Optimization of an ESRF-II-Style Lattice for APS

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Accelerator Systems Division

Constraints and Goals for Upgraded Lattice

- Retain 40 sector configuration
- Retain 35 ID straights serving existing end stations
- Retain location of bending magnet beam lines
- Keep the existing rf systems
  - Cost reduction
  - Compatibility with existing injector
  - Requires fairly close matching of circumference
- Keep the existing injector, with modest upgrades if needed
  - Existing injector comprises a 375+ MeV linac, accumulator ring, and 2 Hz booster
- Performance goals
  - Provide ~100-fold increase in x-ray brightness relative to best devices in APS today
  - Maintain tuning ranges
  - Maintain or increase ID flux
  - Maintain bending magnet flux and spectral range (at least 17 keV critical energy)
  - Approximately maintain timing-mode performance (at least 4 mA/bunch)

Lattice Optimization Approach

- Lattice optimization consisted of three steps
  - Initial matching of linear optics for nominal integer tunes
  - Wide-ranging scan of integer and fractional tunes to understand landscape of solutions
  - Tracking-based multi-objective optimization of optics and sextupoles
- Initial matching started from solution provided by ESRF[1]
  - Changed from 32 to 40 sectors
  - Constraints included
    - Minimum emittance with <3mm dispersion in straights
    - Beta functions of 1-3 m in 4.8-m-long ID straights
    - ID beamline transverse motion less than 5 mm
    - Circumference change on [-8, 0] cm to avoid issues with booster
    - Weak magnets (relative to engineering concepts)
    - Chromaticity of +2 in both planes
  - Variables included
    - All magnet strengths and lengths
    - Two sextupole families at this point (SD-SF-SD in each bump)
    - Relative strengths of 5 segments of the longitudinal dipoles
  - Use “hybrid parallel simplex” optimizer in Pelegant[2]

1: Provided by P. Raimondi, L. Farvacque, N. Carmignani, et al.
2: Y.Wang et al, PAC 11, 787 (2011).

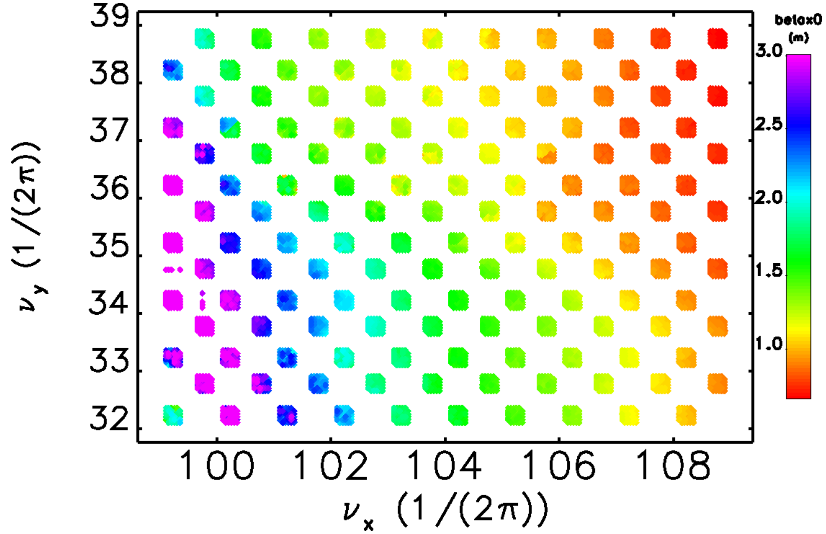
Scan of Working Points

- Next step was a broad survey of possible working points
- In addition to basic properties, evaluated nonlinear properties of working points
  - Dynamic acceptance and tune footprint within stable region
  - Momentum acceptance and tune footprint within stable region
  - Local momentum acceptance
  - These used two features of Pelegant
    - Existing local momentum acceptance search
    - New tune footprint command
- Results were subjected to non-dominated sort[1] to find the Pareto-optimal solutions for best
  - Beta functions at ID
  - Natural and effective emittance
  - Stability limit from tune vs momentum
  - Local momentum acceptance
  - Dynamic aperture (normalized with beta functions)

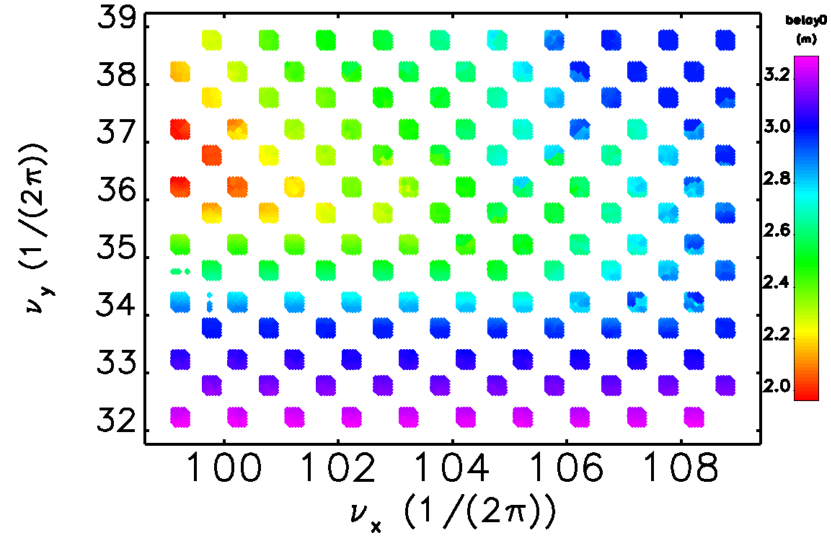
1: K. Deb *et al*., IEEE TEC, 6:182 (2002).

