Ion Effects in the APS Injector and Storage Ring

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Outline

- Ion effects in the APS Particle Accumulator Ring (PAR)
  - Tune shift
  - Emittance growth
- Modeling ion effects
  - FIILINAC
  - FASTION
- Investigating PAR ion mitigations
- Simulation of ion instabilities in storage rings
  - APS
  - APS-U
  - NSLS-II

Introduction

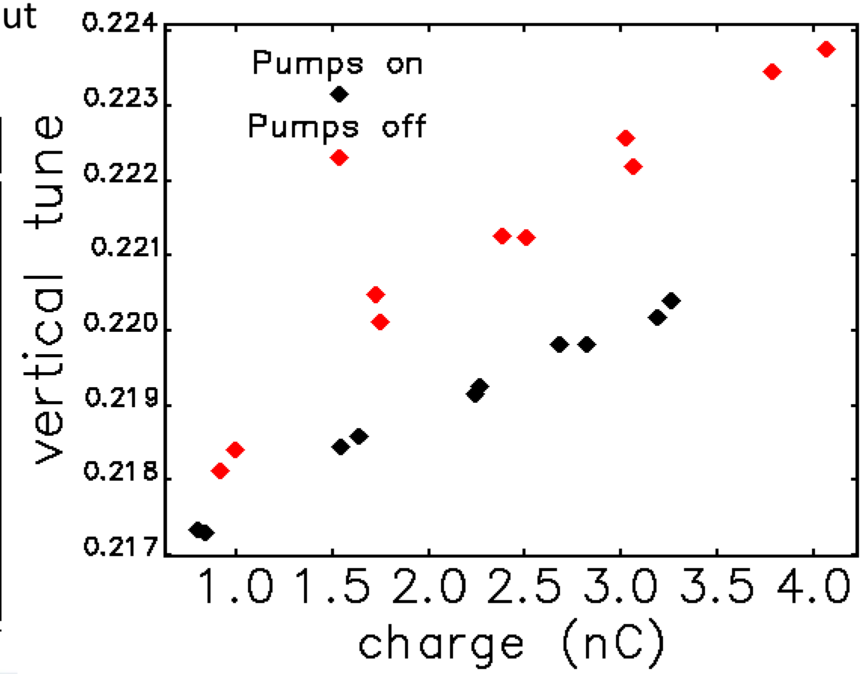
- Ion effects result from interactions between a negatively charged particle beam and ionized residual gas in an accelerator
- Consequences include beam instability and emittance growth
- Typical mitigations include an ion-clearing bunch train gap, beam shaking, or clearing electrodes
- In the current APS…
  - Ion effects have been observed in the Particle Accumulator Ring (PAR), but do not impact normal operation
  - No ion instability is observed in the storage ring
- For the APS Upgrade[1]…
  - The injector will need to provide much higher bunch charge for swap-out injection
  - Storage ring bunches will have higher charge, smaller emittance
  - Renewed concern about ion effects
- Use simulations to model ion effects we observe, and make predictions for the APS-U
  - Code modifications (beam shaking, multiple ionization) needed to get good agreement with data

[1] M. Borland et al., "Hybrid Seven-Bend-Achromat Lattice for the Advanced Photon Source Upgrade", Proc. of IPAC15

PAR Ion Tune Shift

- In the PAR, linac pulses (~1 nC each) are accumulated in a single bunch and damped before injection into the booster
  - Full cycle takes 500 ms
  - Present (top-up) operation only requires ~2 nC
  - Present administrative radiation limit ~5 nC
  - APS-Upgrade will require accumulation up to 20 nC
- We measure a positive tune shift with charge in both planes
  - Tune shift increased when PAR ion pumps were turned off
  - Does not impact current operation, but could be an issue at high charge

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
Zero-current Bunch length	52 - 177 mm



Tune Shift Along the PAR Cycle

- Due to the large beam size and relative short revolution period of the PAR, ions will be trapped for the entire cycle (500 ms)
- To first order, the tune shift is proportional to ion density, so we expect the tune to increase along the cycle, as more and more ions accumulate
- Plot shows measured tune along cycle for different bunch charge
  - Tune shift increases along cycle, eventually saturates
  - Also increases with charge
- Analytical formula[1] overestimates tune shift (dashed line: 4.2 nC), does not explain saturation

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

$r_e \equiv 2.8 \times 10^{-15}$ m

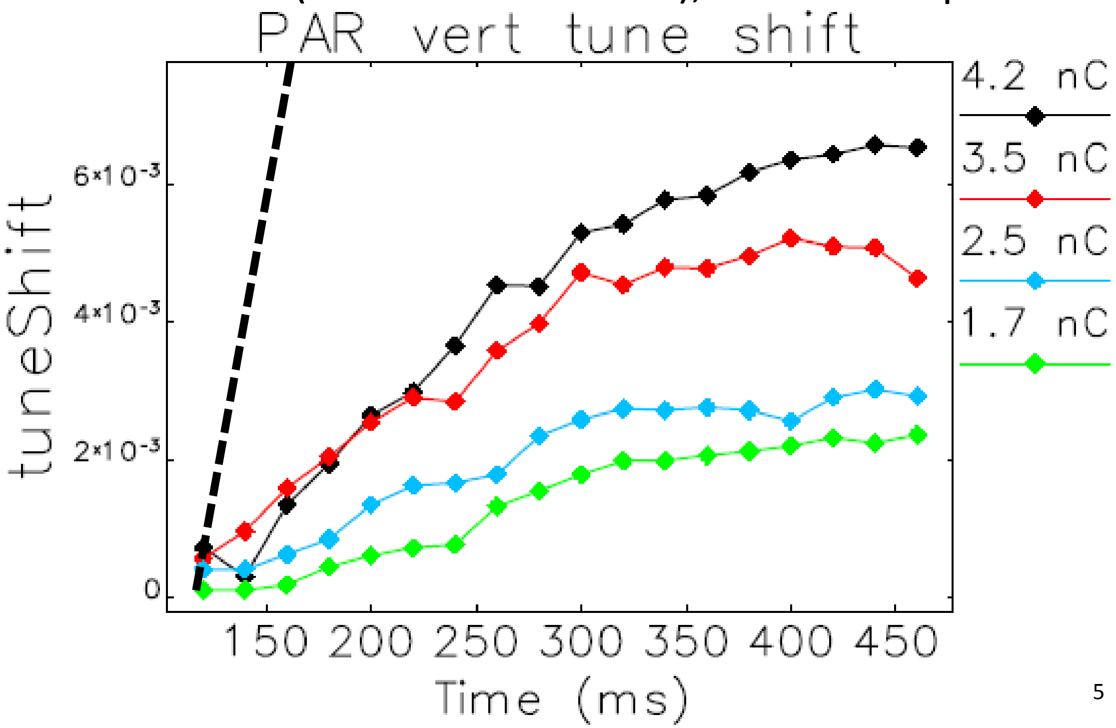
$\gamma \equiv$ relativistic factor

$\beta_y \equiv$ vertical beta function

$\lambda_{ion} \equiv$ ion line density

$\sigma_x \equiv$ horizontal beam size

$\sigma_y \equiv$ vertical beam size



[1] L. Wang et al, PRST-AB 14, 084401 (2011)

