March 2000

Complete Events at RHIC *

James D. Bjorken
Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

1 Introduction

For the last decade, I have been strongly advocating that detectors for seeing complete events in hadron-hadron collisions should be built. This began with a proposal for an SSC detector (FAD), which evolved into an exploratory small test/experiment (MiniMAX) at the Tevatron collider, and most recently continued with involvement in an initiative, FELIX, for the CERN LHC led by Karsten Eggert and my MiniMAX colleague Cyrus Taylor.

None of these projects really attained critical mass, although MiniMAX did run and has just published results on a search for DCC. Nevertheless, I remain convinced of the importance of such detectors. This is true for RHIC and eRHIC as well. This note explores a scratch conceptual design for such a detector. I weigh it 70% toward second-generation ion-ion physics and 30% toward eRHIC. I will in what follows define complete-event observation to mean detection and momentum measurement of all charged tracks in the event, as well as detection and momentum measurement of all gammas.

The detector to be described is, broadly speaking, a cylindrical structure filling the 14 meters of longitudinal free space. From the nominal beam pipe radius of 4 cm outward to about 10 cm, there is a tracking system based on silicon pixel detectors, over 10^8 pixels in all. From 10 to 25 cm from the beam axis is located the electromagnetic calorimeter system, with granularity in lego variables 0.15 $\times$

*Work supported by Department of Energy contract DE–AC03–76SF00515.

0.15—or better, if possible. Enclosing all this, with outer radius somewhat less than a meter, is a string of warm magnets with bores of 20–30 cm radius; there is also the opportunity for some muon-identification apparatus in the forward/backward directions in this outer region. The design is made as boost-invariant as possible, so that the coverage is largely independent of pseudorapidity. The resolution actually improves with increasing pseudorapidity.

The detector is low on tonnage, but it is high on channels and is of nontrivial cost. However, the cost is small in comparison to the cost of the eRHIC machine or of a major RHIC upgrade.

2 Why Complete Events?

Historically there are at least two great examples. One is the bubble chamber of the 1960s. When it was developed, theorists did not know what to do with the multi-particle final states the new machines were producing, and deemed them hopelessly complicated to consider. The bubble chamber allowed a data-driven exploration of them, revealing the world of hadron resonances (almost completely unanticipated by the theorists), and leading directly to the quark model. The other example is the Mark I detector at SPEAR, which did the same for electron-positron annihilation processes, and led directly to the discovery of charm. All alternatives to that classic barrel design (*e.g.* TASSO at DESY) have by now faded away. One can do no better than look at everything.

The Mark I barrel concept has been so successful that it has become *de rigeur* for hadron-hadron collisions as well, despite the fact that the collision geometry is very different, and that rates are so high that selective triggers are almost always used. I certainly agree that for the very important, highest priority hard processes the barrel design is sound and optimal. But for studies of collision-process structure, central to the RHIC program, it is less than obvious that this is the only way to go.

3 RHIC Physics

Why should one consider in particular such a detector for the second generation ion-ion program? Follow-ups of unusual, interesting first-generation observations generically should include looking at the phenomenon in other regions of phase space, if only for comparison reasons, and correlating what happens in one phase-space region with other regions in the event classes of special interest. I have taken ten oft-discussed signatures and looked at how well this detector would address them—in *all* of phase space:

3.1 J/ψ and Upsilon

Should J/ψ suppression occur in the leading particle regions? If not, where is the boundary in the lego plot? This detector is good, but not optimized for dileptons. Muons may be seen in the outer detector but pion decay backgrounds could be reduced in an optimal device (*e.g.* PHENIX). Electrons are calorimetrically identified and momentum measured rather well, but that may not be enough.

Bottom line: it will take some work to figure out how good the gadget is for this, and it is probably work worth doing.

3.2 HBT

The tracker has splendid two-track separation; a few MeV δp_T looks doable,

Bottom line: probably excellent over all of phase space.

3.3 Strangeness

There is no charged $p/K/\pi$ separation, but K_S should be very well reconstructed. Strange baryons should also be reconstructed very well. Already a silicon pixel system of the straw-man design described below has operated at CERN in a Pb-Pb fixed target environment with hit densities as large as expected in this detector and has successfully reconstructed Ω^-'s.

