Filling patterns and timing modes with passive bunch lengthening cavities in APS-U

Michael Borland, Tim Berenc
Accelerator Systems Division

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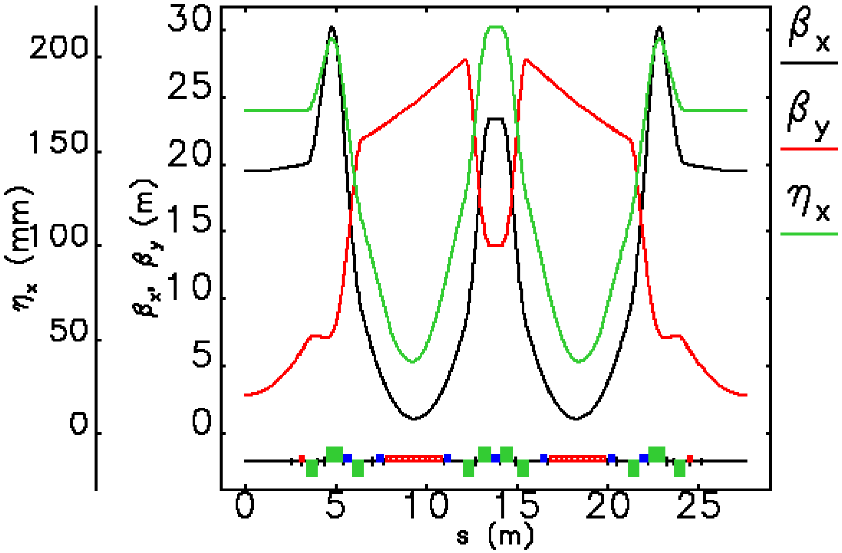
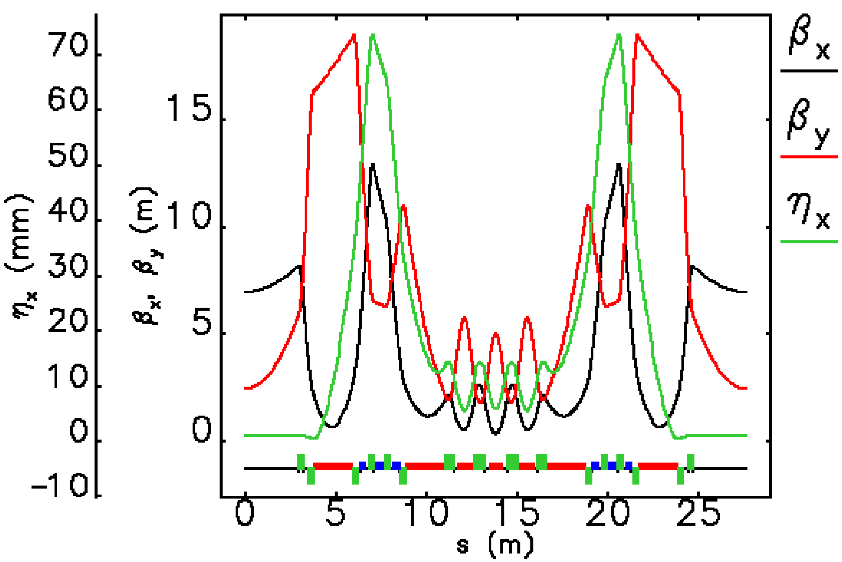
Outline

- Comparison of APS now and APS-U plans
- Modeling methods
- Bunch duration, shapes, and lifetime
- Effects of bunch population variation
- Simulation of effects of loss of a bunch
- Effects of ID gap motion
- Hybrid mode and other options
- Conclusion and plans

Hybrid 7BA Lattice Compared to APS Now





	APS	MBA	
Betatron motion			
ν_x	36.205	95.125	
ν_y	19.272	36.122	
$\xi_{x,nat}$	-90.340	-138.580	
$\xi_{y,nat}$	-43.319	-108.477	
Lattice functions			
Maximum β_x	30.2	12.9	m
Maximum β_y	27.8	18.9	m
Maximum η_x	0.216	0.074	m
Average β_x	13.2	4.2	m
Average β_y	15.9	7.8	m
Average η_x	0.148	0.028	m
Radiation-integral-related quantities			
Beam energy	7	6	GeV
Natural emittance	2527.5	66.9	pm
Energy spread	0.095	0.096	%
Horizontal damping time	9.7	12.1	ms
Vertical damping time	9.7	19.5	ms
Longitudinal damping time	4.8	14.1	ms
Energy loss per turn	5.34	2.27	MeV
ID Straight Sections			
β_x	19.5	7.0	m
η_x	171.88	1.11	mm
β_y	2.9	2.4	m
$\epsilon_{x,eff}$	3142.7	67.0	pm
Miscellaneous parameters			
Momentum compaction	2.84×10^{-4}	5.66×10^{-5}	
Damping partition J_x	1.00	1.61	
Damping partition J_y	1.00	1.00	
Damping partition J_δ	2.00	1.39	

H7BA lattice based on L. Farvacque *et al.*, IPAC13, 79.

Present APS fill and operating modes

- 24-bunch uniform, 100 mA
  - 75% of time
  - 6.5 MHz bunch rate
  - 120s top-up
- 324-bunch uniform, 100 mA
  - 15% of time
  - 88 MHz bunch rate
  - 12 hour “fill-on-fill” interval
- Hybrid (camshaft), 100 mA
  - 10% of time
  - One 16 mA bunch
  - 60-s top-up

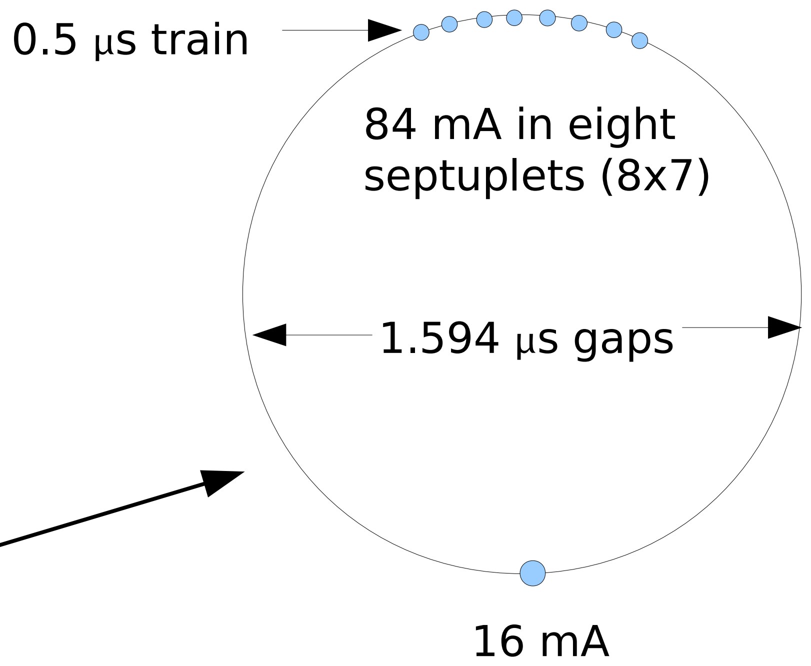


Diagram courtesy L. Emery, APS.

Planned APS-U fill and operating modes

- Minimum beam current of 200 mA
- Swap-out injection
  - Single bunch swapping only
  - 5-15 s interval
- Two fill patterns being advertised
  - 324-bunch uniform
    - Limit of present kicker technology
    - Desirable for long lifetime and possible flat beam operation
  - 48-bunch uniform
    - Desirable for timing experiments
    - Round beam operation required for lifetime reasons
- Possible hybrid or non-uniform modes under study
- Bunch-lengthening needed to reduce IBS, improve lifetime
  - Passive higher-harmonic cavity (HHC) planned
  - 4^{th} harmonic (of 352 MHz)
- Extensive simulations performed to verify effectiveness, beam stability, practical issues

Modeling methods

- Used parallel **elegant** for tracking
  - Latest release (v27.0) has significantly improved performance for bunched beams
  - Domain decomposition shares bunches across processors for best performance with multi-particle bunches
- To make tracking faster and concentrate on relevant physics
  - ILMATRIX element for the ring itself
    - Can include chromatic and amplitude detuning (not relevant here)
    - Can include first- and second-order momentum compaction
  - SREFFECTS for lumped synchrotron radiation
- Turn-by-turn, bunch-by-bunch[1] diagnostics included as needed
  - Phase space coordinates
  - Beam moments
  - Histograms
  - Beam- and generator-induced voltages, phases in cavities
  - Rf feedback system data

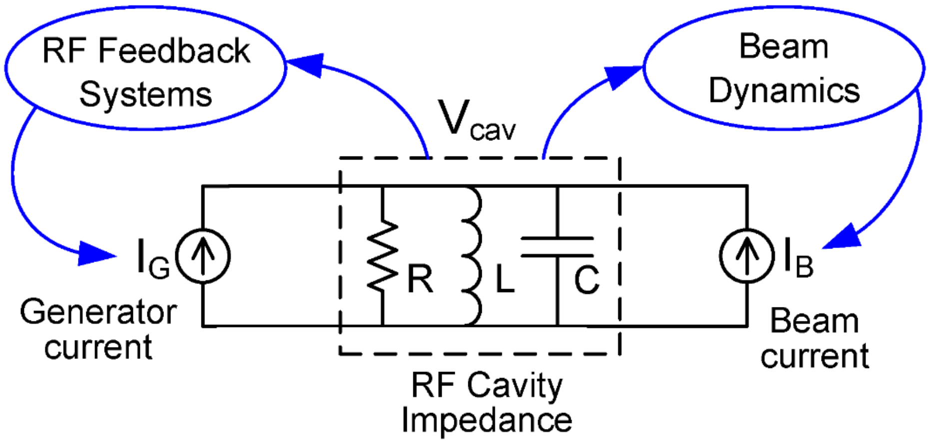
1: Available in next release.

