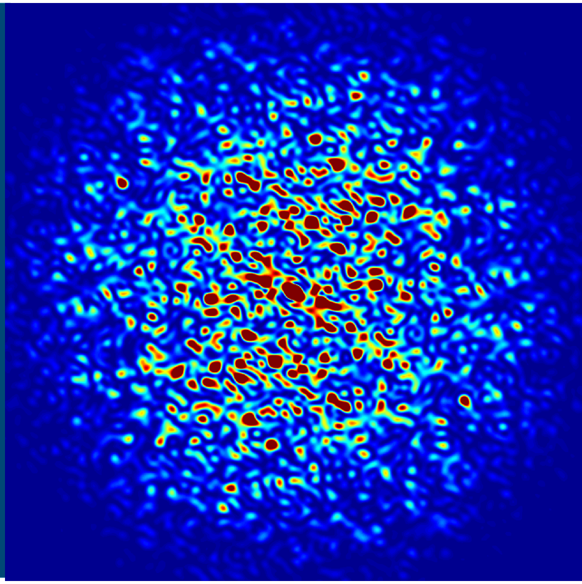
Studies of Ion Instability Using a Gas Injection System



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Introduction

- Ion trapping occurs when a negatively charged beam ionizes residual gas inside the vacuum chamber.
- Trapped ions can couple to the beam motion, leading to a coherent (usually vertical) instability. They can also cause incoherent effects, such as emittance growth.
- Renewed interest for next generation light sources (e.g. APS-U[1]) due to challenging emittance and stability requirements.
- To study ion instability at the present APS, we built a gas injection system[2]:
  - Creates localized pressure bump of N_2 gas: 100 or 900 nTorr
  - Installed at 2 locations: Sector 25 (S25) and Sector 35 (S35)
  - Bump confined to 6 – 10 m with ion pumps
  - Data taken under a wide variety of beam conditions
  - Measurements: pinhole camera, spectrum analyzer, bunch-by-bunch feedback system

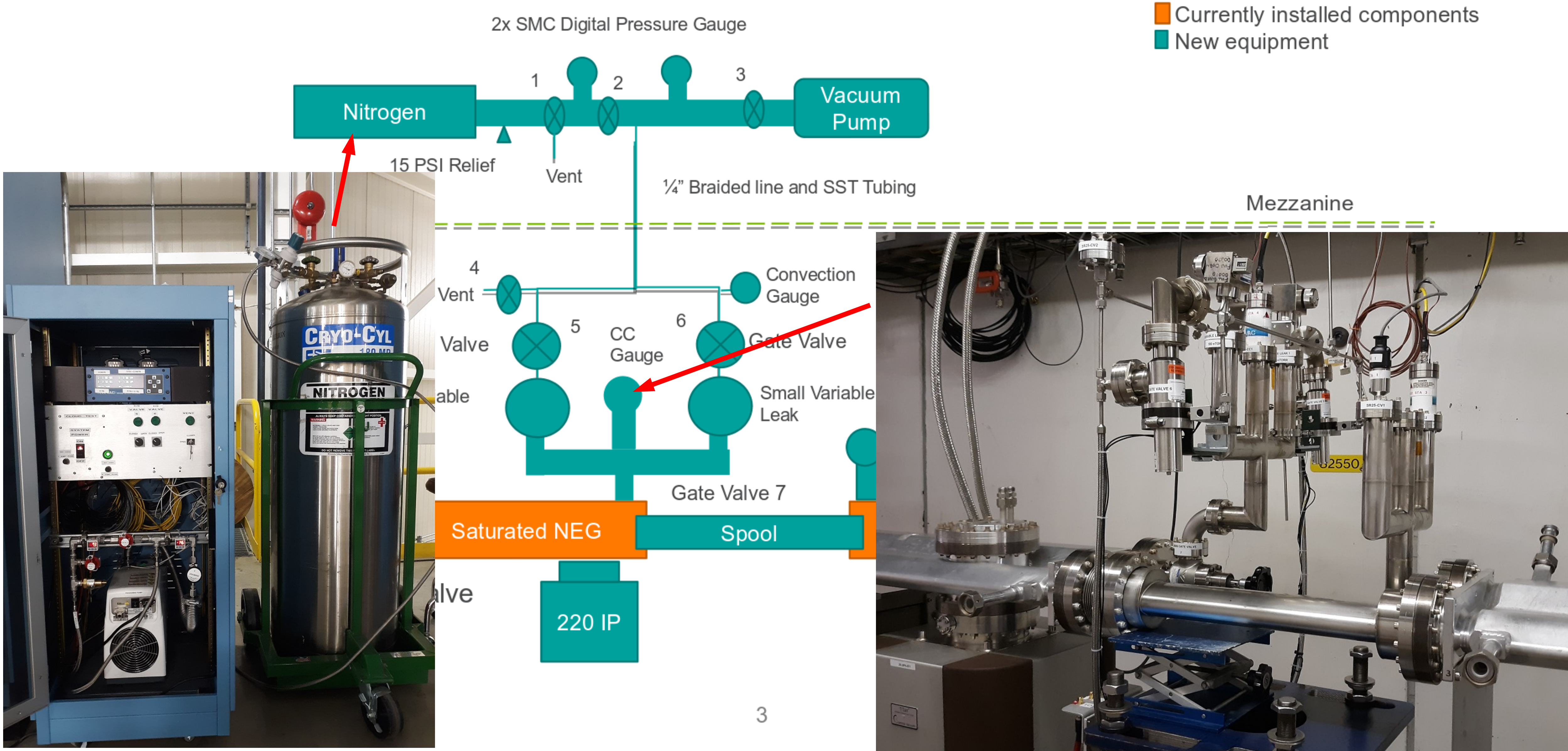
[1] R. O. Hettel, Proc. IPAC’21, pp. 7-12.
[2] J. Calvey, Proc. IBIC’20, pp. 258-262.

