Argonne NATIONAL LABORATORY

APS-U Lattice Design Status Update

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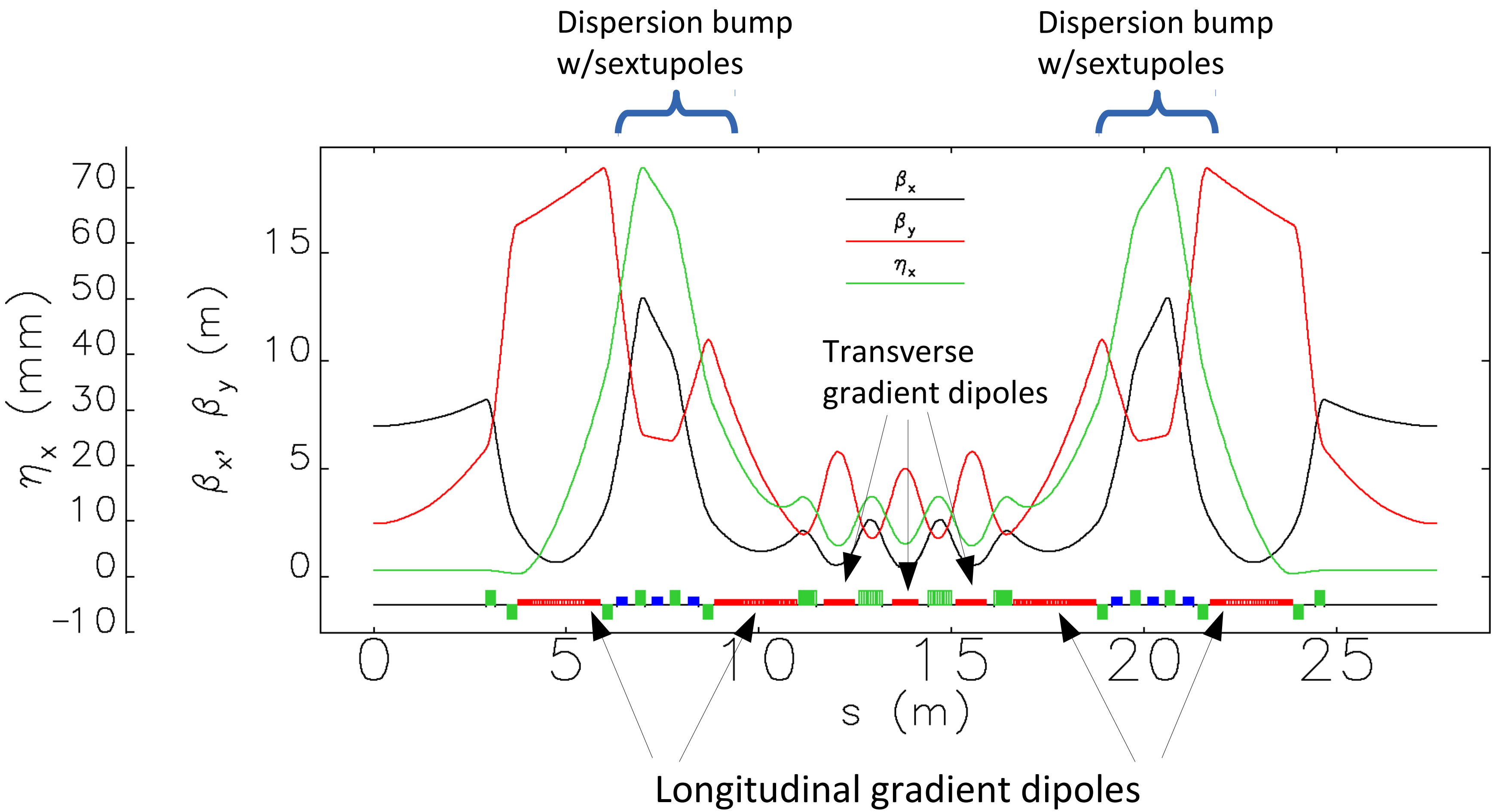
Lattice goals and constraints

- Hard constraints
  - ID and BM beamlines at same angle as now
  - Respect engineering limits on magnet strength
  - Respect space requirements from vacuum design, including diagnostics
  - Sufficient injection aperture for on-axis injection using swap-out mode and existing injector
- Goals
  - Emittance less than 70 pm
  - Preserve fill pattern that supports timing experiments
  - 4.8 m free space for insertion devices
  - Vertical beta functions at IDs close to ideal (for aperture) 2.4m in vertical
  - Horizontal beta functions at IDs not too large (<10m) to improve brightness
  - Small beta functions throughout to reduce effective transverse impedance
  - Lifetime >4.8 hours at 200 mA and 6 GeV, to nominally obviate the need for supplemental shielding

Hybrid 7BA Lattice Concept[1]

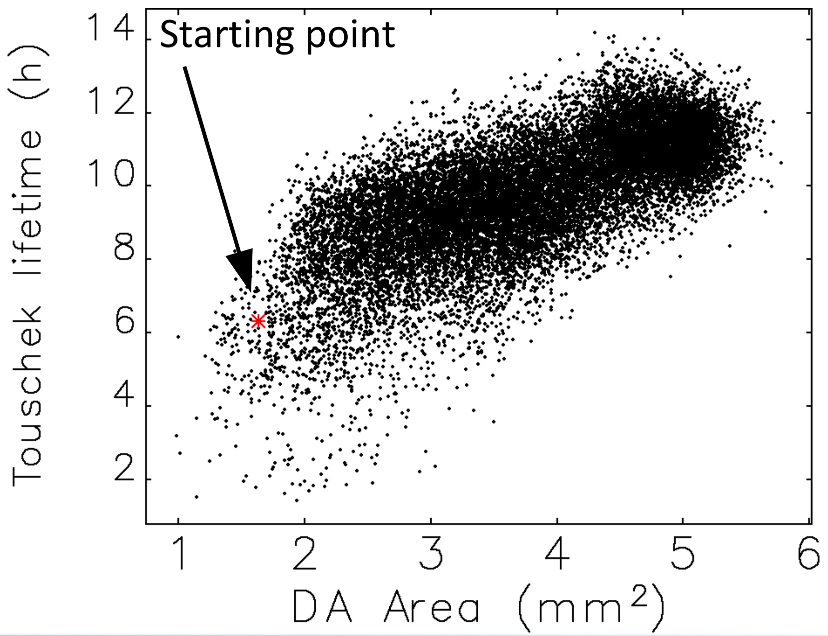


- Phase advance of $\Delta\varphi_x=3\pi$ and $\Delta\varphi_y=\pi$ between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles → cancellation isn't perfect

1: L. Farvacque *et al.*, IPAC13, 79.

Optimization with Tracking-Based Multi-Objective Genetic Algorithm[1,2]

- Tracking-based optimization allows directly optimizing lattice and sextupoles for
  - Large dynamic acceptance
  - Large Touschek lifetime (via local momentum acceptance)
  - Desired positive chromaticity
- Unlike theoretical approaches, can include
  - Effects of likely errors
  - Effects of radiation damping and longitudinal motion
  - Vacuum chamber apertures



Tracking-based MOGA optimization makes significant improvements starting from ESRF-II scheme.

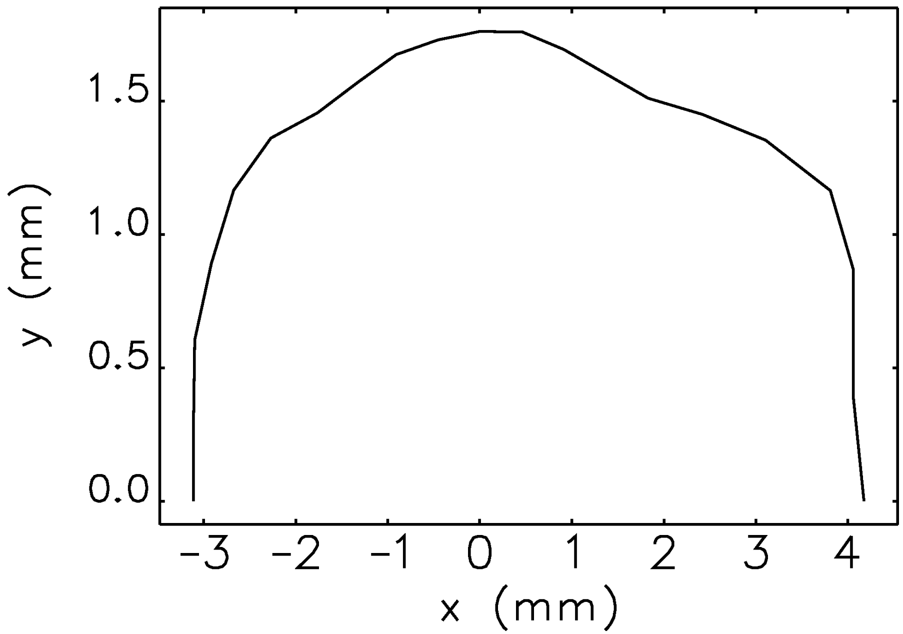
1: See citations in M. Borland, IPAC12, 1035.
2: M. Borland, *et al*. J. Synch. Rad 21, 912-936 (2014).

