Summary/Abstract: Electronics for Fast Vertex Position Measurement (Topic 48c)
Blue Sky Electronics, LLC   Principal Investigator: Lloyd Bridges

Particle colliders such as the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory have circular, counter-rotating particle beams which are focused such that they cross and collide at a few places around the collider ring. Large, complex particle detectors are located at these positions to record and measure the new particles resulting from the particle beam collisions. The location of each collision is called the "primary vertex position" and ideally is centered exactly within the particle detector, but in fact varies over some distance along the beam path. If a fast and precise measurement of this primary vertex position is available, then that information can be used as part of the detector "trigger" to record data from only those collisions which are ideally located. This process will significantly increase the efficiency and sensitivity of the Solenoidal Tracker at RHIC (STAR) and similar existing detectors. For new, smaller detectors such as the proposed Heavy Flavor Tracker (HFT), which have physical dimensions smaller than the distribution of the primary vertex position, the efficiency gains are magnified.

We propose to design and build new electronics to provide a high-resolution, real-time vertex position measurement for collider experiments and other applications. The proposed electronics will provide increased efficiency and sensitivity to the STAR and other detectors in a very cost effective manner, compared to the large capital and operational costs of the detectors and their collider environments. Specifically, a fast vertex position measurement can be used as part of the experimental trigger to provide improved operational efficiency (more useful data for a given experimental run time) by including more "usable" hits for the calorimeters, more accurate track reconstruction seeds for both offline and high-level online triggers (resulting in faster data processing), real-time triggering for events within the very small vertex extent of proposed new detectors and fast detector-only data streams.

The proposed system is based on our existing experience and products for precise timing measurement, developed by Blue Sky Electronics as part of the successful STAR Time-of-Flight (STAR TOF) project. That project involved a close collaboration between Blue Sky and researchers at Rice University and the University of Texas, and we have maintained that strong team for this proposed project. Our team's extensive experience in integrating electronics within the STAR environment will significantly reduce project risk.

Although fast vertex position measurement is a specialized application, the system we will create to make that measurement is fundamentally a low cost set of precision synchronized stopwatches, with the capability to capture, process and transmit extremely precise time interval measurements in real time. That capability is flexible and general, and creates significant commercial opportunities as a key component in diverse systems for 1) time-of-flight mass spectrometry, 2) time-of-flight positron emission tomography, 3) time-resolved confocal microscopy, 4) laser distance measurement for three dimensional imaging and ultra precision machining and 5) remote atmospheric sensing via laser induced, time resolved florescence. These larger systems are addressing cutting edge problems in life sciences, medical imaging, advanced manufacturing, environmental monitoring and homeland security.

Key Words: Vertex position, Time-of-Flight, TOF, STAR, time-to-digital converter.
Summary for Members of Congress: This work will result in new electronics to quickly measure, process and distribute extremely fast timing measurements. It will increase the efficiency of particle collider experiments and provide an important building block for advanced instruments used in the life sciences, medical imaging, manufacturing, and environmental monitoring.

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
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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

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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,

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November 10, 2008

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 achieved that status as a result of successfully completing a Phase-II SBIR during the R&D phase of the project. Blue Sky has delivered the more than 1100 electronics boards that were required for the project, at the agreed time and at the agreed cost. Less than 1% of the boards needed to be returned for repair or replacement. There is no indication of any systemic problem in the board design or manufacture. In summary, the association with Blue Sky was highly successful. Blue Sky Electronics has demonstrated the technical capability for carrying out the proposal to develop fast-vertex electronics.

Heavy-ion collider experiments, and in particular the STAR experiment, typically 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 computing facilities to reconstruct events off-line. In addition, heavy-ion experiments do not “run” a lot of rare triggers that are typical of high-energy proton-proton collider experiments. With rare triggers, it is not desirable to limit the event rate. Thus there is a need to limit the event rate, and also 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 compared to that in proton-proton colliders. Selecting events near the center of the experimental apparatus using a precision vertex detector will greatly improve the event sample and 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 a trigger that is trying to limit the vertex distribution to less than 20 cm.

The nuclear energy research group at Rice supports this proposal.

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

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W.J. Llope, Ph.D.
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November 27, 2007

To Whom It May Concern,

The STAR conceptual design of the early 90's included a very fast timing forward detector called the Vertex Position Detector (VPD). The primary motivation of the detector was two-fold – to provide a high-resolution start time for STAR Time-of-Flight (TOF) detectors, and to provide information allowing precise low-level triggers on the location of the primary collision vertex along the beam-pipe. For various reasons, a detector of this kind was, as of ~2000, not built and there were no plans in STAR to do so.

