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Electronics for Fast Vertex Position Measurement and Medical Imaging

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

Summary

We propose below to design and build new electronics providing a high-resolution, real-time vertex position measurement for collider experiments and medical imaging 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 2.

A fast and precise determination of this 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 [1]. Our new electronics will provide these benefits in a very cost effective manner, compared to the large capital cost 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 a 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 [1] including real-time measurement processing in hardware, to

provide vertex postion measurement on the order of 1 cm on a continuous basis with latency on the order of 200 ns.

Analogous systematic improvements in efficiency and sensitivity can be realized by applying fast timing measurements to find track vertices in Positron Emission Tomography (PET) [2], which we discuss along with other applications, notably time-of-flight mass spectrometry, in our commercialization section.

Our team members are experts at the required time-of-flight measurements and are familiar with the STAR environment (we are currently in the construction phase of a 23,000 channel TOF system for STAR). Our plan is to adapt existing, working hardware to rapidly prototype a vertex position measurement testbed that meets the positional accuracy requirement, and to develop new timing circuits to overcome existing limitations in latency, throughput, and crosstalk.

Background

The main 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, called “Zvtx”. Our system will provide this 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 control of the location of the collision in Z at the earliest levels of the STAR trigger will thus soon become crucial. Some of the major benefits to STAR brought by the proposed electronics are now described in more detail.

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 below) 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 thus provides a high-resolution space-point at (X,Y,Z) of (0,0,Zvtx) which will improve the 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" – see below) 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 □-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 approximately 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 approximately 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 √(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.

Technical Approach

Figure 1 illustrates the proposed technical approach. Due to kinematics, properly-gated leading particles at very forward angles are all traveling at speeds very close to the speed of light, “c”. Thus, the placement of two detector arrays very close to the beam-pipe, one on the east of STAR and one on the west, allows the fast-timing of these v=c particles and thus an accurate reconstruction of the location of their source (the primary vertex). The “east-west” timing of these very forward prompt particles allows the calculation of the Z-position of the primary vertex via

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

Here, Teast(Twest) is the time seen on the east(west), and c is 30 cm/ns.

The major advantage of this approach is its speed. The upVPD detectors used for this measurement are based on photomultiplier tubes, which can handle high input rates and are capable of single-detector timing resolutions of approximately 100ps. The Zvtx resolution possible via accurate east-west timing (described in more detail below) can rival that achieved offline. We propose to bring this level of resolution online. The alternate approach to obtaining this information uses full-event 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 low-level event triggers.

