2006 SEMATECH Lithography Forum

HYPERION DEVELOPMENT

# Resolution Limits of EUV Projection Technology

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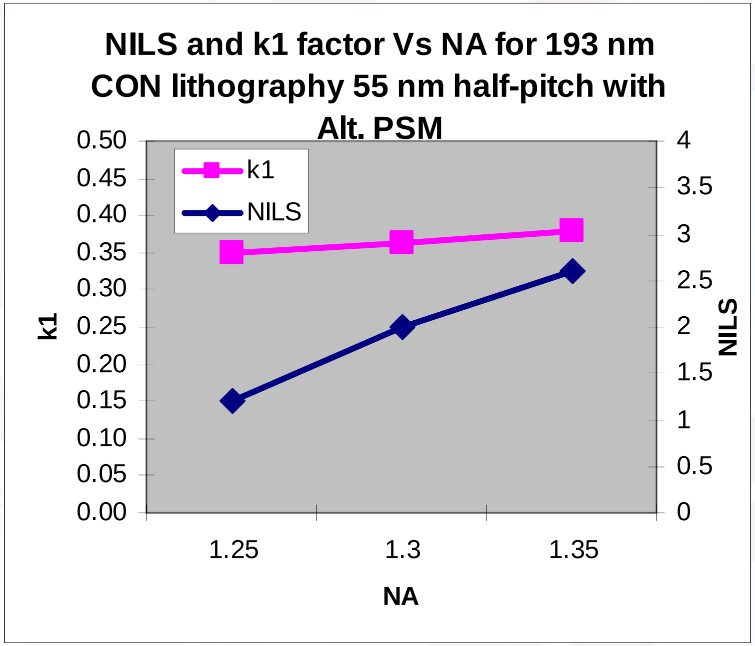
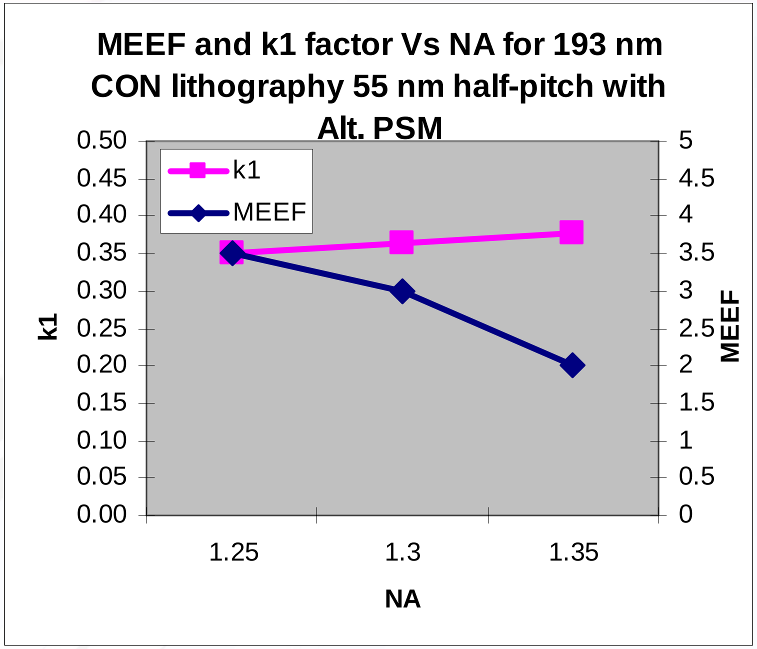
# Study motivation



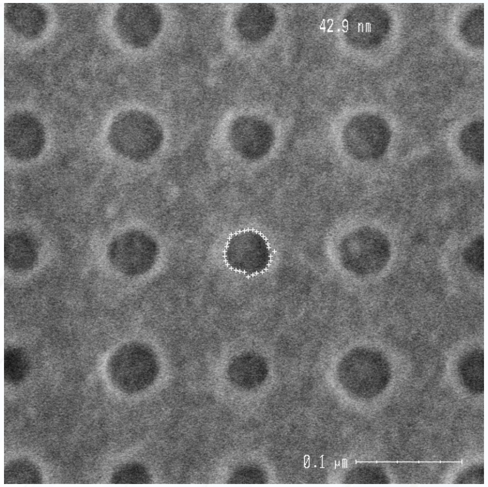




- **Contact patterning using 193 nm lithography has many challenges**
  - **Pitch limited by $\lambda$/NA ($k_1$ ~ 0.37)**
  - **Low Normalized Image Log Slope (NILS < 3)**
  - **High Mask Error Enhancement Factor (MEEF > 3)**
- **RETs & NA scaling at 193 nm lithography is running out of steam**

# MET contact patterning results

**Intel's EUV Micro Exposure Tool**

**44 nm 1:1**




- **$k_1$ of 1 achieved with this resist**

# EUV Extensibility

1) What are the ultimate resolution limits of EUV?
2) What projection architectures are required to achieve these limits?
3) Is the resulting numerical aperture/field size consistent with high volume manufacture?
4) What new risk factors arise?

