Luminosity Limits for the STAR Detector System

STAR Note 125
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1. Introduction

The goal of this study is to arrive at values for the instantaneous luminosity of the RHIC accelerator beyond which the STAR collaboration does not wish to run. This maximum instantaneous luminosity value (L_{max}) will be passed on to the accelerator staff at RHIC to guide them in designing possible luminosity versus time profiles for RHIC operation.

For proton on proton running at RHIC the luminosity versus time profile is essentially flat. The L_{max} value for pp is therefore the luminosity at which all the pp data will be taken.

At the second RHIC luminosity meeting (May 12, 1993 BNL), there were luminosity versus time profiles presented for Au on Au running which had instantaneous luminosities up to ten times the baseline luminosity for Au on Au ($\equiv L_0 = 2 \times 10^{26}$ cm^{-2} sec^{-1}). For these running scenarios with high initial luminosities, the instantaneous luminosity dropped quickly with time, as much as a factor of two within the first half hour. The message from the accelerator people was that there are many parameters which can be varied and they would like some input from the approved RHIC experiments, hence this study.

2. Considerations

1.) As interaction rates approach 10^7/sec the events will start to overlap in the trigger detectors gate times. This is only a consideration for the pp running.

2.) For both pp and Au on Au running one has to worry about the pileup of events in the TPC. These pileup events are those which come within 40 μsec before or after the trigger event.

3.) As the luminosity increases, the effect of the space charge in the TPC increases. One must try to quantify at what luminosity this becomes a problem.

4.) At baseline luminosities, the number of charged tracks entering the TPC per second, and hence the space charge, is ~ 3.5 times larger for pp than for Au on Au.

5.) While most of the calculations presented here were done assuming that P-10 (90% Argon, 10% Methane) will be the counting gas used in the TPC**,** STAR may decide to run with a "slower" gas such as 50% Helium and 50% Ethane.

3. Time scales and input parameters

1.) The baseline bunch crossing times are every 220 nsec. There has been some discussion of a future upgrade of the RHIC running which would have bunch crossings every 110 nsec.

2.) ADC gate times for the trigger detectors are ≈ 100 nsec.

3.) Drift time in the TPC is about:

200 cm * 5 cm/μsec ≈ 40 sec. for P-10 gas (Argon Methane 90 - 10%).

4.) L_0 for Au on Au is 2 x 10^{26} cm^{-2} sec^{-1}.

5.) L_0 for p on p is 1.4 x 10^{31} cm^{-2} sec^{-1}.

6.) Number of bunch crossings per second at a given interaction point is:

$$\#\text{crossings/sec}=\frac{1\text{ crossing}}{220\text{ nsec.}} = 4.546\times 10^6\text{ crossings/sec.}$$

7.) A given bunch crossing has a duration in time of about 5 nsec.

8.) Interaction rate for Au on Au:

$$\text{Rate} = L_0 * \sigma = L_0 * \pi r_0^2\ (193^{.33} + 197^{.33})^2$$

$$= (2\times 10^{26}\text{ cm}^{-2}\text{ sec}^{-1}) * (6.13\times 10^{-24}\text{ cm}^2) = 1225\text{ Int./sec}$$

9.) Interaction rate for pp:

$$\text{Rate} = L_0 * \sigma = (1.4\times 10^{31}\text{ cm}^{-2}\text{ sec}^{-1})*(40\times 10^{-27}\text{ cm}^2)$$

$$= 5.60\times 10^{5}\text{ Int/sec.}$$

10.) The baseline data acquisition and taping rate for events with the TPC is ~ 1 evt/sec for Au on Au and about 30 evts/sec for pp.

4. Proton on Proton running

As calculated above, the interaction rate for pp running, at design luminosity, is ~5.6 x 10^6 Int./sec. Dividing this rate by the number of bunch crossings per second, also calculated above, one finds:

$$\frac{5.60\times 10^6\text{ Int / sec.}}{4.546\times 10^6\text{ crossing/ sec}} = 0.123\text{ Int./crossing}$$

The number of interactions per crossing scales linearly with luminosity, so at two times L_0 the number of interactions per second is ~ 0.25, etc. This value for the number of pp interactions per second can be used to calculate the probabilities to get 1, 2, 3, etc., interactions in a given bunch crossing.