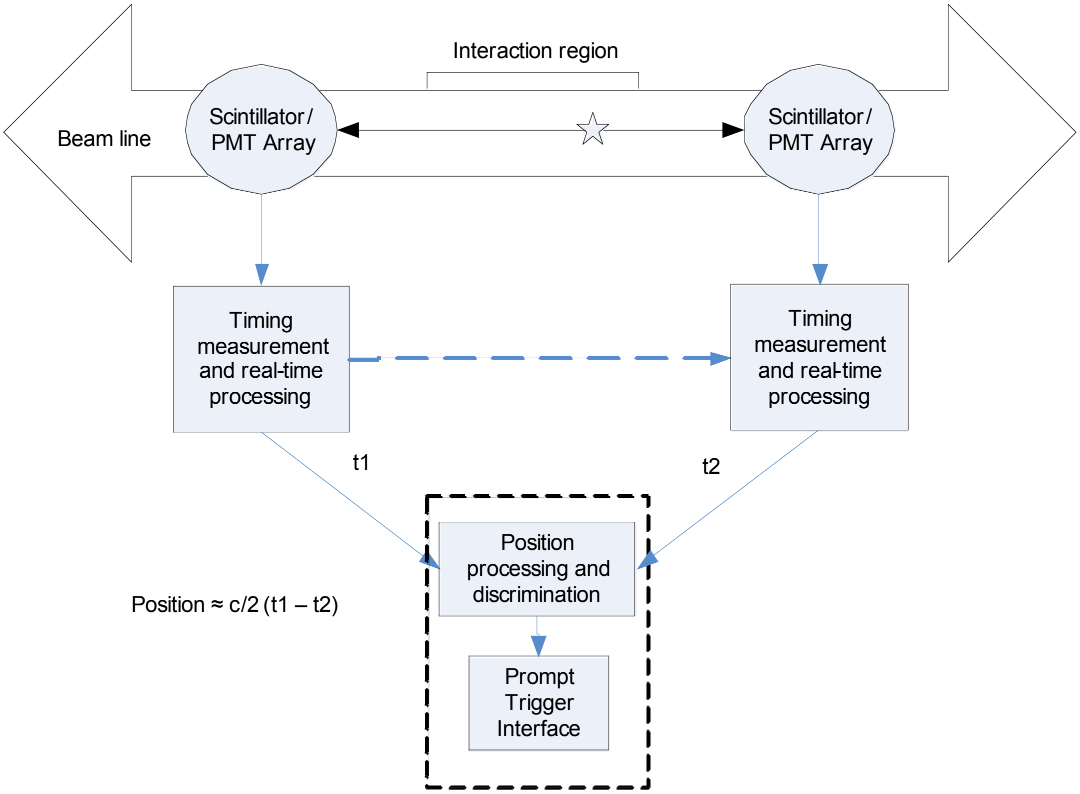


Figure 1: Basic overview of the detectors and proposed digitization electronics

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

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

where σ(detector) is the intrinsic single-detector timing resolution (approximately 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, which is a significant improvement. The increased acceptance to the measurement that would result with the addition of ringtof obvious allows the averaging effect to come into play, leading to a Zvtx resolution in p+p < 2cm.

The benefits from such an improvement to the resolution are made clear in Figure 2. 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.

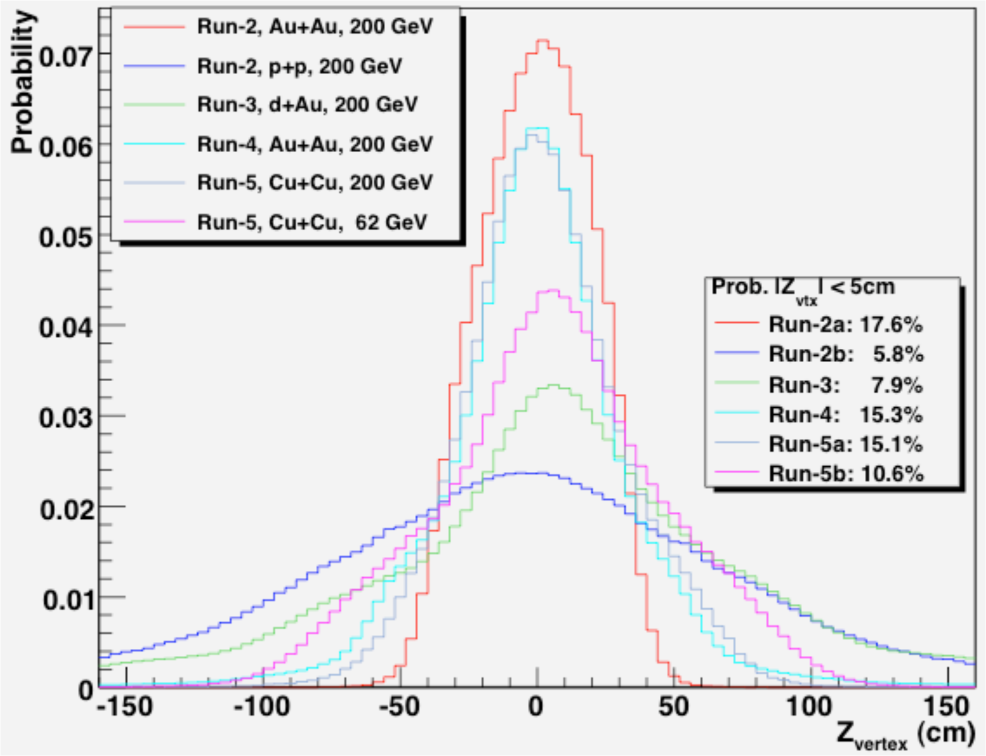


Figure 2: The uncontrollable variation in the Z-location of the primary vertex, Zvtx, for various RHIC runs.

According to Figure 2, 80-90% of the events STAR collects are outside 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. Using the same data as shown in Figure 2, the probability that Zvtx in the events triggered upon, written, calibrated, served to user analyses, and then rejected there with a 30(50) cm cut, is 30-50%.

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, or PETs (which use the same type photomultiplier-based detectors).
2. apply offset and slewing corrections using uploaded 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 result 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.