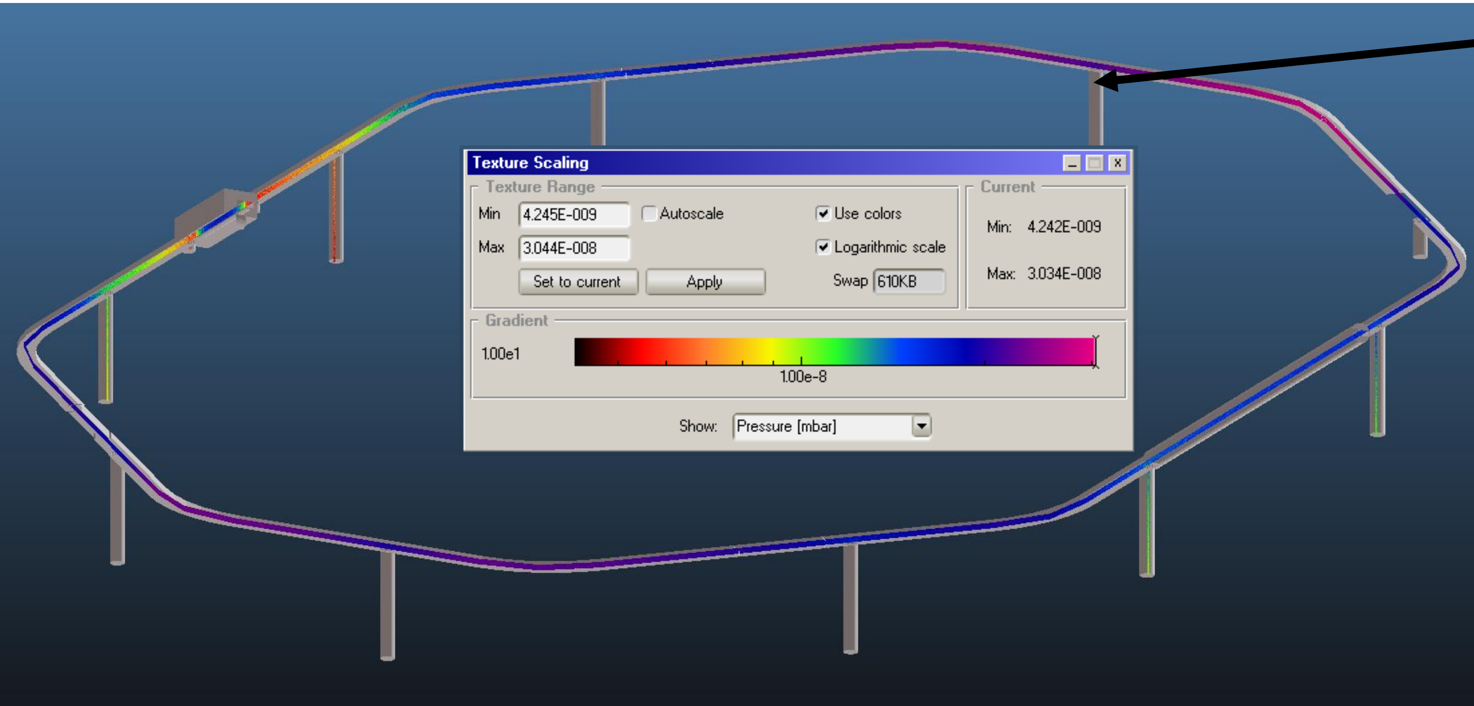
FIILINAC Simulation Code

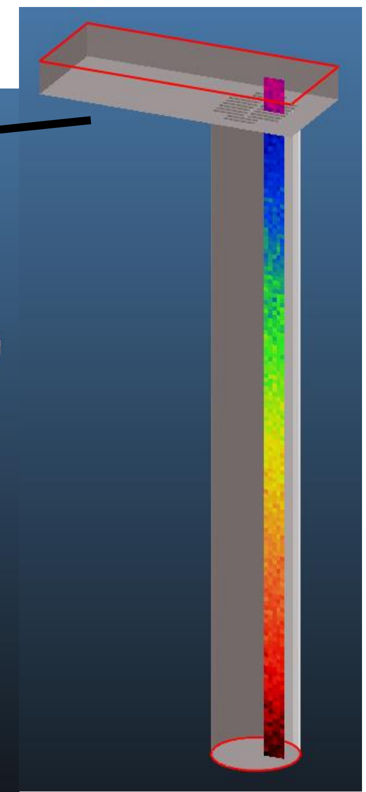
- Ion instability code developed by L. Wang (SLAC)
  - Used to study ion instability at SPEAR3
- Weak-strong code
  - Ions are modeled using macroparticles, tracked under influence of beam field
  - Beam is modeled as single macroparticle with assumed Gaussian field
  - Can model beam motion, instabilities, but not emittance growth
- Simulation parameters:
  - Realistic lattice (twiss parameters, dispersion)
  - Multiple interaction points around ring (~60 for PAR)
  - Pressure can vary around the ring
    - Used measurements from ion pumps
  - Gas composition taken from storage ring RGA reading
- Ion space charge not included
  - Probably ok, measurements indicate we are well below neutralization (tune shift at neutralization = 0.4)
- Initial simulation results also overestimated the tune shift
  - Agreed with simple theory, except some ions escape

Gas	Percent
H_2	87
CO	7
CO_2	3
H_20	1
CH_4	2

Vacuum Modeling (J. Carter)

- A sophisticated vacuum model has been developed for the APS-U, and also employed to study the PAR
- It includes:
  - A 3D model of the vacuum chamber
  - Realistic generation and scattering of synchrotron radiation photons
    - Using the CERN code Synrad+ (M. Ady et al., *Proc. IPAC 2014*, 2348.)
  - Photon stimulated desorption, and diffusion and pumping of the gas molecules
    - Using the code Molflow+ (R. Kersevan, *Proc. PAC 1993*, 3848.)
- Shown: Molflow model of the PAR, including pump tubes





Multiple Ionization

- Ions that are trapped for a long time have a chance of being multiply ionized
  - The ion may dissociate
- Multiply ionized molecules have a different the charge/mass ratio, and may no longer be trapped by the beam
- Ionization cross sections for H_2, CO taken from P.F. Tavares, Particle Accelerators Vol. 43, pp. 107-131 (1993).
- Probability of multiple ionization per turn given below
  - Typical value ~10^{-6}
  - PAR cycle has 5×10^{6} turns

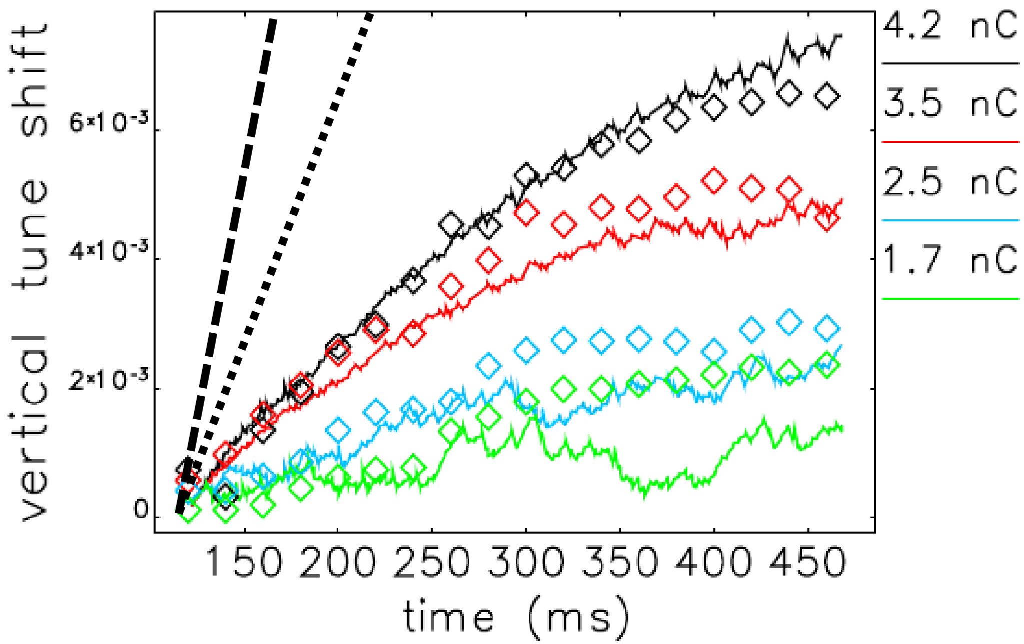
$$P_{mi} = \frac{\sigma^*_{mi} N_e n_b}{\pi \sigma_x \sigma_y}$$

