Beam Dynamics Modeling of a Passive Bunch-Lengthening Cavity for the APS MBA Lattice

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Outline

- Background and motivation
- Simulation method
  - Parallel scaling and convergence checks

  } Mostly moved to backup slides
- Simulation results
  - Exploration of detuning and deQing choices
  - Effects of bunch population variation (see backup slides)
  - Effects of missing bunch
  - Comparison of 3rd, 4th, and 5th harmonic cavities
  - Lifetime calculations
- Next steps
- Conclusion

Background and Motivation

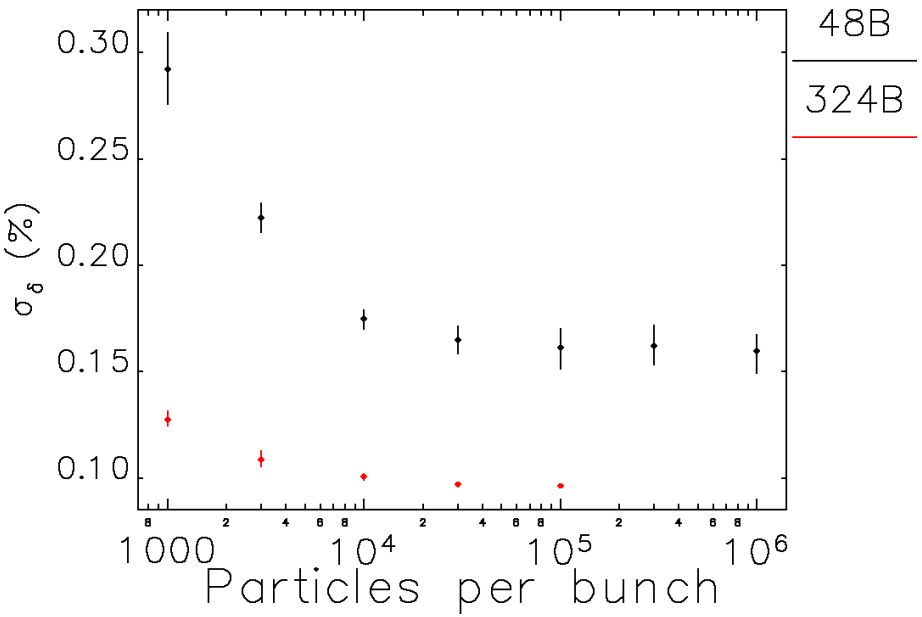
- Bunch lengthening is required for the MBA lattice in order to
  - Increase Touschek lifetime
  - Reduce intrabeam scattering
  - Reduce heating of vacuum chamber components
- Approximate calculations indicate that a ~50 ps rms bunch length was possible
  - Nominal, zero-current bunch length is ~12 ps
- Tracking studies can
  - Include exact time-dependence of rf fields
  - Include interaction of beam with cavity mode
  - Include longitudinal (and transverse) impedances
  - Include higher-order beam transport effects
- We used parallel **elegant**[1] to explore a bunch lengthening cavity in the APS MBA lattice (3PW-V6)
- For now, a passive HHC system is being considered in order to reduce cost
  - Loaded Q can be varied by adjusting coupling to external load
  - Resonant frequency can be varied by adjusting tuners

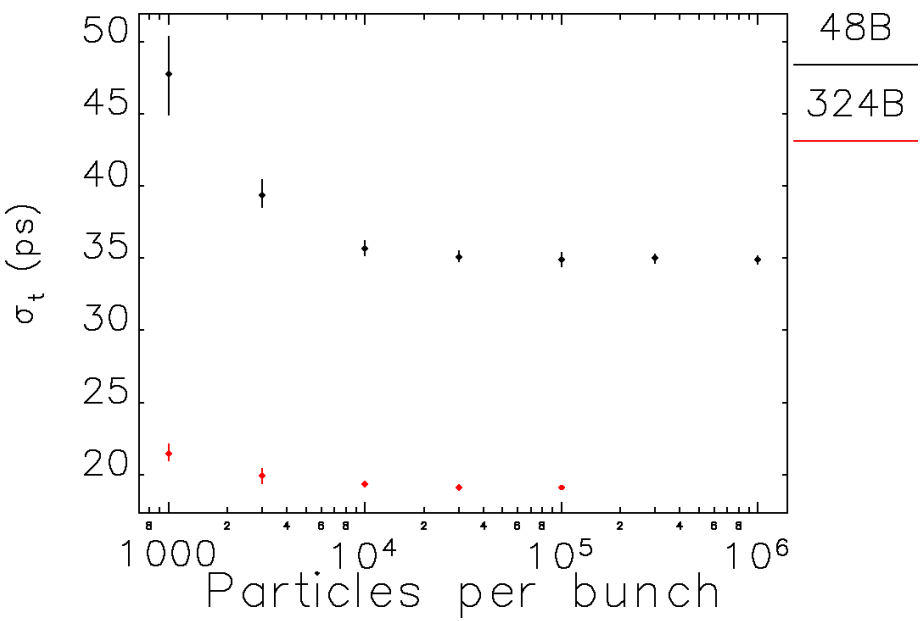
[1]M. Borland APS LS-287 (2000); Y. Wang et al., AIP Conf. Proc. 877 (2006).

Simulation details with main cavities only

- To get started, simulated with main cavity only
- The simulation of the 12 main cavities is done with two elements in **elegant**
  - RFCA: generator-driven fields
  - RFMODE: beam-driven fields
- RFCA driven at nominal frequency given by the circumference and harmonic number
- The RFMODE element must be detuned to negative side to ensure Robinson stability
- To ensure a quiet start, ramp the current from 0 to 200 mA over ~1000 turns
  - Simultaneously ramp RFCA voltage and phase, as well as mode frequency
  - This is precalculated and put in an SDDS file
    - Calculations use “well loved” formulae from P. Wilson, SLAC-2884
    - Ramping uses the modulate_elements command in **elegant**
- Tracking is performed for 16k turns to allow damping and assess stability
- Concentrate on 48-bunch, 200-mA mode

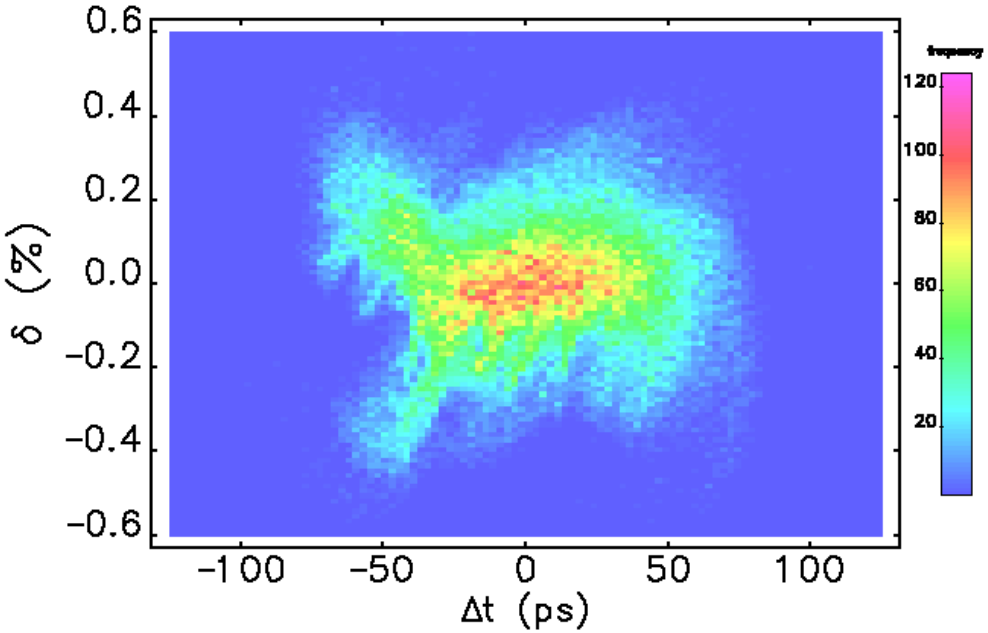
Bunch length and energy spread





- Studied convergence of basic results for 48 and 324 bunch fills
- About 100k particles per bunch are needed for stable results
  - 48 bunches takes about 30 minutes on 128 cores with minimal diagnostics
- Nominal bunch length is 12 ps rms with 0.095% energy spread
- Significant bunch lengthening just due to microwave instability, impedance, and potential well distortion