For any given crossing, if one has a trigger, the calculation above indicates that there is a 12.3% probability to get another pp interaction in the same crossing. Depending on where along the beam axis the second interaction takes place, and when it takes place in time (~5 nsec. window), the trigger will have some ability to identify and veto these multiple interactions.

The rate per second of bunch crossings with n pp interactions (using Poisson statistics) is:

$$\frac{.12^n * e^{-0.12}}{n!} * 4.546\times 10^6\text{ sec}^{-1}$$

This gives rates of 0.484 MHz for crossings with single pp interactions, 29 kHz for crossings with two pp interactions, 1. 16 kHz for those with three interactions, and about 35 Hz for those with four pp interactions per bunch crossing. Fig. 1 shows the number of double, triple, and quadruple interactions in a bunch crossing per second versus luminosity.

Recalling that the baseline taping rate for pp is about 30 evt/sec, one can see that at baseline luminosity, the trigger will have to be quite efficient at discriminating against these crossings with multiple pp interactions. N.B. Triggers based on multiplicity requirements will tend to bias one toward bunch crossings with multiple interactions.

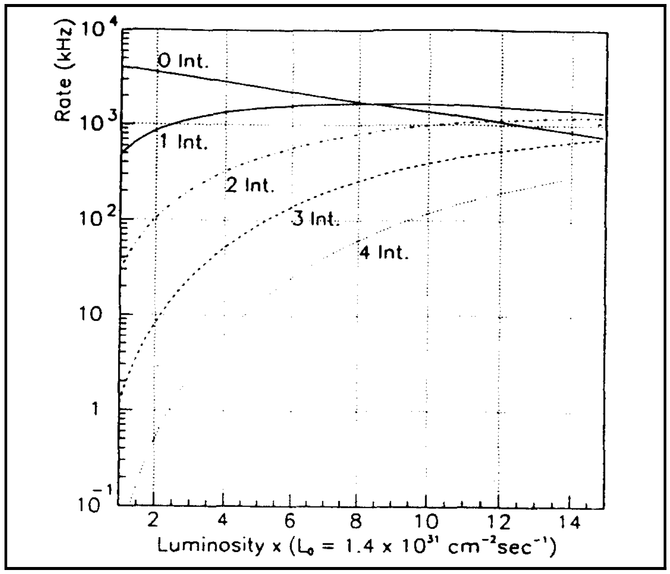

Fig. 1 Rates per second to get bunch crossings with 0,1,2,3 and 4 pp interactions. Bunch crossing time of 220 sec used in calculation.

Due to the relatively long drift time for electrons in the TPC, ≈ 40 μsec. (if P-10 gas), when the TPC is read out it contains tracks from interactions that take place from 40 μsec before to 40 μsec after the event which triggered the detector. Thus, on average, the number of pp events within the TPC for any given event for which one opens the gating grid and reads out the TPC is:

(5.60×10^5 Int/sec) * (80 μsec.) = 44.8 ≈ 45 events for L = L_0. Assuming that the events come uniformly in time this gives, on average, about:

$\frac{80\ \mu\text{sec.}}{45\ \text{evts}} * (5\ cm/\mu\text{sec.}) \approx 8.9\ cm$ along the drift direction (z) between the various pp interactions. If one tracks these events and projects all found track segments back to the z axis, the various "apparent" vertices will be, on average, separated by about 4.5 cm (200 cm/45 evts).

The ability to reconstruct events with multiple interactions piled up in the TPC was investigated via computer simulation. The study (STAR CDR sect.# 4.C.3.i) concluded that STAR will be able to assign tracks with P_t greater than 150 MeV/c to the correct vertices quite well at L_0, using just the tracking information and the reconstructed vertices.