Bottom line: a good contributor.

3.4 Texture studies

By this is meant fluctuations across phase space in particle production properties such as density, mean p_t, composition, *etc.* as evidence of the presence of a phase transition during the collision process.

Bottom line: superb

3.5 Dilepton continuum; direct gammas

This may be too hard. It needs to be studied out. I just don't know.

3.6 Hydrodynamic flow properties

Longitudinal flow of energy and entropy must occur. As the collision process evolves, the initial-state momentum flows from leading-particle regions inward, and the entropy probably follows suit. As (data-driven) modeling of the kinetics of these collisions becomes more advanced, I would expect that the description of the leading regions will be included, and serve as a discriminator of mechanisms.

Bottom line: for longitudinal (and transverse) flow, the detector should be superb. The only weakness I see is in the lack of particle identification.

3.7 Heavy flavor production

In principle this should be good, because of the intrinsic resolution and pattern-recognition capability of the silicon pixel system. The leading problems seem to be the large radius of the beam pipe (it would be better if it could be reduced to 2.5–3 cm) and the delicate issue of beam-pipe design (flares, windows, RF screens, *etc.*—see Section 4). Lack of kaon identification is another potential drawback.

3.8 Jets

The lack of hadron calorimetry is an obvious disadvantage. On the other hand, it may suffice to define the wimpy jet characteristic of RHIC, no more than 10 GeV p_T

typically, as a cluster of observed high p_t charged particles and gammas (threshold 1 GeV?), and to rely on Monte Carlos and data from the other experiments for calibrations. Multiparticle dynamics of jets, such as jet multiplicity distributions, jet-jet correlation functions, and multijet textures, observed over broad regions of phase space, will for sure be of interest to theorists working from PQCD starting points.

Bottom line: a solid contributor.

3.9 Disoriented Chiral Condensate (DCC)

Observation of clusters of very low p_T charged pions is a good search strategy for DCC or other Bose-condensate related effects, and is available to this detector in all of phase space. The low-p_T capability is optimized if the beam-pipe material is minimized; see the discussion above under heavy flavors. In addition, the very forward phase-space region where the pion velocity equals the ion velocity is of special interest. The rest frame of the ion is also the rest frame of such a pion group. Viewing the collision in this frame is interesting. It corresponds to the resting ion being struck by a projectile with momentum density of 20 TeV/nucleon, *i.e.* by an incredibly intense slab of gluons. The smoking ruins remaining, seen by the pattern of more-or-less isotropic emission of remnant hadrons, can only be a collection of rather soft pions, just because of conservation of $E - p_z$ and of the large volume of the emitting region. So this could be a good place to search for DCC, background free. This phase-space region would be available to this detector.

3.10 Diffraction

All rapidity gaps in an event are seen. Roman pots downstream of the DX magnets would be a welcome enhancement, provided they are not added at the expense of zero-degree calorimetry, which is also of great importance.

Bottom line: the detector is optimal.

4 eRHIC Physics

For eRHIC, I have compiled a similar list of ten desiderata:

4.1 Complete acceptance for the electron

There is electron identification everywhere, arguably good enough to isolate the scattered primary. In particular, the photoproduction limit should be very accessible, since the scattered electron will have less than 10 GeV of energy and be swept out of the beam into detectors. There may be a region of large x and low Q^2 which is not easy, like elastic ep scattering in the Rutherford limit.

4.2 BFKL tests

Jettiness and texture in the proton fragmentation region when x is as small as possible and Q^2 is not too large (1–4 GeV^2) will be doable, and can be compared directly with proton fragments in real photoproduction or pp/pA collisions. Jettiness of photon fragments can of course also be looked at.

4.3 Diffraction

Just as for ion-ion collisions, this detector is essentially optimal.

