

Fast Ion Instability at CESR-TA

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What is Fast Ion Instability? (1)

- FII (sometimes abbreviated as FBII, or Fast Beam-Ion Instability) is a multi-bunch effect for electron beams
- Electrons traversing the beamline in a linac or circulating in a storage ring ionize residual gas to produce ions
- Positively charged ions are trapped in the potential well of the electron bunch train
- Transverse motion of the lead bunch in the train is transferred to the ions and then from the ions to the next bunch in the train
- Resulting instability limits the total charge in each bunch and the number of bunches in the train

$$\omega_{i,x(y)}^2(s) = \frac{2\lambda_e r_p c^2}{A} \frac{1}{\sigma_{x(y)}(s)[\sigma_x(s) + \sigma_y(s)]}$$

What is Fast Ion Instability? (2)

- Seminal paper by Raubenheimer and Zimmerman (1995)
- The nature of the instability and the traditional analysis model (called linear model) resembles beam breakup due to transverse wake fields
- The force between the beam and ions is assumed to be linear, a fair approximation when coherent ion oscillations are smaller than beam size
- Instability mechanism is the same in linacs and storage rings assuming ions are not trapped from turn to turn
- In a storage ring, having a long charge-free gap at the end of the train prevents multi-turn ion trapping
- The number of neutral gas molecules is assumed to be large compared to the ions generated during passage of the entire train

Interesting features of FII

- In storage rings, ions are generated by both synchrotron radiation and collision; typically the photoelectric cross section is larger than the collisional cross section
- But radiation-generated ions are equally distributed between the beam and the chamber wall, and because of low density, can be ignored as a first approximation
- If the ions do not have the same frequency (as assumed in seminal paper), but rather a spread, Landau damping reduces instability growth rate by factor of 2-3
- Similarly, a tune spread in the electron beam (e.g. from chromaticity and energy spread) would also suppress the instability
- Ions must have mass larger than critical value to be trapped by electron beam; CO is typically most important, due to its mass and cross section

What is CESR-TA?

- The Cornell Electron Storage Ring (CESR) was used as a e^+e^- collider ($\sqrt{s} = 10$ GeV) in the past (1979-2008)
- CLEO (the detector associated with CESR) was the longest running experiment in the history of particle physics; ended when it was no longer competitive with B factories like BaBar and Belle
- CESR installed sets of wiggler magnets in the early 2000s to allow operation at lower energies for the CLEO-c project
- After the end of CLEO, CESR is mainly a source of high-energy electrons used by the Cornell High Energy Synchrotron Source (CHESS) to generate X-rays
- Additionally, CESR is now a test accelerator (CESR-TA or CTA): a testing ground of damping rings for a future international linear collider
- CESR-TA has a few weeks of operations per year, depending on available funding
- Studies provide insight into phenomena that are likely to limit the performance of next-generation colliders and storage rings (e.g., intra-beam scattering, electron cloud growth, and FII)

History of Observations

- FII has been observed at the Advanced Light Source and Pohang Light Source (1997-1998) by artificially increasing the neutral gas pressure with helium injection into the vacuum chamber, or by turning off vacuum pumps to induce pressure buildup
- This was followed by a period of relative dormancy in the field, at least experimentally
- As observed in PLS (2006), SOLEIL (2007), and Shanghai Synchrotron Radiation Facility (2010), when the vertical beam emittance is reduced, the trapping potential increases and beam-ion instabilities can occur at nominal vacuum pressure

Status of the field a.k.a. Why bother?

- Two of the striking features of FII are growth in bunch centroid vertical oscillation along the train, and growth in the vertical beam size along the train
- Several light sources have injected gas at high pressures to study this, but using crude methods because of limited instrumentation; additionally, while there has been qualitative agreement with theory, quantitative agreement has been lacking
- The XBSM and CBPM of CTA gives us better means of measurement; developing a simulation tool that provides better agreement with data is also useful
- Experiments like CLIC and ILC care about FII because of long trains and small beam sizes; they have done extensive simulations to propose mitigation methods
- Having recent experimental results from CTA could add valuable information

Simulation Efforts

- Starting point: FASTION code developed by Giovanni Rumolo et al to study FII at CLIC
- Electrons and ions are treated as macroparticles; assumes the bunches to be infinitely thin charged disks; ions are assumed to be motionless while they feel the bunch field kick
- Electron-ion interaction points are given as input; this is where ions are generated and then made to interact electromagnetically with the beam
- At each interaction point, calculations are performed using a grid in x and y; ion density is determined by cross section, beam charge, and local gas pressure
- Beam fields are determined by beam width and the Bassetti-Erskine formula
- Only transverse motion is calculated at interaction points; longitudinal motion of ions are ignored
- Code has ability to use wake fields (resistive wall etc), and apply initial kick to bunch train (constant, sinusoidal, random), but these are currently not being used

Updates to FASTION code (1)

- To make code work for ring (rather than linac), allow multiple turns which use the same set of beam-ion interaction points, but with the longitudinal positions updated appropriately
- In original code, electrons are transported linearly using beta functions and assuming fixed phase advance from one point to next
- Initialize 6D coordinates for each beam particle using random Gaussian distribution and appropriate matching conditions (which depend on emittance, twiss parameters α and β of starting point, momentum compaction, energy spread, etc)
- Apply RF kick and chromaticity at a fixed point in the ring (where dispersion is low) once per turn; chromaticity causes tune spread of beam, which causes damping
- Radiation damping and quantum excitation applied once per turn at a point with low α_x and α_y
- Output contains turn-by-turn beam properties for each interaction point and bunch

Relevant Basics of Accelerator Physics (1)

- $x(s) = x_{\beta}(s) + \eta_x(s)\delta$
- $x_{\beta}(s) = A\sqrt{\beta_x(s)} \cos(\varphi(s) - \varphi_0)$
- $\alpha(s) = -1/2 d\beta/ds$
- Emittance: a measure for the average spread of particle coordinates in position-and-momentum phase space → tells us about luminosity of colliders for particle physics and brightness of synchrotron radiation sources
- Energy spread (δ) = dp/p_0 , dp is the maximum difference from the reference z momentum p_0
- Momentum compaction factor = $(dL/L_0)/\delta$, dL is the deviation from L_0 (ideal path length)
- Betatron oscillations: transverse oscillations of a stored beam about the ideal closed path, caused by the focusing properties of the magnetic field
- Synchrotron oscillations: electrons in a bunch oscillate in longitudinal position and energy relative to an ideal reference particle at the center of the bunch
- Dispersion (η) is defined as the change in particle position with fractional momentum offset
- Tune (ν) refers to the fractional part of the oscillation frequency

Relevant Basics of Accelerator Physics (2)

- RF kick: electrons lose energy by synchrotron radiation, which is then compensated by energy gain from RF cavities; only changes δ (hence the longitudinal momentum), not x' or y'
- Radiation damping: inducing synchrotron radiation to reduce the particles' momentum, then replacing the momentum (via RF kick) only in the desired direction of motion (i.e. longitudinal)
- Quantum excitation: damping of all oscillation amplitudes is effectively arrested because of continuous excitation of the oscillations by the noise in the electron energy (because synchrotron radiation is quantized)
- $x_\beta = \lambda_x \cdot x_\beta + r \cdot \sigma_x \cdot \sqrt{(1-\lambda_x^2)}$, where λ_x is the damping coefficient, r is a random number, and σ_x is the equilibrium value of x_β
- Similar formulas apply for the other coordinates

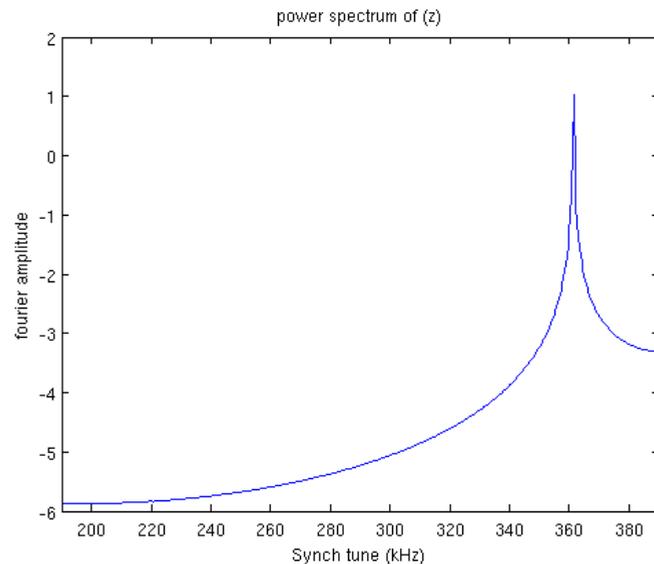
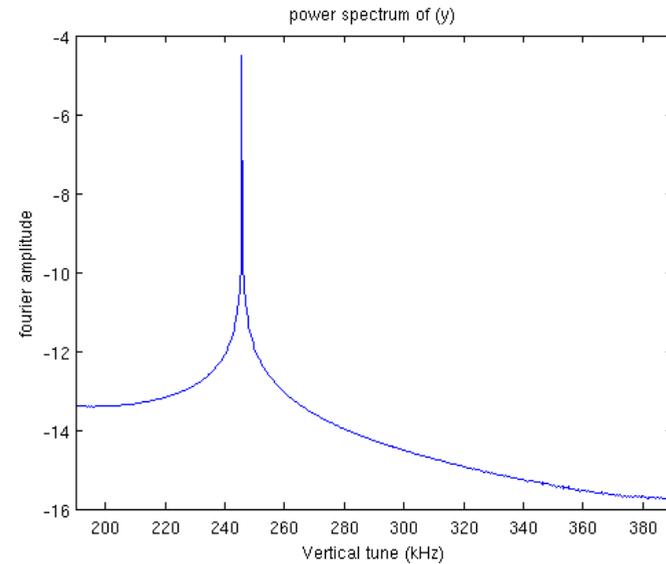
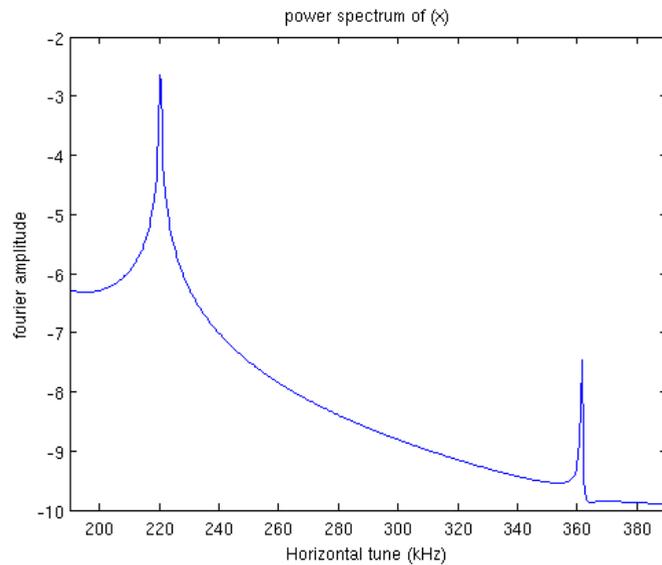
A Note On Chromaticity

- A bunch of charged particles has a tendency to disperse over time → important to include magnets along the beam line in order to keep the beam well controlled, and tightly bunched
- When quadrupole magnets are used, this is known as beam focusing
- Can lead to problems if the bunch contains particles of differing energy → low energy particles will be focused much more tightly than high energy particles (exactly in the same way that longer wavelengths of light will be brought to a focus more quickly than short wavelengths)
- In a storage ring, a high degree of chromaticity can lead to instabilities in the beam's motion, which will result in large movements of the beam → beam can hit the wall of the chamber and be lost and/or damage the machine
- It is advantageous to correct the chromaticity introduced by bending and focusing magnets → can be done with sextupole magnets
- Non-zero chromaticity means that each particle's tune depends on energy → if there is a range in energies, there will be a range in tunes

Nominal Lattice for Simulation

Parameter	Value
Energy	2.085 GeV
Bunch spacing	4/14 ns
Horizontal emittance	2.6 nm
Vertical emittance	0.02 nm
Circumference	768 m
Synchrotron frequency	28.78 kHz
Revolution frequency	390.1 kHz
Energy spread	8.126e-4
Momentum compaction	6.794e-3
Horizontal chromaticity	1.238
Vertical chromaticity	1.093
Horizontal damping/turn	4.532E-05
Vertical damping/turn	4.539E-05
Longitudinal damping/turn	9.076E-05

Tests with RF kick on and chromaticity off (1)

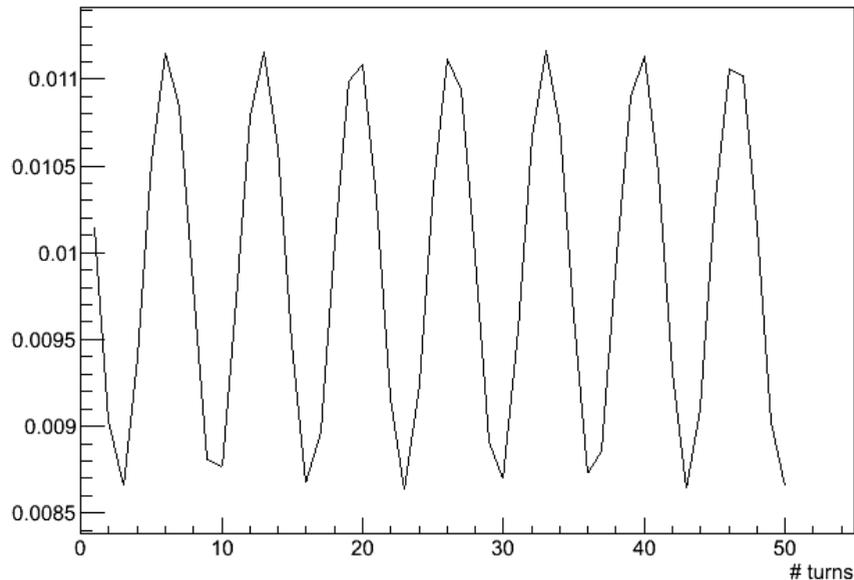


- Plots show the FFT of a single particle's position coordinates after 1024 turns
- The x, y and z tunes show up at the right places

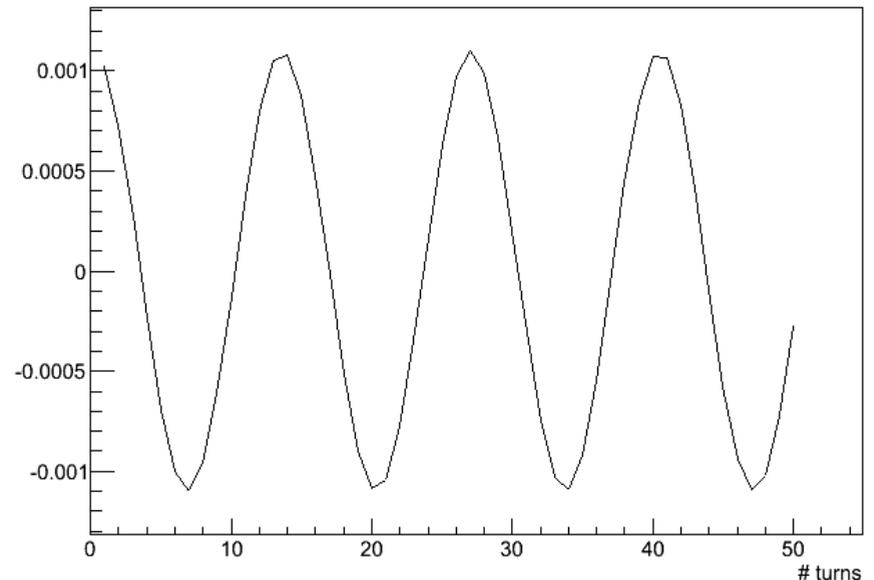
Tests with RF kick on and chromaticity off (2)

- Made the bunch length longer by increasing the initial z for each particle by 10%; The bunch length (of bunch 1) vs turn for a fixed point can be seen in bottom left plot. The frequency is twice the synchrotron frequency, as expected.
- Made the z offset non-zero by doing adding 1 mm to the initial z of each particle; The z centroid (of bunch 1) vs turn for a fixed point can be seen in bottom right plot. The frequency is the synchrotron frequency, as expected.