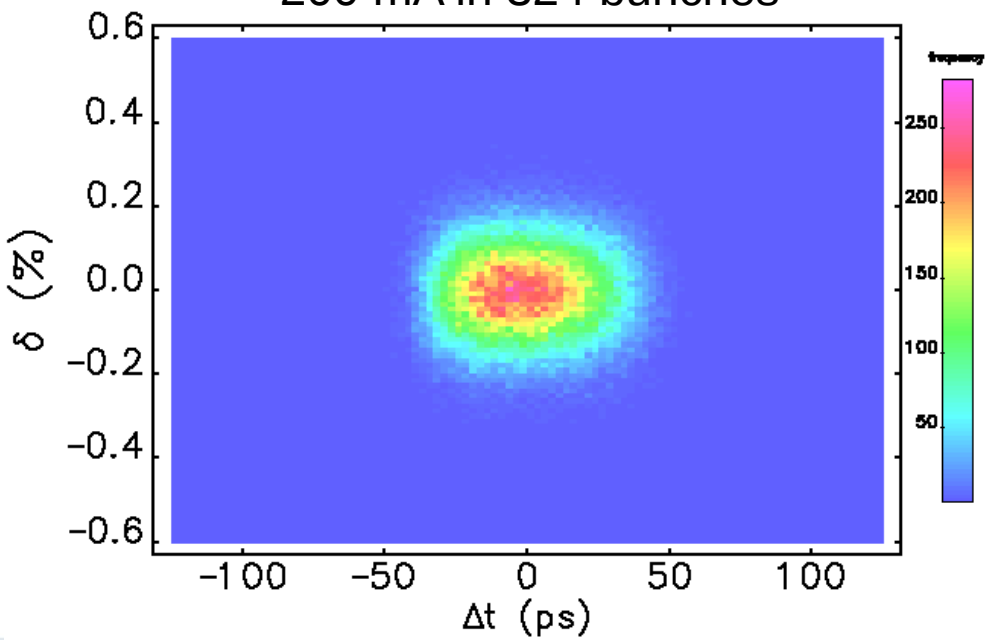
Phase space at 50-turn intervals for 100kP/bunch



200 mA in 48 bunches

Synchrotron period is ~400 turns.

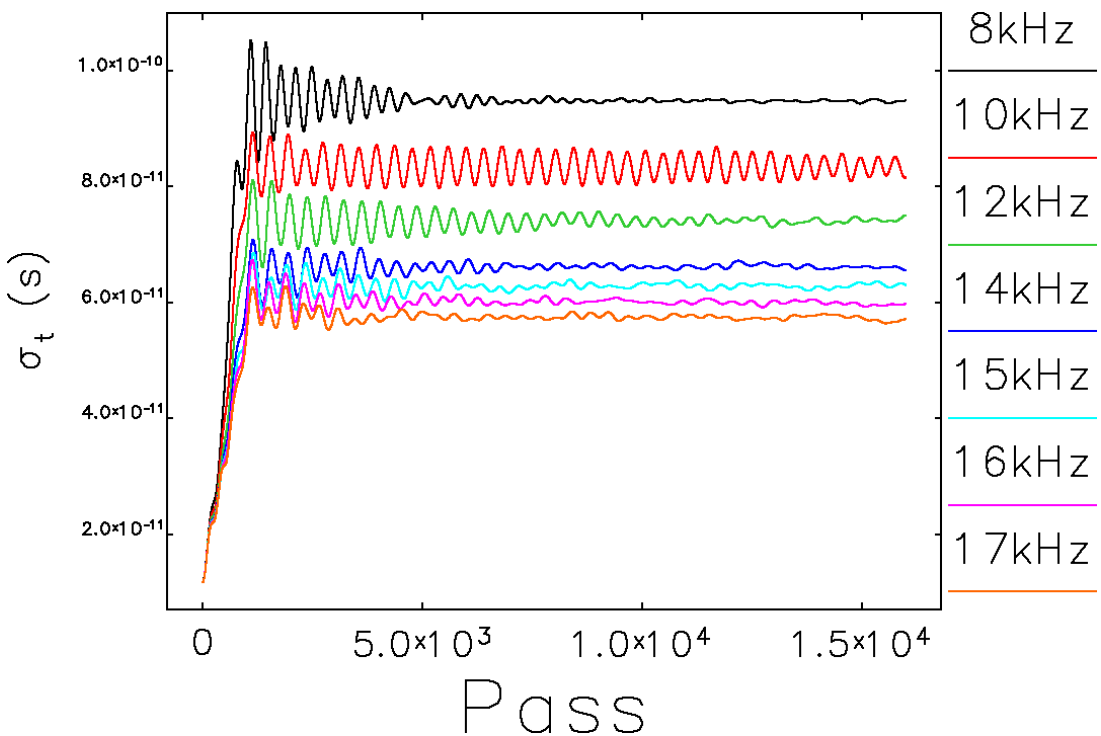
200 mA in 324 bunches



Addition of the higher harmonic cavity (HHC)

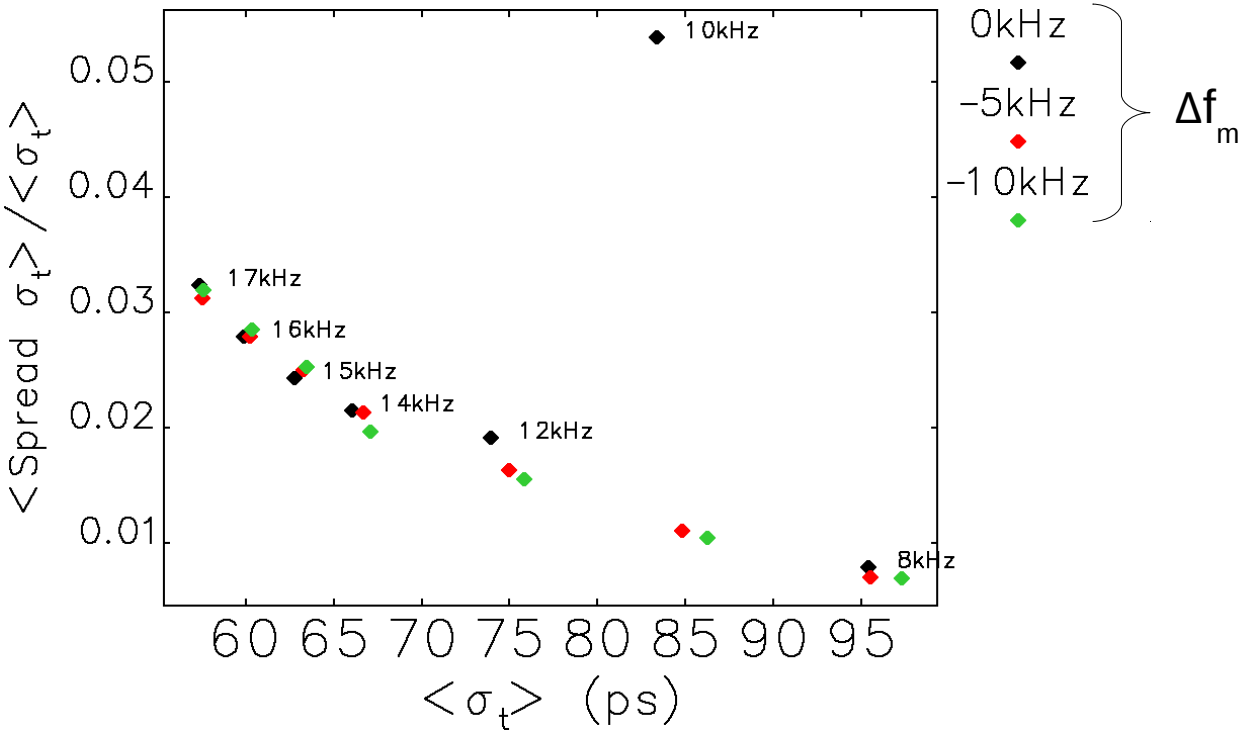
- To lengthen the bunch, detune HHC to positive side
  - Robinson unstable except for damping from main cavity
- Tables provided by T. Berenc gave guidance on HHC loaded Q and detuning vs current
  - Determined by combination of desire to maximally lengthen bunch and need to maintain Robinson stability
- We varied various parameters for the main and HH cavities
  - Varied detuning of the HHC Δf_h
    - Greater detuning means less induced voltage, shorter bunch
  - Kept HHC loaded Q at 600k based on early round of simulations
  - Varied *additional* detuning Δf_m of main cavities beyond SLAC-2884 optimal values
    - May increase Robinson damping (need to verify…)
    - Increases reflected power (tolerable)

Scan of detuning parameters (48 bunches)



