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RHIC DELAYED ABORT EXPERIMENTS*

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Abstract

For RHIC to operate at its top energy (100 GeV/n) while protecting the future sPHENIX detector [1], spontaneous and asynchronous firing of abort kicker modules (pre-fires) have to be avoided [2]. A new triggering circuit for the abort kickers was implemented with relatively slow mechanical relays in series with the standard fast thyratron tubes [3]. The relays prevent unwanted pre-fires during operation, but come at the expense of a long latency - about 7 milliseconds - between the removal of the beam permit and the actual firing of the abort kickers. Protection considerations of RHIC's superconducting magnets forbid delaying energy extraction from the main dipoles and quadrupoles for too long after a quench. The beam has thus to circulate in both RHIC rings for a few milliseconds as the current in dipole and quadrupole circuit is being extracted. We present the results of delayed abort experiments conducted in July 2018 with the analysis of fast orbit and tune measurements and discuss the safety implications of this implementation for future RHIC operation.

INTRODUCTION

During the runs 2014 to 2017 of the Relativistic Heavy Ion Collider (RHIC) a number of pre-fires affected the beam abort system [2]. A pre-fire is a failure case where a thyratron spontaneously discharges a Pulse Forming Network (PFN) through one of the five abort kicker magnets, resulting in the beam being kicked partially into the accelerator aperture instead of the beam dump. These events are considered to be triggered by radiation and mostly happen at the end of the energy ramp-up [4]. In the past, pre-fires have been the cause of magnet quenches [5] as well as damage to the experimental detectors and to quench bypass diodes protecting superconducting magnets [6].

From 2023 onward, an upgraded experiment, sPHENIX [1], will be operating in the RHIC facility with the objective of measuring the collisions of a variety of ions circulating at an energy of 100 GeV per nucleon for ions and 255 GeV for protons. Table 1 lists beam parameters. To protect this experiment from prefires, mechanical relays were added in series with thyratrons in order to veto an unwanted discharge [7]. Mechanical relays are considerably slower than the thyratrons and can take up to 6 milliseconds to be fully closed. In comparison, the thyratrons have a 0.9 microsecond ramping time and a 15 microsecond "flat" top, the shape of their discharge being responsible for painting the RHIC beam on the beam dump.

Due to bandwidth limitations, the first milliseconds of the current decay in the magnet circuits is difficult to measure. Using the beam as a probe, fast tune and orbit measurement can allow reconstructing the current in both dipole and quadrupole magnet circuits. The results of beam experiments conducted in 2018 are presented below, exploring the safety of delayed beam aborts and the precise sequence of events following the closing of a the so called "Quench Switch", which triggers the extraction of Energy from the dipole and quadrupole magnet circuits.

Table 1: RHIC Beam Parameters

Mode	Abort exp.	sPHENIX run
species	Au^{79+}	
Energy (GeV/n)	9.8 - 100	
nb. of bunches	6	111
bunch pop. (ions)	1.2 e9	2. e9
norm. emittance (μm)	2.	2.2

Delayed Abort Sequence

In the original configuration of the Beam Abort system, once the beam permit is removed from the optical loop going around the RHIC ring, the Abort Kicker module takes 1 microsecond to confirm then sends the abort trigger up to three RHIC turns (12.86 µs) later [8]. The 900 nanosecond rise-time of the thyratrons fits into the 1 microsecond-long abort gap and this whole process can take up to 52 microseconds.

With mechanical relays involved this process is made much longer by waiting for the relays to be closed. A first version of the relays required 40 microseconds to close reliably [9]. This delay was improved significantly in a second iteration of the design with increased spring load. The relays now take up to 6 milliseconds to be fully closed and any ringing to be over. With an extra millisecond of margin the process can be done in 7 milliseconds.

PROCEDURE

The delayed aborts were only tested in the Yellow ring, going counter-clockwise, with 6 bunches of medium intensity. This allowed for the tune and orbit feedback, as well as other instrumentation, to function reliably without compromising Machine Protection considerations. Table 1 summarizes various beam parameters for this experiment as well as their values for the planned sPHENIX run. The delayed abort was tested in 4 different configurations :

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- At injection energy (9.8 GeV/n), allowing for lower stored beam-energy, with a 9 millisecond-delay.
- At top energy (100 GeV/n), with a 9 millisecond-delay, exploring further than the minimum 7 milliseconds.
- At top energy, with an 11 millisecond-delay.
- At top energy, with a 9 millisecond-delay of the abort system and a 10 millisecond-delay in the closing of the Quench Switch, serving as a control experiment without current being extracted from the magnet systems.

