# MOGA Techniques for Optimizing MBA Lattices

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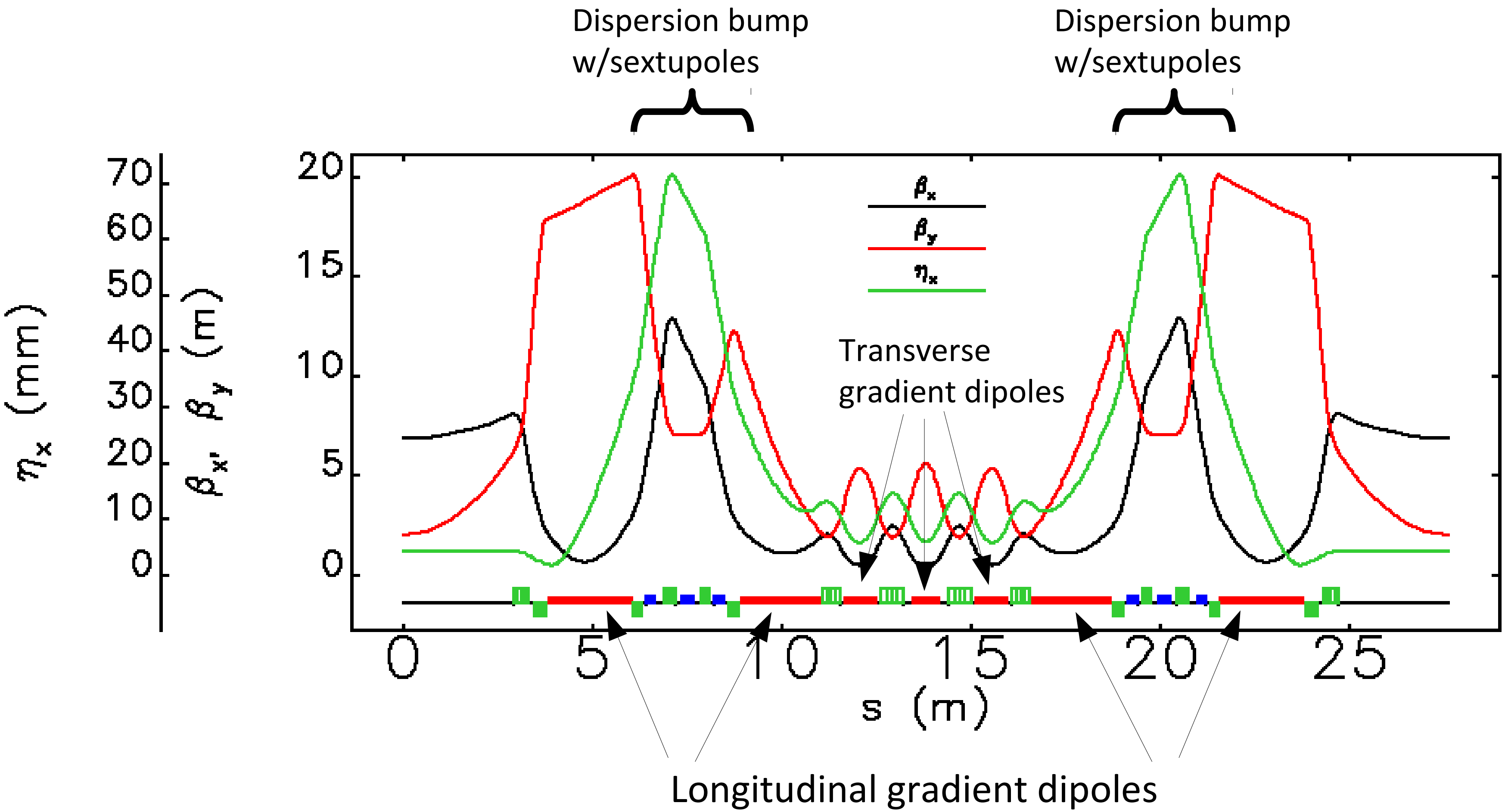
# Outline

- Linear optics
- Nonlinear optics
- APS application

# Hybrid 7BA Lattice Concept (originally from ESRF)



Dispersion bump w/sextupoles

Dispersion bump w/sextupoles

Transverse gradient dipoles

Longitudinal gradient dipoles

- Phase advance of Δϕx=3π and Δϕy=π between corresponding sextupoles chosen to cancel geometrical sextupole kicks
- Thick, interleaved sextupoles → cancellation isn't perfect

# Optimization of Optics

- M=7 appears to be a good balance between difficulty and performance
- Beam energy 6 GeV based on early estimates of the difficulty of the magnets
- Accumulation vs swap-out injection
  - This lattice emphasizes swap-out
    - Weak bunches are replaced, not topped-up
    - Only requires on-axis injection
  - By reducing dynamic aperture requirements, swap-out should
    - Allow lower emittance to be achieved
    - Allow better optimizing momentum aperture
    - Relax tolerances
    - Reduce overall project risk
  - Swap-out permits use of helical and horizontal-gap IDs
  - APS injector appears capable of supporting swap-out
- Two-Stage Optimization
  - Choice of working point by direct scan of integers, starting from lattice provided by ESRF.
  - Tracking-based optimization of selected working point
- Redo optimization as needed when magnet locations are moved (vacuum group) or strengths limits are changed (remove steering coils from main magnets)