Bunch Length



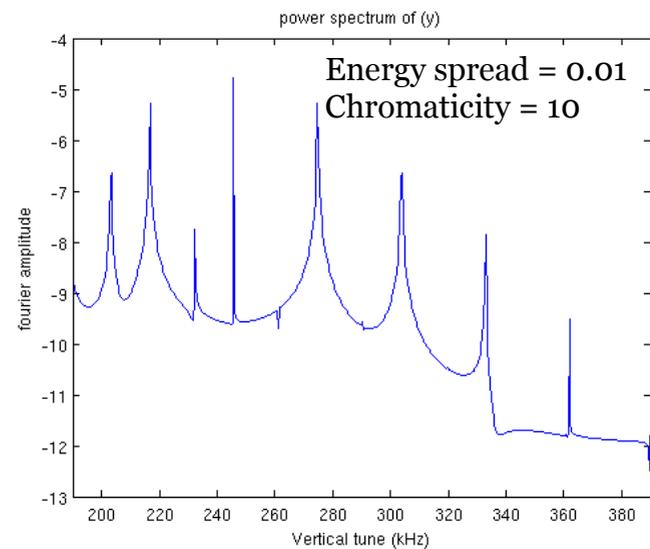
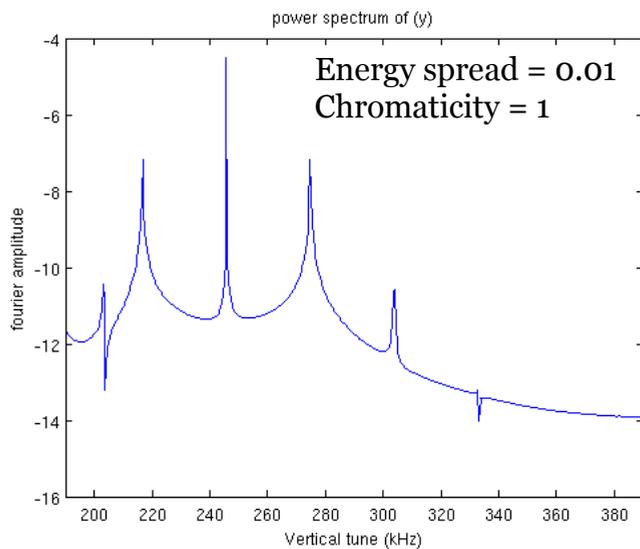
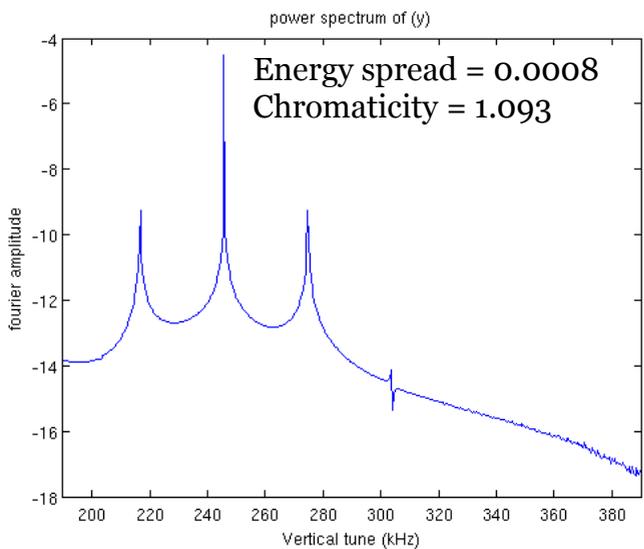
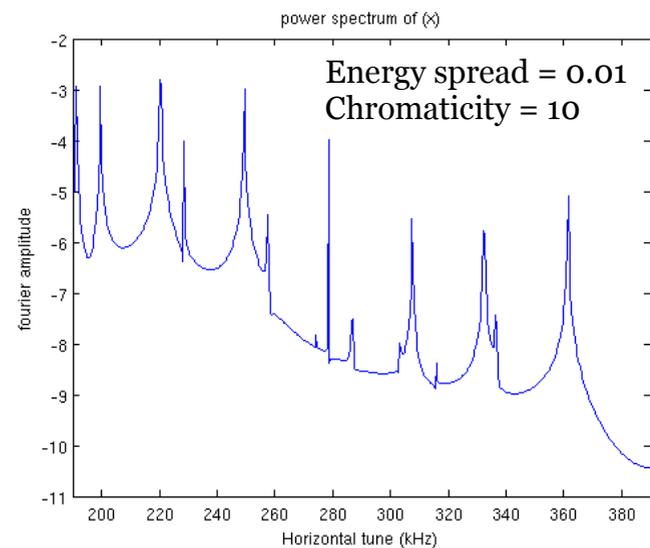
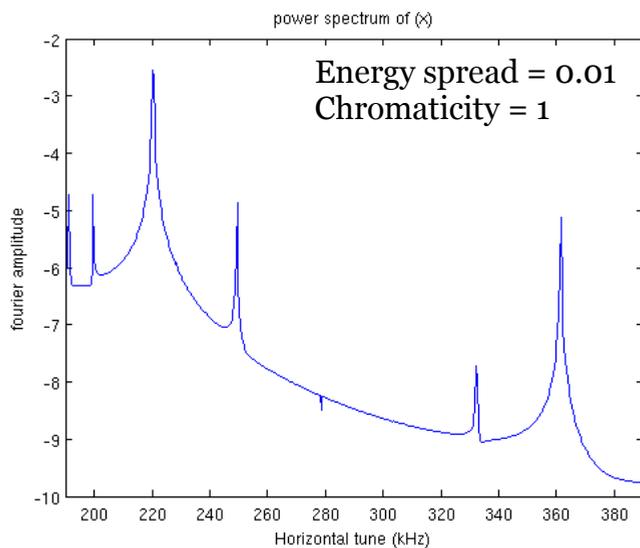
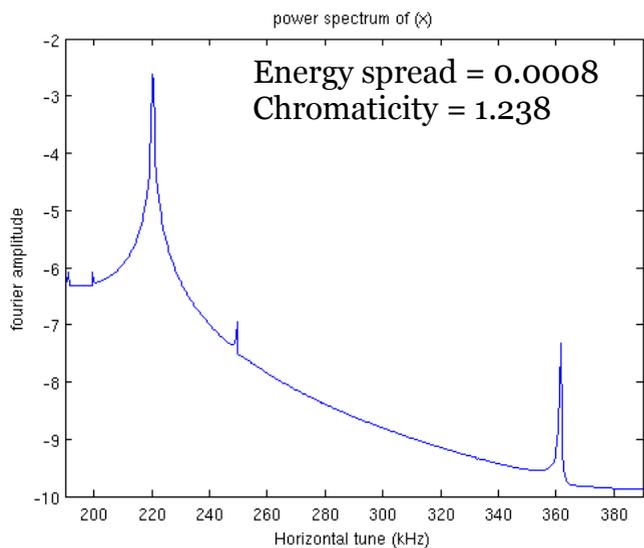
z offset



Test with RF kick off and chromaticity on

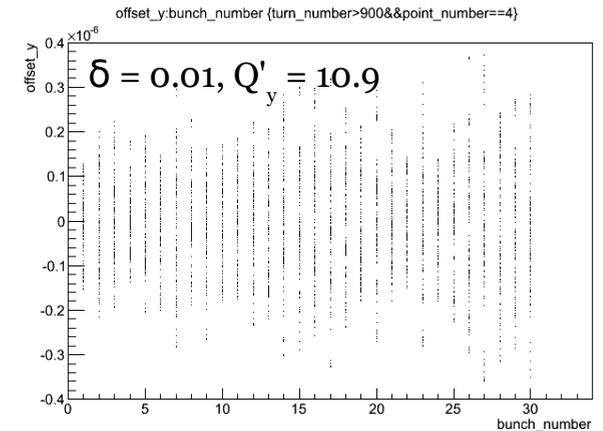
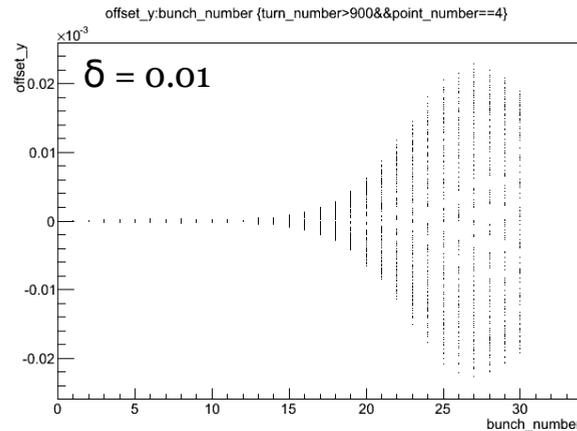
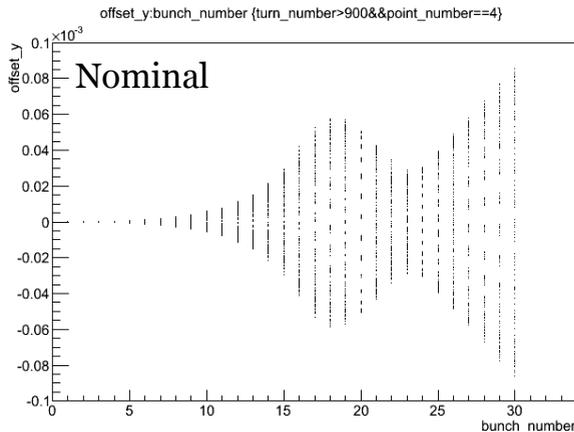
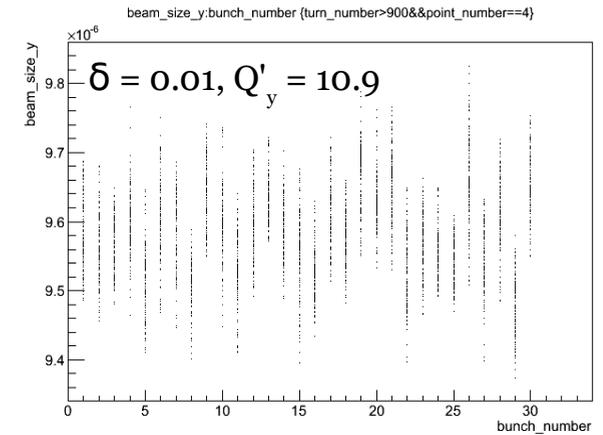
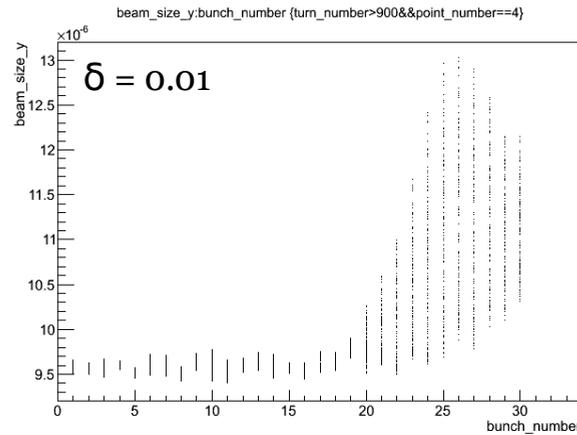
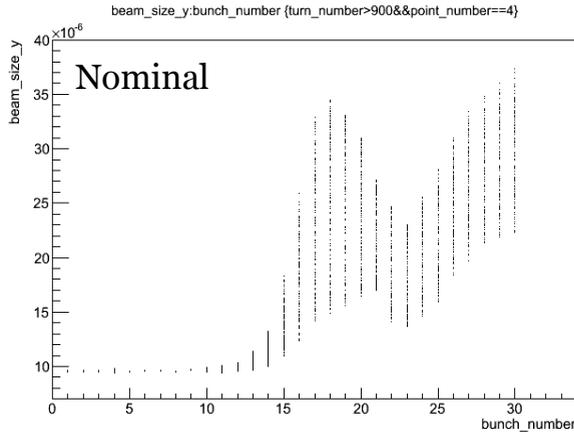
- Initialize 3 particles in a special way: one to have a δ of 0, the other two to have a δ of +/- energy spread
- Since the RF kick is off, the δ coordinates will stay at initial values
- Set the chromaticity to 5 (for both x and y), and the energy spread to 0.01. Since $Q' = \Delta v/\delta$, expect a tune change of 0.05 (in both x and y)
- Track for 1024 turns and do FFT
- Particle 0: $v_x = 0.564$, $v_y = 0.630$
- Particle 1: $v_x = 0.515$, $v_y = 0.580$
- Particle 2: $v_x = 0.615$, $v_y = 0.680$
- Results are consistent with expectations

Test with both RF kick and chromaticity on



Chromatic damping

- When FII is turned on, chromaticity can help mitigate the growth in vertical beam size along the train (top row) and beam motion along the train (bottom row) through chromatic damping
- How effective this mitigation is depends on the value of chromaticity (Q') and energy spread (δ)
- For the nominal operating conditions, chromatic damping is not very effective; however, if energy spread and chromaticity are both increased by a factor of 10 (right column), it can prevent the instability

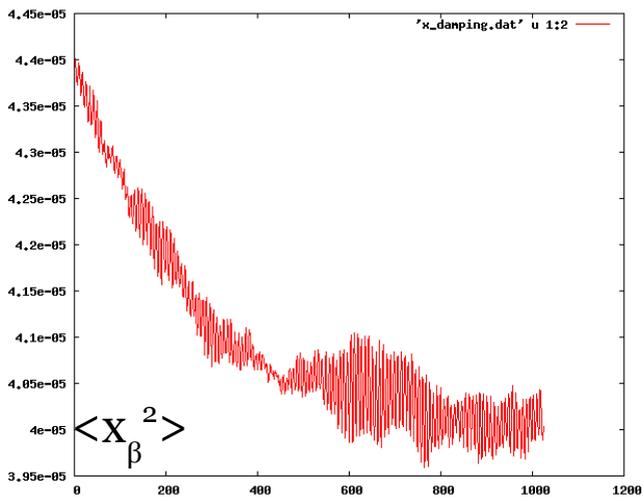


Applying Radiation Damping

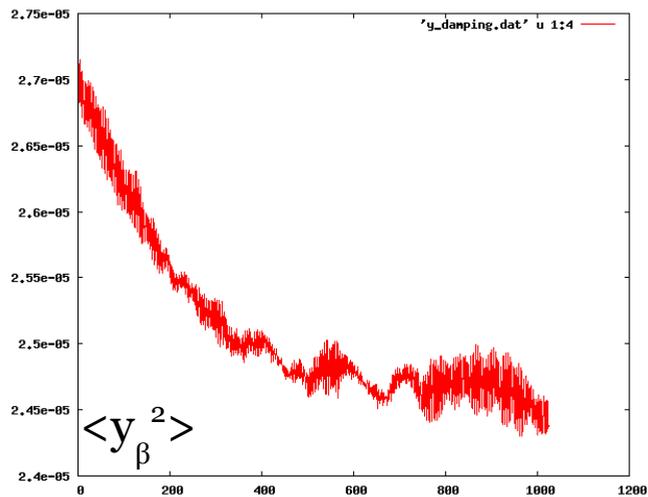
- Effect applied once per turn at a point in the ring with low α_x and α_y
- Dispersive component is taken out of transverse coordinates; all six coordinates are updated to account for radiation damping and quantum excitation [$x_{n+1} = \lambda_x x_n + r\sigma_x \sqrt{(1-\lambda_x^2)}$]; dispersive component is added back in
- To check: three different cases (x_damping, y_damping, z_damping), all with fast ion turned off
- For x_damping: start with horizontal emittance 1.1^2 times the equilibrium emittance; increase horizontal damping rate to 0.002 (in units of 1/# of turns) so that simulation does not take very long
- For y_damping: start with vertical emittance 1.1^2 times the equilibrium emittance; increase vertical damping rate to 0.002
- For z_damping: start with energy spread 1.1 times the equilibrium energy spread; increase longitudinal damping rate to 0.002

Consistency Checks

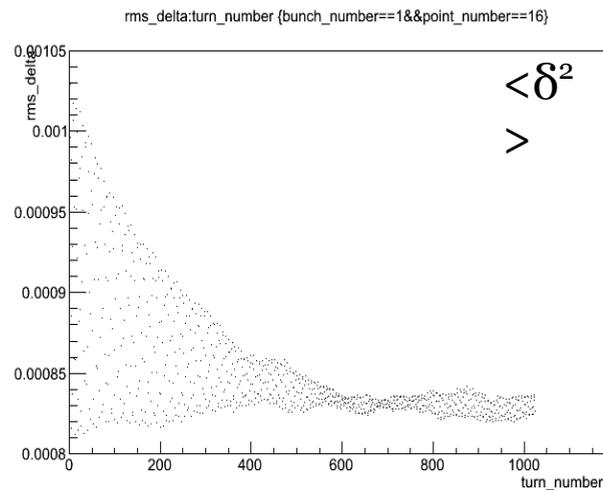
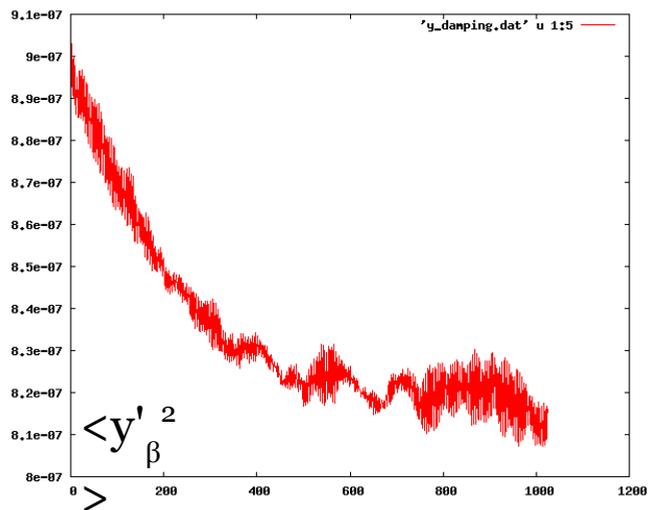
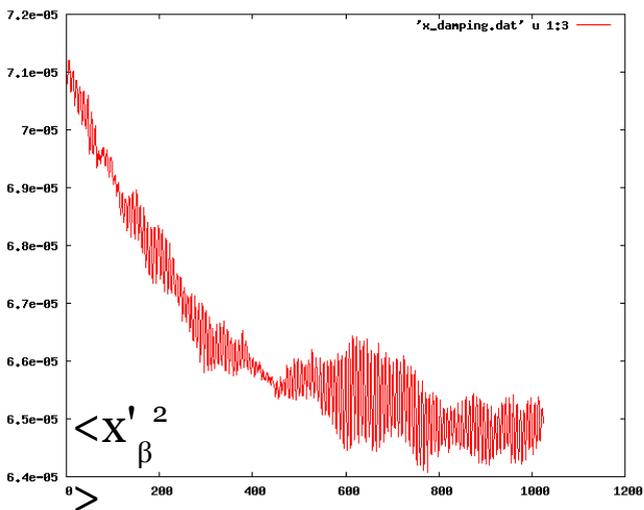
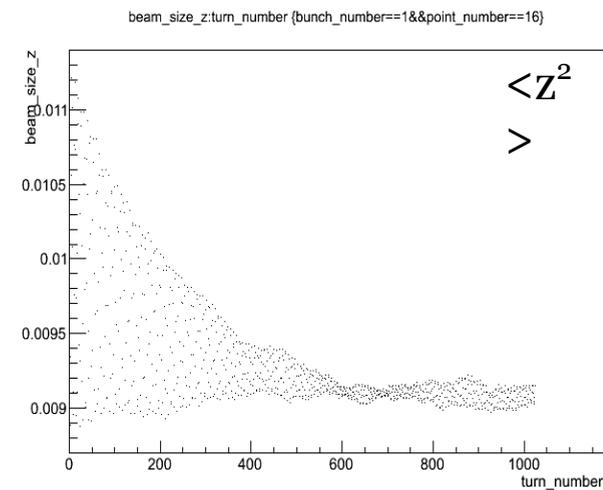
x_damping



y_damping



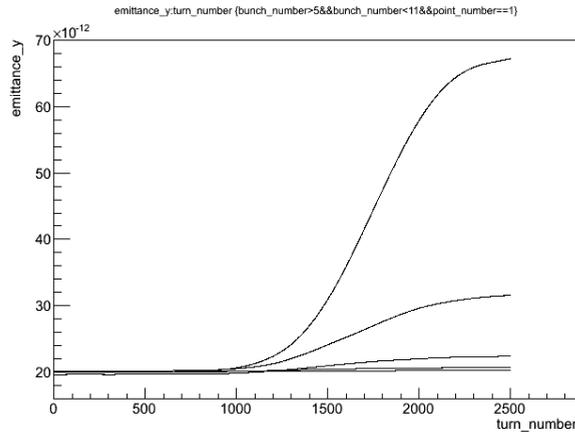
z_damping



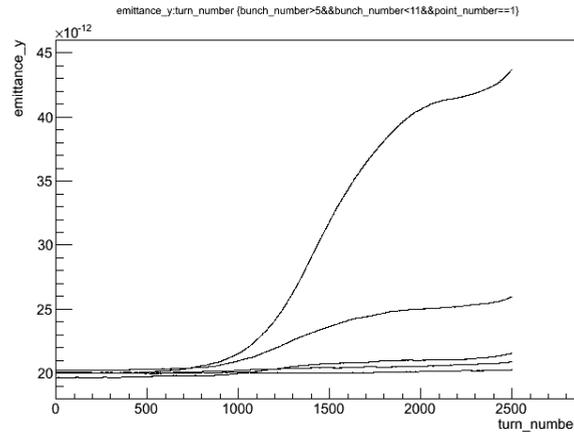
Effect of Radiation Damping

Look at vertical emittance vs turn number to understand the impact of radiation damping on fast ion instability growth

