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SPACE CHARGE DRIVEN THIRD ORDER RESONANCE AT AGS INJECTION*

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Abstract

Resonance line crossings at significant space charge tune shifts can exhibit various phenomena due to periodic resonance crossing from synchrotron motion and manifests as halo generation and bunch shortening along with the more mundane emittance growth and beam loss. An injection experiment is conducted at the AGS using the fast wall current monitor and electron collecting Ionization Profile Monitor (eIPM) to probe third order resonances to better characterize the resonance crossing over a 4 ms time scale. This experiment shows some agreement with previous experiments, save for lack of bunch shortening, possibly due to relative resonance strength.

INTRODUCTION

Resonance crossings with significant space charge effects has been of particular scholastic interest in part due to the inherent non-linearity of space charge effects and the non-trivial interaction of these effects with the resonance terms. A bunched beam of inhomogeneous bunch density will have only specific longitudinal slices of the bunch in resonance at a time. Subsequent synchrotron motion drives particles in and out of resonance periodically. This is known as a periodic resonance.

Previous experimental observations of periodic resonances have been performed at the GSI's SIS [1] and at CERN's PS [2]. Both previous experiments had their periodic resonances saturate comparatively slowly (~1 s). Since this phenomena has only been studied in comparatively few machines, there is value in driving such resonances with another accelerator. The AGS at injection was chosen to perform one of these experiments.

Most of these resonances have been performed with respect to third order resonances. While third order resonances have been studied in the AGS in the past [3] there has been little interest in studying these resonances (specifically $n = 26$) post installation of warm and cold partial snakes [4]. The addition of these optics adjusted the operating tunes away from these resonances to preserve polarization. But even with partial snakes installed it is still possible to cross these resonances. It should also be noted that there are operational compensation sextupole families which can modify third order stopbands strength as necessary.

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Periodic Resonances

In the presence of significant space charge the betatron oscillations will be defocused by these effects [5]. Space charge effects can be split into a coherent linear oscillator and an incoherent nonlinear oscillator. The magnitude of the oscillator detuning is a function of the particle distribution. This means that for smooth distribution particles with different longitudinal positions will oscillate at different frequencies compared to one another. This gives rise to tune variation due to space charge along the longitude. This in combination with chromaticity will splay out a bunch's operating tunes over a wide area of tune space.

If a resonance crosses a bunch's operating tunes, it will resonantly drive some longitudinal portion of the beam causing emittance growth and/or loss. Synchrotron motion will eventually move these particles out of resonance, but other particles will correspondingly move back into resonance. Depending on the exact parameters and speed of tune variation [6], there are two regimes a periodic resonance can enter.

First is the Adiabatic Regime. If changes to the tune as particles cross the resonance are smooth enough, some portion of the particles move to the islands of stability. This limits the particle loss and emittance growth. Particle loss is fairly evenly distributed across the longitudinal domain. If in the Non-Adiabatic regime the changes in tune are not smooth as particles cross the resonance. This causes particles that were in an island of stability in a previous synchrotorn oscillation to no longer necessarily be in a stable island this turn. Over many synchrotron periods this can lead to the loss of particles that cross the resonance, and eventually all particles with a sufficiently large longitudinal position (bunch shortening). That continues until the loss of particles and emittance growth drives the tune shift above the resonance crossing.

EXPERIMENTAL SETUP

The experiment in question was performed at the AGS on April 12th 2022 with protons. Since the objective of the study was to cross the resonance line with the beam, optical parameters should not be adjusted nor energy ramped after injection as that could shift the portion of the bunch in resonance. Thus the study was performed at injection, and the single particle injection tune was adjusted down very close to the resonance line. The horizontal tune for these experiments is $Q_x = 8.73$. Each experiment is injected at a specific vertical tune within the range $8.666 < Q_y < 8.756$ to adjust the resonance crossing.

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Previous experiments performed at the AGS on April 7th 2022 determined there were other loss sources that could not be eliminated by changing the third order stopband correctors which provided a significant background particle loss to the experiments. Since this background loss source is slow, we strengthened the resonance of interest sufficiently to make our resonance separate and resolvable from the other losses. In order to accentuate the relevant resonances the skew correction sextupoles were energized to increase third order stopband integrals and make the resonance crossing more powerful. With this modification it was possible to observe and manipulate the resonance crossing, which was intensity dependent. The vertical tune was then varied across the resonance line, taking eIPM, tune, and intensity measurements along the way. This makes it possible to drive separate longitudinal portions of the bunch with the resonances. Measurements were taken until observed eIPM emittance growth and particle loss end indicating that the bunch is no longer crossing an instability.

