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Run 2b TDC Review Committee Report

Run 2b TDC Review Committee

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I. Introduction

A review of the Run 2b TDC project was held on September 28, 2004. The Charge to the Committee is included as Appendix A. Primarily, the Committee was asked to provide a recommendation on whether or not to proceed with the production order of the Run 2b ("Chicago") TDC. In evaluating this question, there are three fundamental issues:

- If retained, how well can the Run 2a ("Michigan") TDCs perform in high luminosity conditions?
- If installed, how well can the Run 2b TDCs perform in high luminosity conditions?
- What are the relative risks for the two options?

The following document is organized to provide some background on this project, followed by a description of the impressive progress that has been made on both systems. We then present our findings and recommendations.

A recurring theme throughout this document is the outstanding progress that has been achieved in both systems. On behalf of the entire CDF Collaboration, we thank everyone who has contributed to these extensive efforts on both the Run 2a and Run 2b TDC systems. The outstanding progress that has taken place over the last two years is due to the tremendous efforts by a number of people. The Committee also appreciates the well-prepared talks that were presented in the review.

II. Background

The Run 2b TDC project was proposed as part of the CDF Run 2b trigger/DAQ upgrade, and received baseline approval with the rest of the project in September 2002. At that time, the CDF Run 2a detector had observed peak Tevatron luminosity of ~2×10^{31} cm^{-2}s^{-1}. We were attempting to specify system performance at a peak luminosity of 4×10^{32} cm^{-2}s^{-1}, a factor of 20 larger than had been observed. At that time, Run 2a TDC performance was stable, and the production of an additional set of "spare" Run 2a TDCs (Rev. F) was in progress [1].

In extrapolating from observed system performance and COT occupancies, there were three primary concerns associated with operating the Run 2a TDC system at peak Tevatron luminosity [2]:

1. The time to process hit data after a L2 accept (DSP processing time) would lead to large deadtime. For the Run 2a TDC, this included the time to process "out of time" hits.
2. The required data rates would exceed the maximum VME backplane transfer rates, leading to large deadtime.
3. The required data rates would exceed the maximum TAXI transfer rates to the event builder, leading to large deadtime.

Using an extrapolated COT occupancy that was linear in luminosity, these combined effects led to a projected peak readout rate of 150Hz at high luminosity. Because of these limitations in the Run 2a system, a new TDC design was proposed that was based upon a high input bandwidth Altera FPGA. The new design included features to specifically address the limitations of the Run 2a system.

In the past two years, significant progress has been achieved in both TDC systems. In addition, we now have an improved understanding of the high luminosity COT performance. We cannot do justice to the amount of effort that went into these systems in the past 24 months, but we list a few of the important highlights.

IIa. Run 2a TDC Progress

- The Rev. F TDCs were installed and commissioned during the Summer 2003 shutdown. These TDCs were installed on COT superlayers 1-4 and included "fast clear" functionality to alleviate DSP processing time required to handle hits from out-of-time bunch crossings.
- During the Spring 2004, DSP microprocessor code version 45 (DSP v45) was implemented, significantly reducing DSP processing time.
- During the Summer 2004, in conjunction with the Run 2b TDC group, DSP version 65 (v65) was developed. This new version implemented a data format that is common to the one utilized in the Run 2b TDCs. In this new format, the data is significantly compressed (almost a factor of two reduction) relative to the existing Run 2a data format.

IIb. Run 2b TDC Progress

- Significant firmware development, board layout and extensive simulations were performed throughout 2003.
- The first prototype board was available in February 2004.
- By the May 2004 review, there were two teststands (one at Chicago, one at Fermilab) and four prototype boards were under test. The testing results indicated a robust, well-understood design that would meet or exceed the design specifications.
- Five preproduction boards were received the week of September 20, 2004. The preproduction boards included several improvements, such as 64 bit VME transfer. Preliminary tests indicate that these boards would significantly exceed the Run 2b specifications.

The highlights cited above are described in detail in written documents as well as recent reviews [3,4]. Of course, details on recent progress were shown in this review.

