Modeling Ion Effects for the APS-U

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Outline

- Introduction
- Ion instability in the APS-U storage ring
  - Trapping criteria
  - Instability simulations
  - Train gaps
- Modeling incoherent ion effects
  - The IONEFFECTS element
  - Parallelization
  - Emittance growth in the APS particle accumulator ring (PAR)
- Conclusions

Introduction

- Ion trapping occurs when a negatively charged beam ionizes residual gas inside the vacuum chamber. The resulting ions can 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].
  - Because the APS-U storage ring is planned to run with high charge, low emittance electron bunches, trapped ions could be very dangerous for beam stability.
- Trapped ions can also cause incoherent effects, such as emittance growth and tune spread

1: H.G. Hereward, CERN-71-15 (1971)

Trapping Criteria

- Trapping criteria given by simple equation [1]
  - Ions with mass number larger than the "critical mass" will be trapped; lighter ions will not.
  - $A_{crit} \equiv \max(A_x, A_y)$
  - Very high beam density will over-focus the ions, preventing long term trapping
- Because the beam size will vary along the ring, the critical mass will also vary
  - A given ion may be trapped in some parts of a lattice, but not others
- Basic parameters for APS-U operating modes shown in table
  - No trapping is expected for 48 bunch mode (A_{crit} > 700 for entire ring)
  - Next slides assume 324 bunches

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

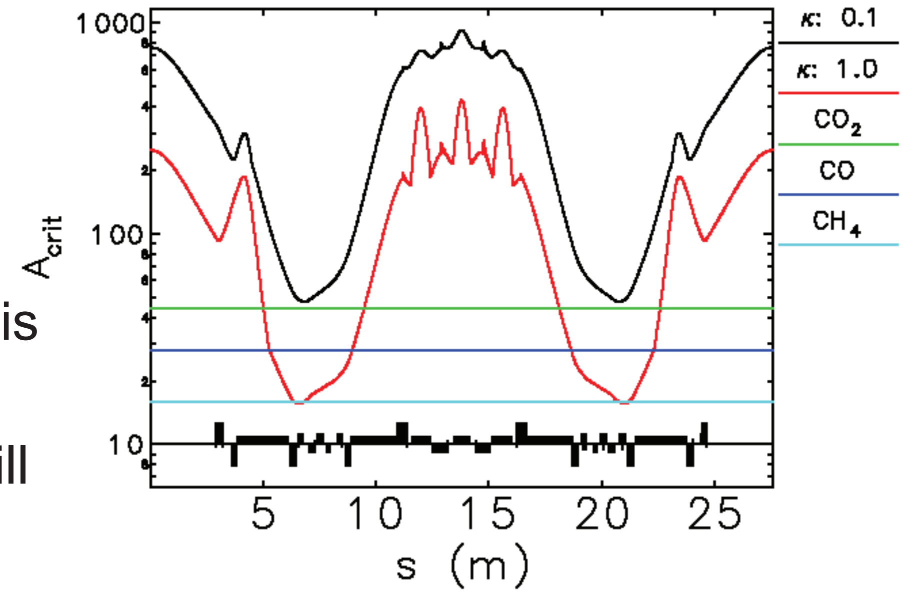
$N_e \equiv$ bunch population
$r_p \equiv 1.5 \times 10^{-18}$ m
$S_b \equiv$ bunch spacing
$\sigma_x, \sigma_y \equiv$ beam size

Quantity	Timing	Brightness
Beam energy	6 GeV	
Beam current	200 mA	
Natural emittance	42 pm	
Bunches	48	324
Bunch spacing	77 ns	11 ns
Bunch charge	15.4 nC	2.2 nC

[1]: Y. Baconier, G. Brianty, CERN/SPS/80-2 (DI), 1980.

Trapping in the APS-U (324 bunches)

- An ion will be trapped at a given point in the lattice if its mass number is greater than A_{crit}
- For round beams (κ = 1.0), trapping occurs in the multiplet sections
- For flat beams (κ = 0.1), no trapping is expected
- Table shows percent of lattice that will trap each ion, for a given emittance ratio

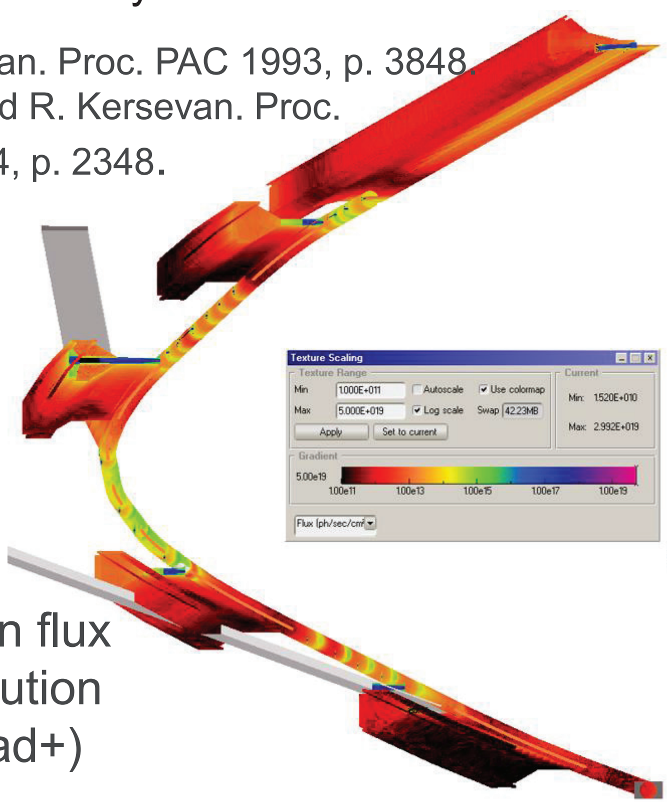


Emit. Ratio	ε_x (pm)	ε_y (pm)	% H_2	% CH_4	% CO	% CO_2
0.1	40	4	0	0	0	0
0.2	39	8	0	0	0	17
0.4	36	14	0	0	12	26
1.0	29	29	0	4	27	32