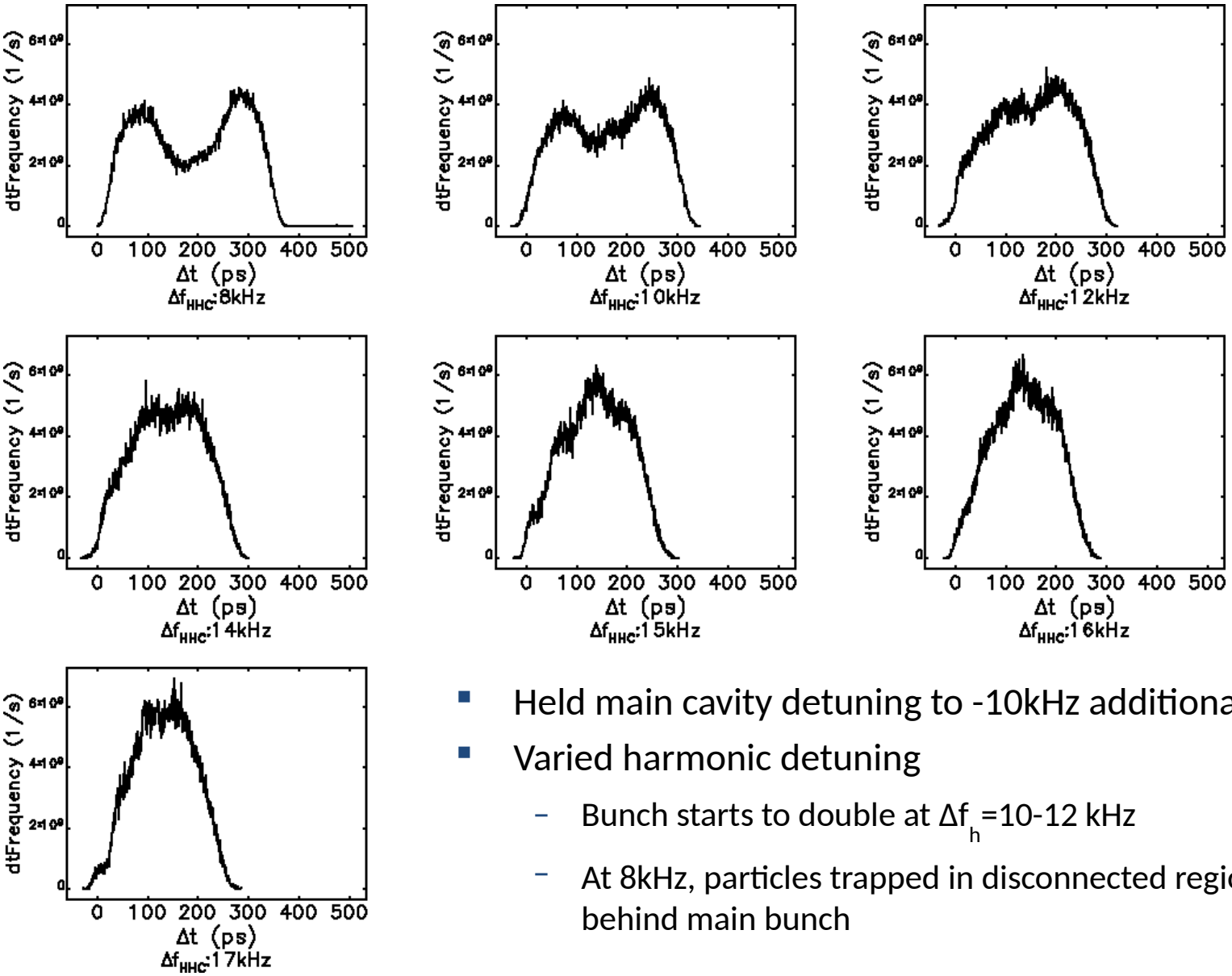
- In this example, main cavities have no additional detuning
- Bunch lengthens as HHC cavity is tuned toward resonance
- At ~10 kHz, bunch is oscillating between one and two humps
- We analyze the last 2000 passes to determine the bunch length and variability

Scan of detuning parameters (48 bunches)



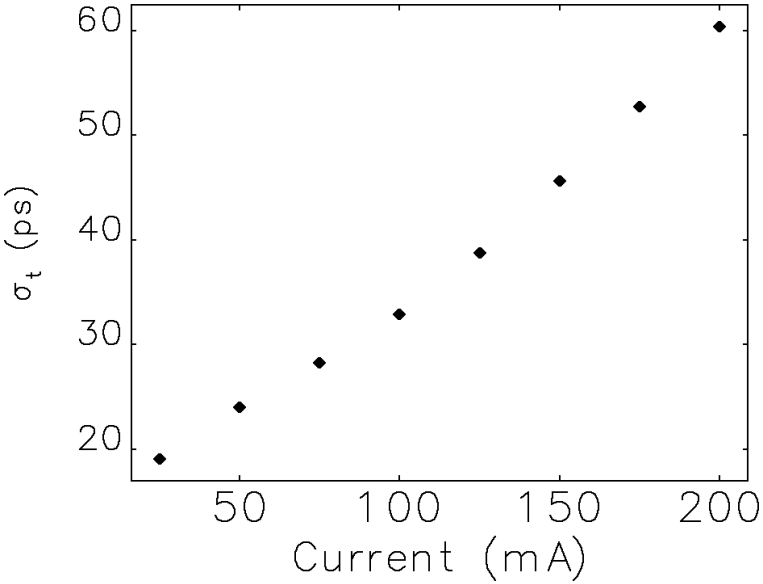
- Seems that we can obtain bunches that are
  - 6-7 times longer than zero-current bunch length, and
  - Stable in bunch length at the ~2% level
- Earlier results indicated a good choice was Δf_m=-10 kHz, Δf_h=16 kHz
  - More recent analysis shows this is probably conservative

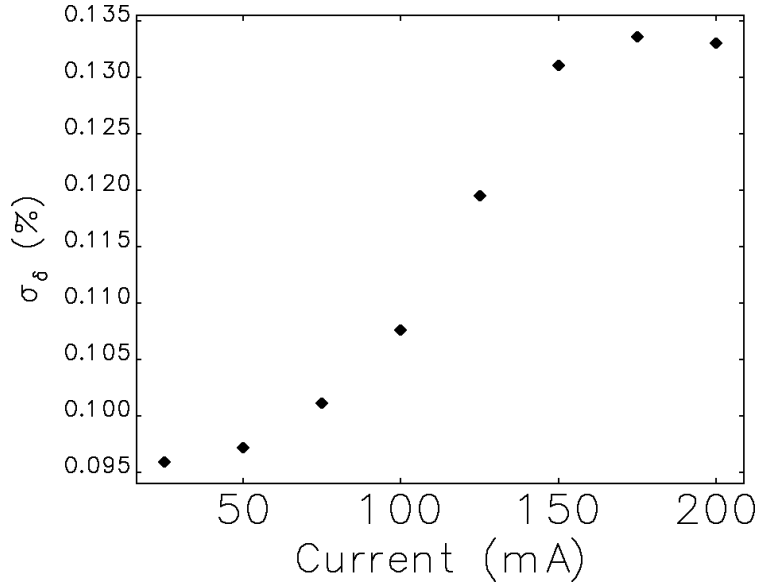
Scan of detuning parameters (48 bunches)

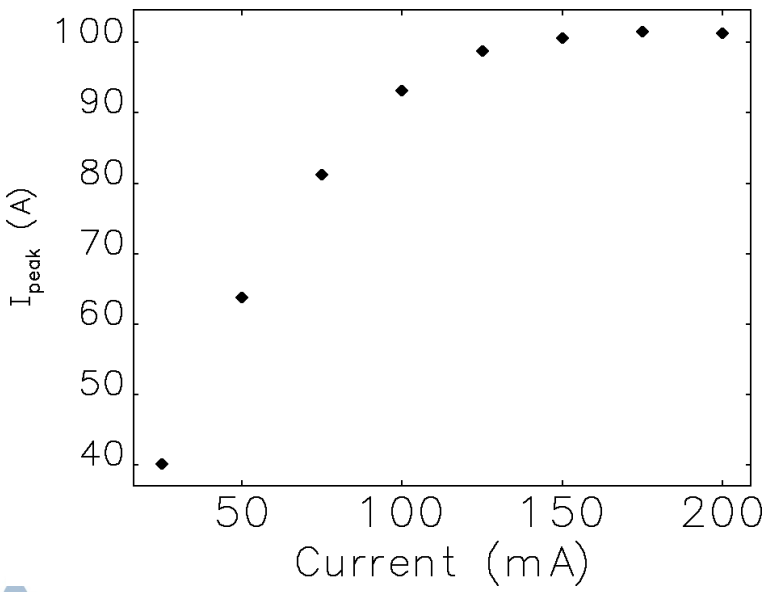


- Held main cavity detuning to -10kHz additional
- Varied harmonic detuning
  - Bunch starts to double at Δf_h=10-12 kHz
  - At 8kHz, particles trapped in disconnected region behind main bunch

