Proposal for the addition of forward TOF rings to the STAR detector

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Abstract

We propose to instrument the forward and backward regions of the STAR detector with MRPC TOF tiles in order to provide reliable rejection of background beam gas events, an efficient start-time for the barrel TOF detector, and particle identification at forward rapidities during the RHIC beam energy scan. The forward TOF rings may also be used to determine the direction of the reaction plane for full energy Au+Au and central U+U collisions if certain technical challenges can be met. The proposed detector subsystem will consist of two rings, each composed of 128 MRPC modules located at $z = \pm 6.5$m. The entire detector will consist of approximately 1024 channels covering approximately $2.75<|\eta|<3.75$ and $-\pi<\varphi<\pi$. Each pad will cover $\Delta\eta=0.25$ and $\Delta\varphi=2.8° = 360°/128$. These specifications will enable this subsystem to function as a forward reaction plane detector for central U+U collisions and as a start-time detector for the barrel TOF. The timing resolution of the detector will be less than 100 ps. This will allow STAR to distinguish between real collisions and beam-gas events and to measure particle ratios and identified particle v_1 at forward rapidities.

Introduction

Two of the primary objectives of future heavy-ion runs at RHIC will be to establish the existence of a critical point in the QCD phase diagram and to confirm whether or not the matter created in 200 GeV $^{197}_{79}\mathrm{Au}+^{197}_{79}\mathrm{Au}$ collisions reaches a zero mean-free-path hydrodynamic limit. The first of these goals will be addressed during a beam energy scan planned for 2010 while the second can be addressed by colliding Uranium ions ($^{238}_{92}\mathrm{U}$) at RHIC. The Uranium nucleus is an oblate spheroid, so central U+U collisions can be very asymmetric. The conversion of that spatial asymmetry to momentum space can test the validity of the zero mean-free-path limit which some believe has been achieved in central Au+Au collisions at RHIC. The new EBIS ion source, which will be commissioned in 2009, will allow RHIC to provide U+U collisions as early as 2011.

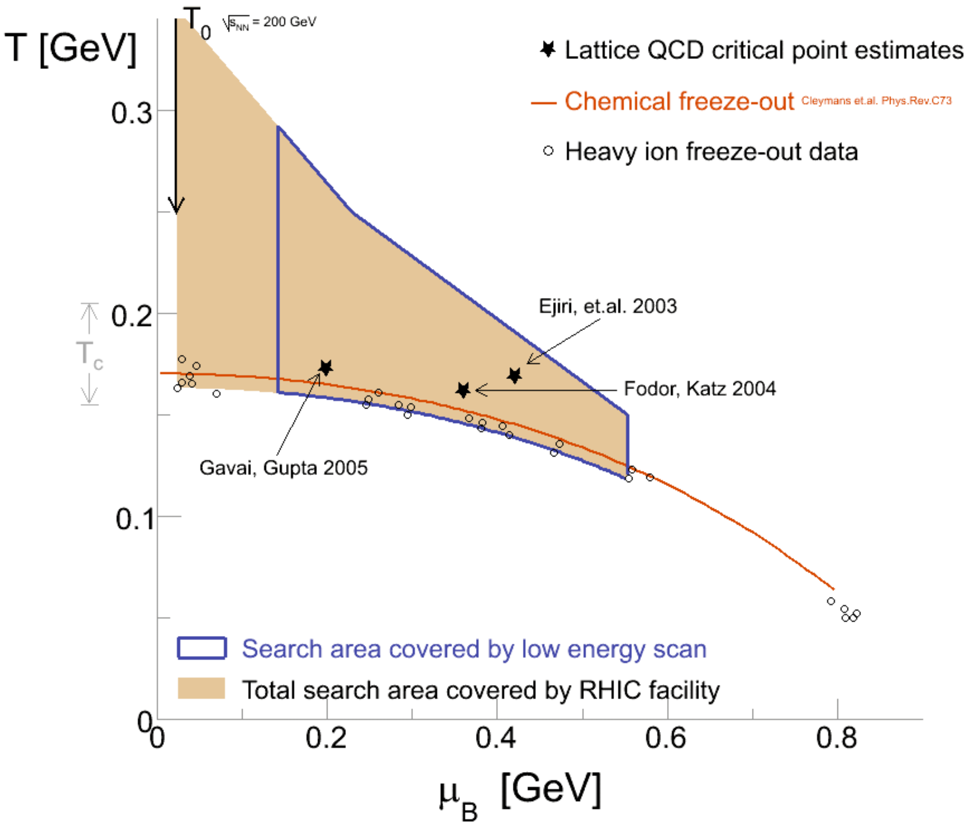

Figure 1. The phase diagram of nuclear matter. An estimate of the area covered by RHIC and the low energy scan are shown along with estimates for the location of the critical point. The RHIC will cover the area containing the best estimates for the critical point.

