Directors Review: sPHENIX MVTX Detector System

Reviewers

Jim Thomas (Chair) LBNL; Hucheng Chen, BNL;
Abhijit Majumder, Wayne State University; Penka Novakova, BNL;
Paul O'Connor, BNL; Gerrit Van Nieuwenhuizen, BNL

Introduction

A Directors Review Panel met on July 10-11, 2017, to evaluate the proposed sPHENIX MVTX detector system. The MVTX is a high resolution silicon vertex detector that will use monolithically active pixel sensors (MAPS) to record tracks inside the sPHENIX TPC. There were presentations on the physics of the MVTX detector, the mechanical construction and the electronics for the detector, as well as integration, infrastructure and the cost and schedule. The committee was asked to listen to these presentations and to assess the technical feasibility of the upgrade. The charge to the committee is included in Appendix A.

The committee would like to thank the collaboration for their hard work and their excellent presentations. It was clear that a great deal of effort went into the design and simulation of the detector; as well as its cost and integration with the other detectors in sPHENIX. The collaboration is to be commended for their clever use of existing technologies and resources at CERN. The Los Alamos National Laboratory is also recognized for its timely and critical investment of LDRD funds in the project; especially for the detector electronics.

Summary Findings

The sPHENIX collaboration proposes to build a silicon micro-vertex detector which will be located at the center of the sPHENIX detector system. The Si tracker will be used to record and capture *b*-tagged jets as well as to identify the decay of open charm and open beauty hadrons. These capabilities will allow the sPHENIX detector system to look for heavy flavor jet suppression and to measure prompt and non-prompt D^0 flow; as well as to estimate the total cross-section for $b\bar{b}$ production at mid-rapidity at RHIC. The b-physics program afforded by the MVTX detector will be complementary to the measurements made at the LHC by providing high quality data in a regime where the mass of the quark is comparable to its momentum (10-15 GeV/c).

Broadly speaking, the scientific case for the MVTX detector is compelling and the program dramatically enhances the physics capabilities of sPHENIX by enabling open heavy flavor measurements in the bottom sector and allows for b-tagged jets.

The conceptual design for the detector is technically sound and it will very likely meet or exceed the expectations for the program. The choice of MAPS sensors is excellent, and dovetailing the sPHENIX stave assembly sequence onto the end of the ALICE assembly line ensures a cost effective program.

The costs for the project are reasonably well understood. The cost for chips and materials are well defined. The costs for electronics are buffered by the Los Alamos LDRD project and this essentially ensures a cost effective electronics program. The mechanical engineering costs will be carried by the project, are well estimated, but should be re-evaluated after the re-design of the MVTX support system is complete and fully integrated with the rest of sPHENIX and RHIC.

The technically driven schedule for the project is well defined and well organized. The schedule for funding the project, and the lack of MOUs with CERN are a concern, however. A delay in funding the project, or a delay in establishing an MOU with CERN could delay the completion of the MVTX or even make it impossible.

The resources for the project are reasonably well identified. The committee does have a concern about the availability of skilled manpower, especially in the contributed labor category, and the continuity of expertise with prior experience on the ALICE project since this project is dependent on the efficient use of ALICE resources and expertise.

The risks associated with the hardware and electronics are well understood and actively being studied by the collaboration. The committee is concerned about the proximity of the detector to the RHIC beam-pipe. Solving this problem is challenging; but well with the reach of the engineering team.

The overall integration of the MVTX with the remainder of the sPHENIX detector is well understood. The electronic integration of the MVTX with sPHENIX is well defined and presents no significant hurdles to the project. The mechanical integration of the detector, however, is not fully defined. Several solutions are being investigated.

The collaboration did not present a Project Management Plan. The institutional responsibilities for each phase of the project are well defined, however, the sub-system leaders are not identified in the Organization Chart. It is possible that the Level I management structure may need to be coordinated with the funding agencies.

