Optical Design for Affordable EUV Lithography

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Background

- **Scaling the cost per device per cm^2 on a wafer has become an increasingly important factor for all lithography technologies**

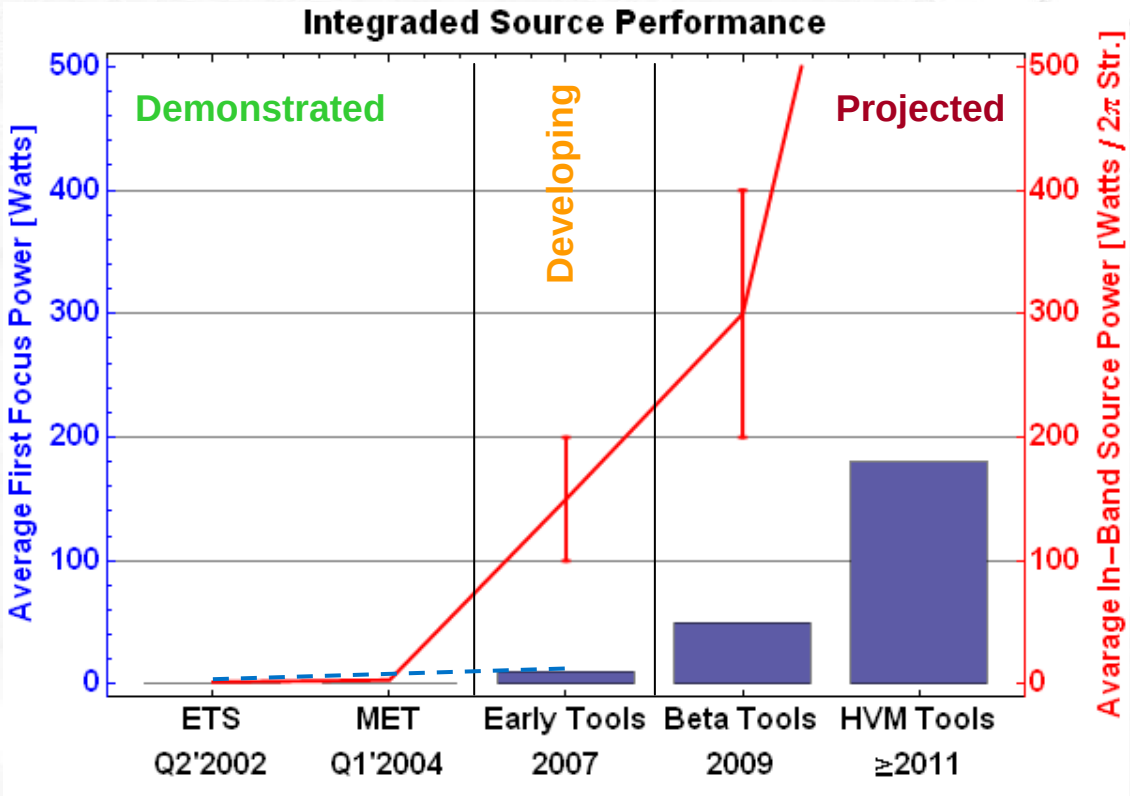
- **The principal factors in EUV lithography are:**
  1. Source power
  2. Resist photo speed
  3. Collection and radiometric efficiency
  4. Reliability, capital cost…

- **At the present time only a few parts per 100,000 of the energy pumped into a plasma will reach the wafer as EUV photons**

- **Increasing collection and radiometric efficiency remains a significant opportunity**

Integrated Source Power, learning rate

- There have been only a few demonstrations of integrated source power and consumable lifetime
- The current learning rate for source power is unlikely to keep pace with EUV specifications



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Reliable Source Power, state of the art

