Beam-Gas Interactions

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Outline

- Introduction
- Gas scattering lifetime
- Calculation of pressure profiles
- Ion trapping
- Instability simulations
- Effect of train gaps
- Commissioning and early operation
- Emittance growth due to ions
- Summary

Introduction

- Vacuum inside accelerator "vacuum chambers" is generally very good, but not perfect
  - Biggest issue is usually photon stimulated desorption (PSD) of molecules on chamber walls
  - Conditioning of the vacuum chamber by beam photons gradually improves vacuum over time
- Residual gas causes two major problems:
  - Collision between a beam electron and gas molecule can scatter the electron outside the dynamic/momentum aperture of the machine, causing shorter lifetime
  - The beam can ionize the gas, and the resulting ions can become trapped in the beam's potential, leading to instability and/or emittance growth
- This talk will describe both effects, how we are modeling them for APS-U, and potential mitigations

Gas Scattering Lifetime

- The gas scattering lifetime includes contributions from elastic gas scattering and gas bremsstrahlung [1]
  - Elastic: electron scatters transversely, outside of dynamic aperture
  - Bremsstrahlung: electron loses energy, falls out of momentum acceptance

$$\frac{1}{\tau} = \frac{c}{L} \sum_{g=1}^{G} \sum_{a=1}^{C_g} \int_0^L \sigma_{g,a}(s) S_{g,a} n_g(s) ds$$

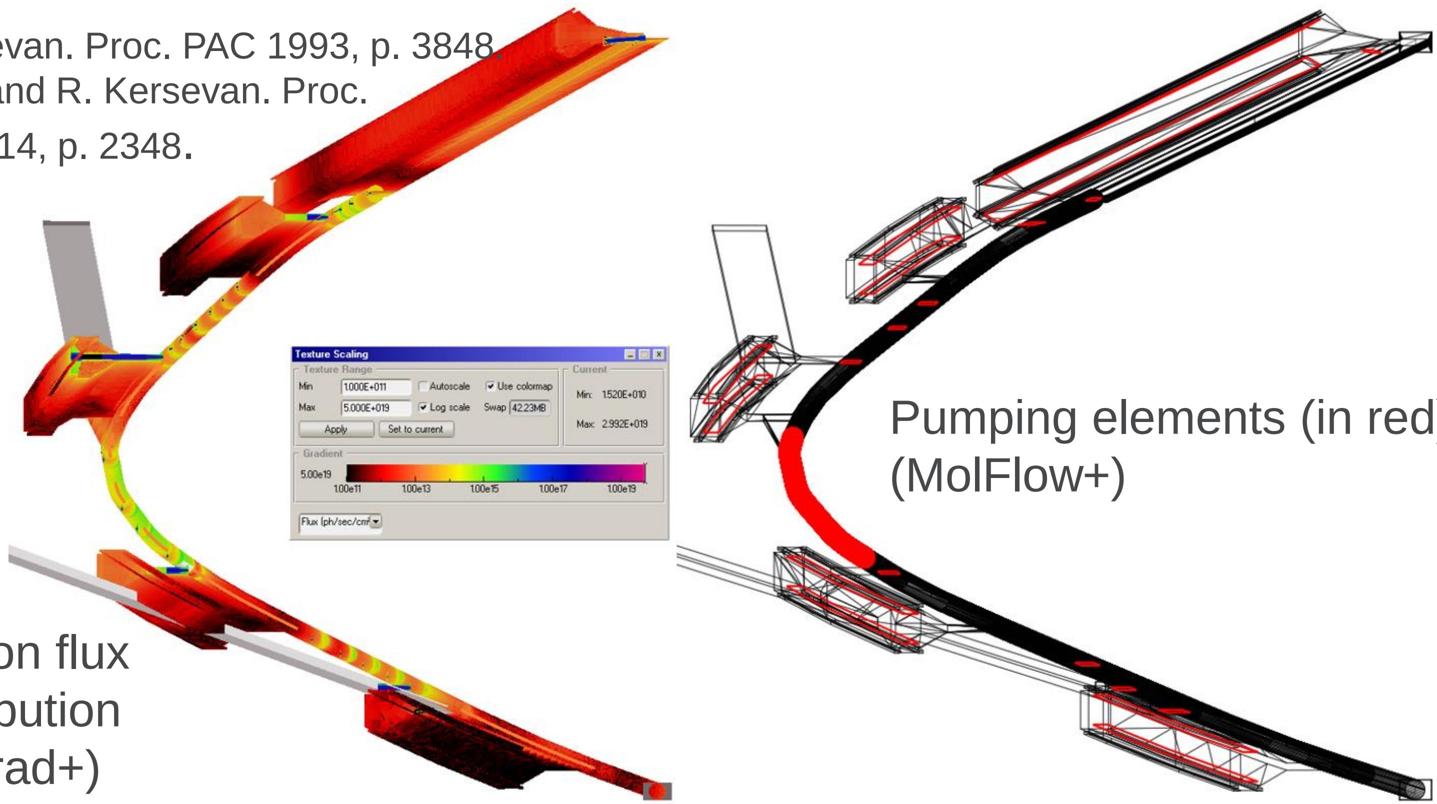
- Local contribution to the lifetime depends on [2]:
  - $\sigma_{g,a}(s)$: out-scattering cross section (depends on DA/LMA)
  - $S_{g,a}$: number of atoms of type a in molecule of gas g
  - $n_g(s)$: density of gas g
- Accurate computation of the lifetime requires partial pressure of each gas around the ring

1: F. C. Porter, NIM A 302 (1992), pp. 209–216
2: M. Borland et al., Proc. IPAC15, pp. 546-548

Computation of Pressure Profile (J. Carter)

- 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+, PSD curves, 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.

