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MEASUREMENTS OF ION INSTABILITY AND EMITTANCE GROWTH FOR THE APS-UPGRADE*

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Abstract

Ions are produced in an accelerator when the beam ionizes residual gas inside the vacuum chamber. If the beam is negatively charged, ions can become trapped in the beam's potential, and their density will increase over time. Trapped ions can cause a variety of undesirable effects, including instability and emittance growth. Because of the challenging emittance and stability requirements of the APS-Upgrade storage ring, ion trapping is a serious concern.

To study this effect at the present APS, a gas injection system was installed. A controlled pressure bump of Nitrogen gas was created over a 6 m straight section, and the resulting ion instability was studied using several different detectors. Measurements were taken using a pinhole camera, spectrum analyzer, bunch-by-bunch feedback system, and a gas bremsstrahlung detector. Studies were done under a wide variety of beam conditions, and at different pressure bump amplitudes. In this paper we report on the results of some of these measurements, and discuss the implications for present and future electron storage rings.

INTRODUCTION

The APS-Upgrade is a 4^{th}-generation light source currently under development at Argonne National Laboratory [1], with a design emittance of 42 pm at 6 GeV. In order to make use of this ultra-low emittance, potential instabilities must be anticipated and mitigated.

One particular source of concern is ion instability. Trapped ions can lead to quickly growing transverse (usually vertical) instability, due to coupled motion between the beam and the ions. The strength of the instability is generally proportional to the average beam current, and inversely proportional to the beam size [2]. Thus ions are particularly dangerous for the APS-U, which will have high current and low emittance. Simulations predict a strong coherent instability for 324 bunch mode, which we plan to mitigate with a compensated gap scheme [3]. But even if the coherent instability is damped, incoherent effects such as emittance growth may still be an issue.

To better understand the ion instability and anticipate issues in the APS-U storage ring, we installed a gas injection system in an empty insertion device (ID) straight section of the present APS storage ring. This enabled us to create a controlled and localized pressure bump, and study the resulting instability. This paper will explain the setup and operation of the gas injection system, describe the instruments used to study the instability, and show the results of some studies we performed.

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SYSTEM SETUP

The gas injection system was installed in a spare insertion device straight section in Sector 25 of the APS. Nitrogen gas was chosen for the experiment, for two reasons. First, it was readily available and well understood by vacuum technicians. Second, it is readily pumped by both ion pumps and NEG coating, making the pressure bump easy to localize.

As shown in Fig. 1, the gas injection mechanism was connected to a port on the flange upstream of the spool piece (where the ID would normally be located). The system is operated from the mezzanine above the mechanism. To create a controlled pressure bump, the gas system is first pressurized with ~10 psi of N_2. The leak rate is controlled by two gate valves, operated manually from the mezzanine. Below each gate valve is a pre-set manual leak. Opening valve 5 in Fig. 1 gives a ~100 nTorr bump, while valve 6 gives a ~900 nTorr bump. Using pre-set leaks helps ensure that the amplitude of the pressure bump does not reach the μTorr scale.

A picture of the gas injection system inside the tunnel is shown in Fig. 2. The trident on the upstream end of the spool piece contains both of the pre-set manual leaks, as well as a cold cathode gauge to monitor the pressure inside the system.

The ion pump located next to the gas injection location is disabled for the study. A cold cathode gauge (`SR25:CC1`) was installed on the downstream end of the spool piece, to measure the pressure near the peak of the bump. In order to localize the bump, the other ion pumps indicated in the figure are kept on. The activated NEG coating in the chambers upstream and downstream of the gate valves provide additional pumping.

For the 900 nTorr leak, the ion pump downstream of the system (`25:2IP1`) reads ~200 nTorr, and the next pump downstream (`26:3IP1`) reads ~40 nTorr. Downstream of this, the ion pump `26:2IP2` reads below 10 nTorr. The same result is seen in the upstream direction: ion pump `25:2IP5` reads a little above 100 nTorr, and `25:2IP4` peaks at ~20 nTorr. Thus the pressure pump is essentially contained in the ~6 m between 25:2IP4 and 26:2IP1.