Finally, the ES&H aspects of the project are well organized and clearly identified. It would be useful for additional manpower, based at BNL, to join the ES&H effort to enable clear and efficient lines of communication with CAD and RHIC.

More specific comments and recommendations are included, below.

Scientific Program

Findings:

- The sPHENIX collaboration has presented a well thought out scientific program using the MVTX, INTT, TOF and TPC to measure b-tagged jets and open heavy flavor in the Bottom and Charm sectors.
- The *b*-jet tagging and open Bottom programs are compelling. v_2 and R_{CP} (R_{AA}) for the daughters from B decay, as well as the total *b*-quark cross section, are vital measurements.
- The open Charm measurements to be made by the MVTX will significantly improve upon what is already available in the literature.
- The b-physics program afforded by the MVTX detector will be complementary to the measurements made at the LHC. The LHC will provide a much harder initial spectrum of b-quarks and a higher temperature. The RHIC program will provide a softer spectrum of particles and most especially provide data in a regime where the mass of the quark is comparable to its momentum.
- The energy loss for light and heavy quarks is expected to be similar at high p_T and this is what is observed. However, at low p_T (10-15 GeV/c), the energy lost in a plasma is expected to follow a strict mass hierarchy depending on the mass of the probe; $\Delta E_b < \Delta E_c < \Delta E_q < \Delta E_g$. The statistical error bars from the experiments at CERN do not yet reveal this hierarchy. The MVTX collaboration indicated that they will be able to gather equal, or higher, statistics than the comparable programs at CERN.

Comments:

- We are excited by the possibility that sPHENIX may be able to resolve the ambiguity caused by the overlapping R_{AA} measurements at the LHC.
- There are now multiple theory approaches to heavy flavor energy loss. Each has a different set of theory assumptions (some with radiative loss, some without, some have transport coefficients, exact model of medium, K factors, running of α_s, etc.). It would be useful to see a wider range of theory curves on the key physics plots.
- The contrast between different theoretical results are often diminished after the theory is placed into an event generator. Event generator predictions on the key physics plots are always better than pure theoretical results.

Recommendations:

- The collaboration is encouraged to solicit multiple theory predictions in the range where new measurements can be made with sPHENIX; including error bars demonstrating how the MVTX can clarify the theoretical uncertainties. Calculations should be done on realistic hydro codes and tuned to soft spectra.

Simulations

Findings:

- B mesons preferentially decay into D^0 and $\overline{D^0}$, or into leptons, and so the MVTX program is focused on measurements in these channels.
- b-jet correlations (two in the same event) can help identify true b-quark jets
- b-tagged jets were simulated and identified by looking for prompt and non-prompt D^0 decays, and by looking for b-quark jet correlations with other jets in the same event
- Two different algorithms were used to define b-tagged jets. A preferred algorithm has not yet been identified.
- D_s and Λ_c are rare, but can also be re-constructed in the simulated events
- The b-jet cross-section was estimated using PYTHIA8+CTEQ6L
- B and D mesons as well as b-jets were embedded in HIJING events
- Event generators, GEANT4 and the latest tracking algorithms were used to estimate the performance of the MVTX detector
- Three key physics plots were shown: The b-jet nuclear modification factor, R_{cp} for non-prompt and prompt D^0 mesons, and v_2 for non-prompt and prompt D^0 mesons.
- The simulations were performed with and without the MVTX, using the projected sPHENIX run statistics
- The simulation techniques are state-of-the-art and were extremely well done

Comments:

- There were different results depending on which b-jet tagging technique was used.
- Of order 240 billion events, 3 years of running, are required for each key physics plot.
- The sPHENIX detector, with the MVTX, is an integrated system. dE/dx capabilities in the TPC could help reduce the runtime for the proposed MVTX physics program.
- Higher efficiency might be achieved if the design and performance of the INTT and MVTX were optimized, simultaneously.