Beam energy scan

The RHIC beam energy scan will provide data that covers a large region of the temperature and baryon-chemical-potential plane in the QCD phase diagram. Figure 1 shows the most up-to-date lattice QCD estimates for the location of the critical point. The beam energy scan will cover the most likely locations. In addition to the critical point, it's possible that the matter created in various energies of a beam-energy scan will pass through exotic phases, such as one with deconfined but chirally symmetric quark-gluon matter.

The search for exotic phases and the critical point hinges on the ability of the accelerator to provide a large sample of events at each beam-energy in an affordable amount of time. In addition, the experiments will be attempting to characterize the events as well as possible while searching for signatures of new forms of matter or critical point fluctuations. The analysis of these events will require a reliable method to eliminate spurious events coming from various background sources such as interactions of the beams with accelerator components and gas.

Some of the most promising signatures for critical point fluctuations are fluctuations in the ratios of various particle species and the pseudo-rapidity and particle-type dependence of v_1. STAR is installing a barrel time-of-flight detector to identify charged particles at mid rapidity $|\eta|<0.9$. A small acceptance detector covering approximately 55% of the area in range $4.4<\eta<4.9$ (VPD) provides the start time signal for the barrel TOF. During the low energy run, the VPD may not provide a reliable start signal because of its small acceptance and the low event multiplicities. A larger acceptance detector with good timing resolution may therefore be very important for the physics objectives of the beam energy scan at RHIC.

Identified particles at forward rapidity

The matter viewed in the forward region during heavy-ion collisions will be baryon rich. One can access information about the nature of this baryon rich matter by studying particle ratios at forward rapidities. During the first several years of RHIC operations the BRAHMS detector measured particle ratios at forward rapidity. Although BRAHMS was decommissioned after run 6, with small upgrades, the STAR detector can replace some of the physics capabilities lost with BRAHMS. Forward tracking already exists (the FTPCs cover $2.0<\eta<4.0$) and can be supplemented with TOF information to provide reliable particle identification at forward rapidities.

With particle identification at forward rapidities, the production asymmetry of nucleons and pions or kaons can be studied separately. This is particularly interesting because it has been argued that, starting from peripheral collisions to central collisions, if protons change the sign of directed flow and begin to follow the direction of pion flow in central collisions, then a clear signature of 1st order phase transition is observed [H. Stocker, Nucl. Phys. A 750 121-447 (2005)]. Measuring directed flow is challenging at midrapidity because the signal is weak around midrapidity and increases with rapidity. Naturally it would be desirable to have PID capability at forward rapidity where directed flow is larger. Note that having a TOF ring at forward rapidity will not only benefit the low energy scan program, it will also benefit flow studies at top RHIC energies, at which the directed flow signal is even smaller (Fig. A) and one needs to check into forward region to see (or to confirm) a clear trend.

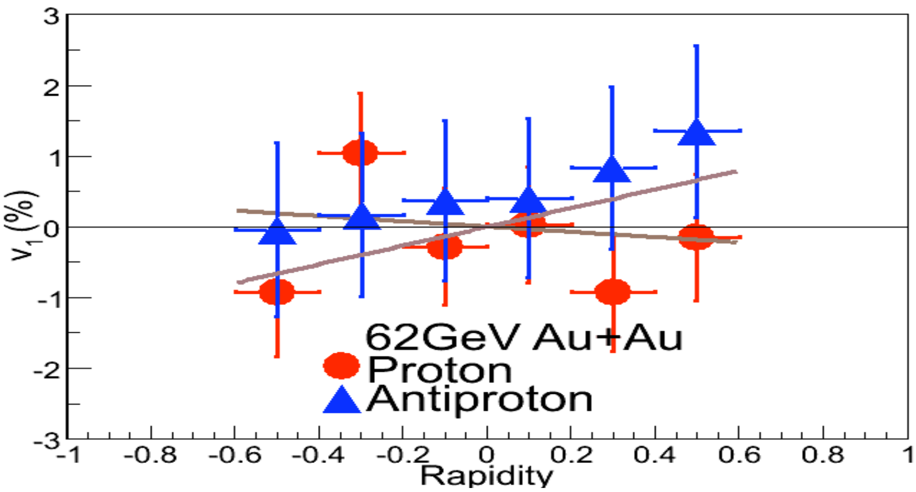

Figure A. STAR's measurement of directed flow of protons and anti-protons. Complemental measurements at forward rapidity will make the trend of directed flow easy to be identified.

Additionally, the larger baryon densities at forward rapidity may allow us to scan to larger values of baryon-chemical potential in the QCD phase diagram to look for signatures of a first order phase transition. For these studies we will measure the proton and anti-proton spectra at forward rapidity.

