ION EFFECTS IN THE APS PARTICLE ACCUMULATOR RING*

J. Calvey, K. Harkay C. Yao, ANL, Argonne, IL 60439, USA

Abstract

Trapped ions in the APS Particle Accumulator Ring (PAR) lead to a positive coherent tune shift in both planes, which increases along the PAR cycle as more ions accumulate. This effect has been studied using an ion simulation code developed at SLAC. After modifying the code to include a realistic vacuum profile, multiple ionization, and the effect of shaking the beam to measure the tune, the simulation agrees well with our measurements. This code has also been used to evaluate the possibility of ion instabilities at the high bunch charge needed for the APS-Upgrade.

INTRODUCTION

Ion trapping can occur when a negatively charged beam ionizes residual gas in an accelerator, and the resulting positively charged ions become trapped in the beam's potential. If the ion density becomes sufficiently high, coupled oscillations between the beam and ions can result. Ions can also lead to tune shifts and emittance growth.

Ion trapping has been observed in the APS Particle Accumulator Ring [1], though it does not impact normal operation. However, the planned APS-Upgrade will require much higher bunch charge to be stored in the PAR, so there is a renewed concern about ion effects. This paper describes a recent effort to study trapped ions in the PAR using coherent tune shift measurements.

Basic Theory

If the displacement of the bunch relative to the center of the ion column is small compared to the beam size, the focusing effect of the ions is linear with the displacement, and the ions' effect on the bunch can be estimated using a wakefield formalism. In particular, a coherent tune shift can readily be calculated [2]:

$$\Delta\nu_y = \frac{r_e}{3\pi\gamma}\int \frac{\beta_y \lambda_{ion}}{\sigma_y(\sigma_y+\sigma_x)}ds \tag{1}$$

Here r_e is the classical electron radius, γ is the relativistic factor, β_y is the vertical beta function, λ_{ion} is the ion line density, σ_x and σ_y are the horizontal and vertical beam sizes, and the integral is done around the ring. Assuming the ions are trapped, the line density is given by Eq. (2), where σ_{ion} is the ionization cross section, P is the pressure, k is the Boltzmann constant, T is the temperature, and n_b is the number of bunches that have passed.

$$\lambda_{ion} = \sigma_{ion}\frac{P}{kT}N_e n_b \tag{2}$$

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PAR PARAMETERS

Some basic parameters of the PAR are given in Table 1.

Table 1: PAR Parameters

Parameter	Value
Energy	375 MeV
Design bunch charge	1 - 6 nC
Circumference	30.7 m
Rev. period	102 ns
Natural emittance	233 nm-rad
Average β_y	8.36 m
Average β_x	2.80 m
Bunch length (damped)	52 - 177 mm

The PAR cycle lasts 500 ms. At the start of the cycle, linac pulses of approximately 1 nC charge are accumulated, with a new pulse being added every 33 ms. Approximately half way through the cycle, the 12th harmonic RF cavity is turned on, reducing the bunch length by a factor of ~3. The bunch is extracted into the PTB transfer line at 483 ms, leaving the PAR empty for 17 ms.

Because there is only one bunch in the PAR, it may seem strange to talk about ion trapping. But because of the large beam size ($\sigma_y \approx 200$ μm, $\sigma_x \approx 800$ μm) and short revolution time in the PAR, most ions will not be able to escape between revolutions. From the ion's point of view, the PAR cycle looks a like a very long bunch train, with bunch spacing 102 ns, lasting for 483 ms. This gives the ions plenty of time to accumulate.

MEASUREMENTS

The primary evidence for ion trapping in the PAR comes from coherent tune shift measurements. The tune is measured using the bunch cleaning system [3]. The beam is excited and its spectrum is measured using a pickup stripline. An HP 89440 VSA is used to control the frequency range of the excitation, and to record the beam response. The beam is excited continuously over the cycle, but the measurement trigger can be varied using a DG535 digital delay generator. This allows us to measure the tunes at different times in the PAR cycle. Figure 1 shows the vertical tune shift as a function of charge (measured near the end of the cycle). We also measured a positive horizontal tune shift of 4×10^{-4}/nC. Additionally, we found the vertical tune shift increased when we disabled most of the PAR ion pumps, leading to higher pressure. All of these measurements point towards the presence of ions. This tune shift is not necessarily dangerous (assuming we are not near any resonances), but the ions could cause a beam instability at higher charge.