- HVM Requirements
  - Power 180 Watts
  - Collector lifetime ~80B pulses at ≥7 KHz repetition rate
  - Total energy per collector is $\text{Power} \times \frac{\text{LifeTime}}{\text{RepetitionRate}} = 2 \times 10^{9}\ \text{Joules}$
- Discharge produced plasma (DPP)
  - Average first focus power is well below ~10 Watts
  - Collector lifetime is approaching ~10^{10} pulses at a ~5 KHz
  - Total energy per collector today is $\text{Power} \times \frac{\text{LifeTime}}{\text{RepetitionRate}} = \sim 2 \times 10^{7}\ \text{Joules}$
- Laser Produced Plasma (LPP)
  - Average power lags DPP today
  - Minimal lifetime data available

Approximately 18× power improvement required

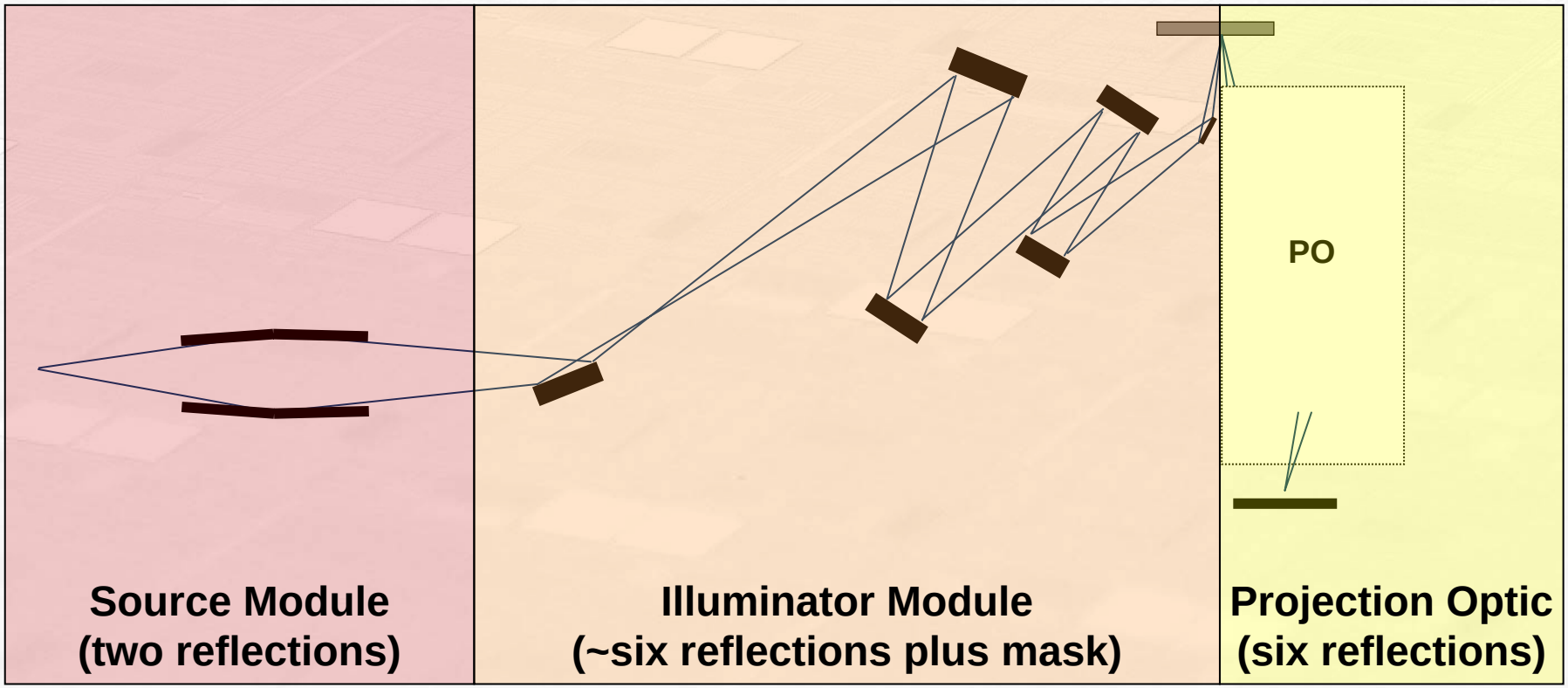
Approximately 100× energy improvement required

