ATF2 Simulation Studies

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SLAC Accelerator Physics & Engineering

Overview

- **Tuning procedure for the final focus system of ATF2.**
- **MAPCLASS optimised lattice including all measured magnet multipole components**
  - No sextupole rolls used
- **Lucretia electron beam modeling code (Matlab)**
  - Heterogenous parallel compute environment for Monte Carlo analysis of errors in non-linear optics.

Online Tuning Algorithm Development

1. **Specify list of errors**
    1. Generate a database which characterises every unknown aspect of the accelerator
2. **Generate 100 versions of machine lattice**
    1. Each lattice has a different set of errors generated from error table.
    2. Typically, each error condition is generated from a gaussian distribution.
3. **Simulate initial steering/BBA/coupling,dispersion correction etc for each lattice seed.**
4. **Calculate list of aberrations present at IP (up to 3rd order required).**
5. **Make a knob to correct most common aberration from 100 seeds being simulated.**
6. **Iterate 4&5, each iteration generate a knob which is orthogonal with other knobs generated previously. Repeat until no further improvement seen in IP spot size on average across simulated seeds.**

Generation of Linear IP Tuning Knobs

- **Calculate linear response of desired set of aberrations at IP to desired set of potential knob coefficients from particle tracking.**
- **Form linear response matrix equation:**
  - M.k = a
    - k = vector of knob coefficients
    - a = vector of IP aberration gradients
    - M = response matrix
- **Use Matlab "lscov" function to solve linear least-squares problem:**
  - $(a-M.k)'.diag(1/w^2).(a-M.k)$
  - Use weight vector w to control solution to give approximately orthonormal knobs.

Required IP Tuning Knobs Generated

- **Main Knobs generated to control dominant aberration sources at IP:**
  - Vertical waist
  - Vertical dispersion
  - <x′y> coupling
  - T326
  - T322
  - T324 (NEW for these optics)
- **Additional aberrations included in constraint vector:**
  - Horizontal waist
  - Horizontal dispersion
  - U3122 (NOT for these optics)

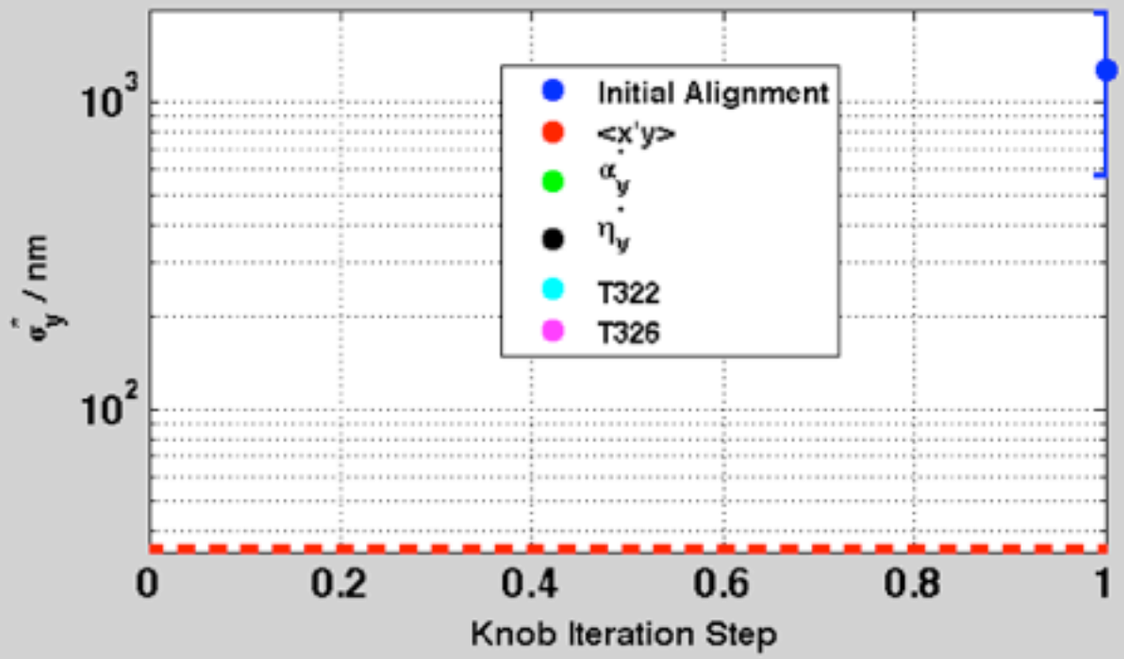
Simulated Tuning Process

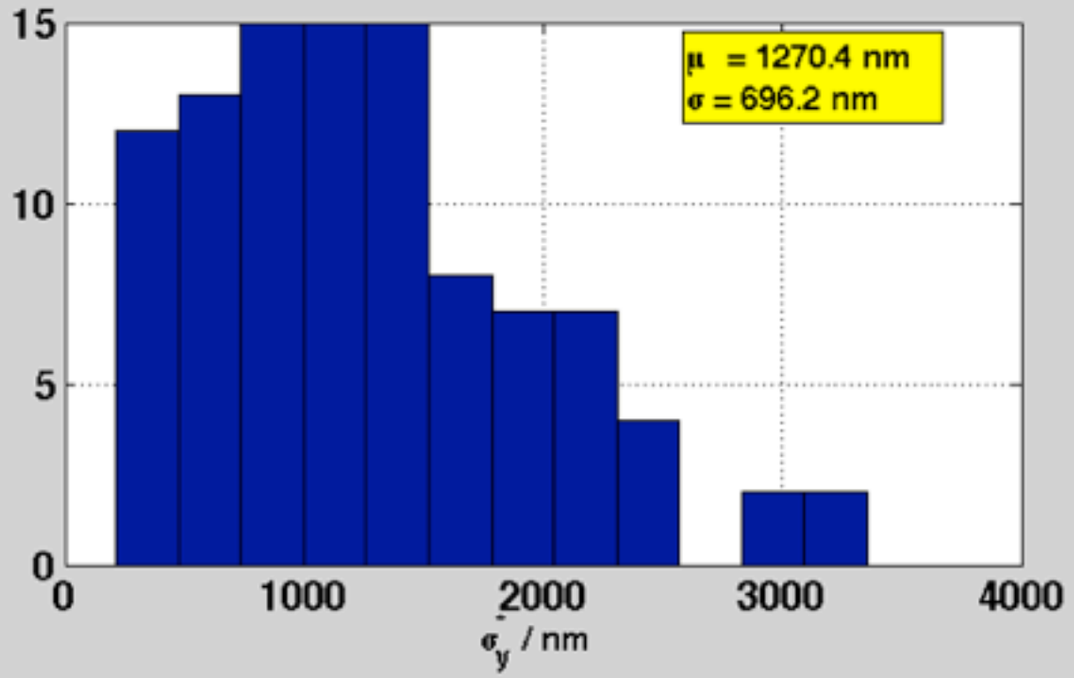
- Apply expected error distributions.
- Use EXT correctors + BPMs (EXT FB) to get orbit through EXT.
- Use FFS FB to get beam through FFS.
- Correct Dy/Dy' in EXT using skew-quad sum knob.
- Correct coupling in EXT using coupling correction system.
- Use FFS FB for launch into FFS.
- FFS Quad BPM alignment using quad shunting with movers.
- FFS Quad mover-based BBA.
- FFS Sext BPM alignment using Sext movers and IP BPM.
- Generate and apply IP tuning knobs.

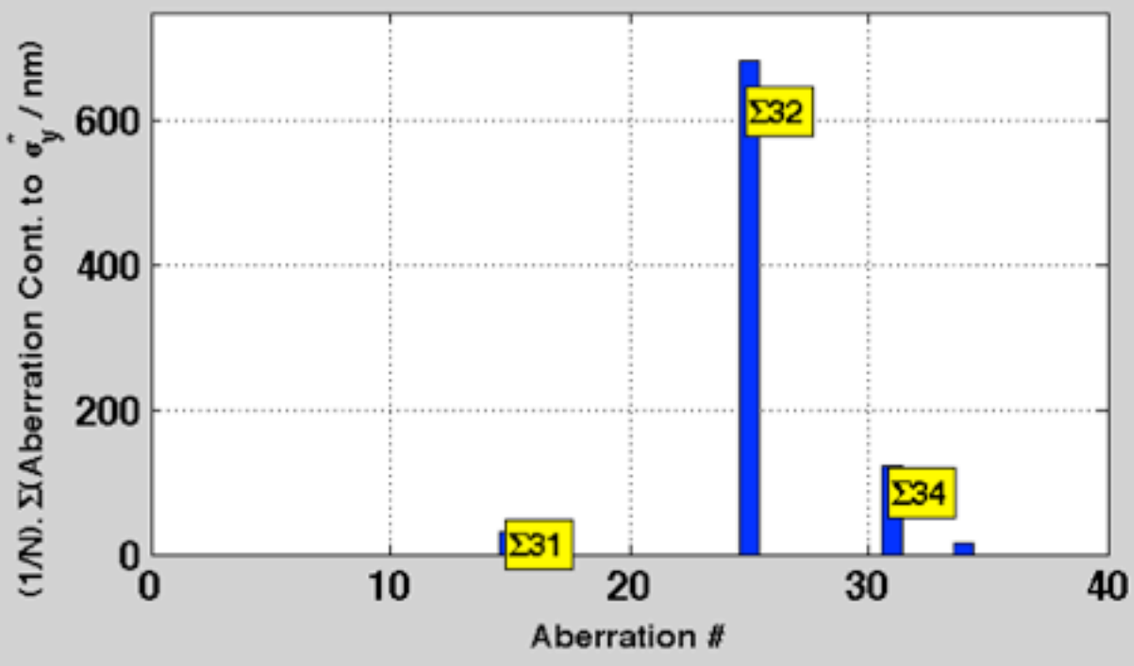
Considered Error Sources

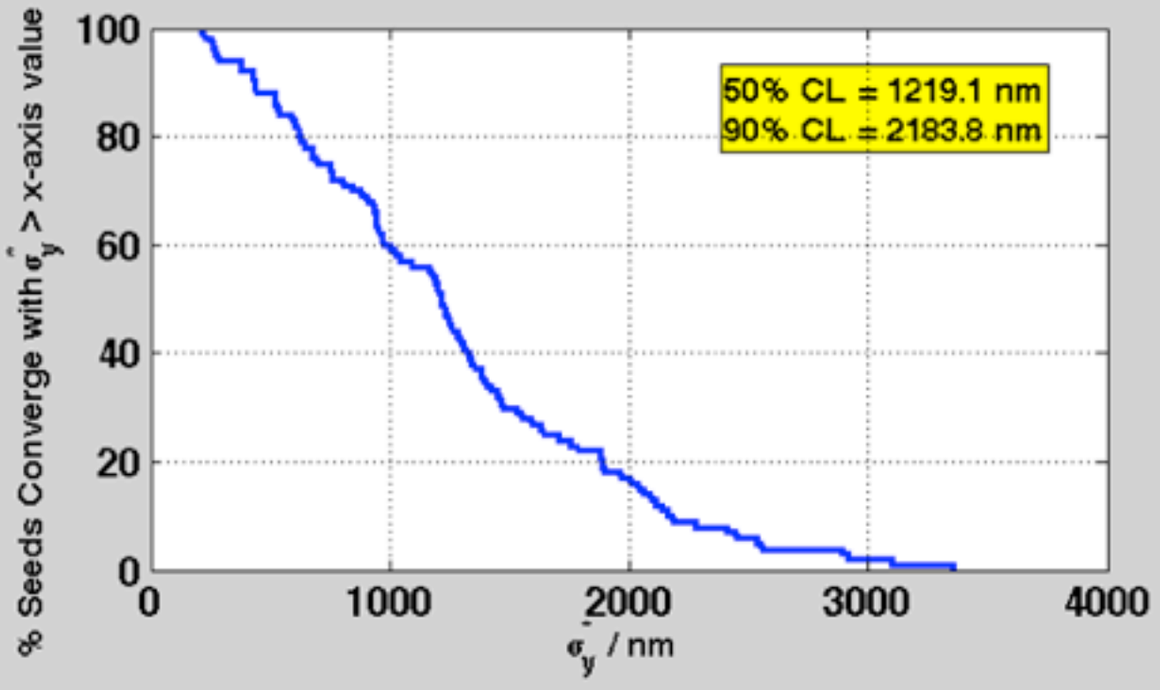
Error Parameter	Error magnitude
x/y/z Post-Survey	200 um
Roll Post-Survey	300 urad
BPM - Magnet field center alignment (initial install) (x & y)	30 um
BPM - Magnet alignment (post-BBA, if BBA not simulated) (x & y)	10 um
Relative Magnetic field strength (dB/B) (systematic)	1e-4
Relative Magnetic field strength (dB/B) (random)	1e-3
Magnet mover step-size (x & y / roll)	300 nm / 600 nrad
Magnet mover LVDT-based trim tolerance (x & y / roll)	1 um / 2 urad
C/S - band BPM nominal resolution (x & y)	100 nm
Stripline BPM nominal resolution (x & y)	10 um
IP BPM nominal resolution (x & y)	2 nm
IP Carbon wirescanner vertical beam size resolution	2 um
IP BSM (Shintake Monitor) vertical beam size resolution	use attached data
EXT magnet power-supply resolution	11-bit
FFS magnet power-suppy resolution	20-bit
Pulse - pulse random magnetic component jitter	10 nm
Pulse - pulse relative energy jitter (dE/E)	1e-4
Pulse - pulse ring extraction jitter (x, x', y, y')	0.1 sigma
Corrector magnet pulse-pulse relative field jitter	1e-4

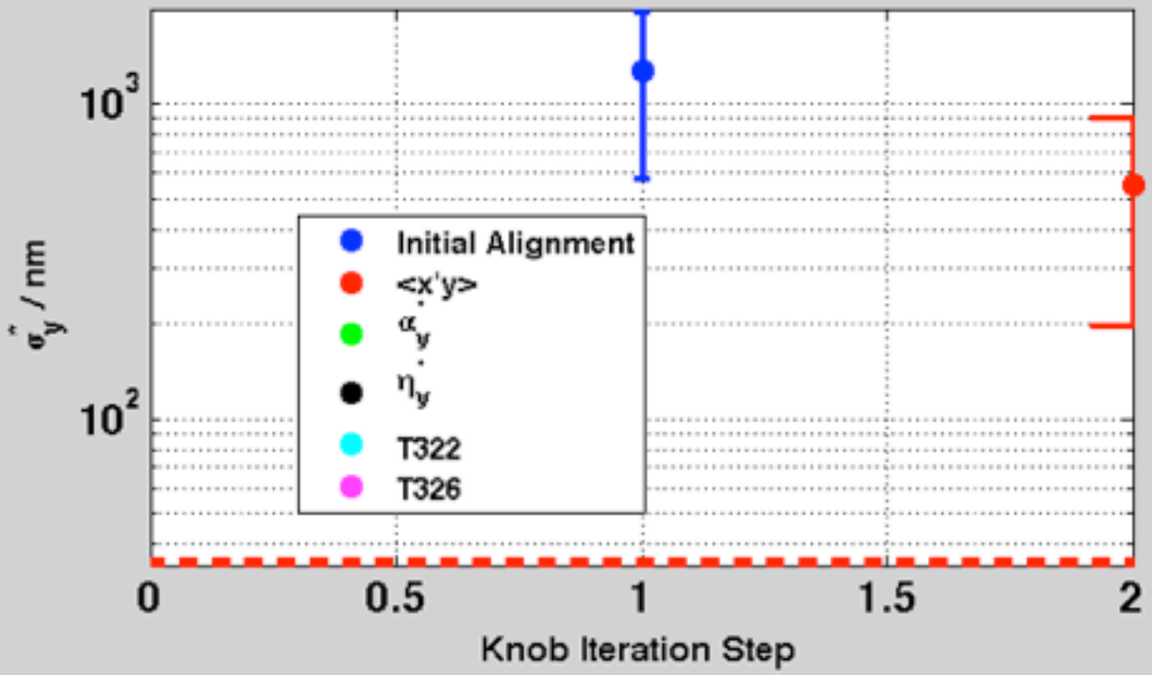
Nominal (1cm/ 0.1mm β) Optics - No Multipoles

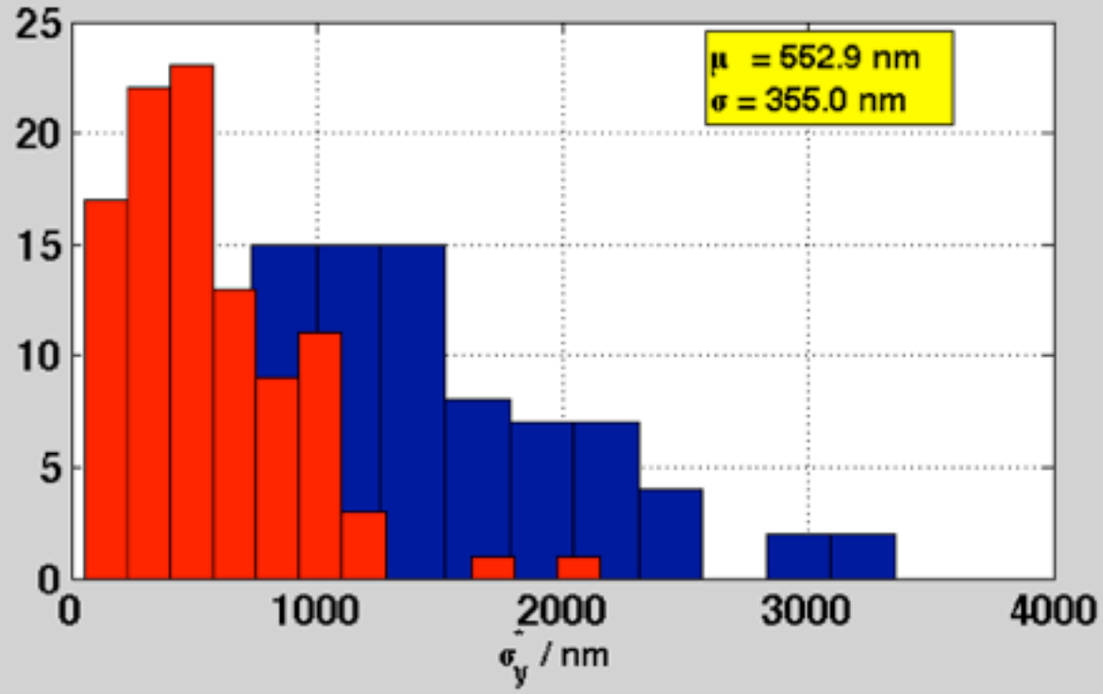

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\tilde{\sigma}_y$ / nm
0
0.2
0.4
0.6
0.8
1
Knob Iteration Step

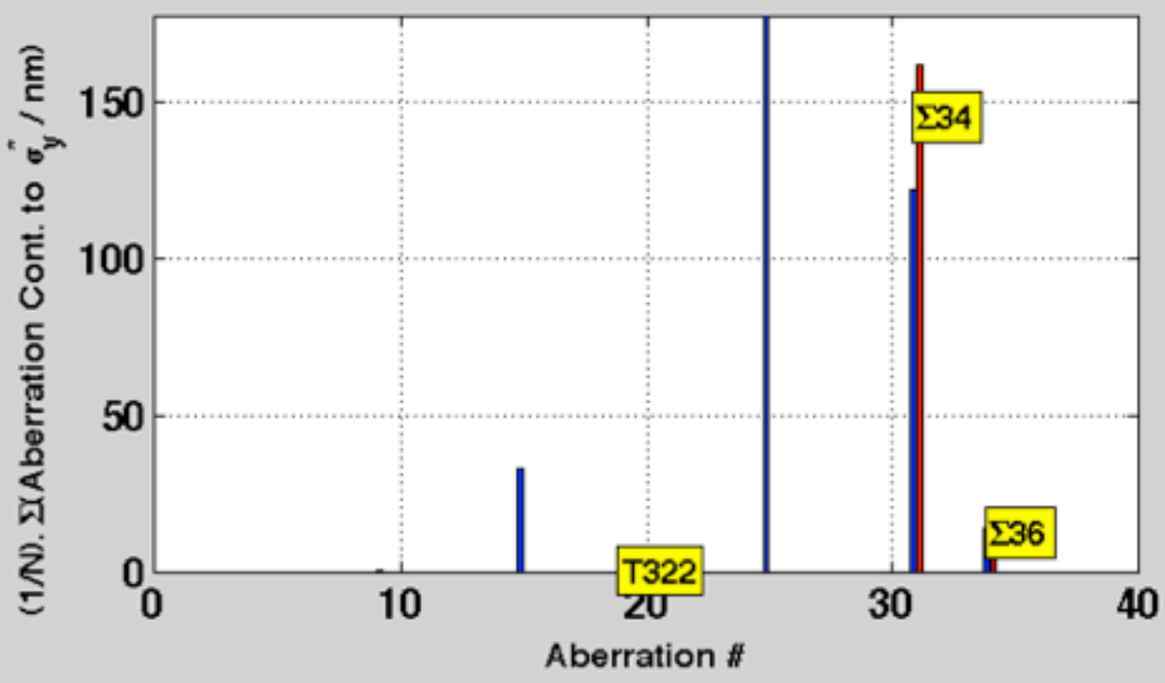

μ = 1270.4 nm
σ = 696.2 nm
15
10
5
0
0
1000
2000
3000
4000
$\tilde{\sigma}_y$ / nm

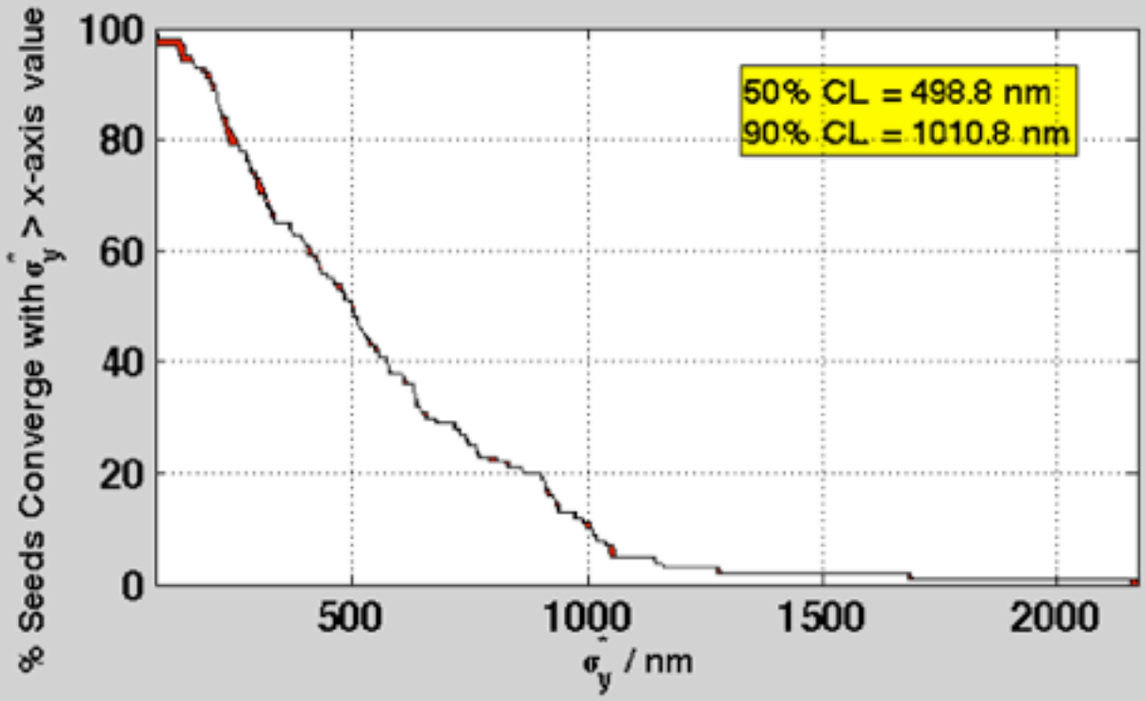

(1/N). Σ(Aberration Cont. to $\tilde{\sigma}_y$ / nm)
600
400
200
0
Σ31
Σ32
Σ34
0
10
20
30
40
Aberration #

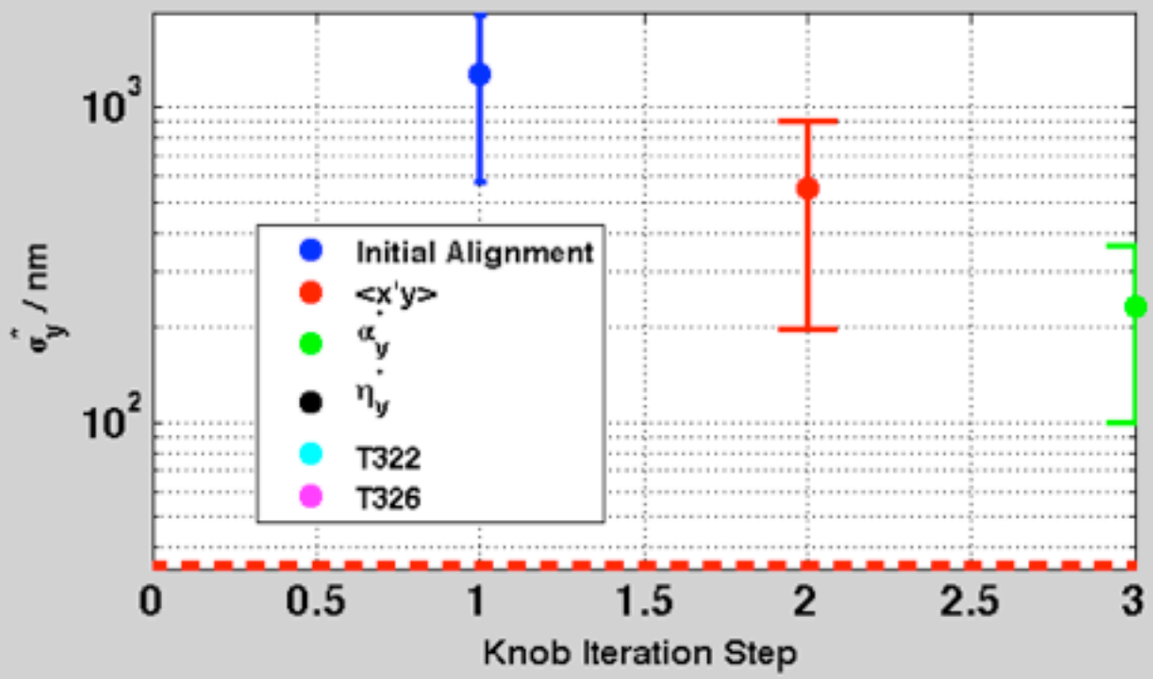

50% CL = 1219.1 nm
90% CL = 2183.8 nm
% Seeds Converge with $\tilde{\sigma}_y$ > x-axis value
100
80
60
40
20
0
0
1000
2000
3000
4000
$\tilde{\sigma}_y$ / nm

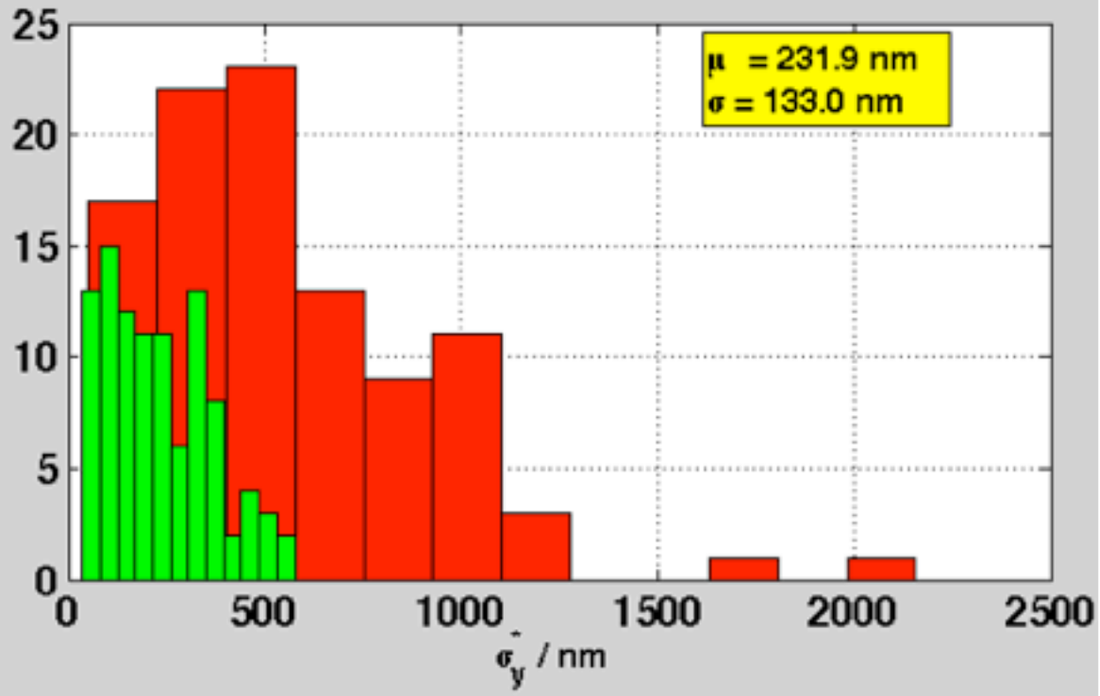

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\tilde{\sigma}_y$ / nm
0
0.5
1
1.5
2
Knob Iteration Step