Collective effects and rf modeling

- RFMODE: Beam- and generator-driven rf cavity mode
  - Beam-induced part
    - Uses loss factor plus phasor addition/rotation/damping
    - Implicitly includes the compressive single-turn wake corresponding to the mode
      - Can be turned off if desired
  - Generator-driven part
    - PID feedback seeks to maintain specified net cavity voltage and phase
    - User provides filter coefficients for the controllers
  - Can add other cavity longitudinal and transverse modes if desired (not in present work)
- ZLONGIT[1]: Longitudinal short-range impedance
  - Present instance includes
    - Short range wake from rf cavity HOMs but excluding fundamental
    - Geometric impedance of vacuum chamber computed with GdfidL[2] and ECHO2D
    - Resistive wall impedance computed analytically
- Part of **elegant** since 1994, but recently
  - Improved parallel performance for multi-bunch beams
  - Added rf feedback

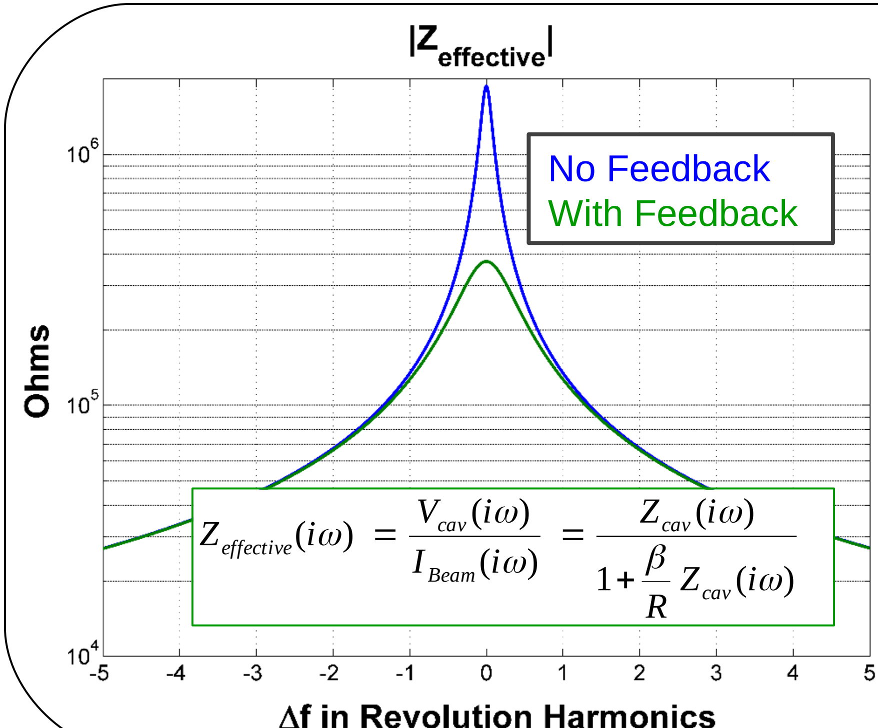
[1]Data courtesy R. Lindberg, A. Blednykh, and Y.-C. Chae.
[2]www.gdfidl.de

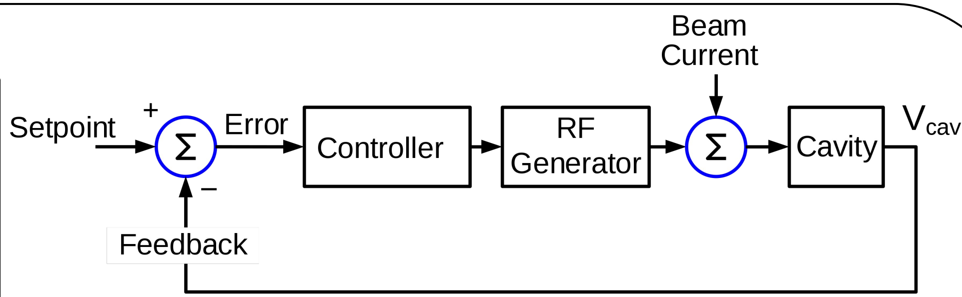
RF Feedback



RF feedback:

- Regulates the RF cavity fields
- Rejects disturbances including beam loading
- Changes the impedance that the beam sees
- Note: in Bunch Lengthening System, main RF contributes to Robinson damping while the harmonic RF cavity contributes to growth





Example: Direct RF Feedback

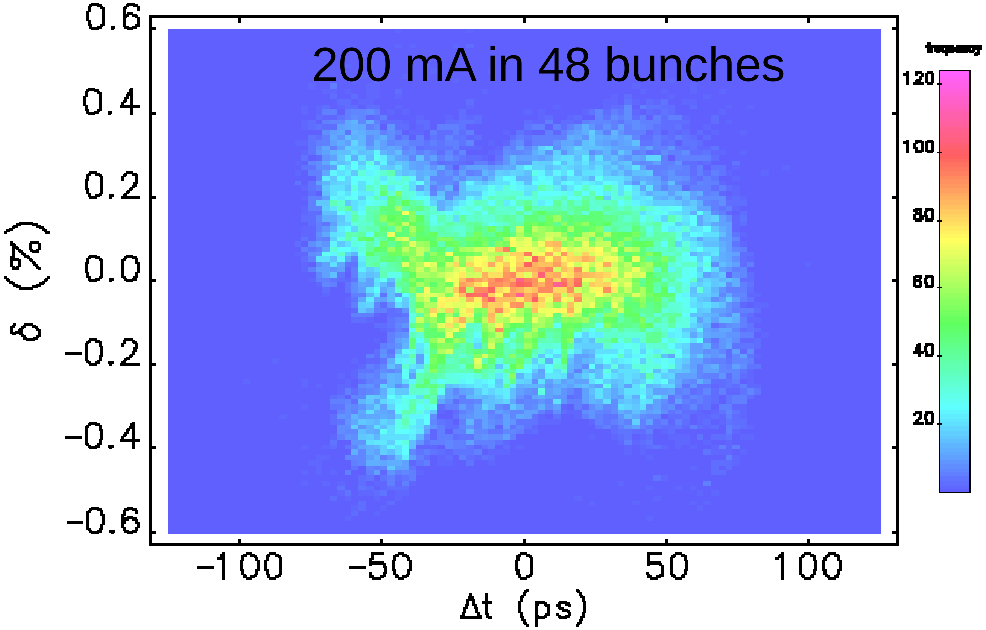
§ Simple Proportional Gain

=> Controller = $\frac{\beta}{R}$, β = Loop Gain at resonance

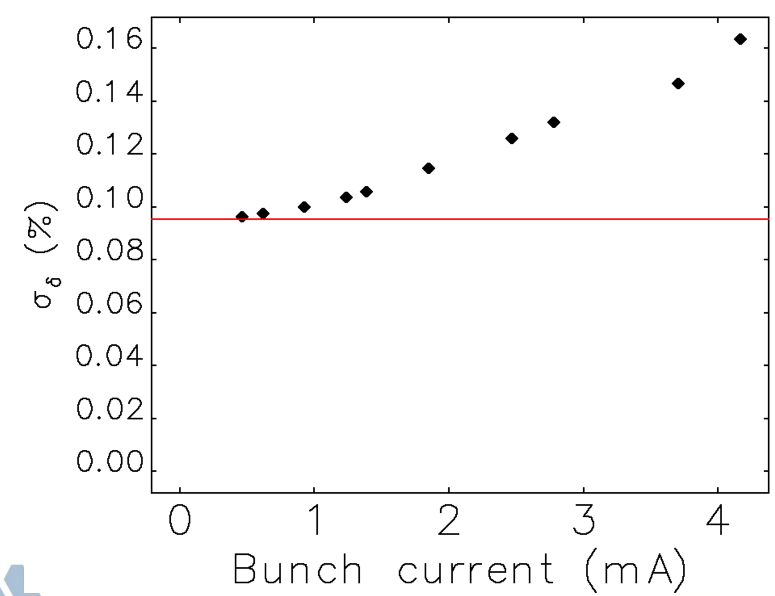
§ R and Q are reduced by (1 + Loop Gain)