In addition to significant progress on both TDC systems, we now have a much better understanding of the detector performance requirements for high luminosity running. We have seen colliding beam data with instantaneous luminosity above 1×10^{32} $cm^{-2}s^{-1}$. Also, thanks to hit merging techniques, the XFT group has assembled overlayed data samples that emulate COT operation for luminosity as high as 4.5×10^{32} $cm^{-2}s^{-1}$, significantly reducing some of the uncertainty in extrapolated chamber occupancy [5].

III. Presentations

In this section, we list some of the important information presented during this review. The agenda for the review is included as Appendix B and all of the presentations are available on the review web page. We thank the speakers for their well-organized, thorough presentations.

Specifications for TDC Performance in Run 2b

Although the exact details of Run 2b specification for the TDC system vary depending upon which document is consulted, the primary specifications are:

- The Run 2b TDC must operate with the COT front-end and be compatible with existing and upgraded XFT operation.
- The TDCs should be able to achieve ~1kHz (1kHz, 1.1kHz) readout rate with small (5%, 2%) deadtime at peak Run 2b luminosity.

The numbers listed in parentheses indicate the variation in the precise specification depending upon the source.

At the time of the Run 2b Lehman review, the specification for the accelerator performance was a peak luminosity of 2×10^{32} $cm^{-2}s^{-1}$ with 396ns bunch spacing, which would be achieved by luminosity leveling. CDF chose to design for a peak luminosity of $4 \times 10^{32} cm^{-2}s^{-1}$ with 396ns bunch spacing to allow for extrapolation uncertainties. In the time since the review, the peak luminosity projections from the Fermilab Accelerator Division have been revised upwards and are now estimated to be $\sim 3 \times 10^{32}$ $cm^{-2}s^{-1}$ (a projected peak luminosity of 2.8×10^{32} $cm^{-2}s^{-1}$ with 396ns bunch spacing was reported at the September 8, 2004 DOE accelerator review.)

The Run 2b TDC project completion date is September 30, 2005. There is little contingency in this schedule.

COT Performance in Run 2b

The XFT group has used a hit-merging technique on Run 2a zero bias data to provide COT occupancy estimates for high luminosity running [5]. The “merged” data compares favorably to data from high luminosity running, and provides hit rates and data volume rates. The primary figures of merit for TDC performance are the "most occupied" TDC (relevant for on-board processing) and "most occupied" TDC crate (relevant for data-transfer limitations.)

Projecting to 4×10^{32} cm^{-2}s^{-1} < $\mathcal{L}$ < 4.5×10^{32} cm^{-2}s^{-1}, using an EM8 trigger plus overlapping minimum bias events (9-10 minimum bias on average) the most occupied TDC shows 2.9 hits per channel (~280 hits in the 96-channel TDC) and the most occupied crate has 3200 hits, which, using the Run 2b TDC data format, translates to 7.3kB/event.

The original Run 2b data volume extrapolations looked at average occupancies, not the "most occupied" board or crate. Even so, these new estimates are significantly lower than the original Run 2b extrapolations for two reasons:

1. The original estimates used the Run 2a data format, which uses 32 bits per hit, while the Run 2b data format uses 16 bits per hit.
2. The original extrapolations did not account for saturation coming from overlapping COT hits. The new analysis shows this effect is significant on the inner superlayers and limits the number of hits per TDC. Linear extrapolations indicate 4 hits/wire on the inner superlayers at high luminosity. Even with *dE*/*dx* disabled, the inner superlayers saturate well below this occupancy.

These studies also indicate that the plan for the Run 2b system to truncate single-channel readout at 4 hits/wire does not affect performance.

Status/Performance of the Run 2a TDCs

One of the recommendations from the May 2004 TDC review was to implement the Run 2b data format in the Run 2a TDCs. The motivation was to improve performance of the Run 2a system as well as aid in commissioning the Run 2b system. Significant progress has been made on this front, and it appears likely that the new format will be implemented as part of standard TDC operations by December 2004. This is referred to as version 65 (DSP v65) of the TDC DSP code.