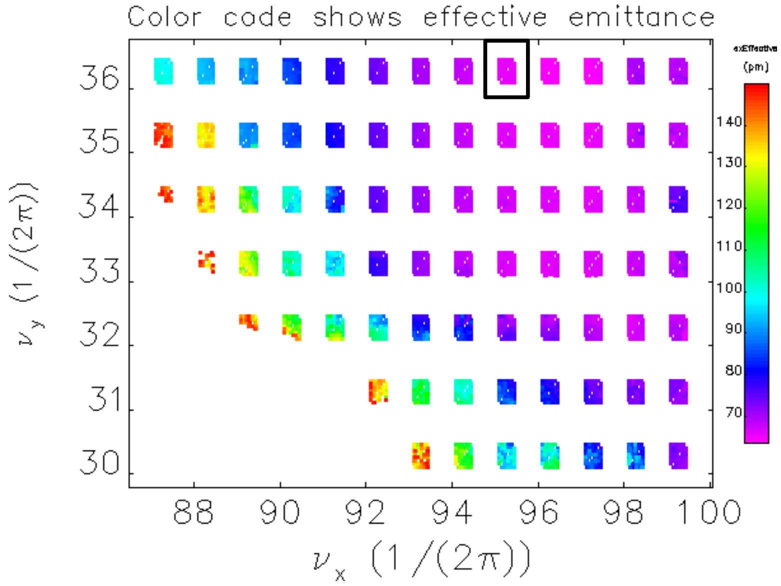
# Two-Stage Optimization

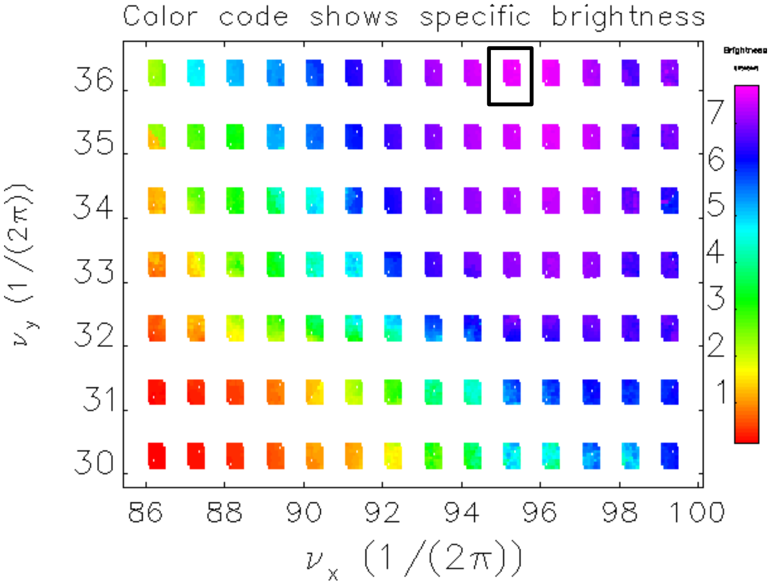
- Choice of working point by direct scan
- Tracking-based optimization of selected working point

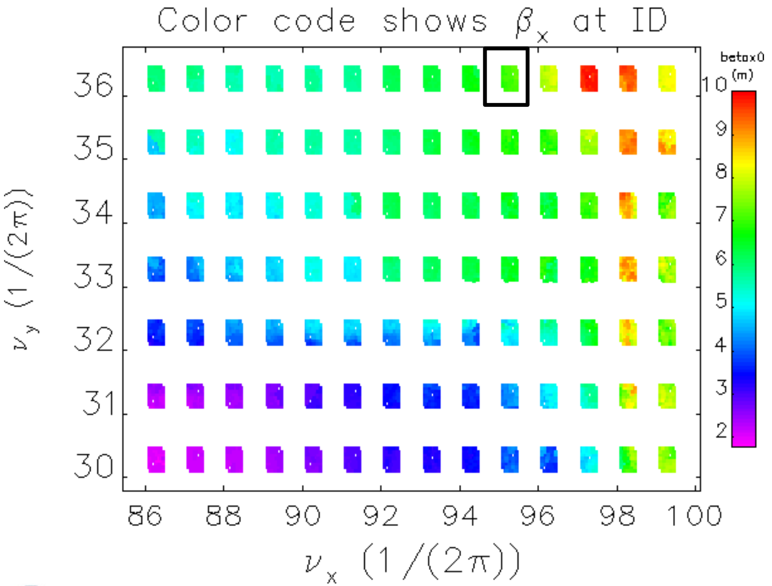
# Choice of Working Point

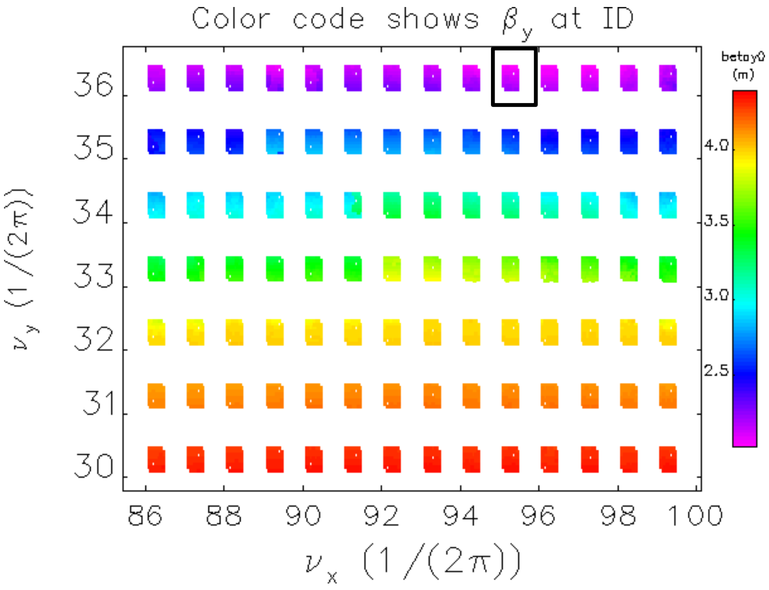
- The basic lattice concept supports a wide choice of working points
  - We started from a lattice provided by ESRF[1], scaled to 40 sectors
  - The ESRF lattice has $\Delta\nu_x$=2.3625 and $\Delta\nu_y$=0.8625
- Performed a wide-ranging scan of working points to examine possible performance
  - Working point affects linear optics, brightness, and nonlinear dynamics
  - This was done with apertures but no errors
- Scanned over many integer working points (next slide)
- Confined fractional tunes to $\nu_x$:[0, 0.5] and $\nu_y$:[0, 0.5]
  - Arguably preferred for resistive wall stability
  - Avoid linear difference resonance

# Working Point Scan[1]


Color code shows effective emittance


Color code shows specific brightness


Color code shows $\beta_x$ at ID


Color code shows $\beta_y$ at ID

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1: M. Borland et al., NA-PAC13, 249-251.

