Response to a Recommendation

of the

Department of Energy Office of Nuclear Physics Biennial Science and Technology Review

of the

Relativistic Heavy Ion Collider (RHIC)

on

23-25 August 2016

26 January 2017

Recommendation

Develop a plan to improve the machine protection system for operation at ultimate luminosity and intensity of ion and proton beams.

Executive Summary

During RHIC Run-15 and RHIC Run-16 detector and machine damage occurred as a result of uncontrolled beam loss, leading to reduced detector capability in Run-15 and machine downtime in Run-16. The damage was either the direct result of abort kicker prefires, or of measures implemented to protect the experiments from the effects of abort kicker prefires.

With this and a planned further increase in the RHIC luminosity an upgrade of the machine protection system is needed. The planned upgrade has 2 principal components:

1. A mechanism to suppress abort kicker prefires. The most cost effective way to implement this is through a slow (30-40 ms) mechanical high-voltage switch in series with the fast (<1 μs) thyratron high-voltage switch for the abort kicker.

2. With the additional 30-40 ms delay of the slow switch, additional inputs from several accelerator systems (beam loss monitors, orbit correctors, beam position monitors and radio frequency cavities) to the permit system are needed to protect the machine. These inputs indicate precursors to beam losses that can be detected 1-300 ms before the actual beam losses occur.

The greatest risk to the machine and experiments is in asymmetric operation due to the reduced aperture in the interaction regions, and in high-energy high-luminosity heavy ion operation due to the generation of secondary beams in the collisions. Operation in these modes in not planned again before the new sPHENIX detector is completed, presently planned for FY 2022. Until then RHIC operation is planned with medium-heavy ions at reduced luminosity and at low energy for the Beam Energy Scan II, for which the existing machine protection system is adequate.

In RHIC Run-17 the 2 upgrade components above will be implemented and commissioned. After Run-17 the implemented upgrade will be evaluated, and further measures can be implemented and tested until sPHENIX is ready.

1. Operational incidents during RHIC Run-15 and Run-16 resulting in machine and detector damage and downtime

During the RHIC Run-15 the PHENIX MPC and VTX detector components were damaged after several abort kicker prefires in p+Au operation. During Run-16 a quench protection diode of a RHIC arc dipole was damaged due to radiation damage from localized beam losses, requiring partial warm-up of RHIC and replacement of the diode.

RHIC Run-15
In Run-15 RHIC operated with p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. In asymmetric collisions the physical aperture in the interaction regions is reduced since the rigidity of the two beams is different and, therefore, the orbits are too.
After several abort kicker prefires the PHENIX MPC and VTX detector components were damaged with beam losses in the PHENIX interaction region.

RHIC Run-16
As a result of the Run-15 detector damage, large orbit bumps were installed in some RHIC arcs so that in the event of a prefire the majority of the uncontrolled beam loss occurs at the location of the orbit bumps and not in or near the detectors. However, the large orbit bumps also localize off-momentum particle losses since they are in a dispersive region. Secondary beams are created in the Au+Au collision, namely $^{197}Au^{78+}$ and $^{196}Au^{79+}$ beams, with 1.3% and 0.5% momentum deviation respectively. While RHIC was operated without stochastic cooling these secondary beams were removed with any other off-momentum beam in a controlled area by means of the RHIC abort gap cleaner (Appendix 1). With stochastic cooling about 90% of all ions lost are in these secondary beams. The beam losses localized at the large orbit bumps led to the failure of a dipole quench protection diode due to the irradiation with hadronic showers. The exchange of this diode required a partial warm-up of one of the RHIC rings, and interrupted the physics program by 19 days.

2. RHIC ultimate luminosity goals and the need for increased machine and detector protection

The RHIC achieved luminosities and polarization for the highest energies, as well as the ultimate RHIC luminosity and polarization goals are given in the table below. An increase in the average store luminosity of a factor 2 for heavy ions, and up to a factor 3.8 for polarized protons is planned, primarily through an increase in the bunch intensity.

parameter	unit	achieved		ultimate goals	
Au-Au operation		**2016**		**≥ 2021**	
energy	GeV/nucleon	100		100	
no colliding bunches	…	111		111	
bunch intensity	10^9	2.0		2.5	
stored beam energy	MJ/beam	0.71		0.88	
avg. luminosity	10^{26} cm^{-2}s^{-1}	**87**		**175** 2× achieved	
p↑-p↑ operation		**2015**		**≥ 2021**	
energy	GeV	100	255	100	255
no colliding bunches	…	– 111 –		– 111 –	
bunch intensity	10^{11}	2.25	1.85	3.0	3.0
stored beam energy	MJ/beam	0.40	0.84	0.53	1.34
avg. luminosity	10^{30} cm^{-2}s^{-1}	**63**	**160**	**175** 2.8× achieved	**600** 3.8× achieved
avg. polarization*	%	**55**	**52**	**60**	**55**

*Intensity and time-averaged polarization as measured by the H-jet. Luminosity-averaged polarizations, relevant in single-spin colliding beam experiments, are higher.

Machine and detector damage can occur when a part of the stored beam energy of about 1 MJ is deposited in machine or detector components not designed for this energy deposition. There are 2 possibilities for such an energy deposition to occur:

1. Due to equipment failure or incorrect set points the beam loss rate increases beyond the tolerable level. To prevent machine or experimental damage from this type of failure loss rates around the ring, and precursors to increased loss rates are continuously monitored. The beam is aborted when the abort thresholds are exceeded.

2. Due to an abort kicker prefire.

To cleanly take out the beam the abort kicker firing is synchronized with a gap in the bunch train, and the abort kicker strength rises during the abort gap. With a synchronized firing all beam is deposited in the beam dump. If the kicker firing is not synchronized with the abort gap up to 10% of the stored beam will be deposited in locations other than the beam dump. These locations must be able to absorb these losses. Abort kicker prefires happen randomly, and can be triggered by, e.g., cosmic rays. RHIC has experienced about 10-20 abort kicker prefires per year (Appendix 2).

Machine and experimental protection is most challenging for (i) operation with asymmetric ion species due to the reduction of the available beam aperture in the Interaction Regions, and (ii) colliding heavy ion beams at full energy due to off-momentum secondary beams generated in the collisions.

Colliding heavy ion beams produce secondary beams in collision from Bound-Free Pair Production (BFPP) and Electromagnetic Dissociation (EMD). The intensity and power of the BFPP and EMD secondary beams is proportional to the luminosity. These secondary beams have large momentum deviations of 1.3% and 0.5% respectively and are lost in dispersive locations. With stochastic cooling about 90% of all beam losses are due to the unavoidable BFPP and EMD processes.
Operation with asymmetric ion species reduces the available beam aperture in the interaction regions (IRs), which can lead to beam losses near the experimental detectors.

3. Measures taken to date to prevent machine and detector damage

The abort kicker prefires are closely tracked and correlations with the various machine states (energies, species, losses near the abort kickers etc) were analyzed (Appendix 2). In addition, extensive tests were made to find operating points of the thyratron high-voltage switches that make them more robust against prefires. These efforts did not reduce the number of observed prefire events significantly. A relocation of the abort kickers to the outside of the RHIC tunnel was considered but is very costly.

In response to the Run-15 damage to the PHENIX MPC and VTX detector components due to abort kicker prefires in asymmetric operation a Task Force on Experimental Protection was created (Appendix 3). For Run-16 the following measures were implemented to protect the experimental detectors:

1. In addition to existing masks (Appendix 4), large orbit bumps were installed in the RHIC arcs so that in the event of a prefire, the majority of the uncontrolled beam loss is located at the location of the orbit bumps, and not in or near the detectors.
2. The PHENIX MPC amplifiers that failed with an overcurrent after large beam losses near the detector were hardened to be able to sustain >10x higher currents without damage.

With these measures, and symmetric operation in Run-16, no detector damage occurred in either PHENIX or STAR. However, the large orbit bumps localized the losses from the secondary beams generated in the collisions, and lead to the failure of a dipole quench protection diode.

Since a suppression of the abort kicker prefires would eliminate the encountered issues with machine and detector protection, alternatives for such a solution were investigated. The most cost effective of these alternatives is the installation of abort kicker serial mechanical switches, in line with the thyratron switches. The abort kickers can only fire when the mechanical switches are closed. However, closing the mechanical switches adds 30-40 ms to an abort.

In order to review a plan to install serial switches an internal Machine Protection Review was held on 18 December 2018 (Appendix 5). This review had 4 recommendations:

1. Study beam aborts of previous runs and estimate the possible energy that could be deposited with a 50 ms delay.
2. Estimate the energy that could possibly be deposited in various accelerator components.
3. Institute a study program to speed up the close of the serial mechanical switches.
4. Add critical BPMs into the beam permit system.

An analysis of all beam aborts in Run-14, Run-15 and Run-16 followed (Appendix 6), which identified all cases in which the beam loss rate rose faster than 40 ms. In these cases beam can be deposited in a location around the ring before being properly extracted into the beam dump. For those cases, additional system inputs into the beam permit link were identified that are precursors for beam losses. An upgrade plan to the machine protection system was formulated to use these additional permit link inputs (see below). The closing time of the mechanical switches could be reduced to 40 ms, and possibly 30 ms.

In addition, RHIC will be warmed up during the annual summer shut-down. A warm-up of the diodes reverses the radiation effects. RHIC has been warmed up in almost all of the previous years.

4. Upgrade plans for the machine and detector protection for the ultimate luminosity goals

Increased machine protection is needed for operation with the sPHENIX detector, presently planned for FY 2022 and FY 2023. Until then RHIC will be operated in Run-18 with Zr+Zr and Ru+Ru, at reduced bunch intensity and luminosity and lower BFPP and EMD cross sections, and in Run-19/20 with low-energy Au+Au collisions with a stored beam energy reduced by more than an order of magnitude below high energy. With sPHENIX RHIC will return to operation with high-energy Au+Au collisions, and possibly asymmetric p↑+Au collisions.

4.1 Commissioning plan for Run-17

Improved machine protection will be based on an upgrade of the beam loss monitor (BLM) threshold system as well as new inputs to the beam permit link. New inputs will rely on power supply statuses, beam position monitors (BPM) readings, and the statuses of individual RF cavities. Permits based on machine components are instrumental in detecting a fault up to hundreds of milliseconds before beam conditions worsen enough to cause beam loss and thus an observable loss signal.

BLM threshold system:
Threshold settings contain enable/disable markers as well as trip levels for each of the 440 loss monitors in RHIC. Several files with settings belong to each RHIC cycle. Each set is activated automatically depending on the accelerator mode (such as “injecting”, “early ramp”, “transition crossing” or “at store”). A masked monitor will not pull the permit regardless of loss levels exceeding the threshold or not. The existing files of threshold settings will be reviewed and thresholds will be lowered significantly based on measured loss levels from Run-13. In addition, more loss monitors will be enabled during most RHIC modes. Such changes will include arc loss monitors during all phases of the ramp. Arc loss monitors were previously excluded from the permit system.

Power supply status:
The permit system based on power supply statuses will have two parts: one based on the existing PLCs (programmable logic controller) and one based on the individual corrector power supplies (CPS). In RHIC there are 468 corrector power supplies distributed over 18 tunnel alcoves. Each alcove contains one PLC and can house up to 6 node cards, which each can be connected to up to 11 individual power supplies.

- PLC based beam permit

This serial system will alarm when a power supply connected to it changes its status to “off”, “standby” or “fault”. The PLC checks on the power supply status as part of a perpetual loop containing all supplies in an alcove. Therefore the time between a reported status and a permit pull has a wide range from about 100 ms to 300 ms. This system is already in place and will be commissioned as soon as RHIC begins startup for the upcoming Run-17.

- CPS based beam permit
  This parallel system will collect the status and voltage of each individual power supply by means of one master board per alcove. The master board connects to all node cards in an alcove and thus to each individual power supply. Dedicated connectors (one for each power supply) and master boards were designed and are in the production phase right now. The system will be installed incrementally with a focus on two tunnel alcoves with the highest radiation levels under normal running conditions. At least one power supply per node card in these alcoves will be monitored. The two prototype master boards are expected to be installed by March 1, 2017. The remaining boards will be assembled by an outside vendor and are expected to be completed by May 1, 2017. This system will cause the beam permit to drop approximately 1 ms after it detects a fault.

RF cavities:

Several RF systems are employed at various modes during RHIC pp operation: 9 MHz, 28 MHz and 197 MHz. A fundamental damper is inserted in any cavity that is not used. A cavity with the fundamental damper inserted will not fail the permit link. All cavities are operated with a mechanical tuner. Tuner position, phase error and tuner power supply are monitored. Starting with Run-17, a tripped tuner power supply or missing heartbeat from position and phase monitoring will fail the beam permit for the 28 MHz and 197 MHz system.

- 9 MHz
  A common 9 MHz 22 kV cavity is used at injection, acceleration and store with two separate (Blue and Yellow) bouncer cavities at low voltages of a few kV. Two new separate cavities at 60 kV are installed and will be commissioned during Run-17. The voltage of the common 9 MHz cavity is monitored continuously and is associated with one permit link input channel. The permit link fails within about 1 ms after the voltage drops below a set threshold at injection, acceleration or store.

- 28 MHz
  The 28 MHz system, comprised of two individual cavities per ring, is brought on at store only. Two permit link input channels are associated with this system. To date, in order to fail the beam permit, both cavities in one ring had to trip. This fail condition will be changed for the upcoming run. A tripped single cavity in accordance with the detection of a tuner position or phase error outside a preset tolerance will fail the beam permit within about 1 ms.

- 197 MHz
  From the 197 MHz system, with 5 blue and yellow cavities, only one per ring is used as a Landau cavity from injection to store. In previous runs, a trip of the Landau cavity did not cause the beam permit to fail. Starting with Run-17, two new permit input channels are reserved for the Blue and Yellow Landau cavity. While a tripped cavity per se does not cause significant beam loss, a trip in accordance with the detection of a tuner position or phase error outside a preset tolerance will fail the beam permit within about 1 ms.

Fast BPM system
The Fast BPM permit system is an update to the existing 10 Hz feedback system. 72 of the more than 300 horizontal RHIC BPM modules are equipped with a custom electronic board to distribute BPM data at a 10 kHz rate via a dedicated data distribution network. For comparison, standard RHIC position data are updated at 1 Hz. New hardware for this system include the addition of 12 vertical BPMs to the 10 Hz feedback network and one custom developed BPM beam permit master board. Firmware and software for the master board is in the process of being developed. We plan to commission the new system in the first weeks with beam in RHIC in 2017. Its purpose will be to detect growing orbit oscillations up to seconds before they cause actual beam loss. It is expected that the system will fail the permit within approximately 1 ms of a detected violation of acceptable beam conditions. Thresholds for these conditions will be set during commissioning and adjusted depending on experience during the run.

4.2 Commissioning plans after Run-17

After Run-17 the new machine protection measures need to be analyzed before making any further changes. The analysis will include:

- Statistics on the effectiveness of suppressing abort kicker prefires, and correlations with relevant parameters (like the analysis in Appendix 3)
- Analysis of loss maps and particle loss rise times of all beam dumps and aborts with the new delay in the abort kicker trigger, and comparison to previous loss maps and particle loss rise times

After this analysis decisions can be made if further improvements to the RHIC machine protection system are necessary for the first RHIC Run with sPHENIX, presently planned for FY 2022. Further changes can be partially or fully tested during the RHIC Run-18 (Ru+Ru and Zr+Zr at full rigidity) and the Beam Energy Scan II (Au+Au at or below the nominal injection rigidity).

5. Appendices

Appendix 1 - A. Drees et al., "Abort gap studies and cleaning during RHIC heavy ion operation", PAC'03, pp. 1685-1687 (2003). [removal of debunched beam]
Appendix 2 - Y. Tan and S. Perlstein, "RHIC abort kicker prefire report", BNL C-A/AP/517 (July 2014).
Appendix 3 - Report of the Task Force on Experimental Protection (July 2015).
Appendix 4 - A. Drees et al, "RHIC prefire protection masks" BNL C-A/AP/533 (January 2015).
Appendix 5 - Close-out slides from the RHIC Machine Protection Review (18 December 2015).
Appendix 6 - A. Drees, "A close look at beam aborts with rise times less than 40 ms from the years 2014-2016. Case studies." BNL C-A/AP/570 (September 2016).

ABORT GAP STUDIES AND CLEANING DURING RHIC HEAVY ION OPERATION*

A. Drees†, L. Ahrens, R. Fliller III, W. Fu, G. Heppner, BNL, Upton, NY 11973
V. Kain, CERN, Geneva, Switzerland

Abstract

Since the RHIC Au-Au run in the year 2001 the 200 MHz cavity system was used at storage and a 28 MHz system during injection and acceleration. The rebucketing procedure causes significant debunching of heavy ion beams in addition to amplifying debunching due to other mechanisms. At the end of a four hour store, debunched beam can account for more than 30% of the total beam intensity. In order to minimize the risk of magnet quenching due to uncontrolled beam losses at the time of a beam dump, a combination of a fast transverse kicker and copper collimators were used to clean the abort gap. This report gives an overview of the upgraded gap cleaning procedure and the achieved performance. The upgraded procedure in conjunction with a new application allows to measure properties of the debunched beam routinely.

INTRODUCTION

While a 28 MHz cavity is used for injection and acceleration in RHIC,thus defining the total number of buckets in RHIC to be 360, a 200 MHz storage system for Au-particles is in use since the 2001 run. Beam debunching of heavy ions is due to a combination of RF failure, rebucketing and IBS [1] and can account for as much as 50% of the total beam. In addition, any species beam can debunch due to RF cavity failures. The two rings, blue and yellow respectively, and the six interaction regions (IR) of RHIC with the four experiments are sketched in figure 1. The abort gap is needed to make sure that the circulating beam is cleanly removed by the abort system [2]. Any significant beam in this abort gap will not be dumped properly and can therefore cause magnet quenches and background peaks for the experiments.

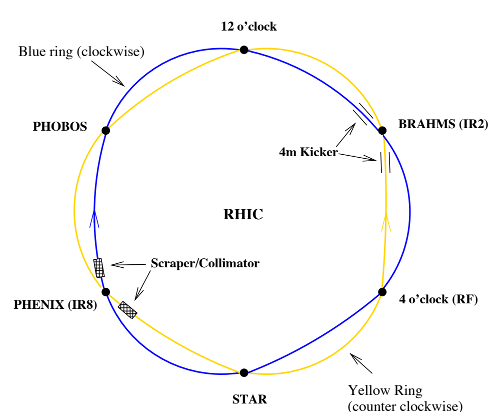

Figure 1: *Location of the kicker and collimators in the RHIC rings.*

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† drees@bnl.gov

HARDWARE

To attack these problems, the existing hardware of the transverse collimators [3] and the transverse kickers used for the tune measurement system [4] are combined. Any beam in the abort gap is excited transversely by the kickers while the collimators are positioned such that they are the limiting aperture in the rings. Figure 1 shows their location in the RHIC ring.

Each ring has one kicker module with four stainless steel striplines, each of which can be powered independently. The pulse voltage cannot be changed. For this application, the kickers are setup to excite beam within the abort gap, buckets 331-360. By selecting a kick frequency close to the horizontal and vertical betatron frequency the beam is kicked resonantly enhancing the effect on the beam significantly if compared with a single or non-resonant kicks. Finding the resonant frequency is crucial for the gap cleaning application and a set point equal to or very close to the betatron frequency was shown to kick bunched beam at storage out of the ring after a few dozens of turns. Typically 300 turns per trigger were used. The horizontal kicks are about 5 times more efficient than the vertical ones due to the different β-functions.

The RHIC collimators [3] consist of 45 cm long L-shaped copper scrapers placed downstream of the PHENIX detector in each ring allowing a positioning resolution of 0.5 μm horizontally and vertically. Four dedicated PIN diode loss monitors and four ion chamber beam loss monitors downstream of each scraper monitor beam losses caused by the collimator.

THE APPLICATION

The new cleaning application supports the two steps of the abort gap cleaning procedure:
(1) excite the debunched beam transversely and
(2) collimate the excited beam with the scrapers.

