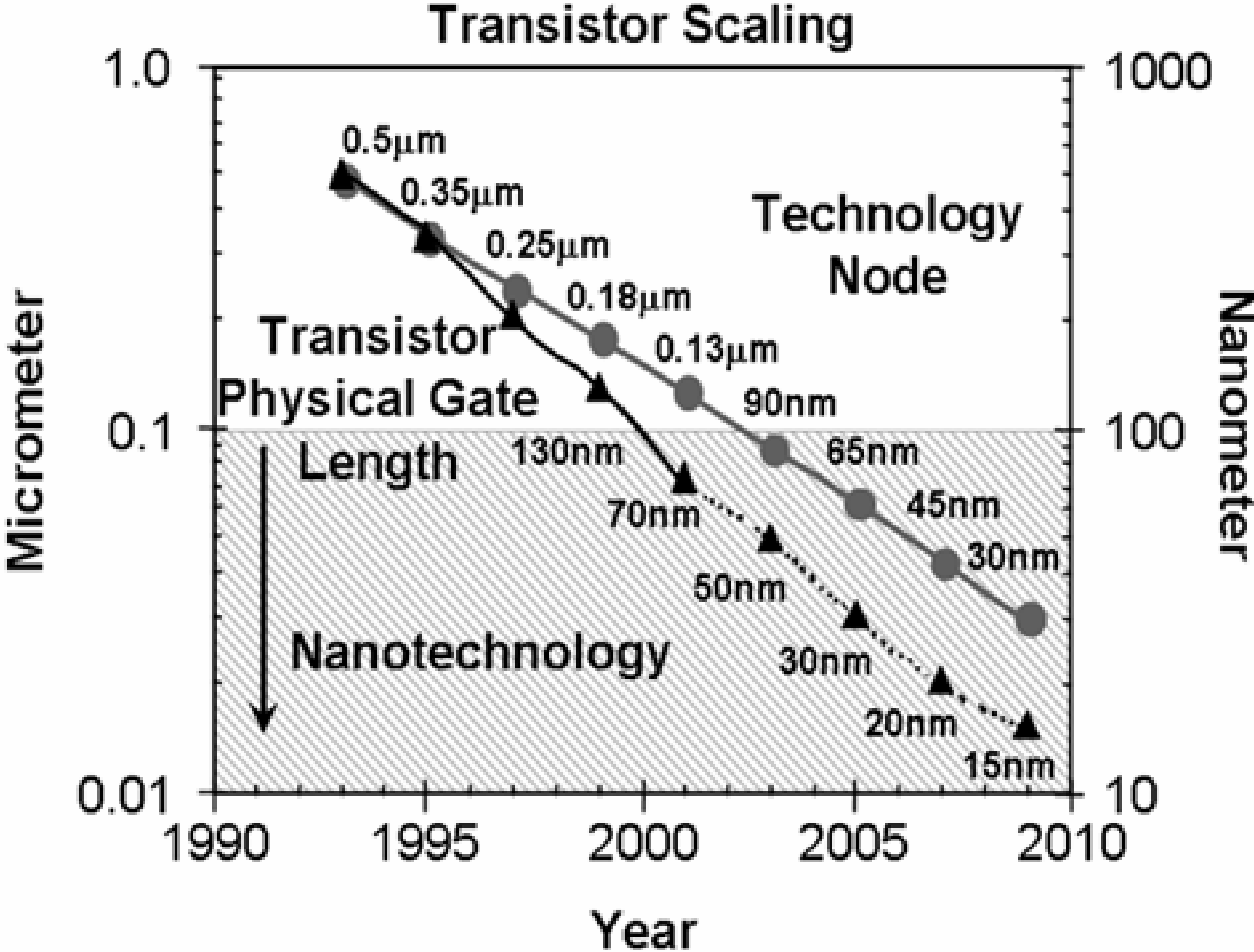


# Microlithographic Lenses

# Moore's Law

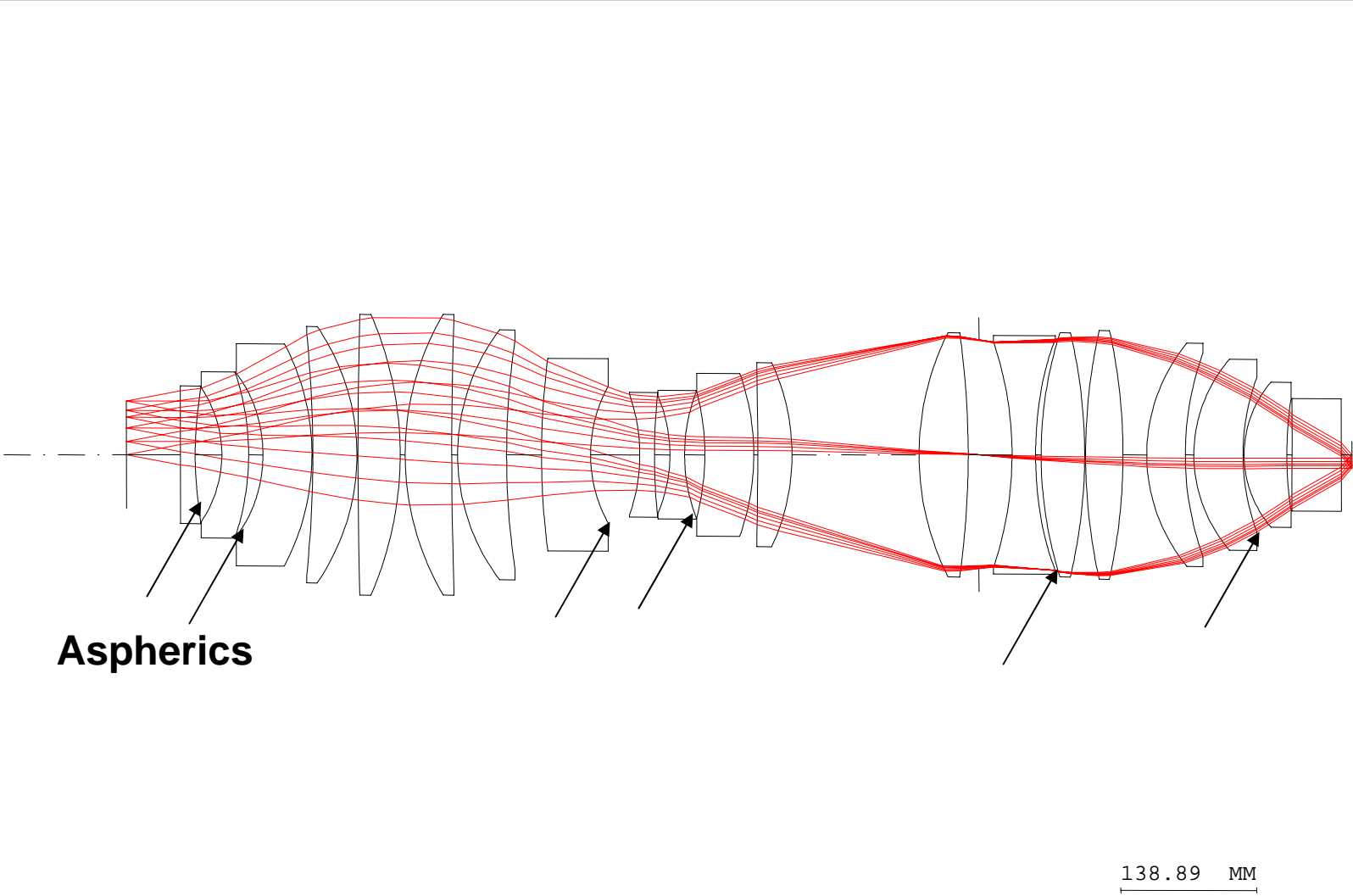


Ref: I. Adesida – Semiconductors in the Nanotechnology era

# Rayleigh scaling formulae

- Applied to Microlithography:
- Resolution =  $k_1 \frac{\lambda}{NA}$
- Resolution increases with increased NA, reduced  $\lambda$ 
  - NA has increased from 0.15 to ~ 0.92
  - Wavelength has reduced - 436, 405, 365, 248, 193, 157, 13 nm
- Depth of focus =  $k_2 \frac{n\lambda}{NA^2}$ 
  - DOF reduces more with increased NA than reduced  $\lambda$
  - Immersion refractive index, n, increases DOF
  - Paraxial formula
- $k_1$  and  $k_2$  are functions of the lithographic process (reticle, photoresist, illumination) and the level of residual aberrations in the projection optics
  - $k_1$  has reduced from 0.8 to 0.35 – 0.25
  - Monochromatic r.m.s wavefront aberrations have reduced from 0.071 waves (Marechal) to < 0.006 waves (Strehl ratio > 0.999)