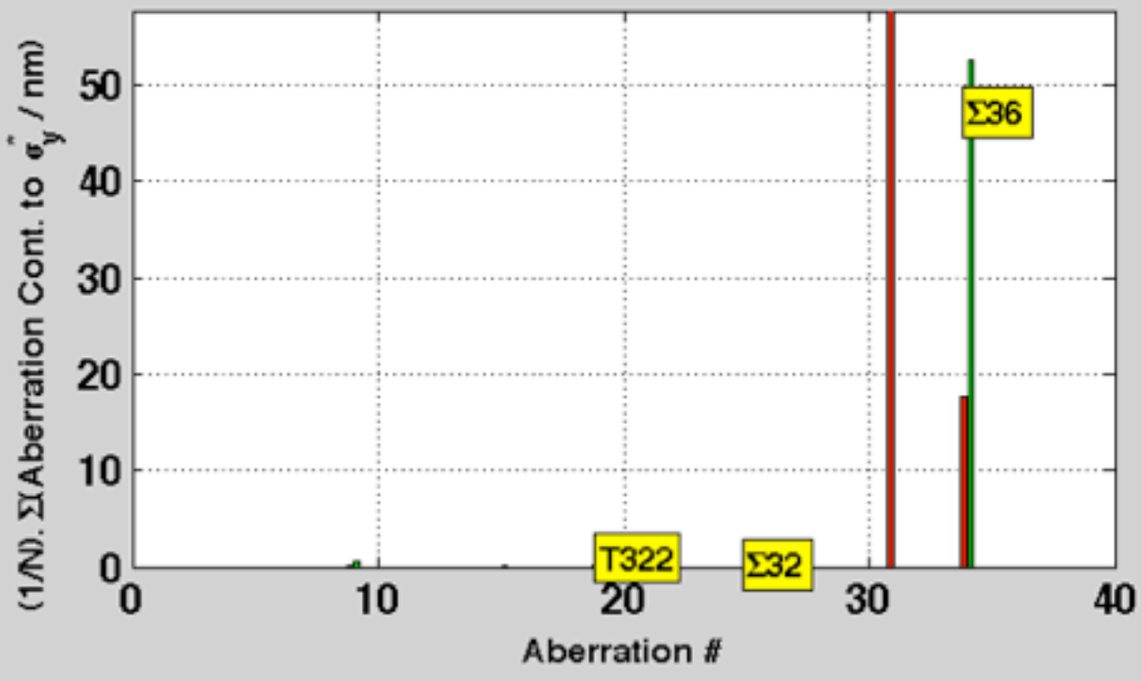

μ = 552.9 nm
σ = 355.0 nm
25
20
15
10
5
0
0
1000
2000
3000
4000
$\tilde{\sigma}_y$ / nm

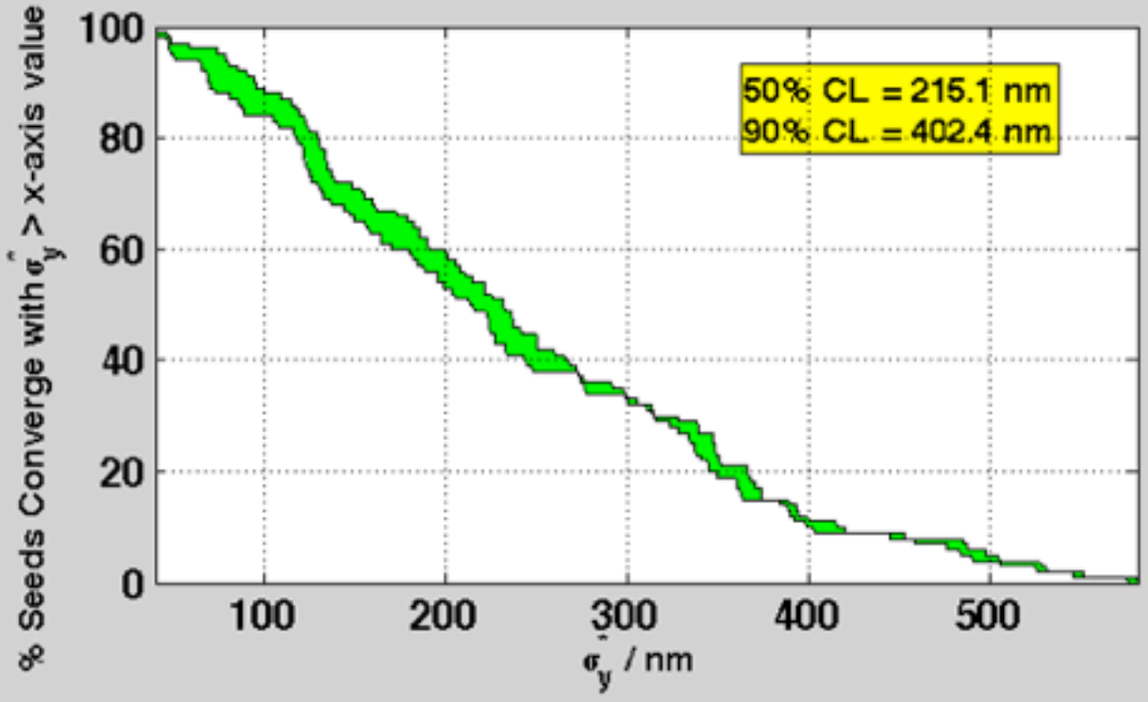

(1/N). Σ(Aberration Cont. to $\tilde{\sigma}_y$ / nm)
150
100
50
0
0
10
20
30
40
Aberration #
Σ34
Σ36
T322

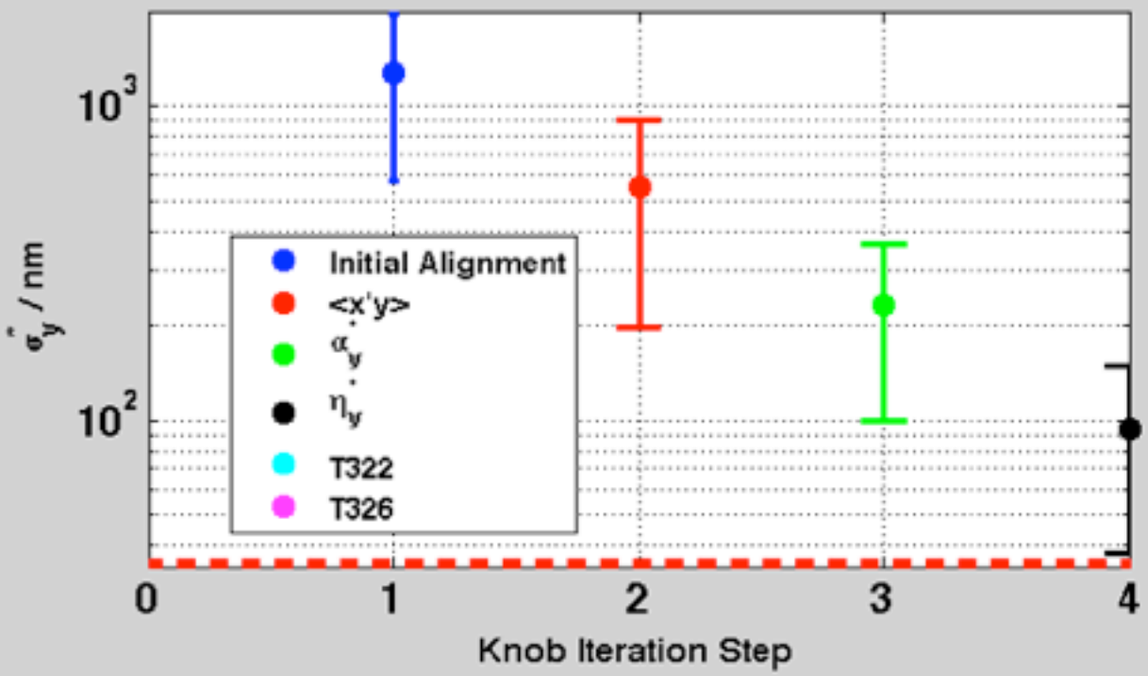

% Seeds Converge with $\tilde{\sigma}_y$ > x-axis value
100
80
60
40
20
0
500
1000
1500
2000
$\tilde{\sigma}_y$ / nm
50% CL = 498.8 nm
90% CL = 1010.8 nm

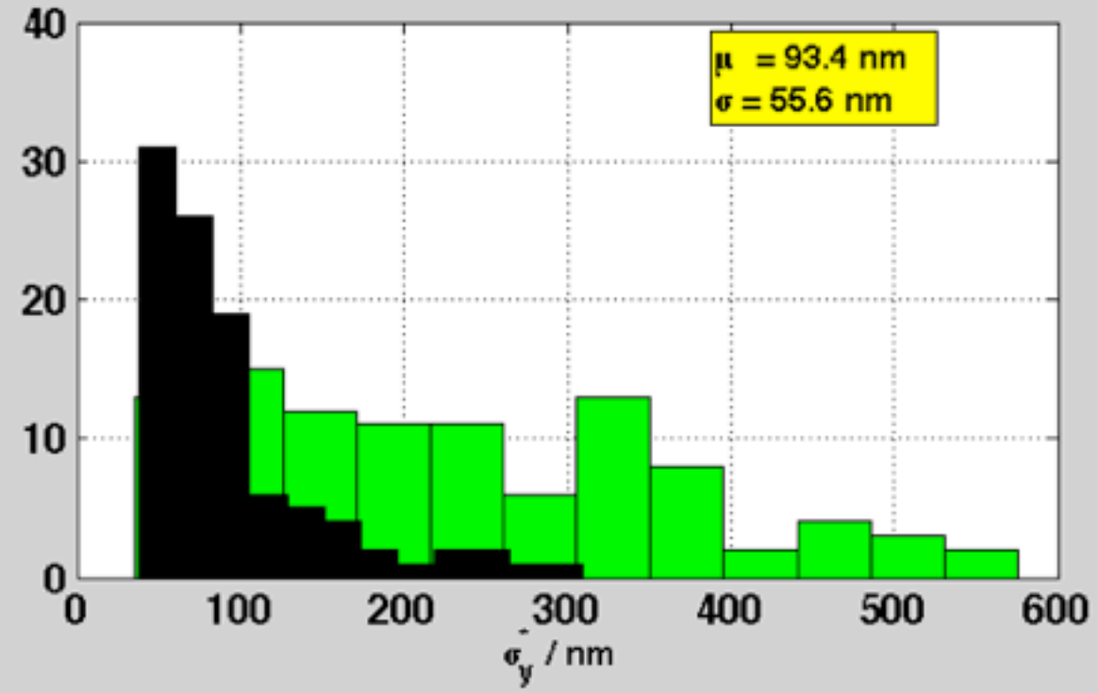

Initial Alignment
<x'y>
α_y^*
η_y^*
T322
T326
10^3
10^2
$\hat{\sigma}_y$ / nm
0
0.5
1
1.5
2
2.5
3
Knob Iteration Step

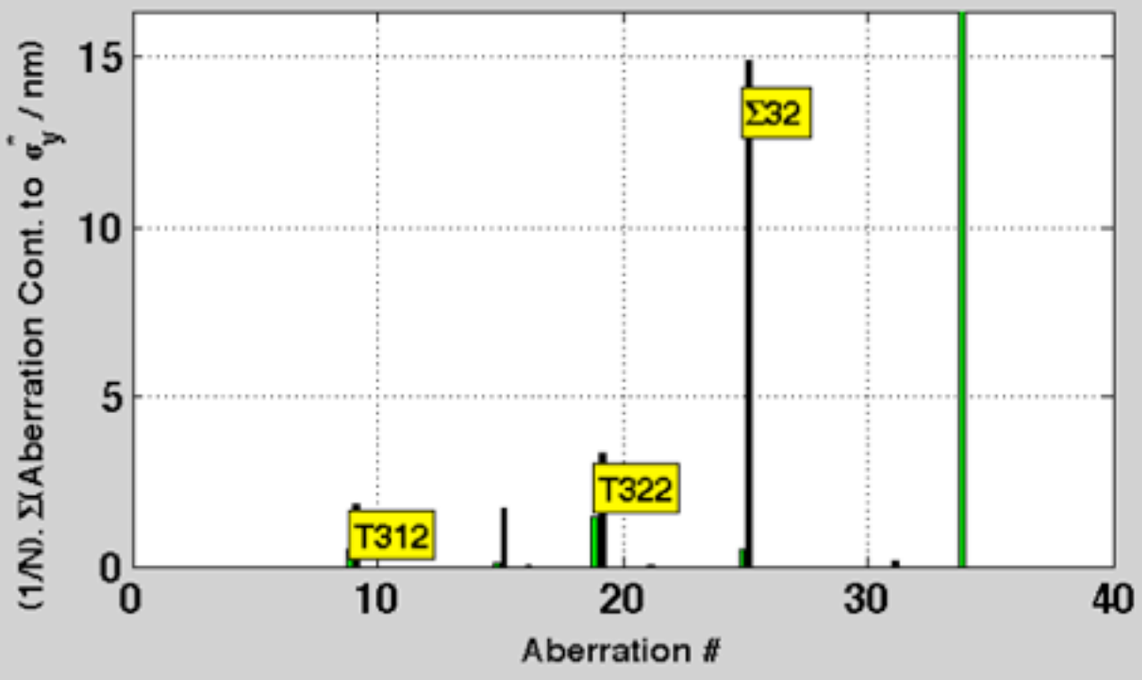

μ = 231.9 nm
σ = 133.0 nm
0
5
10
15
20
25
0
500
1000
1500
2000
2500
$\hat{\sigma}_y$ / nm

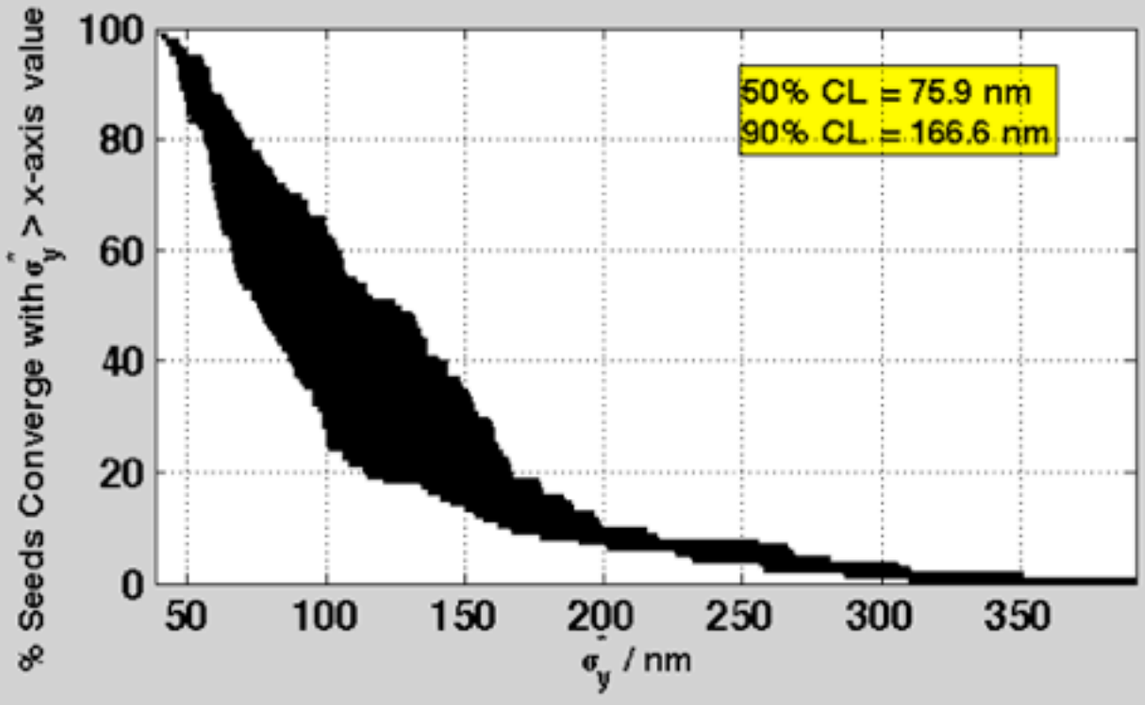

(1/N). Σ(Aberration Cont. to $\hat{\sigma}_y$ / nm)
0
10
20
30
40
50
T322
Σ32
Σ36
0
10
20
30
40
Aberration #

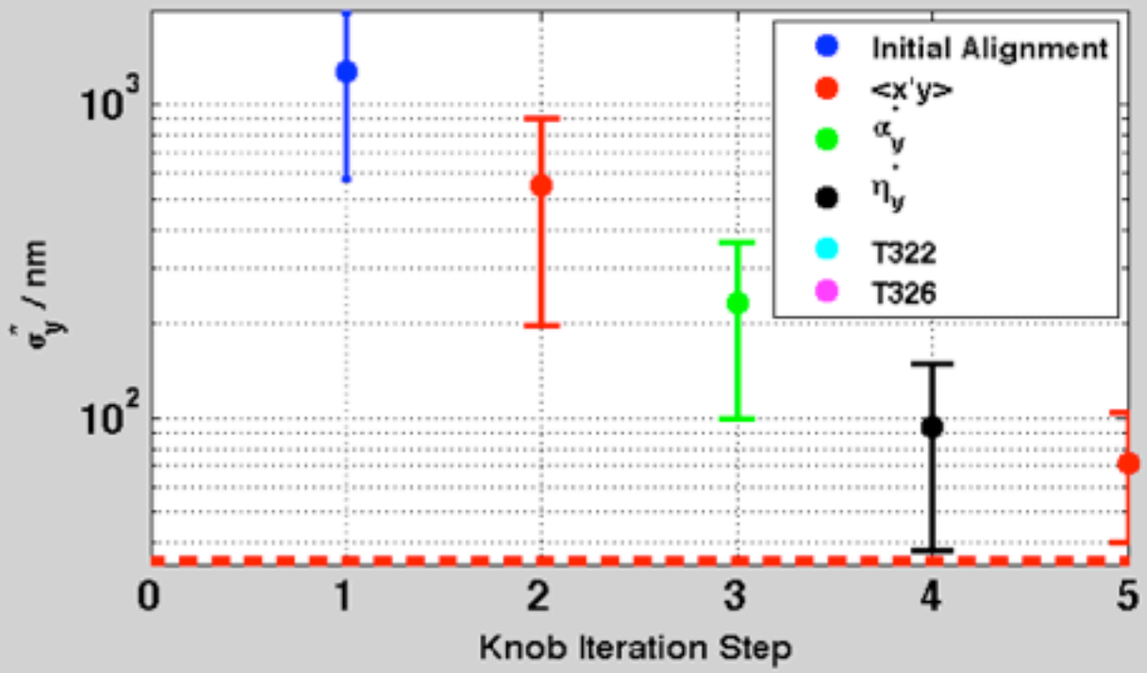

% Seeds Converge with $\hat{\sigma}_y$ > x-axis value
0
20
40
60
80
100
50% CL = 215.1 nm
90% CL = 402.4 nm
100
200
300
400
500
$\hat{\sigma}_y$ / nm

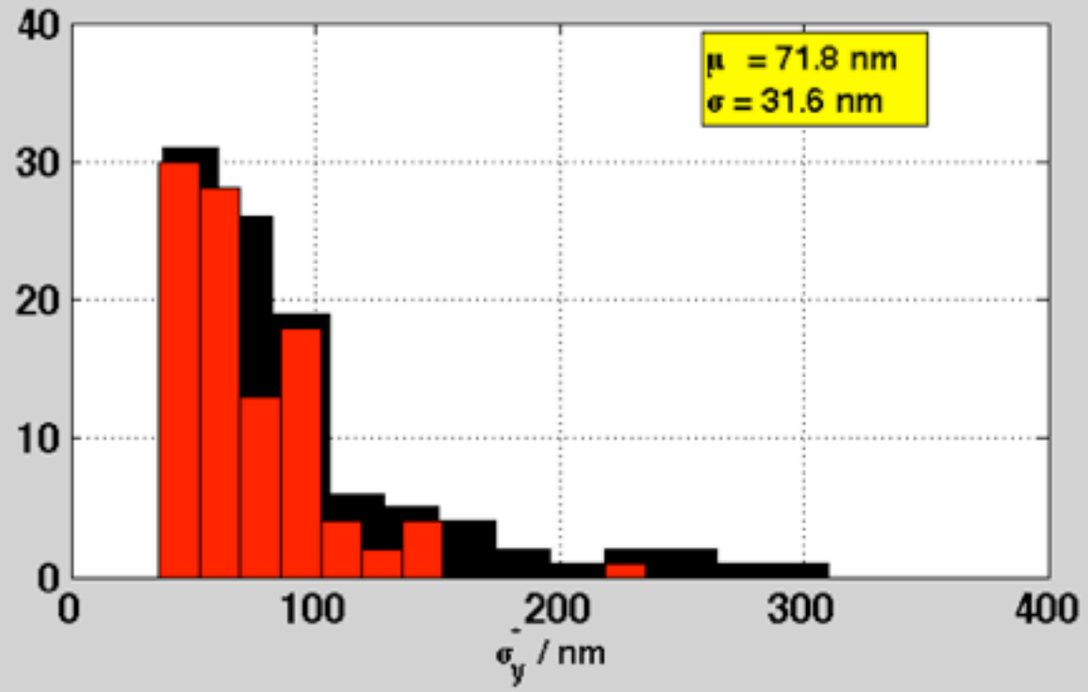

Initial Alignment
<x'y>
α_y^*
η_y^*
T322
T326
10^3
10^2
$\tilde{\sigma}_y$ / nm
0
1
2
3
4
Knob Iteration Step

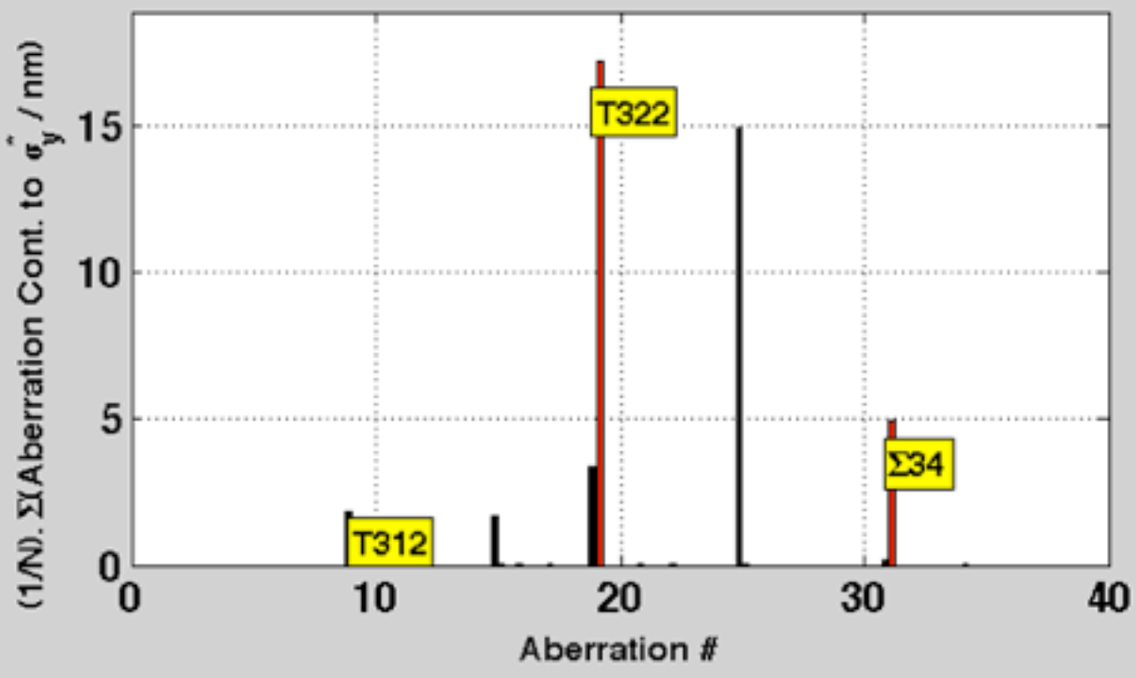

μ = 93.4 nm
σ = 55.6 nm
40
30
20
10
0
0
100
200
300
400
500
600
$\tilde{\sigma}_y$ / nm

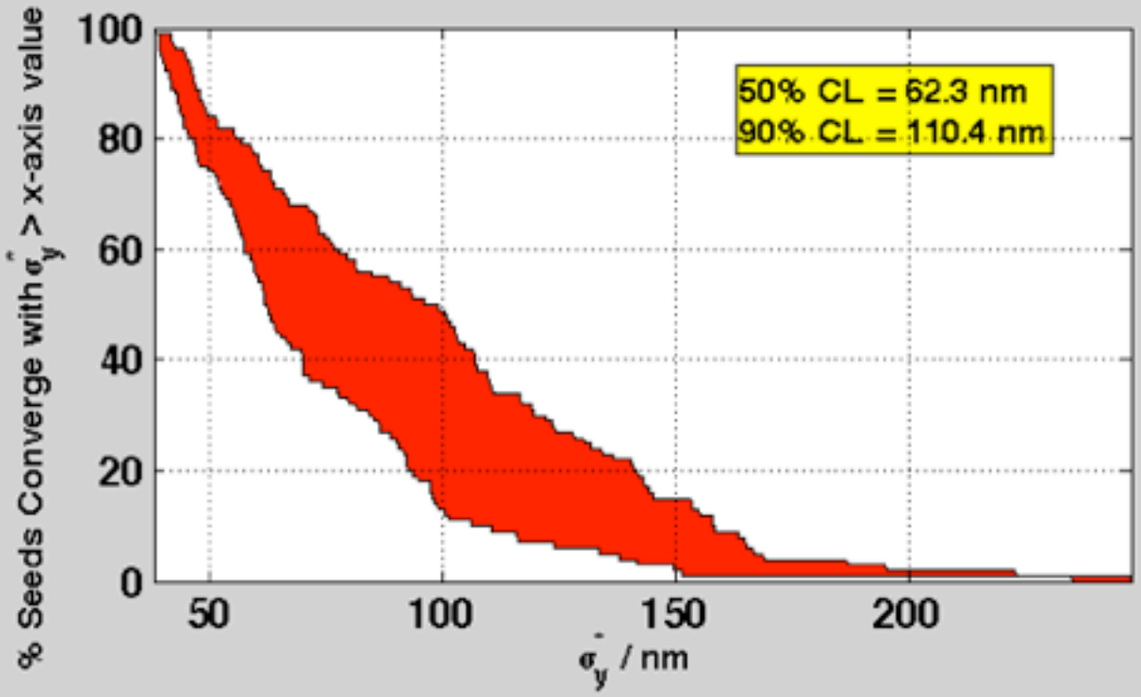

Σ32
T322
T312
15
10
5
0
0
10
20
30
40
(1/N). Σ(Aberration Cont. to $\tilde{\sigma}_y$ / nm)
Aberration #