Instrumentation Involved

The 160 BPMs of the RHIC system [10] allowed measuring the orbit of the first circulating bunch at every turn.

In order to measure the tune with a very high repetition rate, the ARTUS kicker [11] was used to kick the beam in both planes. The beam was kicked for 5 and 20 turns respectively at injection and top energy. A 50 turn delay was implemented between the kicks in the vertical and horizontal planes allowing to measure the tunes every 1.491 millisecond (or at 670 Hz) at top energy and every 1.299 millisecond (or at 770 Hz) at injection, in an alternating pattern. The beam chromaticities were increased in top energy tests to allow for the faster decay of orbit oscillations due to decoherence.

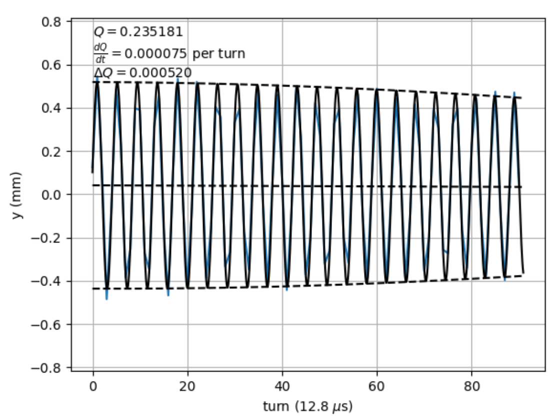

Figure 1: Fitting of the BPM data at injection energy. The resulting tune, tune change per turn and tune spread are indicated.

The data from each of the BPMs was then fitted with the following function :

$$x(t) = A \cdot cos(2\pi \cdot t \cdot (Q + \frac{dQ}{dt} \cdot t) + \phi) \cdot sinc(2\pi \cdot t \cdot \Delta Q),$$

where t is the turn index, Q the tune, $\frac{dQ}{dt}$ is the tune change per turn, ϕ is an arbitrary phase, ΔQ is the tune spread and *sinc* is the sine cardinal function.

Results of such fits for one particular BPM can be found in Figs. 1 and 2 for injection and top energy, with the BPM data in blue and the resulting fit and sine cardinal envelope in black.

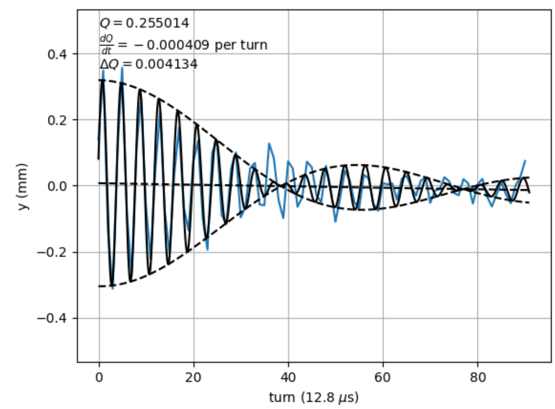

Figure 2: Fitting of the BPM data at top energy. The resulting tune, tune change per turn and tune spread are indicated. Due to the coupling between planes in this setting, the excitation of the beam in the horizontal plane after 30 turns can be seen in the vertical data.

RESULTS

The main results of these experiments are presented in Fig. 3, where the average orbit is shown against time. One can see that the orbit shrunk then drifted outwards at injection.

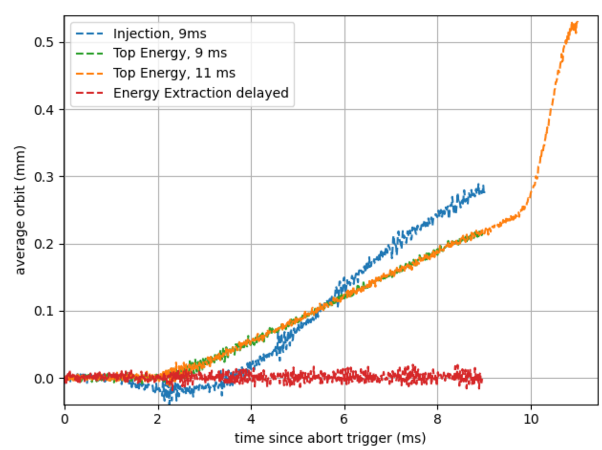

Figure 3: Average orbit offset around the RHIC ring as a function of time for all four tests.