Linear Lattice Properties

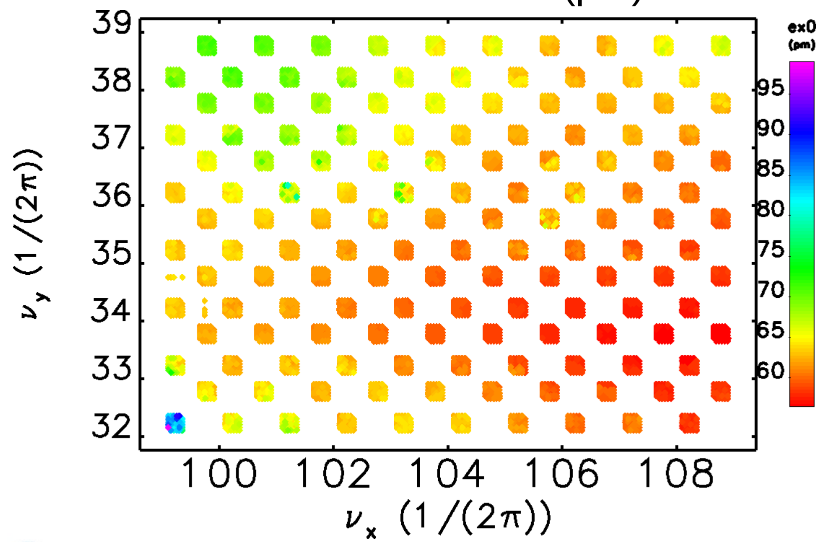
Horizontal beta function @ID



Vertical beta function @ID



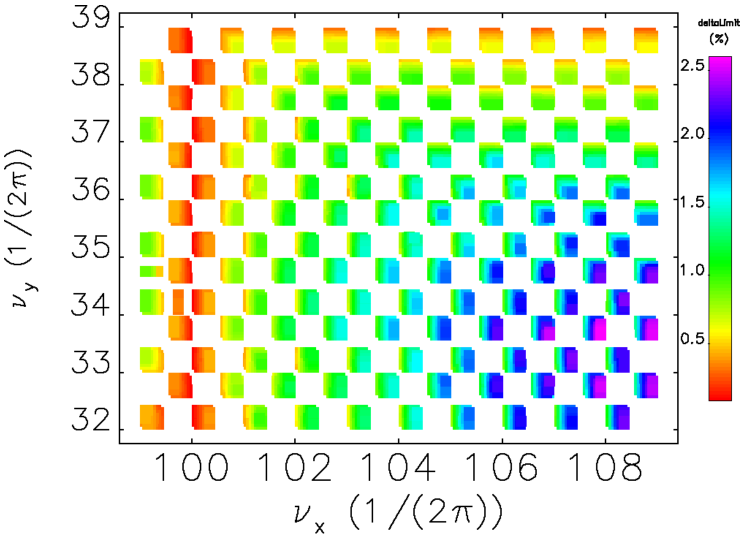
Natural emittance (pm)



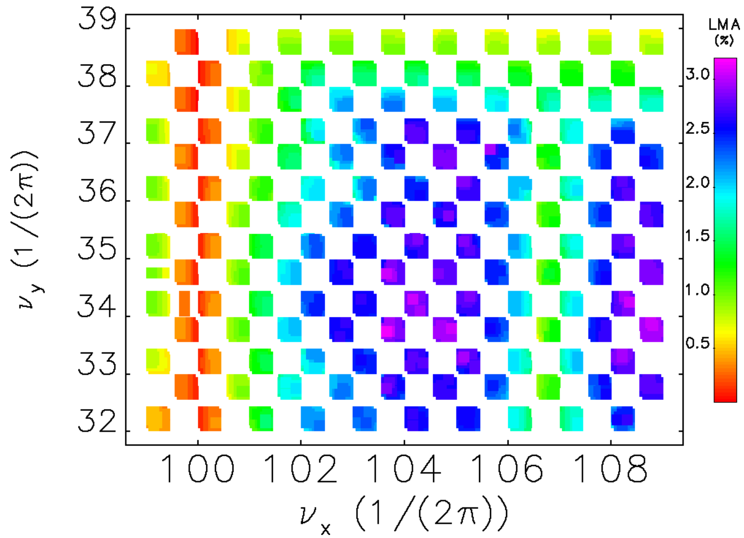
Minimizing the emittance is incompatible with reducing horizontal beta function to the ideal value of ~1.5 m

Nonlinear Properties

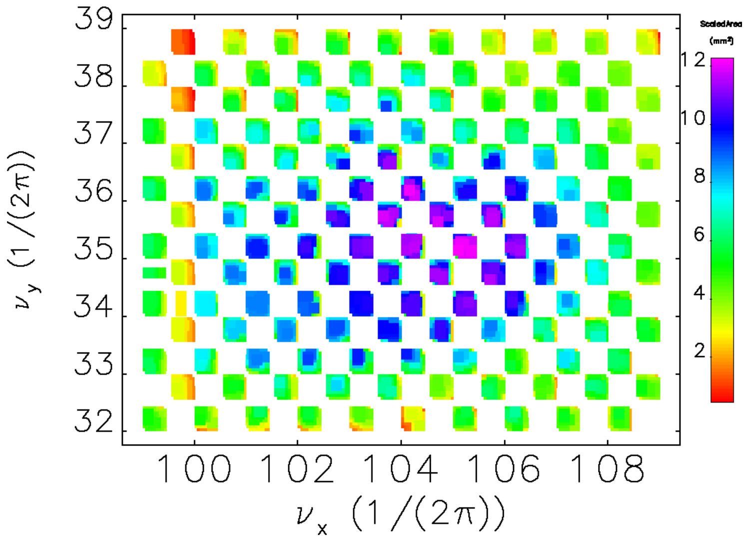
Limit of stable chromatic tune



Minimum local momentum acceptance



DA Area scaled with beta functions



Not possible to simultaneously optimize all of these.