# Analysis of Working Point Scan

- Not possible to optimize all performance measures simultaneously
  - Beta functions at ID
  - Effective emittance
  - “Specific brightness”
    - Inverse of the phase space volume for a 20-keV photon beam from a 4.8-m-long device
  - Stability limit from tune vs momentum
  - Minimum local momentum acceptance
  - Dynamic aperture area (normalized with beta functions)
- Results were subjected to non-dominated sort[1] to find the Pareto-optimal solutions for best working point

Definitions: a solution S1 *dominates* S2 when it is better than S2 in all performance measures.

The Pareto-optimal set P includes only non-dominated solutions.

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

# Tracking-Based Optimization[1]

- multi-objective optimization to refine the solution, emphasizing
  - Maximum dynamic acceptance (DA) area (scaled with beta functions)
  - Maximum Touschek lifetime computed from local momentum acceptance (LMA)
    - LMA artificially capped where tune vs momentum crosses integer or half-integer
  - Minimum effective emittance
  - Desired chromaticities of +5 in both planes
- The algorithm is (typically) 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” typically 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 40-60 minutes on 32 cores

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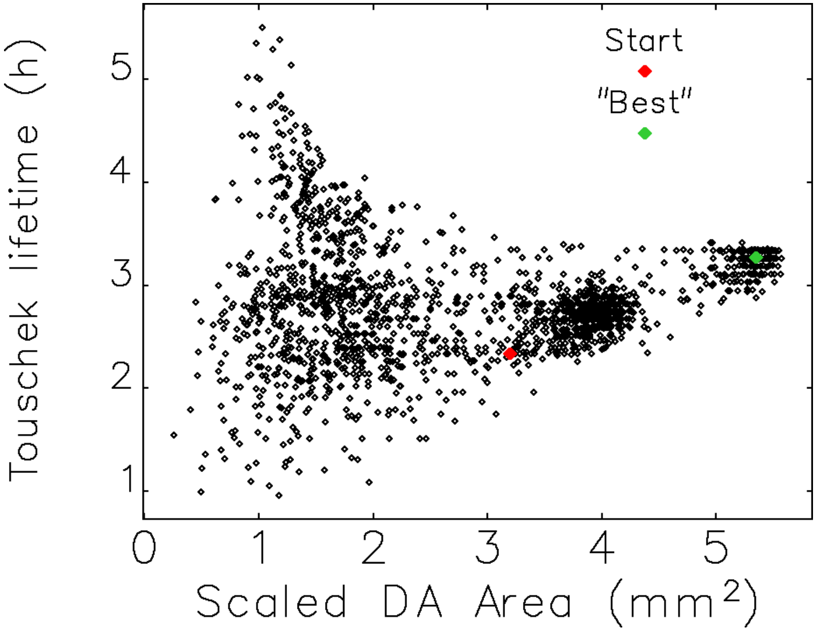
1: See citations in M. Borland, IPAC12, 1035.
2: Y.-C. Chae

# Tracking Details

- Parallel elegant used for tracking for tune vs momentum, DA, and LMA
- Symplectic integration for all magnetic elements
- Second-order matrix for drift spaces
- For DA and LMA
  - Apertures
    - 10 mm radius round aperture in arcs (13 mm bore radius for magnets)
    - 20 mm by 6mm ellipse in IDs
  - Errors (single ensemble) to give lattice function beats and coupling
  - Lumped radiation damping
  - Thin-lens rf cavity set for ±4% bucket height
  - Tracked 400 turns, sufficient for overlap of amplitudes



Normalized to $\beta_x=\beta_y=3$m

# Ensemble Evaluation for Robustness

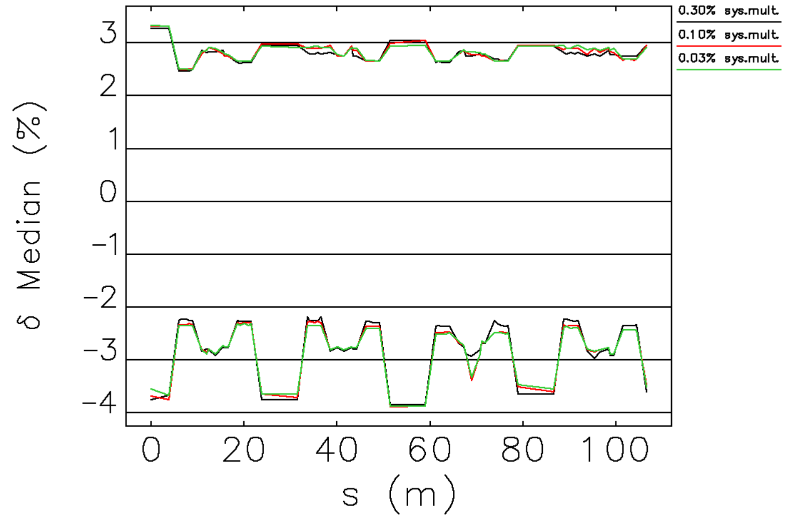
- Evaluated lattice with ~100 random error ensembles
  - Optics errors, including coupling
  - Systematic (i.e., allowed) multipole errors
  - Random multipole errors
- Proxy for orbit/optics correction
  - Add random tilts and strength errors, typically,
    - ±0.12% uniformly-distributed strength errors in gradients (quadrupoles and dipoles)
    - ±0.75 mrad uniformly-distributed tilt errors on quadrupoles and sextpoles
  - Compute lattice functions and emittances for ~12000 ensembles, employing only tune correction
  - Select ensembles providing given level of beta-beating and emittance ratio
    - E.g,. 5-7% beta-beating and 9-11% emittance ratio
    - These  ensembles represent a selection of moderately-corrected lattices
- Systematic multipole errors
  - Set all harmonics to the same level as fraction of main harmonic at R=10 mm
  - Signs are all the same so effects add, to be conservative
  - Quadrupoles: include 12-, 20-, 28-, and 36-pole
  - Sextupoles: include 18-, 30-, and 40-pole
  - Dipoles: include sextupole through 18-pole