So I built it myself, and used it to provide start times to the then new TOFp detector. I was careful to call this detector the "pseudo-Vertex Position Detector" (pVPD) - as the goal of low-level Zvtx triggering was not possible. This detector worked well during RHIC runs 2, 3, 4, and 5, allowing the R&D of new low-cost TOF technologies that resulted in the proposal, and now the U.S. D.O.E.-funded construction, of a large-area TOF system for STAR. I then made a subsequent improvement in the efficiency per event of such a detector by building another one with an increased channel count. This is the "upgraded pseudo-Vertex Position Detector" (upVPD) that is now in operation.

The present proposal would, for the first time, provide the triggering functionality that has been needed all along. Low-level triggers on Zvtx would significantly increase the efficiency by which STAR can recognize and trigger upon useful events near the center of the experiment, where STAR is at its most powerful. I am thus fully committed to the success of this proposal – it is central to my long-time research efforts and crucial for their success. I have been proactive in discussing this direction with my colleagues and will continue in this role to make sure the proposed R&D results in electronics that meet the performance requirements and integrate seamlessly into STAR.

I have also discussed this proposal with the STAR Spokesman, Tim Hallman. Due to scheduling conflicts, I was unfortunately unable to collect a written statement of support for him in time for the submission of this proposal. He is however aware of the proposal and was, during our in-person discussions, supportive and in agreement with the benefits to STAR as a whole.

I am excited about this proposal and its benefits to the entire STAR physics program, and am thus committed to seeing that the proposed R&D is successful.

Signed,
Dr. William J. Llope

RICE

OFFICE OF SPONSORED RESEARCH
HEIDI THORNTON
ASSISTANT DIRECTOR

November 11, 2008

Mr. Lloyd Bridges
Blue Sky Electronics, LLC
Houston, TX 77009

Dear Mr. Bridges:

Rice University is pleased to be included in the application for a Phase I SBIR research project to the Department of Energy. Rice will provide electrical engineering support (Ted Nussbaum) for the research described in the Blue Sky SBIR Phase I proposal to develop Fast Vertex Electronics. Rice will provide electrical engineering support to help implement the development and design objectives described in the SBIR proposal.

Research to be subcontracted to Rice University will be carried out under the direction of Dr. Geary Eppley, Department of Physics and Astronomy. The sum of $10,000.00 including Facilities and Administrative costs, is requested for the period July 15, 2009 through April 15, 2010.

Should you have any questions, please do not hesitate to contact me. We look forward to working with you.

Sincerely,

Heidi Thornton

Heidi Thornton

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

[Note: This proposal is an improved but substantially similar version of an FY08 proposal. Reviewers and the NP Program manager suggested that we resubmit after completion of the STAR TOF construction project. That construction project is now complete. The need for the proposed hardware remains, as indicated by our support letters.]

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.

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.

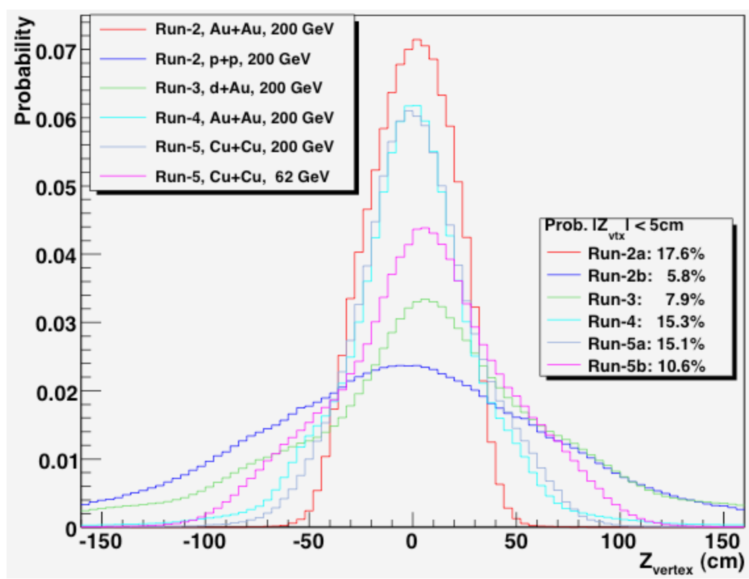

Figure 1: Variation in the Z-location of the STAR primary vertex

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 700 ns. (Our design goal is 300 ns).