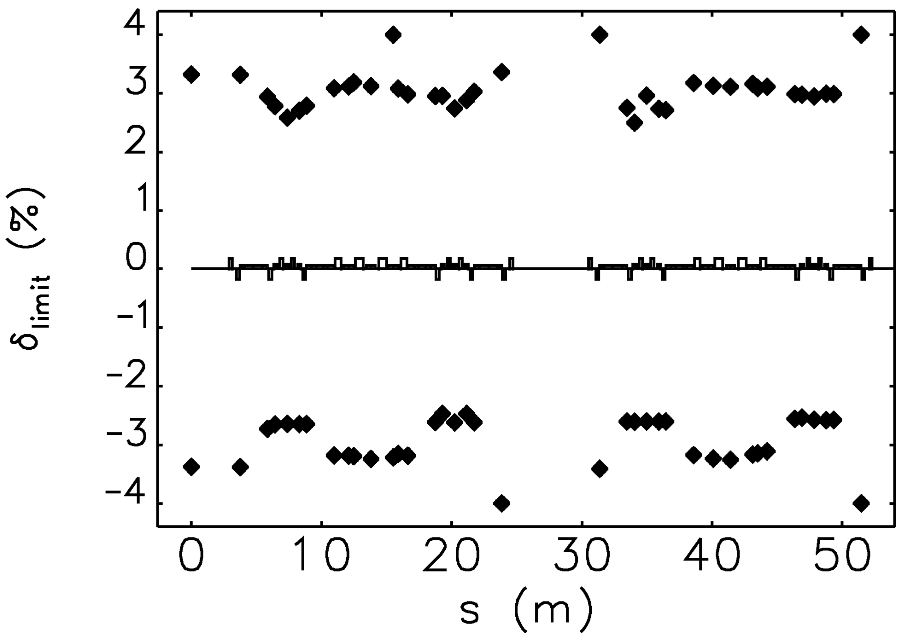
Tracking-Based Optimization Details[1]

- DA and LMA tracking performed with parallel **elegant**[2]
  - Track for 400 turns including rf and synchrotron radiation
    - More details of tracking methods described in CDR
  - One function evaluation takes ~1 hour on 32 cores using 400-turn tracking
  - Lifetime computed from LMA with **touschekLifetime**[3]
    - Assume a nominal (50 ps rms) bunch length and ignore IBS for now
- The algorithm is (typically) allowed to vary
  - Linear optics, using either
    - Direct variation of gradients
    - Variation of linear optics targets (e.g., emittance, tunes, beta functions)
  - 10 sextupole strengths (out of 12 present in two sectors)
- Goals are
  - DA to accommodate booster beam with on-axis injection
    - Expect σ_x=0.65 mm, σ_y=0.2 mm → need ±2 mm by ±0.6 mm
  - Lifetime of >4.8 hours in 48 and 324 bunch modes at 200 mA
    - Motivated by scaling of existing shielding design

1: See citations in M. Borland, IPAC12, 1035.
2: Y. Wang and M. Borland, AIP Conf. Proc. 877 (2006).
3: A. Xiao and M. Borland, PAC07, 3453.

"Best" MOGA Result





- DA comfortably exceeds ±2mm by ±0.6mm goal
- LMA consistent with lifetime of >10 hours in 324 bunch mode with 100% emittance ratio and 50-ps rms bunch duration
- MOGA optimizes configuration to handle specific error ensemble
  - Check with more ensembles
  - Also, must add multipole errors and ID kickmaps

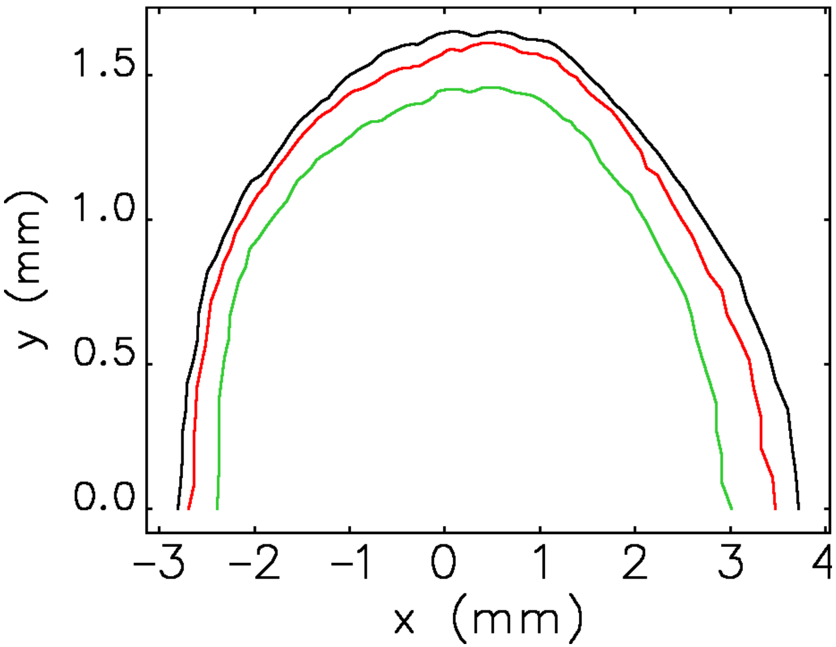
Nonlinear Dynamics Evaluation Methodology

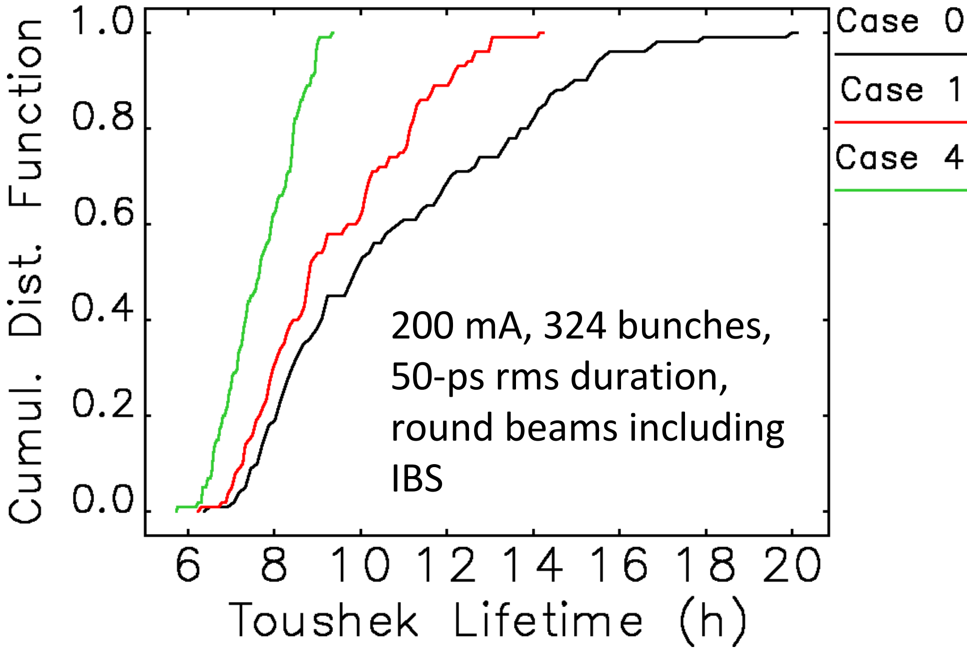
- Basic goal: evaluate with many error ensembles to ensure robustness
- Used 100 error ensembles with correction
  - Simulates the commissioning process
- DA/LMA tracking same as MOGA runs, but
  - 1000 turns instead of 400 (better convergence)
  - Element-by-element synchrotron radiation
- Add multipole errors, levels taken from various sources
  - Systematic or allowed multipoles from magnetic models
  - Random or unallowed multipoles from
    - Scaling of measured NSLS-II errors[1], or
    - Halbach theory for determining random multipole errors from mechanical errors[2].
- In some cases, include
  - Insertion devices
  - Alternatives for ID apertures
- After tracking completes
  - DAs analyzed to find percentile contours over all ensembles
  - LMAs used to compute Touschek lifetime for each ensemble

1: A. Jain, private communication.
2: K. Halbach, NIM A 74, 147 (1969).