# ArF 4x NA 0.75 Chromatic Dioptric lens

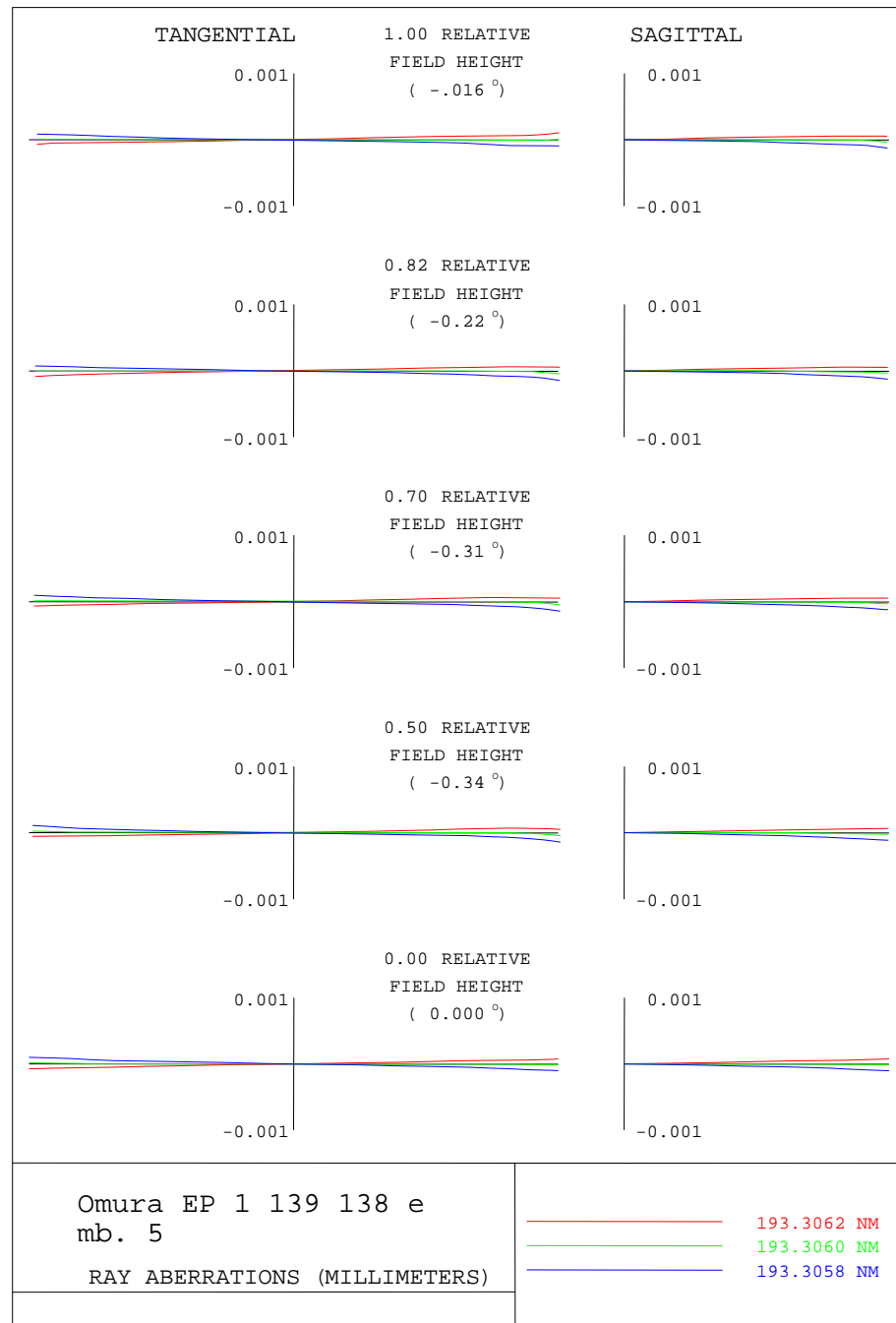


**Aspherics**

Omura EP 1 139 138 emb. 5

Scale: 0.18

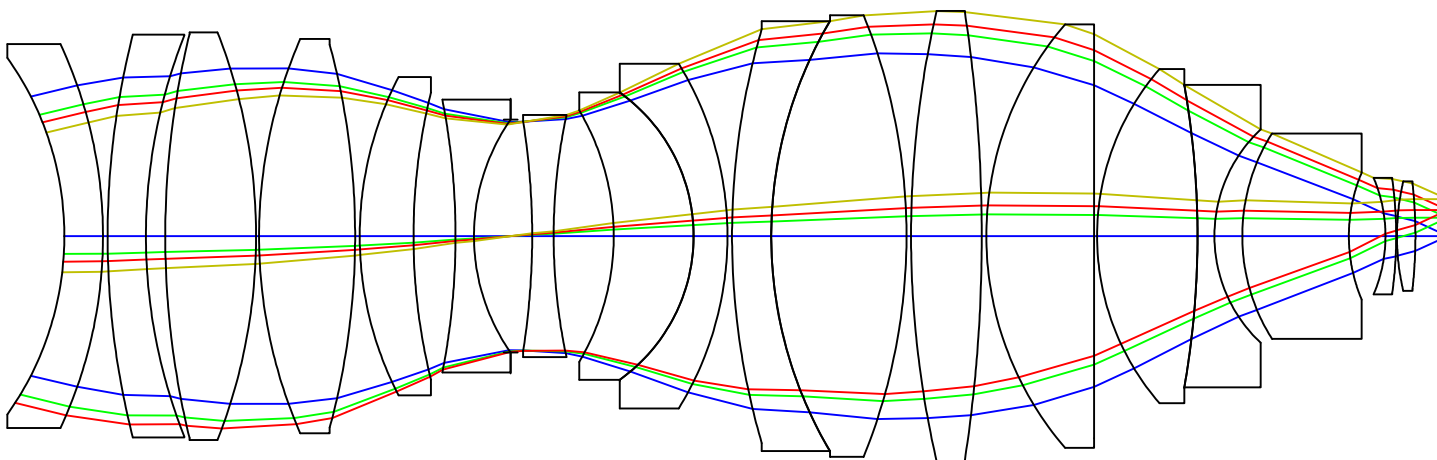
# NA 0.75



# r.m.s. wavefront aberrations @ 193 nm

■	rms	0.0030	0.0030	0.0050	0.0030	0.0030
■	-23	0.0030	0.0030	0.0040	0.0030	0.0030
■	-234	0.0010	0.0030	0.0030	0.0020	0.0020
■	dx	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
■	dy	0.0000000	0.0000000	0.0000010	0.0000000	0.0000000
■	dz	-0.0000060	-0.0000030	-0.0000050	-0.0000040	-0.0000040
■	xch	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
■	ych	0.0000000	-6.8750003	-9.6249995	-11.3437492	-13.7499990
■	Omch	0.0000000	-0.0059767	-0.0054302	-0.0038952	-0.0002826
■	Imch	0.0000000	-0.0000078	0.0002754	0.0005958	0.0012811
■	x	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
■	y	0.0000000	-6.8750003	-9.6249985	-11.3437492	-13.7499990
■	dsy	0.0000000	-0.0000005	0.0000012	0.0000005	0.0000006

