# *Search for Non-Linear Beam Dynamics Causes of Lifetime Reduction at the APS Storage Ring*

# *Or*

# *Search for "Bad" Sextupole*

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# *Introduction*

- Beam lifetime suddenly was reduced by 20%-30% after a shutdown
- Assuming the cause was a bad sextupole magnet, what beam-based tools do we have?
- Over one year, we thought of, developed and tried several things based on the following measurements
  - Tune: tunes dependence on orbits through sextupoles
  - Orbit: Response matrix measurements at different momentum
  - Chromaticity: various sectors of sextupoles turned off
  - Sextupole harmonic: empirical search with sextupole knobs
  - Guidance from tracking simulations
- Some are slow others are fast
- Some are noisy others not
- Some direct, others require much processing
- The best overall was response matrix measurements at different momentum
- Actually we found an inverted-polarity sextupole by requesting a polarity check guided by sextupole optimization solutions

# History

- For a period of a year (Jan 2007-Feb 2008), a sextupole was reversed, which caused a reduction of Touschek lifetime of about 30% for all configurations
- Reduced Touschek lifetime characterized by reduced momentum aperture as measured by rf voltage scan
- During this period we searched for many causes of lifetime degradation using beam
  - Vacuum apertures, impedance measurements (!?!)
  - Lattice symmetry, sextupole symmetry
  - Sextupole gradients
  - Excluded possibility of polarity reversal because it was “impossible” to get miswiring wrong
- Main diversion that confused us:
  - First decrease in lifetime after the Oct 2006 shutdown and another one in Jan 2007. Thus we believed there was a degradation of some sort (apertures? Sextupole coils?)
  - We know now that there were no nonlinear problems in the short Oct 2006-Jan 2007 period.

# More Complications

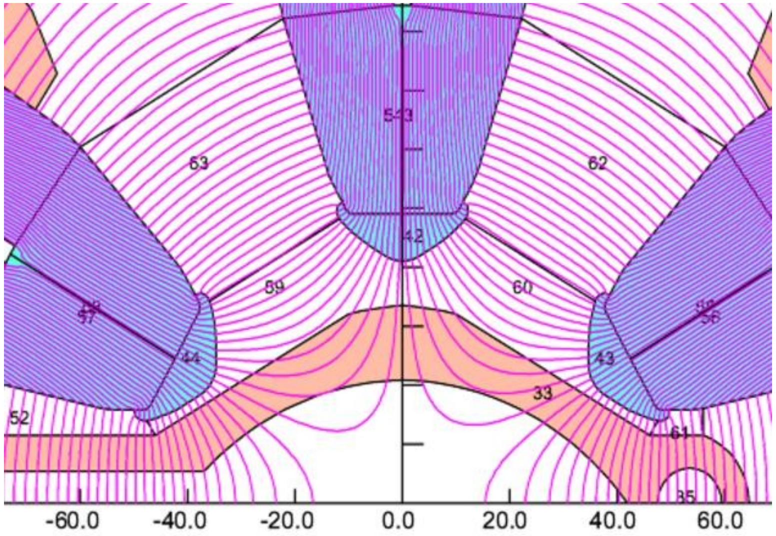
- Frequent operational changes: lattice symmetry, chromaticity of either plane, fractional tune change, bunch patterns and vertical emittance
- Minor girder realignments during shutdowns, beam steering during runs
- Didn't have or keep long-term record of lifetime for a fixed reference lattice
- One family of sextupoles (80) modified in 2006 May shutdown. Suspect problem with modified sextupole.
- New x-ray pinhole system in Oct 2006, which changed vertical emittance values
  - When we set nominal vertical emittance the lifetime decreased. We suspected a mixture of vertical emittance reading change and some real lifetime change

# *Action Plan*

- Assume one or more “bad” sextupole
- Checked sextupole hardware
  - Recent S2-family pole-tip modification
  - Occasional sextupole DC-to-DC converter repairs were not considered a cause of a problem
- Concern with beam-based method: How much does a sextupole gradient have to change before affecting measurable beam dynamics?
- Some measurements that can be compared with simulations
  - Sector-by-sector chromaticity
  - Second-order dispersion
  - Dynamic aperture
  - Momentum aperture
- Eventual visual out-of-tunnel check of polarity after much tracking simulation
- Calculation of lifetime from tracking

# *Sextupole Pole Tip Extension*

- Add extension to the pole tip to effectively reduce the radius by 20%, and increase the strength by 40%




Magnetic modeling by S. Kim

- An initial 2004 study[1] showed that a momentum aperture (i.e. lifetime) improvement could be achieved with higher sextupole gradients in the S2 family given a fixed chromaticity
- S2 family of sextupole magnets were modified in May 2006
- S2 family poles were checked for correct positioning in a 2007 shutdown

[1]Sajaev, ASD/APG/2004-16

# *Beam-Based Methods*

- Sector-by-sector chromaticity change
- Beam bump through sextupole
- Local chromaticity by response matrix fitting
- Second-order dispersion
- Sextupole harmonic knobs
- Guidance from sextupole family optimizations

# Sector-by-Sector Chromaticity (A. Xiao)

- Chromaticity change ($\Delta\xi_x$,$\Delta\xi_y$) due to malfunction from one sextupole. It seems we may only be able to detect a 50% relative error (depends on sextupole)