DIAGNOSTICS

Several diagnostics were employed to study the ion instability- a pinhole camera, spectrum analyzer, feedback system, and gas bremsstrahlung detector. Unless stated oth-

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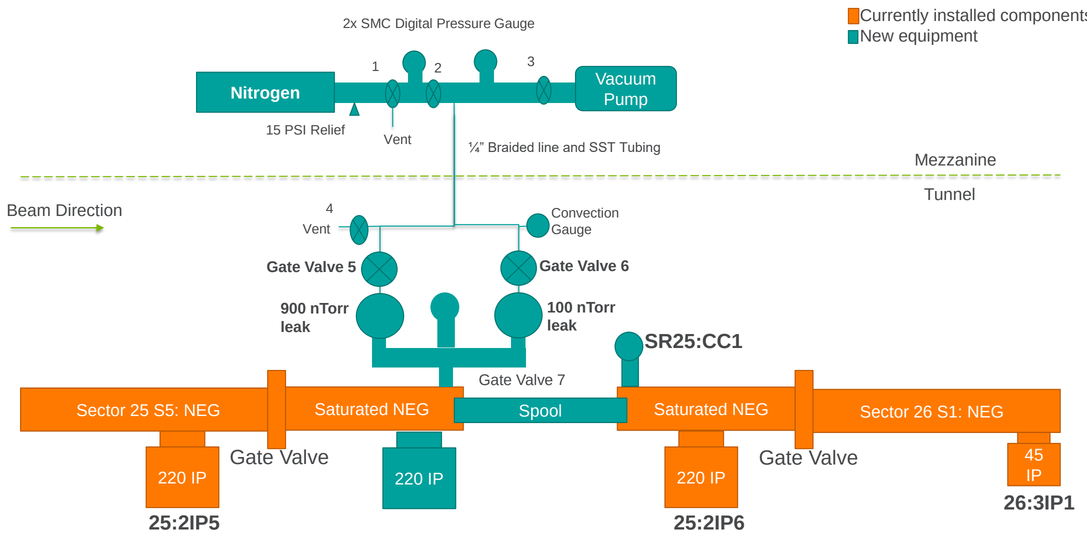

Figure 1: Layout of gas injection system.

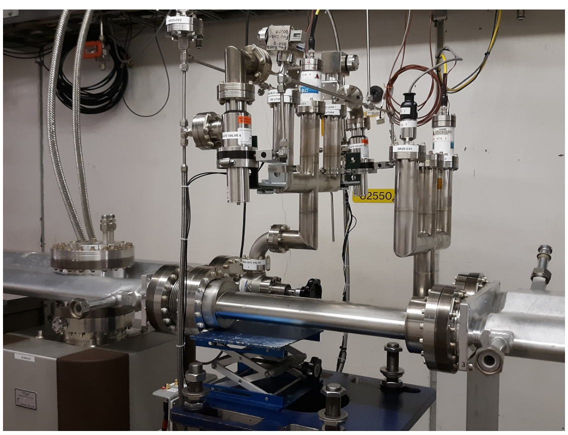

Figure 2: Picture of the gas injection system inside the tunnel.

erwise, the measurements presented here were done with 324 bunches, ~100 mA beam current, at 6 GeV.

Pinhole Camera

The horizontal and vertical beam size at the APS is measured by a pinhole camera located in a bending magnet beamline, and the emittances are calculated from the measured beam size using the beta function and dispersion derived from a calibrated model.

Figure 3 shows two example images from the pinhole camera. The left plot shows a beam image that is blown up vertically due to ions. The right image shows a case where the ion instability has been mitigated using train gaps (see below).

