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# ADVANCES IN UNDERSTANDING OF ION EFFECTS IN ELECTRON STORAGE RINGS*

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*Abstract*

Ion instability, in which beam motion couples with trapped ions in an accelerator, is a serious concern for high-brightness electron storage rings. For the APS-Upgrade, we plan to mitigate coherent ion instability using a compensated gap scheme. To study incoherent effects (such as emittance growth), an `IONEFFECTS` element has been incorporated into the particle tracking code `elegant`. The simulations include multiple ionization, transverse impedance, and charge variation between bunches. Once these effects are included, the simulations show good agreement with measurements at the present APS. We have also installed a gas injection system, which creates a controlled pressure bump of Nitrogen gas in a short section of the APS ring. The resulting ion instability was studied under a wide variety of beam conditions. For cases with no or insufficient train gaps, large emittance growth was observed. `IONEFFECTS` simulations of the gas injection experiment and APS-U storage ring show the possibility of runaway emittance blowup, where the blown-up beam traps more ions, driving further instability.

## INTRODUCTION

Ion trapping occurs when a negatively charged beam ionizes residual gas inside the vacuum chamber, and the resulting ions become trapped in the beam potential. Trapped ions can couple to the beam motion, leading to a coherent (usually vertical) instability. The strength of the instability is proportional to the average beam current, and inversely proportional to the beam size [1]. Ion instability is characterized by a fast initial growth rate, which slows as the beam motion starts to shake out the ions. The amplitude tends to saturate around one beam sigma. Trapped ions can also cause incoherent effects, such as emittance growth and tune spread, which are less well understood than the coherent instability.

An early example of ion instability in accelerators occurred at the CERN ISR [1], where they observed ion-induced emittance dilution of the proton beam. Similar effects were seen at other machines, including the SPS [2], CERN antiproton accumulator (AA) [3], Fermilab AA [4], and CESR [5]. These were observations of what we now refer to as "conventional" ion instability, where the ion density and instability amplitude builds up over many turns. Mitigations of the conventional instability include clearing electrodes, bunch shaking, and clearing gaps [6]. Generally speaking, train gaps have been found to be the most effective clearing method.

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However, even if the ions are completely cleared out between trains, one can still have a "fast" ion instability [7, 8], which builds up over single bunch train. This was initially studied using gas injection experiments [9–12], where the gas pressure around the ring was artificially increased to induce the instability. It was observed directly at, e.g. KEK-B [13], PAL [14], SOLEIL [15], and SPEAR3 [16]. Typically, this instability has a slower growth rate than the conventional one, and can usually be controlled by feedback.

Recently, there has been a renewed interest in ion effects, in particular for next generation light sources. These will have high current and low emittance, so a high instability growth rate is expected. In addition, they will be very sensitive to instability or emittance dilution. Ion effects have already been observed at the ESRF-EBS, where they see a coupled bunch instability correlated with vacuum bursts.

These concerns have motivated ion instability studies for the APS-Upgrade, which is a $4^{th}$-generation light source currently under development at Argonne National Laboratory [17]. Several modes of operation are planned, but only the 324-bunch brightness mode will trap ions [18], so this paper will focus on that bunch pattern. Basic APS-U parameters are given in Table 1.

Table 1: APS-U Storage Ring Parameters for 324 Bunch Mode

| Quantity | Value |
|---|---|
| Beam energy | 6 GeV |
| Natural emittance | 42 pm |
| Circumference | 1104 m |
| Revolution time | 3.68 3.86 µs |
| Beam current | 200 mA |
| Bunch spacing | 11 ns |
| Bunch charge | 2.2 nC |

## ION TRAPPING

For a machine without an ion-clearing train gap [6], ion trapping can be characterized by a "critical mass" number given by [2]:

$$A_{x,y} = \frac{N_e\, r_p\, S_b\, Q}{2\sigma_{x,y}(\sigma_x + \sigma_y)}, \tag{1}$$

where $N_e$ is the bunch population, $r_p \approx 1.5 \times 10^{-18}$ m is the classical proton radius, $S_b$ is the bunch spacing, $\sigma_x$ and $\sigma_y$ are the horizontal and vertical beam sizes, and $Q$ is the charge number of the ion (= 1 for a singly ionized molecule). The critical mass $A_{crit} \equiv \max(A_x, A_y)$. Ions with mass number larger than $A_{crit}$ will be trapped; lighter ions will not.