Scan of beam current (48 bunches)







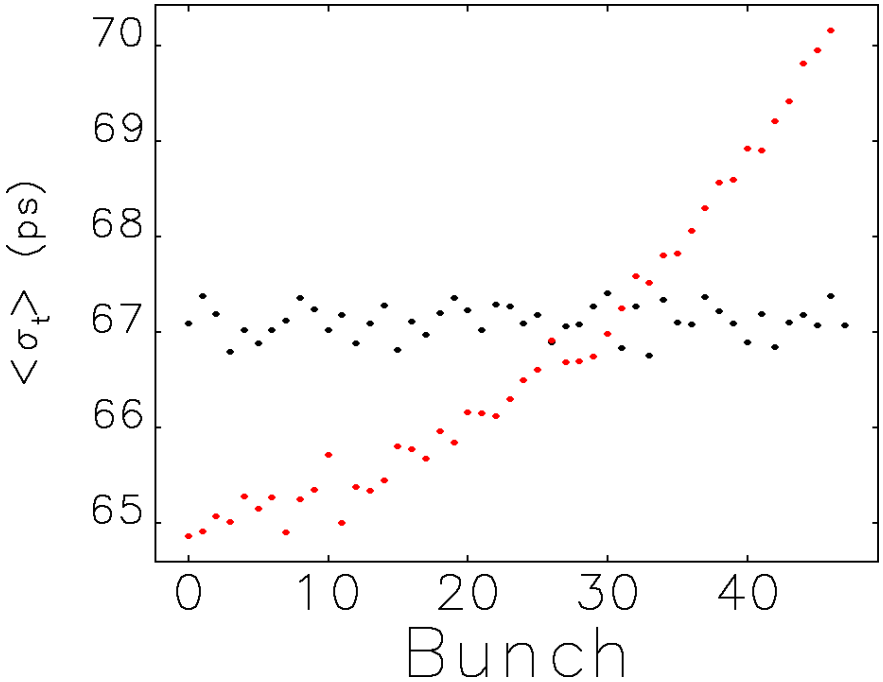
- Established equilibrium at beam currents from 25 to 200 mA
  - HHC detuning: 16 kHz
  - Add'l main cavity detuning: -10 kHz
- Peak current peaks at high average current
- Microwave instability onset at relatively low current (~1 mA/bunch)

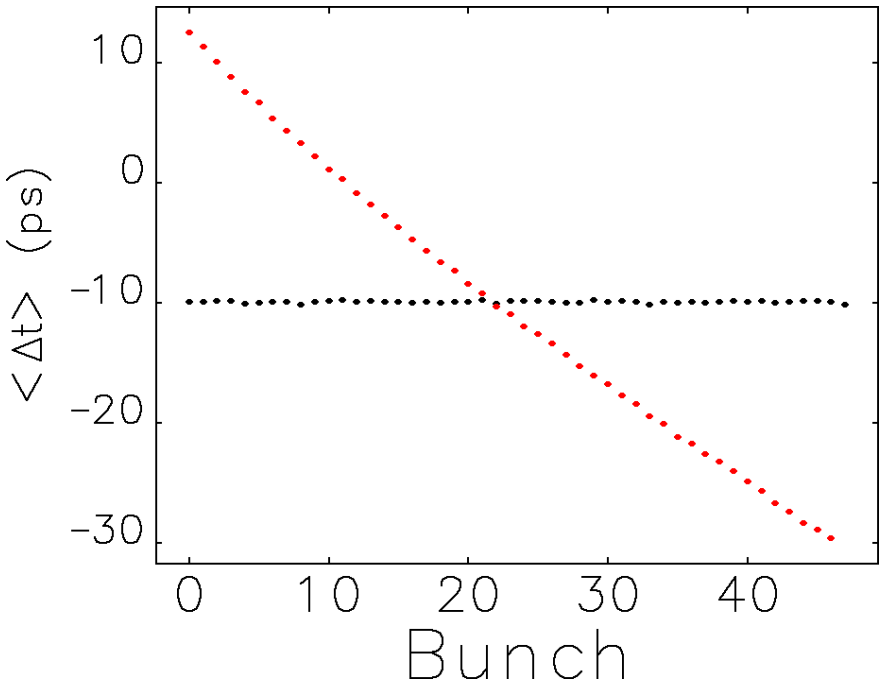
Impact of missing bunch (48 bunches)

- Expect that from time-to-time we'll extract a bunch but fail to inject replacement
- Simulated this by tracking with 47 bunches
  - 100 kP/bunch
  - Current of 200mA/48
  - Uniform population
  - Rf modes and longitudinal impedance included
- This is does not simulate the transients that might occur
  - Simulations running now that involve kicking out one bunch after reaching equilibrium

Effect of missing bunch (48 bunches)