4.4 Charge correlations

Soft QCD predicts that the lego plot for $\gamma^* p$ collisions should be divided into two sections, the photon fragmentation region of length $log\ Q^2$, and the hadronic plateau of length $log\ x$. The contents of the former should emulate what is seen in hadron final states in e^+e^- collisions, while the contents of the latter should emulate what is seen in real photoproduction or nucleon-hadron collisions. The dividing rapidity is the phase-space location of the quark-parton within the incident (light-cone) hadron which is struck by the electron. Therefore there should be a transport of charge from that point to the leading particle region in the photon/struck parton direction. No one has yet studied this charge-correlation effect, which is a discriminant of models of small-x DIS. My appeals to HERA experimentalists have been answered with the claim that the region of interest is too near the edge of the detector acceptance to allow a good analysis.

4.5 High precision structure function studies

I doubt that the high resolution required for few-percent accuracy measurements of F_2, g_1, *etc.* is attained in this experiment. The detector performance for this can only be determined by very detailed studies.

4.6 Jet production

The comments made above under ion-ion collisions apply.

4.7 Heavy flavor production

Ditto.

4.8 Exclusive vector meson production

This should be easy, and comprehensive.

4.9 Polarized e on polarized p

Here one should concentrate on observables involving final state hadrons, as in the HERMES experiment. For those the detector should be extremely good.

4.10 Parton saturation

Texture changes as a function of Q^2, pseudorapidity, and A seem to me to be a class of signatures appropriate for the search for saturation effects. How do final-state features change as one goes over the maximum in the Caldwell plot?

5 Detector Conceptual Design

We shall begin by considering ion-ion collisions only. The modifications needed to accommodate the eRHIC program will be discussed later. Actually, if the layout given by Peggs *et al.* is adopted, nothing much changes. If the (serious) objection of Sebastian White is heeded, the only modification of the design is at most a polarity reversal of some of the downstream spectrometer magnets.

The ideas of the design are based, not surprisingly, on the Full Acceptance Detector proposal for the SSC, as found in Int. J. Mod. Phys. A, 4189 (1992), hereafter called FAD. For the LHC FELIX detector, these ideas evolved into a rather different design, as found in the FELIX LOI, CERN/LHCC 97-45; LHCC/110 (1997). This document, hereafter called simply FELIX, can be obtained from me or the spokespersons (Karsten.Eggert@cern.ch or Cyrus Taylor, cct@po.cwru.edu), or can be downloaded from the FELIX website (www.cern.ch/FELIX). Very important here will be technical components described therein, some of which will be used as straw-man examples in the conceptual design here. Their use here is not to be construed, one way or the other, as implying any involvement of FELIX participants in the RHIC program. I am solely responsible for the contents of this document.

In what follows, none of the numbers should be taken seriously. I make definite choices only to provide an easy target for criticism and as a starting point for further discussion. Other than an investment of over a decade of general thinking along these lines, I have not done much detailed calculation and have not seriously tried for optimization.

5.1 Tracking system

The basis of the tracking system is a sequence of identical planes of silicon pixel detectors, clustered in stations of 4 planes/station. Planes within a station are separated by 3 cm. A plane is chosen to be 20 cm $\times$ 20 cm square with a 8 cm $\times$ 8 cm hole for the beam pipe. The design is by the CERN RD19 group, as being developed for use in the big LHC detectors. A front charge-collecting plane containing 50 $\mu\times$ 300 μ pixels is bump bonded to the rear plane containing readout electronics. It is described in

FELIX (5.2; pp. 107-109). Only the overall dimensions have been changed.

In the two arms of the detector, hereafter called left and right, there are stations placed (in projective, "boost-invariant" geometry) at 6.4 m, 4.5 m, 3.2 m, 2.3 m, 1.6 m, 1.1 m, 80 cm, 55 cm, 40 cm, 28 cm, and 20 cm. We choose a six-plane (??) central barrel detector of length 40 cm, and outer diameter of 20 cm to complete the coverage.

Each arm therefore has 11 stations, or 44 planes, comprising 1.5 m^2 of silicon per arm. The barrel system adds another 0.9 m^2, giving as grand total 3.9 m^2 of silicon. The pixel count is an impressive 280 million. The cost of the system is quoted in FELIX (5.2.6; p.109) as 400 swiss francs (CHF) per cm^2. This gives 15M CHF total for the tracking system. I do not know how to convert this European cost estimate into the US system, nor do I know what has happened to either the design or the costs of the LHC system since the FELIX LOI was written. I do believe, however, that I have been generous in the size of the system, and that careful optimization is likely to reduce, not increase, the number of planes.