Recent performance measures for the Run 2a system indicate that, at high luminosity, the system will be limited by the DSP processing time and not the readout rate. To insure that out of time hits do not become a limitation, it is proposed to implement the "fast clear" option on the SL 5 and 6 TDCs. [As mentioned earlier, this option is already in place in the Rev. F TDCs which instrument SLs 1-4.] The benchmark tests using COT ASD hit pulsing with the "Sparky" phototube trigger indicate that a 1kHz readout rate can be achieved with 5% deadtime. This is seen as the green curve in Figure 1.

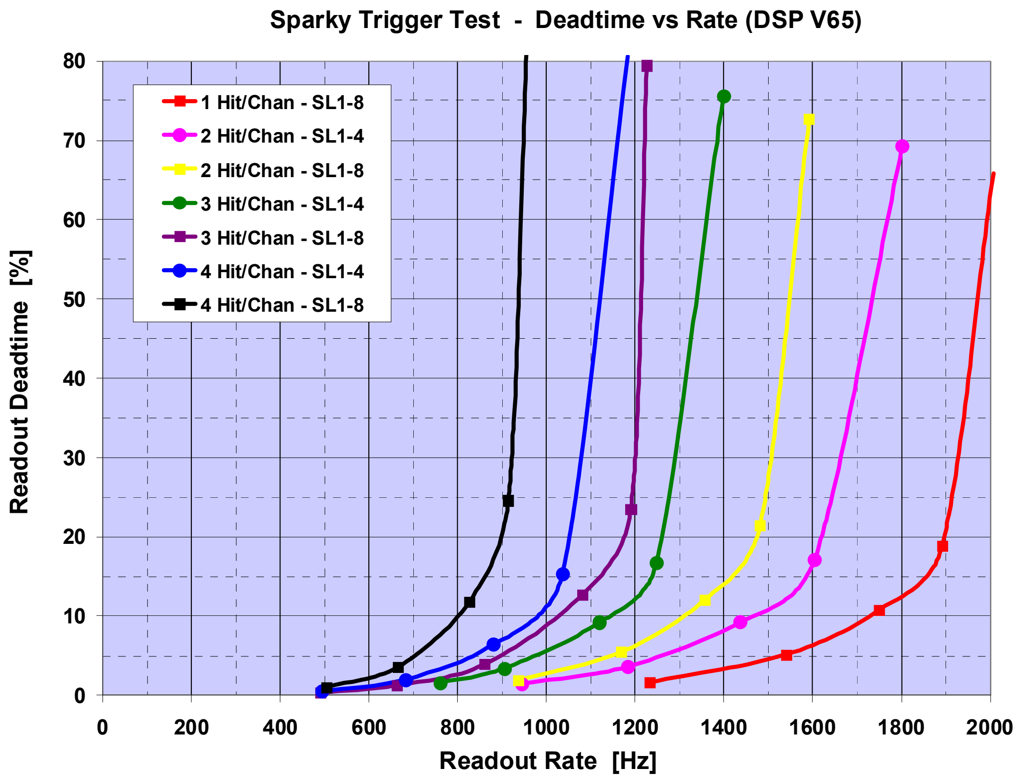

Figure 1. Readout deadtime versus readout rate for the Run 2a TDCs. The readout time is limited by DSP processing time when SL1-4 are pulsed, and limited by readout time when SL1-8 are pulsed. The green curve best mimics the peak luminosity conditions of Run 2b.

Status/Performance of the Run 2b TDCs

Testing of the prototype boards during the Spring/Summer of 2004 has been quite successful. The preproduction order was submitted in August 2004, and five preproduction boards are now in-hand. These boards include some improvements over the highly successful prototype boards. Preliminary performance measures exceed both the proposed and the specified performance. In particular, the preproduction boards are capable of 64 bit VME transfer. The anticipated performance of the Run 2b TDCs is 1.5kHz readout rate using 32-bit VME transfer and 3kHz using 64-bit transfer. These estimates include the effects of both on-board processing and VME backplane transfer rates. The high backplane data rates are achieved using chained block transfer (CBLT).