(1) In order to excite the debunched beam, the tune meter kickers are triggered such that in place of an occupied bucket beam in the abort gap is excited. The kicker is pulsed for 300 turns/trigger with a trigger repetition rate of 1 or 0.25 Hz. To enhance the cleaning efficiency, the frequency has to be as close as possible to the betatron tune of the debunched beam. The new Gap Cleaning application allows a tune scan in the range of suspect, 0.2 to 0.25,

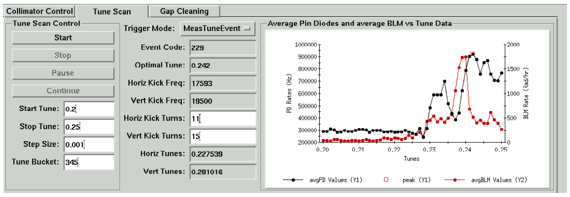

Figure 2: *The application panel to start a tune scan and to find the best resonant tunes for cleaning.*

where the losses at the collimator are recorded as a function of the kicking frequency in terms of betatron tune. Only the horizontal tune is scanned. An example is given in Fig. 2. To monitor the losses we use two independent loss monitor systems, PIN diodes and ion chambers. Once a resonant frequency is found, the application loads it into the gap cleaning procedure. The gap cleaning panel (Fig. 3)

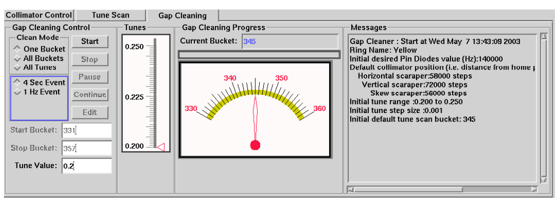

Figure 3: *The application panel to setup the gap cleaning process.*

allows three modes: (i) constant excitation tune and constant bucket, (ii) constant excitation tune but trigger timing is changed to step thru all gap buckets and (iii) constant bucket but excitation tune is varied in a variable range with a variable step size.

(2) At the beginning of the procedure, the scrapers are moved to a predefined position using the collimator control panel of the application (Fig. 4). For fine adjustments, a

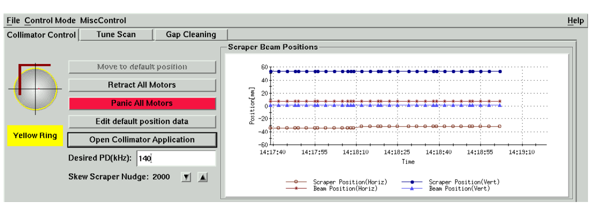

Figure 4: *Collimator control panel of the gap cleaning application.*

"wanted" rate from the PIN diodes, sensitive to scattered particles from the scraper jaw, are used to determine the 'good' location for gap cleaning. To keep high cleaning efficiency, the scraper position typically has to be adjusted a few times during the procedure which lasts approximately 30 minutes.

Regardless of the panel one is working with the application includes a set of convenience graphs as shown in Fig. 5. PIN diodes (top, left) and loss monitors (top, right) are both located downstream of the collimator. Also shown is the amount of debunched current in the blue or yellow

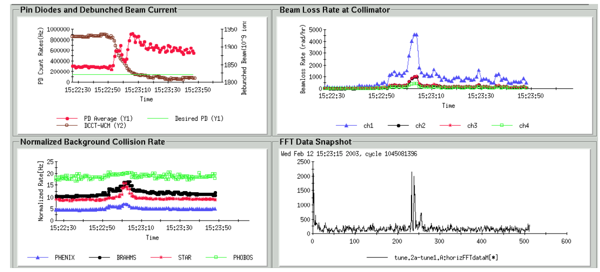

Figure 5: *The convenience graphs as shown in the gap cleaning application during a cleaning procedure on Feb. 12, 03.*

ring in units of 10^9 ions. Note that the tune spectrum (bottom, right) is obtained from debunched beam during the process. Experimental background rates allow monitoring of background increases due to the cleaning procedure while it is in progress. While PHOBOS is unaffected and PHENIX is mildly affected, STAR and BRAHMS see an increase of about 50% during parts of the cleaning.

THE DATA

Table 1 summarizes the magnet quench during the Au run in January and February of 2003. Note that, without RF failures, there is typically no debunching of the blue

Table 1: *RHIC magnet quenches between Jan 01 and Feb. 28 03, caused by either beam dump or aborts involving significant debunched beam I_{deb}.*

fill	**Ring**	$I_{deb.}$		**cause**
		Blue	**Yellow**	
		[10^{11} d]	[10^9 ions]	
2640	Y	-	2	abort kicker
2736	Y	-	2	beam losses
2766	Y	-	2	beam losses
2769	B/Y	9	12	permit
2780	Y	2	6.7	permit
2803	Y	-	6.6	normal dump
2840	Y	-	42	permit
2852	Y	-	3	abort kicker
2859	B	14.5	1	permit
2884	Y	-	9.5	permit (cryo)
2911	B	0.5	3	abort kicker
2930	Y	-	3.6	abort kicker
2945	Y	-	3.5	abort kicker
2955	B/Y	0	8	abort kicker
2982	Y	-	5.5	permit
3006	B	3.5	4.3	permit
3011	Y	-	3.5	beam losses
3061	Y	-	20	permit

beam since it corresponds to deuterons. Accordingly there are much less blue quenches recorded. There are mainly three conditions under which debunched beam can lead to magnet quenches: (i) **abort kicker** prefires, (ii) **normal dumps** and (iii) **permit** pulls for any reason related or unrelated to the debunched beam. Note that abort kicker prefires will, if out of time, lead to quenches without any debunched beam present. In addition to this, high bunched **beam losses** will cause magnet quenches regardless of the amount of debunched beam in the machine.

With one exception (2955) all abort kicker prefires happened at times when the amount of debunched beam alone would not have caused a quench. However, the abort kicker not only prefired but also missed the gap, thus causing an enormous amount of beam losses in certain areas. In fills 2736, 2766 and 3011, the cause of the magnet quenches is most likely the bunched beam loss itself since $I_{deb} \leq 3.5\ 10^9$ Au ions in all three cases. There are 10 candidates left during a period of 2 months were the presence of debunched beam is most likely responsible for the quench. This corresponds to 30% of all recorded real magnet quenches in the two months and to about 10% of all stores during that period. One fill, 2803, ended with a quench because of a regularly initiated dump, ignoring the amount of debunched beam. In fill 3006 the blue magnet quench happened due to a gap cleaning procedure failure. The remaining 8 fills ended with a magnet quench because the permit tripped prematurely before the debunched beam could be removed. $I_{deb} \geq 5.5\ 10^9$ Au ions in all these fills. It should be discussed if loss monitor trip levels could be either disabled or increased significantly if $I_{deb} \geq 5.0\ 10^9$ Au ions. However, there were fills (for instance 2801) which ended without a magnet quench although they had a little more debunched Au beam than this limit. For deuteron beam the statistic is very small since deuteron beams mainly debunch due to RF failures. There is no quench case recorded with $I_{deb} < 9\ 10^{11}$ d but at least one case (fill 2801) where $I_{deb} = 8\ 10^{11}$ d without causing a quench. Therefore, the sustainable limit for debunched deuteron beam seems to be higher, around $I_{deb} = 8\ 10^{11}$ d.

Figure 6, bottom, shows the RHIC yellow beam currents at the end of store 2887. The difference between the total beam, measured by the DCCT [5] and the bunched beam current,measured by the WCM [6], corresponds to the debunched beam. It amounts to 17.5 10^9 Au ions or 63% when the cleaning procedure is started around 17:20. The procedure is stopped after about 35 minutes. Every tune measurement (top of fig. 6) indicates a trigger event for the beam excitation in the abort gap. Note that during the beginning of the procedure, tunes can actually be measured by coherent oscillations of the debunched beam. Tunes are in the order of 0.23 during this example. The cleaning rate here is a record of 0.4410^9 ions/minute. After pausing for about one hour gap cleaning is resumed and the beam is dumped without problems around 19:00. In general, cleaning rates in 2003 were around 0.22 10^9 for Au ions and around 0.15 10^{11} for d. The rates vary from fill to fill and depend strongly on the cleaning efficiency. However, the average for heavy ions could be increased by a factor of about 1.8 compared to the last Au-Au run [7].

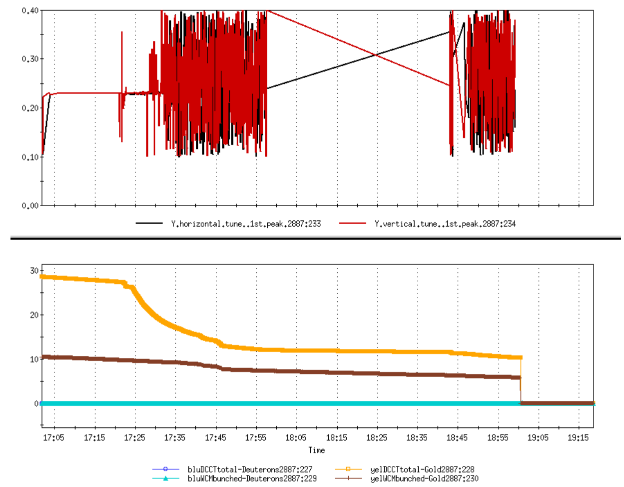

Figure 6: *Top: Tune measurements as a function of time during the end of store 2887, Feb. 03 03. Bottom: Bunched and total yellow beam current as a function of time during the same store.*

CONCLUSION

With the new gap cleaning application the efficiency of the procedure could be almost doubled compared to last year and is found to be 0.22 10^9 Au ions/minute and 0.15 10^{11} d/minute on average. Still, a total of 10 fills, i.e. about 10% of all stores in the examined period of dAu running, ended by a magnet quench due to debunched beam. This number corresponds to 30% of all recorded real magnet quenches. However, 7 of them were caused by premature loss monitor permit trips and disabling or increasing the loss monitor trip level could help avoiding these cases. The sustainable limit for debunched Au beam could be confirmed to be $5.0\ 10^9$ and a preliminary limit for deuterons was found to be $8\ 10^{11}$.

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RHIC abort kicker prefire report

Y. Tan, S. Perlstein

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

RHIC Abort Kicker Prefire Report

Y. Tan, S. Perlstein

Brookhaven National Laboratory, Upton, NY 11973, USA

In an attempt to discover any pattern to prefire events, abort prefire kicker data from 2007 to the present day have been recorded. With the 2014 operations concluding, this comprises 8 years of prefire data. Any activities that the Pulsed Power Group did to decrease prefire occurrences were recorded as well, but some information may be missing. The following information is a compilation of the research to date.

1 Prefire overview

For every run prefires occurred when the abort kicker power supplies were operated at 22kV or higher. The majority of the species were polarized protons (PP) or gold (Au). Other ions accelerated were copper (Cu), uranium (U), deuteron (D) and helium (He). Table 1 describes how prefires are related to the species being accelerated and the voltages used for each species.

Table 1 RHIC Operating Modes and RHIC abort kicker prefires

Run	*Energy GeV/nucleon	*Species	Days	Abort Voltage kV	Prefire Yellow	Prefire Blue
2007	100	Au-Au	128	27	12	18
2008	100	Au-D	82	27/22	2	3
2009	250	PP-PP	60	27	1	9
2010	100	Au-Au	89	26	7	12
2011	250	PP-PP	91	27	8	3
	100	Au-Au	49	27	5	4
2012	255	PP-PP	37	27	1	0
	96	U-U	28	26	2	0
	100	Au-Cu	43	26/22.8	5	1
2013	255	PP-PP	116	27	13	8
2014	100	Au-Au	96	26	12	6
	100	Au-He	22	26/27(three modules)	2	0

*Operation data are from http://www.agsrhichome.bnl.gov/RHIC/Runs/index.html.

Low energy modes are not listed in Table 1 because we never had a prefire while in those modes, except for one in 2009 at 11kV caused by a failed redundant trigger module. Chart 1 shows the total number of prefires experienced in the entire 8 year period and the numbers of prefires occurring in each run.

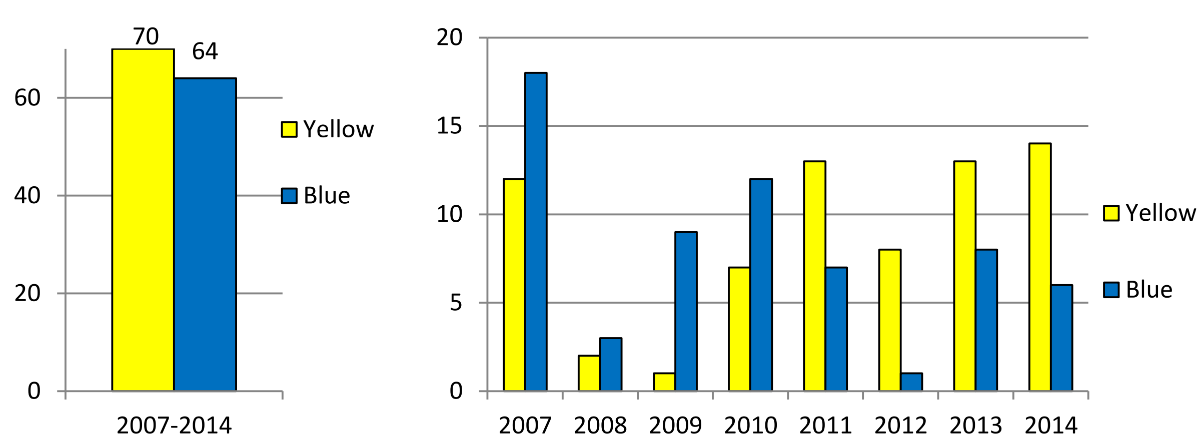


Chart 1 Yellow and Blue Prefires from 2007 to 2014

In terms of total prefires occurring during the period of this study, yellow and blue are very close.

Over the years, prefires of the blue abort kickers seem to decrease while those of the yellow do not.

From 2007 to 2010, yellow had less prefires than blue for each run. Starting in 2011, yellow experienced more prefires than blue.

2007 had the most prefires, a total of 30. But during 2008, the next run, there were only 5.

What did we do during that shutdown? In blue PFN #2 and #4 modules (which had 7 prefires each), the CX3575C thyratron, the 5uF/40kV capacitor, and eight 0.39uF/45kV capacitors were replaced. Interestingly in yellow the prefires dropped down from 12 to 2 without any components being changed except the 5uF/40kV capacitor in blue #2 in the middle of the run.

2 Prefire and species

Table 2 below explores the relationship between prefires, species and length of the runs. There were 23 and 20 prefires for yellow and blue respectively with PP in 304 days; and 47 and 44 prefires with ions other than PP in 537 days. On average there was a prefire every 7.1 days for PP and 5.9 days for other species.

Table 2 Species and Prefires

(a)Prefires for PP

Run	Energy GeV/nucleon	Species	Days	Prefire Yellow	Prefire Blue
2009	250	PP-PP	60	1	9
2011	250	PP-PP	91	8	3
2012	255	PP-PP	37	1	0
2013	255	PP-PP	116	13	8
Total			304	23	20

(b) Prefires for ions other than PP

Run	Energy GeV/nucleon	Species	Days	Prefire Yellow	Prefire Blue
2007	100	Au-Au	128	12	18
2008	100	Au-D	82	2	3
2010	100	Au-Au	89	7	12
2011	100	Au-Au	49	5	4
2012	96	U-U	28	2	0
	100	Au-Cu	43	5	1
2014	100	Au-Au	96	12	6
	100	Au-He	22	2	0
Total			537	47	44

3 Prefires and time of occurrence with relation to ramp and flat top

A prefire may occur either during the charging voltage ramp or the charging voltage flat top. The ramp means the particles are being accelerated in the RHIC rings. A regular ramp takes about 4.5 minutes. The flat top means the acceleration process is completed and the beams are circulating in the RHIC rings. A normal flat top lasts 8 to 10 hours. The ramp and the flat top are shown in Figure 1.

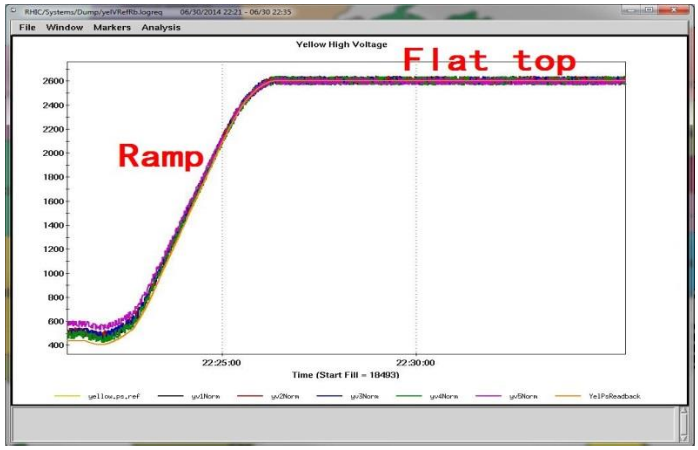


Figure 1 Abort kicker charging voltage ramp and flat top of a run

Table 3 explores prefires with relation to the ramp and flat top.

Table 3 Time of prefire occurrence

Time of Prefire	Yellow	Blue
Ramp	22	22
Flat top <5 minutes	15	11
Flat top 5-30 minutes	10	12
Flat top>30 minutes	23	19
Total	70	64

Chart 2 is a graphic representation of Table 3.

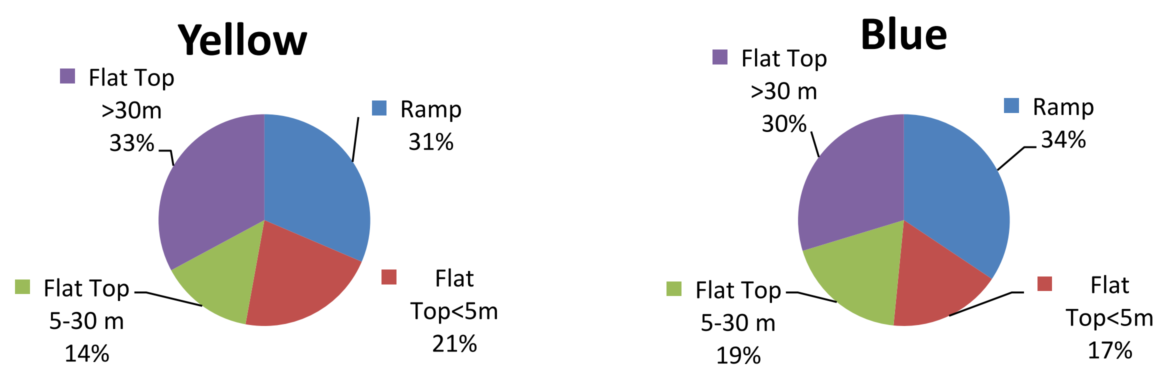


Chart 2 Yellow and Blue Prefire Time of Occurrence

For both yellow and blue, about 1/3 of all prefires occurred during the ramp, and another 1/3 of all prefires occurred more than 30 minutes in to the flat top. The prefires occurring during the ramp and during the first 5 minutes of the flat top represent about 50% of the total. We believe that this statistic is worth investigating because 50% of all prefire events occurring during the first 10 minutes of a run that can last 8-10 hours is a relatively significant number.

4 Prefires by module position

Table 4 enumerates the number of prefires vs. the PFN location over time. For each individual kicker module, there is a unique pattern of prefires. Chart 3 is a graphic representation of total prefires listed in Table 4.

Table 4 Prefires for each module

	Y1	Y2	Y3	Y4	Y5	B1	B2	B3	B4	B5
2007	0	1	3	1	7	1	7	1	7	2
2008	0	1	1	0	0	0	0	0	2	1
2009	0	0	0	1	0	2	0	1	5	1
2010	1	5	1	0	0	4	4	0	1	3
2011	0	2	1	2	8	3	1	0	2	1
2012	1	1	0	2	4	0	1	0	0	0
2013	1	3	2	6	1	3	2	0	0	3
2014	0	7	1	3	3	0	0	0	4	2
Total	3	20	9	15	23	13	15	2	21	13

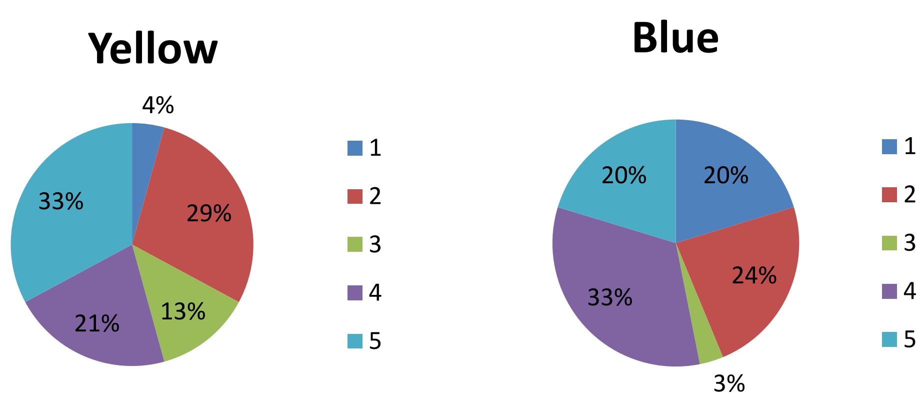


Chart 3 Percentage of total prefires in individual Yellow and blue modules

One module each in yellow and blue had very few prefires. Yellow #1 and blue #3 had only 3 and 2 prefires respectively in the last 8 years. The components in these two modules were seldom changed, while in other modules, such as yellow #2, #4, blue #2, #4, major components had been changed, and some components had been changed more than once.