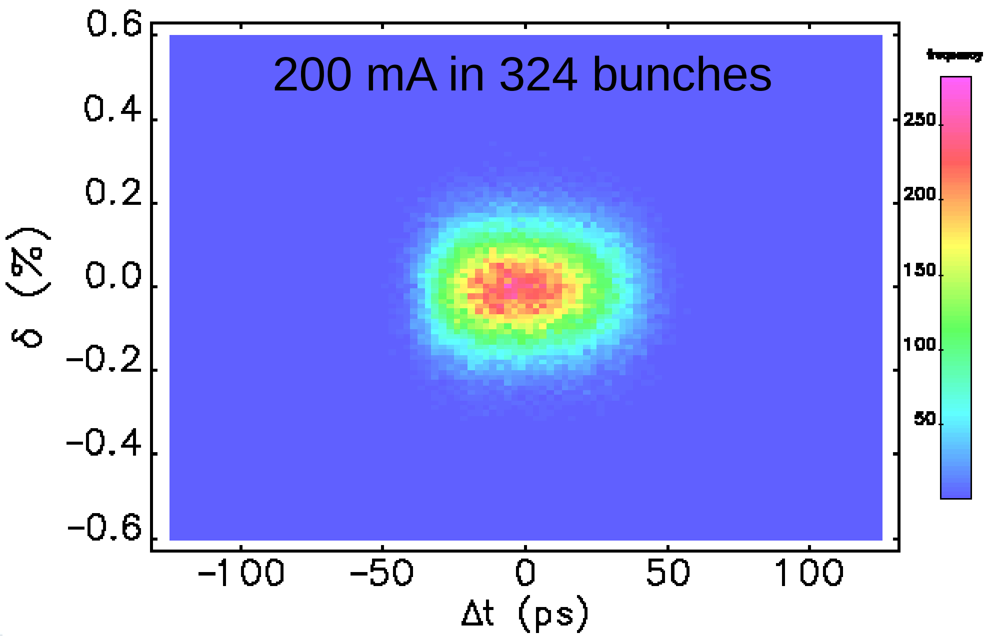
§ R/Q stays the same

Longitudinal phase space without HHC

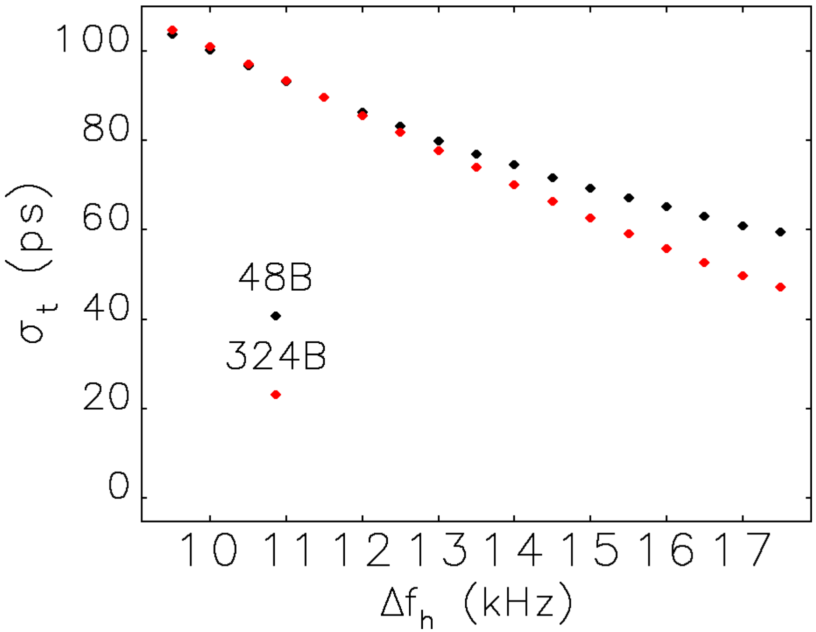


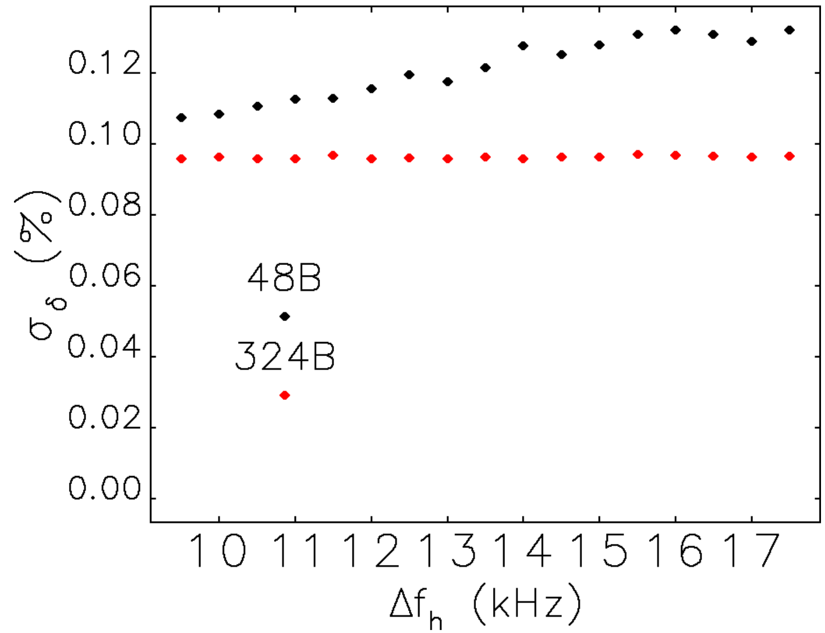
- Results similar with 10^4-10^6 simulation particles/bunch
- Microwave instability threshold is at ~0.5 mA/bunch
  - In APS, threshold is ~7 mA/bunch
- Increased energy spread has a small impact on brightness





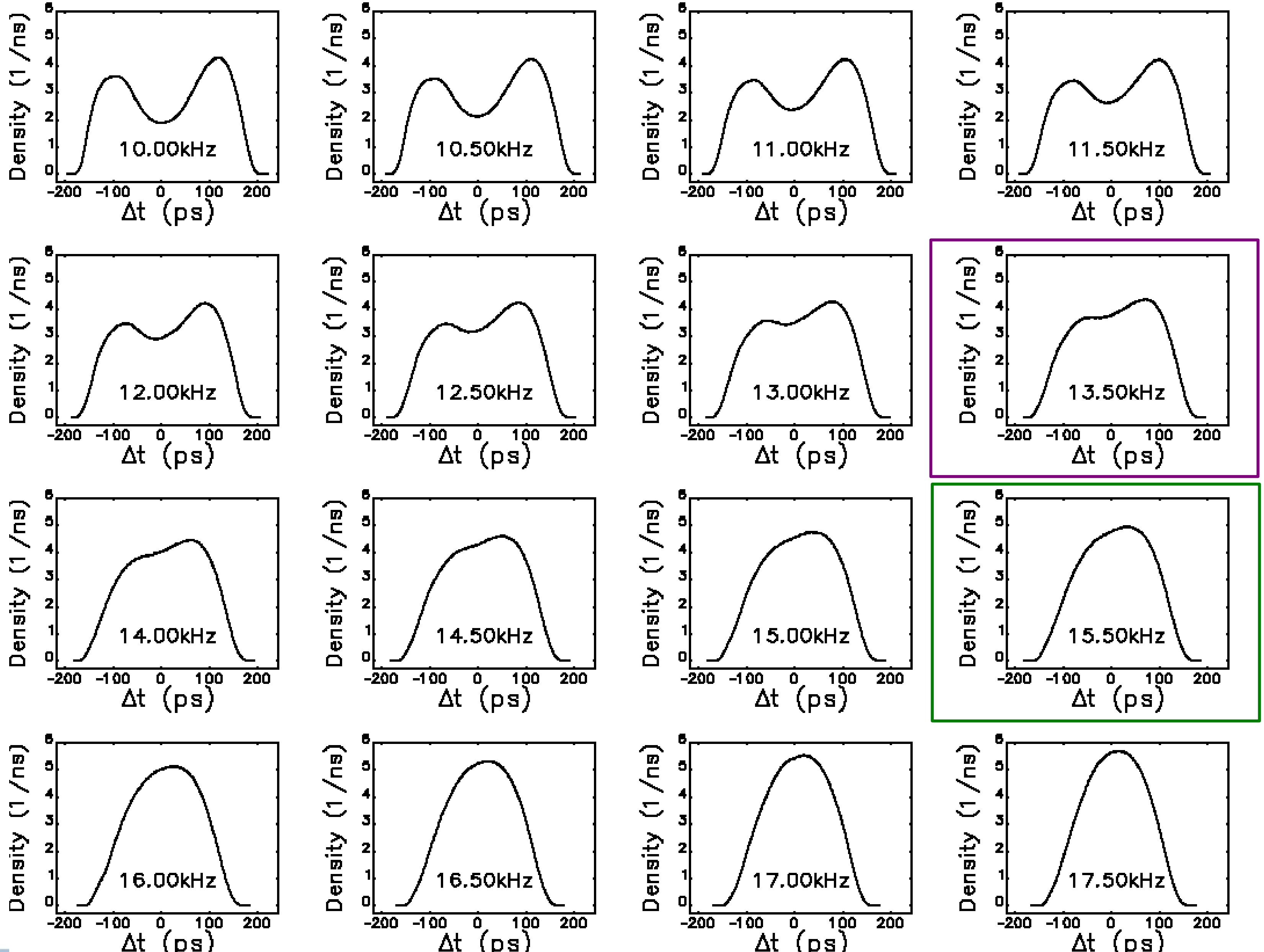
Scan of HHC detuning



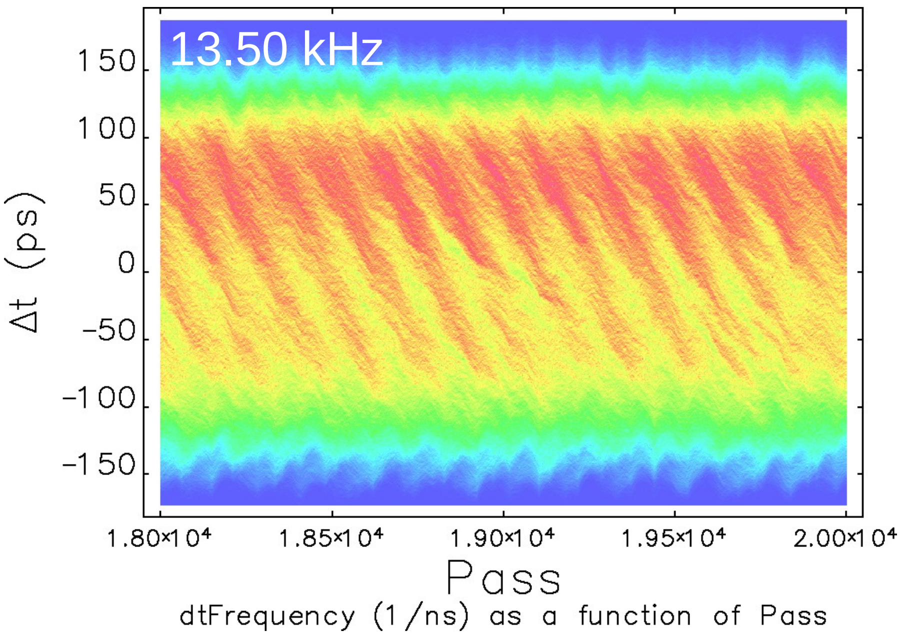


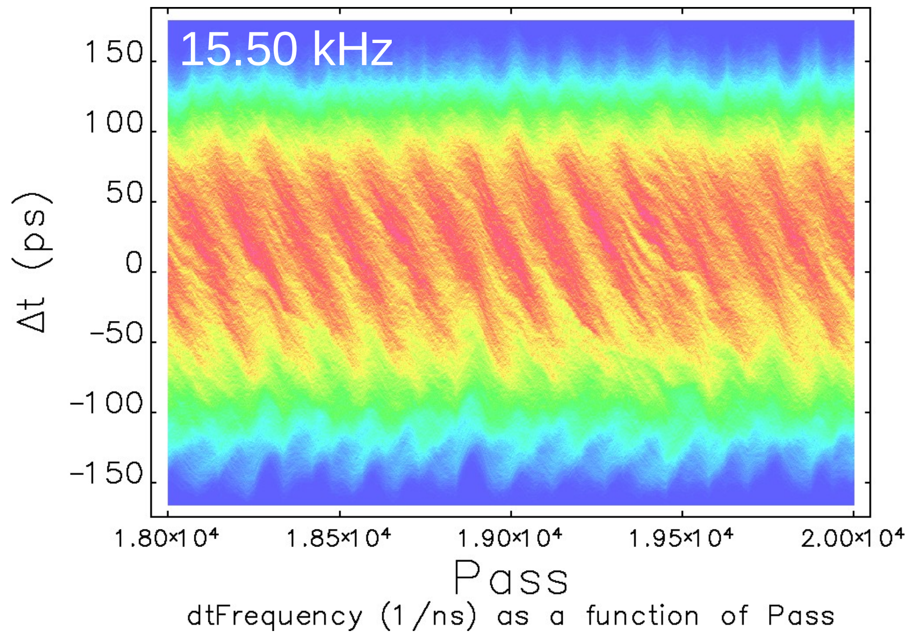
- As expected, bunch lengthens as HHC cavity is tuned toward resonance
- "Beneficial" effect of MWI visible for 48-bunch mode
- As bunch lengthens with decreased detuning, MWI is suppressed and energy spread drops
- Expected optimum bunch length from theory (without impedance) is 50 ps with ~16.5 kHz detuning
  - 324-bunch results agree with this expectation
  - Seems we can go beyond that…