The plan for the Run 2b system is to release the remaining 30 preproduction boards for assembly as soon as possible so that the boards are in-hand by October 15, 2004. The goal is to perform initial full crate tests in the Chicago and Fermilab teststands, followed by a full crate test of Run 2b TDCs in a COT crate on the detector before the end of the Fall 2004 shutdown. The recommendation from the May 2004 TDC review of an on-detector COT full crate test of the Run 2b TDCs is deemed to be a very high priority, and must be completed by early November 2004. To carry out these tests, Run Control software must be in place that can initialize, run and readout the full crate test.

In order to complete the production quantity by September 2005, it is necessary to have board fabrication begin by early January 2005, followed by assembly and checkout in the Spring 2005. The teststand tools are planned to be ready well in advance of the arrival of the production boards, since many components are in place now and others are being developed for the upcoming full crate tests. In addition, a TDCTester board is being developed that will aid in development, checkout and debugging. The TDCTester will provide LVDS input signals in addition to clock and control signals for the TDC board, allowing for standalone full functionality checkout. Board layout and firmware development are ongoing now.

Anticipated Performance & Limitations of the Run 2b DAQ System

The event builder upgrade is well underway, and is specified to handle a 1kHz L2A rate with minimal deadtime at high luminosity. The upgrade is planned to be in place by the Summer 2005.

Other than TDCs, the slowest crates to readout in current running are primarily from trigger systems providing monitoring and debugging information. This can easily be controlled in the future using readout lists. The CLC crate, which includes both ADMEM and TDC, shows a longer time to complete processing. This is under investigation. It is anticipated that calorimeter readout times can be reduced using faster crate processors. In addition, the readout time for non-TDC crates is independent of luminosity. Other uncertainties make detailed projections difficult.

In Appendix C, we argue that it is unlikely that the ultimate system performance can exceed 1.5kHz (independent of TDC performance.)

The planned upgrade to MVME 5500 controllers for the COT crates is underway. Problems observed with lockup are believed to be understood. The MVME 5500 supports both fast and gigabit Ethernet connections. The original plan for gigabit Ethernet feeding a "virtual VRB" appears no longer necessary, given the revised COT data estimates.

IV. Findings

In this section, we report our findings.

Run 2a TDCs

For the prospect of retaining the Run 2a TDCs for the Run 2b CDF experiment, we find:

- Thanks to the improved performance of the DSP code, the implementation of the "fast clear", the implementation of the Run 2b data format, and an improved understanding of the COT performance at high luminosity, the Run 2a TDCs will satisfy the Run 2b specification.
- The estimated peak readout rate shown here (1kHz) is a factor of 7 better than 2002 projection of 150 Hz peak readout rate.
- It will be necessary to implement the "fast clear" in SL5 and SL6 TDCs.

- New TDC mezzanine boards will need to be produced for the XFT upgrade.
- Additional repair work on the TDC mezzanine interface may be necessary on the stereo TDCs so that they may be utilized in the XFT upgrade.
- Reductions in the event readout time can be accomplished in the COT as well as other subsystems with faster VME crate processors. Although the COT crates will not need the gigabit ethernet port, the additional MVME5500's should be procured and deployed in subsystems where there is the most benefit to the readout time.
- Physicist manpower for Run 2b modifications and long-term operation is a concern. The expertise in this system is concentrated in a few individuals.
- The technical risk associated with retaining the Run 2a TDCs is minimal. The schedule risk is also minimal, since both the fast clear modifications and mezzanine boards for the XFT upgrade can be implemented/installed as available.