Calculations for the APS-U show that ion trapping should occur primarily in the multiplet sections, where the beta functions and dispersion are large [18]. For the initial vacuum design, simulations (SynRad+ and MolFlow+ [19]) predicted large pressure bumps in these locations. More recently, it was decided to NEG coat the multiplet and doublet sections [20], which dramatically reduces the pressure in these locations. Ion instability simulations (described below) showed a correspondingly large reduction in the ion density and instability amplitude. In general, it is advisable to take ion trapping into account when designing the vacuum system of a new machine.

## COHERENT INSTABILITY SIMULATIONS [18]

Ion instability at the APS-U has been investigated using a simulation code developed at SLAC [16, 21], which models the interaction between the beam and ions at multiple points around the ring. In this code the ions are modeled using many macroparticles, but the beam is rigid, with only centroid motion allowed, and an assumed Gaussian field. This is sometimes referred to as a "weak-strong" code. The simulations include radiation damping, but not coherent damping or feedback. This code has been benchmarked with ion-induced tune shift measurements in the APS Particle Accumulator Ring [22]. The simulations incorporate realistic pressure profiles generated by SynRad+ and MolFlow+.

Figure 1 (black curves) shows the simulated ion density and instability amplitude for 200 mA, 1000 A-hr beam conditioning, and no train gaps. The instability amplitude initially grows very quickly, then saturates when the beam motion reaches about 10% of the vertical beam size, after which it grows much more slowly. Even this small amount of beam motion is enough to shake out some of the ions, leading to a reduction in the ion density. This general behavior has also been seen in simulations of other rings [7, 21, 23].

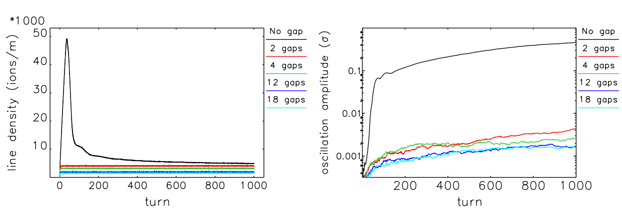


Figure 1: Simulation results with and without compensated gaps, 200 mA, 1000 Ah and 2-bunch gaps. Left: ion density (averaged around the ring). Right: instability amplitude (in units of vertical beam size).

One common technique for mitigating ion instability is to use gaps between bunch trains, to allow the ions to clear out [6, 24]. A downside of this technique is that the missing bunches can cause transients in the rf system, leading to variations in the bunch length, phase, and lifetime along the train [25]. These effects can be minimized by distributing the missing charge to the bunches adjacent to the gaps, which we refer to as "guard bunches". elegant simulations show that this should have only a modest impact on the longitudinal parameters and lifetime of the bunches. In addition, the high charge guard bunches before the gaps will provide a stronger kick to the ions, helping with the clearing process.

Figure 1 shows the impact of this scheme on the ion density and instability amplitude, with increasing number of train gaps. Each gap consists of two missing bunches, with one double-charge guard bunch before and after the gap. With just two gaps, both the density and amplitude are drastically reduced. With 12 or more gaps there is no observable instability. This analysis indicates that two compensated gaps should be sufficient, but if that proves to be optimistic (e.g. if the vacuum pressure is higher than expected), additional gaps can be used to further suppress the instability.

## MODELING INCOHERENT ION EFFECTS

Even if the coherent instability is damped, incoherent effects such as emittance growth may still be an issue. This is a potentially dangerous scenario, as emittance blowup would change the trapping criteria (Eq. (1)), potentially trapping more ions and leading to further instability. To model this, we need a "strong-strong" code, i.e. to model both beam and ions with macroparticles [18, 26, 27]. These simulations tend to be very computationally intensive.

Our approach has been to incorporate an IONEFFECTS element into particle tracking code elegant. This has a few advantages: elegant is massively parallelized [28], and the beam is already modeled with macroparticles. In addition, this approach allows us to study the interaction of ion effects with other elements, e.g. feedback [15] and impedance. The IONEFFECTS element was designed to be flexible, allowing the user to specify the gas species, pressure profiles, interaction points, and bunch pattern.