Advancing State-of-the-Art

- The learning rate and current status of EUV source technology necessitates improved optical methods:
  - New illuminator designs with superior radiometric efficiency
  - Increased etendue, NA, and collection efficiency
  - Balance the problem by accepting optical fabrication difficulties or performance trade-offs to reduce the burden on source technologies

Introduction to the Optical Path

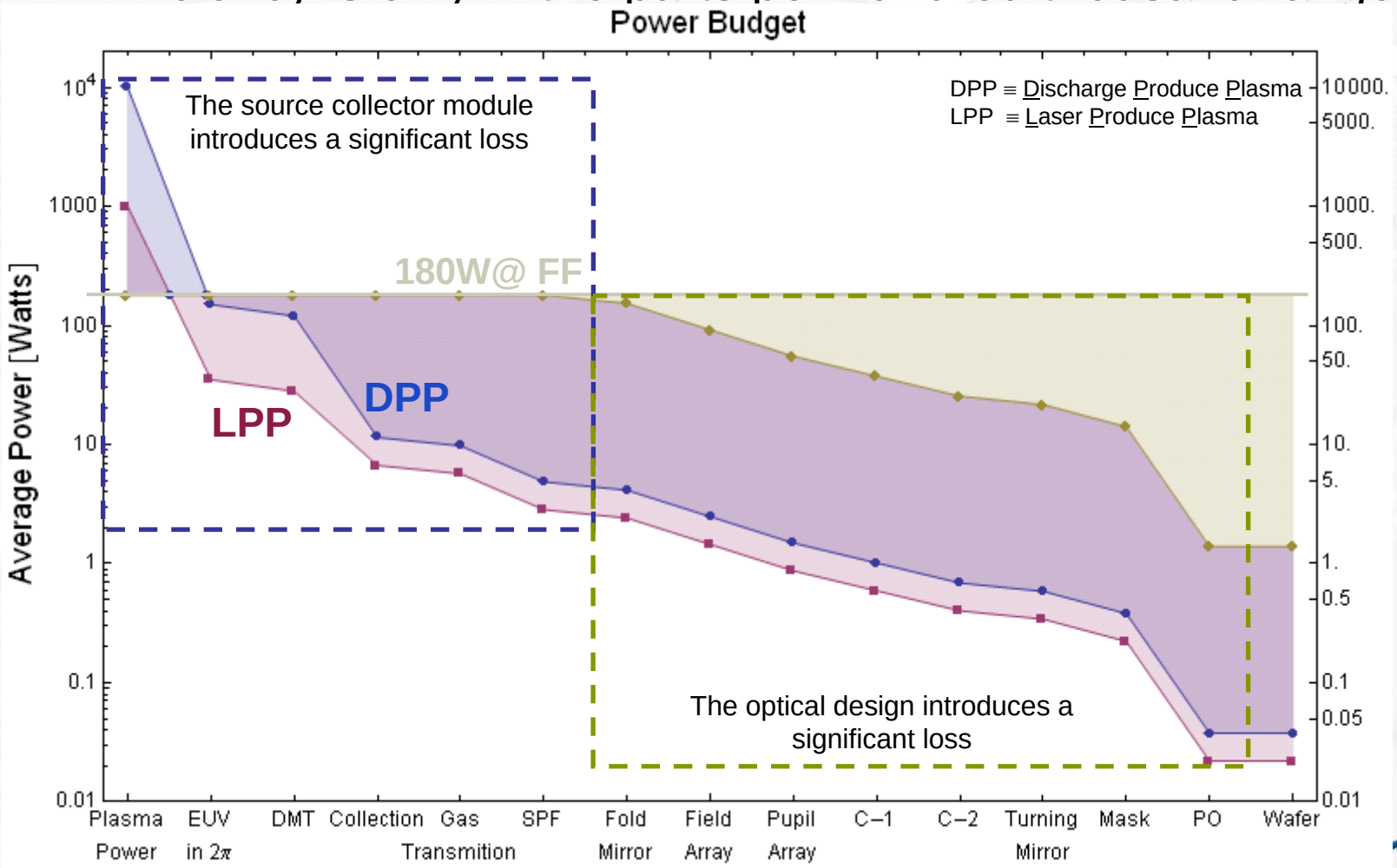
- Illustration analogous of early full field tools***
  - Low collection efficiency
  - Low illuminator efficiency (six reflections)
  - Modest etendue (0.25NA) projection optic