Uranium+Uranium collisions

Grazing (non-central) collisions of spherical nuclei produce elliptic shaped overlap areas. The expansion of and radiation from the produced spatially asymmetric fireball can yield asymmetries in momentum space. The momentum space anisotropy is a sensitive probe of the dynamics of the expanding system. For nearly central Au+Au collisions at 200 GeV, the momentum space anisotropy seems to reach the value predicted for a system with zero mean-free-path or a unitarity limit where a hydrodynamic description of the expansion may be valid. Figure 2 shows heavy-ion data for the ratio of the momentum anisotropy to the intial spatial anisotropy ε (v_2/ε). The data at the right of the plot are for central 200 GeV Au+Au collisions where the transverse charged particle density (1/S dN/dy) is largest. Since the hydrodynamic limit appears to be just reached for the most central Au+Au collisions, it's difficult to verify the validity of this picture. Recent theoretical work suggests that v_2 in central Au+Au collisions is still 30% below the ideal hydro limit. Ideally one would like to probe well into the region of hydrodynamic scaling to confirm the relevance of such a limit.

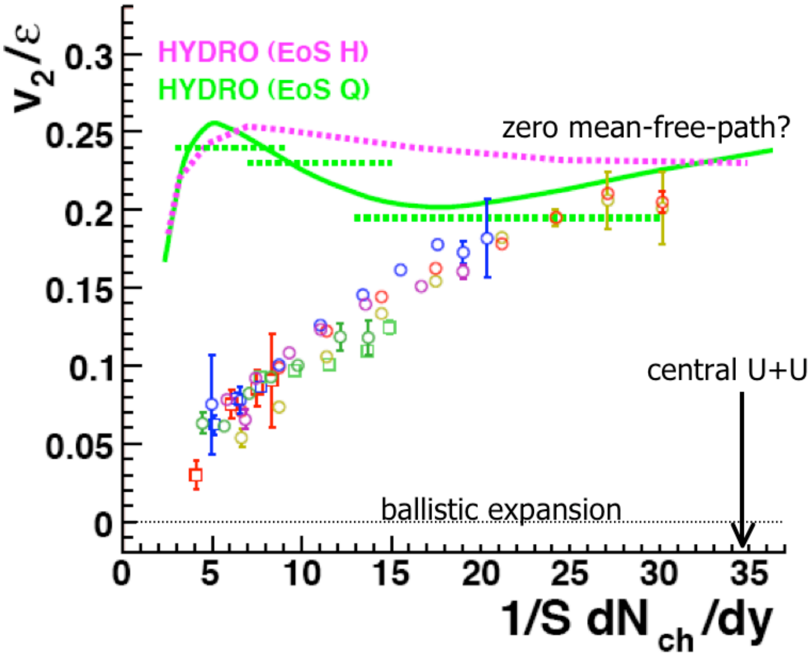

Figure 2. Heavy ion data on eccentricity scaled v_2 vs transverse particle density. A central U+U collision is expected to reach densities 30% larger than central Au+Au while the eccentricity is large.

Figure 3 shows an example of such an experiment conducted by studying the expansion of a strongly interacting degenerate Fermi gas from an asymmetric magnetic trap. The aspect ratio of the cloud of Fermions is plotted as a function the evaporation time. The cooler systems have a larger evaporation time. While the hotter systems expansion is ballistic, the cooler the system the closer it gets to the unitarity limit. Eventually the aspect ratio in the coldest systems reaches a plateau confirming that the hydrodynamic limit has been reached.

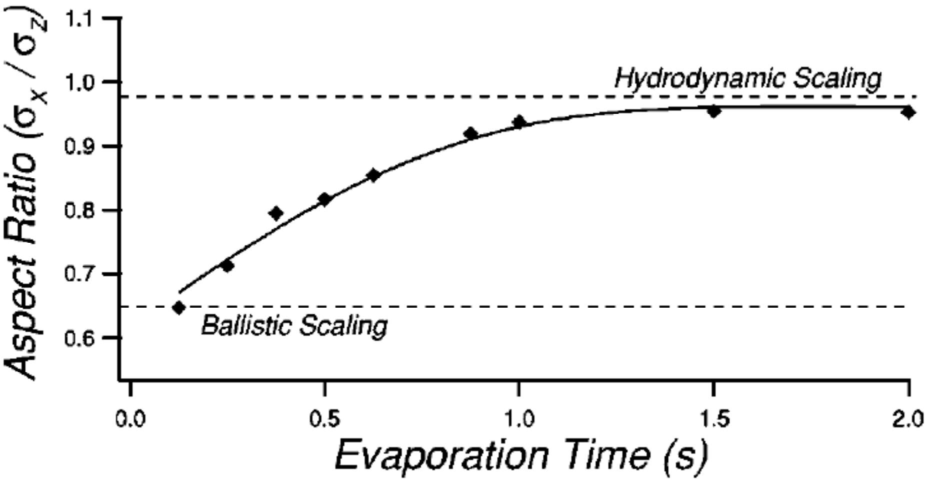

Figure 3. The aspect ratio of a strongly interacting Fermi gas after 0.6 ms of free expansion as a function of the evaporation time. The longer evaporation times correspond to cooler clouds of gas. The figure shows a progression from balistic expansion in the hottest gasses to a hydrodynamic scaling in the coolest.