Results for Δf_m=-10kHz additional, Δf_h=14kHz

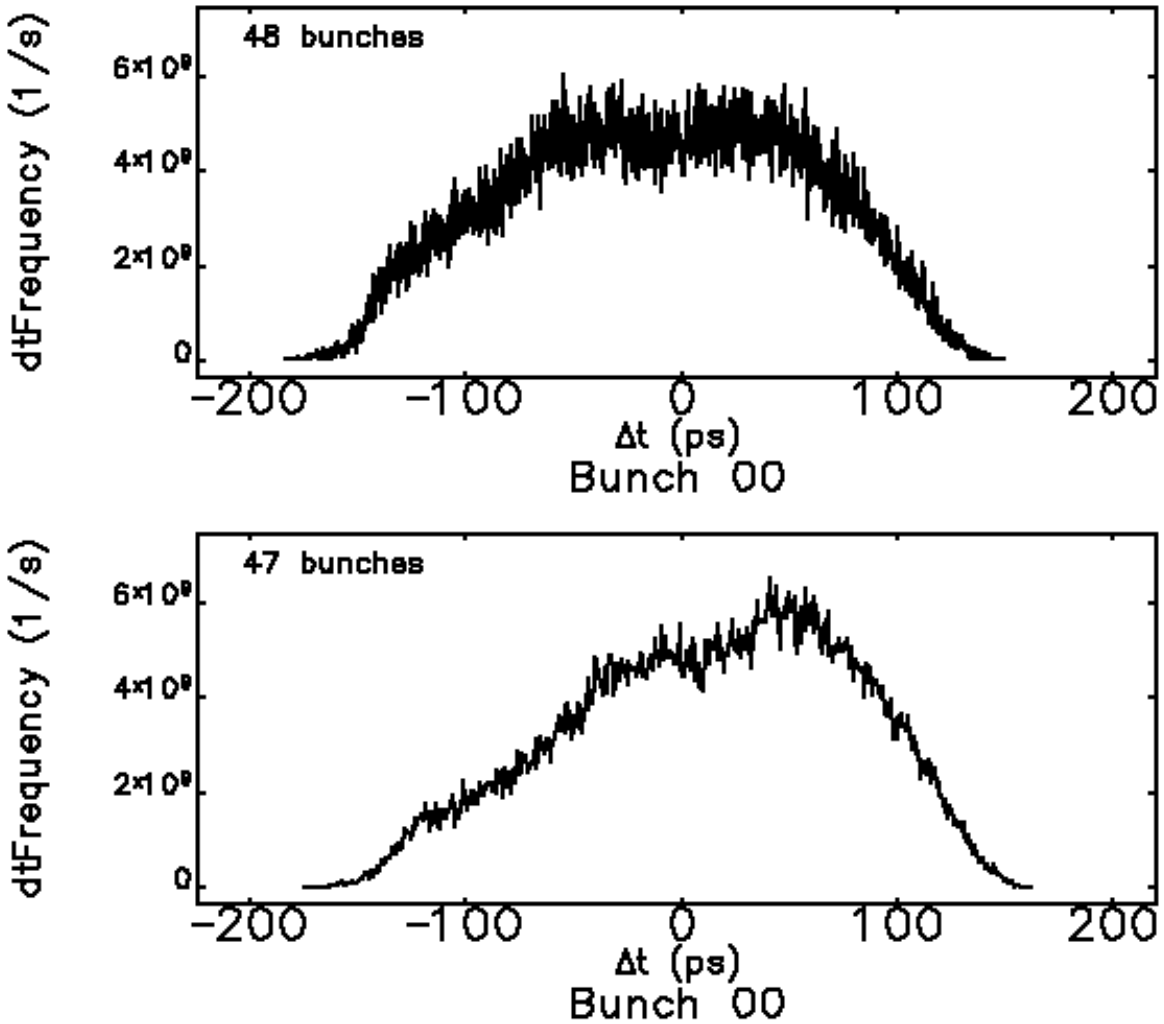




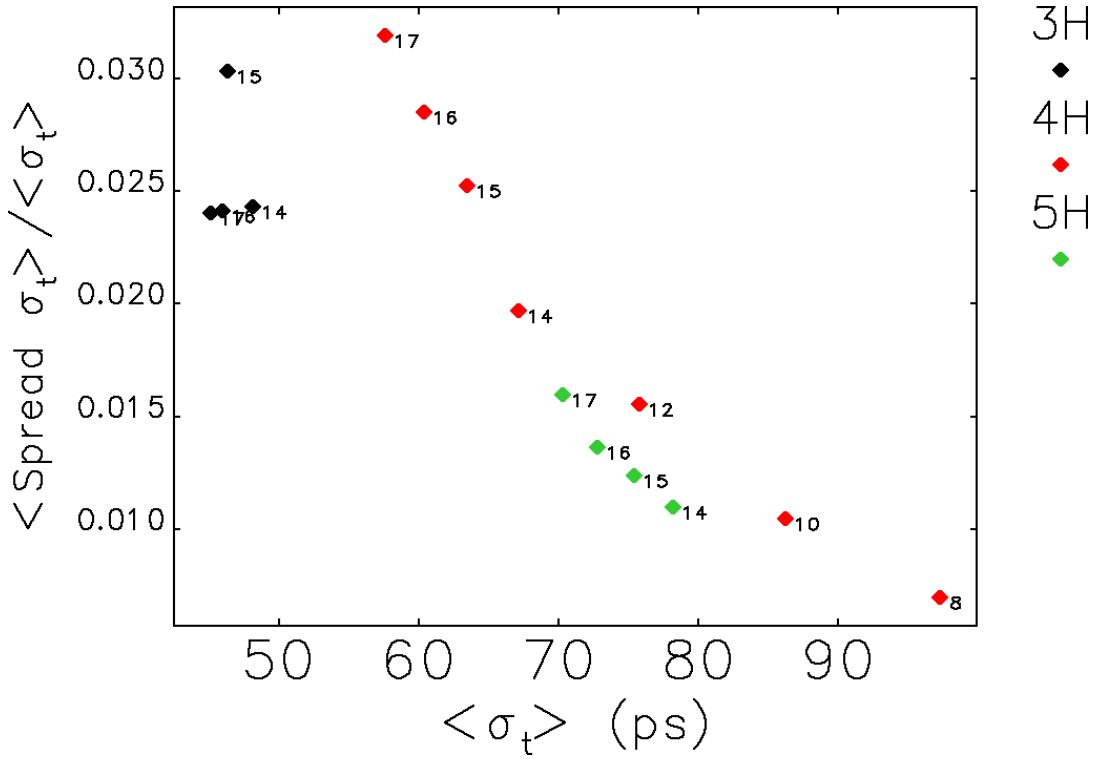
- Not surprisingly, see variation in the bunch lengths and arrival times when bunch is missing
- Don't see increase in variability of bunch length
- Need to simulate this dynamically, by kicking out a bunch
  - Transients may be a problem for some users

Effect of missing bunch (48 bunches)

Results for $\Delta f_{..}$=-10kHz additional, $\Delta f_{.}$=14kHz



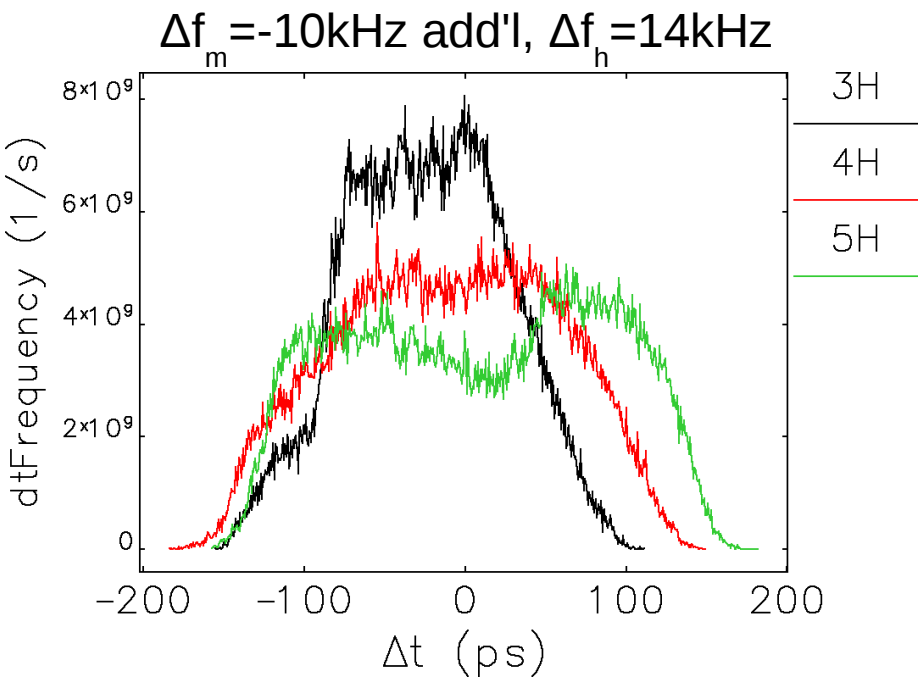
Comparison of different harmonics (48 bunches)

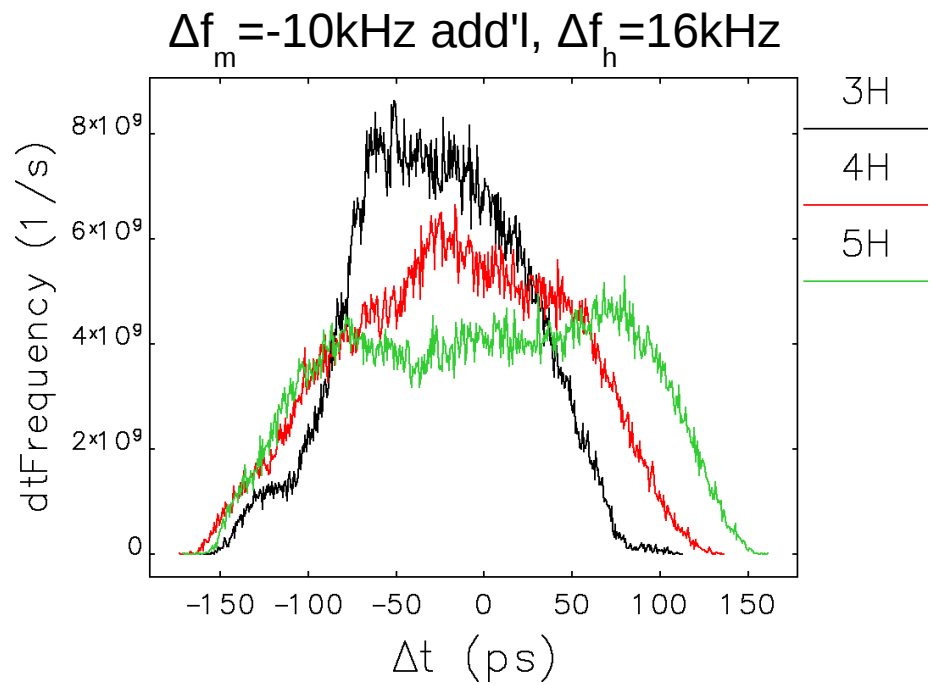


- Repeated simulations for 3rd and 5th harmonic
  - Note that R/Q doesn't change as the cavity is scaled to change frequency[1]
- 4th harmonic (of 352MHz) was chosen because of available power sources
  - However, if passive cavity works, don't need to consider this
- For fixed detuning parameters 5th harmonic provides
  - ~15% longer bunch
  - Factor of two greater stability

1: J. Tuckmantel, SPL-f-Review 30/4/08 (found by Google).