Sensitivity to Multipole Errors

- Case 0: no multipole errors
- Case 1: nominal multipole errors
- Case 4: double quad random errors





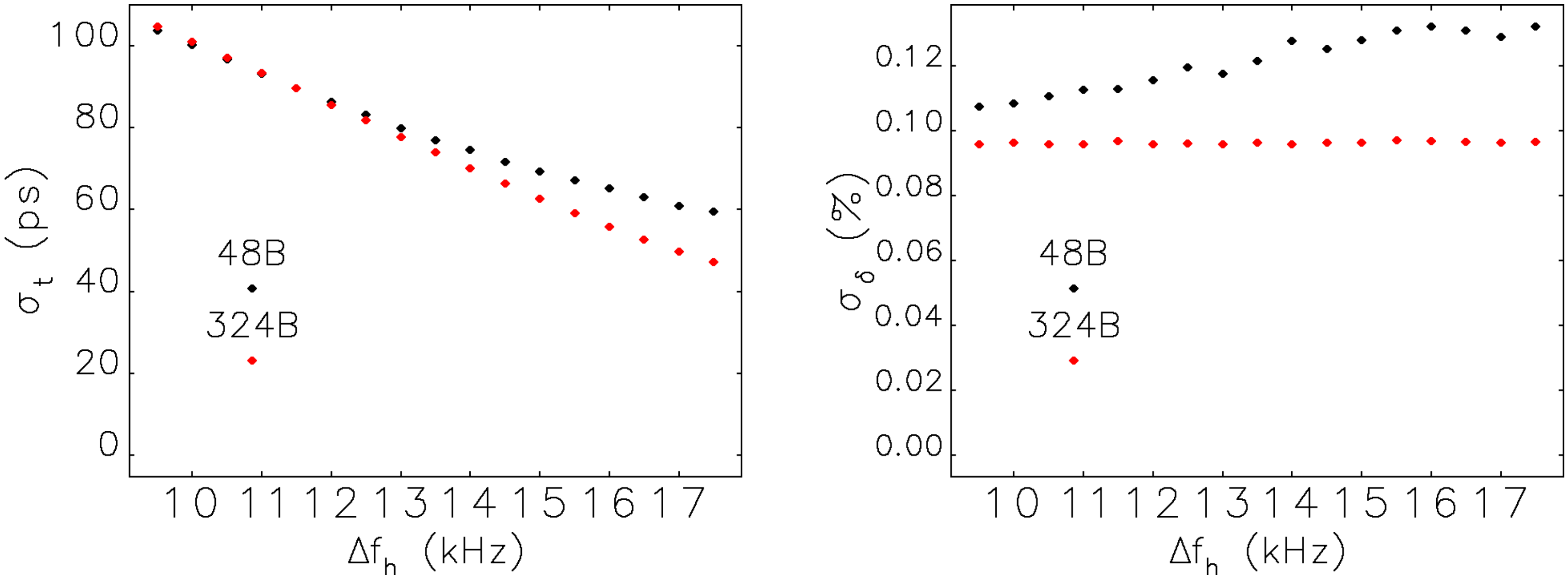
- Conclusion:
  - Multipole errors do not excessively impact DA or lifetime
  - Most errors could be increased with little negative impact
  - Good to maintain quad random errors at nominal levels

Beam Dynamics with HHC[1,2,3]

- Assumed above that bunch duration is 50 ps
  - Zero-current natural length is ~12.5 ps
  - Lengthens to 20-35 ps with longitudinal impedance
  - Must use harmonic cavity to further lengthen bunch and improve lifetime
- Detailed studies performed using parallel **elegant**, including
  - Beam-loaded main rf system with feedback system
  - Passive bunch lengthening cavity
  - Longitudinal impedance
  - 48- and 324-bunch fill patterns
- Studies include
  - Variation of HHC loaded Q and detuning
  - Effect of filling from zero
  - Effect of bunch population variation
  - Effect of kicking out a bunch
  - Multibuch stability
- Time permits showing only a few highlights

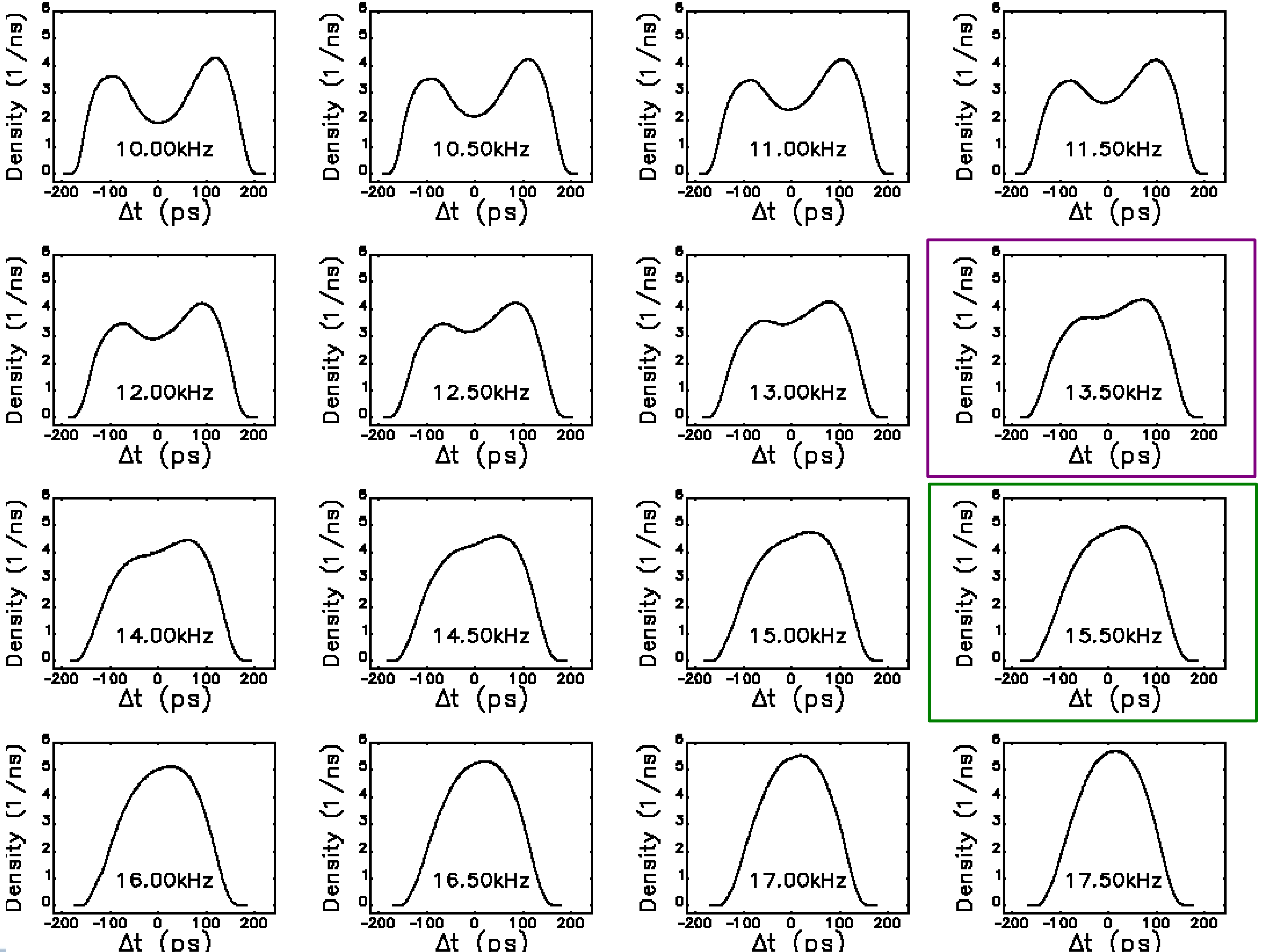
1: M. Borland et al., IPAC15, MOPMA007.
2: T. Berenc et al., IPAC15, MOPMA006.
3: L. Emery et al., IPAC15, TUPJE065.