It also should be noted that the cost scales with the square of the transverse size of the system, so that reducing beam pipe radius would have a lot of leverage in bringing down the cost.

The planes have been clustered into stations with an eye to enlarging the beam pipe in the sectors between stations to a diameter of 40 cm, thereby removing material away from the neighborhood of the beam axis (background reduction) and reducing the amount of material seen by real tracks (resolution). Four planes per station were chosen to allow local reconstruction of track segments, with a negligible number of fake segments remaining. It is easy to make a scratch estimate of the critical hit density beyond which this is not possible. My result is 4 hits/cm^2 (see the next paragraph if you are curious about the details). If these are dominated by hits from signal particles as opposed to background, the critical $dN/d\eta$ is 1500. This is about the upper limit of what is expected even for Au-Au collisions. Of course, simulation exercises are a necessity before drawing any conclusions at all.

(Details of the scratch estimate: Let N = 2 $\times$ 10^6 be the number of pixels per plane and n the number of hits per plane. The number of "roads" for candidate tracks, defined by a hit in the front plane and another in the rear plane, is n^2. The probability that the intermediate-plane pixels within the "road" are hit is $(n/N)^2$. Requiring that the number of fake tracks per station per event be no larger than order unity gives $n^4 < N^2$. This gives $n = 1\times\ 10^3$, leading to the density quoted above. Note that we have made no angle cuts on the roads, and that we could tolerate a considerably larger number of fakes per station per event. So this estimate appears to me to be conservative.)

5.2 Calorimetry

A series of annular calorimeters are placed at distances of 6.6 m, 3.3 m, 1.7 m, 90 cm, 60 cm, and 30 cm. Each is 40 cm $\times$ 40 cm, with an aperture of 20 cm $\times$ 20 cm for the tracking system. In addition there is a barrel calorimeter of inner radius 15 cm and length 60 cm to cover the central region. The upstream/downstream endwall calorimeters at 6.6 m should of course have a central aperture of beam-pipe dimensions, 8 cm $\times$ 8 cm. These calorimeters are electromagnetic only; hadron calorimetry with such extreme miniaturization looks very unpromising.

This multistage layout is "edgy", and many tend to dislike this approach, preferring as few walls as possible. However, if we take a 5 mm band around the inner edge as the region of degraded performance, this amounts to 7% of the lego area that is affected. This should be compared with the generic problem of cracks between individual modules on a single wall. If individual modules are 4 cm $\times$ 4 cm, and the width of the crack region is taken to be 1 mm, this amounts to a 5% degradation of the phase space, quite comparable.

I leave open the choice of calorimeter type, if only because of total lack of expertise. The FELIX LOI does have a variety of types proposed. One which looks appropriate for all but the central barrel region, suggested by the IHEP group under V. Polyakov, is the "BAYAN" design (FELIX, 6.2, pp. 128-129), that is used in the near-beam portion of the detector. The cell size is 1.7 cm $\times$ 1.7 cm and uses a tungsten-scintillating fiber sandwich aligned at a small angle to the beam axis. The energy resolution is claimed to be $10\%/\sqrt{E}$. The typical $\delta\eta \times \delta\phi$ is about 0.15×0.15, with no crack problem.

In the central barrel region and near central walls at 30 cm and 60 cm, where space is tight, a design based on a sandwich of tungsten and silicon pad detectors might be considered. These have been used for beam-beam counters at the SLC.

The total area of one calorimeter arm is 0.72 m^2. The barrel area is about 0.56 m^2, leading to a grand total of about 2 m^2 of calorimetry. The number of pixels is about 6700.

Again, these options are only meant as suggestions for initiation of a discussion; nothing very substantive has been explored.

5.3 Magnets

Upon looking at options such as the quadrupoles featured in the FAD EOI or the solenoid in the FELIX LOI, it appears more favorable to simply use a string of dipole magnets from one end to the other, including the central barrel region, for reasons given below. There should be spaces between magnets for access to calorimeters and tracking elements. But for the purposes here, it is good enough to simply assume an average vertical magnetic field of 1 T throughout the fiducial region of the detector. The aperture of the magnets in this string would be typically 40–50 cm pole-tip to pole-tip; a square aperture is acceptable. In between the individual magnets could go muon tracking stations, but that option will not be considered in detail.