5 Prefire occurrence vs. average radiation

A radiation survey was conducted in 2013. The results are shown in Table 5.

Table 5 Radiation survey results (unit: mR/Hr)

	Y1	Y2	Y3	Y4	Y5	B1	B2	B3	B4	B5
2013	0.9	0.4	0.1	0.5	0.5	2.4	1.0	0.23	0.05	0.05

There does not appear to be a correlation between the radiation survey results and prefires.

6 What do we do when there is a prefire with no clearly discernible cause?

We usually do one or both of two things before accessing the RHIC ring: (1) condition the modules, and (2) lower the thyratron reservoir voltages.

Are these procedures effective?

By checking the prefire history, we found that on occasion, during the conditioning or a few hours after the conditioning, there was another prefire. We also found that sometimes a few hours after reservoir voltages were decreased, there was a prefire. This is understandable, because there are several factors which may contribute to prefires, such as the thyratron self-firing, radiation triggering the thyratron, a loose connection, high voltage break-down, etc. Because of these factors, it is not clear whether performing the above mentioned two procedures is effective or not.

The same applies to our other procedures, such as replacing the thyratrons, replacing the 5uF/40kV capacitors, replacing 0.39uF/45kV capacitors, etc.

For now, for lack of better procedures, we recommend we continue to do what we have been doing.

7 What is the solution to the prefires?

As was mentioned before, there was not a single prefire at the voltage of 11kV or less except the one caused by a failed trigger module. One solution we can suggest is the installation of a higher voltage thyratron. The thyratrons currently in use are CX3575C, 60kV. A higher voltage rating thyratron, CX1193C, for example, is rated at 130kV, and might resist prefiring. There are some concerns, however, such as the larger size may cause more prefires if radiation is the cause of prefires, or that thyratron may not be triggered at low injection voltage.

Jianlin Mi also had a solution. He suggests adding one more abort kicker module in each ring, thus reducing the HV by 1/6 of 26kV, i.e., 4.3kV. But this would require significant changes in the RHIC ring.

8 Summary

From the previous data we may conclude that

(1) Abort kickers don't prefire at low energy modes (PFN voltages<11kV) except for component failure.
(2) Heavy ions appear to make the abort kickers more likely to prefire than polarized protons.
(3) About 50% of prefires occurred within the first 10 minutes of a run.
(4) One PFN module each in blue and yellow had very few prefires. This may be related to position in the beam line and is worthy of investigation. Perhaps we should consider swapping yellow PFN#1 with PFN#2, and blue PFN#3 with PFN#4.

References:

[1] RHIC run overview, http://www.agsrhichome.bnl.gov/RHIC/Runs/ .

[2] Analysis of RHIC beam dump pre-fires, W Zhang, etc, 2011 Particle Accelerator Conference (PAC'11), http://www.bnl.gov/isd/documents/75266.pdf .

Attachments:

1. Abort Kicker area radiation survey in 2013.

BNL RADIOLOGICAL SURVEY FORM

Bldg. #: RHIC ☐ Routine
Location: 1010 Kickers ☒ Special Request
Date/Time: 2-25-13 1800 ☐ RWP#

Smear Survey Results (DPM/100cm²)

	^3H	$\beta-\gamma$	α		^3H	$\beta-\gamma$	α
1.	N/A ↓			16.	N/A ↓		
2.				17.			
3.				18.			
4.				19.			
5.				20.			
6.				21.			
7.				22.			
8.				23.			
9.				24.			
10.				25.			
11.				26.			
12.				27.			
13.				28.			
14.				29.			
15.				30.			

Masslinn Survey Results (DPM/LAS)

1.	N/A ↓			8.	N/A ↓		
2.				9.			
3.				10.			
4.				11.			
5.				12.			
6.				13.			
7.				14.			

Legend: ○ Smear Location ☐ Masslinn Location
Δ Airborne
xxx y / zzz
xxx=Contact Reading
zzz=Reading@ 30cm
y= Radiation Type

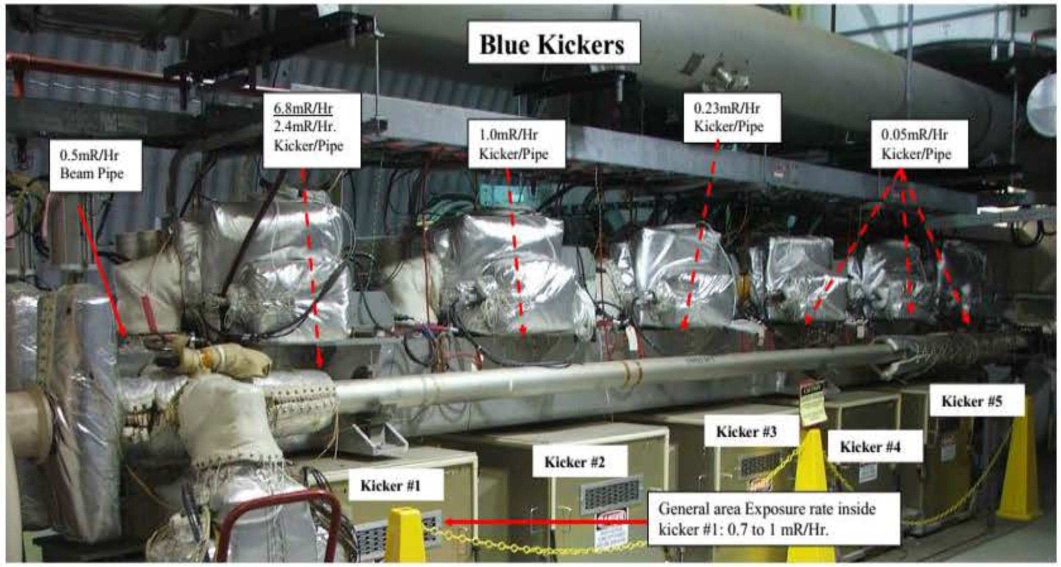
Exposure Rates (Highest)		Airborne Contamination		
Contact	6.8mR/Hr.	Time	µCi/cc	%DAC
General Area	2.4mR/Hr.	N/A	N/A	N/A

☐ All Exposure Rates are in mR/hr and taken at 12 inches (30 cm) unless otherwise noted.

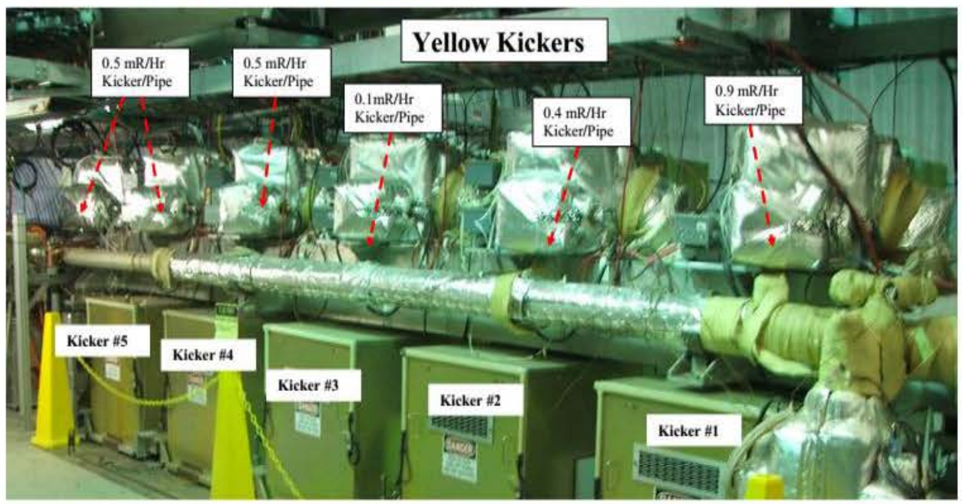
Model	telepole	Model 19	N/A
Serial #	093	291420	↓
Cal Due Date	8-3-13	5-2-13	
Source Checked (Yes or No)	y	y	

Form FS-1000.1

File Code: FS72SR.09



Front view, with cover removed, of blue kicker #1. General area dose rates: 0.8 to 1.7mR/Hr



Exposure rates on capacitors removed from blue kicker #1
Small white cylinder shaped capacitor: 150/30 µR/Hr.
Large square shaped capacitor: 24µr/Hr.

Surveyed By: Fintan Woods 2-25-13
Signature/Date

Reviewed By:
Signature/Date

Report of the Task Force on Experimental Protection, July 2015

Members: James Dunlop (chair), Michael Blaskiewicz, Mickey Chiu, Bill Christie, Angelika Drees, Wolfram Fischer, Xiaofeng Gu, Chuyu Liu, Guillaume Robert-Demolaize

Executive Summary

This task force has been charged with assessing the risk of damage to the detectors of an abort kicker prefire within the proposed running conditions in Run 16, given past experience, along with assessing possible ways to ameliorate this risk. The risk of damage to the detectors is the product of the probability of a prefire occurring in any machine configuration and the severity of damage should a prefire occur. There is currently some protection in the machine for damage to the experiments due to a prefire, but this was shown to be inadequate in Run 15 with the damage to the PHENIX Muon Piston Calorimeter (MPC) and Silicon Vertex (VTX) detectors during the p+Au running at $\sqrt{s_{NN}}$ = 200 GeV. The working hypothesis is that this protection is inadequate because of the closeness of the masks to the PHENIX intersection region in conjunction with the reduced beam aperture at the DX magnets due to the different charge-to-mass ratios of the p and Au beams. This results in showering of secondary particles into the detector when a prefire event occurs and primary particles are lost at DX magnet in front of the PHENIX detector. The protection was adequate for configurations with beams of the same charge-to-mass ratio in both rings in Run-13 and Run-14. The STAR MTD, which sustained damage in previous runs due to a prefire, sustained no damage in Run 15, presumably due to the orbit bumps and masks, installed in response to the initial damage, that deposit the beam far from the detector.

Based on historical data, the rate of abort kicker pre-fires is seen to depend on the voltage at which the abort kicker power supplies operate. A detailed analysis of the historical data leads to the following estimate of the probabilities for a run plan optimized to put the largest risk latest, and so maximize the chance that the bulk of the data be collected without incident:

p+Au @ 20 GeV for 2 weeks, with total pre-fire probability: (0.54 +/- 0.54)%
p+Au @ 39 GeV for 2 weeks, with total pre-fire probability: (0.95 +/- 0.95)%
p+Au @ 62 GeV for 1.5 weeks, with total pre-fire probability: (1.4 +/- 1.4)%

Under this scenario, the chance is 97+/-3% that the run would occur without incident.

The PHENIX MPC was severely damaged by abort kicker prefires under two running conditions, in Run 12 Cu+Au and Run 15 p+Au. In both cases, key transistors in the MPC pre-amplifier electronics sustained overcurrent damage. Repairs of these circuits are possible during a summer shutdown, but the repairs cannot be done during a run. Bench studies have been able to reproduce this failure mode with signal size equivalent to approximately 30 TeV of energy (i.e. the energy of 1.5 Au ions at 100 GeV/nucleon) deposited into a single MPC crystal. A protection circuit has been designed and tested, which will raise this protection threshold by a factor of 400 and may completely protect the component from failure. This protection circuit will be installed on the MPC electronics during the shutdown prior to Run 16.

No further protection will be available for the VTX stripixel detector, which sustained irreparable damage in Run 15 over a significant fraction of the detector. The PHENIX collaboration has stated that the physics program of the low-energy p+Au running does not critically depend on the use of this detector, and there are no plans to re-use the detector after Run 16.

Studies of the instantaneous radiation dose into the PHENIX detector from an abort kicker prefire, using particle tracking and GEANT, have begun, but could not be completed to provide a quantitative answer in the timescale of this task force. Therefore the task force cannot quantify the effect of changes in the machine conditions on the instantaneous dose into PHENIX, should a prefire occur. This includes the preferability of Au+p over p+Au running and the effect of orbit changes. That said, major damage has only occurred in asymmetric running, in which the orbits of the beams come close to the DX magnets. It was realized during the task force meetings that the DX magnets could be moved for d+Au running to make the apertures nearly equivalent to that of symmetric running, during which there has been only minor damage to the MPC (twice) despite several more prefires. At lower energies there is also enough margin in power supplies and magnets to maximize the aperture for the beam coming into PHENIX at the DX magnet as long as there is sufficient aperture for the outgoing beam. Further optimization of aperture at the DX may be possible by optimizing the location of the DX magnets, especially in the Au+p configuration that has never been run, but this needs investigation into the limitations imposed by shielding configurations.

There are further measures that can be taken to reduce the chance of prefires. One possibility would be to install, in series with the existing gas discharge thyratrons, mechanical relays capable of switching state in several milliseconds. This project is estimated to cost ~$300k to $400k, and would necessitate a detailed machine safety review, since the mechanical relays increase the latency between an abort trigger and the firing of the abort kickers. A further measure would be to move the abort dumps and masks to another place in the machine, well away from PHENIX. A compact movable mask ($50-70k) after the beam dump was proposed for detector protection as well. It reduces possible pre-fire beam loss by 1-2 orders of magnitude for any species and any existing lattice design. This mask can be used as protection not only for PHENIX detectors, but also for STAR detectors and CeC wiggler. These options are not possible in the summer shutdown before Run 16, due to the scale of the work, but should be actively investigated prior to running with sPHENIX.

Probability Assessment of Prefires at Low Energies

The RHIC beam abort kicker system consists of five identical systems for each beam, each comprising a pulsed power supply driving a kicker magnet [1]. The pulsed power supplies deliver a 12.8 μs long pulse, with a peak voltage and current of 27 kV and 21 kA at the maximum RHIC energies of $\sqrt{s}$ = 200 GeV Au+Au of 510 GeV p+p. Each power supply consists of energy storage capacitors that form a pulse forming network, a thyratron switch to hold off the high voltage until triggered, and the associated control systems. The pulse forming network is designed to modulate the voltage so that when the kicker is activated the magnet is supplied with a varying current, thus spreading the beam in the dump to prevent overheating in a local area.

Prefires have been attributed to various sources, but the leading hypothesis is an unintentional discharge of the deuterium gas thyratron. In some cases, faulty capacitors may have discharged accidentally [2]. Extensive studies have been done of the prefire rates in previous runs by C-AD [2-3]. In the most recent study, the authors report that since 2007, there have been 134 prefires at or near the maximum RHIC energies, one prefire at 200 GeV p+p, and none at low energies [3]. The dependence on abort kicker voltage for the yellow ring is shown in Figure 1. The point at 11 kV corresponds to 200 GeV p+p.

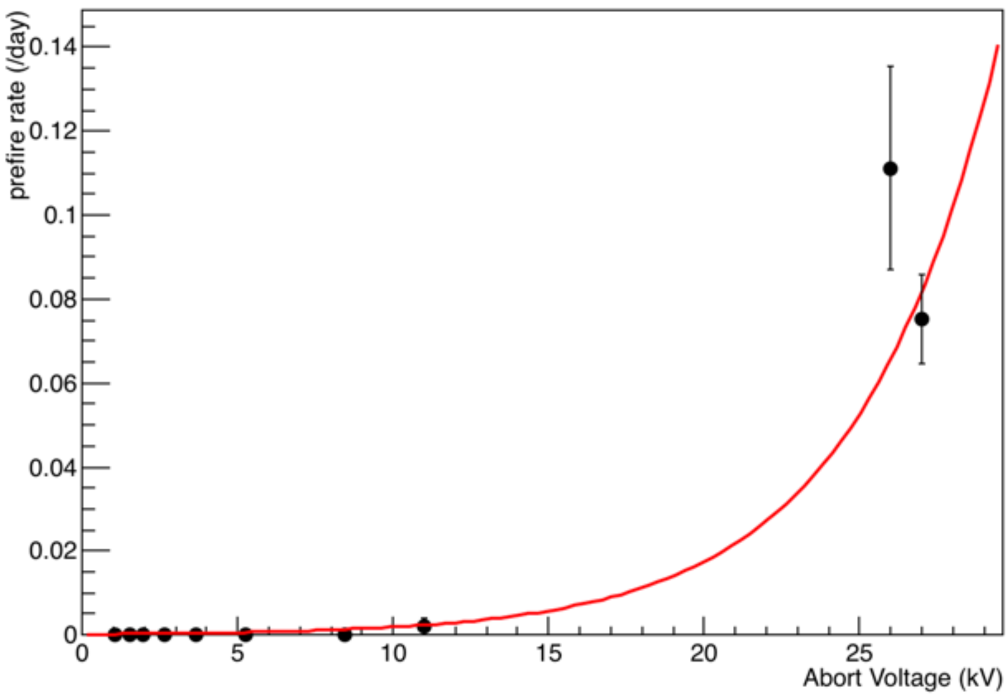


Figure 1: Prefire rates in the yellow ring vs. abort voltage, with a fit to an exponential.

While there seems to be a clear dependence on voltage, one can quantitatively check whether the behavior at low energy is different from that at high energy, i.e., were we just "lucky" to not have any prefires at low energy? We assume that the number of prefires follows a Poisson distribution,

where n = the number of prefires and λ = the mean number of prefires for a given time interval. We also tabulate the amount of time spent at the low energy heavy ion runs and p+p runs in Table 1, since they were not included Ref. [3]. All the runs listed in Ref. [3] are from 2007 and later, since the accounting on prefires was changed then and it is difficult to go back further. In Table 1 we also include the p+p runs from 2002, since it is known that there were no prefires in 200 GeV p+p since then.

System	Energy	Abort Voltage	Weeks running	Days Running
Au+Au	3.85	1.0395	4.6	32.2
Au+Au	5.75	1.5525	1.4	9.8
Au+Au	7.3	1.971	3.4	23.8
Au+Au	9.8	2.646	1.4	9.8
Au+Au	13.5	3.645	1.1	7.7
Au+Au	19.5	5.265	1.8	12.6
Au+Au	31.2	8.424	2.9	20.3
p+p	100	11.0	28.6	200.2
p+p (from 2002)	100	11.0	74.5	521.5

Table 1: Abort voltages and run lengths for 200 GeV p+p energies and below.

Going back to the question of whether low energy running is different from high energy running from the perspective of the abort kickers, we find from Ref. [3] that there was an average rate of 134 prefires over 841 days of running at high energy. This is an average rate of 0.16 prefires per day in RHIC high energy running. The probability that we would have had no prefires in the 113 days of low energy running, assuming that the abort kickers prefire at the same rate as at high energy, is 1.4×10^{-8}. Thus, it seems extremely unlikely that there were no prefires at low energy just due to chance. In fact, based on our understanding of the thyratrons, which are gas-filled tubes which must be ionized to start the arc discharge, we would expect that running them at lower voltages makes them more stable. The same consideration is true for the storage capacitors.

Since it is natural to expect a drop of the prefire rate as one goes to lower voltages, for this study we fit the prefire rate data to an exponential distribution, which decreases sharply with reduced voltage. Of course it could also be that the prefire rate stays constant at the 200 GeV p+p rate when going to lower abort voltages. It may also be that the prefire rate goes to zero at the lower beam energies, if the voltage falls below some critical threshold for the kicker system. The uncertainty in the behavior of the prefire rate at low voltages (<11 kV) is bracketed by the above two scenarios: an upper limit where it is assumed that the prefire rate stays constant at the 200 GeV p+p rate, and a lower limit of zero. The probabilities per week of experiencing a prefire, assuming that the prefire rate follows the exponential given in Figure 1, is

Probability of prefire for 1 week running @ 62.4 = 0.0095
Probability of prefire for 1 week running @ 39.0 = 0.0047
Probability of prefire for 1 week running @ 20.0 = 0.0027

For the upper limit the probabilities are roughly twice the above values, and for the lower limit it is zero.

[1] "The RHIC Beam Abort Kicker System", H. Hahn et al., Proceedings of the 1999 Particle Accelerator Conference, New York
[2] "Analysis of RHIC Beam Dump Pre-fires", Hahn, H. et al. Conf.Proc. C110328 (2011) 2327-2329 PAC-2011-THP108
[3] "RHIC abort kicker prefire report"epo abort kPerlstein, S., BNL-105539-2014-IR
[4] A. Drees et al., "RHIC prefire protection masks", BNL-107-380-2015-IR

MPC Repair and Protection Modification

The MPC is an electromagnetic calorimeter composed of PbWO4 crystals with avalanche photodiodes (APD) to read out the scintillation light generated when particles shower in the calorimeter. The APD is readout with a charge-sensitive preamplifier. One crystal assembly is shown in fig. 1. The design is a copy of the Alice PHOS detector, and in particular the preamp was designed to be extraordinarily sensitive, with an equivalent noise charge (ENC) of just 500 electrons, since one of the major PHOS goals was to measure thermal photons.