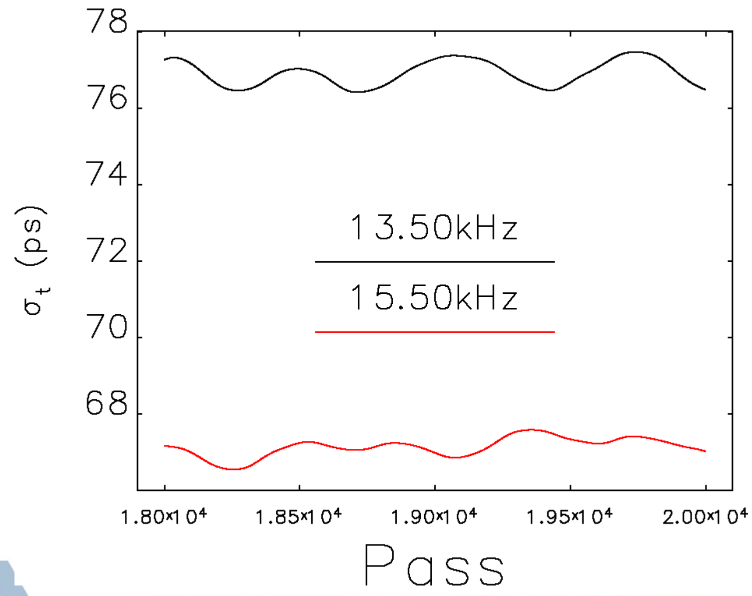
Longitudinal density averaged over 2000 turns (48B)



Longitudinal density is noisy, but rms is stable (48B)







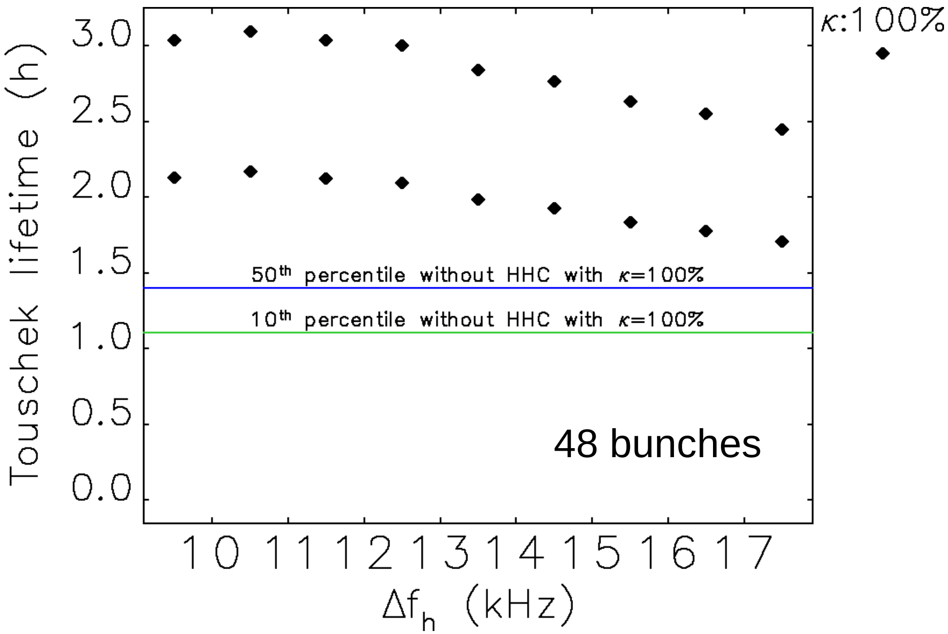
- Results on previous slide average out the effect of MWI
- Turn-by-turn variation seems mostly MWI-driven
  - Present with cavity detuned by +136kHz ($f_{rev}/2$) as well
- Not related to rf feedback
- How much do users care about this?

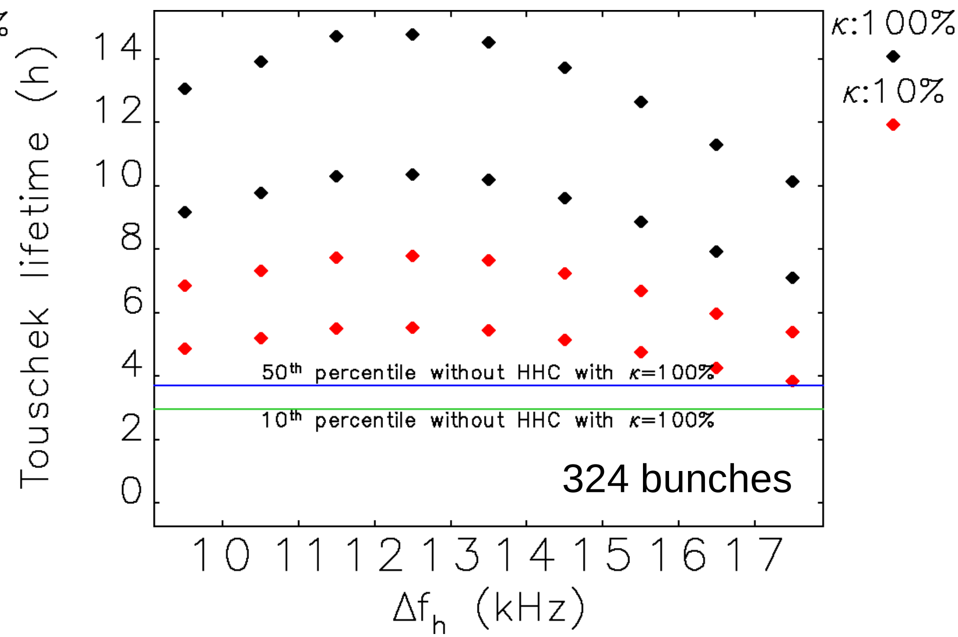
Touschek lifetime analysis

- Touschek lifetime is main reason for introducing HHC
- Normally, one just uses gaussian bunch duration
- Using tracking results improves fidelity of calculations
  - Tracking results give bunch distribution turn-by-turn
  - Slice analysis of bunch on each pass gives current density and slice energy spread
    - Slice energy spread includes MWI
  - Program **touschekLifetime** allows slice-based Touschek lifetime calculation[1]
- Also included IBS effect on emittance and energy spread
  - Computations used **ibsEmittance**[2]
- In addition, need local momentum acceptance[3]
  - Used 100 error ensembles with lattice correction[4] as input to tracking
- Computations provide a Touschek lifetime value for each error ensemble, averaged over many bunch samples
- Method not fully self-consistent, but allows combining effects of intrabeam scattering, HHC, and microwave instability

1: A. Xiao and M. Borland, PRSTAB **13** 074201 (2010); and A. Xiao, to be published.
2: A. Xiao, Proc. Linac 08, 296-298.
3: C. Steier et al., Phys. Rev. E 65-056507 (2002); M. Belgroune et al., PAC 2003, 896.
4: V. Sajaev, to be published.

Touschek Lifetime Improvements due to HHC



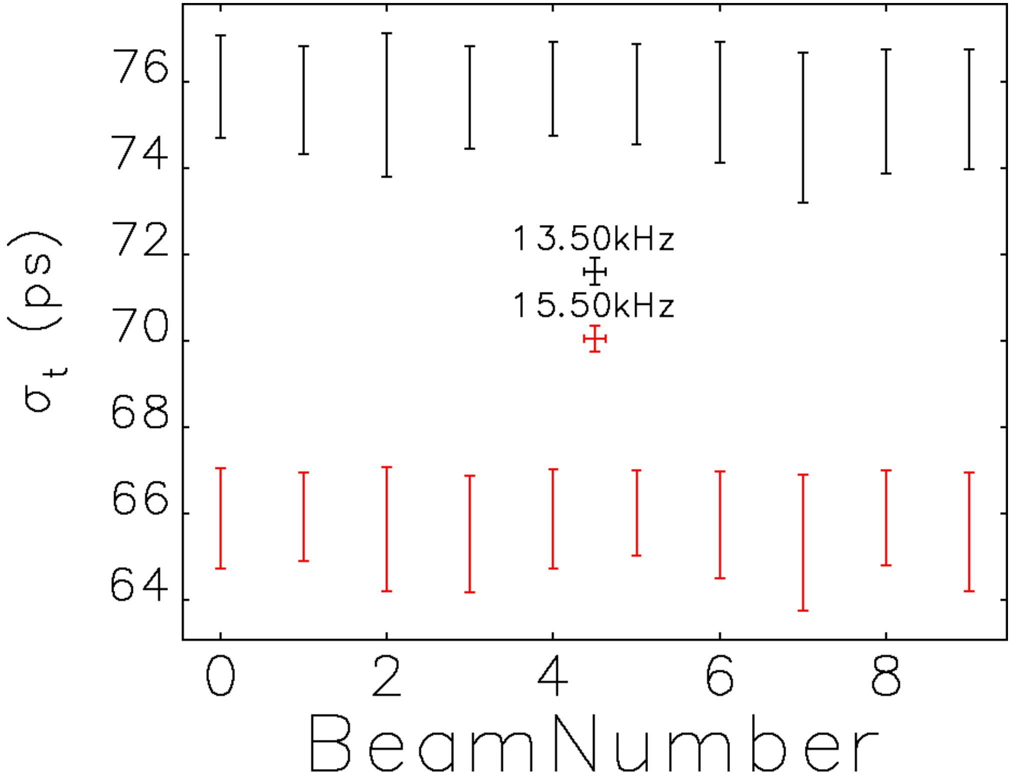


- In both cases, have 200 mA, Q_L=600k, κ≈1
- For 48 bunches, get factor of ~2 for 13.5 kHz detuning
  - Bunch is already significantly lengthened by the ring impedance
  - Do not reach the desired 7.5 h value
  - Has implications for shielding, TBD
- For 324 bunches, get factor of ~3 for 13.5 kHz detuning
  - Total lifetime (including gas scattering) expected to meet goal for round beams
  - Flat beams (2x higher brightness) more challenging