# Hg I-line Achromatic Dioptric reduction lens



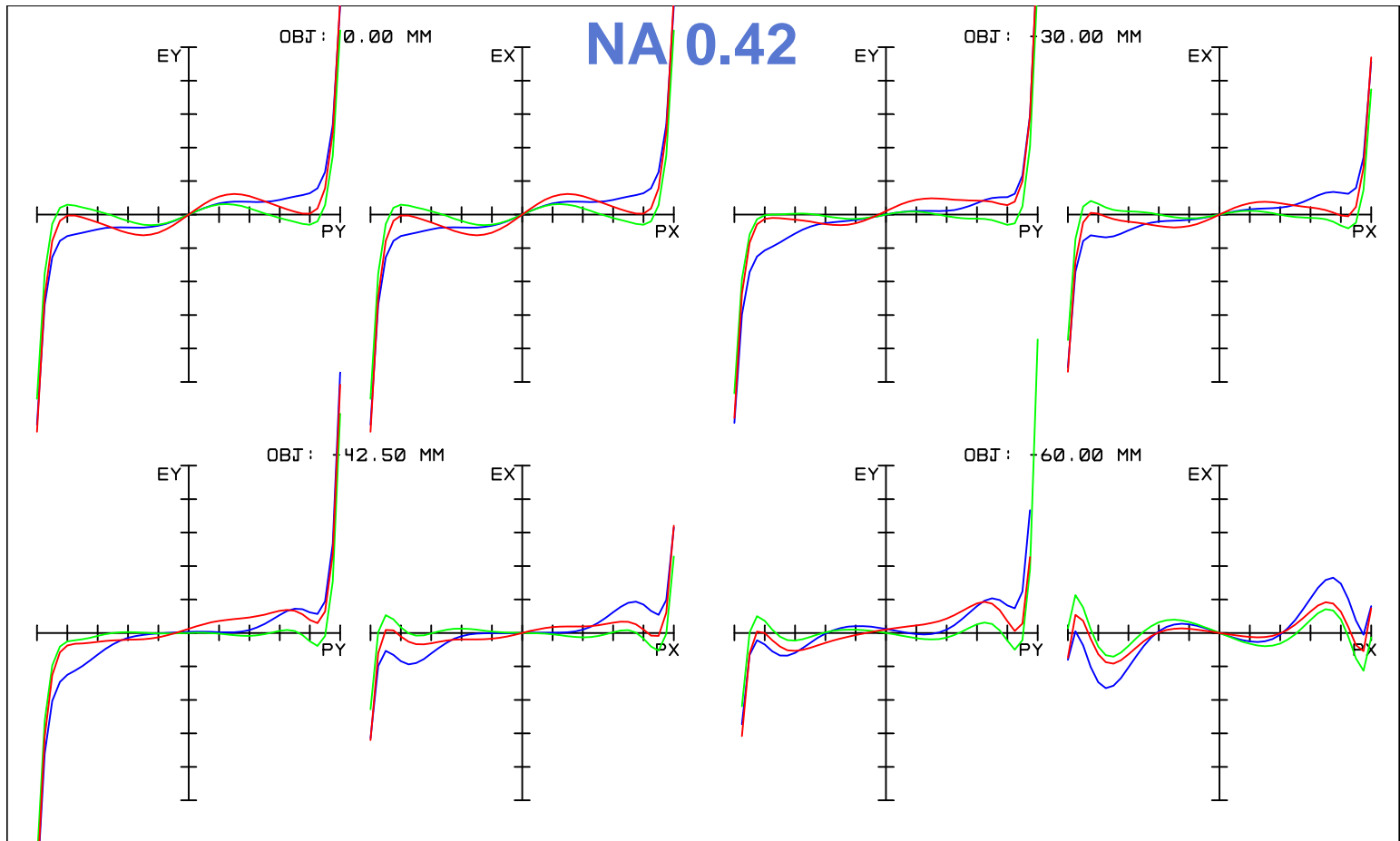
Ref: Williamson, *The Monochromatic Quartet explained*,  
SPIE Proc. CR41, Lens Design (1992)