$\sigma^*_{mi} \equiv$ multiple ionization cross section
$N_e \equiv$ bunch population
$n_b \equiv$ number of bunches
$\sigma_x \equiv$ horizontal beam size
$\sigma_y \equiv$ vertical beam size

Process	M_0^2	C_0	Cross-section (Mbarn)	Reference
$e^- + H_2 \longrightarrow H_2^+ + 2e^-$	0.70	8.1	$\sigma_1^* = 0.32$	Rieke[24] – exp.
$e^- + H_2 \longrightarrow 2H^+ + 3e^-$	0.0020	0.036	$\sigma_2 = 0.0013$	Edwards[30] – exp.
$e^- + H_2^+ \longrightarrow 2H^+ + 2e^-$	0.046	1.1	$\sigma_3^* = 0.031$	Liu[31] – theor.
$e^- + H_2^+ \longrightarrow H + H^+ + e^-$	1.04	12.2	$\sigma_4^* = 0.48$	Liu[31]
Total inelastic $(\sigma_3 + \sigma_4)$	1.08	13.3	$\sigma_5 = 0.51$	Liu[31]
Proton production $(\sigma_3 + 2\sigma_4)$	1.1	14.3	$\sigma_6 = 0.54$	Liu[31]
$e^- + CO \longrightarrow CO^+ + 2e^-$	3.7	35.1	$\sigma_7^* = 1.54$	Rieke[24]
$e^- + CO \longrightarrow C^+ + O + 2e^-$	0.35	3.0	$\sigma_8^* = 0.14$	Orient[32] – exp.
$e^- + CO \longrightarrow C + O^+ + 2e^-$	0.11	0.97	$\sigma_9 = 0.044$	Orient[32]
$e^- + CO \longrightarrow CO^{++} + 3e^-$	0.035	0.30	$\sigma_{10} = 0.01$	Hille[33] – exp.
Dissociation of N_2^+	7.37	65.8	$\sigma_{11}^* = 3.0$	Van Zyl[34] – exp.
$e^- + C^+ \longrightarrow C^{++} + 2e^-$	0.84	7.7	$\sigma_{12}^* = 0.35$	
$e^- + C^{2+} \longrightarrow C^{3+} + 2e^-$	0.36	3.0	$\sigma_{13}^* = 0.14$	
$e^- + C^{3+} \longrightarrow C^{4+} + 2e^-$	0.16	0.13	$\sigma_{14}^* = 0.062$	
$e^- + C^{4+} \longrightarrow C^{5+} + 2e^-$	0.048	0.31	$\sigma_{15}^* = 0.017$	
$e^- + C^{5+} \longrightarrow C^{6+} + 2e^-$	0.038	0.24	$\sigma_{16}^* = 0.014$	

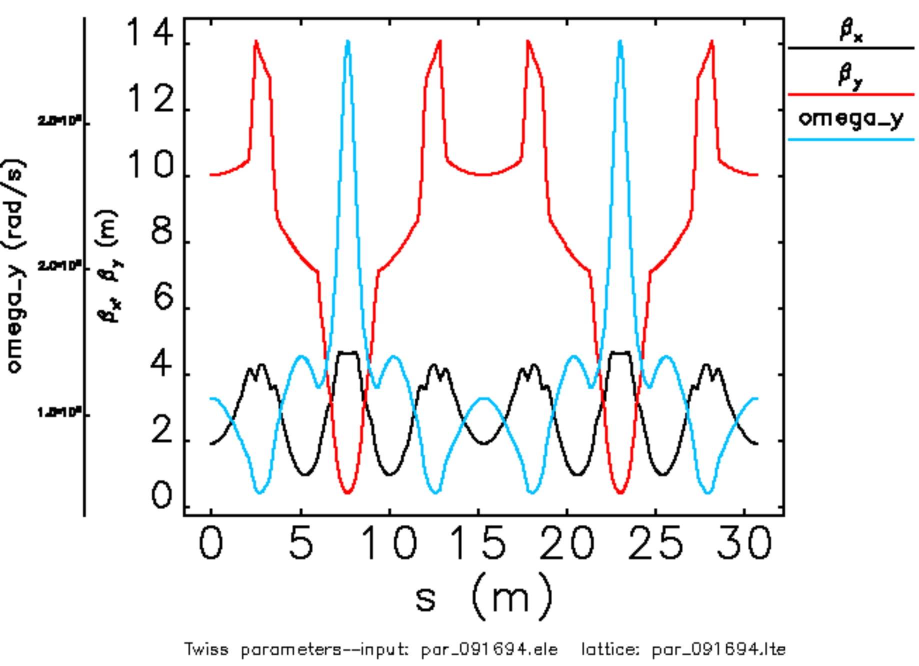
Comparison with Data

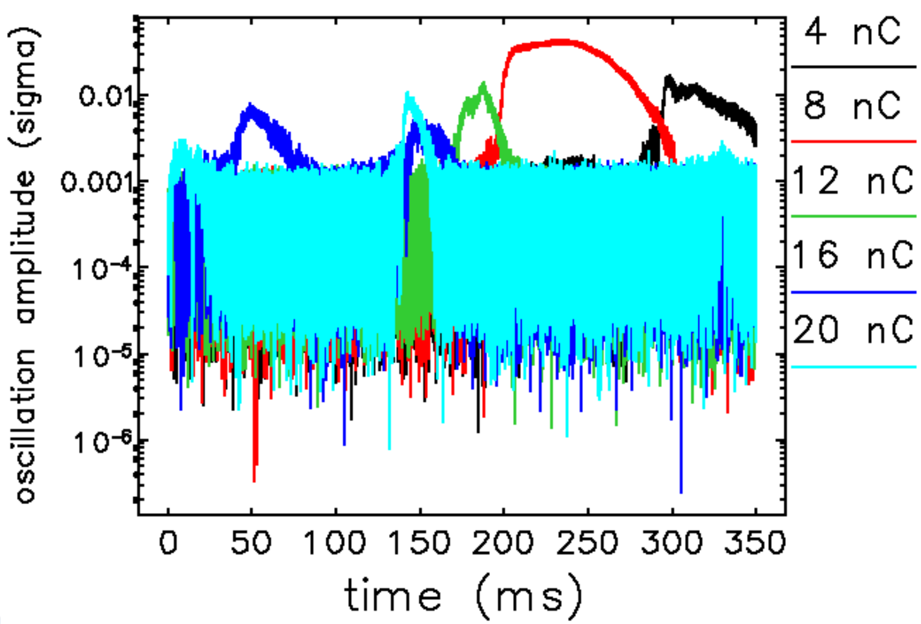
- Simulation now includes:
  - Pressure variation around the PAR
    - Measured pressure corrected for pump conductance
  - Pressure and beam size increase with charge, using measurements
  - Multiple ionization for H_2 and CO
  - Realistic beam chirp (used to measure the tune)
    - Drives ions away from the beam, resulting in a smaller measured tune shift
    - Don't have an accurate measurement of beam kick, allowed some variation of this parameter
- Agreement with data is excellent at high charge
- Initial simulation shown for comparison (dotted line)
- Caveat: for reasonable run time, simulated one tenth the number of PAR turns, and multiplied relevant parameters (pressure, damping times, multiple ionization cross sections) by 10
  - Comparison with the "full" simulation agreed within 20%