For each bunch passage, each IONEFFECTS element generates ions (based on the local gas pressure of each species and ionization cross sections), calculates the beam-ion and ion-beam kicks, and advances the ions during the gap between bunches. The kick on the ions from the beam is calculated using the Basetti-Erskine formula [29], which assumes the beam is Gaussian in both transverse dimensions. For the simulations shown in this section, this method is also used to calculate the kick that the ion cloud gives to electrons in the bunch (other options are discussed below).

The simulation also includes multiple ionization [30]. Ions that are trapped in the beam's potential will continue to interact with the beam, and can become further ionized or dissociate into constituent atoms. Either way, the charge/mass ratio of the resulting particle(s) will be changed, and it/they may no longer be trapped.

The IONEFFECTS element has been parallelized, and is fully compatible with Pelegant [28]. A typical APS simulation (described below) takes ~600 hours on a single core. Running Pelegant with 12 cores reduces this time by nearly an order of magnitude; with 192 cores, the simulation completes in only 6 hours.

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## APS SIMULATIONS

Ion instability simulations have been run for the present APS storage ring. Comparing results with measurements at the APS helps to validate our code, and give confidence in our predictions for APS-U. The simulations shown here are for 324 bunches, 100 mA beam current, at 7 GeV. The gas pressure is assumed to be a flat 0.5 nTorr around the ring.

Initial APS simulations did show a standard ion instability, saturating at about $0.9\sigma_y$ (Fig. 2, black curves). Starting from here, additional effects were added one a time: multiple ionization (described above), transverse impedance (relevant because of head-tail damping), and bunch-to-bunch charge variation. An uneven bunch charge results in a variation in the focusing force seen by the ions, which changes the ion trapping criteria and may allow more of them to escape.

Figure 2 shows the impact of each of these effects individually, on the ion density and instability amplitude. When including all three of them, the amplitude is reduced by a factor of 3. Of particular note is the strong effect of uneven bunch charge- even a 10% RMS variation has a significant impact on the instability.

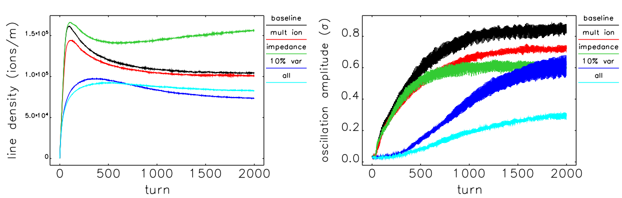


Figure 2: Ion density and instability amplitude, comparing different effects: multiple ionization (red), transverse impedance (green), and 10% RMS charge variation (blue). The result of including all three effects is shown in cyan.

### *Comparison with Measurements*

A long unsolved mystery at the APS is why ion instability is not seen during normal operation in 324 bunch mode (as predicted by both theory and weak-strong simulations). A significant instability would be observed primarily as a vertical emittance increase in the synchrotron light monitor. A typical bunch pattern seen in 324 bunch operation is shown in Fig. 3 (left). The uneven fill is a result of top-up injection. An FFT of the bunch waveform (Fig. 3, right) reveals a peak at 31 MHz.

A key signature of ion instability is peaks in the lower vertical betatron sidebands at a characteristic ion frequency [21], given by Eq. (2). A measurement of these sidebands (taken with a spectrum analyzer, for the bunch pattern in Fig. 3) , is shown in Fig. 4 (red points). Here we see that there is, in fact, an observable ion peak at ~7 MHz, which is approximately the average ion frequency for $CO_2$ around the ring. The second peak at ~38 MHz is an artifact of the uneven bunch pattern. Effectively, the amplitude of the signal seen by the spectrum analyzer will be modulated at the frequency shown in Fig. 3. This results in sidebands at the ion frequency ± the modulation frequency, i.e. 7 MHz + 31 MHz = 38 MHz

$$\omega_{i,y} \approx c\left(\frac{4N_e r_p Q}{3AS_b(\sigma_x+\sigma_y)\sigma_y}\right)^{1/2}. \qquad (2)$$

The measured bunch pattern was used as input to an `IONEFFECTS` simulation, with other input parameters the same as described above. The results of the simulation are also shown in Fig. 4 (black points). The simulation accurately reproduces both the real ion peak at 7 MHz, and the artificial peak at 38 MHz. The relative height of the two peaks is also approximately correct.