Comparison of different harmonics





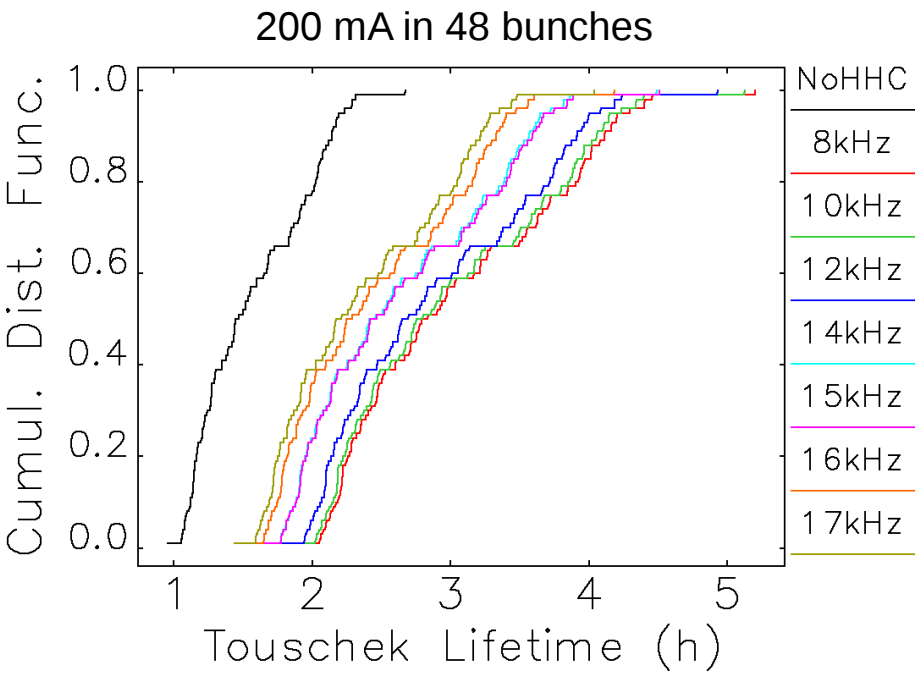
- Choice is between 4th and 5th harmonics
- Unclear how much users (or we) care about double-humped distributions

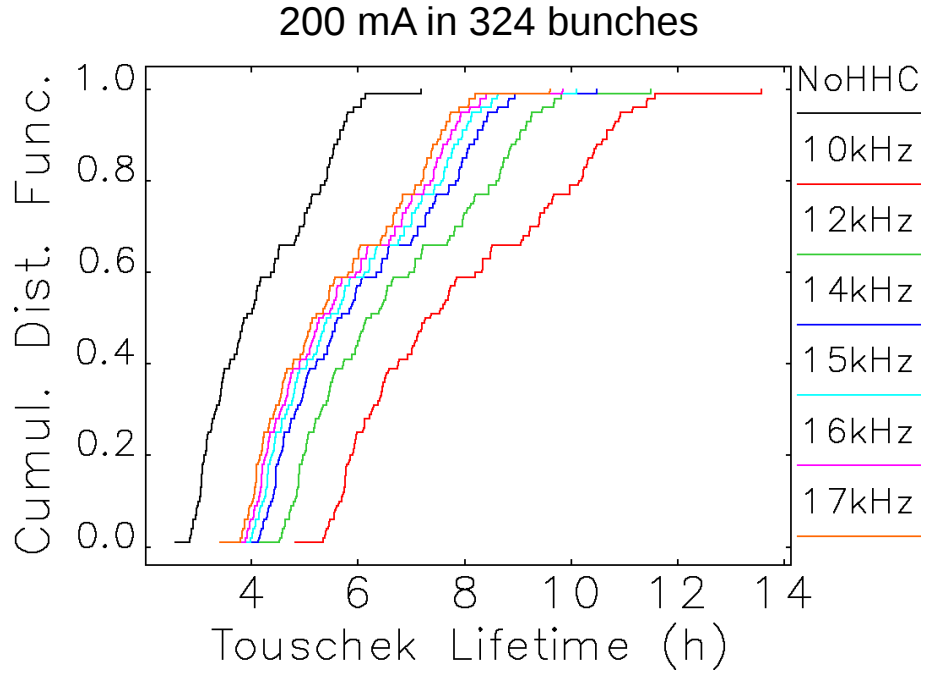
Computation of lifetime with HHC

- Want to compute Touschek lifetime including IBS and bunch lengthening
  - To do self-consistently requires tracking, which is computationally very intensive
- Can also model IBS using the program **ibsEmittance**[2]
  - Uses gaussian approximation for beam shape to give bunch length, emittance, and energy spread
- Program **touschekLifetime**[1] can compute Touschek lifetime using
  - Local momentum aperture (LMA) from **elegant** tracking
  - Longitudinal beam profile from **elegant** tracking
  - In addition, to approximately include IBS
    - Use emittance from **ibsEmittance** with rms bunch length from tracking
    - Use energy spread from quadrature addition of tracking and **ibsEmittance** results
- Used 100 sets of LMA data from simulations of lattice with errors
  - Errors are outcome of perturbation and "commissioning" simulation by V. Sajaev
- Used 16 bunch profiles from simulation of each main/HH cavity configuration
  - Used 20 slices to analyze profiles
- Averaged lifetime over all bunches, then perform statistics over error ensembles

[1]A. Xiao, M. Borland, Proc. PAC07, 3453.
[2]A. Xiao, M. Borland, L. Emery.

Touschek lifetime cumulative distributions





- All cases for 4th harmonic cavity with Δf_m=-10kHz additional
- Operation on coupling resonance ($\varepsilon_x \approx \varepsilon_y$)
- For 48-bunch mode, detuning less than 12 kHz doesn't help much
  - Double-humped distribution is not actually better
- 324 bunch mode needs bunch lengthening more than 48 bunch mode
  - Differences (48 vs 324) well explained by simple scaling

Questions and Next Steps

- Simulate filling from zero (adding one bunch at a time)
  - Will need some code development
  - Does it matter in what order we fill the buckets?
- Simulate kicking a bunch out after equilibrium has been reached
- Simulate replacing weakest bunch with a full-current bunch
- Include effects of IDs (energy loss per turn, energy spread, extra damping)
  - What happens as gaps are varied? Must HHC be adjusted?
- Perform more self-consistent simulations of IBS and lifetime
- Set up simulations using a single bunch to represent the entire beam
  - Saves computing resources when simulating uniform fill
- Look at tolerances, e.g., microphonics
- Look at effect of AM/PM modulation of the main cavity
- Add model for main cavity feedback

Conclusion

- Simulations of a passive bunch lengthening cavity for APS MBA are well advanced
- Appears that lengthening to ~75 ps rms for 200 mA/48 bunches is possible
  - Microwave instability and potential well distortion help
  - Optimum cavity detuning and loaded Q don't completely agree with expectations
- Impact of 10% bunch population variation is negligible
- Impact of missing bunch also appears manageable but needs discussion
  - Users may not appreciate ~40 ps centroid shifts
- 5th-harmonic cavity should allow longer bunch without double-hump
- Improvements in lifetime are significant for both 48 and 324 bunches

- Thanks to Tim Berenc, Ryan Lindberg, and Vadim Sajaev for discussion and input
- Simulations made use of the Blues cluster at ANL's Laboratory Computing Resource Center

Backup Slides

Simulation Method

- Simulations used parallel **elegant**, version 27.0
  - Improved performance for collective effects with multi-bunch beams
  - New diagnostic features for multi-bunch beams
  - Release planned shortly
- Eight element types are used
  - ILMATRIX:
    - Provides fast single-turn beam transport using an Individualized Linear MATRIX
    - Longitudinal, chromatic, and amplitude non-linearities supported
    - Set up using a script that processes “twiss” output file
  - SREFFECTS:
    - Lumped-element synchrotron radiation
    - Set up using a script that processes “twiss” output file
  - WATCH:
    - Beam phase space output to SDDS file
    - Separate file for each bunch makes file size manageable
  - HISTOGRAM:
    - Beam phase space histogram output to SDDS file
    - Separate file for each bunch makes file size manageable