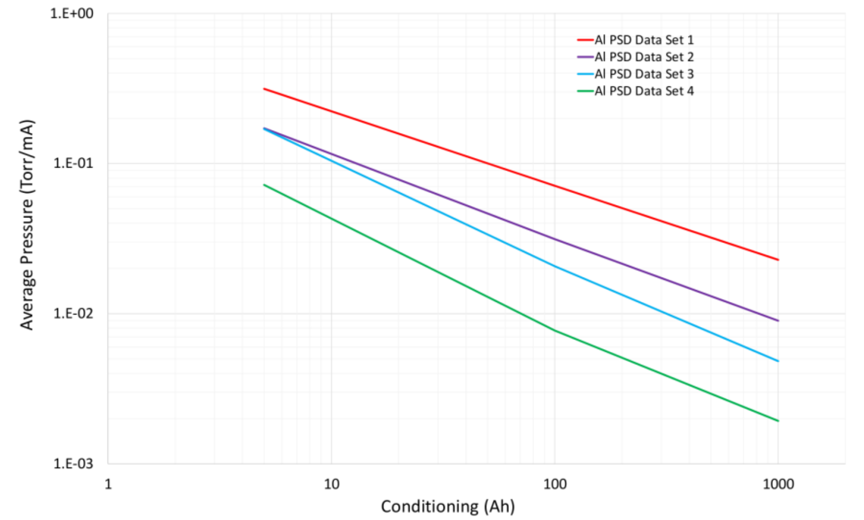


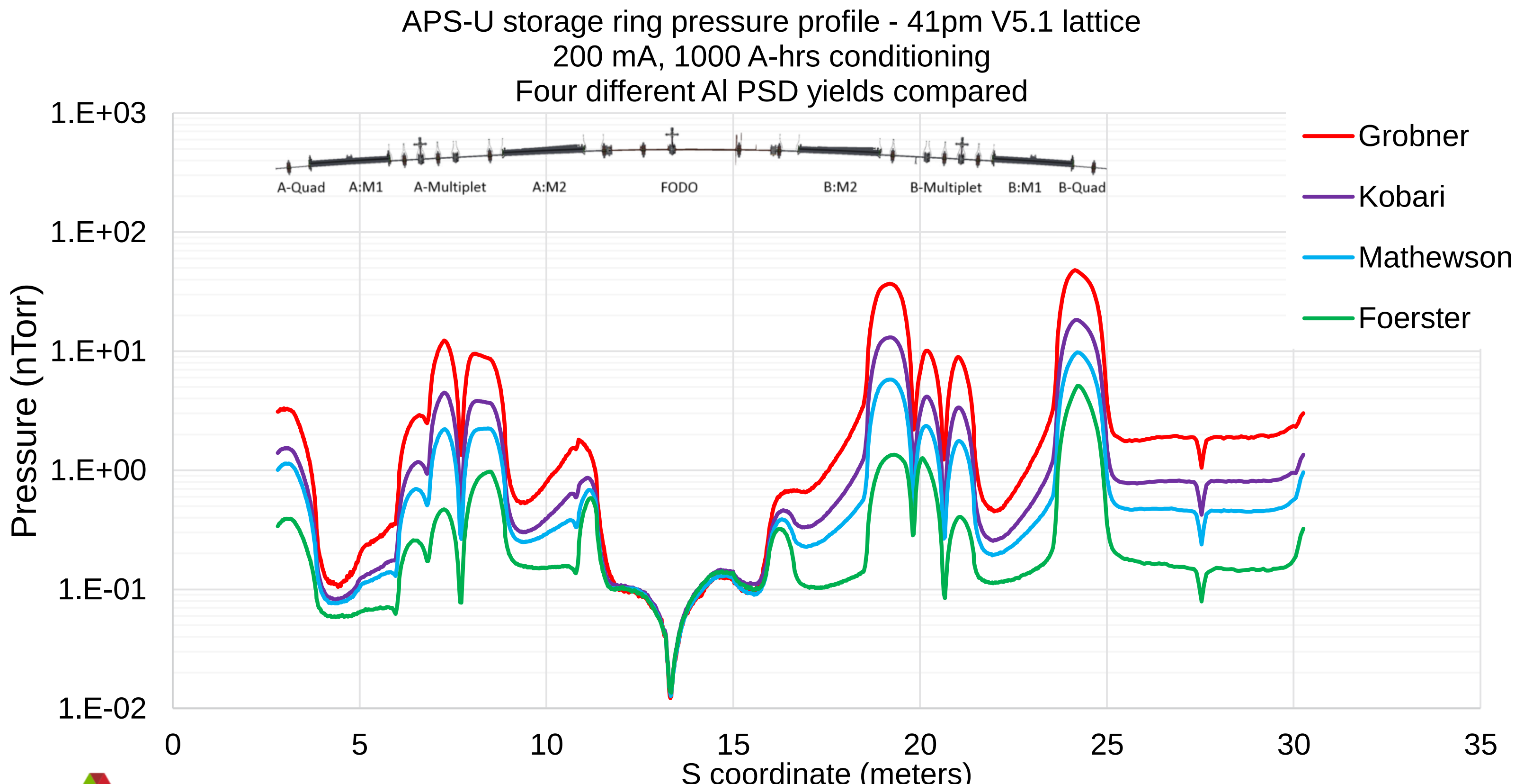
Pumping elements (in red) (MolFlow+)

Photon flux distribution (Synrad+)

Effect of PSD Model

- Computed pressure profile using PSD curves from four different sources
  - Average pressure varies significantly between models
  - All four show similar rate of beam conditioning