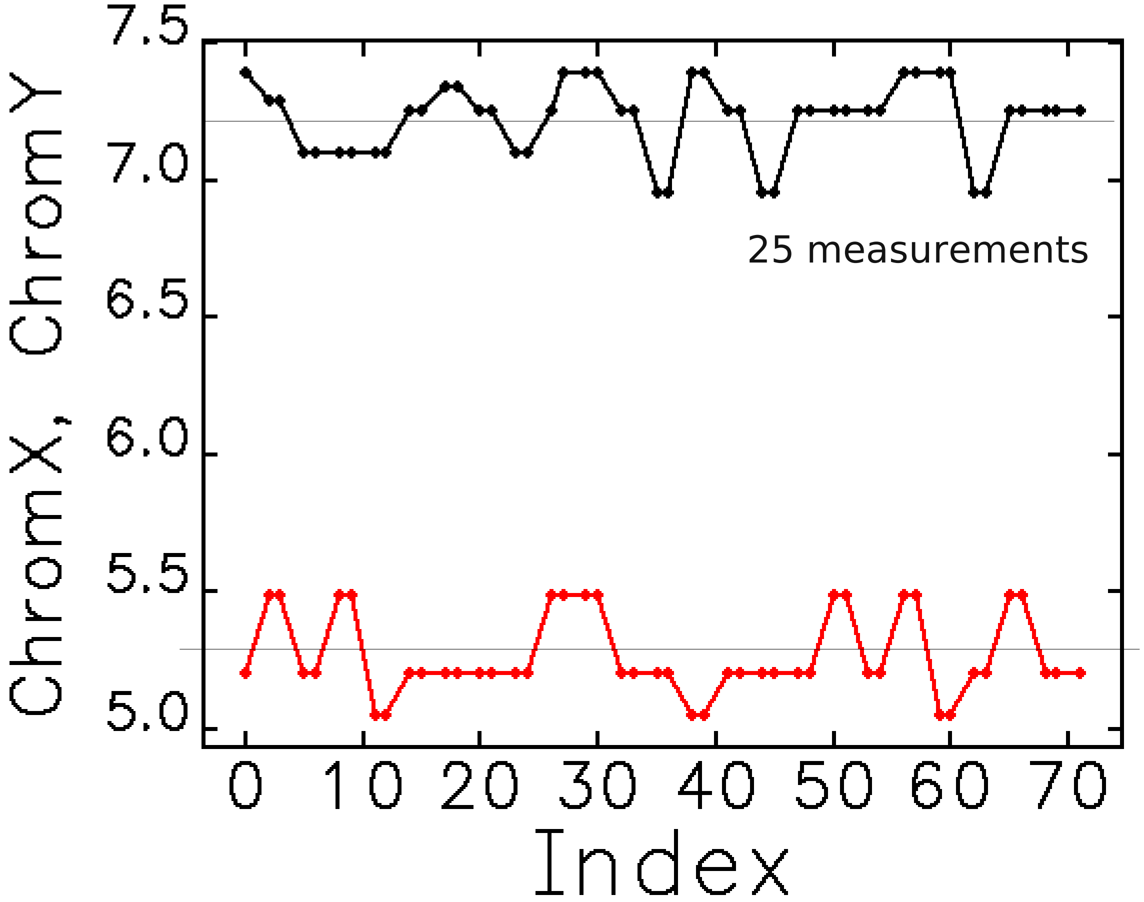
| | 100% Error | | 10% Error | |
|---|---|---|---|---|
| | $\Delta\xi_x$ | $\Delta\xi_y$ | $\Delta\xi_x$ | $\Delta\xi_y$ |
| S1A:S1 | 0.5 | -0.49 | 0.05 | -0.05 |
| S1A:S2 | -0.13 | 0.72 | -0.01 | 0.07 |
| S1A:S3 | -0.15 | 0.9 | -0.02 | 0.09 |
| S1A:S4 | 1.7 | -1 | 0.17 | -0.01 |

Sextupole type that was actually reversed. Effect was 0.3 in x and -1.8 in y.

- Check sextupole contribution to chromaticity sector by sector
- Method:
  1) Measure chromaticity with nominal conditions
  2) Ramp down sextupoles for one sector
  3) Remeasure chromaticity
  4) Turn back on sextupoles with no standardization
  5) Repeat for other sectors

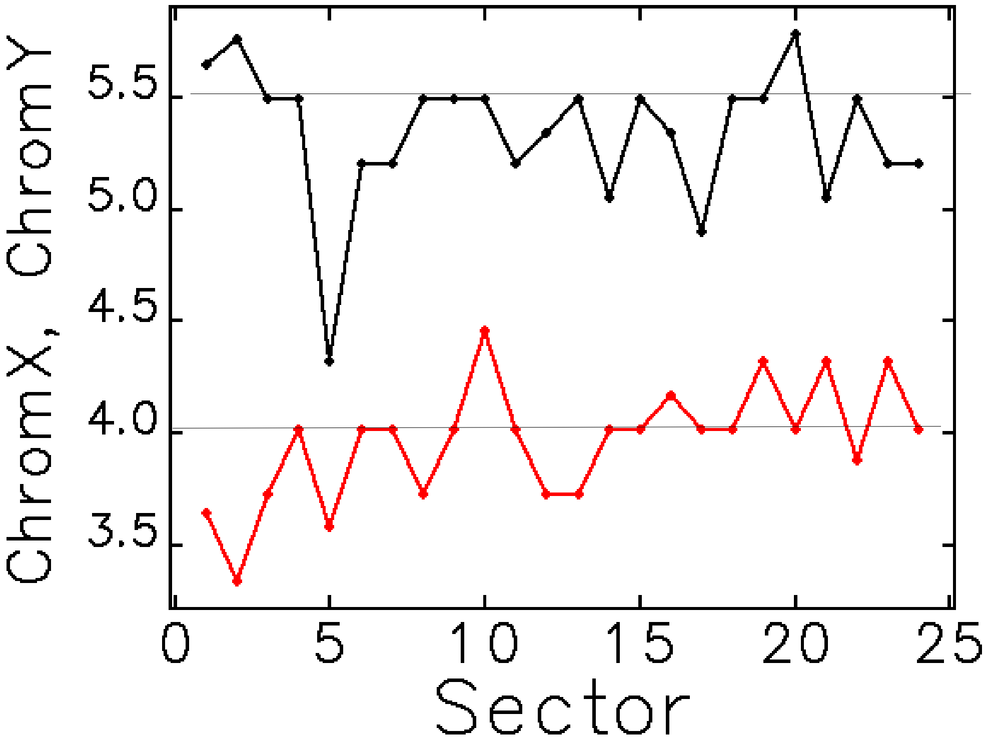
# Sector-by-Sector Chromaticity

- Measurement Accuracy: Chromaticity reading before each sector of sextupoles are turned off, about 0.25 units.