*** J. Jonkers, "High power extreme ultra-violet (EUV) light sources for future lithography, Plasma Sources Sci. Technol. 15 (2006) S8-S16.

Approximate Power Budget for Existing Tools

- Loss accrues along the optical path***
  - Efficiency is only in the parts per hundred thousand range!



*** **Excluding additional losses in etendue transformation, illumination uniformity tuning, and contamination.**

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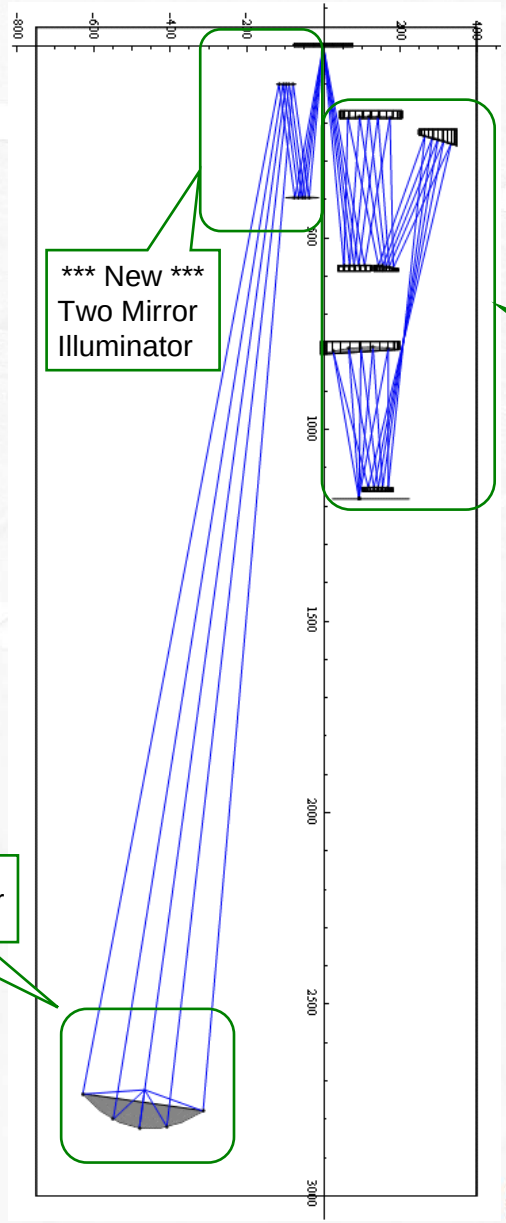
Combining Functionality

- Two-reflection illuminator
  - Perhaps an efficiency limit with acceptable performance

- Optical approach
  1. Move source into sub-fab
  2. Use collector to fill the pupil
  3. Use a single fly's eye to
     - Shape the arcuate field
     - Provide illumination unif.
     - Correct condenser aberrations
  4. Single mirror condenser
  5. Eliminated fold mirrors