Symbols show 10th (lower) and 50th (upper) percentile points in lifetime distributions

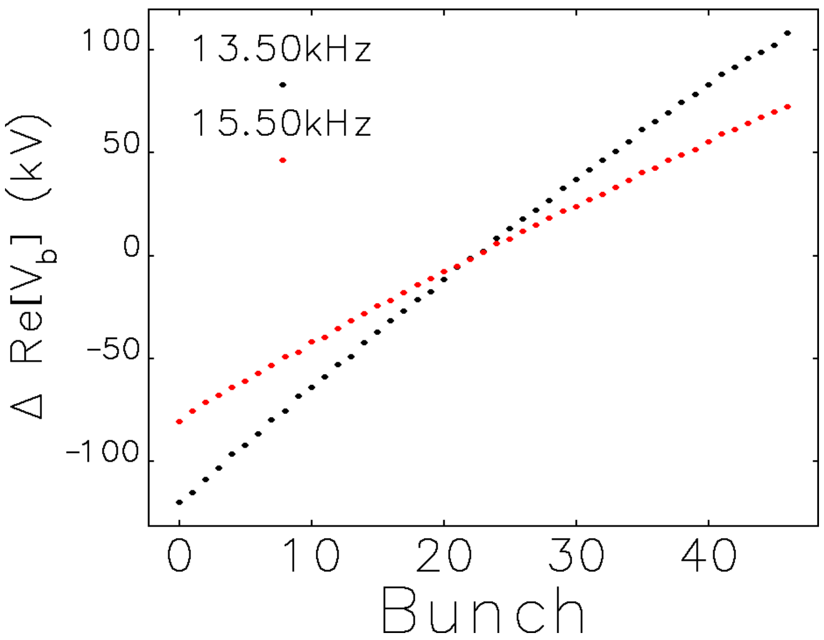
Effect of bunch population variation

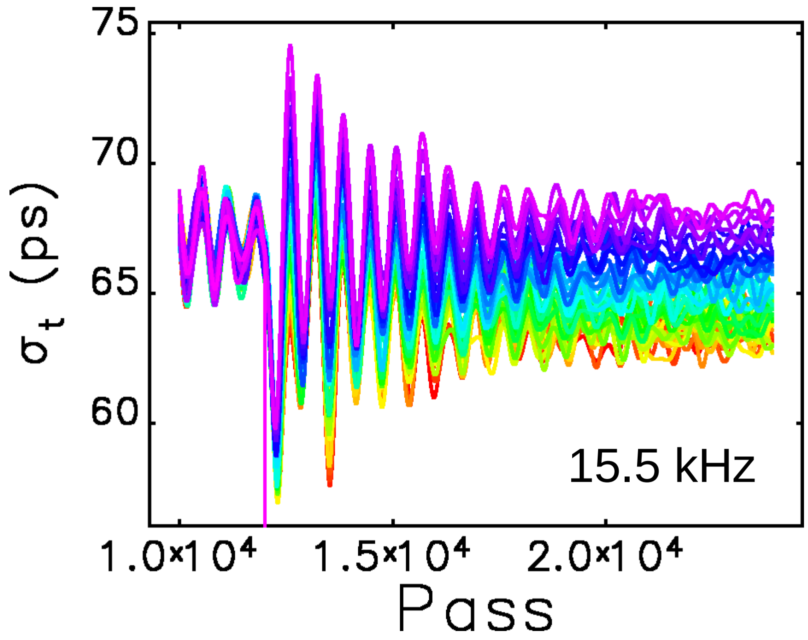
- Bunches will be swapped out when they fall to 90% of initial charge
- Expect to have randomly-ordered (in time) bunches with uniform distribution of charge between 105% and 95% of the average value
- Simulated 10 random 48-bunch fills of this type
- Modest variation among bunches within a fill and over time



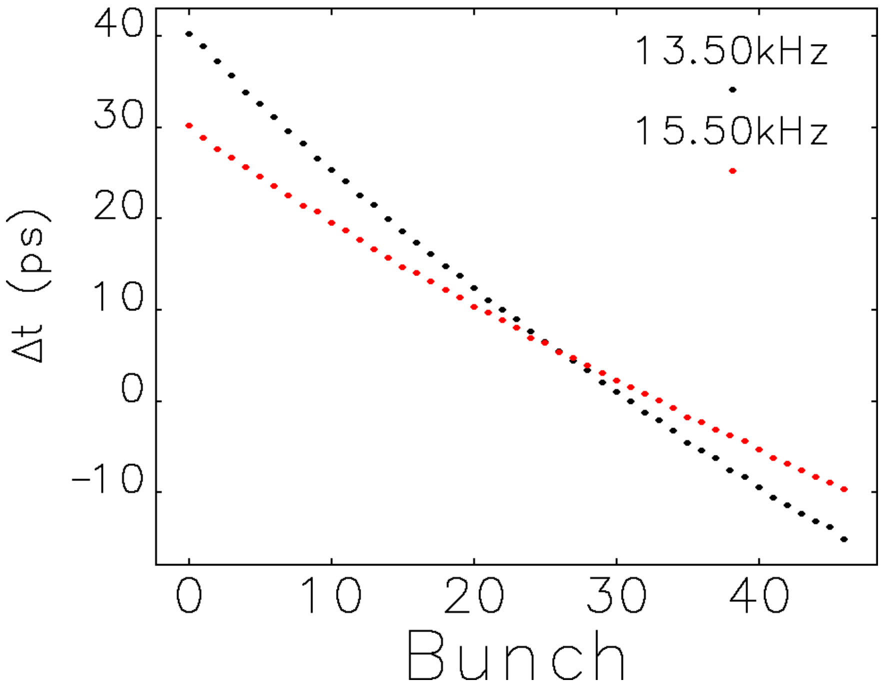
Effect of lost bunch (48 bunches, minus 1)

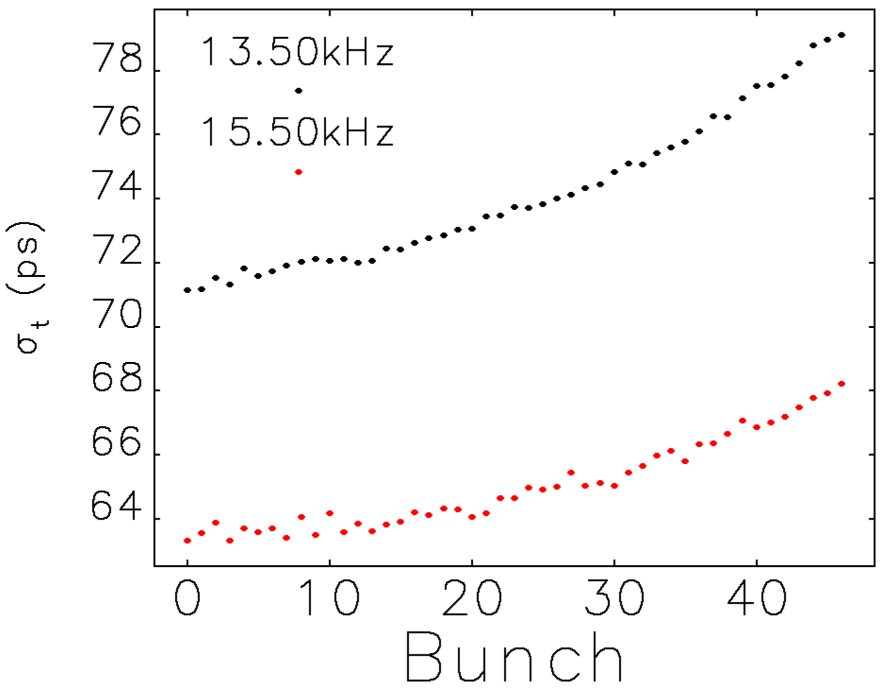
- Swap-out involves kicking out one bunch and immediately injecting replacement
  - May fail sometimes to inject the replacement
- Simulated kicking out of last bunch in 48-bunch fill, then return to equilibrium
  - No particle loss observed even with ±2% momentum acceptance
- Real part of beam-induced field in main cavity has ~160-230 kV sawtooth
  - Forces bunches to shift phase
  - Changes effect of HHC





Effect of lost bunch (48 bunches, minus 1)

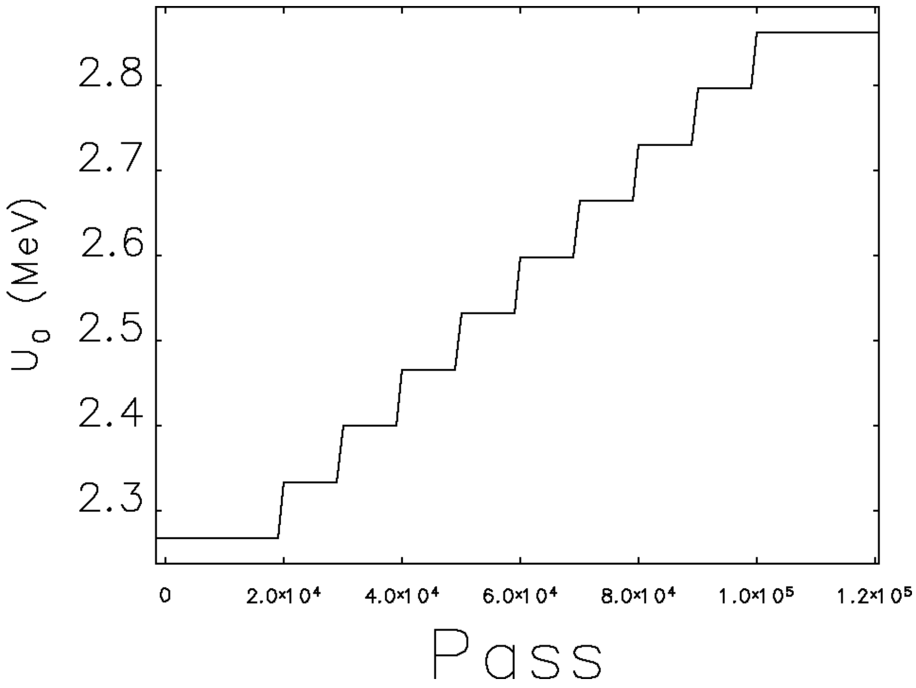




- Variation in the bunch centroid is a significant fraction of the bunch length
  - Is this a problem for users?
- ~7 degree phase shift on main rf system
  - May want to adjust injector phase to hit the optimum point in the bucket
- Bunch length variation is under 10%, presumably tolerable
- Could provide gate to users to indicate when a bunch is missing

