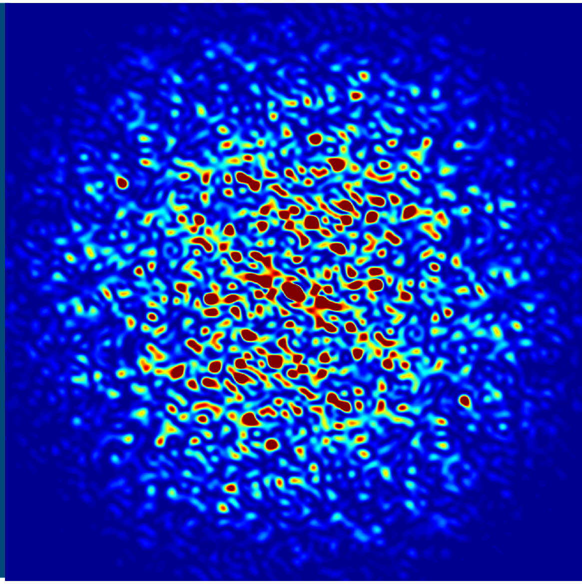
Ion Instabilities in Low Emittance Storage Rings



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Outline

- Introduction
- Coherent instability simulations
- Compensated gap scheme for APS-U
- Modeling incoherent effects with the `IONEFFECTS` element
  - Features and capabilities
  - Effects: multiple ionization, impedance, charge variation
  - Simulations for the present APS
- Gas injection experiment
  - Design and operation
  - Results for different bunch patterns and injection locations
  - Simulations with different ion-beam kick methods
- APS-U simulations with `IONEFFECTS`

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].
  - Fast initial growth rate, slows as instability starts to shake out the ions.
  - Amplitude tends to saturate around one beam sigma.
- Trapped ions can also cause incoherent effects, such as emittance growth and tune spread. These are generally less well understood than coherent instability.

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

History

- "Conventional" ion instability- ions build up over many turns
  - Observed at CERN ISR[1], SPS[2], CERN antiproton accumulator[3], Fermilab antiproton accumulator[4], CESR[5]
  - Mitigations include clearing electrodes, bunch shaking, and clearing gaps[6]
- "Fast" ion instability[7,8]- builds up over single bunch train
  - Studied with gas injection experiments[9,10,11,12]
  - Observed at SOLEIL[13], SPEAR3[14], PAL[15], KEK-B[16]
  - Slower growth rate than conventional instability, can be controlled by feedback
- Renewed interest for next generation light sources
  - High current, low emittance → fast growth rate
  - Very sensitive to instability or emittance dilution
  - Observed at ESRF-EBS: coupled bunch instability correlated with vacuum bursts

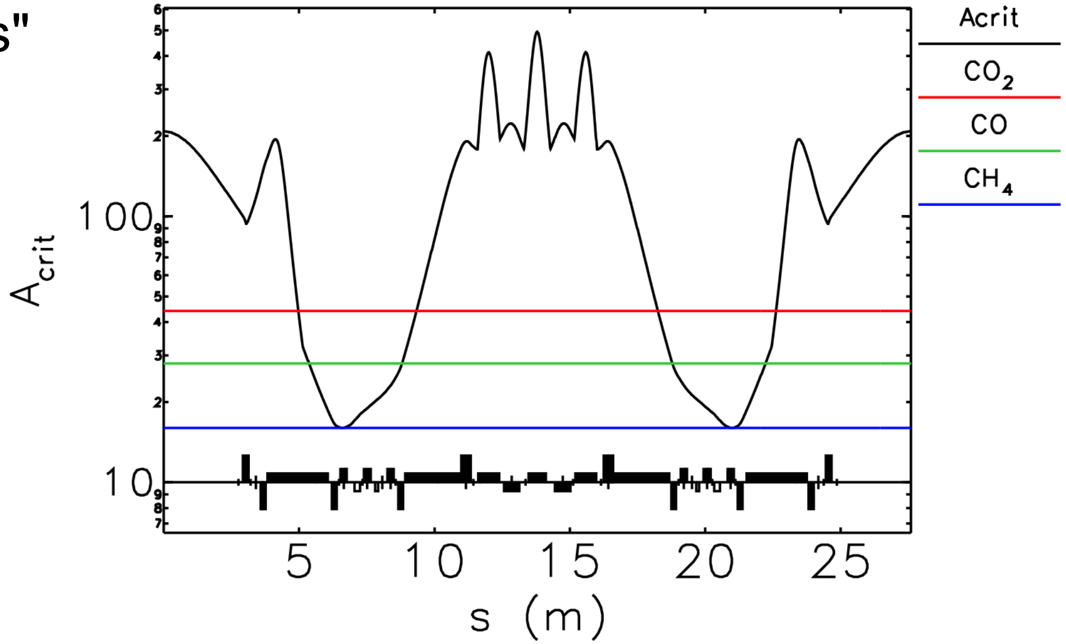
[1] H.G. Hereward, CERN-71-15 (1971).
[2] Y. Baconier, G. Brianty, CERN/SPS/80-2 (DI), 1980.
[3] H. Pires, PAC 1989, pp. 800-802.
[4] S. Werkema et al., PAC 1993, pp. 3573-3575.
[5] D. Sagan and A. Temnykh, NIMA 344, pp. 459-469 (1994).
[6] D. Villevald & S. Heifets, SLAC-TN-06-032 (1993).
[7] T.O. Raubenheimer. F. Zimmermann, PRE 52, 5487 (1995).
[8] G.V. Stupakov et al., PRE 52, 5499 (1995).
[9] J. Byrd et al., PRL 79, No. 1 (1997).
[10] M. Kwon et al., PRE 57, 6016 (1998).
[11] J. C. Lee et al., PAC 1999, pp 1605-1607
[12] A. Chatterjee et al., IPAC 2014, pp 1638-1640.
[13] R. Nagaoka et al., IPAC10, pp. 1985-1987 (2010).
[14] L. Wang et al., PRST-AB 16, 104402 (2013).
[15] J. Huang et al., PRL 81, 4388 (1998).
[16] K. Ohmi, PRE 55, No. 6,7550 (1997).

Ion trapping criterion

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

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

- Trapping criterion is given by the 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
- Basic parameters for APS-U operating modes are shown in table (assuming full coupling)
- No trapping is expected for 48 bunch mode
  - (A_{crit} > 700 for entire ring)
  - Next slides assume 324 bunches, where trapping is expected in the multiplets

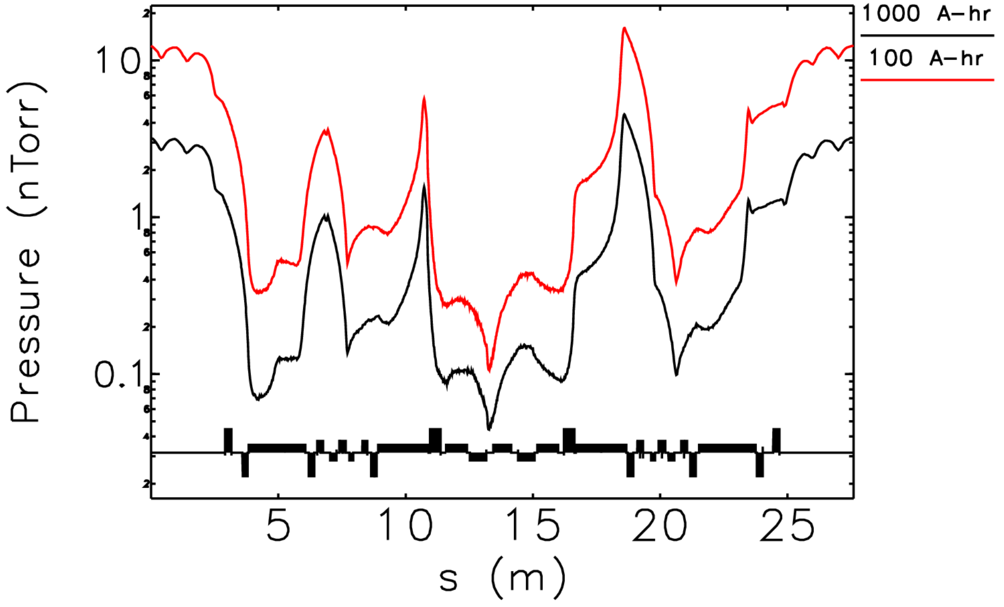


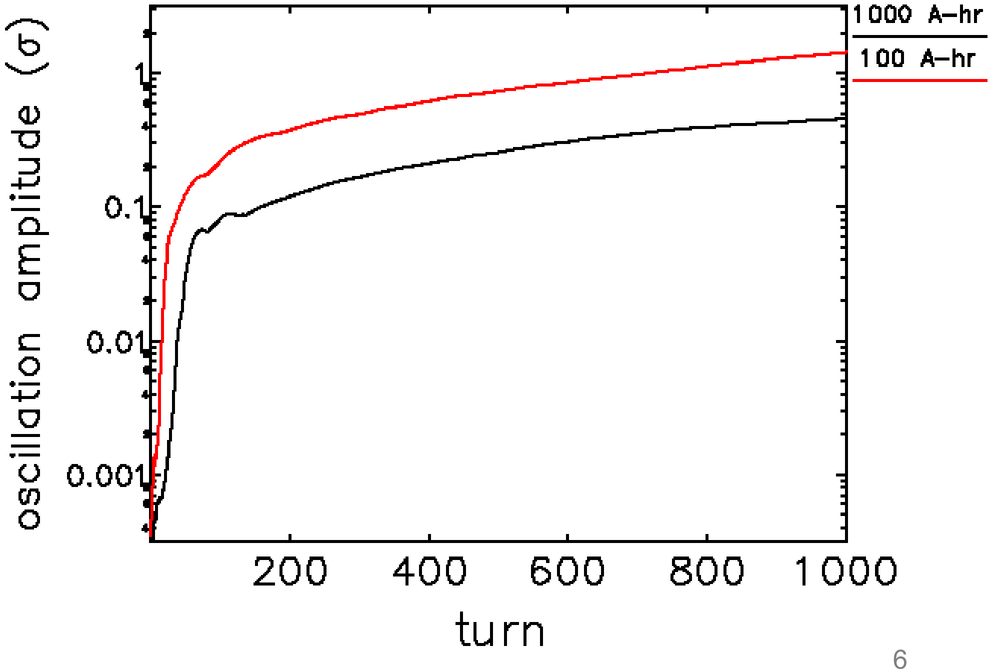
Quantity	48 Bunch	324 Bunch
Beam energy	6 GeV	
Beam current	200 mA	
Horizontal emittance	30 pm	
Vertical emittance	30 pm	
Bunch spacing	77 ns	11 ns
Bunch charge	15.4 nC	2.2 nC

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

Coherent instability simulations

- We use an ion instability code developed at SLAC[1]
  - Ions are modeled using many macroparticles
  - Bunch is a single macroparticle (only centroid motion allowed) with assumed Gaussian field
  - Sometimes called “weak-strong” code
  - Benchmarked with ion-induced tune shift measurements in APS Particle Accumulator Ring[2]
- Incorporates realistic pressure profiles generated by CERN codes SynRad+[3] and MolFlow+[4]
- Plots compare APS-U results for 100 A-hr (early operation) and 1000 A-hr (~1 year) pressure profiles
- Both show very fast initial growth, saturation at around 10% beam sigma (as beam motion shakes out ions)
- 100 A-hr case shows higher instability growth rate





[1] L. Wang et al. PRSTAB 14-084401 (2011).
[2] J. Calvey et al., Proc. NAPAC16, THPOA14. (2016)
[3] R. Kersevan. Proc. PAC 1993, p. 3848.
[4] M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.

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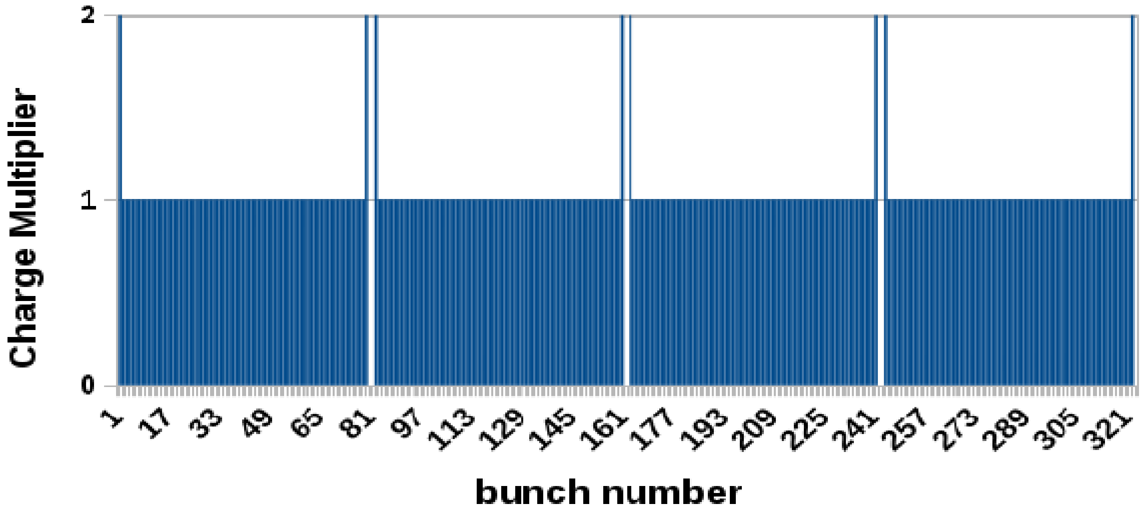
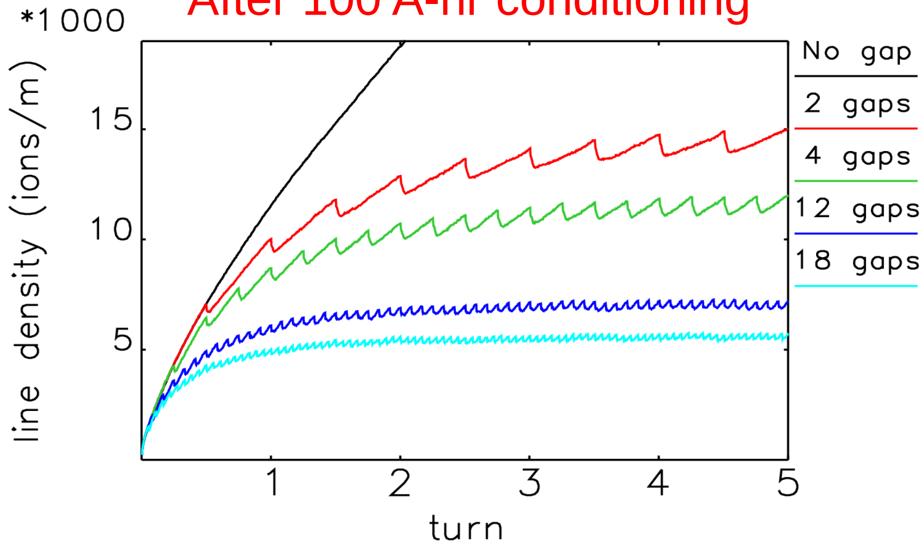
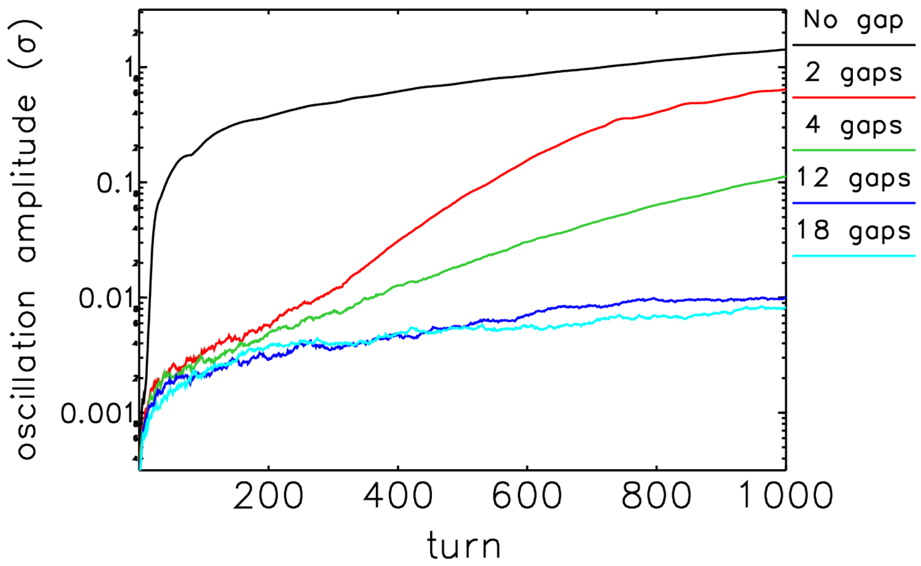
Compensated gaps can control the ion instability[1]

- Gaps between bunch trains will introduce time for ions to escape[2,3]
- We minimize transients in the RF system by distributing the missing charge to the bunches adjacent to the gaps ("guard bunches")
  - High charge bunches before the gap will also provide a stronger kick to the ions
  - Simulations show modest impact on bunch distribution and Touschek lifetime, no impact on MBI growth rates
- Ion simulations show that even 2 gaps of 2 bunches each reduces trapping and instability, 12 gaps eliminates it (100 A-hr case)
- 1000 A-hr case only needed 2 gaps



After 100 A-hr conditioning





[1] J. Calvey and M. Borland, PRAB 22, 114403 (2019).
[2] M. Barton, NIMA 243, 278 (1986).
[3] D. Villevald and S. Heifets, SLAC-TN-06-032 (1993).

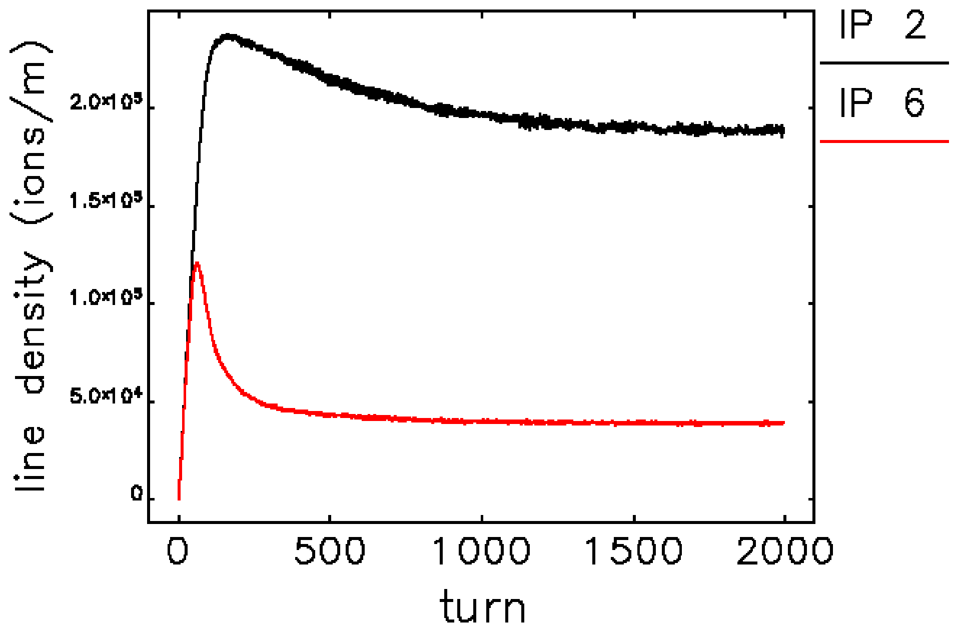
Modeling incoherent ion effects

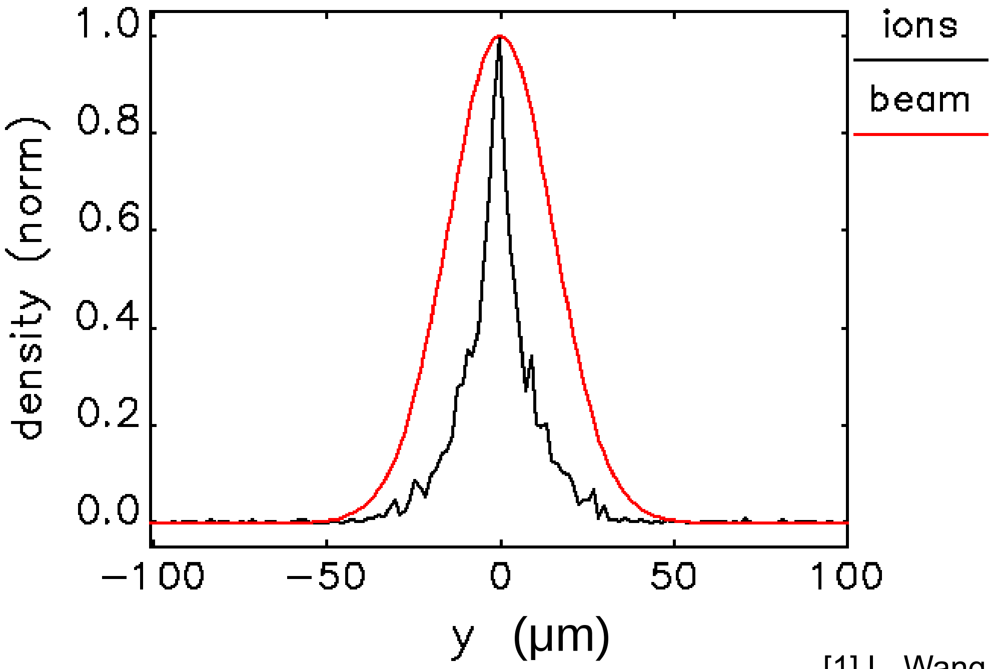
- Emittance growth is possible, even if coherent instability is damped
- Potentially dangerous scenario: emittance blowup → more trapping → more blowup
- Need a "strong-strong" code: model both beam and ions with macroparticles[1,2,3]
  - Very computationally intensive
- Our approach: incorporate an `IONEFFECTS` element into particle tracking code `elegant`[4]
  - Massively parallelized: ~100x faster with ~200 cores
  - Beam is already modeled with macroparticles
  - Study interaction of ion effects with other elements, e.g. feedback[5], impedance
- Inputs: location of ion elements, pressure profiles, ion properties, arbitrary bunch pattern
- An `IONEFFECTS` element simulates ion generation, ion motion between bunches, beam/ion kicks
  - Kick from beam to ions derived from Bassetti- Erskine formula[6] (assumes Gaussian beam)
  - Kick from ions to beam can also use this method, though other options exist
- Includes multiple ionization[7]: Ions have a chance of being multiply ionized or dissociating and becoming untrapped (e.g. $CO_2^+ \rightarrow CO_2^{2+}$, $CO_2^+ \rightarrow C^+ + O_2$, etc.)