INSTALLATION CONFIGURATION

WITH 2 CALIBRATED VARIABLE LEAKS

J. Hoyt, T. Clute

🟧 Currently installed components
🟩 New equipment

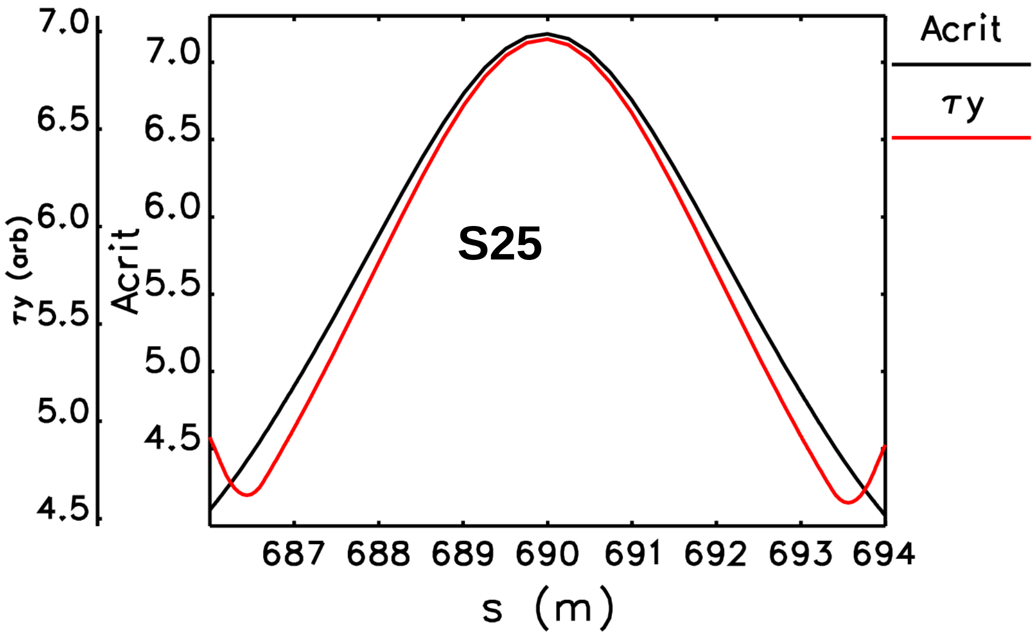


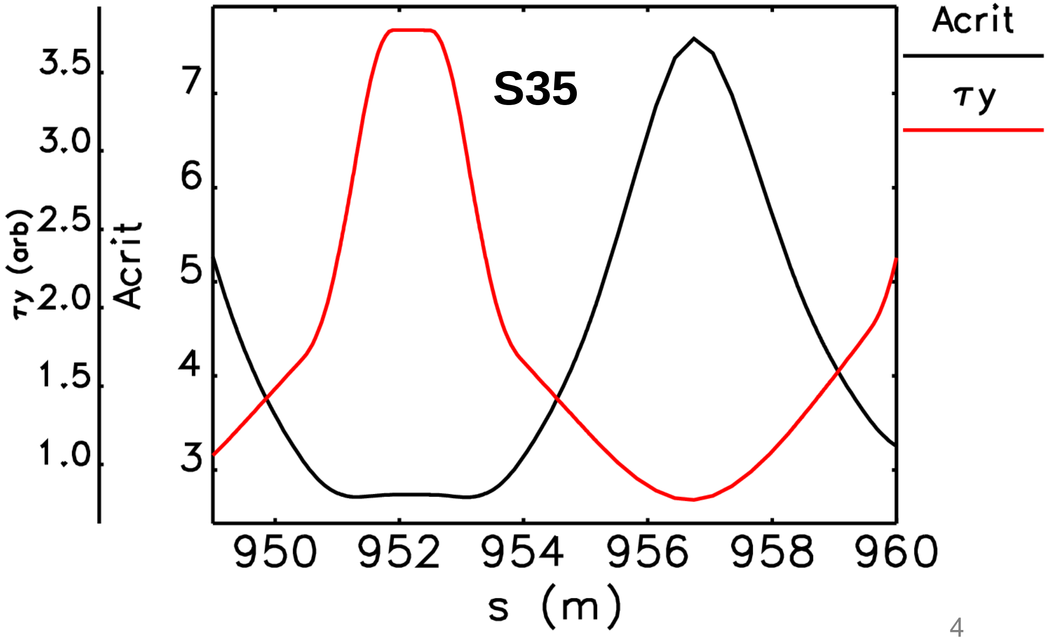
Comparison of S25 and S35

- 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

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

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