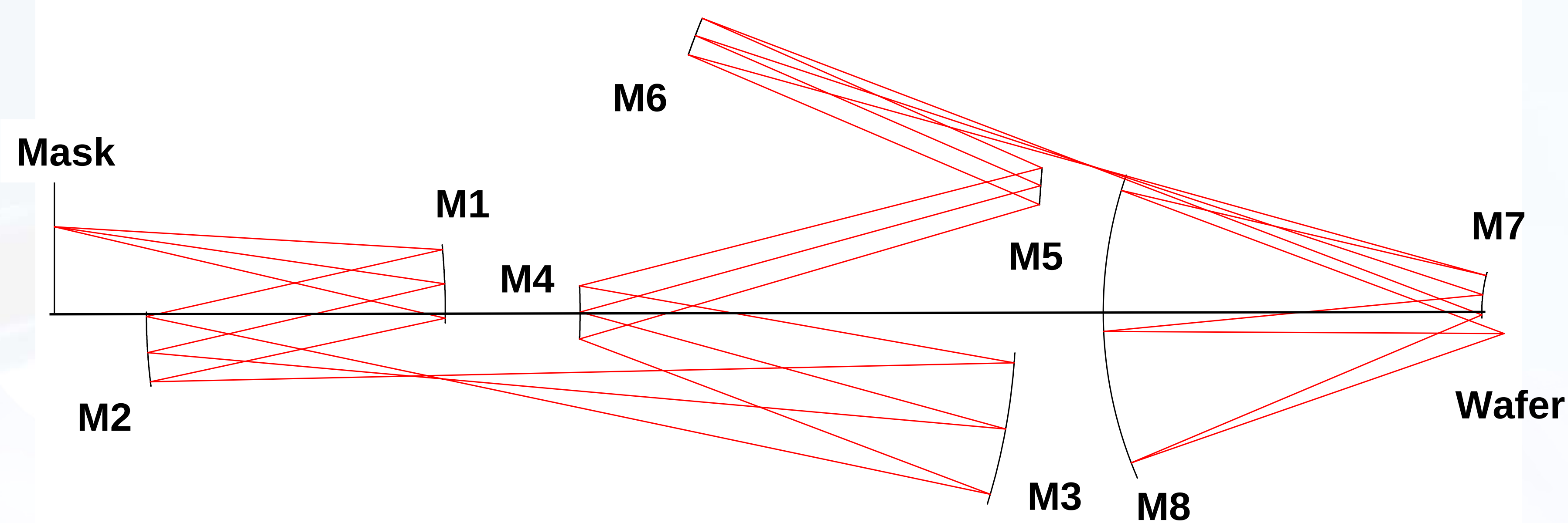
# Extensibility learning (+)

1) An unobscured 8-mirror system can achieve a minimum 0.40 NA with a minimum ring field width of 2.0 mm
2) An obscured 8-mirror system can achieve a 0.53 NA with a minimum ring field width of 1.5 mm
3) The obscuration is small and is unlikely to have a material impact on partially coherent imagery
4) Etendue increase of obscured 8-mirror system mitigates transmission loss provided source match
5) Designs are MoSi multilayer compatible

# Extensibility learning (-)

1) Chief ray angle at mask must increase to a minimum of 7-8° based on current knowledge
2) Aspheric mirror complexity increases
   - Diameter
   - Peak aspheric departure from best fit sphere
   - (Note that peak aspheric slope actually decreases)
3) Aspect ratio on M7 mirror in unobscured system is poor (~20:1)
4) Back working distance is small (~ 1-2 mm)
5) DOF at NA limits will pose process challenge