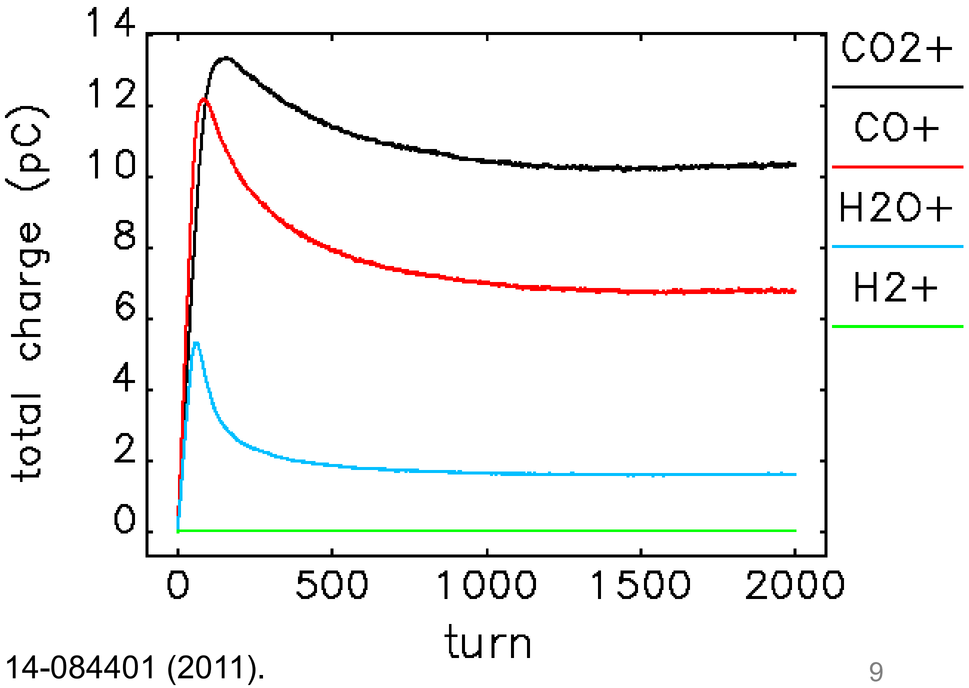
[1] K. Ohmi et al., KEK report 96-73 (1996).
[2] G. Rumolo and D. Schulte, EPAC08, pp. 655-657 (2008).
[3] C. Li et al., PRAB 23, 074401 (2020).
[4] M. Borland. ANL/APS LS-287, (2000).
[5] R. Nagaoka et al., IPAC 2011, pp. 712-714 (2011).
[6] M. Bassetti, G. Erskine, CERN ISR TH/80-06 (1980).
[7] P.F. Tavares, Particle Accelerators Vol. 43, pp. 107-131 (1993).

Example output: ions

- Present APS: 324 bunches, 100 mA, 7 GeV, 0.5 nTorr
- Ion density can be broken down by interaction point (IP) or ion species
  - IP6 has higher Acrit than IP2
  - H_2^+ not trapped, CO_2^+ dominates
- Ion histogram shows peaked distribution (expected[1])







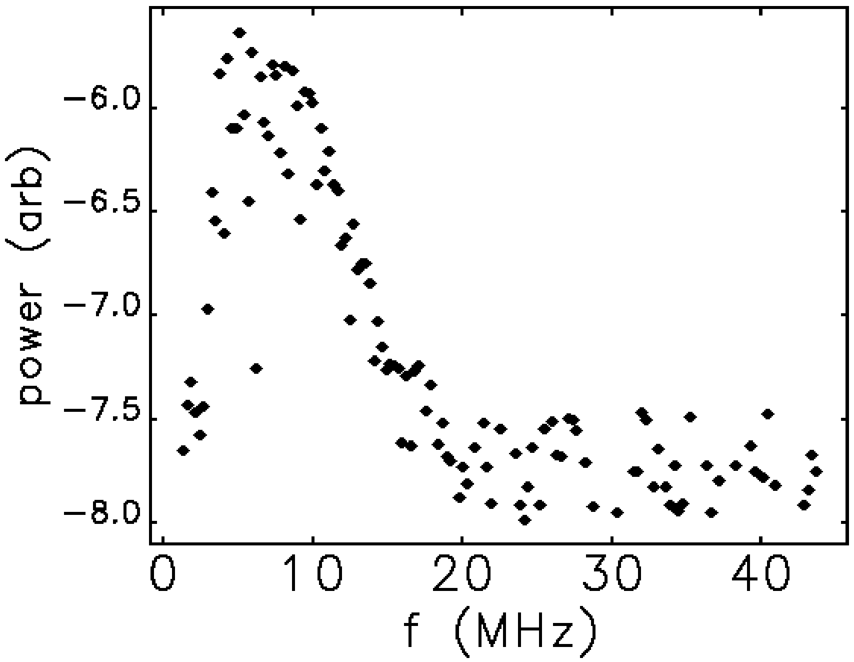
[1] L. Wang et al. PRSTAB 14-084401 (2011).

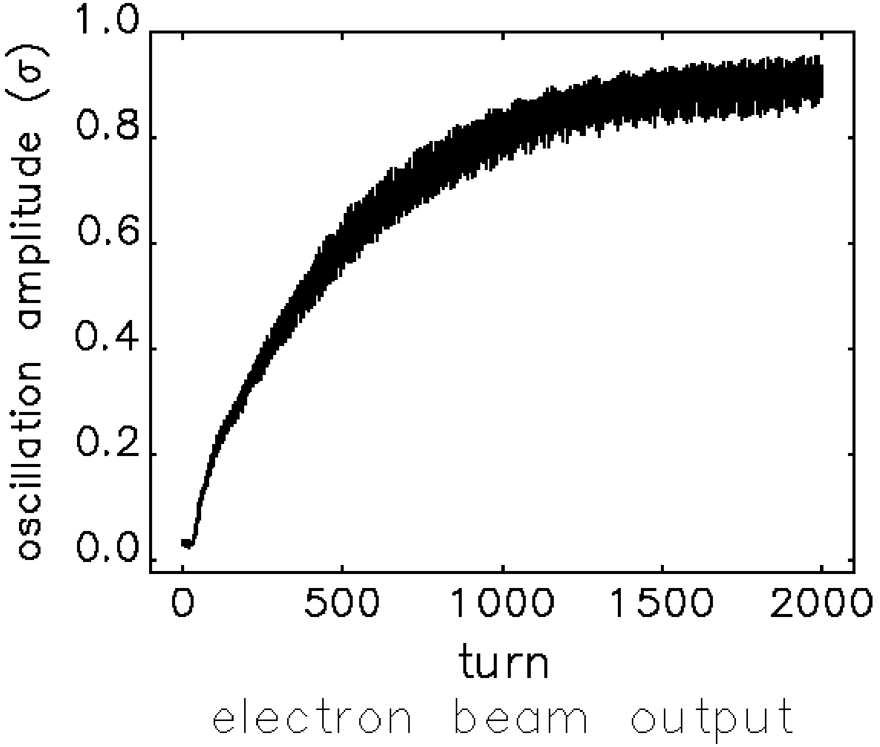
Example output: beam

- Instability amplitude saturates ~0.9 sigma
- Beam spectrum shows peaks in lower vertical betatron sidebands near characteristic ion frequency[1] (~7 MHz for CO_2)

[1] L. Wang et al. PRSTAB 14-084401 (2011).

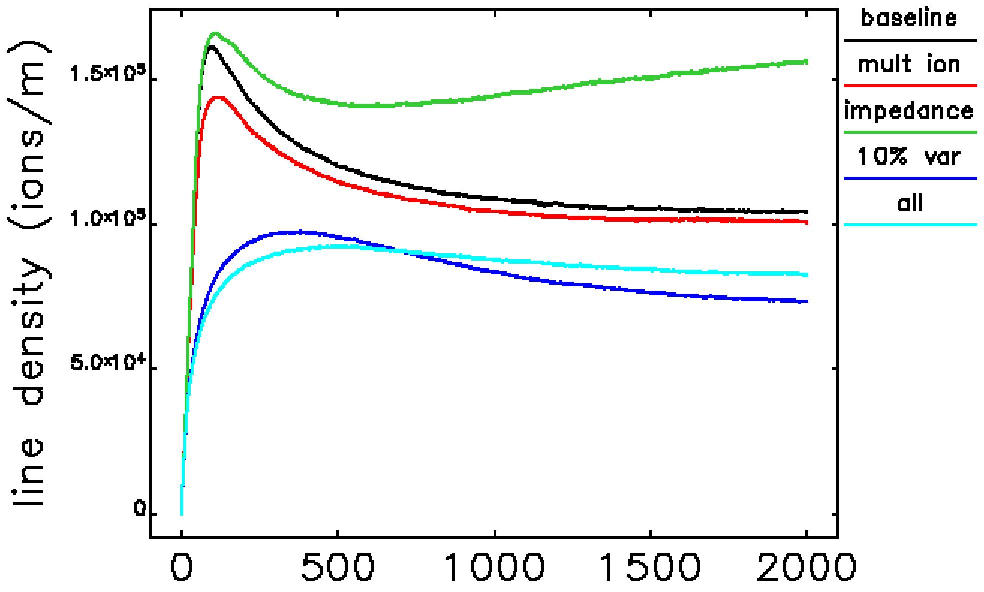
$$\omega_{i,y} \approx c \left(\frac{4 N_e r_p Q}{3 A S_b (\sigma_x + \sigma_y) \sigma_y} \right)^{1/2}$$

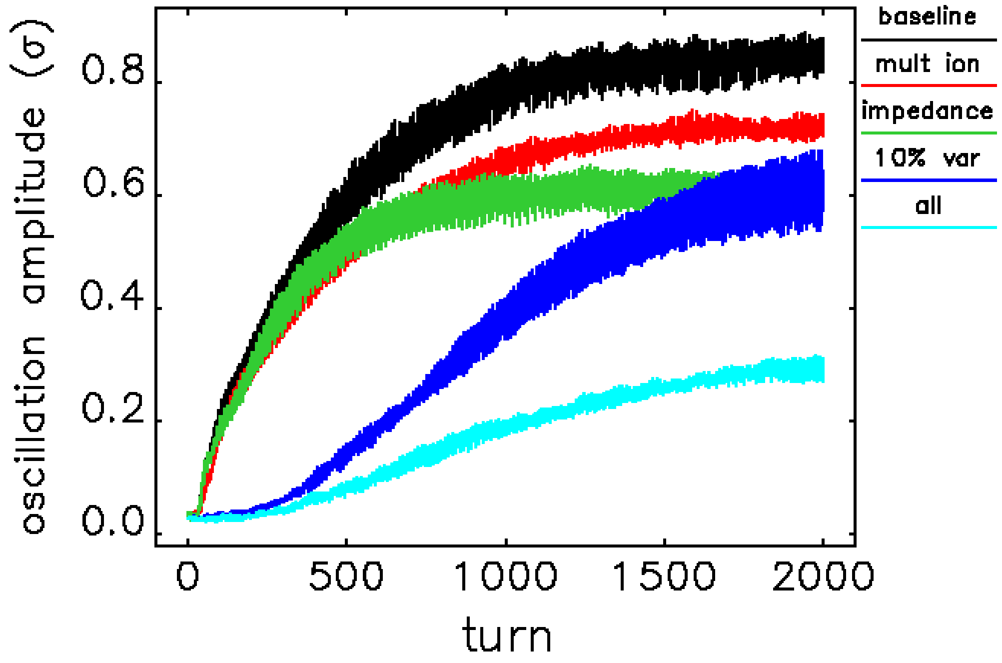




Simulations for the present APS

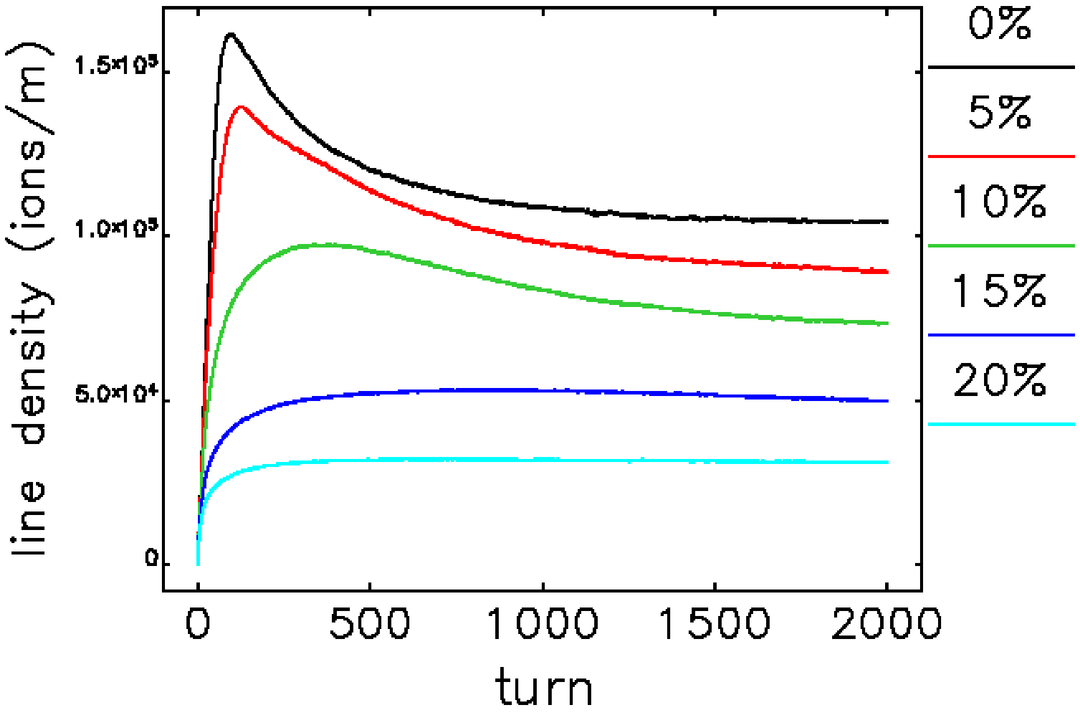
- Motivations:
  - Understand why ion instability is not observed in present APS, as predicted by theory and weak-strong simulations
  - Help validate `IONEFFECTS` code
- 324 bunches, 100 mA, 7 GeV, 0.5 nTorr
- Adding important effects one at a time
  - Black: baseline simulation
  - Red: include multiple ionization
  - Green: include transverse impedance (head-tail damping)
  - Blue: include charge variation: ±10% rms
- Together, reduce amplitude by factor of 3

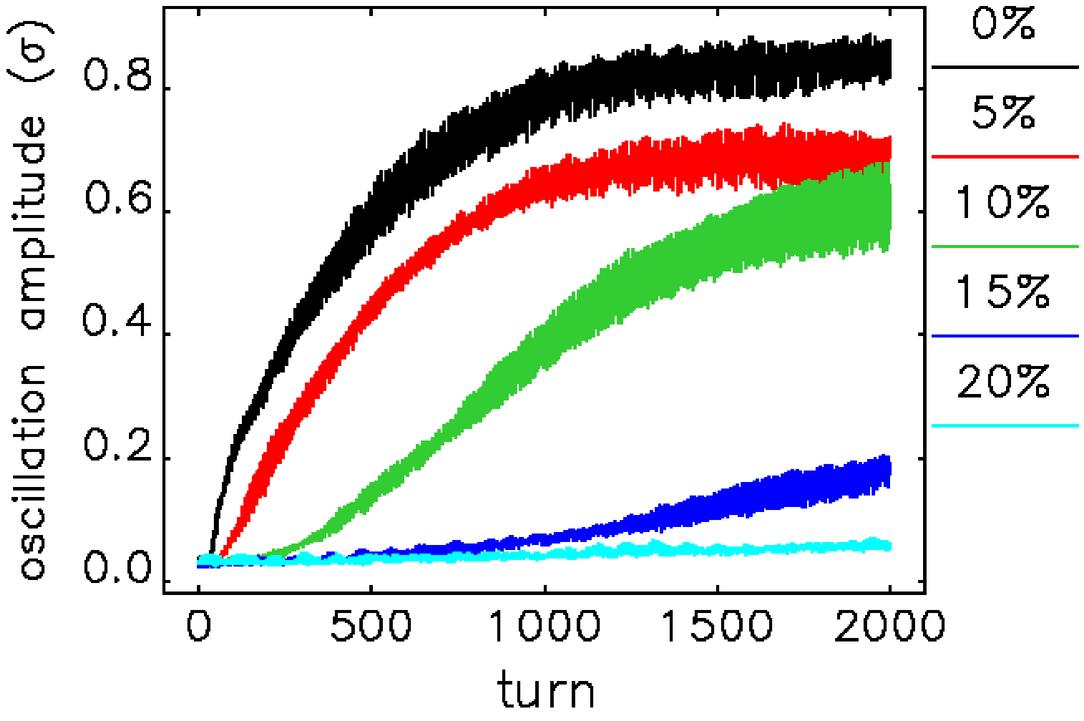




Charge variation

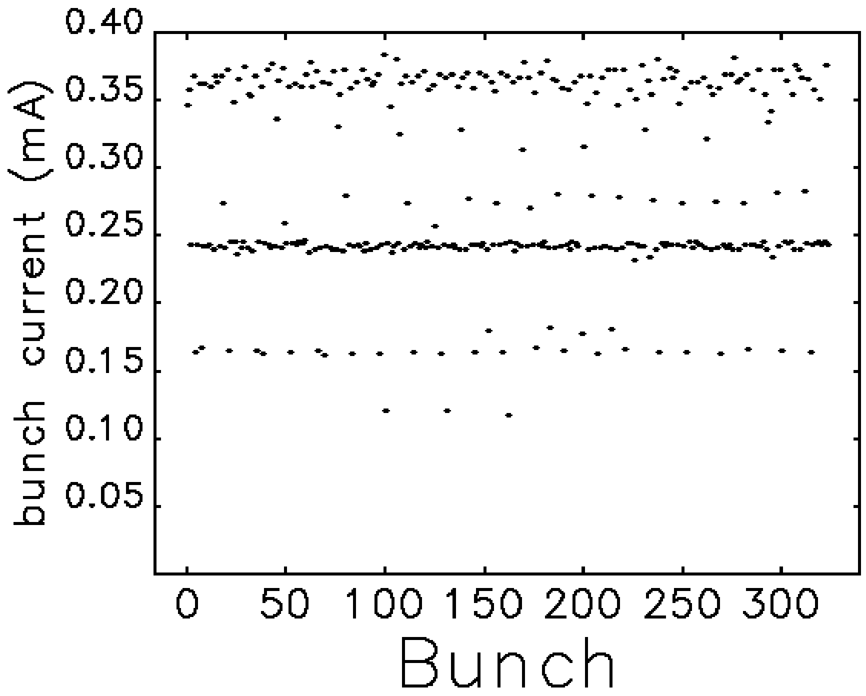
- Modify bunch charge following Gaussian distribution with given rms
- Significant effect on ion density and instability amplitude, especially for 15+% variation
- Uneven focusing modifies trapping criteria
- Suggests possible mitigation?

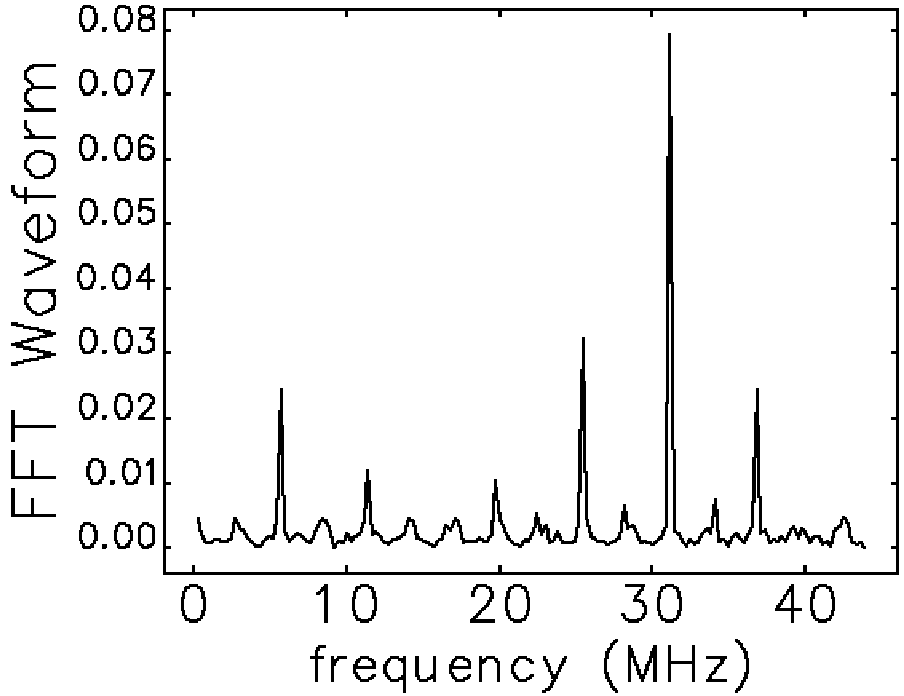




Using measured fill pattern

- Use measured bunch pattern during normal operations as input
- Very uneven due to “fill-on-fill” injection
- FFT of waveform shows peak at ~31 MHz (bunch rep rate 88 MHz)

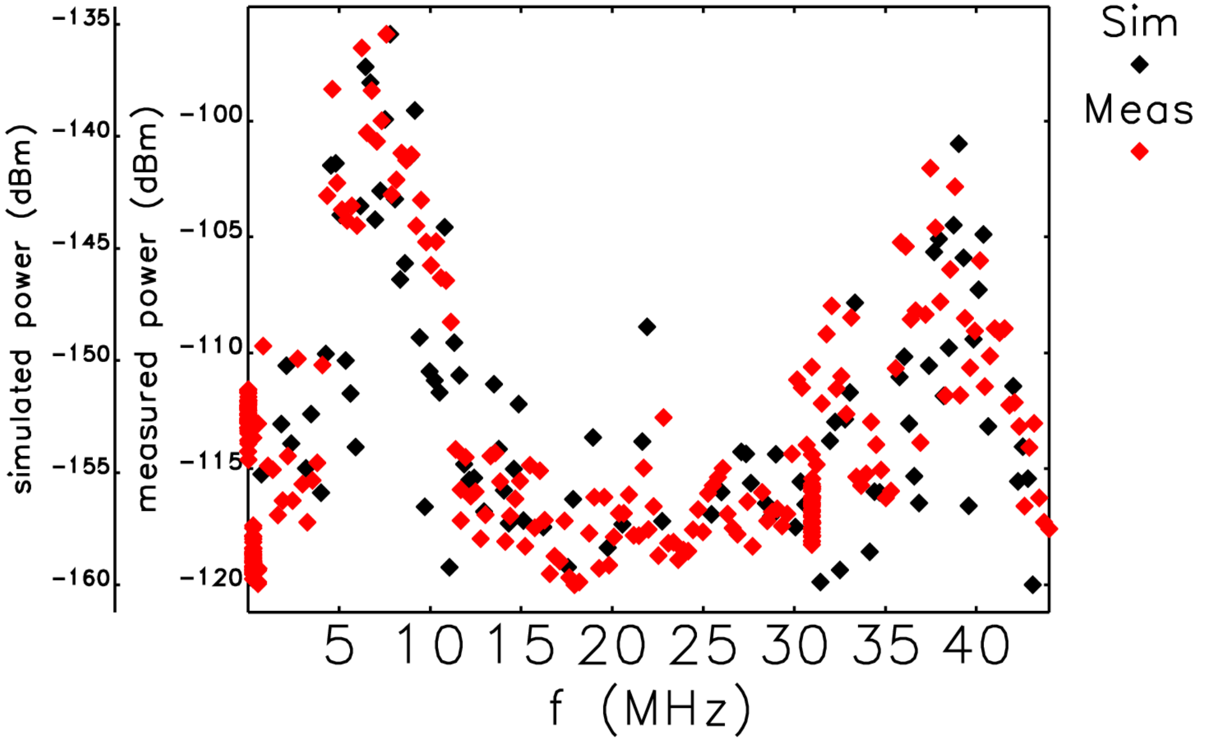




Agreement with measurement in normal conditions

- Instability observed as emittance growth and/or peaks in lower vertical betatron sidebands near characteristic ion frequency
- Ion peaks observed in measurement, simulation shows good agreement
  - First peak ~7 MHz (ion frequency for CO_2)
  - 2nd peak due to uneven bunch pattern at 7+31 = 38MHz (amplitude modulation)
- Simulation shows negligible (~0.3%) increase in observed vertical emittance (including oscillation)