PAR Ion Instability

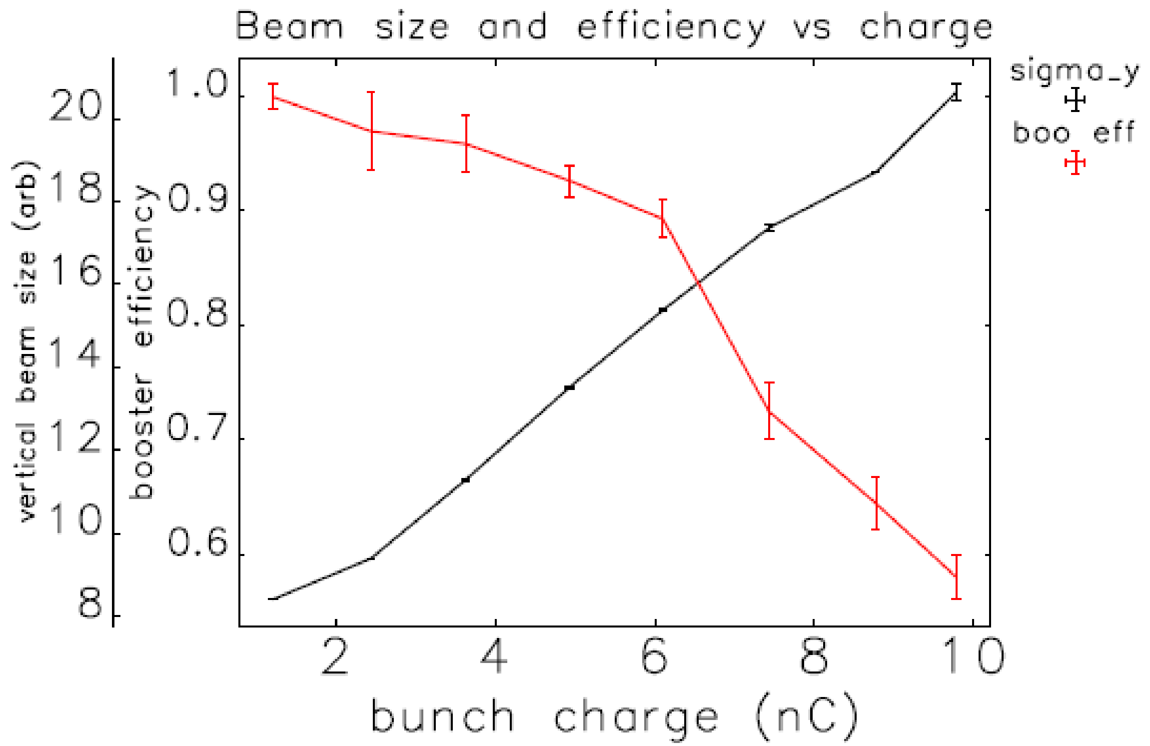
- The good agreement of the simulation with the tune shift data gives us confidence that it can be applied to predicting instabilities at high charge
- Simulate with same parameters at higher charge
  - Vertical beam size and pressure extrapolated from measurements
- Some cases show small oscillations (< 10 µm), but no sustained instability
  - Large beam size, variation in vertical beta function leads to spread in ion frequency, which suppresses instability
  - Implies PAR should be safe from ion instability at high charge required for APS-U





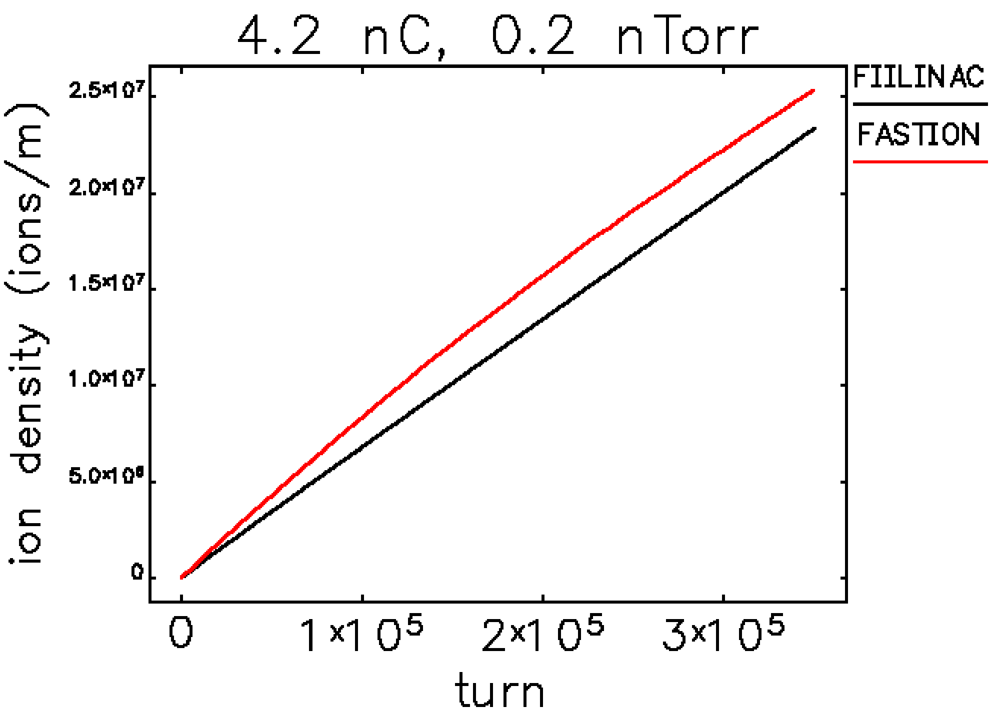
PAR Emittance Growth

- We observe a charge dependent vertical emittance blowup in the PAR
  - Beam size measured with synchrotron light monitor
  - Correlated to a drop in booster injection efficiency
- Is this blowup caused by ions?
  - Probably: beam size was ~50% larger after recent vacuum intervention
  - What can we do about it?