LAYOUT

DELTA I-LINE NA.42 24MM IMAGE DIA 20DGC  
FRI AUG 2 2002  
TOTAL LENGTH: 450.17442 MM

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CONFIGURATION 1 OF 1



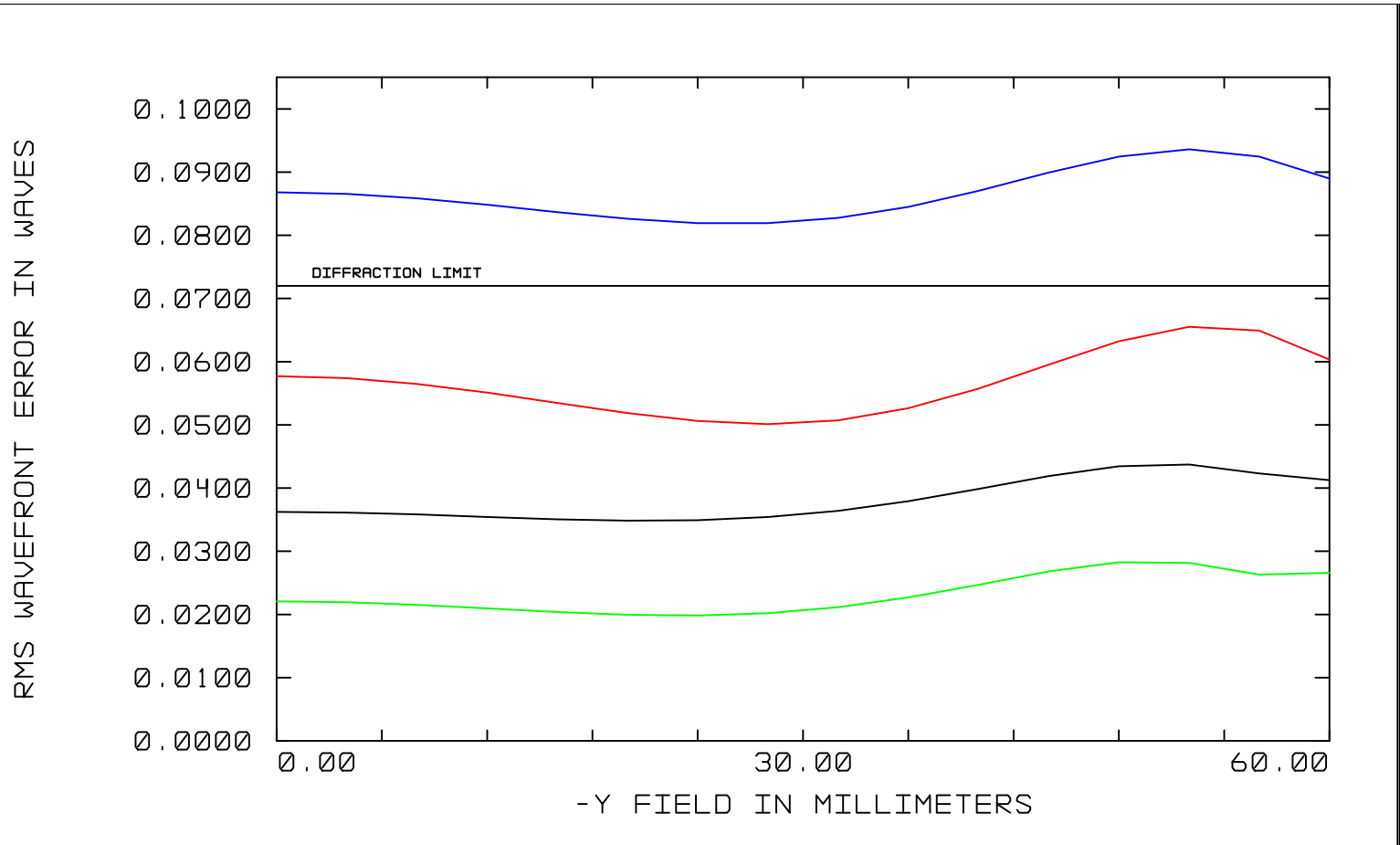
TRANSVERSE RAY FAN PLOT

DELTA I-LINE NA.42 24MM IMAGE DIA 20DGC  
 FRI AUG 2 2002  
 MAXIMUM SCALE: ± 2.500 MICRONS.

0.364   
 0.366   
 0.369

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 CONFIGURATION 1 OF 1



RMS WAVEFRONT ERROR VS FIELD

DELTA I-LINE NA.42 24MM IMAGE DIA 20DGC  
 FRI AUG 2 2002  
 POLY 0.364 0.366 0.369

NIKON RESEARCH CORPORATION OF AMERICA

REFERENCE: CENTROID

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 CONFIGURATION 1 OF 1

# Residual design aberrations

YOB	0.0000	-30.0000	-42.5000	-60.0000	
Standard Zernike Polynomial Coefficients					Waves r.m.s at 366.5000 nm
6	0.0000	0.0081	0.0159	0.0069	$p^2 * \cos(2A)$
7	0.0000	0.0000	0.0032	0.0035	$(3p^3 - 2p) * \sin(A)$
9	-0.0000	-0.0069	<u>-0.0128</u>	<u>0.0061</u>	$p^3 * \sin(3A)$
11	-0.0038	-0.0070	-0.0067	0.0021	$6p^4 - 6p^2 + 1$
12	0.0000	0.0057	0.0065	-0.0025	$(4p^4 - 3p^2) * \cos(2A)$
14	0.0004	-0.0000	-0.0016	<u>-0.0111</u>	$p^4 * \cos(4A)$
21	0.0000	-0.0000	-0.0005	-0.0049	$p^5 * \sin(5A)$
22	<u>-0.0199</u>	-0.0119	-0.0041	<u>0.0095</u>	$20p^6 - 30p^4 + 12p^2 - 1$
37	-0.0058	-0.0062	-0.0069	-0.0088	$70p^8 - 140p^6 + 90p^4 - 20p^2 + 1$
RMS	0.0233	0.0212	0.0254	0.0255	
y	0.0000000	6.0000080	8.4999997	12.0000259	
z	10.5021627	10.5022625	10.5021961	10.5022204	

## Manufacturing Issues

- The challenge is to produce a production run of lenses that each approach the nominal design residual aberrations - within a few milliwaves, rms - and distortion - within a few nanometers - so that **every** lens will meet specified CD (critical dimension) control and overlay requirements over the full field
- Since a computer chip's speed is determined by position and size of the transistor gates, there is a strong economic motivation to reduce residual aberrations, even if it involves an increase in lens cost – this cost is retrieved many times over during the life of a lens (~ 10 years)
- This has been achieved by continuous improvements in:
  - 1. State-of-the art tolerances on individual elements and their assembly
  - 2. Multi-stage compensation strategy that cancels as many of the manufacturing-induced aberrations as possible

# Manufacturing Issues

- Compensation of lens manufacturing errors
  - pre-assembly recomputation of the design
  - post-assembly adjustments
- It is important to distinguish between aberrations that can be easily compensated and those that cannot, or at least are more difficult
- Use and selection of compensators
- Example of basic compensators for this specific design

# Compensation strategy

- Stage 1 - Pre-assembly (recomp.)
  - Each assembly of elements is re-optimized to minimize aberrations introduced by non-zero element fabrication tolerances:
    - re-spacing
    - clocking
  - This includes selection of elements from a production batch, to minimize tolerance buildups and maximize error cancellation, rather than rss-ing
- Stage 2 - Post-assembly (fine alignment)
  - Selected elements are moved axially, tilted, decentered or rotated to compensate for assembly and metrology errors
  - Some elements may be re-polished – radius changes to correct Petzval sum, Zernike aspherics to correct overall Zernike aberrations across the field

## Pre-assembly Recomp.

Tolerance	Typical range	Compensator
Surface radius	1 fringe *	airspaces
Axial thickness	5-100 microns	airspaces
Refractive index	+/- 100 ppm	Airspaces **
Surface asphericity	2 milliwaves rms*	Airspaces **
Surface astigmatism	2 milliwaves rms*	Rotations **

\* at 632.8nm test wavelength over the clear aperture

\*\* including element selection, based on element metrology

## Pre-assembly Recomp.

- Optical element tolerances are prescribed to be small enough to ensure that the as-built system differs from the nominal design mostly in the low-order Seidel aberrations. Higher-order aberrations - which in general are not so easy to compensate - change more slowly with parameter departure from nominal, and have to be more tightly controlled within individual tolerances such as surface shape, and refractive index inhomogeneity
- From the Seidel formulae,  $S_I$ ,  $S_{II}$ ,  $S_{III}$ ,  $S_V$  are all functions of conjugate shift and will therefore change with re-spacing between individual elements
- Petzval sum,  $S_{IV}$ , does not change with element position, so generally has to be compensated by means of a power change – surface radius
- Higher-order Zernike aberrations can only be compensated by element selection or re-polishing (figuring)

## Post-assembly fine alignment – corrects element metrology and assembly errors

Parameter	Typical range	Compensator
Surface radius	+/- 5 microns	airspaces
Axial thickness	+/- 2 microns	airspaces
Refractive index	+/- 10 ppm	airspaces
Surface asphericity	1 milliwave rms*	Airspaces**
Surface astigmatism	1 milliwave rms*	Rotations**
Glass inhomogeneity	1 ppm	Airspaces**

\* at 632.8nm test wavelength over the clear aperture

\*\* some elements may be re-polished

## Post-assembly fine alignment

Parameter	Typical range	Compensator
Element spacing errors	+/- 2 microns	airspaces
Element tilts and decentrations	1 microns	tilts or decentrations
Mount-induced astigmatism	1 milliwaves rms*	Rotations**