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



Gas injection study[1]

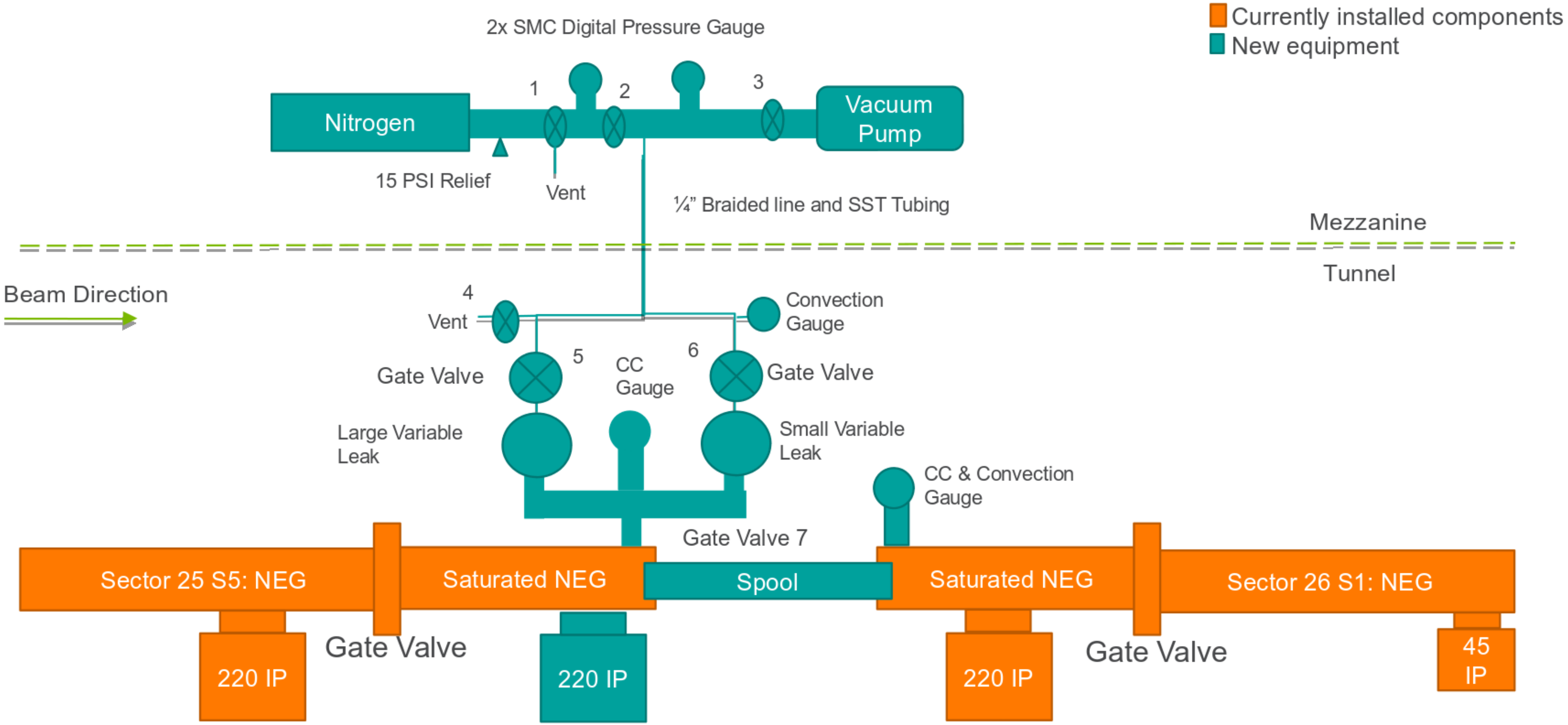
- Studies with artificially increased gas pressure have been performed at several machines[2,3,4,5]. Typically H_2 or a noble gas is filled around the ring.
- We decided to try a localized pressure bump:
  - Know beta functions at injection point, can vary them
  - Precisely know and control pressure
  - Use N_2 gas without contaminating whole ring
  - Use one of two pre-calibrated leaks- ~100 or ~900 nTorr
  - Pressure bump mostly confined to ~6-10 m section between ion pumps
- Measurements:
  - Beam spectrum (spectrum analyzer)
  - Beam emittance, lifetime (standard monitoring)
  - Unstable modes (Dimtel feedback system)[6]
  - Bremsstrahlung dose (calorimeter)[7]
- Installed at 2 locations: Sector 25 (S25) and Sector 35 (S35)

[1] J. Calvey et al., IBIC2020, pp. 258-262 (2020).
[2] J. Byrd et al., PRL 79, No. 1 (1997).
[3] M. Kwon et al., PRE 57, 6016 (1998).
[4] J. C. Lee et al., PAC 1999, pp 1605-1607
[5] A. Chatterjee et al., IPAC 2014, pp 1638-1640.
[6] S. Heifets and D. Teytelman, PRST-AB 8, 064402 (2005).
[7] J. Dooling et al., MOPAB044, IPAC21.

INSTALLATION CONFIGURATION

WITH 2 CALIBRATED VARIABLE LEAKS

J. Hoyt, T. Clute



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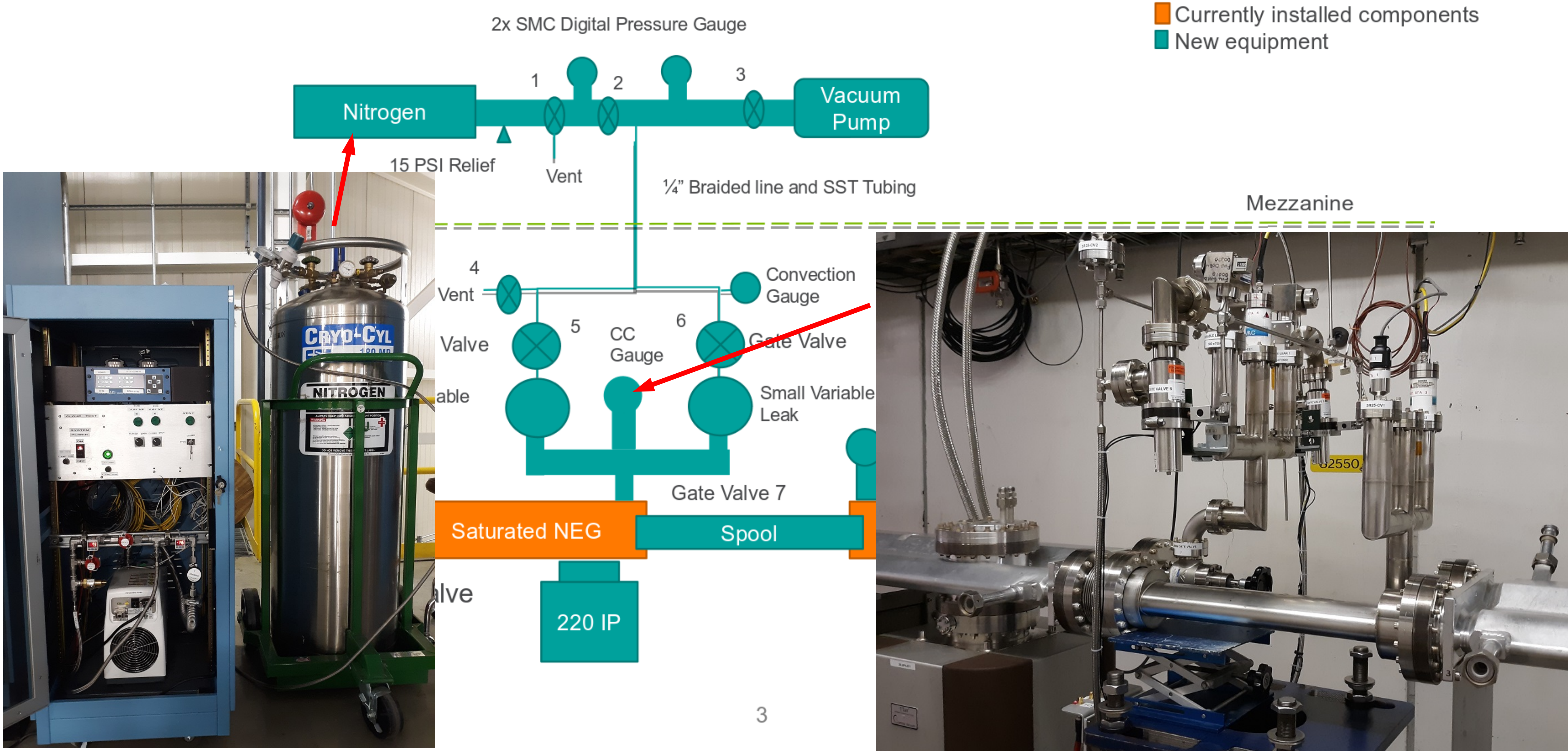
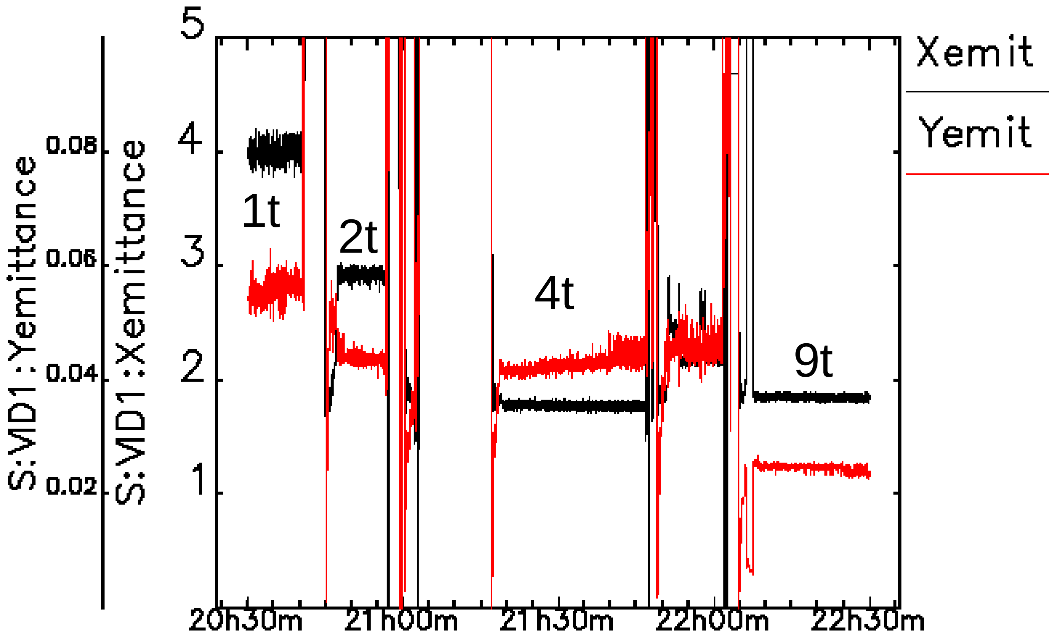
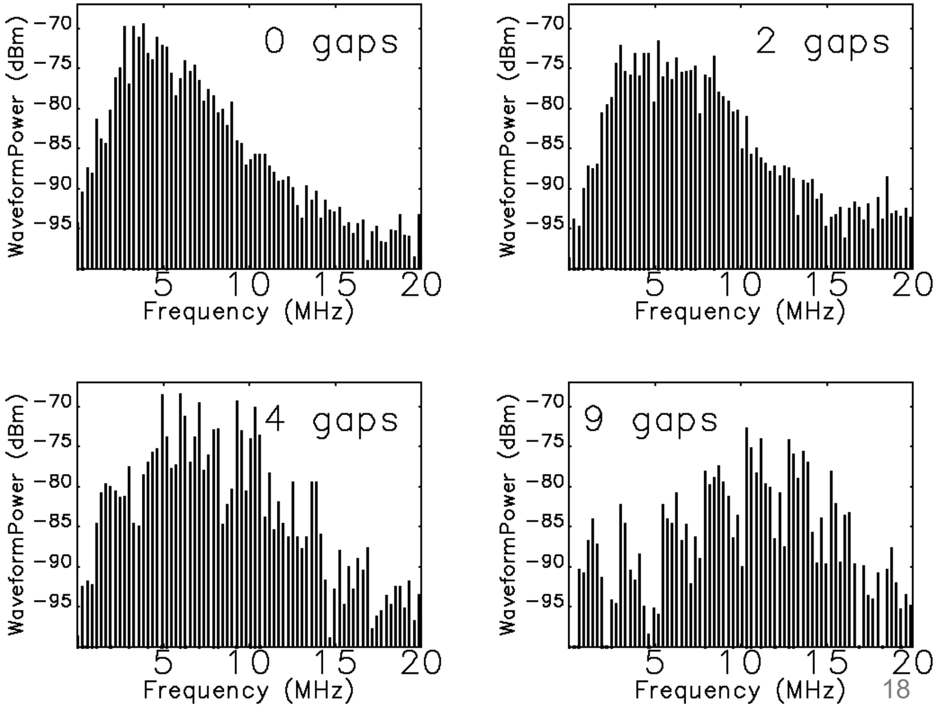


Example measurement: train comparison (S25)

- 6 GeV, 100 mA, 900 nTorr bump
- Increasing number of trains with gaps
- From theory, expected ion frequency for N_2 ~10 MHz
- Gaps are 12 bunches long- should be enough to clear out N_2 ions
- Large emittance blowup in both planes
  - Results in lower ion frequency (~4 MHz with no gaps)
- As more trains/gaps are used, vertical amplitude decreases, moves to higher frequency
  - Result of beam size deceasing
  - With 9 trains, vertical spectrum peak back at 10 MHz





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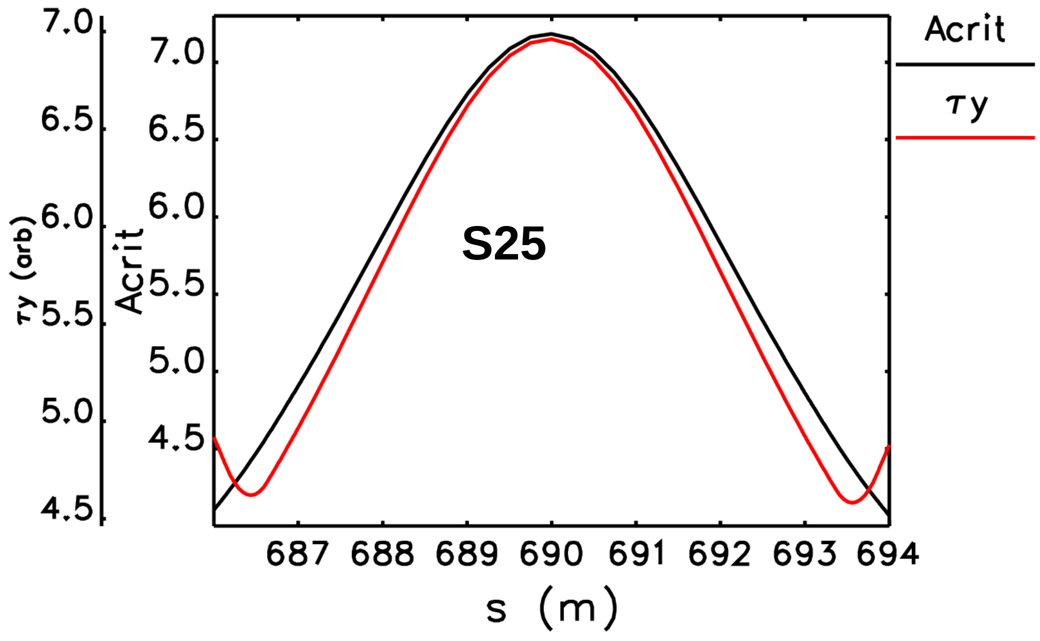
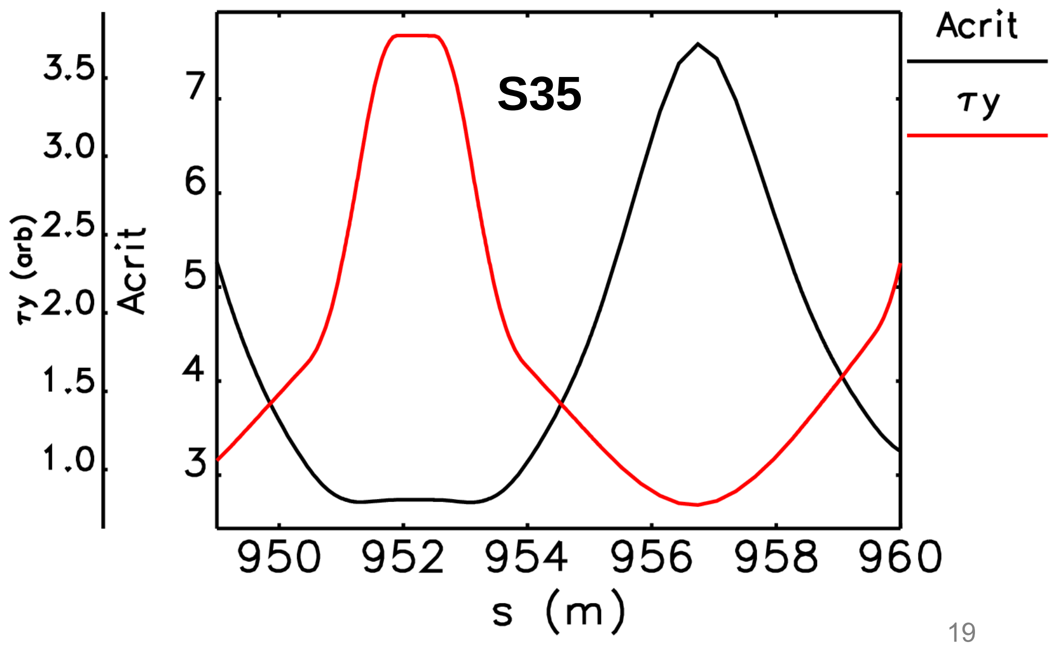
Comparison of S25 and S35

- Lattice functions very different at two locations
- Compare two parameters:
  - Critical mass[1]: lower A_{crit} → more trapping
  - Vertical growth time parameter: lower τ_y → faster initial growth
- S35 has lower A_{crit} and τ_y → stronger instability
- S25: two parameters highly correlated
- S35: anti-correlated: locations with the most trapping have the slowest initial growth

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

$$\tau_y \equiv 10^{10}\, \sigma_y(\sigma_x + \sigma_y)/\beta_y$$

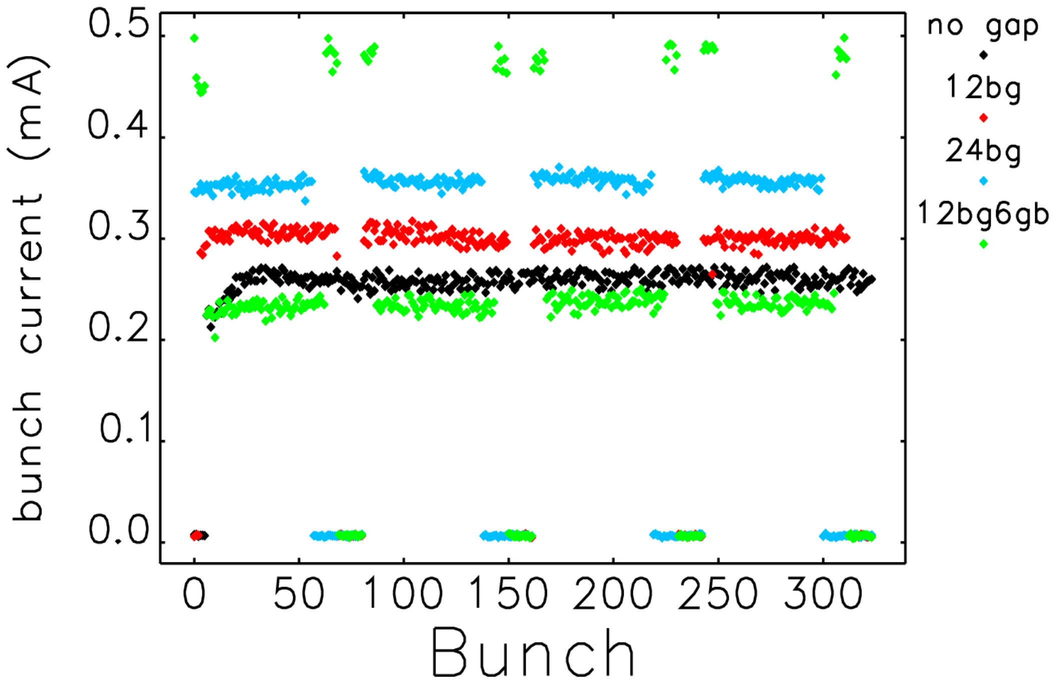




[1] H.G. Hereward, CERN 71-15 (1971).

Train gap studies

- Measure instability for four bunch patterns:
  - 1 train, no gaps (324 bunches)
  - 12bg: 4 trains, 12 bunch gaps
  - 24bg: 4 trains, 24 bunch gap
  - 12bg 6gb: 4 trains, 12 bunch gap, 6 double-charge guard bunches[1]
- Bunch charge adjusted to give ~80 mA total current
- Took data for 900 and 100 nTorr bump
- Done for S25 and S35



Quantity	Value
Beam energy	6 GeV
Horizontal, vertical emittance	1.83 nm, 24 pm
Revolution time	3.68 μs
Beam current	~80 mA
Bunches (no gaps)	324
Bunch spacing	11 ns
horizontal,vertical chromaticity	~6,~3

[1] J. Calvey and M. Borland, PRAB 22 p. 114403 (2019).