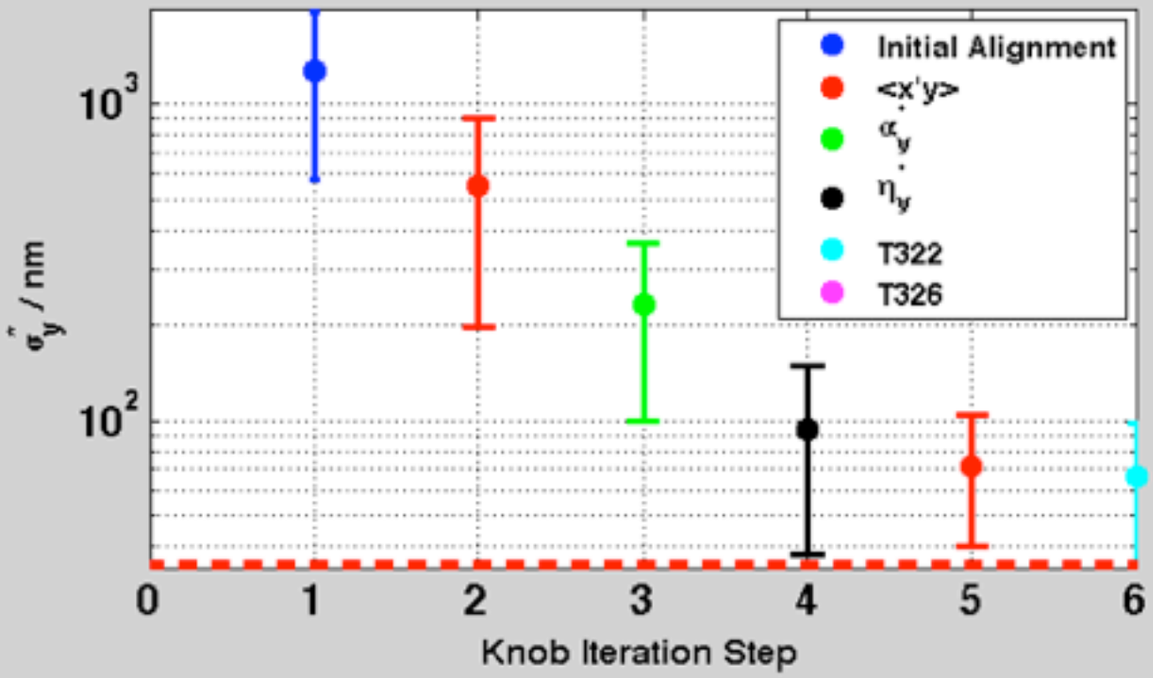

50% CL = 75.9 nm
90% CL = 166.6 nm
100
80
60
40
20
0
50
100
150
200
250
300
350
% Seeds Converge with $\tilde{\sigma}_y$ > x-axis value
$\tilde{\sigma}_y$ / nm

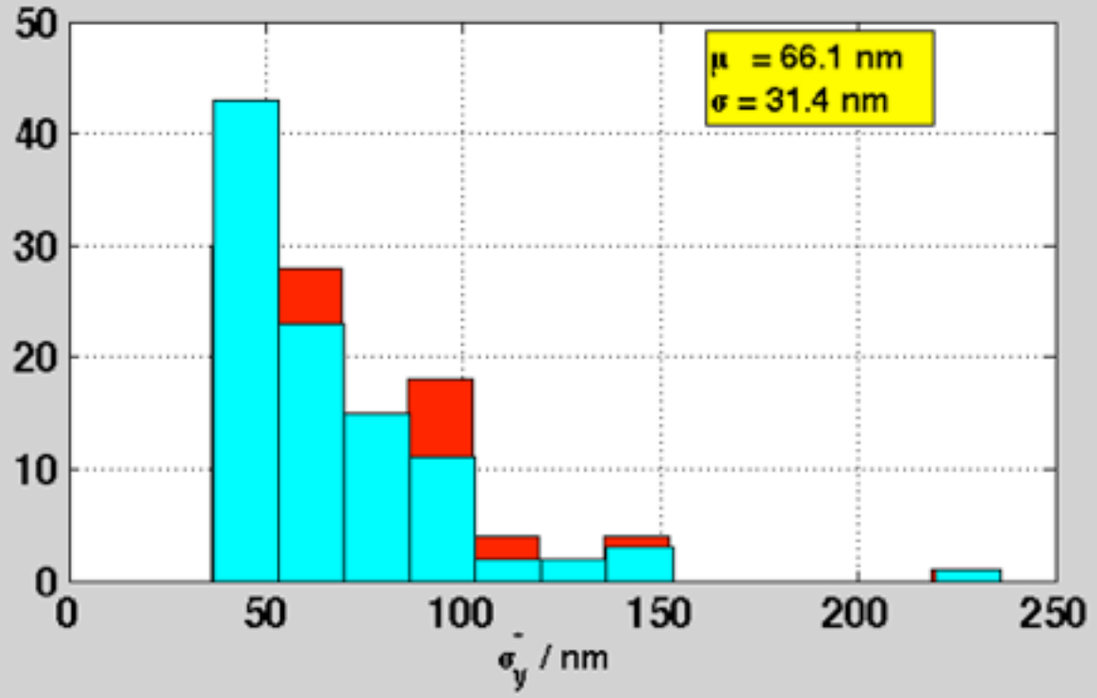

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
σ_y / nm
0
1
2
3
4
5
Knob Iteration Step

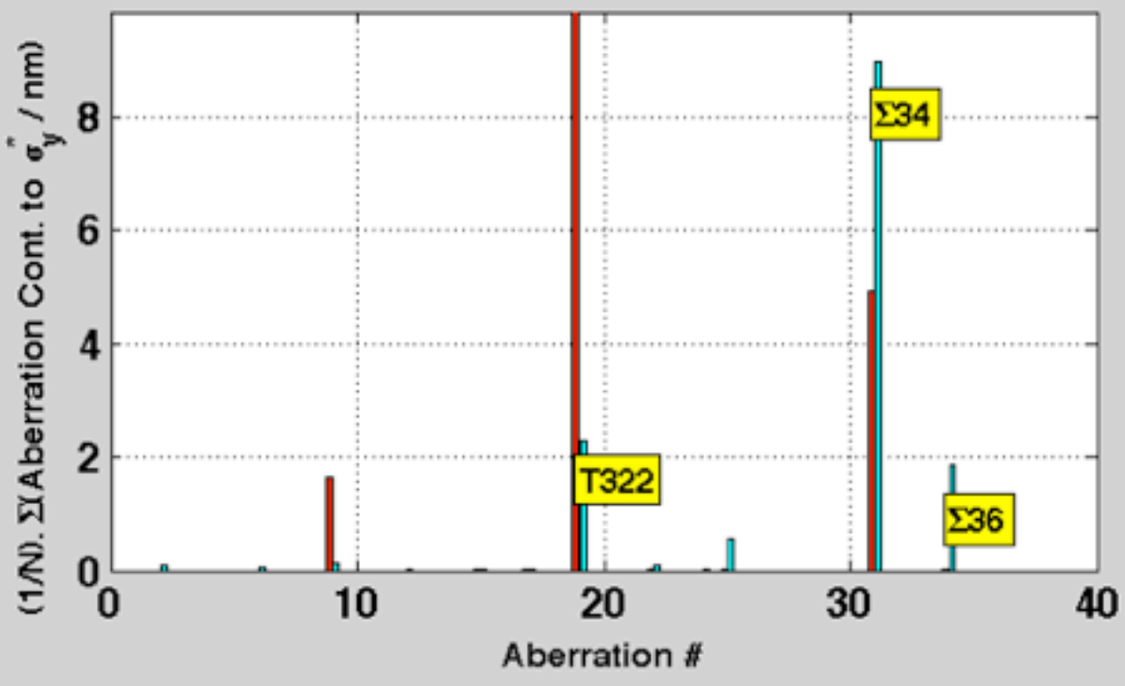

μ = 71.8 nm
σ = 31.6 nm
40
30
20
10
0
0
100
200
300
400
σ_y / nm

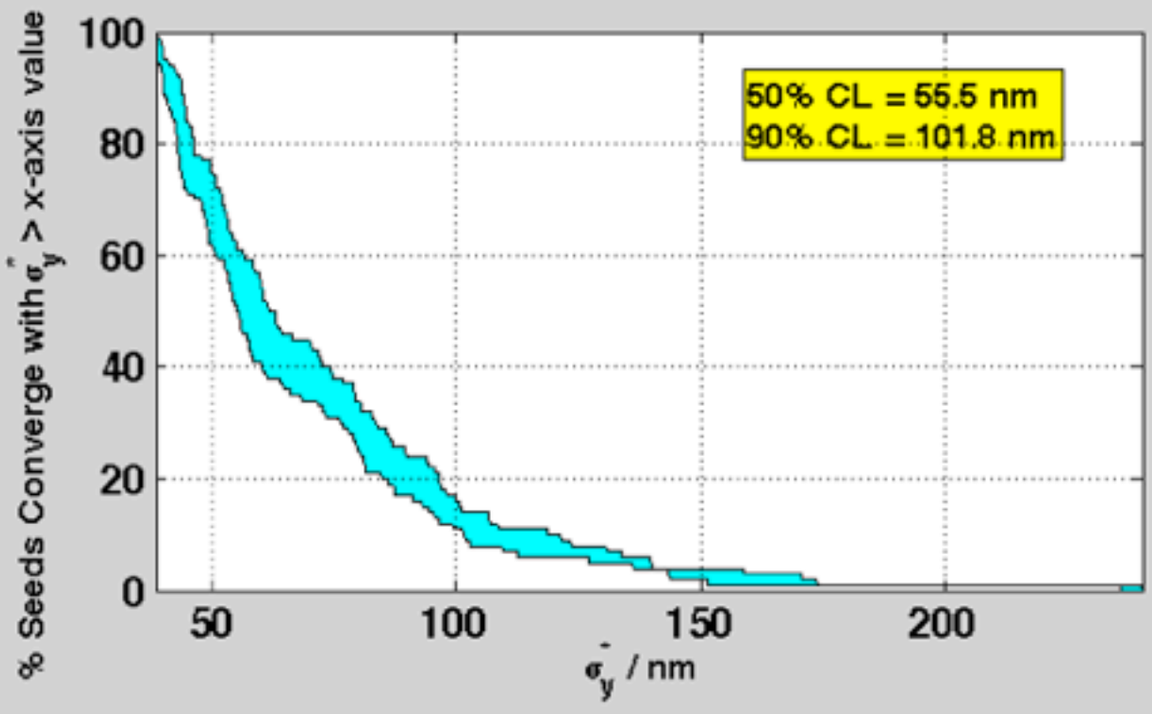

T322
T312
Σ34
(1/N). Σ(Aberration Cont. to σ_y / nm)
15
10
5
0
0
10
20
30
40
Aberration #

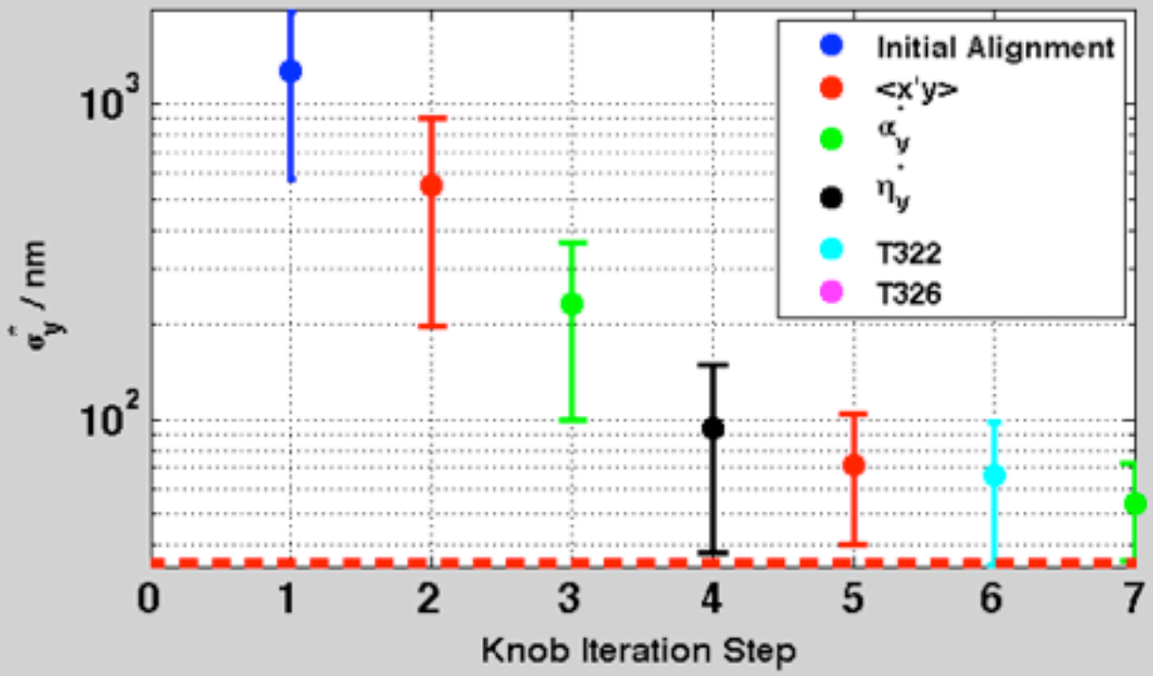

50% CL = 62.3 nm
90% CL = 110.4 nm
% Seeds Converge with σ_y > x-axis value
100
80
60
40
20
0
50
100
150
200
σ_y / nm

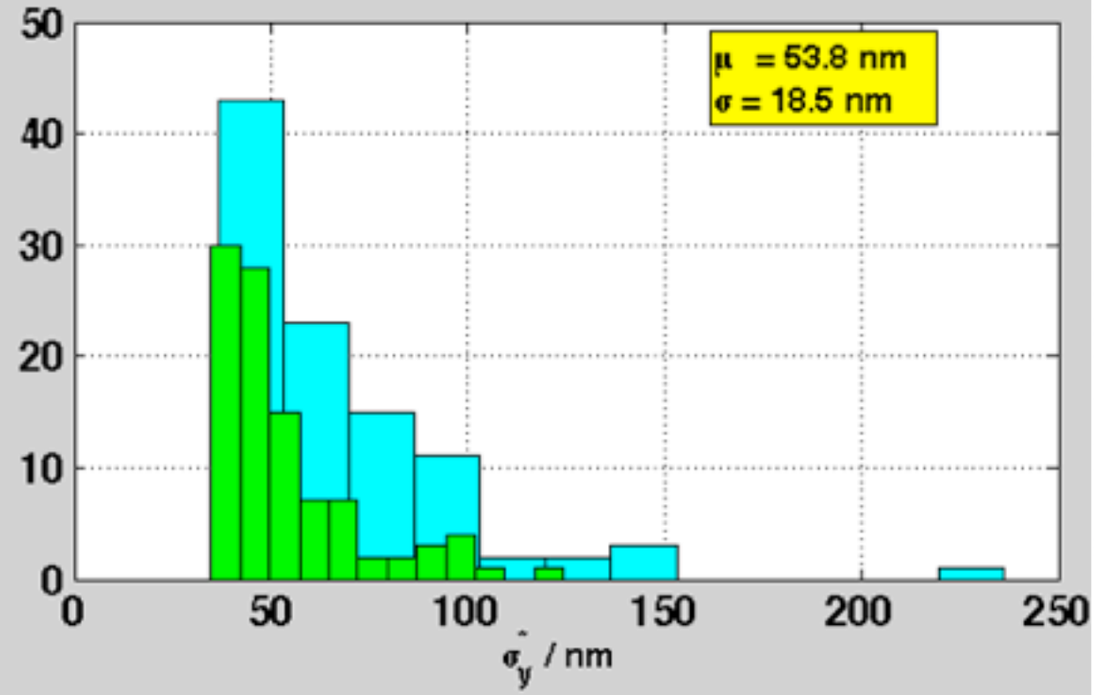

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\tilde{\sigma}_y$ / nm
0
1
2
3
4
5
6
Knob Iteration Step

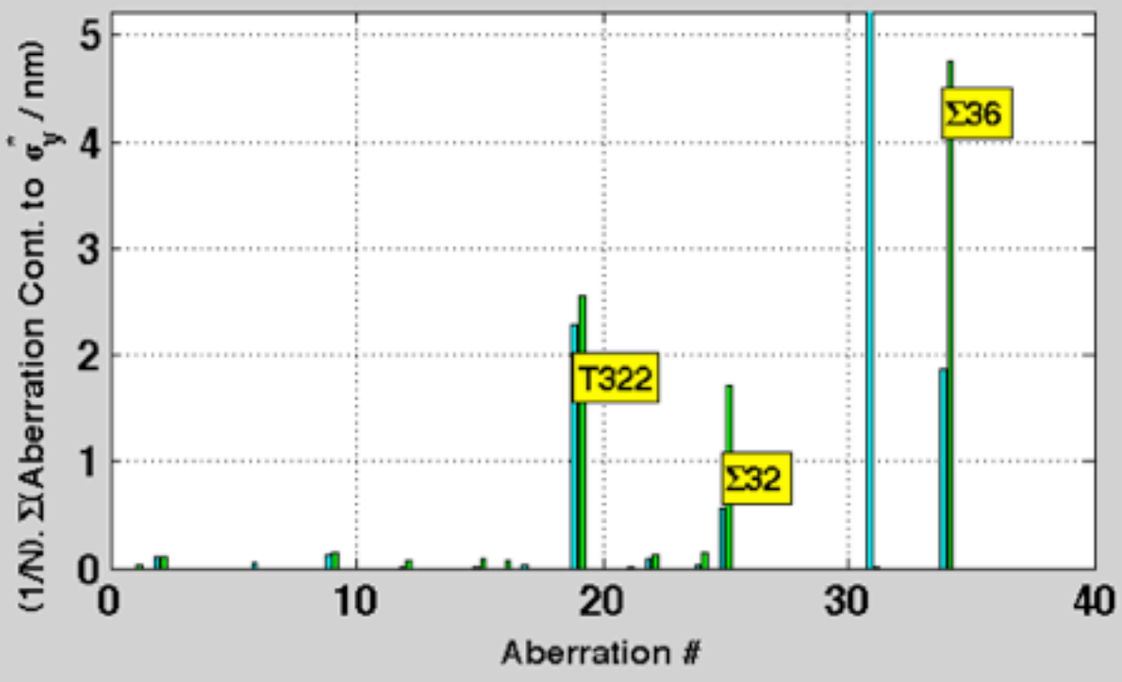

μ = 66.1 nm
σ = 31.4 nm
0
10
20
30
40
50
0
50
100
150
200
250
$\bar{\sigma}_y$ / nm

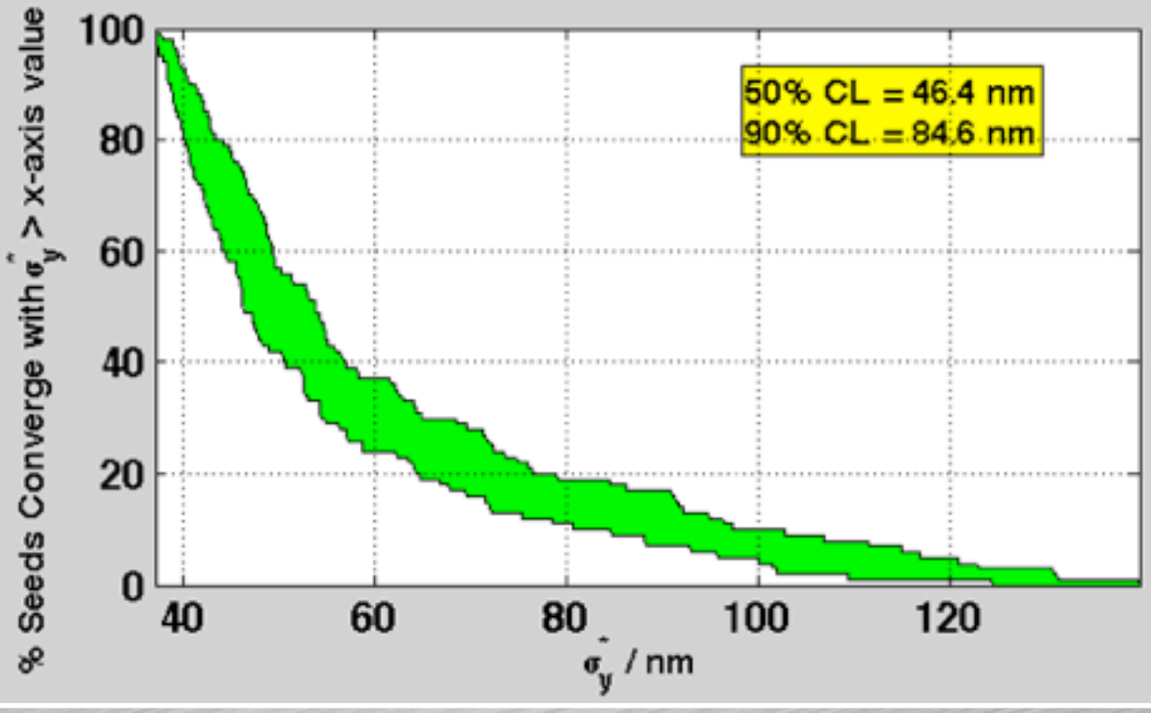

(1/N). Σ(Aberration Cont. to $\tilde{\sigma}_y$ / nm)
Σ34
T322
Σ36
0
2
4
6
8
0
10
20
30
40
Aberration #

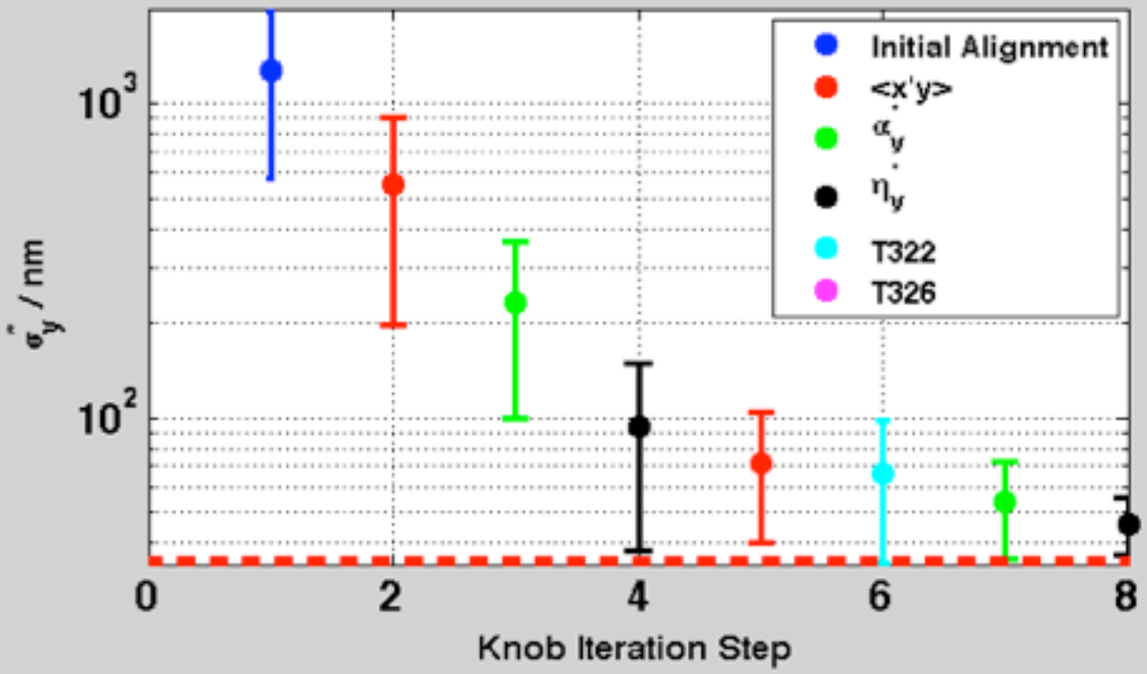

50% CL = 55.5 nm
90% CL = 101.8 nm
% Seeds Converge with $\tilde{\sigma}_y$ > x-axis value
0
20
40
60
80
100
50
100
150
200
$\bar{\sigma}_y$ / nm

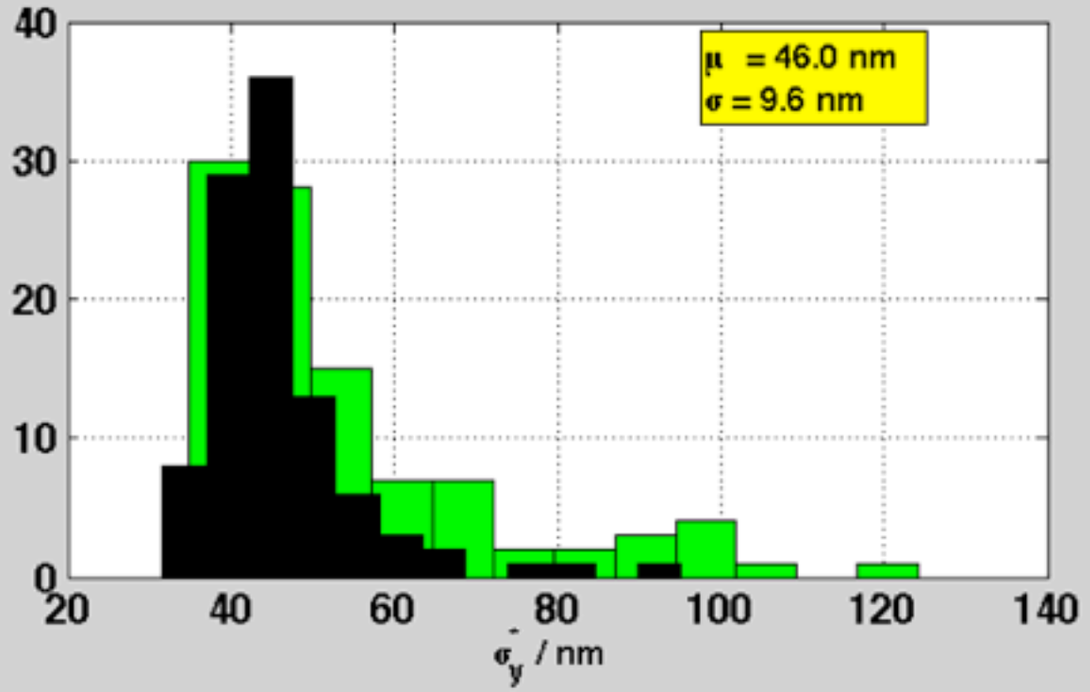

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\hat{\sigma}_y$ / nm
0
1
2
3
4
5
6
7
Knob Iteration Step

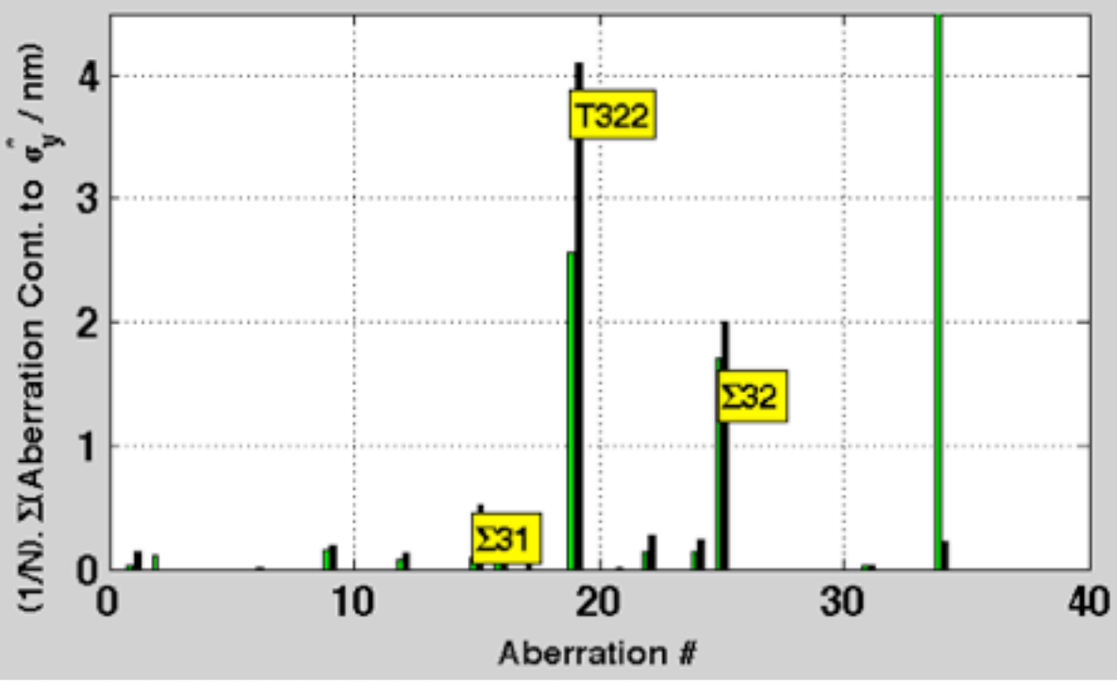

μ = 53.8 nm
σ = 18.5 nm
50
40
30
20
10
0
0
50
100
150
200
250
$\hat{\sigma}_y$ / nm