# *Sector-by-Sector Chromaticity*

- Result for 24 sectors
- The scan didn't cover the problem area of sector 27, where the reversed sextupole was found the following day
- Sectors 2, 5 and 10 appear suspicious, but turned out not to have problems
- Method slow, moderately accurate



# Beam Bump Method (Emery, Sajaev)

- Uses tune measurements to determine whether a horizontal steering through a sextupole result in a predicted tune shift
- Four tune measurements (use one measurement plane, say x)
  1) Nominal steering, nominal sextupole strength, $\nu_1$
  2) Create Bump, nominal sextupoles, $\nu_2$
  3) Nominal steering, sextupole ramped down, $\nu_3$
  4) Same bump, sextupole ramped down, $\nu_4$
- Bump may contain more than one sextupole that is not varied. The effect of sextupole is removed from subtracting the tunes. Also we need to make sure beam energy is not changed by bump.
- Effect is

$$(\nu_2-\nu_1)-(\nu_4-\nu_3)=\frac{\beta_x}{4\pi}\Delta x\,\Delta(ml)$$

# Beam Bump Method (Emery, Sajaev)

- Bump can be replaced with global orbit
- Processing can include opposite-bump data
- Method slow, potentially accurate
  - Remnant field is not taken into account however
- Only did a handful of sextupoles
- We couldn't understand the discrepancies with prediction with the sextupoles known to be good

```
K2_1 - from x tune and +1mm bump
K2_2 - from x tune and -1mm bump
K2_3 - from y tune and +1mm bump
K2_4 - from y tune and -1mm bump
```

| | K2_1 | K2_2 | K2_3 | K2_4 | K2_model |
|---|---|---|---|---|---|
| S1A:S1 | 6.9 | 6.7 | 7.0 | 6.9 | 10.1 |
| S1A:S2 | -12.4 | -14.4 | -15.0 | -15.5 | -22.1 |
| S1B:S2 | -20.2 | -21.8 | -18.8 | -18.9 | -22.1 |
| S1B:S1 | 9.0 | 9.2 | 8.5 | 8.7 | 10.1 |
| S40B:S2 | 18.5 | -17.7 | -18.5 | -18.0 | -22.1 |
| S40B:S1 | 8.3 | 8.1 | 8.1 | 8.5 | 10.1 |

# Local Chromaticity Measurement (Sajaev)

- Local chromaticity is a series of positive and negative pulse-like functions along the circumference, i.e. $(\beta/4\pi)(k-m\eta)$, whose average over a short distance can be determined through the phase advance differences
- We are looking for variations in the $m\eta$ term
- Method (inspired by LEP measurement with bpm phases 1996):
  - For several rf frequencies (three), measure response matrix
  - Obtain from three models the phase advance along circumference
  - Fit $\phi_{x,y}(s)$ vs $\delta$, whose slope $d\phi_{x,y}(s)/d\delta$ gives cumulative chromaticity (chromatic phase advance)
    - Slope of $\phi_{x,y}(s=C)$ vs $\Delta p/p$ is the chromaticity
  - Detect perturbation in local chromaticity by plotting

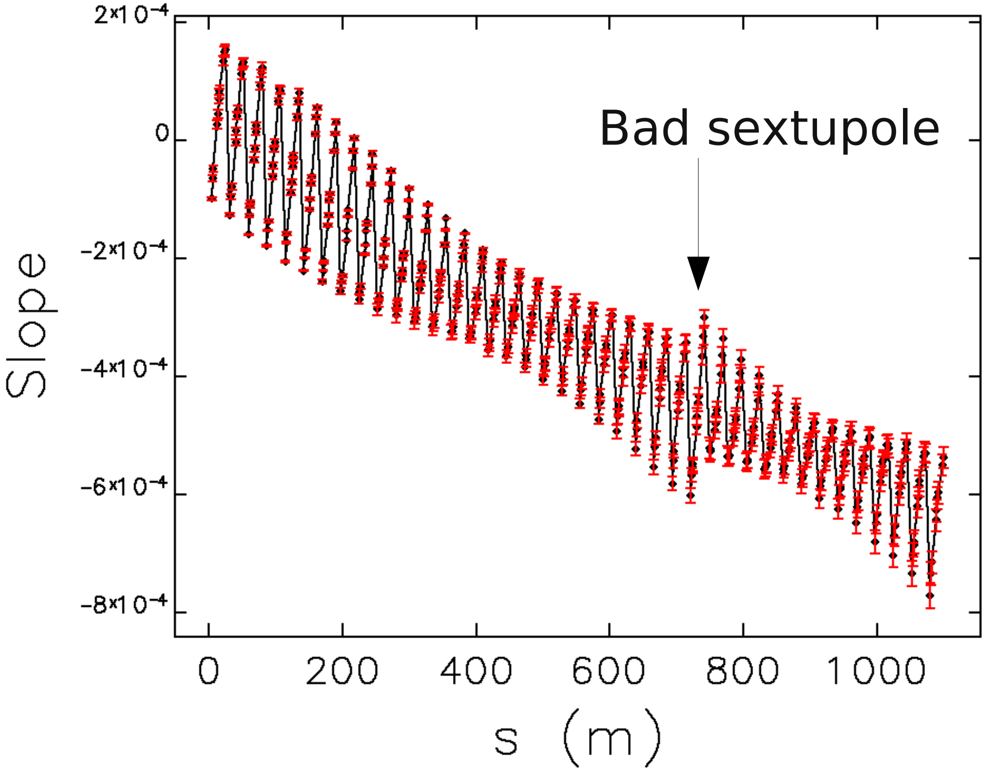
    $d\phi_{x,y}(s)/d\delta - d\phi_{x,y}(s-L)/d\delta$

