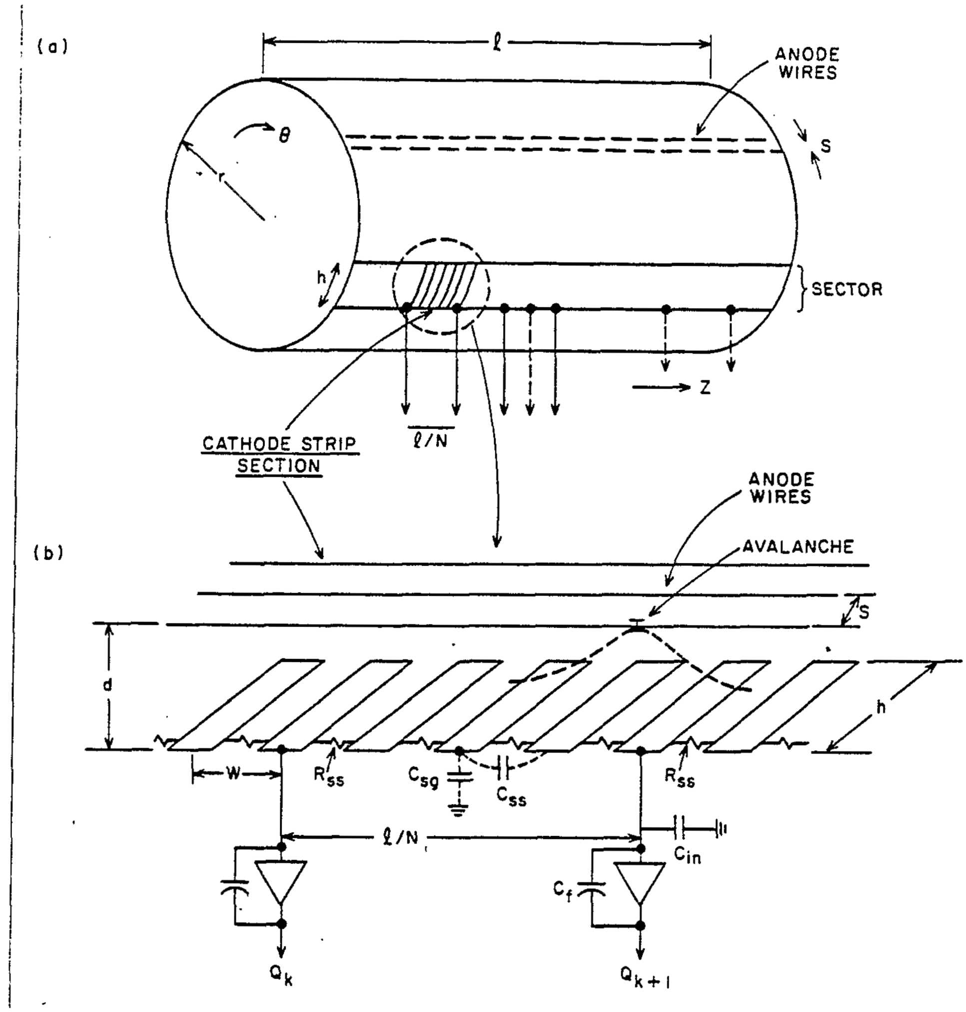

FIGURE 11. Method of improving the number of pixels in a drift chamber by adding cathode pads.

$\sigma < 100\ \mu m$ with a two track resolution of $\approx 500\ \mu m$. The data from a two track event is pictured in Fig. 13.

6. CONCLUSIONS

The study of heavy ion collisions is anxiously awaiting experimental data from higher energy densities, Although existing experiments are not able to meet the challenges that lie ahead, the individual detector elements required seem to be within the state of the art. This is to be contrasted with the situation for the SSC where a significant amount of detector R&D is required.

We gratefully acknowledge stimulating conversations with C. Fabjan and V. Radeka.

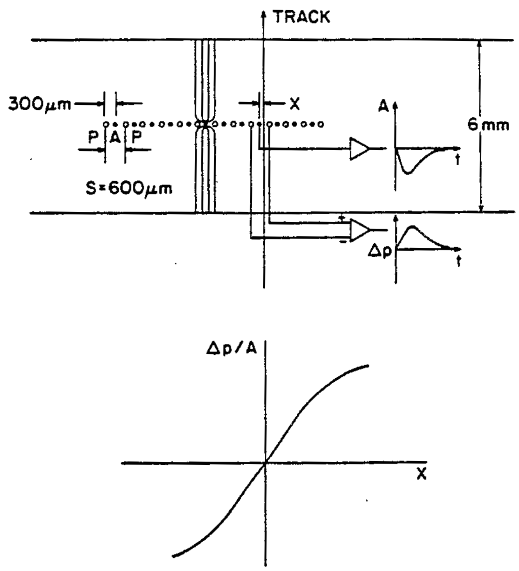

FIGURE 12. Schematic design of the induction chamber. The curve shows the ratio of the difference of the potential wire signal to the anode signal versus position.

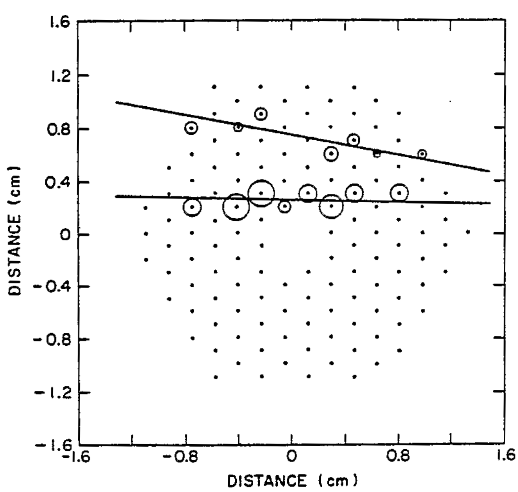

FIGURE 13. A picture of a two track event as seen in the multicell drift chamber. The dots indicate the position of the sense wires, the circles the measured drift times.

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