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

Longitudinal density averaged over 2000 turns (48B)

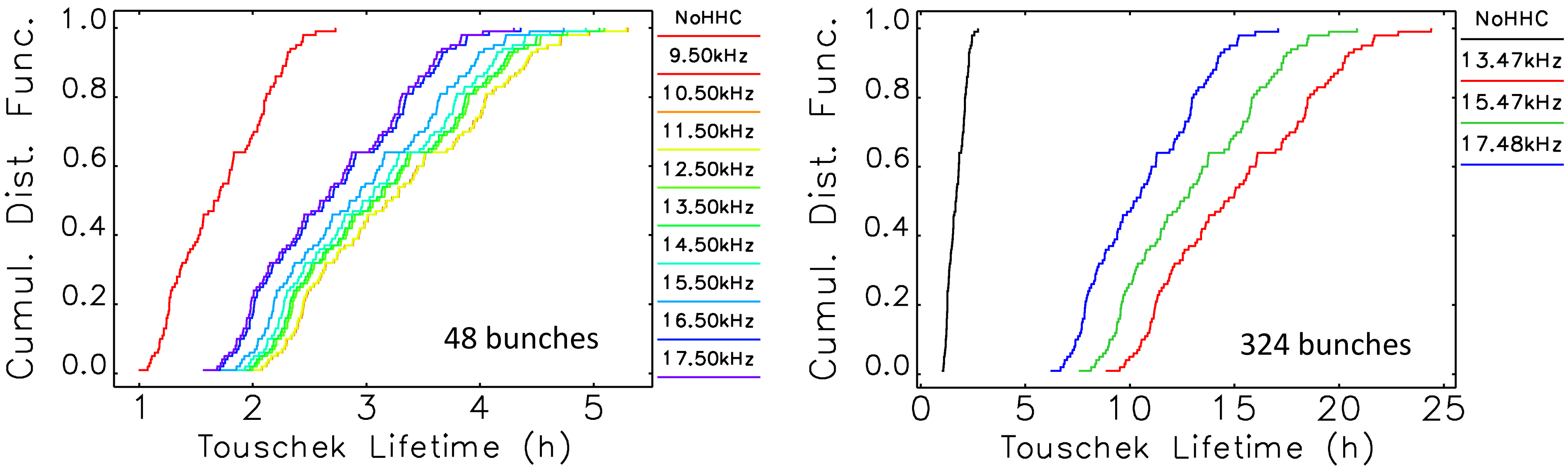


Touschek Lifetime Analysis

- Two dominant lifetime effects are Touschek and gas scattering
  - Of these, Touschek is typically the most important
- Above analysis of Touschek scattering made some assumptions
  - Notional bunch lengthening to 50-ps rms, gaussian shape
  - Emittance increase from IBS computed from this base
- Using results of tracking with HHC, can improve Touschek lifetime estimates
  - Uses new slice-based Touschek lifetime calculation[1] in **touschekLifetime**
  - 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 IBS, HHC, and microwave instability
    - Fully self-consistent studies planned in future

1: A. Xiao and M. Borland, IPAC15, MOPMA012.

Touschek Lifetime Distributions



- In both cases, have 200 mA, Q_L=600k, κ≈1
- For 48 bunches, get factor of 1.7 for 15.5 kHz detuning
  - Bunch is already significantly lengthened by the ring impedance
- For 324 bunches, get factor of 3.7 for 15.5 kHz detuning
- Some additional benefit from pushing to lower detuning
  - Have to watch for double-bunching, higher coupler power
  - Use 15.5 kHz for subsequent calculations

Commissioning Simulation[1]

- Commissioning involves coming to grips with imperfections of the real machine
- Performed a realistic simulation of commissioning steps, including
  - Error generation (see table)
  - First-turn trajectory correction and first orbit correction
  - Orbit correction with reduced BPM displacement errors
    - Reflects expected improvement from beam-based alignment
  - Beta function correction based on response matrix fit
  - Coupling correction (minimizing cross-plane response matrix)
  - Emittance ratio adjustment to 10% at separated tunes
- Algorithm has ~98% success rate
  - Use results to determine robustness of nonlinear dynamics

Girder misalignment	100 μm
Elements within girder	30 μm
Initial BPM offset errors	500 μm
Dipole fractional strength error	$1 \cdot 10^{-3}$
Quadrupole fractional strength error	$1 \cdot 10^{-3}$
Dipole tilt	$4 \cdot 10^{-4}$ rad
Quadrupole tilt	$4 \cdot 10^{-4}$ rad
Sextupole tilt	$4 \cdot 10^{-4}$ rad

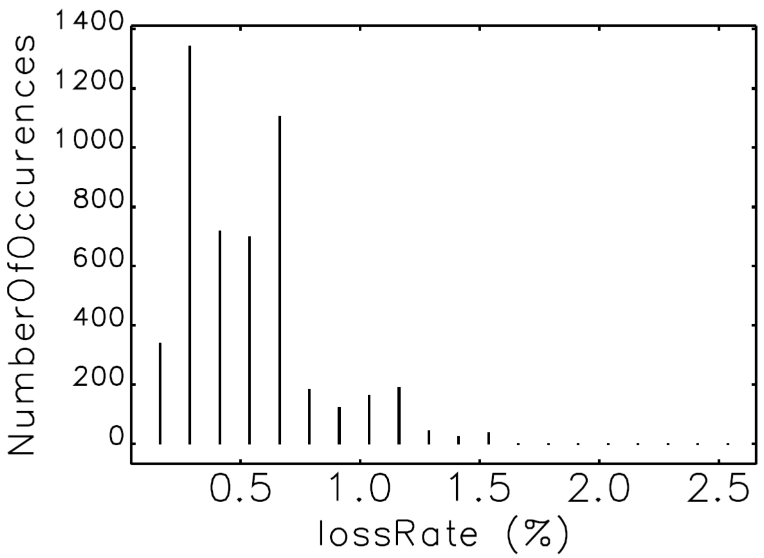
These error levels appear readily achievable based on recent experience, e.g., NSLS-II.

1: V. Sajaev et al., IPAC15, MOPMA010

Swap-out Injection

- On-axis "swap-out" injection[1,2,3] is an alternative to accumulation
  - Each injector shot replaces an existing stored bunch
  - DA must accommodate only the injected beam size
- Swap-out seems advantageous on balance
  - Pro: — Smaller horizontal physical apertures possible in IDs
    - — Emittance can be pushed to smaller values
    - — Less disturbance to stored beam
  - Con: — Single-bunch current limited by injector capability
    - — Maximum number of bunches limited by fast kicker technology

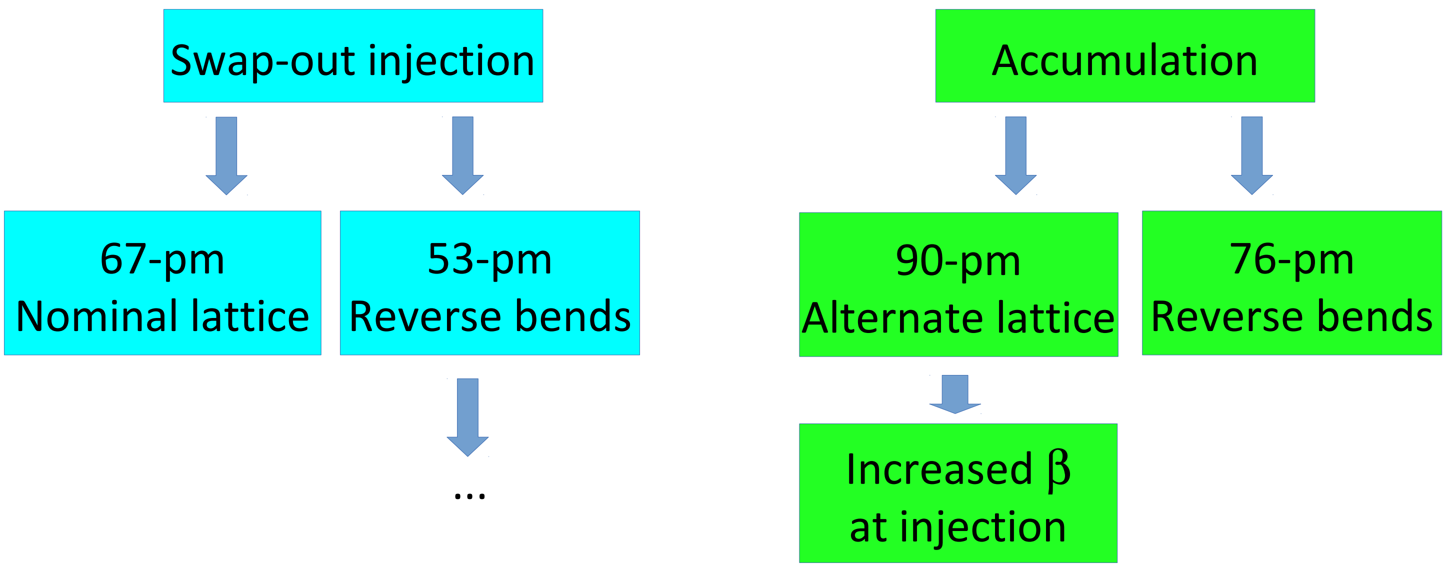
1: E. Rowe *et al.*, Part. Accel. 4, 211 (1973).
2: R. Abela *et al.*, PAC91, 486 (1992).
3: L. Emery *et al.*, PAC03, 256 (2003).