Gas Scattering Results (M. Borland)

- Three different conditions simulated:
  - 25 mA with 5 A-h dose (beginning of user operations)
  - 200 mA with 100 A-h dose (after ramp-up to 200 mA)
  - 200 mA with 1000 A-h dose (year of operation)
- Table lists the elastic, bremsstrahlung, and total gas-scattering lifetime, for each condition and each PSD model
- There is significant disagreement among the models
- To introduce a measure of conservativism without excessive pessimism, take second-lowest lifetime for each case
- Resulting lifetime is ~24 hours after 1000 A-h beam conditioning
  - Compare to expected Touschek lifetime of ~4 h in 48 bunch mode, ~19 h in 324 bunch mode

Model	τ_e h	τ_b h	τ_g h
25 mA after 5 A·h			
Foerster	49.2	49.5	24.7
Grobner	16.4	17.6	8.5
Halama	18.2	19.4	9.4
Mathewson	14.4	15.6	7.5
Notional	16.4	17.6	$\boxed{8.5}$
200 mA after 100 A·h			
Foerster	60.0	60.5	30.1
Grobner	8.8	9.4	4.5
Halama	12.7	13.7	6.6
Mathewson	16.5	17.7	8.5
Notional	12.7	13.7	$\boxed{6.6}$
200 mA after 1000 A·h			
Foerster	244.4	251.0	123.8
Grobner	26.2	28.3	13.6
Halama	45.4	49.0	23.6
Mathewson	74.6	79.9	38.6
Notional	45.4	49.0	$\boxed{23.6}$

Ion Trapping

- Ion trapping occurs when a negatively charged beam ionizes residual gas inside the vacuum chamber
- If the ions can't escape between bunches, they will accumulate until their motion couples to the beam motion, leading to a transverse (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.
- However, if the beam density is sufficiently high, the ions can receive a very strong kick from a single bunch, and escape before the next bunch arrives. In this regime we should be safe from instability, since the ions will not persist long enough to couple to the bunch motion.

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

Trapping Criteria

- Trapping criteria given by simple equation
  - Ions with mass number larger than the "critical mass" will be trapped; lighter ions will not.
  - $A_{crit} \equiv \max(A_x, A_y)$
- 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
  - Table shows percent of lattice that will trap each ion, for a given emittance ratio (324 bunch mode)
- No trapping is expected for 48 bunch mode
  - $A_{crit} > 700$ for entire ring

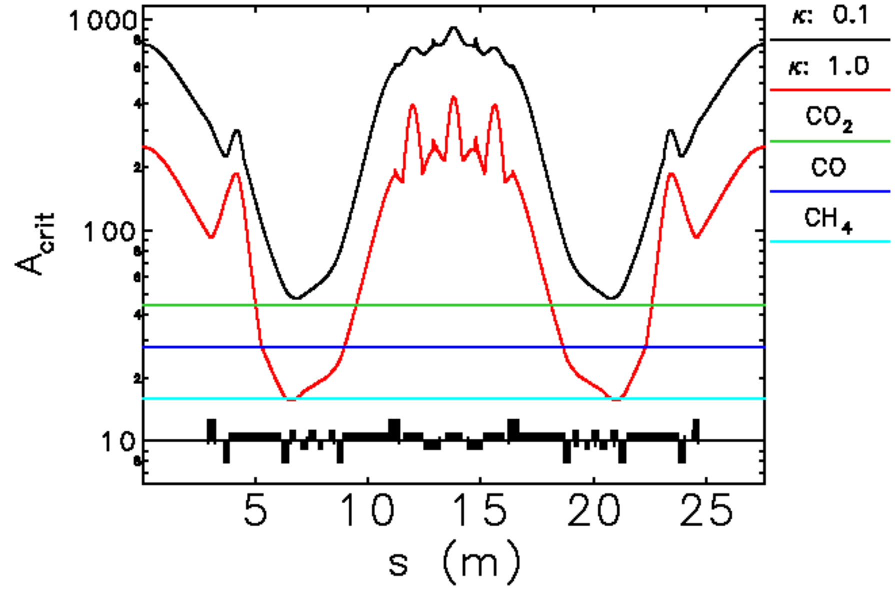
$$A_{x,y} = \frac{N_e r_p S_b}{2(\sigma_x + \sigma_y)\sigma_{x,y}}.$$

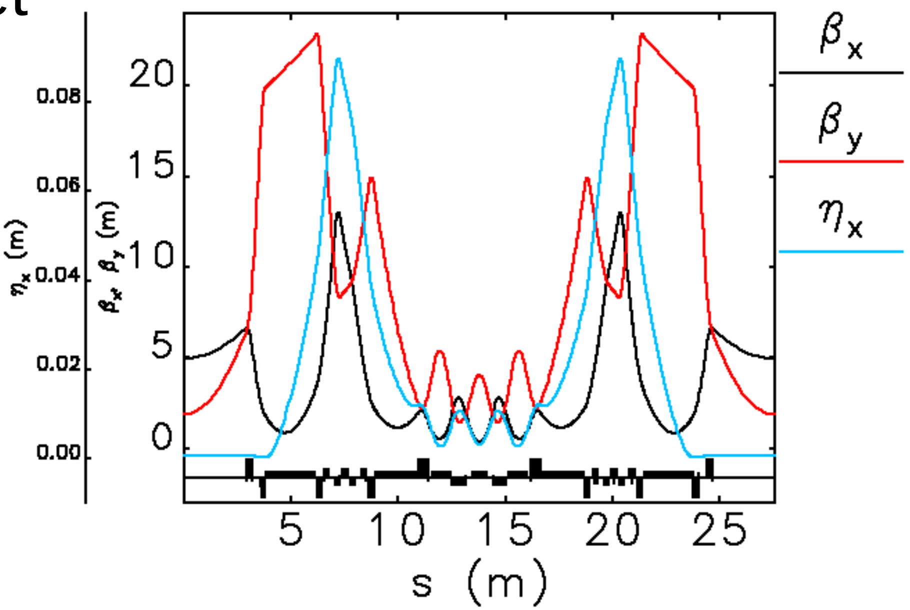
$N_e \equiv$ bunch population
$r_p \equiv 1.5 \times 10^{-18}$ m
$S_b \equiv$ bunch spacing
$\sigma_x, \sigma_y \equiv$ beam size