Recommendations:

- The three key physics plots are an essential component of the Science case for the MVTX detector. As such, these plots should be refined. The committee recommends using the same style (and location) in each plot to highlight the theoretical predictions and to demonstrate the projected statistical and systematic error bars.
- Continue to improve the simulations. Demonstrate the degree to which sPHENIX can resolve the situation at the LHC where light and heavy flavor R_{AA} overlap each other.

Si Sensors

Findings:

The MVTX detector will upgrade the sPHENIX tracking system with three layers of monolithic active pixel sensors and will significantly enhance the sPHENIX heavy flavor program, especially bottom physics. The three layers will consist of 48 identical staves, each carrying 9 ALICE Alpide sensors. The staves will be assembled at CERN in the same facility that will produce the ALICE pixel staves (and the work will be done by the same technicians). Work on the MVTX staves will commence when the ALICE staves are finished and that transition is currently scheduled for the summer of 2018. Testing of the staves will be done by MVTX personnel, who will be stationed at CERN, and using the same equipment that was used for testing the ALICE staves. In addition to the 48 staves needed for the 3 layers of the MVTX there will also be 20 spare staves produced that can be used for repair of the MVTX during its lifetime in sPHENIX.

In the US, the staves will be assembled into (half) barrels at LBNL and shipped to BNL for insertions into sPHENIX. Quality Assurance will take place at all stages of assembly and installation.

Comments:

Implementing an ALICE-like pixel detector follows the recommendations of previous review committees. Taking into consideration the resources available and especially the very tight schedule, adopting (and basically copying) the inner three ALICE pixel layers for use in sPHENIX seems to be the only viable path to success.

We feel that only production at CERN by the people that were responsible for the ALICE staves guarantees the best possibility to get MVTX staves that are comparable in quality to the ALICE staves.

Using the existing ALICE expertise and infrastructure at CERN to assemble the necessary MTVX staves is fully supported by the review committee, although we note that closely tying the MVTX schedule to the ALICE pixel detector schedule is risky and raises some concerns.

The scenarios for testing and repairing staves need to be worked out in detail. After shipment from CERN to LBNL all staves should be tested and graded again before they are used in the barrel assembly. Also after reception of the completed barrel assembly at BNL, and before insertion into sPHENIX, the assembled detector should be tested again. This part of the MVTX work was not sufficiently defined at the review and there was insufficient accounting for facilities and infrastructure needed at BNL. To be able to fully test the system before insertion the MVTX team should be able to read-out a significant portion (preferably all) of the MVTX which also requires a suitable cooling system at BNL.

It is a distinct possibility that some or all of the MVTX could be damaged early in its life-cycle; beam excursions are a real possibility. This will most likely result in extended damage that requires replacement of a substantial part of the detector. At the moment it is unclear how the MVTX team will handle such an occurrence.

Recommendations:

- The MVTX stave assembly is dependent on the ALICE infrastructure at CERN. The BNL based MVTX project will be using CERN facilities and resources. It will also have to fit the ALICE stave assembly schedule and will only be used after ALICE is done. Considering this significant dependency, the committee strongly advises the sPHENIX management team to negotiate a Memorandum of Understanding, as soon as possible, between CERN and the sPHENIX project to protect the MVTX production schedule.
- Refine the Alpide purchase cost estimate with CERN. Costs for the chips were in a state of flux during the review (although in a good way). The acquisition costs need to be rigorously defined.
- The committee urges the MVTX team to fully work out a QA plan for the MVTX. It should be made certain that readout and cooling systems are available for use at any point from arrival of the staves at LBNL to insertion of the MVTX into sPHENIX at BNL. The necessity for multiple readout and cooling systems could have a significant impact on the cost and schedule for the project.
- Taking into consideration the sometimes disastrous beam excursions that did extensive damage to the PHOBOS, STAR and PHENIX silicon detectors, we strongly encourage the MVTX team to come up with a plan to deal with such an occurrence. For example, building a full copy, or at least the first two inner layers of the MVTX, is more useful than a plan to simply have twenty spare staves.
- Refine scenarios for repair and replacement of bad staves. Estimate how long it takes to disassemble sPHENIX, remove staves, repair or replace staves, align them, and re-install sPHENIX.