Run 2b TDCs

For the prospect proceeding with the Run 2b TDC project for the Run 2b CDF experiment, we find:

- The Run 2b TDCs will comfortably exceed the Run 2b performance specifications.
- The preproduction schedule, including the full crate test on the detector, is very aggressive.
- The production schedule itself seems accurate, although the time to begin construction (tied to the previous item) is aggressive.
- The XFT interface requires further testing, but appears to satisfy the interface and timing constraints of the XFT.
- The physicist manpower for TDC checkout, software, commissioning and operation is inadequate. The engineering and technical support is strong.
- The primary risks associated with the Run 2b project are time (or schedule) related. It is necessary to fully replace the Run 2a TDCs during a single shutdown. Once this occurs, this will be the first opportunity to observe "system level" issues. The risk comes in the uncertainty in the time necessary to commission the system.

Data Acquisition System Performance

For the rest of the DAQ, event builder and trigger, it is unclear what the ultimate performance of the system will be. Operating the system at 1kHz L2A appears likely. We find it unlikely that the system will be able to run at significantly higher rates (>1.5kHz L2A) regardless of the TDC technology.

V. Recommendations

Based upon the information presented at this review, it seems clear that the Run 2a TDCs will achieve the specifications for the Run 2b CDF experiment, and provide minimal risk to the operation of the experiment. The Run 2b TDCs significantly exceed the Run 2b performance specifications, but bring an additional risk factor that is naturally associated with commissioning a large-scale system of this type. The Committee considered the possibility of going to higher rates with the Run 2b system, but find it unlikely that the remainder of the CDF data acquisition system can handle readout rates significantly higher than 1.5kHz. For these reasons, the Committee recommends retaining the Run 2a TDCs for the Run 2b experiment.

We further make the following recommendations for the Run 2a TDC:

- DSP version 65, which includes the new TDC data format, should be implemented as soon as possible. We recommend that it become default for operations by January 2005.
- CDF should immediately begin modifying spare TDC boards with the fast clear option. The installation of modified boards can be staged, but it is important to understand the scope, timescale and success rate of this modification.
- To improve the spares pool, consideration should be given to the feasibility of modifying all Rev. D TDCs with the fast clear option.
- A teststand at Fermilab should be established to test Run 2a TDCs with XFT mezzanine boards. During Run 2a commissioning, a fraction of the stereo TDCs failed XFT interface testing. With the Run 2b XFT upgrade, the mezzanine card interface will be utilized on 294 of the 315 TDCs in the COT system. Only the 21 TDCs which serve COT Superlayer 1 will not be instrumented with mezzanine boards.
- Run 2 MOUs should be updated to clarify responsibilities for long-term maintenance and operation of the Run 2a TDCs throughout the remainder of Run 2. These responsibilities should include maintenance on-site and off-site, firmware and software support, DAQ support and daily pager coverage.

We make the following recommendations for the Run 2b TDC:

- The preproduction order should be completed, fully tested and commissioned. These boards should ultimately become the TDCs used in the EM timing crate, so that longer-term experience can be gained with this technology.
- The TDCTester board should be completed and fabricated. It will be used to commission the preproduction TDCs and will additionally be of use in maintaining the Michigan TDCs throughout the remainder of Run 2.

VI. Conclusion

Again, the Committee thanks the proponents for both projects for their hard work and tremendous progress. Both projects have benefited greatly from the existence of parallel efforts. As a consequence of these efforts, CDF is in a better position to maximally utilize Run 2 luminosity and exploit the fullest physics potential of the experiment.

References

[1] Run 2a TDC Review, May 23, 2002.
http://www-cdf.fnal.gov/upgrades/front-end/tdc/tdc_review_020523.html

[2] CDF Run 2b Technical Design Report, CDF Note 6261, September 2002.
http://www-cdf.fnal.gov/upgrades/run2b/Documents/tdr_sep02.pdf

[3] Run 2b TDC Review, May 21, 2004.
http://www-cdf.fnal.gov/internal/run2b/review/TDC_May04/TDC_May04.html

[4] Run 2a TDC Workshop, July 27, 2004.
http://fcdfwww.fnal.gov/internal/WebTalks/Archive/0407/040727_run_2a_tdc_workshop/

[5] B.Kilminster *et al*., CDF Note 7039, July 19, 2004; P.Wilson *et al*., CDF Note 7259, September 24, 2004.