Taking into account the beam oscillation (by adding it in quadrature with the beam size), the effective vertical emittance is increased by about 0.3%. This is far too small to be observed by the synchrotron light monitor, or have an impact on normal operations. In short, there is ion instability at the APS, just at too small a level to observe directly.

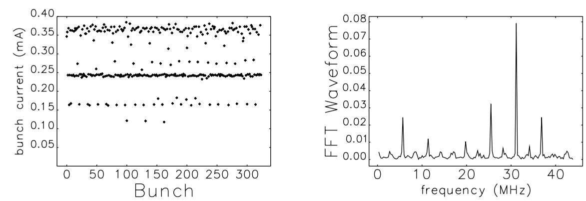


Figure 3: Left: measured bunch pattern corresponding to Fig. 4. Right: FFT of this pattern.

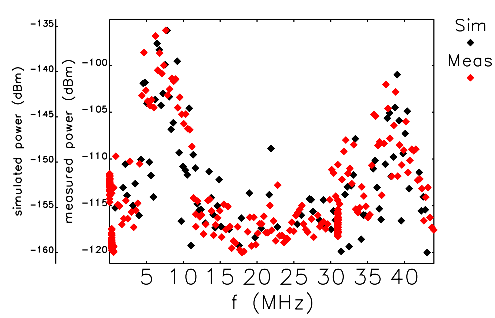


Figure 4: Measured and simulated vertical beam spectrum for normal 324 bunch operation. The points shown are the lower vertical betatron sidebands.

## GAS INJECTION STUDY

Experiments with artificially increased gas pressure have been performed at several machines [9–12]. Typically, $H_2$ or a noble gas is filled around the ring, and the resulting ion instability is studied. Following in these footsteps, we installed a gas injection system in an empty insertion device (ID) straight section of the present APS storage ring. Rather than filling the whole ring with gas, we decided to create a strong but localized pressure bump of $N_2$ gas. By taking this approach, we know and can precisely control the amplitude of the pressure bump. We also know the lattice functions in the bump (can can vary them in studies), which makes

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data analysis more straightforward. Finally, we don't have to worry about contaminating other parts of the ring.

The system is described in detail in [31]. In short, the gas injection mechanism was connected to a port on a flange upstream of the spool piece (where the ID would normally be located). 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-one produces a 100 nTorr bump, and the other produces a 900 nTorr bump. Ion pump readings showed that the bump was mostly contained within a ~6 m section. A detector for measuring gas bremsstrahlung dose was also installed [32]. The system was in place from January through August 2020, and was just re-installed in different location.

Data were taken with the gas pressure bumps, under a wide variety of beam conditions. For one such study, we examined the effect of different train gaps on the instability. In each case, the bunch charge was adjusted to give 80 mA total current. Four different bunch patterns were used:

- 1 train, no gaps.
- 4 trains, 12 bunch gaps (labeled "12bg" below).
- 4 trains, 24 bunch gap ("24bg").
- 4 trains, 12 bunch gap, with 6 double-charge guard bunches before and after the gap ("12bg 6gb").

The measured horizontal and vertical emittance for each case with a 900 nTorr bump is shown in Table 2. With no gaps, there is a strong instability in both planes. The horizontal instability is mostly suppressed with any gaps.

The observed emittance blowup in the vertical plane is much larger than the horizontal. A 12 bunch gap reduces, but does not eliminate the instability. The case with guard bunches does significantly better, demonstrating the clearing effect of the high charge bunches before the gap. A 24 bunch gap shows a slight improvement over the guard bunch case.

Figure 5 shows measurements taken with the spectrum analyzer for each case (in the vertical plane). The expected ion frequency at the gas injection point is ~10 MHz. The no gap case has a peak at much lower frequency: around 4 MHz. This indicates that there is significant beam size blowup, which lowers the ion frequency (Eq. (2)). As longer gaps are introduced, the peak moves to a higher frequency and lower amplitude (compare the 0, 12, and 24 bunch gaps). With additional train gaps, the peak moves back to the expected 10 MHz [31].