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

Trapping Locations

- 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, in particular where the dispersion is high
  - Unfortunately, this is also where the pressure is highest
- For flat beams (κ = 0.1), no trapping is expected





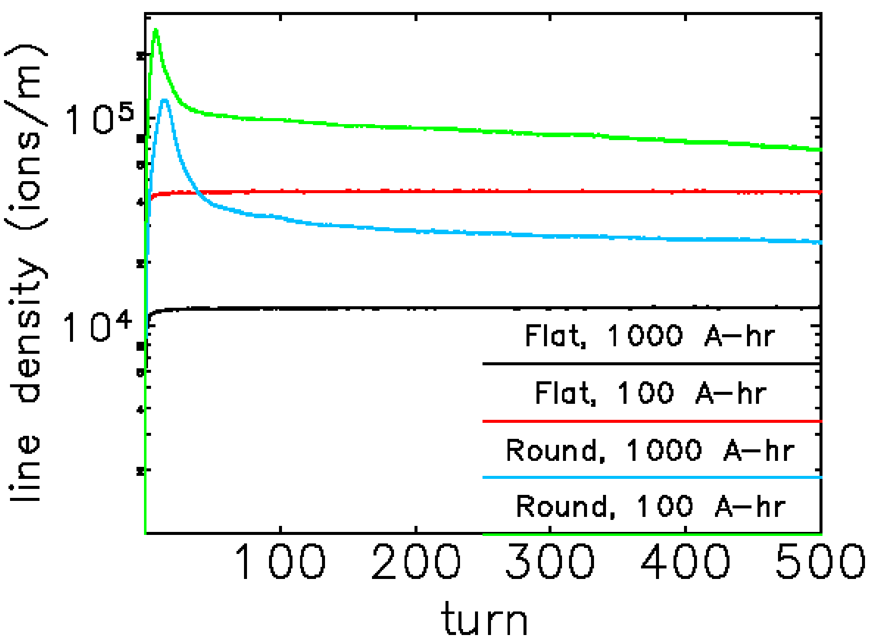
Instability Simulation

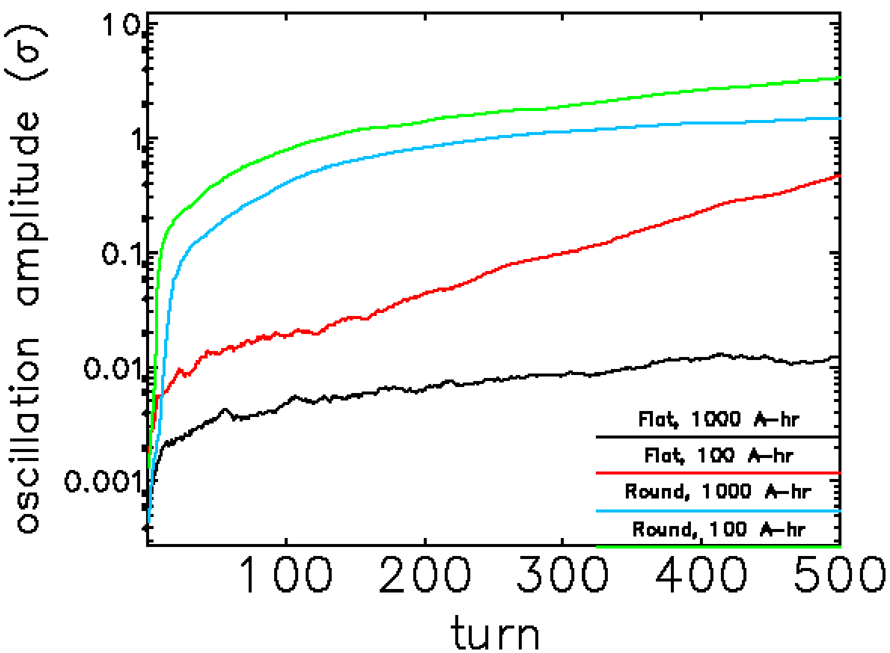
- Ion instability code developed at SLAC [1]
  - Ions are modeled using macroparticles, tracked under influence of beam field
  - Beam is rigid (only centroid motion allowed) with assumed Gaussian field
- Simulation parameters:
  - Realistic lattice (twiss parameters, dispersion)
  - Multiple interaction points around ring (~800 for APS-U)
  - Includes radiation damping (but not coherent damping or feedback)
  - Incorporate realistic pressure profiles generated by vacuum simulation codes
- Benchmarked against tune shift measurements in APS Particle Accumulator Ring [2]

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

Simulation Results (324 bunches, 200 mA)

- Left plot shows the simulated ion density vs time for round beams (emittance ratio = 1.0) and flat beams (emittance ratio = 0.1), and for 1000 A-hr and 100 A-hr beam conditioning
- No trapping is observed for the flat beam cases (i.e., the ion density does not increase with time)
- Ions are trapped in the round beam case.
- Trapped ions in the round beam case do lead to an instability, even after 1000 A-hrs of conditioning.
  - 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