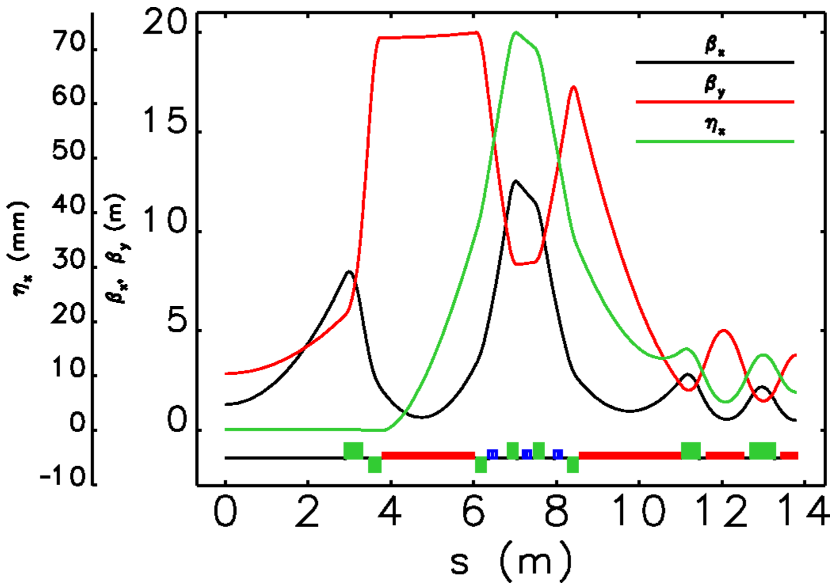
Three Pareto-optimal solutions subjected to tracking-based optimization, including (105.35, 34.15), which has <60 pm natural emittance

Tracking-Based Optimization[1]

- We used tracking-based optimization to refine several solutions, emphasizing
  - Maximum dynamic acceptance area
  - Maximum Touschek lifetime computed from local momentum acceptance
  - Minimum emittance
  - Desired chromaticities of +2 in both planes
  - These are optimized in a multi-objective sense (MOGA)
- The algorithm is allowed to vary
  - Tunes, restricted to fixed quadrant of the tune diagram
  - Target value for maximum dispersion in the bump
  - 10 sextupole strengths (out of 12 present in two sectors)
  - Target values of horizontal and vertical phase advance between sextupoles
- Each “function evaluation” involves
  - Matching to change tunes, phase advance, etc., while minimizing emittance
  - Adjustment of free sextupoles to obtain desired chromaticities
  - Tracking to determine stable range of chromatic tunes
  - Tracking with errors for dynamic acceptance
  - Tracking with errors for local momentum acceptance (first two sectors only)
  - Typically takes 20-40 minutes on 32 cores

1: See citations in M. Borland, IPAC12, 1035.