The first test at top energy being conducted without observation of extra beam losses, it was decided to explore the delay 2 milliseconds further. The movement of the orbit in the last millisecond lead to swings of +/- 10 millimeters that can be seen in the following GIF [12]. This large offset of the orbit in the recombination magnets (so-called “DX”) lead to significant beam losses and ultimately the quench of one such magnet.

The good overlap of data from the second and third test suggest a good reproducibility of the orbit drift during the abort experiments. As expected the beam was not affected

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during the abort where closing of the Quench Switch was also delayed.

Tune Change

The fast tune measurements mentioned earlier allowed investigating how the beam tunes were affected by the quadrupole current decaying at the same time as the dipole's. Figures 4 and 5 illustrate the resulting reconstructed tunes. Error bars there are representative of the standard deviation of the distribution of reconstructed tunes from the data of the individual 160 BPMs.

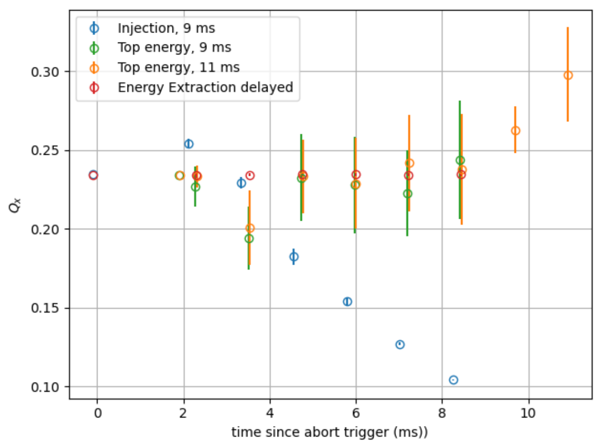

Figure 4: Reconstructed horizontal tunes during all four tests, the error bars come from the distribution of fitted tunes from the 160 BPMs.

Similarly to the orbit, the horizontal tune at injection drifts up and down with the same timing. The vertical tune drifts up and crosses the quarter integer resonance after 7 milliseconds,

Results from the experiment at top energy feature large error bars, due to the large orbit offsets, especially towards the end of the experiment. The horizontal tunes appear to reach the fifth integer resonance after 3 milliseconds and reach the quarter integer resonance after 8 milliseconds.

As of previously, the tunes were not affected during the test where the Quench Switch closing was also delayed.

CONCLUSION

The RHIC abort kickers triggering was updated to include mechanical relays in series with thyratrons to prevent prefires. The relays introduce a 7 milliseconds latency in the firing of the abort kickers. The impact of delayed aborts was tested successfully in both RHIC rings. Fast tune and orbit measurements allowed monitoring the condition of the circulating beam while current is being extracted from the superconducting magnet circuits.

Based on the previously mentioned results, it has been demonstrated that the RHIC beam abort system can be operated with a 7 ms, and up to 9 ms, delay without significant losses in the aperture and experimental areas. It is therefore considered safe to operate with a high intensity beam at an energy of 100 GeV/n with the sPHENIX detector, the most demanding beam conditions for this facility. This abort system has also been tested thoroughly and monitored for reliability in later runs. Additional relays were added for redundancy and monitoring purposes.

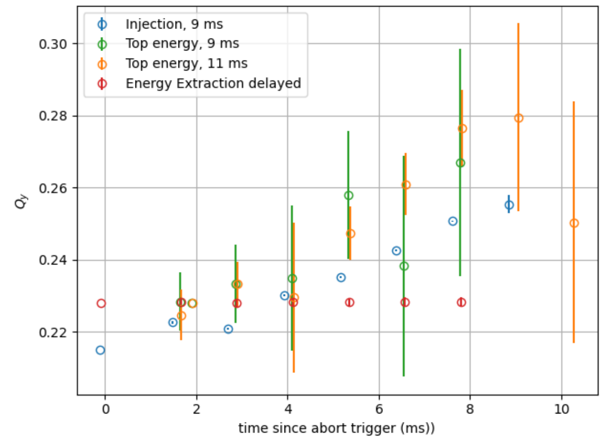

Figure 5: Reconstructed vertical tunes during all four tests, the error bars come from the distribution of fitted tunes from the 160 BPMs.

As the beam cannot be dumped faster than the delay induced by the mechanical relays, failures with timescales shorter than a few milliseconds should be studied with each new machine mode and investigated when occurring. Emphasis should be put on early monitoring systems for all devices and beam parameters in order to gain precious milliseconds [13]. This is especially important in view of the upcoming EIC era of the RHIC facility, when higher beam intensities will be used in conjunction with an electron beam.

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