Our team members are experts at the required time-of-flight measurements and are intimately familiar with the STAR environment. We are currently completing installation and commissioning of a 23,000 channel time-of-flight detector system for STAR. Our low risk Phase I plan is to adapt existing, working hardware to rapidly build a vertex position measurement prototype that meets the positional accuracy requirements, mainly by modifying on-board programmable logic. Then we will develop and test new timing circuits to overcome existing limitations in latency, throughput, and crosstalk.

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.

A. Background – Collider Triggering

Our system will provide event selection with a resolution on the order of 1 cm at the earliest possible trigger level. As described below, this capability can in effect improve the overall productivity of the STAR detector and so will substantially improve STAR’s use of RHIC’s limited and expensive beam-time. Given the capital and operational costs of STAR and RHIC, such a productivity improvement would represent an excellent return on the developmental 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” where small size compounds the inefficiencies of low resolution vertex position measurement to unacceptable levels.

The RHIC collision rates are increasing every year, and the so-called RHIC-II upgrade promises an increase of another large factor in the event rate. The need for precise measurement of the location of the collision in Z at the earliest levels of the STAR trigger will thus soon become crucial. 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 'sweet spot' of 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 the 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 thus provides a high-resolution space-point at (X,Y,Z) of (0,0,Zvtx), improving online track reconstruction and hence 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. There is thus the additional benefit that a "high-rate-only-detector" data stream can collect specific interesting spectra at rates of several kHz - an order of magnitude beyond what STAR can do when having to digitize 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.

Also, 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: Both the newly proposed “ringtof” detector and the existing 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 $|Z|$~5.7m. The upVPD has a kinematic acceptance of approximately $4.3 < |\eta| < 5.1$. The ringtof is a pair of annuli on each side of STAR at a distance of $|Z|$~6.5m. Each annulus consists of 512 channels of Multi-gap Resistive Plate Chambers in a kinematic acceptance of approximately $2.5 < |\eta| < 4.0$.

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.

B. Background – other instrumental applications

Time-of-Flight Mass Spectrometry (TOF-MS) measures 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. Discoveries of 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 < 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. We have included a letter of interest from MassTech, a leading mass spectrometry manufacturer.

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. Our proposed system is almost directly applicable as a TOF-PET data acquisition system – the required modifications, which we will investigate in Phase I and propose as a complete set in Phase II, would include smaller detectors (e.g. avalanche photodiodes, as are already being used in TOF-PET implementations), front end modifications to accommodate these detectors, and programmable logic firmware changes (e.g. no signal averaging, coincident window event labelling). Our existing hardware for Phase I prototyping already implements the required precision clock distribution (15 ps jitter over large over hundreds of boards and 10s of meter distances) and Gbps data readout.

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. 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

$$\text{(1)}\quad Zvtx = (c/2) * (Teast - Twest).$$

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.