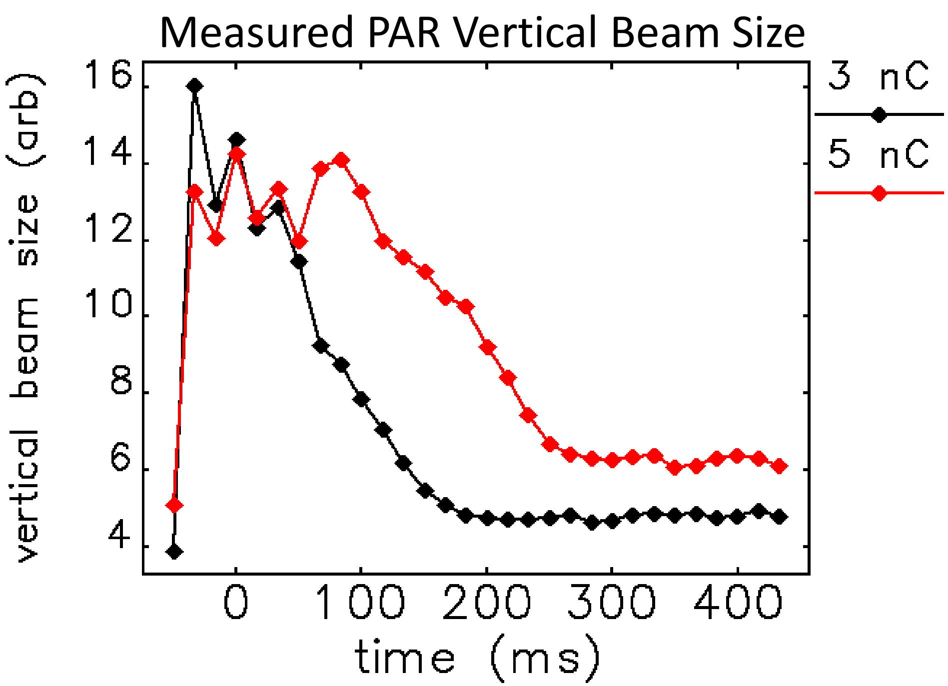
FASTION Code

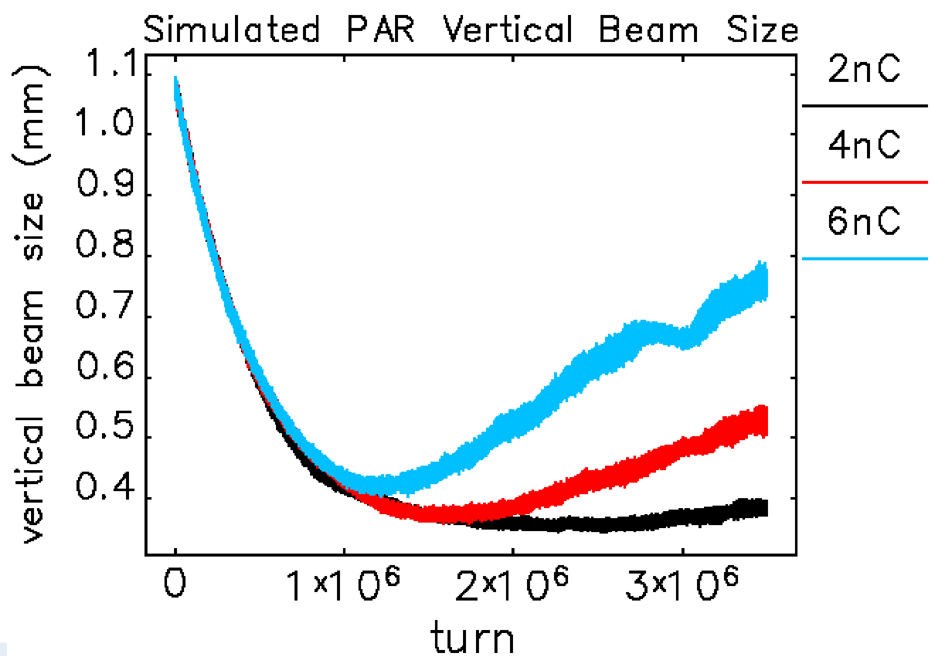
- Developed at CERN (G. Rumolo) for CLIC main linac
- Modified at Cornell for ion studies at CESR storage ring
- Both beam and ions are modeled using macroparticles
  - Can simulate emittance growth
- Specify limited number of interaction points (4 for PAR)
- Modifications to model PAR emittance growth:
  - Made ions persist turn-to-turn
  - Added beam shaking
  - Allow generation of < 1 macro-ion / turn
- Optimizations (B. Soliday):
  - Parallelized using OpenMP
  - Use Intel Math Kernel Library (optimized math routines)
- Optimizations reduced run time for full PAR simulation from ~1 week to ~6 hours
- For test case (with low pressure so the beam doesn't blow up), ion density agrees with FIILINAC to ~10%



Modeling PAR Emittance Growth

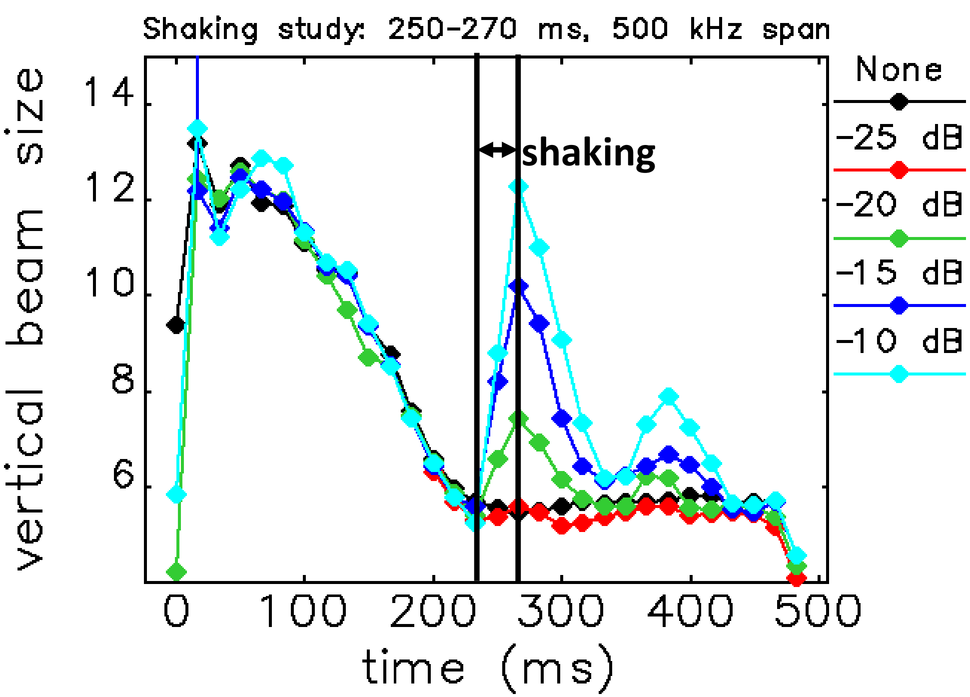
- Measure beam size along the PAR cycle with synchrotron light monitor
  - Beam size large during injection, damps to equilibrium size that depends on charge
- Simulate effect with FASTION (preliminary)
  - Beam size does increase with charge, but does not reach equilibrium
  - Injection is not modeled
  - Multiple ionization not included yet
  - Need to investigate numerical parameters





