Electronics for Fast Vertex Position Measurement (Topic 48c)

Blue Sky Electronics, LLC

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Identification and Significance of the Problem or Opportunity, and Technical Approach

[Note: This proposal is submitted in response to a 21 May 2010 deadline. The subject Phase I SBIR grant was awarded on short notice several months after the normal award cycle, and prior commitments forced a late start. A no-cost extension to our Phase I work has been requested and approved by the SBIR program manager. A final technical report will be submitted in July 2010.]

Summary

We propose to design and build new electronics that will provide a high-resolution, real-time vertex position measurement for collider experiments. This measurement capability will improve the efficiency of existing detectors and enable new small detectors.

At circular particle colliders such as RHIC, counter-rotating particle beams are focused such that they cross at a few locations around the ring and are nearly collinear along the beam-axis. The position of a collision between the two beams along the beam-line (i.e. the Z-axis) is called the “primary vertex location” and cannot be externally controlled. The measured distributions at RHIC’s STAR detector are +/- 50 cm or more, as shown in Figure 1.

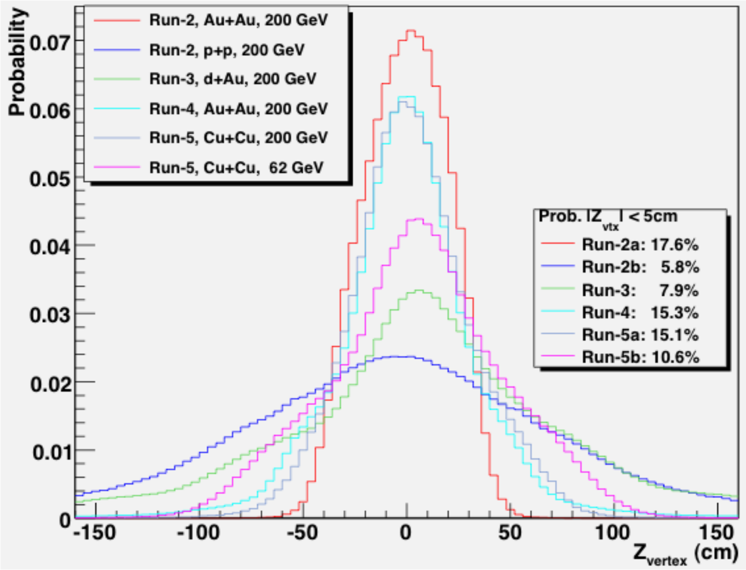

Figure 1: Variation in the Z-location of the STAR primary vertex

A fast and precise determination of the primary vertex location will significantly increase the efficiency and sensitivity of STAR and similar detectors, and will enable the use of new, smaller tracking detectors such as the proposed Heavy Flavor Tracker. (The Star Collaboration, 2006) Our proposed electronics will provide these benefits in a very cost effective manner, compared to the large capital costs of the detectors and the large operational costs of their collider environments.

More specifically, the current resolution (in online triggers) of the Z-position of the primary vertex in STAR is approximately 10 cm. A higher resolution calculation of this position in real-time (sufficient for decisions at the lowest level of the STAR trigger system) will improve the accuracy and efficiency of existing and planned detectors at STAR by providing:

- More accurate track reconstruction seeds for both offline and high-level online triggers

- Improved efficiency of the experiment as a whole, more “usable” hits for the STAR calorimeters, as well as enabling very high-rate (~4 kHz) data streams including only the vertex detector and deadtime-less detectors such as the STAR calorimeters

- Real-time triggering for events within the very small Z-extent of proposed inner tracking detectors (e.g. the Heavy Flavor Tracker)

We will determine vertex position using very high resolution differential timing measurements (Gao & Partridge, 1991), including real-time measurement processing in hardware, to provide vertex position measurement on the order of 1 cm on a continuous basis with latency less than the STAR L0 requirement of 400 ns. (Our design goal is 300 ns).

Our combination of precise timing measurement, hardware data processing and high output data rate provides an important tool in several commercial data acquisition applications. Our commercialization plan addresses applications in time-of-flight mass spectrometry and scintillator based neutron detection.

Background

The main physics goal of the proposed electronics is to improve the resolution at which STAR can select events based on the Z-position of the main collision vertex (Zvtx). Meeting that goal will result in a powerful, multi-channel, stand-alone and very flexible precision timing system that can be used in a variety of advanced instrumentation applications. Those applications are discussed below, after the detailed discussion of the collider trigger application.

Background – Collider Triggering

Our system will provide event selection with a resolution on the order of 1 cm at the earliest possible trigger level. This capability can improve the overall productivity of the STAR detector and thus improve STAR’s use of RHIC’s limited and expensive beam-time. Since the RHIC’s capital and operational costs are large, such a productivity improvement - more “good” data events per operational interval - would represent an excellent return on the investment in our proposed electronics. At the same time, prompt and precise vertex position measurements will enable the efficient use of new inner tracking detectors such as HFT, where small detector size compounds the inefficiencies of low resolution vertex position measurement to unacceptable levels.

Major benefits to STAR brought by the proposed electronics include:

Efficiency: STAR's acceptance becomes strange, and backgrounds increase (relative to "real" collisions), for collisions well outside the center of the collision diamond. So, in practice, significant fractions (see Fig. 1) of STAR's events in the Zvtx tails are typically thrown away in the offline analyses in order to gain reasonable control over the efficiency corrections and signal/background ratios. If the resolution on Zvtx at the earliest level of the STAR trigger was increased significantly, these later-discarded events would never have been written in the first place, increasing STAR's online live-time significantly, and decreasing the effort required to reconstruct and calibrate the data offline.

High-resolution inner tracking upgrades: Major efforts are underway in STAR to improve the tracking both at a very small radius (the Heavy Flavor Tracker (HFT)) and at very forward angles (new GEM-based trackers). The HFT extends approximately 10cm on either side of the center of STAR at Z=0. The geometry of the forward tracking is likewise optimized for collisions very close to Z=0. STAR is presently able to require at Level-0 that the Z-position of the primary collision vertex is within some limits with a resolution of approximately 10cm. This resolution is very large compared to the optimal vertex position for data acquisition by the HFT and forward tracking upgrades, and hence implies considerable inefficiency.

Higher-resolution seeds for tracking on upper-level tracking triggers: Another advantage of the proposed electronics results from the availability of a high-resolution Zvtx value for each event in the trigger data stream. STAR bases higher-level triggers on trigger data and crude tracking information in order to reconstruct and trigger upon events containing, for example, a J-Psi meson. The improved resolution on Zvtx already existing at Level-0 would provide a high-resolution space-point at (X,Y,Z) of (0,0,Zvtx), improving online track reconstruction and the performance of these higher-level triggers.

Fast-detector-only streams: The detectors that provide inputs to the proposed electronics (the upVPD and potentially another called “ringtof”) are intrinsically high-rate. A "high-rate-only-detector" data stream can collect specific interesting spectra at rates of several kHz, which is an order of magnitude greater than the rate of full STAR events that include the slow time projection chamber (TPC & FTPC) tracking detectors.

A number of measurements important to the STAR spin physics program can be performed with calorimeter-only data. These include inclusive π^0 spectra, π^0-π^0 correlations, the neutral component of jets, and even γ-jet correlations. These measurements are particularly important at forward angles where the (F)TPC tracking is poor and the useful rates are higher than can be accommodated by these tracking detectors. The currently achievable vertex resolution hampers taking data with only the "deadtime-less" calorimeters and upVPD by limiting the resolution on the particle transverse momenta. In addition, a fast determination of the vertex would allow the removal of the correlations between the transverse momentum and Zvtx at the trigger-level, eliminating events below the true desired calorimeter energy thresholds.

Finally, the calorimeter towers are projective to the center of the collision diamond at Zvtx=0. For calibrations with electrons, STAR often requires that they enter and exit the same tower. Thus, an ability to trigger on the events from the center of the collision diamond improves the overall efficiency for usable electrons in the calorimeters.