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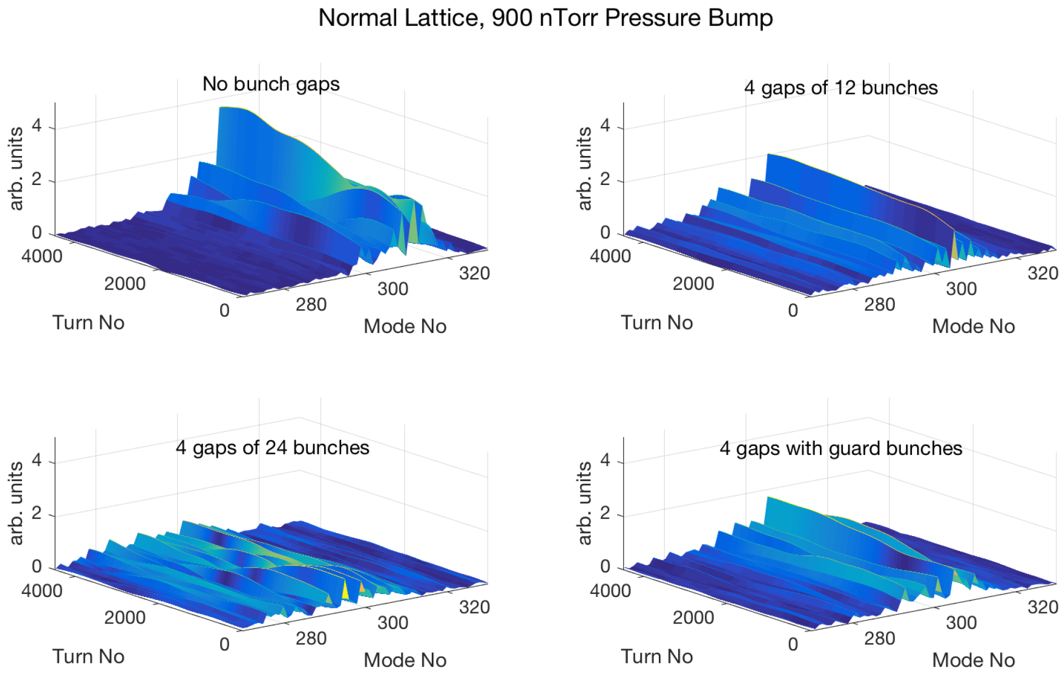
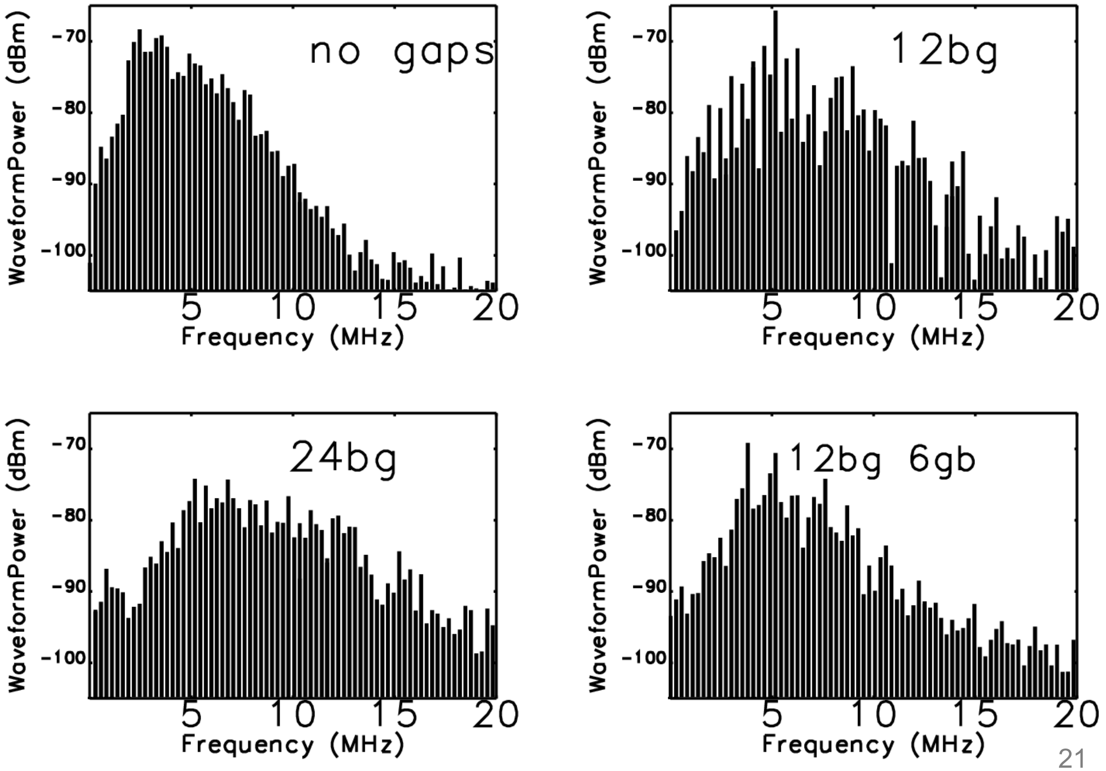
Train gap results: 900 nTorr, S25

- Horizontal instability suppressed with gaps
- Vertical: with gaps, ion peak moves to higher frequency, reduced amplitude
- Guard bunches help clear ions
- Dimtel data shows unstable modes over 4000 turns
  - Modal amplitudes not constant

Bunch pattern	ε_x (nm)	ε_y (nm)
No gap	3.6	0.124
12bg	**2.06**	**0.049**
12bg 6gb	**2.05**	**0.031**
24bg	2.09	0.027

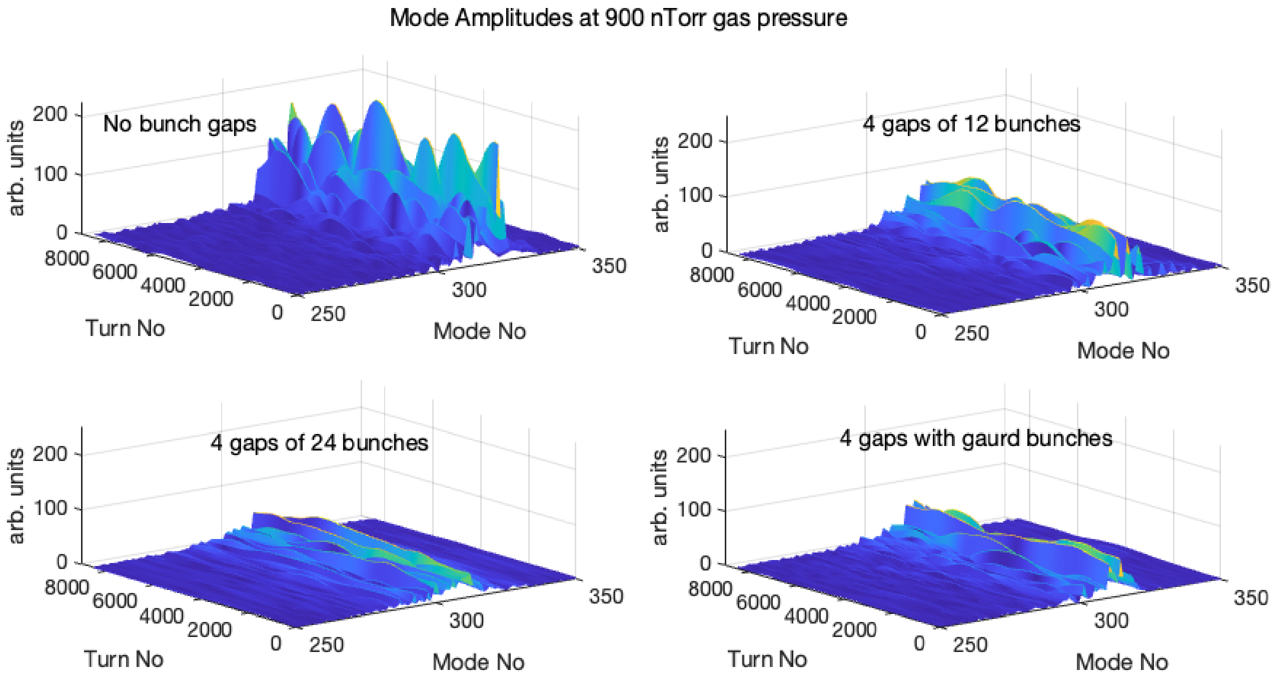


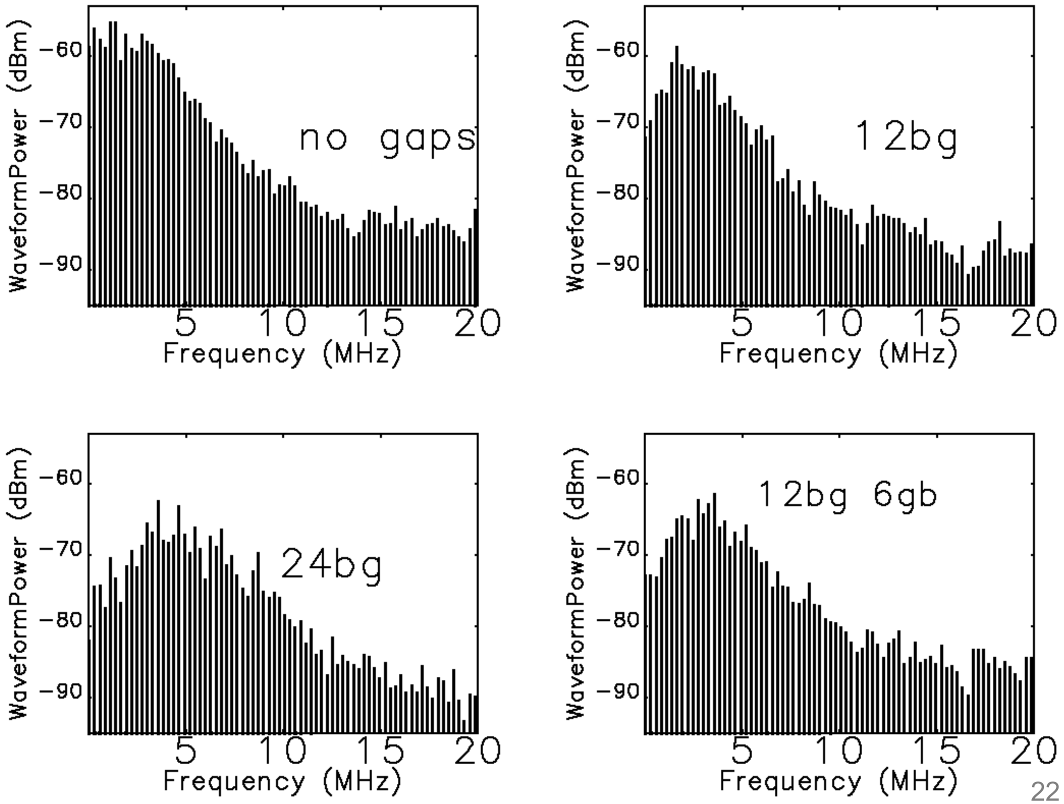


Train gap results: 900 nTorr, S35

- No horizontal instability
- Huge vertical blowup with no gaps
- Gaps effective- reduce blowup, move ion frequency higher
- Guard bunches help clear ions
- Vertical emittance and instability amplitude >> S25
- Wild mode instability in Dimtel data

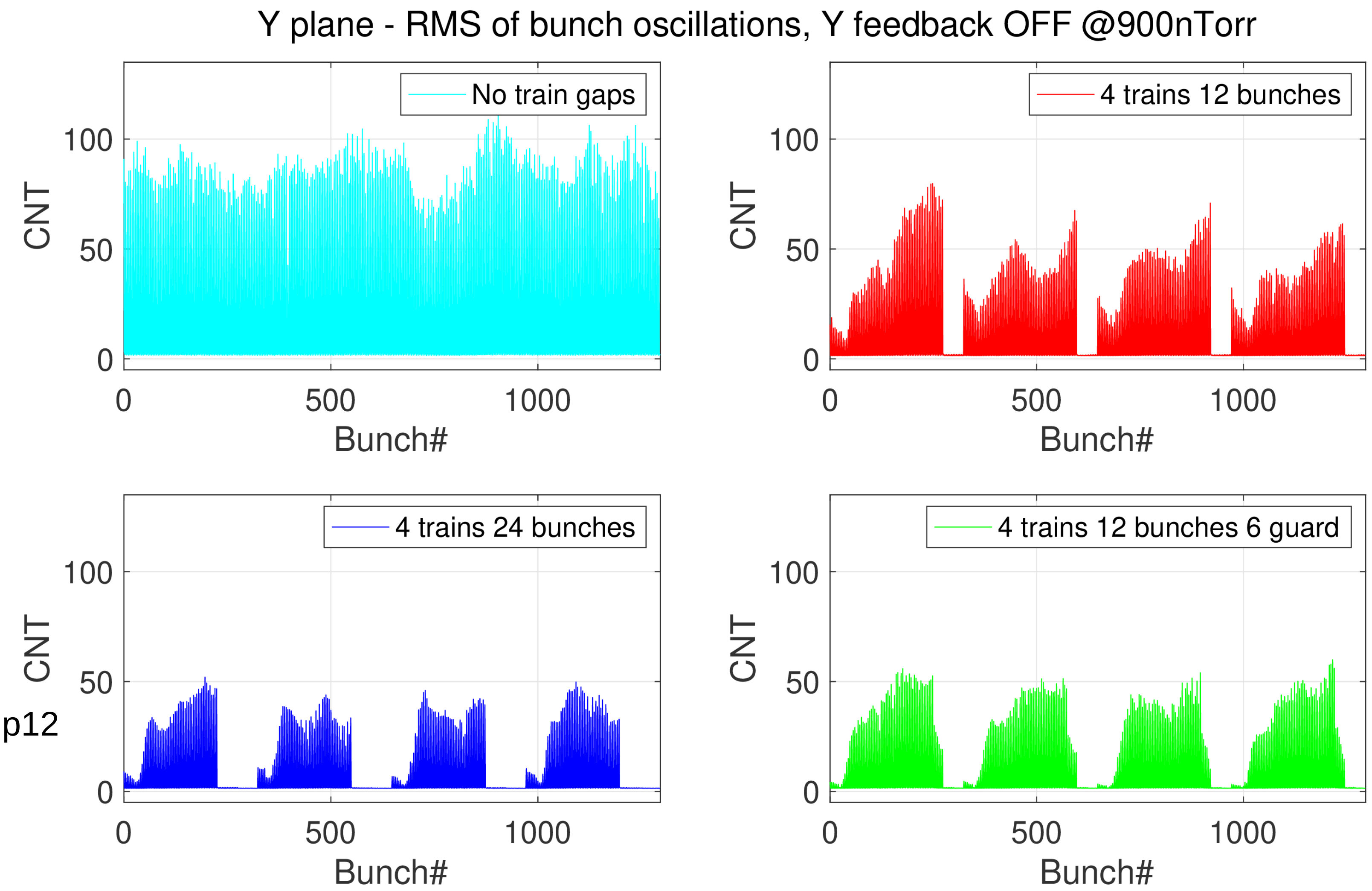
Bunch pattern	ε_x (nm)	ε_y (nm)
No gap	1.98	1.55
12bg	**1.83**	**0.188**
12bg 6gb	**1.78**	**0.043**
24bg	1.77	0.051





Bunch by bunch RMS motion (900 nTorr, S35)

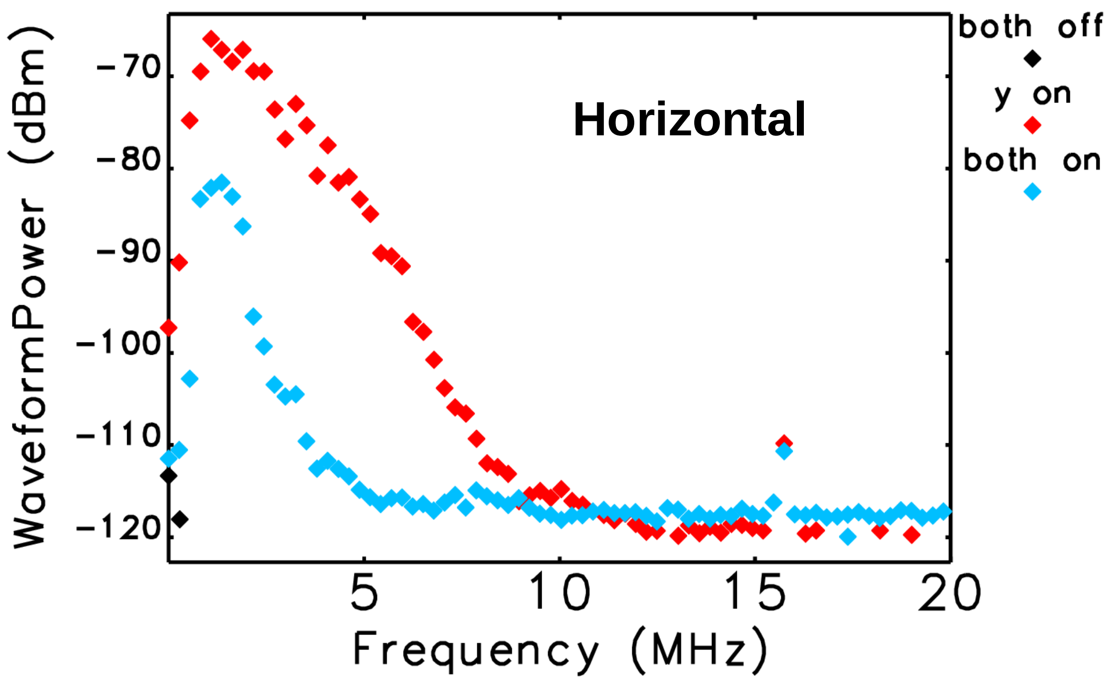
- Measured by Dimtel feedback system[1]
- Buildup along bunch trains- fast ion instability[2]
- First few bunches higher than following ones.
- Train gaps are effective.

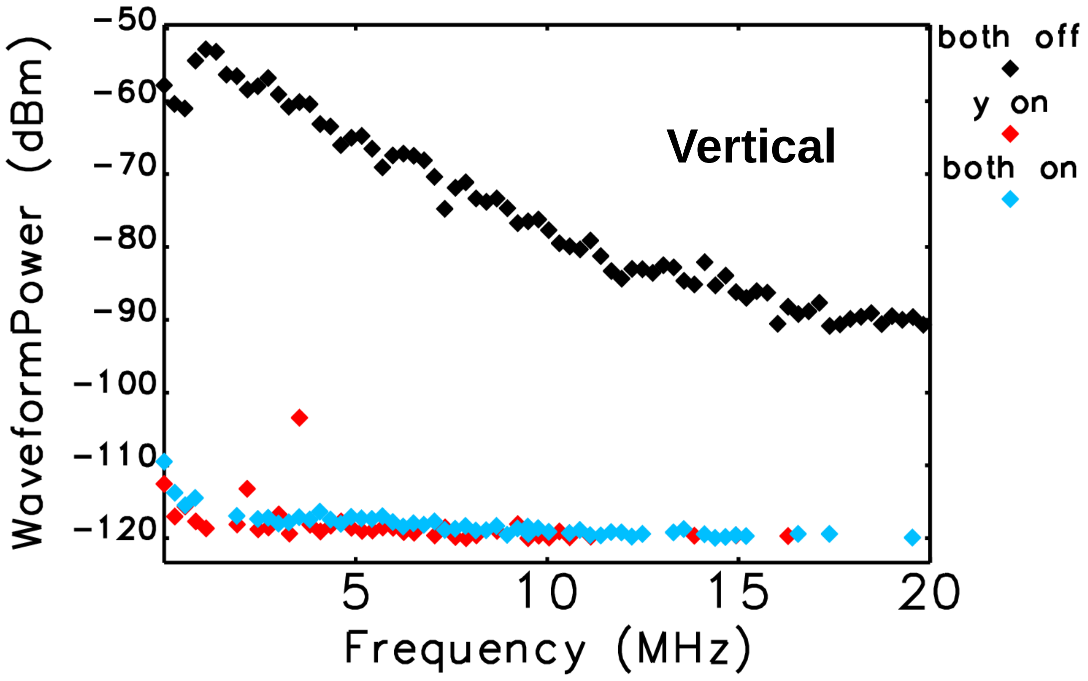


[1] https://www.dimtel.com/products/igp12
[2] J. Byrd et al., Phys. Rev. Lett. 79, pp. 79-82 (1997).

Transverse feedback (900 nTorr, no gaps, S35)

- Dimtel system is used to measure and suppress transverse instabilities.
- Vertical feedback extremely effective, but leads to horizontal instability
  - Emittance blowup also suppressed
- Vertical instability damped → more ion trapping → horizontal instability
- With feedback on in both planes, still have (smaller) horizontal instability

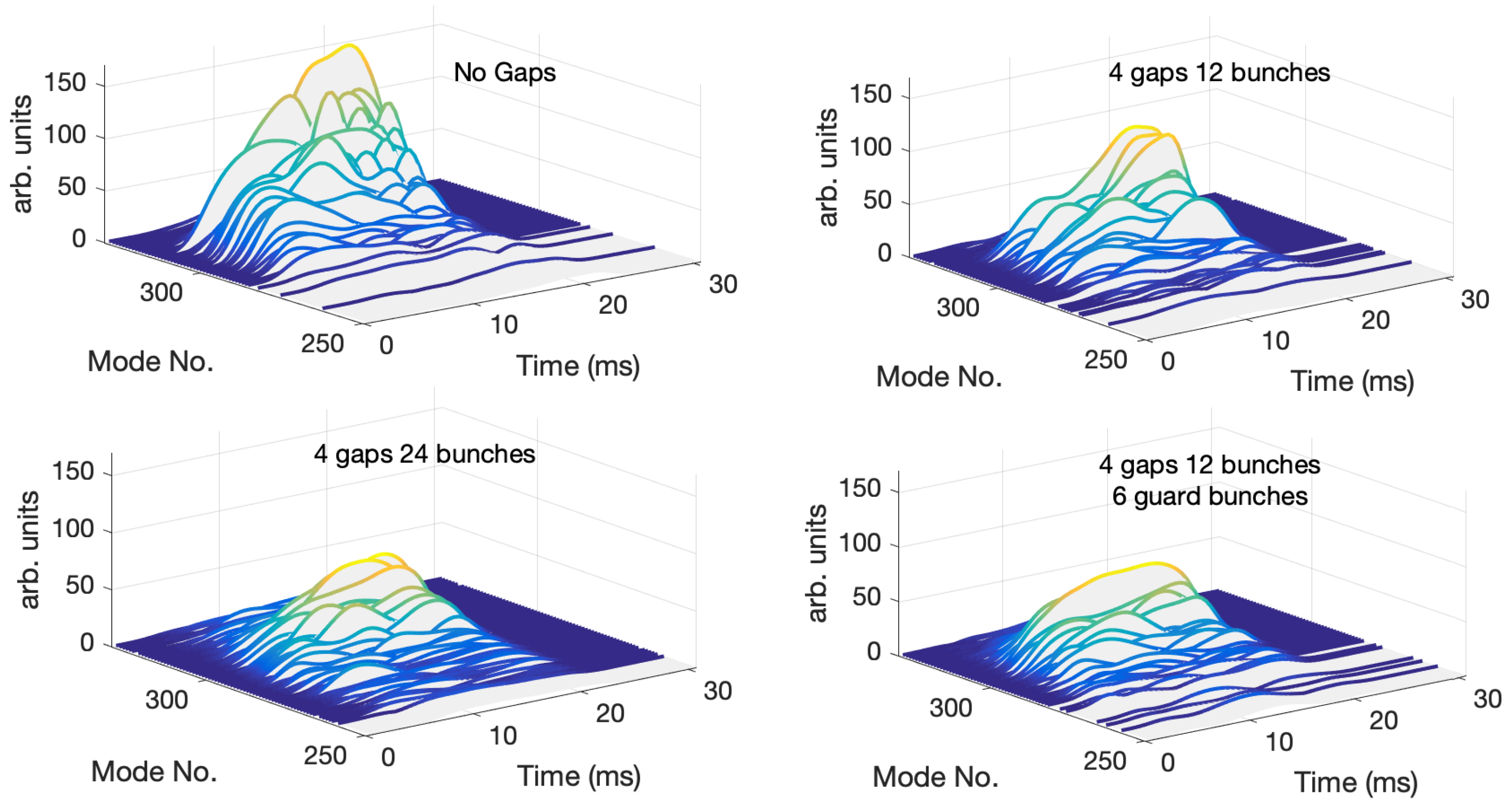




Grow-damp measurements (Dimtel system)