Central U+U collisions at 200 GeV will probe larger values of the charged particle transverse density and allow RHIC to test for the presence of a hydrodynamic limit. The ratio v_2/ε may continue to rise, as the current trend indicates or it may begin to saturate. A leveling off of the trend would be a strong indicator of the attainment of a zero mean-free-path, hydrodynamic limit. Due to the oblate shape of the Uranium nucleus, the geometry of U+U collisions will be more complicated than that of Au+Au collisions. A detector at forward rapidity with good azimuthal segmentation and a linear response to charged particle multiplicity can help to ensure accurate determination of v_2 and to attain a better understanding of the initial overlap geometry in U+U collisions.

We propose a detector that will provide

- particle identification at forward rapidity,
- a reliable start-time signal for the barrel TOF,
- background rejection during the low beam energy scan
- and a good estimate of the reaction-plane direction in U+U collisions.

The detector is designed with the above requirements in mind and is based on proven technology that can be easily adapted to these needs.

Detector design

To fulfill the purposes laid out above, the detector needs to have better than 100 ps timing resolution, segmentation in ϕ smaller than 30 degrees, large acceptance at forward rapidity, and proportional response for multiplicities up to central U+U collisions. Figure 4 shows charged hadron pseudo-rapidity distributions for Au+Au collisions at 19.6, and 200 GeV. We assume that the multiplicity in U+U collisions will be 35% higher than in central Au+Au collisions. Following this assumption we anticipate that at η=3.5, dN/dη for central U+U collisions will be approximately 500.

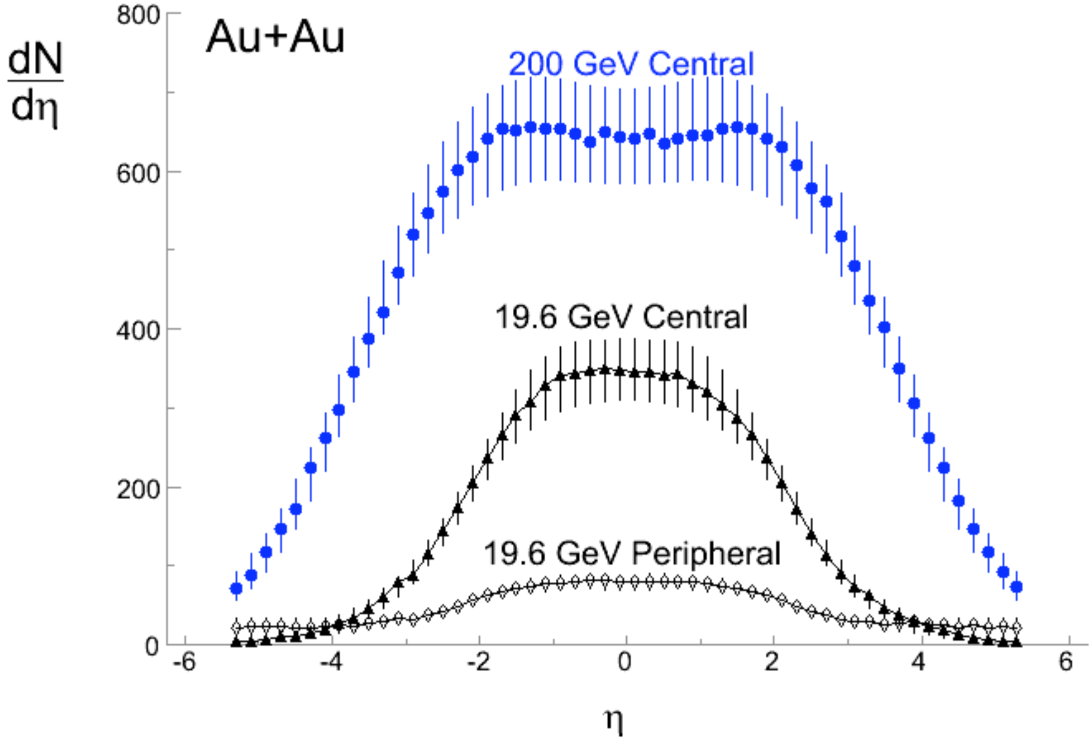

Figure 4. dN/dη distributions for Au+Au collisions.

Multi-gap Resistive Plate Chamber (MRPC) technology is being used to construct a barrel TOF detector for STAR. This same technology with minor modifications to pad and module geometry and gas mixture can be adapted to meet the requirements listed above. We propose to install two MRPC TOF rings at z=±6.5 m from the center of the STAR TPC, covering approximately $2.75<|\eta|<3.75$ and $0<\phi<2\pi$. Each ring will be comprised of 2 trays containing 64 MRPC modules. Each module will have 8 pads so that the total number of channels is 2x1024 to cover both sides of the STAR experiment. Figure 5 shows a possible design for a forward TOF ring. The cost of the proposed detector can be kept moderate by varying the pads to be read-out depending on the expected occupancy so that no more than 1024 electronics channels will be needed.