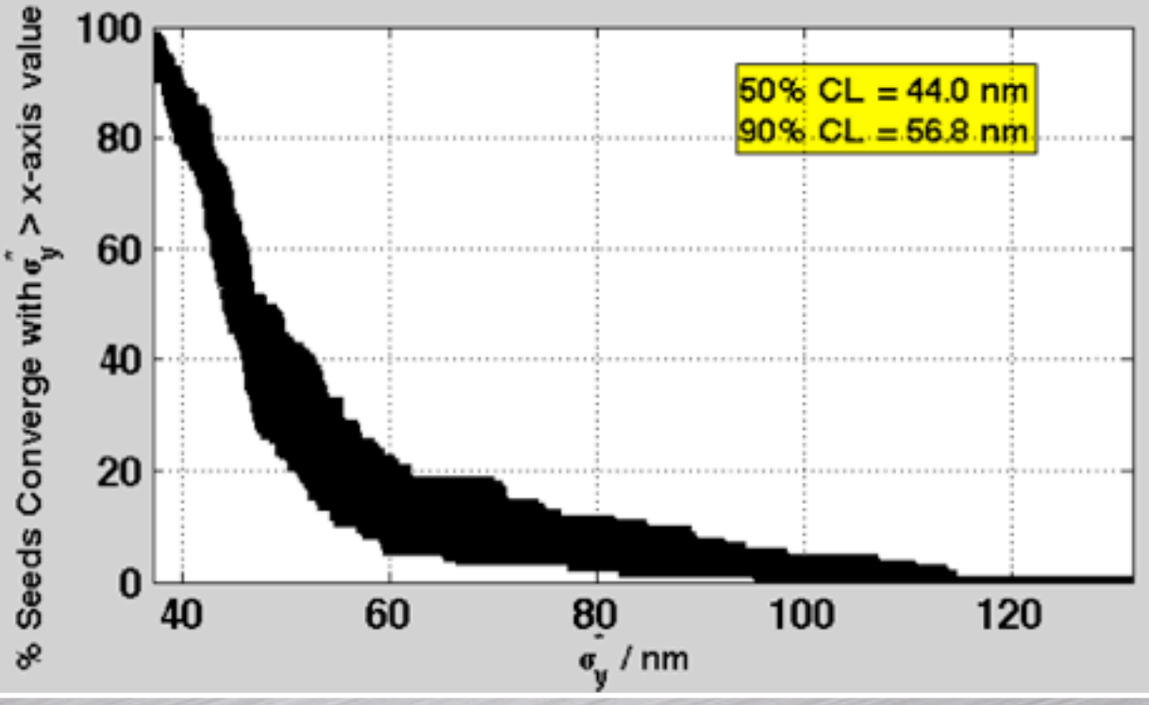

(1/N). Σ(Aberration Cont. to $\hat{\sigma}_y$ / nm)
5
4
3
2
1
0
0
10
20
30
40
Aberration #
T322
Σ32
Σ36

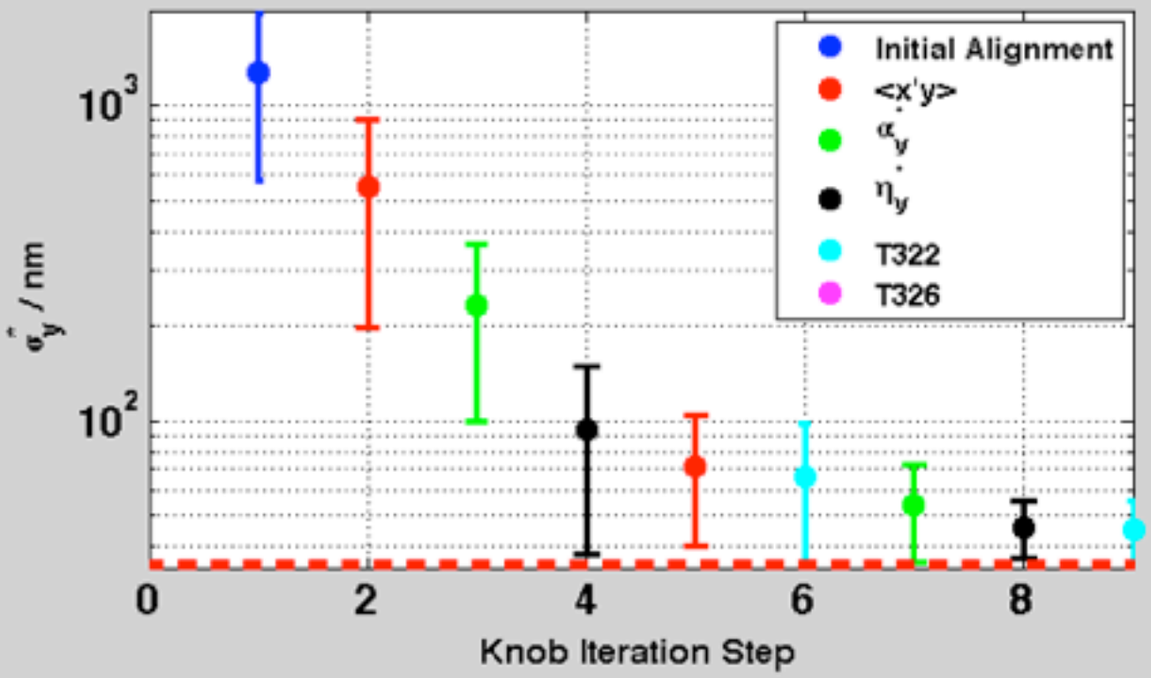

% Seeds Converge with $\hat{\sigma}_y$ > x-axis value
100
80
60
40
20
0
40
60
80
100
120
$\hat{\sigma}_y$ / nm
50% CL = 46.4 nm
90% CL = 84.6 nm

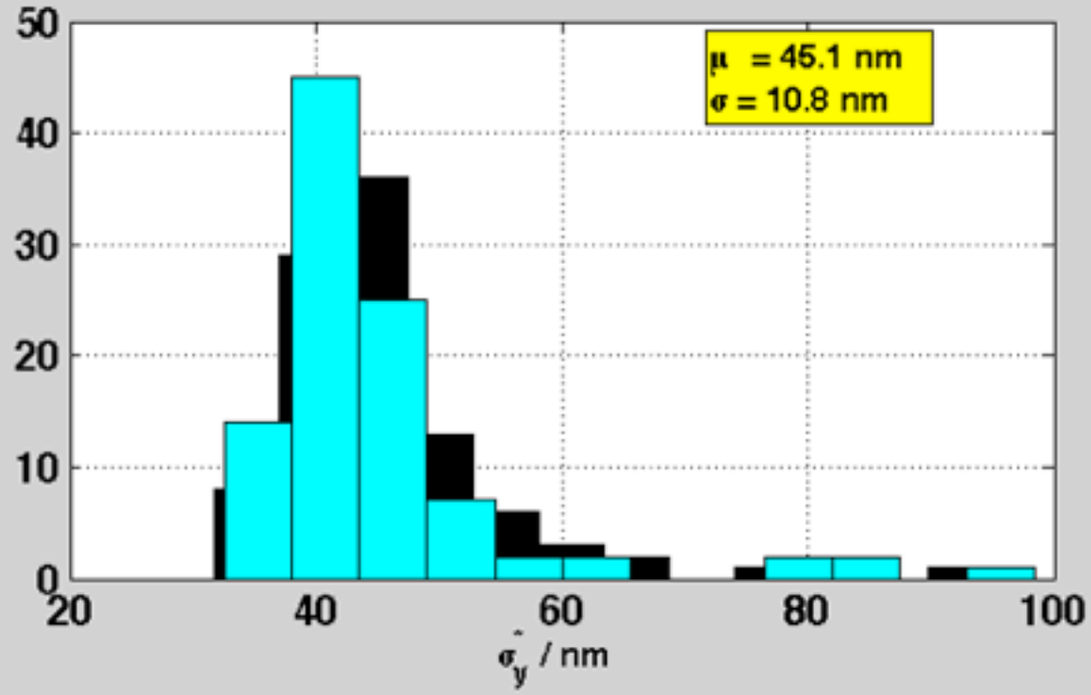

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
σ_y / nm
0
2
4
6
8
Knob Iteration Step

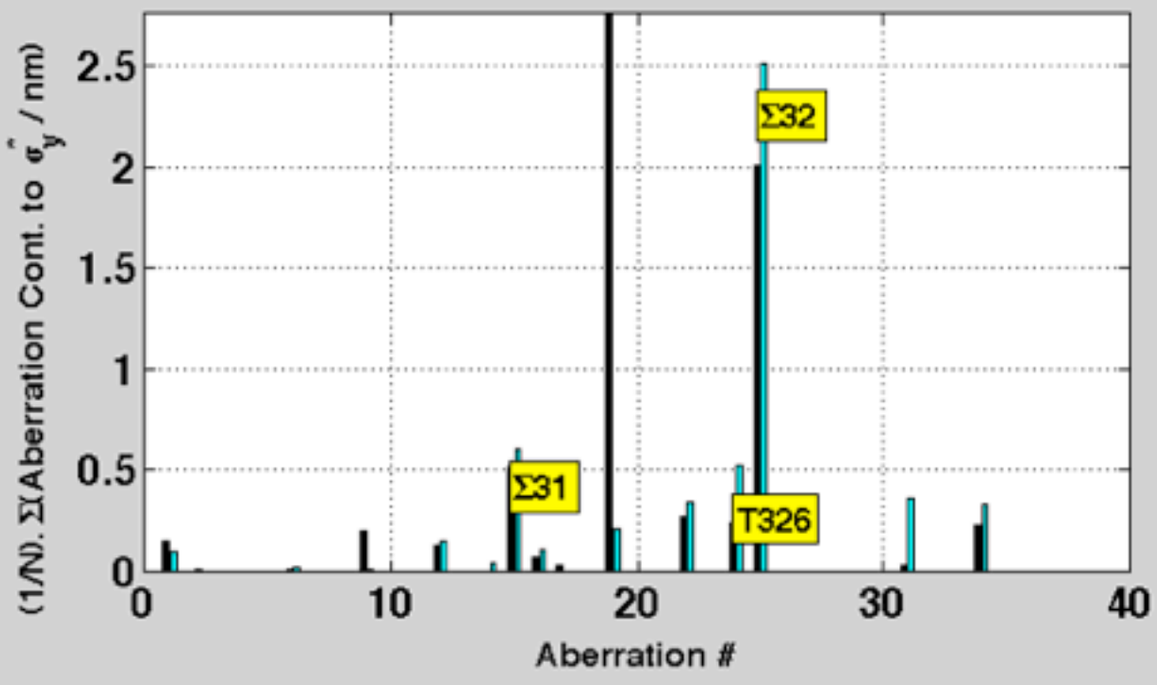

μ = 46.0 nm
σ = 9.6 nm
40
30
20
10
0
20
40
60
80
100
120
140
σ_y / nm

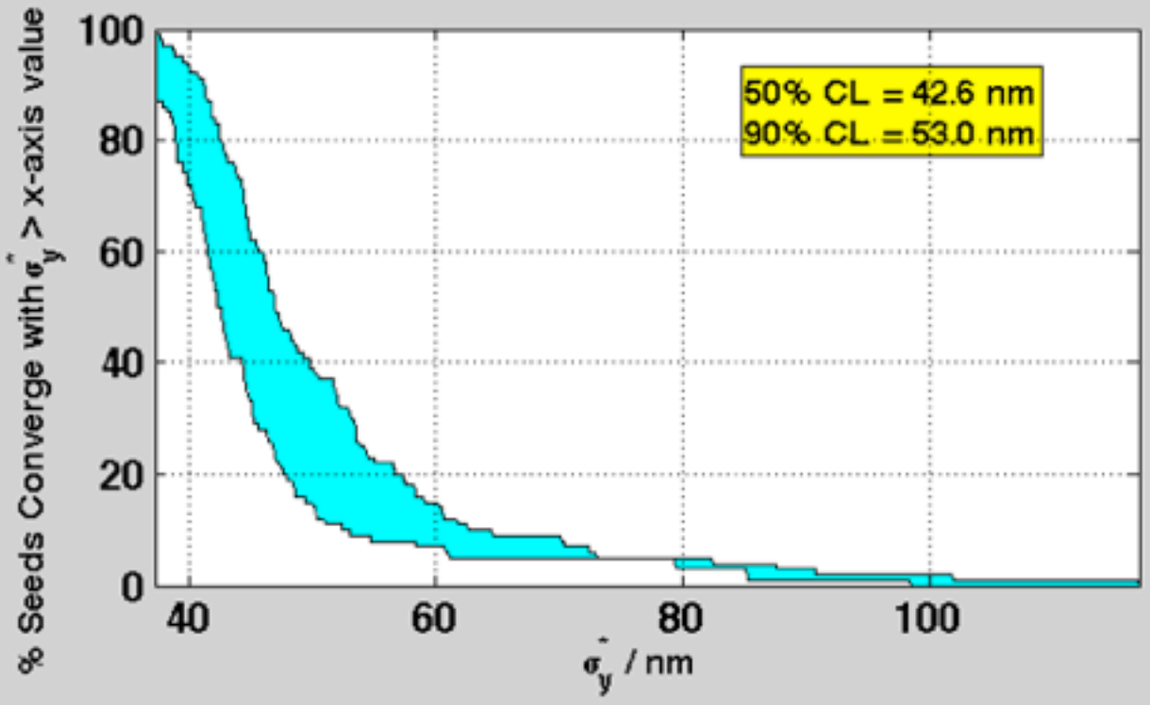

T322
Σ32
Σ31
(1/N). Σ(Aberration Cont. to σ_y / nm)
4
3
2
1
0
0
10
20
30
40
Aberration #

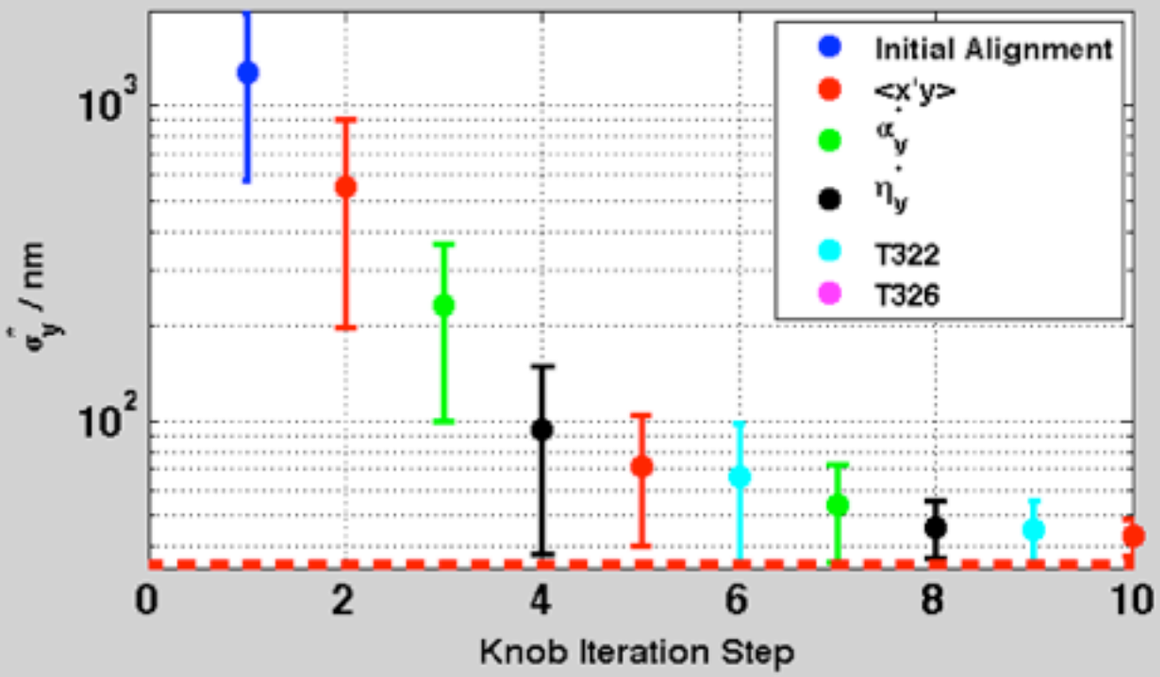

50% CL = 44.0 nm
90% CL = 56.8 nm
% Seeds Converge with σ_y > x-axis value
100
80
60
40
20
0
40
60
80
100
120
σ_y / nm

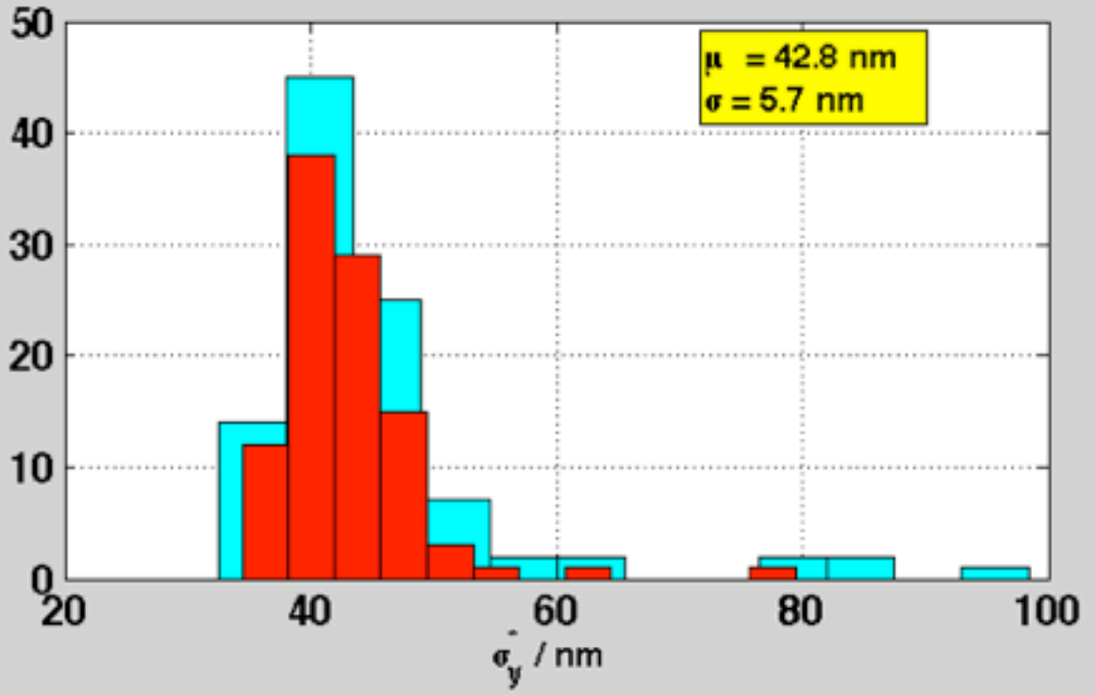

Initial Alignment
<x'y>
α_y^*
η_y^*
T322
T326
10^3
10^2
$\hat{\sigma}_y$ / nm
0
2
4
6
8
Knob Iteration Step

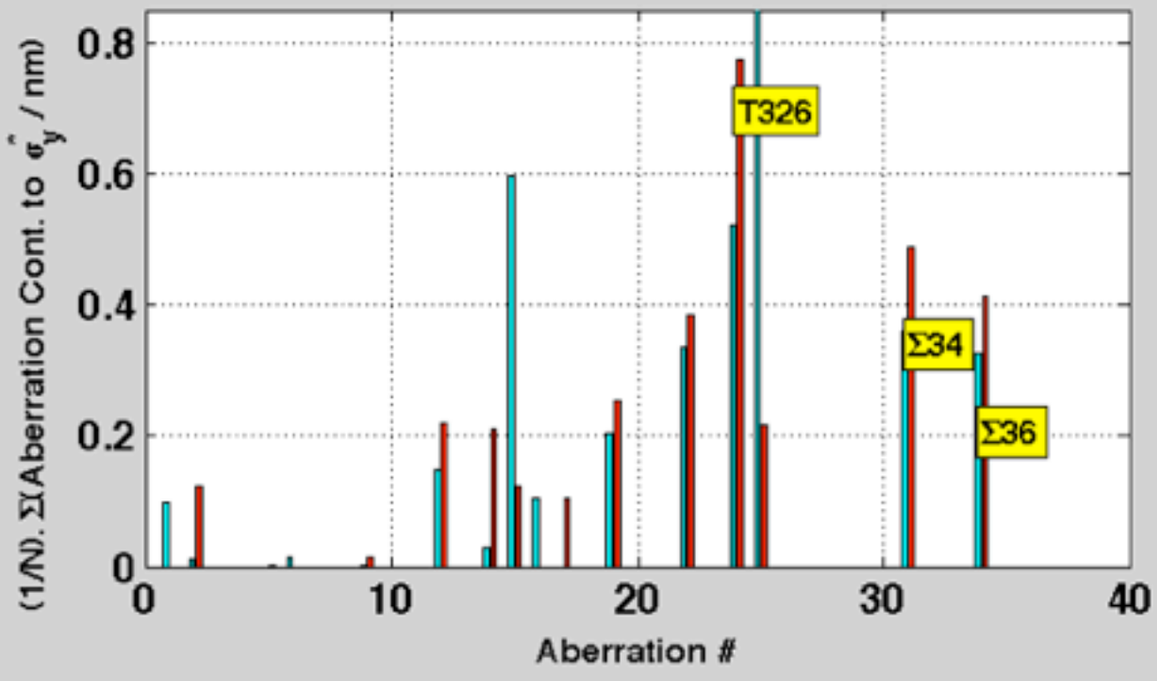

μ = 45.1 nm
σ = 10.8 nm
50
40
30
20
10
0
20
40
60
80
100
$\hat{\sigma}_y$ / nm

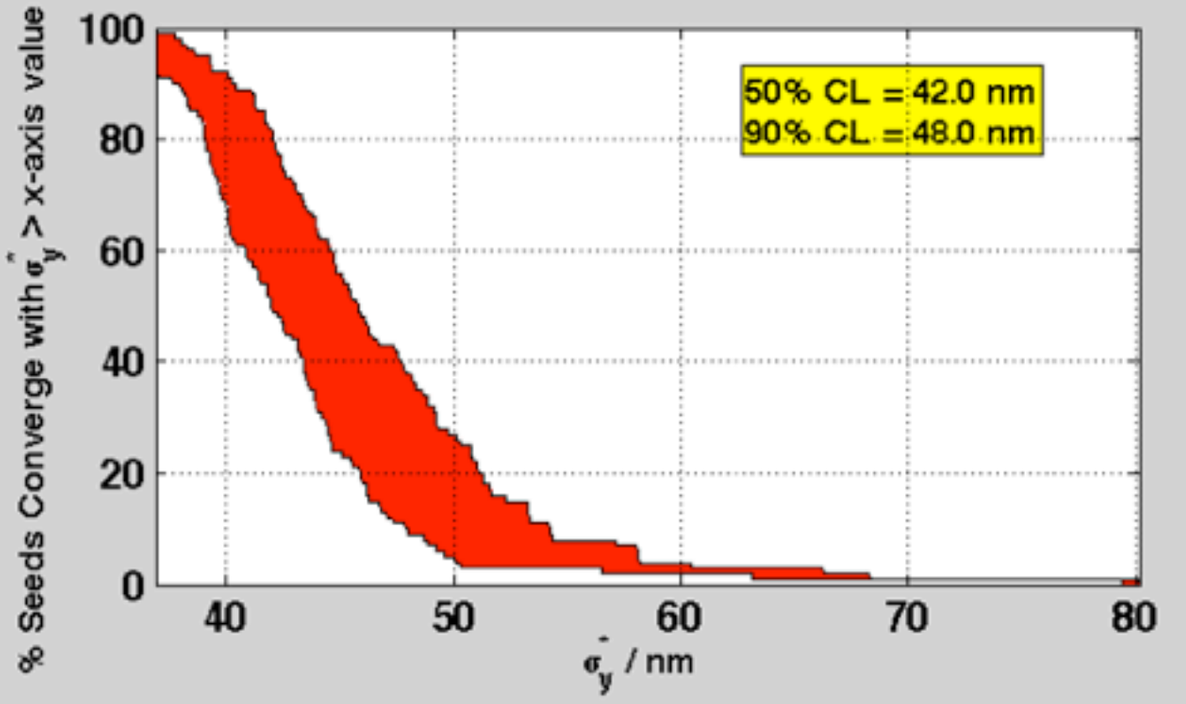

(1/N). Σ(Aberration Cont. to $\hat{\sigma}_y$ / nm)
2.5
2
1.5
1
0.5
0
Σ32
Σ31
T326
0
10
20
30
40
Aberration #

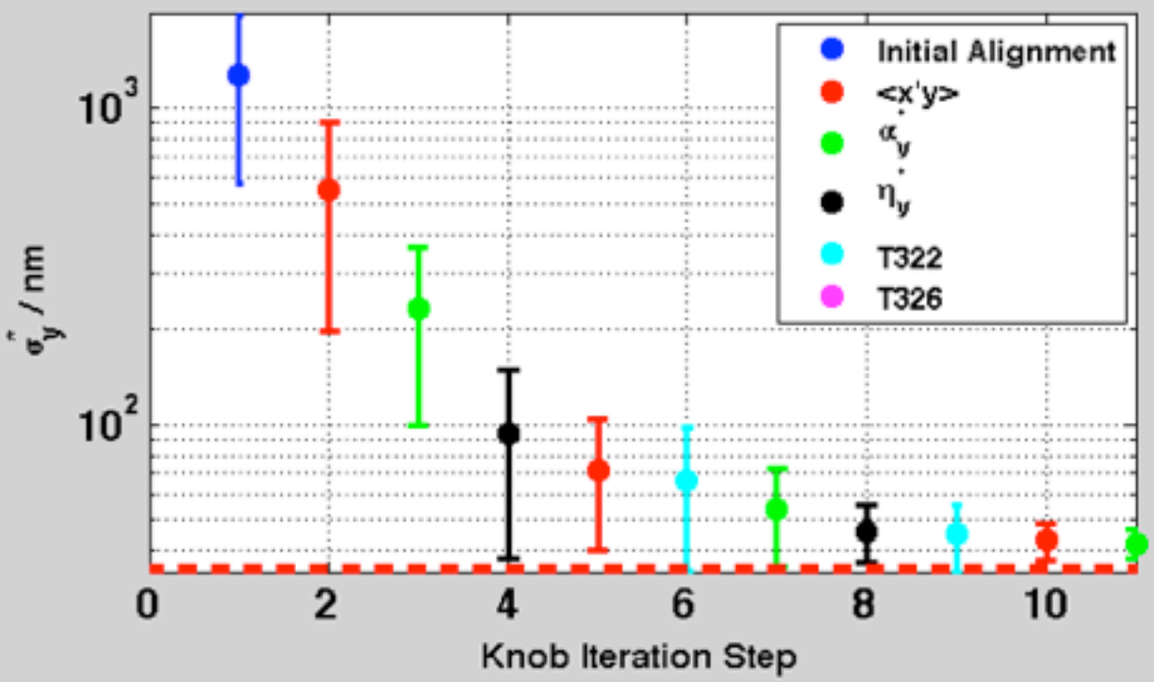

% Seeds Converge with $\hat{\sigma}_y$ > x-axis value
100
80
60
40
20
0
50% CL = 42.6 nm
90% CL = 53.0 nm
40
60
80
100
$\hat{\sigma}_y$ / nm

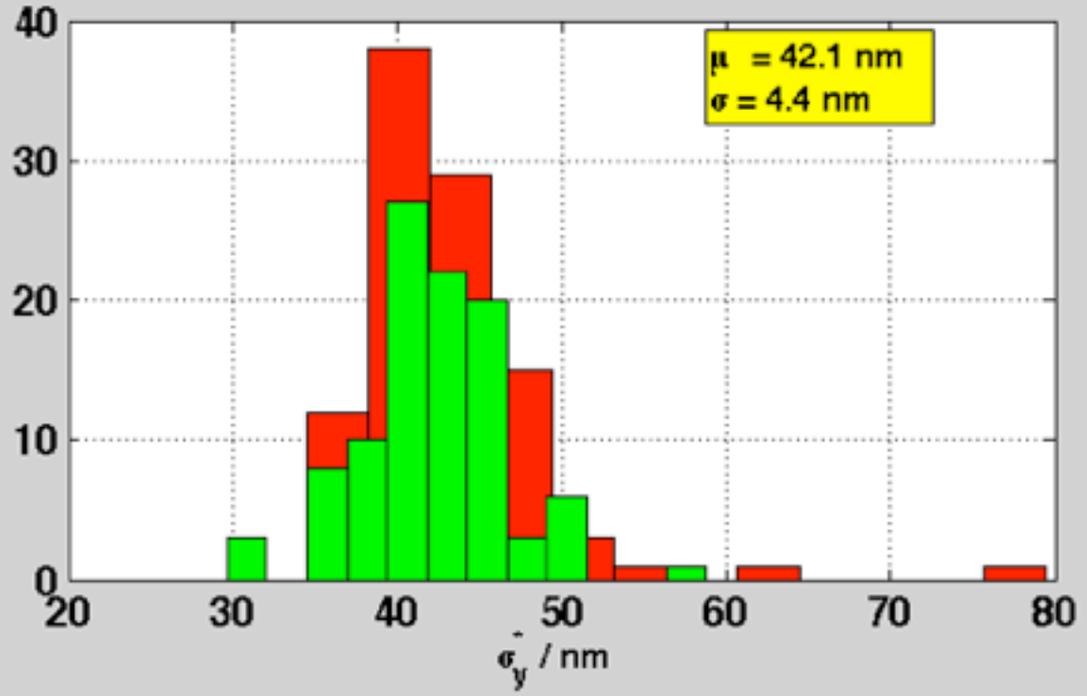

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
σ_y / nm
0
2
4
6
8
10
Knob Iteration Step