Improved Time-of-Flight Start Timing and Event Plane reconstruction: The upVPD would provide inputs to the proposed electronics. The upVPD is a pair of PMT-based detectors very close to the beam-pipe, one on each side of STAR, at a distance of $|Z|\sim5.7$m. The upVPD has a kinematic acceptance of approximately $4.3 < |\eta| < 5.1$.

The upVPD is 100% efficient in full-energy heavy ion + heavy ion collisions. In Au+Au, every read-out channel on each side is lit by multiple prompt hits in all but the most peripheral collisions, leading to huge boosts to the Zvtx resolution from the averaging effect (resolution improves like sqrt(ndetectors/side)). However, in full-energy d+Au and p+p collisions, and also for low-energy ion+ion collisions (expected in RHIC run-10), the forward multiplicity is much smaller. Thus, the upVPD efficiency per event in these light-ion collisions drops below 50% per event.

We intend to combat this unavoidable fact and provide the required Zvtx performance in two ways. The first is via the use of an out-of-time outlier rejection algorithm on-board. The second involves provisions to the system design to also accept inputs from MRPCs, *i.e.* the proposed ringtof. By using ringtof to supplement the kinematic coverage of the upVPD detectors feeding the proposed electronics, the resulting Level-0 Zvtx triggers would be sufficiently efficient no matter what beams RHIC is providing. This increased acceptance also improves the overall efficiency of the STAR Time-Of-Flight system, which requires both a “start time” (from the upVPD+ringtof) and a “stop time” (from the TOF barrel) in order to identify particles near mid-rapidity.

Background – other instrumental applications

Electronics for precise measurement of time intervals has application in

- Collider Physics
- Scintillator-based neutron detectors
- Time-of-Flight Mass Spectrometry (TOF-MS)
- Time-of-Flight Positron Emission Tomography (TOF-PET)
- Time Resolved Confocal Microscopy
- Three-dimensional imaging and precision machining
- Ultrasonic Flow Metering (transit time variety)

These application areas are described below, and we believe that the programmable logic at the core of our data acquisition architecture will allow customization for application in each area. However, our commercialization plan concentrates on time-of-flight mass spectrometry and on an exciting new opportunity in scintillation-based neutron detectors.

Scintillator-based Neutron Detectors Neutron detectors have traditional applications in basic research and reactor control, but are increasingly in demand as detection systems for illicit nuclear materials. These detectors have been predominantly implemented using ^{3}He, but the recently the supply of ^{3}He has decreased rapidly, even as demand has increased.

A promising alternative architecture is based on scintillator detectors, ***where fast timing electronics with hardware pulse processing are key to high-rate, robust discrimination between gamma and neutron events***. PartTec Inc. (Bloomington, IN) has successfully produced scintillator-based neutron detectors for the Spallation Neutron Source and has recently licensed this technology. We consider this new opportunity to be very interesting and an excellent application for the electronics proposed here. A letter of interest from PartTec is attached.

Time-of-Flight Mass Spectrometry (TOF-MS) instruments measure the molecular mass distribution of a chemical sample by first ionizing and then electrostatically accelerating its molecules. The molecules transit a flight region with flight times dependent on their mass/charge ratio, and are detected by an electron multiplier device, typically a microchannel plate. Detector pulses are timed relative to the acceleration pulse and give mass directly according to $t = k\sqrt{m/q}$, where constant k depends on acceleration voltage and other instrument characteristics.

Advantages include effectively unlimited mass range and high efficiency (sensitivity), since all masses are scanned simultaneously. Discovery of two non-fragmenting ionization techniques, Electrospray (Fenn, Mann, Meng, Wong, & Whitehouse, 1989) and MALDI (Tanaka, Waki, Akita, Yoshida, & Yoshida, 1988), for high molecular weight biological molecules revolutionized the field and have made TOF-MS a workhorse technique for molecular biology researchers.

This technique was impractical from its invention (Wiley & MacLaren, 1955) until the early 1980s when electronics could measure time intervals in the range of several nanoseconds. Cost effective performance depends directly on precision measurement of spectrographic peak centroids and remains problematic today, since current instrumental resolution combined with current microchannel plate detectors can produce spectrographic widths less than 500 ps wide, requiring very expensive multi-Ghz analog to digital converters.

Time-to-digital converters, applied to low ion current electrospray machines or to MALDI machines with segmented detectors, are an attractive option. Specifically, the multichannel TDCs with fast processing capability that we are proposing can overcome the dynamic range limitations compared to ADCs for these systems.

Time-of-Flight Positron Emission Tomography (TOF-PET). PET imaging uses positrons which are emitted from radiolabelled molecular probes to image and quantify localized biological activity. The positrons annihilate close to their production site to produce two 511 keV photons with almost exactly 180 degree trajectories. Coincidence detection of a photon pair defines a scan line that intersects the annihilation event vertex. Adding time-of-flight vertex position measurement further localizes the annihilation event along this line and so can filter noise events and reduce the image reconstruction search space, speeding reconstruction.

Time Resolved Confocal Microscopy uses point illumination and a pinhole aperture to localize image information. Laser scanning using digital micromirrors can produce rapid three dimensional images, allowing live cellular imaging with a large variety of fluorescent contrast agents. Adding the capability for precise time tags on individual detected photons can greatly increase sensitivity to the point of imaging biological activity at the molecular level (Wahl, Koberling, Patting, & Rahn, 2004). We believe that current microscopes of this type are using time-to-amplitude converters for timing measurement, and that our TDCs can significantly increase stability and throughput.

Three-dimensional imaging and precision machining use reflected laser timing measurements to measure three dimensional structures at some distance. Two examples that have been brought to our attention by industrial robotics engineers are precision air piston actuator positioning (with micron resolution) and aircraft wing surface inspection. This family of applications involve specialized fixtures and varying requirements, but we believe our modular architecture, extremely high precision and multiple channel capability can provide attractively high throughput measurement performance in these industrial applications.

Ultrasonic Flow Metering (transit time variety) uses differential timing of same-path (ultrasonic) pressure wave propogation to measure the movement of fluid in a pipe. The pressure waves follow a substantially similar path through the fluid medium, and the wave that propogates in the direction of fluid flow has slightly less transit time. Basic accuracy depends on timing accuracy, but anisotropic media degrade performance for a single path measurement. Our very high timing precision combined with low cost per channel can be combined in a multiple path implementation to provide increased accuracy, at reasonable cost, for nonuniform flow profiles.

Remote sensing of aerosol pollutant emissions and toxic agents can be achieved by remote laser excitation and time-resolved photon detection of fluorescent signatures. Our extremely high timing precision, combined with the capability to triangulate with multiple channels, could give good performance in these applications.

Technical Approach

Figure 2 illustrates the proposed technical approach to collider vertex position measurement. Due to kinematics, leading particles at very forward angles are all traveling at speeds very close to the speed of light, “c”. Two detector arrays very close to the beam-pipe, one on the east of STAR (measuring Teast) and one on the west (measuring Twest), allow the collection of these v = c particles. With the detectors positioned at approximately ±6m, the high-resolution timing of the very forward prompt particles allows the calculation of the Z-position of the primary vertex via

$$(1)\quad Zvtx = (c/2) * (Teast – Twest).$$

Here, Teast(Twest) is the time seen in the east(west) upVPD, and c is the speed of light (30cm/ns).

The major advantage of this approach is its speed. The detectors used for this measurement are based on photomultiplier tubes, which can handle input rates of many tens of kHz) These upVPD detectors already exist in STAR. An alternative approach to obtaining this information is uses track reconstruction to locate the primary vertex, which limits the rate to hundreds of Hz, and cannot be performed quickly enough in real-time to form the basis of event triggers.