The pad geometry necessary to accommodate central U+U collisions will significantly exceed the granularity requirements for the beam-energy-scan program. In addition, for a reaction-plane measurement, timing information is not required. We are exploring options that will provide the flexibility to accommodate both requirements. Chaining together pads for the beam-energy scan (two pads per channel), then decoupling them after run 10 (one pad per channel), can do this. The excess pads remaining may then be chained together in larger 4x4 arrays for example and the ADC sum can be read-out with only 64 additional channels. We intend to explore further design options that satisfy our physics goals. While the exact optimization is not yet settled on, it is clear that a modest upgrade can meet these goals.

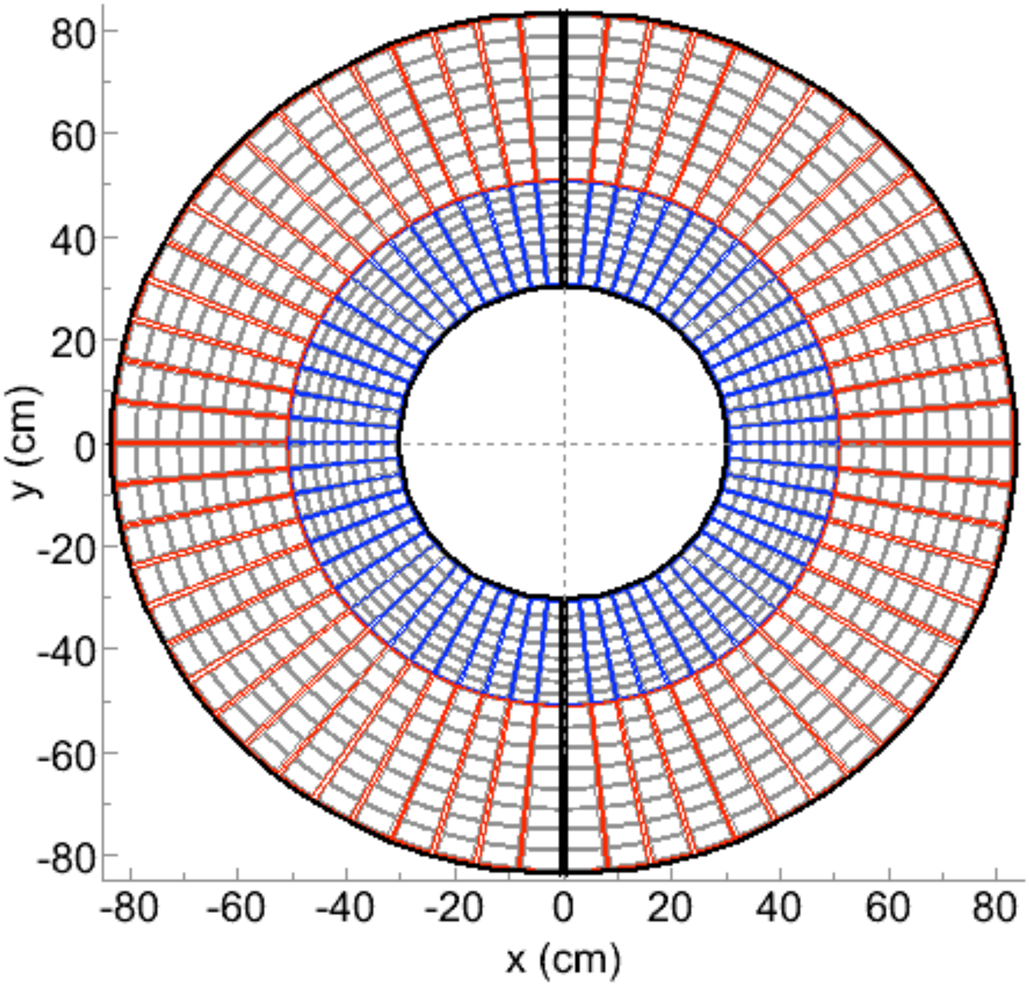

Figure 5. The trays, modules, and pads of the proposed forward TOF ring.

Figure 6 shows a close up view of the module and pad geometry. The design would provide 4 bins in η and 128 bins in ϕ (depending on the arrangement of the read-out electronics). The fine binning in ϕ will be an advantage for making di-hadron correlation measurements between hits in this detector and tracks in STARs time projection chamber. For z=6.5 m, the inner and outer radius of the forward TOF rings will be 30.5c m and 82.6 cm respectively.