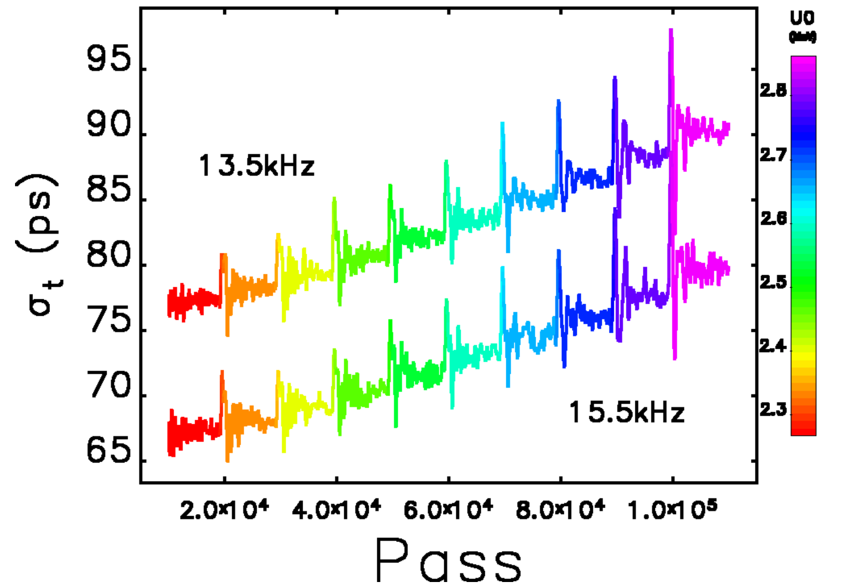
Effect of variation in energy loss per turn

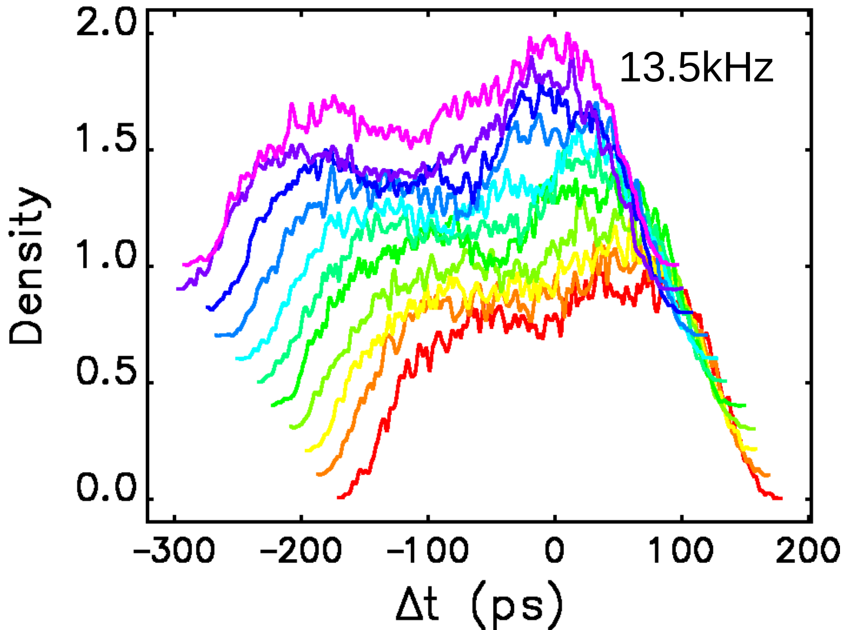
- As ID gaps are varied, the energy loss per turn varies
  - Could vary by a significant fraction of the 2.27 MeV/turn nominal loss
  - Presently, without pre-conditioning APS rf systems trip when closing all ID gaps rapidly
- Feedback will maintain cavity voltage and phase relative to the source, but
  - Beam will move to a different rf phase
  - Incoming bunches may suffer losses from energy oscillations due to phase offsets
  - Bunch duration will change
- Simulated unrealistically rapid variation of energy loss per turn by 0.6 MeV
  - Took 10 equal steps at 10k turn intervals
  - Ramped loss between levels over 1000 turns
  - Included effect on damping times and energy spread
  - Kept (slow) tuners for main, HHC fixed

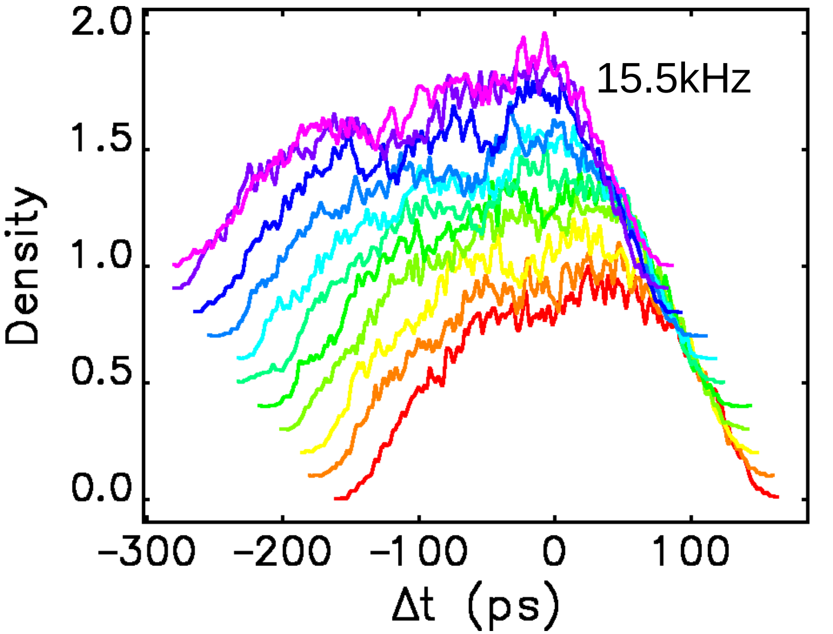


Effect of variation in energy loss per turn

- Increased energy loss moves beam higher on the main rf waveform
- Reduced slope of main rf means longer bunches
  - Good news for beam lifetime
- For 13.5 kHz bunches begin to take double-humped appearance
- Shifting phase complicates injection
  - Booster may need to track SR bucket