# Conceptual unobscured 0.35NA 8-mirror system



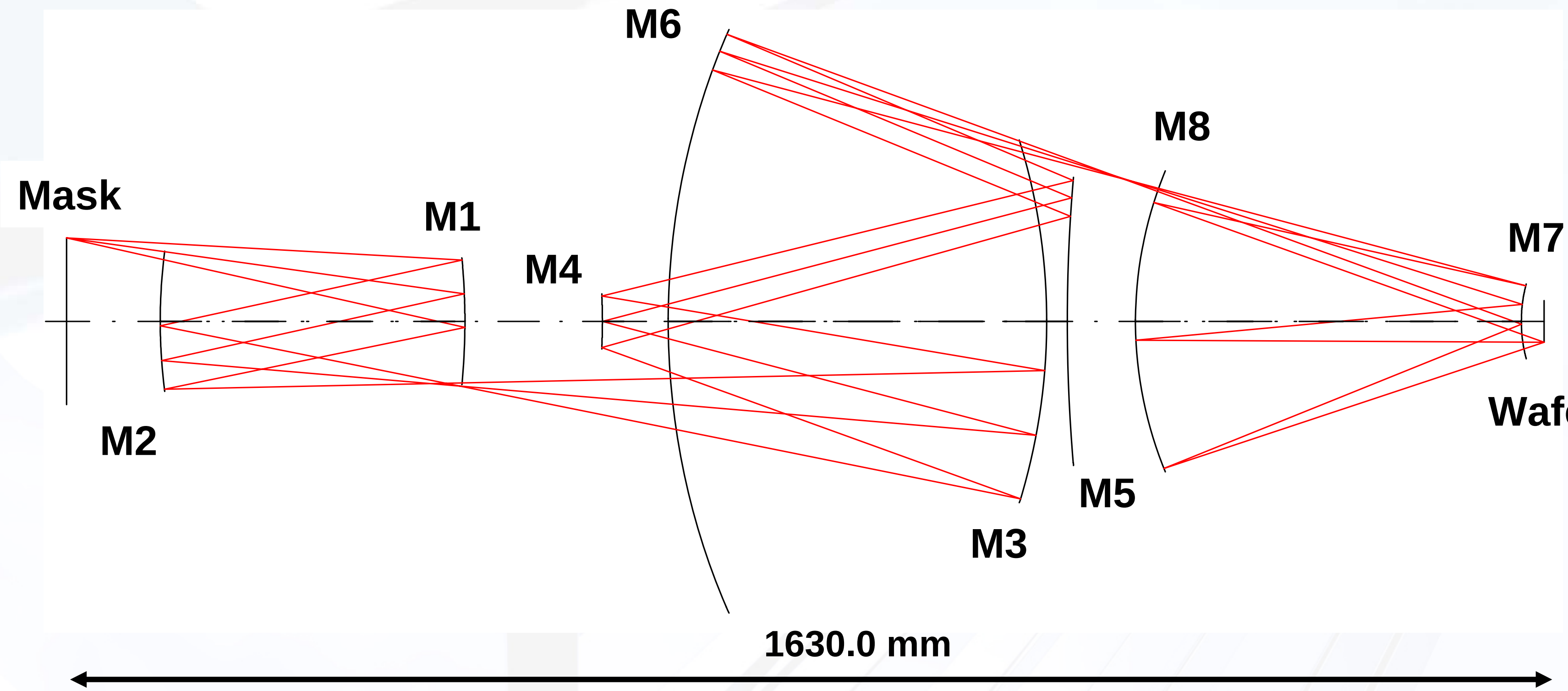

**Mean ray incidence angle**

**Mask: 8.3° M1: 10.7° M2: 9.1° M3: 5.1° M4: 15.4°**
**M5: 19.4° M6: 2.6° M7: 11.9° M8: 2.9°**

**Reduction = 4x**
**NA = 0.35**
**RFW = 2.0mm**
**Dist. < 0.20nm**
**Comp. RMS < 25m$\lambda$**

**1630.0 mm**

# Conceptual 0.35NA system w/ full parents



# *Design performance*

| *Parameter* | *Values* | *Notes* |
|---|---|---|
| *Design* | *8-mirror* | *-* |
| *Obscuration* | *No* | *-* |
| *Resolution* | *22.0 nm* | $R = k_1\lambda/NA$ ($k_1$= 0.57) |
| *Numerical aperture* | *0.35* | *Maximum 0.42 to 0.45* |
| *Field size* | *22 mm x 2.0 mm* | *Scanning ring field* |
| *Wavelength* | *13.5 mm* | *MoSi* |
| *RMS Wavefront error* | $< 25.0\ m\lambda$ | *Field composite* |
| *Distortion* | *< 0.15 nm* | *Lower possible* |
| *Field curvature* | *< 1.0 nm* | *No astigmatism or FC* |
| *Chief ray angle at mask* | $8.3^\circ$ | *-* |

# Design performance (cont'd)

| Parameter | Values | Notes |
|---|---|---|
| *Telecentricity at wafer* | *< 1.0 mrad* | *Similar to alpha tools* |
| *Free working distance mask* | *> 25.0 mm* | *Can be improved* |
| *Free working distance wafer* | *~ 4.0 mm* | *-* |
| *Mean incidence angles* | *M1*: 10.7°<br>*M2*: 9.1°<br>*M3*: 5.1°<br>*M4*: 15.4°<br>*M5*: 19.4°<br>*M6*: 2.6°<br>*M7*: 11.9°<br>*M8*: 2.9° | ***Key Point***<br>*Angle control is fair with angles approaching 20 deg.* |

# As-designed RMS wavefront

W A V E F R O N T   A N A L Y S I S

EMA 14 (0.35NA, 2mm) POSITION 1

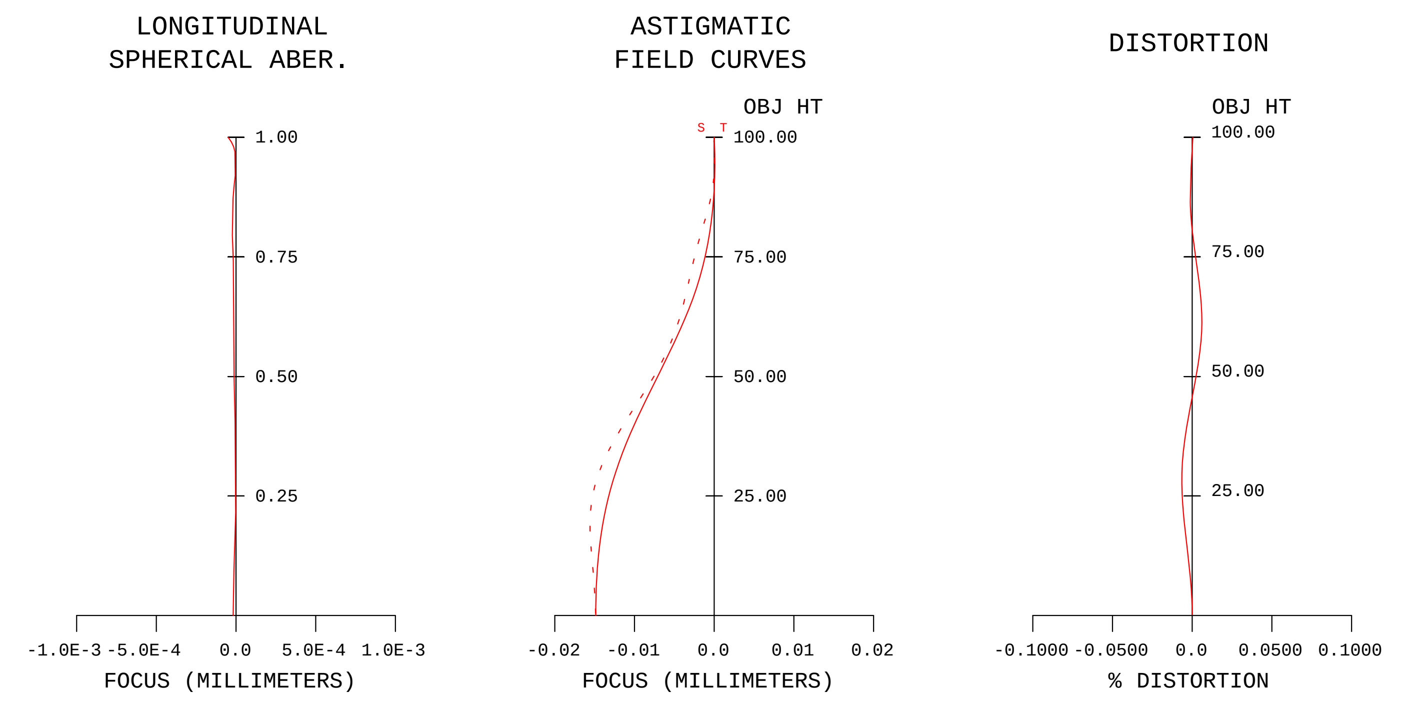
| | | | | | |
|---|---|---|---|---|---|
| X REL. FIELD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y REL. FIELD | 0.92 | 0.94 | 0.96 | 0.98 | 1.00 |
| WEIGHTS | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| NUMBER OF RAYS | 324 | 324 | 322 | 320 | 316 |

| | FIELD FRACT | DEG | SHIFT (MM.) | BEST INDIVIDUAL FOCUS FOCUS (MM.) | RMS (WAVES) | STREHL | SHIFT (MM.) | BEST COMPOSITE FOCUS FOCUS (MM.) | RMS (WAVES) | STREHL |
|---|---|---|---|---|---|---|---|---|---|---|
| X | 0.00 | 0.00 | 0.000000 | -0.000009 | 0.0237 | 0.978 | 0.000000 | 0.000000 | 0.0263 | 0.973 |
| Y | 0.92 | -8.02 | 0.000001 | | | | 0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000014 | 0.0184 | 0.987 | 0.000000 | 0.000000 | 0.0265 | 0.973 |
| Y | 0.94 | -8.18 | 0.000000 | | | | 0.000000 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000002 | 0.0166 | 0.989 | 0.000000 | 0.000000 | 0.0169 | 0.989 |
| Y | 0.96 | -8.34 | -0.000001 | | | | -0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | -0.000015 | 0.0255 | 0.975 | 0.000000 | 0.000000 | 0.0322 | 0.960 |
| Y | 0.98 | -8.49 | -0.000001 | | | | -0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000006 | 0.0185 | 0.987 | 0.000000 | 0.000000 | 0.0204 | 0.984 |
| Y | 1.00 | -8.65 | 0.000001 | | | | 0.000001 | | | |