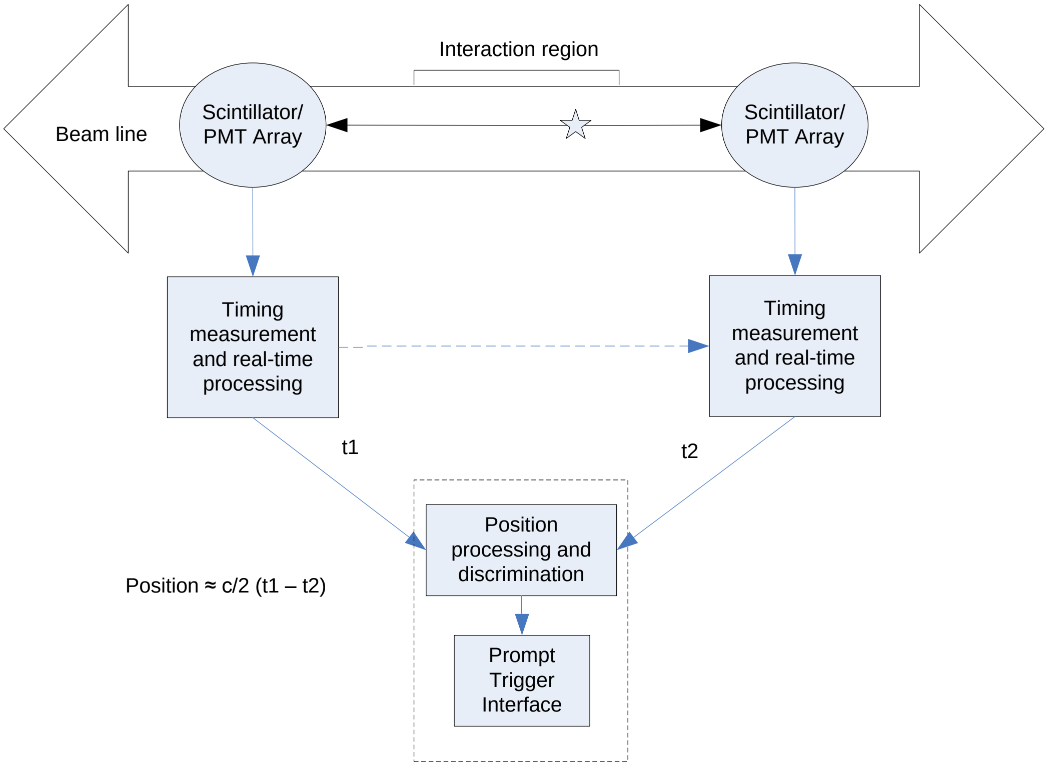

Figure 2: Basic overview of the detectors and proposed digitization electronics

The timing measurement electronics operate from a phase coherent, low-jitter multiple of the collider reference clock. (The dashed line indicates an optional connection that allows the final timing subtaction to take place prior to the trigger interface.)

The resolution in centimeters on Zvtx obtained by east-west timing is given by

(1) $\sigma(Zvtx) = [c/\mathrm{sqrt}(2)] * [\sigma(detector)/\mathrm{sqrt}(Ndetector)]$

where σ (detector) is the intrinsic single-detector timing resolution (approximately 100-150ps), and Ndetector is the number of in-time channels on each side of the collision zone that fired in a given event. The upVPD consists of nineteen detector channels on each side of STAR. Thus, for a single-detector resolution is 150 ps, the resolution on the primary vertex is then ~0.7cm in Au+Au collisions, an order of magnitude better than that presently possible in STAR.

In p+p collisions, the forward multiplicity is much smaller, and thus, the “averaging effect” on each side of STAR cannot be exploited. However, a single read-out channel on each side of STAR would, with the proposed electronics, result in a trigger-level Zvtx resolution of 3cm.

The benefits from such an improvement to the resolution are made clear in Figure 1. This figure shows the “size” of the collision diamond for different RHIC beams over a number of RHIC runs. In light-ion runs (p+p and d+Au) the collision diamond can extend ±100cm on either side of the center of STAR, while in A+A collisions (A=Au or Cu), the collision diamond can extend ±35cm.

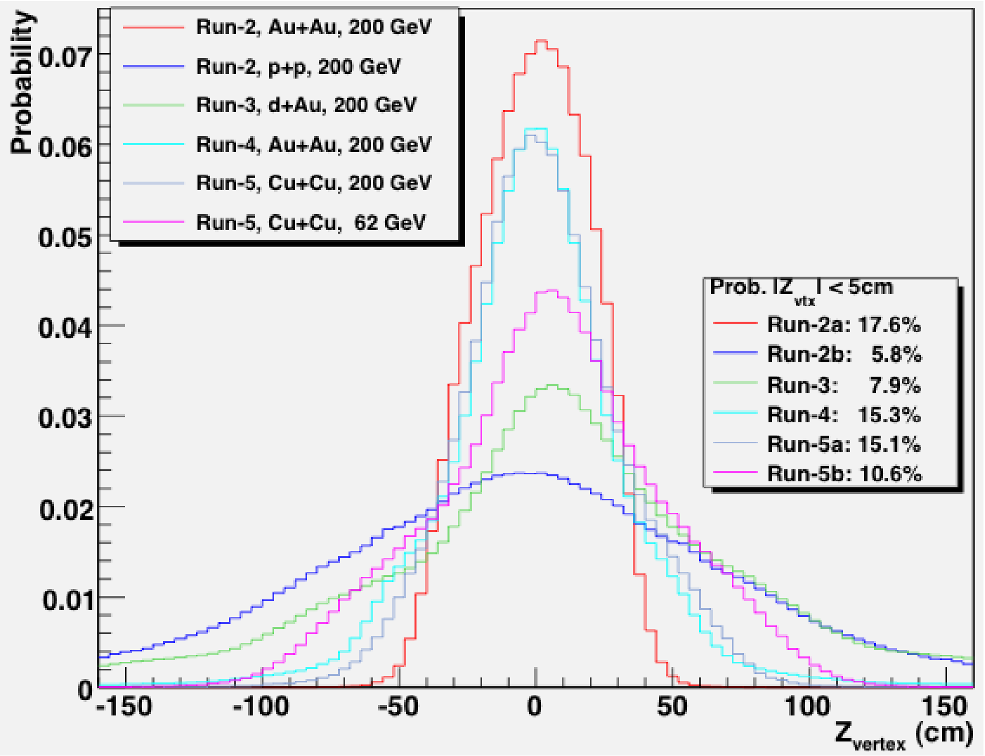

Figure 3: Variation in the Z-location of the STAR primary vertex

According to Figure 1, 80-90% of the events STAR collects are outside the central ±5cm of the detector (and the most desirable "sweet-spot" of the inner tracking). Even without consideration of the inner tracking, significant increases in the overall efficiency of STAR are possible with the proposed electronics. In typical heavy ion+ion(p+p) collisions, events outside of ±30(50) cm are typically rejected in order to achieve a reasonable balance between the size of the data samples and the effort required to efficiency-correct physics spectra in the presence of backgrounds. The importance of these backgrounds increases with |Zvtx|. Thus, the ability to concentrate only on the inner ±30(50) cm of the collision diamond *at the trigger level* saves a considerable amount of time and effort both online (system dead-time) and offline, as all recorded events need to be reconstructed, calibrated, stored, and then distributed to STAR users for physics analyses.

Functions of the Proposed Electronics

The proposed electronics exist as two electronics systems, one on the east of STAR and one on the west, each very close to the detectors. In order to achieve the required ~1cm resolution on Zvtx, the proposed electronics must perform the following operations:

1. Accept the detector signals from STAR upVPD or ringtof
2. Apply offset and slewing corrections using pre-programmed calibration parameters.

3. Reject outlier corrected times with respect to a reference clock.
4. Form the arithmetic average over all “in-time” corrected times in each board.
5. Ship the result (from each side) to STAR Trigger as digital data for use in triggering and online analyses.

Advantages of the proposed electronics over what has been performed to date in STAR arise from outlier rejection and the application of offset and slewing corrections in real-time.

In the absence of these improvements, the averaging effect cannot be exploited and the single detector timing resolution is degraded by slewing. Current Zvtx resolution is , at best, approximately 6cm both in Au+Au and p+p collisions. This has been shown during RHIC Run-7, where the upVPD signals were sent to the STAR trigger system over long cables. The trigger was stable and was the primary minimum bias trigger for STAR over the entire Run-7. The resolution was however very poor (relative to the intrinsic detector resolution), due to the long cables and the lack of offset and slewing corrections.