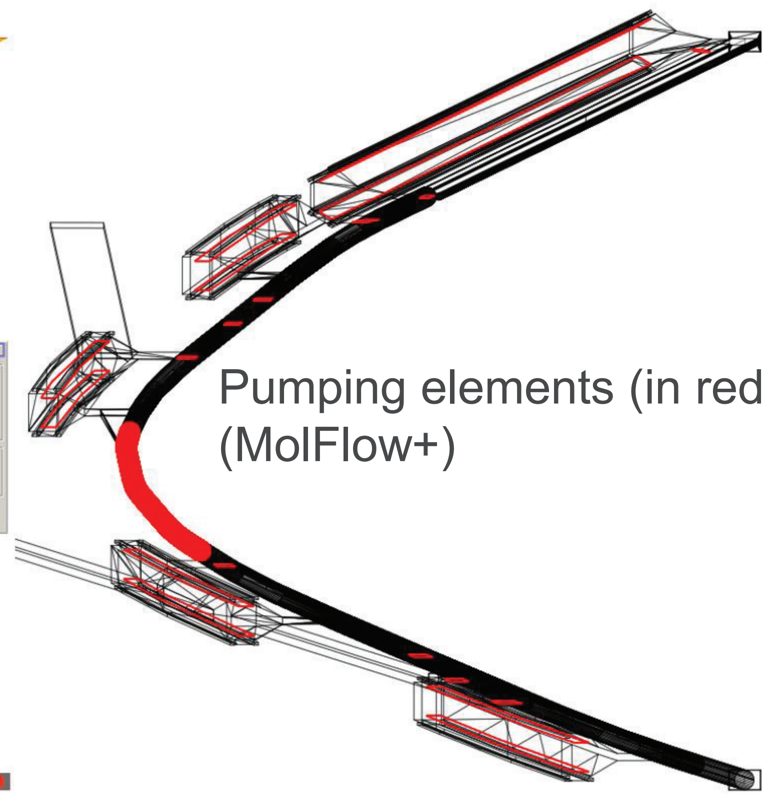
Computation of Pressure Profile (J. Carter)

- Since trapping is localized, we want to know the local pressure around the ring
- Photon flux distribution calculated by SynRad+ [1]
  - Includes scattering of photons off vacuum chamber elements
- Pressure profiles calculated by MolFlow+ [2]
  - Inputs: photon flux from Synrad+, photon stimulated deorption, pumping elements
  - Note that only FODO section is NEG coated in present APS-U design

1: R. Kersevan. Proc. PAC 1993, p. 3848.
2: M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.



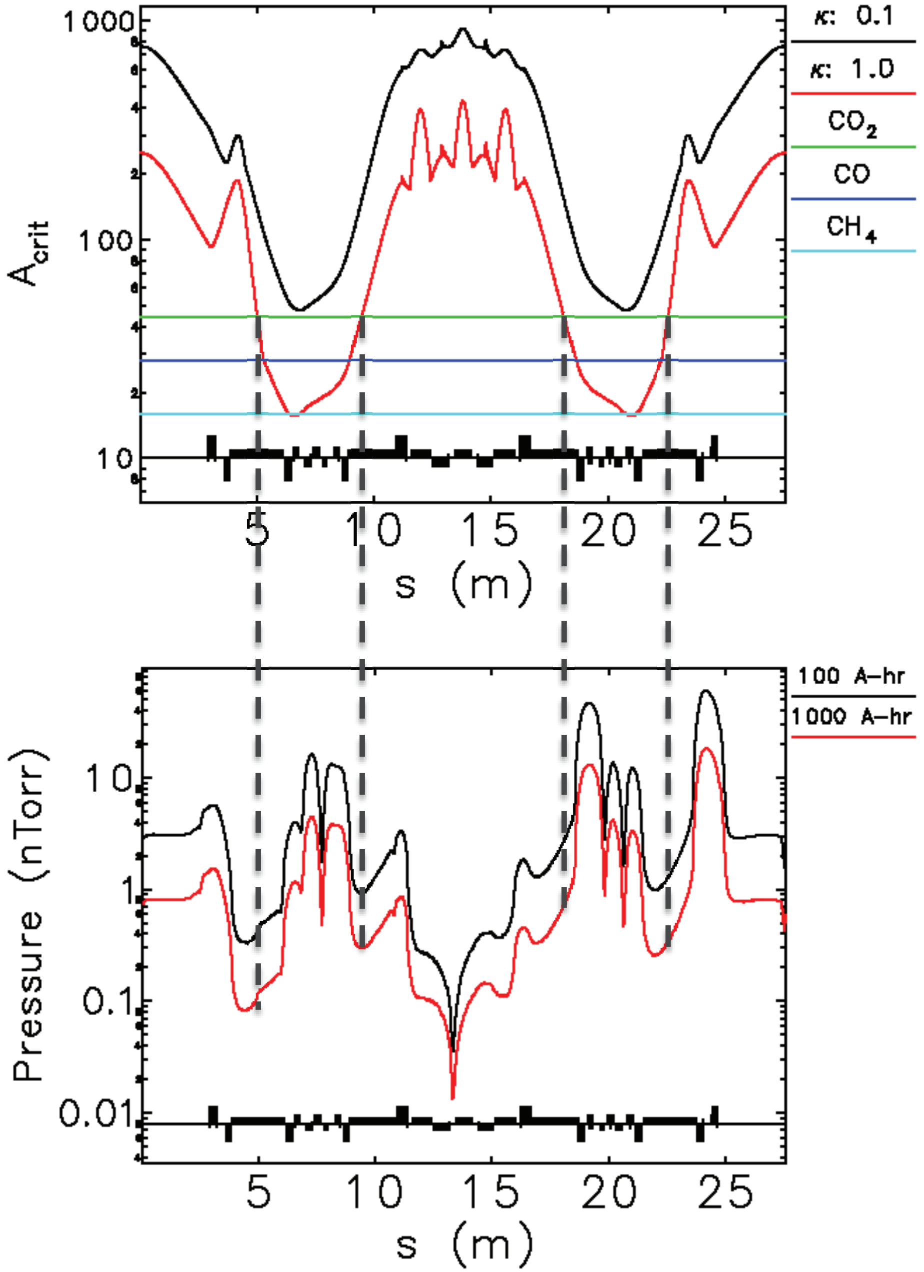
Photon flux distribution (Synrad+)