- Injection efficiency is simulated directly
  - 100 static optical and multipole error ensembles, as above
  - Realistic beam distribution from booster, with optical errors
  - Injection trajectory errors and pulsed power supply jitter

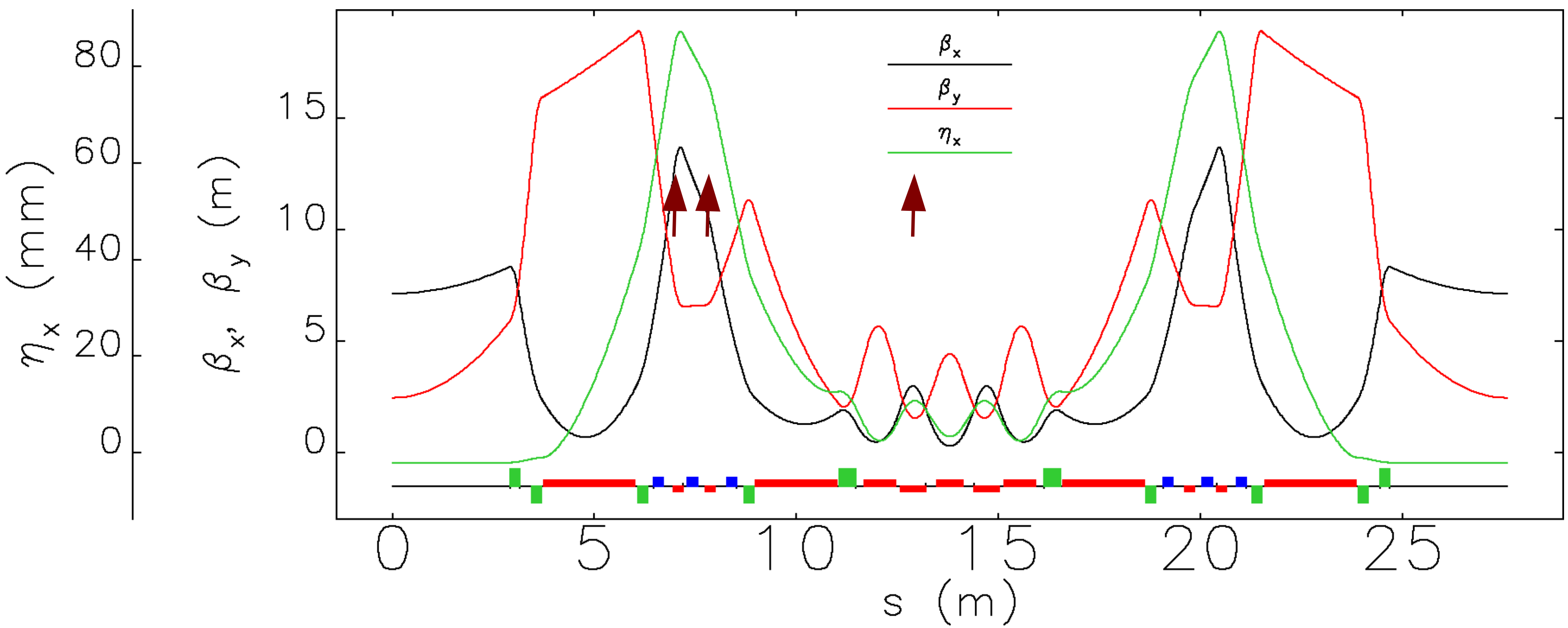
Alternate lattice development

- Nominal lattice
  - emittance pushed to the lowest achievable value
  - dynamic acceptance not large enough for accumulation
  - on-axis swap-out injection is the only workable method
- Alternate lattice work follows two directions
  - Possibility for off-axis accumulation
  - Lower-emittance lattices



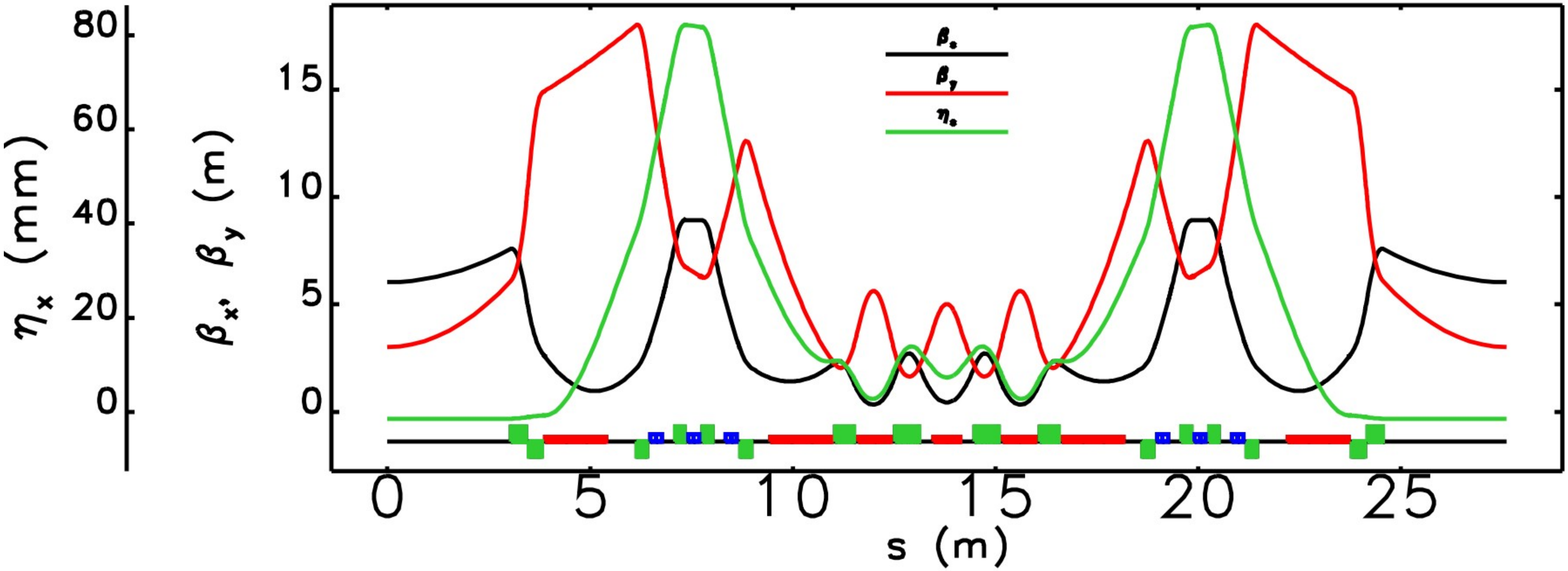
53pm swap-out injection lattice with reverse bends

- Reverse bends in Q4, Q5, and Q8
- Emittance reduced from 67 pm to **53** pm
- Dx from **70** mm to above **80** mm
- Nonlinear optimization is ongoing but initial results show improved performance compared to the 67pm lattice