# Post-Optimization Nonlinear Dynamics Evaluation Methodology

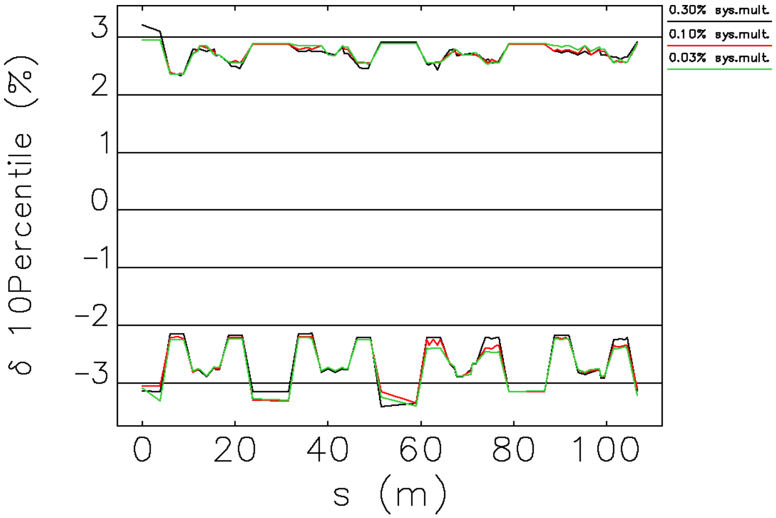
- Basic goal: evaluate with many error ensembles to ensure robustness
- Used 100 error ensembles with correction (V. Sajaev)
- DA/LMA tracking same as MOGA runs, but
  - 1000 turns instead of 400 (better convergence)
  - Element-by-element synchrotron radiation
- Add multipole errors, levels taken from 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].
  - Tables of nominal multipole errors appear in the CDR (3.2.3.1)
- 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
    - For this stage, use nominal beam parameters, but include IBS

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

# Local Momentum Acceptance



nominal: 5-7% beta beats 9-11% emittance ratio



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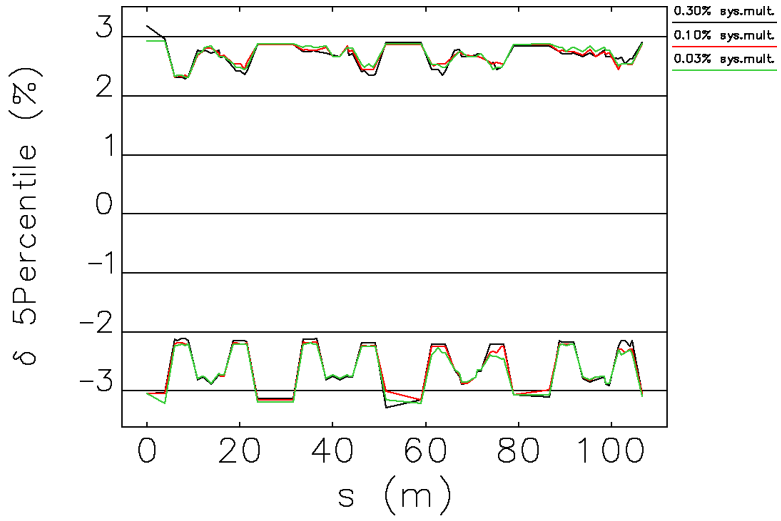
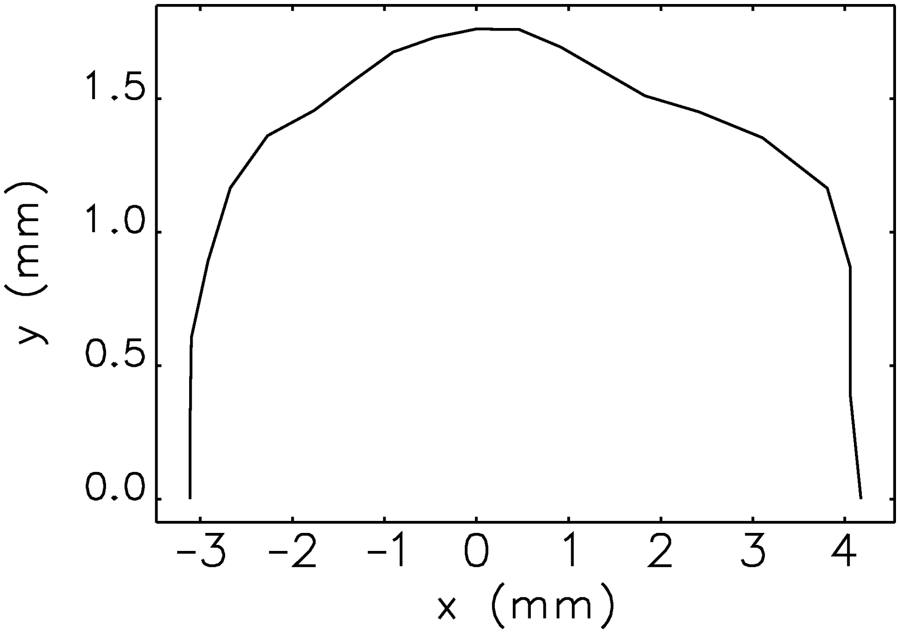
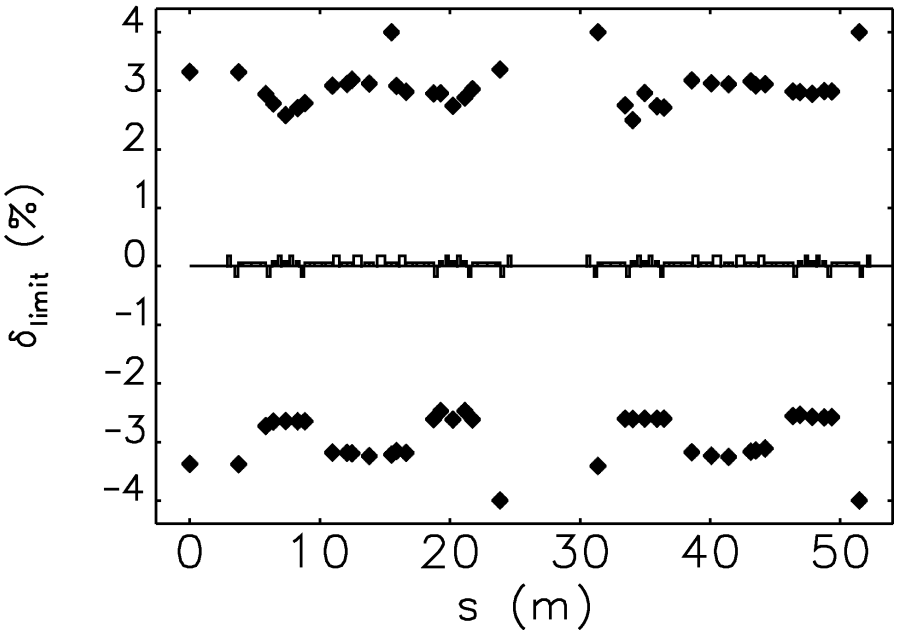