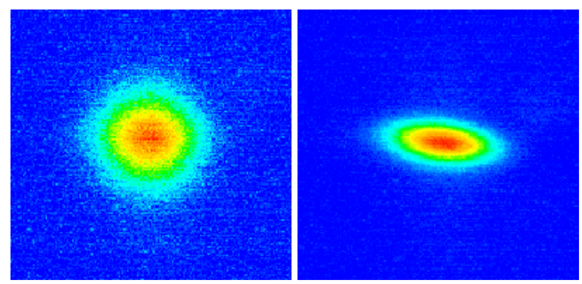

Figure 3: Pinhole camera images. Left: one train with no gaps; the beam is blown up vertically due to ion instability. Right: 4 trains with gaps; the instability is suppressed.

Spectrum Analyzer

The clearest signature of ion instability is peaks in the lower vertical betatron sidebands of the revolution harmonics, near a characteristic ion frequency given by Eq. (1). Here N_e is the bunch population, $r_p \approx 1.54 \times 10^{-18}$ m is the classical proton radius, S_b is the bunch spacing, σ_x and σ_y are the horizontal and vertical beam sizes, and A_{ion} is the atomic mass of the ion.

$$\omega_{i,0} \approx c \left(\frac{4 N_e r_p}{3 A_{ion} S_b (\sigma_x + \sigma_y) \sigma_y} \right)^{1/2} \tag{1}$$

Measurements of the vertical beam spectrum were taken using a Keysight N9020B MXA in spectrum analyzer mode. The spectrum was taken using ten consecutive sweeps, in order to get good frequency resolution (150 Hz) over the whole range (88 MHz for 324 bunches). The spectrum data is postprocessed to find peaks, and filtered to pick out peaks at the lower vertical betatron sidebands, where ion instability is observed. This process is illustrated in Fig. 4. Here we observe a clear ion frequency peak at ~7 MHz.

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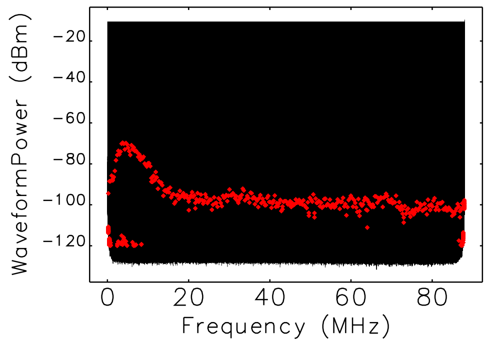

Figure 4: Example spectrum analyzer measurement for 324 bunches. The full measurement is shown by the black lines and is dominated by revolution harmonics; peaks at the lower vertical betatron sidebands are shown as red diamonds.

Feedback System

A Dimtel iGp12-1296F feedback processor [4] is used to directly measure bunch-by-bunch beam motion. Vertical displacement output from a BPM processor is connected to the Dimtel front-end. There are three independent data acquisition engines available: two multi-bunch and one single-bunch. For the present measurements we have used the multi-bunch unit with SRAM memory. It can capture up to 34 ms of beam motion every 500 ms. Two types of data are measured with the Dimtel system:

- Multi-turn data: Y-plane motion of all 324 bunches over several thousand turns is measured. The strength of the modes as a function of time is computed from frequency spectrum of this data.
- Modal amplitudes from iGp12: The processor computes modal amplitudes instantaneously for the selected side band frequency (the vertical tune in our case).

Figure 5 shows an example of multi-turn data taken with the Dimtel feedback system. It shows the strength of the 324 modes over ~9,000 turns. The upper half of these (i.e. modes 161 – 323) have a direct correspondence with the lower vertical betatron sidebands, as shown in Fig. 4. It is interesting to note that the mode amplitudes are not constant in time. Rather, the instability seems to shift between different modes.

Gas Bremsstrahlung Detector

Gas bremsstrahlung (GB) radiation is generated when high-energy electrons circulating in the storage ring interact with residual background gas molecules in the vacuum chamber. The interaction leads to the generation of high-energy photons. For our experiment, a detector was set up to measure GB photons generated inside the pressure bump. If properly calibrated, such a detector can provide a direct measurement of the gas pressure at the beam location.