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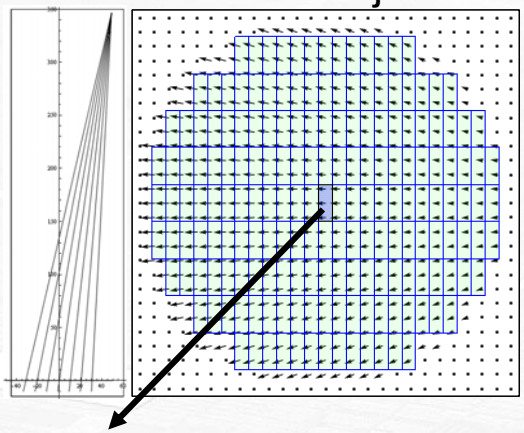
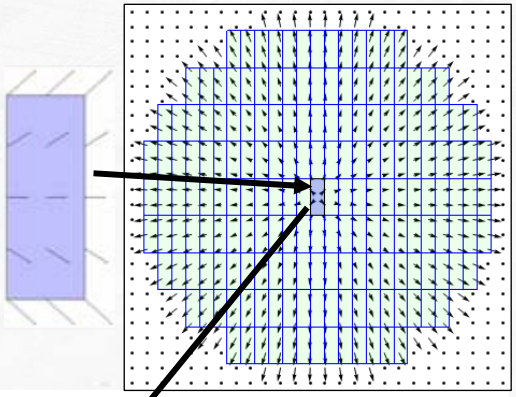
Novel Fly's Eye

- The fly's eye is doing all of the work
- Design method
  - Calculate incident vectors
  - Map fly's eye array
  - Calculate reflection and unit normal vectors
  - Calculate surface sag function for fly's eye elements