The study was extended to investigate the possibilities of running at higher luminosities (STAR Note #80). In this study a luminosity of 2.0×10^{32} cm^{-2} sec^{-1} was used. At this luminosity the interaction rate is ~9 MHz. If one assumes a bunch crossing rate of one every 110 nsec (twice the baseline bunch crossing rate), this leads to an average of one pp interaction per bunch crossing. Using the drift time in the TPC of ~5 cm / sec one finds that the vertices from events that occur at the center of the event diamond, in consecutive crossings, are separated by only ~5 mm. If one includes the distribution of vertices in the crossing diamond (rms ~7.5 cm, which is equivalent to about 1500 nsec of drift in the TPC) one finds that there could be about 14 vertices within the diamond for any given triggered event. The resulting distribution of vertices along the z axis was thus found to be essentially uniformly distributed and smooth, with no separation between vertices. One thus concludes that using tracking alone, one could not tell which tracks were in the triggered pp event.

What the study investigated was the possibility of using the Time-of-Flight (TOF) information from the Central Trigger Barrel (CTB) to select the tracks associated with a given bunch crossing. Note that this does not place a stringent requirement on the timing resolution of the trigger barrel, as all one is after is which slats are hit in a given bunch crossing. The bunch crossings are separated in time by 110 nsec, and the CTB signals are digitized every bunch crossing. The study concluded that one could identify which tracks were associated with a given bunch crossing on which one triggers, provided that the tracks reach the CTB. This places a minimum P_t value of ~150 MeV/c and a pseudorapidity cut of $|\eta| \leq 1.0$. Once one has identified the tracks which satisfy the criteria above, one can reconstruct the. primary vertices for the events within the triggered bunch crossing. Further study to determine how well one can do in associating the tracks from these events which did not hit the CTB is still to be done.

As seen above, and ignoring space charge effects for the moment, the large interaction rate for pp at L_0 leads to two complications for STAR.

First is the high rate of bunch crossings with multiple interactions. This presents a formidable challenge for the STAR trigger group. Depending on what information one is trying to extract from the pp running, one may have to select pp events which come from crossings with only one pp interaction (484 kHz), and discriminate against the 29 kHz of double, 1.2 kHz of triple, and 35 Hz of quadruple interactions at L_0. Recall that out of the 5.60 x 10^6 int./sec, STAR can write to tape ~ 30 evts./sec.

Second is the piling up of events in the TPC. At L_0 one gets about 45 pp events in the TPC for every pp event for which one reads out the data from the TPC. The average separation between the pp interactions at this luminosity is ~9 cm along the drift direction which leads to an average separation of about 4.5 cm between apparent vertices along the z axis. If one hopes to use only the tracking information to identify which pp interaction triggered the detector, and do a good job associating all the tracks which belong to the interaction, this is probably about as close as one wants to allow the vertices to get. As was discussed above, if one uses the CTB to help in finding the events which trigger the detector one can go higher in luminosity. The usefulness of this method depends on how well one can do in finding all of the tracks associated with the interactions in the triggered bunch crossing which do not strike the CTB, and the importance of these tracks for the physics analysis one is investigating.

5. Gold on Gold running

The lower interaction rates for Au on Au at L_0 as compared to the pp rates discussed above, will allow STAR to run at greater than design luminosity. As will be shown in what follows, STAR can not only run at luminosities higher than L_0, one can do so with a criteria that one only accepts "clean" TPC events. Clean, as used here, means that there are no Au Au interactions for 40 μsec. before or after the event which one accepts for writing to tape.

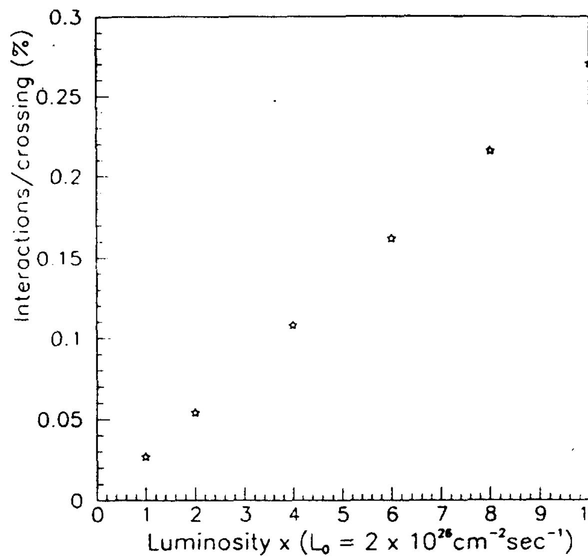

Fig. 2. The average probability to get a Au on Au interaction in a bunch crossing, versus luminosity.