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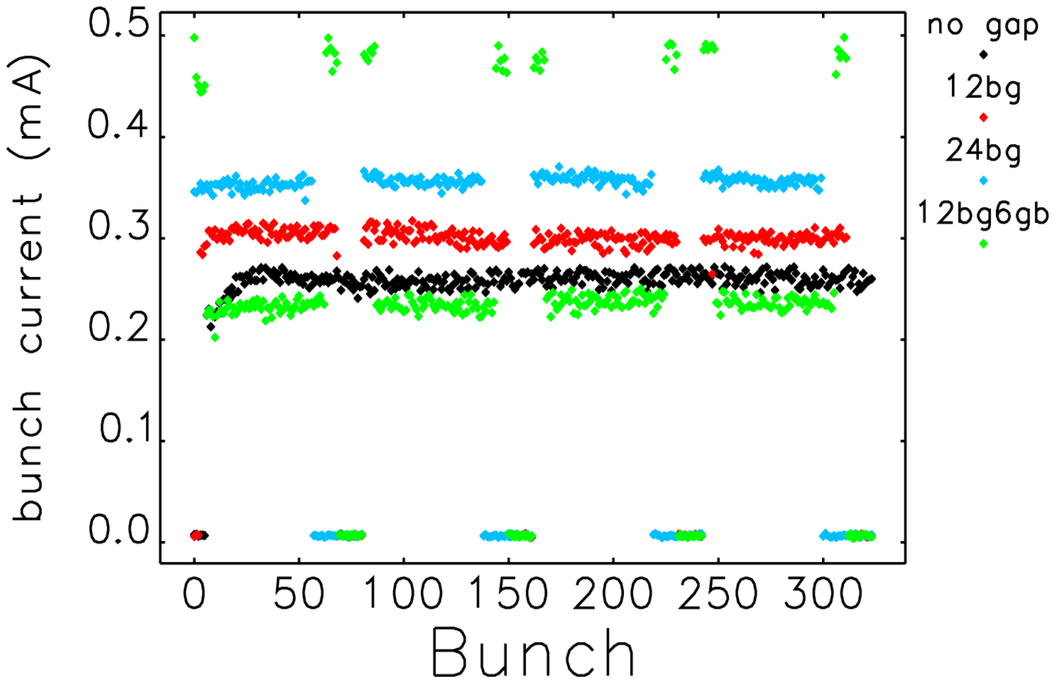
[1] H.G. Hereward, CERN 71-15 (1971).

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



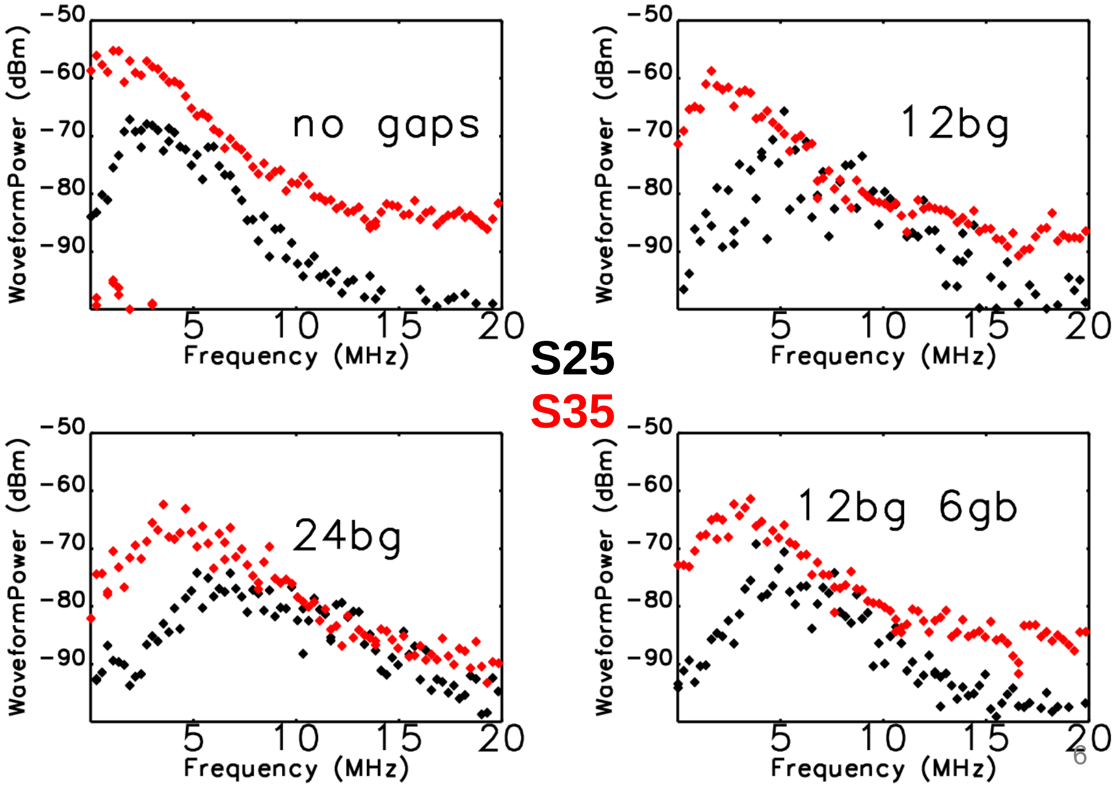
Quantity	Value
Beam energy	6 GeV
Horizontal, vertical emittance	1.83 nm, 24 pm
Revolution time	3.68 μs
Beam current	~80 mA
Bunches (no gaps)	324
Bunch spacing	11 ns
horizontal,vertical chromaticity	~6,~3