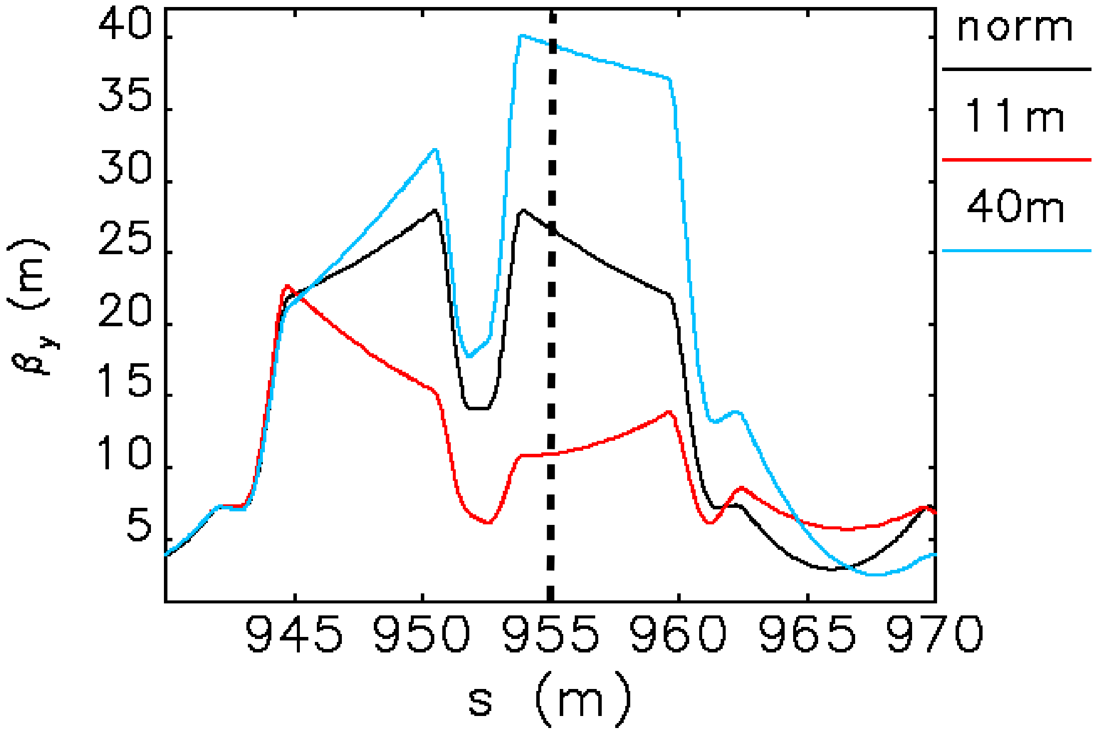
- Feedback disabled at 0 ms, re-enabled at 20 ms
- Study instability on a mode-by-mode basis
- Faster growing modes saturate at a lower amplitude
- Complex mode behavior after initial saturation

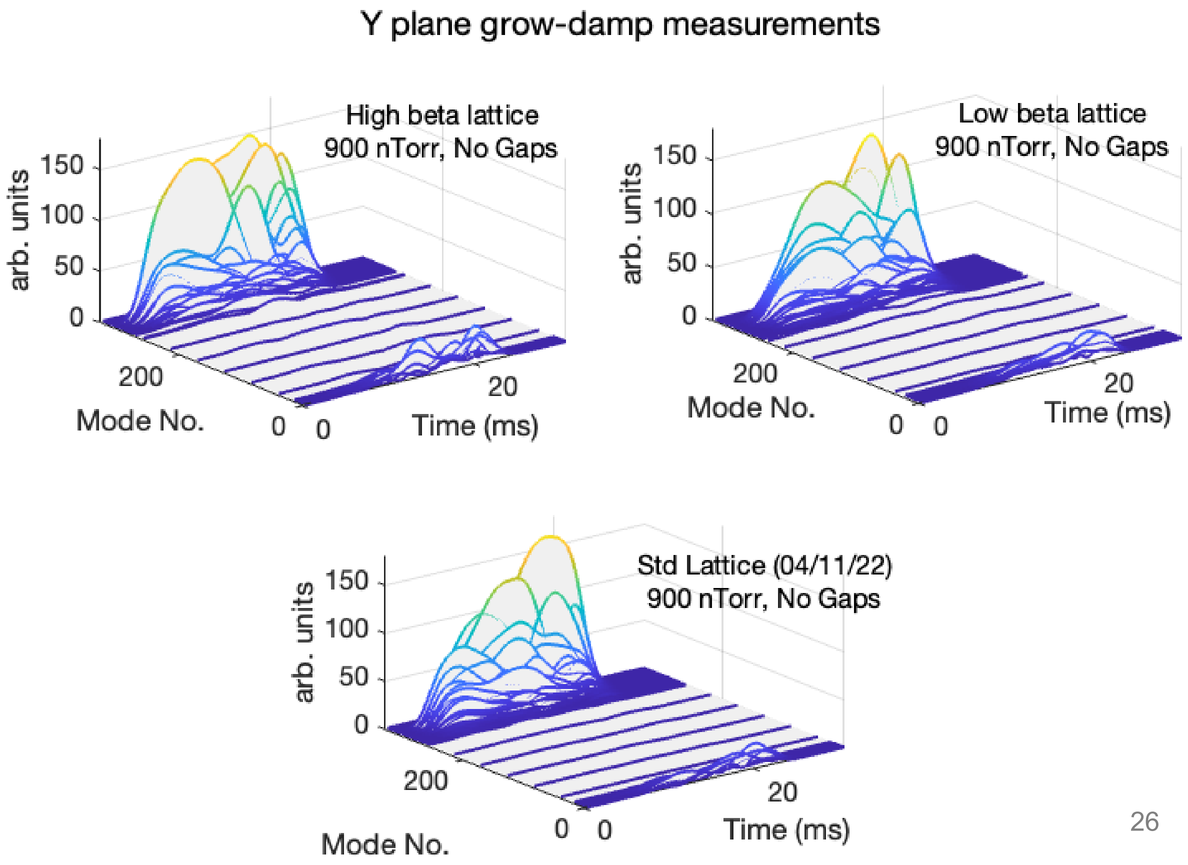
Mode amplitudes - Grow damp measurements @900 nTorr



Beta function study (900 nTorr, S35)

- Goal: study effect of varying beta function on ion instability
- Three lattices designed with different vertical beta function at gas injection point
- Saturation level about the same for each lattice, but mode behavior is different



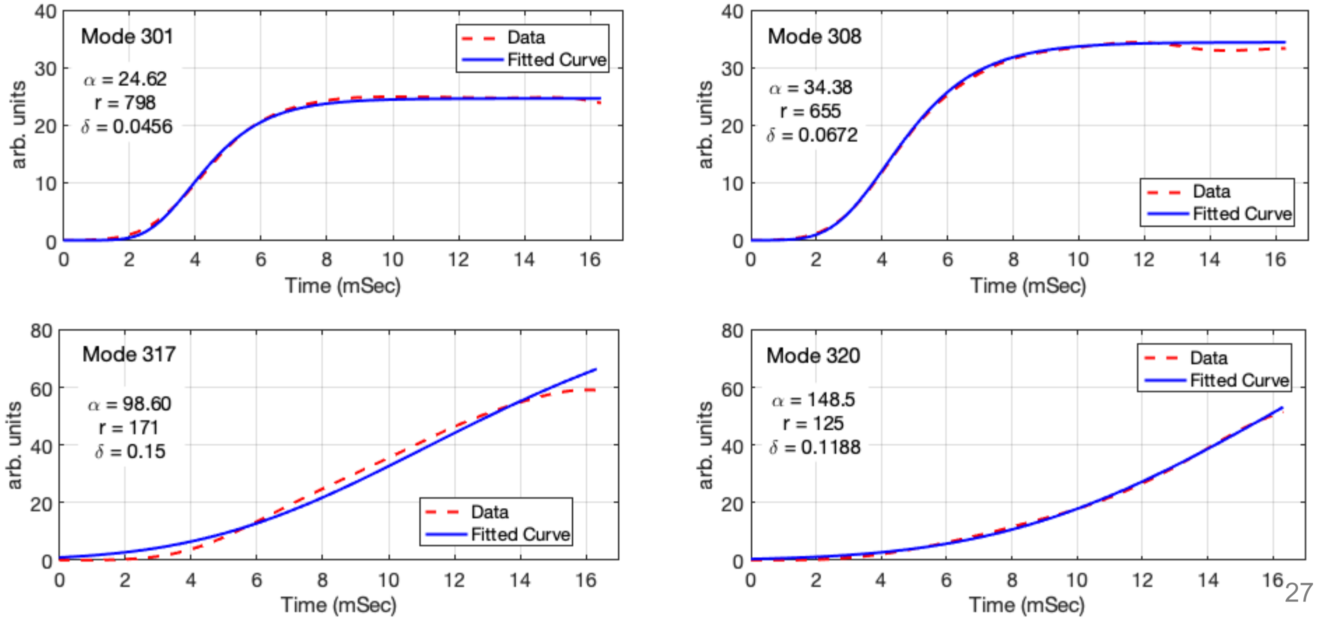


Characterizing growth and saturation

- Initial growth and saturation can be modeled by logistic function
- Saturation level given by α
- Time of inflection point: $t_i \equiv -\ln(\delta)/r$
- Higher amplitude modes have slower growth time
- Recall anti-correlation between growth rate and trapping in S35
- Modes with the highest amplitude are driven by locations with the most ion trapping, rather than the fastest initial growth.

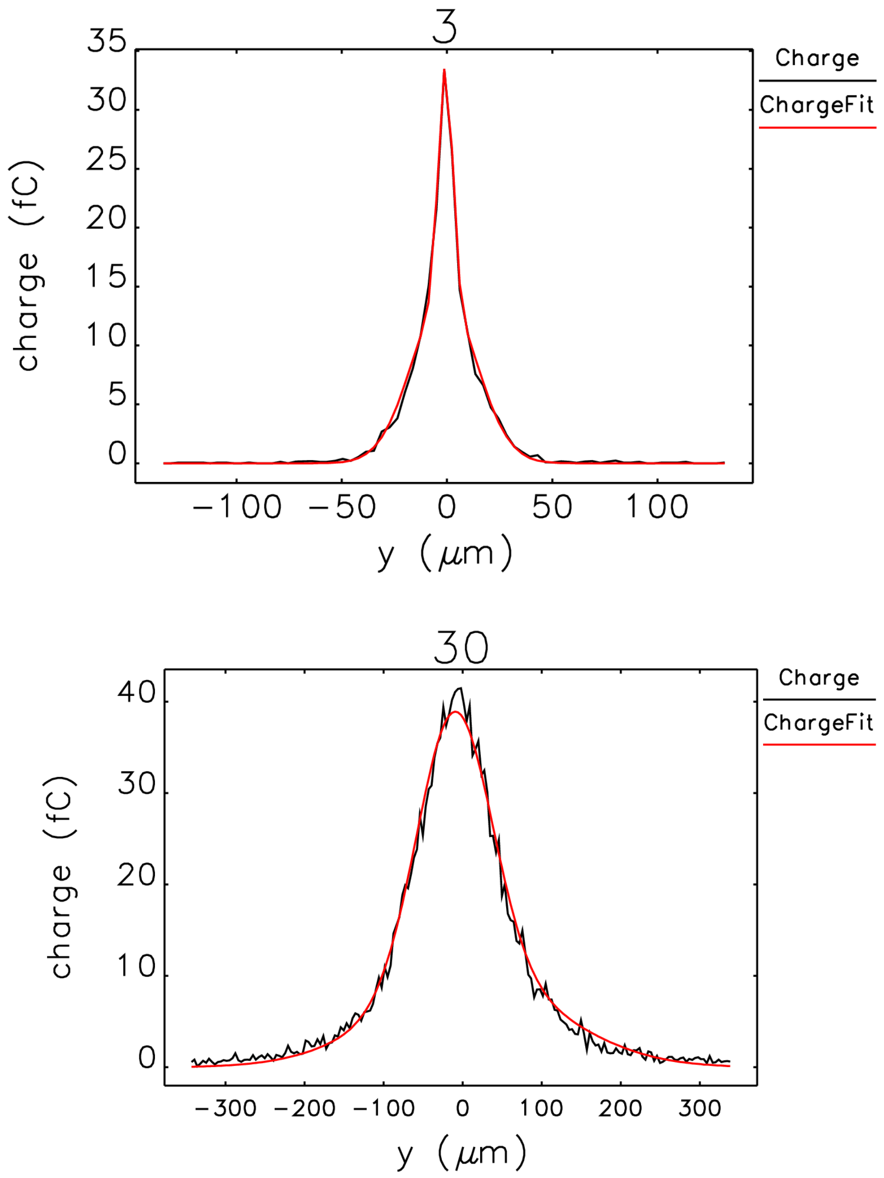
$$y(t) = \frac{\alpha}{(1 + e^{-rt})^{1/\delta}}$$

mode	freq (MHz)	α	t_i (ms)
301	6.2	24.6	3.9
308	4.3	34.4	4.1
317	1.9	98.6	11.1
320	1.1	148.5	17.0



Bi-Gaussian beam kick[1]

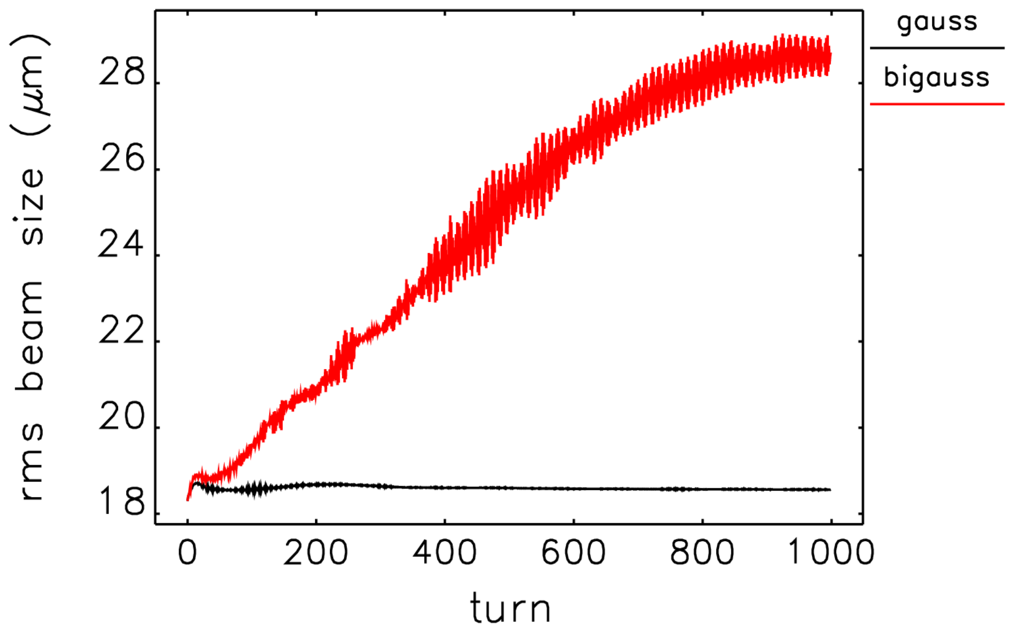
- Initial simulations of gas injection experiment did not show much blowup
- So far, Gaussian distribution is assumed for both beam and ion kicks
  - Bad assumption for ions
  - But a bi-Gaussian fit does much better
- Fit x and y distributions separately, using two Gaussians each
  - rho(x,y) = [G1(x) + G2(x)] * [G3(y) + G4(y)]
- Options for tri-Gaussian and bi/tri-Lorentzian have also been added

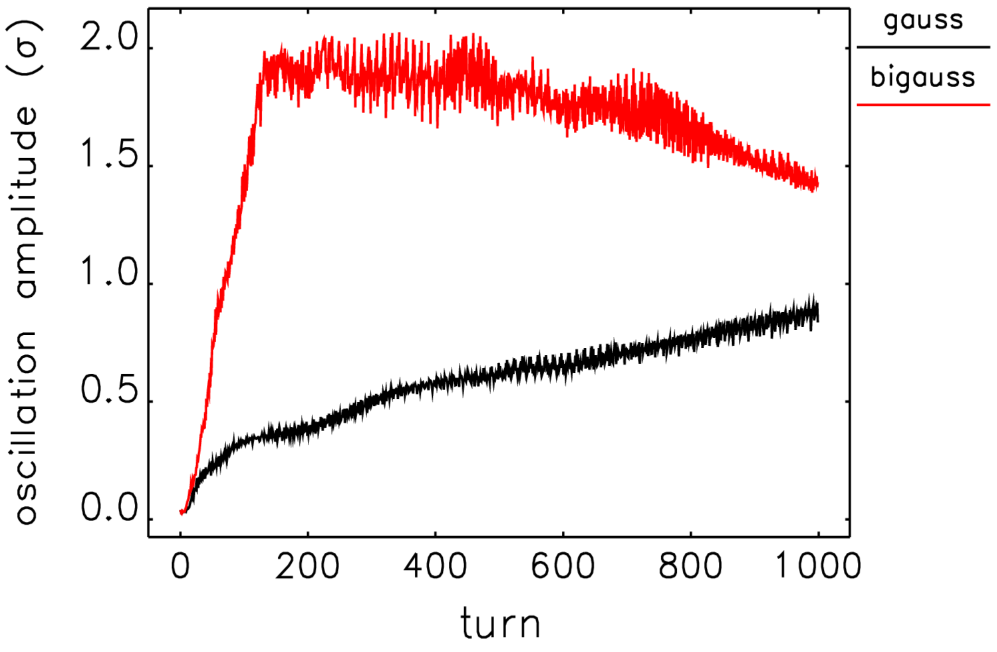


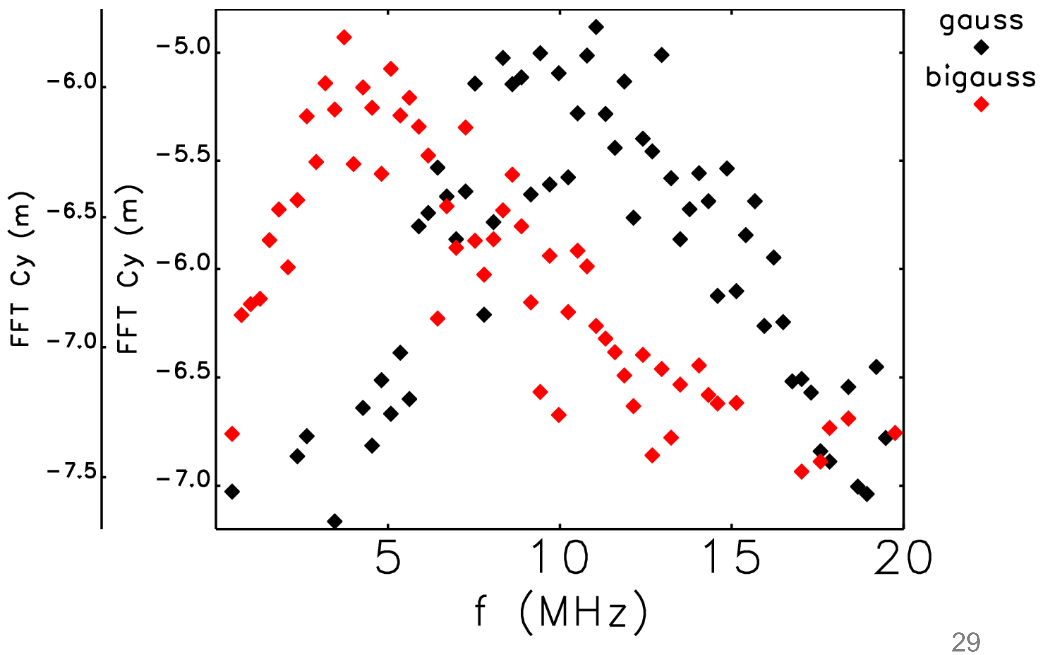
[1] J. Calvey et al., Proc. IPAC’21 pp. 1267–1272.