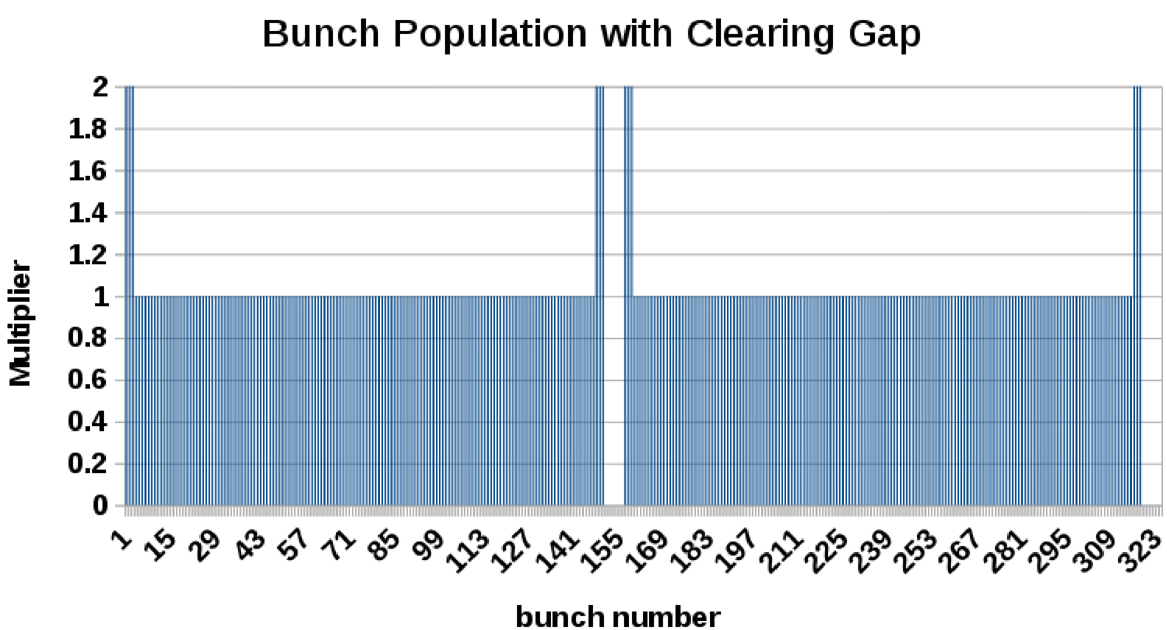




Train Gaps

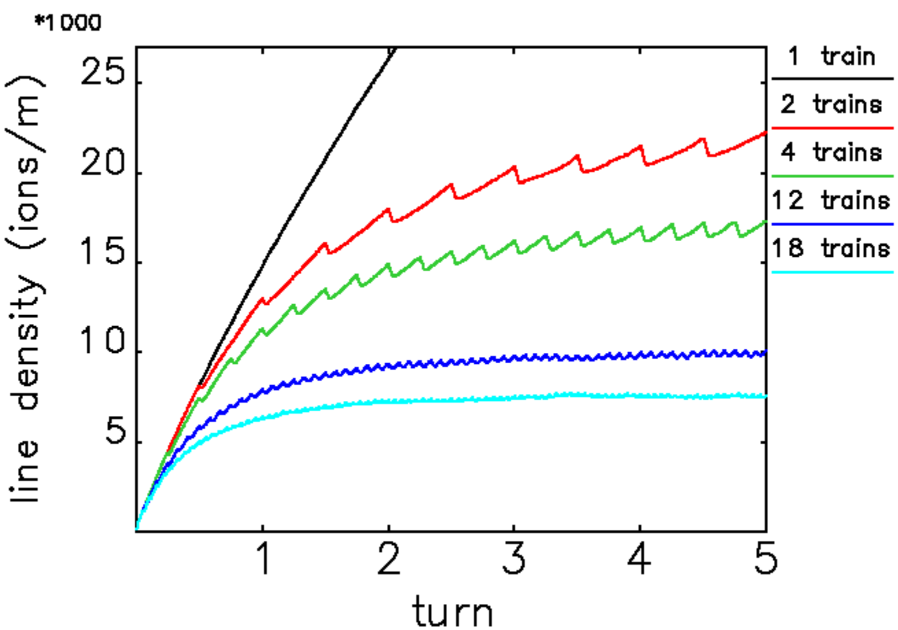
- Use gaps between bunch trains, to allow the ions to clear out [1].
- To minimize transients in the RF system, distribute the missing charge to the bunches adjacent to the gaps.
  - Simulations by M. Borland have shown that the impact of this arrangement on the RF system should be relatively modest
  - High charge bunches before the gap will provide a stronger kick to the ions
  - Downside: high charge bunches have shorter lifetime
- Example: 2 trains with a 6 bunch gap; 3 bunches before and after gap have double charge