nominal: 5-7% beta beats 9-11% emittance ratio

- Compute LMA for first 4 sectors only to save time
  - Haven't seen any surprises when doing entire ring
- Even 5th percentile results are relatively insensitive to level of systematic multipole errors
- Could probably tolerate errors at 0.3% level (per multipole at R=10 mm)

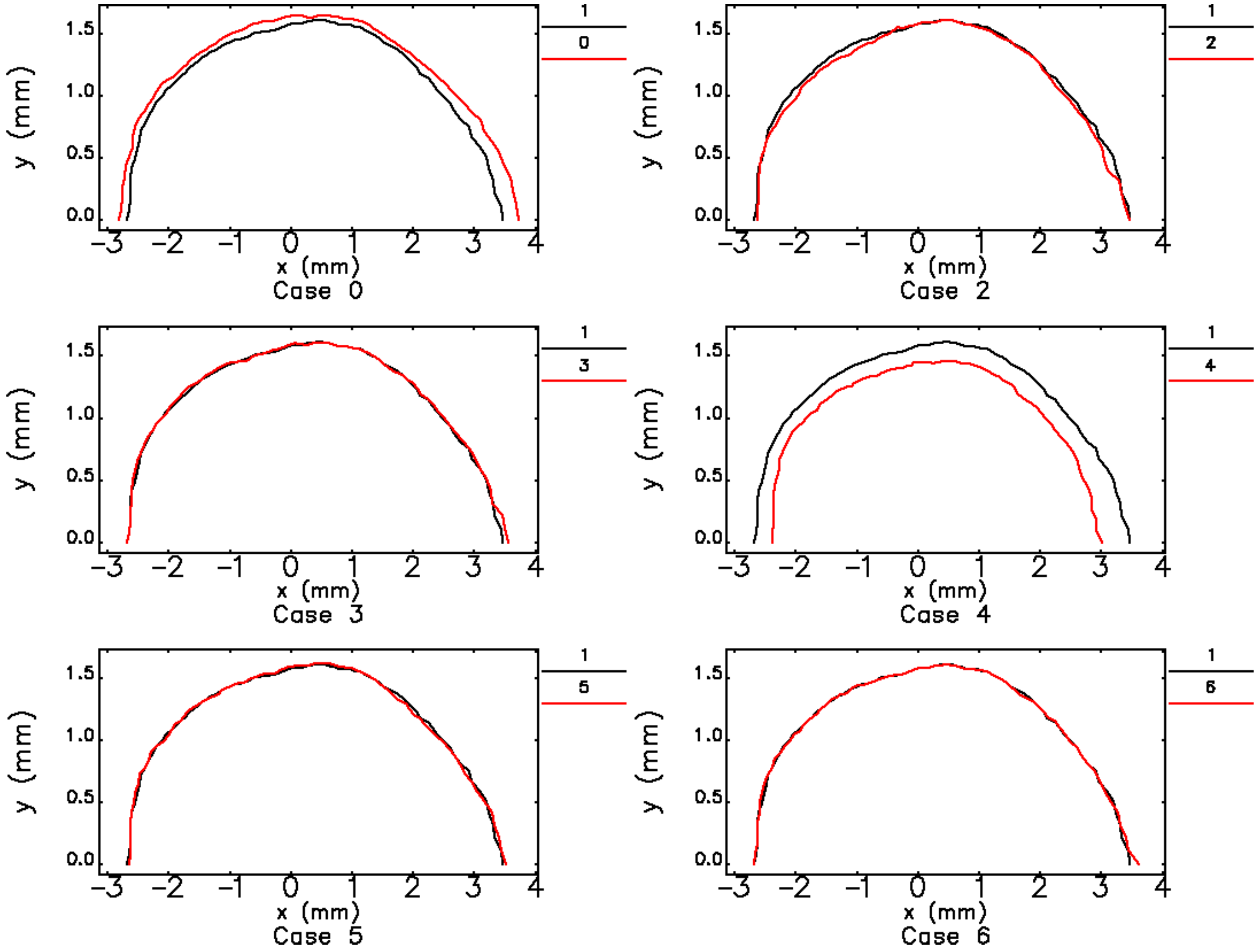
# “Best” MOGA Result





- DA exceeds comfortably exceeds ±2mm 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