Longitudinal shortening was studied using a fast Wall Current Monitor (WCM). The profile is represented as an oscilloscope trace with a starting injection value compared with another profile some set time later. Pictures of traces need to be saved manually for later analysis.

AGS eIPMs

The AGS uses two eIPMs to obtain high time resolution transverse profile data. The beam interacts with a vented residual gas and ionizes some of the particles. Electrons produced by the ionization are then swept by a high voltage (6 kV) onto a Micro Channel Plate (MCP) in the presence of a magnetic field, which creates a transverse projection of the beam on the MCP.

The AGS eIPMs are located at D5 (horizontal) and D15 (vertical) straight sections. These monitors have turn by turn (tbt) resolution with 64 transverse bins. Several of these bins give obviously erroneous results that force them to be excluded. Each of the other bins have their own noise and sensitivity that must be calibrated. The noise in a bin is centered around some nonzero count number. Averaging a bin's raw counts over multiple turns will resolve this noise into a constant offset. A well characterized beam can then be swept over the detector bins to determine the effective sensitivity and the constant offset. This calibration is performed regularly during AGS operation to account for long term drift in bin sensitivity. After calibration has been performed, one needs to apply a bin's offset and effective sensitivity to correct the raw data into a calibrated transverse profile. In Fig. 1 we can see the calibration applied to an experiment data set. The Raw Single Turn counts (red dots) from a single turn are averaged over 50 turns to eliminate the stochastic portion of the noise and yield Averaged Raw counts (red line). Finally, the constant offset and sensitivity are applied to each bin and a Calibrated Profile is created (blue line).

There are several ways to calculate emittance values from the transverse profile. Only the relative emittance is used for our analysis to not rely on characteristics that are not well understood in the AGS for this parameter space. Due to the shape of the resolved distribution, it is important to be careful when calculating beam size for emittances. It should be noted that an emittance value is automatically calculated by AGS online tools, this assumes that the distribution is sufficiently Gaussian and that all detector bins are functional. These assumptions break down for our eIPM profiles due to its large tails and the number of nonfunctional 'dead' bins (see Fig. 1). The eIPM background contributes large nonphysical tails that do not evolve with the rest of the beam contaminating the data counts and making calculation of the emittance from distribution moments also untenable. The best results for emittance evolution were found by using the full width half max of the Calibrated Profile distribution as a characteristic length which eliminates the backgrounds but still allows for transverse growth.

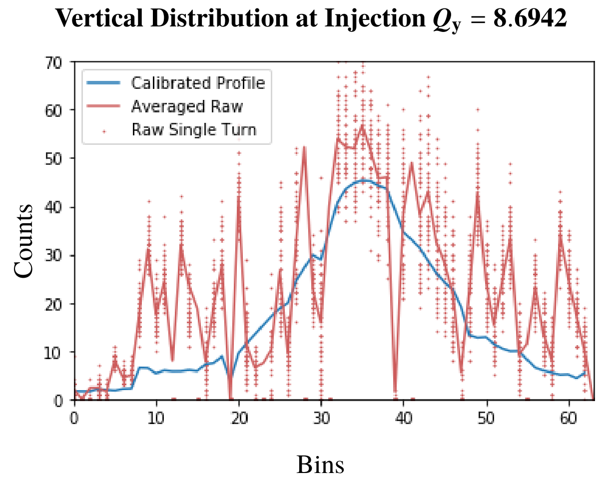

Figure 1: A vertical eIPM distribution taken at AGS injection. Raw profiles are in red, calibrated final profile is in blue. Any bins with obviously incorrect results are considered 'dead' and are removed from the data. Large tails are also observed, and are most likely overstated. Since this data is taken at injection, this is not due to the 3rd order resonance. Tails could be a calibration error or growth from the AGS Booster.

Using the eIPM counts for intensity calculations is more straightforward. Each eIPM bin has a number of detected counts along with an effective sensitivity. Together these yield a corrected count number, the sum of all of these in the device gives a total count number. This can then be fit to intensity data from the fast current transformer. This makes it possible to determine beam intensity alternatively using eIPM data.

RESULTS

The performed experiments were successful if limited in scope. Observations of significant emittance growth are shown in Fig. 2 along with intensity loss. These emittance and loss figures are consistent with previous observations of the periodic resonance in a non-adiabatic regime. However, the resonance saturates in less than 4 ms rather than the second taken in previous experiments at other machines.