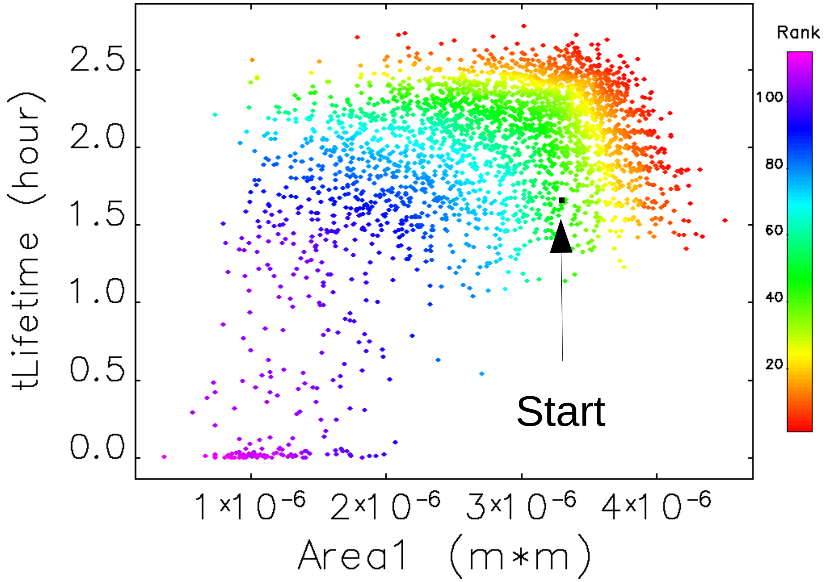
"Best" Solution from Optimization



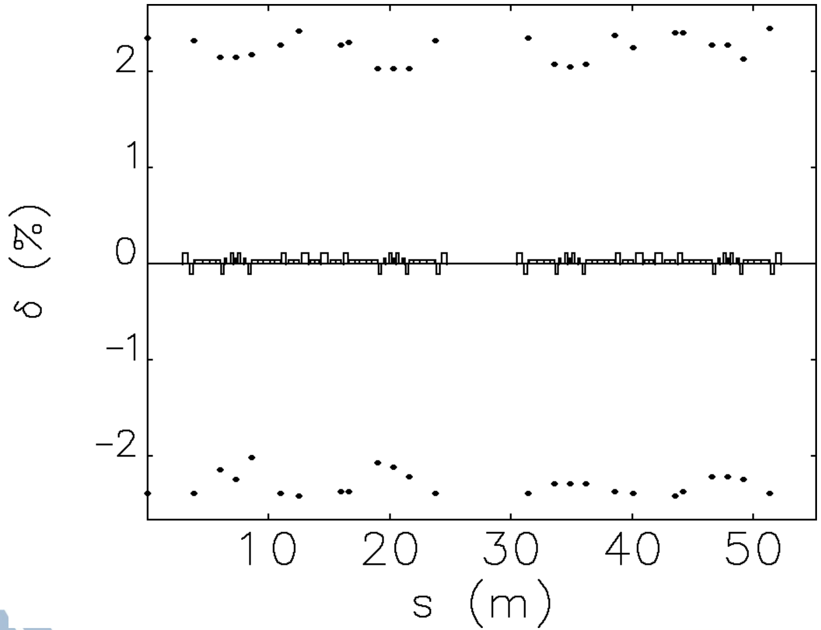
Betatron Tunes		
Horizontal	105.445	
Vertical	34.146	
Natural Chormaticities		
Horizontal	-152	
Vertical	-127	
Lattice functions		
Maximum β_x	12.498	m
Maximum β_y	19.997	m
Maximum η_x	0.073	m
Average β_x	3.490	m
Average β_y	9.325	m
Average η_x	0.032	m

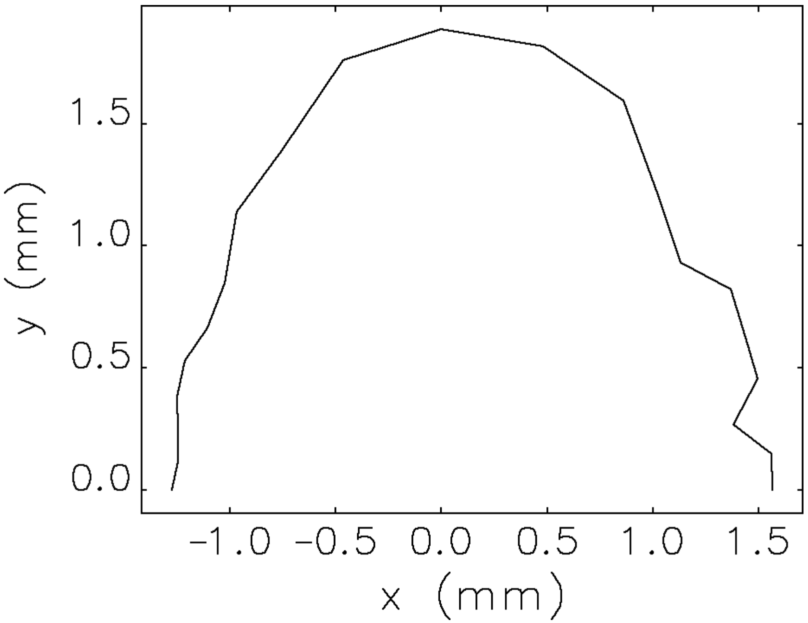
Radiation-integral-related quantities at 6 GeV		
Natural emittance	58.679	pm
Energy spread	0.094	%
Horizontal damping time	13.520	ms
Vertical damping time	21.342	ms
Longitudinal damping time	15.014	ms
Energy loss per turn	2.071	MeV
ID Straight Sections		
β_x	1.298	m
β_y	2.853	m
Miscellaneous parameters		
Circumference	1103.984694	m
Momentum compaction	6.131×10^{-5}	
Damping partition J_x	1.579	
Damping partition J_y	1.000	
Damping partition J_δ	1.421	