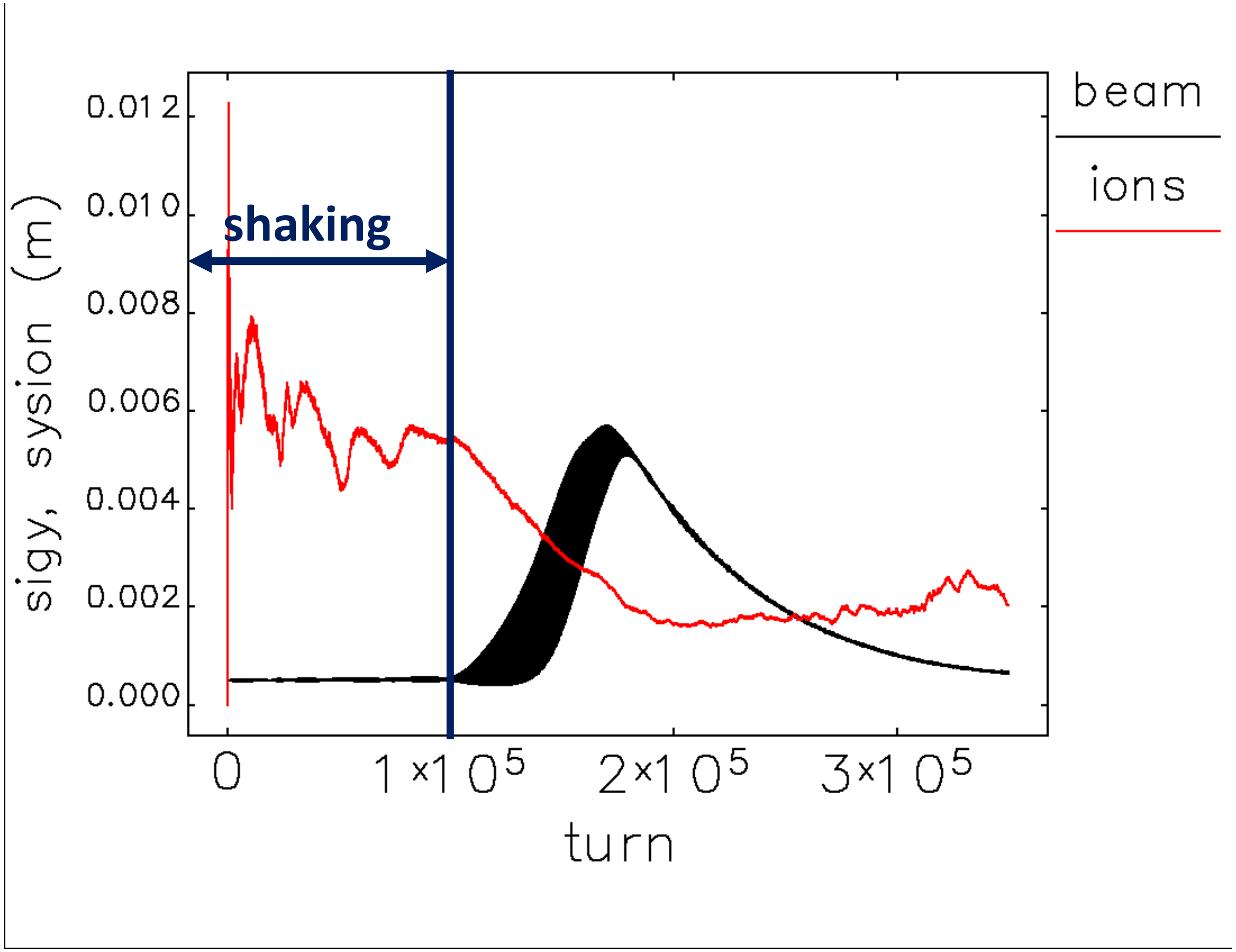
Options for PAR Ion Mitigation

- Beam shaking to drive away ions
  - Tried various combinations of shaking strength, start time, duration, and frequency
  - Nothing seems to reduce vertical beam size at the end of the cycle
  - Plot shows measured beam size along cycle, driving from 250-270 ms
    - Secondary blowup seen around 350 ms
- Reducing pressure
  - PAR ion pumps just replaced, now have ~50% higher pumping speed
- Clearing electrodes
  - Expensive modification
  - Would need ~2.5 kV to clear CO ion in 100 ns
- Run PAR at higher energy
  - Tried this (at 437 MeV), no noticeable effect on beam size



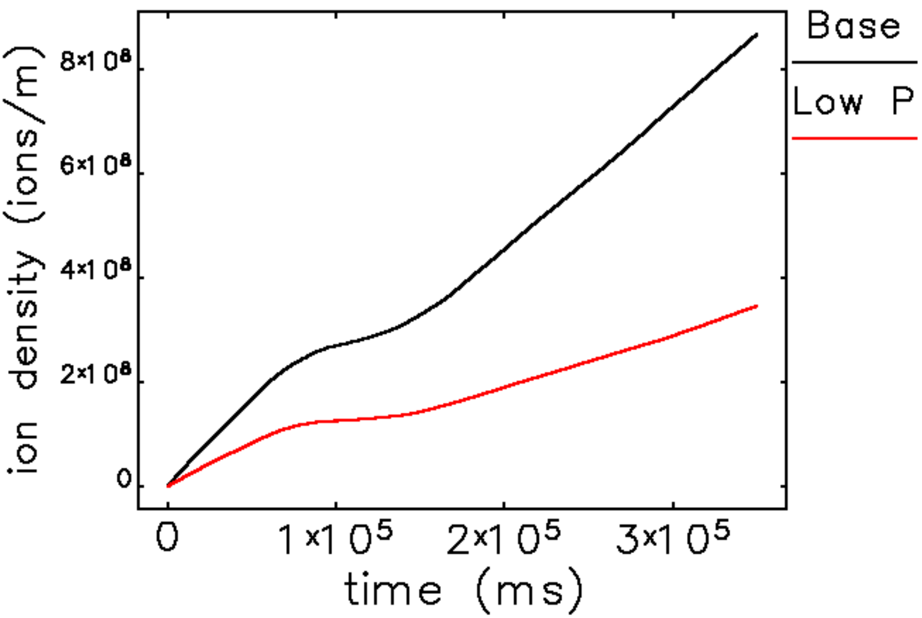
Beam Shaking Simulation

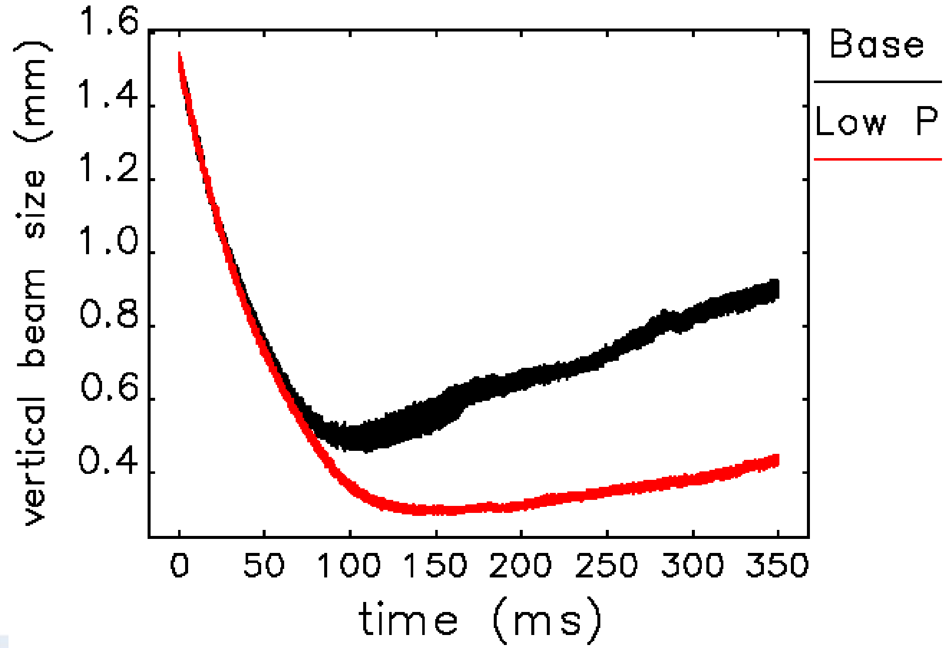
- Simulation indicates ions are driven away from the beam, but not actually lost
- Shaking causes ion cloud to blow up -> beam blows up after shaking
- Example: shaking until turn 100k



Low pressure simulation: 10 nC

- Try half nominal pressure (~3.2 nTorr → ~1.6 nTorr)
- Ion density ends up less than half nominal
  - Generate fewer ions
  - Less beam blowup → fewer ions are trapped
  - Final vertical beam size much smaller
- Lowering pressure could be effective at preventing blowup