The offset and slewing corrections for the upVPD are already well-understood from offline analyses. The proposed new electronics will perform these corrections in real-time on-board, reducing the amount of data post-processing.

Anticipated Public Benefits

The proposed work will significantly improve the efficiency of existing detectors at RHIC and will enable the efficient use of proposed inner tracking detectors there. In an environment of limited, uncertain operational funding and short physics runs, data taking efficiency is a particularly important figure of merit for overall operational quality.

Given the large operational costs, the high expected value, and the low implementation risk, we believe the proposed work represents an excellent return on invested research dollars. The resulting basic scientific research activity is crucial to national security, economic competiveness, and the hands-on training of a new generation of experimental physics researchers.

DOE investment in the technical development of the proposed state-of-the-art electronic hardware is directly beneficial to the maintenance of the national electronics design infrastructure necessary for modern physical science, and so for maintaining national leadership in fundamental physics research. This investment is also crucial to national economic competiveness, since the intellectual capital involved in the creation of high performance electronic designs remains a major driver in the national economy.

As described in detail above in “background – other instrumental applications” the proposed research will result in a high performance building block for a diverse array of high performance instruments:

- time-of-flight mass spectrometers
- **scintillation-based neutron detectors**
- time-of-flight positron emission tomographic imaging systems
- time-resolved confocal microscopes
- three dimensional imaging and precision machining equipment
- transit time ultrasonic flow meters
- remote environmental sensing instruments

Enabling, improving their performance and reducing the cost of such instruments will have direct public benefits from life science research, improved security, improved medical diagnostics, improved manufacturing capabilities and environmental pollution control.

Degree to which Phase I has Demonstraded Technical Feasibility

Phase I technical objectives:

1. Verify the system design requirements with STAR experts for a vertex position detector.

2. Implement a multichannel timing electronics system with existing TDC and readout hardware, adding FPGA logic for real-time slewing correction and signal averaging.

3. Investigate and compare candidate approaches to efficient multichannel timing circuits. Prototype and test a small number of channels for at least one candidate architecture, with design goals of 50 to 200 ps single channel resolution, low timing crosstalk and low readout latency.

4. Design the architecture for a final timing system to be built in Phase II. Optimize the architecture for general use as a subsystem in commercial instrument systems.

Status of objective 1:

Ongoing discusssions with members of the STAR trigger group have yielded a solid set of requirements for vertex position measurement.

In addition, these discussions have resulted in a modular electronics packaging design that will plug directly into STAR trigger VME motherboards in a generic fashion. As a result our timing electronics will be useful in several trigger detectors with only firmware modifications.

We list below the current requirements, and the list of subsystems where we expect to apply the hardware. Agreement on requirements and the expanded scope of application indicate that this objective has been met and exceeded.

Requirements:

- Timing resolution: 35ps single-channel start/stop interval measurement precision, including discriminator jitter and dispersion.
- Timing range: minimum 200 ns; compensate in real time for free running coarse counter overflow.
- Data acquisition: TDC data captured synchronously with RHIC clock and corrected timing showing input pulse delay relative to the RHIC clock rising edge.
- Nonlinearity correction: standard HPTDC INL correction applied in real time using an FPGA lookup table.

- Slewing correction: use either digitized pulse charge or leading/falling pulse interval to perform slewing correction in real time using an FPGA lookup table.
- Timing crosstalk correction: correct for timing crosstalk when 2 inputs occur within 10 ns to the same HPTDC device, using an FPGA lookup table.
- Signal averaging: signal average up to 19 corrected timing values in real time.
- Readout speed: readout corrected time values to STAR DSM s within 400 ns worst case.
- Form factor/Interfaces: provide 4 data acquisition channels on a plug in card with the same form and fit as existing QT Daughtercards. Each data acquisition channel to provide a constant threshold discriminator, a digital TDC measurement using the HPTDC, and an integrated charge measurement.

Other STAR subsystems, in addition to the Vertex Position Detector, that will be able to use these modules (with some firmware changes) are:

Zero Degree Calorimeter
Beam-Beam Counter
Forward Meson Spectrometer
Muon Telescope Detector

Status of objective 2:

In consultation with our Rice collaborators, we determined that this objective is met with existing data from our existing TDC board (TDIG) used in the current STAR vertex position detector. Implementing the slewing correction and signal averaging is straightforward and low risk. Implementing those functions in hardware without fast readout would not be useful at STAR, but would require substantial effort to test in the system. We consider that this objective has been met by measurements using the existing VPD (which demonstrates adequate timing resolution) and the stipulation that offline table lookup corrections for integral nonlinearity and slewing can easily be ported to FPGA firmware.

Status of objective 3:

For this objective, we evaluated available TDC approaches and determined that the demonstrated performance of the HPTDC device, and our substantial experience in using it, make it the obvious first candidate for this application. We have completed design of a prototype parallel-readout HPTDC board, and are in the process of fabrication and testing. Based on our long experience with HPTDC and FPGA design, we are confident this board will work as intended. A block diagram and pcb layout diagram for this board are shown below.

We have also discovered in the literature a new TDC architecture, the “stochastic TDC” (Kratyuk, 2009) which uses a common input to a set of comparators with a random threshold distribution to obtain picosecond timing resolution (on full custom silicon over short timing intervals). We are investigating whether this approach can be implemented in standard FPGAs with the required precision and timing range.

In both cases our results will be reported in our Phase I final report in July 2010. As of this proposal submission, this objective is provisionally incomplete, mainly because we have not completed hardware testing of the HPTDC board.