Mechanical Design and Cooling (WBS 1.5.3 and 1.5.4)

Findings:

- WBS 1.5.3 covers mechanics and detector assembly, including Staves, carbon structure, barrel assembly and Q/A. WBS 1.5.4 includes cooling plant, interface issues, and installation.
- The project takes maximum advantage of existing ALICE ITS components. In particular, the key component (stave) is mature and will be adopted without modification.
- Carbon structure includes end wheels, CYSS (cylindrical structural shell) and COSS (conical structural shell).
- There are two aspects of the ALICE carbon structures designs that need to be modified to fit into the constraints imposed by sPHENIX:
    - there is an interference between the service cone of the ALICE design and the INTT detector
    - there is inadequate clearance between the inner MVTX layer and the sPHENIX beam pipe
- Conceptual design solutions to these two problems are being developed in the context of the LANL LDRD. For example, an extension cable to the FPC has been identified with CERN/ALICE group as a solution to extend the high speed data lines as a mean to solve the interference between MVTX and INTT. The mechanical design of a corresponding extension of the support cone is not yet well developed. The final design will be done within the MVTX project.
- Barrel assembly has developed a detailed plan including QA, metrology and validation at BNL.
- Cooling plant design is based on the ALICE development and uses a negative-pressure, demineralized water cooling plus dry gas purge. A prototype of the cooling system will be exercised at LANL as part of the ongoing LDRD.
- Simulation study shows that increasing the radial distance of the inner layer to 2.8 mm from beam pipe does not affect the physics performance.
- An sPHENIX-wide integration team has been convened to formally define stay-clear geometries and interfaces.

Comments:

- sPHENIX mechanical constraints require additional design work on the carbon fiber mechanical structure. Committee consensus was that the plan and resources need further definition, and may be underestimated in the current cost and schedule.
- ALICE Stave production for MVTX will need close coordination with CERN. A backup option with CCNU as a production site has been proposed, the cost and schedule impact have yet to be understood.
- Delayed funding and final design of carbon structure construction will risk the overlap with other commitments at LBNL. Mitigation strategies need further development.
- Interference between INTT and MVTX has been identified by the sPHENIX Inner Detector Integration Task Force (IDITF), however the decision process for choosing mechanical design updates such as extension of support, cone angle are still to be defined.

- Preliminary study shows the feasibility of changing the inner radius of the detector to avoid conflict with the beampipe. The decision process and development plan is still to be defined.

Recommendations:

- Refine estimates of the engineering required to modify the ITS carbon structures designs.
- Consider including UV sterilization of the demineralized water in the cooling plant
- Move forward with MOUs with key production sites such as CERN, LANL and LBNL.

Electronics, DAQ and Readout

Findings:

- LANL LDRD is supporting the R&D of the readout electronics. System will be tested, validated and ready for production by Jan 2019.
- Significant development cost and technical risk are avoided by adopting ALICE/ATLAS hardware. Production costs are reduced by opting in with ALICE/ATLAS procurement.
- The MVTX readout electronics system includes FEE (Front-End Electronics) and BEE (Back-End Electronics) and EBDC (Event Buffering Data Compressor), plus interface cabling to staves and the power distribution system.
- FEE is using ALICE Readout Unit (RU), which is based on Xilinx Kintex Ultrascale FPGA and CERN developed radiation tolerant GBTx/GBT-SCA/VTRx components.
- BEE is using ATLAS FELIX card with PCIe Gen3 x16 interface and 48 duplex optical links. V1.5 FELIX card is available at LANL for integration test. V2.0 FELIX card will have timing mezzanine which provides flexibility to interface to RHIC timing system.
- Power system is using ALICE power board with CAEN power supplies, sophisticated control, monitoring, protection and diagnostics functions are included.
- Samtec Twinax Firefly cable will carry data, clock and control/trigger signal and interface to the staves.
- FELIX server will serve as EBDC, and interface to sPHENIX DAQ system though 10+ GbE crossbar switch, which is the responsibility of the baseline sPHENIX project.
- RU and power board will be installed in the experimental hall with up to 10 kRad TID exposure. Scrubbing will be implemented in FPGA to mitigate the Single-Event Effect (SEE).
- 20% spares have been planned in the readout electronics system WBS and cost estimate, in addition 35% contingency has been applied with total cost of $1285k.
- Readout board production test is planned to take place at BNL in 2019 after the hardware production.
- LANL personnel will go to CERN for training with ALICE Stave readout and production, which will build expertise in debugging, stave assembly and testing for MVTX.
- One ALICE stave is available at LANL, three more testing staves will be available by September that will be the main test platform for readout electronics development, test and integration. Full readout chain is expected to be established by the end of this year.
- Readout of ALICE Stave at 10MHz RHIC clock will be carried out at LANL.