Pumping elements (in red) (MolFlow+)

Instability Simulation

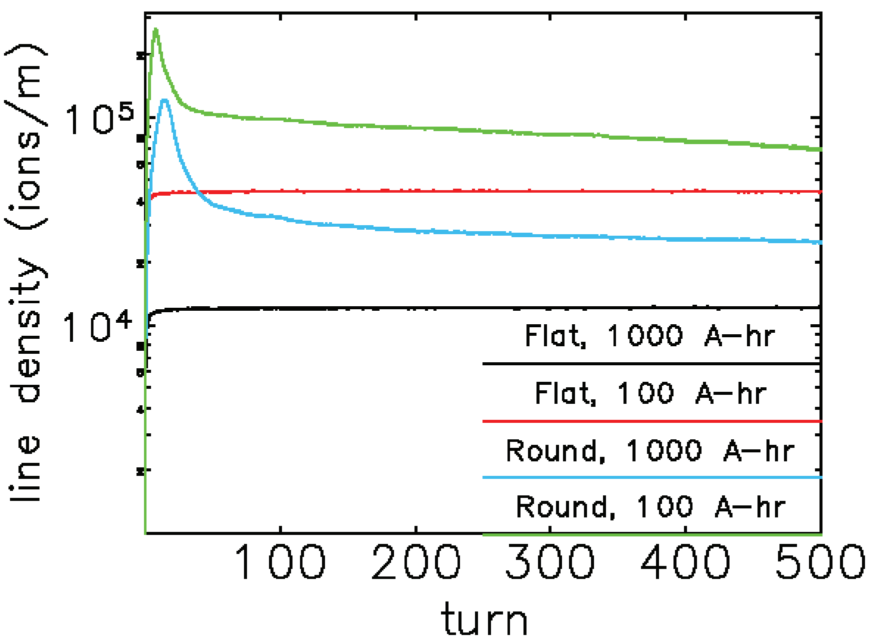
- Ion instability code developed at SLAC [1]
  - Ions are modeled using macroparticles
  - Beam is rigid (only centroid motion allowed) with assumed Gaussian field
- Benchmarked against tune shift measurements in APS Particle Accumulator Ring [2]
- Incorporated realistic pressure profiles generated by vacuum simulation codes
  - Codes give partial pressure for each gas around the ring
  - Vacuum improves with beam processing
  - Pressure is highest in the multiplets (unfortunately where trapping occurs)

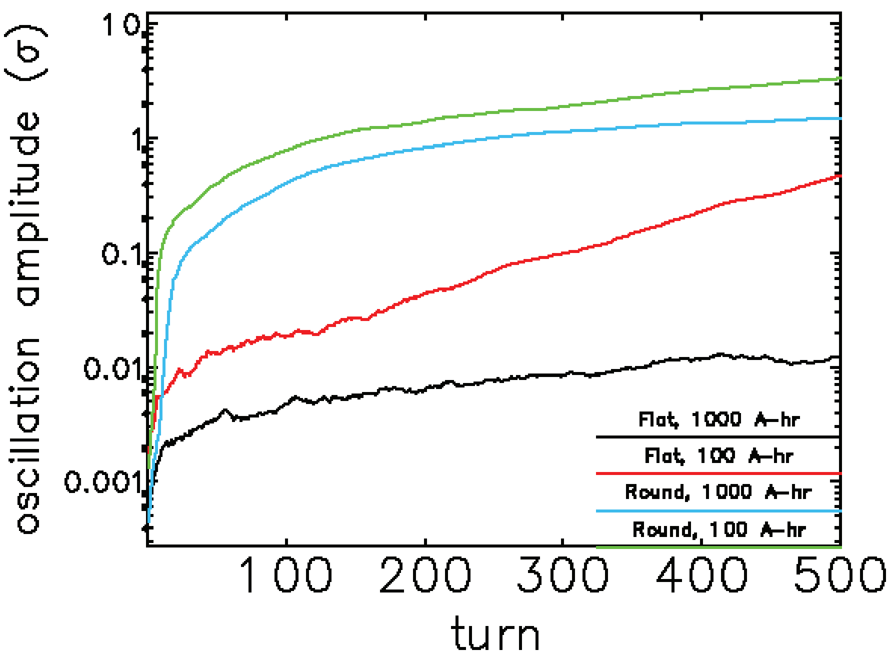


1: L. Wang et al. PRSTAB 14-084401 (2011).
2: J. Calvey et al., Proc. NAPAC16, THPOA14. (2016)

Simulation Results (324 bunches, 200 mA)

- Simulated round (κ = 1) and flat (κ = 0.1) beams, with 1000 A-hr and 100 A-hr beam conditioning
- No trapping is observed for the flat beam cases (ion density does not increase with time)
- Trapped ions in the round beam case do lead to an instability
  - The instability 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.
  - The beam motion is enough to shake out some of the ions, leading to a reduction in the ion density
- The flat beam simulations also show an instability, though with a much lower growth rate
  - Flat beams will have shorter lifetime, so this is not an ideal solution