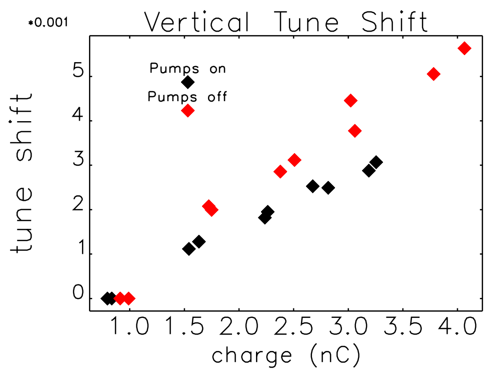

Figure 1: PAR vertical tune shift vs charge. Disabling the pumps increased the pressure by roughly a factor of 2.

Tune Shift Along the PAR Cycle

The large beam size and relatively short revolution period of the PAR results in ions being trapped for the full cycle, until the beam is extracted. Because the tune shift is proportional to ion density (Eq. (1)), we expect the tune to increase along the cycle, as more and more ions accumulate.

The vertical tune as a function of time is plotted in Fig. 2, for four different bunch charges. As expected, we do observe an increasing tune shift with time, though it seems to saturate towards the end of the cycle. No beam instability was observed for any of these conditions (i.e. we did not observe any self-excited coherent motion).

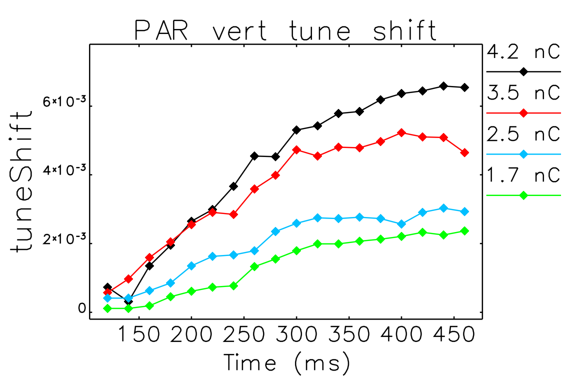

Figure 2: PAR vertical tune shift along the cycle.

Beam Size Blowup

We also observe a vertical beam size blowup with charge in the PAR. Figure 3 shows the vertical beam size measured by a synchrotron light monitor in the PAR. The blowup was significantly more pronounced after a vacuum intervention, when the PAR pressure was higher than normal. This blowup may be a factor in limiting booster injection efficiency at high charge [4].

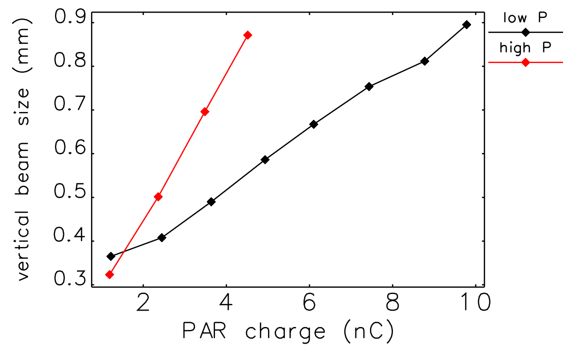

Figure 3: PAR vertical beam size vs charge, with normal and increased vacuum pressure.

SIMULATIONS

To study this effect in more detail, we obtained an ion simulation code which was developed at SLAC [2]. It is a “weak-strong" code, meaning that the ions are modelled using macroparticles, but the beam is rigid. Thus the code can model coherent effects (such as tune shifts or instabilities), but not incoherent effects (such as tune spread or emittance growth). The code tracks the beam through a realistic lattice, and models its interaction with the ions at each element (about 60 locations in the case of the PAR). It also allows for multiple gas species with different ionization cross sections, as well as pressure variation around the ring.

The measured beam size blowup with charge (Fig. 3) is included as input in the simulation. The pressure variation around the PAR (measured by the ion pumps), as well as a dynamic pressure rise with charge are also included.

Preliminary simulations showed a large tune shift that was linear in bunch charge, pressure, and time. This is consistent with the simple analytical model (Eq. (1)), but not the measured data. Since then, two additions have been made to the simulation: multiple ionization, and the effect of beam shaking.

Multiple Ionization

Ions that are trapped for a long time have a chance of being multiply ionized. This usually results in dissociation of the ion. For example, an CO^+ ion can be split into a C^+ ion and an oxygen atom. This process is relevant to our studies for two reasons. First, the multiply ionized atom will have a higher charge to mass ratio, and may no longer be trapped by the beam. If it remains trapped and is further ionized (e.g. $C^+ \rightarrow C^{2+}$), it will have a stronger effect on the beam than a singly ionized molecule.