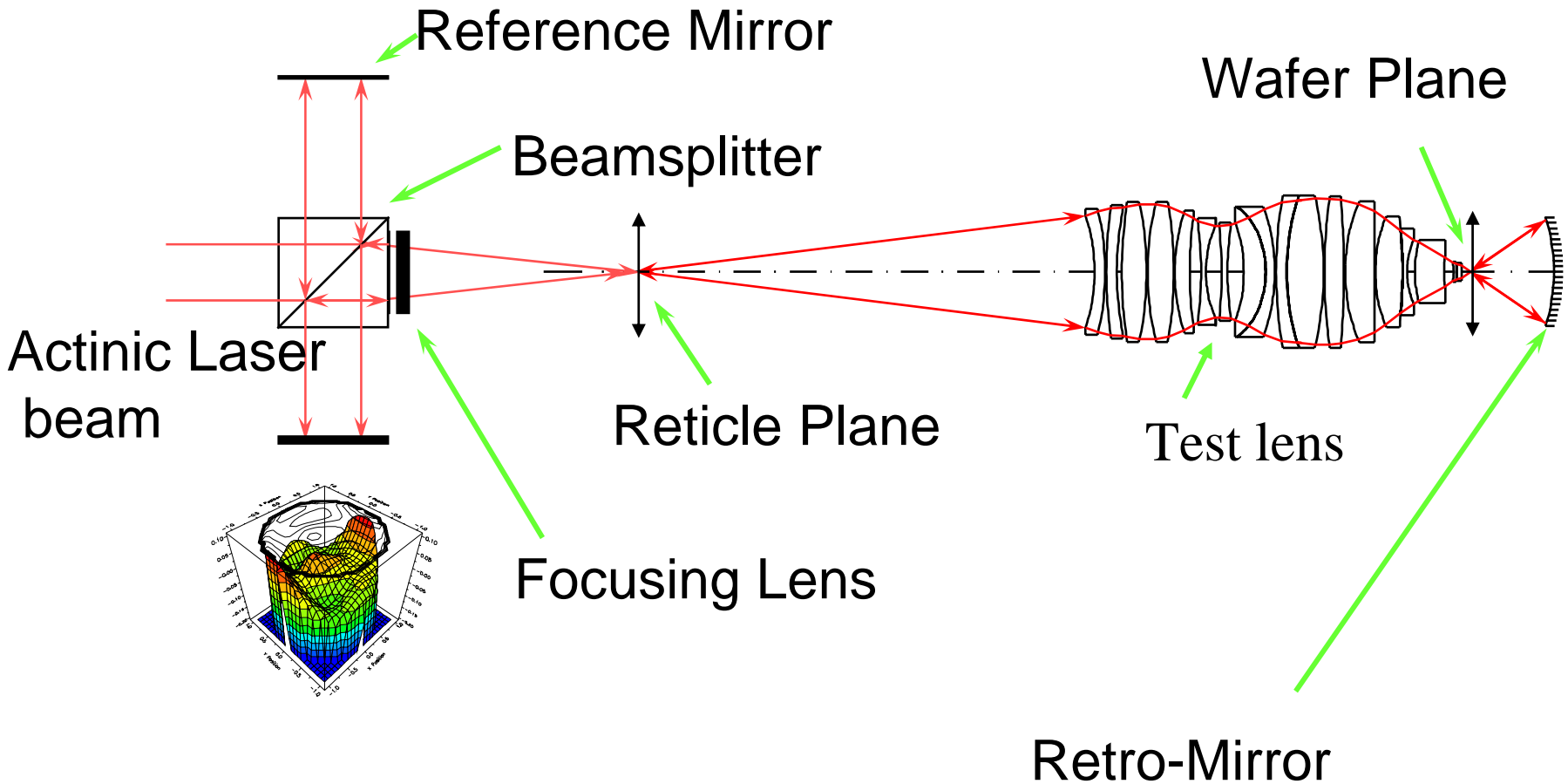
\* at 632.8nm test wavelength over the clear aperture

\*\* some elements may be re-polished

## Aberrations compensatable by element shifts

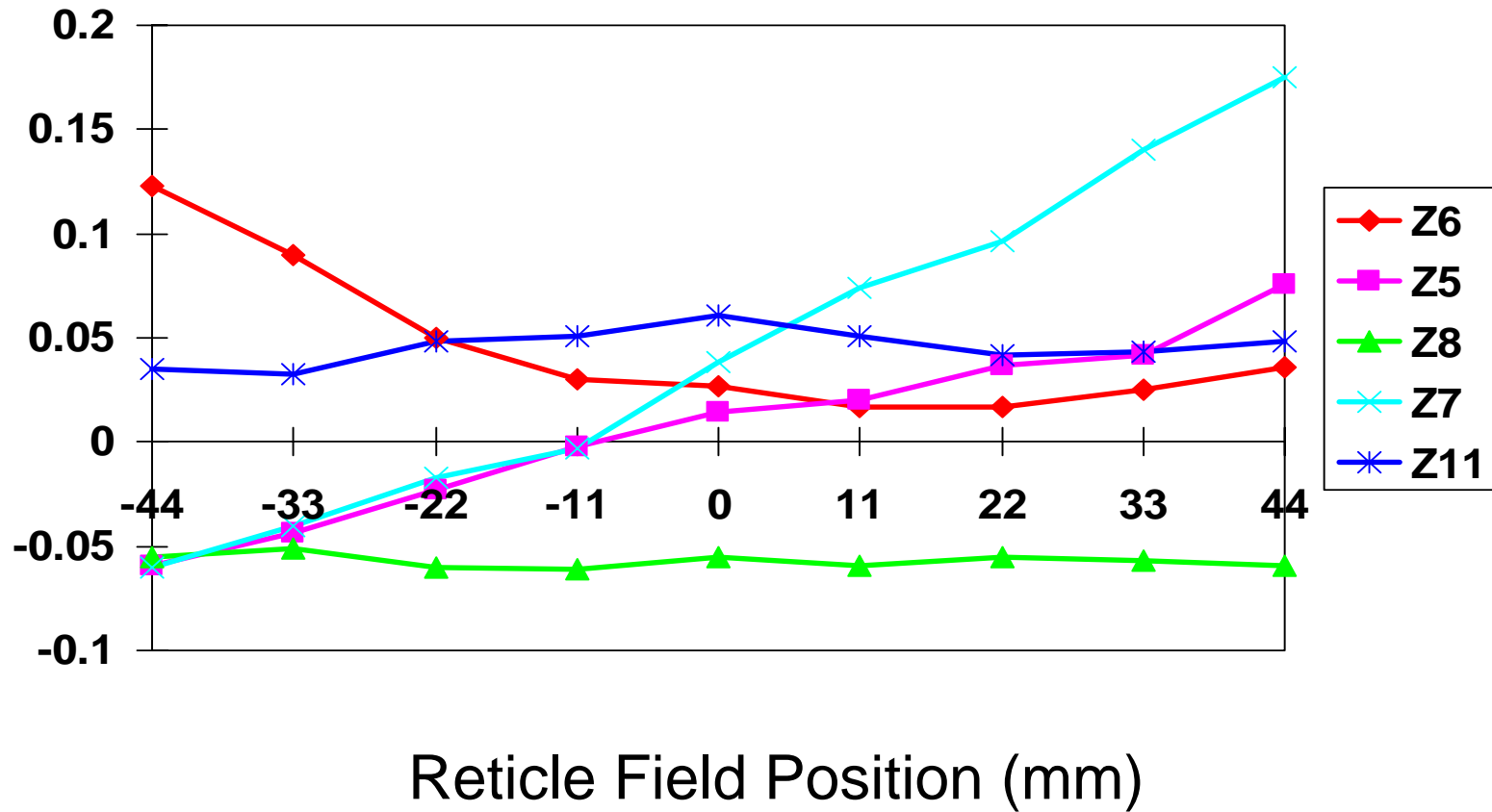
	Zernike # (OSA)
■ Symmetrical 3rd order	
■ Spherical aberration	Z11 mean
■ Coma	Z7 tilt
■ Astigmatism	Z6 bow
■ Distortion (Barrel-Pincushion)	Z2, Z3 cubic
■ Asymmetric 2nd order	
■ On-axis coma	Z7, Z8 mean
■ On-axis astigmatism	Z5, Z6 mean
■ Astigmatic field tilt	Z5, Z6 tilt
■ Tangential, Sagittal distortion	Z2, Z3 quadratic