Measurements were also taken with a recently acquired Dimtel feedback system [33]. Figure 6 shows the amplitudes of unstable modes over 4000 turns. There is a direct correspondence between the modal amplitudes and elevated lower betatron sidebands (Fig. 5). It is interesting to note that the modal amplitudes are not constant in time; rather, there seems to be sharing of the instability between different modes. In future experiments, we plan to take grow-damp measurements, allowing us to directly measure the instability growth rates.

Table 2: Measured Emittances with the 900 nTorr Bump

| **Pattern** | $\epsilon_x$ **(nm)** | $\epsilon_y$ **(nm)** |
|---|---|---|
| No gap | 3.6 | 0.124 |
| 12bg | 2.06 | 0.049 |
| 12bg 6gb | 2.05 | 0.031 |
| 24 bg | 2.09 | 0.027 |

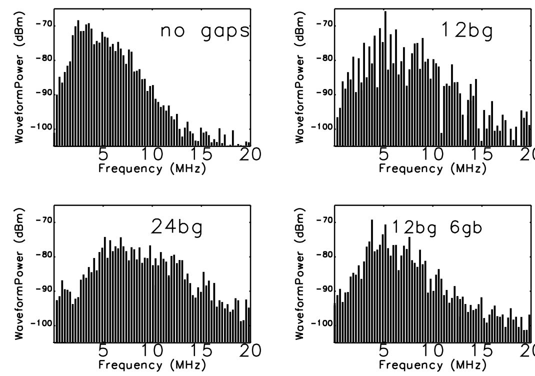


Figure 5: Spectrum analyzer measurements showing the lower vertical betatron sidebands, for each case in Table 2.

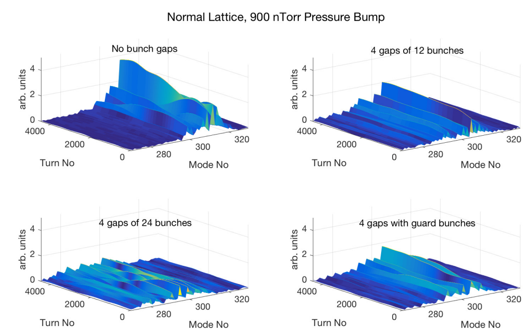


Figure 6: Dimtel system measurements showing unstable modes vs time, for each case in Table 2.

## *Simulations*

Initial simulations of the gas injection experiment did not show much emittance blowup, or a reduction in the ion frequency. The simulations described so far assume a Gaussian distribution for both beam and ion kicks. Of course, this is not generally true of the ions.

To better model the ion distribution, we implemented a bi-Gaussian fit method. Here, the ions are binned in the x and y planes separately. For each plane, a fit is done with two Gaussian distributions, using a simplex method. In two dimensions, the ion distribution is now:

$$\rho(x,y) = \left(G_1(x) + G_2(x)\right) \times \left(G_3(y) + G_4(y)\right), \qquad (3)$$

where $G_i$ is a one-dimensional Gaussian function. The resulting kick to the beam is the sum of four Gaussian kicks. As shown in Fig. 7, the bi-Gaussian fit is typically much more accurate than a single Gaussian. This method avoids some potential numerical issues with a Poisson solver (e.g. grid

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size, noise). Options for tri-Gaussian and bi/tri-Lorentzian fitting have also been added to the code.

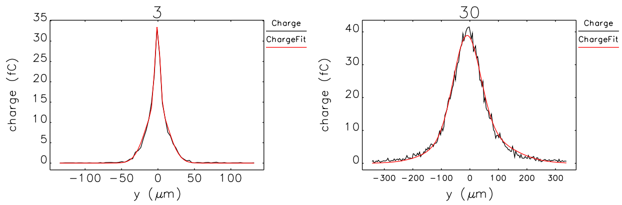


Figure 7: Example vertical ion distributions (black) and bi-Gaussian fits (red). Left: turn 3; right: turn 30.