COMPOSITE RMS FOR
POSITION 1: 0.02504

Units of RMS are waves at 13.5 nm.

# 0.35NA Concept Field Curves



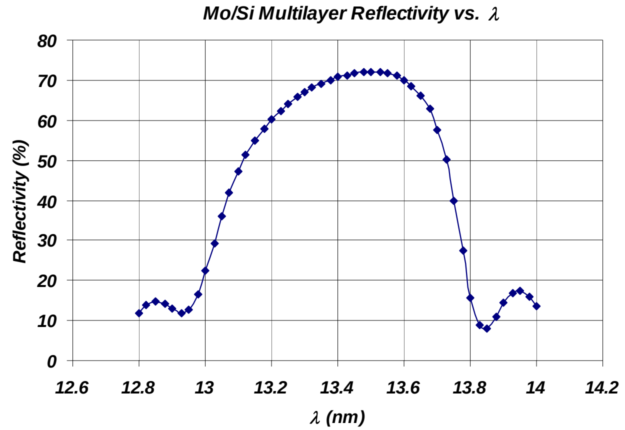

EMA (0.35NA, 4X, 2.0mm)

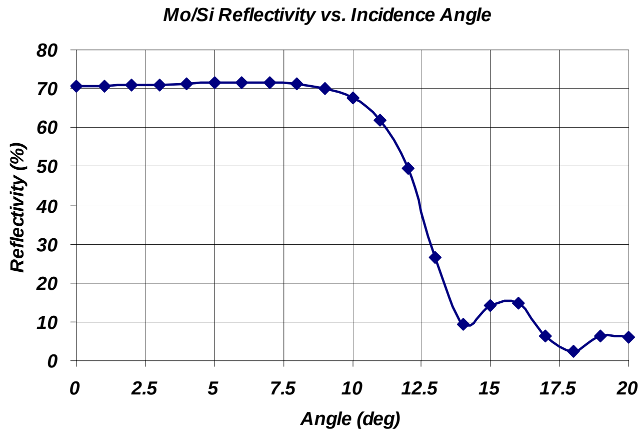
# Mean incidence angle scaling poses design challenges

## Mean incidence angle scales with NA

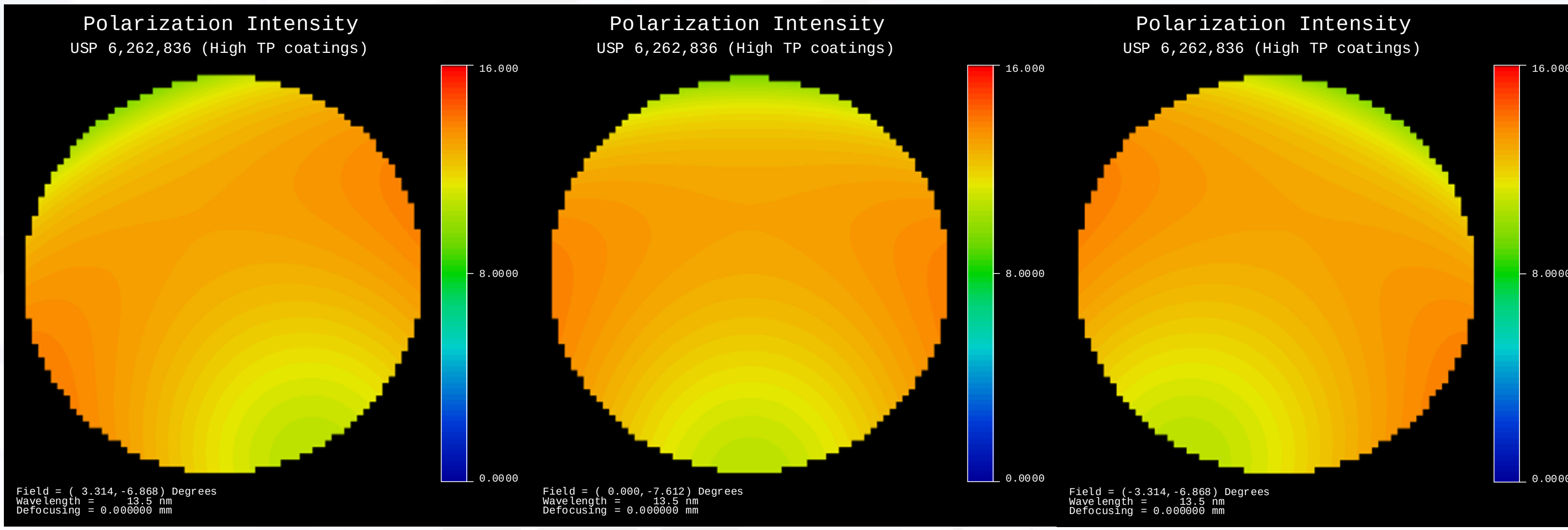
| Mirror | 0.35NA | 0.45NA |
|---|---|---|
| M1 | 10.7° | 12.0° |
| M2 | 9.1° | 10.3° |
| M3 | 5.1° | 5.7° |
| M4 | 15.4° | 17.4° |
| M5 | 19.4° | 22.6° |
| M6 | 2.6° | 3.1° |
| M7 | 11.9° | 15.3° |
| M8 | 2.9° | 3.2° |