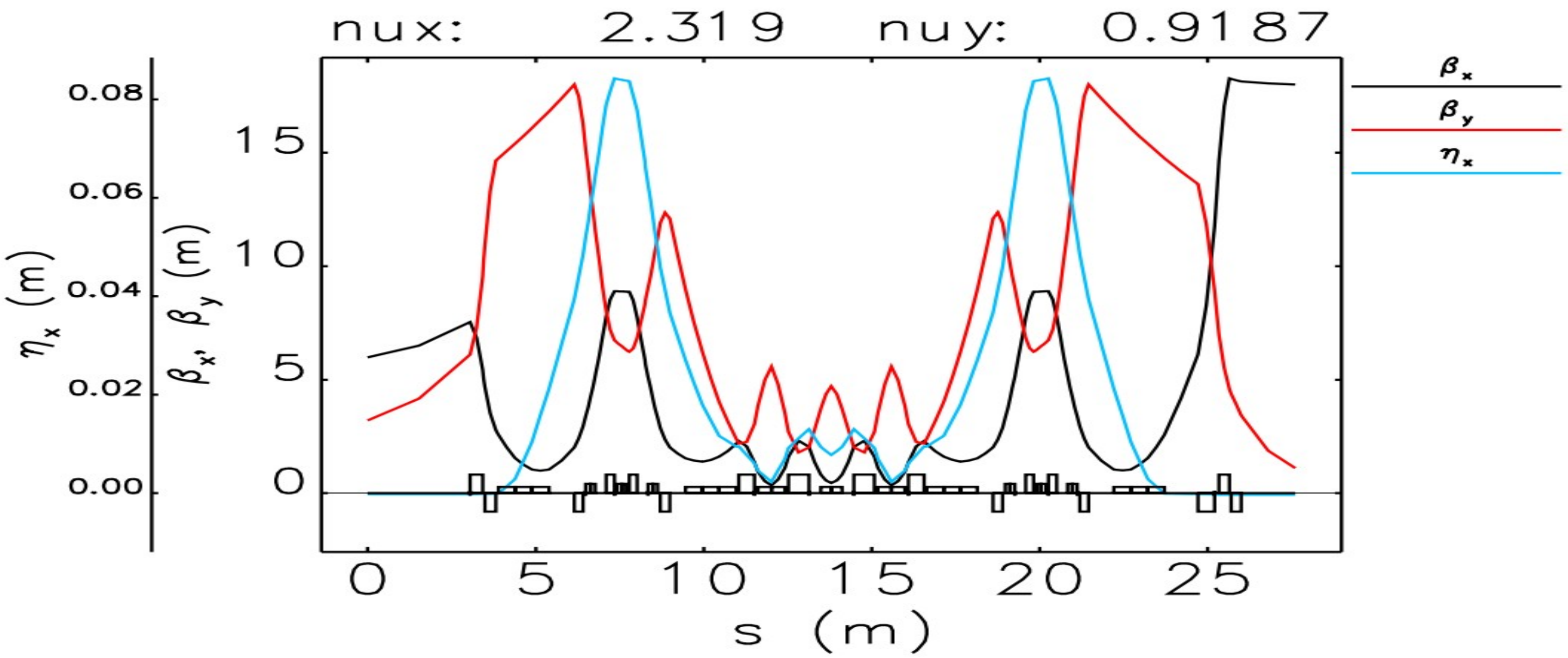
90pm lattice with accumulation

- Emittance is 90pm compared to 67pm for the nominal lattice
- Very close to the nominal lattice but provides larger DA and space for injection kickers
- Utilizes four octupoles per sector



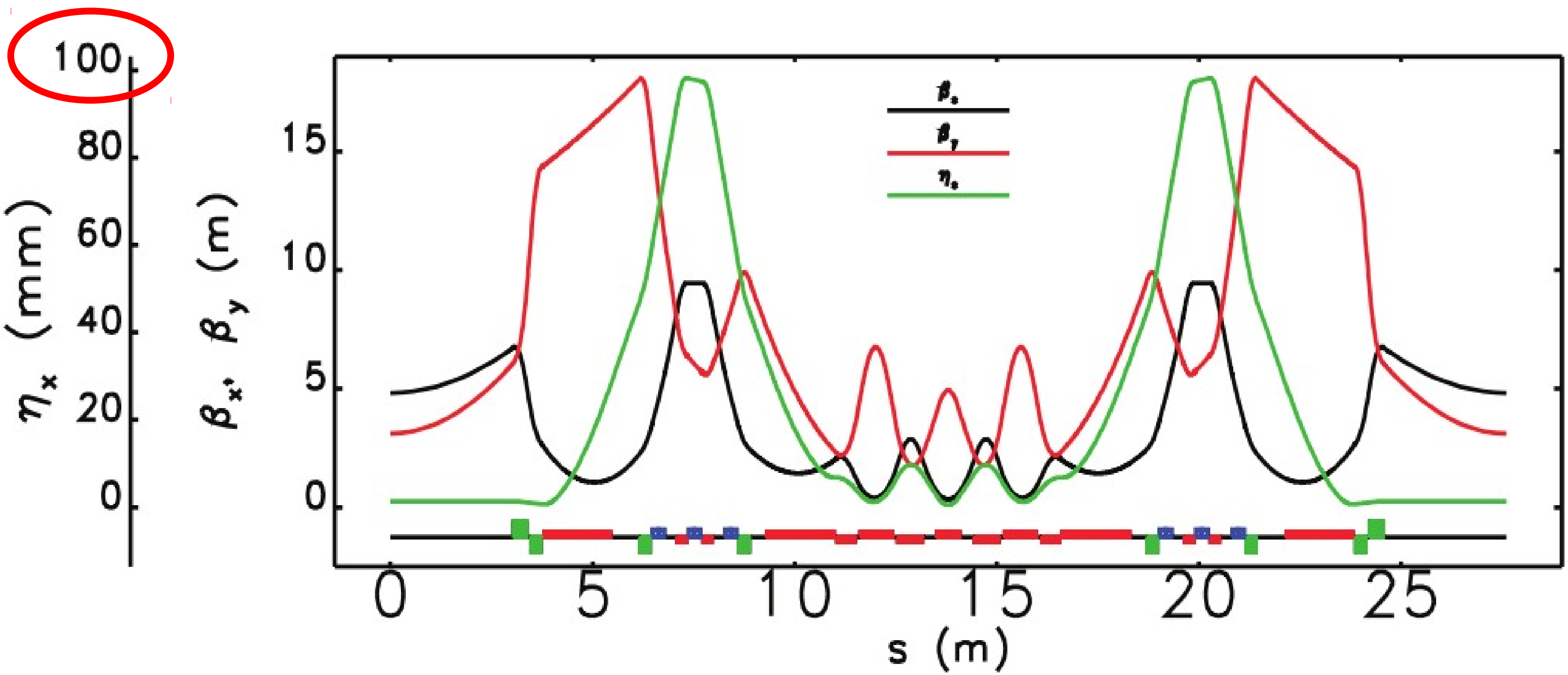
Injection cell with larger beta function

- Minimum changes: several different quads in one straight
- Horizontal beta function increased to 18m
- Need to tune sextupoles in two nearby cells
- Nonlinear optimization is ongoing



76pm lattice with accumulation and reverse bends

- Reverse bends in Q4, Q5, Q7, and Q8
- Emittance reduced from 90 pm to **76** pm
- Dispersion increased to 100 mm
- Utilizes four octupoles per sector



Conclusion

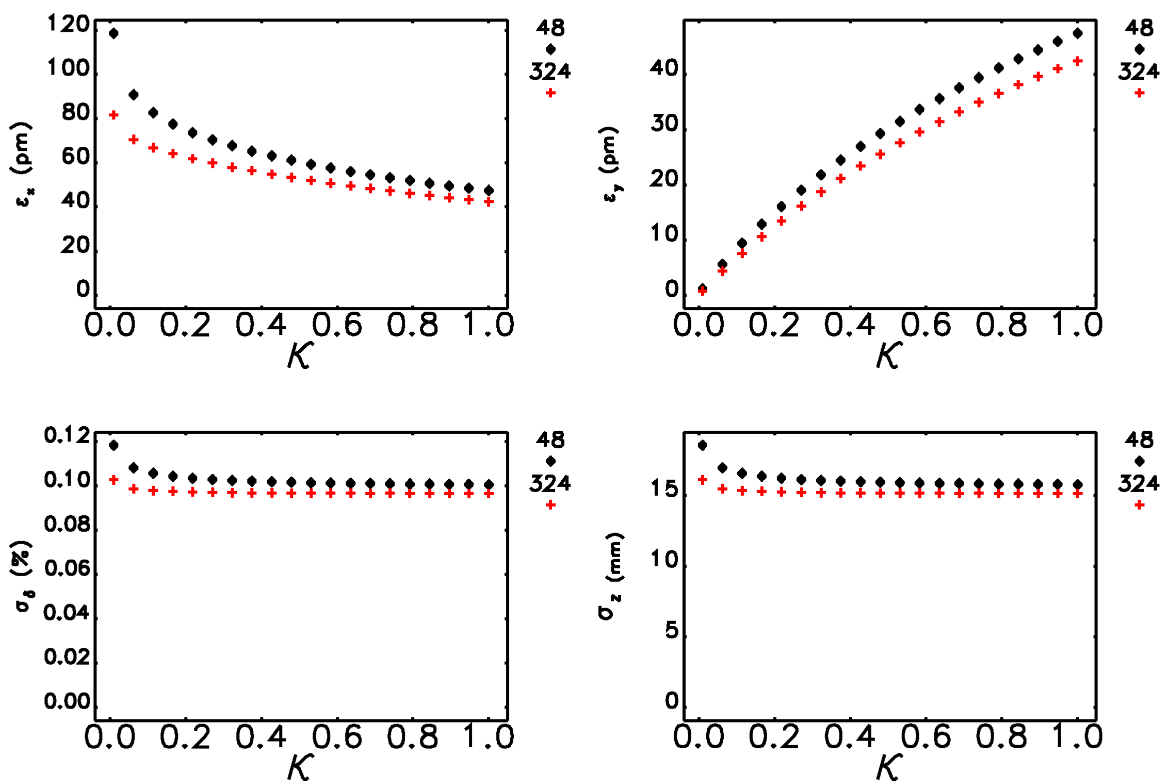
- A lattice design has been developed that is consistent with engineering constraints and satisfies goals
  - Primary goal is ~100-fold increase in brightness for hard x-rays
- Lattice robust in the presence of errors
- Intrabeam scattering has moderate effect on brightness
- Simulations of harmonic bunch lengthening cavity indicate ability to increase rms bunch duration to 66 ps or more in 48-bunch mode
  - Detailed simulations show this improves Touschek lifetime considerably
- Beam lifetime not as long as desired
  - Study of loss patterns, collimation, and supplemental shielding to be undertaken
- Work on alternative lattices is ongoing
  - The goal is to reduce emittance and provide accumulation