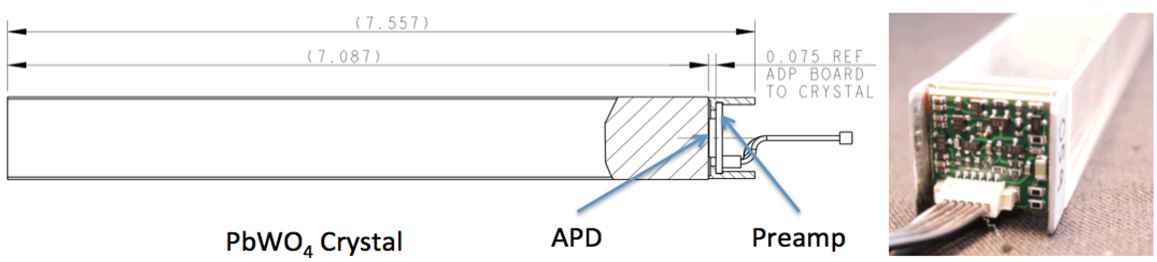


Figure 1: MPC Crystal Assembly, consisting of the PbWO4, APD glued on the front face, and the preamp with cable attached to the APD and ensconced in a holder.

The MPC's location in the forward region of PHENIX, about 8 cm from the beam-pipe places it in a very advantageous location for low-x physics measurements. However, this proximity to the beam-pipe also means that there is the possibility of damage when beam remnants deposit more instantaneous energy then the preamp was designed to handle. This can happen, for instance, when the collider loses control of the beam during an abort kicker prefire event, and up to 10 bunches from the yellow ring are lost near the PHENIX. In the only three instances when major damaged occurred to the MPC, all have been associated with prefire events during asymmetric running (2012 Cu+Au and twice during 2015 p+Au). Two of the events have been traced back and determined to have originated from spray coming from the vicinity of the upstream (north)

PHENIX DX magnet. It should be noted that in addition to the three major incidents, there was one incident when about 10 crystals were lost during a Au+Au run.

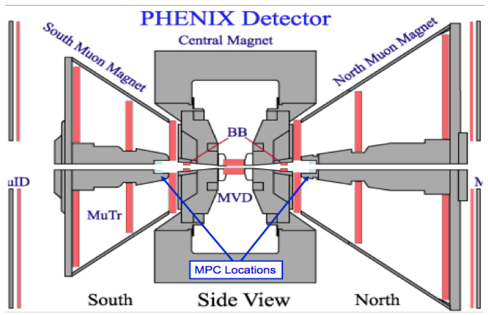


Figure 2: Locations of the MPC in the PHENIX detector

For every MeV of energy deposited the PbWO4 crystals produces about 1.45 photoelectrons in the APD over a typical scintillation timescale of 30 ns. At a typical APD gain of 50, a current of 0.3 μA per GeV deposited is expected going into the preamp. At the initial stage of the preamp is a JFET with a 10 mA current limit, which we have verified in the lab holds for even short bursts of current. The JFET is shown in the schematic in fig. 3 below. Energy deposits of about 33 TeV would be enough to damage this event. Typically, we expect a maximum of only about 200 GeV of energy deposited during normal running, so the preamp was designed to handle up to 100x the current enhanced RHIC luminosity.

However, during an abort kicker prefire event, a large amount of energy can and has been deposited in the PbWO4 scintillating crystal. This large burst of light in the MPC from the spray of the ion bunches hitting the PHENIX IR near the MPC overwhelms the 10 mA current limit, damaging the JFET. The signal comes correlated over a very short period of time since the ion bunches have a RMS width of only ~5 ns. A gold ion in RHIC has an energy of 20 TeV energy, not far from the 33 TeV limit of the preamp. However, a gold ion striking the MPC would deposit roughly just 10% of it's energy in the struck crystal since the showering process will spread the energy deposition across neighboring crystals. Thus, we expect somewhere around 10 direct gold ions would be enough to destroy one crystal. Since we believe many of the previous events come from the fragments of an upstream interaction, of degraded energy and charge, probably many more particles are needed to destroy the JFET. Geant4 studies are underway to try to quantify this and understand more completely the level of energy deposited during these prefire events.

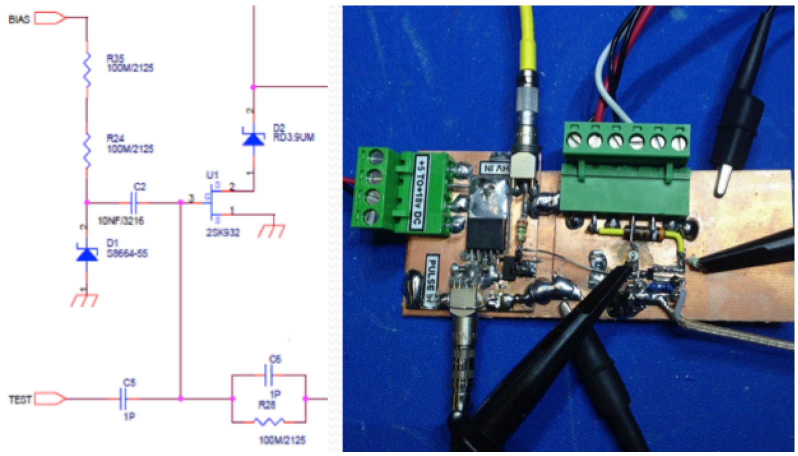


Figure 3: The schematic for the initial stage of the MPC charge sensitive preamp. The APD is D1 and the JFET is U1. The charge integrating circuit can be seen in the lower right of the schematic. The right picture is the test circuit used by Steve Boose.

To understand better the functioning of the MPC preamp, Steve Boose built a test circuit of the initial stage in the preamp, shown in the right of fig. 3. From this it was verified that when the JFET reaches 10 mA or 33 V it would succumb to damage. Previously, in 2012, a study was initiated to test adding a protection diode after the last major MPC damaged incident. We found that various diodes which we expected to work instead made the preamp completely non-functional. From that experience, this time in 2015 we suspected that the previous failures were due to the very tiny leakage current of even just μA or even nA draining the charge integrating capacitor, since this preamp was designed to be extraordinarily sensitive. A BAS416 diode was found for trial as part of a protection circuit. This diode has among the lowest leakage currents available, 3 pA, and is encapsulated in a SOD323 package which makes it possible to install in the cramped preamp space. This time around during testing with LED the preamp remained functional with the diode installed. It should be noted that there are maybe 3-4 diodes with the right parameters to have worked in this preamp.

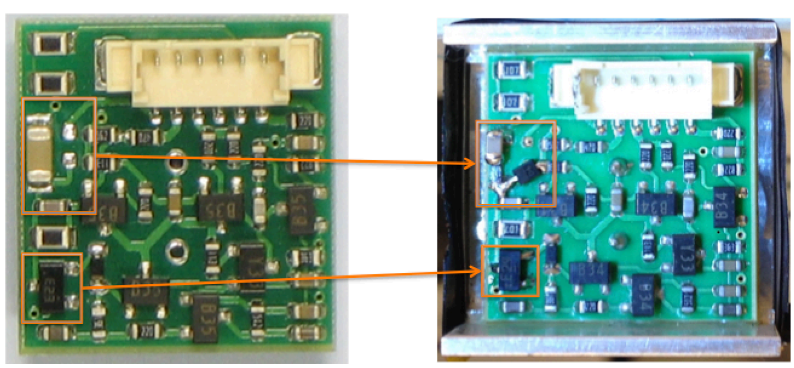


Figure 4: Original preamp and modified preamp. The lower orange boxes indicate the location of the replaced JFET, while the upper box shows the new protection circuit consisting of a diode in series with a resistor, and the replacement capacitor.

To fit this new diode in the space available on the preamp, the input blocking capacitor was replaced with a smaller capacitor. In addition, in order to protect the diode, which can handle a maximum current of 4A, a 100Ω resistor was added in series (see fig. 4 for a picture of the modified circuit). With this new diode protection system, based on pulse injection tests we have done in the lab we believe the MPC preamps can now sustain at least 400 times the previous level of current with no resistor in series. With a 100Ω resistor, the MPC preamp should be able to sustain any amount of current, but at the cost of a small increase in noise.

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January 2015

RHIC Prefire protection masks

**A. Drees, C. Biscardi, T. Curcio, D. Gassner,
V. DeMonte, L. DeSanto, W. Fu, C.J. Liaw,
C. Montag, P. Thieberger, K. Yip**

**Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973**

**U.S. Department of Energy
Office of Science, Office of Nuclear Physics**

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January 7, 2015

1 Introduction

The protection of the RHIC experimental detectors from damage due to beam hitting close upstream elements in cases of abort kicker prefires requires some dedicated precautionary measures with two general options: to bring the beam close to a limiting aperture (i.e. the beam pipe wall), as far upstream of the detector components as possible or, alternatively, to bring a limiting aperture close to the circulating beam. During the FY 2014 RHIC Heavy Ion run the first option was chosen because of the limited time available for preparation before the start of the run. For future runs the second option, in this case the installation of dual-sided movable masks, is preferred. The installation of the masks, one per ring, is planned before the start of the FY 2015 run.

2 History

Spontaneous and random prefires of abort kicker modules (Pulse Forming Network, PFN) have a history as long as RHIC is being operated. The abort system in RHIC consist of 5 kickers in per ring, each of them equipped with its own dedicated PFN. The kickers are typically operated with a voltage of about 27 KV for 100 GeV Au operation or 250 GeV proton operation. With full voltage all five modules add a 1.6 mrad angle to the beam trajectory, deflecting the beam safely into the dump.

2.1 Prefires and Damage

Since 2009 a total of 48 blue and 59 yellow prefires happened. Their distribution over the years and the PFNs is displayed in Tab. 1. The number per year varies greatly and so does the involvement of the PFNs. The perhaps only noteworthy characteristic appears to be the consistently small number of prefires caused by the middle PFN, number 3. Out of the sum of 107 events, 44 occur during the ramp and a total of 9 without beam in the machine. Both the large number of events during ramps and the distribution over

Ring	'09	' 10	'11	'12	'13	'14	PFN1	PFN2	PFN3	PFN4	PFN5	Sum
Blue	11	12	9	2	8	6	13	9	2	13	9	48
Yellow	2	8	15	8	14	12	3	16	5	14	20	59

Table 1: Summary of blue and yellow prefires since 2009.

the years is illustrated in Fig. 1. In Fig. 1 the time of a prefire is shown as a function of the fill number, thus spanning 6 years of operation as indicated and separated by the vertical dashed lines. The time is calculated with respect to the time of reaching flattop (ev-flattop) in a given ramp. Negative time values correspond to a prefire occurring before flattop is reached, i.e. during the ramp. 40% of prefires happen before flattop is reached. This is even more significant considering that, on average, much less time is spent ramping compared to the time spent at store and injection. Fig. 2 illustrates more details about

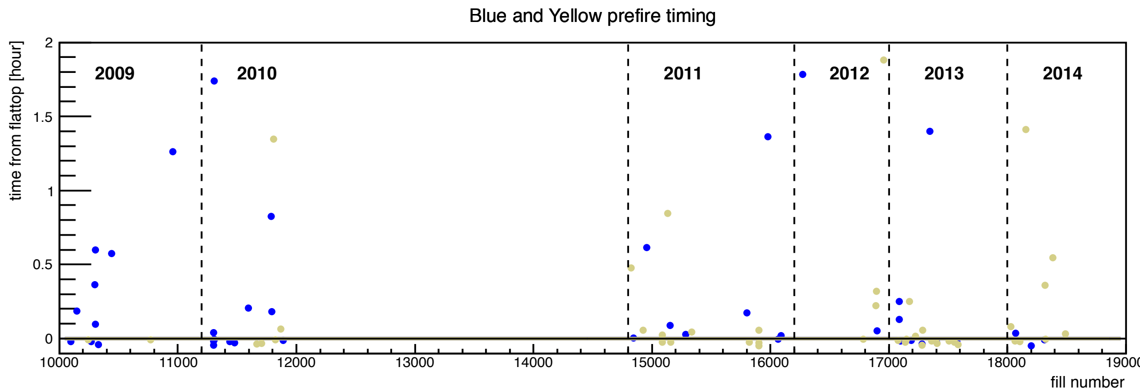

Figure 1: Prefire timing as a function of the fill number since 2009.

the timing distribution such as that 80% of all prefires happen within the first 2 hours of a fill with a mean value of 20 to 25 minutes (after ev-flattop) and an RMS of 40 to 50 minutes. The prefire with the lowest voltage occurred at 10.85 kV in fill 10957 in 2009,

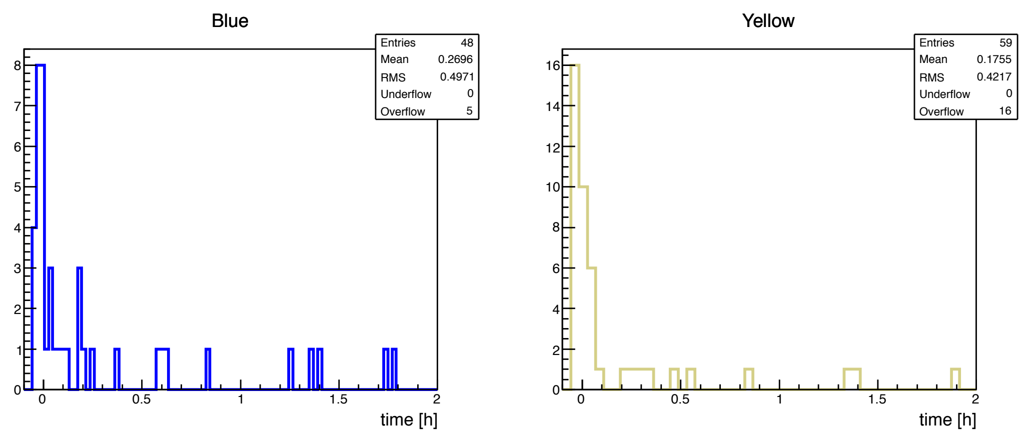

Figure 2: Number of prefire events as a function of time before or after flattop in the blue ring (left) and the yellow ring (right).

a run with 100 GeV polarized protons. Coincidentally this is also the fill with the first reported damage to an experimental detector component.

A complete list of prefire incidents with damage to the STAR MTD electronics and the PHENIX MPC respectively is given in Tab. 2. The first MTD detector module was installed during the 2009 run on May 4th, the PHENIX MPC in 2006. No damage was reported from the PHENIX MPC prior to 2010, a year during which two incidents with

year	fill	species	intensity	comment
2009	10957	pp 100GeV	$133 \cdot 10^{11}$	STAR MTD electronics is damaged with the 1st blue prefire incident of the run with the detector installed and on
2010	11593	AuAu 100 GeV	$113 \cdot 10^{9}$	STAR MTD electronics is damaged with the 1st blue prefire incident with the detector on
2010	11679	AuAu 100 GeV	$79 \cdot 10^{9}$	PHENIX MPC detector loses 5 channels
2010	11808	AuAu 100 GeV	$131 \cdot 10^{9}$	PHENIX MPC detector loses additional 4 channels
2012	16890	CuAu	$90 \cdot 10^{9}$	PHENIX MPC detector destroyed
2013	17347	pp 255 GeV	$102 \cdot 10^{11}$	STAR MTD electronics is damaged with the 1st blue prefire incident of the run (# 17347) with the detector on

Table 2: Overview of blue and yellow prefires since 2009 leading to detector damage.

minor damage happened (losing 4 and 5 preamps respectively). In 2011 and 2012 none of the prefires happened while the MTD detector was powered preventing any damage. The quoted intensity in Tab. 2 is the total intensity of the offending beam at the time of the prefire. In the case of the MTD, detector damage always occured at the first "opportunity", i.e. the first prefire of a run with the detector powered. In the case of the PHENIX MPC the situation is not quite as simple. In 2010 there were 2 instances with rather minor damages and one instance in 2012 with major damage, losing 300 out of 416 crystal readout units, i.e. more than 70% of the MPC in this one event [4]. Coincidentially, it happened during the first heavy ion prefire incident in that year. It is not understood why other prefires before and/or after this event did not have the same destructive effect.

2.2 Prefire Protection Bumps

In order to prevent any further damage after the latest MTD incident in 2013 (see Tab. 2) and due to the lack of time for design, manufacturing and installation of dedicated prefire protection devices, the first of the two available options was chosen. The beam was brought close to the aperture by means of 20 mm horizontal orbit bumps in two arcs: sector 10 and 11 for the blue beam and sector 9 and 8 for the yellow beam. Fig. 3 shows the orbit bumps (design and measured orbit) for the blue ring.The second bump in sectors 11 (blue) and 8 (yellow) is for path length and dispersion compensation purposes. Equivalent bumps in Yellow sector 9 and 8 were installed in the yellow ring. Those bumps were present during the entire 2014 run and its 6 Blue and 12 Yellow prefire events. Comparison of loss patterns with and without prefire protection bumps should show the redistribution of the majority of losses away from experimental triplets towards the bump areas.

Fig. 4 indeed plainly demonstrates the positive effect of the protection bumps in case of a blue abort kicker prefire. While without the bumps the losses outside the dump area are concentrated in the STAR sector 5 triplet area, such losses are significantly reduced in the case with the bumps present. Losses are concentrated in the protection bump area with some others lighting up as well (such as collimators and compensation bump area)

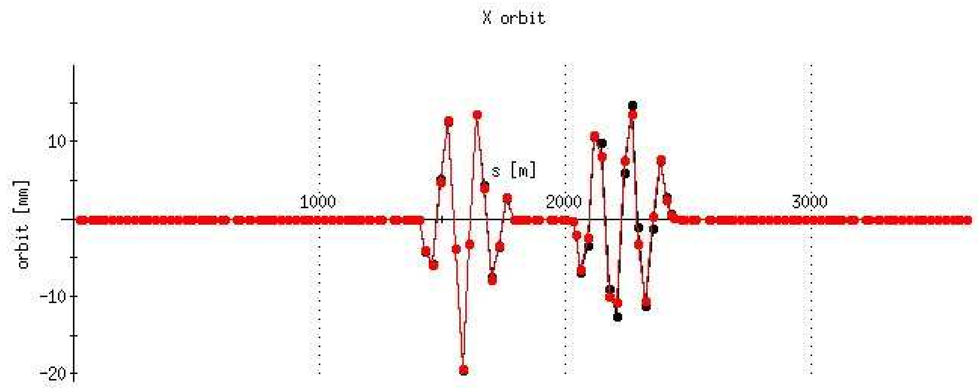

Figure 3: 20 mm orbit bumps installed in the blue ring for run 2014 prefire protection.

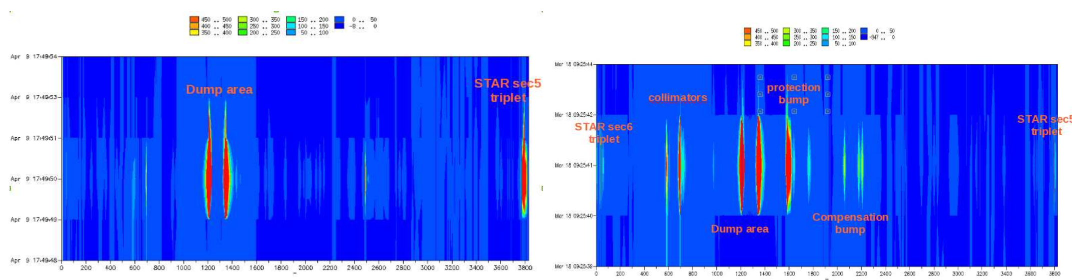

Figure 4: Left: Loss pattern after a blue abort kicker prefire in store 17347 (pp, run 13) without protection bumps. Right: after another prefire in store 18066 (AuAu, run 14) with protection bumps installed.

whereas STAR triplets are mostly spared. Given this success, one could argue to simply keep running with prefire protection bumps.

Unfortunately, besides absorbing beam during a prefire, the protection bumps had detrimental side effects. Increased continuous losses and subsequent increased radiation in the arcs caused FEC memory upsets and network switch resets in the alcoves [1]. Increased continuous losses, unusual for the center of an arc, are shown in Fig. 5. The figure shows loss patterns over 3 hours of a physics store in May 2014, during fill 18371. The red bands with losses of 50 rad/hr and above are created by the collimators placed around IP8. However, two other bands between 1500 m and 1600 m are also clearly visible. These two bands correspond to the Blue prefire protection bump area in sector 10. They clearly indicate continuous losses in that area of about 5-10 rads/hr. It is noticeable that no such losses are visible in sector 9, the arc that hosts the yellow prefire protection bump.