Best Solution from Optimization

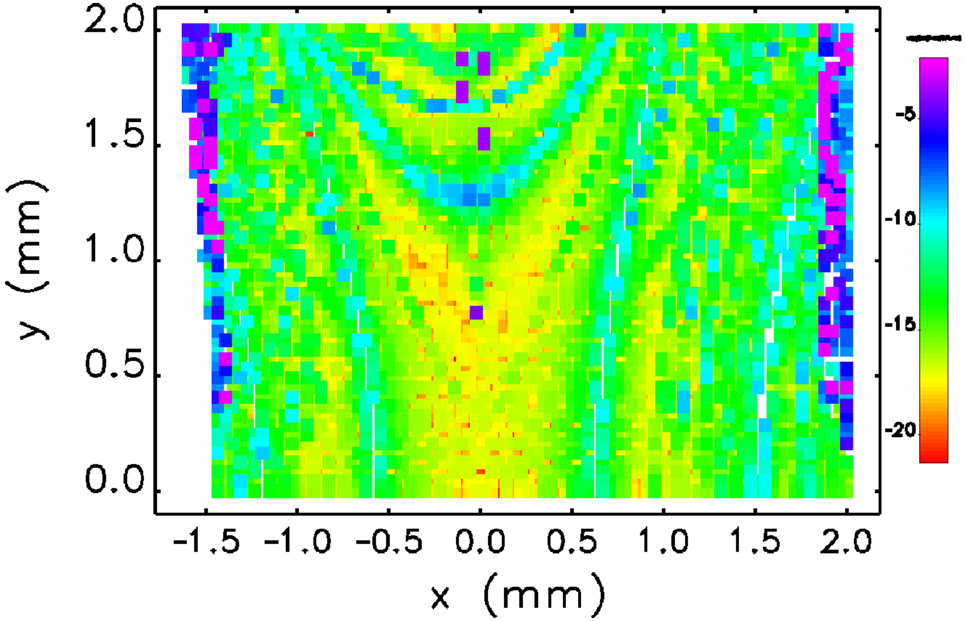


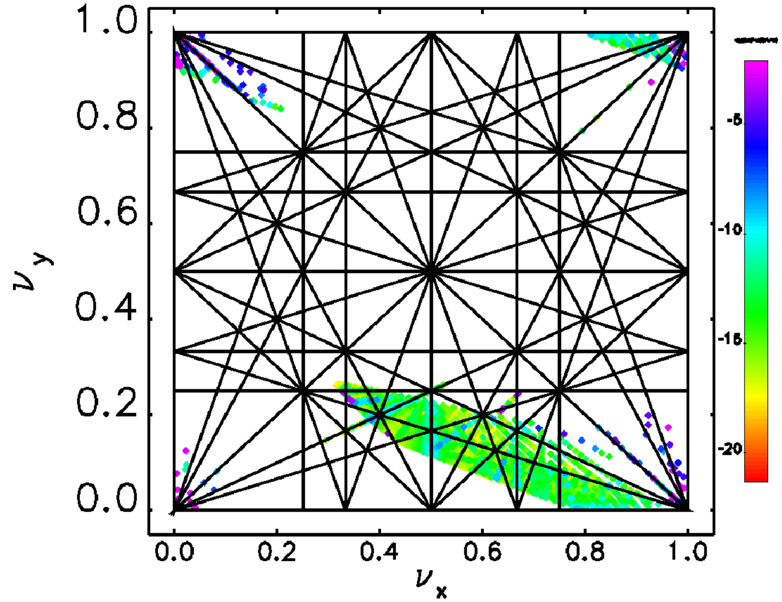
- Touschek lifetime is computed with 10% coupling, 200 mA, 432 bunches, and 20 mm bunch length, which requires a harmonic cavity
- DA is only large enough for on-axis injection
- LMA is above 2%, similar to APS today





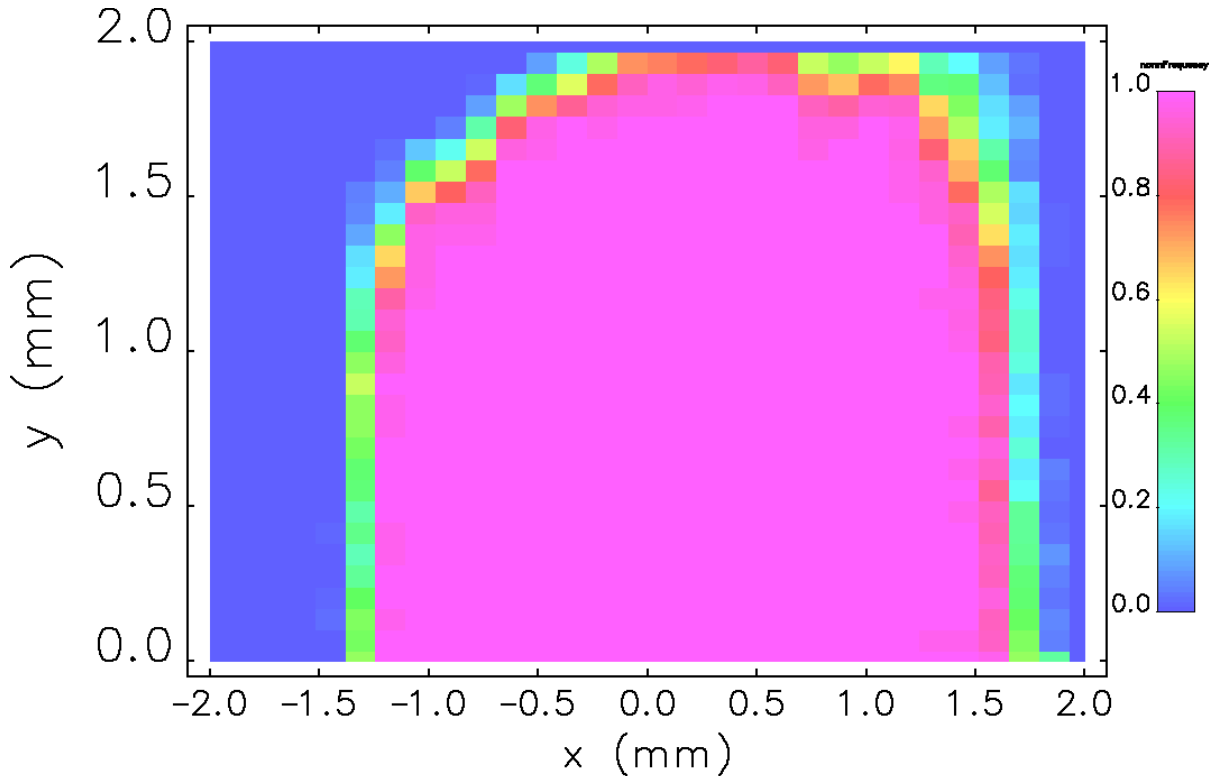
Frequency Map Analysis (x-y)