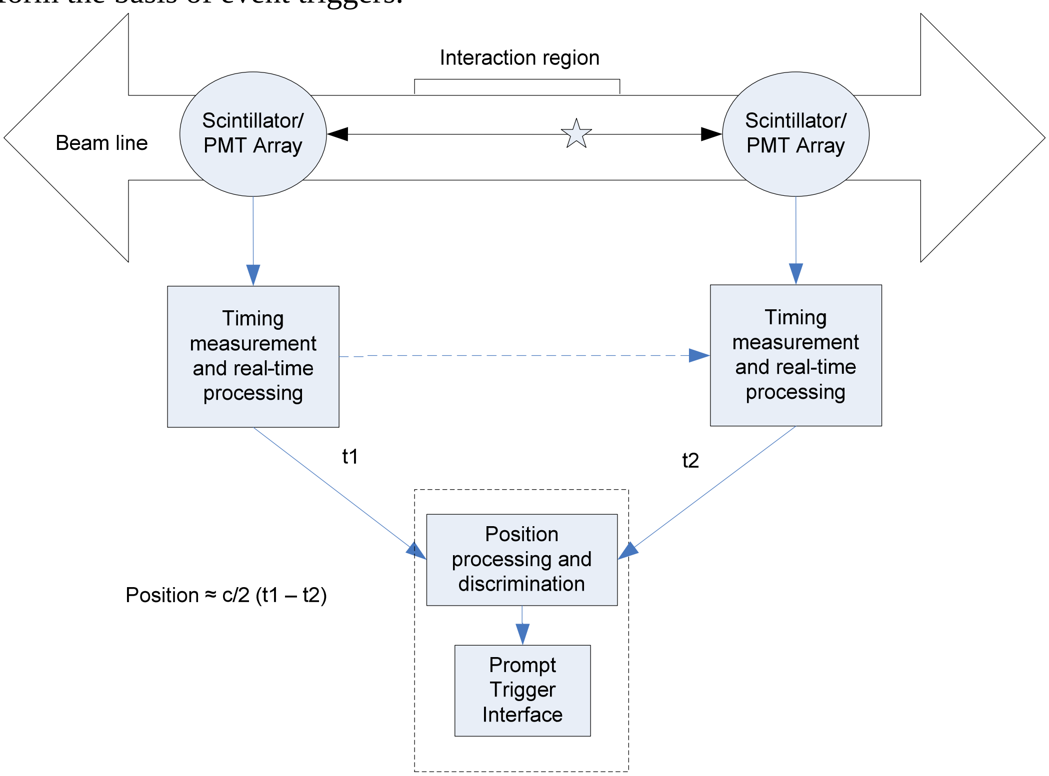

Figure 2: Basic overview of the detectors and proposed digitization electronics

The timing measurement electronics operate from a common, low-jitter 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) σ(Zvtx) = [c/sqrt(2)] * [σ(detector)/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.

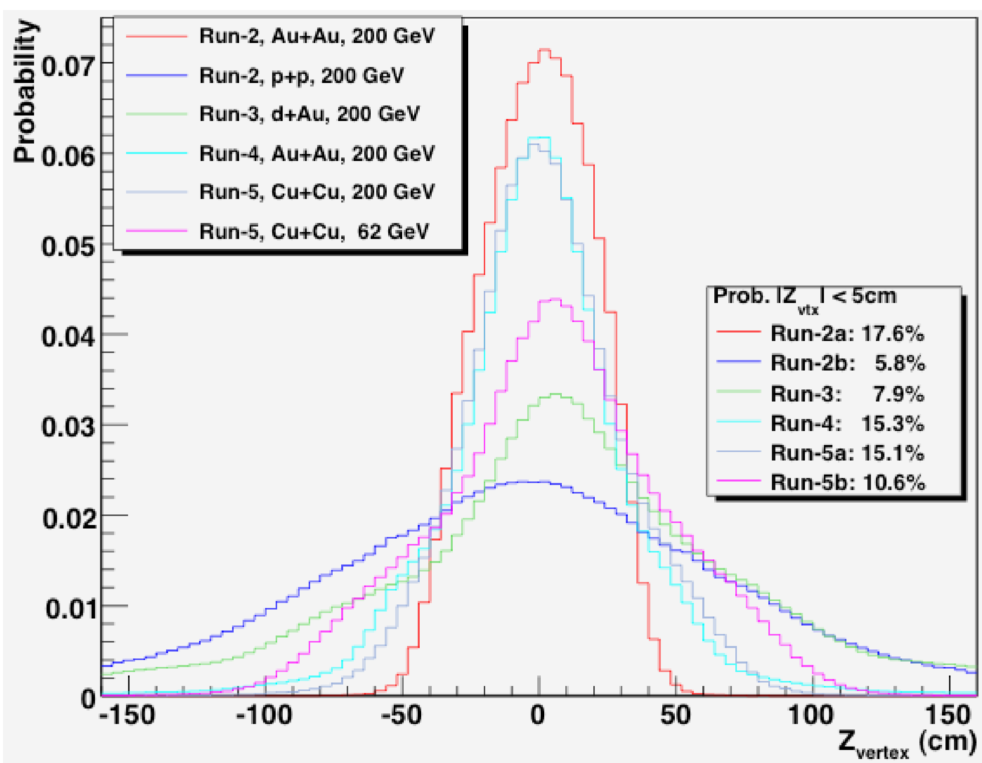

Figure 1 (repeated): Variation in the Z-location of the STAR primary vertex.

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.

Major advantages of the proposed electronics over what has been performed to date in STAR arise from much shorter signal cable lengths before the digitization, the addition of 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. The resulting Zvtx resolution is thus, 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.

D. Anticipated Public Benefits

The proposed work will significantly improve the efficiency of existing detectors at RHIC and will enable the efficient use of pr oposed 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
- 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 medical diagnostics, improved manufacturing capabilities and environmental pollution control.

E. Technical Objectives

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.