Comments:

- Electronics risk analysis and mitigation strategies have been presented during the review, which is commendable.
- LANL LDRD on MVTX is an important effort with goals well aligned with the goals of the proposed DOE MVTX project. The LDRD will demonstrate flawless operation of ALPIDE+RU+FELIX readout chain, which has been identified as key risk mitigation for readout electronics of the MVTX project.

- LANL LDRD is supporting the R&D for the readout electronics. Failure to meet the LDRD milestones could have an impact on the cost of the MVTX project. These milestones should be tracked, carefully, by the project management team.
- DCS will likely involve a new hardware design, though it is not considered as a critical or difficult development.
- Interface to sPHENIX DAQ system is well planned, which should be coordinated with the development of other sPHENIX subsystems, e.g. TPC.
- Adopting ALICE/ATLAS hardware is a good approach to reducing cost and technical risk, however availability of resource and expertise from the responsible institutes (e.g. UT Austin for RU) is a concern.
- The interface cable to the stave will need to be evaluated to confirm the feasibility (e.g. lower readout data rate of 600Mbit/s) of the extension to accommodate the MVTX mechanical constraints.

Integration with sPHENIX

Findings:

- There is a conflict between the space occupied by the INTT detector and an ALICE style MVTX detector
- A task force has been established to look at integration issues for the inner detectors
- Integration of conventional systems (power, cooling, cables, grounding, etc.) for the MVTX has begun and procedures are well defined. Stay clear zones are less well defined.
- The MVTX detector can co-exist with the INTT, but only if the support cone for the MVTX is reduced in size and extended in length. This requires mechanical and electrical engineering design changes.
- Mechanical Engineering costs associated with copying the ALICE design appear to be appropriately estimated in the cost and schedule. However, changes to that design will be expensive and are probably not fully covered in the current cost and schedule.
- The MVTX detector cannot be repaired or maintained during a normal RHIC run maintenance period. Maintenance requires a summer shutdown.
- The MVTX detector comes within 1.3 mm of the beam pipe. This is a safety concern.

Comments:

- If the INTT design is fixed and final, then it is likely that changes to the MVTX design are required that go beyond the current cost and scope estimated by the MVTX project.
- The cost effectiveness of the MVTX detector is dependent on a simple engineering plan and upon making as few changes to the ALICE design, as possible. Few resources, and little time, are available to re-engineer the ALICE components. The MVTX may be lost as a subsystem if the re-engineering costs rise too high.
- CAD may have some advice regarding where the limiting aperture is located at RHIC, and how small it can be made.

Recommendations:

- Optimize the mechanical design of INTT and MVTX, simultaneously.
- Re-evaluate the mechanical engineering costs once the INNT and MVTX integration exercise is complete and locked under Engineering controls.

Cost & Schedule

Findings:

- The estimated cost for the MVTX project has exceeded the $5 M barrier.
- The total project cost (TPC) of the MVTX project is estimated at $5.7M which includes 35% contingency. Cost for materials is well understood; it based on the ALICE and ATLAS cost estimates for the staves and the electronics. Full cost recovery for the labor at CERN is estimated at $500k. The labor rates are fully burdened and 3% of escalation per year was used.