  …

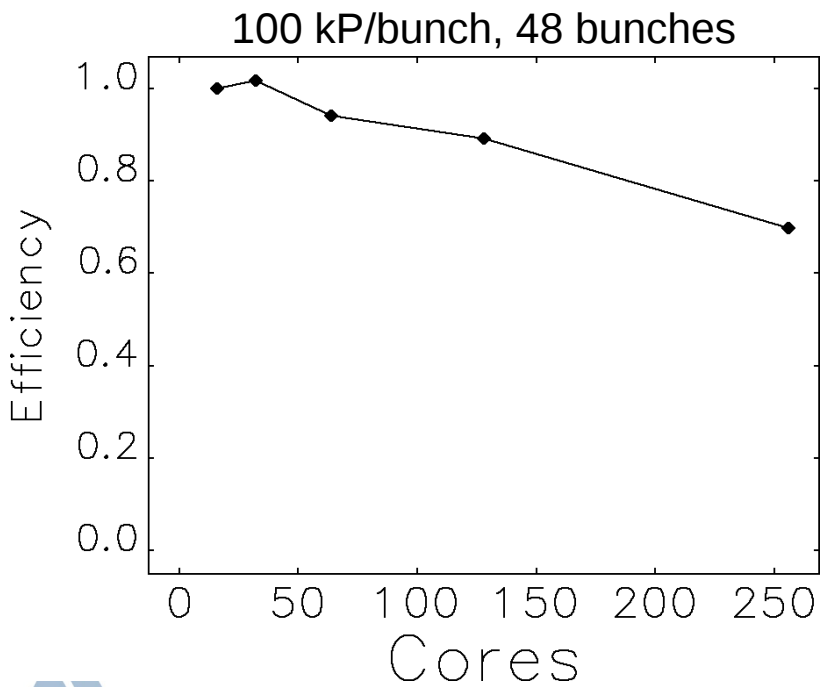
Simulation Method (continued)

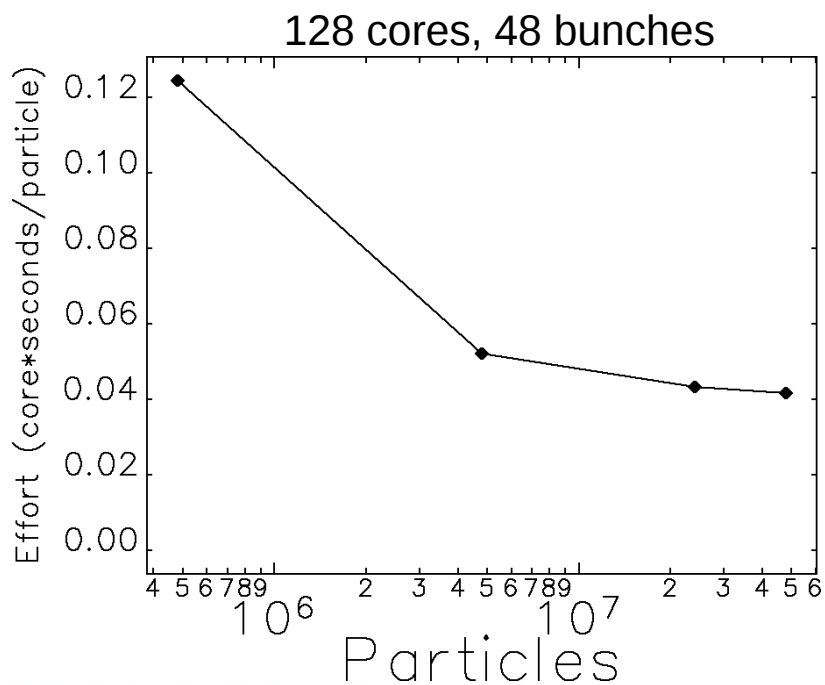
- RFCA:
  - Externally-driven rf cavity
  - Imposes $V \cdot \sin(\omega t)$ energy change on particles
  - Used to provide generator-imposed part of the main cavity fields
- CHARGE:
  - Imparts charge to macroparticles or changes their charge
  - Allows ramping up the beam current simultaneously with rf parameters
- RFMODE:
  - Beam-driven rf cavity mode
    1) Beam-driven part of the main cavity fields
    2) Fields in passive harmonic cavity
  - Uses loss factor plus phasor addition/rotation/damping
  - Implicitly includes the single-turn wake corresponding to the mode
    - Can be turned off if desired
- ZLONGIT[1]:
  - Longitudinal short-range wake including rf cavity HOMs
  - Geometric impedance of vacuum chamber computed with GdfidL[2]
  - Resistive wall impedance computed analytically

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

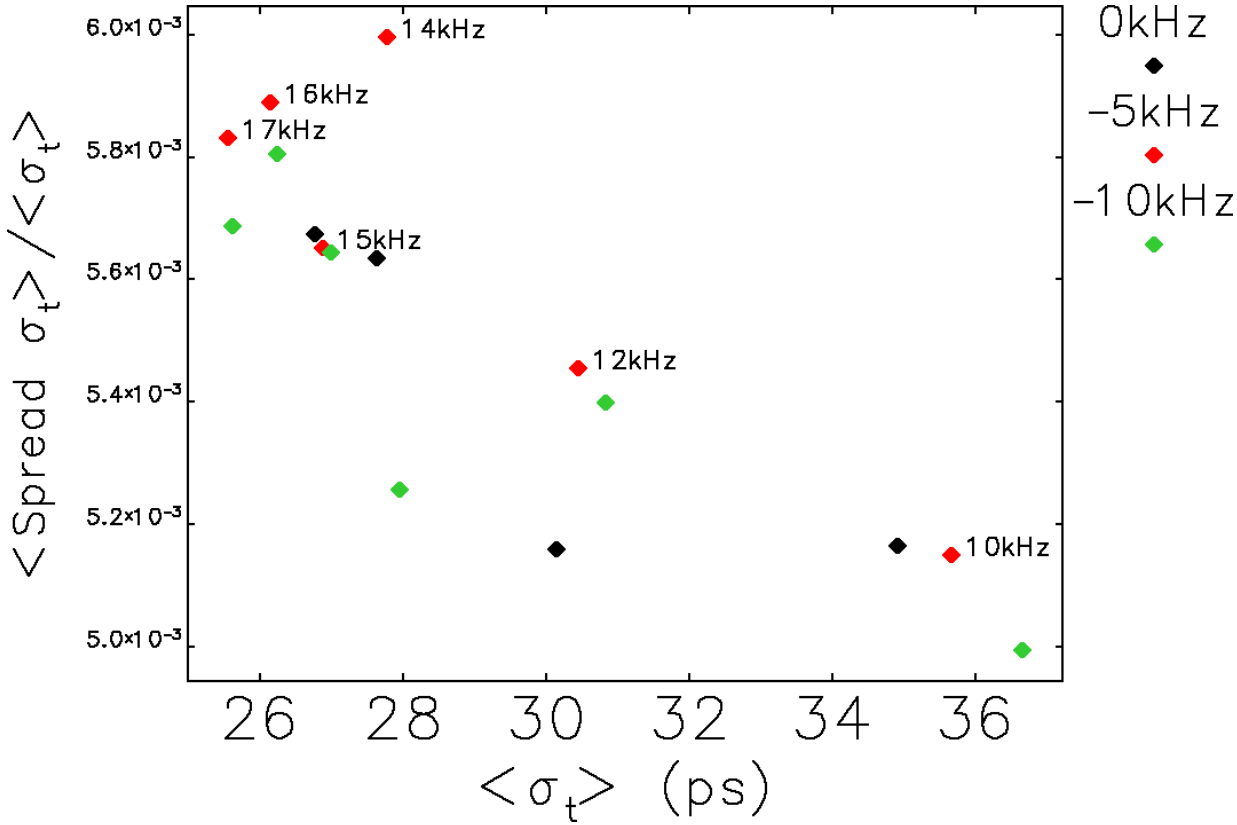
Parallel efficiency

- Tested parallel efficiency with main cavity and longitudinal impedance
- Parallel efficiency for 100 kP/bunch good for 256+ cores
- For 128 cores, 1 MP/bunch shows no bottlenecks
- 10 MP/bunch with 1024 cores should be fine if needed
- Post-processing becomes a bottleneck with > 100 kP/bunch
  - Large files are time-consuming to transfer to analysis cluster, process
  - Several recent improvements to **elegant** help reduce file sizes