    where L is the optics period length, or some other short distance

## *Local Chromaticity Measurement*

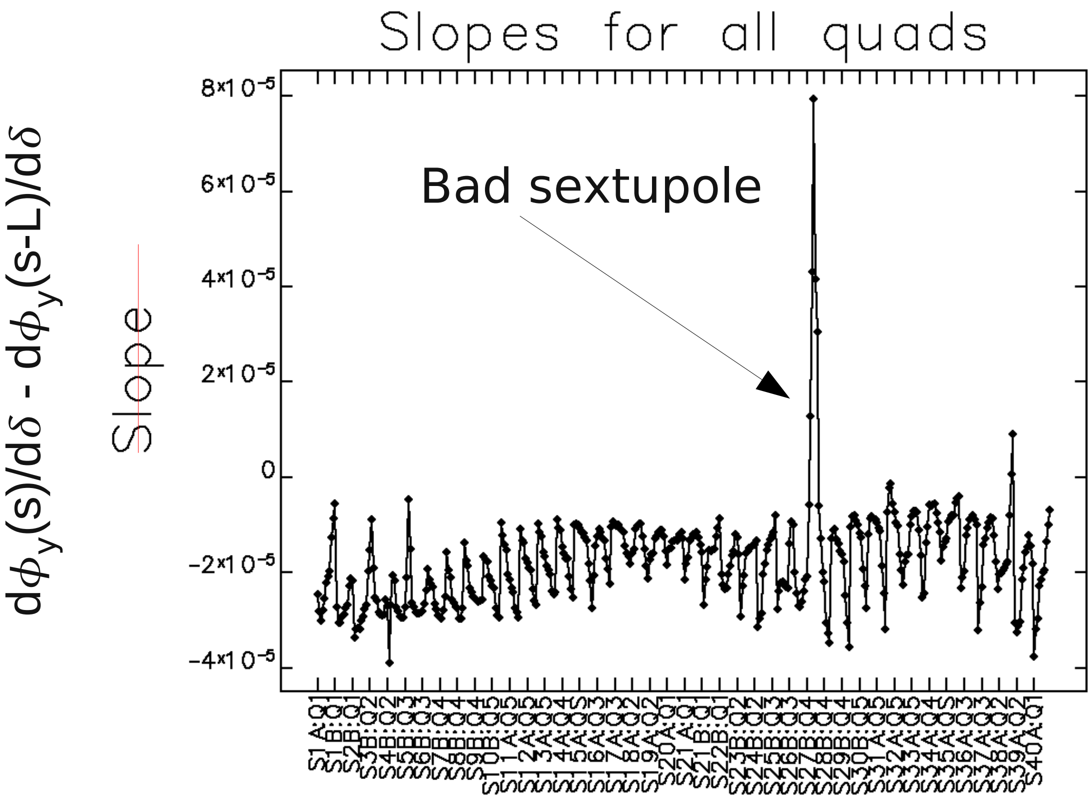
- $d\phi_y(s)/d\delta$
- The data for $d\phi_x(s)/d\delta$ shows less variation because the bad sextupole actually didn't perturb the x plane that much
- Data taken Nov 2007, but not analyzed until after the problem was discovered and corrected three months later

- Fast and accurate
- Requires much post-processing
- Method can't take credit for solving our problem this time, but can be used in future



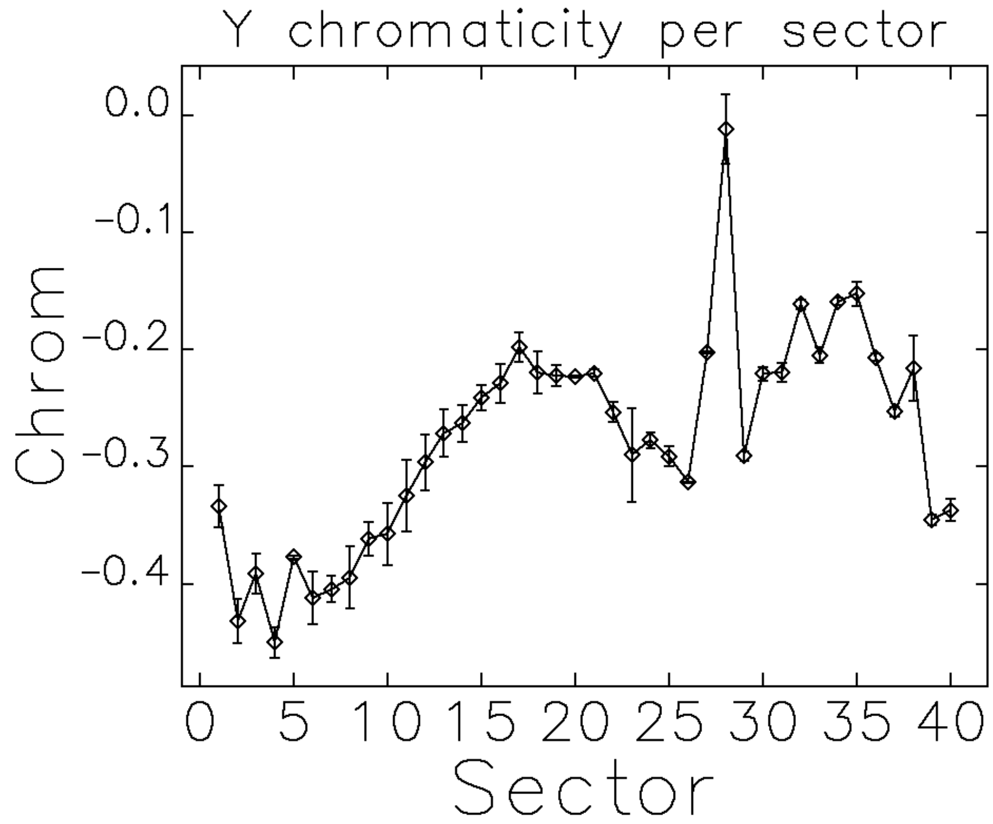
# *Local Chromaticity Measurement*

- $d\phi_y(s)/d\delta$ - $d\phi_y(s\text{-}L)/d\delta$ at quadrupoles, where L is sector length, for a better detection of perturbation
- From periodicity L, in an ideal lattice the quantity would be constant