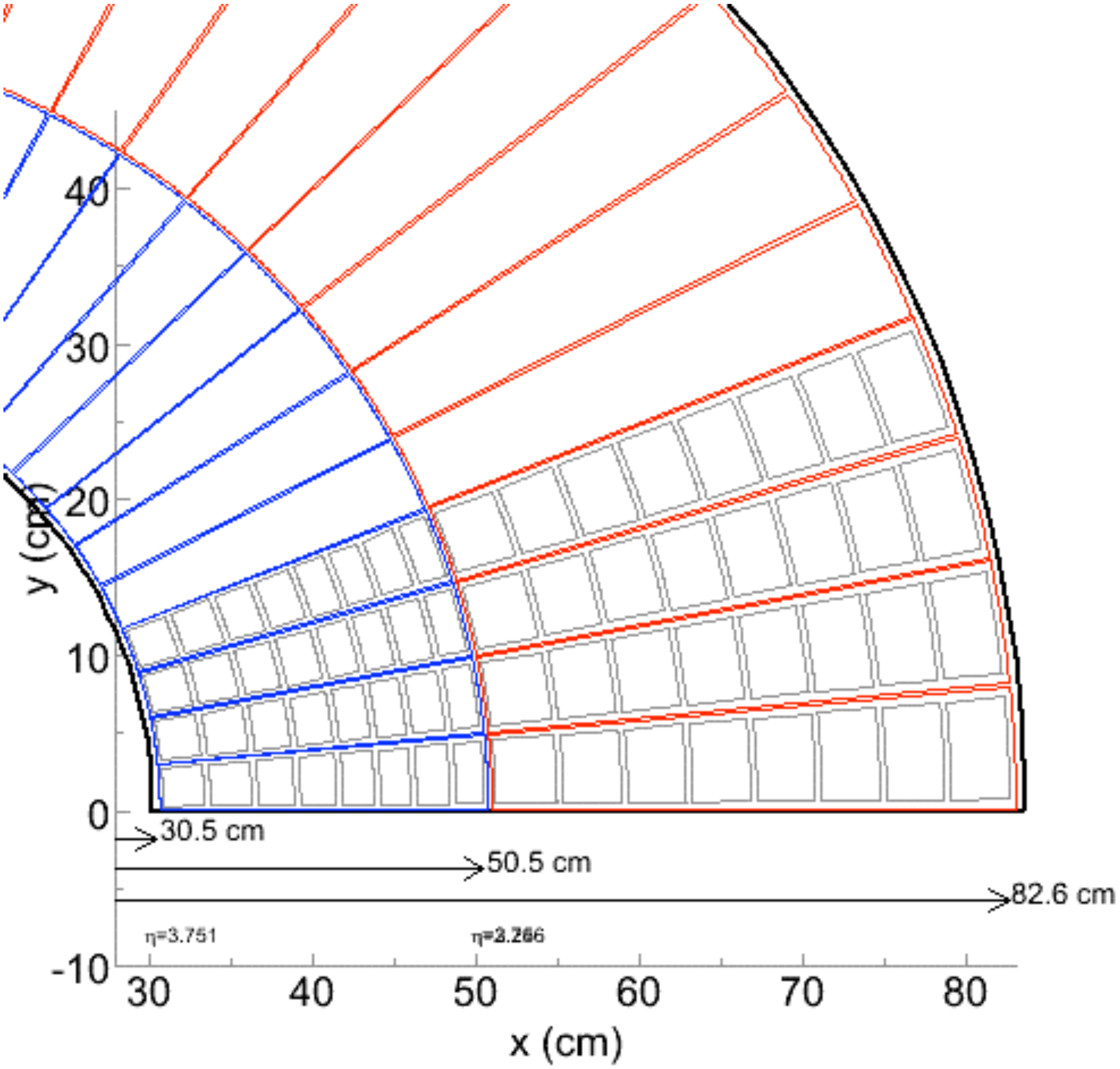

Figure 6. A close-up view of the module and pad geometry. Each module contains 8 wedge-shaped pads.

The modules will be constructed of 7 layers of glass with nearly the same design as the barrel TOF. Inner modules will be 5cm wide, 20 cm long and 1.8 cm thick while outer modules will be 9 cm wide, 31 cm long and 1.8 cm thick. Figure 7 shows a side view of an MRPC TOF module. The trays will be filled with 93% $C_2F_4H_2$ and 7% SF_6.

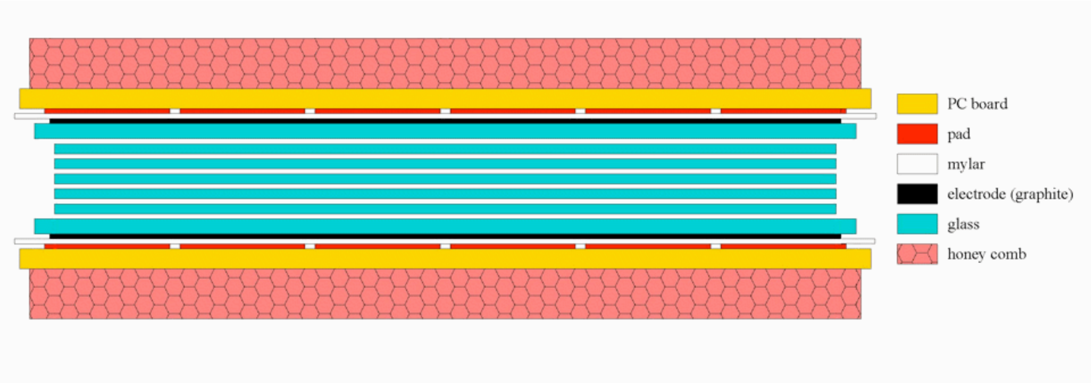

Figure 7. End view of an MRPC TOF module.