- Early version of H7BA lattice used file provided by ESRF.
- Most of the simulations used the Blues cluster at Argonne's Laboratory Computing Resources Center

Backup slides follow

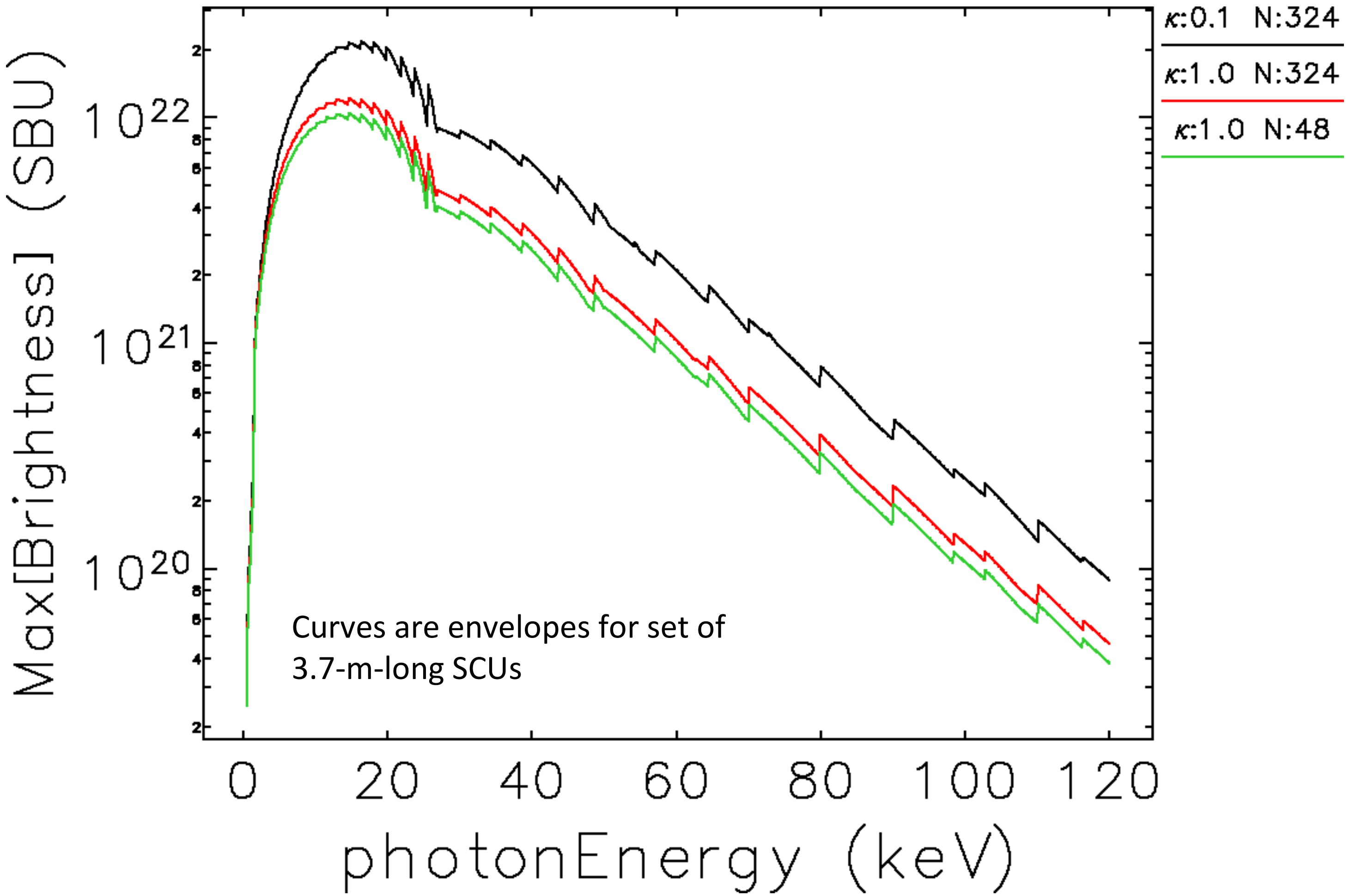
Intrabeam Scattering

- Used **ibsEmittance**[1] to model intrabeam scattering
  - Assumed nominal rms bunch length of 50 ps (15 mm)
  - Conservative, as shown below
- Uses Bjorken-Mtingwa formalism[2] to compute the IBS growth rates
- Iterates to find self-consistent beam parameters
  - Total growth rates equal synchrotron radiation damping rates in all planes
  - Fixed ratio of bunch length to energy spread is assumed
  - Fixed ratio κ of vertical to horizontal emittance is assumed



1: A. Xiao, L. Emery, M. Borland; A. Xiao, Linac08, 296-298.
2: J. D. Bjorken and S. K. Mtingwa, Part. Acc. 13 (1983) 115.

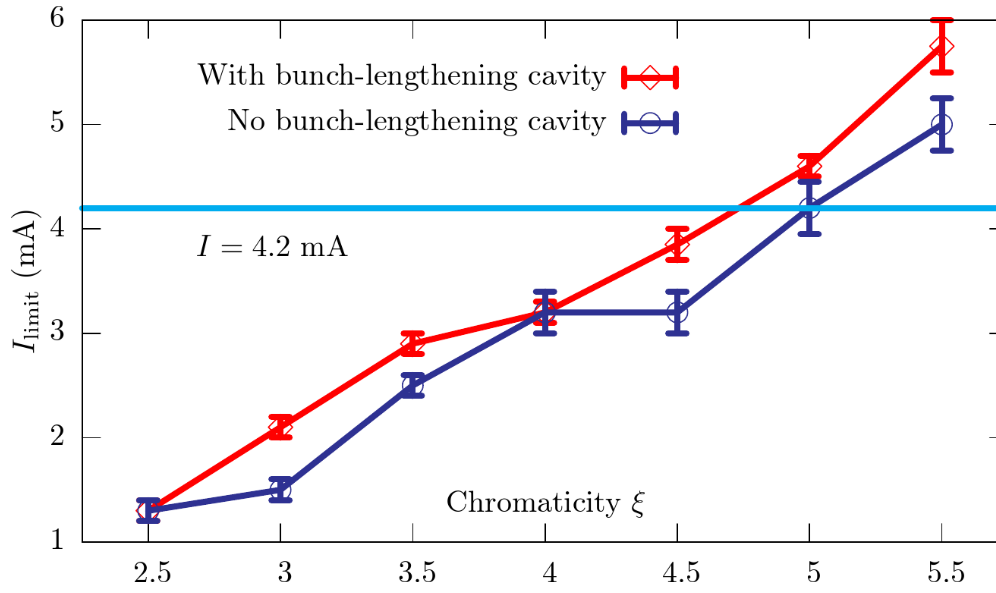
Brightness Impact of IBS



- For 324 bunches, can enhance brightness ~2-fold with lower coupling
- With round beams, 48 and 324 bunches very similar

Single Bunch Current Limit[1]