The reason for dipoles is that, with such a compact tracking system, one needs as much bending power as possible; the more magnetic field the better. My preferred figure of merit for a tracking system is the sagitta s of the measured track segment versus its momentum p and transverse momentum p_t. For the 1 T uniform transverse field, and for tracks which bend very little (usually the case), this can be written as

$$s = Bpx^2/8p_t^2$$

where x is the transverse coordinate interval over which the track is measured. I take this as 10 cm, not the 6 cm actively sampled. The collision point should be well determined statistically from all of the measured tracks, and its value can be used in the fit of any given track (with impact-parameter corrections for tracks from charm and strange particle decays).

Thus for reference tracks with $p_t = 1$ GeV we have simply

$$s = s_0/\theta$$

with numerically

$$s_0 = 400\mu \ .$$

This is the sagitta for a 90 degree particle emitted at right angles to the B field. A stronger-than average field in the central barrel region improves this further.

Far downstream the formula will not apply. The amount of deflection in the 6 meter free space is what matters. For example, 100 GeV proton evaporation fragments are deflected by 5.4 cm from the beam axis and can be captured.

For the eRHIC option, this choice of magnetic field would give a deflection of the electron of the right magnitude to clear the DX magnet. One would have to arrange that the polarities of the magnets for which the electron traverses "through the yoke" (transverse coordinate larger than 20 cm) are reversed so that the electron deflection is of the right sign. These magnets would be a little exotic in their design, but are surely buildable. And the effect on the spectrometer optics and beampipe design will need to be assessed.

The effect of the string of dipoles on the circulating protons, in either the RHIC or eRHIC options is at the 1–2 cm magnitude of displacements. I expect that upstream tunings of DX and trim magnets together with careful design choices will make this not a big problem.

It is my intention that all tracks pass through at least two tracking stations; this would give a generous minimum of eight samples per track. This is not quite the case in the layout that has been described, and parameters would need to be tuned on the basis of detailed tracking studies. However, to do this seems very premature; some consensus on the basic concepts of the detector is needed before time is invested on that problem.

5.4 Beampipe

A straight, 8 cm diameter beampipe going through the entire free space would lead to major degradation of the accuracy of the tracking system, and even to a significant loss of primary particles via interaction with the beampipe. Ideally one may consider enlarging the beampipe to a diameter of 40 cm, throughout almost all the fiducial region, with only some short sections of smaller radius in the neighborhood of calorimeter walls or tracking stations. Were the main part of the beampipe of such a large radius, one might also consider each tracking station to be comprised of two or four Roman-pot insertions into the tank. Conical sections of pipe are also a popular and natural concept. No matter what the approach, there are many problems to address. A summary of these, as well as a beam-pipe design, can be found in the FELIX LOI (5.6; pp. 117-122).

For this scratch design, I do choose to keep the beampipe as large as possible (40 cm diameter), but to keep the tracking system exterior to the pipe, with the transitions from the small 8 cm diameter constrictions to the 40 cm tank abrupt, with thin windows in front of and behind the tracking systems. A major reason for this is concern over the cooling of the tracking planes, which give off about 400 watts of power apiece. It would be nice to provide sampling of the tracks nearer the beam axis with a few small single planes in Roman pots (for the heavy flavor application in particular), but this must await a more thorough look at everything.

The effect of 10 meters of large diameter vacuum tank on the circulating beams is sure to be of concern to the accelerator physicists. An interior "pipe" of nominal 8 cm diameter to transport the charge induced by the circulating beam down the detector will probably be needed, and of course it should contain a minimum of material. One solution might be to make the "pipe" out of chicken-wire (figuratively speaking); if this provides enough conduction of charge, it looks to be an adequately small amount of material from the point of view of the tracking performance.