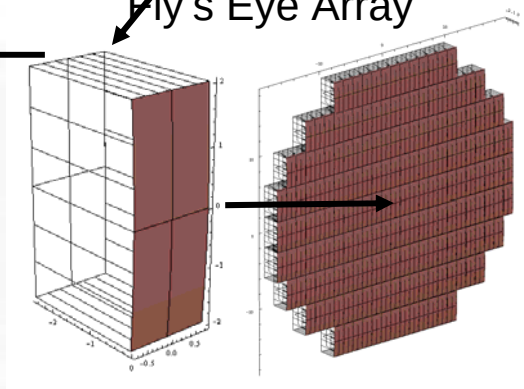
Incident Vector Projections

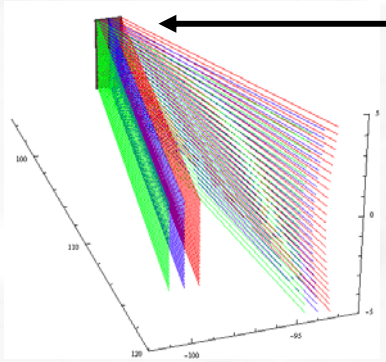


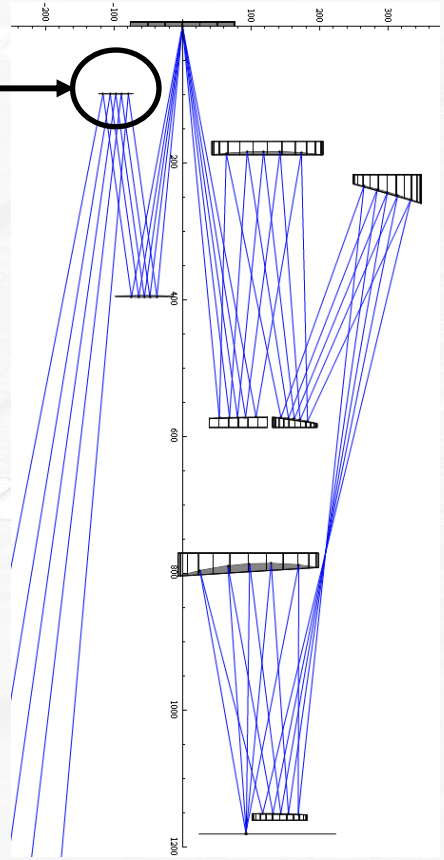
Reflection/Normal Vectors



Fly's Eye Array

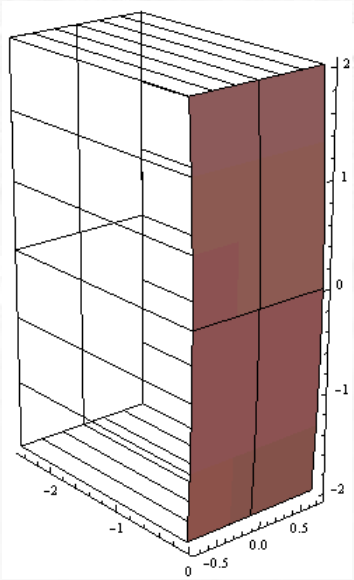


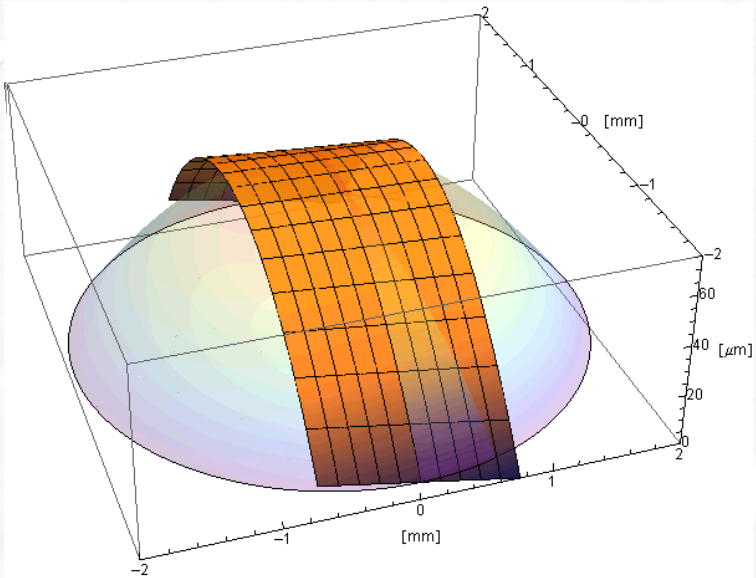




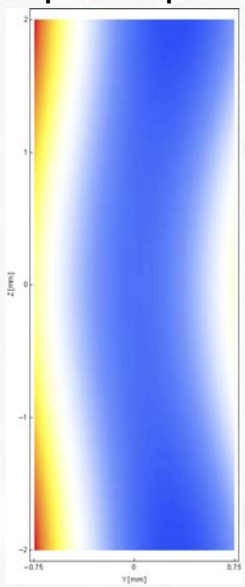
Fly's Eye Fabrication

- Example element:
  - Element: Center, 93 of 185
  - Element size: 1.5 x 4.0 mm
  - Surface sag: 71 μm
  - Aspheric departure: 16 μm
- Development is needed however fly's eye mirrors have achieved ~mm scale dimensions, 0.1 μm surface accuracy, and sub-nm roughness**