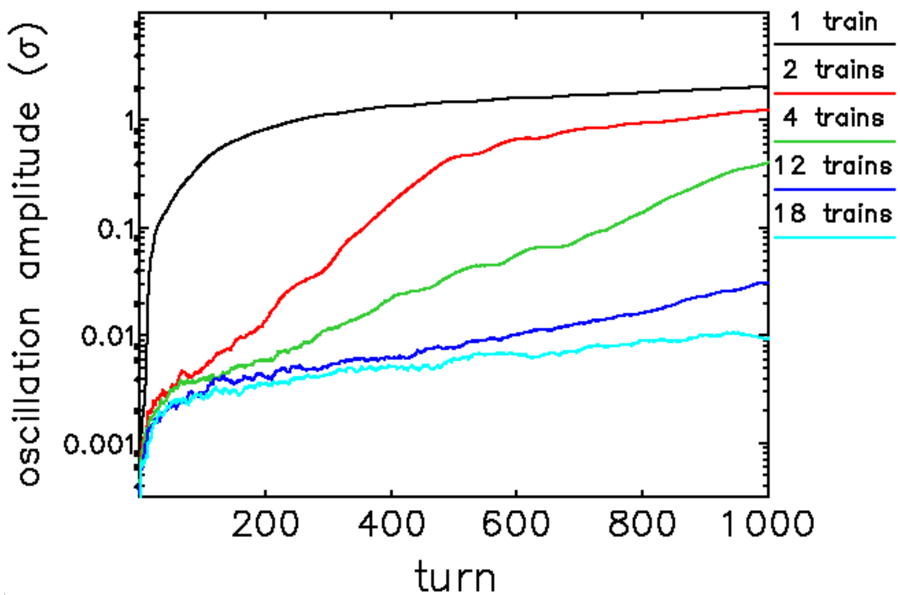
1: D. Villevald and S. Heifets, SLAC-TN-06-032 (1993).



Train Gap Comparison: 1000 A-hr

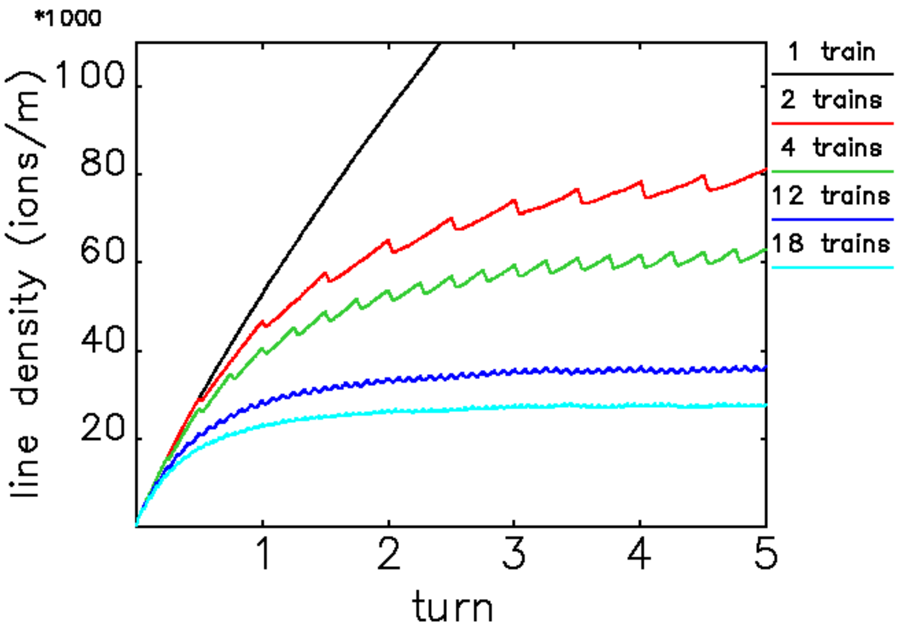
- Modified ion simulation code to test this scheme
- Results not sensitive to the number of bunches in the gap
  - Even a two bunch gap is effective at clearing out the ions (minimum A_{crit} is 76).
- Plots compare ion density and growth rate for different numbers of trains
  - Two bunch gap, one double-charge bunch before and after the gap
  - With two trains, peak ion density is reduced by more than an order of magnitude
  - Using more trains further reduces the density.
- The instability growth rate is also significantly reduced with two trains
  - Growth rate is further reduced with more trains; with 18 trains it is essentially zero.

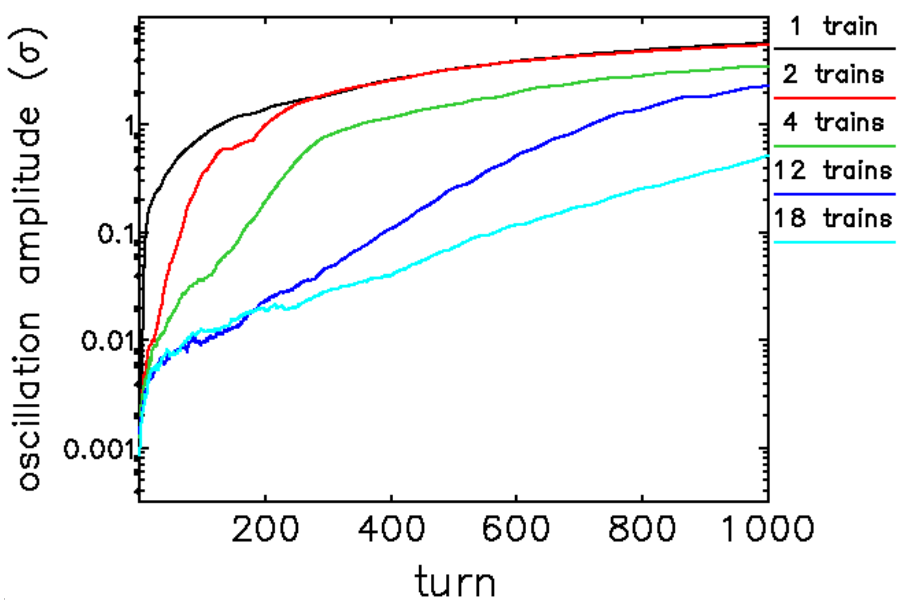




Train Gap Comparison: 100 A-hr

- Modified ion simulation code to test this scheme
- Results not sensitive to the number of bunches in the gap
  - Even a two bunch gap is effective at clearing out the ions (minimum A_{crit} is 76).
- Plots compare ion density and growth rate for different numbers of trains
  - Two bunch gap, one double-charge bunch before and after the gap
  - With two trains, peak ion density is reduced by more than an order of magnitude
  - Using more trains further reduces the density.
- Growth rates are much higher at 100 A-hr
  - Still noticeable growth with 18 trains