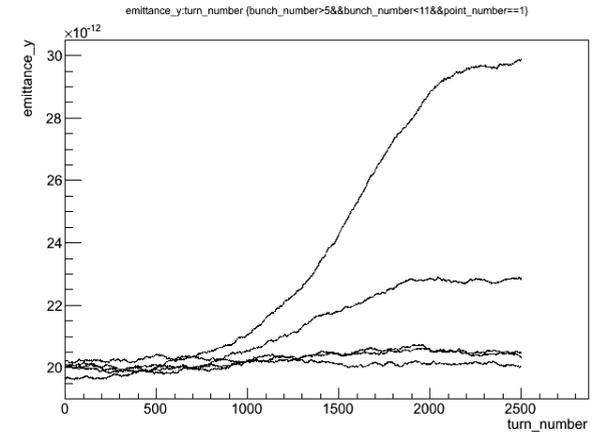
No Damping



Nominal Damping

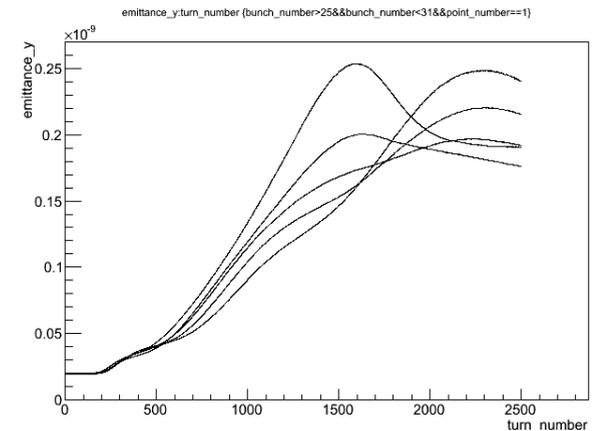
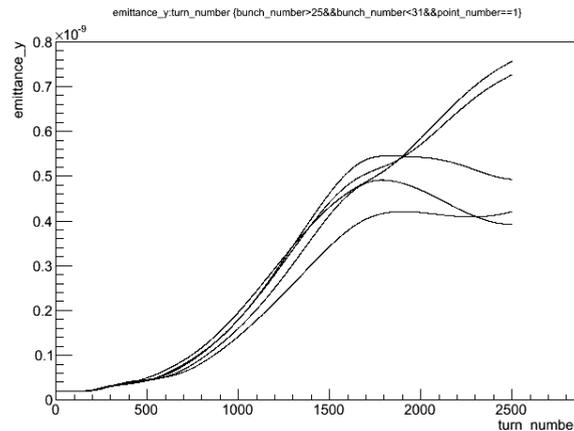
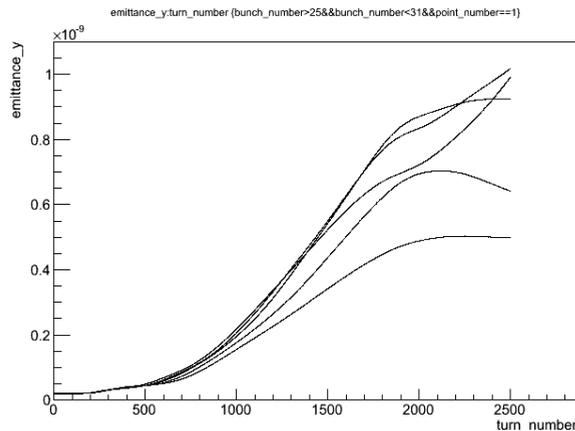


Damping x 10



Bunches 6-10

Bunches 26-30



Updates to FASTION code (2)

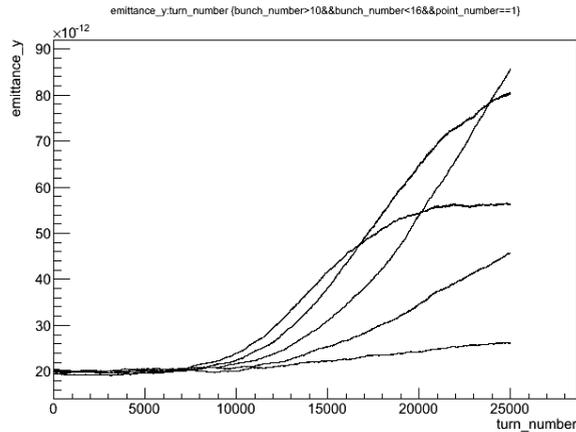
- Modify the code to allow the pressure to be different at different interaction points (i.e. not a constant value all along the ring)
- Specifically, the pressure is high at just one interaction point (where we inject a gas to study the effect of increased pressure)
- Introduce a feedback system that allows the transverse motion to be damped; this is done by using a two-point system (pickup and kicker)
- The appropriate feedback is calculated at the pickup (by recording the particle's transverse spatial coordinates), and then applied at the kicker
- $\Delta y'_k = G \cdot y_p / \sqrt{(\beta_p \cdot \beta_k)}$, where G is the feedback gain, p and k are pickup and kicker
- For weak damping, damping rate = $-G/2 \sin(\psi)$ turns⁻¹ (ψ is the phase advance between p and k) ; for optimal damping rate and no tune-shift, $\psi = \pi/2$
- So pick two interaction points with a phase difference of roughly $\pi/2$

Effect of variable pressure along ring

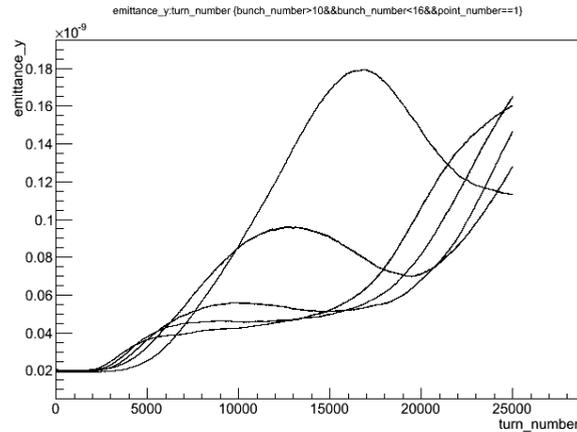
Look at vertical emittance vs turn number to understand the impact of injecting gas at a single point on fast ion instability growth

Bunches 11-15

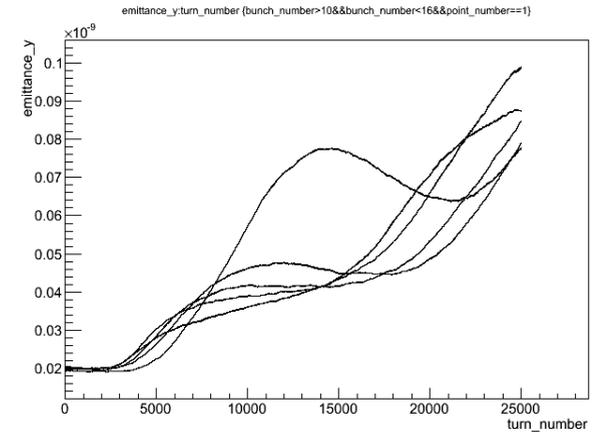
Uniform pressure (1 nTorr)



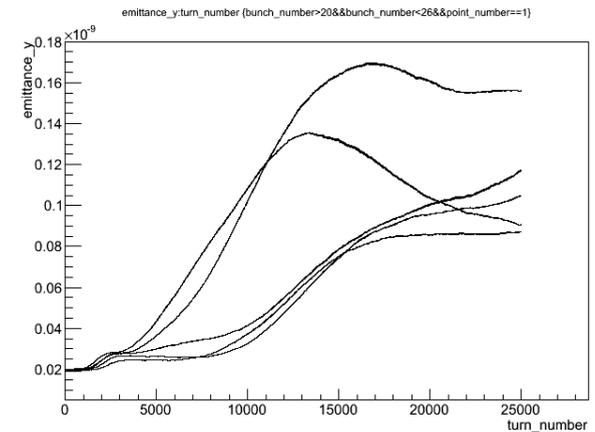
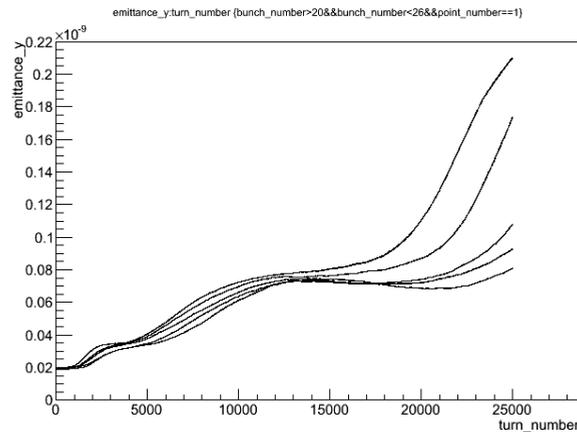
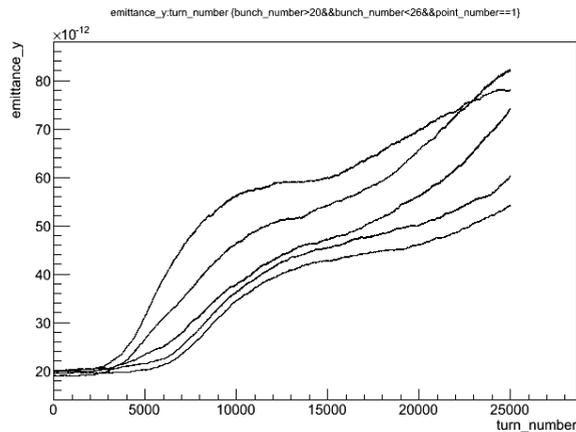
Added CO (10 nTorr)



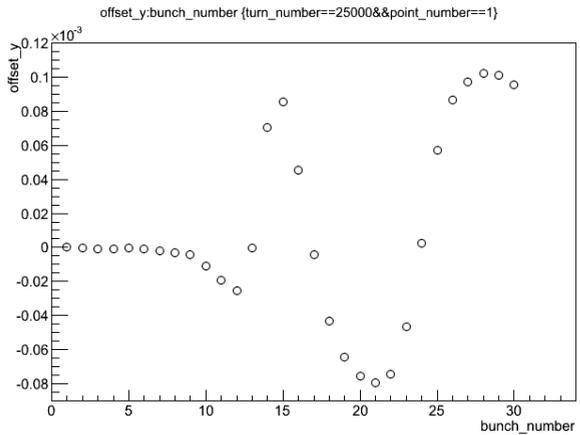
Added Ar (10 nTorr)



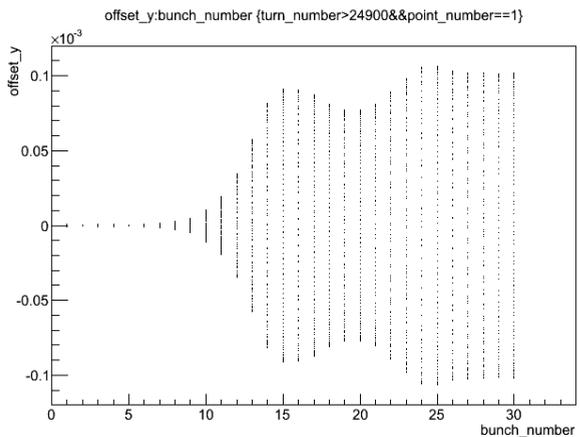
Bunches 21-25



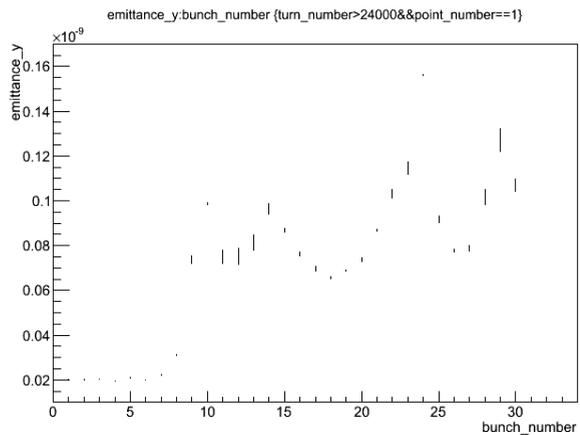
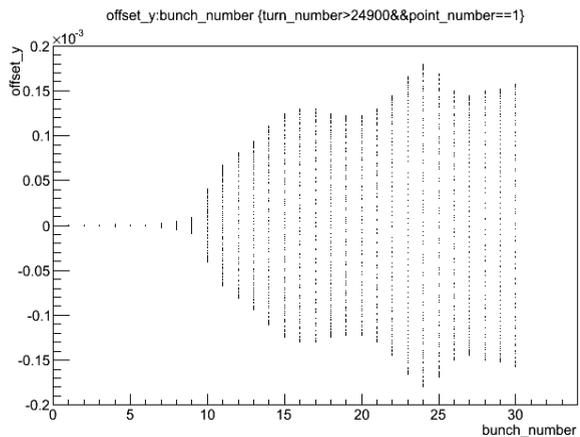
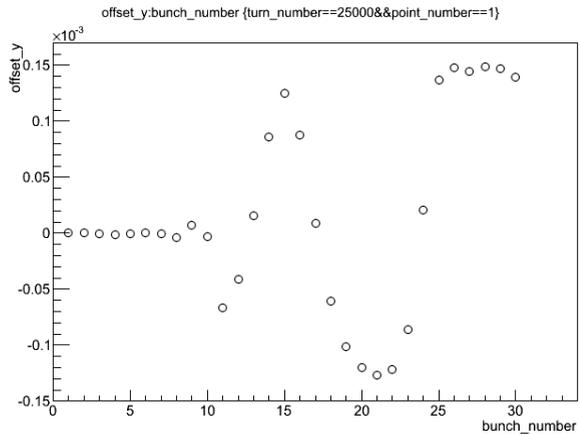
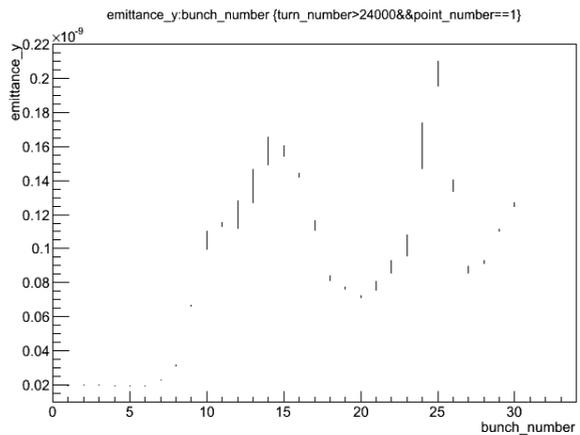
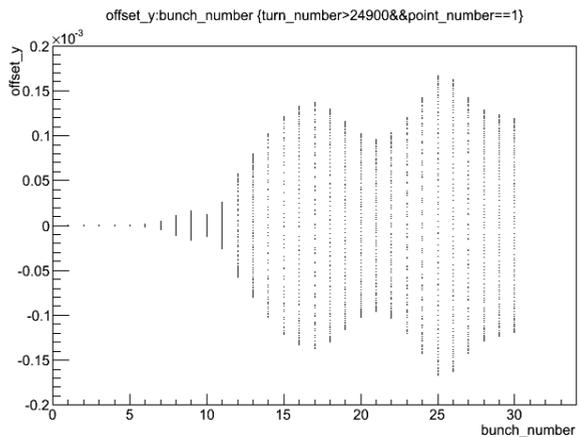
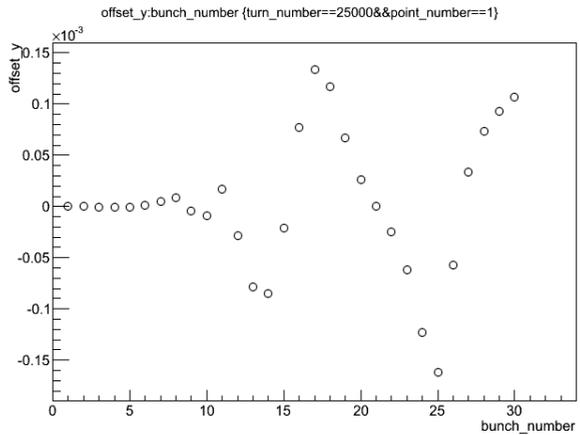
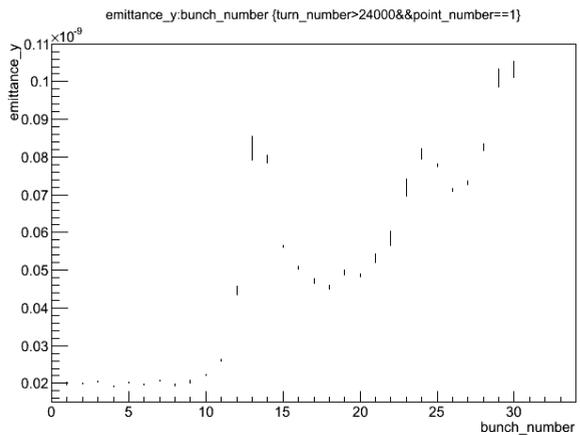
Vertical offset (1 turn)