# *Local Chromaticity Measurement*

- Derived sector-by-sector chromaticity. Expect a constant line with a spike at sector 27.
- Note the smooth variation of chromaticity outside of sector 27



# *Second-Order Dispersion (Sajaev)*

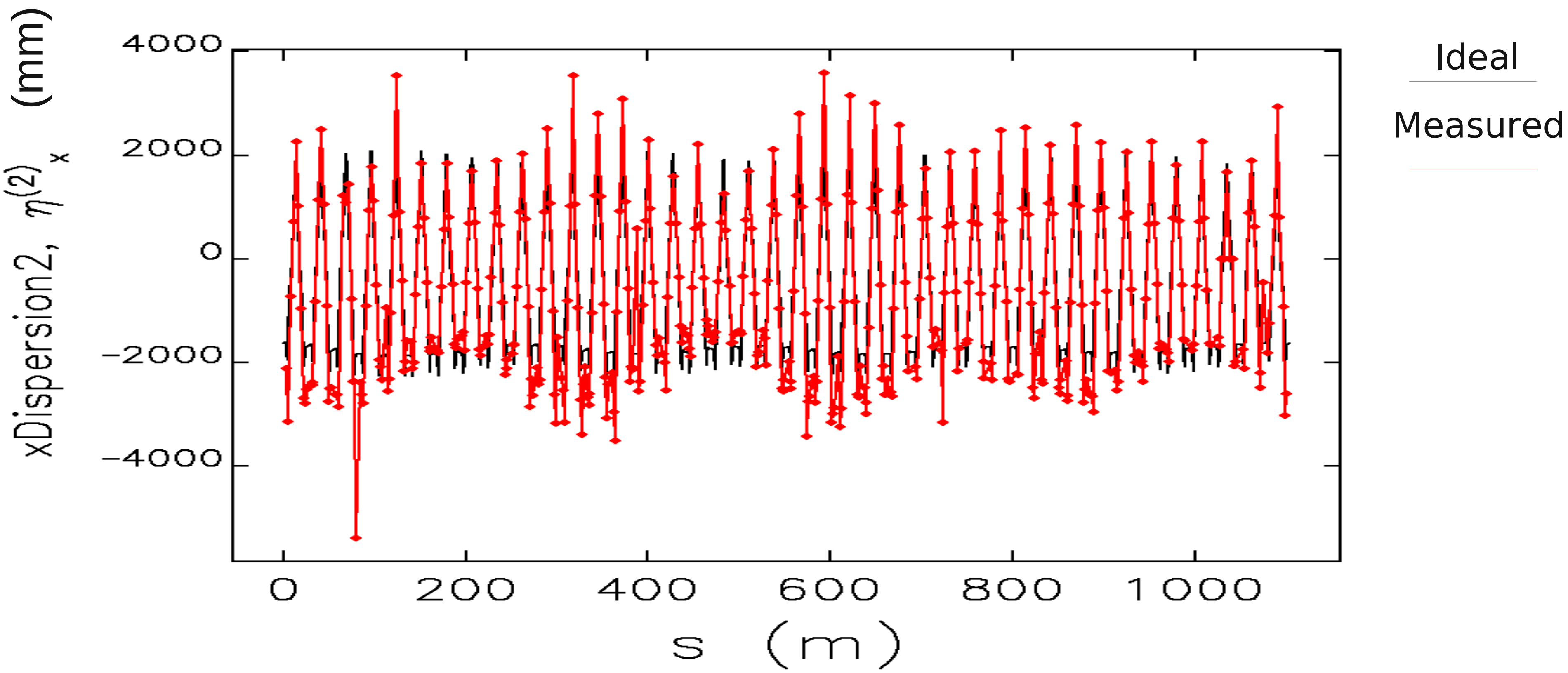
- From H. Wiedemann Particle Accelerator Physics II, p.106,

$$\eta_1''-k\eta_1=-h+\frac{1}{2}m\eta_0^2+(h^3+2hk)\eta_0^2+\frac{1}{2}h\eta_0'^2+h\eta_0\eta'_0+(2h^2+k)\eta_0$$

- Sextupoles appear in only one driving term, the others are mostly small
- A measurement of second-order dispersion $\eta_1$ of a sextupole problem would reveal an oscillation superimposed on a periodic function (see next figure)
  - Assumes that the first order dispersion is well corrected in the first place
- Calculation of optics in an ideal lattice with a reversed sextupole shows a small signal in $\eta_1$ (see later figure)
  - May be difficult to see in actual measurements because there are many non-periodic driving terms from first-order dispersion $\eta_0$
- Very fast, but may be too noisy