Appendix A: Charge to the Committee

<u>Charge to Run 2B TDC Review Committee</u>
Review Date: September 28, 2004 Version 2 14 Sept 2004

A major component of the CDF Run IIb DAQ and Trigger upgrades is a project to design and build replacement TDCs to readout the COT. This project was initiated due to concerns that the existing ("Michigan") TDC design would not be able to meet the Run IIb readout specification of 1 kHz in light of increasing hit occupancies at high luminosities. The new TDC-II (or "Chicago TDC") is designed to be plug compatible with the Michigan TDCs they would replace but with higher readout bandwidth capabilities. Prototypes of the TDC-II have been built and have been undergoing tests for several months. Following a readiness review in May 2004, PreProduction boards sufficient to populate a full crate test were ordered with delivery of the first boards expected in mid-September.

Since the effort to build new TDCs was started in 2002, there has been tremendous progress in improving the rate capabilities of the Michigan TDCs. These improvements initially addressed limitations from onboard DSP processing and more recently limitations from readout over the VME backplane and the Taxi link to the Event Builder. The on-board processing was improved by speeding up the DSP code and by installing new boards for the inner superlayers (SL1-4) which implement a fast clear function. The fast clear removes additional processing needed to clear out-of-time hits from the TDC chips. The May 2004 Run IIb TDC review recommended pursuing a new more compact data format, very similar to the one adopted for the Chicago TDC, to reduce the bandwidth needed on the backplane and Taxi link. Implementation of this new format has proceeded far enough to provide rate measurement tests in the past month.

The charge for the review committee is to determine whether we should continue pursuing construction of the Chicago TDCs in light of the current performance of the Michigan TDCs. The primary consideration in this decision is maximizing the physics of the CDF experiment weighing improved bandwidth against operational losses from testing and commissioning. At a minimum, to continue with the Michigan TDC, it must achieve the high level Run IIb DAQ upgrade specification that the readout of the detector (including FE and Event Builder) achieve a rate of 1kHz with no more than 5% deadtime at an instantaneous luminosity of $4\times10^{32}cm^{-2}s^{-1}$. The high level specification implies that the TDCs must function with specific COT occupancy but the occupancy was not specified. The committee should also consider whether the additional bandwidth that the Chicago TDC provides would be usable in light of anticipated trigger scenarios for Run IIb and bandwidth limitations in either the other front-end systems or the upgraded event builder. Finally, the committee should consider the necessary effort to maintain and operate the Michigan TDCs and compare this to the effort required to commission, maintain and operate the Chicago TDCs with a view toward which option would maximize the useful data accumulated in 2006-2008.

The Run IIb management requests that the committee provide a written recommendation on whether or not to proceed with the Chicago TDC production by October 5. A full report is requested by October 15.

Appendix: Questions for Speakers

For the committee to make its recommendation, backup materials and speakers at the review are expected to answer (at least) the following specific points:

1. What is the expected occupancy for Run IIb using a conservative approach (extrapolation to $4x10^{32}cm^{-2}s^{-1}$)
   a. What is the average number of hits per channel in the most occupied TDC in SL1? (sets DSP speed) How does this change if a linear extrapolation is made from low luminosity (assume no hit merging)?
   b. What is the occupancy of the most occupied TDC in SL5 both in terms of in-time (triggered crossing) and out-of-time hits? (i.e. do we need fast clear on SL5 if we retain the Michigan TDCs)
   c. What is the average crate occupancy? (Sets readout rate limit)
   d. What is the effect of turning off dE/dx on inner SLs?
2. Does the Michigan TDC meet the Run IIb specification for operation with the occupancies anticipated at $4x10^{32}cm^{-2}s^{-1}$?
   a. Given anticipated occupancies, what is the maximum rate at which the Michigan TDC can operate with less than 5% deadtime?
3. Does the Chicago TDC meet the Run IIb specification for operation with the occupancies anticipated at $4x10^{32}cm^{-2}s^{-1}$?
   a. Given anticipated occupancies, what is the maximum rate at which the Chicago TDC can operate with less than 5% deadtime?
4. Would bandwidth beyond the capability of the Michigan TDC be used?
   a. What will the limitation of upgraded EVB be (factoring in a smaller COT event size)?
   b. What are the limitations from other crate readout (e.g. Calorimeter and ShowerMax)? Can these be improved through changes to readout code, bank formats, hardware (e.g. new crate processors)?
   c. Can we achieve 1.3kHz, 1.5kHz…?
5. Are there sufficient spare boards in hand (Michigan) or planned (Chicago)?
6. Is there sufficient institutional commitment and individual effort to maintain the boards both in B0 and at repair stations (both Michigan and Chicago)?
7. What additional effort will be needed to complete production and commissioning of the Chicago TDCs?
   a. Include software requirements for Run Control, diagnostics, offline and databases.
   b. Are there sufficient labor resources available to complete these tasks in a timely fashion?