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Interestingly this has better agreement with some of the simulations in [1] which saturate much more quickly that the associated experiments. Saturation time should be sped up by the resonance strength, but it is unclear if this is enough to account for this.

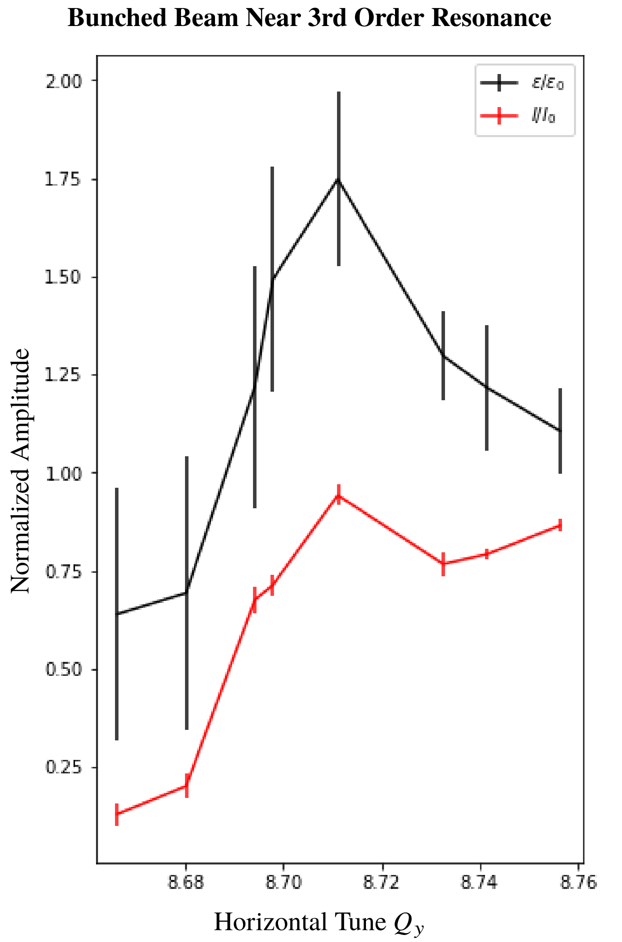

Figure 2: Saturated intensity and emittance of AGS experiments near resonance crossing. Growth seems consistent with that of high intensity bunched beam in SIS [1] including possible secondary resonance.

No evidence of longitudinal shortening (Fig. 3) was observed. This would suggest that the beam is adiabatic, or that the speed of the resonance has some effect on longitudinal shortening causing the phenomena observed in [1, 2] to not occur. For normal periodic resonances, particles with sufficient longitudinal amplitude will transit a resonance causing possible emittance growth and particle loss. Perhaps with strong enough resonance the system may be non-adiabatic even without bunch shortening. Future studies are needed to determine if that is the case.

FUTURE WORK

In the AGS the need for future studies of periodic resonances is a mainly theoretical one. The machine's working point is no longer close to the resonances in question. But it is possible to correct these resonances, make secondary

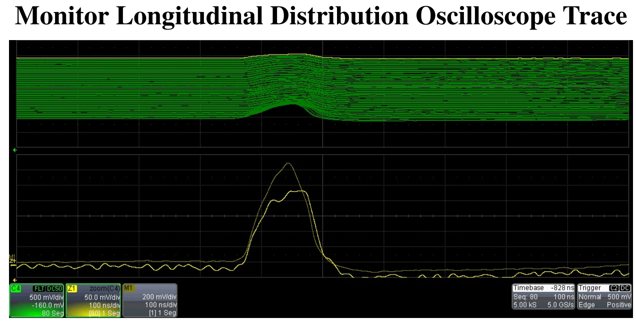

Figure 3: Trace of Wall Current Monitor data for an experiment. The upper half of the figure shows turn by turn longitudinal distributions while the resonance saturates. The bottom part of the figure shows the initial longitudinal distribution in brown and the final longitudinal distribution in yellow. The final distribution has a fourth of the intensity due to resonant loss; the signal is multiplied by four times to compare the final distribution shape with the initial. The expected non-adiabatic bunch shortening is not observed.

observations of various other beam parameters, and expand upon this method to better understand periodic resonances as a whole.

The AGS has the ability to interrogate two questions that are of particular interest. Adjustable sextupole families offer a way to study the interchange from an adiabatic scheme to a non-adiabatic one without changing the particle number and input distribution shape. In combination with this, it is also necessary to determine how saturation speed of the periodic resonance affects the dynamics. Perhaps this would shed light on why bunches in the AGS had phenomena identifiable with both the adiabatic and non-adiabatic regimes.

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