## MoSi Reflectivity Properties



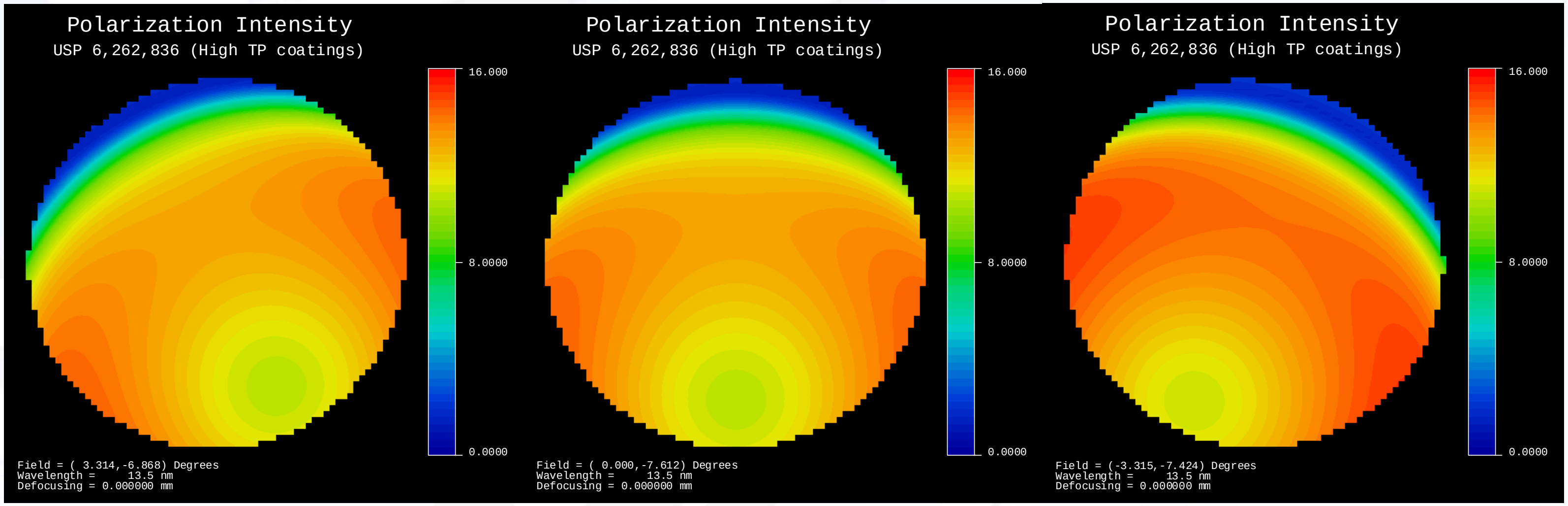
# Apodization functions at 0.35NA




(a) (b) (c)

Figure 9. The exit pupil apodization functions of projection system described NA 0.35 show insignificant amplitude errors. The projection system uses a fairly sophisticated multilayer coating design set that effectively maximizes throughput and is process capable using current coating technology. The data is presented across the "smile" starting with leftmost (a), center (b), and rightmost (c) field points, respectively, along the central radius of the arcuate ring field.

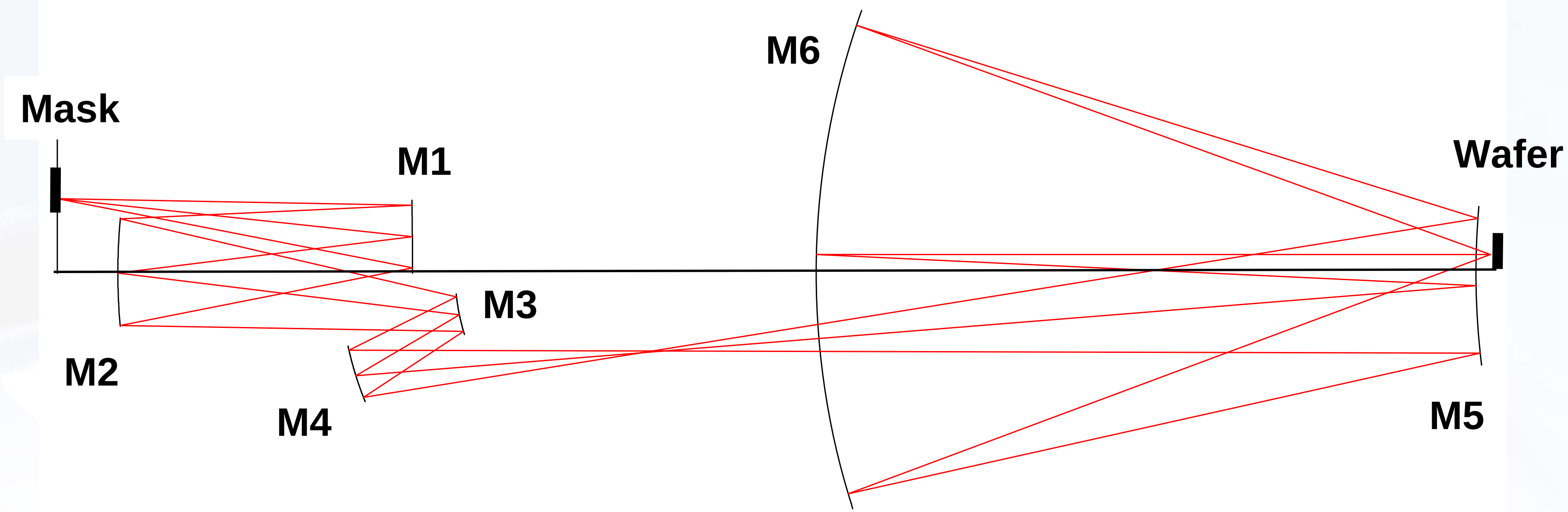
# Apodization functions at 0.45NA illustration pupil dimming




(a) (b) (c)

Figure 10. Pupil dimming (blue) becomes apparent in as the projection system is scaled from NA 0.35 to NA0.45. Again the projection system uses a fairly sophisticated multilayer coating design set that has been reoptimized, but the result fails to overcome this effect. This egg-shaped pupil causes a loss of effective numerical aperture and an orientation dependent imaging bias. These apodization maps across the exit pupil are again from the leftmost (a), center (b), and rightmost (c) field points along the central ring field radius.