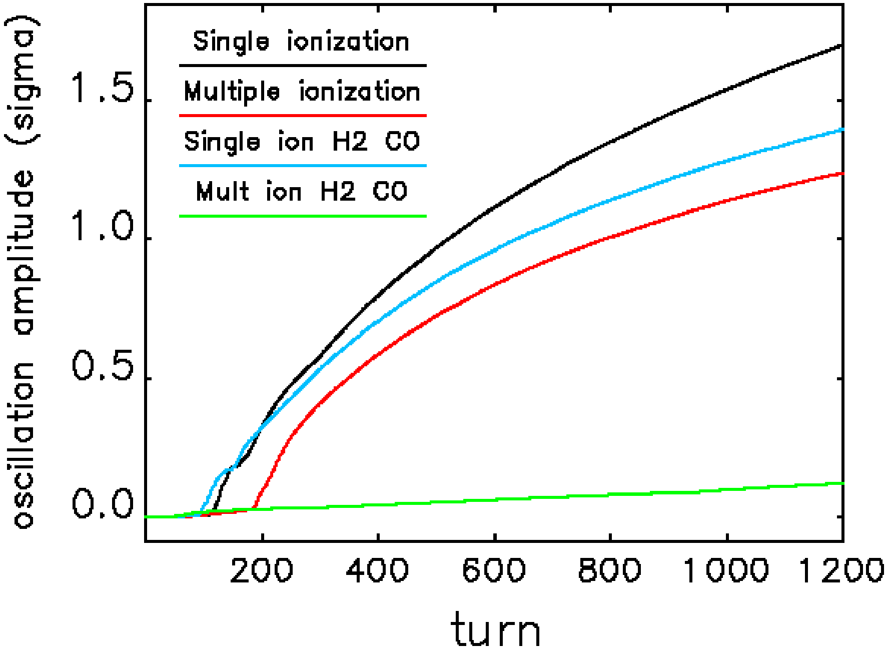




Storage Ring Instability

- Why don't we see ion instability in the APS storage ring?
  - No ion clearing gap
  - Instability is predicted by both analytical calculations and simulation (for 324 bunches)
- Simulate ion instability with FIILINAC
  - Shows instability (with same gas composition as above, average pressure 1 nTorr)
  - Multiple ionization of H_2 and CO delays onset of instability
  - With multiple ionization of H_2 and CO, and no other gasses, instability is suppressed
    - Multiple ionization is not implemented for other species
- Multiple ionization provides a limiting mechanism for instability due to ion trapping

Parameter	Value	Units
Energy	7	GeV
Circumference	1104	m
Bunches	324	
Bunch charge	1.1	nC
Bunch spacing	11.4	ns
Horizontal emittance	3100	pm-rad
Vertical emittance	40	pm-rad

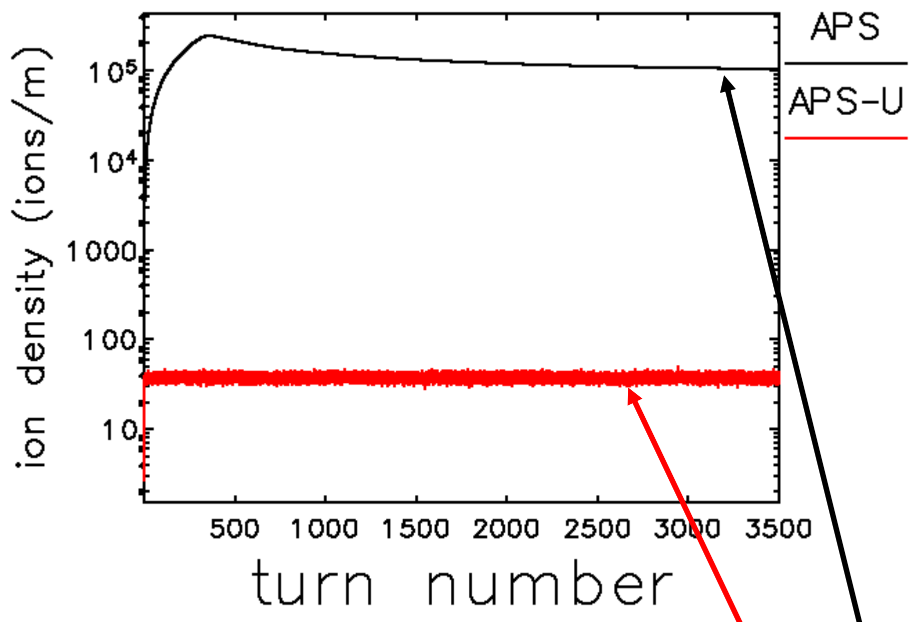


Ions at APS-U

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

$N_e \equiv$ bunch population
$r_p \equiv 1.5 \times 10^{-18}$ m
$S_b \equiv$ bunch spacing
$\sigma_x, \sigma_y \equiv$ beam size

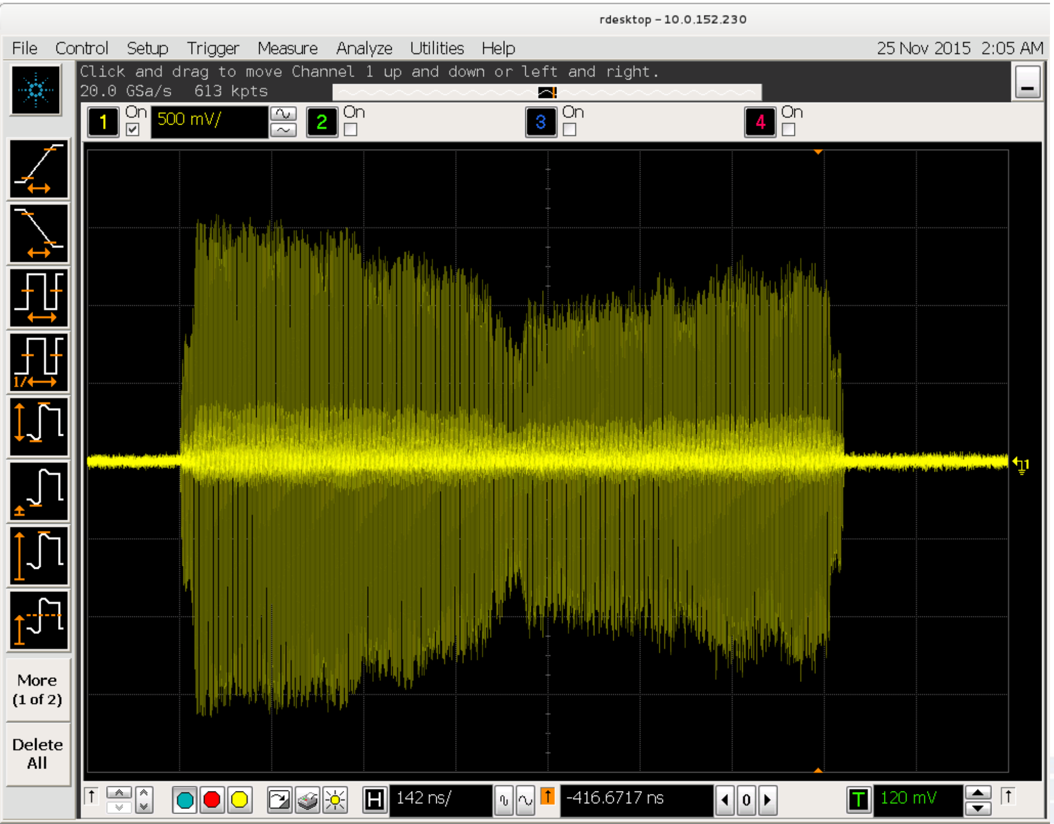
- Since no train gap is planned for APS-U, ion trapping could be a concern
- Only ions above a certain mass A are trapped
  - For APS, 324 bunch mode, A = 6, so all ions other than H_2^+ are trapped
  - For APS-U, 324 bunch mode, A = 354, so no ions are trapped
- High charge, low emittance beams tend to overfocus ions, preventing long term trapping
- Simulation also shows no trapping