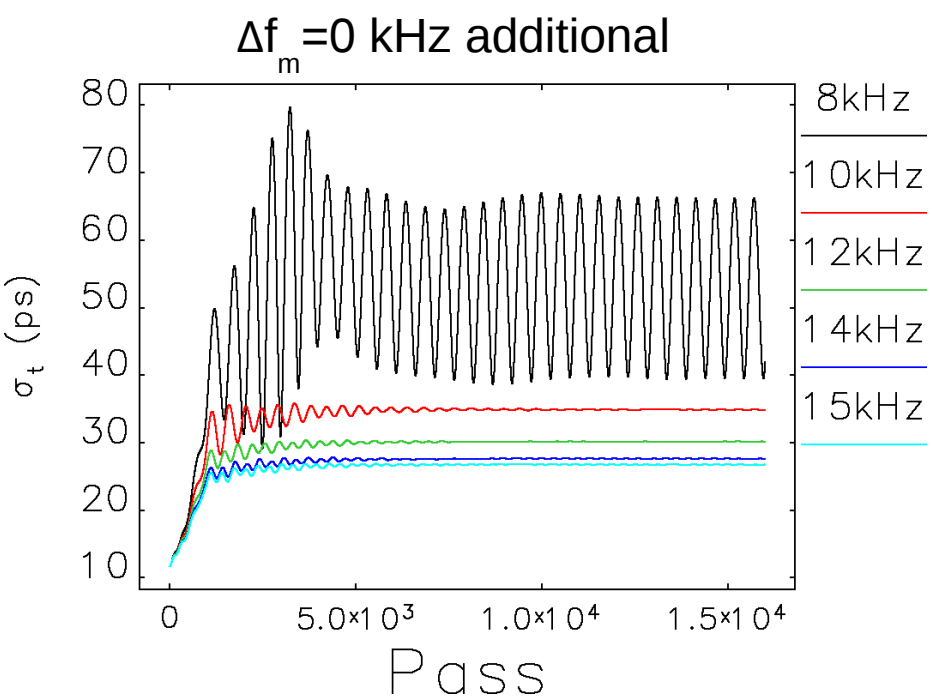


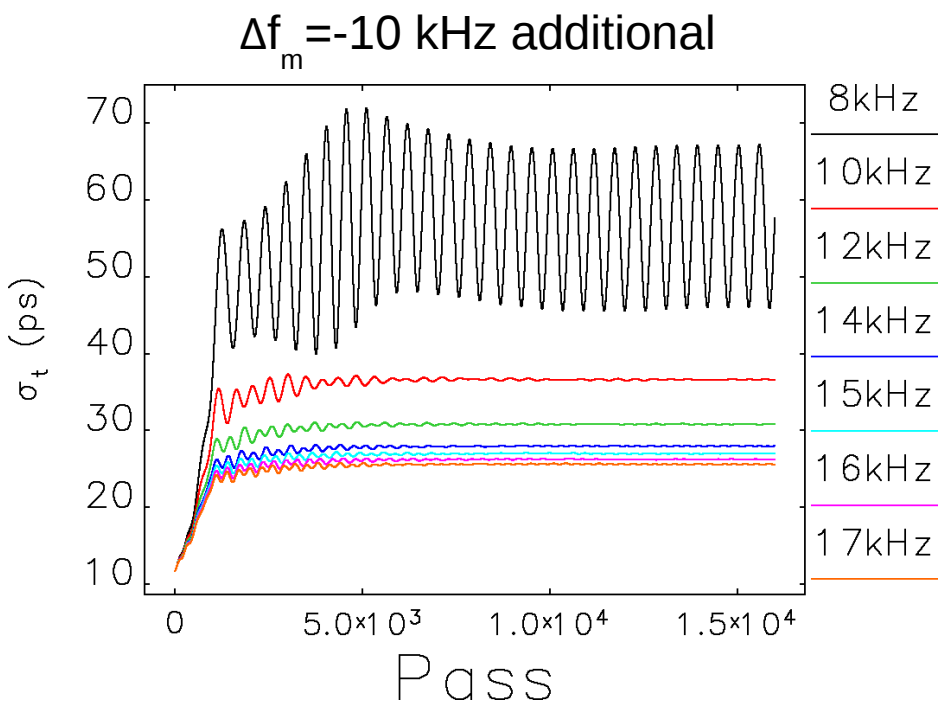
Scan of detuning parameters (324 bunches)



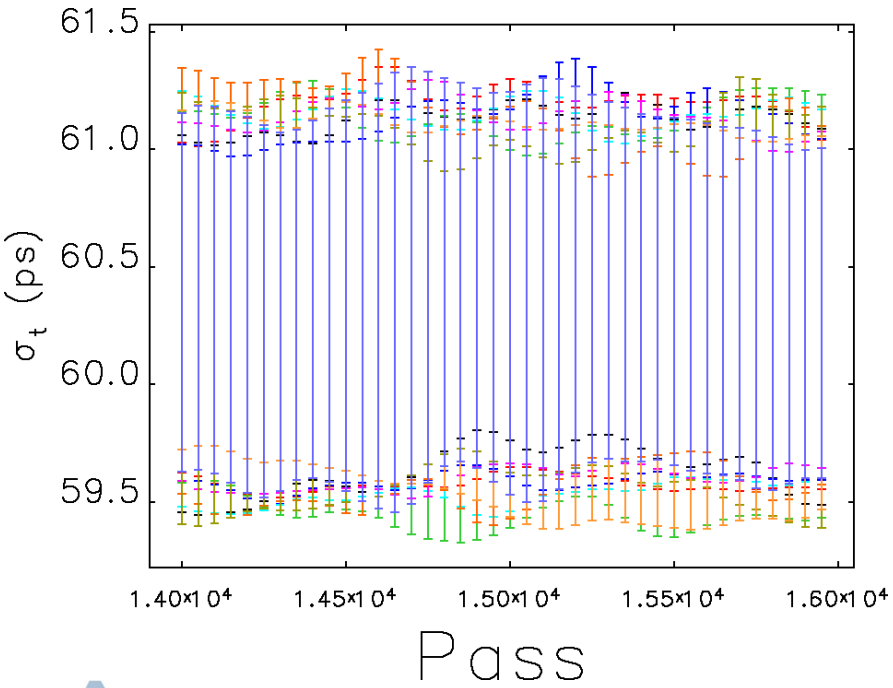
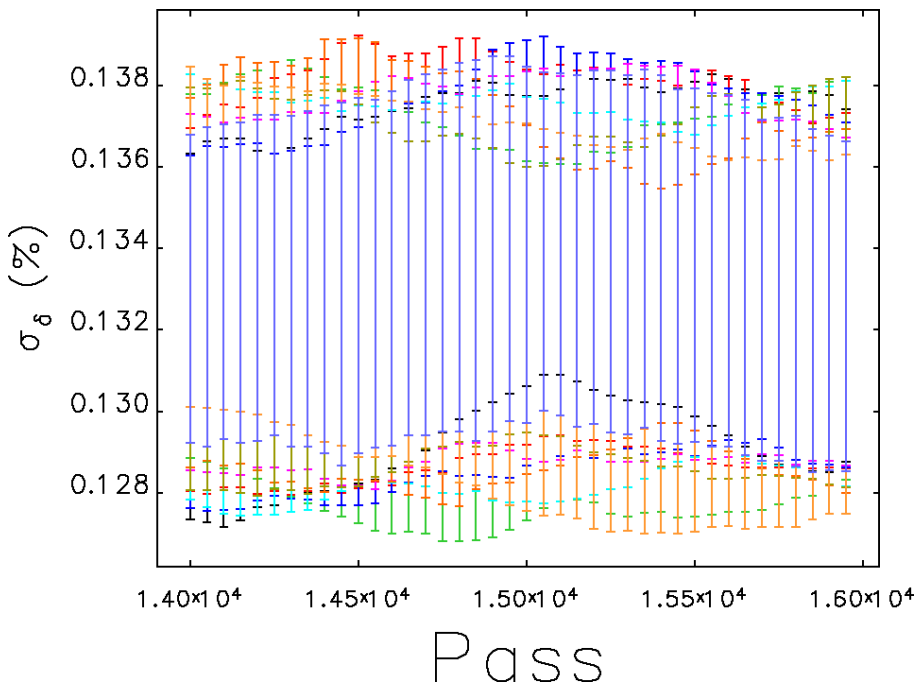
- Can lengthen to about 36 ps rms
  - 3x the zero-current bunch length, but less than 50 ps target
  - 1.8x the bunch length without HHC
- Stability is better than for 48 bunches
  - Additional detuning of main cavities seems to help sometimes
  - Detuning HHC less than ~10 kHz results in instability

Scan of HHC detuning (324 bunches)





- Additional detuning of the main cavities appears to be moderately helpful
  - Less unstable with 8 kHz HHC detuning
  - Slightly longer bunch with 10 kHz HHC detuning

Effect of bunch population variation (48 bunches)

- In operation, specify 10% variation in bunch population
  - Helps to keep swap-out interval from getting very short
- Bunch population variation will presumably have no pattern around the ring
- Simulated this with 10 different cases w/Δf_m=-10kHz additional, Δf_h=16kHz
  - Cases differed in exact populations and order of bunches
- Doesn't appear to be anything to worry about