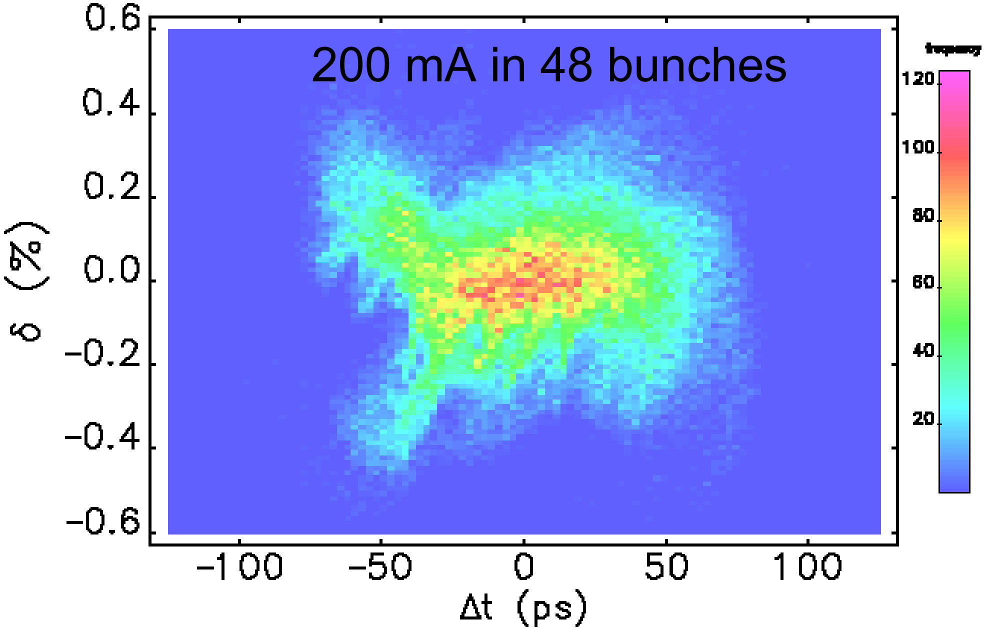
- Achieving 200 mA in 48 bunches (4.2 mA/bunch) requires
  - Careful iteration of vacuum system design
  - Design of a lattice with sufficient positive residual chromaticity
- Prediction is that 4.2 mA is possible with chromaticity of +5
  - Margin increased with latest design (post CDR)



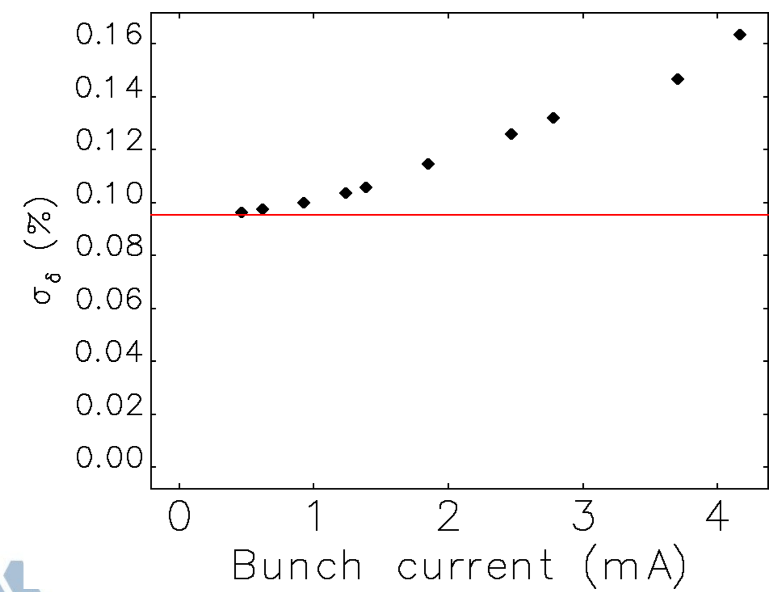
1: R. Lindberg et al., IPAC15, TUPJE077, TUPJE078.

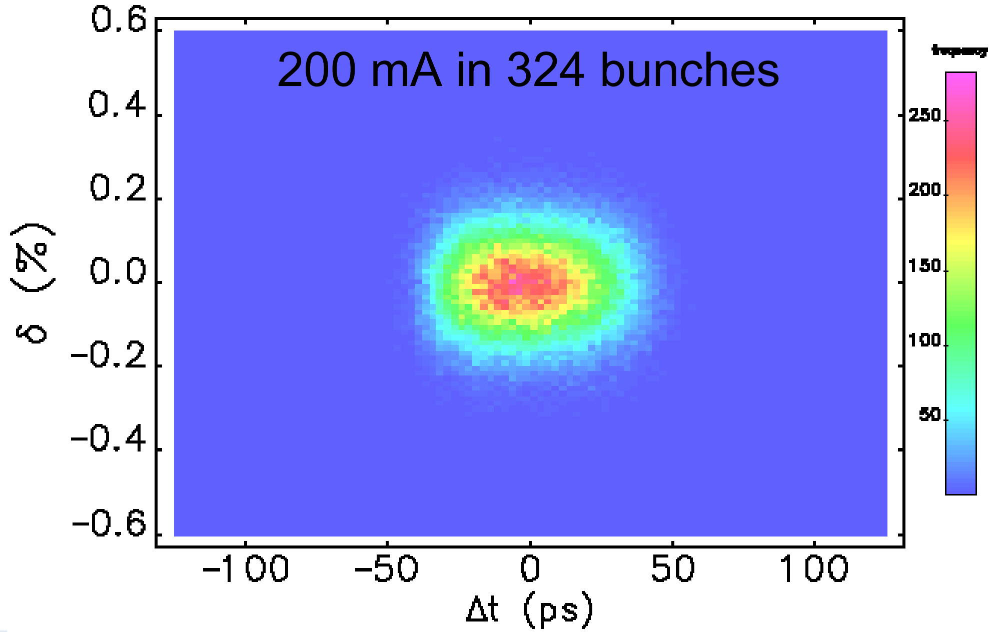
Resistive wall			Geometric contributions			
			Sector (×40)		Ring	
Metal	**Diameter**	**Length**	**Element**	**Number**	**Element**	**Number**
Cu	22 mm	224 m	Regular BPM	12	Injection kicker	4
Al	22 mm	605 m	ID BPM	2	Extraction kicker	4
SS	22 mm	80 m	ID transition	1	Feedback	2
Al	6 mm	175 m	Bellow	14	Stripline	1
Al	140 mm	20 m	Flange	52	Aperture	2
			Crotch absorber	2	Fundamental cavity	12
			In-line absorber	12	Rf transition	4
			Gate valve	4	4^{th} harmonic cavity	1

Longitudinal phase space impacted by impedance

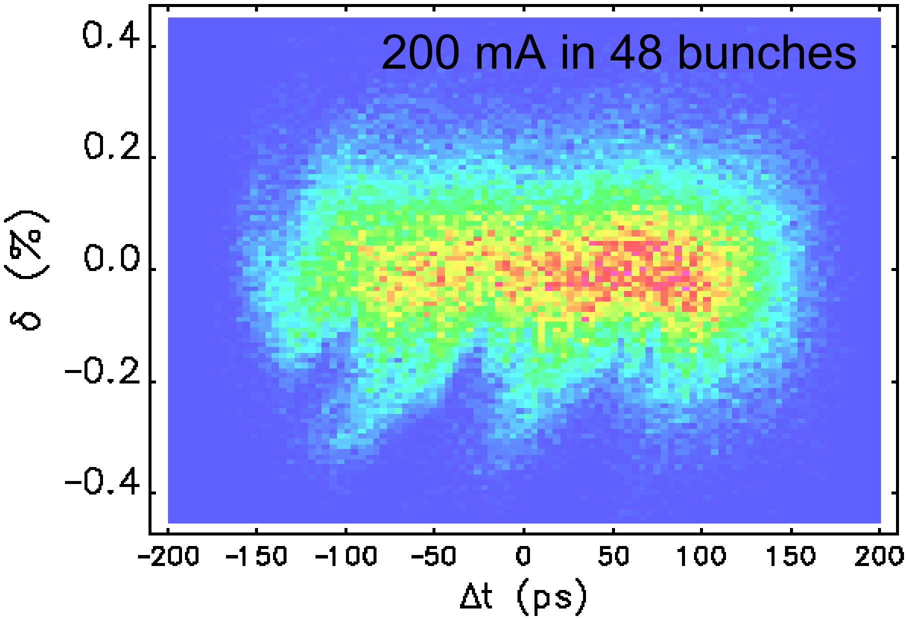


- Intense bunches are disrupted by microwave instability
  - No beam loss, but energy spread is inflated
- Threshold is at ~0.5 mA/bunch
  - In APS, threshold is ~5 mA/bunch





Effect of HHC (13.5 kHz detuning)



- Rms bunch duration exceeds 75ps
- Microwave instability is considerably quieter
- 324 bunch case has a somewhat split bunch

- For 48 bunches, lifetime improves ~2-fold
  - Less than nominal 4-fold because MWI already lengthened the bunch
- For 324 bunches, lifetime improves ~3-fold