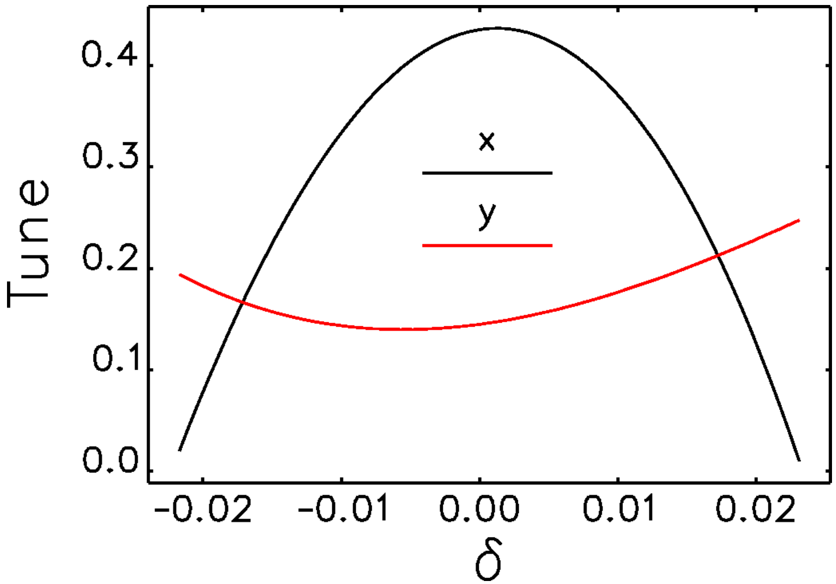
- FMA shows that the tune footprint of the stable region extends across the horizontal half integer
- DA search algorithm should detect this if it was an issue
  - Search uses sufficiently small steps and sufficiently large number of turns to damp across the resonance
  - Errors included in tracking
- Presumably this works because the horizontal tune shift with amplitude is very large

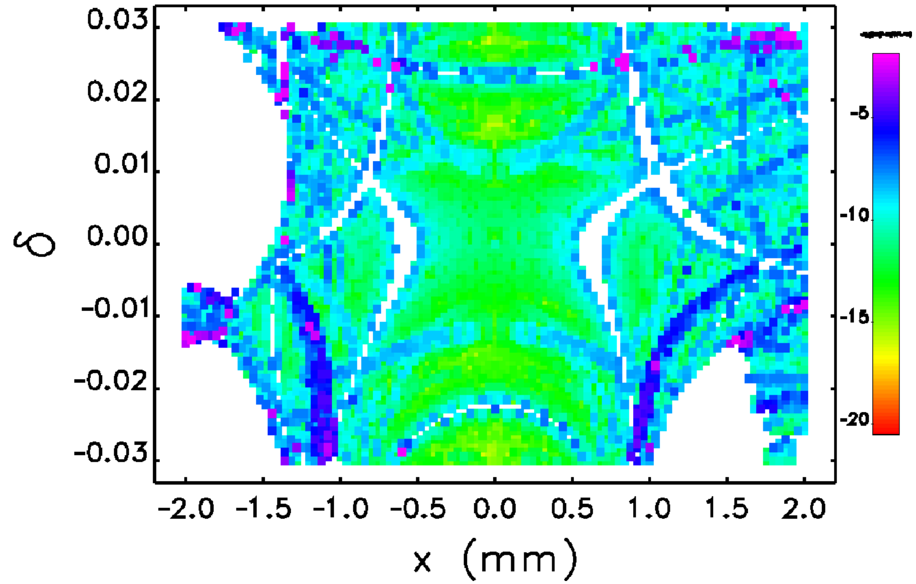
Additional Tracking to Confirm DA

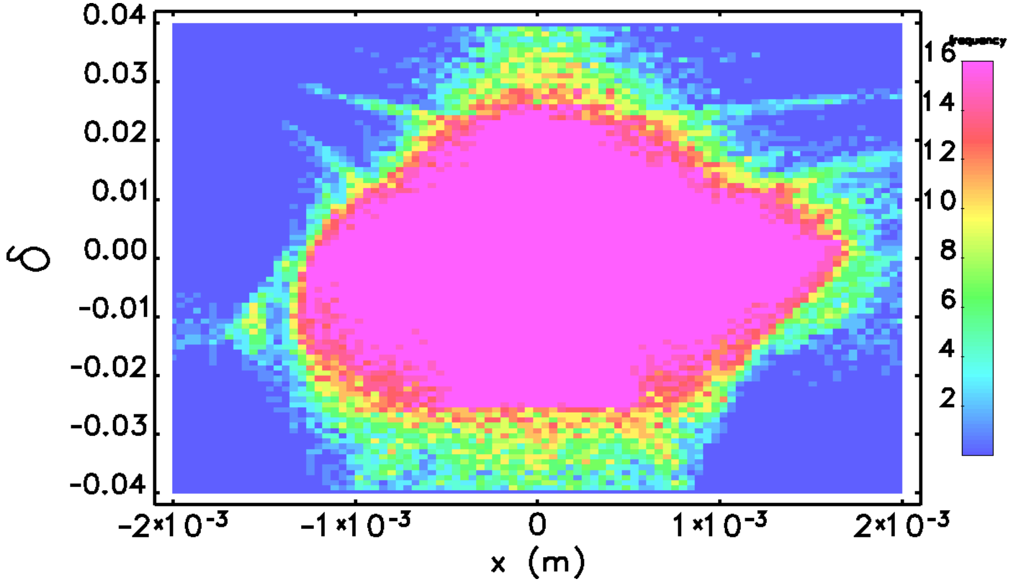


- We tracked a grid of particles for 3000 turns with synchrotron radiation
- Tracked for all 93 error ensembles
- Some trapping on the half-integer resonance evident, but no losses
  - Reduced if quantum excitation added, but needs more investigation
- Note that DA search only uses 400 turns, which this test confirms to be adequate

Frequency Map Analysis (x-δ)