The proposed boards are closely related to similar electronics already developed by Blue Sky Electronics (in collaboration with the same participants from Rice and Texas) as part of the STAR TOF project. The intended use of these boards both in STAR and in the medical imaging community does not compromise either direction.

D. Anticipated Public Benefits

The first public benefit from the proposed work will be to facilitate the physics objectives described above. These objectives will be achieved through new inner tracking detectors, and through more efficient use of existing detectors at STAR. Achieving these physics objectives in turn will help to maintain national leadership in fundamental physics research, and to maintain the high performance electronics infrastructure necessary for that research. Scientific leadership and state-of-the art technical infrastructure are important for both economic innovation and national security.

The second, and very direct public benefit is increased capability for medical and biological imaging. The proposed system is directly applicable to data acquisition for Positron Emission Tomography (PET) and Secondary Photon Emission Computed Tomography (SPECT). Time-of-flight PET is an emerging technique for diagnostic medical imaging, and SPECT is likewise increasingly used for in-vivo metabolomic studies of pharmaceuticals. High-rate, high-resolution time measurement is a key component of time-of-flight mass spectrometry and the proposed electronics will fit that instrument as well.

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 in TOF mass spectrometry, and in PET, SPECT imaging systems.

As discussed below, the majority of the work in Phase I will be expended on objective 4. The rapidly prototyped system from objectives 2 and 3 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 4 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, particularly for use with Positron Emission Tomography (PET) and Single Photon Emmision Computed Tomography (SPECT) imaging systems. 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.

4. Perform more advanced real-time processing, including coincidence triggering and particle tracking.

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 two team members, Bill Llope and Jo Schambach, 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
- 100 to 300 ns response latency
- 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 construction of this 23,000 channel TDC system is underway, with hundreds of channels currently installed for RHIC Run 8, and with Blue Sky proceeding with production of over 1000 total electronics circuit cards under a Phase III SBIR contract.

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 [3].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 (100 to 300 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 to 2 cm position resolution, 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. 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 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.

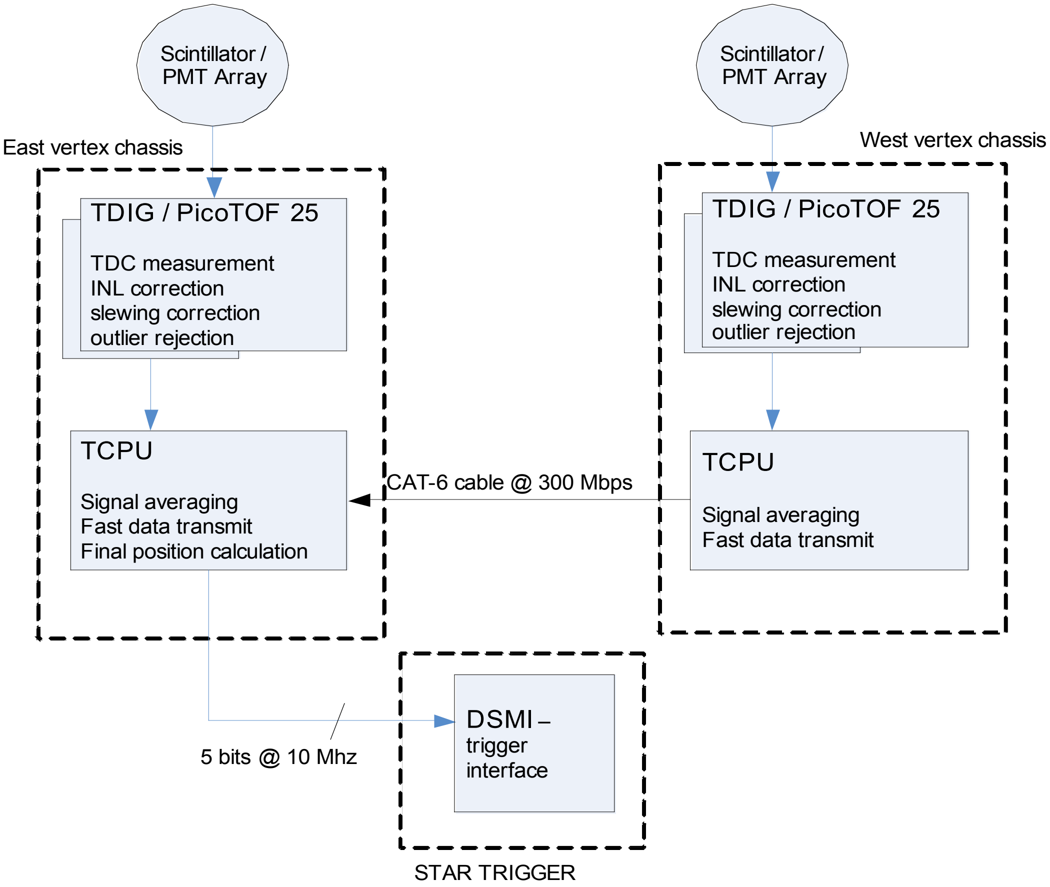
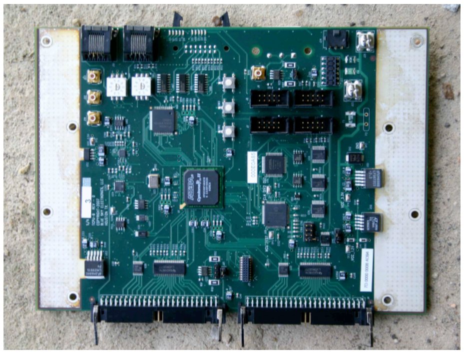