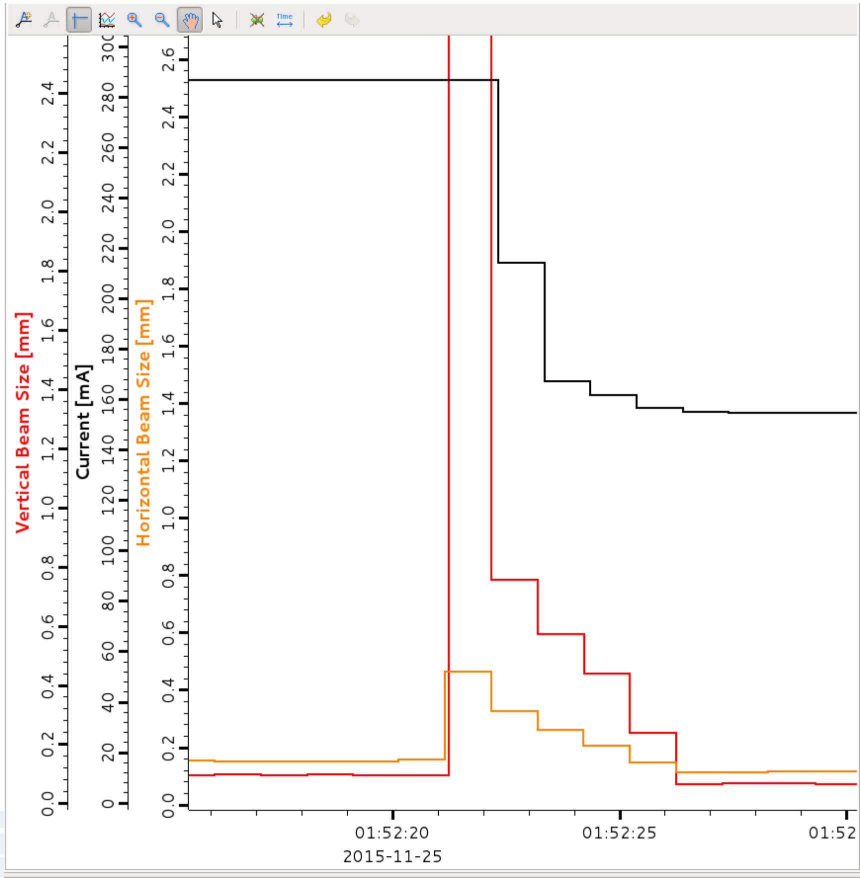


	N_e	$S_b(m)$	σ_x (μ m)	σ_y (μm)	A
APS (324)	7.1×10^9	3.4	275	10	$\boxed{6.4}$
APS (24)	9.6×10^{10}	46	275	10	1160
APS-U (324)	1.4×10^{10}	3.4	21.2	4	$\boxed{354}$
APS-U (48)	9.6×10^{10}	23	17.8	10.2	5800

Ion Instability at NSLS-II

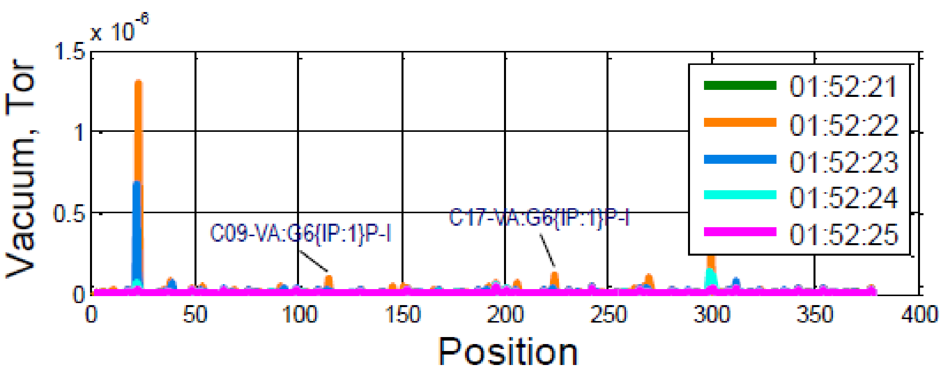
- Observe ion instability with 300 mA in 1050 bunches, but it is controllable with feedback
- Concern for eventual operation at 500 mA
- Attempted to store 300 mA in 500 bunches, lost current in the middle of the train
- Beam loss accompanied by beam size blowup, local pressure spikes

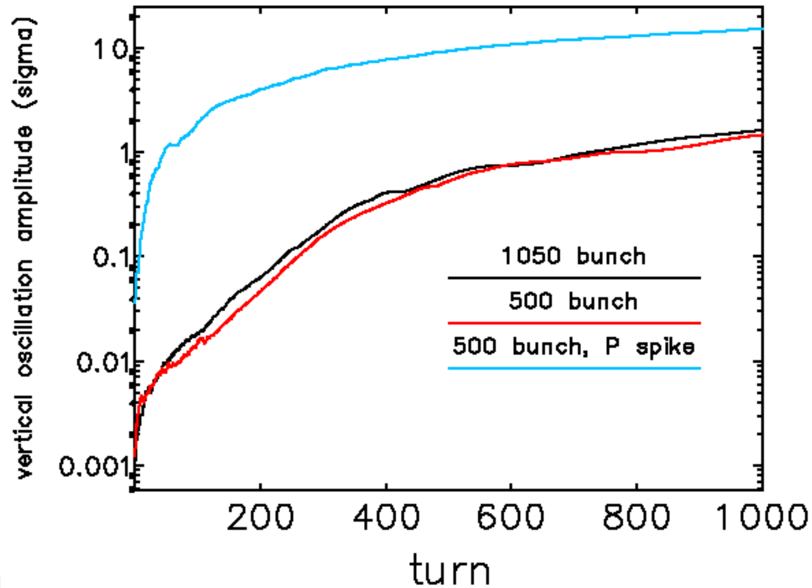




Ion Simulations for NSLS-II

- Studying the instability using FIILINAC code
  - NSLS-II parameters, gas composition, pressure profiles from A. Blednykh
- Simulation indicates similar growth rate for 500, 1050 bunches
- During beam loss vacuum profile shows very large spike (> 1 μTorr) at one location, corresponding to the position of an in-vacuum undulator
  - Is this a cause or effect of the beam loss?
  - Similar to SOLEIL?: "These FBIIs were attributed to localized vacuum pressure bursts arising from beam (wakefield) induced vacuum chamber heating"[1]
  - Simulation with vacuum spike shows much higher instability growth rate





[1] R. Nagaoka et al., "Fast Beam-Ion Instability Observations at SOLEIL", Proc. of IPAC10

Conclusions

- We observe an ion induced coherent tune shift in PAR, which increases along the PAR cycle. This effect has been modeled with the simulation code FIILINAC, with several modifications:
  - Realistic vacuum model (made with Synrad+ and Molflow+)
  - Multiple ionization of trapped ions
  - Beam shaking
- Simulations indicate the PAR should be safe from coherent ion instabilities at high charge (needed for the APS-Upgrade)
- Ion induced emittance growth is observed in the PAR. This effect is being modeled with the simulation code FASTION
  - Optimized to be able to simulate full PAR cycle
- Both measurements and simulations indicate beam shaking is ineffective at clearing out the PAR ions
  - Lowering the pressure looks like a better option
- Lack of ion instability in the present APS may be due to multiple ionization
- We do not expect ion trapping in the APS-U storage ring with nominal parameters
- Ion instability is observed at NSLS-II with high bunch current
  - May be caused by outgassing due to vacuum chamber heating

Acknowledgements

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