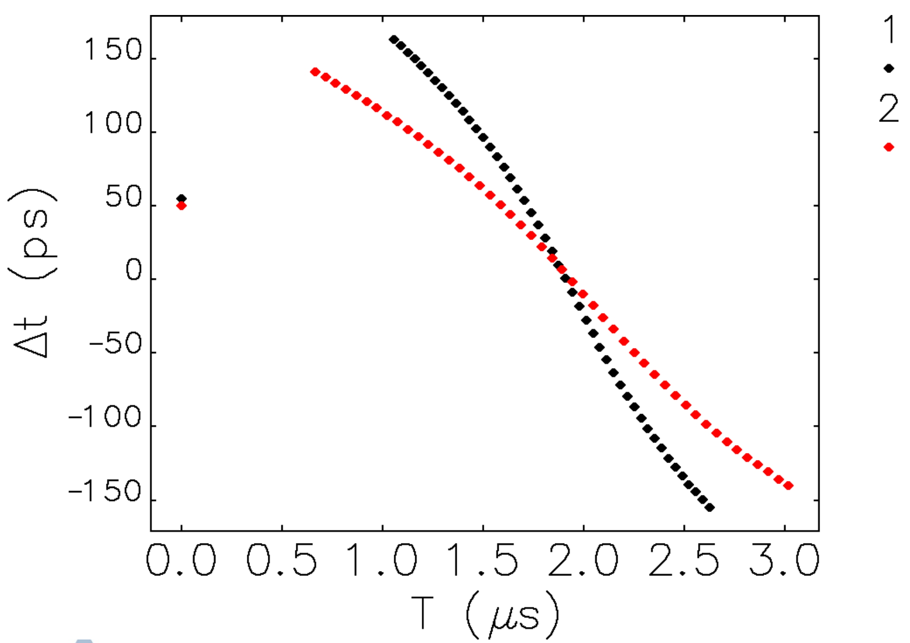


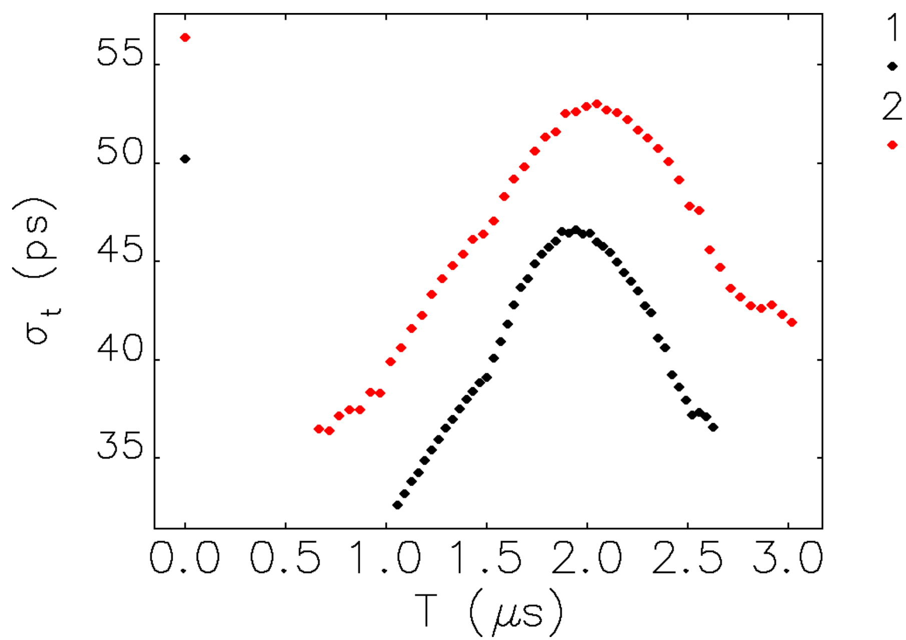




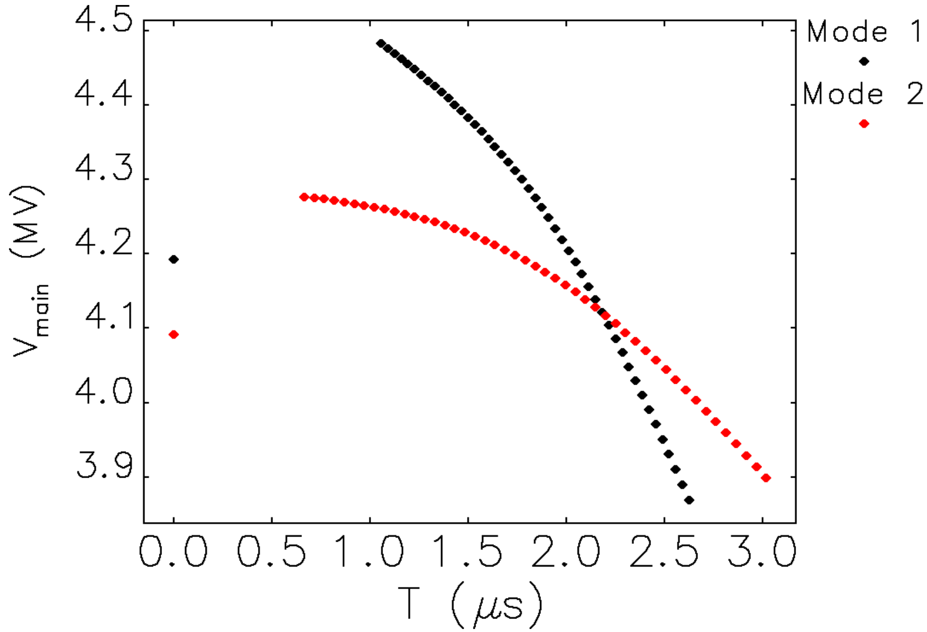
Hybrid mode

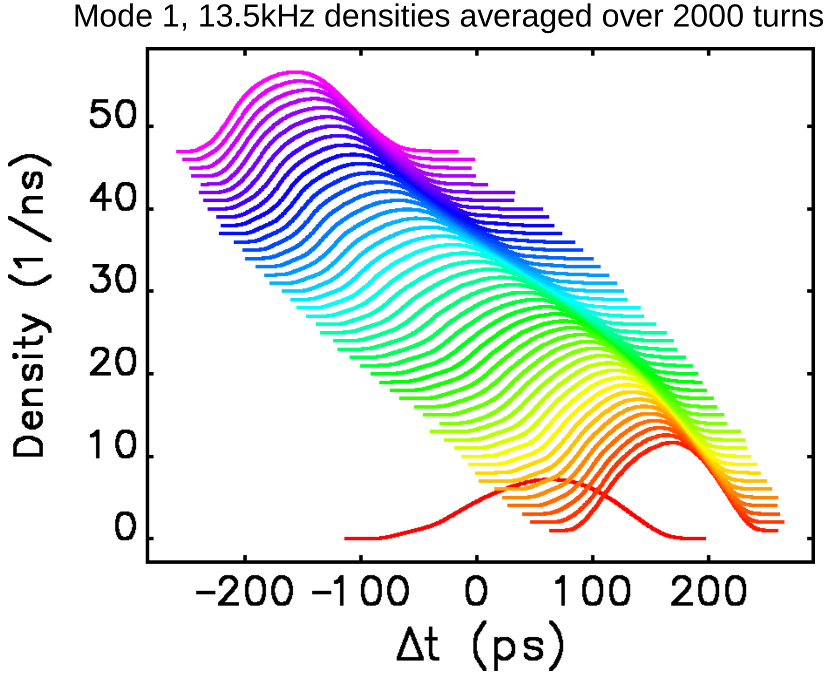
- Looked at two possible hybrid or camshaft modes with 4.25 mA/bunch
  - Mode 1: 47 bunches at 12 bucket spacing with ±1.05 μs gap from single bunch
  - Mode 2: 47 bunches at 18 bucket spacing with ±0.66 μs gap from single bunch
- As expected, significant non-uniformity in bunch properties
  - Do not achieve >67 ps bunch duration seen in uniform 48-bunch mode
  - Already-difficult lifetime situation made significantly worse
- Results shown have detuning of 15.5 kHz
  - Variations are slightly worse for 13.5 kHz

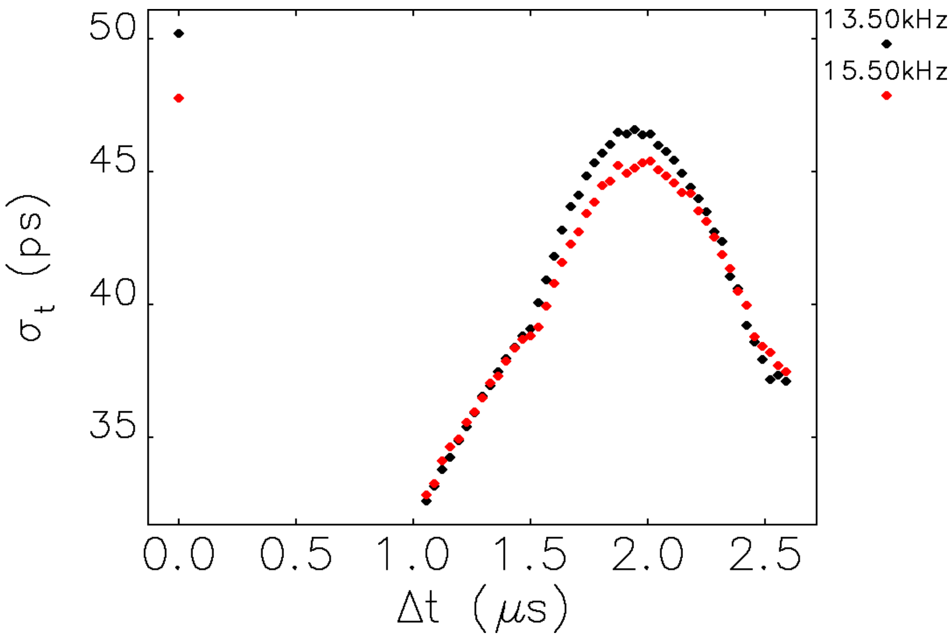




Hybrid mode







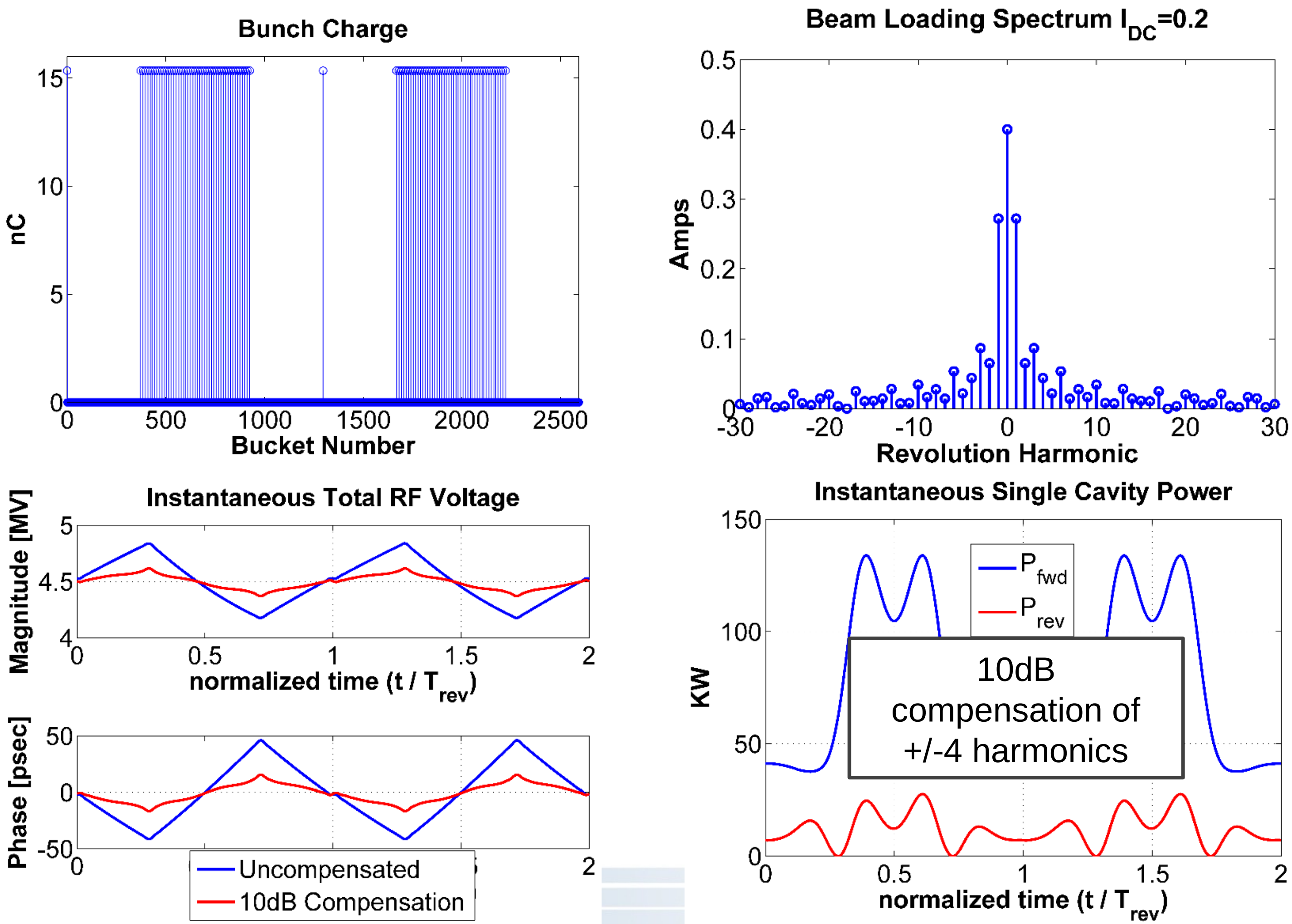
- Main cavity voltage shows a significant modulation
- Present rf feedback system is not fast enough to counteract this
  - Response time is about 20 ms
- Studying a faster system that should better compensate