Growth Rate Comparison

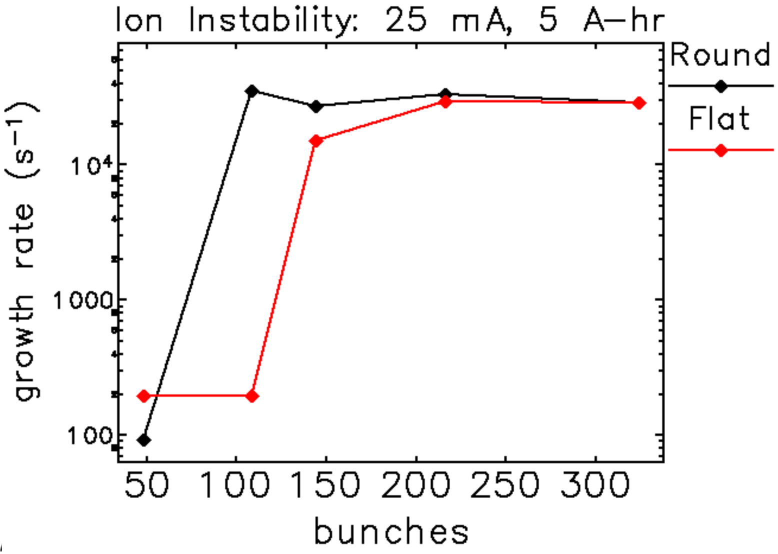
- Instability growth rates (defined in exponential growth region, before saturation) can be compared with expected coherent damping rate (6800/sec) and feedback damping (10000/sec)
- As long as at least two trains (or flat beams) are used, beam should theoretically be stable
- Caveats: feedback damping rate is not precisely known, coherent damping (due to momentum spread) is not exponential
  - Emittance growth is possible even when instability is damped
- Still, if the growth rate is << 10000/sec, coherent instability should be effectively damped

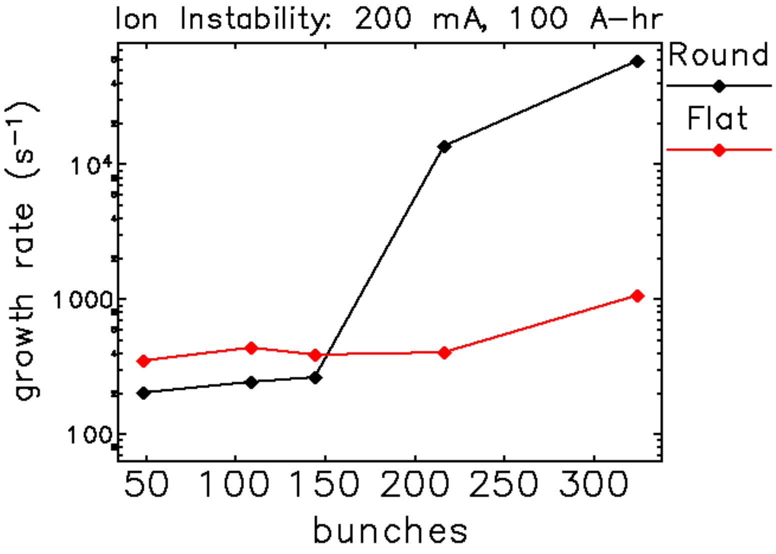
Growth rates (1/sec)

Trains:	1	2	4	12	18	Flat
100 A-hr	75000	6200	2000	890	510	1000
1000 A-hr	43000	1400	650	310	140	320