Fig. 6 summarizes the number of network switch resets during the last 3 Heavy Ion runs. The immense increase in the number of network switch resets necessary in Run 14 compared to the earlier two runs is obvious. The increase is most significant for the 11B alcove which is the closest to the maximum of the blue protection bump. Sector 9 alcoves are located in the Yellow protection bump area.

In addition, the DX magnet shifts planned for 2015 cause significantly altered local orbits in the insertion areas. This in combination with a 90 degree F0D0 cell phase advance lattice needed for the ATS scheme (achromatic telescopic squeeze [2]) adds another layer of

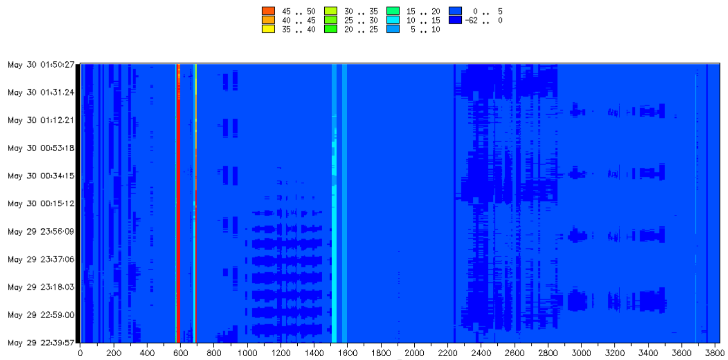

Figure 5: Loss pattern during a 100 GeV AuAu store (18371) in run 14 with prefire protection bumps in place.

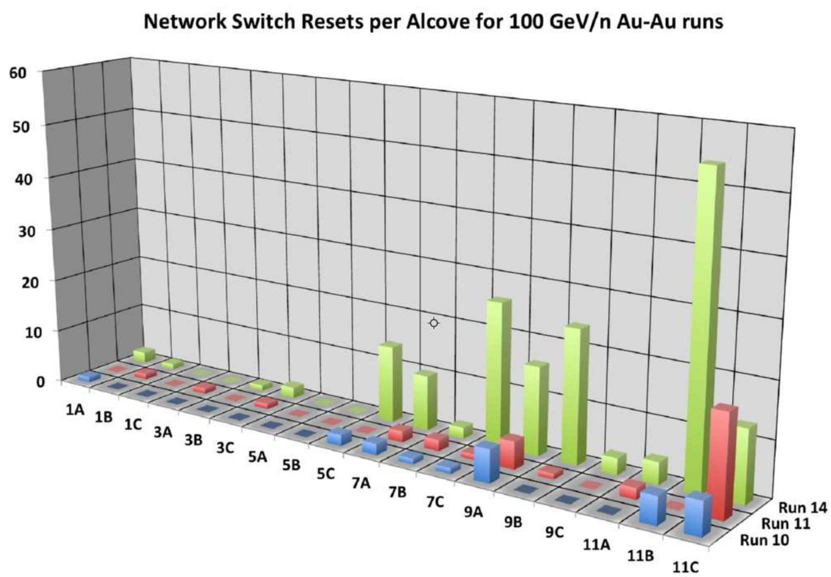

Figure 6: Network switch resets in RHIC alcoves during the last 3 heavy ion runs. Graph courtesy K. Brown [1]

complexity to the modeling effort that cannot be accomodated yet. The special lattice is required to provide a passive correction of non-linear chromaticities as well as to maintain a reasonable dynamic aperture. Both are essential in the quest to further improve RHIC's luminosity and are not compatible with 20 mm bumps in two arcs.

3 Mask Design

For a reasonable mask design aspects such as time schedule, availability, location, versatility and mask material had to be considered.

3.1 Location

It would be most beneficial to install any prefire protection mask right in the beam abort area. Such a nearby installation would provide independence from lattice, phase advance and tune changes. At the same time, a warm space area with accessible beam pipe far enough away to allow for enough transverse deviation of the kicked beam from the closed orbit is needed. No such space is available downstream of the abort kickers in the same interaction region. The next available warm spaces are one arc away in both directions, i.e.

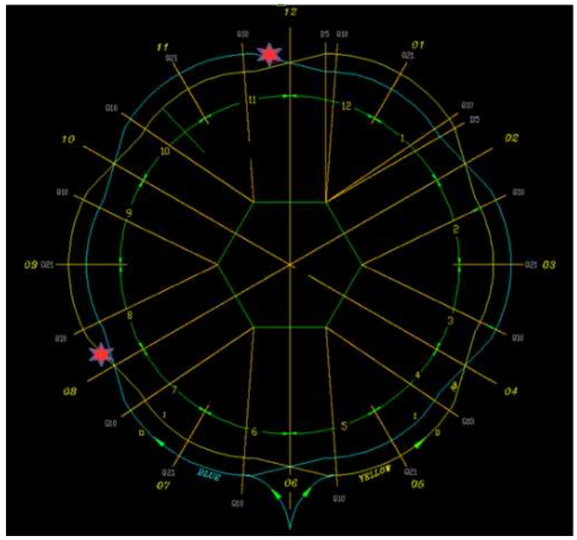

Figure 7: New mask locations in the RHIC rings (indicated by red stars).

between the Q4 and Q3 magnets on the sector 11 side of IP12 and sector 8 side of IP8. For the yellow ring no other location is possible since the PHENIX experiment is immediately down stream. Fig. 7 illustrates the chosen locations in RHIC. Due to already installed equipment in the opposite rings and the spin rotators in sector 8, the masks cannot be put right up to the Q4 magnets but need to be placed some distance away. This leads to a distance of 54.5 m in Yellow and of 65.6 m in Blue from the IP in question. Tunnel pictures and detailed drawings are provided in the Appendix (chapter A). No further equipment is installed between the masks and the Q3 magnets but there is further down stream, i.e. the PHENIX experiment in IP8 and the jet polarimeter in IP12. However, given the more than 50 m and 60 m distances, no additional shielding is required [5]. In fact, extra shielding close to the mask assemblies would provide material for particle showering and would not decrease radiation levels in the vicinity [5]. The configuration for the future mask is comparable to the radial material considered in [6]. Thus the maximum equivalent dose to an individual from an MCI (Maximum Credible Incident) is expected not to exceed 130 mrem [5], [7]. An MCI is defined as one half of the beam, i.e. $2.5 \cdot 10^{13}$ protons, in a ring hitting a magnet at maximum considered beam energy (300 GeV). Assuming the largest passable neutron flux in soil is $2 \cdot 10^{-6}$ cm^{-2} per proton, it takes $7.6 \cdot 10^{15}$ protons to reach the limit of 1000 pCi/L for tritium. This corresponds to more than 300 times the amount of beam considered in an MCI or 1267 times the amount considered for a prefire [5]. Even assuming an average of 10 prefires per ring and per year these numbers do not give cause for concern.

In order to be versatile and to be prepared for different possible lattices and phase advances (given that the chosen mask location is one arc away from the abort) the masks should be dual-sided. To allow for different beam sizes and a variety of RHIC operational modes such as low energy and injection they need to be movable and adjustable. This way continuous losses during stores (see Fig. 5) are also preventable. It turns out that

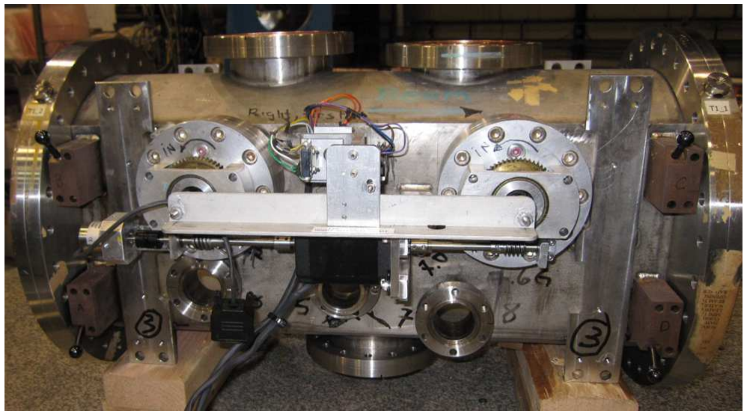

Figure 8: A FermiLab Style Cooling Tank on the bench before modification.

the retired FermiLab-style longitudinal stochastic cooling tanks provide all the necessary features and proportions to be turned into tanks for the prefire protection masks. Each tank is 77 cm long; 6 tanks are available, 2 of which will be used. Fig. 8 shows one of the existing tanks before modification. Obviously the inside of the tank needs to be modified, the stochastic cooling cavities need to be removed and mask jaws have to be inserted.

3.2 Material

One important input parameter for material heating and stress considerations is the maximum number of bunches affected by a prefire. Fig. 9 represents scope traces of the beam

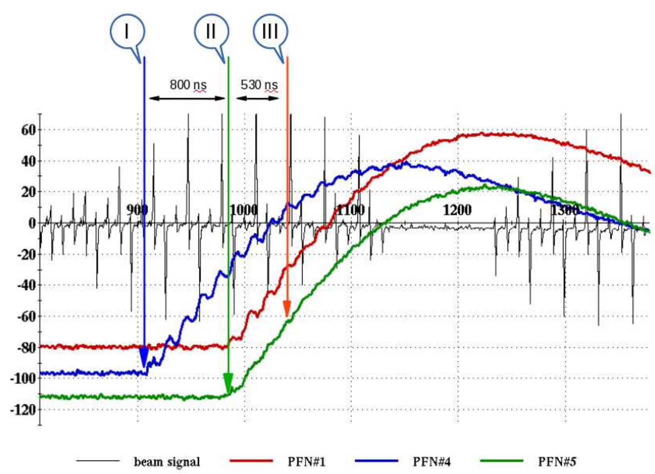

Figure 9: Blue abort kicker scope traces during a prefire ending store 18066 in run 14.The vertical scale is in arbitrary units, the horizontal scale corresponds to time in units of 10 ns.

signal and 3 PFN signals. The PFNs belong to the blue abort system. The data shows a snapshot from a prefire ending store 18066 in run 14. The three arrows, labeled I, II and III, indicate the following events:

(I) PFN#4 prefires. The prefire can be identified by the early firing of one module in the middle of the bunch train signified by the presence of the beam signal (black trace).

(II) PFN#1 and PFN#5 follow approximately 800 ns later.

(III) Another 530 ns later, the sum of the three shown PFN signals reaches the nominal value encountered by the first bunch during an intended beam dump.

The total time lapsed between the start of the prefire and reaching the nominal value is approximately 1330 ns, corresponding to about 13 bunches passing the abort kickers before a kick angle sufficiently large is reached to cleanly dump a bunch in the RHIC abort. This number is an already conservative estimate since the first few bunches will not receive enough of a kick angle to be intercepted by a mask or, likewise, a low beta triplet magnet. In addition, even a bunch with much less than the nominal deflection is supposed to hit the abort window and a deflection angle of as little as 0.82 mrad is considered covered [8]. In this case, the minimum deflection is reached after about 1 μs leading to only 10 affected bunches. However, in the following a conservative upper limit of 15 bunches to be intercepted by the mask material is assumed. The 15 affected bunches all receive different kick angles, starting at nearly zero and monotonically increasing to a nominal value of 1.6 mrad. Therefore they will spread horizontally over the mask surface as shown in Fig. 10. With 15 bunches superimposed as depicted here the maximum energy

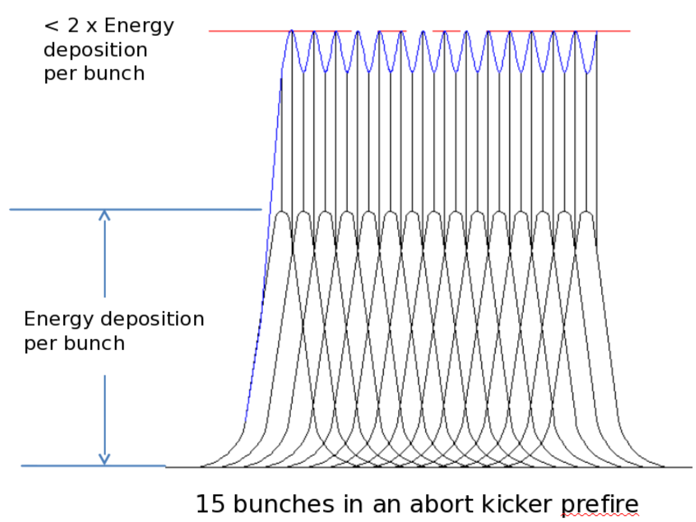

Figure 10: Sketch of energy deposition of 15 bunches distributed laterally on the mask material.

deposition on the surface corresponds to less than 2 x the bunch intensity, as indicated by the horizontal red line in the sketch in Fig. 10. For our calculations we assumed an RMS beam size of 0.5 mm, a per bunch proton intensity of $4 \cdot 10^{11}$ and a per bunch Au intensity of $2 \cdot 10^{9}$. Therefore heat and stress calculations were done for $8 \cdot 10^{11}$ p and $4 \cdot 10^{9}$ Au. Fig. 11 shows one of the simulations done for Au beam with these parameters [9]. These

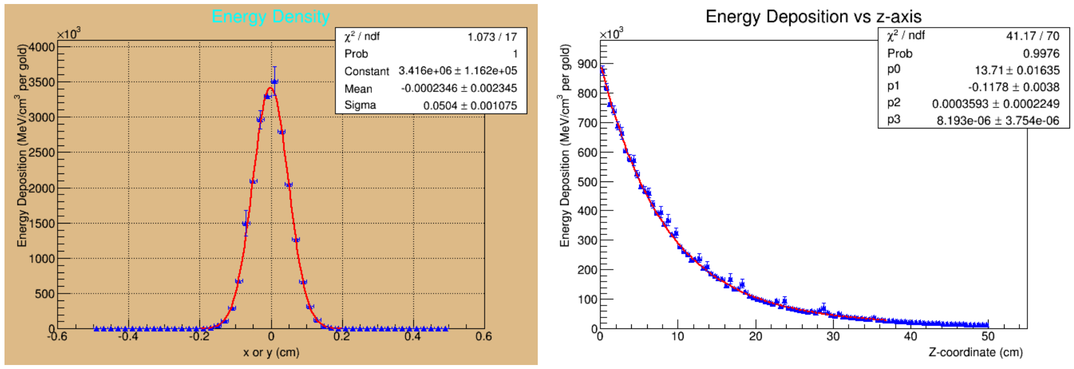

Figure 11: Energy deposition of Au beam on Ti (simulated).

energy density and deposition distributions are needed as input for the heat and stress simulations below.

We considered the following mask material candidates: stainless steel (SST 304), copper, Titanium (Ti-6Al-4V) and graphite. It turns out that proton beam impact would stay within limits even with 15 bunches for all materials while Au beams are more problematic causing over-heating (melting) or fracture of some materials (over-stressing). Tab. 3

	protons			Au			data sheets	
Material	N_{bunch}	T_{max} $[^oC]$	σ_{max} [MPa]	N_{bunch}	T_{max} $[^oC]$	σ_{max} [MPa]	T_{melt} $[^oC]$	$\sigma_{tensile}$ [MPa]
SST 304	15	542	379	1	511	370	1400	459 at 542^oC
	-	-	-	2	962	399	1400	43 at 960^oC
	-	-	-	15	6415	-	1400	-
Copper	15	652	-	15	6967	-	1085	26 at 652^oC
Ti-6Al-4V	-	-	-	1	394	243	1650	690 at 394^oC
	-	-	-	2	709	464	1650	400 at 709^oC
Graphite	-	-	-	2	580	16	3627	25.5 at 580^oC

Table 3: Heat and stress analysis (ANSYS) results for the considered materials.

summarizes the simulation results [10] for the considered materials. The stress limit of a material depends on the particular temperature reached in the impact resulting in decreasing stress limits with increasing temperatures. In cases of a temperature above the melting temperatures there is, obviously, no matching stress limit that could be quoted. Since protons are compatible with even the heaviest material (SST), no further simulations were done for the lighter ones. The decision to use the T-6Al-4V material rather than graphite is due to its higher material strength, higher melting temperature, easier machining, and higher density (which will therefore not be chipped off during the operation). Cutting graphite due to its dust production and dispersion is not handled at BNL. Similarly graphite causes concerns when installed inside the vacuum chamber. Beam power dissipation in two materials was modelled using Particle Studio [11]. 111 proton bunches of $3 \cdot 10^{11}$ p per bunch with an RMS bunch length of 20 cm were used in the model. The results are summarized in Tab. 4. Permeability is given normalized to empty space. None

Material	Resistivity [Ω cm]	Permeability	Dissipation [W/jaw]
SST 304	$0.70 \cdot 10^{-4}$	1.008	0.20
Ti-6Al-4V	$1.78 \cdot 10^{-4}$	1.00005	0.52
Graphite	$8.50 \cdot 10^{-4}$	1.00	2.51

Table 4: Electric properties of considered materials and resulting power depostion in the jaws.

of the studied materials would be cause for concern, i.e. there is no need for cooling of the jaws.

3.3 Assembly

Fig. 12 provides a drawing of the new assembly including the mask layout and dimensions. The angled mask surface along the beam direction allows for a grazing impact and helps to spread the bunches in the longitudinal direction. Each mask assembly holds two such jaws. The dimensions of the jaws were kept such as to not exceed the maximum weight limit on the weight bearing shafts. The weight of approximately 14 lbs is significantly below that of the original stochastic cooling equipment (22 lbs).

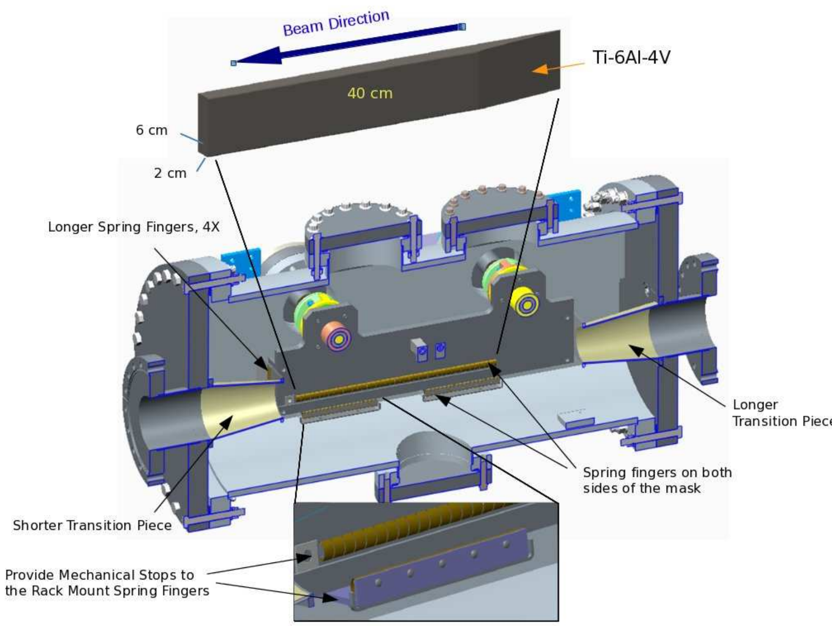

Figure 12: Y-Z cross section of the new mask assembly including jaw geometry and pointers to necessary modifications.

After the modifications to the former stochastic cooling tanks the mask assembly's aperture will range from a minimum gap of 1 cm (store) to a maximum of 4.87 cm (injection). Each mask jaw is moved laterallyl and independently of the other by one stepping motor via two shafts. There will be no rotatry motion.

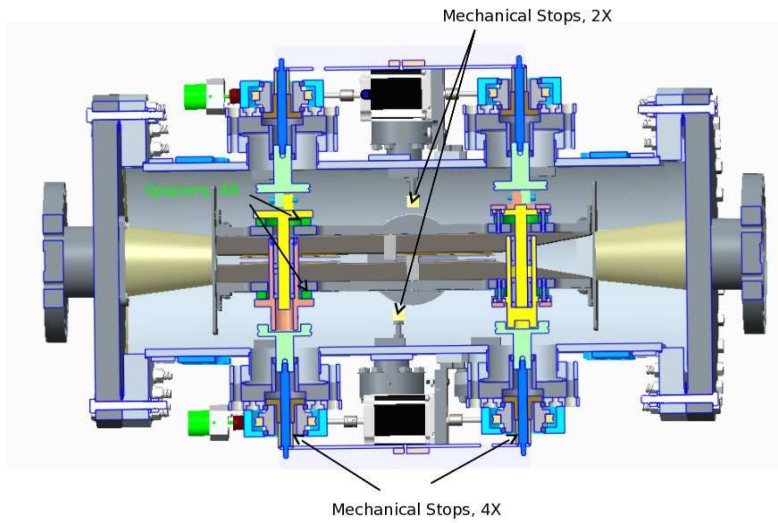

Figure 13: X-Z cross section of the new mask assembly indicating the needed mechanical stops. View from the top.