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

Train gap results: 900 nTorr

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

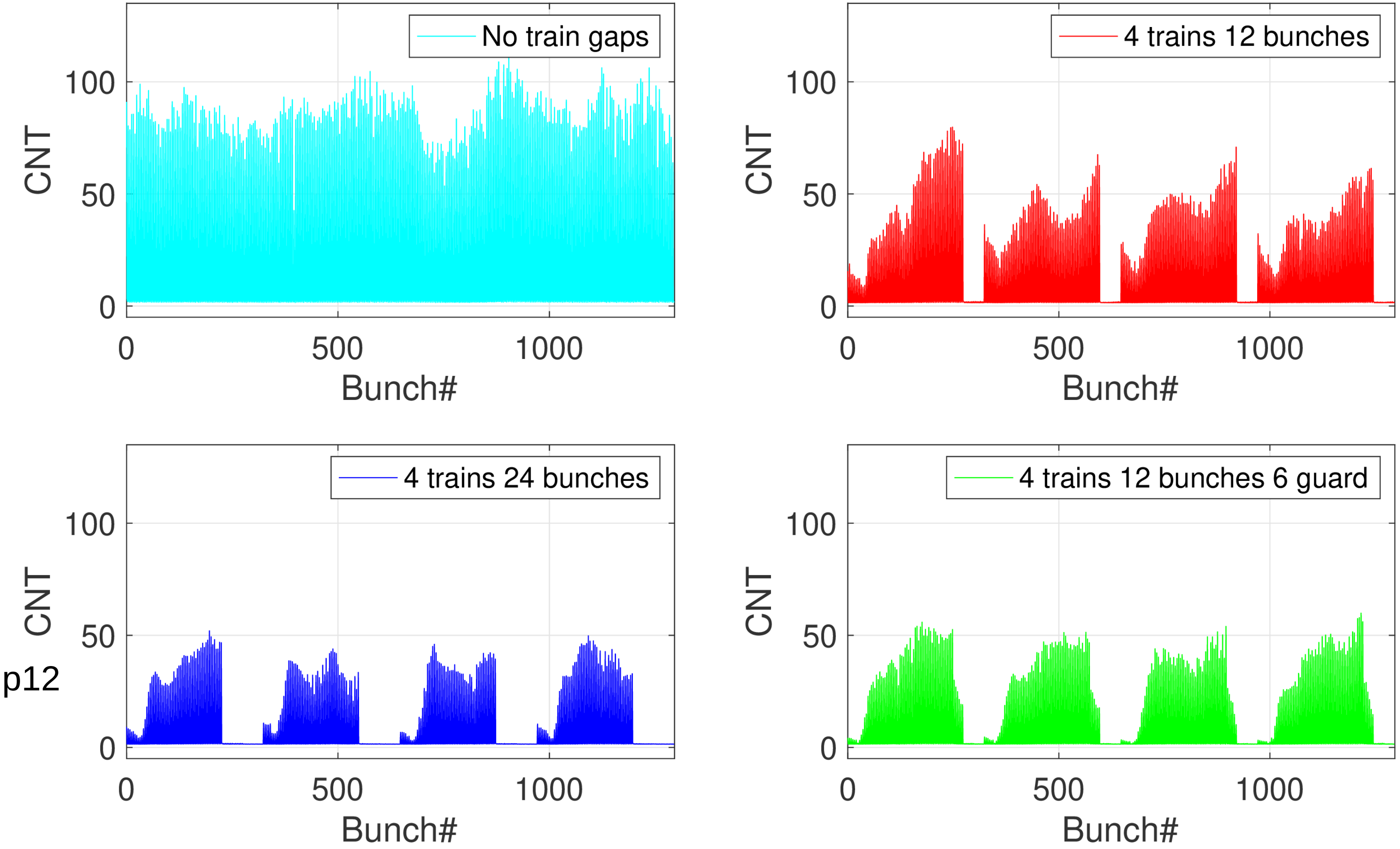
pattern	S25 ϵ_x (nm)	S35 ϵ_x (nm)	S25 ϵ_y (nm)	S35 ϵ_y (nm)
No gap	**3.6**	1.98	**0.124**	**1.55**
12bg	2.06	1.83	0.049	**0.188**
12bg 6gb	2.05	1.78	0.031	0.043
24bg	2.09	1.77	0.027	0.051