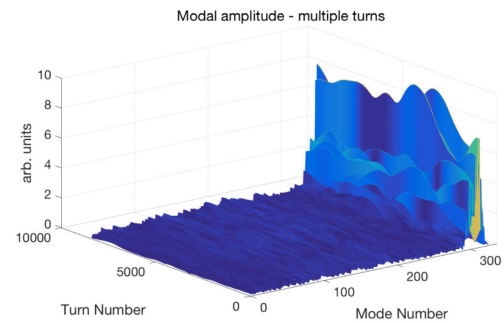

Figure 5: Measurement from the Dimtel feedback system, showing unstable modes over ~9,000 turns.

GB photons enter the upstream end of a Pb:Glass detector. Low-energy photons are blocked by a disk of tungsten located just upstream of the detector. A high-energy photon will enter the Pb:Glass and create an electromagnetic shower consisting primarily of electrons, positrons, and photons. The shower constituents are high enough energy to generate visible Cerenkov radiation. The Cerenkov pulse is detected by the a photo-multiplier tube (PMT), which in turn generates a negative output electrical signal. The height of the pulse recorded by the calorimeter PMT corresponds to photon energy. There are four channels with different set thresholds; pulses exceeding the threshold are counted. Thus the detector also provides a rough measurement of the photon energy spectrum.

Figure 6 shows an example measurement taken with the GB detector. The three channels shown have different thresholds, but all the signals are roughly proportional to the beam current. Quantitative analysis of these data is underway.

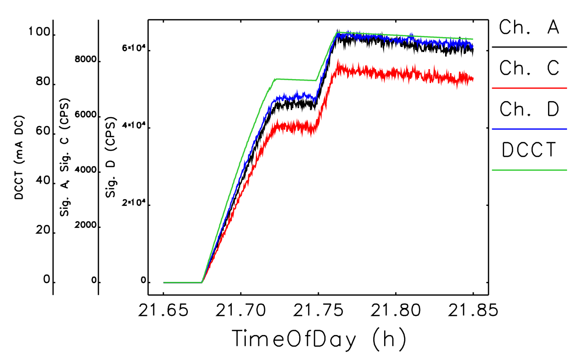

Figure 6: Gas bremsstrahlung detector measurement. Each channel corresponds to a different photon energy threshold.

RESULTS

Measurements have been taken with the instruments described above as a function of pressure bump amplitude, coupling, chromaticity, and bunch pattern. Here we describe one interesting experiment, in which data was taken as a

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function of the number of bunch trains. All of these data were taken at 100 mA, 6 GeV, and with the 900 nTorr bump.

It is well known [5] that using gaps between bunch trains can clear out the ions and prevent instability. For this experiment, we divided the standard 324 bunch train into 2, 4, and 9 trains, with a 12 bunch gap in between them. This gap length was chosen to be large enough to clear out most of the N_2^+ ions. In each case, the individual bunch charge was adjusted to give approximately 100 mA total current.

Table 1 lists the horizontal and vertical emittance measured by the pinhole camera, for each of the bunch patterns listed above. The nominal emittances are $\epsilon_x = 1.83$ nm and $\epsilon_y = 0.024$ nm. For a single train with no gaps, both emittances are significantly blown up due to the ions. With 2 trains with a gap between them, both emittances are reduced, though still much larger than their nominal values. There are two possible explanations for this. First, for a sufficiently high ion density, the instability can grow to a significant amplitude over a single bunch train (the "fast-ion" instability [6]). In addition, the blown up beam sizes will change the trapping criteria [7], and a 12 bunch gap may no longer be sufficient.