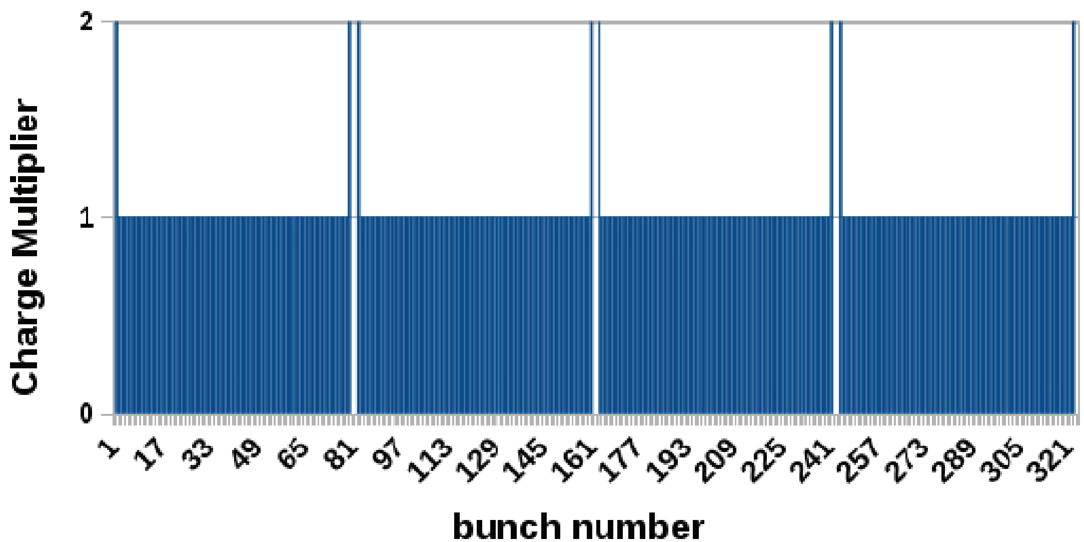




Train Gaps

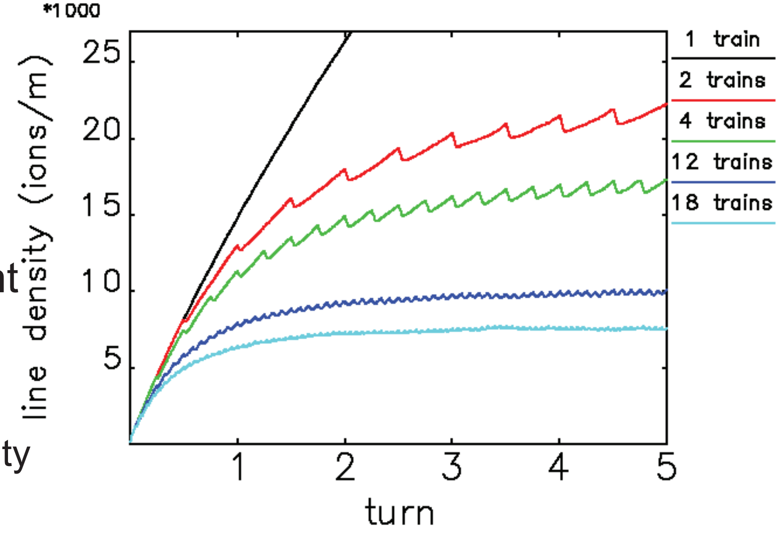
- Use gaps between bunch trains, to allow the ions to clear out [1,2].
- To minimize transients in the RF system, distribute the missing charge to the bunches adjacent to the gaps (“guard bunches”)
  - Simulations by M. Borland have shown that the impact of this arrangement on the RF system should be relatively modest (see talk by R. Lindberg)
  - High charge bunches before the gap will provide a stronger kick to the ions
  - Downside: high charge bunches have shorter lifetime
- Example: 4 trains with a 2 bunch gap; bunches before and after gap have double charge

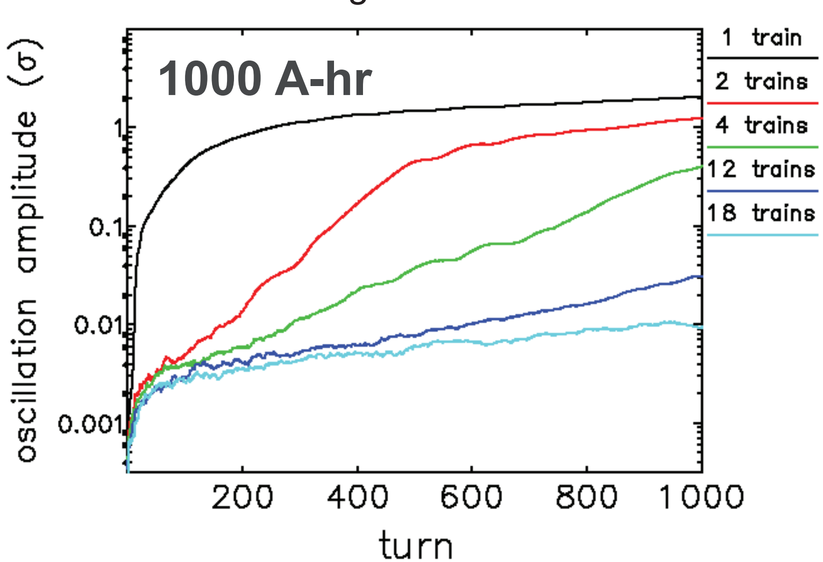
1: M. Barton, NIMA 243, 278 (1986).
2: D. Villevald and S. Heifets, SLAC-TN-06-032 (1993).