Appendix B: Review Agenda

Agenda:

- Introduction and Charge (10min) - Pat Lukens
- Expected COT Data Rates at 4E32 (20min) - Greg Veramendi
- Case for the Michigan TDC (30min) - Ron Moore
- Case for the Chicago TDC (30min) - Ting Miao
- Rate Capability of Run IIb DAQ (20min) - Frank Chlebana
- Summary (10min) - Peter Wilson
- Discussion
- Executive Session

Copies of all talks are available through the archived WebTalks page:
http://fcdfwww.fnal.gov/internal/WebTalks/Archive/0409/040928_run_iib_tdc_review/

Appendix C: Readout Rate Projections

In this appendix, we use the benchmark measurement of processing time to estimate readout limitations in the rest of the system. Table I shows the relationship between processing time and rate, where we assume that the relationship scales as observed in the Run 2a TDC readout tests. The largest uncertainty is "Other crate" category, although processing times below 350μs seem unlikely.

Table I. Estimated readout limitations in the Run 2b system. Processing times and rates listed below correspond to approximately 5% deadtime. Although the exact details of the performance of the "other crates" is not known, it appears unlikely that processing time will be much below 350μs. This means that system rates beyond 1.5-1.6kHz is unlikely.

System	Occupancy	Processing time	Limitation	Rate
Run 2a TDC	2 hits/channel	410μs	DSP	1.25kHz
Run 2a TDC	3 hits/channel	583μs	DSP	975Hz
Run 2b TDC (VME32)	3 hits/channel	430μs	Readout	1.3kHz
Run 2b TDC (VME64)	3 hits/channel	250μs	Readout	2.3kHz
Central calorimeter*	Fixed	300μs		1.9kHz
Other crates**		<350μs		1.6kHz

*Assumes faster crate processor.
**Muon, CLC, trigger crates.

For the event builder, data volumes are relevant. From CDF Note 5824 the data size for Muon+Calorimeter+ Trigger is 82kB. We assume no compression of that and in fact growth to 100kB. Next assume COT of 100kB at high luminosity. That gives 100kB spread among 6 VRB crates, which is 16.6kB/crate. Assuming 30MB/s for SCPU (conservative estimate) it takes 553μs per event to read the VRBs. If this behaves like TDC readout we will incur deadtime starting around 1kHz.

If we now consider cutting data size per crate in half (either move COT to virtual VRB or go to 12 VRB crates), we have a data volume similar to most occupied TDC crate (8.3kB) and readout rate of VME64. So now the scan time is 275us.

From the above estimates, we draw three conclusions:

1. With current EVB configuration and Run 2a TDC, at peak luminosity we will probably incur deadtime at about 1kHz, with contributions from both the EVB and TDC.
2. Splitting up VRB crates should make EVB contribution minimal and leave TDC readout/DSP as bandwidth limiter in 1-1.3kHz range depending on luminosity.
3. The Run 2b TDC + virtual VRB would be limited by readout of other FE crates and scanning VRBs for those crates. This limitation is probably limited at something closer to 1.5kHz independent of luminosity.