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.
- Guard bunches have less motion
- Train gaps are effective

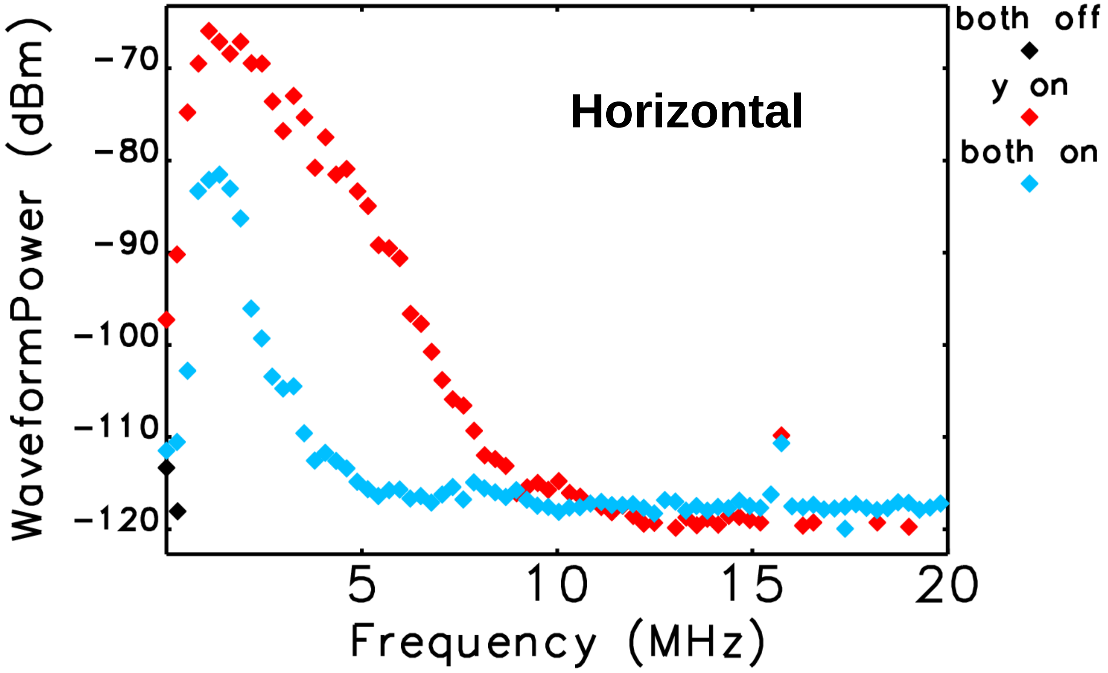
Y plane - RMS of bunch oscillations, Y feedback OFF @900nTorr