Using the Au on Au interaction rate, and the bunch crossing rate, given in section 3, one calculates the probability per bunch crossing of getting a Au Au interaction:

$$\frac{1225 \text{ Int./sec}}{4.546 \times 10^6 \text{ crossing / sec}} = 2.695 \times 10^{-4} \text{ Int./crossing}$$

Thus, at L_0 for any given bunch crossing, if one triggers on a Au on Au interaction the probability of getting another Au Au interaction in the same crossing is 0.027%. For reference, the average interaction probability per bunch crossing is plotted versus multiples of L_0 in Fig. 2.

As was done for the case of pp, one can use this probability to calculate the rate for 1, 2, etc. Au Au interactions to occur in the same bunch crossing. The rate per second of bunch crossings with two Au Au interactions of any kind at design luminosity L_0 is (using Poisson statistics):

$$(4.546 \text{ x } 10^6 \text{ crossings/sec}) * (2.7 \text{ x } 10^{-4})^2 * e^{-2.7 \text{ x } 10^{-4}})/2! = 0.\ 16 \text{ Hz.}$$

The rate per second of bunch crossings with 1, 2, and 3 Au Au interactions is plotted versus multiples of L_0 in Fig. 3. Recalling that the baseline event rate for STAR for Au on Au is 1 event per second, one sees that the trigger will have to discriminate against a double interaction/bunch rate of only 10 Hz at eight times L_0. This appears to be quite feasible.

With the low interaction rates for a rather large range in Au on Au luminosities, and the low number of events/sec which STAR can record, one can impose the requirement that only "clean" TPC events are 'written to tape. As defined earlier, "clean" denotes those events which are neither preceded or followed by another Au on Au interaction within the drift time of the TPC.

To illustrate this point, consider the following. If one is running Au on Au at the design luminosity of L_0 the number of interactions in the TPC drift time is:

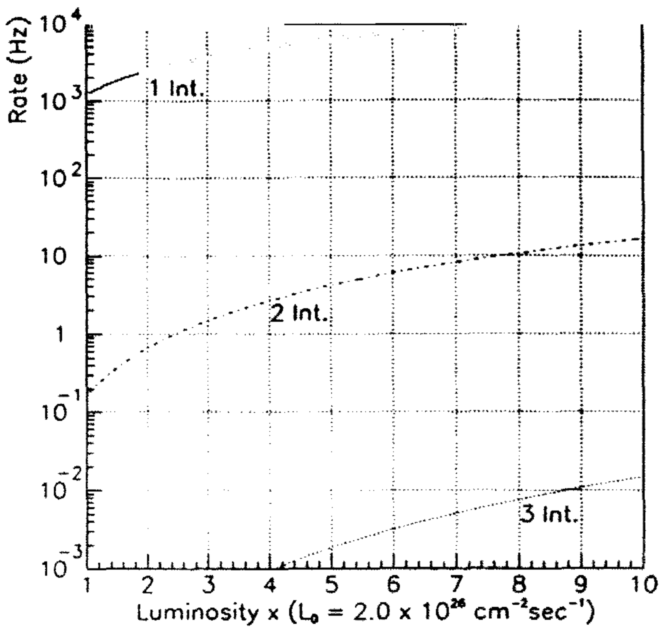

Fig. 3. Rate per second of bunch crossings with l, 2, and 3 Au on Au interactions.

1225 Int./sec * 40 μs = 0.049 Int./ TPC drift time.

The TPC records events (or parts of events) which occur one drift time before or after the event which is triggered on. Doubling the number calculated above, one finds that by imposing this requirement one rejects ~ 10 % of the triggered events.

The percentage of triggers vetoed with this requirement imposed increases with luminosity, and is plotted in Fig. 4 (using Poisson statistics). Note, this criteria of only taping clean events is quite easy to implement in the trigger logic.