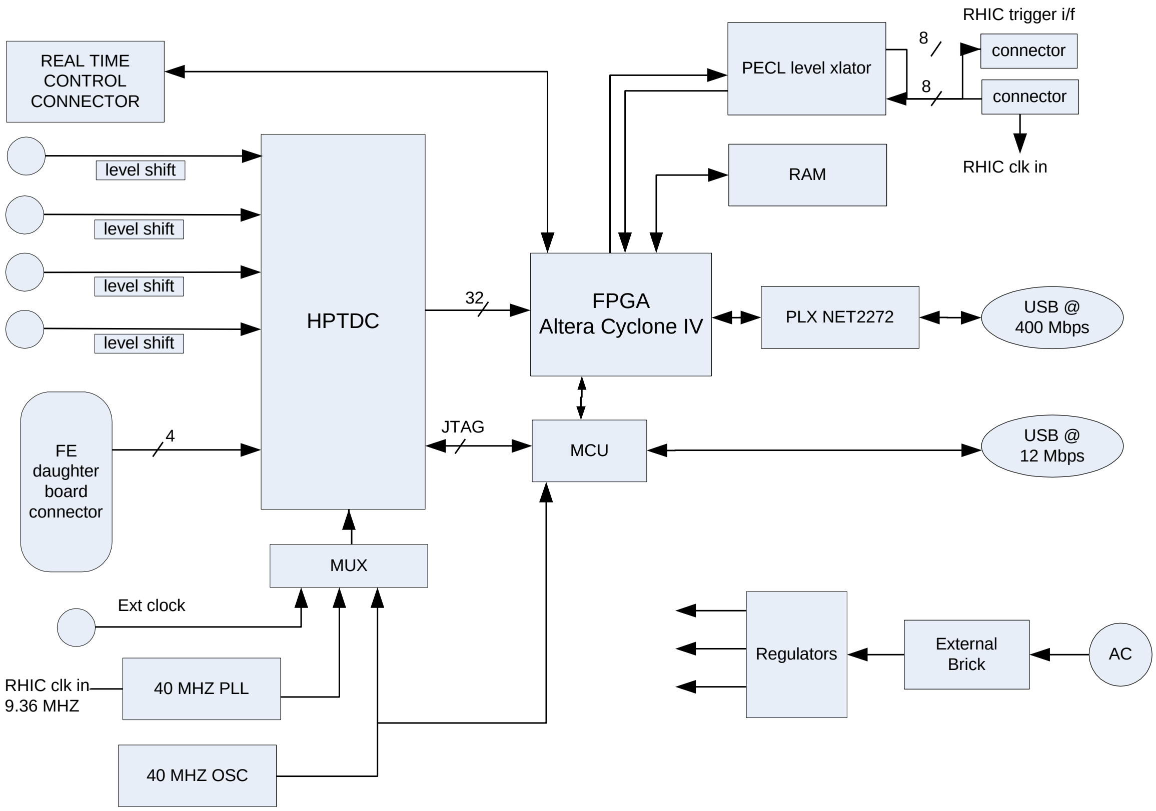

Figure 4: Phase I prototype block diagram

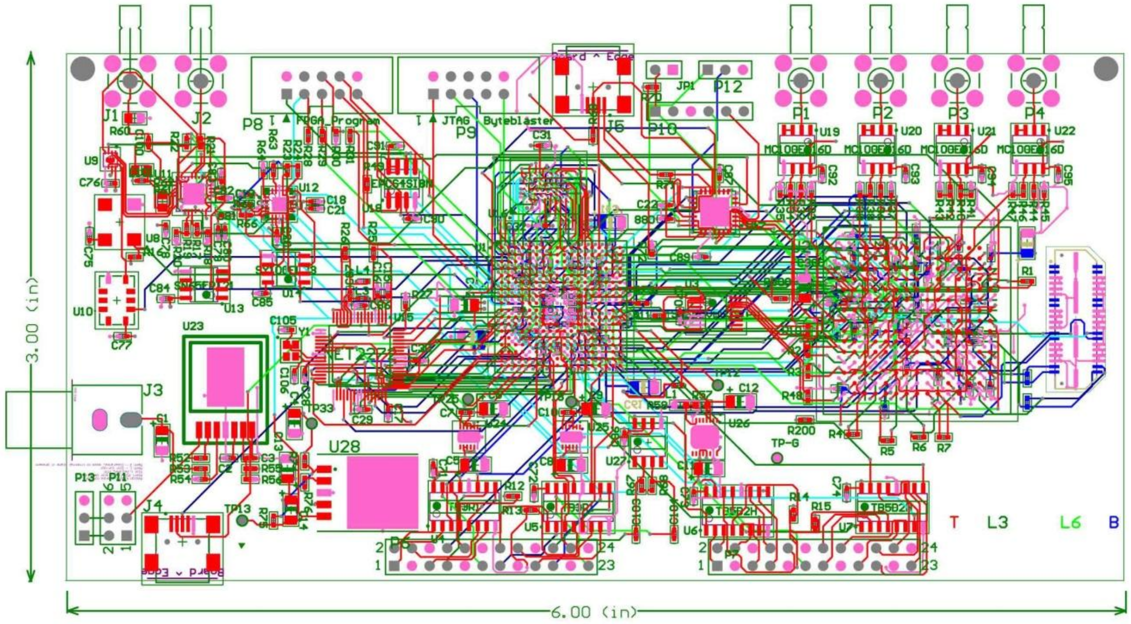

Figure 5: Phase I prototype PCB layout

Status of objective 4:

We have designed the architecture for the final timing system for implementation in Phase II. We believe this system will meet the requirements identified in objective 1. Top level and detailed block diagrams are shown below. This objective is complete. Our Phase II work plan includes detailed design reviews with the STAR Trigger group during the design and implementation of this board.

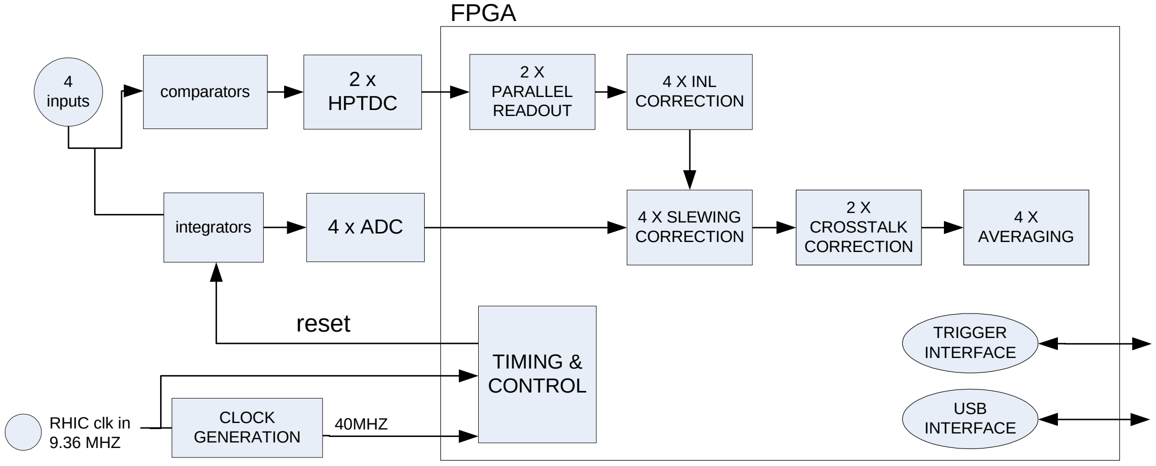

Figure 6: Vertex daughter card functional block diagram

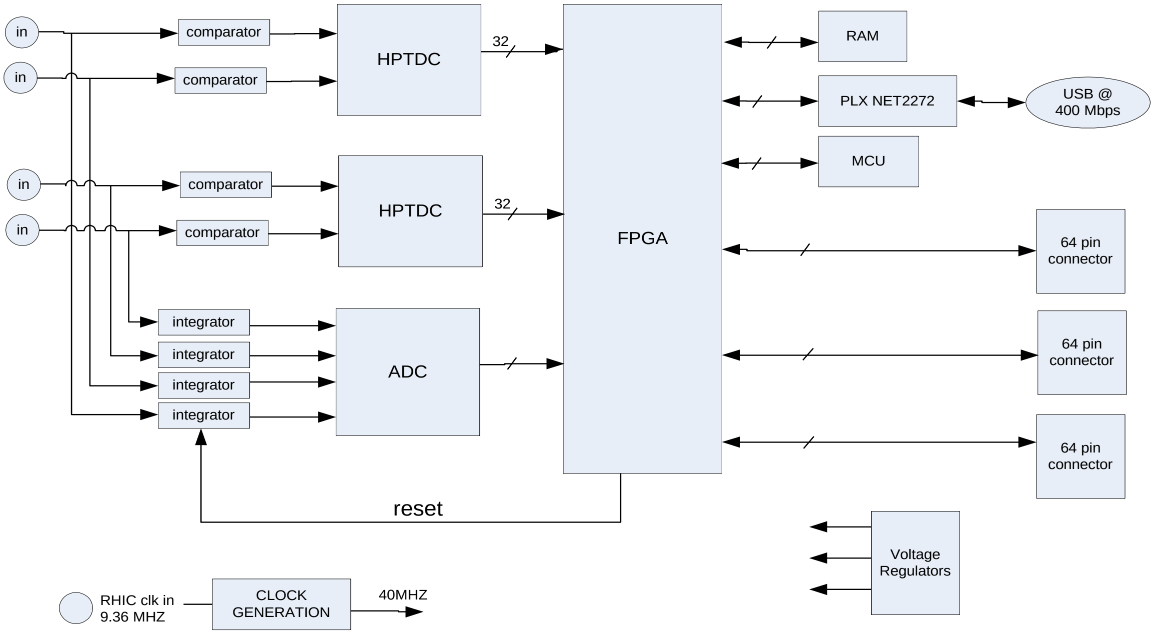

Figure 7: Vertex daughter card hardware block diagram

The Phase II Project

Technical Objectives

1. Design and build a high performance Vertex Position measurement system for the STAR Trigger, which meets the detailed requirements identified in Phase I. Implement the data acquisition electronics with the "QT Daughter card" form factor, so that they plug directly into STAR Trigger infrastructure.