While the beampipe design is a major challenge for this detector concept, there is working experience from which to draw. The HERA-B vertex detector is in most ways more challenging than what is suggested here, containing a complex silicon-strip system inserted into a 1.2 m diameter vacuum tank 2 meters long. At MINIMAX, we installed a large diameter tank in the TeVatron collider, 2 m of which was about 30 cm diameter and 1.5 m of which was 60 cm in diameter. Detailed measurements of the resonant modes were made, and dampers were inserted into the tank. No other RF shielding was provided; no effect on the beam (or power drawn from the beam) was observed.

5.5 Backgrounds

We have not addressed the survivability of the detector to backgrounds. The calorimeter should be reasonably robust, although the showers from individual gammas will overlap in the case of Au-Au collisions. For counts of photons, sampling in preradiators may mitigate this problem somewhat.

The tracking system is essentially inside a long hollow cylinder of iron (the magnet yokes) of radius R = 20–30 cm. If we idealize this problem, we may make a simple estimate of the background a tracking plane will see. This is because, for a flat pseudorapidity distribution of produced particles, the amount of energy per unit length impinging upon the iron pipe is a constant, given by

$$\frac{dE}{dz} = \frac{\langle p_T \rangle}{R} \cdot \frac{dN}{d\eta} \ .$$

The most dangerous reradiation is soft electromagnetic particles. Idealizing these as 20 MeV electrons or positrons emitted at 45 degrees, a detector plane will see roughly a number N given by

$$N = \frac{2Rf}{(20 \text{ MeV})} \cdot \frac{dE}{dz}$$

where f is the fraction of energy reradiated in electrons and positrons. The value of f can hardly be more than 10%, but cannot be assumed to be less than 1%. Putting in numbers gives an upper limit on hit density of typically a few per cm^2, below the limiting density that we estimated in Section 1 that the tracking planes can handle.

The real situation must be studied via simulation. The arguments above do not claim success, only that defeat is not obvious. There are also mitigating effects. The primary gammas are designed to be efficiently absorbed by calorimeters. The soft electrons and positrons will be trapped in the magnetic fields of the dipoles, so careful placement of the tracking planes should mitigate the amount of background from that source as well.

There will be lots of neutrons emitted from the iron. Here the question is radiation damage to the silicon. About it I have nothing to offer, although it is hard to believe that the RHIC problem is worse than what is faced at the LHC.

6 Costs and Staging

The cost of the silicon tracking system, as estimated by FELIX, lies in the 10-20 million dollar range, if renormalization from CERN accounting to US accounting is not a big factor. The cost of the calorimeter system, taken from the FELIX estimates, could double this. In comparison to this the cost of magnets and the beampipe system should be small. The total detector is, not surprisingly, not to be thought of as inexpensive. However, its open structure makes staging very viable. A first stage could be the magnets and beampipe, plus enough tracking and calorimetry for the far forward region in one arm, and more incomplete coverage, PHOBOS style, for the remainder. The cost of such a Stage I might be the total cost divided by a factor 3 or so. Growth would then proceed toward the center, as well as within the center itself, with the second arm, in the electron direction, as the final stage. Nevertheless, even the Stage I is serious, and would require a sizeable, dedicated group with serious support.

7 What next?

This detector could be a new, independent enterprise put into a new collision region, in particular the one at 12 o'clock. Or it might be synthesized into an existing experimental area; the most obvious candidate is PHOBOS. I of course hope this document will be considered and criticized by that collaboration. But the timing is not very good for attracting serious attention from that very busy group.

No matter what, I hope there are at least a few readers of this document that feel, as I do, that it is important to advance these ideas at BNL. More important than this scratch conceptual design is my conviction that complete events deserve measurement and that it is practical at RHIC to do so. There needs to be enough of a critical mass to create a working group to harden (or kill) these ideas, and to start to draw up a prioritized list of issues to address. The eRHIC activity provides a good catalyst. And sooner or later the question of follow-ups to the initial RHIC program will be entertained by the laboratory, and it would be good to have some real homework in place at the time that happens. And while nothing is likely to happen right away, the cost of initial conceptual-design work is only the time expended. And I, here wearing the hat of an experimentalist, find this kind of work a rare opportunity in these days of committee-designed detectors; simply a lot of fun.

If you are interested in the detector ideas and/or in the complete-event physics, please contact me at bjorken@slac.stanford.edu.