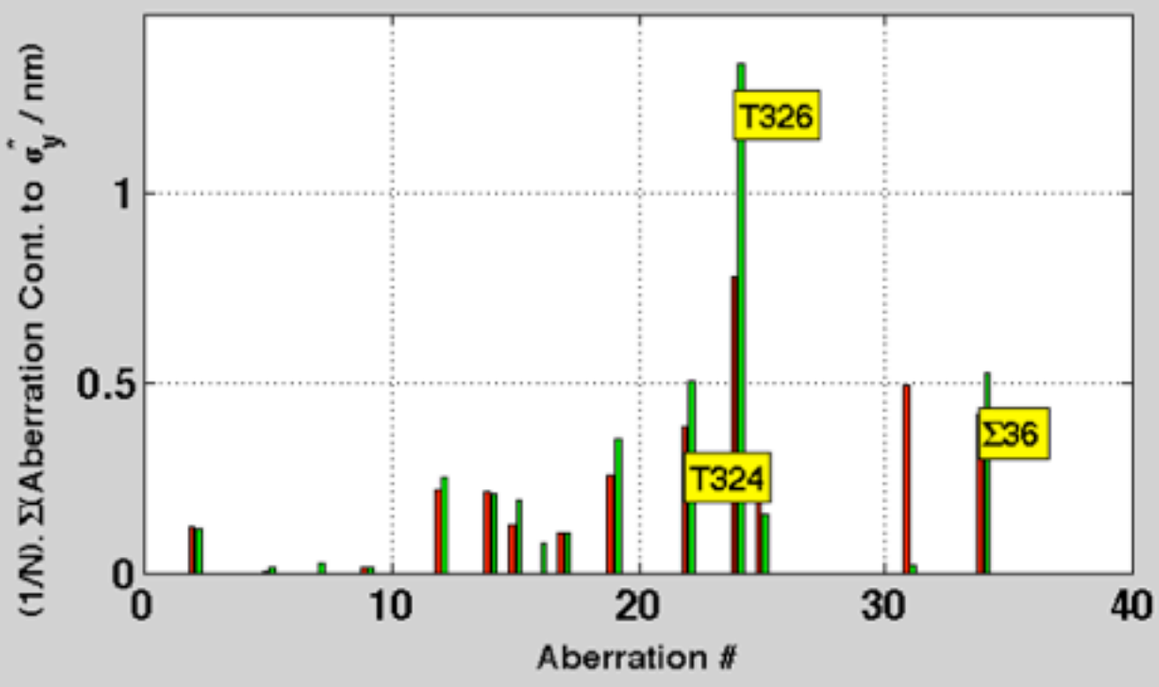

μ = 42.8 nm
σ = 5.7 nm
50
40
30
20
10
0
20
40
60
80
100
σ_y / nm

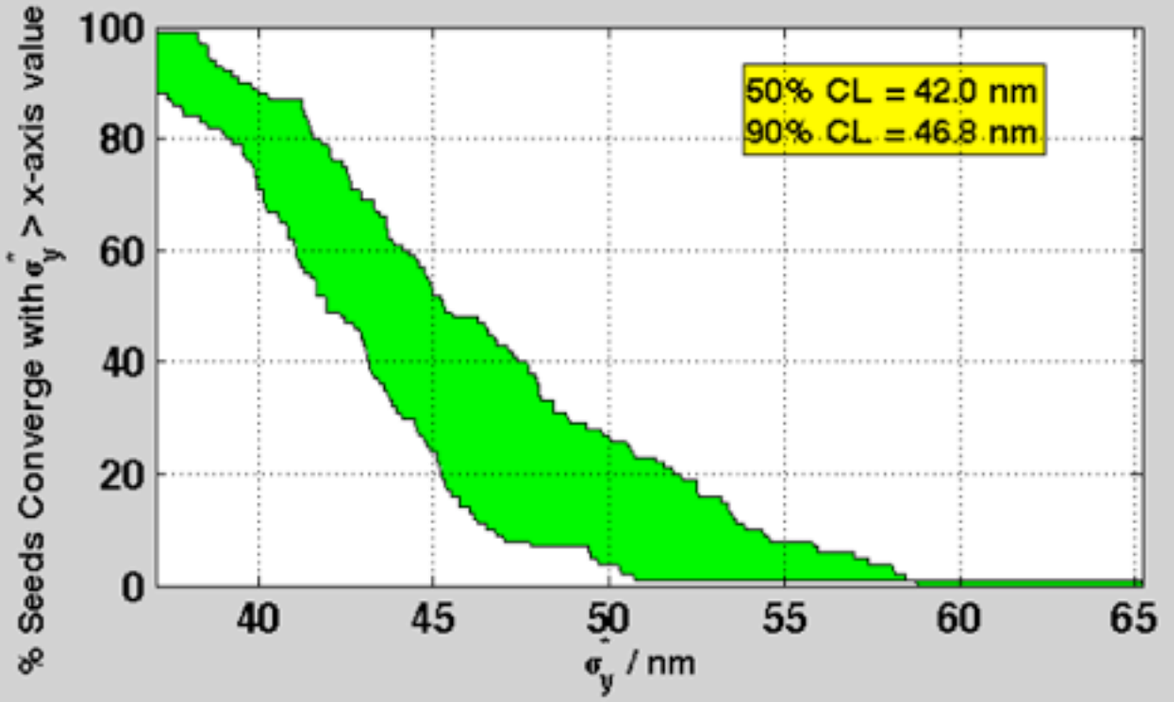

T326
Σ34
Σ36
0.8
0.6
0.4
0.2
0
0
10
20
30
40
(1/N). Σ(Aberration Cont. to σ_y / nm)
Aberration #

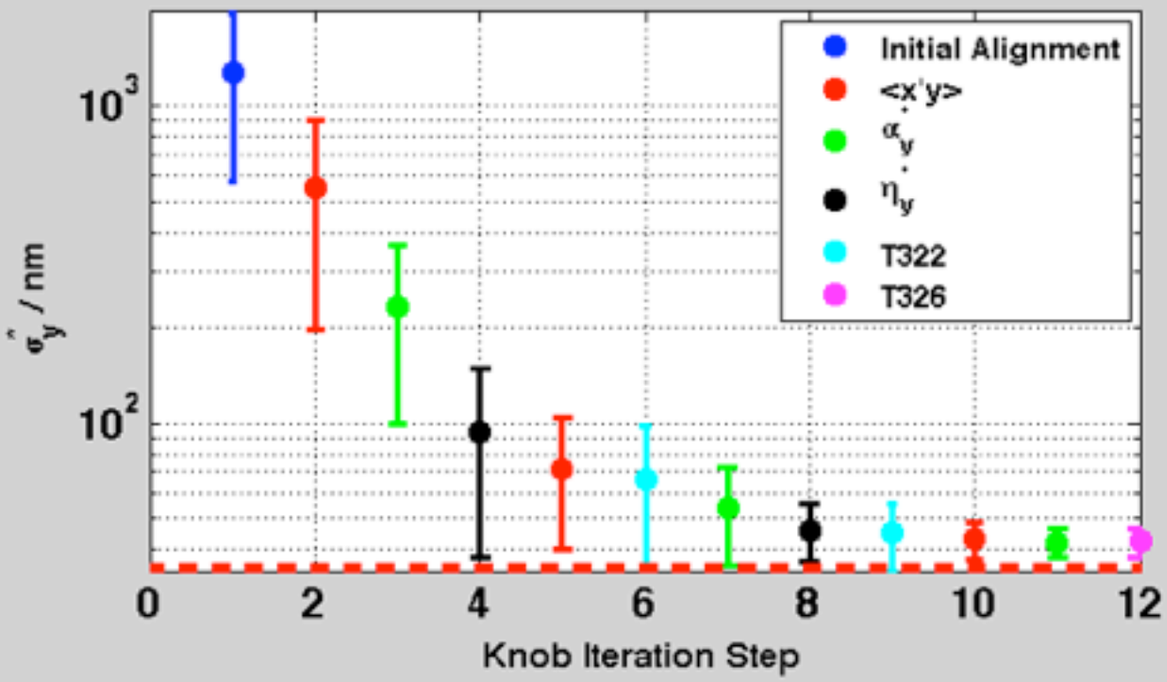

50% CL = 42.0 nm
90% CL = 48.0 nm
100
80
60
40
20
0
40
50
60
70
80
% Seeds Converge with σ_y > x-axis value
σ_y / nm

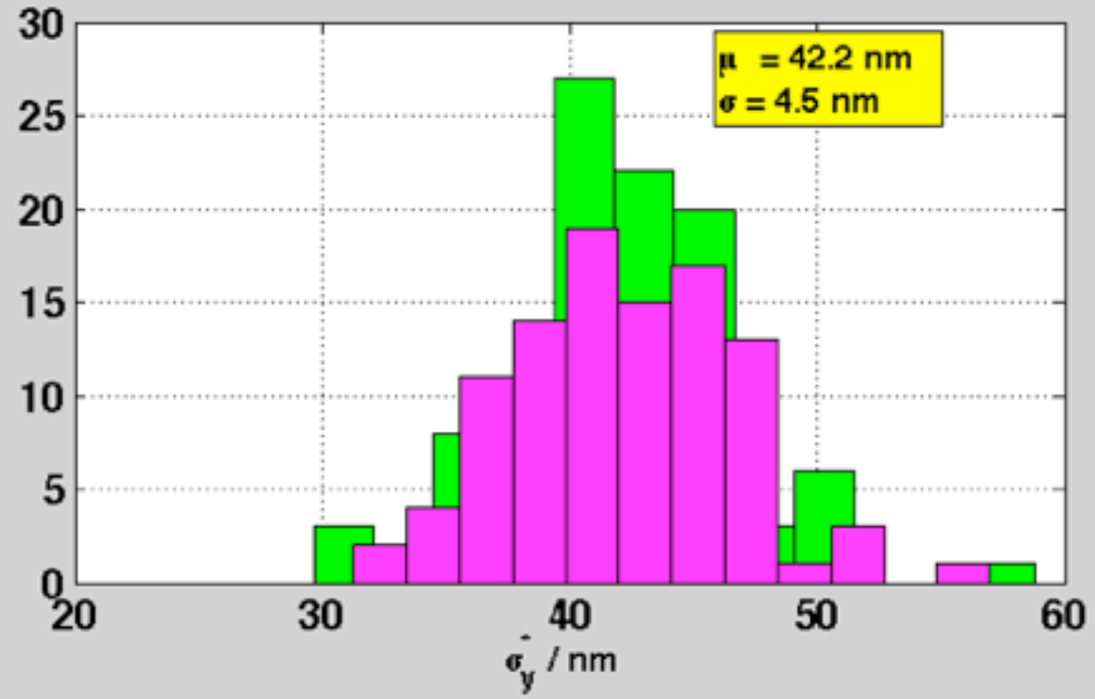

Initial Alignment
<x'y>
α_y^*
η_y^*
T322
T326
10^3
10^2
σ_y^* / nm
0
2
4
6
8
10
Knob Iteration Step

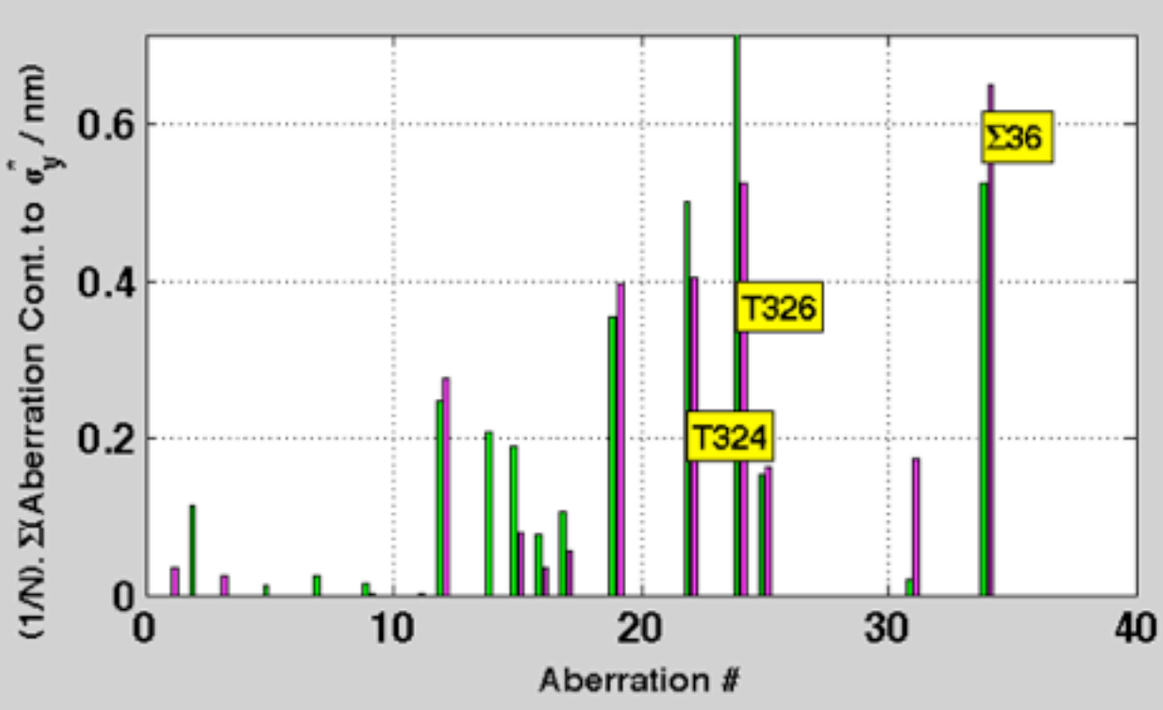

μ = 42.1 nm
σ = 4.4 nm
40
30
20
10
0
20
30
40
50
60
70
80
σ_y^* / nm

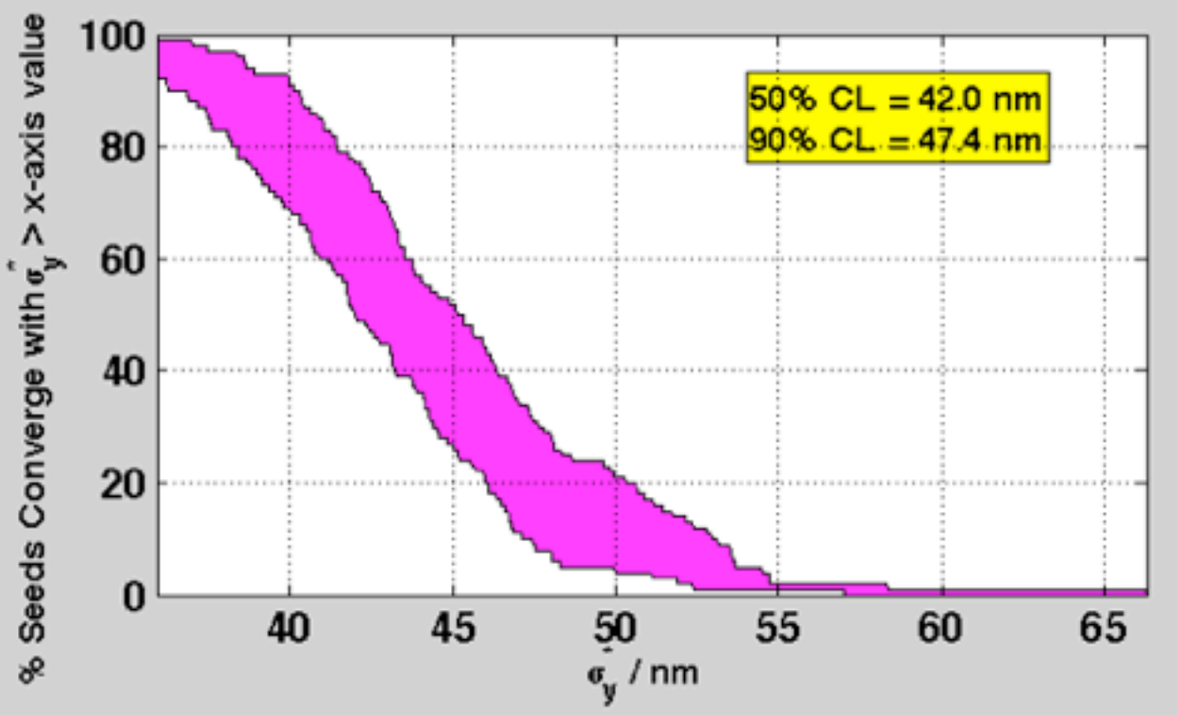

T326
T324
Σ36
(1/N). Σ(Aberration Cont. to σ_y^* / nm)
1
0.5
0
0
10
20
30
40
Aberration #

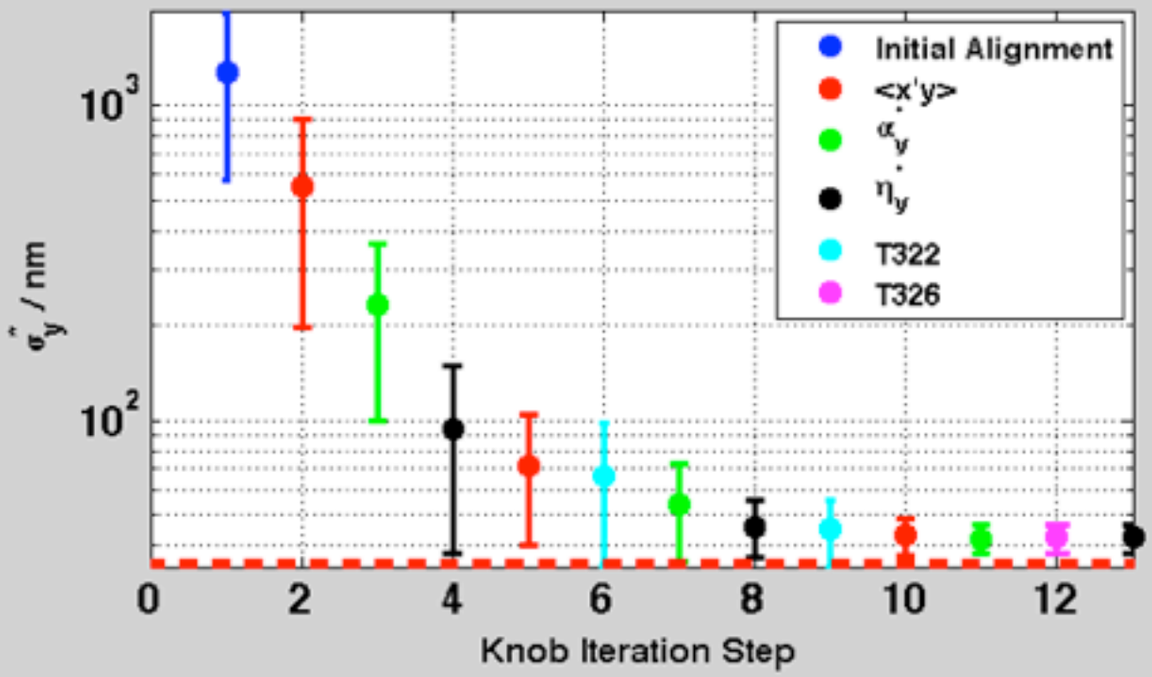

50% CL = 42.0 nm
90% CL = 46.8 nm
% Seeds Converge with σ_y^* > x-axis value
100
80
60
40
20
0
40
45
50
55
60
65
σ_y^* / nm

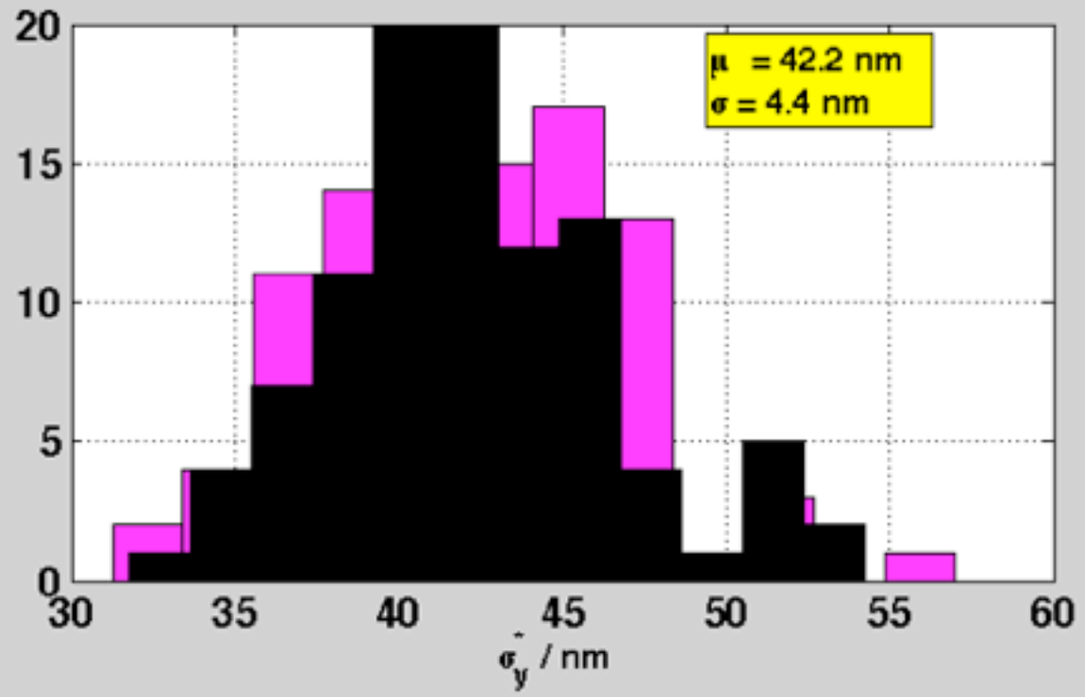

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\hat{\sigma}_y$ / nm
0
2
4
6
8
10
12
Knob Iteration Step

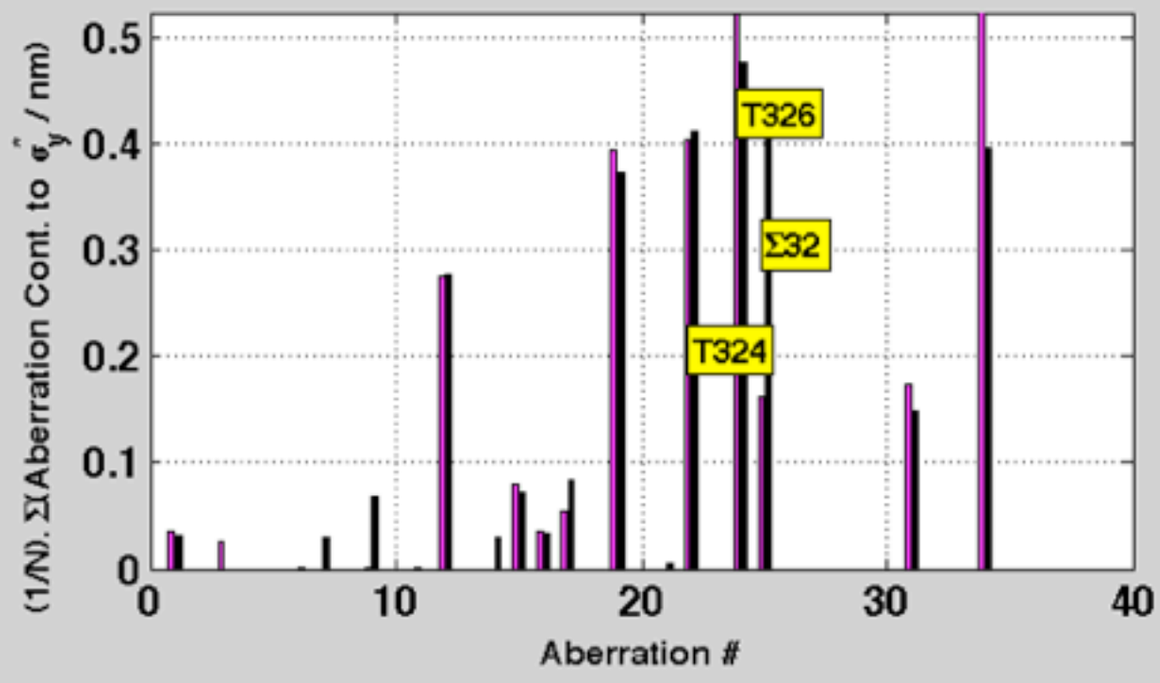

μ = 42.2 nm
σ = 4.5 nm
0
5
10
15
20
25
30
20
30
40
50
60
$\hat{\sigma}_y$ / nm

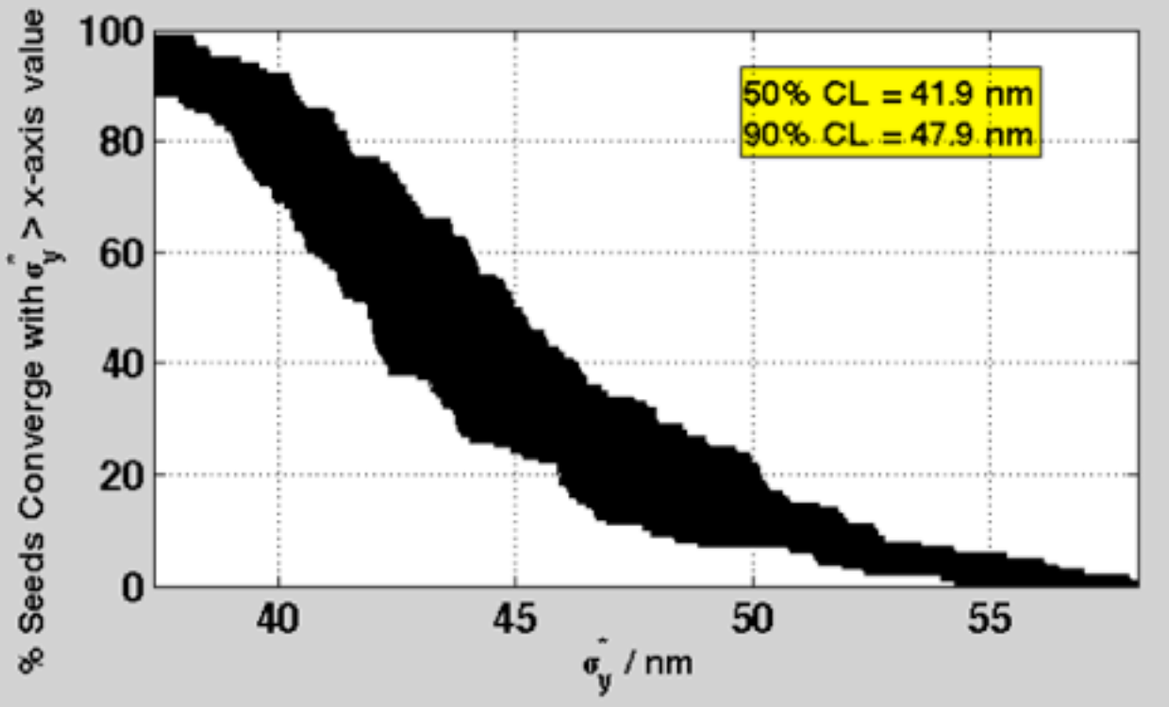

(1/N). Σ(Aberration Cont. to $\hat{\sigma}_y$ / nm)
0
0.2
0.4
0.6
0
10
20
30
40
Aberration #
Σ36
T326
T324


% Seeds Converge with $\hat{\sigma}_y$ > x-axis value
0
20
40
60
80
100
40
45
50
55
60
65
$\hat{\sigma}_y$ / nm
50% CL = 42.0 nm
90% CL = 47.4 nm