2. Design necessary firmware for interfacing the Vertex Position measurement system within the STAR Trigger. Integrate and test performance within STAR.

3. Verify form, fit and function of the Vertex Position daughter card prototype.

4. Manufacture, deliver, integrate and commission 20 daughter card units to the STAR trigger group.

5. Adapt firmware to use the daughter cards in other STAR triggers: Zero Degree Calorimeter, Beam-Beam Counter, Forward Muon Spectrometer, Muon Telescope Detector. Integrate and commission daughter cards to work within these detectors.

Work Plan

Objective 1: Design and build a high performance Vertex Position measurement system for the STAR Trigger, which meets the detailed requirements identified in Phase I. Implement the data acquisition electronics with the "QT Daughter card" form factor, so that they plug directly into STAR Trigger infrastructure.

Requirements definition is essentially complete. Architectural design is complete at the top level and meets these requirements.

The top level block diagram below shows the system using two existing scintillator – photomultiplier tube detector arrays configured along the beam line. Each detector array gives 19 channels of data to the proposed Vertex Position daughter cards (4 channels per card). Vertex position daughter cards plug into existing QT motherboards (4 daughter cards per QT motherboard), which provide power, RHIC clock distribution, and digital interface to the existing trigger data processing infrastructure.

A block diagram of the Vertex Position daughter card is repeated below. A microcontroller is used to configure, control and monitor the HPTDC devices using existing firmware developed in the STAR TOF project. This firmware is non-trivial and allows an efficient design-in of the HPTDC device.

A dedicated high speed USB interface allows at-speed testing prior to integration into STAR QT motherboards with their extensive VME crate support system, and also, importantly, allows us to deploy these cards in other commercial data acquisition applications.

The three 64 position connectors comprise the board's interface to the QT motherboard and the larger STAR trigger environment. These interfaces include parallel daisy chain connections between daughter card FPGAs, which allows distributed pulse processing. In particular, this will allow as an option very rapid time measurement signal averaging and first edge detection across 16 channels with the appropriate FPGA firmware.

Milestones for this objective are:

1.1. Complete detailed architectural design, including evaluating component choices on the existing QT daughter card and choosing the discriminator, integrator op amp, ADC and FPGA.

1.2. Complete detailed hardware design. Prototype single-channel integrator and/or discriminator circuits as necessary.

1.3. Complete printed circuit board design.

1.4. Fabricate several prototype boards.

1.5. Perform initial performance testing using firmware from the Phase I prototype, reading out data over USB.

1.6. If necessary, eliminate any hardware errors in schematic or printed circuit board and fabricate revised boards.

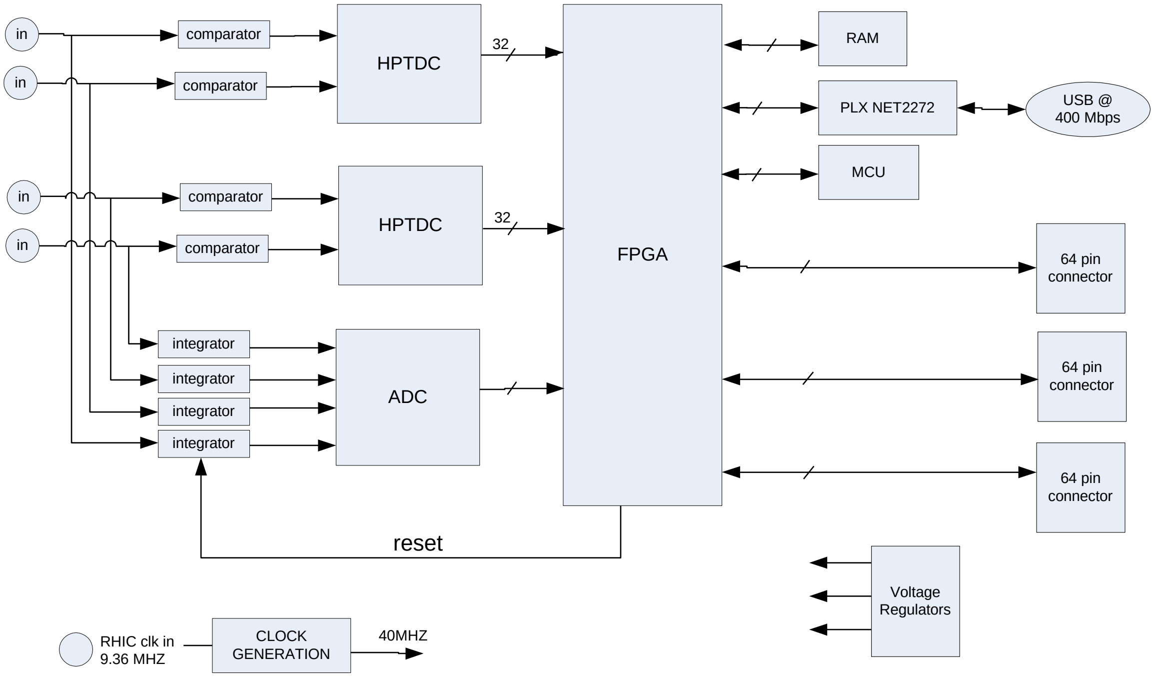

Figure 8: Vertex daughter card hardware block diagram

Objective 2: Design necessary firmware for interfacing the Vertex Position measurement system within the STAR Trigger. Integrate and test performance within STAR.

Firmware from our Phase I prototype to perform HPTDC readout, INL correction, and slewing correction will be available and working on the Phase I prototype at the start of the Phase II project. This code will port directly to the new Vertex daughter card, so we will use the Phase I prototype to test and develop FPGA code in parallel with objective 1 (testing and/or developing new code for TDC readout, INL correction, slewing correction, crosstalk correction, and Trigger interface).

Milestones for this objective are:

2.1.Define, implement and test an FPGA crosstalk correction algorithm.

2.2.Define and implement and test and FPGA signal averaging algorithm.

2.3.Verify in hardware the readout latency performance under worst case input conditions: 2 hits per HPTDC, every 100 ns. Measure the readout performance from the HPTDC alone, and measure the aggregate latency when each stage of processing is added, including INL correction, slewing correction, and crosstalk correction. Verify that aggregate latency including hardware processing is less than 400 ns.

2.4.Define and implement control and configuration interfaces to the QT motherboard.

Objective 3: Verify form, fit and function of the Vertex Position daughter card prototype.

Once objectives 1 and 2 have been met, the Vertex daughter card can be tested within a QT motherboard. This testing will take place initially at UT Austin, where Dr. J. Schambach has a fairly complete trigger setup used for integration testing of the STAR TOF system. Dr. Schambach's setup will include a QT Motherboard and the necessary crates, clock distribution units, and DSM units. We will perform as much testing and integration as possible at UT, before scheduling and undertaking integration within the trigger system at Brookhaven Lab.

Integration work at Brookhaven Lab will have an uncertain schedule, due to variability in the experimental run schedules. We have the interest and support of the STAR Trigger group, as indicated in the attached letter from the head of that group. We will work closely with the STAR Trigger group to plan and execute these important tests.

Milestones for this objective are:

3.1. At UT Austin, verify operation of Vertex daughter cards on a QT Motherboard. Verify configuration, data acquisition, FPGA data processing, and data readout to STAR DSM modules. Verify data quality using cable delay test fixtures. Verify aggregate readout latency with respect to the start clock, including FPGA data processing.

3.2. At Brookhaven lab, test basic operation within the STAR trigger system, particularly data readout. Perform as much testing as possible without an active beam.

3.3. At Brookhaven lab, test operation of the complete vertex position measurement system, including 2 scintillator detector arrays, and 2 or more QT motherboards stuffed with a full complement of Vertex daughter cards. Compare vertex position measurements with measurements from processed RHIC data.

Objective 4: Manufacture, deliver, integrate and commission at least 20 daughter card units for the STAR trigger group.