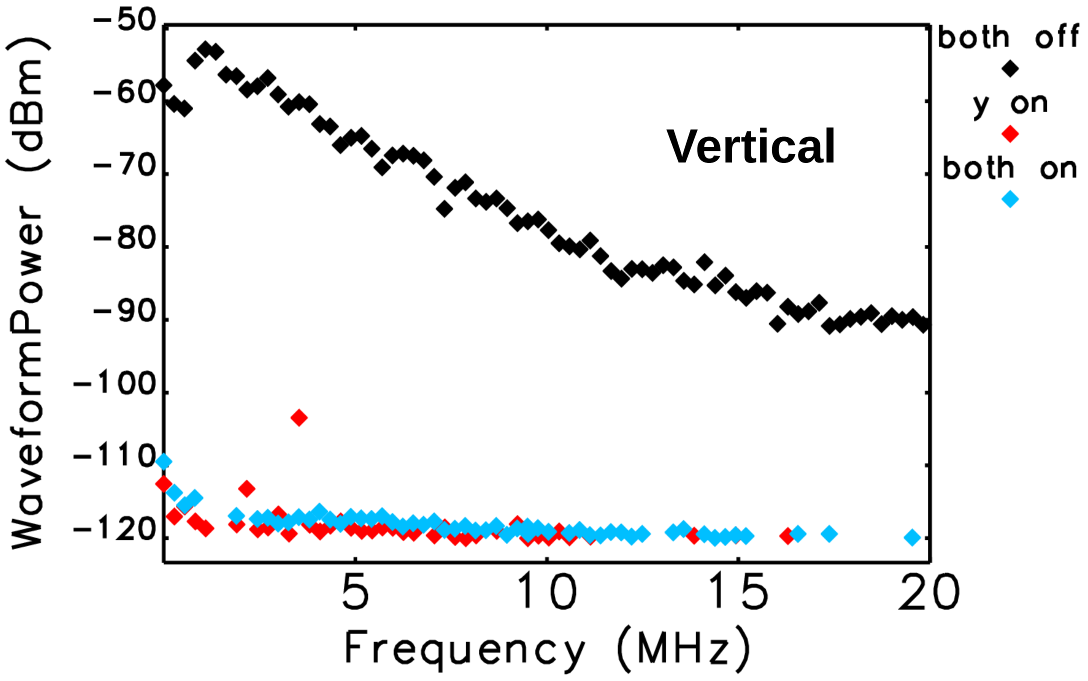


[1] https://www.dimtel.com/products/igp12
[2] J. Byrd et al., Phys. Rev. Lett. 79, pp. 79-82 (1997).

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
- Vertical instability damped → more ion trapping → horizontal instability
- With feedback on in both planes, still have (small) horizontal instability
  - NB: one of the horizontal amplifiers was broken

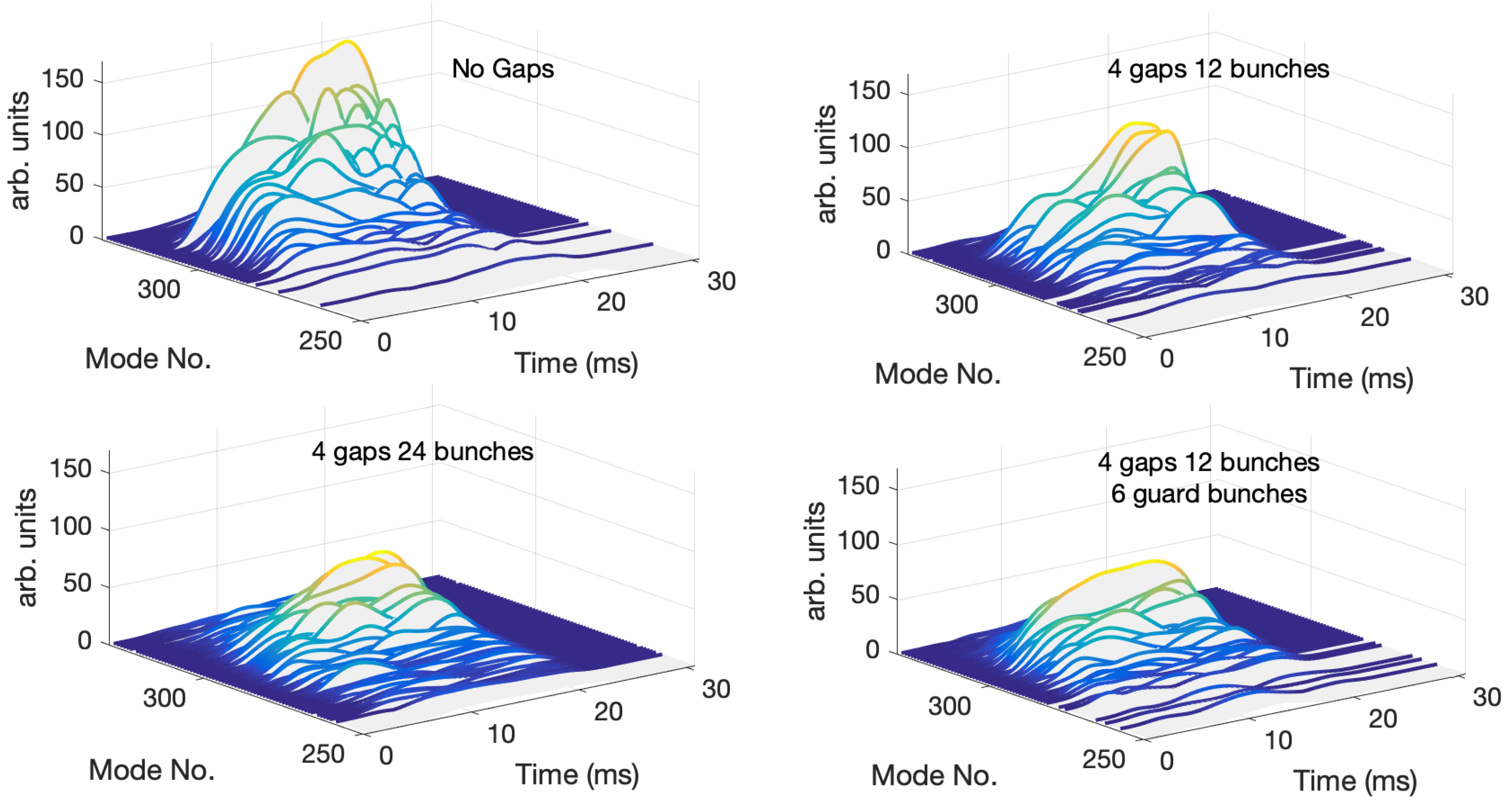




Grow-damp measurements (Dimtel system)