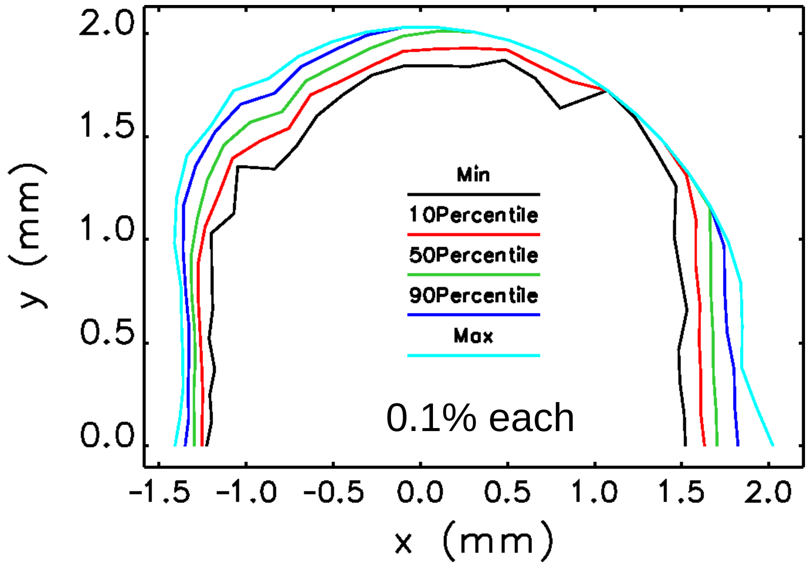


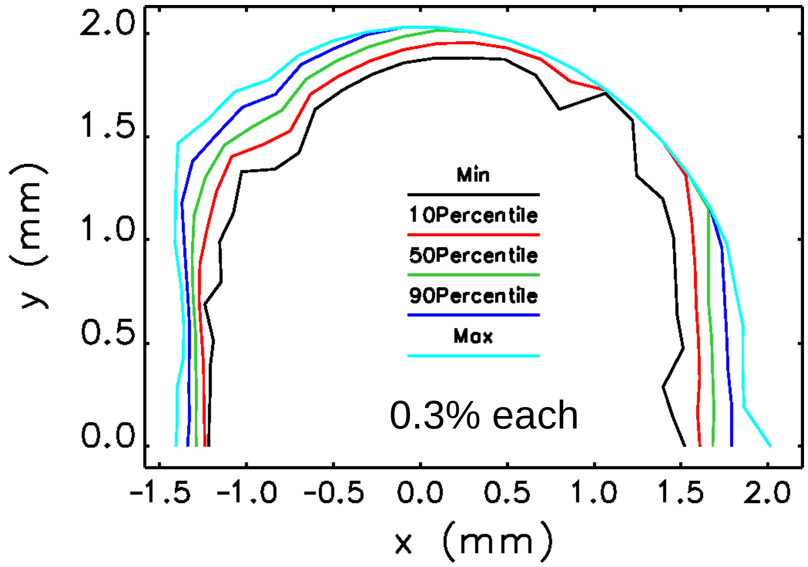
- Horizontal chromatic tune footprint extends in opposite direction from amplitude tune footprint
- Voids in FMA correspond again to half-integer resonance
- Particles are not lost, but rather have ill-defined tunes
- Tracking a grid of particles with errors and radiation damping for one damping time confirms this