# 10th-Percentile DA for Different Multipole Errors

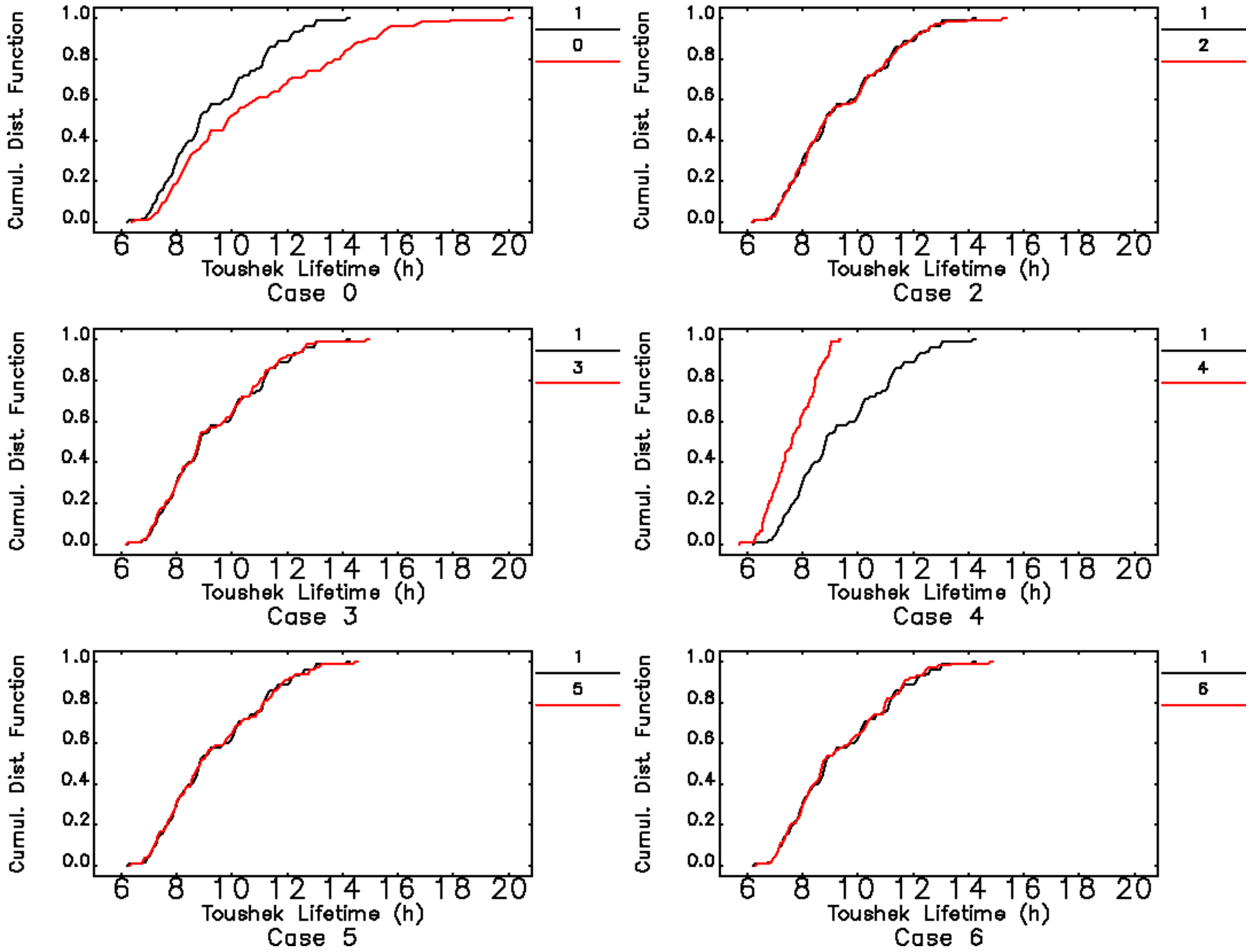


- Case 0: no multipole errors
- Case 1: nominal multipole errors
- Case 2: double dipole systematic errors
- Case 3: double quad systematic errors
- Case 4: double quad random errors
- Case 5: double sext systematic errors
- Case 6 double sext random errors

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

# Touschek Lifetime for Different Multipole Errors

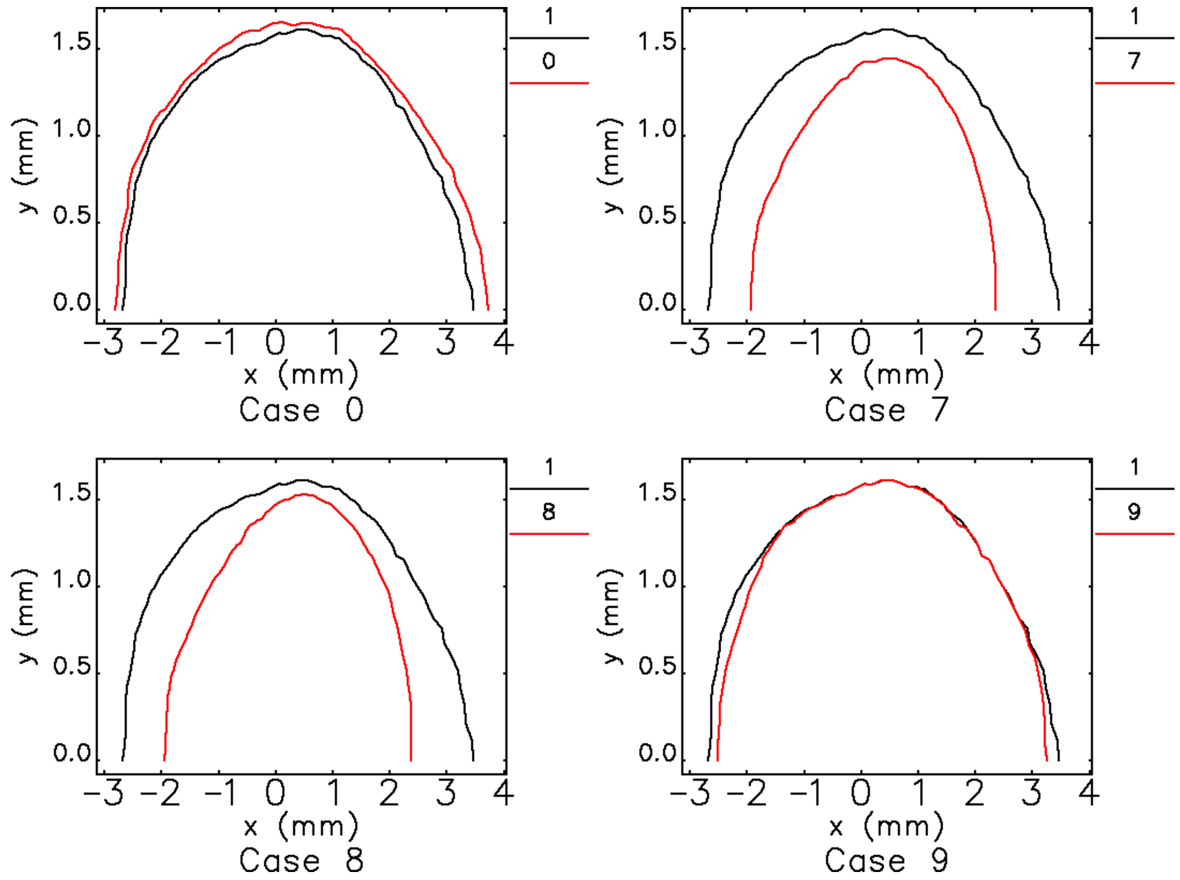
- Comparison with 200 mA, 324 bunches, 50-ps bunch duration, round beams including IBS