# Conceptual 0.35NA 6-mirror system reduces mean angles

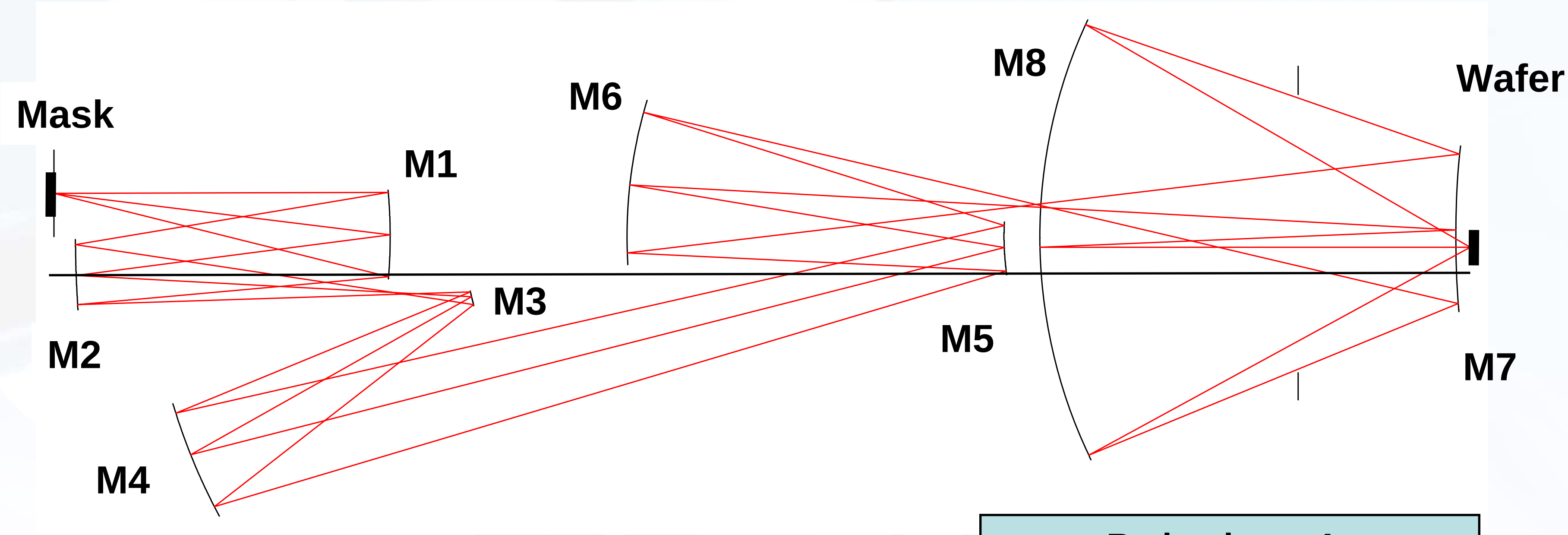



| Mean ray incidence angle |
|---|
| Mask: 6.0° M1: 6.5° M2: 7.0° M3: 18.7° |
| M4: 12.9° M5: 3.7° M6: 1.4° |