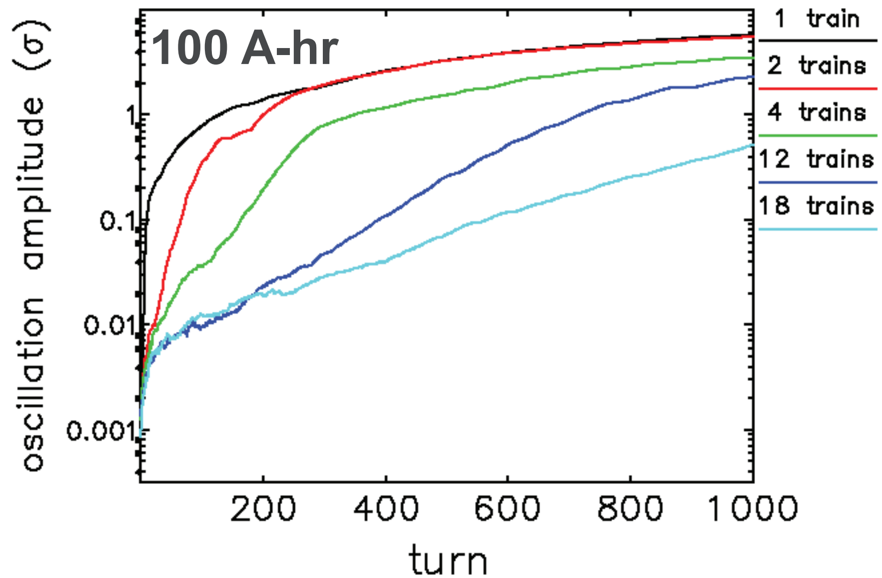


Train Gap Comparison

- Modified ion simulation code to test this scheme
- Results not sensitive to the number of bunches in the gap
  - Minimum A_{crit} is for a 2 bunch gap 76
- Plots show ion density and growth rate for different numbers of trains, with a 2 bunch gap
  - Both are significantly reduced with 2 trains
  - Using more trains further reduces the density/instability
  - At 1000 A-hr, growth rate is ~0 with 18 trains
  - Still some growth at 100 A-hr







Growth Rate Comparison

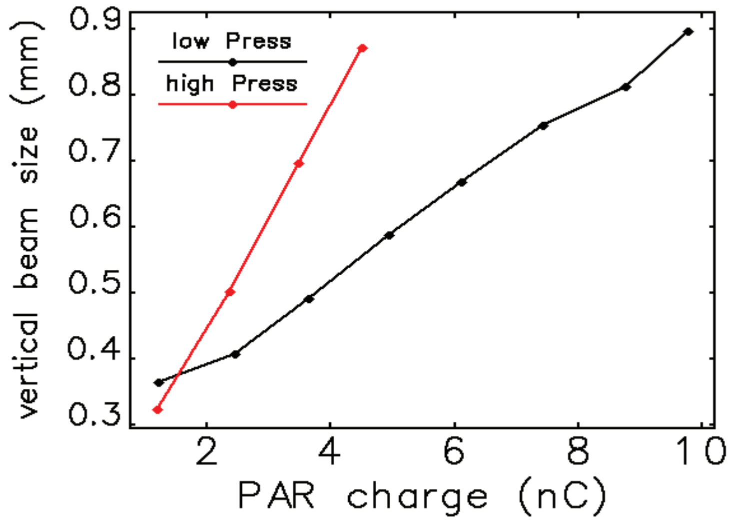
- Instability growth rates (defined in exponential growth region, before saturation) can be compared with expected coherent damping rate (6.8/msec) and feedback damping (10/msec)
- As long as at least two trains (or flat beams) are used, beam should theoretically be stable
- Caveats: coherent damping (due to momentum spread) is not exponential; we would prefer not to depend on feedback
- Still, if the growth rate is << 10/msec, coherent instability should be effectively damped
- NEG coating the multiplets is another option under study

Growth rates (ms^{-1})

# of trains	1	2	4	12	18	1 (flat)
100 A-hr	75	6.2	2.0	0.9	0.5	1.0
1000 A-hr	43	1.4	0.7	0.3	0.14	0.3

Ion-induced Emittance Growth

- Emittance growth is possible, even if coherent instability is damped
  - A concern for the upgrade, since significant emittance growth will change the trapping criteria
- Example: ion-induced vertical emittance growth observed in the APS Particle Accumulator Ring (PAR)
  - PAR accumulates linac bunches (~1 nC) up to desired charge (~20 nC for 48 bunch mode)
  - Observe a vertical beam size blowup with charge
  - Blowup was more severe at high pressure
  - Can impact injection efficiency into the booster synchrotron



PAR Parameter	Value
Energy	375 – 425 MeV
Revolution period	102 ns
Cycle time	1 sec
Accumulated charge	2 – 20 nC
Natural emittance (425 MeV)	300 nm