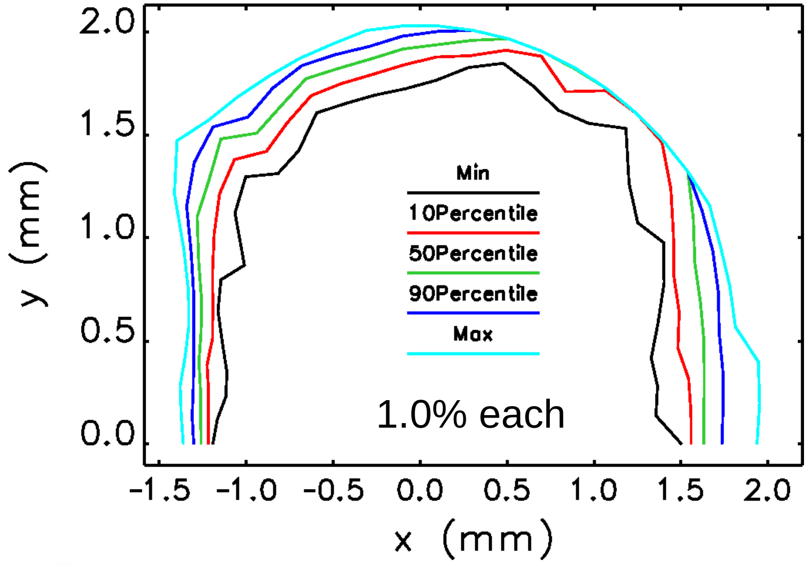
Checking Robustness of Solution

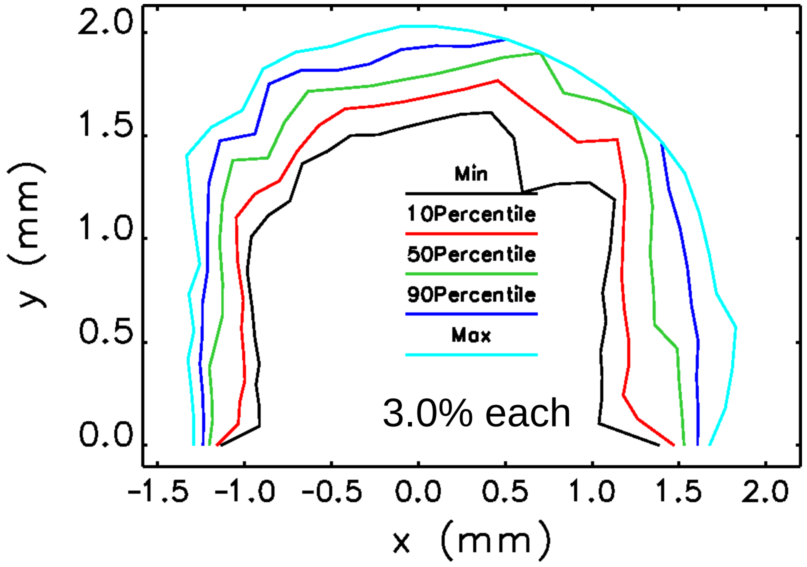
- To check the robustness of the solution, want to look at DA, LMA, lifetime for many error ensembles
- We don’t have correction algorithms set up yet, so we used a proxy method
  - Generated a large number (12000) of error ensembles with
    - 0.06% rms errors in quadrupoles and sextuoples
    - 1 mrad tilt errors in quadrupoles and sextupoles
  - Corrected tunes (using quads near IDs), then computed lattice functions and coupled beam moments
  - Selected those ensembles giving
    - 7-10% beta function beats
    - Emittance ratio of 0.1 to 0.2
  - The 93 remaining ensembles are proxies for somewhat badly corrected lattices
- Included physical apertures
  - 20mm ID round aperture in arcs
  - 20mm by 6 mm ellipse in ID straights
  - These appear to have no effect on the acceptances
- Included allowed multipoles in quads and sextupoles, up to 42-pole
  - Fractional error at 10mm radius set to the same value for all multipoles
  - I.e., they all add up, which is presumably the worst case

DA vs Systematic Multipole Level

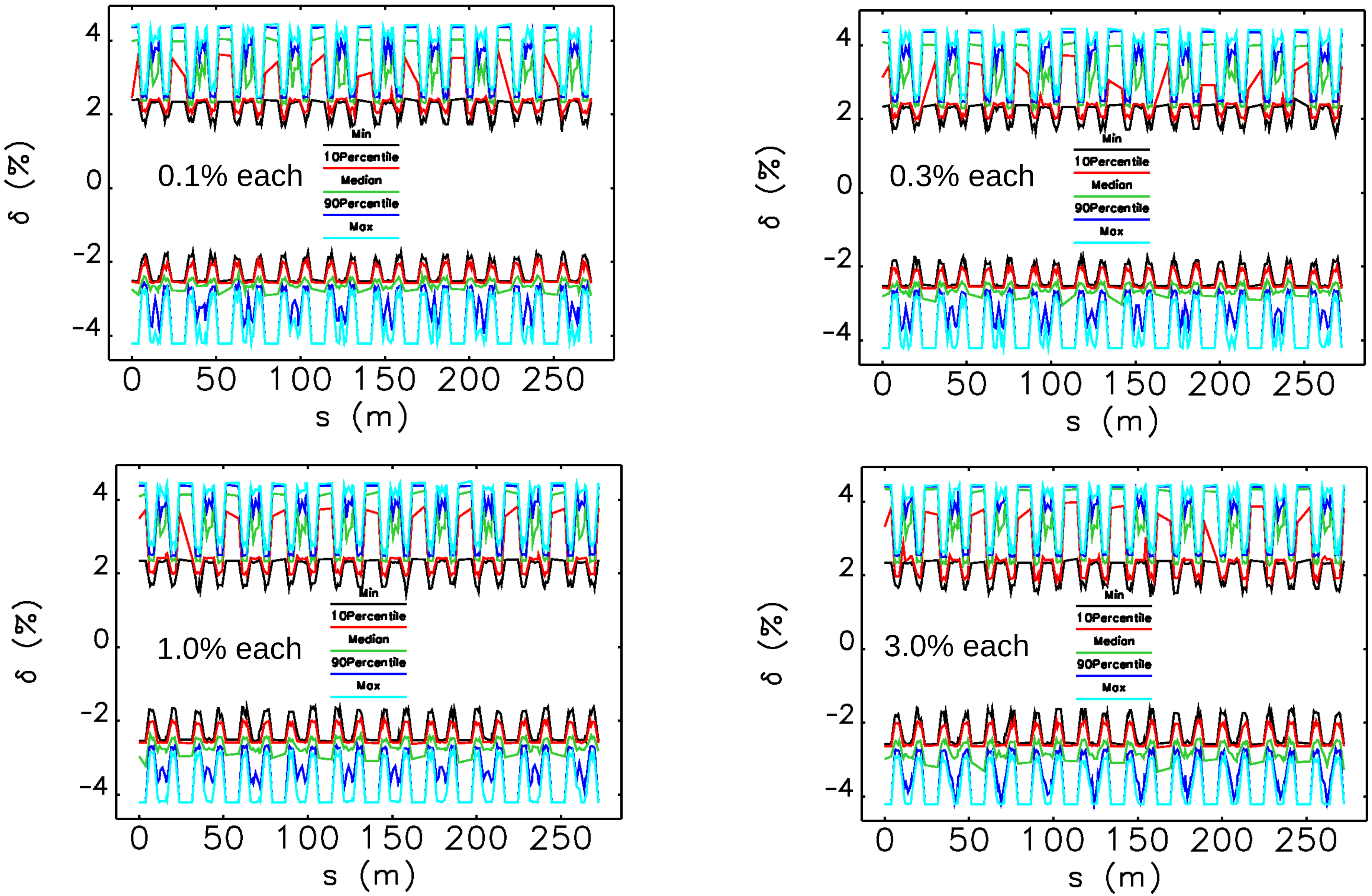








LMA vs Systematic Multipole Level



Acknowledgements

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  - Y.-C. Chae, L. Emery, G. Decker, K. Harkay, V. Sajaev, N. Sereno, Y.-P. Sun, A. Xiao, C.-Y. Yao, A. Zholents
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