Aspheric Departure

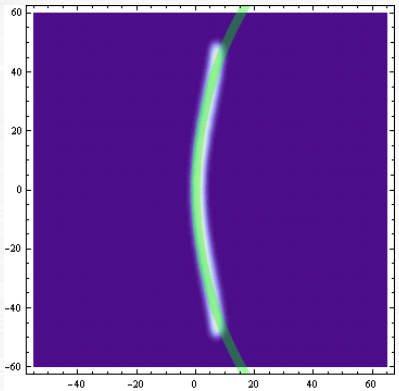


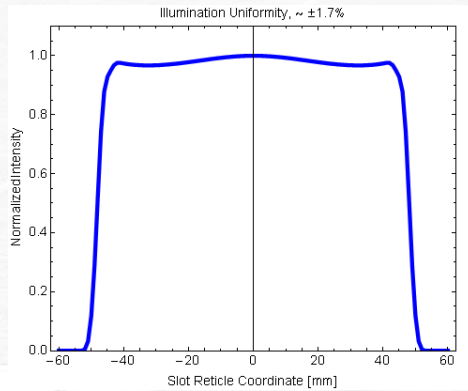
** H. Takino, T. Kobayashi, N. Shibata, M. Kuki, A. Itoh, H. Komatsuda, "Fabrication of a fly-eye mirror for extreme ultraviolet lithography illumination system," 576 – 584,Proceedings of SPIE, 4343 (2001).

*** F. Salmassi, P.P. Naulleau, E.M. Gullikson, "Spin-on-glass smoothing of diamond-turned cylindrical fly eye illumination mirrors," CXRO, Poster OP-P06 in this symposium.

Field and Pupil Uniformity

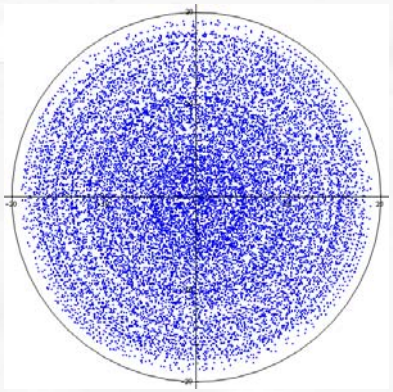
❑ Illumination uniformity

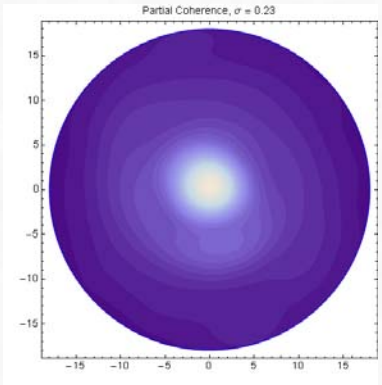




- Performance is limited by systematics and further optimization is possible
  - Uniformity → ~±1% (150μm plasma R3σ)
  - Slit width → ~ 2 – 3 mm.

❑ Pupil fill





- The pupil fill is centrally weighted for a near normal incidence (NNI) collector
  - Low coherence → $\sigma \approx 0.233$
  - Wolter GI collector → Annular σ
  - NNI+GI collector → Soft annular

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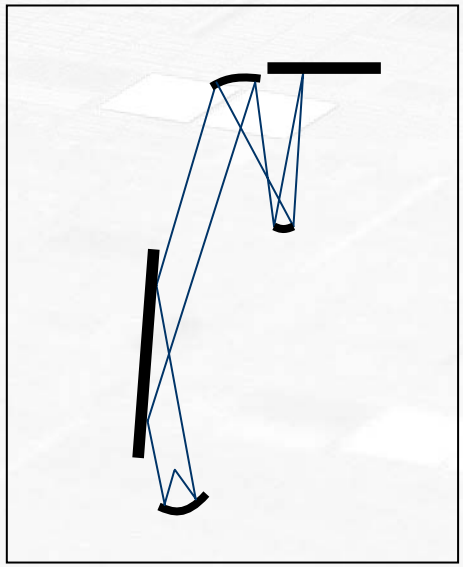
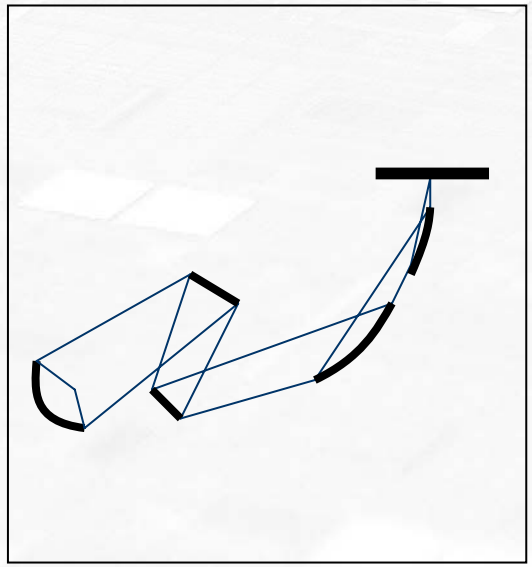
Examples in the literature***