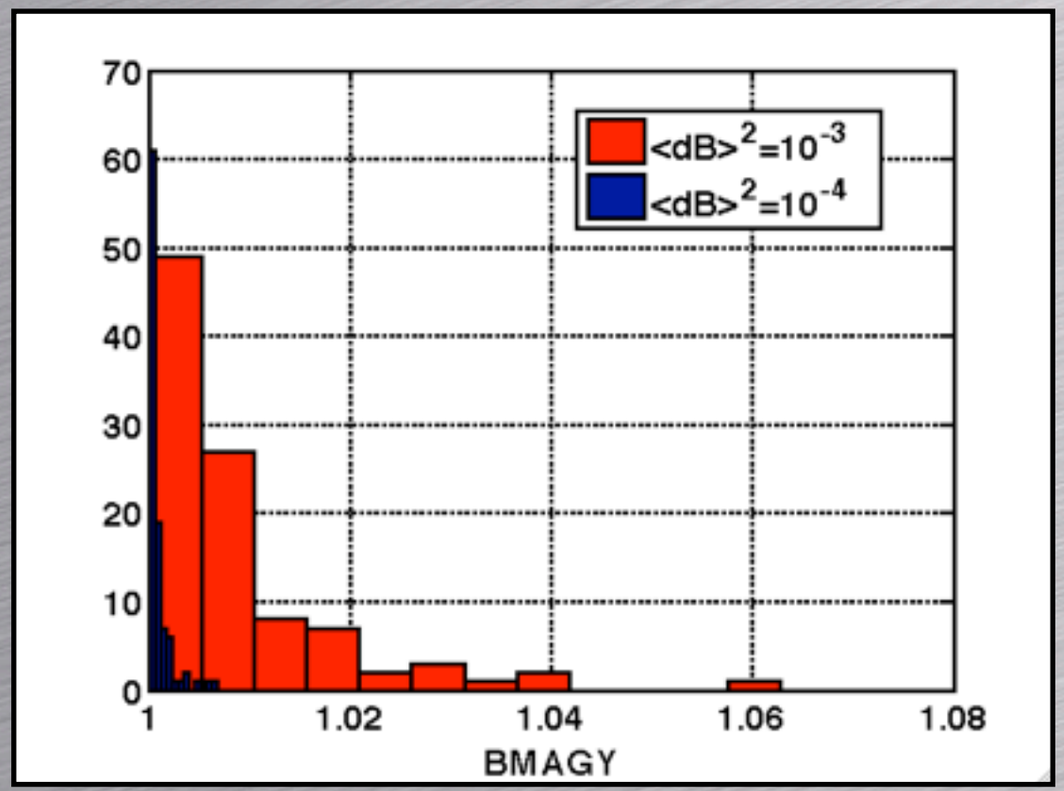

Initial Alignment
<x'y>
α_y
η_y
T322
T326
10^3
10^2
$\hat{\sigma}_y$ / nm
0
2
4
6
8
10
12
Knob Iteration Step

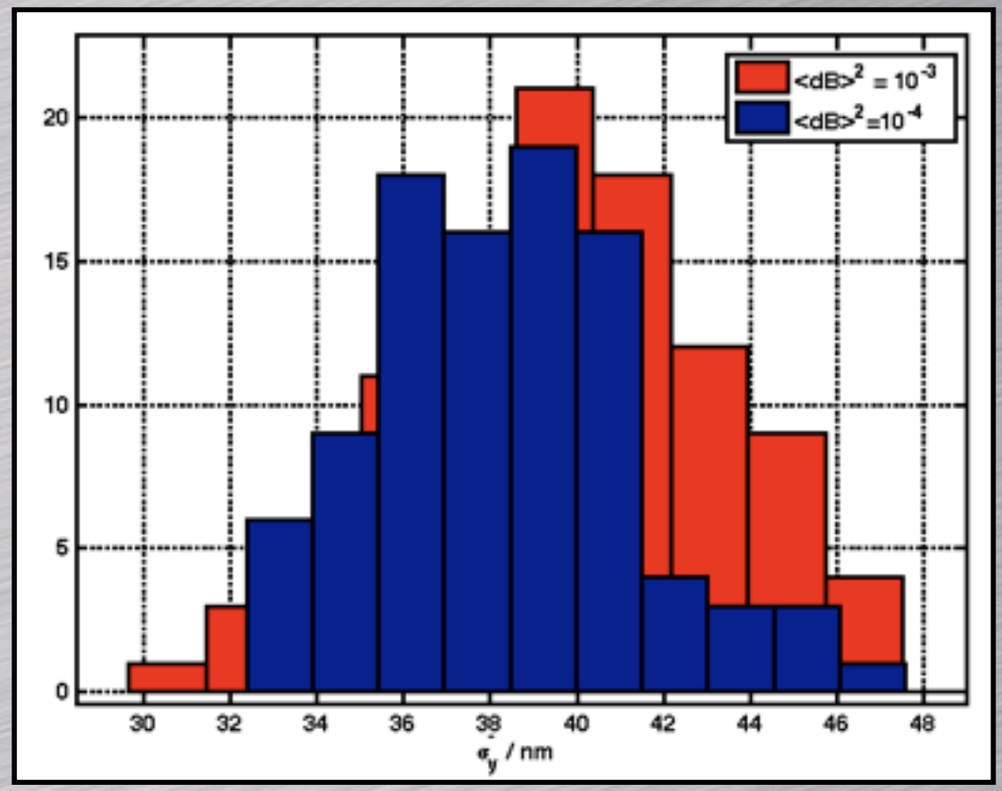

μ = 42.2 nm
σ = 4.4 nm
20
15
10
5
0
30
35
40
45
50
55
60
$\hat{\sigma}_y$ / nm

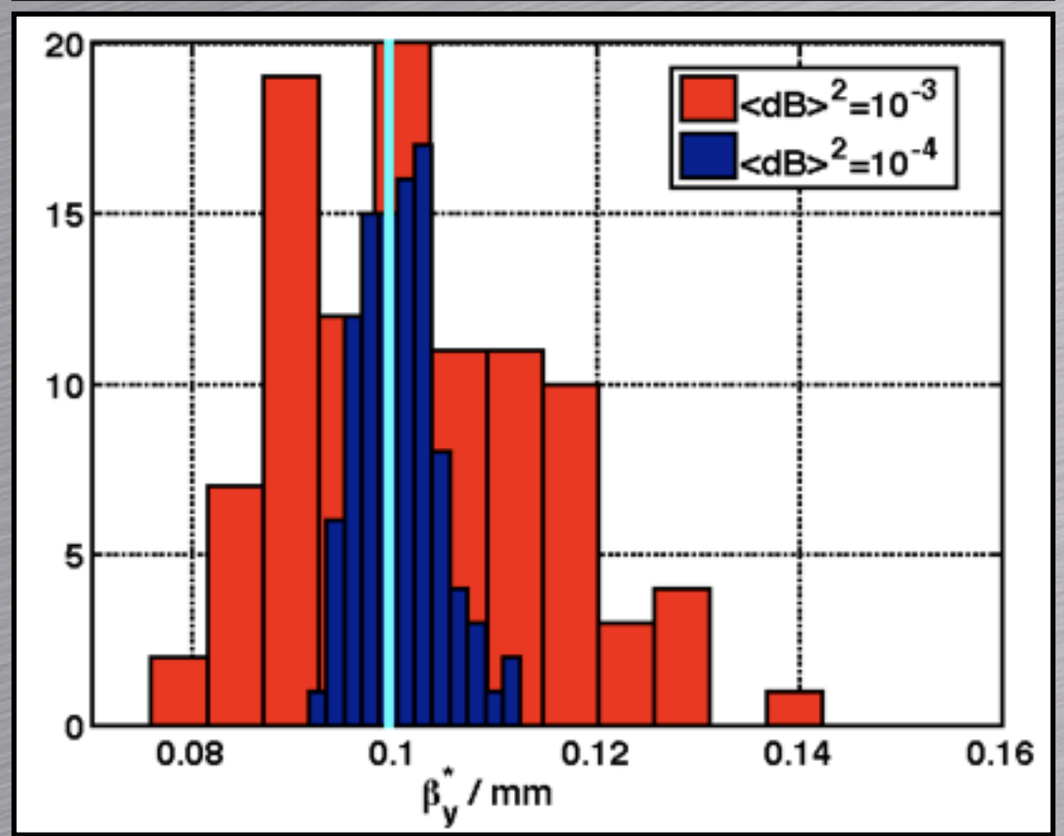

T326
Σ32
T324
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
(1/N). ΣAberration Cont. to $\hat{\sigma}_y$ / nm)
Aberration #


50% CL = 41.9 nm
90% CL = 47.9 nm
100
80
60
40
20
0
40
45
50
55
% Seeds Converge with $\hat{\sigma}_y$ > x-axis value
$\hat{\sigma}_y$ / nm

Effect of Magnet Field Errors

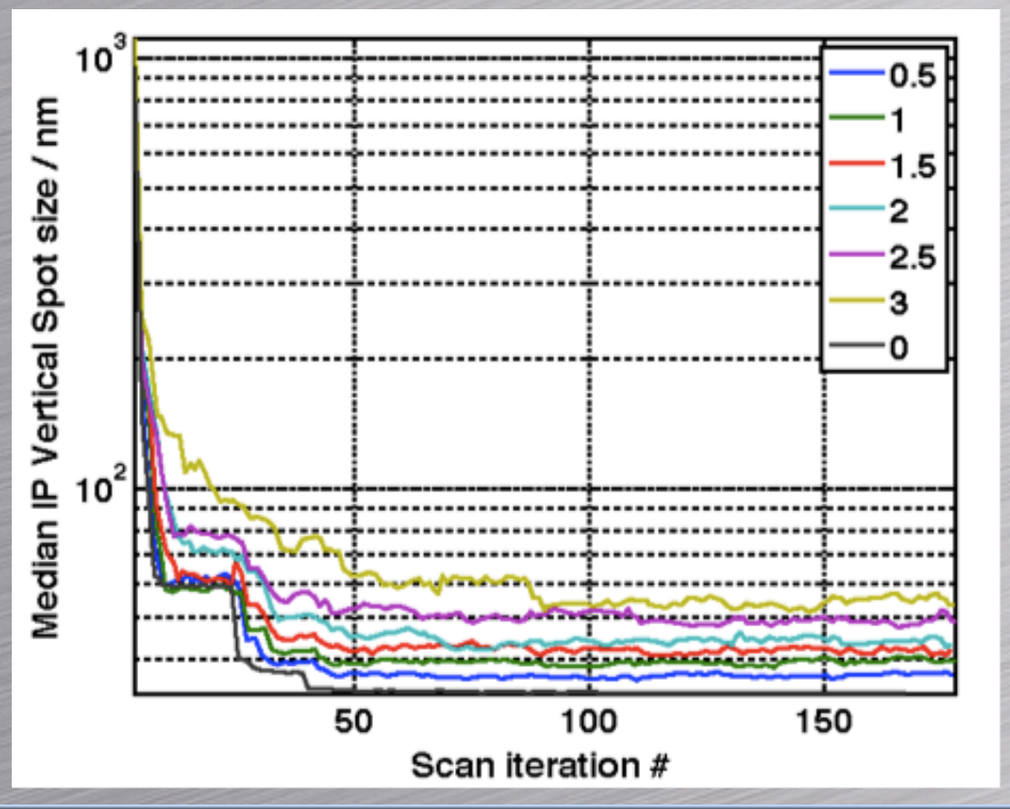


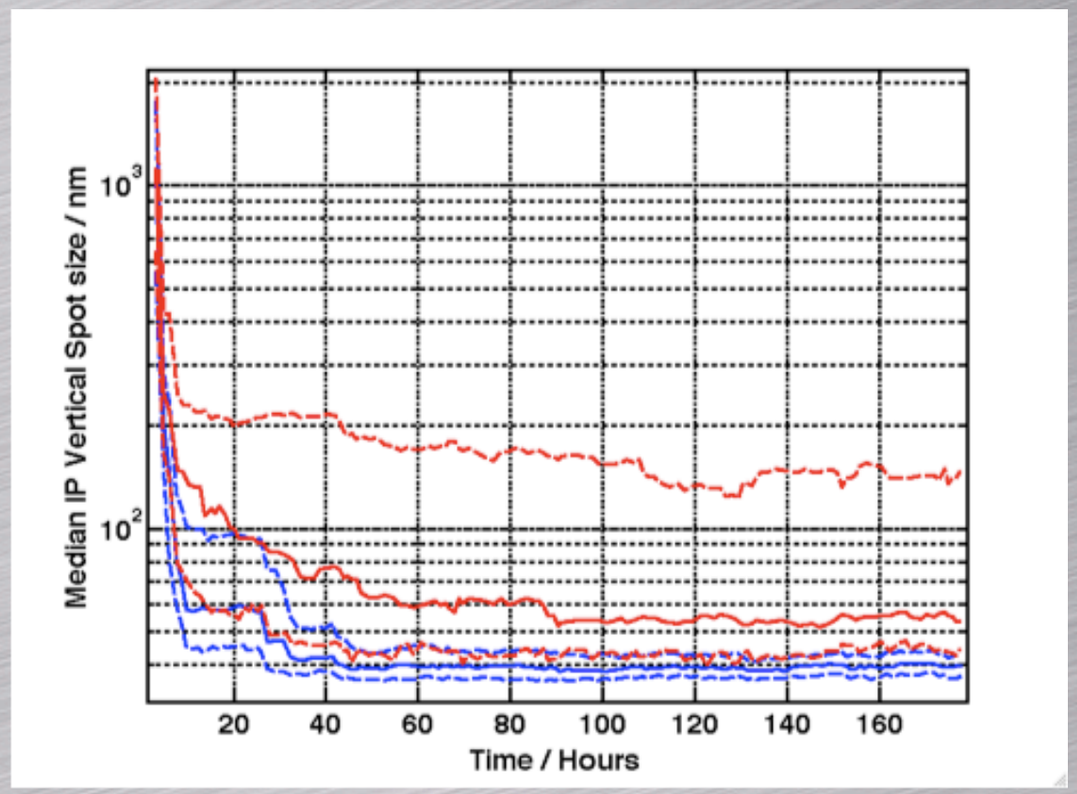


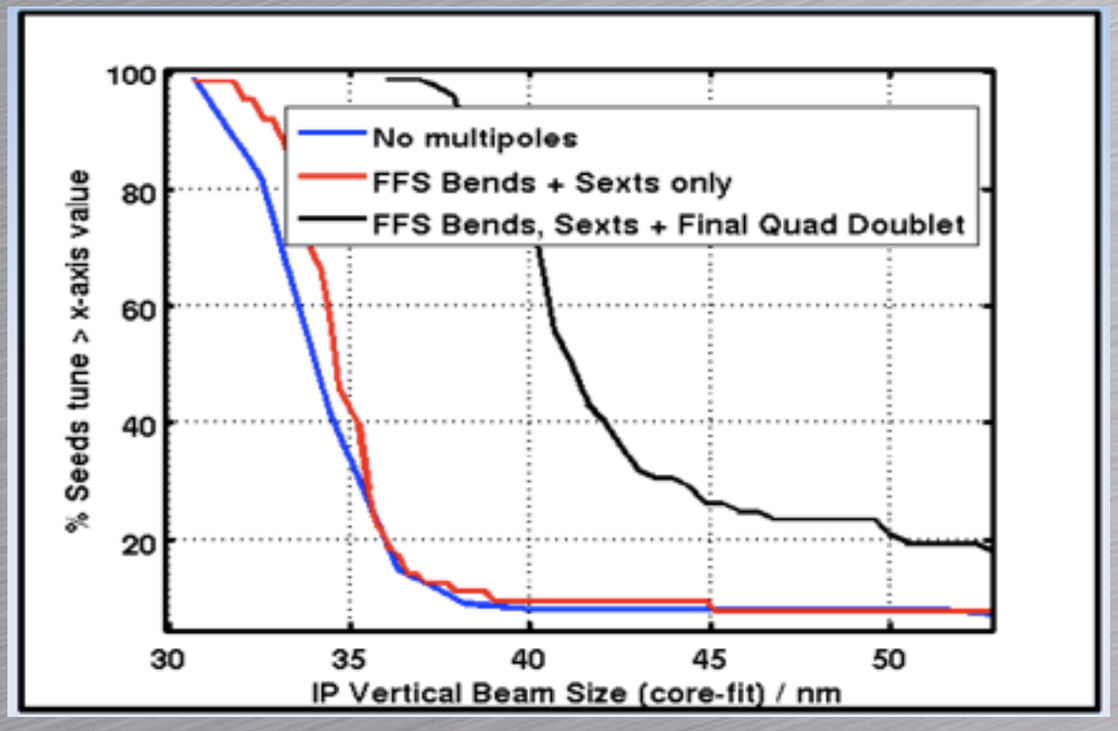


- **Increased magnetic field errors produce undetectable betatron mismatch at IP.**
  - Produces small spread in beam size due to variable focusing, but also damages performance of Sextupole aberration compensation and degrades orthogonality and operability of designed multiknobs.
- **Work to keep small where sensitivities highest.**

Long-Timescale Tuning





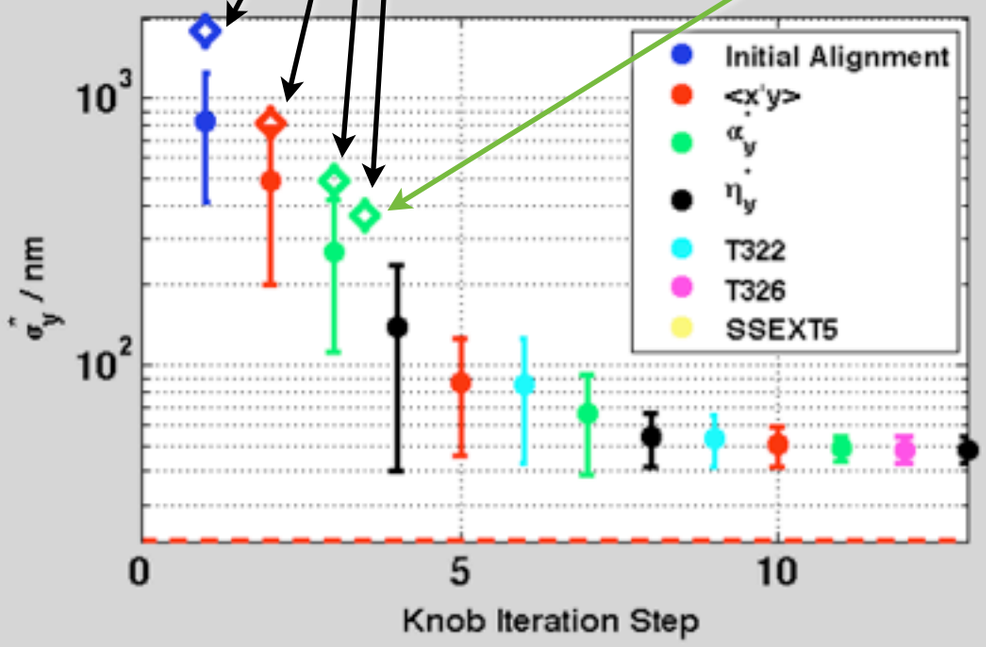


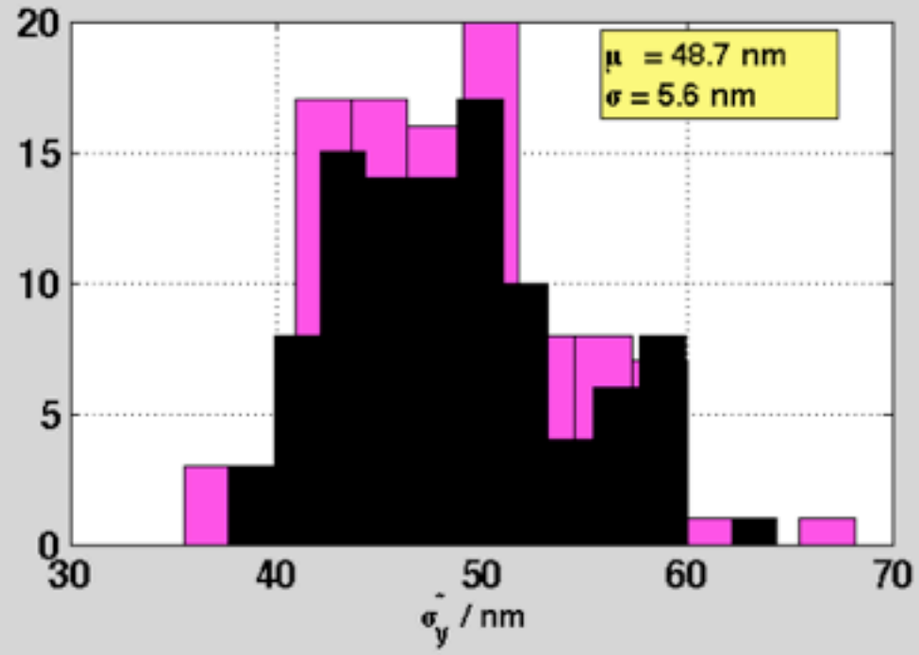
- Application of more basic tuning knobs over long timescales
- Strongly dependent on tuning source noise (here Shintake Monitor)

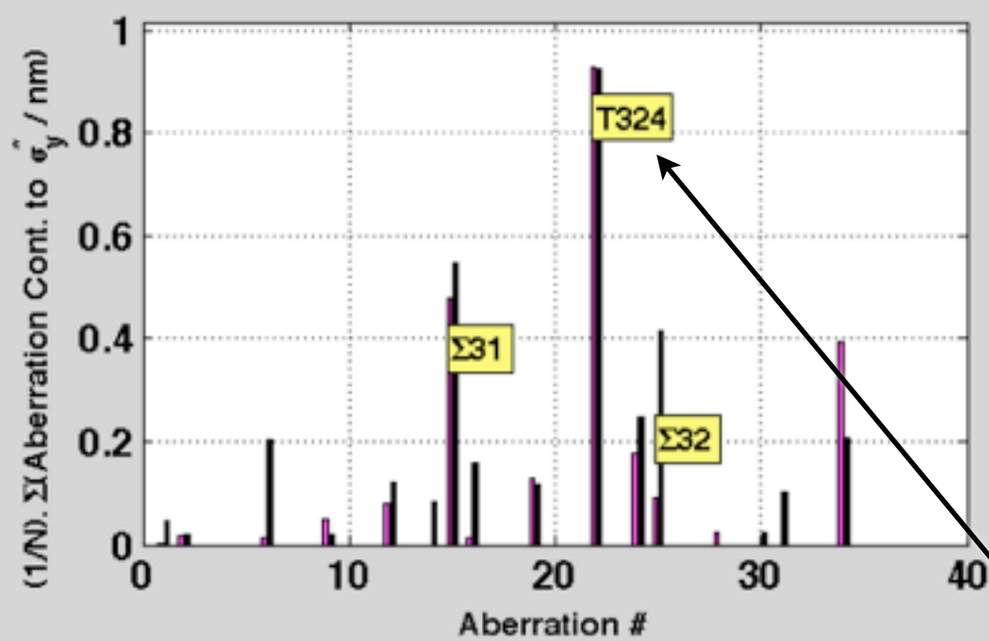
MAPCLASS Tuned Optics with Multipole Data Added (No SEXT Rolls)