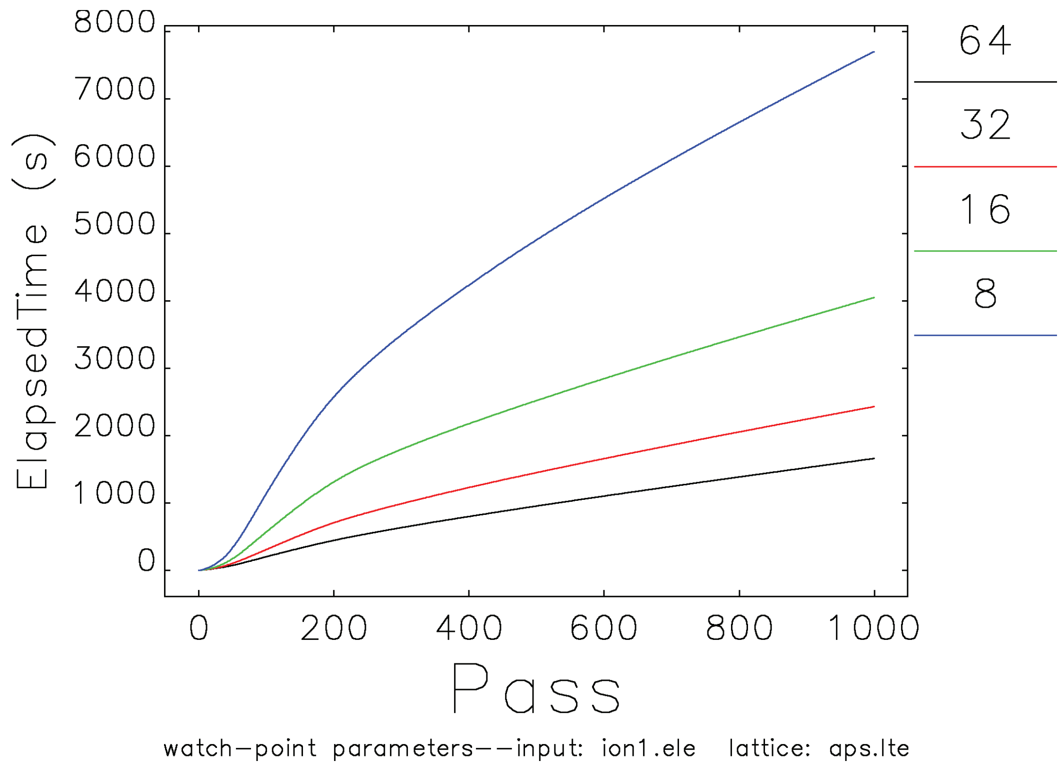
Modeling Emittance Growth

- SLAC ion code assumes a rigid beam, so it can't model this
- We have incorporated an IONEFFECTS element into ELEGANT
  - Model both ions and beam with macroparticles
  - Model intra-bunch effects such as emittance growth and decoherence.
  - Self-consistent modeling of ion effects in combination with other elements, including feedback and impedance
- Inputs: location of ion elements, pressure profiles, ion properties
- An IONEFFECTS element simulates ion generation, ion motion between bunches, beam/ion kicks
  - Both distributions are assumed to be Gaussian; the kicks are derived from the Bassetti-Erskine formula [1] . This is not a good assumption for the ion cloud; we plan to incorporate a Poisson solver into the code.
- Includes multiple ionization [2]
  - Ions that are trapped for a long time have a chance of being multiply ionized or dissociating
  - Multiply ionized molecules have a different the charge/mass ratio, and may no longer be trapped by the beam

[1] M. Bassetti, G. Erskine, CERN ISR TH/80-06 (1980).
[2] P.F. Tavares, Particle Accelerators Vol. 43, pp. 107-131 (1993).

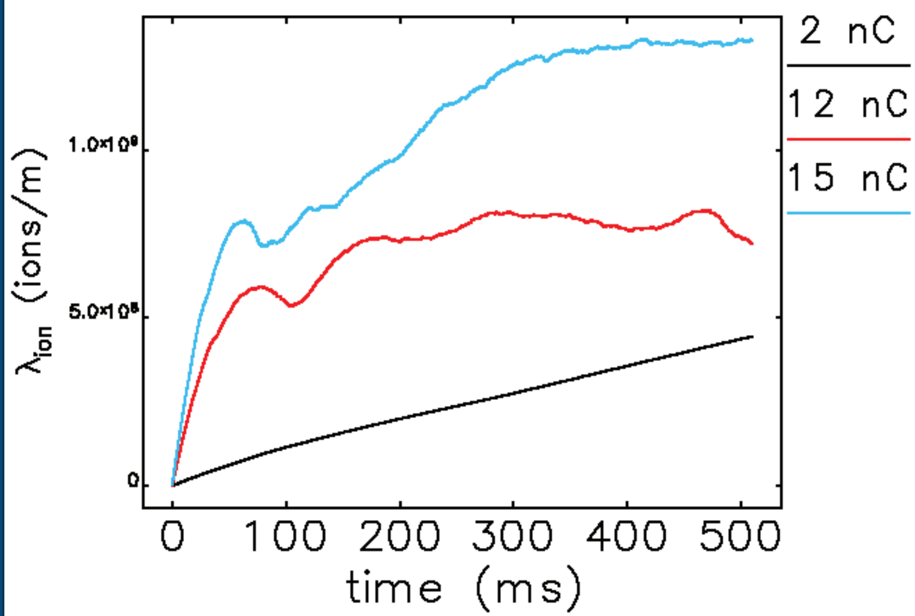
Parallelization

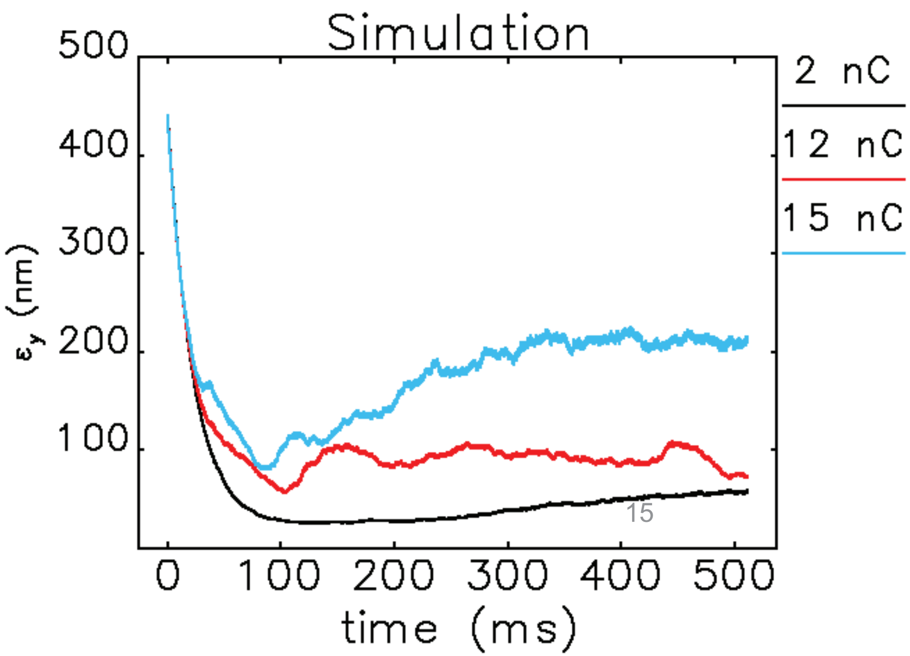
- Parallelized using MPI library
- Simulations are typically run with between 12 and 72 cores
- With 64 cores, gain a factor of ~20 relative to serial
  - Scaling should improve further with larger simulations