# Phase-Measuring Interferometry – wavefront and distortion measured across reticle and wafer fields



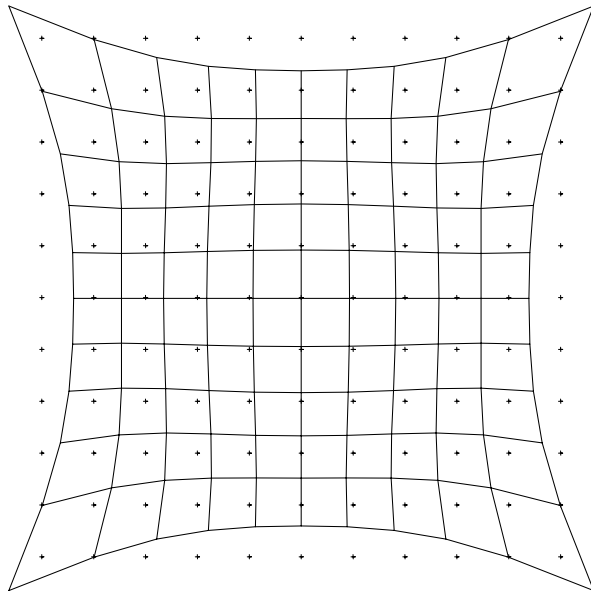
# PMI-measured Zernike aberrations across field

waves r.m.s.

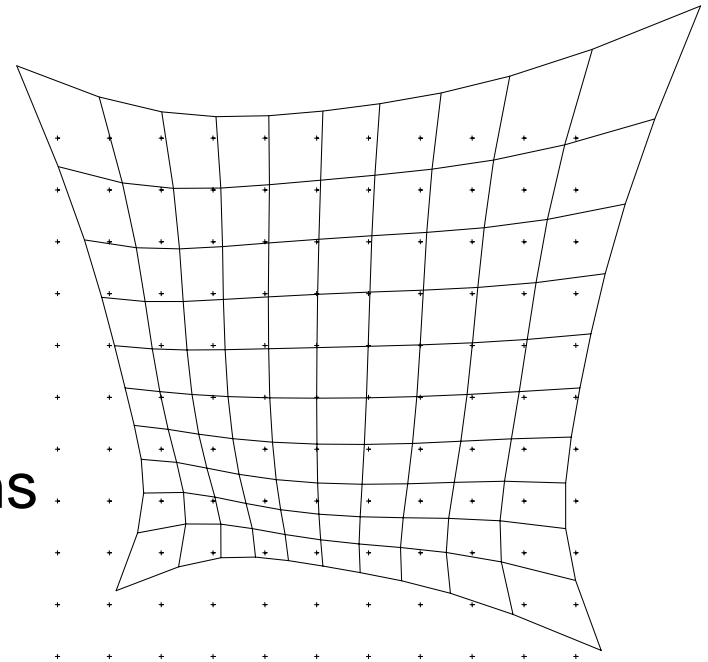


# Sym. and asymmetric Distortion – measured by Zernike wavefront tilt - Z2, 3 terms

Barrel/Pincushion  
3rd and 5th order



Keystone and bow  
2nd order



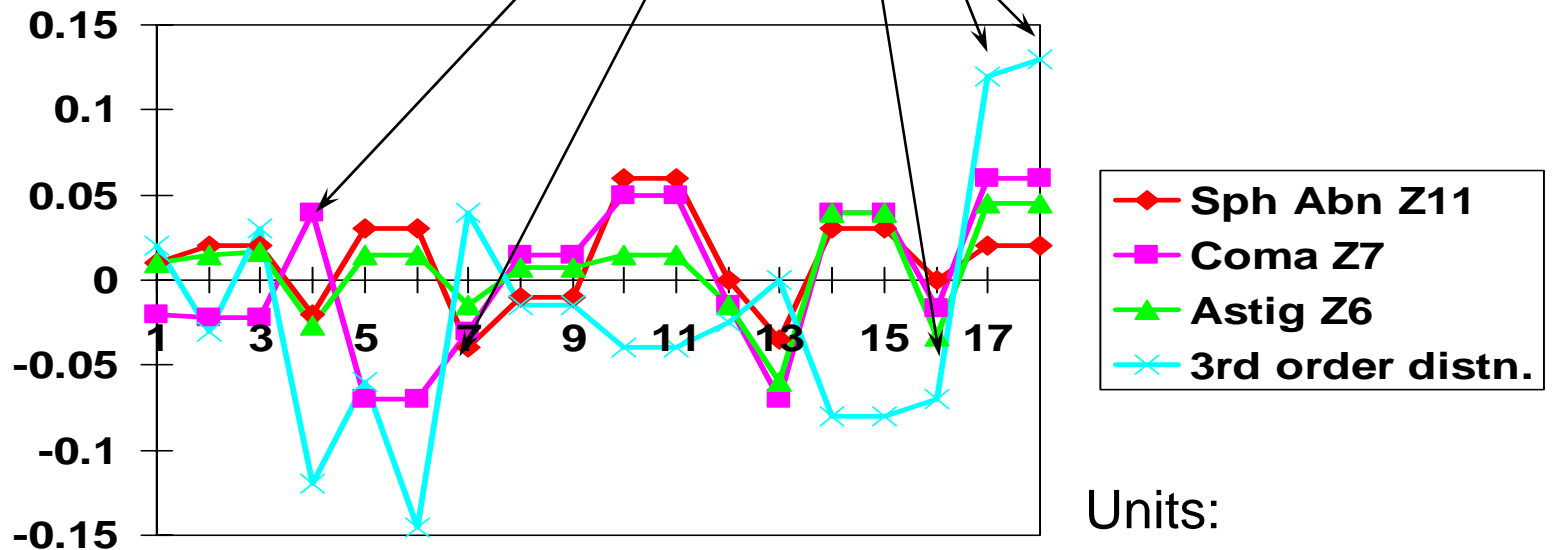
↕  
0.02  
microns

# Compensators

- To have independent control of all the second and third-order aberrations effected by element movements requires:
  - 4 independent axial adjustments
  - 4 independent decentration adjustments
  - clocking, or change of astigmatic elements
- In addition to first-order image parameters:
  - symmetrical - linear magnification and focus
  - asymmetric - image tilt and decentration