- Case 0: no multipole errors
- Case 1: nominal multipole errors
- Case 2: double dipole systematic errors
- Case 3: double quad systematic errors
- Case 4: double quad random errors
- Case 5: double sext systematic errors
- Case 6 double sext random errors

- Conclusion same as from DA
  - Also: Cutting quad random errors will improve lifetime (not shown)

# 10th-Percentile DA for Different ID Apertures



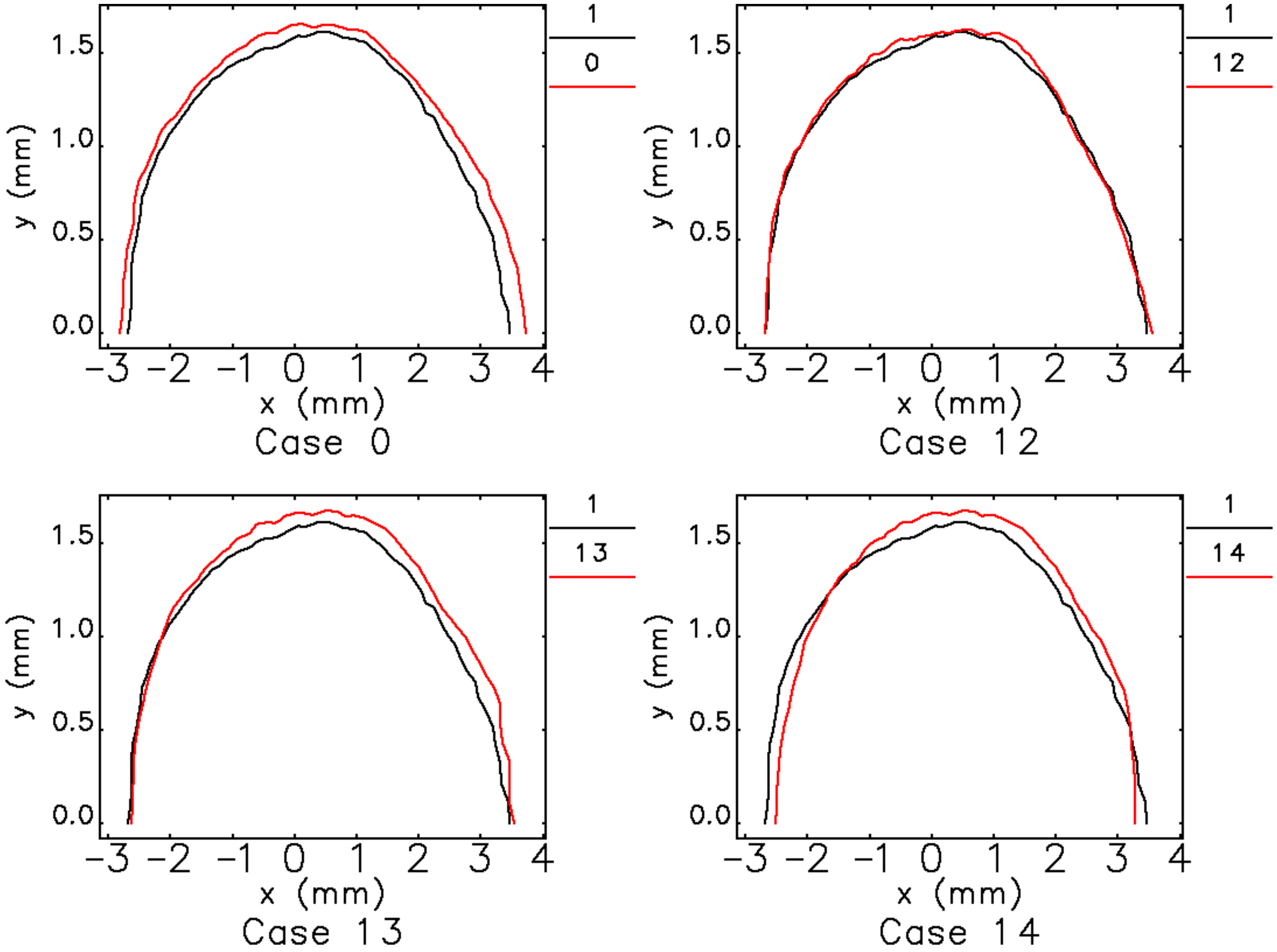
- Case 0: 20mm by 6mm elliptical ID apertures; no multipole errors
- Case 1: add nominal multipole errors
- Case 7: use 6-mm round ID apertures
- Case 8: use 6mm by 6mm, n=6 super-elliptical ID apertures
- Case 9: use 8mm by 6mm, n=6 super-elliptical ID apertures