Each mask assembly contains 2 stepping motors for independent motion control of the inside and the outside jaw. Pin diodes provide dedicated loss monitoring for setup and alarming purposes. Alarm levels have to be set by the system expert. Loss levels above alarm limit will create a software warning on the MCR alarm screen. There are two instances of identical software for mask operation, maskman.blue and maskman.yellow. A GUI similar to the collimator control application will be available for operation. The masks will be fully retracted each time beam is injected (4.87 cm aperture) and gradually moved in during the ramp once the abort kicker voltage exceeds 10.8 KV. This lower limit corresponds to the prefire incident with the lowest voltage to date (in 2009, see chapter 2.1). Minimal aperture is $\pm$ 0.5 cm, centered around the center of the beam pipe by default. However, in order to allow a deviation of the closed orbit from the center of the beam pipe, the center position can be moved to the inside or outside within the allowable motion range. In this mode the controls software will move both jaws synchronously. For setup, however, each jaw can be moved independently. Each store the masks will move to a fixed and predetermined position. Positioning will be part of the overall accelerator ramping process ("tape sequences") once the masks and the managers are commissioned and the store positions are determined. Setup will be done with no more than 6 bunches in a particular ring. The desired positions contain 2 parameters (one position for each jaw) that have to be found during setup and stored. It is expected that the positions will have to be changed for each new lattice and ramp.

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[10] ANSYS simulation software, http://www.simutechgroup.com/Software/ANSYS/

[11] Particle Studio software, https://www.cst.com/products/cstps

A Appendix

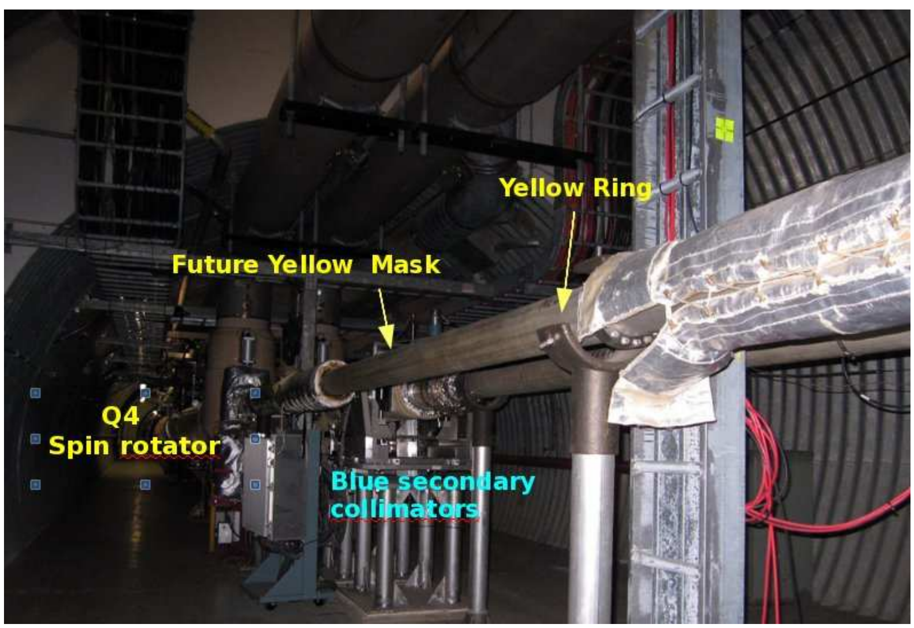

Figure 14: Picture of Yellow Installation Sector 8

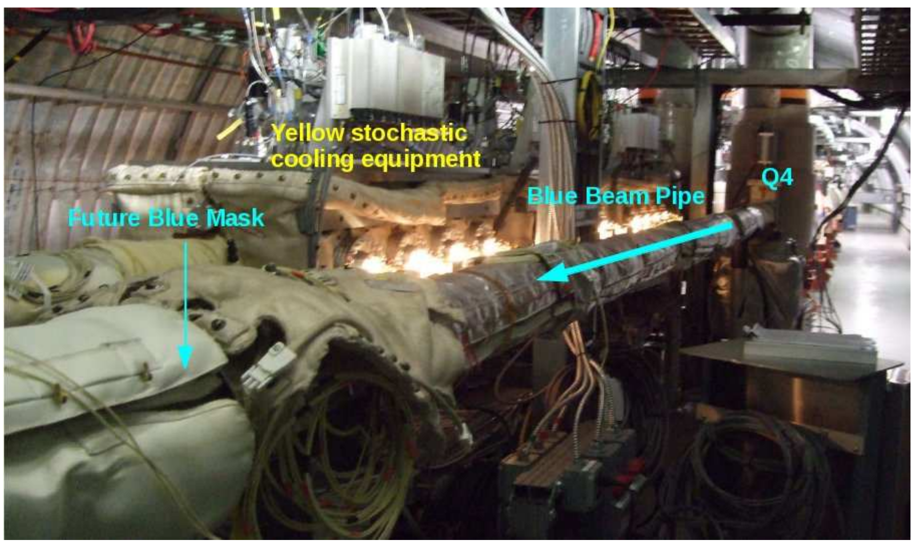

Figure 15: Picture of Blue Installation Sector 11

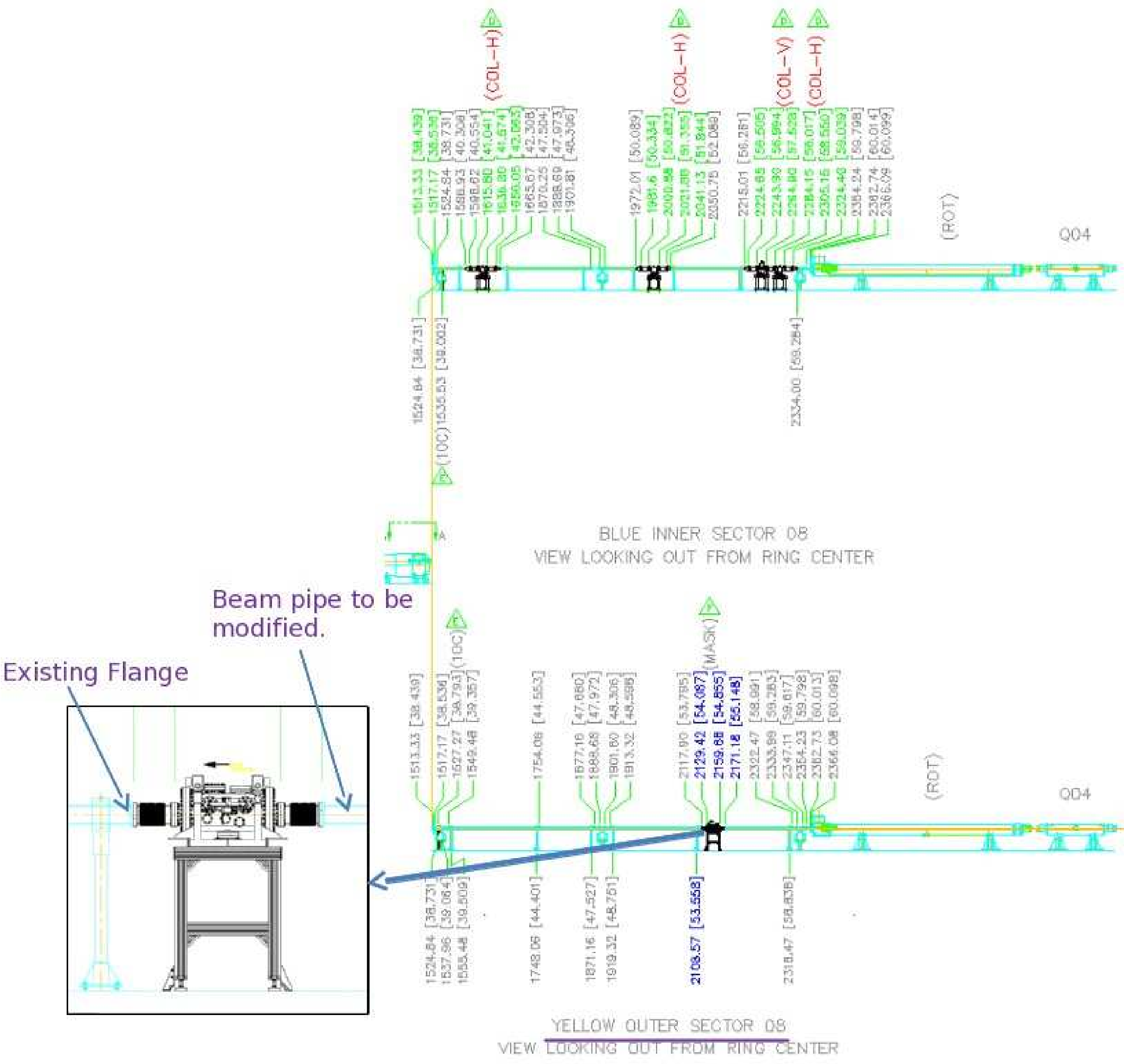

Figure 16: Drawing of Yellow Installation Sector 8

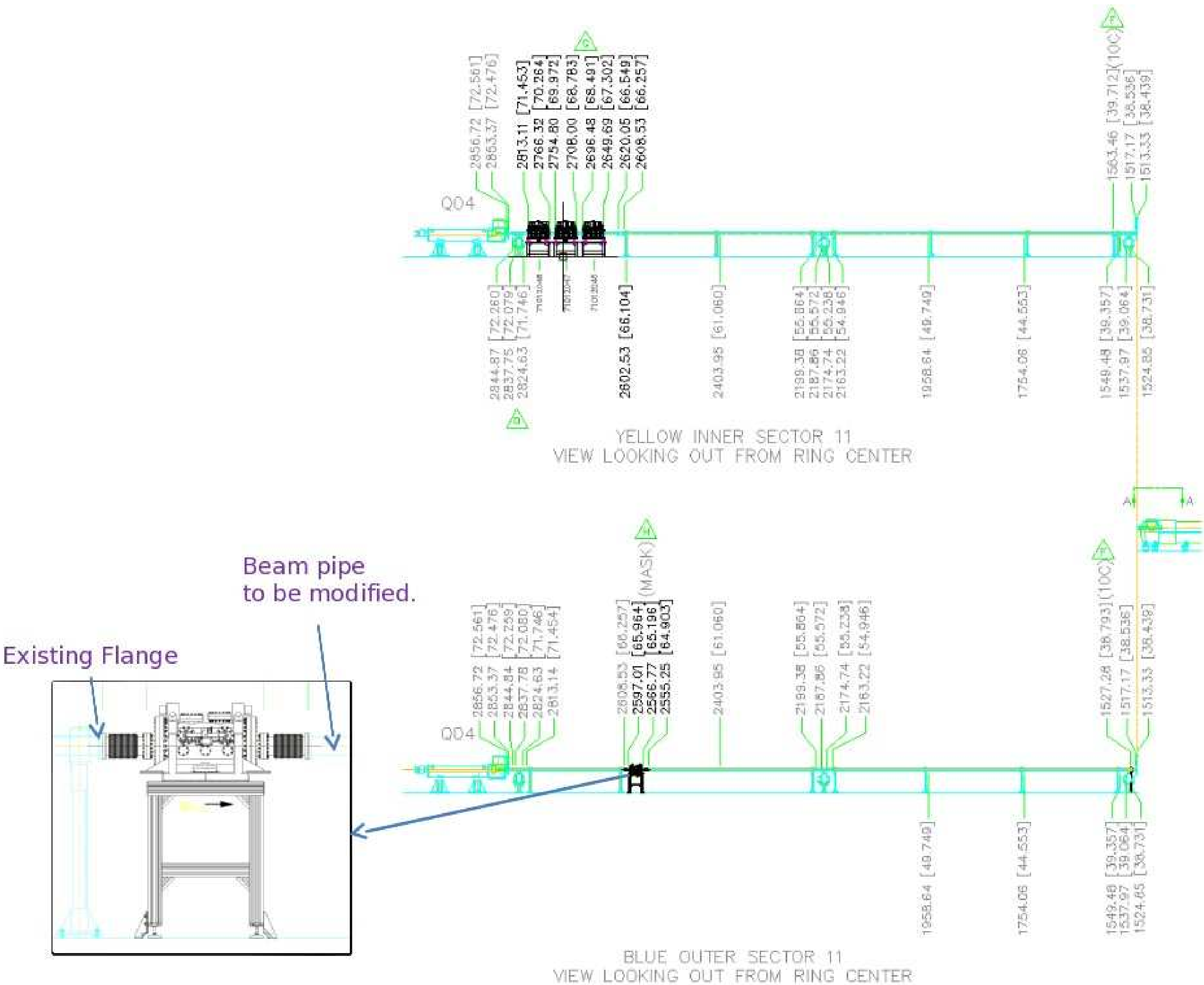

Figure 17: Drawing of Blue Installation Sector 11

RHIC Machine Protection Review

12/18/2015

Charge

- Is the plan to add a switch in series to the RHIC abort kicker thyratron switches technical sound, and will this modification suppress abort kicker pre-fires?
- Will RHIC still be protected with the delay in the abort kicker firing (up to 50 ms)?
- Are pre-fires a problem for the magnet lifetime?
- If serial switches are implemented, should they be on or off on the ramp (most pre-fires are on the ramp but no detector damage occurs on the ramp).
- What is the effect of a large beam loss over 50 us on, e.g. bellows or diodes.
- Which of the proposed switch technologies is best (HV relay in air - 50 ms delay, high speed relay in vacuum - 5 ms delay, solid state - 120 ns delay)?

Reviewers

- Deepak Raparia (ASSRC Chair and review chair)
- George Ganetis
- Mike Harrison
- Pete Zuhoski
- Dejan Trbojevi

Agenda

- 20+10 min A. Drees, "Past abort kicker pre-fires, statistics and effects"
- 40+20 min J. Sandberg/A. Zhang, "Options for serial switches, delay times and failure modes"
- 40+20 min C. Theissen, “Present permit system inputs and delays, effect of additional delay"
- 20+10 min G. Robert-Demolaize, “Beam energy deposition in pre-fire with present abort system and additional delay”
- 20+10 min J. Muratore, “Possible damage to superconducting magnets with additional delay"
- 60 min Discussion

Answers to Charge

- Is the plan to add a switch in series to the RHIC abort kicker thyratron switches technical sound, and will this modification suppress abort kicker pre-fires? YES

- Will RHIC still be protected with the delay in the abort kicker firing (up to 50 ms)? TBD (Insufficient information)

- Are pre-fires a problem for the magnet lifetime? TBD (Insufficient information)

- From all the pre-fries over the past 15 years there does not seem to be any case where a magnet has been damaged, but the pre-fires are not the same as a 50 msec. delay to the abort system.

- If serial switches are implemented, should they be on or off on the ramp (most pre-fires are on the ramp but no detector damage occurs on the ramp). On during ramp

- turn the series switches on during the ramp and off when the detectors are prone to damage.

- What is the effect of a large beam loss over 50 us on, e.g. bellows or diodes. TBD (Insufficient information) That is what the more analysis might be able to determine.

- Which of the proposed switch technologies is best (HV relay in air - 50 ms delay, high speed relay in vacuum - 5 ms delay, solid state - 120 ns delay)? HV relay in air with shorter delay ~10 ms

Comments

- The basic concept of adding a high voltage switch in series with the thyatron switch seems workable. Having a series connected switch should greatly reduce time the thyatron will be susceptible to pre-fires where they might be eliminated.
- The new switch (and associated electronics) must not be susceptible to the same type of pre-fire condition
- The Vacuum Relay and it's drive electronics and the Semiconductor Switch could have problems in a radiation environment.

Comments (cont.)

- A simple high voltage relay design for this fast high current pulse seems the best suited for this task. The problem is the 50 msec. time it takes for the relay to close. This is ~ 500 times slower than the present system.
- The information given on the consequences of the pre- fires in terms of magnet quenching does not directly answer if a 50 msec. delay to the beam abort will cause damage to magnets or other components in the RHIC machine.

Recommendations

- A thorough study be made of past beam aborts that were delayed by a system failure or other causes. With 15 years of operations there should be some data on these type of events. With the information from these events try to estimate the maximum energy that could be deposited on components the beam would hit. If possible try to determine if a 50 msec. delay would be similar to past conditions of delayed aborts.

Recommendations

- Another study would be to determine what the beam energy would be deposited on various beam chamber components for various machine faults (magnet quenches, power supply faults, RF faults, etc.). Would the energy levels cause component damage by the 50 msec. delay?

With the above studies one might be able to determine what the maximum delay one could apply to the abort signal.

Recommendations

- In parallel with the studies, a simple R&D program to speed up the closure of the air relay. Changes to the mechanical design, coil, armature, coil drive circuit could significantly improve the closure times.
- For next year add crucial BPMs in the beam permit system.

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A close look at beam aborts with rise times less than 40 ms from the years 2014-2016. Case studies.

A. Drees

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, NY 11973

U.S. Department of Energy
Office of Science, Office of Nuclear Physics

A close look at beam aborts with rise times less than 40 ms from the years 2014-2016. Case studies.

A. Drees

September 14, 2016

1 Introduction

In an effort to understand the risks of operating RHIC with an additional delay of 40 ms in the abort system, all beam aborts triggered by loss monitors at store from the years 2014, 2015 and 2016 were analyzed and particularly fast cases selected. The results were presented at the RHIC retreat on Jul 29, 2016 [1]. All beam aborts at injection, during the ramp and at flattop but before the "ev-lumi" event were ignored since the additional delay of 40 ms is proposed for operation at store only.

2 Available Data

For all beam aborts by loss monitors a rise time leading up to the abort trigger was calculated by Yun Luo. The rise time, according to [2] was defined as the time between reaching 10% of the signal maximum and 90% of the signal maximum. Fig. 1 represents a sketch of the

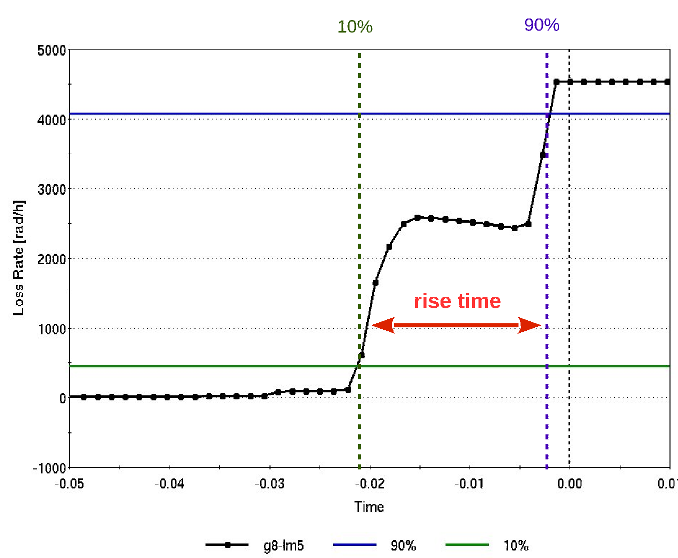

Figure 1: Definition of risetime as the time between 10% and 90% of the loss monitor data. Showcase fill is 19769.

definition. In this example the saturation level of 4530 rad/h for g8-lm5 constitutes the maximum. The time of the abort trigger is indicated by a black dashed vertical line. In this particular case the rise time appeared to be 19.4 ms. The Post Mortem database provides loss monitor data with a granularity of 720 Hz for each abort. Due to the 720 Hz granularity all rise times constitute an integer multiple of 1/720 = 1.39 ms.

fill	**date**	**time**	**ring**	**species**	**rise time [ms]**
18061	03/17/2014	17:23:13	B	Au	2.78
18070	03/18/2014	21:28:05	Y	Au	1.39
18304	05/11/2014	13:20:13	B	Au	4.17
18361	05/27/2014	23:19:34	B	Au	2.78
18483	06/26/2014	19:06:28	B	p	2.78
18969	04/29/2015	23:17:45	B	p	4.17
19009	05/03/2015	01:49:00	B	p	4.17
19234	06/19/2015	09:28:47	B	p	1.39
19374	01/28/2016	03:19:10	B	Au	0
19519	02/11/2016	17:21:10	B	Au	4.17
19761	04/13/2016	16:29:16	Y	Au	4.17
19769	04/14/2016	16:24:19	B	Au	19.40
19834	04/28/2016	18:26:40	B	Au	2.78
19848	05/01/2016	19:16:49	B	Au	18.05
19894	05/11/2016	09:59:19	Y	Au	4.17

Table 1: List of fills aborted by loss monitors with a signal rise time of $\leq$ 40 ms

15 cases with rise times below 40 ms were found in 2014 to 2016. The cases are listed in Tab. 1, 4 cases with protons and 11 with Au. 12 happened in the blue ring, the remaining 3 in the yellow ring. Each case is discussed individually below. The figures in this analysis were generated using the PMViewer GUI [3] and LogView [4]. For each case a reason, as quoted in [1], is listed for reference with the more detailed analysis.