Bi-Gaussian results show beam size blowup with gas injection

- 900 nTorr, 324 bunches, no gap, 100 mA
- Large beam size blowup
  - Leads to reduced ion frequency
  - More consistent with measurement







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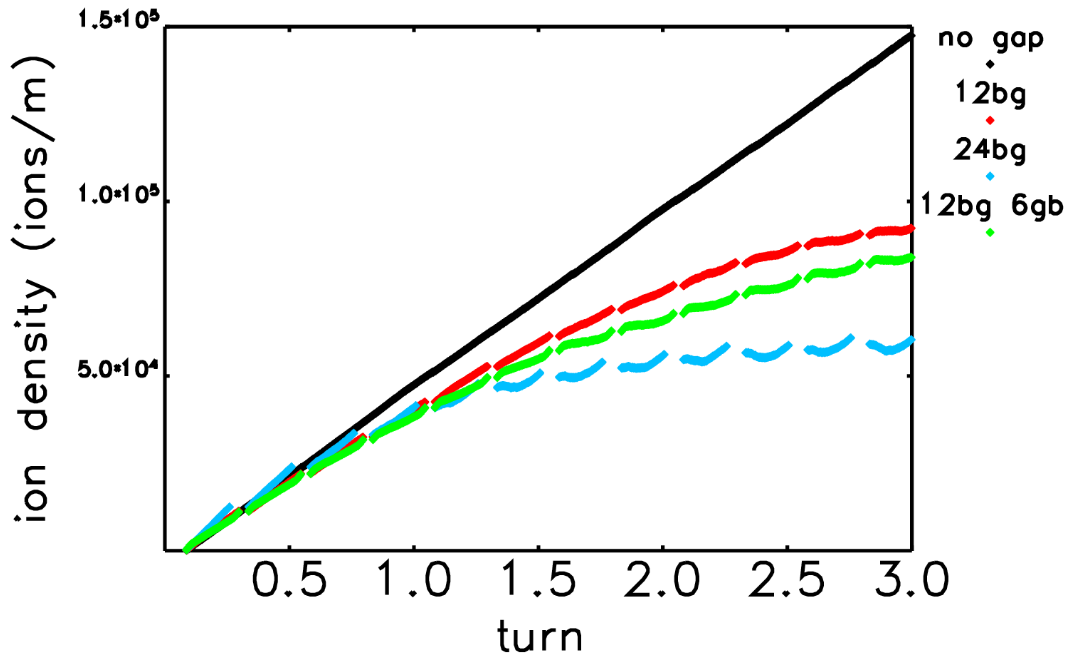
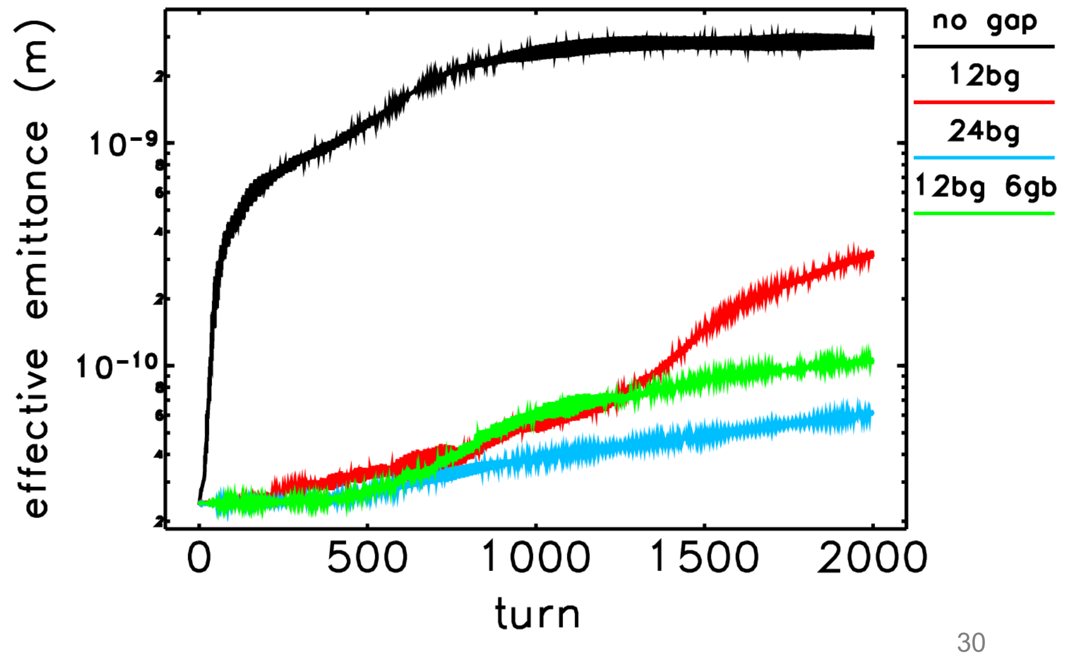
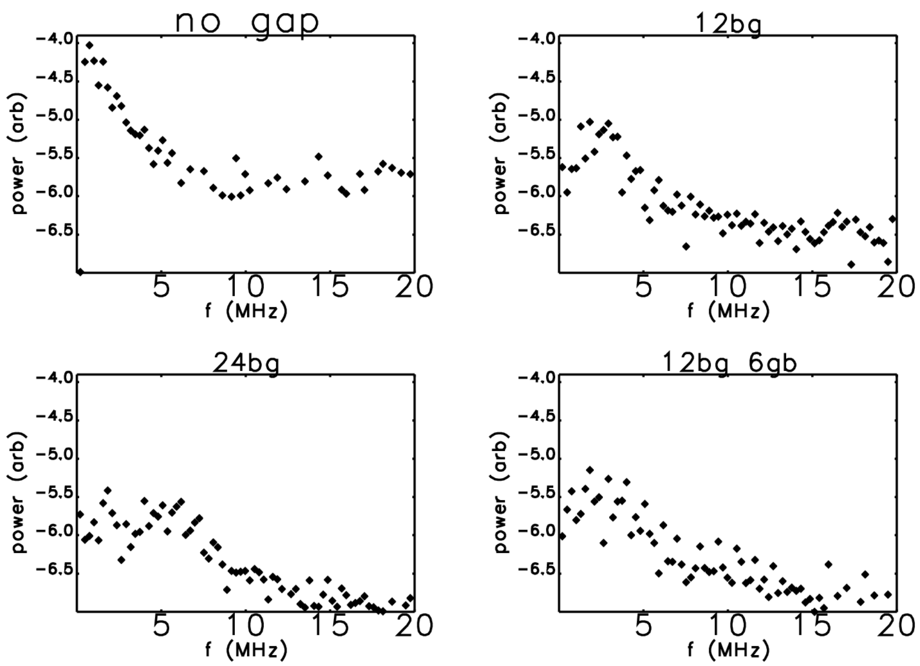
Gas injection simulations

- Simulations of S35 train gap study, done with bi-Gaussian kick method
- Clearing effect from train gaps clearly seen
- Compare effective vertical emittance (beam size and rms motion added in quadrature)
  - Qualitative agreement- train gaps are effective
  - Simulation overestimates instability amplitude
- Beam spectra also show qualitative agreement







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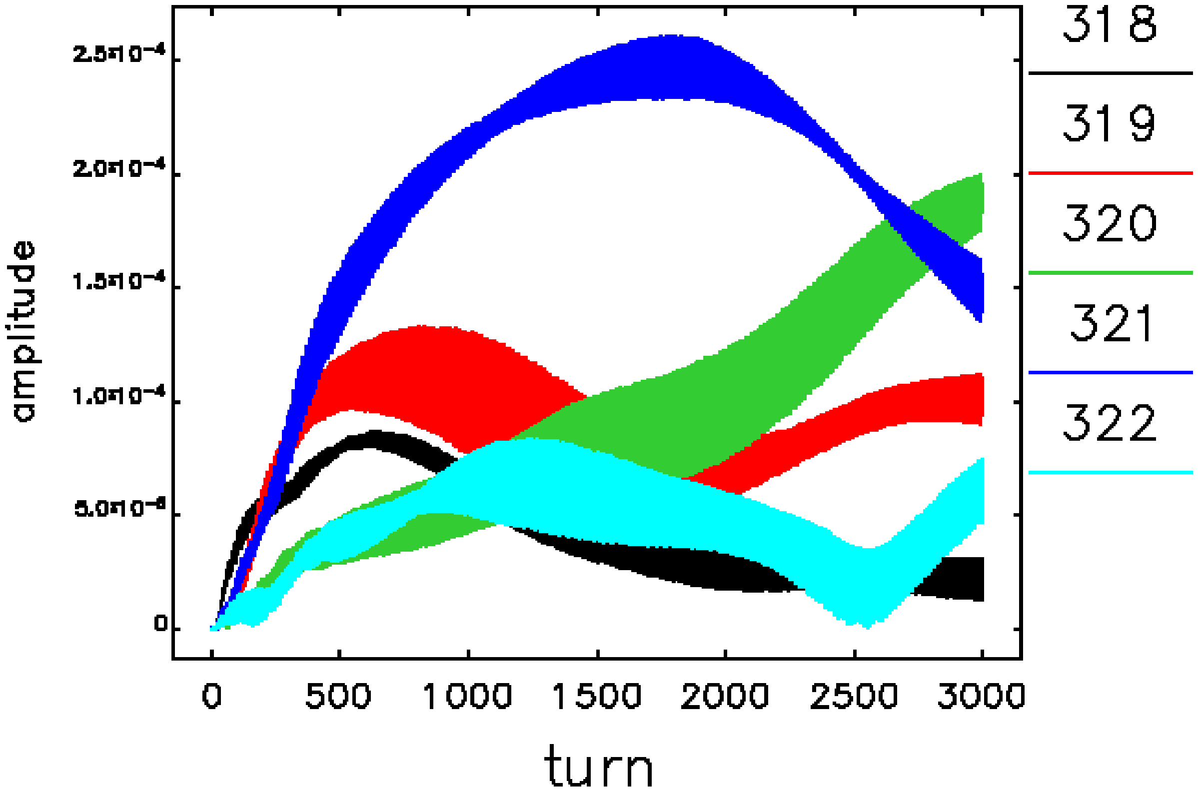
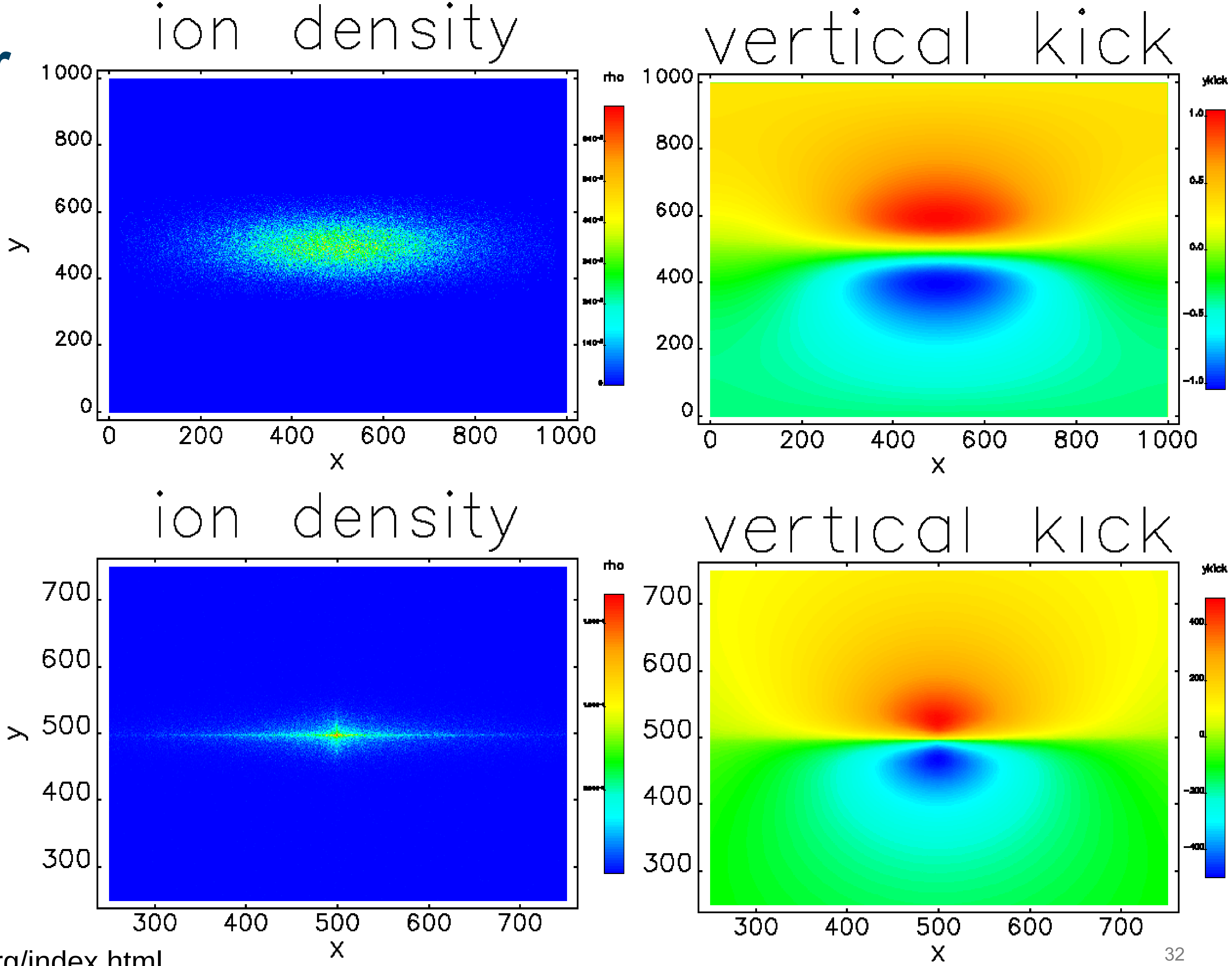
Growth of unstable modes

- Growth of modes in simulation mirrors measurement
- Most unstable ~320
- Fastest growing modes saturates at lower value
- "Sharing" of instability between modes



Poisson Solver

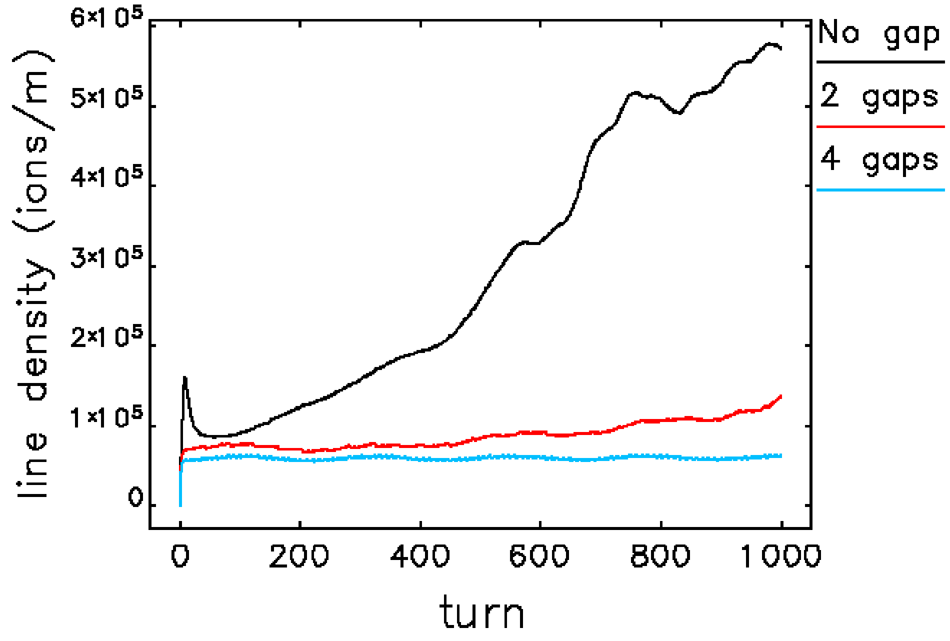
- Developing a Poisson solver for elegant
  - Calculate ion-beam kick for any ion distribution
  - Decided on FFT based method using FFTW library[1]
  - Fast, can be parallelized
- Plots show ion density and calculated kick
  - Top: first bunch
  - Bottom: after first turn

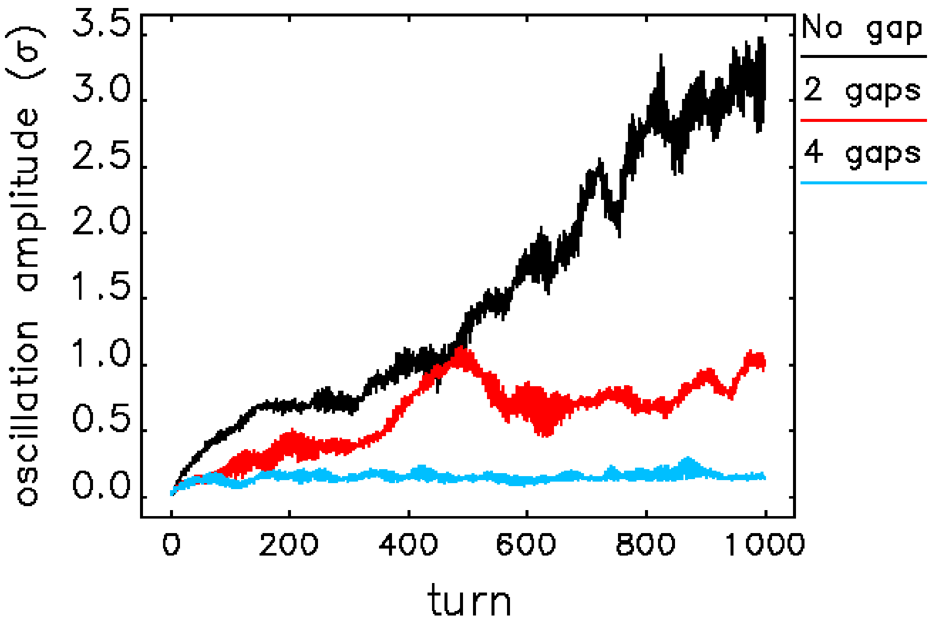


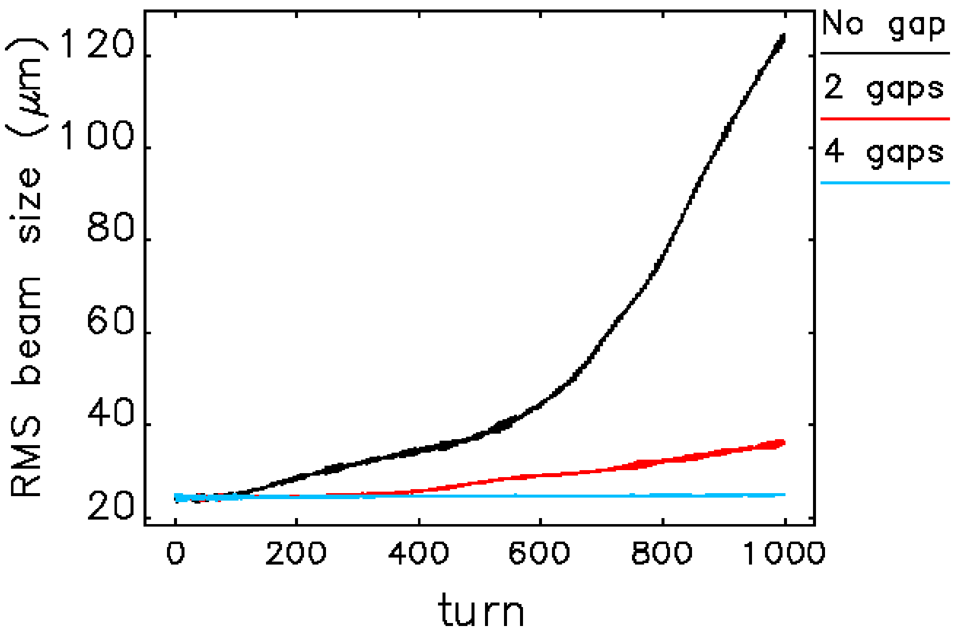
[1] http://www.fftw.org/index.html

APS-U simulations

- 200 mA, 6 GeV, 100 A-hr pressure profile
- Bi-Gaussian kick method
- Simulate effect of compensated gaps
  - 2 bunch gaps with 1 guard bunch
- No gap case shows larger amplitude, beam size blowup → more trapping → more instability
- Compensated gap scheme still effective







Conclusions

- Ion instability is a major concern APS-U 324 bunch mode.
- We plan to mitigate coherent instability with a compensated gap scheme.
- Developed `IONEFFECTS` code to model incoherent effects.
  - Shows good agreement with present APS measurements when multiple ionization, transverse impedance, and charge variation are included.
- Gas injection experiment was installed and operated at two locations in the APS.
  - Observe both coherent instability and emittance blowup.
  - Train gaps are an effective at mitigation. Guard bunches help with the ion clearing.
  - Dimtel transverse feedback is very effective.
  - Grow-damp measurements allow for studying the instability on a mode-by-mode basis.
- IONEFFECTS simulations using a bi-Gaussian kick method show qualitative agreement with the gas injection measurements.
- Work is underway to implement a Poisson solver in the code, and to perform simulations using a model of the transverse feedback.
- APS-U simulations show potential for runaway emittance blowup.
  - Compensated gap scheme should still be effective.

Thanks for your attention!

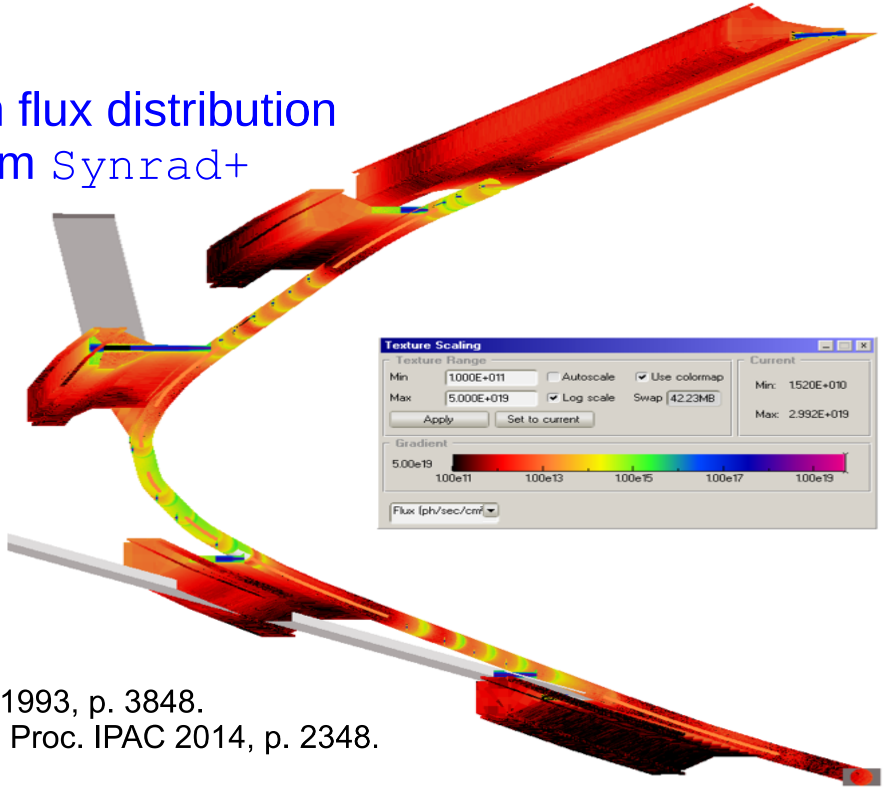
- Questions?