Milestones for this objective are:

4.1. Obtain performance signoff from the STAR Trigger group based on results from objective 3.

4.2. Create an acceptance test procedure for Vertex daughter cards, based on test schemas created in objectives 2 and 3.

4.3. Finalize and document the baseline firmware.

4.4. Obtain agreement on required quantities, including spares. Manufacture deliverable boards, and maintain as-built documentation. Test the boards in a standard fashion according to the acceptance test procedure.

4.5. Deliver the boards to Rice/UT Austin for final integration and commissioning.

Objective 5: Adapt firmware to use the daughter cards in other STAR triggers: Zero Degree Calorimeter, Beam-Beam Counter, Forward Muon Spectrometer, Muon Telescope Detector. Integrate and commission daughter cards to work within these detectors.

Once firmware is complete for vertex position measurement, we will demonstrate the flexibility of our approach by implementing firmware for other STAR trigger detectors.

Milestones for this objective are:

5.1. Obtain agreement from the STAR Trigger group on which detectors to implement, in what order, and on the hardware processing algorithms.

5.2. Implement firmware changes to support the use of the Vertex daughter card in a different trigger detector; one of the following: Zero Degree Calorimeter, Beam-Beam Counter, Forward Muon Spectrometer, Muon Telescope Detector.

5.3. Implement firmware changes to support the use of the Vertex daughter card in a second alternative trigger detector.

Resource allocation: Principal Investigator and other Key Personnel

Lloyd Bridges (PI) will have overall system design responsibility, and will design the overall architecture for the system, in consultation with Bill Burton, Ted Nussbaum and our scientific collaborators: W.J. Llope, J. Schambach, and G. Eppley. His primary responsibility will be FPGA firmware and system testing.

William D. Burton, Jr. (Systems Analyst) will have primary responsibility for circuit and printed circuit board design, but will be closely involved in system testing. He will be responsible for manufacturing boards throughout the project.

Ted Nussbaum (Rice University Electrical Engineer) will provide electrical engineering support to implement the development and design of the fast vertex electronics. He will be primarily responsible for analog circuit design, system level performance testing and STAR integration. He will be closely involved in all design reviews and will assist in FPGA firmware development.

Scientific Advisors

Dr. W. J. Llope of Rice University will advise on requirements, architecture, testing and integrations at STAR. No costs for his time will be charged to the project.

Dr. G. Eppley of Rice University will advise on requirements, architecture, testing and integration at STAR. No costs for his time will be charged to the project.

Dr. J. Schambach of the University of Texas at Austin will advise on requirements, architecture and firmware implementation. He will directly assist in firmware development, testing and interfacing and integration at STAR. No costs for his time will be charged to the project.

Performance Schedule

Month													Year1	Year 1
Objective	1	2	3	4	5	6	7	8	9	10	11	12	labor wks	labor mos
1.1	2	2	2										6	1.50
1.2		2	3	2	1								8	2.00
1.3				2	2								4	1.00
1.4										1			1	0.25
1.5							3	4	3				10	2.50
1.6									2		2		4	1.00
2.1	2	3											5	1.25
2.2		1	3										4	1.00
2.3			1	3	3				3				10	2.50
2.4						4	5			1	1		11	2.75
3.1										3	2	2	7	1.75
report											1	1	2	0.50
Totals	4	8	9	7	6	4	8	4	8	5	5	2	72	18.00

Table 1: Year 1 schedule and labor allocation

Month													Year 2	Year 2
Objective	13	14	15	16	17	18	19	20	21	22	23	24	labor wks	labor mos
3.2	2	3	3										8	2.00
3.3				3	3	4							10	2.50
4.1						3							3	0.75
4.2			1	2									3	0.75
4.3			2	2	2	1							7	1.75
4.4							2	2	4				8	2.00
5.1					1		1						2	0.50
5.2						1	2	2					5	1.25
5.3								2	2	2	1		7	1.75
report											1	2	3	0.75
Totals	2	3	6	7	6	9	5	6	6	2	1	0	56	14.00

Table 2: Year 2 schedule and labor allocation

Facilities/Equipment

Blue Sky Electronics, LLC occupies 1100 square feet of commercial office space at 401 Studewood, Suite 203 in Houston, Texas. Blue Sky has been prototyping and manufacturing electronics for over 16 years and has all the required equipment, tools and software necessary for system, circuit, printed circuit and firmware design and troubleshooting. We have longstanding and close business relationships with high quality local assembly shops who can quickly and reliably assemble our prototypes.

In addition, Rice's Bonner Nuclear Laboratory has a fully equipped electronic development lab that will be available for use.

Blue Sky's hardware development tools include:

- **Tektronix TDS7154B digital oscilloscope (4 channels, 1.5 Ghz input bandwidth, 20 Gsamples/sec real time sampling).**
- Stanford Research Systems CG635 2 Ghz synthesized clock generator
- Tektronix 2465A 350 MHz analog oscilloscope (2);
- Stanford Research Systems DG535 delay generator;
- Tektronix 3001GPX 1 GHz logic analyzer;
- Hewlett Packard 33120A function generator;
- HP 8570A 22 GHz spectrum analyzer;
- HP 5342A microwave frequency counter;
- VME chassis and extender cards;
- CAN-bus USB and PCI interface modules (several)
- National Instruments I/O cards (digital and analog) (several for creating programmable test fixtures)
- Numerous high capacity linear and switching power supplies
- Numerous cables, RF connectors
- Comprehensive PCB rework and soldering tools

Blue Sky's software includes:

- **Altium Designer 2009 (2 seats): efficient and highly integrated electronic schematic capture, printed circuit board design and fpga coding and simulation**
- SolidWorks 2008: 3D mechanical design
- National Instruments LabView 8.5: graphical test suite creation environment
- National Instruments LabWindows: – GUI and driver development environment
- Altera, Lattice and Xilinx programmable logic design suites
- Orcad Capture: schematic capture;
- PADS: circuit board design software;
- Microsoft Office, Visio, Project;
  StateCad - state machine design;

Consultants and Subcontractors - none

Research Institution

Rice University:
Office of Sponsored Research-MS16; P.O. Box 1892; Houston, Texas 77251
Certifying official: Dr. Heidi Thornton 713-348-6204 heidi@rice.edu
Total subcontract amount: $128,895.29

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Geary Eppley
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713-348-4742(Talk)
713-348-5215(Fax)

May 19, 2010

To Whom It May Concern:

Blue Sky Electronics LLC was the major subcontractor for electronics boards for the STAR Large-area Time-of-flight construction project. Blue Sky earned that status by successfully completing a Phase-II SBIR during the R&D phase of the project. Blue Sky delivered more than 1100 electronics boards at the agreed time and cost. Less than 1% of the boards needed to be returned for repair or replacement. The boards have been in use for two years and there is no indication of any problem in the design or manufacture. In short, the association with Blue Sky was highly successful. Blue Sky Electronics has demonstrated the technical capability for carrying out this proposal to develop fast-vertex electronics.

Heavy-ion collider experiments see event rates in the detector that are much larger than the maximum DAQ rate. There is also an annual event limit imposed by the capability of offline computing facilities to reconstruct events. In addition, heavy-ion experiments do not use a lot of rare-event triggers, where it is not desirable to limit the event rate, that are typical of high-energy proton-proton experiments. Thus there is a need in heavy-ion experiments to limit the event rate, and an opportunity to select events of the highest quality. Since collider detectors have finite size, they have a limited acceptance for collisions. The collision vertex distribution for heavy ions is wide. Selecting collisions near the center of the experimental apparatus using a precision vertex position detector will greatly improve the quality of the event sample, hence the efficiency of the detector, and the efficiency of the collider research program.

STAR's current vertex trigger has a precision of about 5 cm. Improving this resolution to 1 cm will provide obvious benefit to the trigger required for the new HFT vertex detector that needs to limit the vertex distribution to less than 20 cm.

In addition, developing the electronics in a format that can be used as a daughter card to an existing STAR trigger (QT) board will provide 16 channels of precision, fast-timing measurements on a single VME card. TACs are currently used in STAR for this purpose. The new daughter card will provide an improved timing measurement for the various STAR trigger detectors that require a timing constraint in the trigger decision. Since this card is VME based, it can be used by any particle physics experiment requiring a fast timing measurement in the trigger.