Reduction = 4x
NA = 0.35
RFW = 2.0mm
Dist. < 1.0nm
Comp. RMS < 33mλ

1240.0 mm

# Conceptual 0.53NA 8-mirror system drives resolution




**Mean ray incidence angle**

**Mask: 7.1° M1: 7.2° M2: 5.2° M3: 16.2° M4: 7.5°**
**M5: 11.9° M6: 3.2° M7: 2.8° M8: 1.2°**

**Reduction = 4x**

**NA = 0.53**

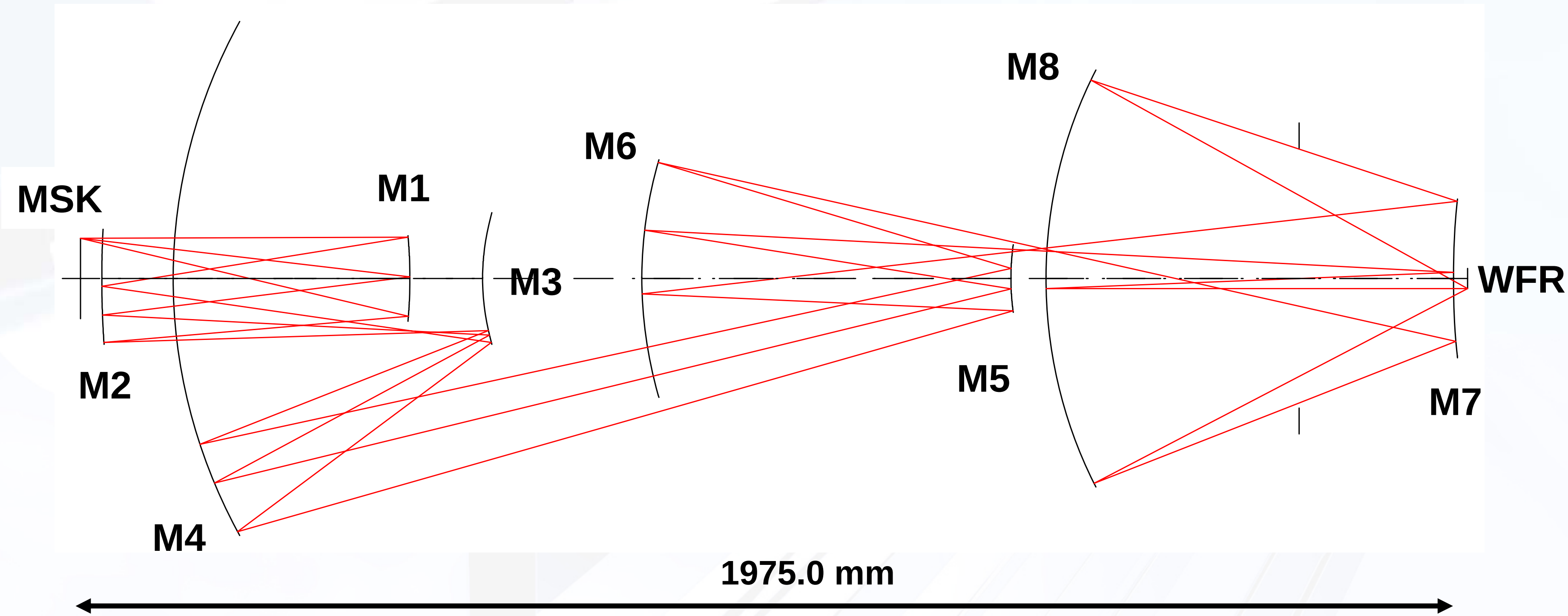
**RFW = 1.50mm**

**Dist. < 0.15nm**

**Comp. RMS < 22mλ**

**1975.0 mm**

# Conceptual 0.53NA system w/ full parents



# Design performance

| Parameter | Values | Notes |
|---|---|---|
| Design | 8-mirror | - |
| Obscuration | Yes | See graphic |
| Resolution | 11.0 nm | $R = k_1\lambda/NA$ ($k_1$= 0.43) |
| Numerical aperture | 0.53 | Maximum |
| Field size | 20 mm x 1.5 mm | Scanning ring field |
| Wavelength | 13.5 mm | MoSi |
| RMS Wavefront error | < 22.0 m$\lambda$ | Field composite |
| Distortion | < 0.15 nm | Lower possible |
| Field curvature | < 1.0 nm | No astigmatism or FC |
| Chief ray angle at mask | 7.10° | 7.0° to 8.0° possible |

# Design performance (cont'd)

| Parameter | Values | Notes |
| --- | --- | --- |
| Telecentricity at wafer | < 1.0 mrad | Similar to alpha tools |
| Free working distance mask | > 25.0 mm | Can be improved |
| Free working distance wafer | ~ 1.0 mm | Can't be improved, assumes a 12:1 aspect ratio M7 mirror |
| Mean incidence angles | M1: 7.2°<br>M2: 5.2°<br>M3: 16.2°<br>M4: 7.5°<br>M5: 11.9°<br>M6: 3.2°<br>M7: 2.8°<br>M8: 1.2° | **Key Point**<br>Angle control is similar to ETS and contemporary 0.25NA systems |

HYPERION DEVELOPMENT

# As-designed RMS wavefront

W A V E F R O N T   A N A L Y S I S

Obscured EMA (0.53NA, 4X, 1.5mm) POSITION 1

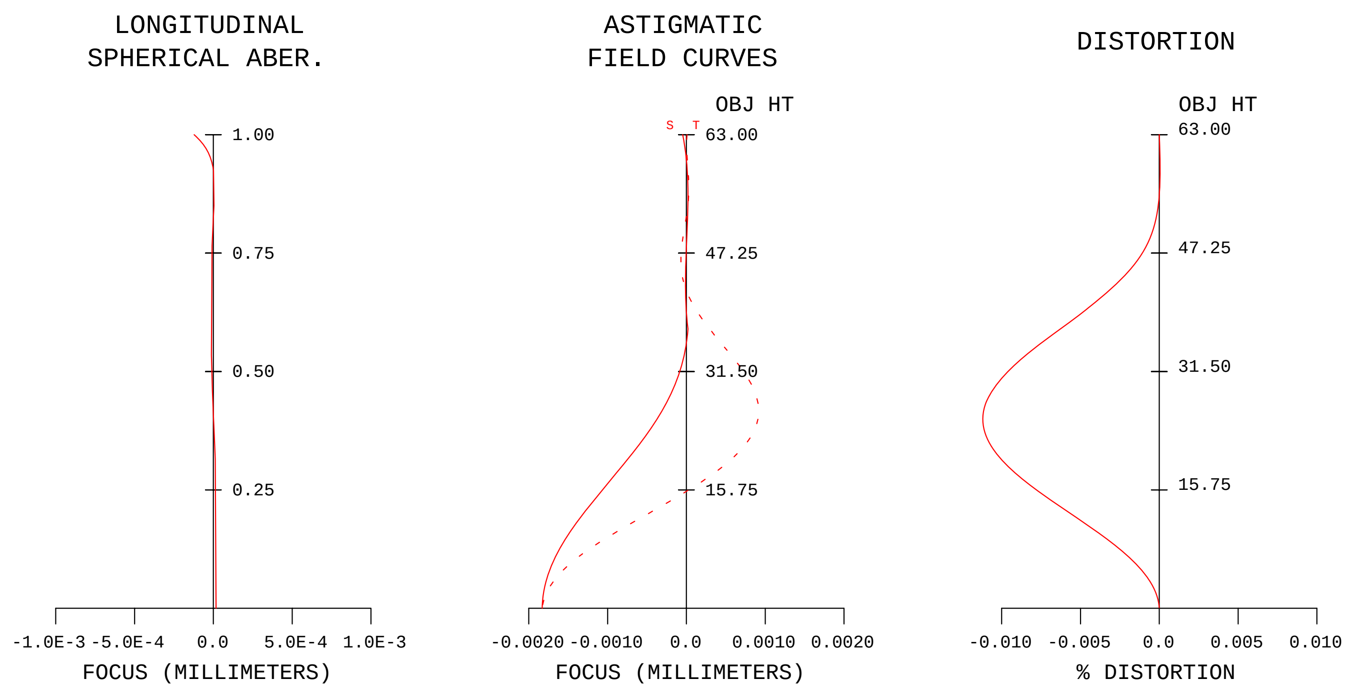
| | | | | | |
|---|---|---|---|---|---|
| X REL. FIELD | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Y REL. FIELD | 0.90 | 0.93 | 0.95 | 0.98 | 1.00 |
| WEIGHTS | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| NUMBER OF RAYS | 306 | 304 | 304 | 304 | 302 |