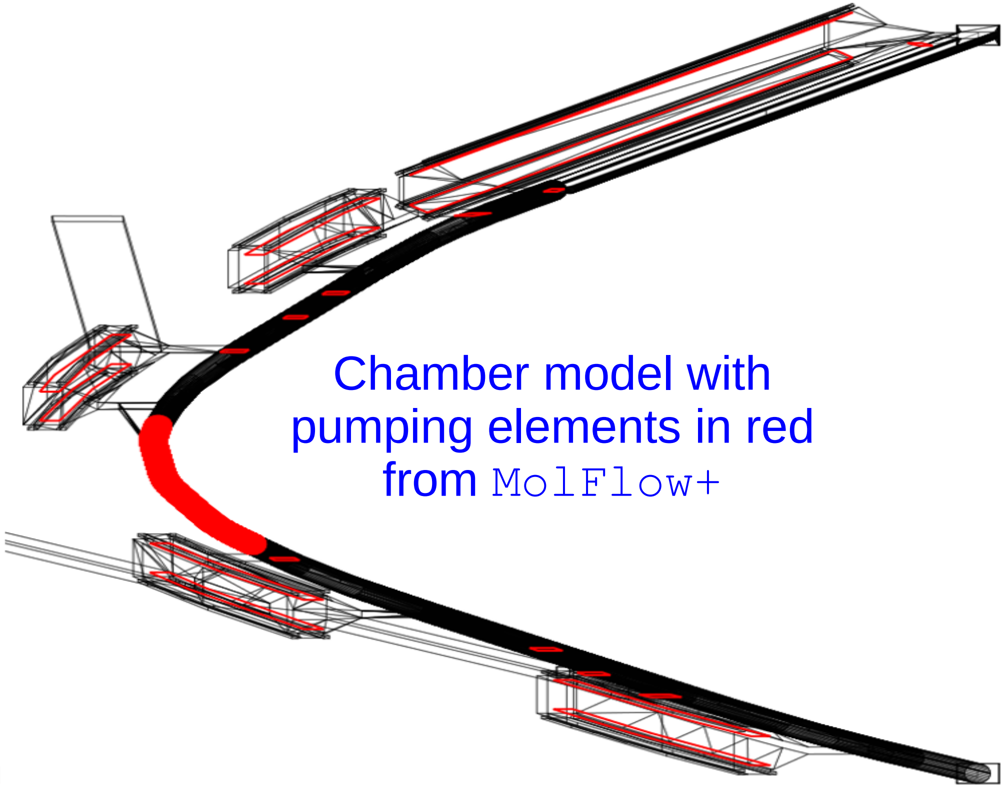
Backup slides

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+`[10]
  - Includes scattering of photons off vacuum chamber elements
- Pressure profiles calculated by `MolFlow+`[11]
  - Inputs: photon flux from `Synrad+`, photon stimulated desorption, pumping elements

Photon flux distribution from `Synrad+`



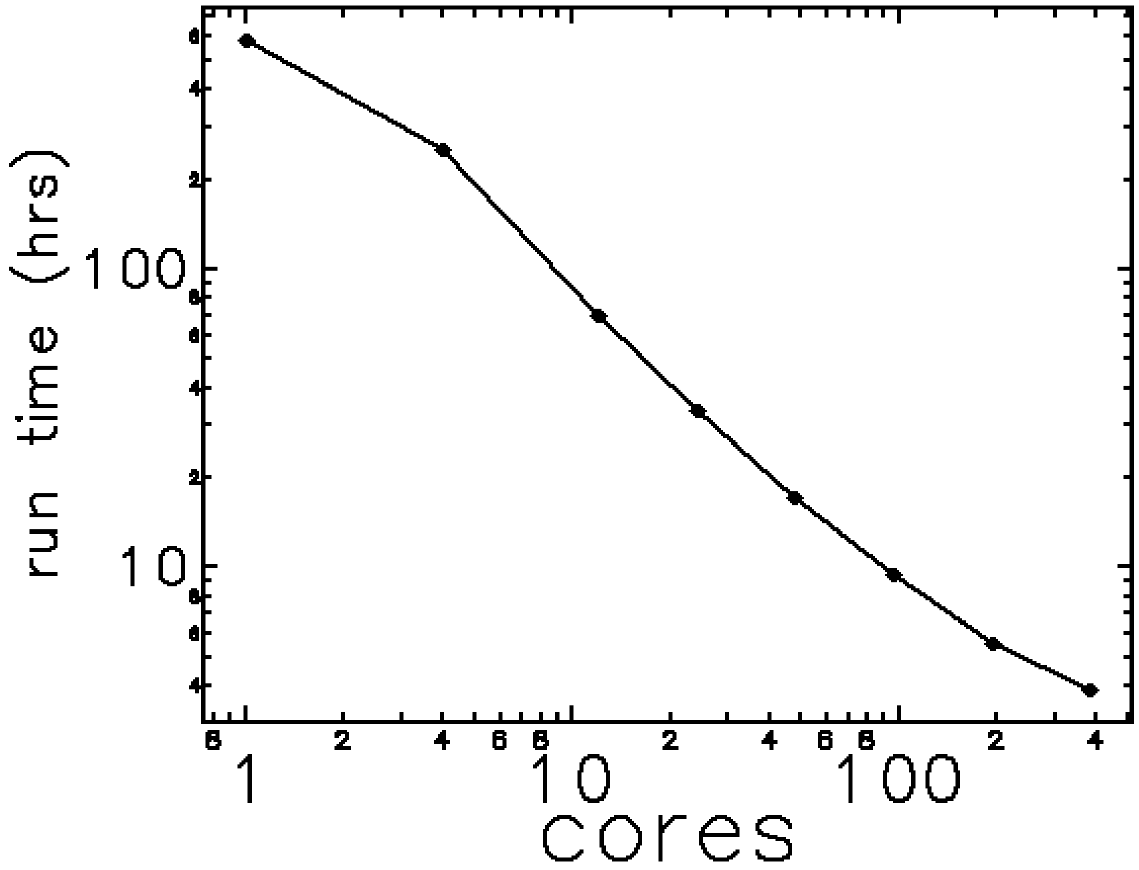


Chamber model with pumping elements in red from `MolFlow+`

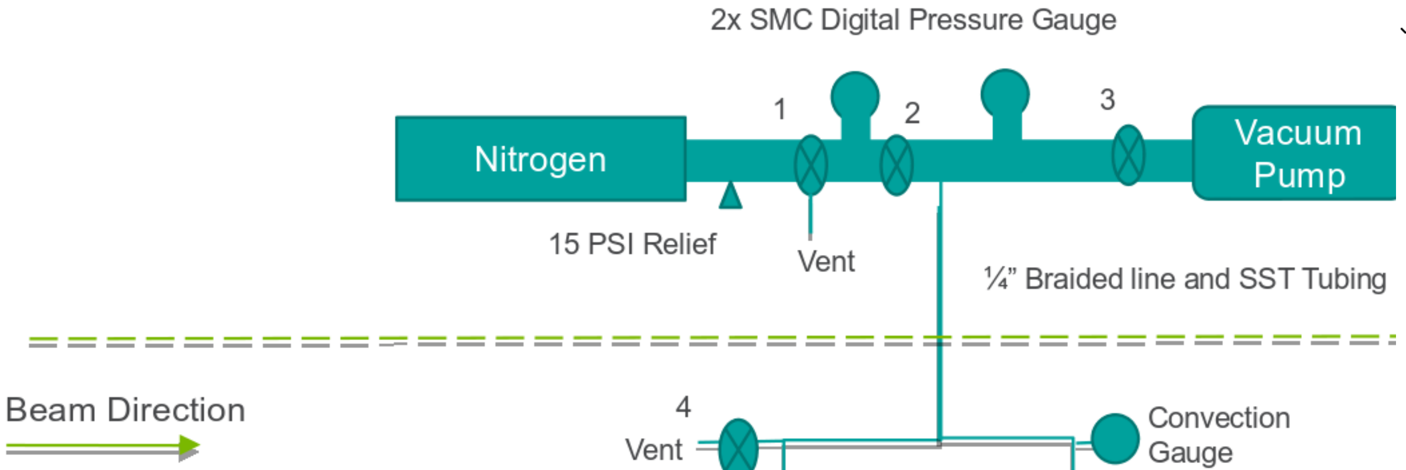
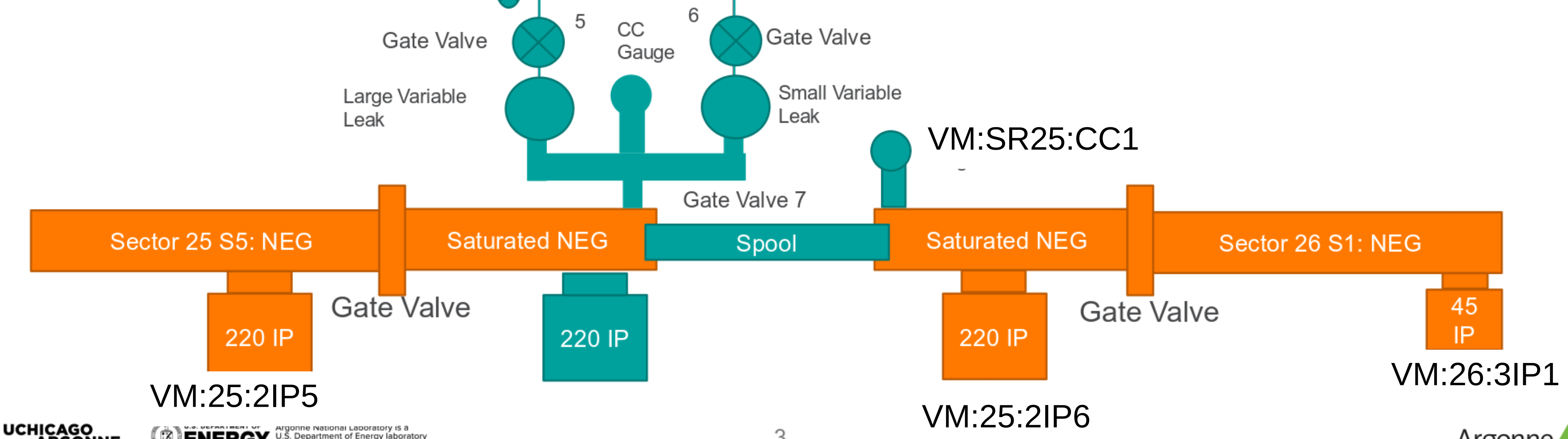
[10] R. Kersevan. Proc. PAC 1993, p. 3848.
[11] M. Ady and R. Kersevan. Proc. IPAC 2014, p. 2348.

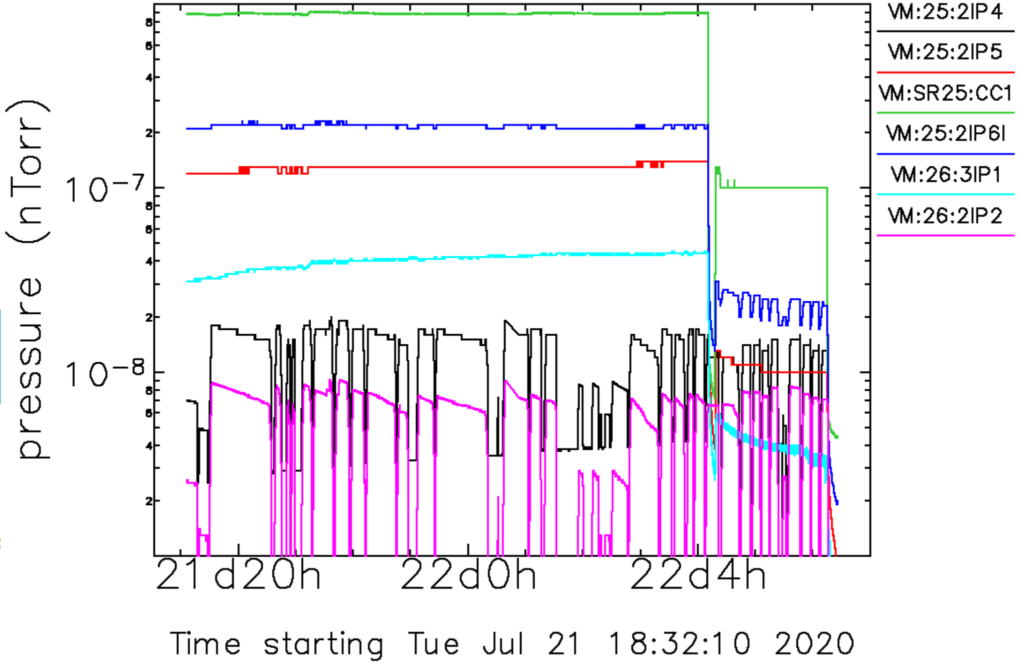
Parallelization

- Parallelized using MPI library
- For standard simulation, relative to serial:
  - Almost 10x faster with 12 cores
  - ~100x faster with ~200 cores



Pressure bump is well contained

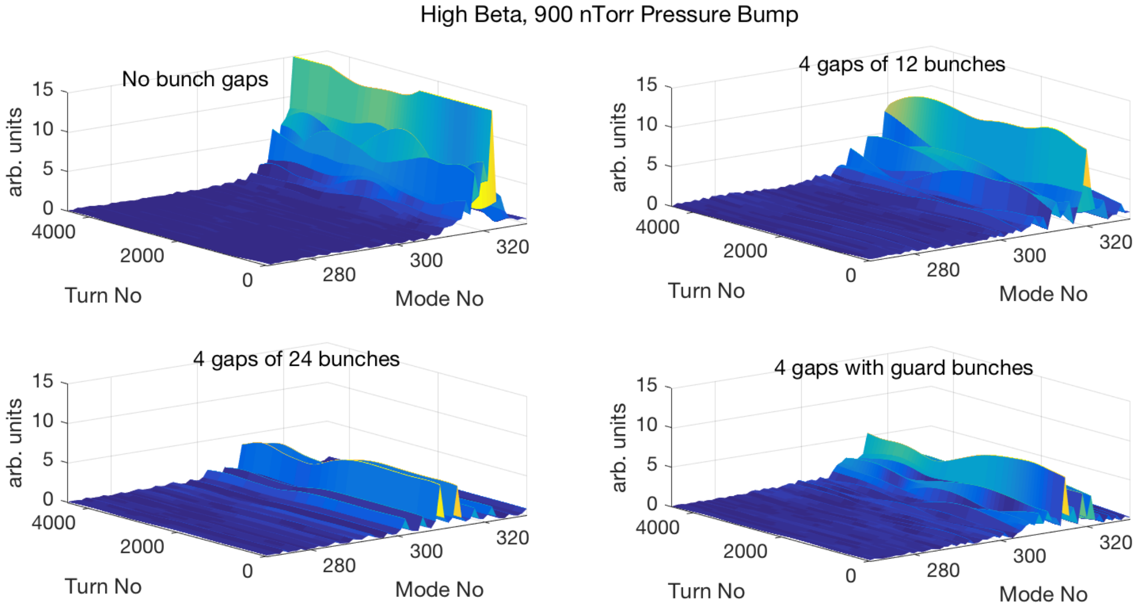



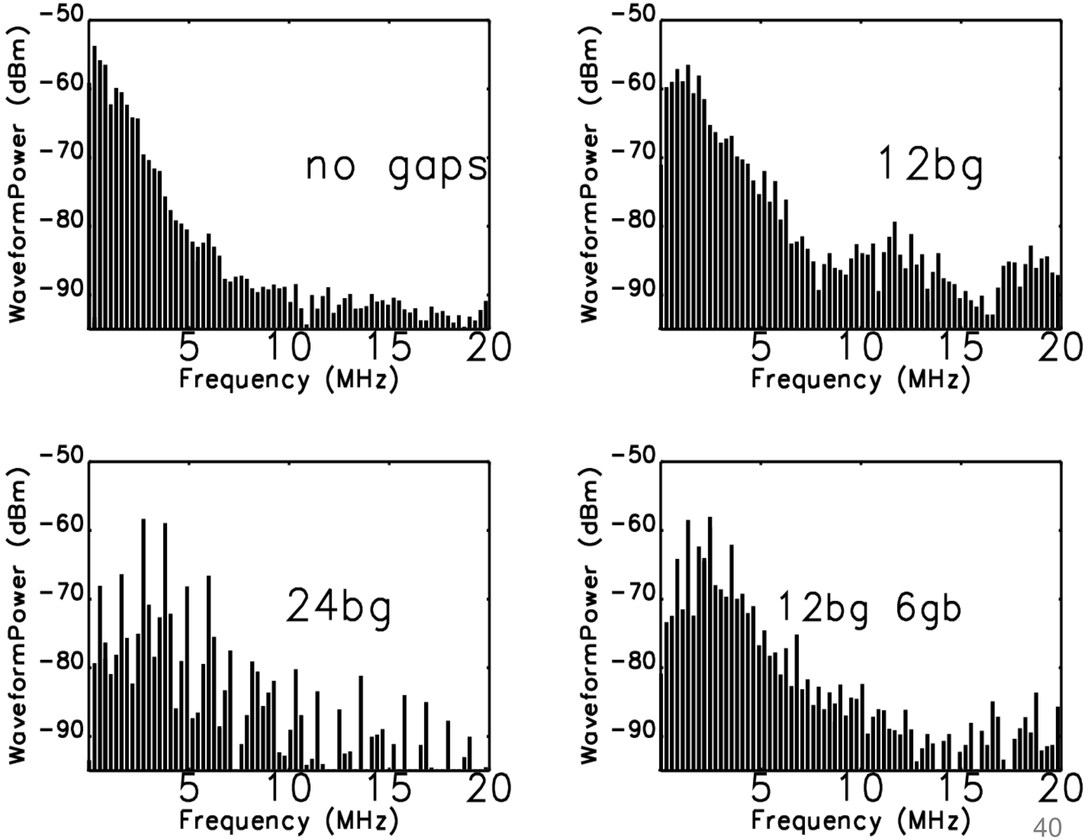


Train gaps: 900 nTorr, lattice with high β_y in S25

- Nothing in horizontal
- Huge vertical blowup → very low ion frequency
- 12 bunch gap not effective
- 12bg 6gb shows lower emittance than 24bg, but stronger spectrum

Bunch pattern	ε_x (nm)	ε_y (nm)
No gap	1.52	0.53
12 bg	1.91	0.34
12 bg 6 gb	2.07	0.074
24 bg	1.93	0.141

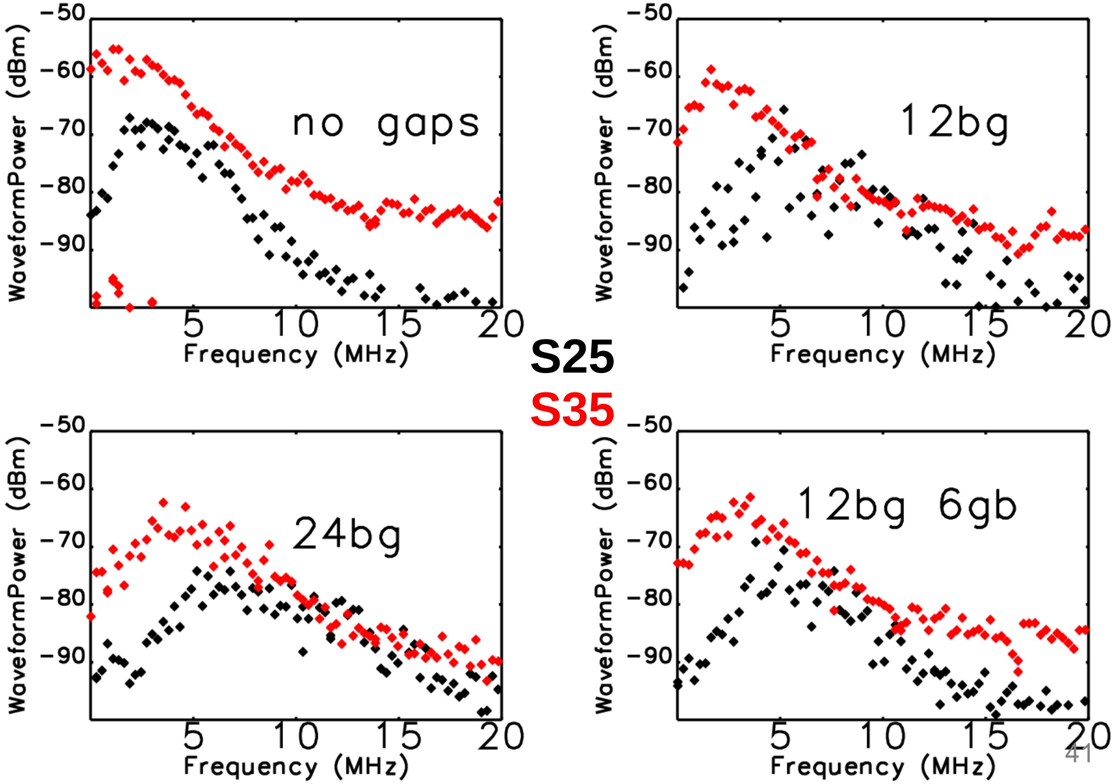




Comparing S25 and S35, 900 nTorr

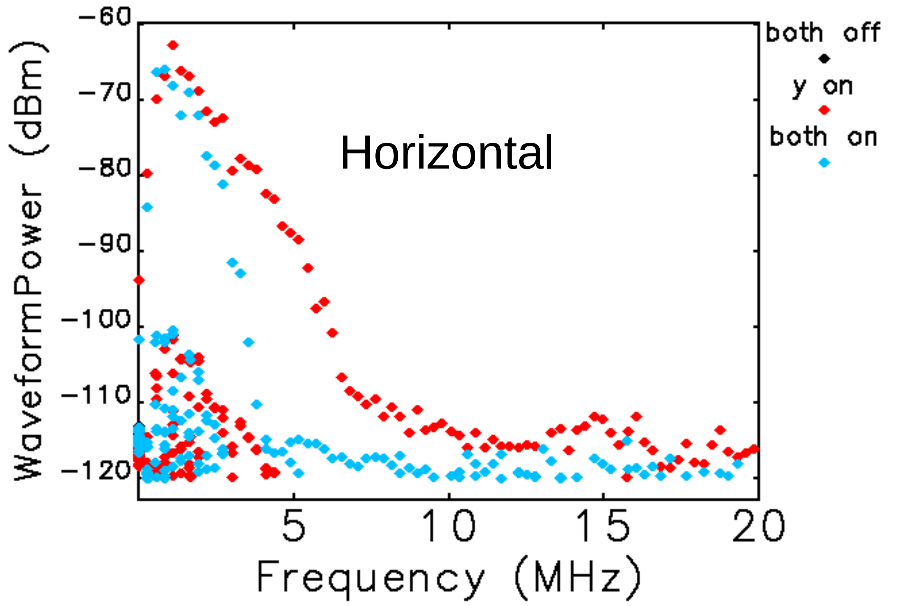
- Top: measured emittance
- Bottom: beam spectrum (lower vertical betatron sidebands)
- S35 has much larger vertical blowup and sideband amplitude than S25
- S25 no gap case also has horizontal instability
- Train gaps reduce blowup and instability amplitude, increase ion frequency
- 12bg 6gb performs better than 12bg, about the same as 24bg

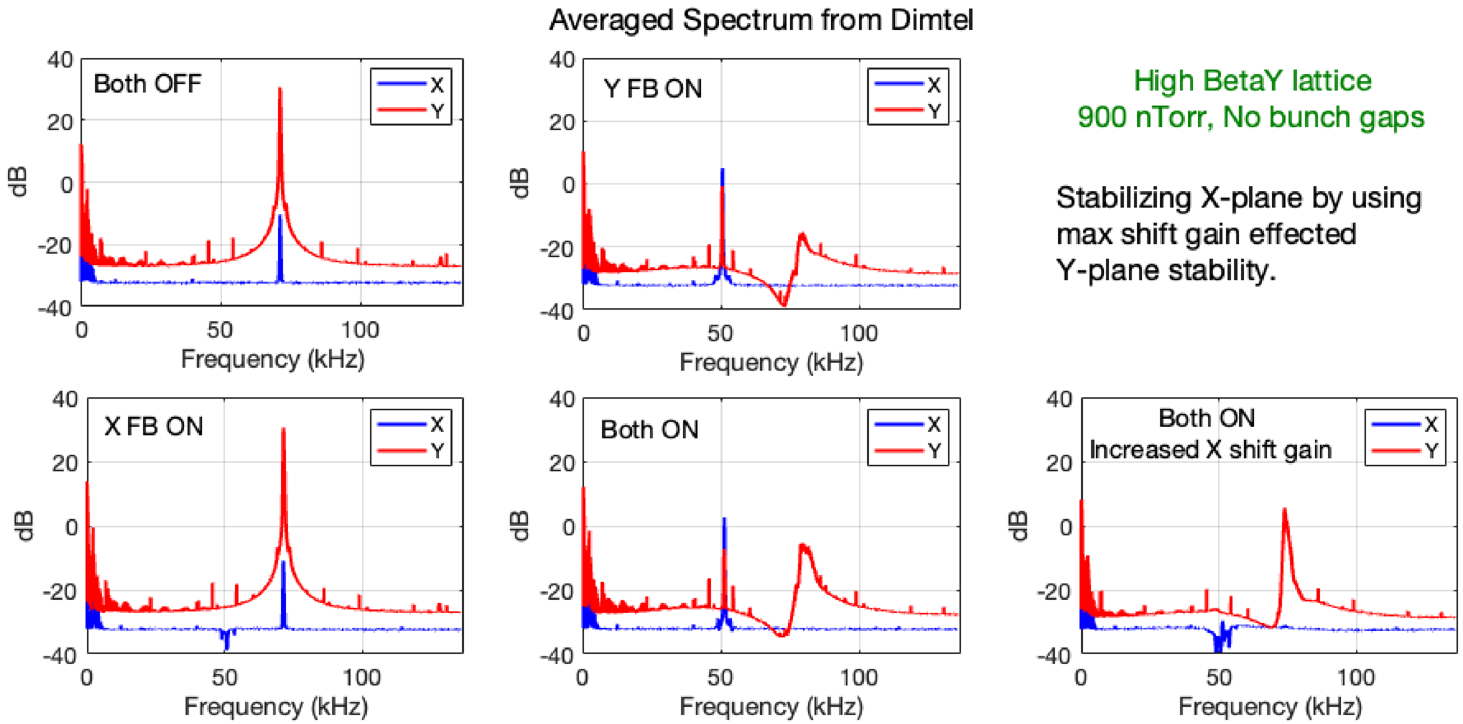
pattern	S25 ϵ_x (nm)	S35 ϵ_x (nm)	S25 ϵ_y (nm)	S35 ϵ_y (nm)
No gap	**3.6**	1.98	**0.124**	**1.55**
12bg	2.06	1.83	0.049	**0.188**
12bg 6gb	2.05	1.78	0.031	0.043
24bg	2.09	1.77	0.027	0.051