Vertical offset (1k turns)

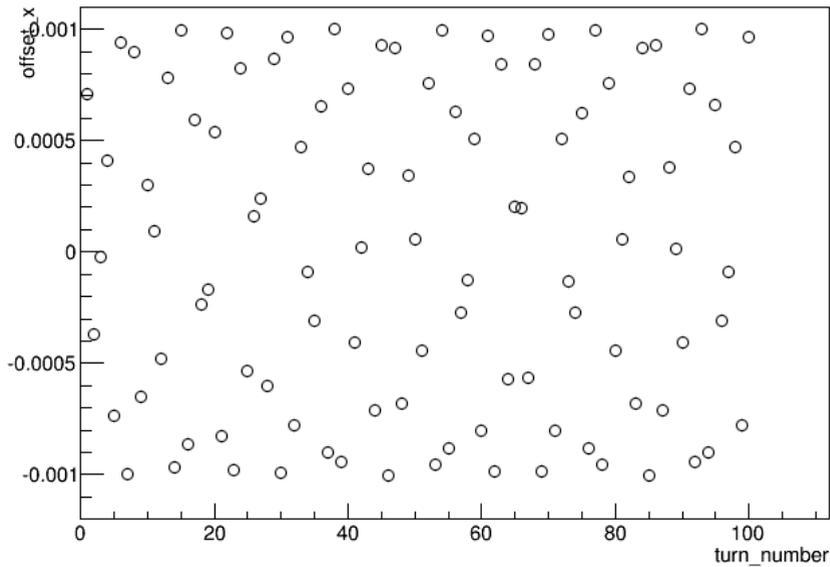


Vertical emittance

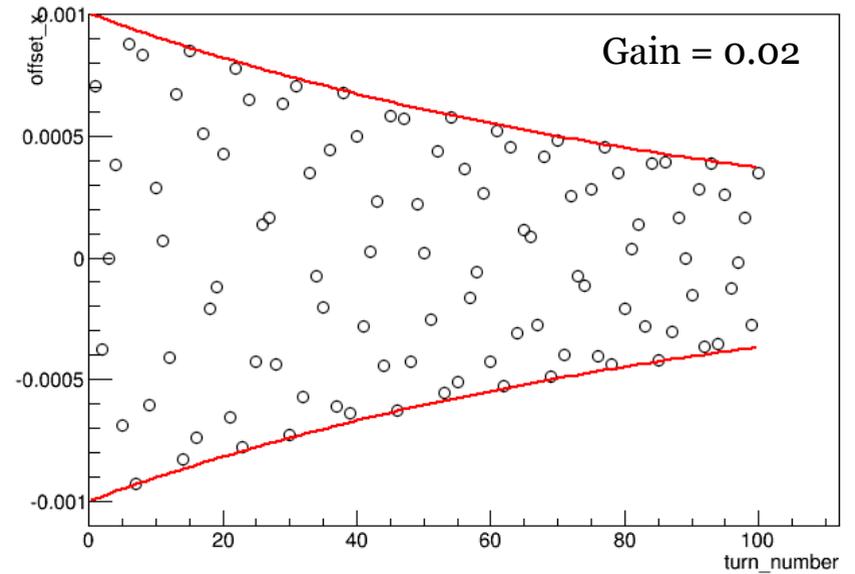


Consistency Check for Horizontal Feedback

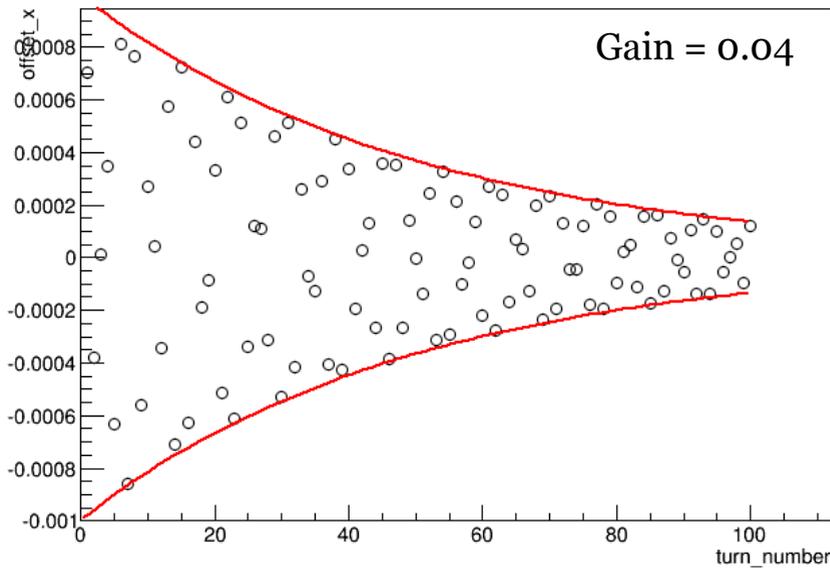
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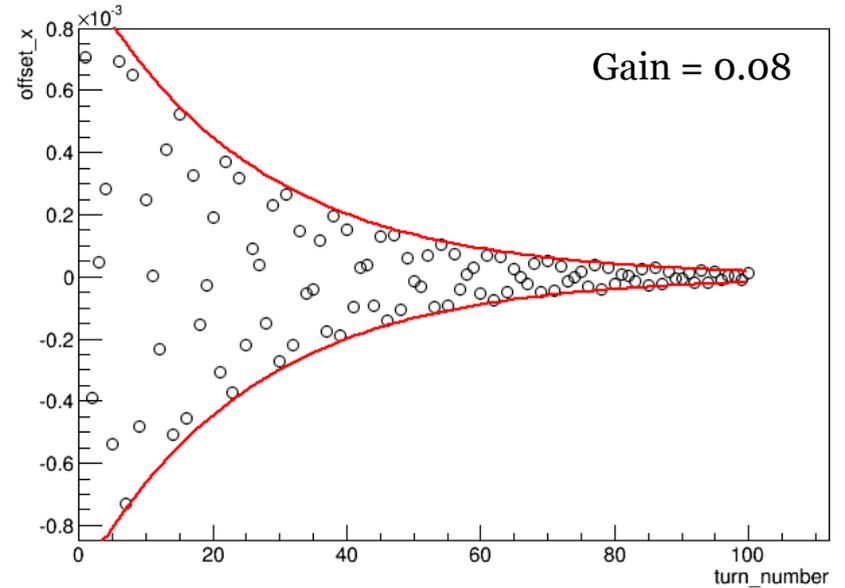
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offset_x:turn_number {bunch_number==20&&point_number==1}

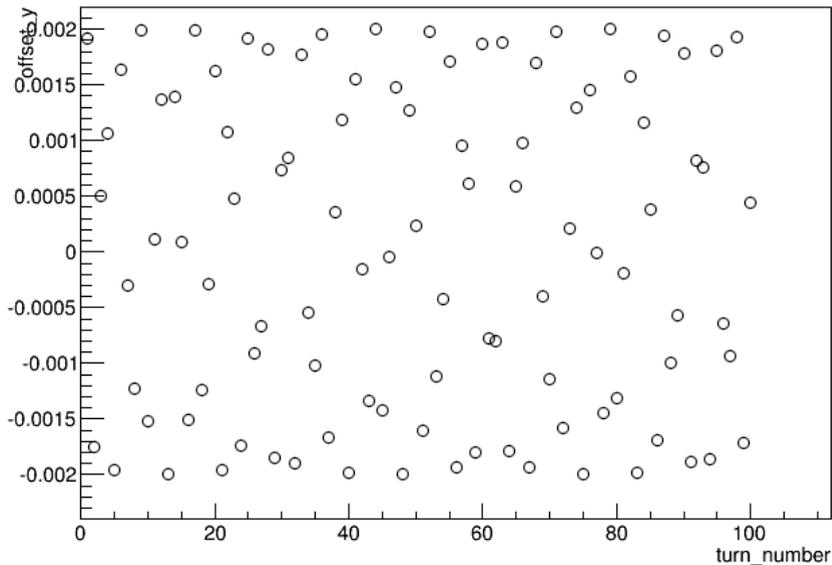


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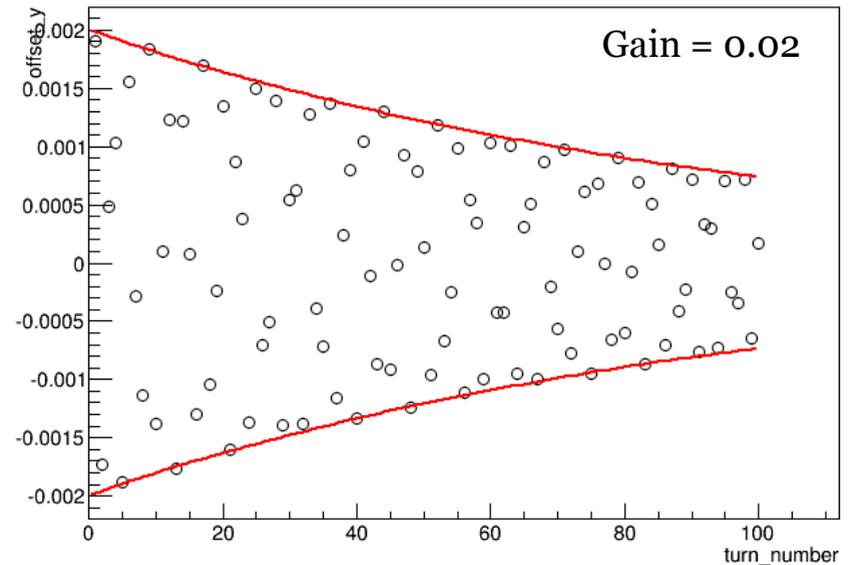