RF Feedback: Other Types of Feedback

- Polar (Amplitude / Phase) or Cartesian (in-phase / quadrature): can be narrowband or wideband
- Comb Filters: reduce impedance & beam-loading at revolution harmonics & synchrotron sidebands
- Feed-Forward: feed wall-current monitor to generator to cancel the beam-current directly

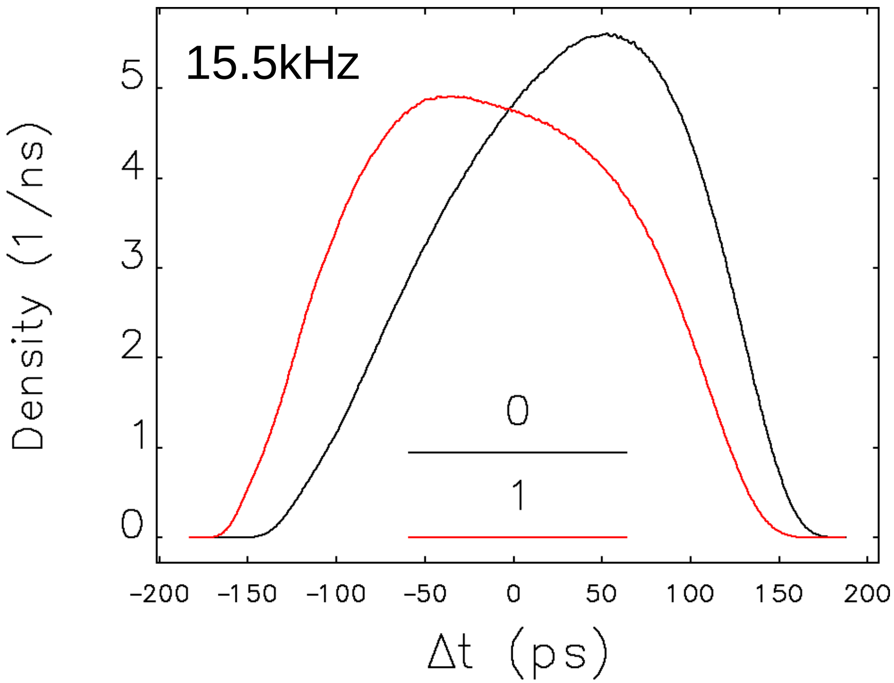
Example of Transient Beam-Loading Compensation for Hybrid Fill

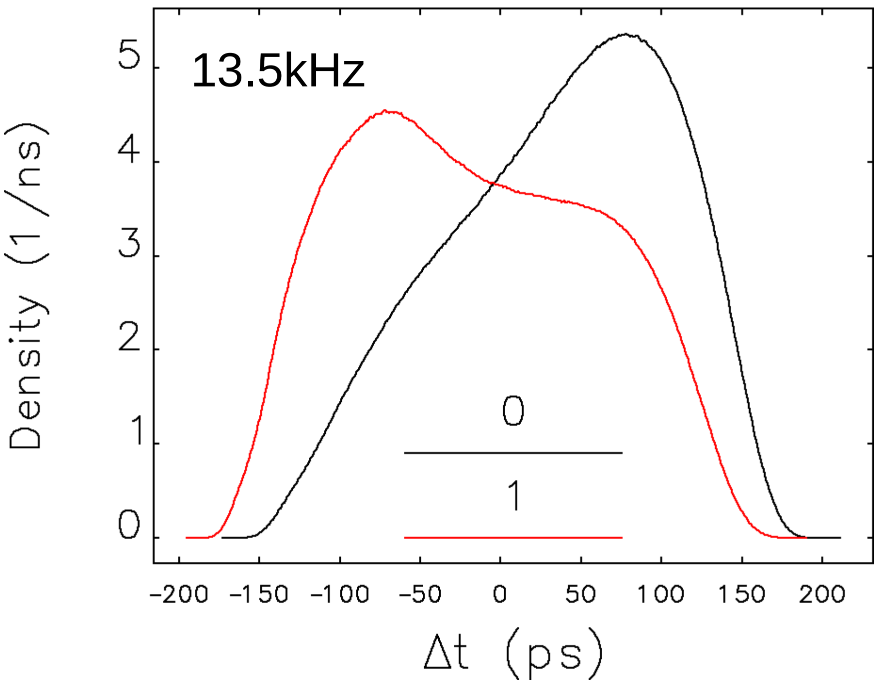
(can be achieved with combination of above)



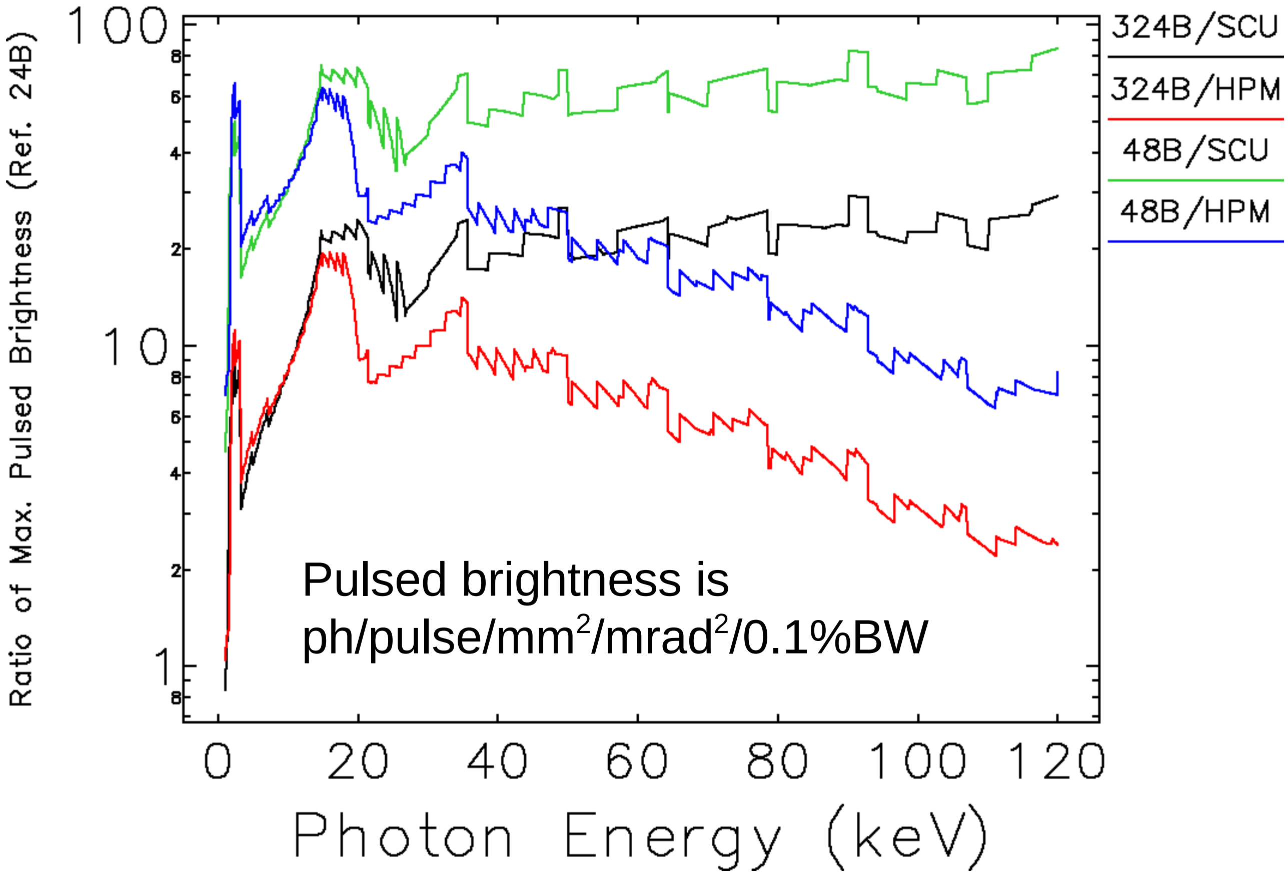
Another possibility: 24 doublets

- Could fill 24 pairs of buckets with uniform separation between pairs
  - Pair forms a “super-bunch” 2.9 ns in duration
  - 151 ns gap between pairs
- This actually works pretty well
  - 13.5kHz: 70-76 ps rms bunch duration
  - 15.5kHz: 63-67 ps rms bunch duration





X-ray Pulsed Brightness Compared to APS Today



- Assumptions:
  - APS: existing insertion devices and front ends; 24-bunch, 100 mA mode
  - APS-U: 4.8-m HPM and 3.7-m SCUs, high-heat-load front ends, 200 mA
- Increases of 40-80 fold for hard x-rays

Conclusions

- APS presently runs in timing modes about 85% of the time
- APS MBA upgrade seeks to preserve timing capabilities
  - 48-bunch, 200 mA mode
  - Pulsed brightness shows a significant increase
  - Exploring hybrid modes, other possibilities
- The necessity for a bunch-lengthening cavity complicates matters
- Extensive simulations show little issue with
  - 48-uniform, 324-uniform, and 2x24 fill modes
  - Accidentally kicking out a bunch
  - ~10% variation in bunch-to-bunch charge
  - Rapid ID gap variation
- Beam-phase detectors seem advisable to keep booster and ring synchronized
- On-going work includes
  - Simulation of filling from zero
  - Use of faster rf feedback with goal of improving results for hybrid mode
  - Modeling of multi-bunch instabilities with additional cavity HOMs
  - Add transverse impedance and verify single bunch stability limits

Acknowledgments

- Impedance model: R. Lindberg, A. Blednykh (BNL), Y.-C. Chae
- Error enembles for lattice evaluation: V. Sajaev
- Computing: Argonne Laboratory Computing Resources Center (LCRC)