Staggering the modules in z will give the appropriate coverage and wedge-shaped geometry. The modules will overlap on the inner side of the detector but the pad design will be adjusted to provide uniform coverage without any overlapping pads. Figure 8 shows a detail of the overlapping modules with uniform pad distribution. This design has the advantage that the modules can be constructed with a simple rectangular geometry. The pads are simply a layer of copper on a printed circuit board that can be easily adjusted to suit our requirements.

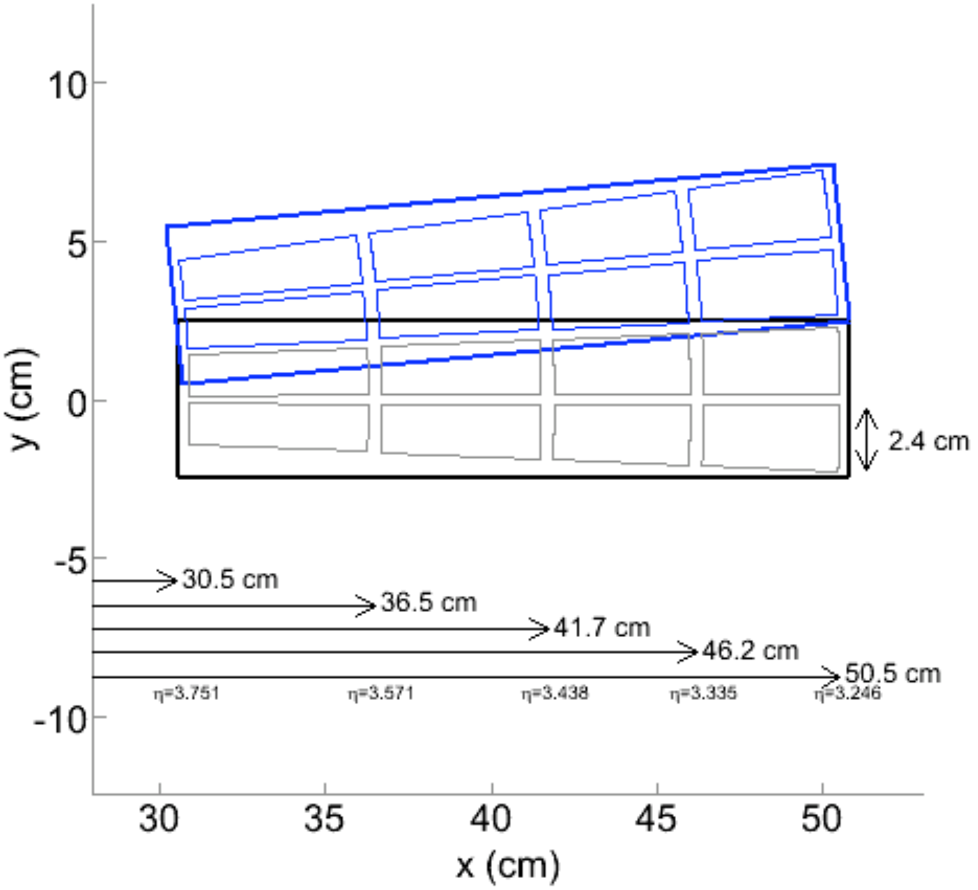

Figure 8. A detail of the inner module and pad design. The module glass will be rectangular. Successive modules will be staggered in z. The pads are made of a layer of copper on a printed circuit board. The pads will provide the necessary wedge-shape.

R&D and performance estimates

One motivation for placing the TOF rings at large z is to increase the distance of the inner ring from the beam pipe. The current design places the first ring at 30 cm from the beam pipe. Research needs to be carried out to study the effect of radiation on the module glass at this distance. Two aspects can be considered: recovery time of the glass after each hit, and ageing. Ageing of the glass is not expected to be problematic: no sign of ageing has been detected in prototypes after 6 months of constant exposure to hit-rate-densities of 2.5 kHz/cm^2 [A. Alici, et al. Nucl.Instrum.Meth.A579:979-988,2007]. The recovery time however, may be problematic.