Consistency Check for Vertical Feedback

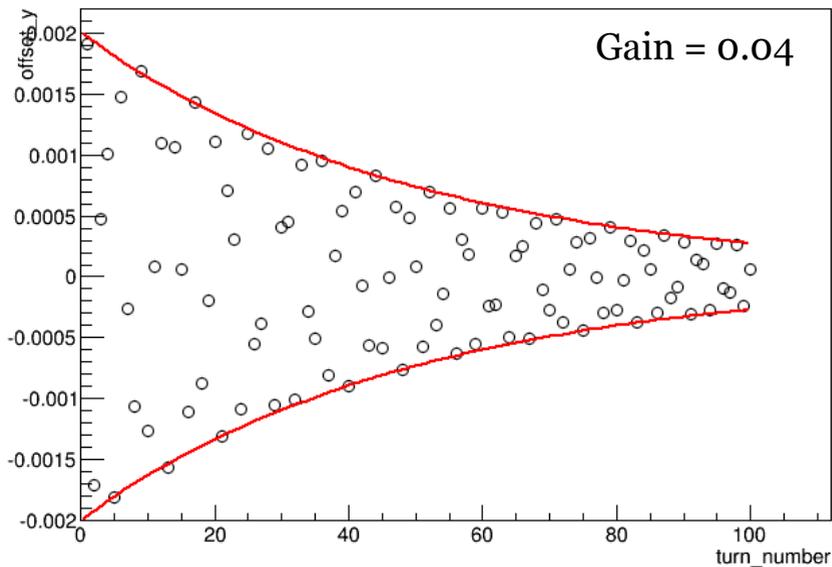
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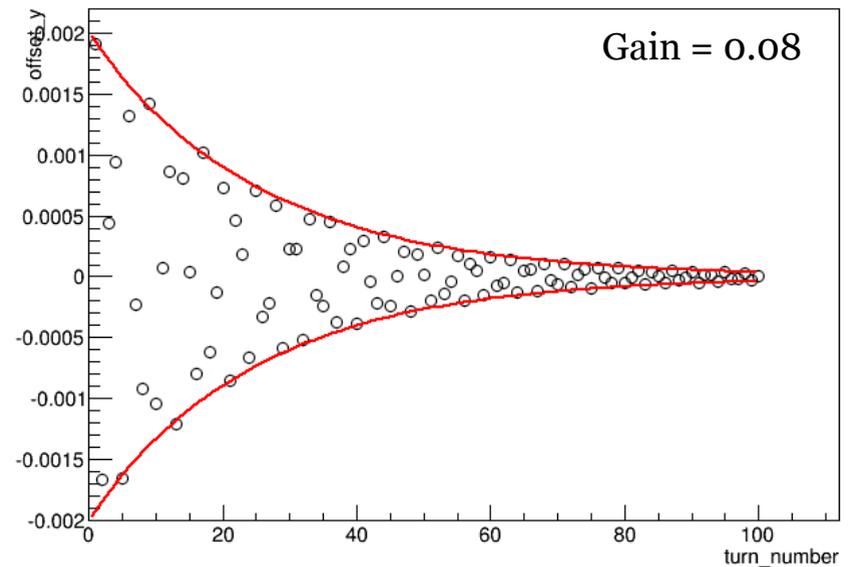
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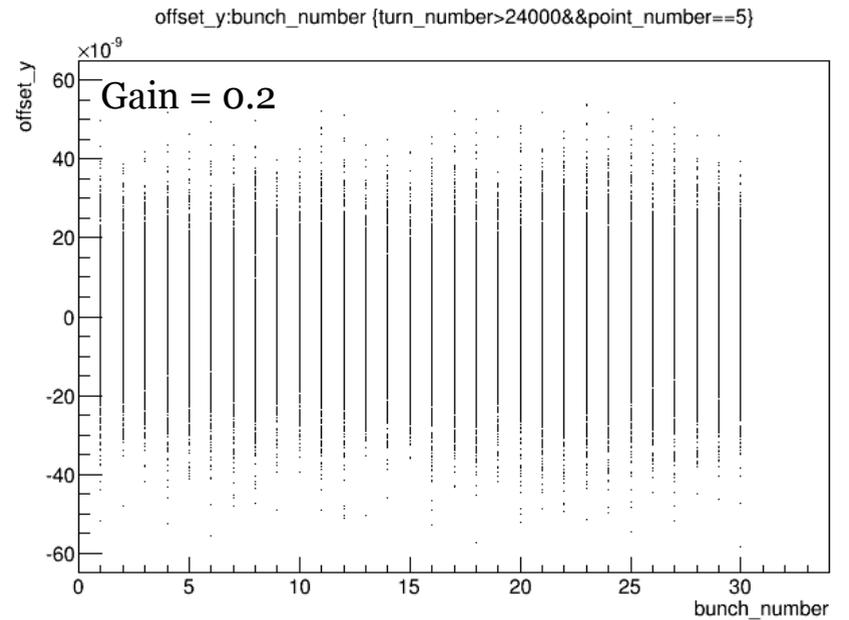
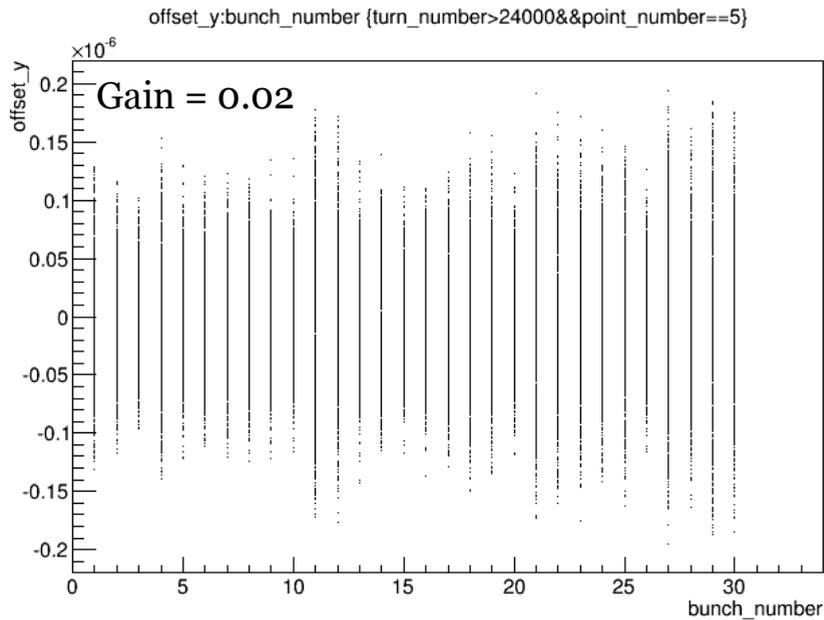
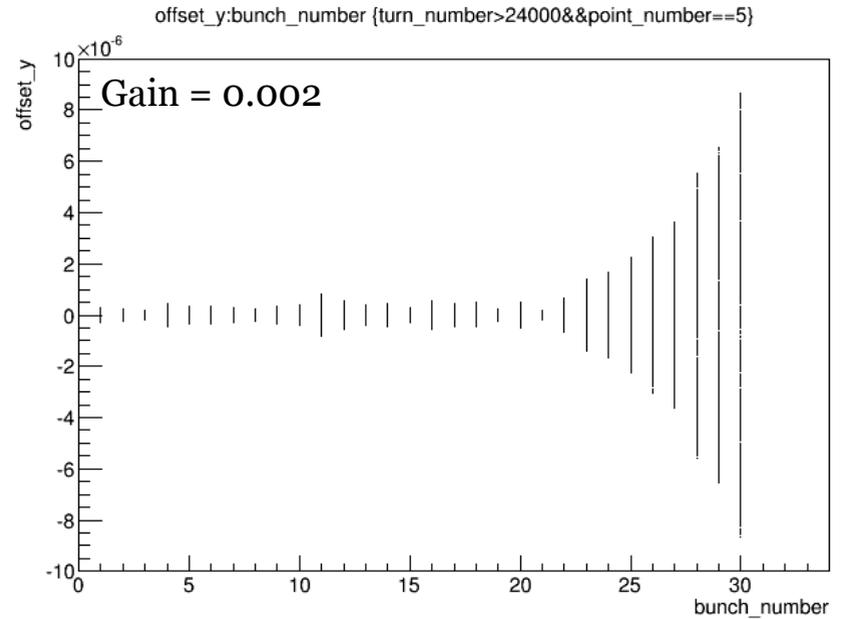
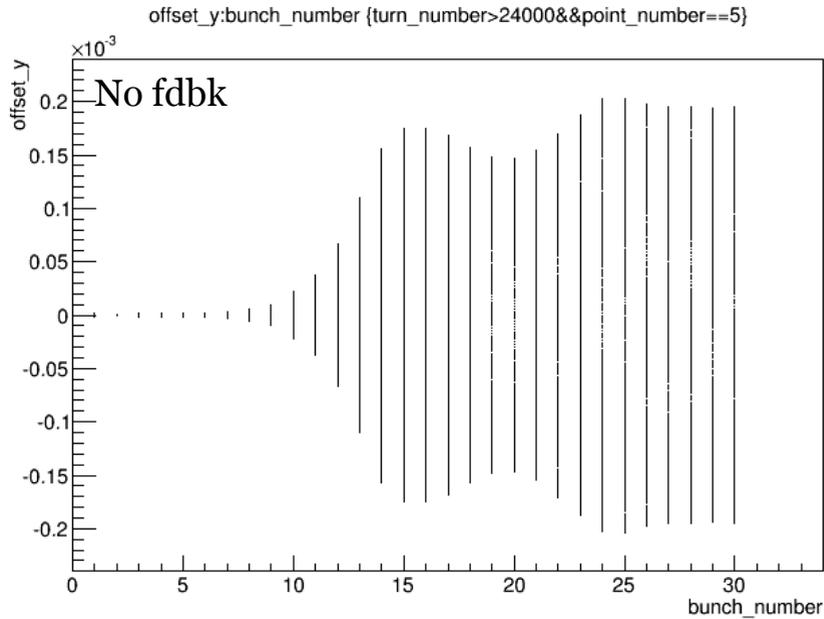
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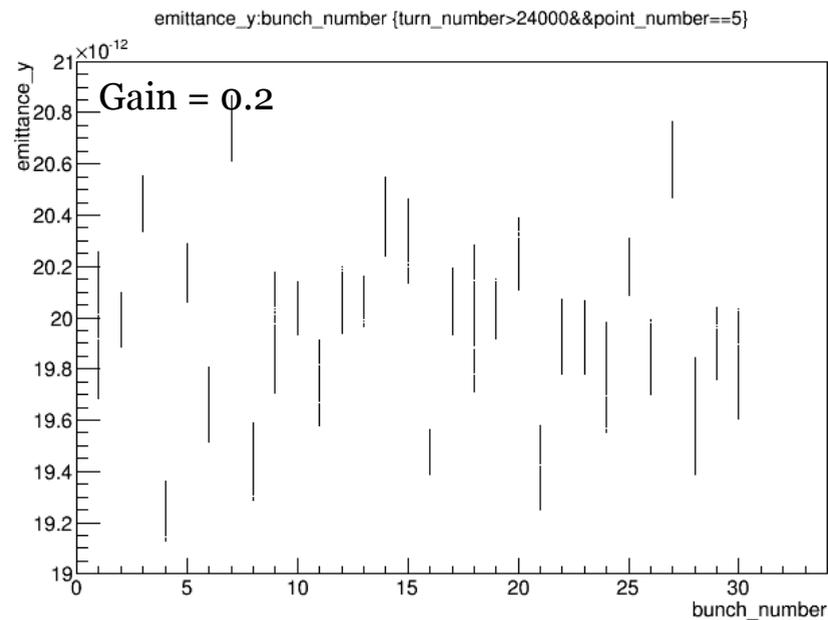
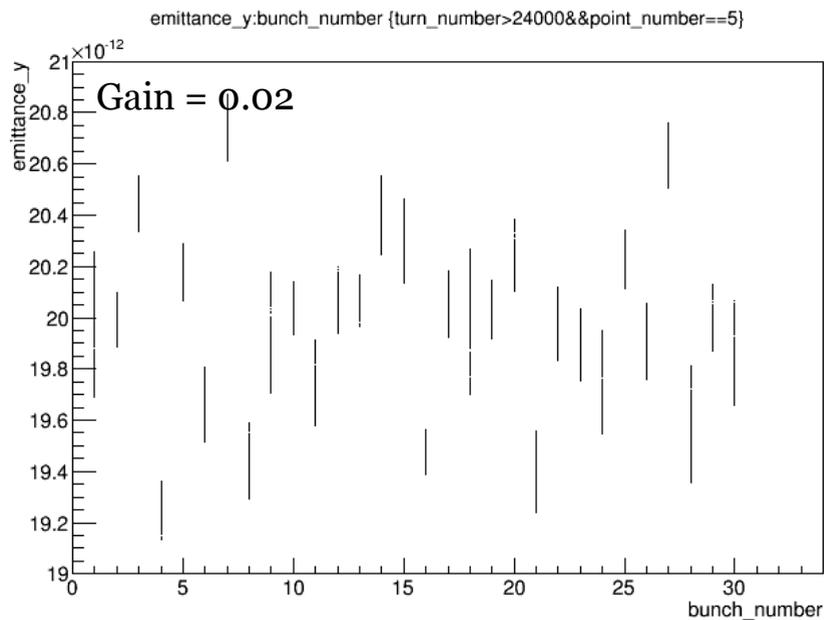
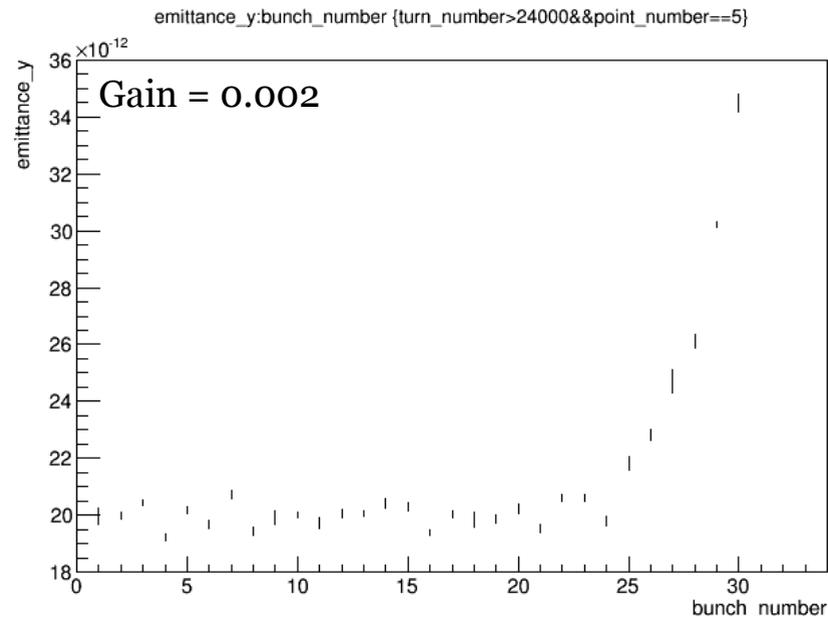
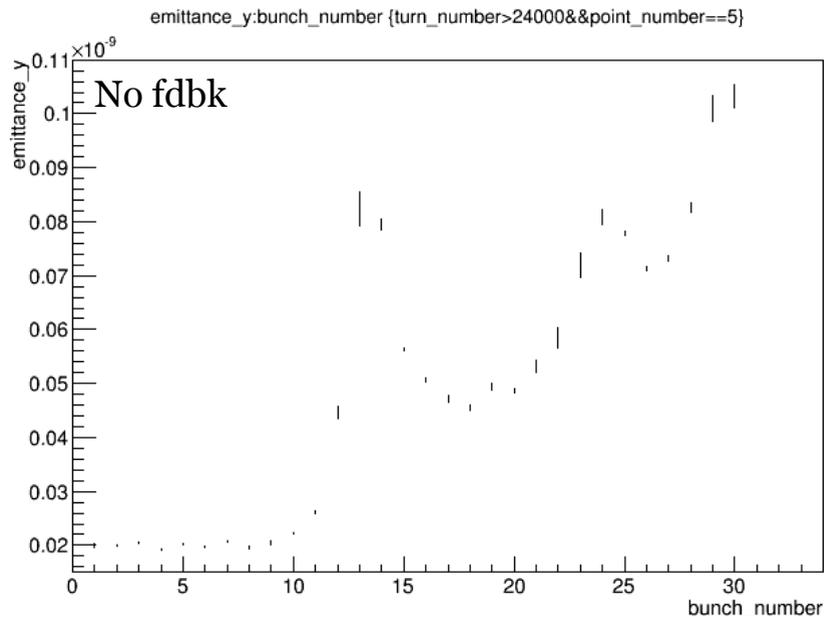
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Effect of vertical feedback on vertical motion



Effect of vertical feedback on vertical emittance

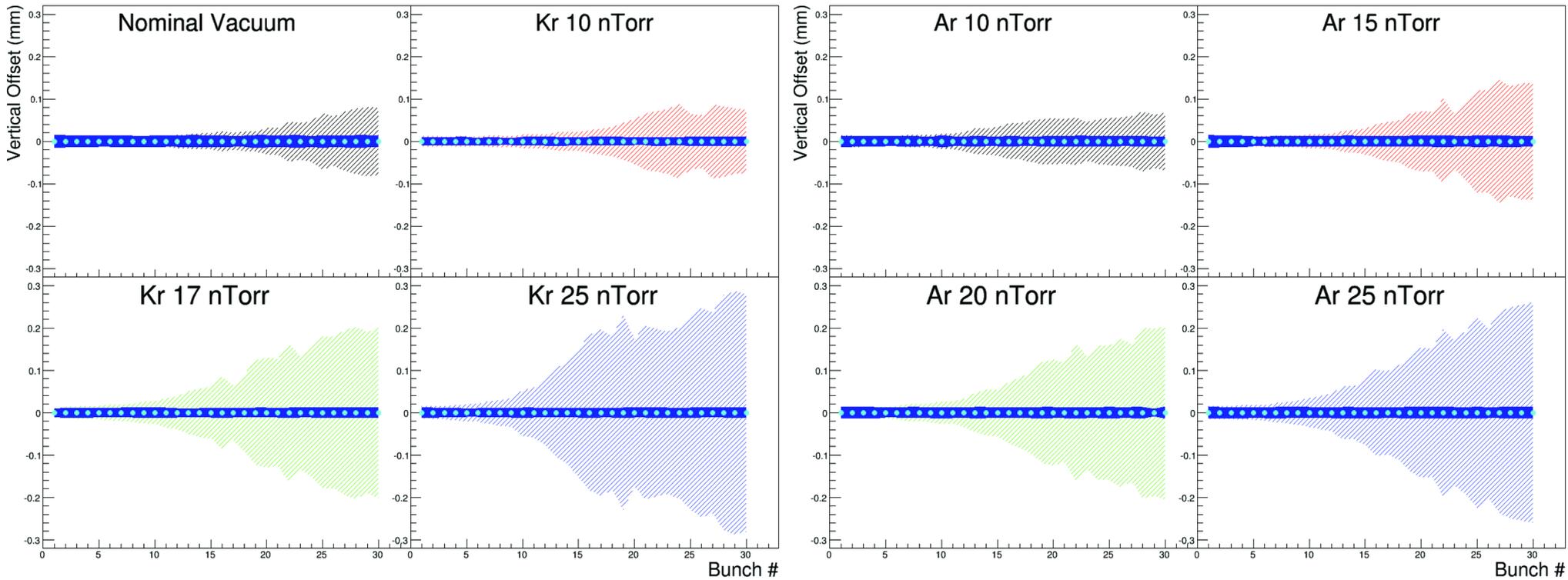


Results from the April Data

Pressure Dependence of FII

- Nominal vacuum pressure in CESR is 1 nTorr
- Established three pressures of Kr ($\sim 10, 17$ and 25 nTorr) during one shift, and four pressures of Ar ($\sim 10, 15, 20,$ and 25 nTorr) during another
- Pressure “bumps” occupied about a 10 m portion of the CESR ring; established pressures are uniform to 10-20%
- 30 bunch train with 0.75 mA/bunch (1.2×10^{10} particles) and 14 ns bunch spacing
- For each pressure, we measured 4k turns of CBPM data, 1k turns of xBSM data, and the power spectrum of the train
- Each measurement done with (as well as without) multi-bunch vertical feedback to determine if there is incoherent emittance growth due to the ions

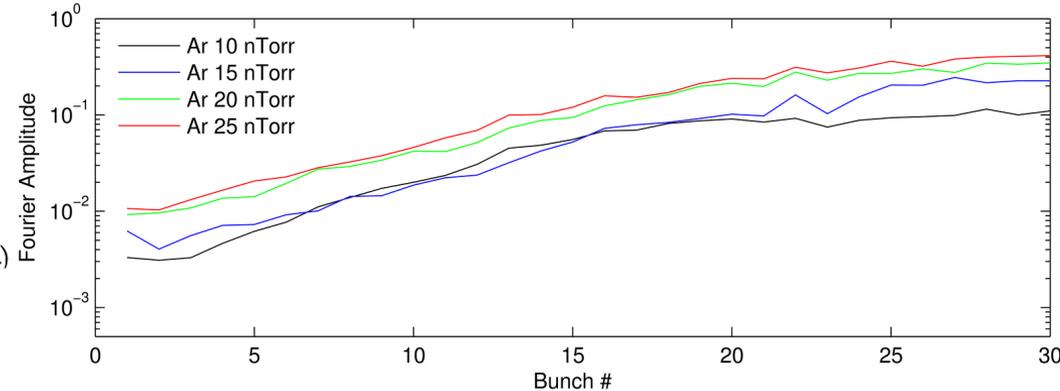
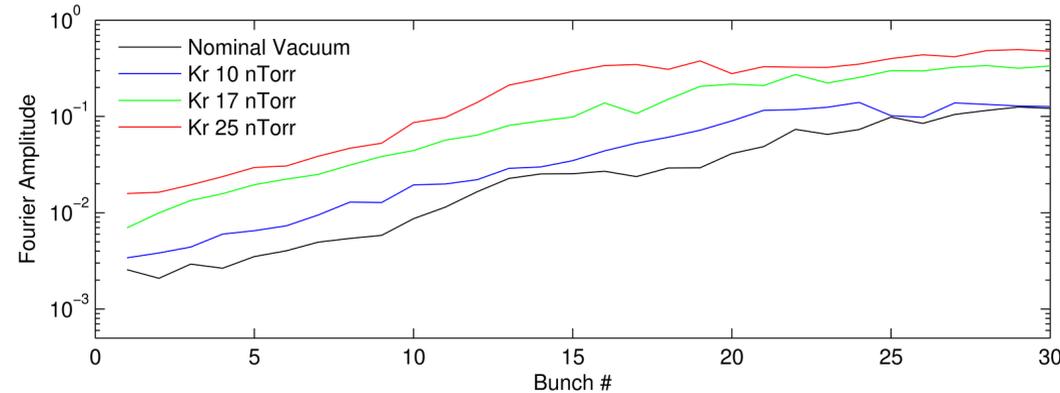
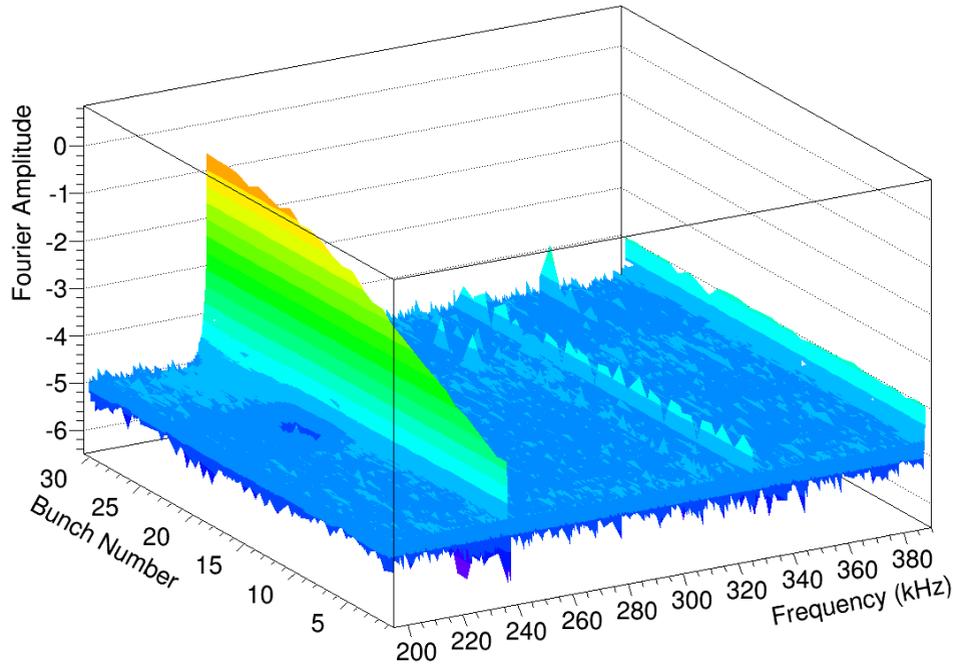
BPM Data



- Lightly shaded region: motion with vertical feedback system turned off; filled regions: motion with feedback turned on
- As the pressure of the injected gas is increased, the amplitude of the motion becomes larger for the tail of the train, and the train is less stable
- When the feedback is turned on, the motion is damped to a small RMS amplitude that is independent of pressure