2.1 Case 18061

| B | g8-lm5 | 2.78 ms | MCR: FEC reboot while gap cleaning |

No quenches were associated with this abort. Fig. 2 (left) summarizes the event, including the loss data (red line), various thresholds and the beam current data. The data shows a 10 Hz structure (0.1 s steps), representing the fastest of the gap cleaning options of 10Hz, 1Hz or 0.25Hz. The g8-lm5 LM saturates with only 0.3% of the beam lost (and most of that would be lost on the collimators, not at g8-lm5). Due to the ongoing reboot of the FEC (cfe-2a-tune1) the status of the gapCleaner [5] cannot be reconstructed fully. However, as can be seen in Fig. 2 (right), the bunch-by-bunch losses clearly move from the gap to a location in middle of the bunch train. The blue trace is taken 1s before the abort, the red trace shows the data accumulated during the second in which the abort happened. The peak appears 'smeared' due to varying arrival times of particles in the collimator Pin Diodes.

Conclusion: The amount of beam loss is actually small (about 1/3 of one bunch), too small for damage beyond, perhaps, a quench. The gapCleaner, due to its kicker pulse length

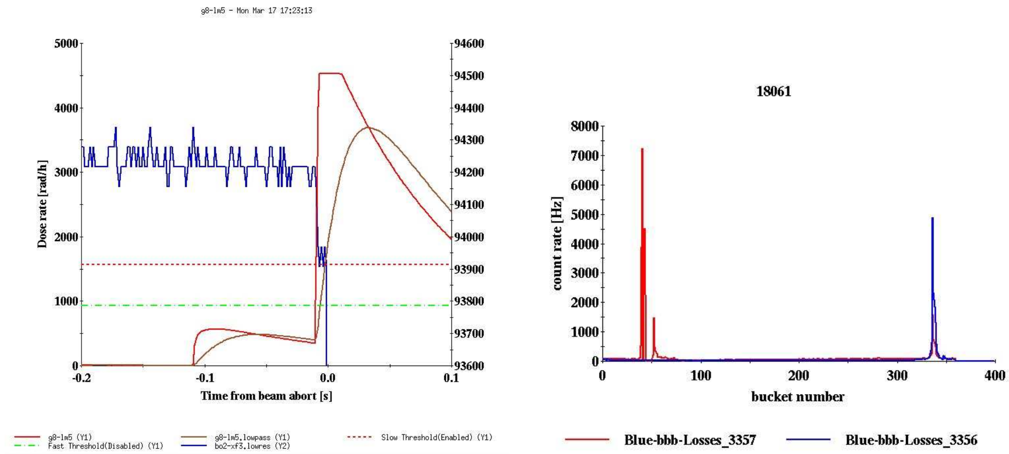

Figure 2: 720 Hz loss monitor and current transformer data from PMViewer (left). Two traces corresponding to two consecutive seconds of bunch by bunch (bbb) loss data from the abort in 18061.

of only about 100 ns [5], affects only one bunch at a time but cannot impact the entire beam. The fastest time for it to switch from one bunch to another is 10 Hz, i.e. 100 ms, plenty of room for an additional 40 ms.

2.2 Case 18070

Y	y3-lm4	1.39 ms	MCR: Lisa steering with a bad activation

No quenches were associated with this abort. Current transformer and loss data are shown in Fig. 3, left. It is interesting that the losses appear to stall after a fast initial drop over the first 2.8 ms. The losses correspond to 0.7% of the total beam, a bit less than one full bunch. MCR attributed the abort event to a bad lisa [6] steering. Following are two excerpts from the appropriate 2014 lisa logfile:
Tue Mar 18 21:27:21 2014 -1 ERROR: MultiOptimizeScan: error activating - aborting scan
After the error message MCR tries to optimize again:
Tue Mar 18 21:28:08 2014 0 Retrying parallel optimization after failure
This last automatic message and the accompanying retry appears to happen 3 seconds after the time of the beam abort making lisa steering unlikely to be the cause. This timing can be confirmed by checking the logged PS current data for the involved correctors and the timing of the abort- and auxramp2-events as can be seen in Fig. 3 on the right. Indeed, all correctors in question are at nominal values until the ramp-down starts (well after the abort).
In addition, y3-lm4 is an unusual loss monitor to be first responder in a failure caused by corrector magnets around IP6 and IP8. It is, on the other hand, close to a stochastic cooling tank which was indeed moving at the time and losses spike on yi3-ksch3-pd (the pin diodes associated with the yellow horizontal stochastic cooling kickers in sector 3) at the time. The extremely fast loss rise time, however, makes the move of a large mechanical system equally unlikely to be the root cause of this very fast event. Unfortunately, all abort kickers are accounted for and not one PS was alarming or reporting an issue at the time of question.

Conclusion: The abort was not due to a bad lisa activation. The SC kicker as a me-

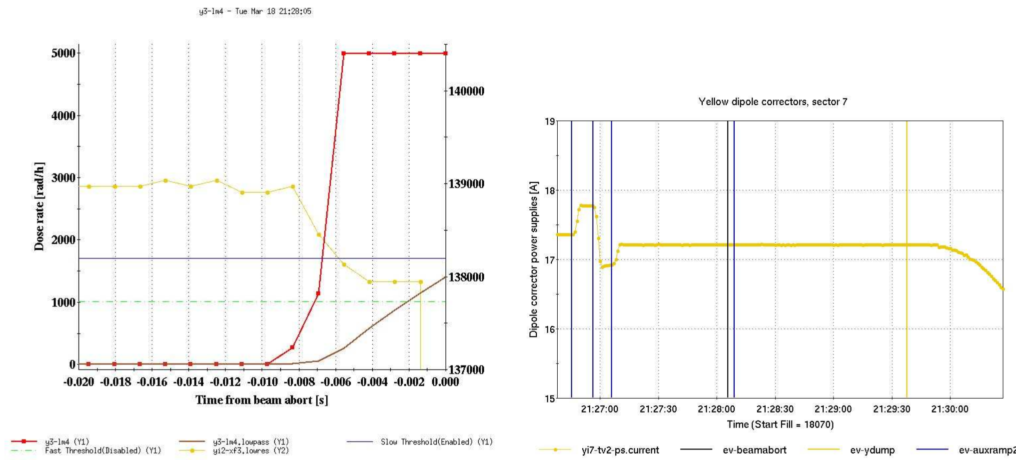

Figure 3: 720 Hz loss monitor and current transformer data from PMViewer. Dipole corrector data during store 18070, before and after the abort.

chanical system is too slow to be the culprit. No other culprit candidate could be found and this case remains a mystery.

2.3 Case 18304

| B | g8-lm5 | 4.17 ms | MCR: FEC reboot while gap cleaning |

No quench associated with this abort. The gapCleaner was set to a 1 Hz frequency and the losses, as shown in Fig. 4, left, clearly show a 1 Hz structure. During the trigger at -1.0 s about 0.1% of the beam was lost and just before the abort another 0.2%. The bunch-by-bunch losses, shown in Fig. 4, right, were accumulated in a second before (trace 516) and during the abort (trace 518). They clearly show how the losses moved from the gap to an occupied bucket. A modest lowering of the trip threshold would have aborted the beam easily 1 s earlier. The FEC (cfe-2a-tune1) apparently rebooted itself spontaneously. A warning

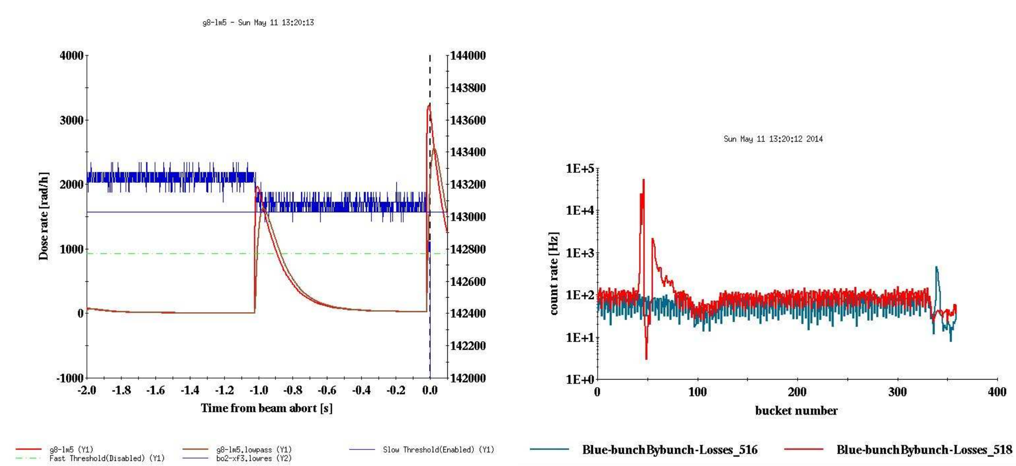

Figure 4: Left: 720 Hz loss monitor and current transformer data from PMViewer. Right: Bunch by bunch losses accumulated two seconds before and the second including the abort.

message (not to reboot with beam in the machine) has been added since.

Conclusion: The gapCleaner, due to its kicker pulse length of only about 100 ns, affects only one bunch at a time and cannot impact the entire beam. Hence the associated beam loss is relatively modest and not close to a damaging amount.

2.4 Case 18361

B	**g10-lm5**	**2.78 ms**	**MCR: Blue abort kicker prefire**

Module 4 of the blue abort kickers prefired. This was the 15^{th} prefire in run 14. At least one magnet in the blue sector 10 protection bump area quenched (B10DSA4_A3VT). This is the very event we are trying to prevent by adding the 40 ms delay (aka the mechanical switches). Noteworthy is the rise time of 2.78 ms, which isn't even close to the "real" risetime of one turn in a prefire. This demonstrates that +/- 2.78 ms is the limit of accuracy for the rise time determination which is based on 720 Hz data and is thus much slower than 12.8 μs.

Conclusion: This event can be ignored for the purpose of this study.

2.5 Case 18483

B	**g10-lm5**	**2.78 ms**	**MCR: APEX, fins of the target clipped through the beam tail**

There were no quenches associated with this event. Fig. 5, left, shows g10-lm5 data. g10-lm5, showing losses caused by an ordinary beam dump, actually did not trigger the beam abort but b12-lm4 did (Fig. 5, right). The actual rise-time for b12-lm4 is well above 100 ms and

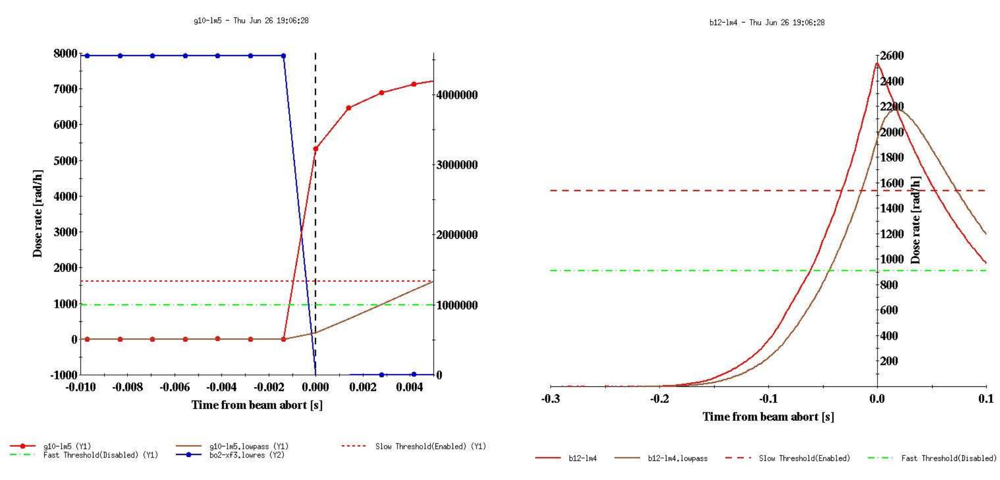

Figure 5: Left: 720 Hz loss monitor b12-lm4 data from PMViewer. Right: 720 Hz loss monitor g10-lm5 data from PMViewer

thus of no concern for the extra 40 ms delay. This event got into the list by accident. However, it indicates that a rise time of 2.78 ms can be falsely calculated from the 720 Hz data, here due to the continuous rise of the loss rate after the abort (thus shifting the maximum to after the abort). The actual rise time in this case is less than 1.39 ms (i.e. one 720 Hz bin). In addition, it is suggested to exclude APEX time from operating the aborts with the additional 40 ms. There are, of course, failure modes during APEX that could happen at any other time as well and therefore need to be checked.

Conclusion: This event can be ignored for the purpose of this study.

2.6 Case 18969

B	**b10-lm4**	**4.17 ms**	**MCR: Ramp development, abort reason not found in elog**

There were no quenches associated with this event. In principal, this event should not be listed here since it happened during ramp development. However, we need to check if this type of failure could not happen at other times as well. In any case, looking closely at the time of events as shown in Fig. 6, it shows that the permit pull by b10-lm4 comes following an ordinary beam dump. According to the list of RHIC event times, the two are 10 ms apart. b10-lm4, the first loss monitor down stream of the blue abort, is prone to and known for

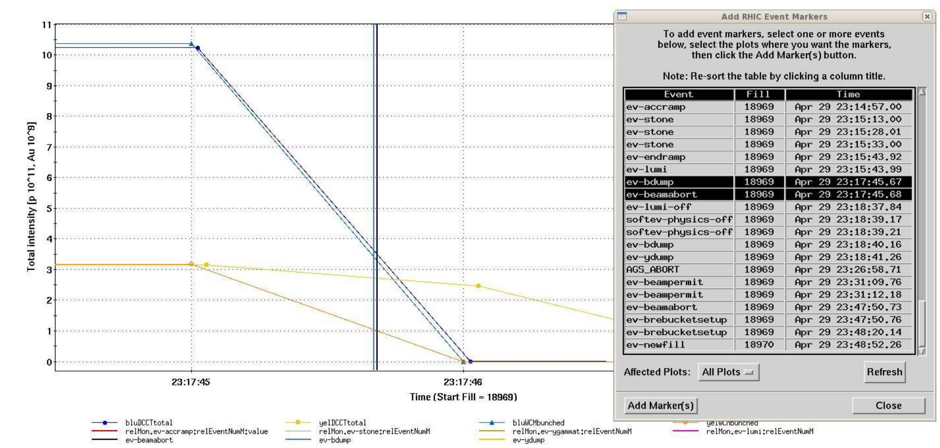

Figure 6: LogView graph showing beam current data and list of events for end of store 18696.

permit pulls due to ‘’spilled” losses from an ordinary beam dump, particularly during proton operation.

Conclusion: This event can be ignored for the purpose of this study.

2.7 Case 19009

B	**y9-lm4**	**4.17 ms**	**MCR: Taking a “quick” polarimeter.**

No quenches were associated with this abort. y9-lm4 (yellow!) actually goes above threshold after the abort and the triggering loss monitor is b12-lm4 (blue!). Fig. 7 shows the corresponding data. The rise time for this monitor is approximately 100 ms. Therefore this case is of no interest for this study. y9-lm4, the first loss monitor down stream of the yellow abort, is the yellow LM known for permit pulls due to “spilled” losses from an ordinary beam dump, particularly during proton operation.

Conclusion: This event can be ignored for the purpose of this study.

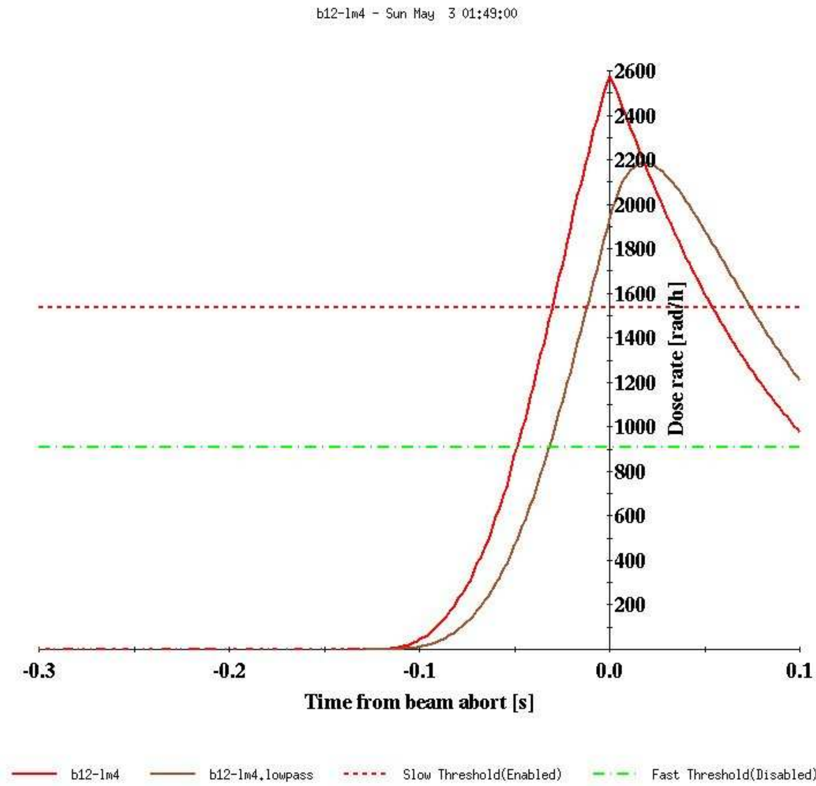

Figure 7: PM 720 Hz b12-lm4 data

2.8 Case 19234

B	**b6-lm3.1**	**1.39 ms**	**MCR: Blue Quench Link Interlock, BS2 tripped off early.**

B6Q3 triplet quadrupole quenched in this case. This abort portrays the perfect storm of cavity trips where a faulty damper was not secured when the trip happened. Fig. 8 summarizes the course of events. Shown are the BS2 gap volts (black squares) in kV, the radius (red line) in micron and the beam current transformer data (blue line). The cavity trips 100 ms before the abort (t=0). The unsecured tuner starts moving towards the beam, changing the cavities tune in the process. 20 ms before the abort very fast instabilities entail, visible as rapid oscillations of the cavity voltage as well as the radius. Actual beam loss is concentrated in the last 5 x 1.39 ms = 7 ms before the abort.

Conclusion: Only if the BS2 cavity would have been in the permit (it wasn't) this quench (with or without an additional 40 ms of delay) could have been prevented.

2.9 Case 19374

B	**g10-lm20**	**0 ms**	**Travis: 0.10 mrad angle bump at IR8**

This case happened outside physics, during setup and commissioning and would therefore be done without a modified abort system. However, it was actually a prefire (module 3), at least two magnets quenched in B10DSA4_A3VT and B10QFA3_A2VT. There were only 6

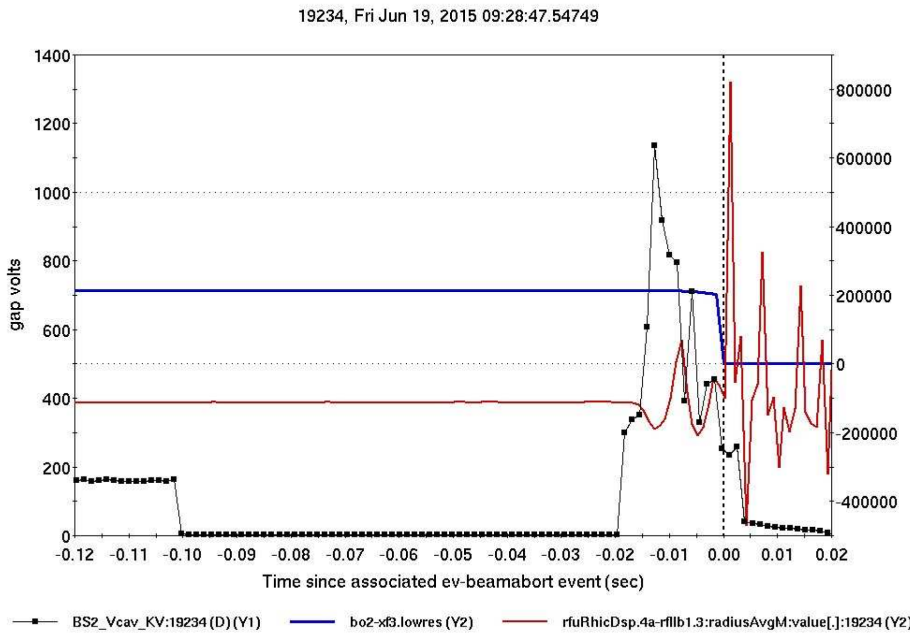

Figure 8: 720 Hz RF BS2 voltage data, radius data and beam current transformer data.

blue bunches in the machine, i.e. a prefire with a very unlucky timing.