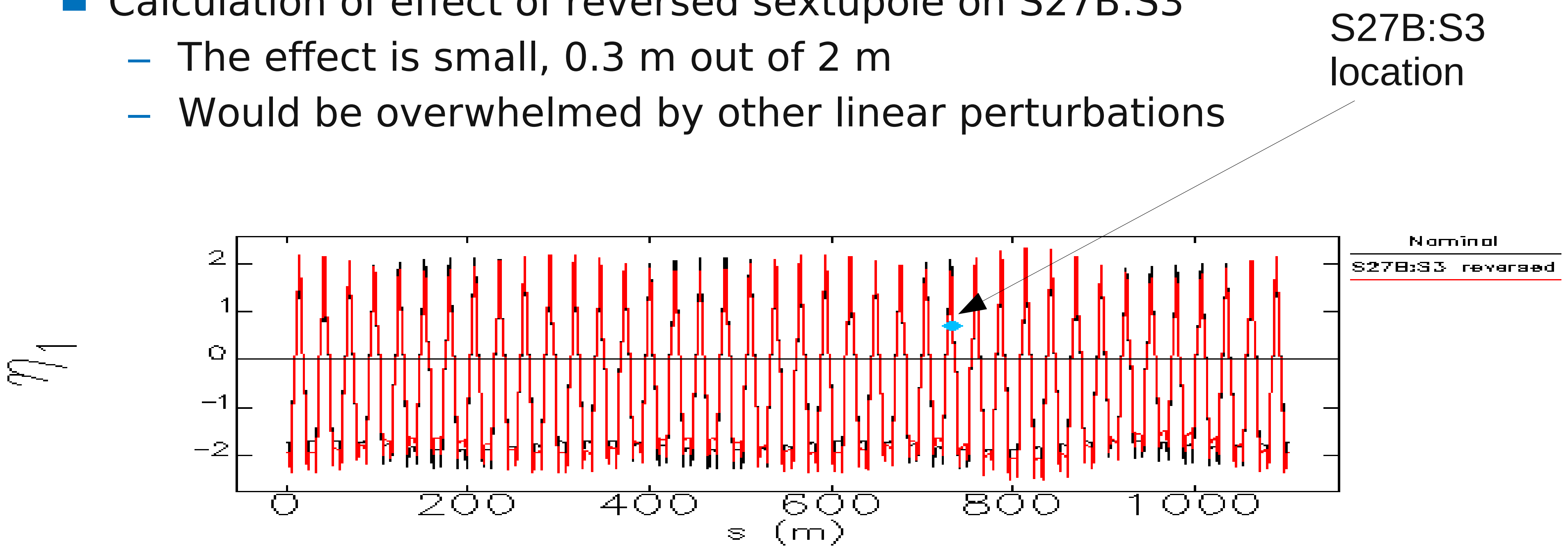
# Second-Order Dispersion

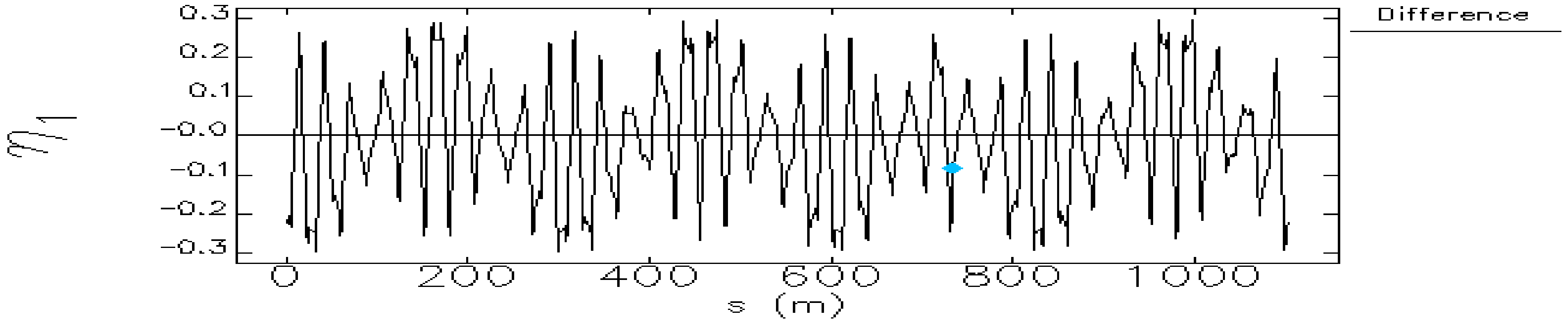
- Actual measured second-order dispersion (in mm) during a time when sextupole was reversed



# Second-Order Dispersion

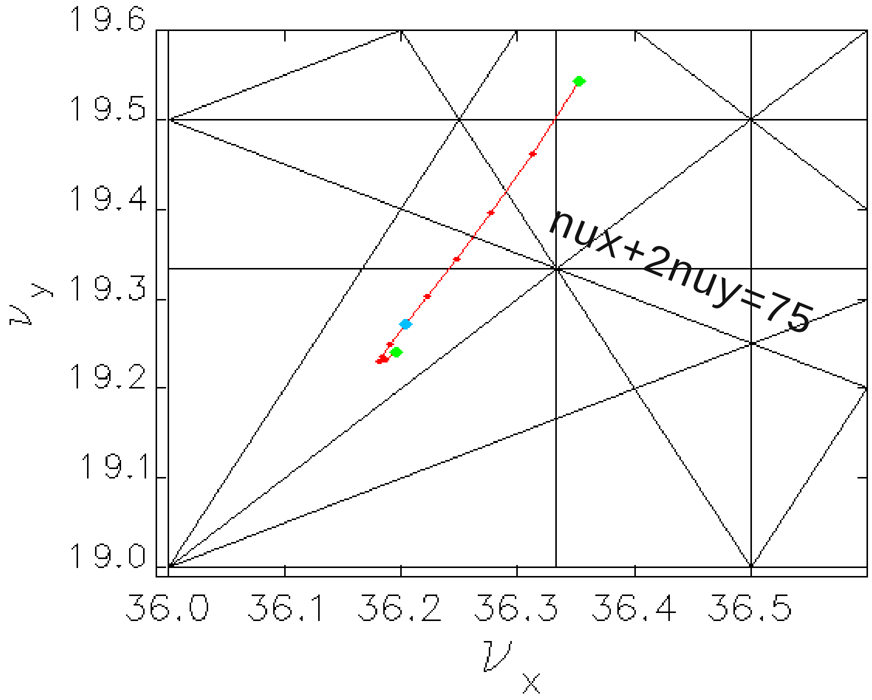
- Calculation of effect of reversed sextupole on S27B:S3
  - The effect is small, 0.3 m out of 2 m
  - Would be overwhelmed by other linear perturbations



# Sextupole Harmonic Application

- Tune diagram shows a crossing of a $\nu_x + 2\nu_y$ line (figure not available). Possibly the lack of symmetry enhances that line.