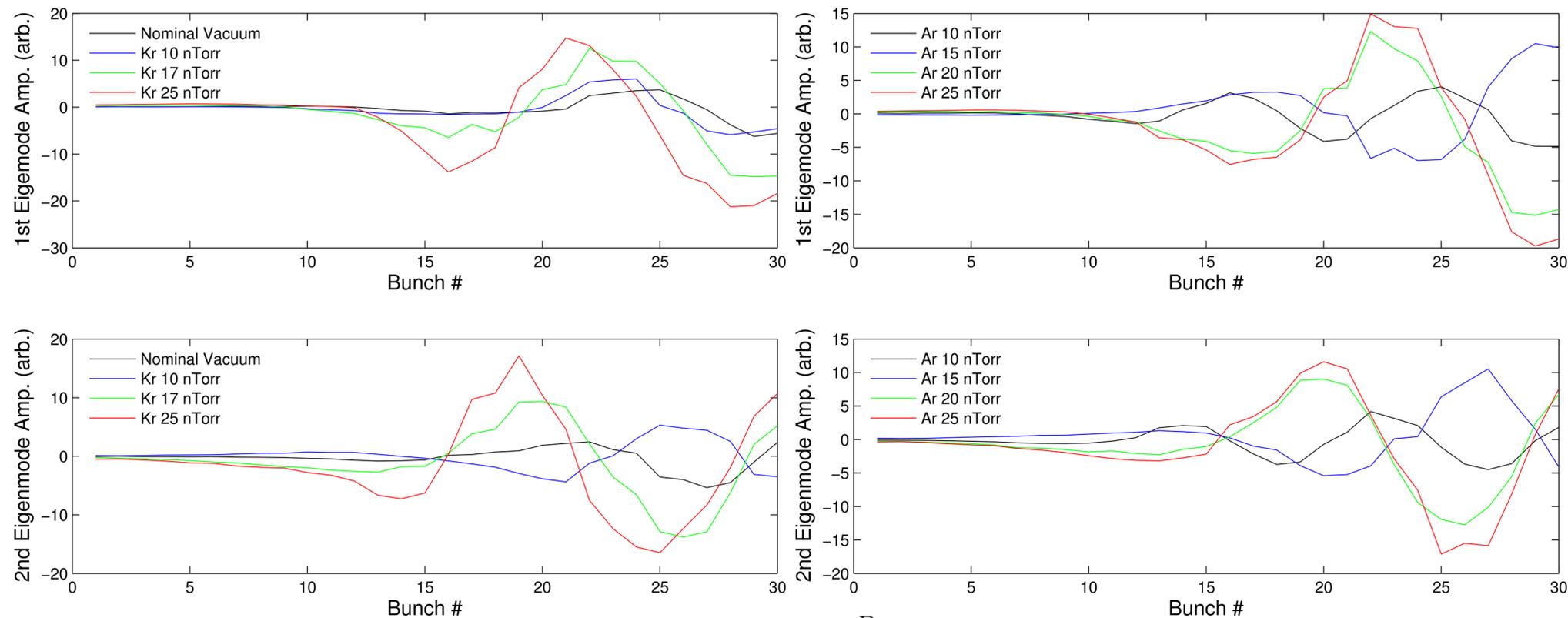
Position Spectrum Amplitude Analysis

Ar 25 nTorr, 0.75 mA, VFB off



- Left: Position spectrum of each bunch in train for a fixed pressure
- Right: Comparing such position spectra (at the vertical tune) for various pressures
- As the pressure is increased, the growth in the amplitude along the train becomes stronger
- Consistent with our expectations, since the ion density increases linearly with gas pressure

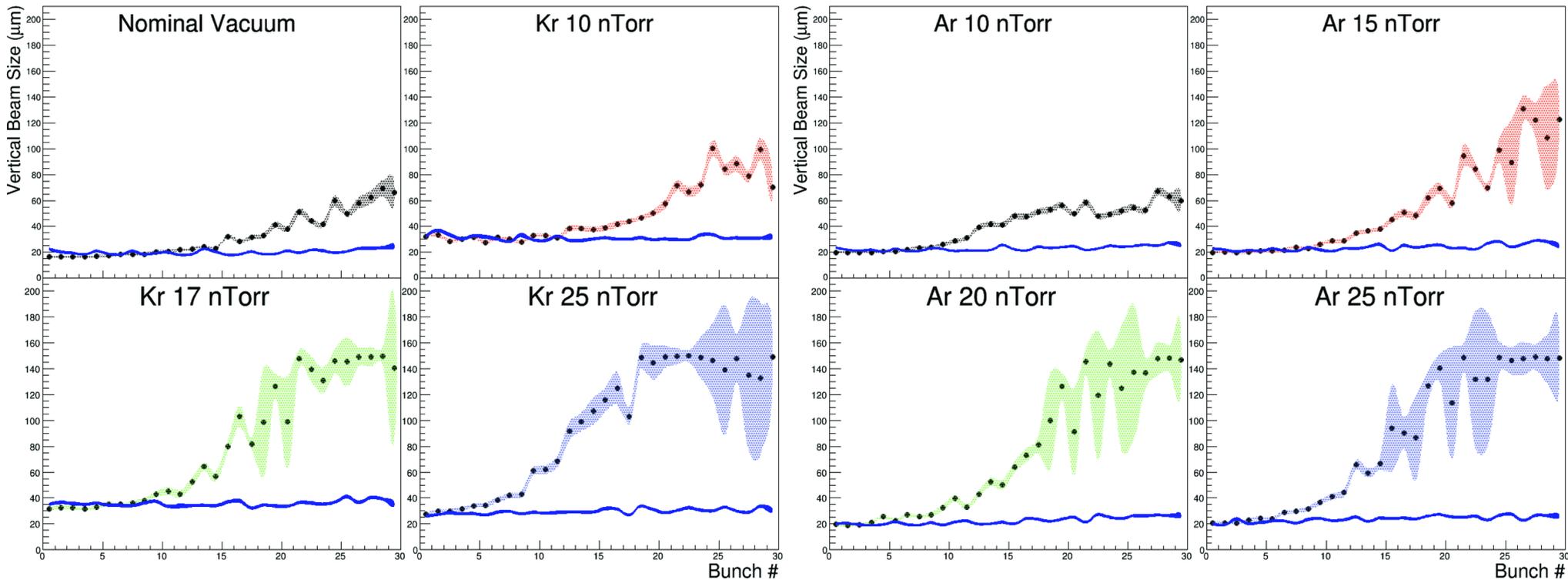
Eigenmode Analysis



$$\mathbf{P} = \mathbf{T}\mathbf{\Lambda}\mathbf{\Pi}^T = \sum_{i=1}^B \tau_i \lambda_i \pi_i$$

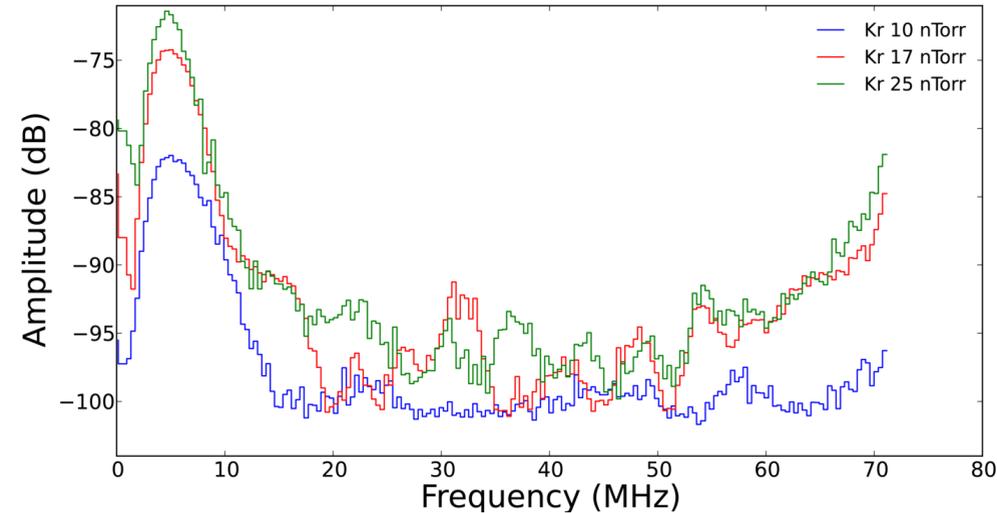
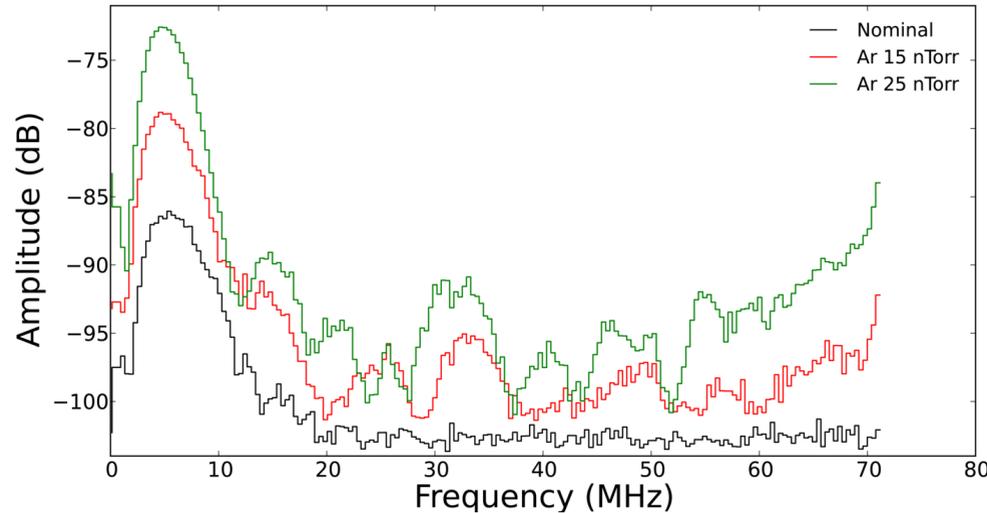
- The vertical displacements (at a fixed time) of the bunches along the train are determined by the ion oscillation frequencies
- Can infer the oscillation pattern of the ions via SVD (a.k.a. eigendecomposition) of the position history matrix
- Can order the eigenvectors based on descending eigenvalues, and the top eigenvectors then correspond to the most important eigenmodes
- As the pressure of the injected gas is increased, the amplitudes of the eigenmodes increase

XBSM Data



- Lightly shaded region: motion with vertical feedback system turned off; filled regions: motion with feedback turned on
- As the pressure of the injected gas is increased, the beam size growth becomes stronger, and the measurements for the later half of the train become more uncertain
- When the feedback is turned on, the beam size is reduced to $\sim 20 \mu\text{m}$ regardless of pressure
- No incoherent growth of the vertical emittance due to the beam-ion interaction

Train Spectrum Data

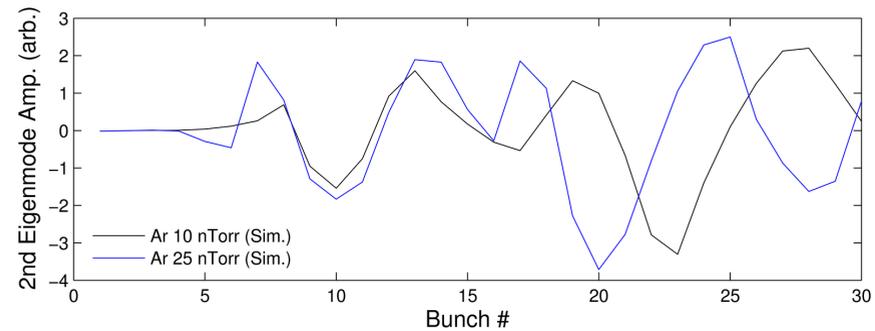
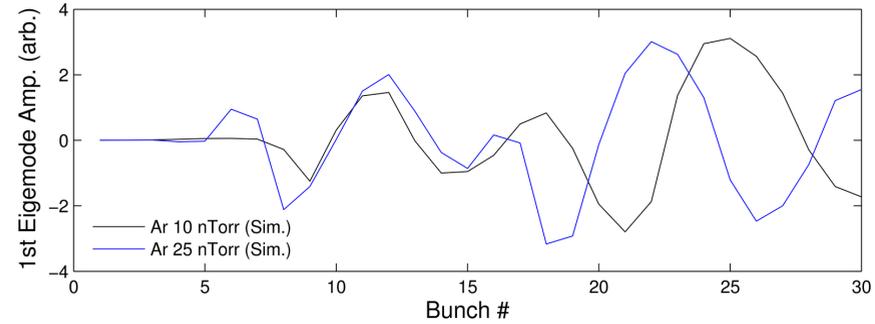
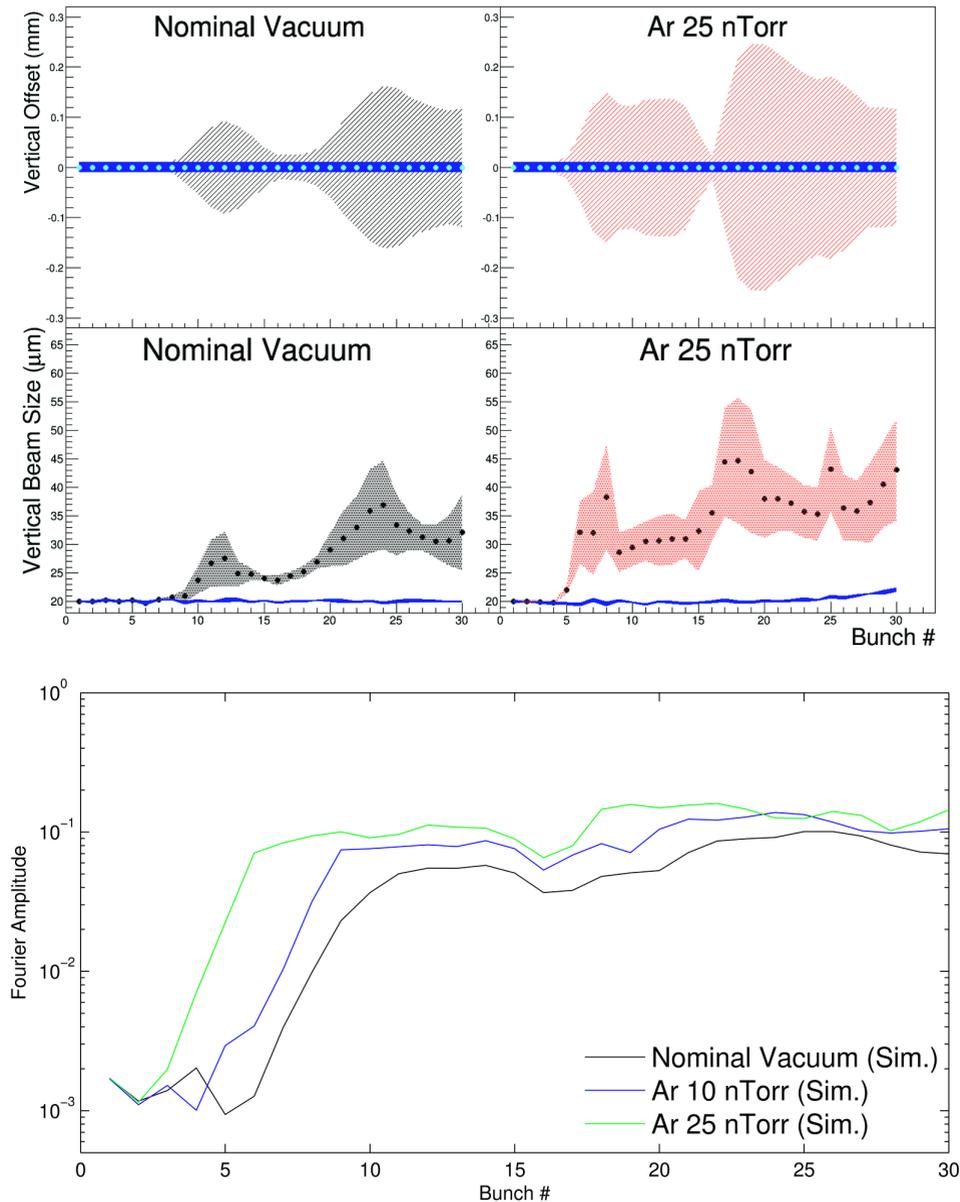


- Bunch spacing of 14 ns corresponds to a frequency range of 72 MHz
- As the pressure increases, so does the amplitude of the vertical lower sidebands
- Since the only known multi-bunch instability that is affected by increasing vacuum pressure is FII, we can infer that the observed sidebands are a consequence of beam-ion coupling

Some remarks about simulations

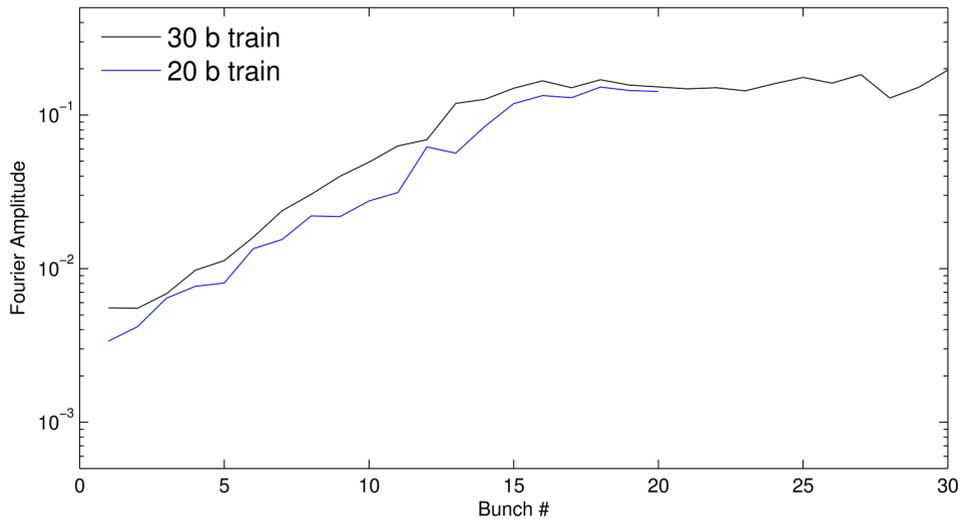
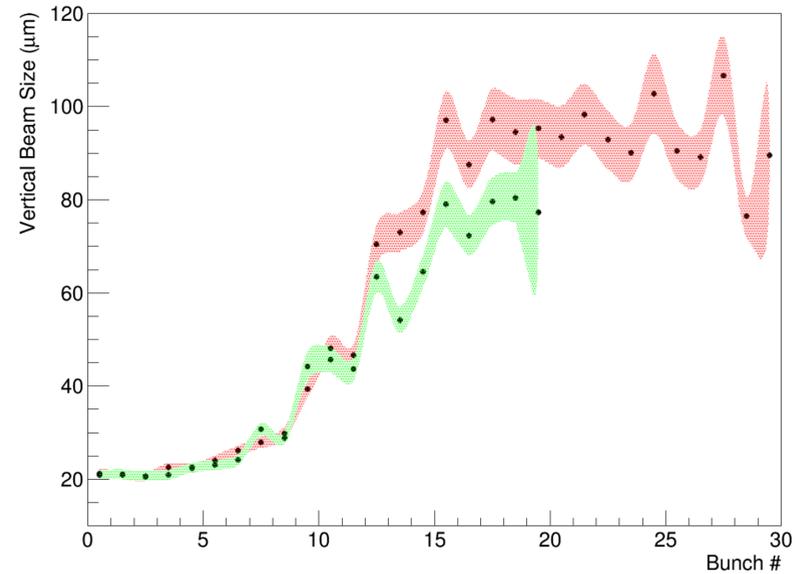
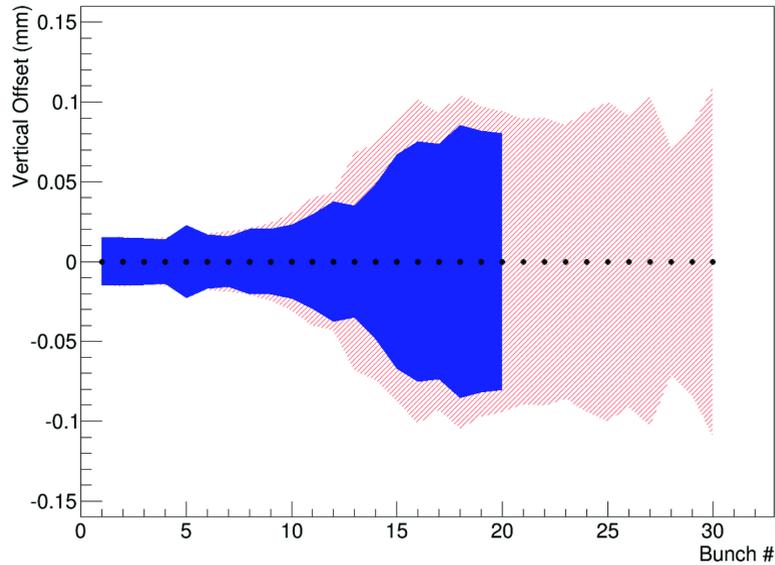
- Simulation plots correspond to the beam behavior for the last 1k turns of a 25k turn simulation (we do not track for more turns in the interest of computation time)
- Since the damping time of the CESR ring is larger (about 50k turns), the beam has not reached equilibrium
- However, the 25k turn simulation is sufficient to see whether the predicted dependence on pressure agrees with our observations
- Simulations, based on a simplified model of the storage ring and the beam dynamics, necessarily provide only qualitative comparison with the measurements.
- Nominal vacuum is defined as 0.5 nTorr each of Ar and CO
- The location and extent of the pressure bump used in simulation is consistent with our experiment
- Ionization cross section of Ar and CO are assumed to be 1.5 and 2 MBarn
- Assuming a larger cross section would create a greater number of ions, increasing the instability