If the recording rate for STAR is one event per second for Au on Au, and one always wants to record events at this maximum rate, the minimum cross section which one wants for the trigger can be calculated as follows:

Rate = L * σ

$$\Rightarrow \quad \sigma_{\min} = \frac{1 \text{ evt/sec}}{L} \qquad \text{Eqn. 1}$$

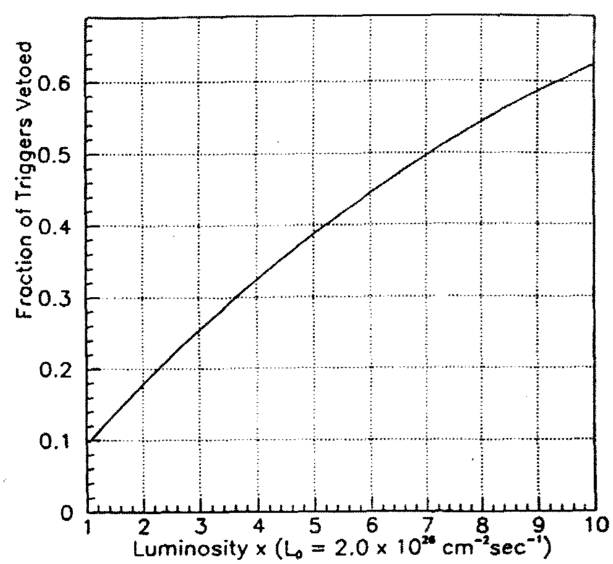

Fig. 4. Percentage of triggers vetoed, on average, versus luminosity if one takes only "clean" events.

This minimum trigger cross section, which in practice would probably be the sum of a prescaled factor of "central" or minimum bias events and whatever other trigger conditions one has, is plotted (filled stars) versus luminosity in Fig. 5.

One can also see how this minimum trigger cross section is affected if one imposes the criterion that the events written to tape are "clean". The resulting formula is:
σmin (mb) =

$$\frac{\left(1.0 \times 10^{27}\right)/(1.0 - \mathrm{Frac})}{L}$$

Eqn. 2

where:

L = Luminosity (cm^{-2} sec^{-1})

Frac = Fraction of triggers vetoed (see Fig. 4).

This minimum cross section for the trigger, including the criteria of taping only clean events, is also plotted in Fig. 5 (open circles). Notice how little the minimum trigger cross section rises when the criteria of clean events is imposed. In practice one would run with some sort of priority override of this clean TPC event criteria for rare events. At the higher luminosities one could change the criteria for clean to be triggered events with no preceding or trailing events within a smaller time, say ± 20 μs if one wanted to reduce $\sigma_{\min}$. The tracks from these events should be easy to identify and eliminate. What this exercise illustrates is that pileup of events in the TPC is not a problem, even for luminosities up to ten times L_0.

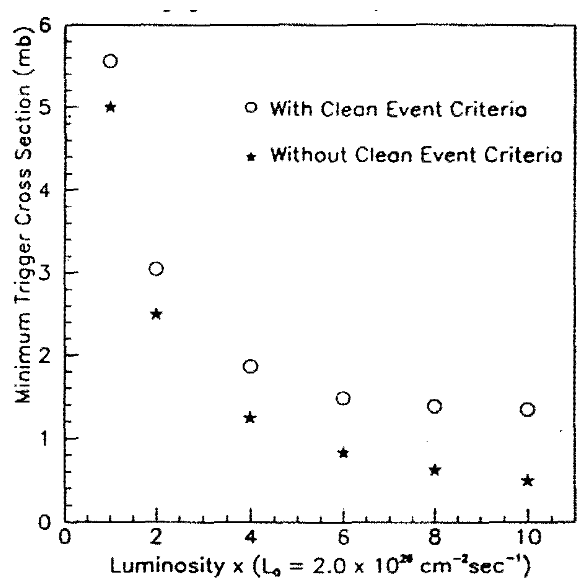

Fig. 5. Minimum cross section for the trigger vs luminosity

In summary, ignoring space charge effects for the moment, STAR can run up to ten times L_0 and beyond for Au on Au, without suffering from high rates of multiple interactions per bunch crossing (only ~20 per second at 10^*L_0), and without suffering from events piling up in the live time of the TPC (± 80 μs for P-10 gas).