- Feedback disabled at 0 ms, re-enabled at 20 ms
- Study instability on a mode-by-mode basis
- Complex mode behavior after initial saturation

Mode amplitudes - Grow damp measurements @900 nTorr

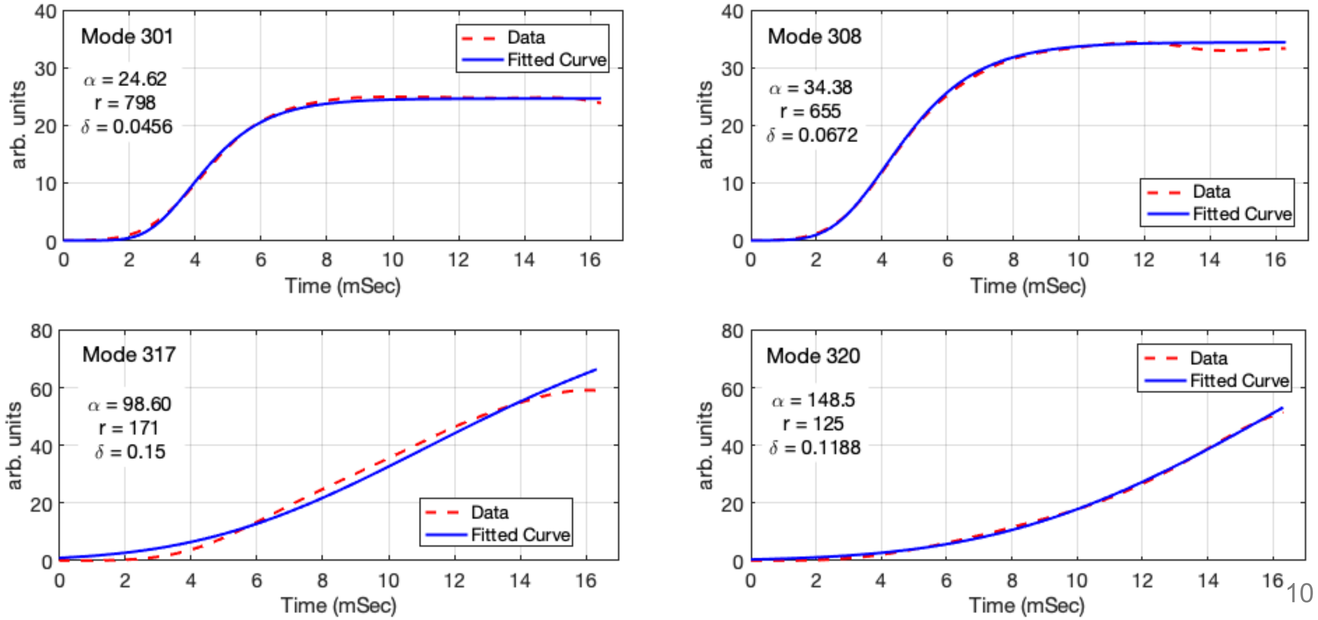


Characterizing growth and saturation

- 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.

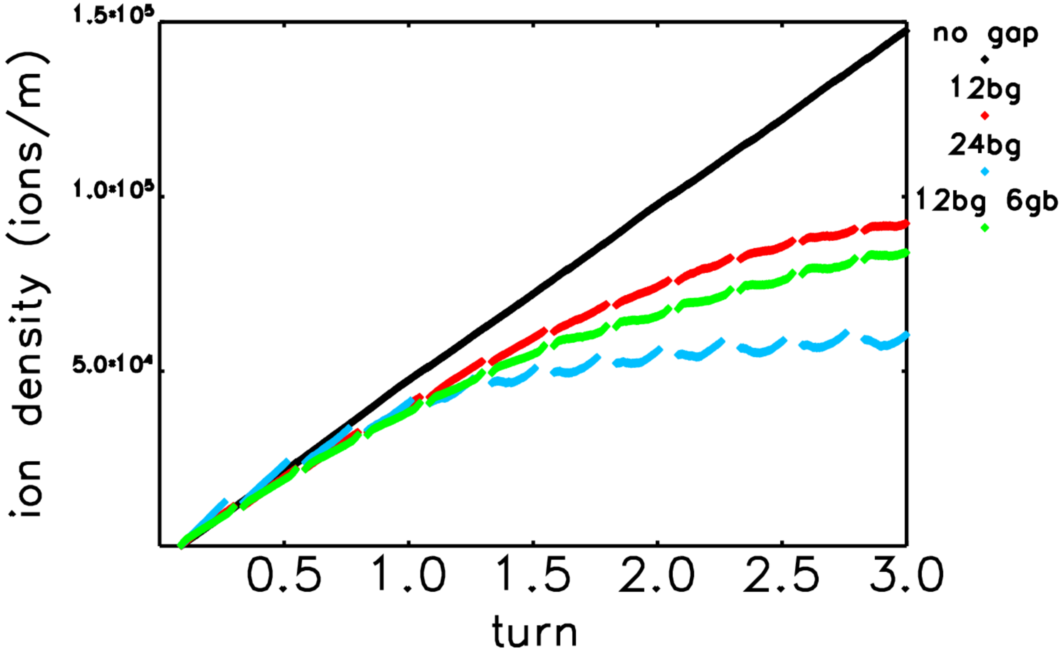
$$y(t) = \frac{\alpha}{(1 + e^{-rt})^{1/\delta}}$$