Simulation Results



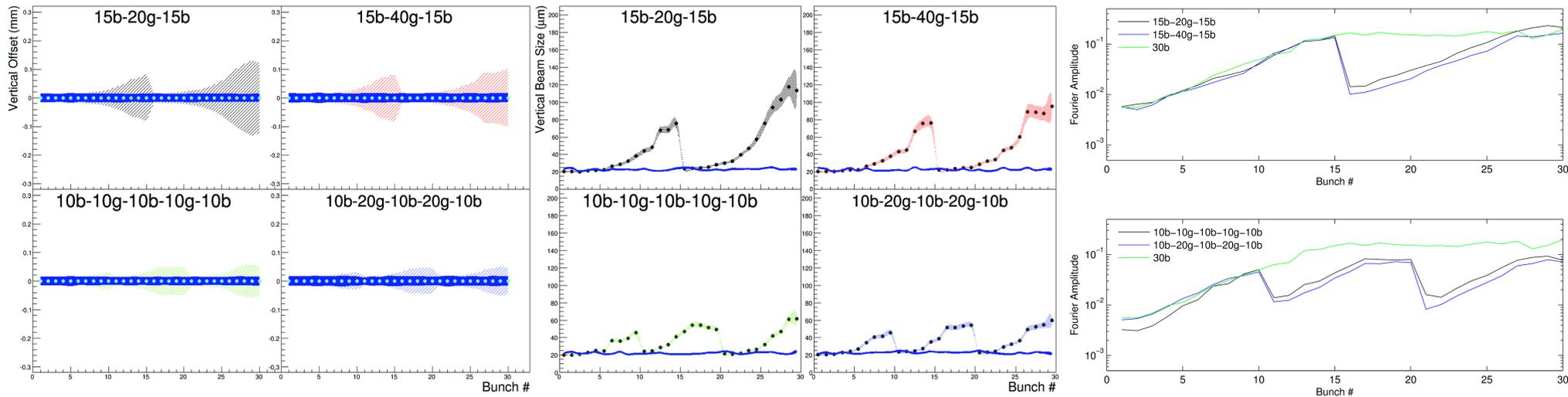
- Good qualitative agreement with measurements (e.g. more instability with more gas, feedback removes emittance growth)
- Differences, when they exist (e.g. lower Fourier amplitude for first half of train, higher eigenmode frequency in simulation), have reasonable explanations

Trapping Check



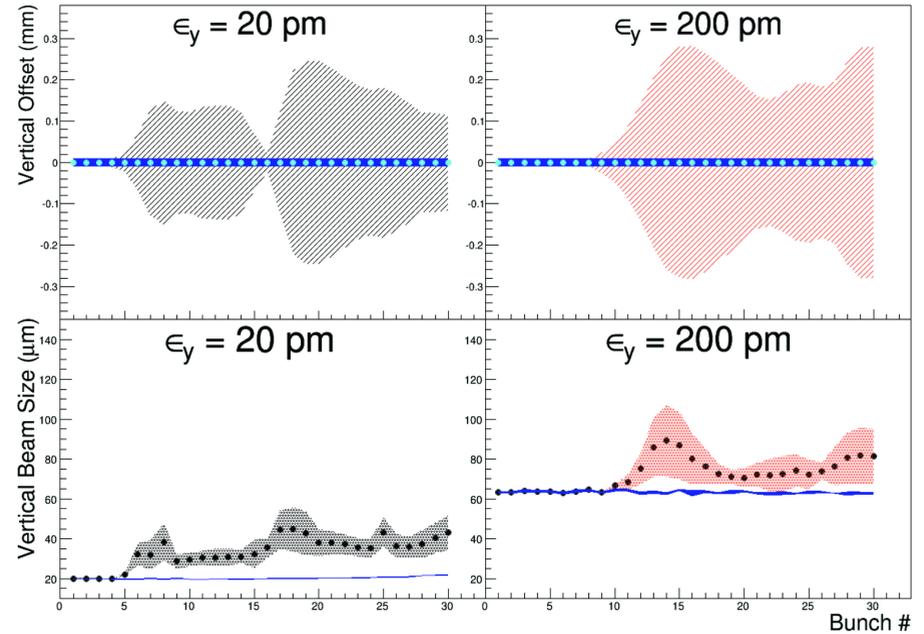
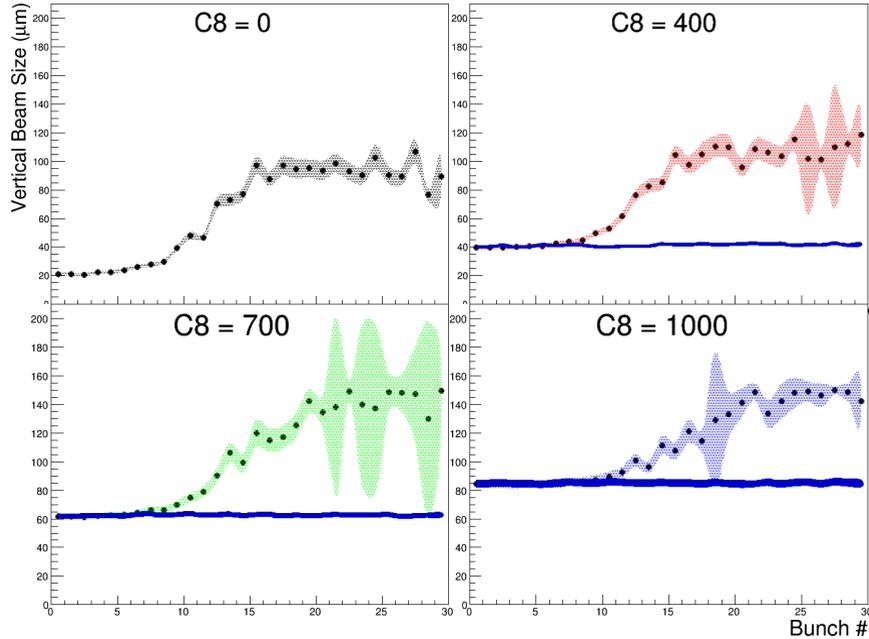
- Make measurements with the standard 30 bunch train, as well as a 20 bunch train substantial differences for the first 20 bunches for the two cases would indicate multi-turn ion trapping
- Difference is of the same order as the reproducibility of measurements under nominally identical conditions i.e. not significant

FII Mitigation via Mini-Trains



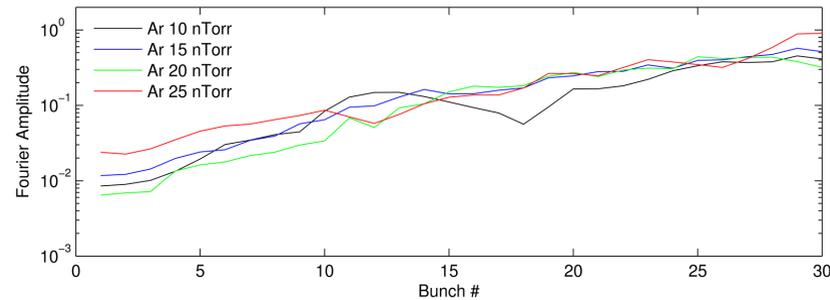
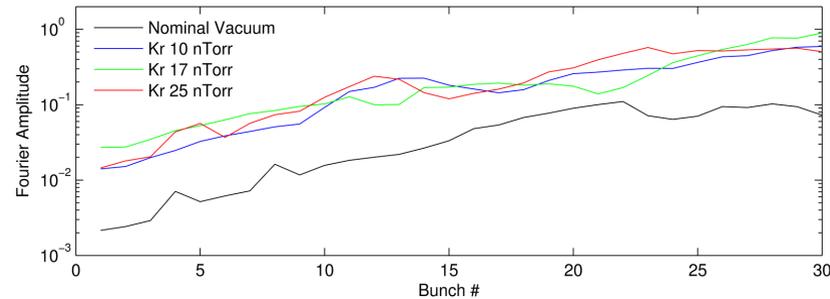
- “b” refers to a bunch, and “g” refers to a gap
- With two trains, longer gap allows more time for the ions to disperse, reducing instability
- With three trains, longer gap less effective, since FII is weak and therefore less sensitive to further mitigation
- Three mini-trains are more stable than two mini-trains, consistent with what has been observed elsewhere

FII mitigation via increased vertical emittance



- Increasing the vertical emittance reduces the ion-trapping potential \rightarrow possible mitigation method
- In data, as the emittance is increased, the bunch position at which beam size starts to grow is pushed back very little, whereas the maximum bunch size actually grows
- Simulation agrees qualitatively; there is a small (understood) discrepancy with respect to where in the train the beam size growth starts
- Conclude that when the pressure is high, increasing the initial vertical emittance is no longer an effective mitigation technique, since the decreased ion-trapping potential is not enough to compensate for the high density of ions

Unresolved Issues

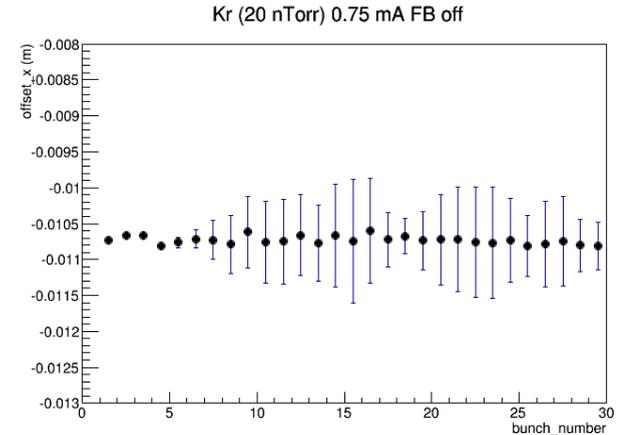
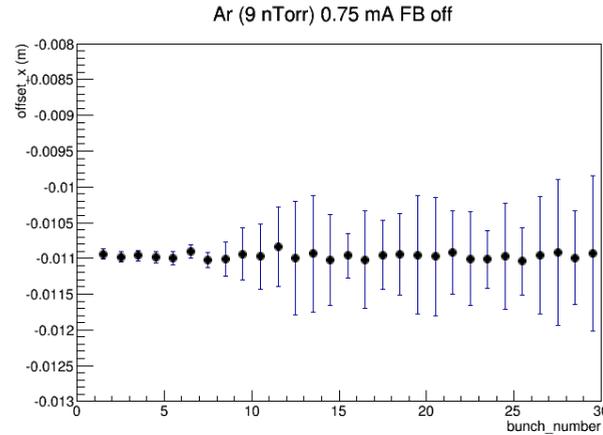
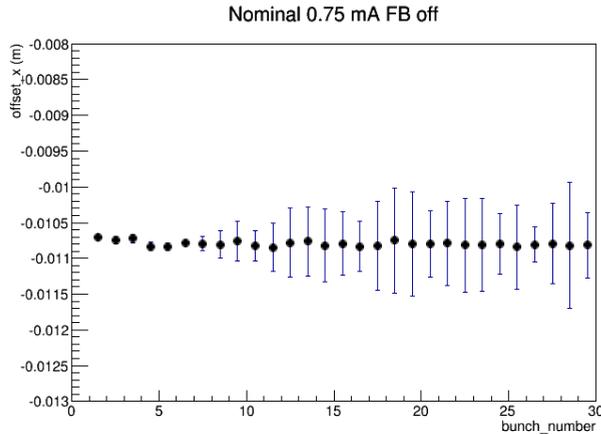


- Most significant unresolved issue that emerges from our measurements is the observed current dependence of the instability threshold
- Current in above plot is 0.5 mA/bunch instead of 0.75 mA → unlike the 0.75 mA case, the growth in the amplitude along the train does not increase monotonically with gas pressure
- No reason to expect that 0.5 mA should behave differently from 0.75 mA in terms of FII
- Suggests that there is another collective effect that is significant at 0.5 mA, but not at 0.75 mA
- To understand this anomaly, we have further explored current and chromaticity dependence of the instability
- Further measurements are needed to resolve the issue

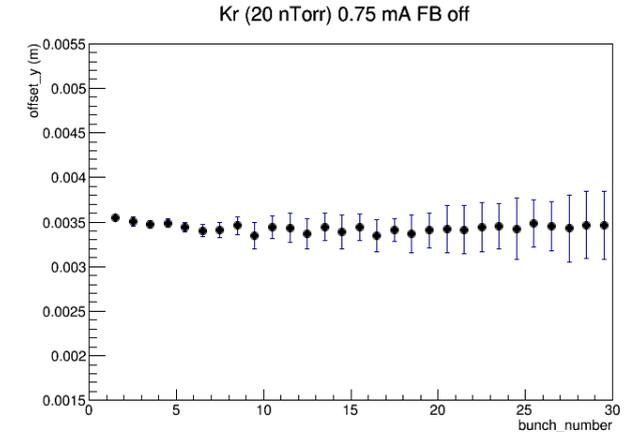
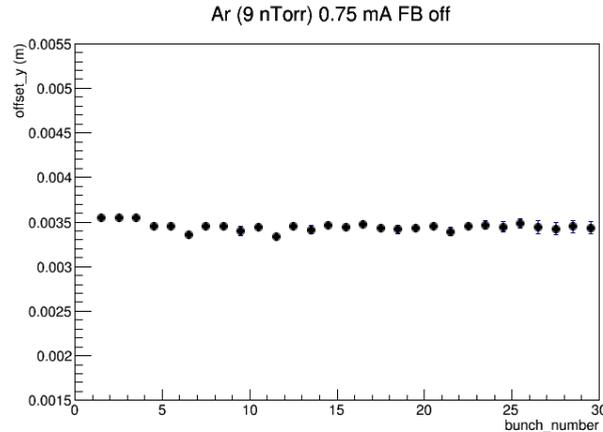
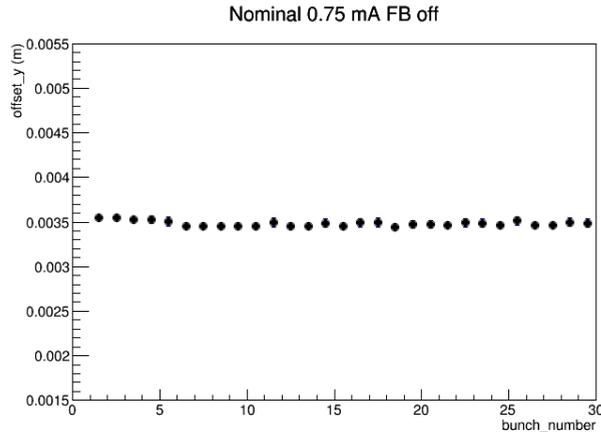
Anomaly Seen in December Data