Space Charge

One of the concerns of the STAR group has been that as one increases the luminosity, the space charge in the TPC, due to the accumulation of the relatively slow moving (~ 1000 times slower than electrons) positive ions, would distort the individual space points in the TPC, and have an unacceptable effect on the extracted momentum for the tracks. An investigation into the size of this effect was done by Gulshan Rai. He found that the magnitude of the displacement increased linearly with the luminosity, and that the effect on the momentum resolution, averaged over momentum, became equal to that due to Multiple Coulomb Scattering (MCS) at about 18 times L_0, *on average,* for Au on Au. What was averaged over in his study is the momentum distribution of particles from Au on Au events at $\sqrt{s}$ = 200 GeV. The conclusion of the study was that space charge would not pose a problem for most of the panicles which STAR would have to deal with. At baseline luminosities I calculate that the space charge for pp is about 3.5 times larger than for Au on Au. Thus one expects that for pp the effect of space charge on the momentum resolution becomes equal to that due to space charge at about 5 - 6 times L_0.

As the effect of MCS on the momentum resolution decreases as the momentum increases, and the curvature of the tracks in the B field also decreases, one might expect that the importance of the space charge induced distortions becomes significant at lower luminosities for the high momentum tracks. Fig. 6 (fig. 4c-26 in STAR CDR) shows the magnitude of the displacement of the space points, in both the radial and azimuthal directions, as a function of the space points location in the TPC. For space points which are at a radius of greater than 75 cm, the maximum value for these displacements is less than 20 μm for all Z coordinate locations in the TPC, for a luminosity equal to L_0. Recall that these distortions scale linearly with the luminosity, i.e. at $L = L_0$ the azimuthal distortion at z =0 cm and r =195 cm (see Fig.6) is about 1 00 m.

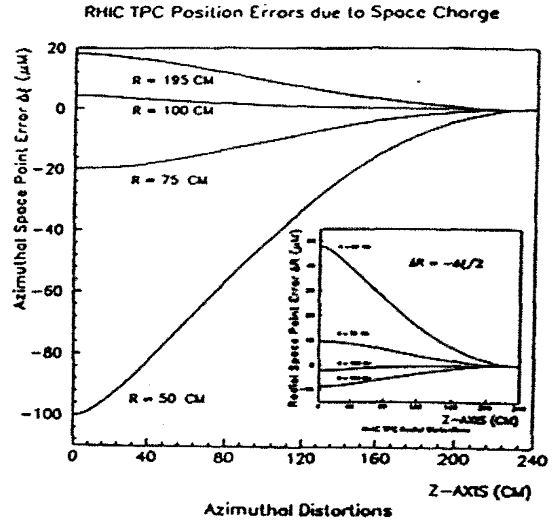

Fig. 6. Results of an electrostatic calculation showing the displacements errors due to space charge along the azimuthal and radial (inset) directions as a function of distance in z.

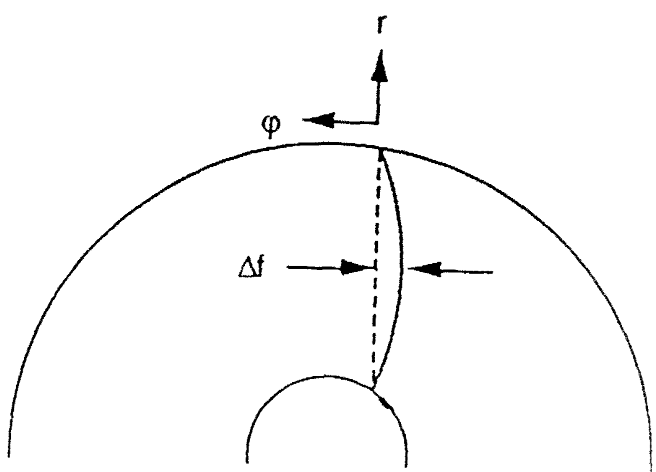

Fig. 7. A projection of a track onto the endcap of the TPC. f is the sagitta for the track.

Due to the complex manner in which the space points are displaced (negative azimuthal displacements for r < 100, positive for r > 100, displacements decrease with z, etc.) there is not a straight forward way to calculate the magnitude of the space charge distortions on the momentum resolution of the higher momentum tracks. What will be necessary is to incorporate these distortions in the Fast Simulator code for the TPC (FST). These modifications are planned, but at present are unavailable.