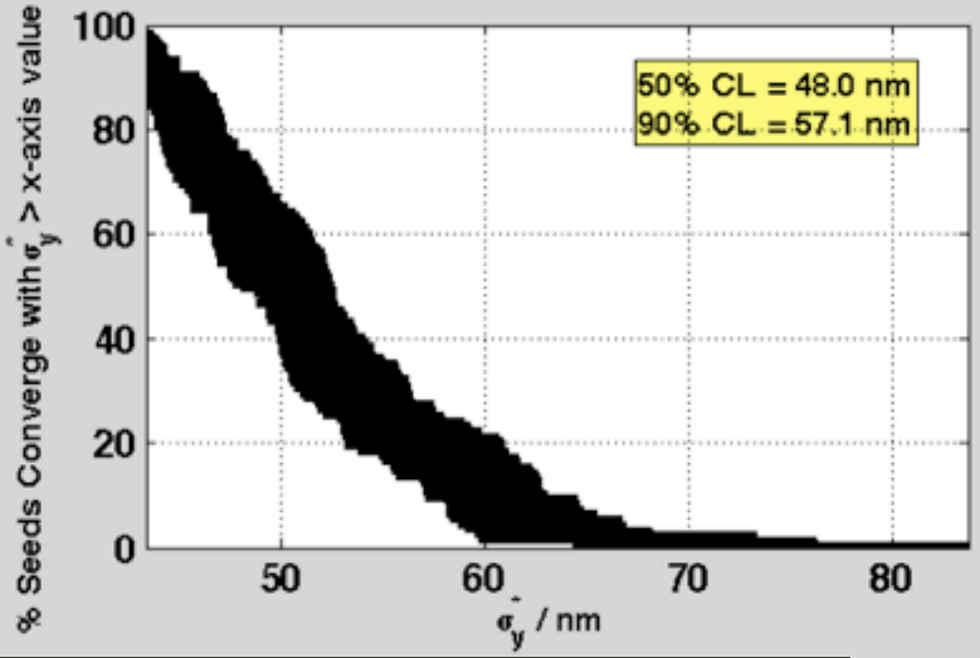
Dec 2010 Tuning Data

<xy> Correction



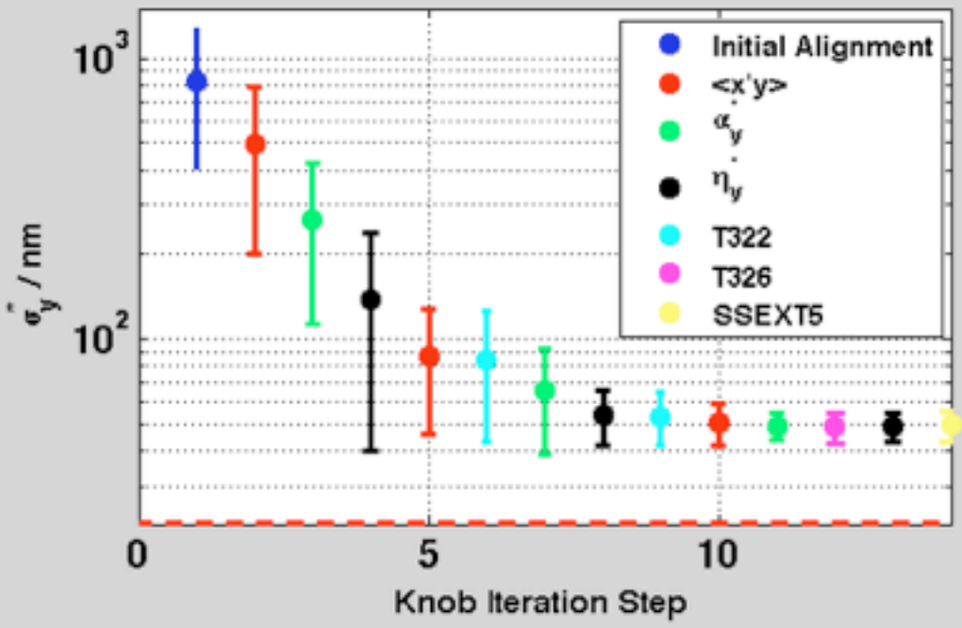


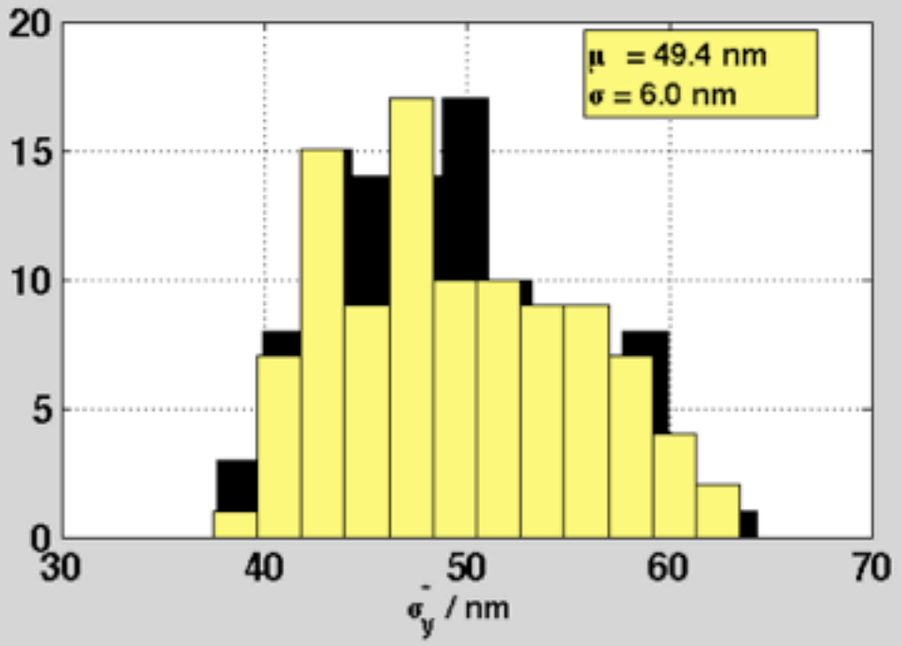


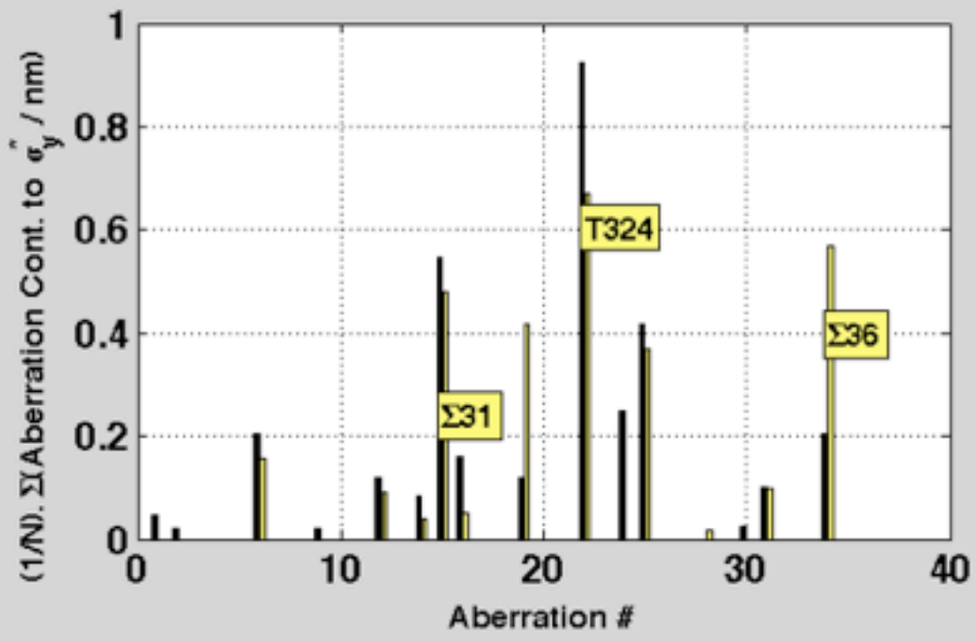


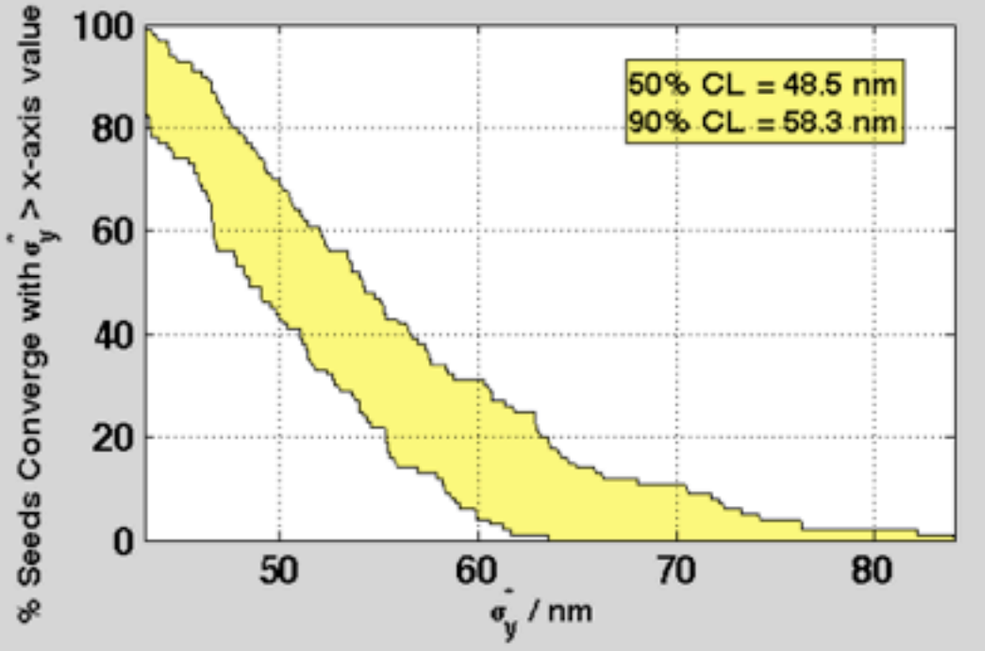
New Aberration Term

Scanning strength of skew sextupole magnet has little effect









"Alternate" Knob Definitions from V-System Interface

Multi-knob Definition Panel

Multi-knob Definition Panel

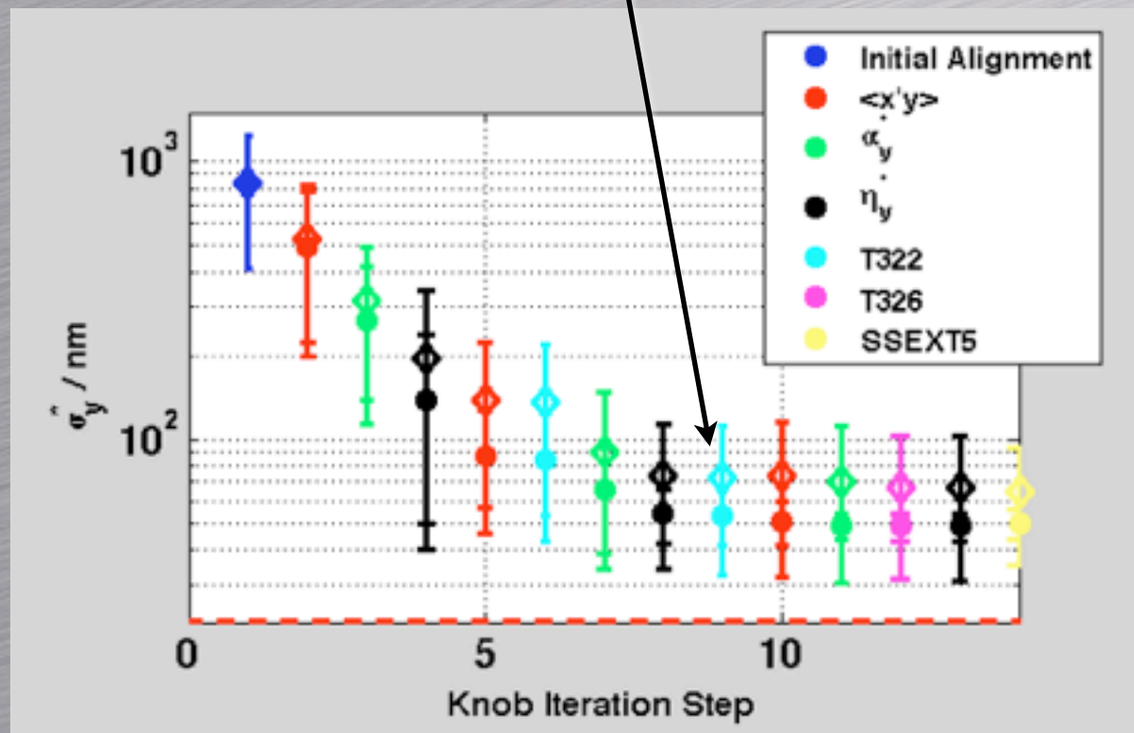
	Ax x	Ax y	Ax tilt	Ex x	Ex y	Ex tilt	Ay x	Ay y	Ay tilt
SF6FF	204.0	0.0	0.0	-95.0	0.0	0.0	7.0	0.0	0.0
SF5FF	-68.0	0.0	0.0	-566.0	0.0	0.0	3.0	0.0	0.0
SD4FF	17.0	0.0	-1.0	-165.0	0.0	0.0	-7.0	0.0	0.0
SF1FF	-74.0	0.0	0.0	355.0	0.0	0.0	-5.0	0.0	0.0
SD0FF	-88.0	0.0	0.0	436.0	0.0	0.0	-10.0	0.0	0.0

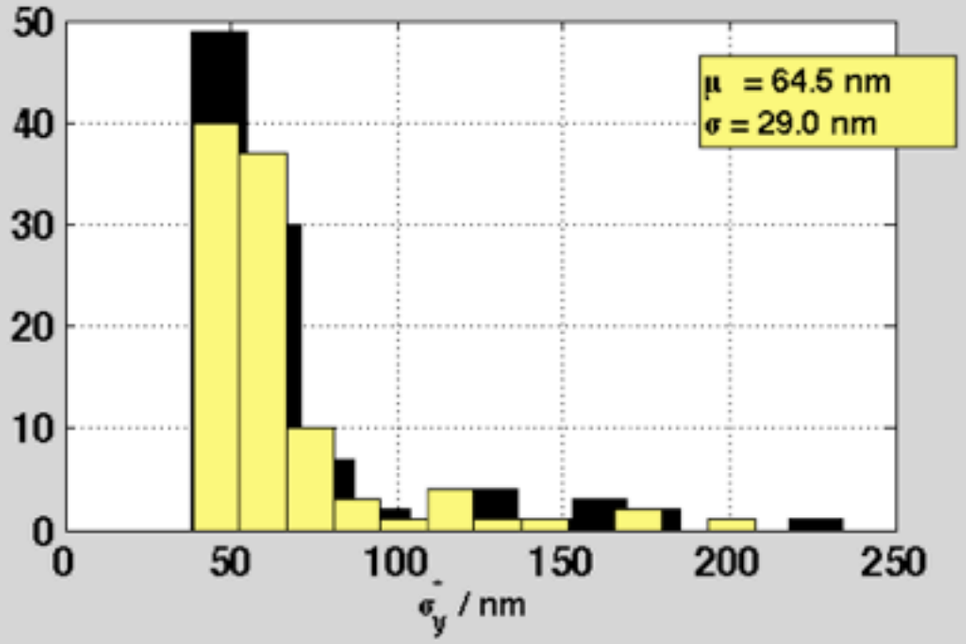
	Ey x	Ey y	Ey tilt	Coup1 x	Coup1 y	Coup1 tilt	<x'y> x	<x'y> y	<x'y> tilt
SF6FF	0.0	-112.0	0.0	0.0	0.0	0.0	0.0	24.0	0.0
SF5FF	0.0	-169.0	0.0	0.0	0.0	0.0	0.0	15.0	0.0
SD4FF	0.0	-337.0	0.0	0.0	0.0	0.0	0.0	49.0	0.0
SF1FF	0.0	164.0	0.0	0.0	100.0	0.0	0.0	-45.0	0.0
SD0FF	0.0	483.0	0.0	0.0	-100.0	0.0	0.0	9.0	0.0

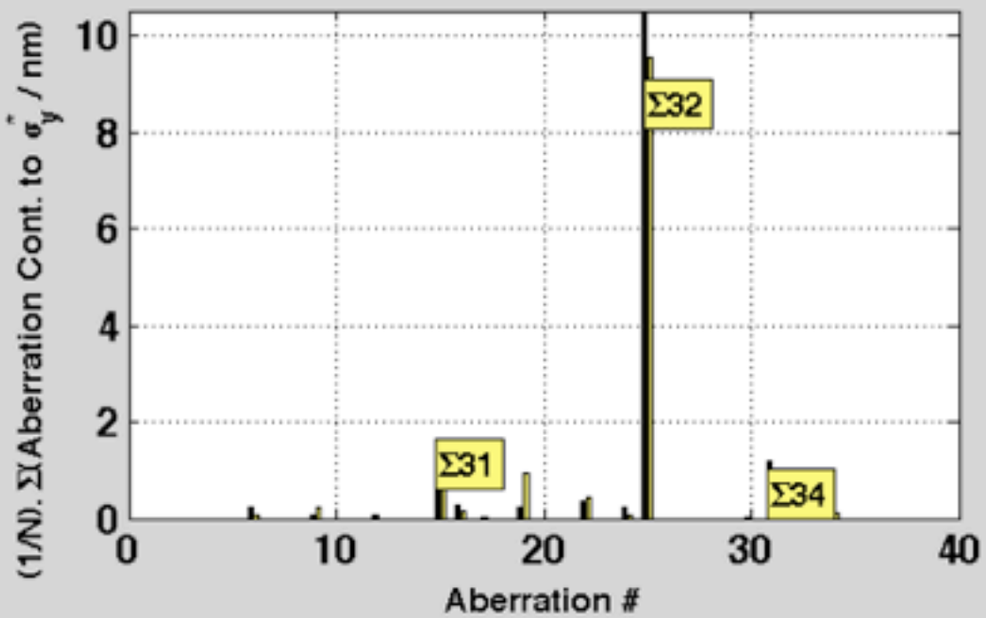
	Spare1 x	Spare1 y	Spare1 tilt	Spare2 x	Spare2 y	Spare2 tilt	Spare3 x	Spare3 y	Spare3 tilt
SF6FF	0.0	-66.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SF5FF	0.0	-165.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SD4FF	0.0	-14.0	0.0	0.0	0.0	0.0	0.0	200.0	0.0
SF1FF	0.0	233.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SD0FF	0.0	117.0	0.0	0.0	800.0	0.0	0.0	0.0	0.0

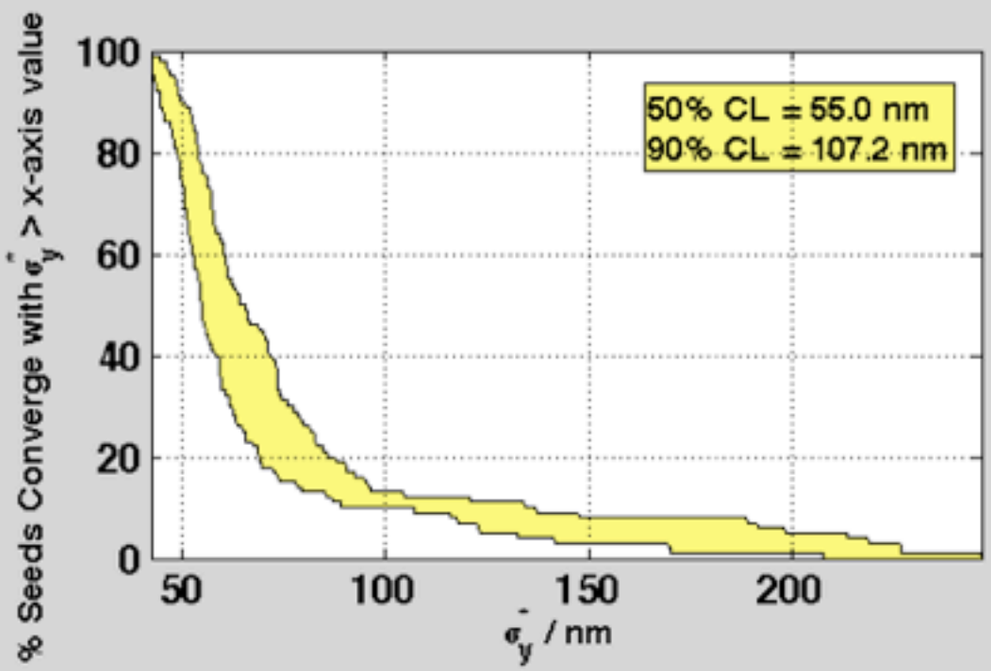
- **Compare expected tuning performance of these knobs substituted with the similar knobs developed earlier.**

Diamonds = Alternate Knobs
Circles = Previously demonstrated knobs



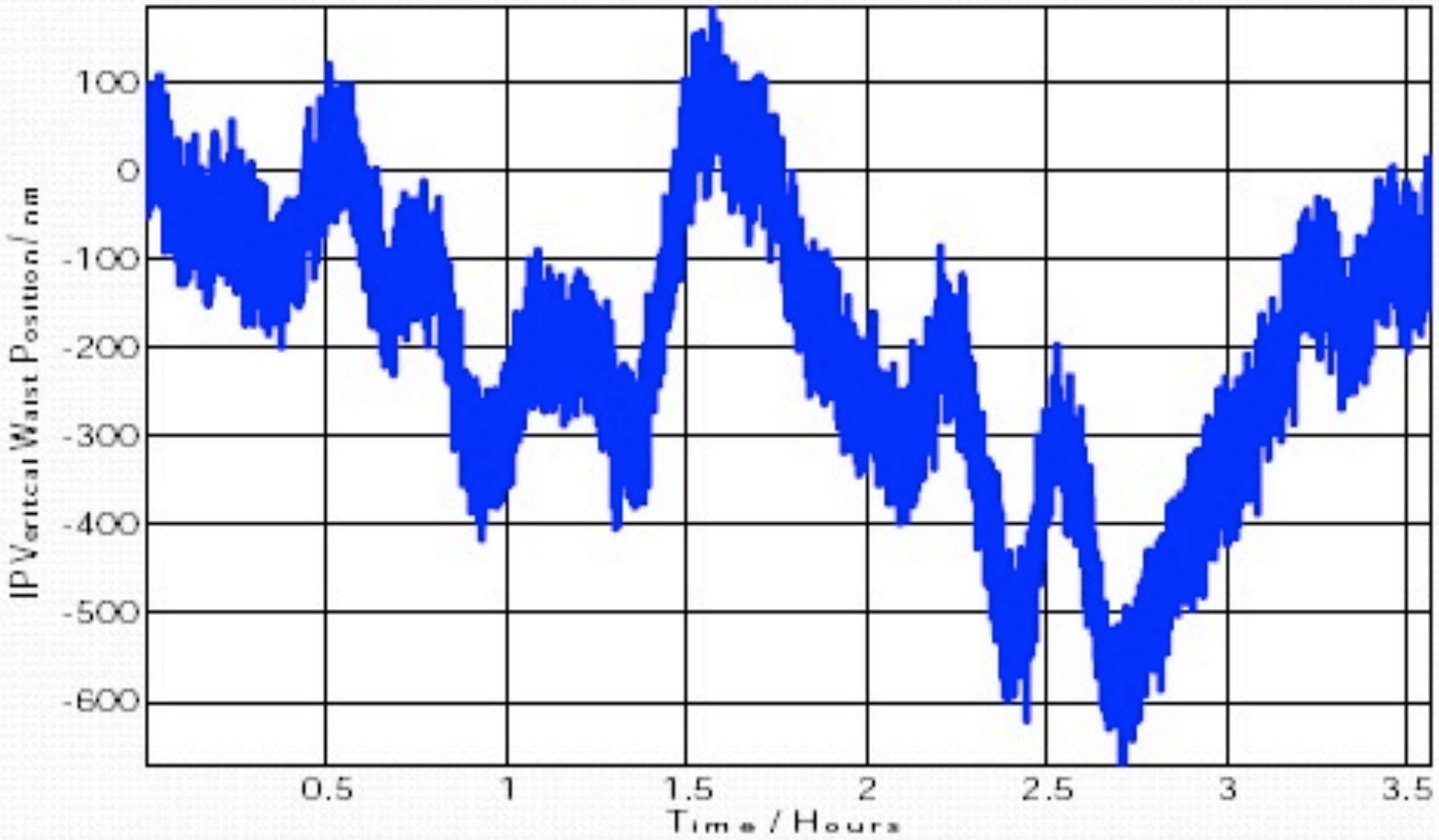






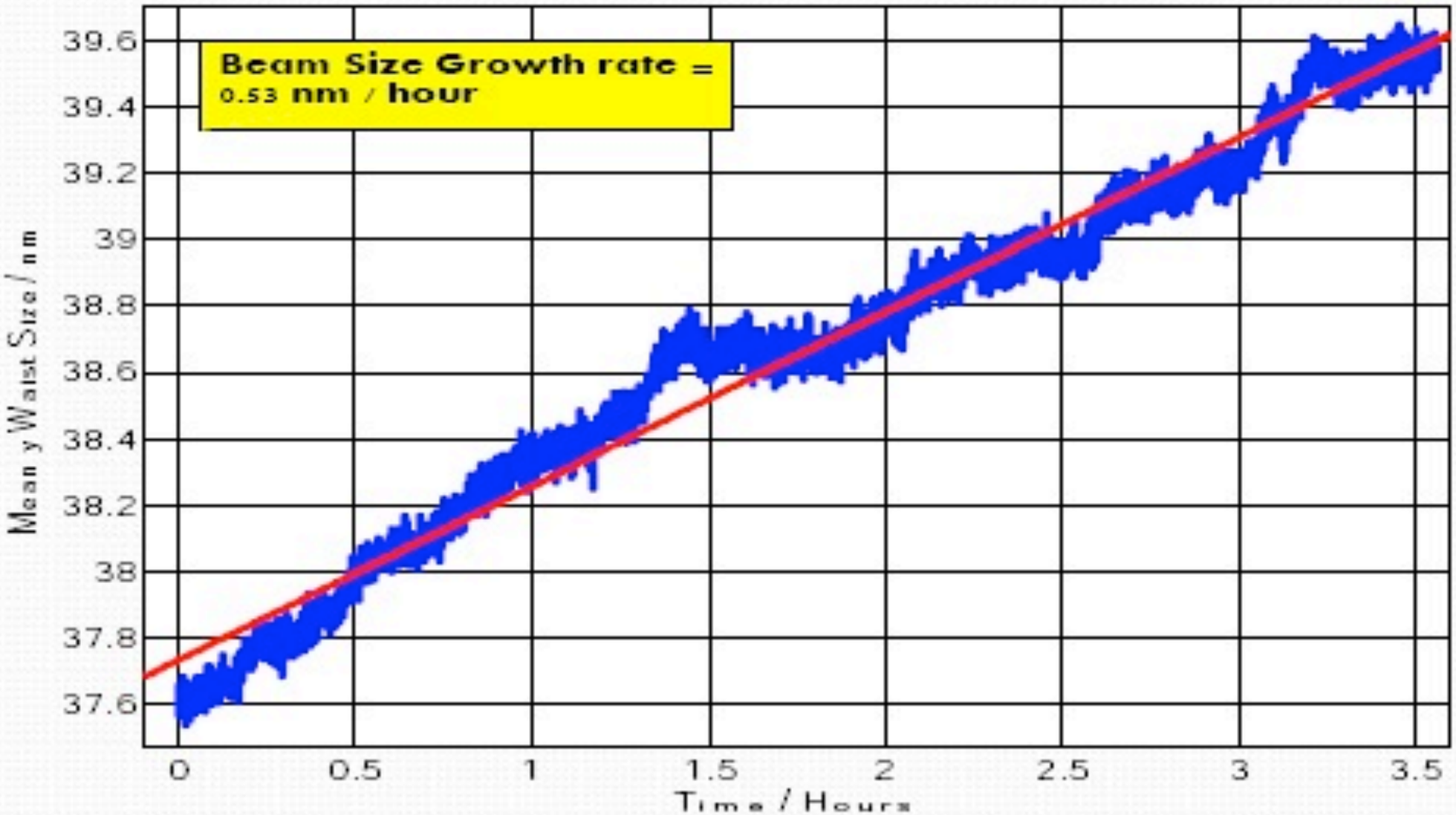
Dynamic Effects

IP Motion



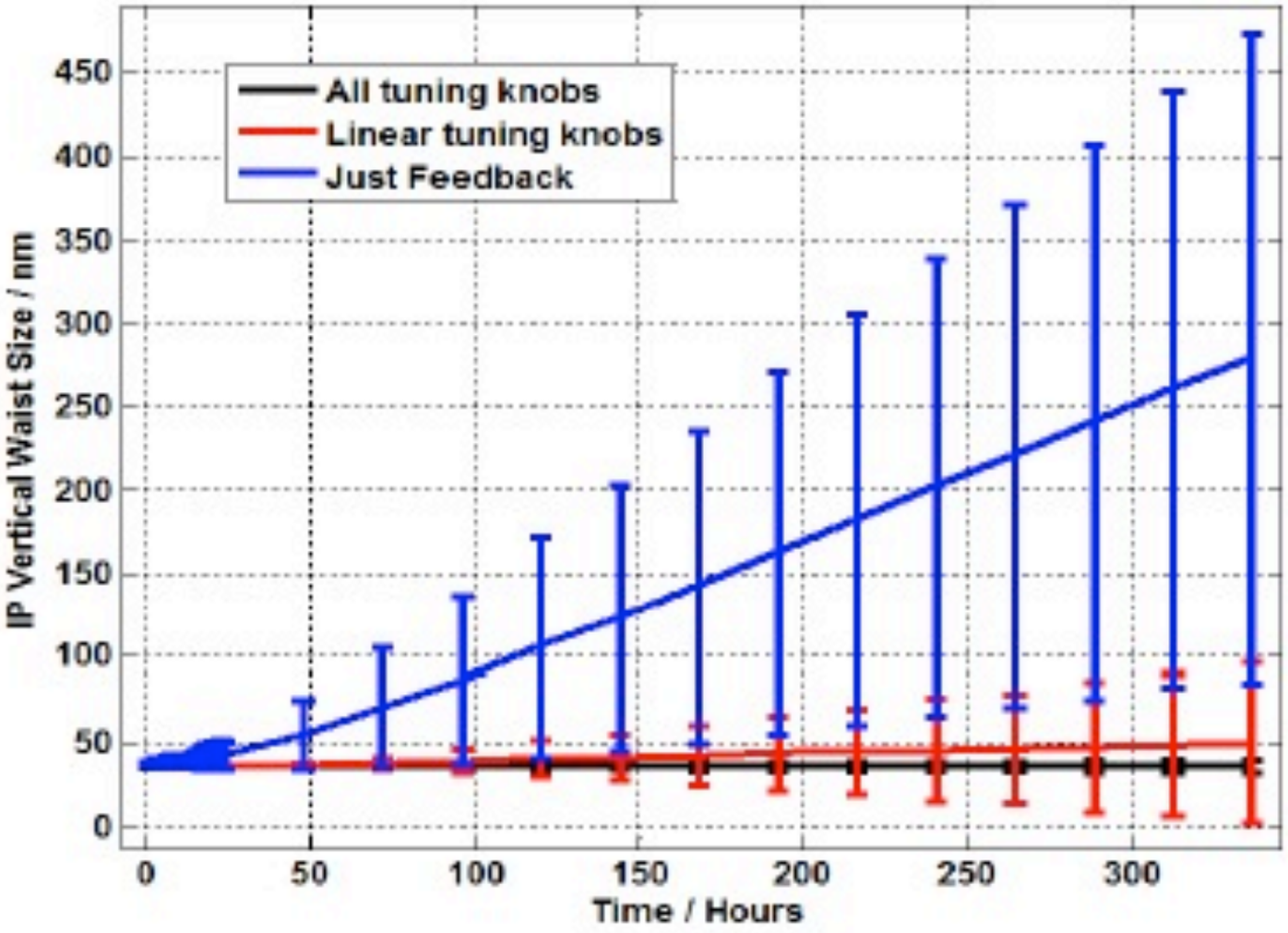
- 20,000 pulses @ 1.56 Hz (1 seed)
- IP vertical position drifts around on scales of a few 100 nm an hour.
- Slow enough that this can be 'de-trended' using Shintake Monitor as IP position monitor.

Beam Size Growth



- With feedbacks on, y beam size at IP as a function of time
- Mean of 100 seeds shown
- Growth rate ~ 0.5 nm per hour

Long – Timescale Performance



At each point, none, linear (waist, dispersion and coupling) and full tuning knobs (include sextupole strength and tilt scans) applied. For blue, red and black respectively.

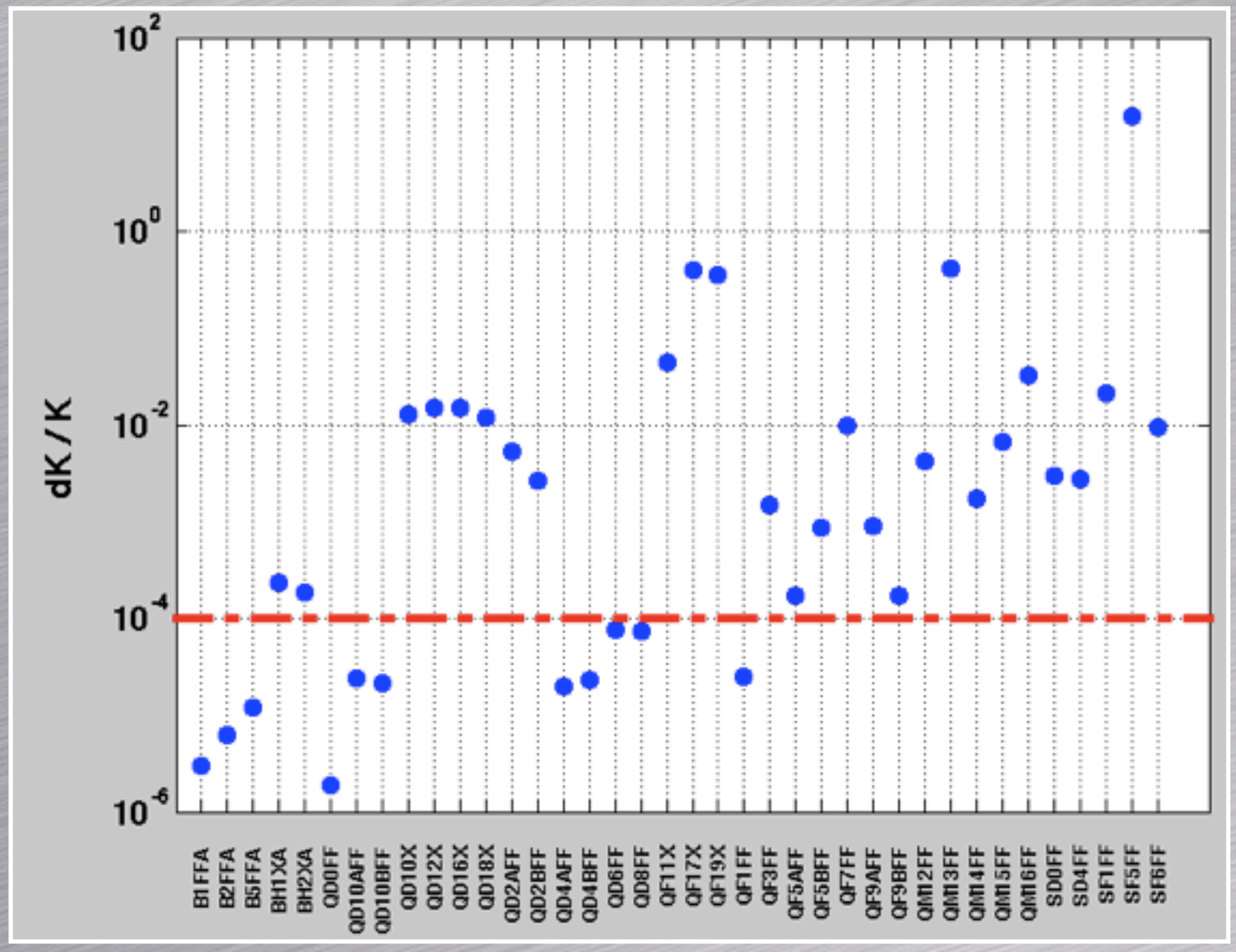
- Vertical IP beam size over 2 week period
- Mean and +/- 1 sigma RMS from 100 seeds shown at each point

Summary

- Established tuning procedure for normal optics configuration (no multipoles) which produces goal IP spot size in a timescale of a few shifts.
- Including the measured multipole values introduces additional aberrations which are harder to remove and a reduced performance is expected, vertical IP spot size expected 50-60 nm after tuning.
- Adding single skew sextupole and adding strength as a knob does not have any effect, needs to be set based on MAPCLASS initial matching prior to tuning and not used as a knob.
- Adding T324 knob may improve results, will investigate next.

backup slides

Magnet Strength Sensitivities



- Relative setting error of magnets to produce an increase in vertical spot size at IP of 1nm.