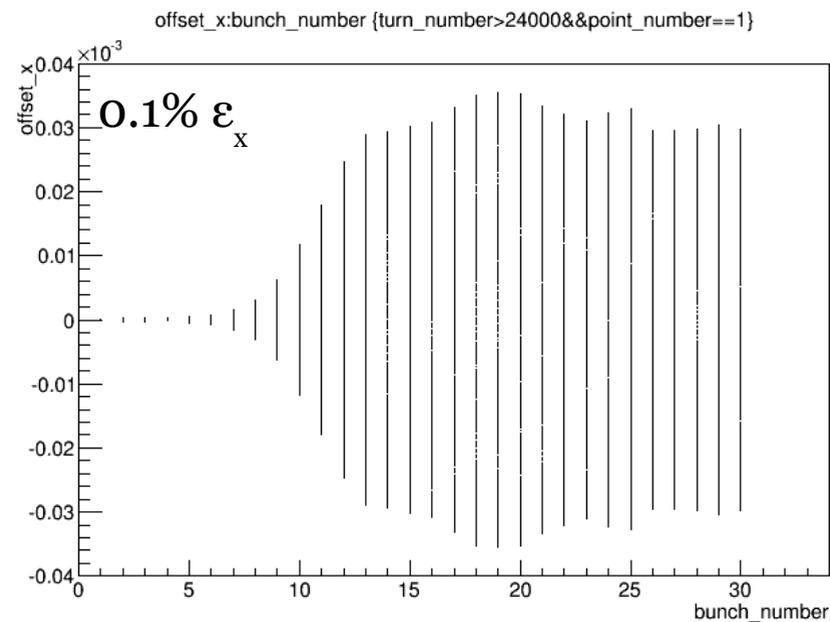
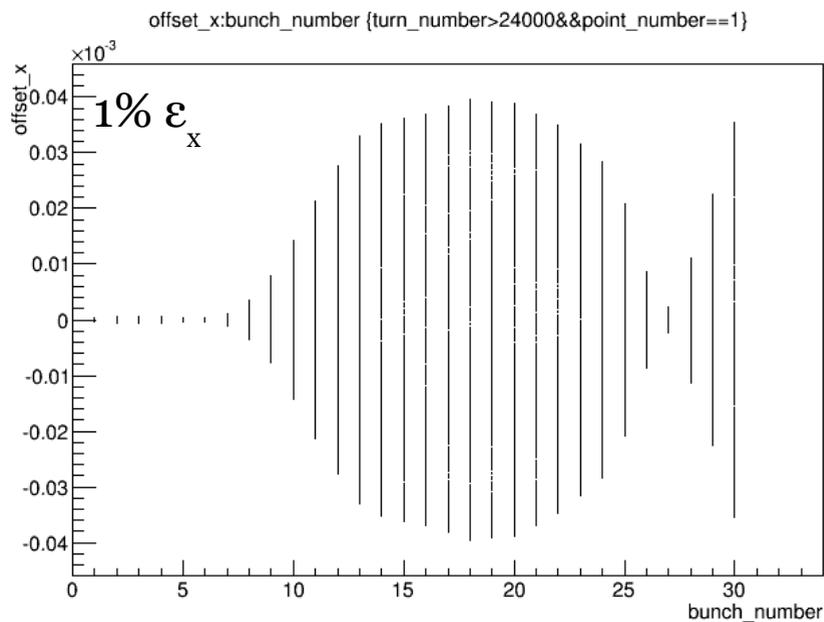
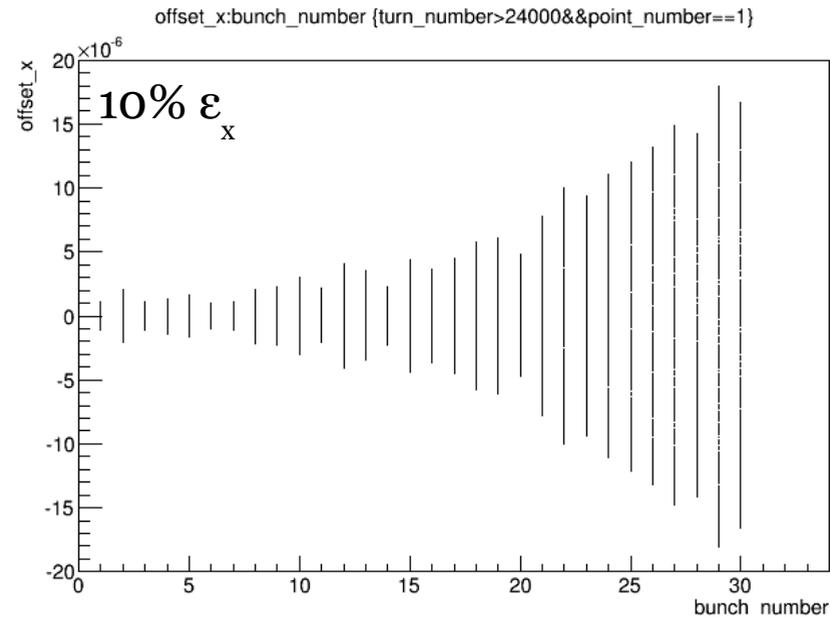
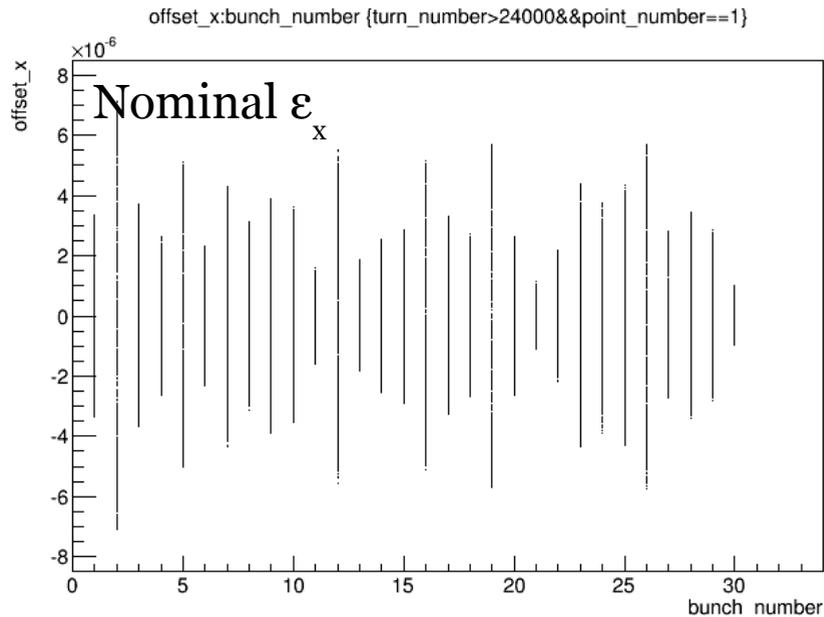
- In the data collected in Dec. 2013, not only was there large horizontal motion for the various pressures, it was actually larger than the vertical motion
- From simulation, we expected horizontal motion to be small (consistent with theory, since FII is strong in the dimension where initial emittance is small, and $\epsilon_x \gg \epsilon_y$ at CTA)
- First suspect was a bug in the simulation (next slide)

Horizontal offset



Vertical offset



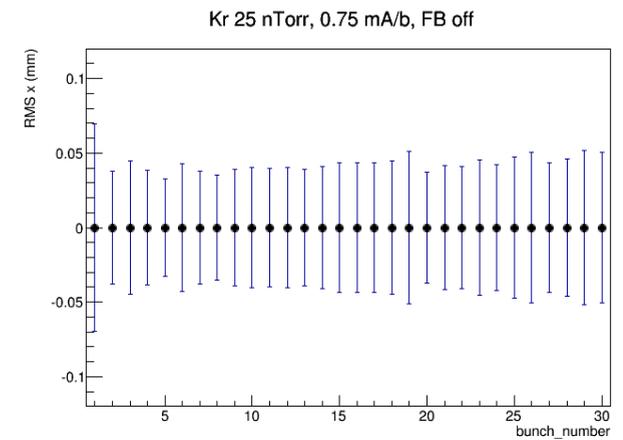
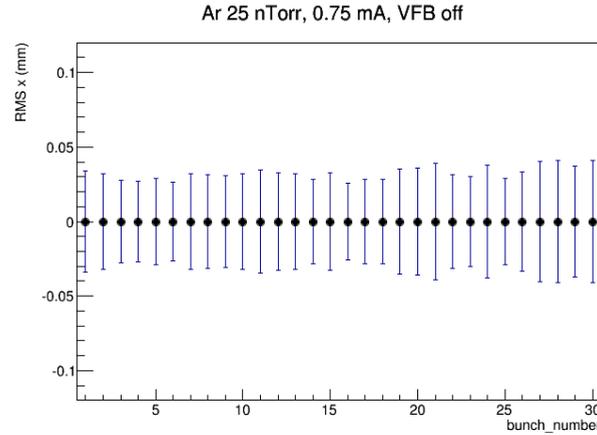
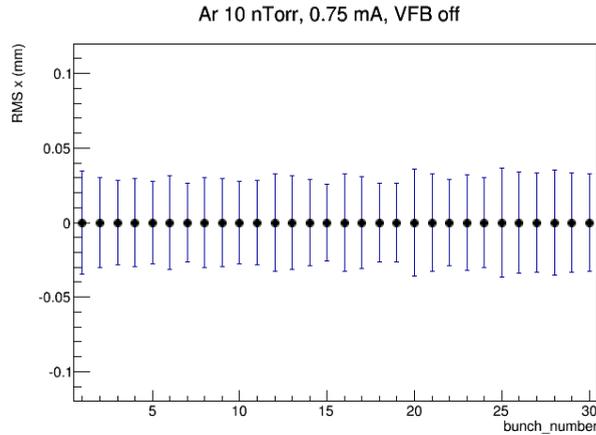


Simulation does not include whatever effect is causing horizontal motion seen in data at nominal emittance.

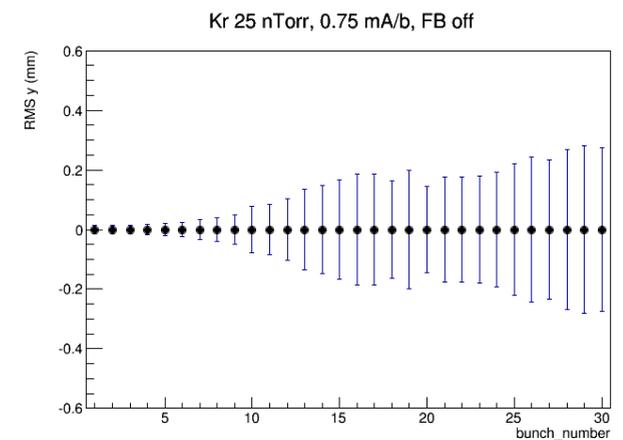
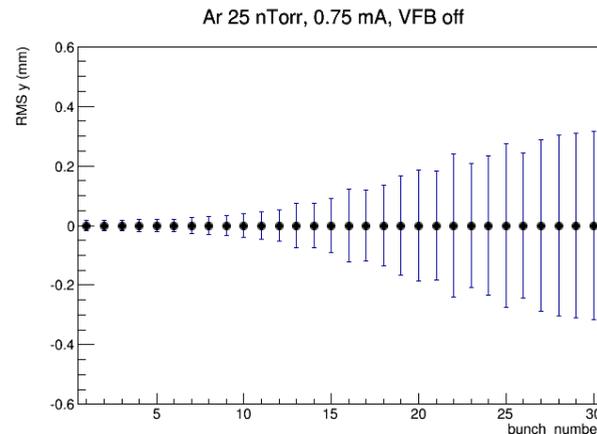
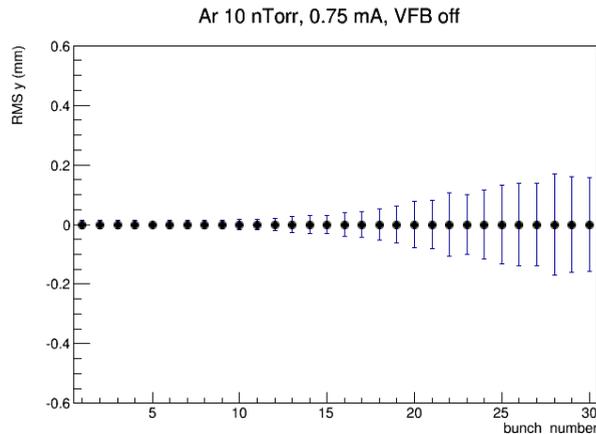
Anomaly Resolved in April Data

- We realized that the horizontal motion seen in data was a result of an x-z coupling effect not modeled in the simulation
- When we turned on longitudinal feedback during the April data-taking, this eliminated the horizontal motion

Horizontal offset



Vertical offset

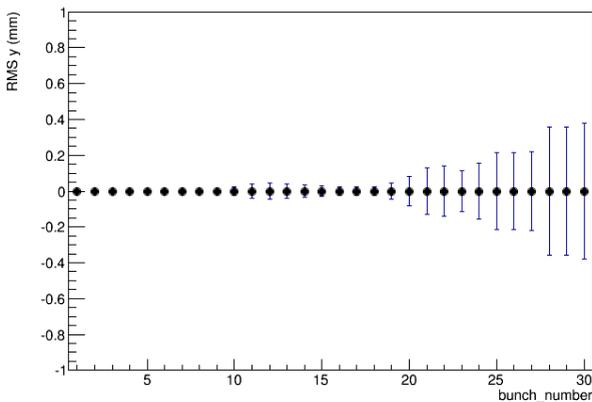


Conclusions

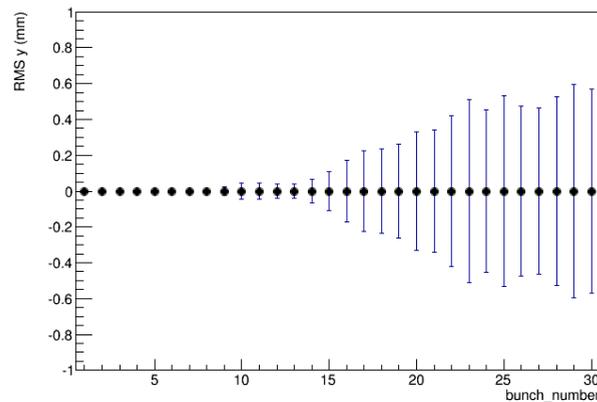
- Looked at the latest measurements of FII at CESR-TA, and the simulation software that has been developed for qualitative comparisons
- The observed increase in beam motion and beam size along the train is correlated with pressure, and the location (along the train) and magnitude of the instability agree well with simulation
- With vertical feedback, the emittance growth due to FII is eliminated, in both measurement and simulation
- Ion-trapping is not significant for a train that occupies one-sixth of the ring's circumference
- Mini-trains are an effective FII mitigation technique, unlike increasing the nominal emittance (at high pressure)
- Current dependence of multi-bunch instability is not well-understood, and will be the subject of future research

Backup Slides

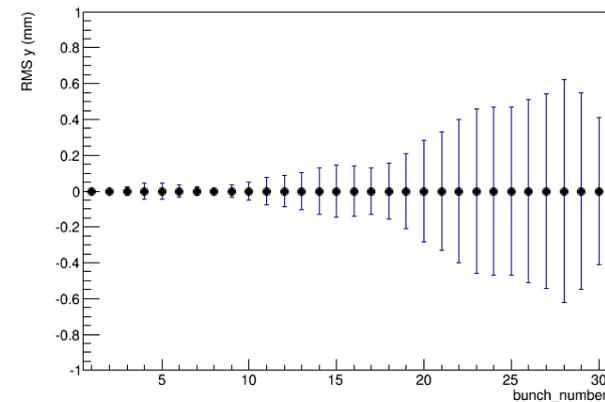
Nominal Vacuum, 0.3 mA, XQ1 = 1600



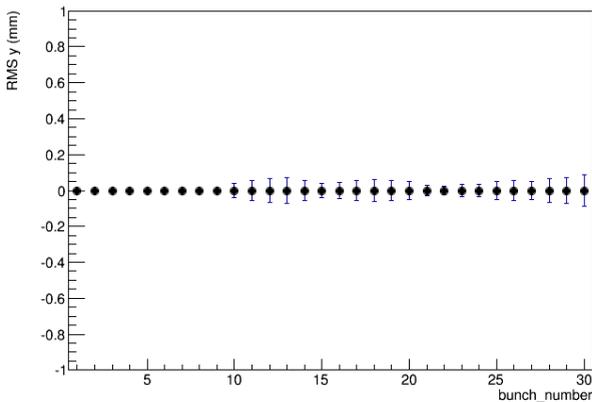
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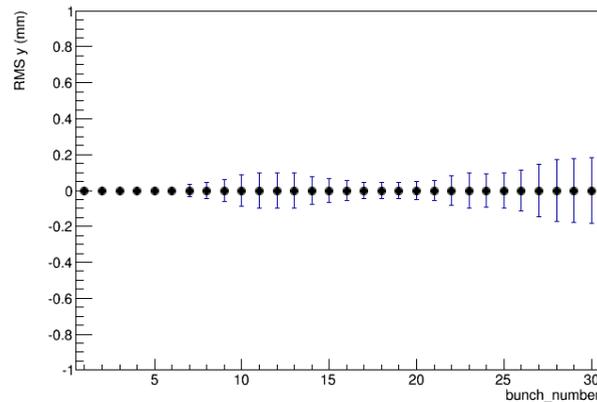
Nominal Vacuum, 0.5 mA, XQ1 = 1600



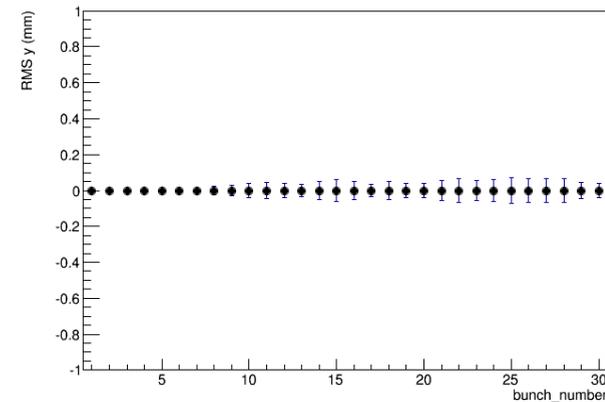
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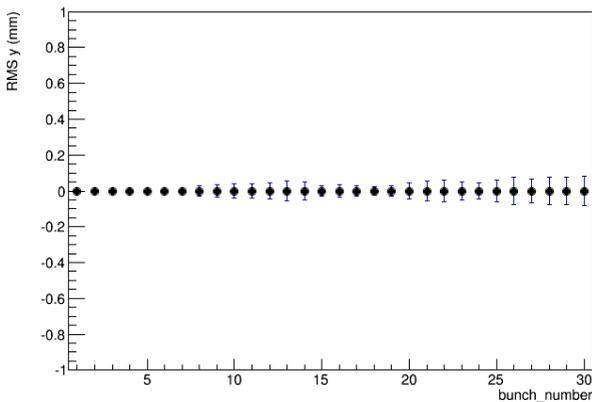
Nominal Vacuum, 0.7 mA, XQ1 = 1600



Nominal Vacuum, 0.75 mA, XQ1 = 1600



Nominal Vacuum, 0.8 mA, XQ1 = 1600



Current scan with 14 ns bunch spacing, XQ1 = 1600