nux 36.21
nuy 19.27
x-chrom 4.0
y-chrom 6.5
dp/p -2% - 2%

# Sextupole Harmonic Application

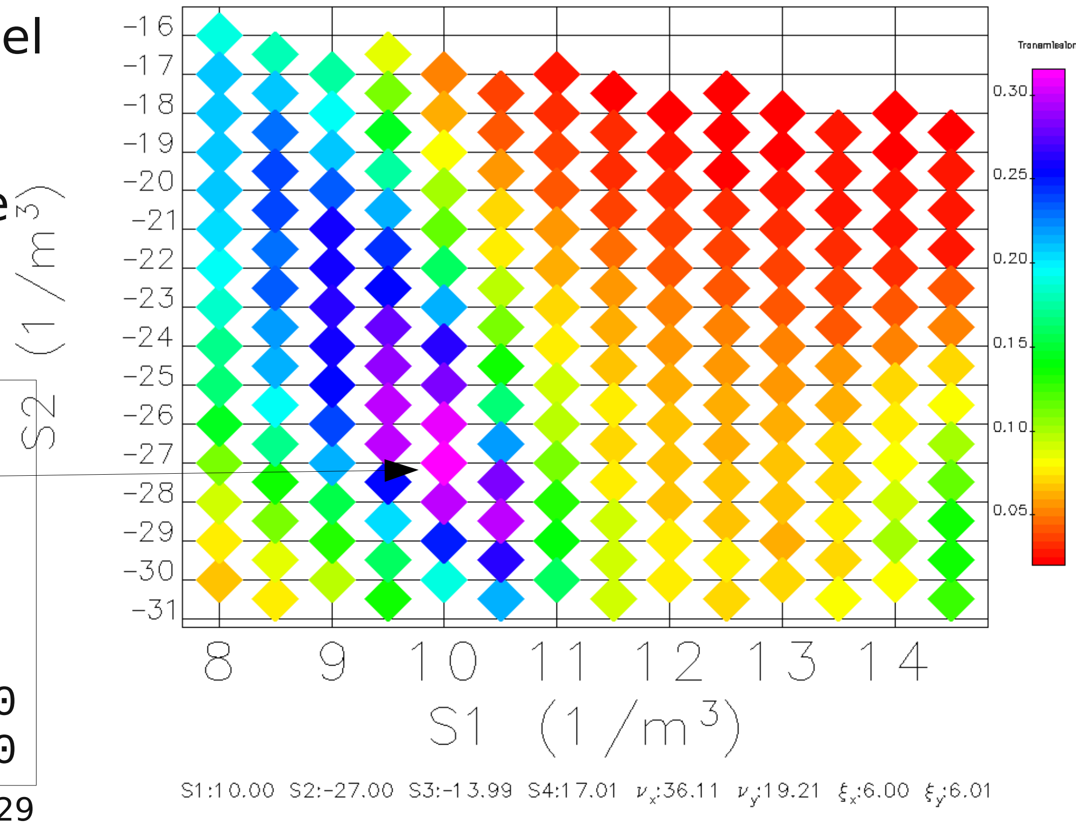
- Apply a sextupole harmonic to lattice to recover some symmetry
  - ESRF 95PAC paper reports that is has corrected DA with correction of harmonics of sextupoles
- Applying a $\nu_x+2\nu_y = 75$ harmonic to a special non-symmetric lattice increased the lifetime of a beam from 250 to 340 minutes
  - Momentum aperture was not increased !?!
  - Note the unknown bad sextupole was included in the non-symmetric lattice study
- Harmonic knob had much less effect on symmetric lattice with bad sextupole
- Could not reproduce this correction in simulation of a lattice with symmetry broken by turned-off sextupole
- Though this fast method doesn't identify bad sextupoles, it has some potential in recovering some of the lifetime loss.

# Sextupole Family Optimization (Borland)

- APS has 4 families, so there are two free parameters for optimizing DA, MA or a mixture of both
  - Applicable for symmetric lattice
- Difficult to do empirical search

- Solutions found in simulation using linux cluster and parallel `elegant`: Optimize the transmission of a group of particles with large 6D phase space*: +/- 10 mm in x +/- 2 mm in y, +/- 2.5% in $\delta$

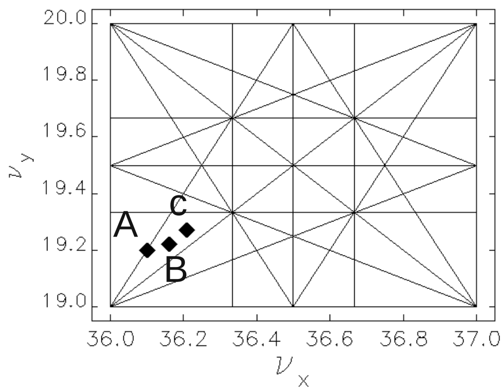
```
S1: 10.0
S2:-27.0
S3:-14.0
S4: 17.0
nux: 36.11
nuy: 17.01
x-chrom: 6.0
y-chrom: 6.0
```