Conclusion: This event can be ignored for the purpose of this study.

2.10 Case 19519

| B | g8-lm5 | 4.17 ms | MCR: APEX, squeeze to 50 cm in Blue |

No quenches in this case. The abort happened during an APEX, a time during which no change to the abort system is planned. At the time of the abort were 12 bunches in the machine and a new ramp to squeeze IP8 to 50 cm was tested. As part of the ramp development TbT orbits were triggered every 4 s which include a trigger to the ARTUS tune meter kickers. The losses due to two of those triggers can be seen at -6.5 s and -2.5 s in Fig. 9 (left), precisely 4 s apart. There are two corresponding TbT data sets stored in the orbit archives. Only one bunch (# 31) is affected by the TbT triggers. However, beginning about 15 s before the abort (and 47 s into the ramp), all 12 bunches start to oscillate (+/- 3 mm peak to peak, approximately 140 Hz frequency) and to show some beam losses according to the bbb beam loss monitor. The amplitude more than doubles about 25 ms before the abort as can be seen in Fig. 9 (right). Even though losses are visible on the loss monitors, there is no noticeable beam loss seen in the current transformers up to 1.39 ms before the abort.

Conclusion: No single cause of abort could be identified for this case although it is likely associated with the ongoing beta-squeeze. One could argue to ignore it since it happened during APEX and during a ramp, if only a squeeze. Alternatively one could establish a maximum allowable oscillation amplitude of, say, +/- 2 mm (at store). In this case this ramp could have been aborted 15 s earlier than it actually did.

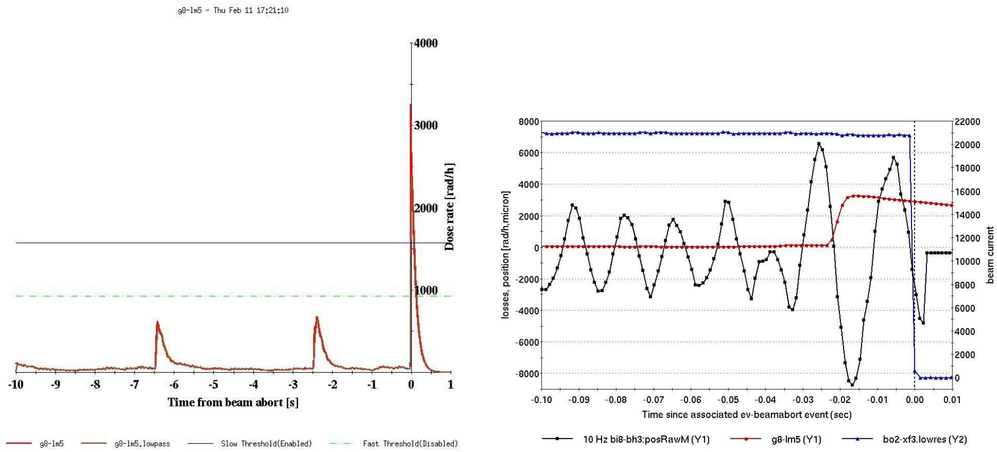

Figure 9: Left: g8-lm5 PM data from abort of store 18519. Right: The last 0.15 s before the abort depicting 1kHz data from GOFB_10Hz BPM bi8-bh3, current transformer and g8-lm5.

2.11 Case 19761

Y	**g8-mlmx.1**	**4.17 ms**	**MCR: APEX, angle steering at IR6 during lumi leveling**

No quenches were associated with this event. This abort happened during an APEX study and would as such have happened without any changes to the abort system. However, this loss scenario is not associated with APEX activities such as the quoted angle steering in IR6 (which is not the root cause for this abort). The beam loss happened very fast (see Fig. 10, left). As can be seen in Fig. 10, right, most of the angle steering in IR6 was already completed when about 15 s prior to the abort angles start drifting again in both IPs and beam is lost at angles much smaller than the ones achieved before. At the time of abort all of the supplies in

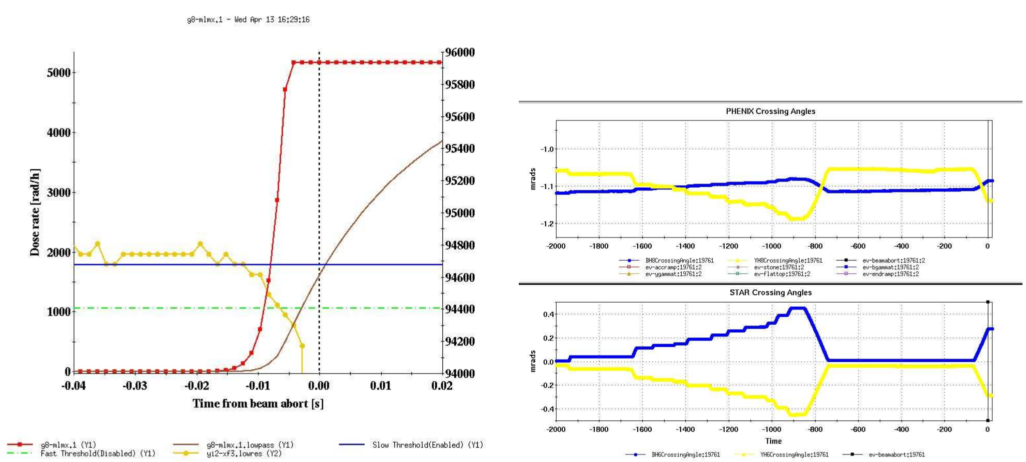

Figure 10: left: g8-mlmx.1 PM data from abort 19761. Right: IP8 and IP6 crossing angles during APEX leading up to the abort.

alcove 9A, 9B and 9C tripped on a lead flow fault. Cryogenics replaced a power supply in the 1008B valve box for 8Q3. Yet, a lead flow fault alone does not quite explain the very short rise time seen in this event. In another similar case (19837, in which the yellow injection kicker got damaged) the rise time was of the order of a few 100 ms.

Conclusion: It is unclear if the likely reason (lead flow fault) is enough to explain the very short rise time. No other reason could be found however. Therefore no recommendation in anticipation of an extra 40 ms delay can be made.

2.12 Case 19769

B	**g8-lm5**	**19.4 ms**	**MCR: store following 56 MHz study, caused by 10Hz PS**

No quenches were associated with this case. This abort is caused by a failure of a GOFB_FB 10Hz PS without any connection to the 56 MHz RF cavities. As can be seen in Fig. 11, the power supply and the orbit start oscillations about 70 ms before the abort (indicated by the dashed black vertical line), significant losses appear about 20 ms before.

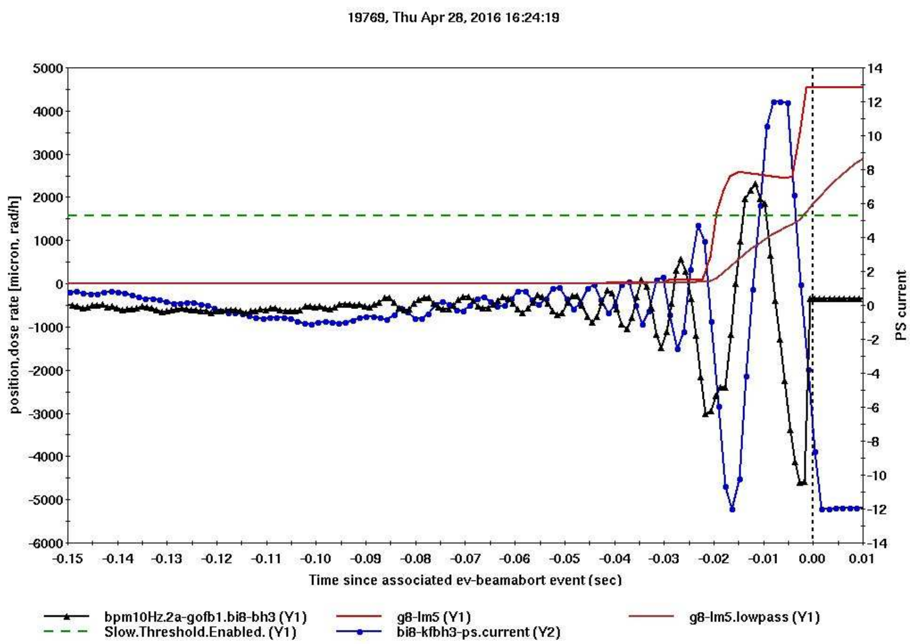

Figure 11: Orbit oscillations, power supply current and loss monitor data during 0.15 s before the abort.

Conclusion:In order to trigger an abort 40 ms before the recorded time here, either a BPM based permit or a 10 Hz PS based permit would be needed with a response time of approx. 10 ms.

2.13 Case 19834

B	**b8-lm4**	**2.78 ms**	**MCR: likely linked to 56 MHz**

There were no quenches associated with this abort. The culprit in this case was not the 56 MHz cavity but operator error. b8-lm4 is the first loss monitor down stream of the blue collimators with an enabled permit threshold. As can be seen in Fig. 12, left, gap cleaning was in progress at a modest level at 0.25 Hz, one of the three frequency options. This can be confirmed by the configuration setup for the blue gap cleaning kickers (Fig. 12, right). Acquisition mode is set to “3”, i.e. the 4secEvent, minutes before the abort. At the same time the default bucket for gap cleaning, was changed by operators from 347 to 336 and eventually to 334. Note that bucket numbers are offset by +1, starting from 0 and going up to 359. In addition, it can be expected that the kicker pulses are not perfectly centered on the occupied buckets. Timing shifts can occur during the ramp to store. The effect of the

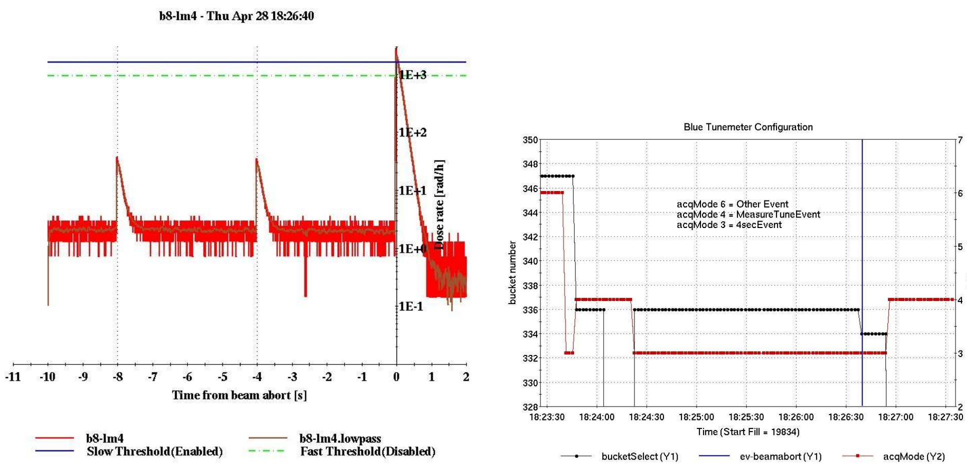

Figure 12: Left: b-lm4 PM data, right: blue tune meter kicker setup before and during the abort.

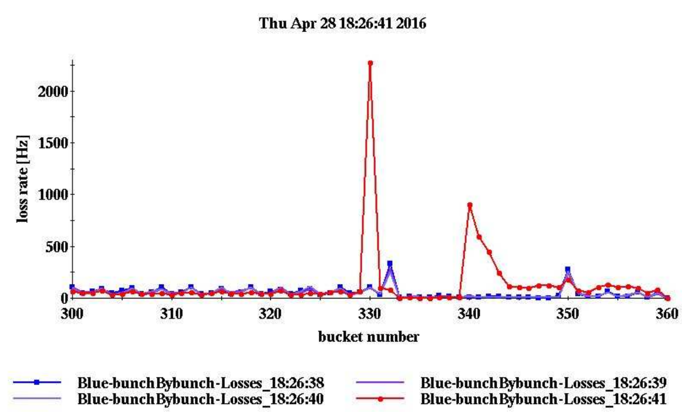

Figure 13: Bunch by bunch loss monitor for the seconds leading to (blue lines) and including the abort (red line).

bucket switch is apparent in Fig. 13. In the seconds leading up to the abort modest losses are evident at buckets 331 and 350. Both buckets are part of the gap. The last data set, including the abort (shown as a red line) shows a peak at bucket 330, the last one of the occupied buckets. The kickers were set to bucket 333, but due to the pulse length of about 110 ns, the last occupied bucket got hit, causing the abort.

Conclusion: There is very little risk for damage since the gap cleaner kickers will only affect one bunch at a time with a repetition rate of 0.1 s or slower. Adding a delay of 40 ms would still have aborted the beam well before the next trigger could have occurred, even if it was set to 10 Hz.

2.14 Case 19848

B	g2-lm16	18.0 ms	MCR: Blue longitudinal pick-up error

No quenches were associated with this abort. The blue longitudinal pick-up was certainly not involved in this event. Actually, about 700 ms prior to the abort a total of 11 dipole corrector supplies controlled by cfe-5c-ps1 started to fail. It is likely that cfe-5c-ps1 was compromised by the bad vacuum in sector 5, causing the concerted trips of many corrector supplies. One of the power supplies is shown in Fig. 14, together with the PM data for LM g2-lm16, at the maximum of the blue protection bump. Losses in g2-lm16 start showing over 500 ms after the dipole correctors first signs of errors. Only the LM down stream of the blue collimators experience some earlier losses, reaching only about 450 rad/h about 50 ms before the abort.

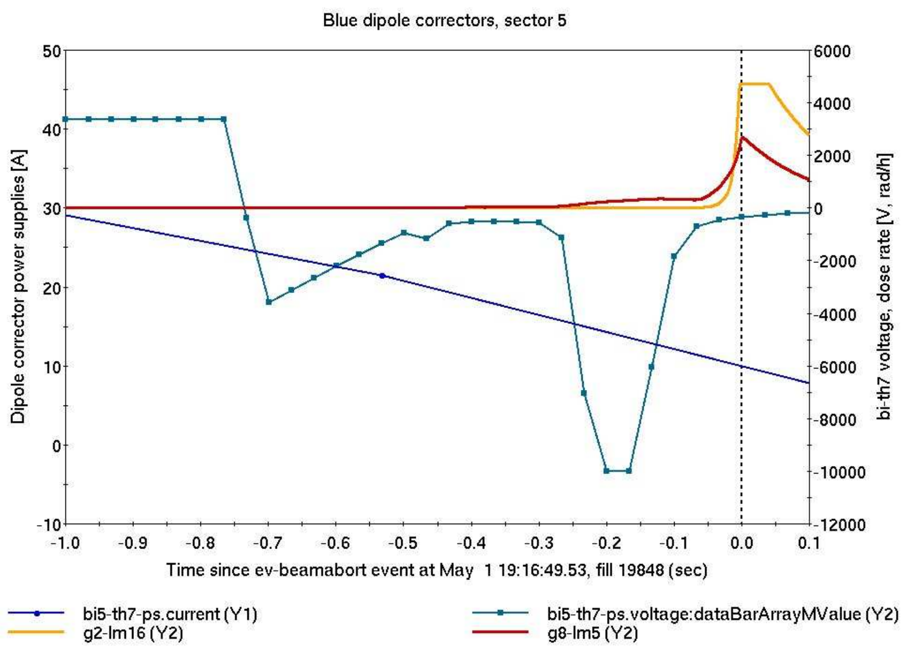

Figure 14: PM data from g2-lm16, g8-lm5, and bi-7th. LogView current data from bi-5th.

Conclusion: In order to violate the beam permit 40 ms earlier than the current abort time, a PS based permit system appears most promising. A much reduced permit threshold (about 25% of current level) for g8-lm5 could potentially do the same with the added risk of unnecessary and premature permit pulls. In addition, it relies on the collimators being in the proper position.

2.15 Case 19894

Y	g8-Mlle.1	4.17 ms	MCR: y8-q6 QLI

This event happened during dAu operation. A quench of Y7Q2 was associated with this abort. As can be seen in Fig. 15, the y8-q6 power supply started oscillating 0.5 s before the abort. It is in a steady error state at 0.4 s before the abort. Nevertheless, losses appear only at 0.01 s prior and the abort cannot prevent the quench of Y7Q2. No other loss monitor in the area sees earlier losses either.

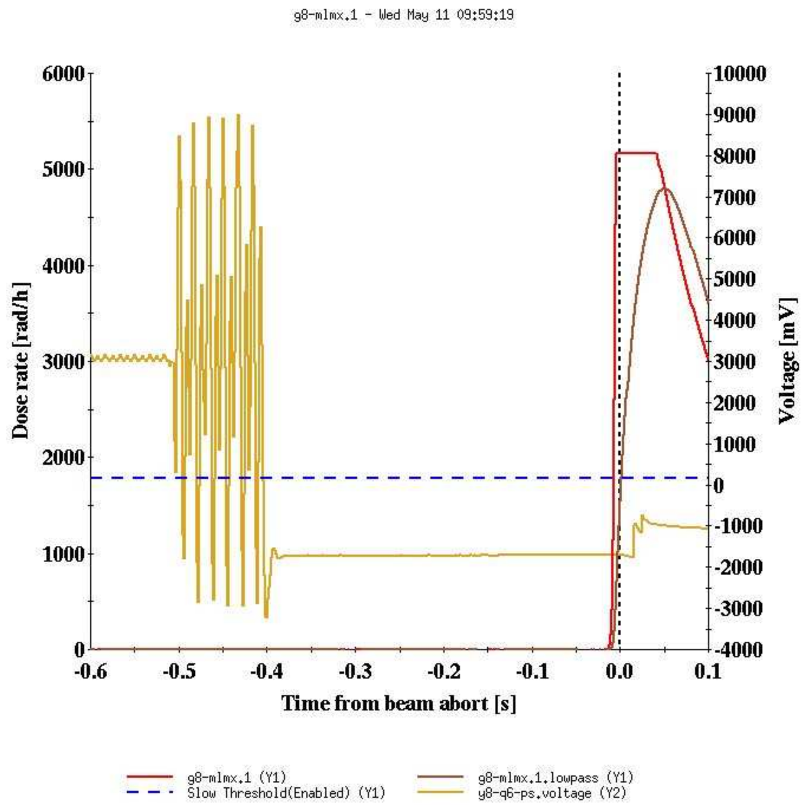

Figure 15: g8-mlmx.1 and y8-q6-ps PM data during the 0.6 s prior to the abort.

Conclusion: Since there are no evident losses early enough only a permit system based on PS data could have prevented the quench. Given the time scale of 0.5 s, an additional 40 ms delay should not pose a problem.

3 Conclusion

Many (but not all) of the 15 studied cases are of no concern. To summarize I put the studied cases into four categories, summarized in Tab. 2.

All aborts in category 3 (not damaging levels) involved the gap cleaner. Permit input other than loss monitors (LM) include BPM, RF (storage cavities) and a permit system based on power supply input. In all cases of category 4 there appears to be enough time to allow an extra delay of 40 ms, provided the new permit systems would be able to act within a few 10 ms. This is a lower limit since in some cases there would have been much more time available than that. Of course, it is unknown if in any of the listed cases damage would have occurred **IF** the beam would have been aborted later.

There is one exception, 19234. In this case the abort even with the existing fast system

#	category	fill	total
(1)	can be ignored	18361, 18483, 18969, 19009, 19374	5
(2)	cannot be explained	18070, 19761	2
(3)	not damaging levels	18061, 18304, 19834	3
(4)	need permit inputs other than LM	19234, 19519, 19769, 19848, 19894	5

Table 2: Cases sorted by category.

happens so late that by the time of the abort most of the beam was either debunched or already lost (there were little to none traces of beam visible on the abort scopes). The resulting damages, however, were modest (compared to a vacuum leak in the injection kickers or a diode failure) and only one triplet quadrupole quenched.

Cases with high damage potential are rare - but not rare enough. In order to make an added 40 ms during physics store conditions as safe as reasonably possible, additional permit inputs such as 10 Hz BF power supplies (19769), RF storage cavities (19234), power supply error states (19894) or BPMs (19519) in addition to significantly reduced LM thresholds for selected LM (19848) should be commissioned. Unnecessary additional down time will be likely, certainly during commissioning. Nevertheless, such times need to be compared to a diode replacement, a vacuum leak in the injection kickers or a scenario in which an experimental detector is damaged in a prefire. Given those additional permit inputs the extra 40 ms delay should be permissible for physics store conditions. For added safety we could consider turning experimental detectors off (and using a fast abort system) during any kind of ramp.

References

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