As discussed below, the majority of the work in Phase I will be expended on objective 3. The rapidly prototyped system from objective 2 will mostly use existing hardware. It will meet the position resolution requirement, but not other requirements. Except for the TDC cards, it will be used as a realistic testbed for the new timing electronics developed in objective 3 and in Phase II.

Planned Phase II technical objectives:

1. Design and build a high performance Vertex Position measurement system for STAR, including a fast interface to STAR trigger.

2. Scale up the number of channels in the system, the channel areal density and the processing and readout bandwidth. Add provision for local storage. Channel density, including front end discriminators, is particularly important for PET, while readout speed is particularly important in hybrid ion-mobility/TOF mass spectrometers. One option here will be to produce a custom integrated circuit incorporating the successful approaches from Phase I’s objective 4.

3. Interface the timing electronics with newly emerging detectors, particularly avalanche photodiode (APD) arrays, including any necessary modifications to the digital signal processing. Add interface capability for driving system excitation sources (lasers and ultrasonic sources) for 3D imaging, remote sensing and flowmeter applications.

4. Perform more advanced real-time processing, including coincidence triggering and particle tracking. This effort would mainly involve firmware development which (combined with high readout bandwidth or local storage capability from #1) would position the system to work as a small-scale, self contained DAQ suitable for small experiments or prototype detector testing.

F. Phase I Work Plan

Objective 1: Verify the system design requirements with STAR experts for a Vertex Position measurement system.

Based on the extensive STAR experience of Bill Llope, Jo Schambach and Geary Eppley we believe that a vertex position system meeting the following requirements will satisfy STAR's needs for some years, including anticipated needs from increased luminosity and small inner tracking detectors. We currently consider the major system-level requirements to be:

- 1 cm position resolution along the beam axis
- < 700 ns response latency (300 ns design goal)
- Interface to standard STAR trigger hardware
- 10 Mhz data rate

We will discuss these requirements directly with the STAR trigger group, verifying and modifying them as necessary. We will also flesh out secondary requirements relating to final installation in Phase II, such as resistance to single-event upsets, power limitations, installation form factors and radiation cross section issues (interference with other detectors).

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

Blue Sky Electronics has been involved for several years in providing TDC and readout electronics for the barrel TOF detector at STAR. Final board delivery for this 23,000 channel TDC system is now complete. At least 60% of channels will be online for RHIC Run 9, with the remaining availability depending mainly on installation issues.

To meet objective 2, we will use these existing TDC and readout boards, with new on-board signal processing firmware, to rapidly prototype two timing subsystems – one for each side of the STAR detector – using the 19-channel scintillation detectors already in place at STAR.

Our existing TDC boards (known internally as TDIG and marketed as the PicoTOF 25) are based on the CERN HPTDC device. These boards use a low-complexity serial readout scheme that requires 900 ns to read each TDC word. As a result, this "off-the-shelf" system will not meet the final latency requirement (< 700 ns) necessary for participation in the Level 0 trigger.

Nevertheless, there are two important benefits to this "rapid prototyping" objective:

1. We will demonstrate ~ 1 cm position resolution (with full detector occupancy), using real-time INL correction, time slewing correction, and signal averaging.

This is an important proof-of-concept demonstration for precise real-time vertex position measurement.

2. STAR's Level 2 readout rate is 1 kHz. If our latency of approximately 10 microseconds allows participation in Level 2 trigger aborts, we could provide a substantial increase in STAR's efficiency by providing a real-time vertex position gate that would reject useless events that have nevertheless passed the existing, but coarser position trigger. Any improvement in rejection of "long tail" events that were saved for processing, but then rejected during off-line processing, would increase the overall detector efficiency.

Figures 3 and 4 show the proposed prototype setup and the existing TDC and readout cards. The discriminator front end cards will either be the existing Rice-designed "TAMP" cards from the STAR TOF start detectors, or Blue Sky's new modular 8 channel discriminator card (Figure 2), which is currently under development using internal research funds.