The nuclear energy research group at Rice University supports this proposal.

Geary Eppley
Research Scientist
Contractor Project Manager
STAR Large-area Time-of-flight Project

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BERKELEY, CALIFORNIA 94720-7450

May 19, 2010

To Whom It May Concern:

This letter concerns the SBIR proposal for "Electronics for Fast Vertex Position Measurement" by Lloyd Bridges of Blue Sky Electronics.

I am the leader of the STAR Trigger group operating at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC). The STAR Trigger is designed to facilitate the search for, and characterization of, new states of matter such as the quark-gluon plasma. It is a pipelined system in which digitized signals from the fast trigger detectors are examined at the RHIC crossing rate (10 MHz). This information is used to determine whether to begin the amplification, digitization, and acquisition cycle for slower, more finely grained detectors. These slower detectors provide the momentum and particle identification on which our physics conclusions are based, but they can only operate at rates of a few hundred Hz. Interaction rates exceed 1 MHz for the highest luminosity beams, so the fast detectors must provide means to reduce the rate by more than four orders of magnitude. Interactions are selected based on the distributions of particles, energy obtained from the fast trigger detectors, and the position of the collision vertex.

This SBIR project proposes to develop an electronic circuit that could be utilized by our fast detectors to determine the collision vertex by providing a digitized measure of the time difference between a detected particle and a reference RHIC clock pulse. The proposed circuit will have a 10 MHz sampling rate and be able to apply alignment offsets and slewing corrections to the time measurement providing input to our trigger logic within 400ns. The ability to remove much of the detector bias, coupled with the anticipated <100ps resolution, is expected to provide a determination of the collision vertex to within +/-1 cm, an improvement of a factor of more than five over our current capability.

In summary, this project is of interest to the STAR Trigger program and we intend to use these boards if they perform to our specifications. We are happy to support this proposal.

Sincerely yours,

Henry J. Crawford
hjcrawford@lbl.gov; 510-486-6962

BERKELEY LAB
ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

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26-November-2007

To Whom It May Concern:

We fully encourage the SBIR development of a high resolution, on-detector, electronics package that can be used to implement a Level-0 trigger for STAR with vertex resolution on the order of ±1 cm in the Z direction. This would be a significant improvement for the STAR HFT program.

This SBIR proposes to develop an electronics module that can be placed on a fast timing detector, such as the STAR upVPD detectors, and which will provide digitization and slewing corrections at the detector. This is important because previous generations of fast-timing systems have relied upon long cables to deliver the signals to the digitizer and calibration circuits. These circuit boards are usually several meters from the detectors and the rise time and distortion characteristics of the cable are the fundamental limit on the timing resolution that can be achieved by the system. By eliminating the long cables, the ultimate timing resolution of the detector can be achieved.

A Z_{vtx} Level-0 trigger for STAR would benefit the HFT pixel detector because the detector is finite in length (~20 cm) and is shorter than the 2-σ width of the RHIC interaction diamond (~70 cm). Therefore, any device that helps us trigger on events directly under the detector is extremely valuable. The finite length of the HFT is a necessary trade off to achieve optimum pointing resolution for topological D^0 reconstruction and minimum cost. The proposed development of a Level-0 trigger would greatly improve the data quality for this program as only the sweet spot of events directly under the detector would be recorded. In addition starting with precise z vertex information will improve the tracking code performance since hit ambiguities in the pixel detector can be resolved in the first pass of the software without resort to approximations or estimates.

In summary, the proposed Z_{vtx} Level-0 trigger is of direct benefit to the STAR HFT program and we strongly encourage the development of the innovative electronics that is required to make this possible.

Sincerely,

Howard H. Wieman
Senior Staff Scientist

Jim Thomas
Staff Scientist

Ernest Orlando Lawrence Berkeley National Laboratory

November 11th, 2008

To Whom It May Concern:

I'm writing to support the SBIR proposal for "Electronics for Fast Vertex Position Measurement" by Lloyd Bridges of Blue Sky Electronics.

I am Dr. Nu Xu and am spokesperson of the STAR experiment that is one of the two major experiments at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory, New York. RHIC is the highest energy nuclear collider in the world: it provides nucleus-nucleus collisions at $\sqrt{s}$ = 200 GeV and polarized proton-proton collisions up to $\sqrt{s}$ = 500 GeV. The primary goal of the STAR experiment is to study the properties of the quark-gluon plasma (QGP), the primordial form of matter few micro-seconds after the Big Bang, created in Au+Au collisions. We also study the intrinsic helicity structure of protons in polarized p+p collisions at RHIC.

The proposed high-resolution electronics package will allow the experiment to develop a fast trigger with the vertex resolution in the order of ±1 cm in the beam direction. It will significantly improve the STAR data taking efficiency and will be necessary for STAR's upgrade project Heavy Flavor Tracker. For details of the improvement for the project see the letter from Drs. H. Wieman and J. Thomas.

In summary, this project is crucial for STAR physics program. I strongly support the proposal.

Sincerely yours,

Nu Xu

Senior Scientist
Spokesperson for the STAR Collaboration
Lawrence Berkeley National Laboratory

Nuclear Sciences Division One Cyclotron Road MS 70-319 Berkeley, CA 94720
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MassTech, Inc.
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Dear Lloyd Bridges, 11.19.2008

You’ve asked me to write a letter of support for your proposed new multi-channel pulse timing data acquisition system.

First, let me thank you for the opportunity to endorse the commercial prospects for your proposed system. I’ll state for the record that my company is an existing customer of your time-to-digital converter product, and that we’ve had numerous and fruitful technical discussions over several years regarding the data acquisition problems involved in time-of-flight mass spectrometry.

As you know, MassTech develops and manufactures components and systems for time-of-flight mass spectrometers (TOF-MS), and my work as a research physicist for some years has centered on new, higher performance instrument designs. I can state that I’m quite familiar will all available high performance ADC and TDC data acquisition products on the market.

MassTech is an important vendor in this industry as high performance mass spectrometry continues to revolutionize biomedical research. Higher mass accuracy, increased sample throughput and increased ion flux (e.g. ion-mobility mass spectrometer) continue to drive data acquisition system requirements to the limits of available technology. We would like to reiterate our support for your important research in developing a basic component that will enable important new innovations in our industry.

Your new proposed system is very attractive to myself and my colleagues here at MassTech since it will combine high timing accuracy with many channels, on-board signal processing (digital slewing correction and signal averaging) and considerable latitude for custom real-time pulse processing due to the on-board programmable logic. No product that meets all of these requirements is currently available on the market.

In short, let me say that if you build it, we’ll try it out. And if it works, we’ll strongly consider purchasing it, in quantity, for new TOF-MS systems under development. Good luck and please keep me closely informed regarding your progress on developing this exciting new product.

Sincerely,

Maciej Bromirski, M.Sc.
Director of Business Development, Mass Spectrometry
mbromirski@apmaldi.com

PartTec, LTD
PARTNERS IN TECHNOLOGY

Phone 812.323.0541 ♦ Fax 812.323.0734

2620 N. Walnut Street, #805 ♦ Bloomington, IN 47404

May 21, 2010

Mr. Lloyd Bridges
President
Blue Sky Electronics
401 Studewood, Suite 203
Houston, TX 77007

Dear Mr. Bridges:

PartTec, Ltd. strongly supports your efforts to obtain a grant for the development of the system using fast timing electronics coupled with real-time pulse processing. This technology's development is of significant importance in areas such as scientific instrumentation and detectors and high speed signal processing applications for defense and homeland security. PartTec is particularly interested in the advancement of this technology and is looking forward to including new, advanced signal processing electronics in both our Research neutron detector products and in our Security neutron detector products.

I believe that you and your company are uniquely qualified to perform this work at this time and I support your application for research funding for your project.

Sincerely,

Herschel Workman
Chief Executive Officer