- Lifetime (not shown) not sensitive to these changes
- Minimum ID aperture is 8mm by 6mm, n=6 super-ellipse

$$\left(\frac{x}{4}\right)^6 + \left(\frac{y}{3}\right)^6 = 1$$

# 10th-Percentile DA for Different IDs

- Added planar IDs with 20, 21, 22, 28, 30, and 36-mm periods; corrected tunes



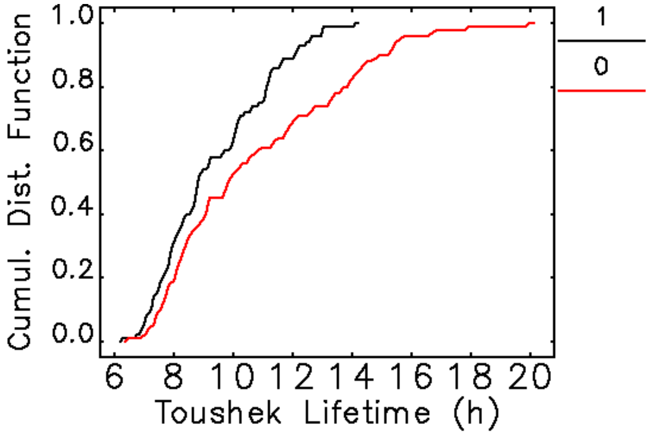
- Case 0: nominal apertures; no multipole errors
- Case 1: add nominal multipole errors
- Case 12: add 72, 2.4-m long horizontally-deflecting IDs
- Case 13: rotate 12 of the IDs into vertical plane
- Case 14: 8mm by 6mm super-elliptical ID apertures

- Conclusion: planar IDs have little effect on DA

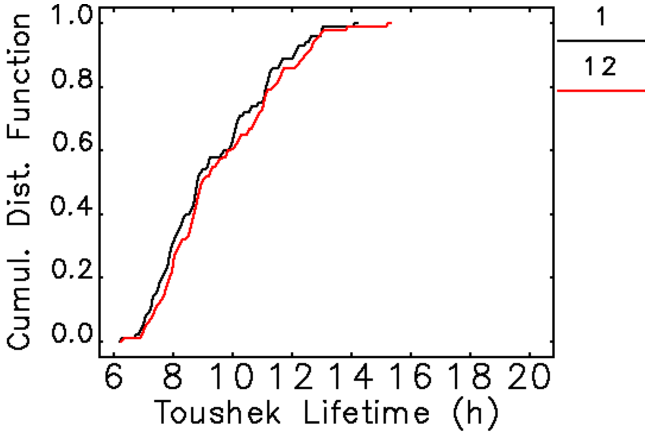
20, 21, 22-mm ID kickmaps courtesy W. Guo, BNL.
28, 30, 36-mm ID kickmaps courtesy A. Xiao, ANL.

# Touschek Lifetime for Different IDs

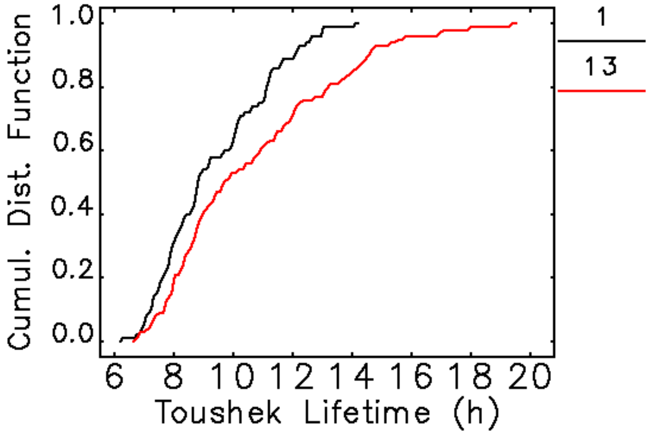
- Added planar IDs with 20, 21, 22, 28, 30, and 36-mm periods; corrected tunes



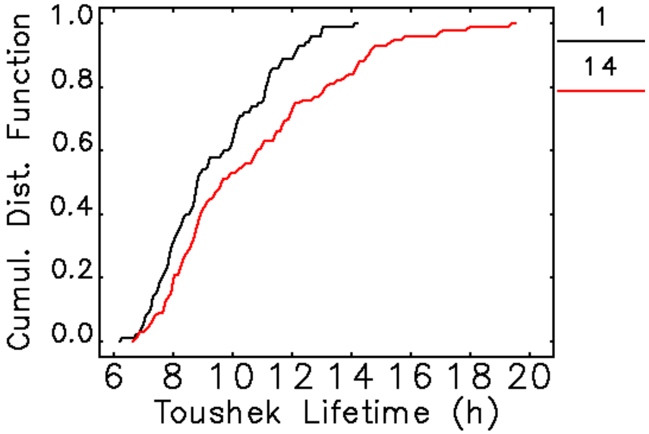
Case 0



Case 12



Case 13



Case 14

- Case 0: nominal apertures; no multipole errors
- Case 1: add nominal multipole errors
- Case 12: add 72, 2.4-m long horizontally-deflecting IDs
- Case 13: rotate 12 of the IDs into vertical plane
- Case 14: 8mm by 6mm super-elliptical ID apertures

- Conclusion: planar IDs appear to help the lifetime significantly
  - Rotated devices particularly helpful

# Application to Present APS Operations

- 7 sextupole families are no longer symmetric about arc midpoint for the high-chromaticity operation
  - 40-fold symmetry for the 40 sectors. Same NL phase space at middle of all straight sections
  - 5 effective degrees of freedom (two are for chromaticity)
  - Several years operation
- With new narrow gap chamber with “possibly” reduced horizontal aperture, may need to manipulate nonlinear phase space in X in one place
  - < 15 mm X-aperture, need “rounder” phase space
  - 18 mm aperture at injection point, need “triangular” point for injected beam.
- Add all individual sextupoles in the two adjacent sectors (2x 7 sextupoles) to
  - 7x2 + 5 = 19 degrees of freedom
  - Repeat optimization for each chromaticity values
    - 21-parameter solutions are different, almost not related
- Set up a few of these during start-up week , but finally didn’t need them as separate injetion issue was fixed