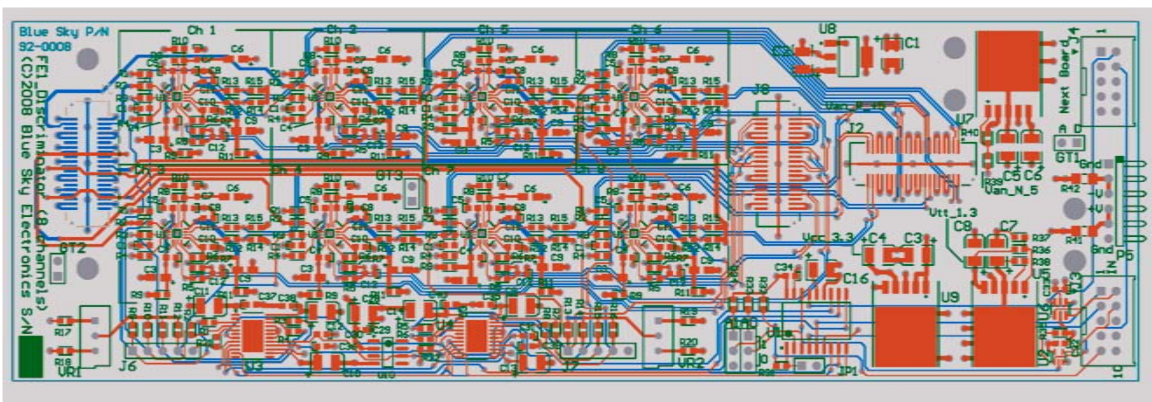

Figure 2: New 8 channel discriminator with independent thresholds

Each of Blue Sky's TDC boards contains 3 HPTDC devices configured so that each board has 24 TDC channels, each with 25 ps resolution. Data readout to an on-board FPGA is serial and takes 900 ns per word. The HPTDC devices experience substantial (about 75 ps) internal timing crosstalk when capturing 25 ps data, so in this high occupancy environment we will use the devices in 100 ps mode to reduce timing crosstalk, or will restrict their use to 1 channel per device (3 channels per board). Depending how we decide this tradeoff, and what restrictions we place on latency, we will use one to six TDIG boards in each chassis. Fewer channels per TDC device will reduce readout latency. Blue Sky (or Rice University) will loan the necessary boards from production inventory to the project for this Phase I demonstration, so the project budget will not be impacted by their use.