This process has been implemented in the simulation as follows: every turn, each ion in the accelerator has a chance of being multiply ionized by the beam. The probability of multiple ionization is:

$$P_{mi} = \frac{\sigma_{mi} N_e n_b}{\pi \sigma_x \sigma_y} \tag{3}$$

Here σ_{mi} is the multiple ionization cross section for the ion. Multiple ionization cross sections for H_2 and CO are taken from Tavares [5]. Typical values for this probability are on the order of 10^{-6}. Since the PAR cycle takes millions of turns, this can be a significant effect. At the moment, multiple ionization for heavier ions has not been implemented.

Effect of Beam Shaking

In order to measure the tune in the PAR, we excite the beam using the drive stripline. For the measurements presented above, the beam was excited for the entire cycle. Recently, we discovered this tune measurement method has a strong effect on the ions themselves, since they are less likely to be trapped by an oscillating beam.

A realistic model of the beam shaking has been added to the simulation. The tune is measured using a chirp, where the frequency of the shaking is swept over a betatron sideband of some revolution harmonic. The shaking amplitude is on the order of the beam size. Shaking significantly reduced the number of trapped ions, by as much as a factor of 4.

Results

Modelling the full PAR cycle ($\sim 5 \times 10^6$ turns) takes weeks of simulation time. To complete these simulations in a reasonable amount of time (on the order of a day), one tenth the number of turns are simulated, and relevant parameters (pressure, damping times, and multiple ionization cross sections) are multiplied by 10. These simulations agreed with "full" simulations within 20% when shaking is included, and within 1% without shaking.

Figure 4 shows the simulated tune shift along the PAR cycle, after including all of the effects and approximations described above. The simulation now agrees qualitatively with the measured data. Quantitative agreement is excellent at high charge, but the simulation underestimates the tune shift at low charge. In the simulation, as in the measurements, the ions do not destabilize the beam.

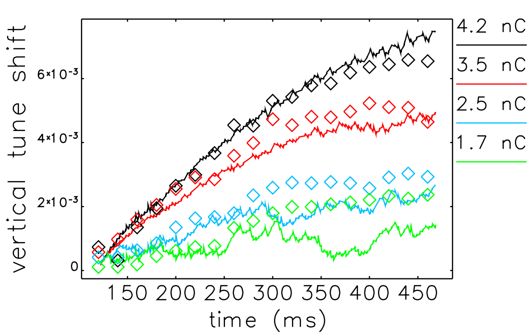

Figure 4: Simulated PAR vertical tune shift (solid lines), compared with data (diamonds).

The beam size blowup (Fig. 3) is being investigated using the CERN code FASTION [6]. Preliminary results confirm an ion-induced blowup that increases with charge and pressure. Quanitiative comparisons with the data are ongoing.

HIGH CHARGE SIMULATIONS

The good agreement of the simulation with the tune shift data gives us confidence that it can be applied to predicting instabilities at high charge. A series of simulations were run with the same set of parameters described above, except that the beam size and pressure were extrapolated from measureements at lower charge. Figure 5 shows the vertical oscillation amplitude predicted by these simulations, up to 20 nC. While some cases show small oscillations (on the order of a few percent of the beam size), there is no sustained instability predicted up to 20 nC. This implies that the PAR should be safe from ion instability at the high charge required for the APS-Upgrade.

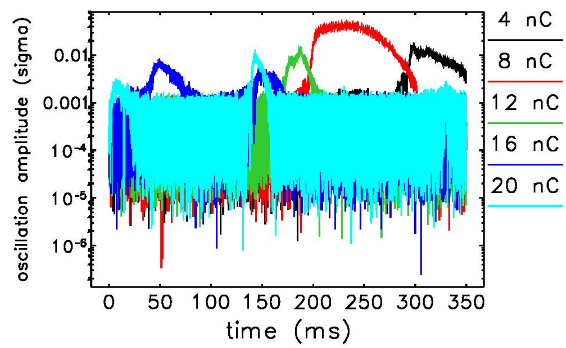

Figure 5: Simulated PAR vertical oscillation at high charge.

CONCLUSIONS

Because of trapped ions in the PAR, we observe a positive vertical (and horizontal) tune shift, which increases along the PAR cycle. We have used an ion simulation code to model this effect. After including multiple ionization and the effect of shaking the beam to measure the tune, the simulation agrees well with our measurements. Simulations of high charge bunches in the PAR predict that the beam should remain stable up to 20 nC. Future efforts will focus on understanding the ion induced beam size blowup in the PAR, and evaluating the possibility of ion instability in the APS-U storage ring.

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