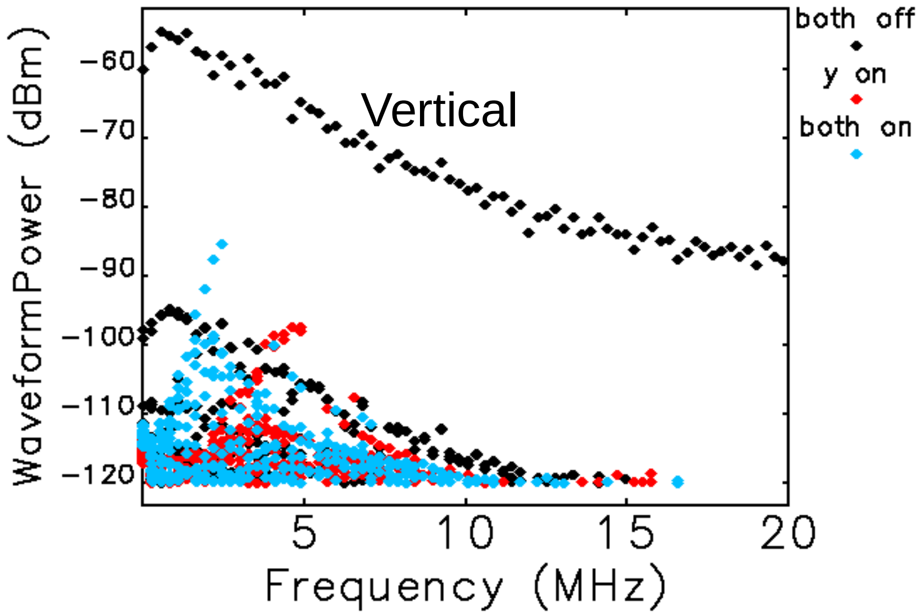


Results: 40m lattice, no gaps

- Very strong vertical instability
- Vertical feedback still very effective, but leads to horizontal instability
- Can't completely suppress both planes at once

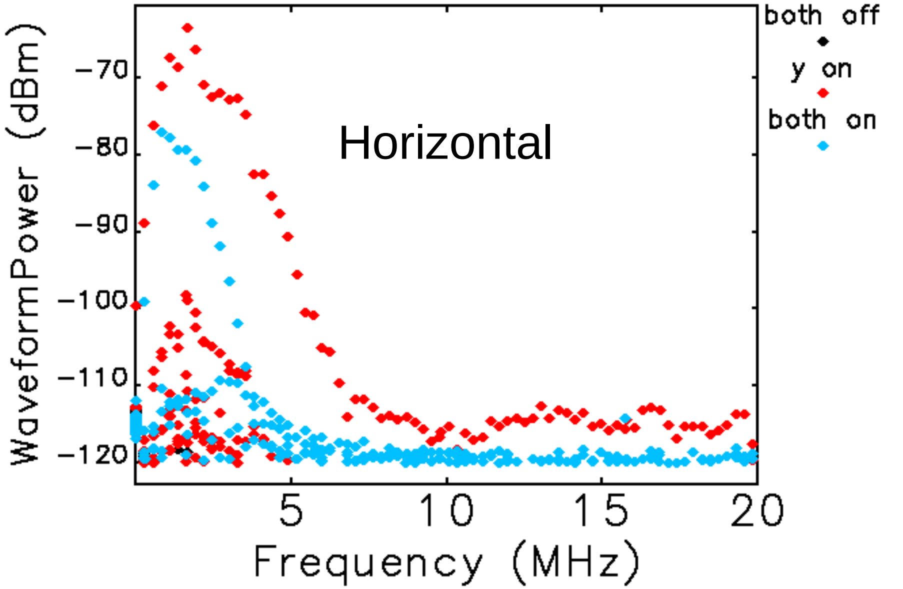




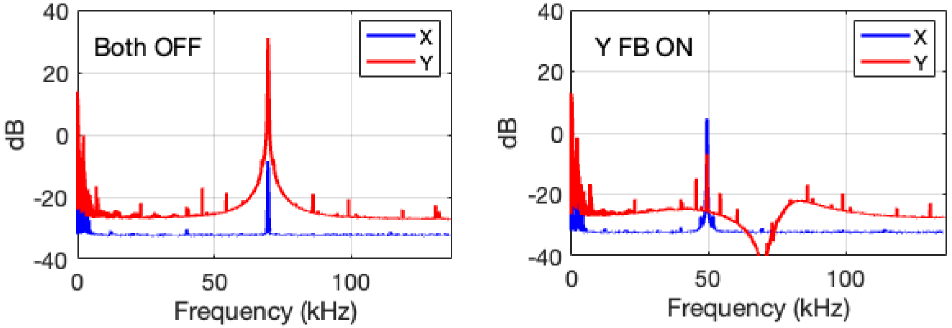


Results: 11m lattice, no gaps

- Very similar to 40m case (!)
- Can't suppress both planes at once

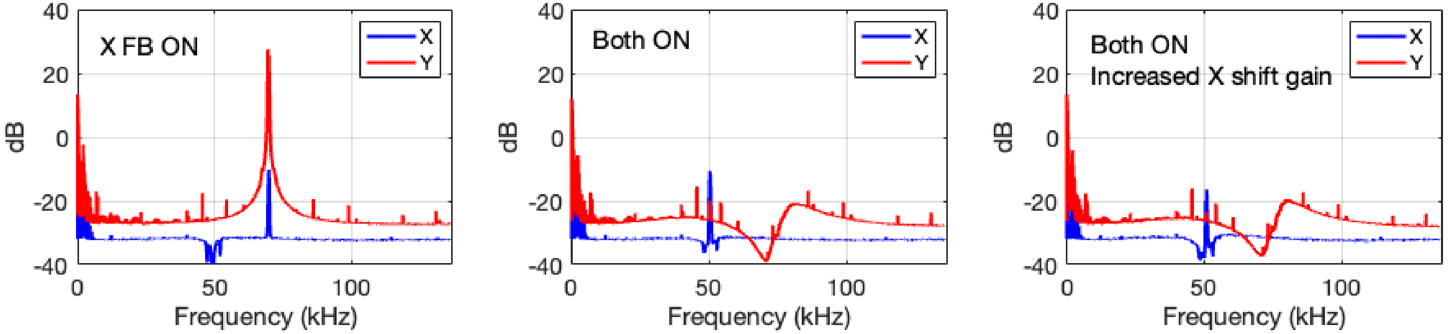


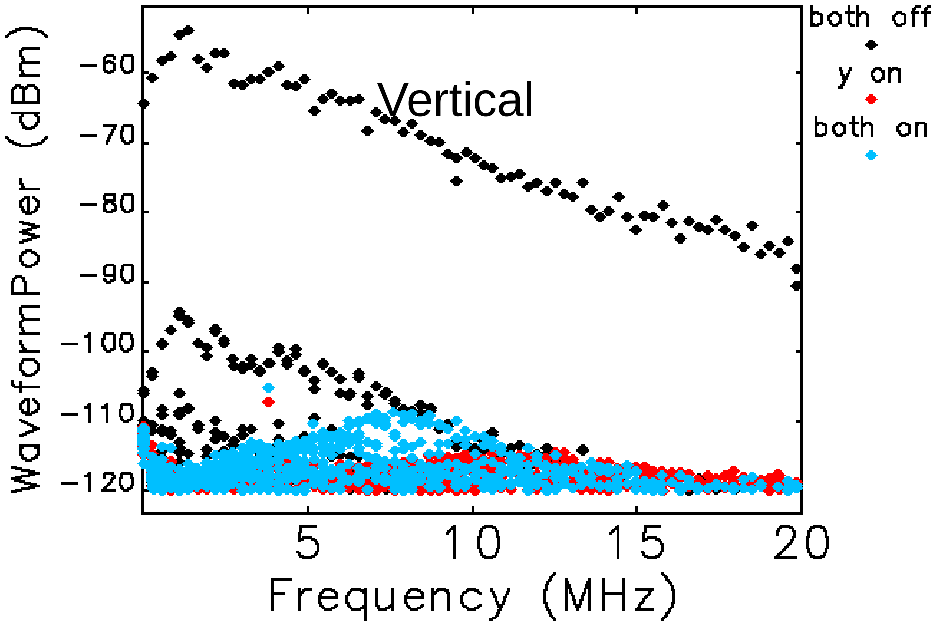
Averaged Spectrum from Dimtel



Low BetaY lattice
900 nTorr, No bunch gaps

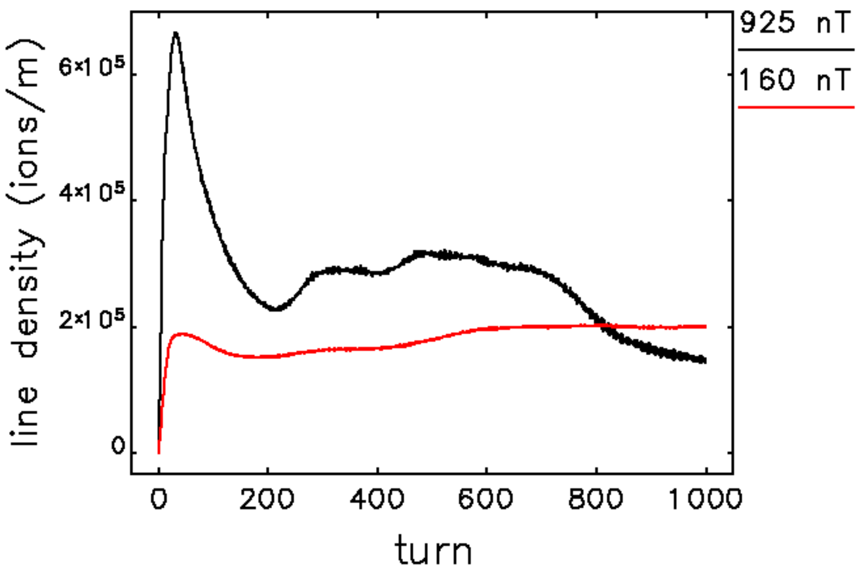
Could not stabilize X-plane when Y feedback is ON

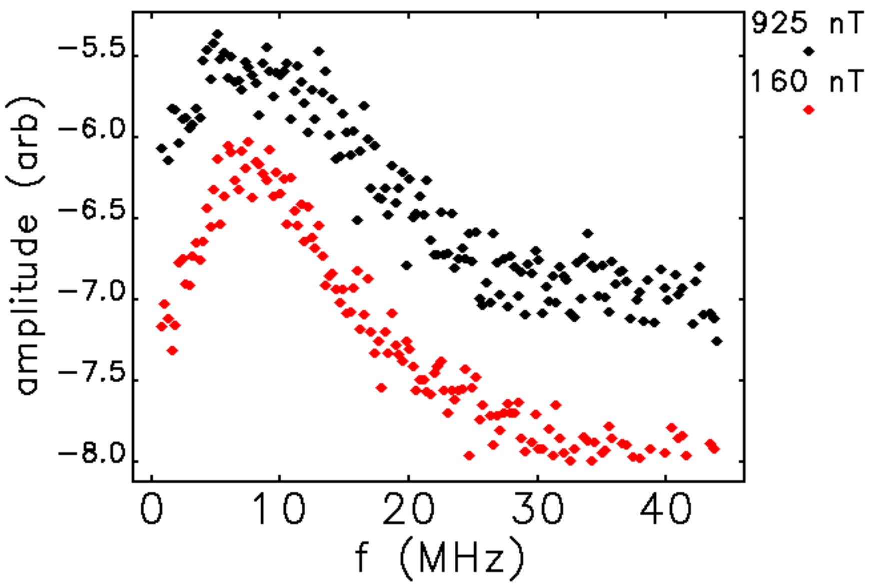


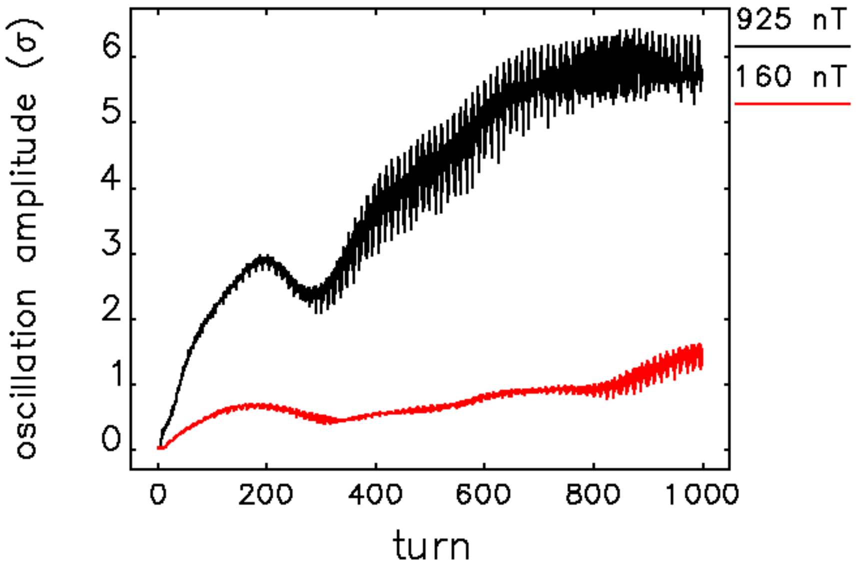


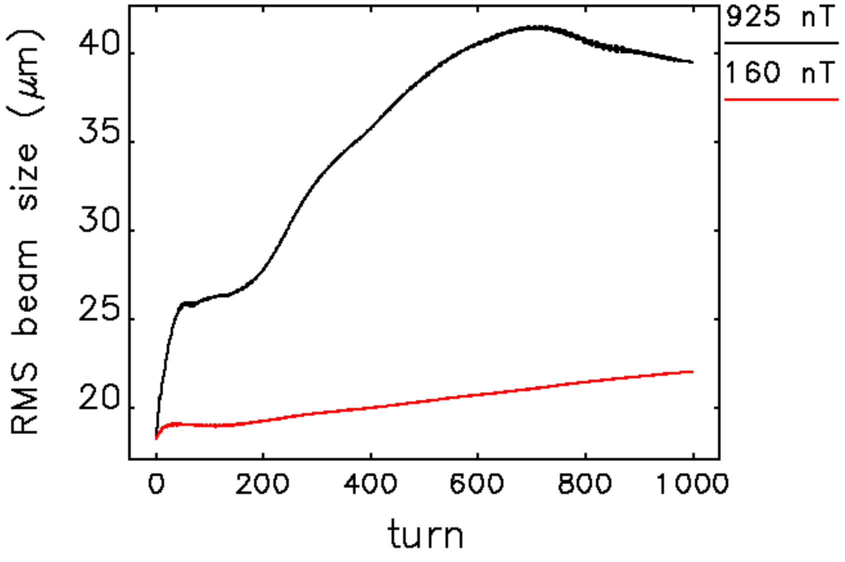
Simulations for S35 gas injection: Gaussian kick method

- Underestimated instability for S25 experiment
- Much stronger instability predicted than for S25
- Beam size blowup predicted even for low pressure case
- NB- Instability in units of original beam sigma









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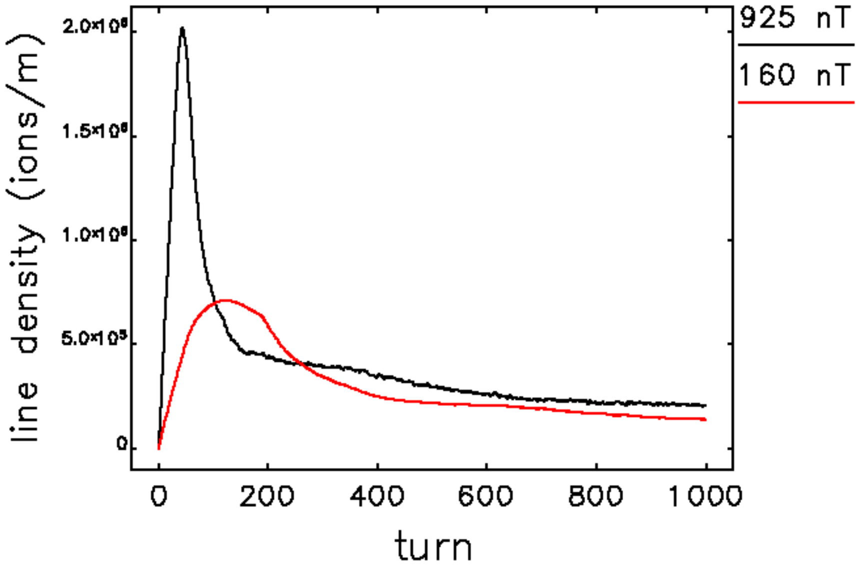
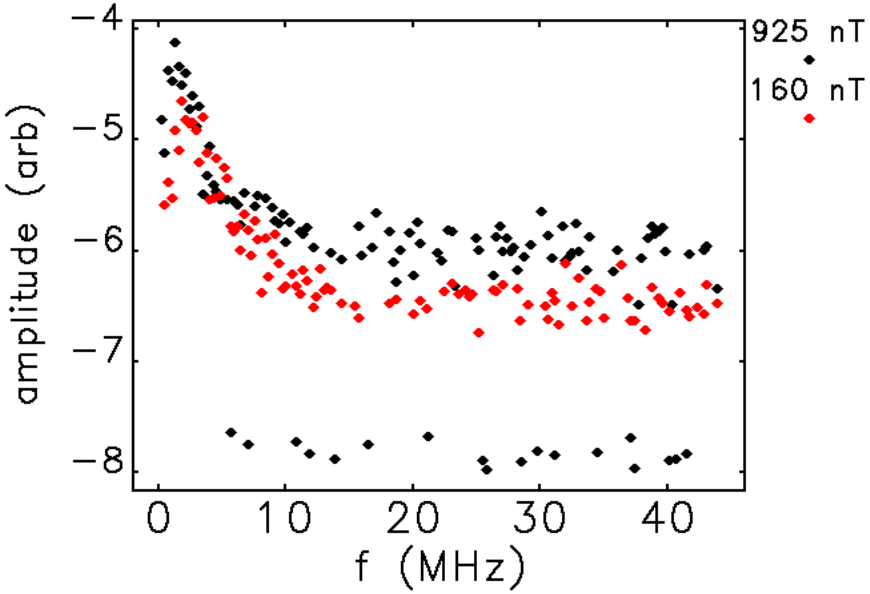
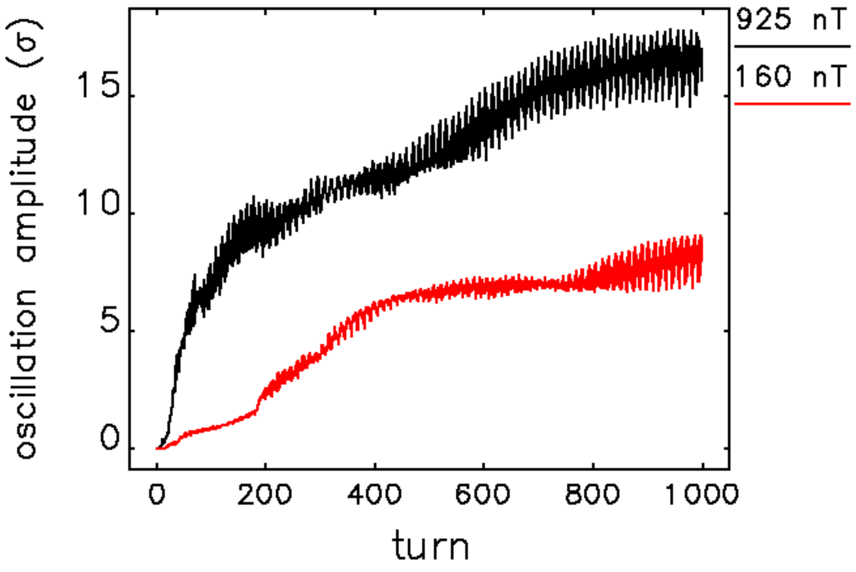
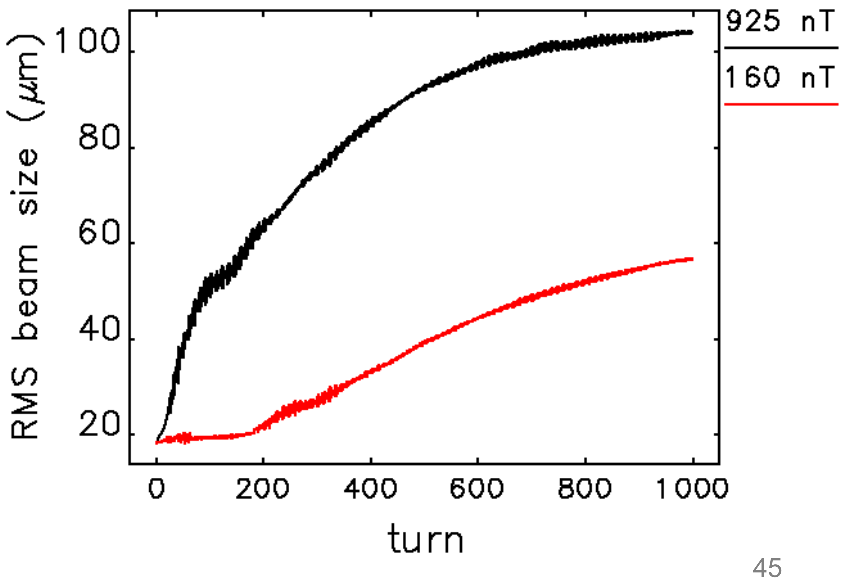
Simulations for S35 gas injection: bi-Gaussian kick

- Even stronger instability
- Very low ion frequency, due to huge beam size blowup









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