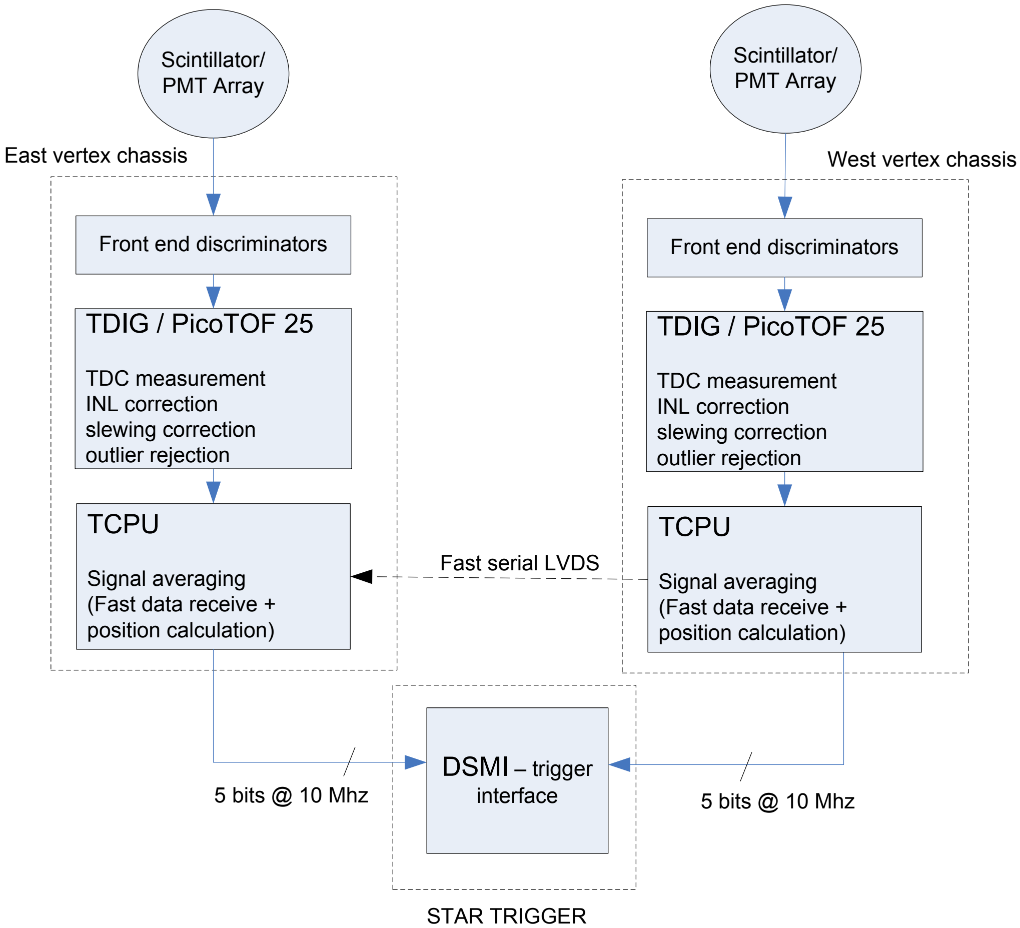

Figure 3: Rapidly prototyped system with existing components and new firmware

The TDC boards will implement INL correction, time slewing correction and outlier rejection (based on timing phase with respect to the RHIC clock) in their on-board FPGAs, and then transmit the data to the TCPU readout card over fast LVDS links. INL correction, time slewing correction and outlier rejection will be implemented with new FPGA firmware in the TDIG circuit cards.

Each TCPU board will accept data from the attached TDC board(s) and compute a channel average from corrected time measurements, using new FPGA firmware. Each TCPU will then send its average to STAR trigger's DSM interface cards over the existing parallel PECL interface (used in STAR TOF to transfer multiplicity data to STAR trigger). We are currently testing this interface with upgraded DMSI cards at STAR.

As described, the final position calculation will take place within STAR trigger. Optionally, a high speed connection is available between TCPU boards (dashed line in Fig. 3) that would allow us to transfer one TCPU's signal average result to a second TCPU, which could then calculate the final vertex position and a position dependent trigger signal, but with some cost in additional latency.

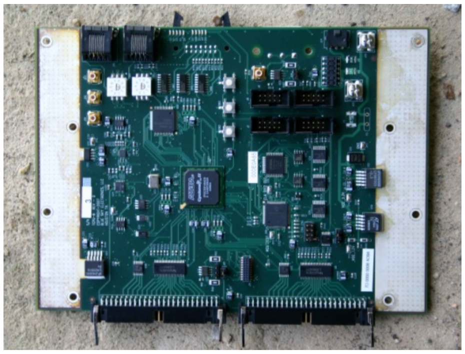
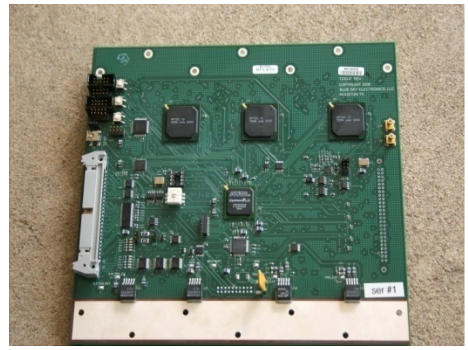

Figure 4: TCPU data readout card (left) and TDIG (PicoTOF 25) TDC card (right)

Objective 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.

It is important to balance the requirements for low latency, high resolution, and low deadtime. The fastest TDC with the highest channel count is not the goal. The candidate approaches we will consider include the following:

1. Using the CERN HPTDC with parallel readout. This is the lowest risk approach, due to our very extensive experience with the HPTDC device. We will verify with existing boards the crosstalk at 100 ps bin width operation, and the actual readout latency (using the "data ready" output signal). If we choose this approach, we will prototype a TDC card that uses a single TDC with parallel readout to an FPGA and measure actual latency performance. The full design will likely be a daughtercard / motherboard architecture allowing flexible arrangements of inputs to TDCs. It will be important to balance channels per TDC with readout rates. We recently learned that CERN is possibly creating a new version of the HPTDC with new packaging to reduce crosstalk; if it becomes available in time, we will evaluate it for use in this prototype.

2. Discrete DLL interface to FPGA. The actual TDC mechanism in the HPTDC and the commercially available ACAM TDC devices is a delay locked loop, whose state is saved by incoming data pulses. A DLL consists of a ring of buffer gates, with a controller that adjusts the bias on the gates so that the propagation delay through all the gates remains constant. The nominal resolution (degraded by differential nonlinearity due to individual gate delay variation) is one gate delay, while the frequency of oscillation to be controlled is 1 / N * gate delay. So for a 10-tap DLL with 200 picosecond gate delay, the ring oscillator frequency would be 500 Mhz. Digital gates for telecom applications are available in this performance range. For example the Micrel 58051 has a propagation delay below 200 picoseconds, a small MLF-16 package, and low cost (~ $6 each). These gates are well capable of fanout > 1, so multiple channels of TDC can be created by using separate PECL register logic to latch the state of the ring oscillator when incoming pulses arrive. One stage of

parallel demux would allow data to be clocked into an FPGA at 200 Mhz with sub-nanosecond dead time. A faster, and possibly smaller implementation of the DLL portion could utilize discrete transistors as inverters for the ring oscillator, but our current thinking is that 100 to 200 ps resolution is adequate, given the signal averaging gain available from high-multiplicity events, and a fully digital implementation will be flexible and robust.