# Sensitivity to element axial shift

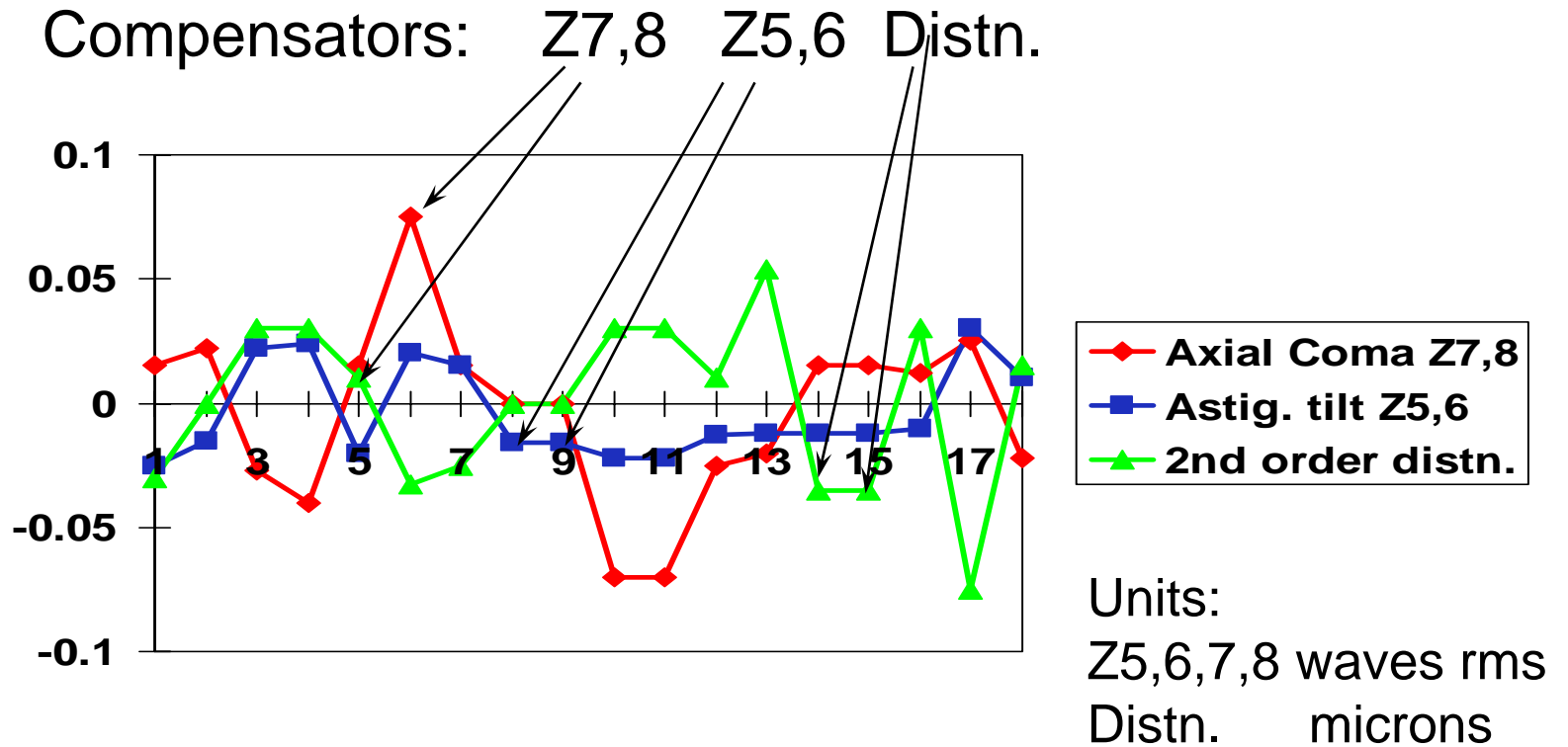
Compensators: Z7 Z11 Z6 Distn.



Units:  
 Z6,7,11 waves r.m.s  
 Distn. microns

Element # moved axially by 25 microns

# Sensitivity to element decentration

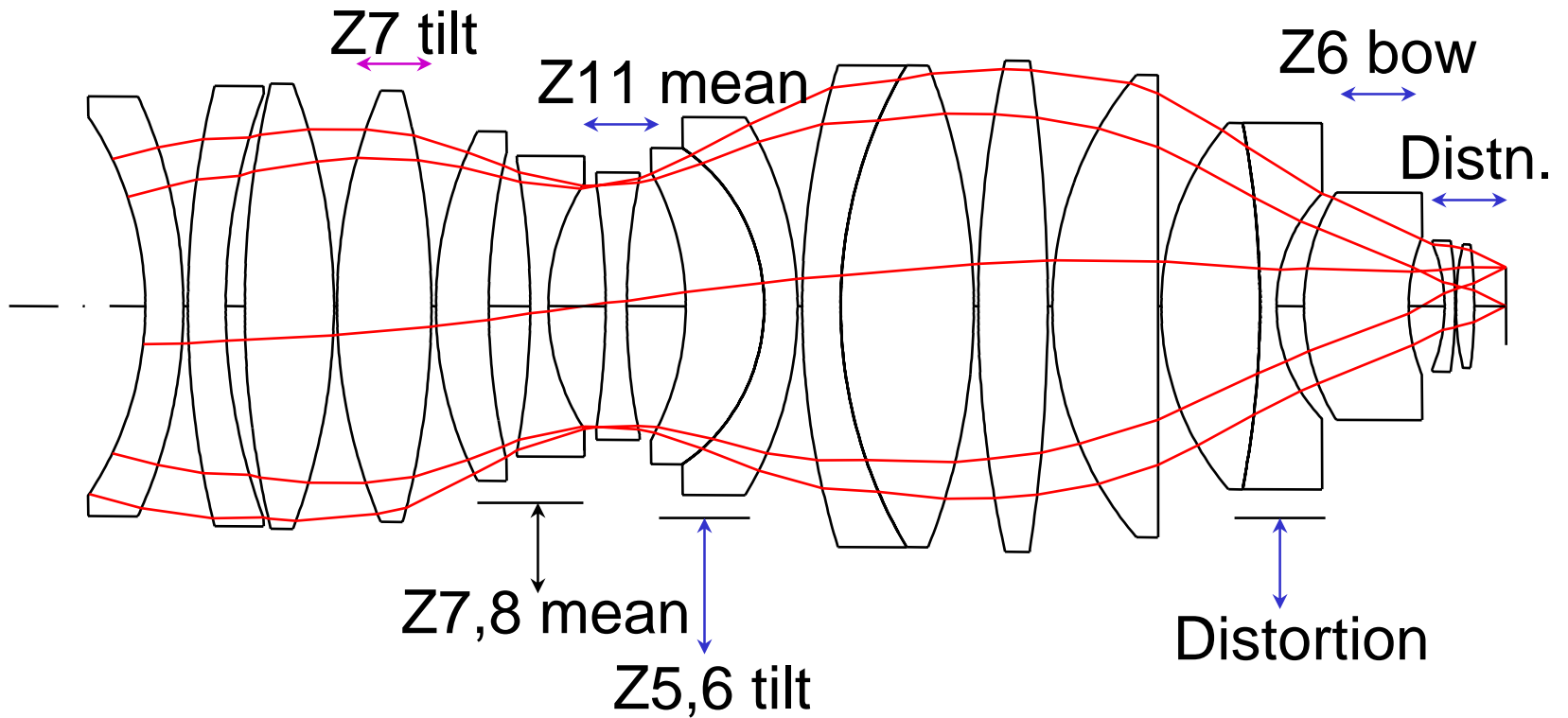


Element # decentered by 5 microns

## Compensator selection

- Historically, this has been done manually by the optical designer, looking at the aberration sensitivity matrix, working within practical constraints, and negotiating with the mechanical designer:
  - Which elements are most easily moved?
  - Which elements are too sensitive?
  - Which elements have the most independent effects on different aberrations? – orthogonality
- More recently, selection is assisted by Singular Value Decomposition (SVD) of the sensitivity matrix, which computes the most orthogonal set of compensators