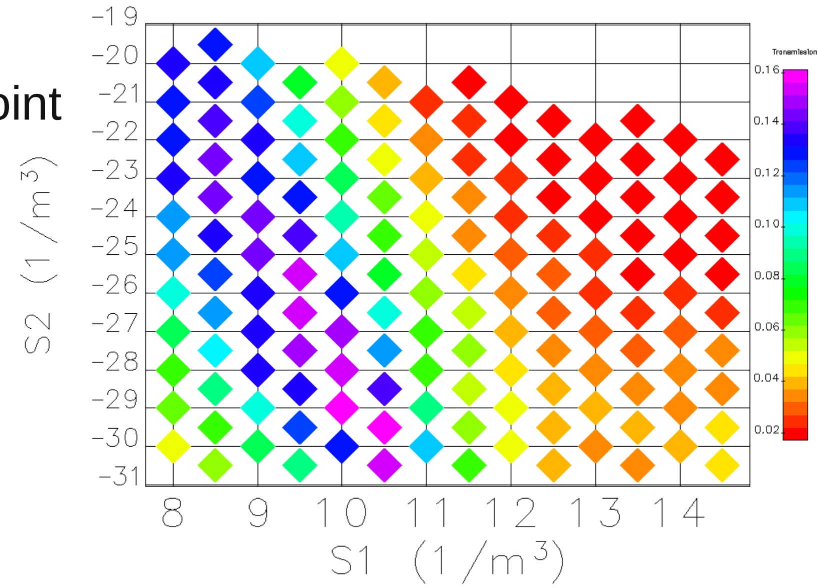

*Borland, OAG-TM-2007-040, OAG-TN-2007-029

# Sextupole Optimization

Example of solution as a function of working point

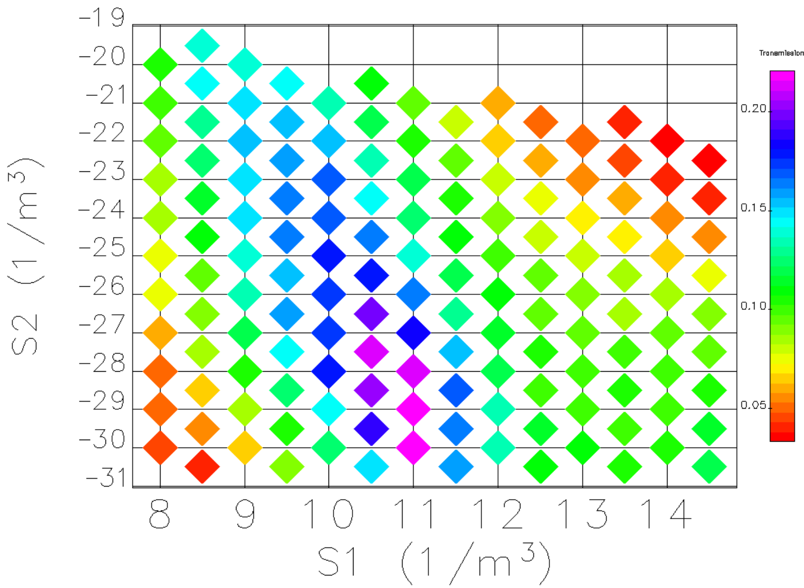



A



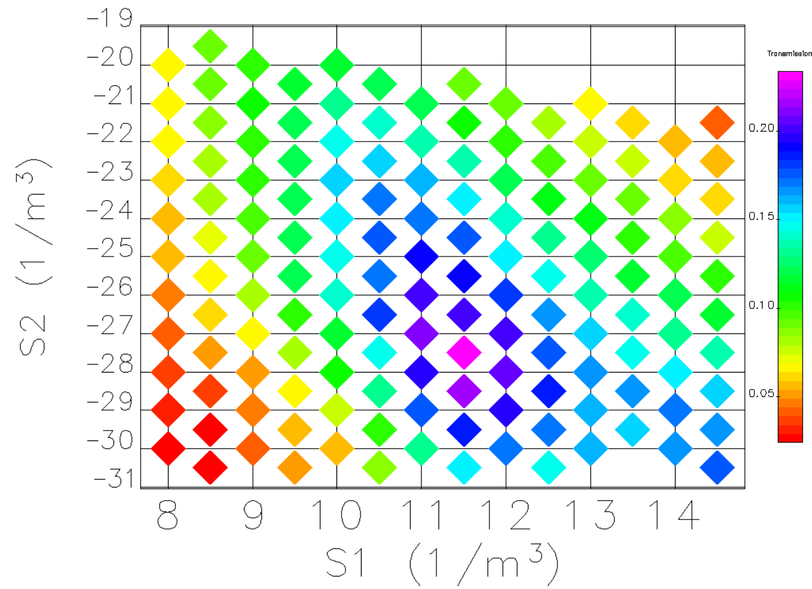

S1:10.50 S2:−29.50 S3:−14.64 S4:17.98 $\nu_x$:36.10 $\nu_y$:19.20 $\xi_x$:11.00 $\xi_y$:11.01

B




S1:11.00 S2:−30.00 S3:−14.59 S4:17.57 $\nu_x$:36.16 $\nu_y$:19.22 $\xi_x$:11.00 $\xi_y$:11.01

C




S1:11.50 S2:−27.50 S3:−16.27 S4:17.04 $\nu_x$:36.21 $\nu_y$:19.27 $\xi_x$:11.00 $\xi_y$:11.01

# Sextupole Family Optimization

- Optimized with large errors for chrom=(+11,+11)
  - Solution has high S1 values (~14)
  - Improved lifetime over the previously saved configurations
  - Eventually noticed to be a problem for high charge bunch 250 ns away from target (special hybrid mode)
- Optimized with small errors for chrom=(+11,+11)
  - Solution has lower S1 values (~11)
    - Note the optimum depends on magnitude of errors
  - Applied solution was worse for injection and momentum aperture !?!
- (We don't have the contour plot for different error magnitudes)

# Sextupole Family Optimization

- Note that:
  1) Different solutions from simulations are obtained for different magnitude of errors
  2) Sextupole solution from high errors give better result in actual ring; we concluded there is a strong error in the ring.
- At this point we finally checked the polarities of the sextupoles with some easy out-of-tunnel visual check of wiring, and we found a sextupole with reversed polarity.

# Conclusion

- Much work was done to identify bad sextupoles. Also much work done during this one-year period in maximizing lifetime (with DA) with sextupole optimization, and injection trajectory optimization.
- Response matrix method would have given accurate enough result for partial short of a sextupole magnet
- Table of method evaluations:

| | | | |
|---|---|---|---|
| 2nd order dispersion | yes | no | need processing |
| Response matrix | yes | yes | need processing |
| Beam bump | no | ? | yes |
| sector chromaticity | no | yes? | yes |
| Sextupole harmonic knob | yes | doesn't identify source | not applicable |

- Not known at the time is Tomas's Hamiltonian-term analysis from bpm histories