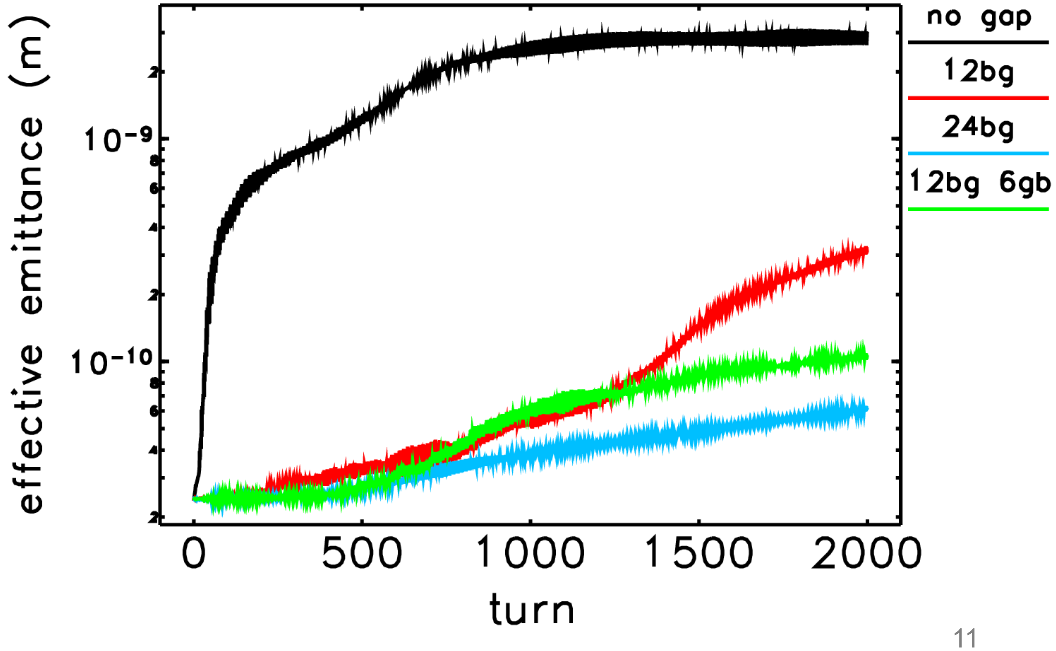
mode	freq (MHz)	α	t_i (ms)
301	6.2	24.6	3.9
308	4.3	34.4	4.1
317	1.9	98.6	11.1
320	1.1	148.5	17.0



Simulations (900 nTorr, S35)

- Particle tracking simulations done with IONEFFECTS element in elegant[1,2]
- Includes transverse impedance, multiple ionization, actual measured bunch pattern[3]
- Bi-Gaussian kick method[4]
- Clearing effect from train gaps clearly seen
- Non-monotonic growth along bunch trains
- Effective vertical emittance (beam size and rms motion added in quadrature)
  - Simulations overestimate by up to factor of 2
  - Show effectiveness of train gaps, especially guard bunches





[1] M. Borland, Rep. LS-287, APS, Sep. 2000.
[2] Y. Wang and M. Borland, Proc. AAC 877, p. 241, 2006.
[3] J. Calvey and M. Borland, PRAB 24, p. 124401, 2021.
[4] J. Calvey et al., Proc. IPAC’21 pp. 1267–1272.

Conclusions

- A gas injection system has been installed and used to study ion instability, at two different locations in the APS ring.
- Train gaps are effective at mitigating the instability. Guard bunches help with the ion clearing.
- Dimtel transverse feedback can effectively damp the instability in both planes simultaneously.
- Grow-damp measurements have been performed, and used to study the growth of the instability on a mode-by-mode basis.
- Strongest modes are driven by locations with the most ion trapping
- IONEFFECTS simulations using a bi-Gaussian kick method show qualitative agreement with the measurements.
- Work is underway to implement a Poisson solver in the code, and to perform simulations using a model of the transverse feedback.