Increasing the number of trains to 4 eliminated the horizontal blowup, but did not have much effect on the vertical. This suggests that (at least some of) the horizontal blowup was due to resistive wall instability. This motion in the horizontal plane can potentially shake out some of the ions, reducing the ion instability in the vertical plane. Thus the benefit of additional ion clearing with four trains is mostly canceled out. Finally, the 9 train case shows very little blowup in the vertical plane. The combination of shorter trains and more ion clearing gaps is enough to nearly eliminate the instability.

Table 1: Emittances Measured by the Pinhole Camera, with Different Numbers of Train Gaps

Gaps	ϵ_x (nm)	ϵ_y (nm)
0	4.0	0.056
2	2.94	0.044
4	1.78	0.043
9	1.85	0.025

These conclusions are supported by measurements of the vertical beam spectrum (Fig. 7). Based on calculations (Eq. (1)), the expected ion frequency for N_2 at the gas injection location is about 10 MHz. With no gaps, the measured frequency is actually ~4 MHz, due to the beam size blowup in both planes. As the number of gaps is increased, the ion frequency moves to a higher and higher frequency, as the beam size gets smaller. With 9 gaps, the peak ion frequency is back at the expected 10 MHz. The overall amplitude of the spectrum also decreases with more gaps.

The same trend is seen in the Dimtel data. Figure 8 plots the modal amplitudes for each of these cases. Because these modes are above the Nyquist frequency, their frequency is actually $(323 - n_{mode}) \times f_{rev}$, where the revolution frequency f_{rev} = 271 kHz. So this plot is consistent with Fig. 7: as the number of trains is increased, the modal amplitudes are reduced and shift to higher frequency.

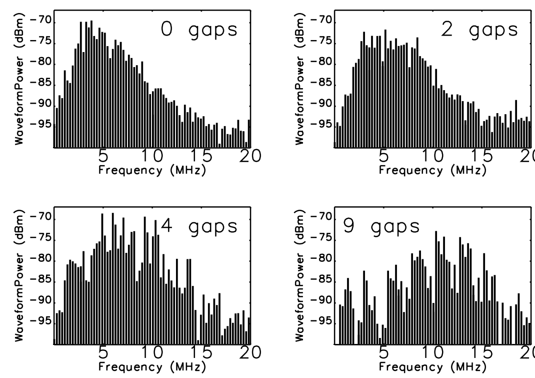

Figure 7: Vertical beam spectrum for different numbers of trains.

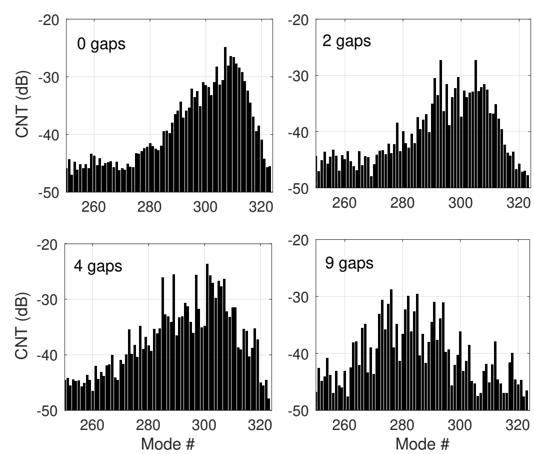

Figure 8: Modal amplitudes for different numbers of trains.

CONCLUSIONS

A gas injection system has been designed and installed in the APS storage ring, for the purpose of studying ion instability. The system works as designed, and allows for two localized pressure bump amplitudes. Measurements have been taken with a pinhole camera, spectrum analyzer, feedback system, and gas bremsstrahlung detector, in a wide variety of beam conditions. Measurements taken with a single train with no gaps show a significantly blown up beam size in both planes, and a corresponding reduction in the ion frequency. These effects persist (at a lower level) when ion clearing gaps are introduced, suggesting that the ion-induced beam size blowup reduces the effectiveness of the gaps. Using more gaps helped mitigate the instability further, with 9 gaps mostly eliminating the effect.

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