I've done a crude calculation of the effect on the .momentum resolution, using formulas from STAR Note #14 (a study of E and B field precision constraints in the TPC). Fig. 7 is reproduced from this report and illustrates a track in the TPC. One gets the radius of curvature for the track by measuring the sagitta (f):

$$f = \rho^* \{1 - \cos(S/(2\rho))\} \qquad \text{Eqn. 3}$$

where:

s = arc length of circle segment (m).
ρ = radius of curvature (m).

$$= \frac{P}{e^* H} \quad \text{(e and H defined below)}$$

When $\rho >> s$, $f \equiv s^2/(8\rho)$. The propagation of uncertainties gives:

$$\left|\frac{\partial P}{P}\right| = \left|\frac{\partial P}{\rho}\right| = \left|\frac{\partial f}{f}\right| \left[\frac{8P}{eHs^2}\right] \partial f \qquad \text{Eqn. 4}$$

where:

P = magnitude of the momentum (GeV/c)
e = constant x elementary charge = 0.2998 GeV/c T^{-1} m^{-1}
H = magnetic field strength (Tesla)

Plugging in the appropriate values for STAR one gets:

$$\left|\frac{\partial P}{P}\right| = 13.34 * P * \partial f \qquad \text{Eqn. 5}$$

For reference, table 1 lists the radius of curvature and sagitta for various P_t tracks in STAR. For the high P_t tracks which I investigate here, I assume that one gets a point or points on the track at small radii using either the primary vertex for the interaction (determined very well for large multiplicity events) or space points from the Silicon Vertex Tracker (SVT). Thus the sagittas in table 1 are those from the center of STAR to the outer radius of the TPC (2 m).

Table 1

P_t (GeV/c)	(m)	f (mm)
2	13.34	37.55
5	33.36	14.99
10	66.71	7.50
15	100.1	5.00
30	200.1	2.50

I approximated the magnitude of the distortion to the momentum resolution as follows. Imagine the high P_t tracks to be straight lines. From table 1 one sees that a ten GeV/c track only has a sagitta of 7.5 mm over a distance of 2 m, so this straight line approximation is fairly good. Now if one end of this line is held fixed at the origin and the other end is moved say 100µm, the displacement at a point half way along the line will be half of the displacement at the end, i.e. 50µm in this example. I use this displacement at the midpoint of the line as an approximation to the error in the sagitta. Using the calculated sagitta, and this approximated error to the sagitta, one can then calculate the momentum resolution using Eqn. 4 ($|\partial P/P)| = (\partial f,f)|$) or Eqn. 5.

From Fig. 6, the maximum azimuthal displacement at the outer radius of the TPC is 20µm (at z=0) for $L = L_0$. As noted earlier the magnitude of this displacement scales linearly with the luminosity, thus the maximum displacement at the end of the straight line would be 200µm at 10 * L_0. The error in the sagitta can thus be given as a function of the ratio of the luminosity to L_0:

$$\partial f = \frac{L}{L_0} * 20\mu m$$

and eqn. 5 can be written as:

$$\left[\frac{\partial P}{P}\right] = 13.34 * P * \left\{\frac{L}{L_0} * 20\ \mu m\right\} \qquad \text{Eqn. 6}$$

Fig. 8 shows the expected momentum resolution of STAR, both with and without the inclusion of space points from the SVT (taken from Fig. 4C-5 of the update to the STAR CDR). The momentum resolutions plotted include MCS in all the detector material, the position resolution of the hits in the SVT and the pad row crossings in the TPC, as well as the loss of some fraction of the space points at the inner radius of the TPC due to hit merging. These resolutions were extracted in the environment of a central Au on Au event. The momentum resolution due to space charge, calculated using eqn. 6, is also plotted for luminosities of 5, 10, and 20 times L_0. It is apparent that, based on this crude approximation, the effect of the space charge on the momentum resolution of the high P_t tracks is not a problem until one approaches about 20 times L_0 for Au on Au. As the space charge for pp at L_0 is about three times that for Au on Au, the effect of the space charge on the momentum resolution of the high P_t tracks becomes a problem at about 6 times L_0 for pp. N.B. This effect will be reinvestigated when the space charge distortions are incorporated in the FST code.