The recovery time is associated with the time needed for charge on the glass electrode to neutralize after an avalanche. This time is proportional to the chamber capacitance and the plate resistance. While the MRPCs used in the STAR barrel TOF are expected to be efficient for hit-rate-densities up to about 0.5-1 kHz/cm^2, estimates based on BBC and ZDC rates for run 7 suggest that the hit-rate-density at 30 cm from the beam pipe will be about 1kHz/cm^2, near the limit. The hit-rate-density in our estimates is dominated by multiplicity from real collisions. We can expect the hit-rate-density to increase by a factor of three therefore for RHIC II luminosities. We do not anticipate the radiation being a problem for the low energies of the beam-energy-scan because luminonsity and multiplicity will significantly reduced.

The maximum hit-rate-density allowed by the chamber can be increased if the plates used are made from less resistive material. RPC plates made of phosphate glass for example (with bulk resistivity 10^{10} Ω cm) were recently studied for the CBM experiment [Nucl.Instrum.Meth.A572:676-681,2007]. Tests for those indicate that they retained greater than 95% efficiency with rates up to 17 kHz/cm^2. The noise rate with this glass however was large (~100 Hz/cm^2 at 0.5 kV/mm) and depended strongly on the high voltage applied. Low-resistivity silicate glass (10^8 –10^9 Ω cm) has shown much greater promise [Nucl.Instrum.Meth.A576:331-336,2007]. In recent tests, a four-gap MRPC prototype with silicate glass maintained 110 ps timing resolution and greater than 95% efficiency for counting rates up to 20 kHz/cm^2. The efficiency drops precipitously above those rates. Similar performance was achieved with ceramics. We propose to install proto-type modules to study their efficiency in this high flux region. We will investigate the use of 93% $C_2F_4H_2$ and 7% SF_6 for the gas mixture. This mixture may increase allowable radiation [Nucl.Instrum.Meth.A579:979-988,2007].

The installation of a prototype will also allow us to test our track matching between the FTPCs and the TOF rings. This matching will require tracking through a non-uniform magnetic field that has not been mapped, but only modeled. By correlating hits in the prototype with tracks in the FTPC we can study how well we will be able to match FTPC tracks to hits in the TOF rings. We can better understand the occupancy for which the matching will be reliable once the width in azimuth and pseudo-rapidity of the self-correlation peak between the TOF ring hits and the FTPC tracks is known.

The mass resolution achieved by this detector will depend on the momentum resolution of the FTPCs, the path-length resolution, and the timing resolution: $\frac{\delta m}{m} = \frac{\delta p}{p} \oplus \gamma^2\left(\frac{\delta L}{L} \oplus \frac{\delta t}{t}\right)$. For the low energies of the beam energy scan, γ will be approximately 21, 6.2, and 3.4 respectively for pions, kaons, and protons. The momentum resolution of the FTPC depends on momentum and η but is approximately 10% for p=3.0 GeV and η=3. In this case, we find that the pion-kaon separation will be 2 standard deviations and the kaon-proton separation will be 4.5 standard deviations.

Cost estimate

This project will benefit from the R&D that has already been invested in the STAR barrel TOF. We estimate that the cost of completing this project will be approximately $250k. New R&D will be required to study the effect of the large radiation levels near the beam (30 cm) and to determine the matching capability to the FTPC. This study will involve installing prototype modules for the inner and outer rings with electronics configured for high multiplicity and for low multiplicity. The R&D costs are as follows:

$20k for tray design, construction and mechanical support

$10k for the gas system

$15k for 32 large outer modules of conventional glass

$25k for 32 small inner modules of low resistivity glass

$20k for electronics to read-out 16x8 channels of pads configured for low multiplicity

$10k for electronics to read-out 8 channels of ADC information for outer pads (4x4 pads per channel)

$5k for HV supply

The remaining costs to complete the project are estimated as follows

$60k for module construction

$50k for remaining electronics

$35k for gas box and mechanical support

Construction time-line

The two rings will be installed before run 10. The prototype will be built by September 2008 with the full detector being ready for installation by September 2009.

Conclusions

For minimal cost, our physics goals can be met by installing forward and backward TOF rings. These rings will provide a reliable start time and good background-rejection/event-selection during the beam energy scan. The particle identification provided by the TOF information will extend the physics capabilities of STAR during the low energy run. For full energy Au+Au and U+U collisions, the rings will function as forward reaction-plane detectors allowing for better isolation of flow from non-flow effects. Additional measurements will include $\Delta\eta$ correlations that cover $\Delta\eta$ up to 4.5 for TPC forward-TOF-ring correlations, or 7 units of rapidity for forward-TOF-ring, backward-TOF-ring correlations. Given below is a short summary of important observables that can be studied with this upgrade.

Physics Objectives

1. Background rejection and event selection for beam-energy-scan
2. Start-time detector for TOF in low energy runs
3. Proton and pion v_1
4. Forward particle ratios
5. 1st order reaction plane detector for low energy runs
6. 2nd order reaction plane selection for U+U
7. Forward-Backward multiplicity correlations
8. Long range $\Delta\eta$–$\Delta\phi$ correlations