Simulating PAR Emittance Blowup

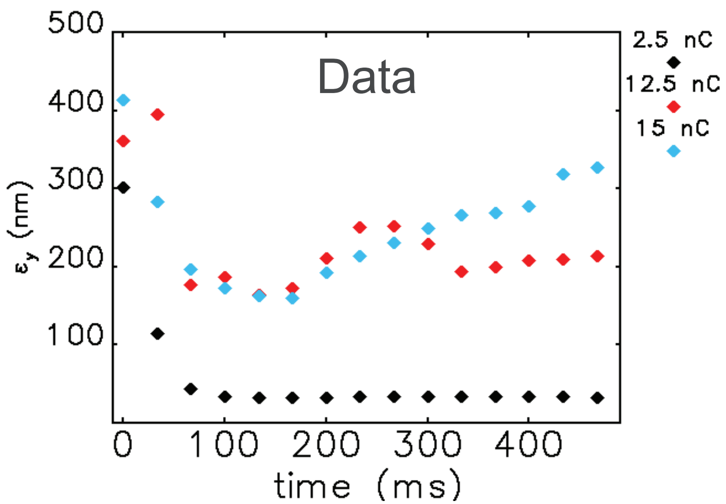
- Simulate evolution of beam size over PAR cycle
- Ion density saturates at high charge, due to a combination of beam instability and multiple ionization
- Vertical emittance shows large linac bunch damping to charge dependent equilibrium size, with fluctuations at high charge

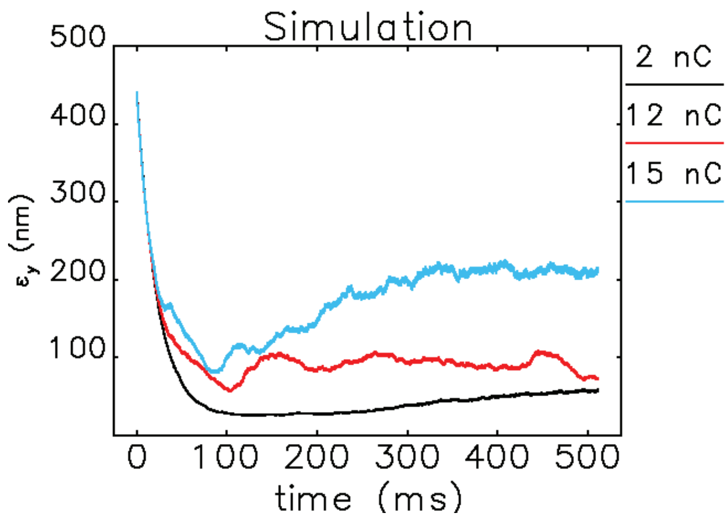


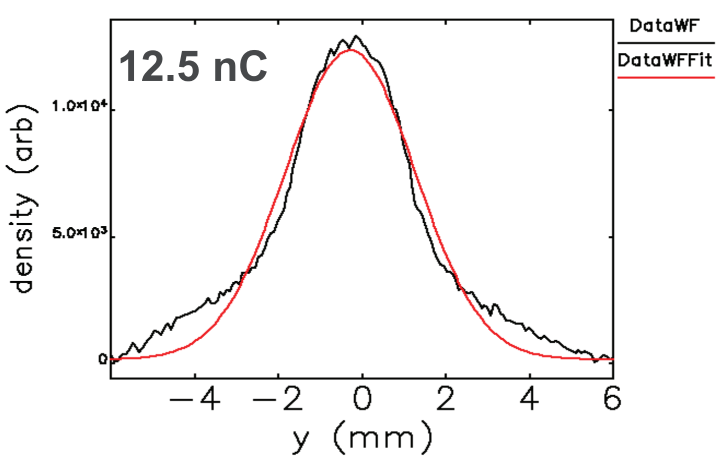


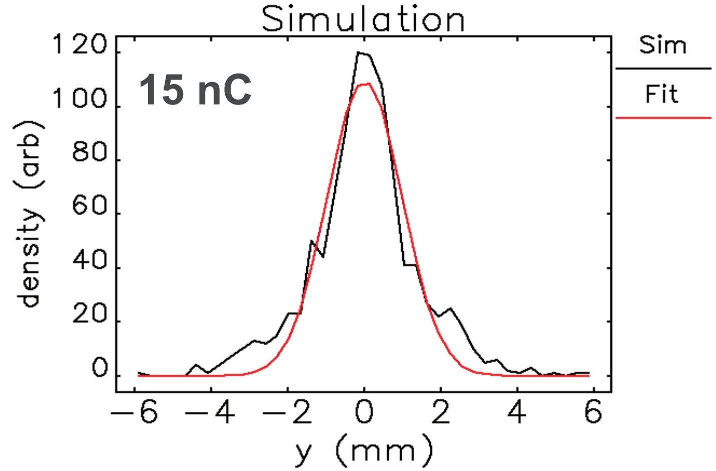
Comparison with Data

- Simulated and measured beam size vs time show qualitatively similar behavior
- Both data and simulation show tails in the vertical beam profiles