3. Precision measurement of sinusoidal phase. All digital TDCs measure the total time interval as a sum of a coarse count and an offset relative to the coarse counter's clock edge. A very precise TDC can be realized by locking a sinusoid to the coarse counter clock, then storing the value of the sinusoid via a sample and hold operation when the input pulse arrives. If the stored sinusoid amplitude is measured with high precision, then the phase of the sinusoid (and hence the delay) with respect to the reference clock is also known with high precision.

Objective 4: Design the architecture for a final vertex position measurement system to be built in Phase II. Optimize the architecture for general use as a subsystem in commercial instrument systems.

Based on the work done to meet objectives 1 to 3, we will design a complete vertex detector measurement system, conduct design reviews and present the design as the basis for our Phase II proposal. We will design the final architechture to be modular and adaptable for application in some of the following instrument systems: time-of-flight mass spectrometers, time-of-flight positron emission tomographic imaging systems, time-resolved confocal microscopes, three dimensional imaging and precision machining equipment, transit time ultrasonic flow meters and remote environmental sensing instruments

G. Related Research or R&D

Our long term and and successful experience during Phase I, II and III work on the STAR TOF project makes us uniquely qualified for this project. Relevant details are discussed above.

H. Principal Investigator and other Key Personnel

Lloyd Bridges (PI) will have overall system design responsibility, and will design the overall architecture for the prototype system, in consultation with Ted Nussbaum and our scientific collaborators: W.J. Llope, J. Schambach, and G. Eppley. He will be responsible for the important managerial and technical communication involved in solidifying the requirements definition for Objective 1, and will implement new FPGA firmware for Objective 2. He will be involved at the architectural level in Objective 3, choosing candidate approaches for new front-end and timing circuits. He will have final responsibility for defining and articulating the architectural solution resulting from Objective 4.

William D. Burton, Jr. (Systems Analyst) will have primary responsibility for circuit and printed circuit board design for the new front-end and timing circuits for Objective 3. He will participate in assist in design reviews of system interface requirements definition (Objective 1), design reviews of prototype system functionality (Objective 2), design reviews of new front-end and timing circuits (Objective 3), and design reviews of the final architecture (Objective 4). With assistance from Ted Nussbaum, he will design test fixtures, test, and evaluate test results from the prototype system (Objective 2) and the new front end and timing circuits (Objective 3).

Ted Nussbaum (Rice University Electrical Engineer) will provide electrical engineering support to implement the development and design of the fast vertex electronics. His primary responsibility will be to assist in design reviews of system interface requirements definition (Objective 1), design reviews of prototype system functionality (Objective 2), design reviews of new front-end and timing circuits (Objective 3), and design reviews of the final architecture (Objective 4). He will assist in testing and evaluating test results from the prototype system (Objective 2) and the new front end and timing circuits (Objective 3).

Scientific Advisors

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

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

I. Facilities/Equipment

Blue Sky Electronics, LLC occupies 900 square feet of commercial office space at 401 Studewood, Suite 203 in Houston, Texas. Blue Sky has been prototyping and manufacturing electronics for over 14 years and has all the required equipment, tools and software necessary for system, circuit, printed circuit and firmware design and troubleshooting.

In addition, Rice's Bonner Nuclear Laboratory has a fully equipped electronic development lab that will be available for use, including a very high speed digital oscilloscope.

Blue Sky's tools include:

- 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;
- SBS PCI/VME interface 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 power supplies
- Numerous cables, RF connectors
- Comprehensive PCB rework and soldering tools

Blue Sky's software includes:

- SolidWorks 2008: 3D mechanical design
- Altium Designer 2008: integrated electronic schematic capture, printed circuit board design and simulation
- 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;
- Chronology Timing Designer - timing diagram editor;
- Model Technology ModelSim (Altera version) - VHDL and Verilog compiler;

J. Consultants and Subcontractors

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: $10,000

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