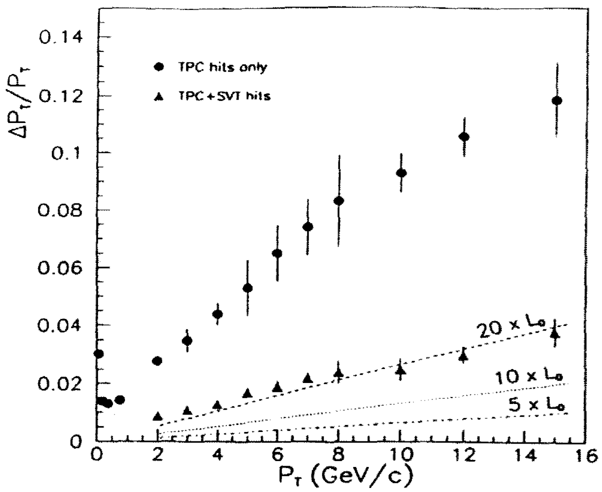

Fig. 8. A comparison of the Pt momentum resolution for primary tracks in the high resolution straight pad row design, with and without the addition of SVT hits. The dashed lines show plots of eqn. 6 for luminosities of 5, 10, and 20 times LO.

Effect of Slower gas in TPC

There is an ongoing investigation of what counting gas should be used in the TPC. At present the baseline gas is P-10. To decrease the longitudinal diffusion of the electron clouds in the TPC as they drift to the anode plane, STAR is contemplating using a mixture of 50% Helium and 50% Ethane. This change would primarily effect STAR's luminosity considerations in three ways.

First, the ratio of the drift velocities in P-10 relative to He-Ethane depends on what electric field is used in the TPC. From considerations to date it appears that the drift velocity in the He-Ethane will be about one half of that in P-10. Recalling the earlier discussion on the piling up of events in the TPC, for pp running at L_O, there would be approximately twice as many pp interactions in each read out TPC event (~45 for P- 10 and ~90 for He-Ethane). This would lower the maximum pp luminosity at which STAR could run if the analysis required that all tracks from the triggered pp interaction are identified. For the Au on Au running it would double the probability that one gets another Au Au interaction in the "livetime" (± 80 μsec) of the TPC.

Second, while it hasn't been documented yet, the space charge effects will likely be less for He-Ethane than for P-10. I believe that the positive ions, which are responsible for the space charge, will drift at about the same speed or perhaps faster in the He-Ethane. The number of ion pairs formed is less in the He-Ethane mixture and therefore the magnitude of the space charge distortions should be less at a given luminosity than those for P-10.

Third, the longitudinal diffusion will be less for the He-ethane than for P-10. This will lead to smaller effective pixel sizes in the time direction in the TPC. This has the desirable effect of reducing the number of space points which get "merged", and should lead to some improvement in the momentum resolution in the TPC and the tracking efficiency for low P_t tracks.

Summary

The first stage of STAR's data taking will be a general survey of central and minimum bias events. During this stage the data rate for STAR will be taping limited for both the pp and AA data, and hence we will not need high luminosities. The most desirable running scenario for this early stage of data taking would be as flat a time profile as possible.

For the later stages of STAR running we will want to use more restrictive triggers to search for rare events in AA collisions. At this time, if the data rate becomes trigger rate limited, the approaches discussed at the last luminosity meeting (May 12, 1993), where one sacrifices a flat luminosity versus time profile in favor of maximizing the integrated luminosity, would be appropriate.

For pp running the analysis gets more difficult as one increases the luminosity due to the high rates of multiple interactions per bunch crossing, the pile-up of events in the TPC, and the distortions due to space charge. For any analysis which requires that *all* of the tracks originating from the interaction that triggered the system be identified, L_0 is about as high a luminosity as one could run. If the analysis only requires that the high P_t tracks ($|\eta| \leq 1$) from the interaction be identified, one can utilize the information from the CTB (and EMC when it gets built) to run at higher luminosities.

N.B. This Summary, at this time, does not represent the STAR policy as pertains to running scenarios for RHIC. This matter must first be considered by the STAR Technical Committee.