| FIELD | | | BEST INDIVIDUAL FOCUS | | | | BEST COMPOSITE FOCUS | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | FRACT | DEG | SHIFT (MM.) | FOCUS (MM.) | RMS (WAVES) | STREHL | SHIFT (MM.) | FOCUS (MM.) | RMS (WAVES) | STREHL |
| X | 0.00 | 0.00 | 0.000000 | -0.000001 | 0.0254 | 0.975 | 0.000000 | 0.000000 | 0.0255 | 0.975 |
| Y | 0.90 | -6.66 | 0.000001 | | | | 0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | -0.000001 | 0.0160 | 0.990 | 0.000000 | 0.000000 | 0.0162 | 0.990 |
| Y | 0.93 | -6.84 | -0.000001 | | | | -0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000000 | 0.0242 | 0.977 | 0.000000 | 0.000000 | 0.0242 | 0.977 |
| Y | 0.95 | -7.01 | -0.000001 | | | | -0.000001 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000002 | 0.0147 | 0.992 | 0.000000 | 0.000000 | 0.0153 | 0.991 |
| Y | 0.98 | -7.19 | 0.000000 | | | | 0.000000 | | | |
| X | 0.00 | 0.00 | 0.000000 | 0.000000 | 0.0260 | 0.974 | 0.000000 | 0.000000 | 0.0260 | 0.974 |
| Y | 1.00 | -7.36 | 0.000000 | | | | 0.000000 | | | |

COMPOSITE RMS FOR
POSITION 1: 0.02194

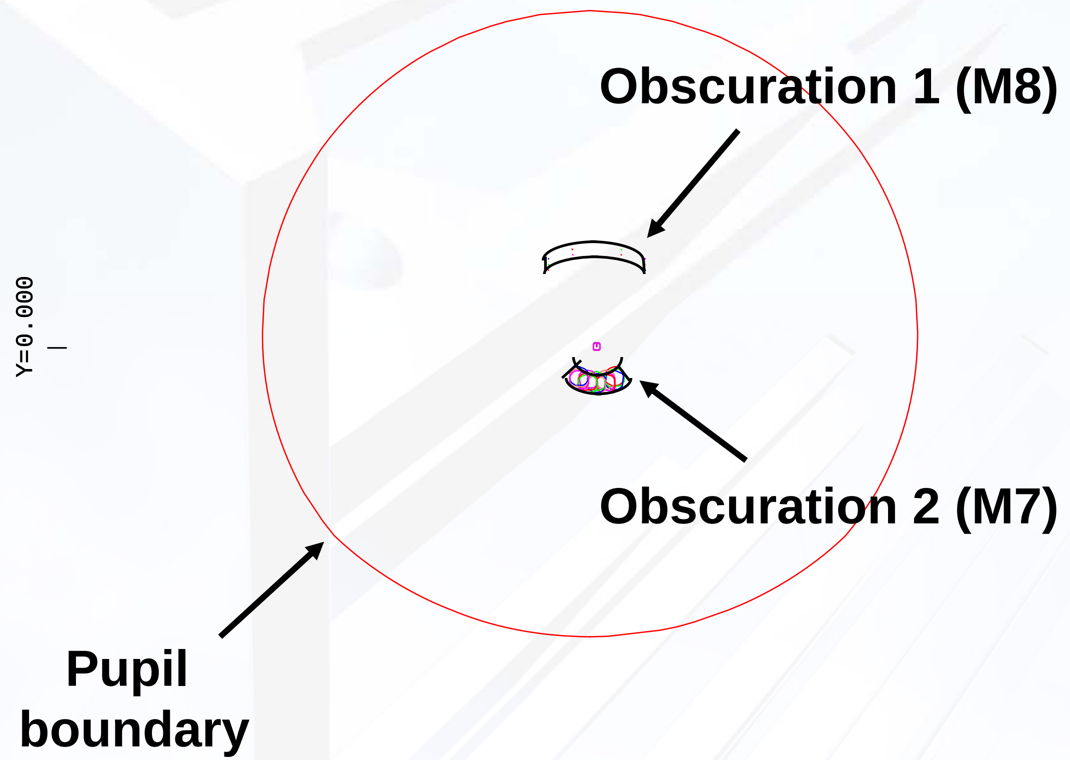
Units of RMS are waves at 13.5 nm.

# 0.53NA Concept Field Curves




Obscured EMA (0.53NA, 4X, 1.5mm)

# Design minimizes pupil obscuration function



# If Etendue can be used, system transmission can be increased

$$E_{opt} = w \times h \times \pi \times \sigma^2 \times NA^2$$

$$T_{ratio} = \left(\frac{R^{m_\beta}}{R^{m_\alpha}}\right)\left(\frac{E_\beta}{E_\alpha}\right)$$

| NA | Width (mm) | Height (mm) | σ | $E_{opt}$ ($mm^2$-sr) |
|---|---|---|---|---|
| 0.25 | 2.0 | 26.0 | 0.50 | 2.55 |
| 0.35 | 2.0 | 22.0 | 0.60 | 6.10 |
| 0.50 | 1.5 | 20.0 | 0.60 | 8.48 |

**Relative Étendue**

| NA | Etendue ($mm^2$-sr) | Bounces (m) | $T_{ratio}$ |
|---|---|---|---|
| 0.25 | 2.55 | 6 | 1.00x |
| 0.35 (O) | 6.10 | 8 | 1.20x |
| 0.35 (U) | 6.10 | 6 | 2.40x |
| 0.50 | 8.48 | 8 | 1.63x |

**Relative Transmission**

# Source development impact

- Previous analysis holds if etendue is <u>usable</u>
- For some time, integrators demanded smaller source volumes to match etendue of source/collector geometry to projection system
- High numerical apertures will allow larger sigma, also potentially improving throughput
- Questions:
  - Does it help source suppliers to make sources a bit bigger?
  - Can we use this larger source for better etendue matching?
  - Can we utilize a larger sigma to improve throughput?

# Conclusions

- EUV projection solutions exist for 22 nm, 16 nm, and 11 nm half pitch
- DOF becomes stressed as half pitch is decreased
- Unobscured systems can be considered for numerical apertures in excess of 0.40
- Obscured system can be considered for numerical apertures in excess of 0.50
- Projection system throughput can be further optimized
- Multiple solution paths exist moving forward
- EUV's required improvements are similar to 193 nm's historical advances