Lucretia Software Development

- **LucretiaMC**
  - Extension to Matlab-based Lucretia particle tracking program to enable real-time parallel consideration of multiple Beamline ‘seeds’.
  - Use Matlab “Distributed Computing Server and toolbox” tools to distribute multiple versions of beamline arrays across multiple host machines and operate on these globally.
- **Extend Lucretia tracking engine to deploy in a parallel fashion on either a GPU or multi-core CPU**

Vertical Dispersion Knob

	SF6	SF5	SD4	SF1	SD0	QD0
X						
Y	-0.623		-0.126	0.514	0.549	
Roll						-1

<x'y> Coupling Knob

	SF6	SF5	SD4	SF1	SD0	QD0
X						
Y	0.516		-0.176	0.032	0.242	
Roll						1

Vertical Waist Shift Knob

	SF6	SF5	SD4	SF1	SD0	QD0
X	0.461		-1	0.206		
Y	-0.154		0.047	0.696	0.418	
Roll						

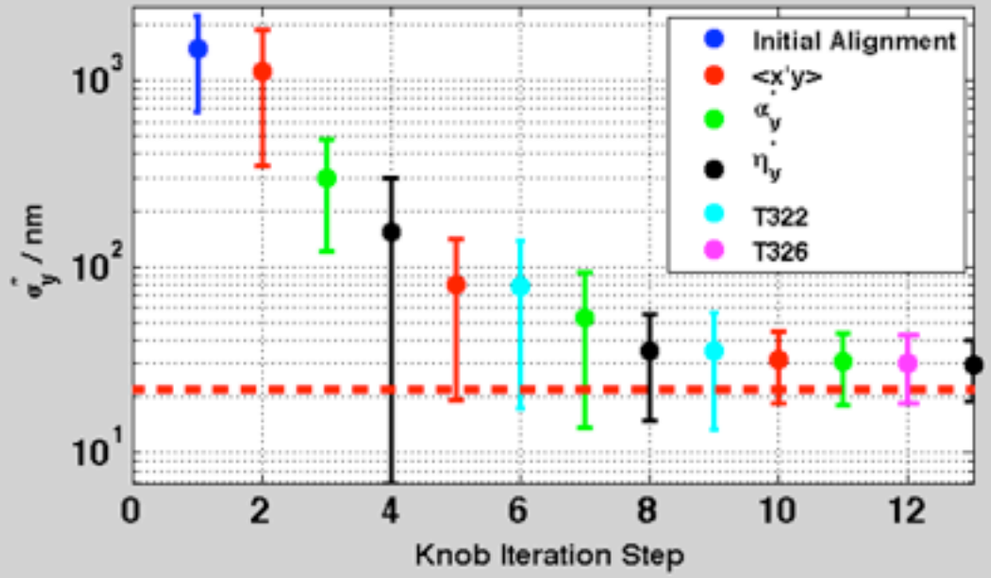
T322 Knob

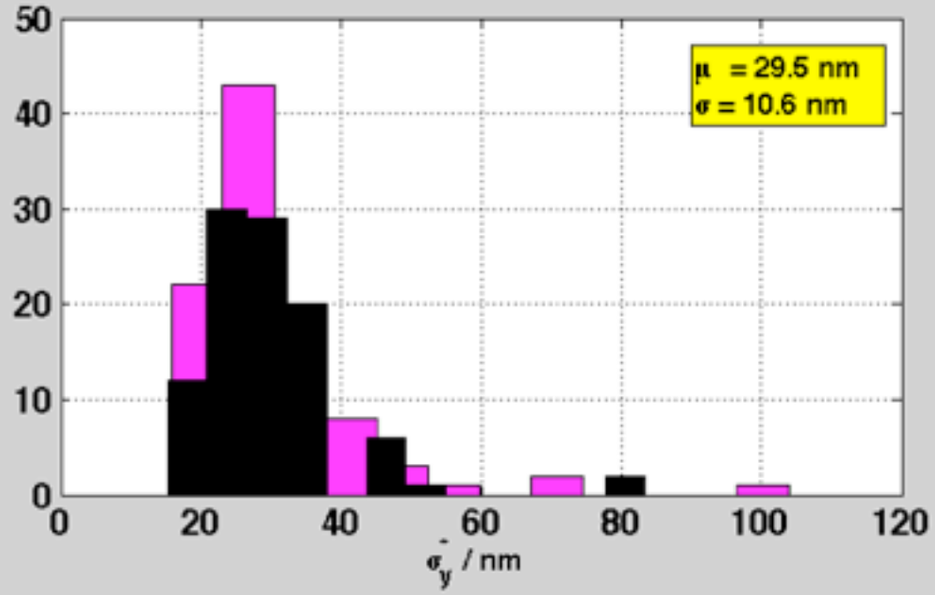
	SF6	SF5	SD4	SF1	SD0	QD0
X						
Y	0.417		-0.17	0.833	0.649	
Roll						1

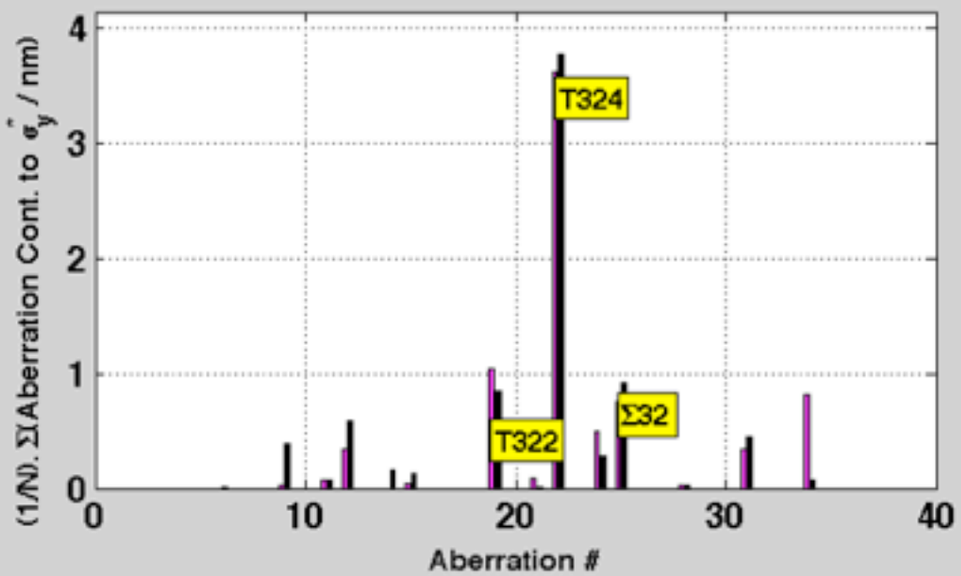
T326 Knob

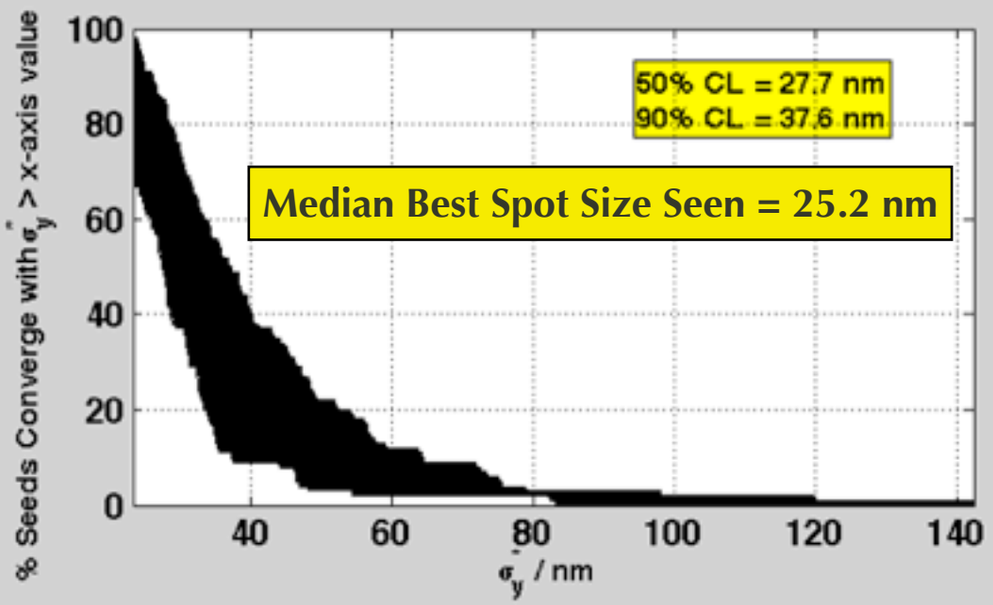
	SF6	SF5	SD4	SF1	SD0	QD0
X						
Y	-0.717		0.294	0.311	0.035	
Roll						-1

0.03mm β_y Optics Test

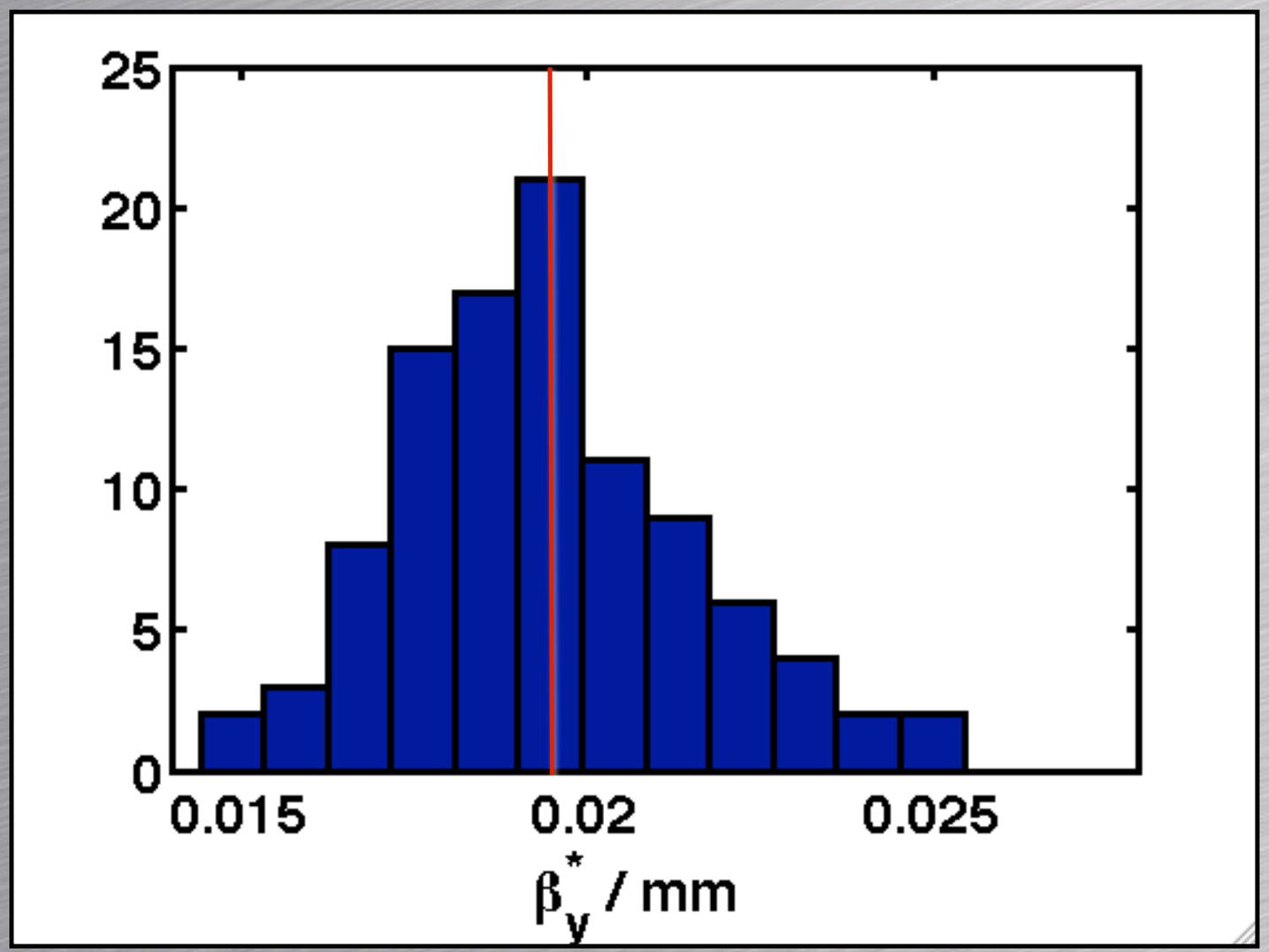






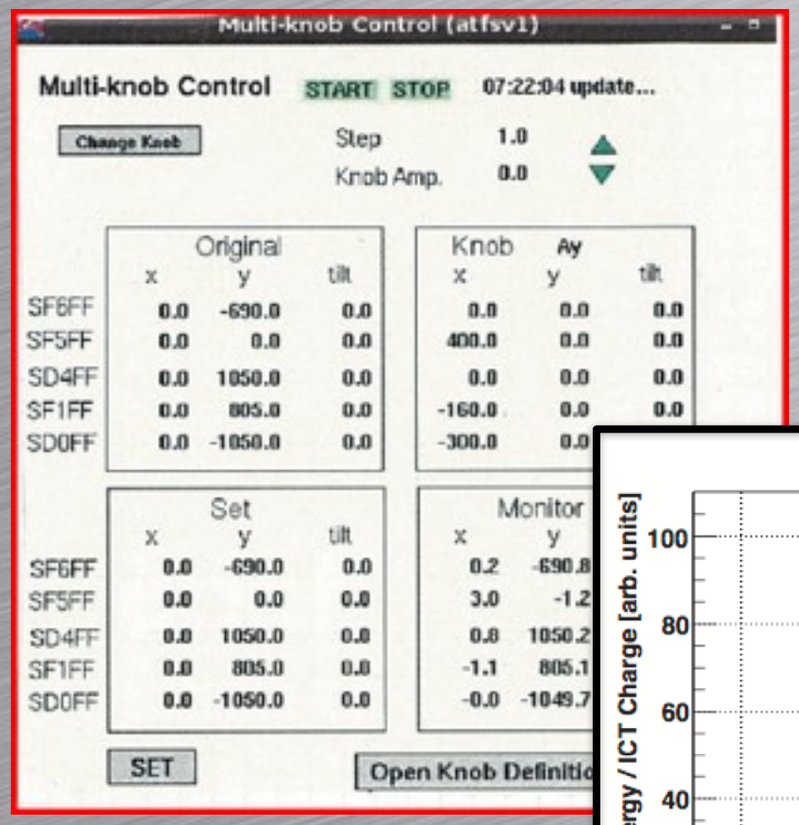


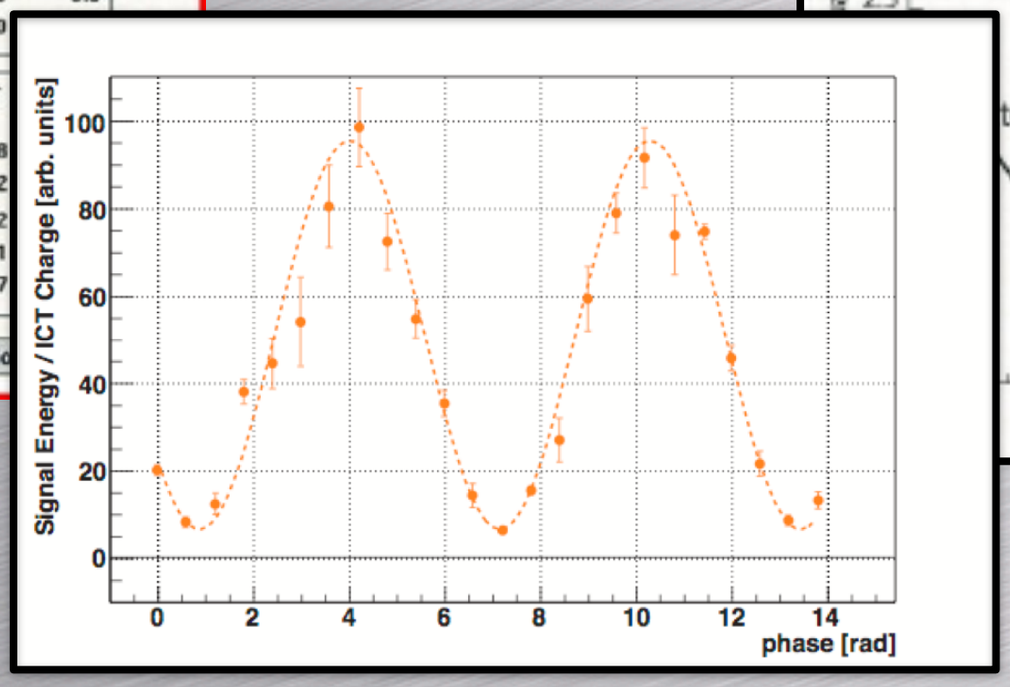
0.03mm β_y Optics Test

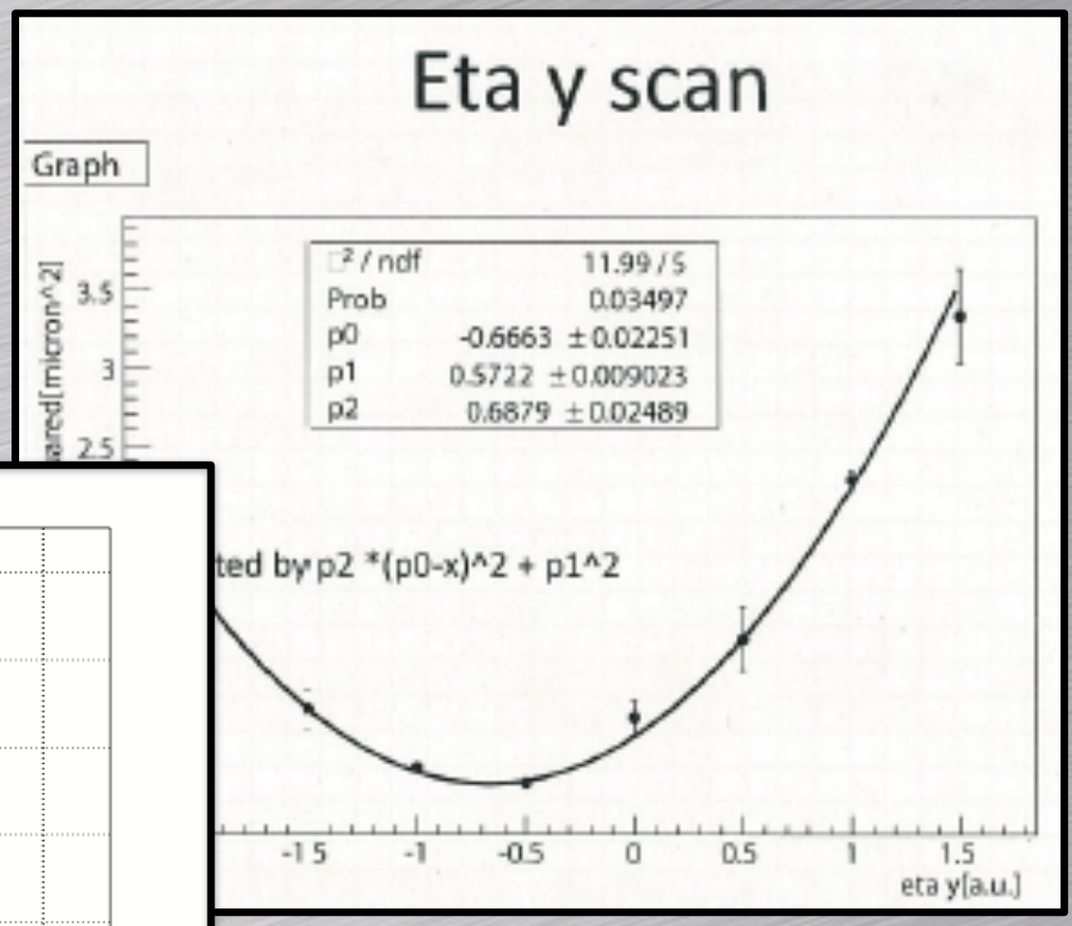


- Spread in effective IP beta function post tuning.
- **Initial**
  - betay 0.019 mm
  - emitx 3um
  - emity 12pm
  - sigy (Fit) 18nm
  - sigy (RMS) 21nm
  - sigy(1/2/3) 19.1/19.2/15.1 nm

IP Tuning with FFS Sextupole Multiknobs @ ATF2

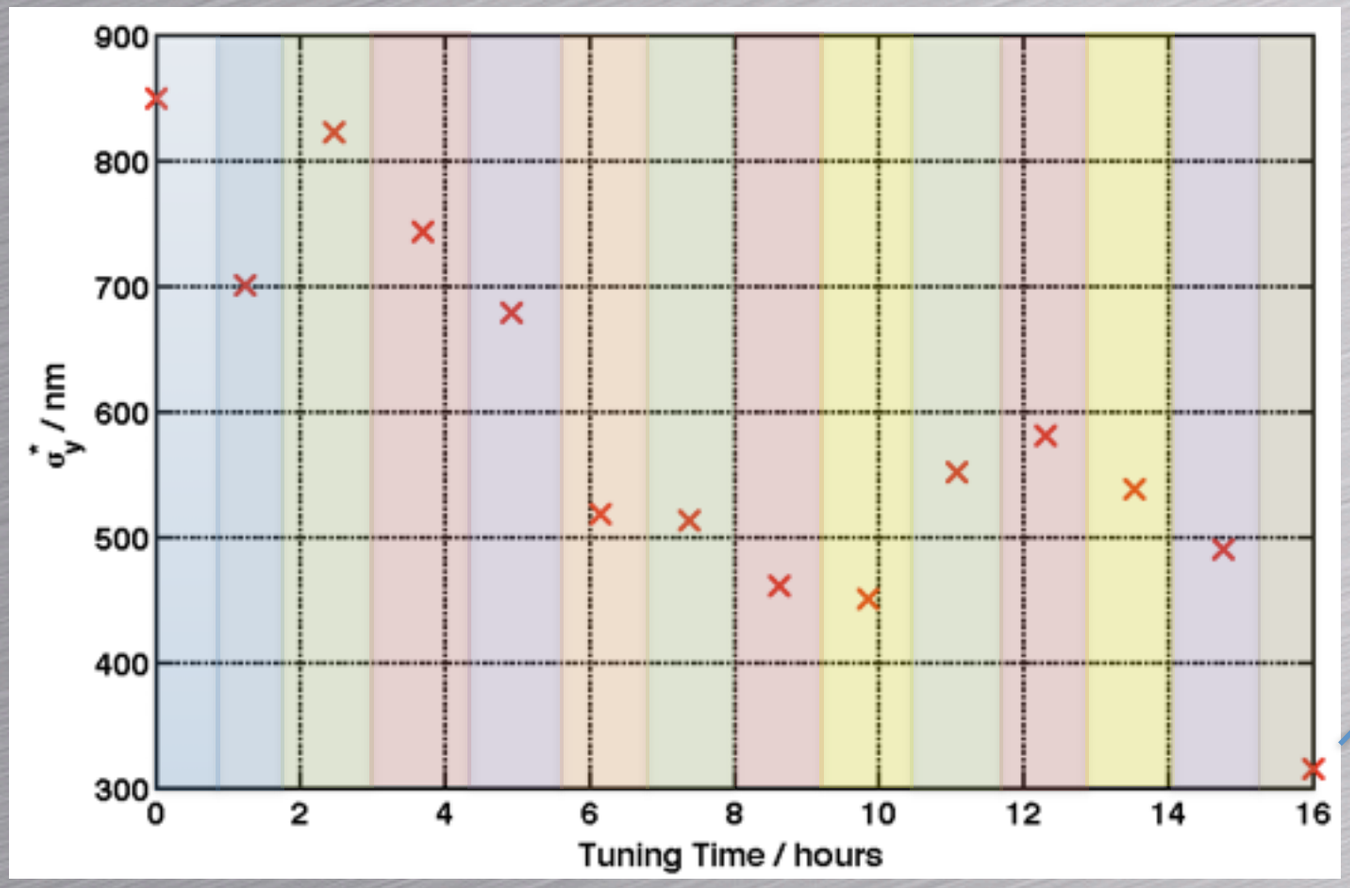


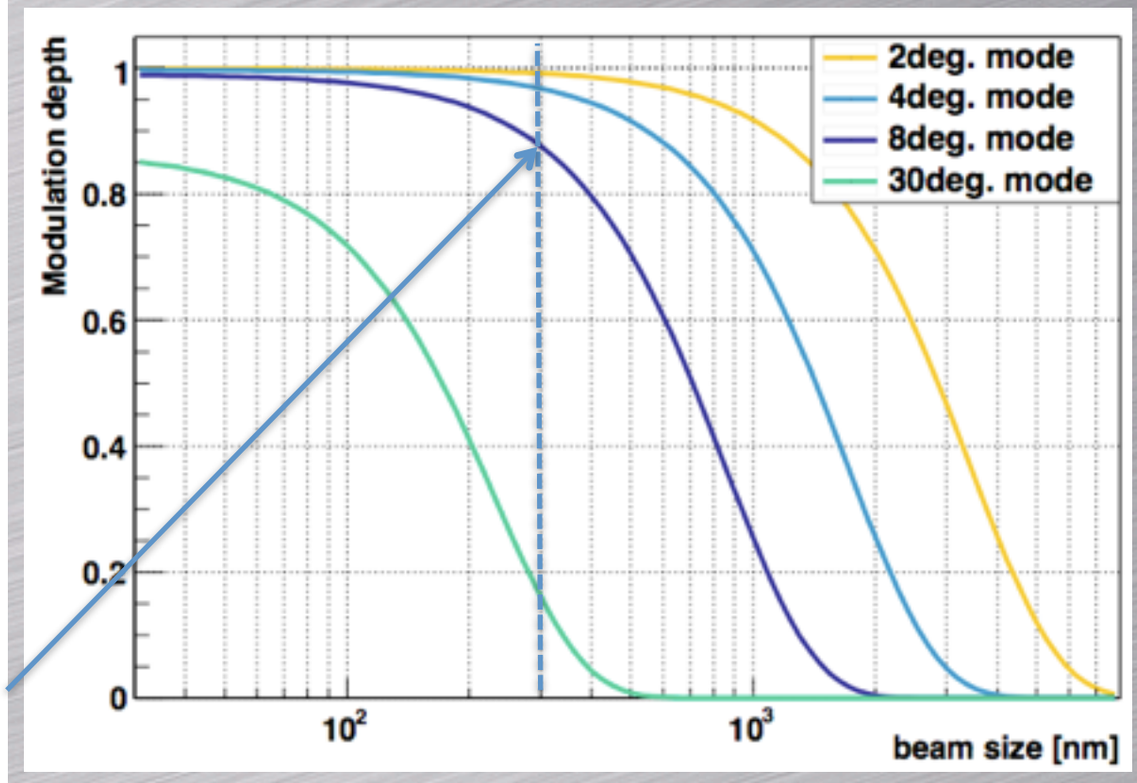




- **Iterative use of various knobs to bring down IP spot size by scanning with IPBSM.**

IP Tuning Results During Continuous Operations Week





- Experience of application of tuning knobs during May running period at ATF2 with 10X nominal β^* optics (expected beam size ~150nm).