Figure 8 compares the Gaussian and bi-Gaussian kick methods, for a simulation of the gas injection experiment (900 nTorr, no gaps, 100 mA). Unlike the Gaussian case, the bi-Gaussian method shows significant beam size blowup. As a result, the ion frequency is reduced to around 4 MHz. This is much more consistent with the measurement (Fig. 5).

These results indicate that an accurate fit to the ion distribution is needed to model the nonlinear focusing that leads to emittance growth. However, we have observed that the bi-Gaussian simulations can be sensitive to the exact choice of numerical parameters, so more work is needed before these results can be considered conclusive.

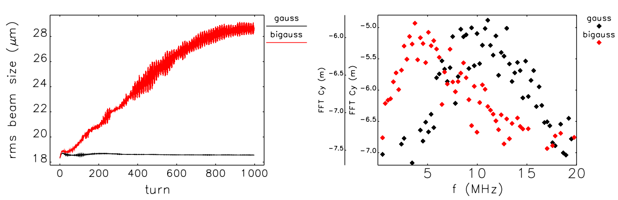


Figure 8: Comparison of beam-kick methods for a gas injection simulation. Left: RMS vertical beam size of the bunch train. Right: vertical beam spectrum. 100 mA, 6 GeV, 324 bunches without gaps, 900 nTorr bump.

## APS-U SIMULATIONS

Preliminary IONEFFECTS simulations have also been run for the APS-U storage ring. Here the beam conditions are 200 mA, 6 GeV, 324 bunches with no gap, and a 100 A-hr pressure profile. The vertical chromaticity is ~5.

Compared to the weak-strong results, the simulations shows a strong coherent damping effect (Fig. 9). For the Gaussian beam kick case, the vertical instability amplitude saturates at around 0.2 beam sigma. The bi-Gaussian case shows a stronger instability, which initially saturates at around 0.5 sigma, then increases after turn ~300. Neither case shows a horizontal instability.

The bi-Gaussian case shows a large vertical beam size blowup. This blowup allows more ions to be trapped (increasing the ion density), which drives further blowup and instability. This is the dangerous feedback scenario described above, which must be avoided in APS-U operations. IONEFFECTS simulations with compensated gaps will be performed in the near future.

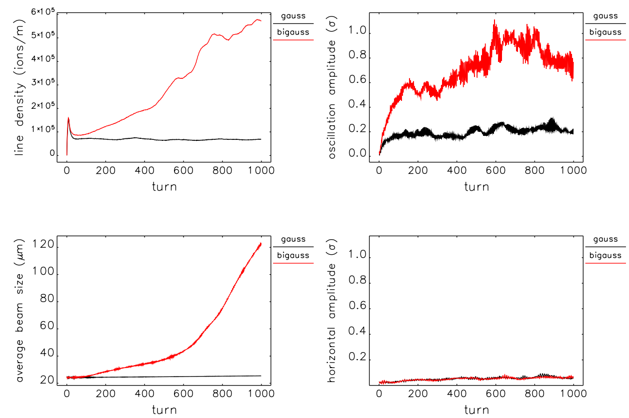


Figure 9: Preliminary APS-U simulation results, comparing the Gaussian and bi-Gaussian kick methods. Top left: ion density. Top right: vertical instability amplitude. Bottom left: RMS vertical beam size. Bottom right: horizontal instability amplitude.

## CONCLUSION

Ion instability is likely to be a problem for next generation electron storage rings. For the APS-U, we plan to mitigate coherent instability with a compensated gap scheme. However, emittance growth is still a concern. To model incoherent ion effects, we have developed an IONEFFECTS element for elegant. Simulations of the present APS show good agreement with measurements, once multiple ionization, transverse impedance, and charge variation are included.

A gas injection experiment was installed and operated at the APS. We observe large beam size blowup in both planes with pressure bumps. This can be mitigated with train gaps, though the size and number of gaps is important.

The Gaussian ion-beam kick method in IONEFFECTS works well for modeling modest instability, but appears to be insufficient for strong instability and emittance growth. We are developing multi-function fit method to better model nonlinear focusing of ions, though other methods (e.g. Poisson solver) could also be implemented.

Preliminary simulations of APS-U storage ring with no train gaps show potential for runaway emittance blowup. In general, understanding and mitigating incoherent ion effects will be crucial for meeting emittance and stability goals for next generation light sources.

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