Figure 3: Rapidly prototyped system with existing components and new firmware

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. Each TCPU board will accept data from the attached TDC board(s) and compute a channel average. One TCPU will send its average to the second TCPU over the existing high speed copper link. The second TCPU will then compute the final vertex position and send it, or a position gated trigger signal, to the DSM interface card over the existing parallel PECL interface (used in STAR TOF to transfer multiplicity data to STAR trigger).

INL correction, time slewing correction, outlier rejection, time measurement averaging and position computation will be implemented with new firmware.



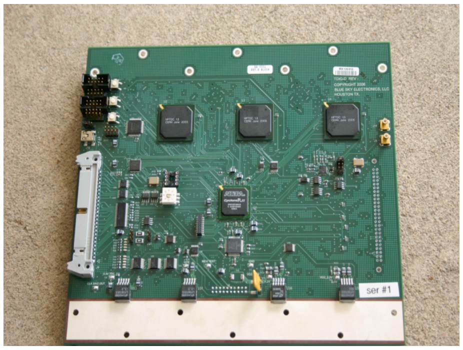


Figure 4: TCPU data readout card (left) and TDIG TDC card (right)

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.

This objective is central to the Phase I and II projects, and will consume the balance of the work effort in Phase I. 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 our system design process chooses 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 creating a new version of the HPTDC, if 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 ps 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 propogation delay below 200 ps, 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, 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 timing system to be built in Phase II. Optimize the architecture for general use in TOF mass spectrometry, and in PET, SPECT imaging systems.

Based on the work done to meet objectives 1 to 3, we will design a complete vertex detector timing system, conduct design reviews present the design as the basis for our Phase II proposal.

References
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[3] [M. Mota, J. Christiansen, S. Debieux, V. Ryjov, P. Moreira, A. Marchioro, "A flexible multi-channel high-resolution time-to-digital converter ASIC," 2000
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[3] The Star Collaboration. A heavy flavor tracker for STAR. Nuclear Physics A 2006 Volume 774, p. 907-910].

G. Related Research or R&D

Related research is discussed and referenced above.

H. Principal Investigator and other Key Personnel

Lloyd Bridges (**Principal Investigator and electrical engineer)** will direct the research project and be responsible for meeting objective 1 (Requirements definition). He will oversee objectives 2 (Configuration of VPD with TDIG, TCPU) and 3 (STAR trigger interface). He will design the intial multichannel timing circuits and write 2 progress reports and the final report.

William D. Burton, Jr. (Systems analyst) will design and implement objectives 2 (Configuration of VPD with TDIG, TCPU) and 3 (STAR trigger interface). He will design the revised multichannel timing circuits.

W. J. Llope, PhD will advise on requirements and architecture. No costs for his time will be charged to the project.
J. Schambach, PhD will have a similar advisory role. 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 10 years and has all the required equipment, tools and software necessary for system, circuit, pcb and firmware design and troubleshooting.

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;
- Numerous high capacity power supplies
- Numerous cables, RF connectors
- Comprehensive PCB rework and soldering tools

Blue Sky's software includes:

- 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

None will be used on this project.