Summary

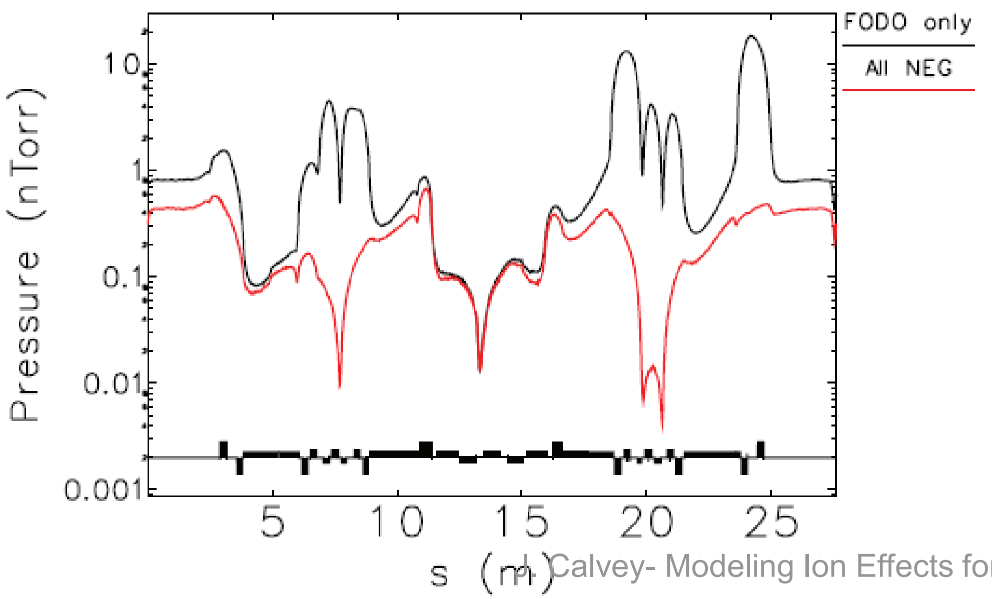
- No trapping is expected in the APS-U storage ring in 48 bunch mode, or 324 bunches with small coupling
- For 324 round bunches, ions will be trapped in the multiplet sections. This is where vacuum simulations predict the pressure will be highest.
- Ion instability in the APS-U storage ring has been studied using a rigid-beam simulation. The simulation shows that the instability can be mitigated by using train gaps, with double-charge guard bunches at the beginning and end of each train.
- An IONEFFECTS element has been incorporated into ELEGANT, and used to model beam size blowup in the PAR.
- Future work for IONEFFECTS:
  - Implement Poisson solver
  - Model APS-U storage ring
  - Detailed study of multiple ionization
  - Study (lack of) instability in present APS
  - Model longitudinal motion of ions

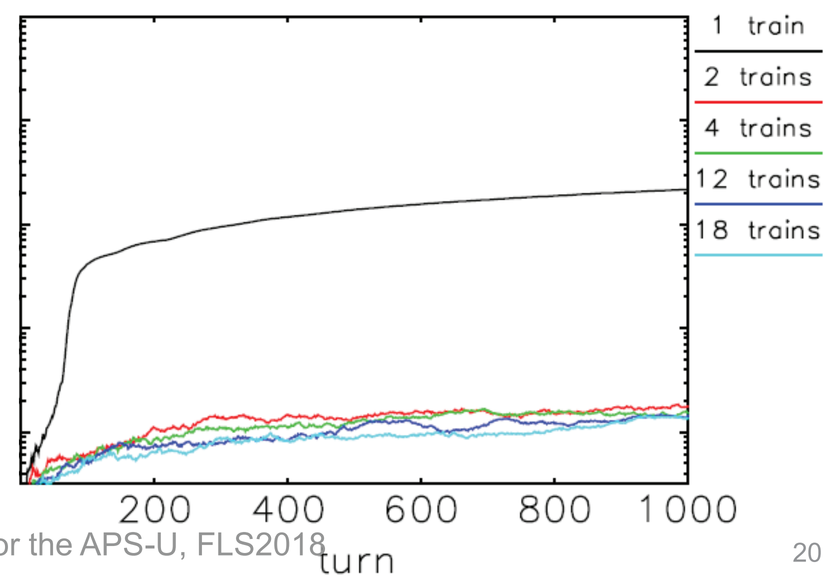
Thanks for Your Attention!

Backup slides

NEG Coating

- In the present APS-U vacuum design, only the FODO sections are NEG coated. One potential upgrade would be to coat the entire ring.
- A Synrad/Molow+ predict this would reduce the average pressure from 0.97 nTorr to 0.24 nTorr.
  - Even better in the multiplets (where ions are trapped) (Fig. 1)
  - Benefit comes primarily from reduced photon-stimulated desorption
- Simulation shows dramatic suppression of ion instability





Calculation of beam/ion kick

- Beam kick can be calculated from Bassetti-Erskine formula*, assuming beam is Gaussian:

$$\Delta p_y + i\Delta p_x = \frac{cN_b r_e m_e}{\gamma}\sqrt{\frac{2\pi}{\sigma_x^2 - \sigma_y^2}}\left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - exp\left(\frac{-x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{\frac{\sigma_y}{\sigma_x}x + i\frac{\sigma_x}{\sigma_y}y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

– N_b = bunch population

– γ = relativistic factor

– σ_x, σ_y = beam size

– w = complex error function

- Note that this expression appears to diverge when $\sigma_x = \sigma_y$

– This is not actually the case; however one can run into issues with machine precision due to the large numbers involved in evaluating the complex error function.

* M. Bassetti, G. Erskine, CERN ISR TH/80-06 (1980).

IONEFFECTS Results: Present APS

- Ion density grows linearly until it causes an instability
- Beam motion grows exponentially until it reaches ~1 um (10% of beam size), then grows more slowly
  - Unstable beam shakes out ions
- Beam spectrum should have peaks in lower betatron sidebands at ~9 MHz
  - Peaks appear between 5-10 MHz
  - Spread due to nonlinearity of ion fields