  Major Cost drivers are

1.5.2 Electronics	$1,285K
1.5.3 MAPS and Detector	$2,900K
1.5.4 Mechanical integration	$ 910K

- Cost for the electronics design is covered by an LDRD program at LANL. This appears to be well integrated with the plan for receiving MIE funds for construction.
- The MVTX schedule is developed in MS Project and is resource-loaded. There are interface milestones that link the schedule to the ALICE and sPHENIX schedules. The interface milestones are coordinated with ALICE and sPHENIX project leads.
- Risks have been evaluated for each WBS, for most WBS elements 35% of cost contingency is assigned. The only system that has 40% contingency is the Carbon structure, WBS 1.5.3.2. In general, the technical risks are low to moderate since the technology has been used by ALICE and the design is sound.

Comments:

- There are (only) 6 months of schedule float until the start of sPHENIX operations with beam.
- The assumption that the project will receive construction funds in January 2018 seems optimistic.
- The assumption that most of the labor for testing and fabrication is contributed by scientific resources introduces high risk to the project.
- It appears that the labor for mechanical design of the carbon structure is underestimated.
- Funding for fabrication of the staves at CERN is needed in summer of 2018 in order for the project to use the ALICE facility and expertise. A total of 68 staves – 48 needed for the detector and 20 spares are estimated to be produced at CERN. The schedule for production is 6 months. The MOU and contract with CERN are not yet developed. If this activity is delayed, the project will face a risk of losing critical expertise and the schedule will slip.

Project Management Plan

Findings:

- A Project management plan was not presented.
- The project team is growing rapidly. Significant institutions include, but are not limited to LANL, LBL, MIT and BNL.
- The project management team is well established. All L3 managers attended the review and have presented their respective subsystems. They all appear very knowledgeable regarding project management and technical issues.

Comments:

- MOUs between different institutions have not yet been signed.
- Higher risk is introduced by resource availability since most of the labor is contributed. The team may consider a retaining plan for critical project management and technical resources.
- It is very important for the project management team to establish an MOU with CERN and to clarify the contract terms and conditions as soon as possible.

Recommendations:

- Develop a Project Management Plan which provides guidance for managing the project; including the responsibilities for the team members, processes for change control and approvals, reporting, progress tracking, communications, etc.
- Clearly define the scope of the project by developing a WBS dictionary and a list of deliverables
- Consider evaluating and documenting all risks associated with costs, schedule, and procurements. The estimated contingencies in the project files should reflect this analysis.

Conclusions & Final Recommendations

We would like to thank the MVTX team for their hard work in preparing for the Review and we thank the three external laboratories (LANL, LBNL and MIT) for sending their speakers to BNL during these tight financial times.

The MVTX project has made excellent progress since the last review and it is worth noting that the Science case for the detector has been especially well articulated with up to date simulations and performance studies.

We recommend that the MVTX project proceed with the process of submitting a full proposal to the DOE Office of Nuclear Science.

Appendix A:

The Charge to the Committee from Associate Director Berndt Mueller

The purpose of this review is to assess the technical feasibility of the upgrade of the sPHENIX vertex detector project, MVTX, within cost and schedule constraints, and to assess the risks that the MVTX introduces to the overall RHIC program.

- Are the merit and significance of the project well justified and the conceptual design technically sound to meet the performance expectations?
- Are the costs of the project sufficiently well understood, and are all the resources required to complete the project fully identified?
- Is the schedule of the project sufficiently well understood and matched to the plan for installation in sPHENIX?
- Are the risks introduced by the project into the successful operation of the sPHENIX detector fully understood, and are sufficient plans to mitigate this risks in place?
- Are the interfaces and integration with the sPHENIX detector and RHIC well understood?
- Is the management and ES&H structure effective and the institutional responsibilities well defined?