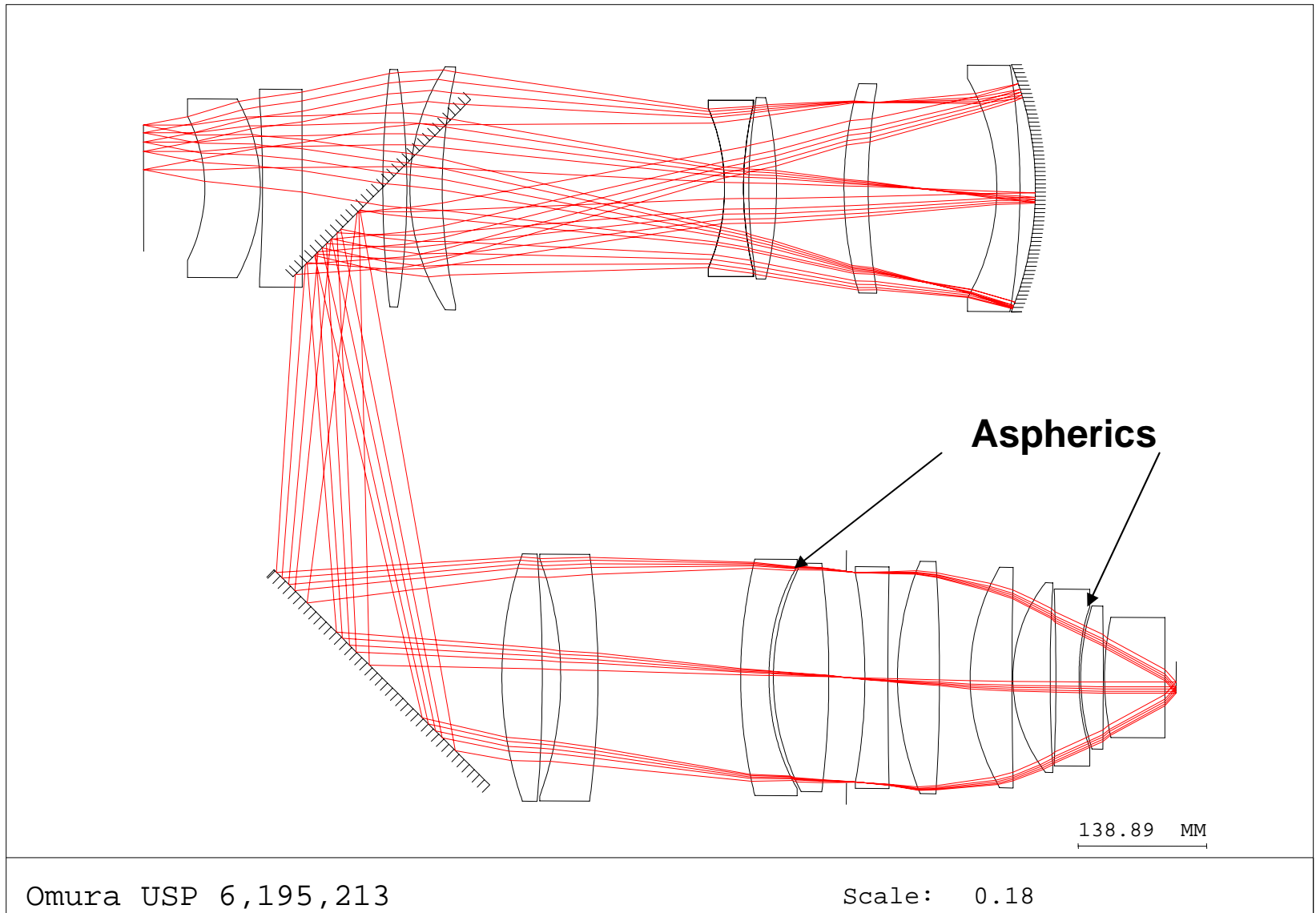
# Moveable element compensators



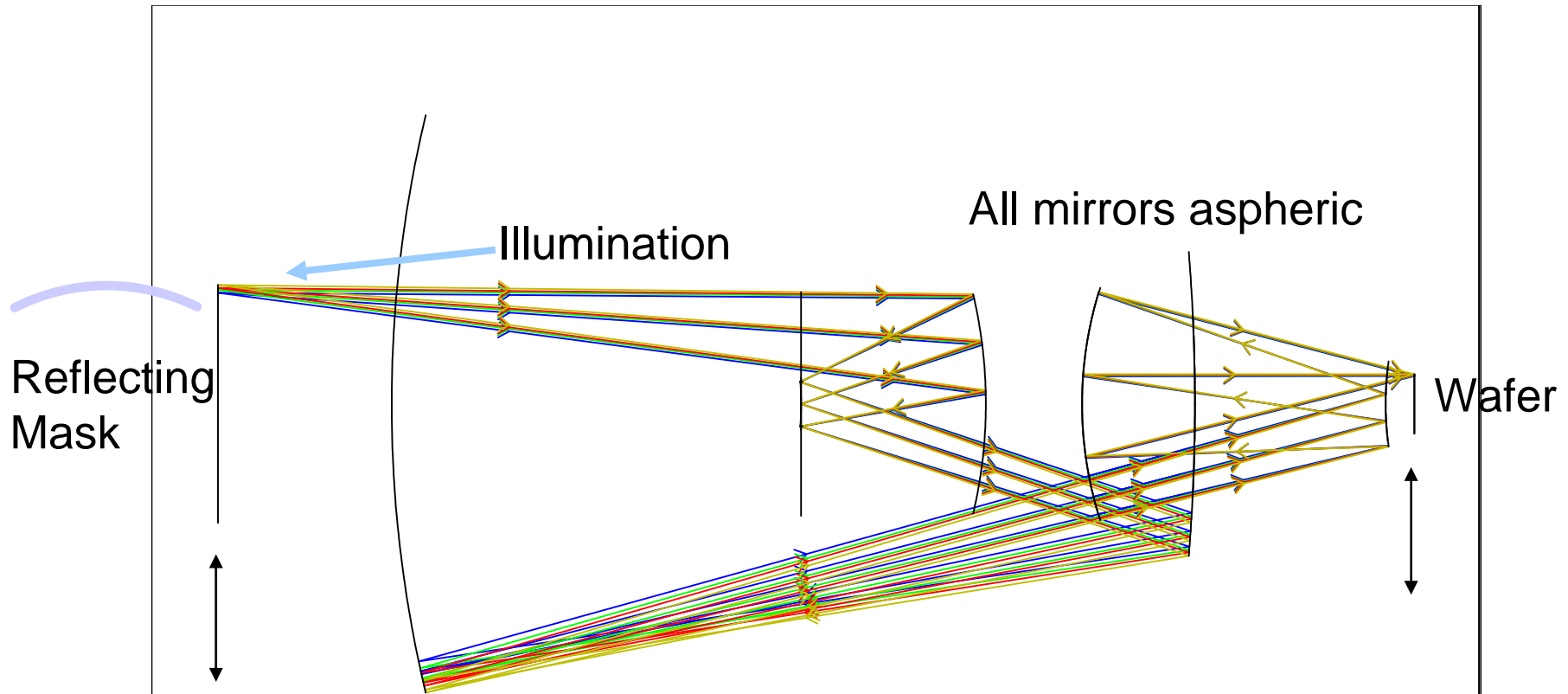
# Catadioptric advantages and disadvantages

- **Field curvature of positive-powered refracting elements may be corrected by one or more positive-powered mirrors, rather than separated negative and positive-powered lens elements**
- **Chromatic aberrations are smaller, because of lower refracting power, without the need for negative-powered lens elements that are made from a second refracting material of higher dispersion**
- **Catoptric designs allow operation at wavelengths shorter than practical material transmission cut-off  $< 157$  nm**
- **Mirrors are  $\sim 4$  times more sensitive to surface errors – figure and tilt**
- **Many catadioptric designs operate off-axis and/or have multiple, folded, optical axes**
- **Similar compensation strategies apply**
- **Deformable mirrors are an option – easier than lenses**

# ArF NA 0.75 off-axis Catadioptric design



# EUV – 13.4 nm - NA 0.25 off-axis Catoptric design



Ref: Williamson USP 5,815,310 (1995)

LAYOUT

NA 0.25 30MM RING FIELD  
FRI AUG 2 2002  
TOTAL LENGTH: 1248.51695 MM

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CONFIGURATION 1 OF 1

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