Commissioning and Early Operation

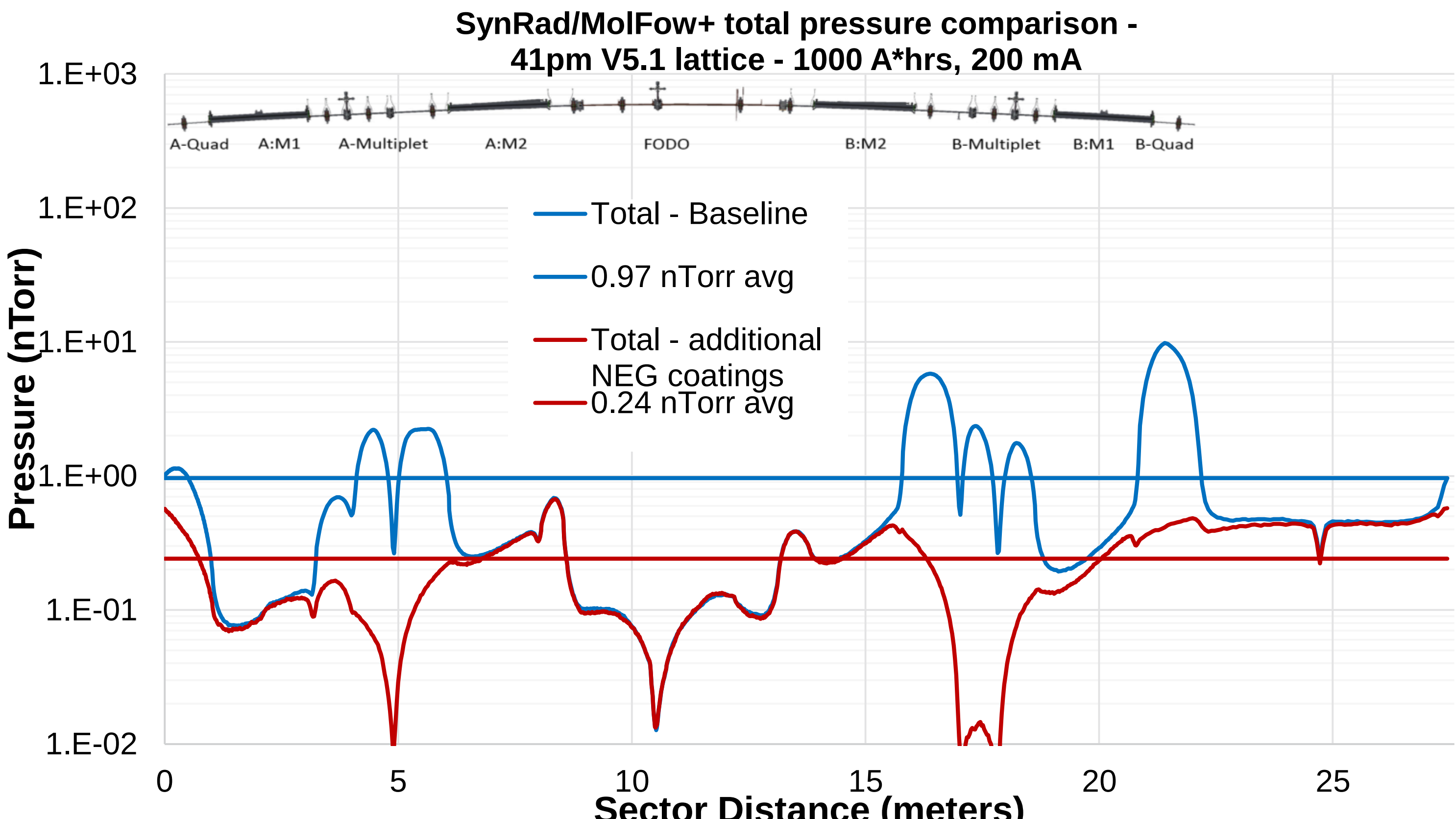
- During the ramp up to full current, APS-U can be operated with a relatively small number of equally spaced bunches, so ions should not be trapped
- Left plot: growth rates for 25 mA, 5 A-hr
  - Below the ion trapping threshold (108 bunches for round beams, or 144 bunches for flat beams), the instability growth rate is very low
- As the vacuum chamber conditions, we can increase the number of bunches and bunch charge while staying below the threshold of ion instability.
- Right plot: 100 A-hr and 200 mA
  - Instability growth rate for round beams is low for 144 (or fewer) bunches.
  - Around this time we can transition to 324 bunch mode, with train gaps or flat beams





Additional NEG Coating

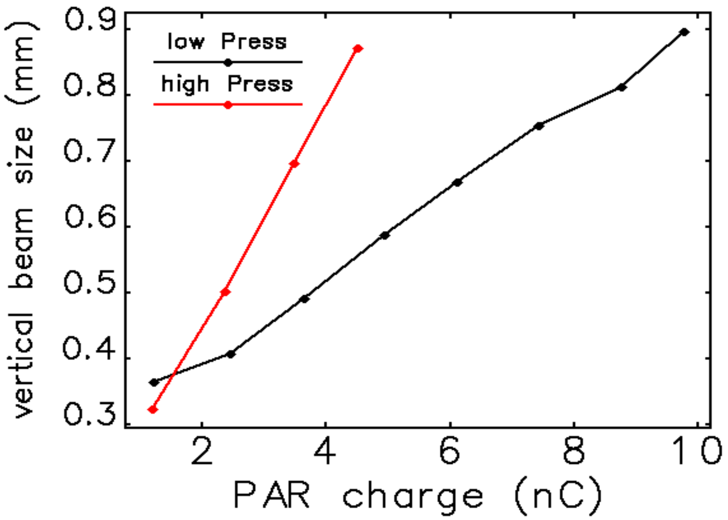
- NEG coating the entire ring would reduce average pressure by a factor of ~4
- Effect is even more significant in the multiplets, where ions are trapped
- Expect this to greatly suppress ion instability (simulations are underway)
- Also helpful for gas scattering lifetime



Emittance Growth

- Trapped ions can also cause emittance growth
  - Observed in the PAR
  - A concern for the upgrade, since significant emittance growth will change the trapping criteria
- SLAC ion code assumes a rigid beam, so it can't model this
- Ion effects are presently being incorporated into elegant
  - 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

Measured PAR Vertical Beam Size



Summary

- Realistic pressure profiles are important for both gas scattering and ion trapping calculations
- Expected gas scattering lifetime for present APS-U design is shorter than desired, though still longer than Touschek lifetime
- Ions will be trapped primarily in the mulitplets
- Ion instability can be suppressed by running with multiple bunch trains (with missing charge distributed to adjacent bunches) or flat beams
- During early operation we plan to run with low charge and few bunches, slowly increasing both while staying below the ion trapping threshold
- Additional NEG coating (especially in the multiplets) should significantly reduce ion effects and improve gas scattering lifetime
- Possibility of emittance growth will be investigated using IONEFFECTS element in elegant

Thanks for your attention!

- Thanks also to:
- M. Borland, for providing material on gas scattering
- J. Carter, for generating pressure profiles
- B. Stillwell, R. Lindberg, K. Harkay, CY Yao, U. Wienands, J. Byrd, A. Blednykh (BNL), R. Nagaoka (SOLEIL) for helpful discussions