- The three reflection ripple plate concept below uses orthogonal Kohler and critical illumination in the x and y directions.
- The four reflection example uses two fly's eye mirrors.
- Both of these methods, like the proposal given in this presentation, require moderate improvements in optical fabrication and testing.



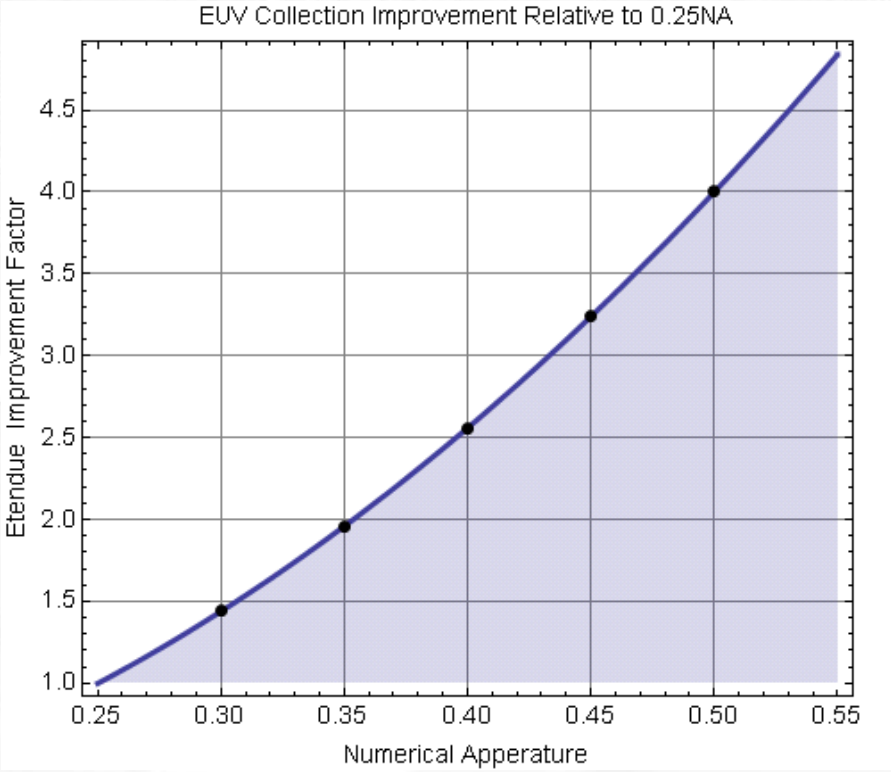


*** H.N. Chapman, K.A. Nugent, "Anovel Condenser for EUV Lithography Ring-Field Projection Optics," Proceedings of SPIE 3767, pp. 225 – 236 (1999).

*** M. Antoni, W. Singer, J. Schultz, J. Wangler, I. Escudero-Sanz, B. Kruizinga, "Illumination Optics Design for EUV-Lithography," Soft X-Ray and EUV Imaging Systems, Proceedings of SPIE Vol. 4146 (2000).

Increasing Etendue

- Historically, NA is only increased for improved resolution
- However, light collection also scales with increasing NA
- A 6-mirror PO at 0.35 NA has 2× the Etendue of a 0.25 NA PO
- A 0.5 NA 8-mirror PO also has 2× the Etendue of a 0.25 NA PO



Comment:

- The maximum possible NA for 6-mirror and 8-mirror projection optics needs further investigation.
- A small central obscuration facilitates increasing NA without added reflections and should also be studied.

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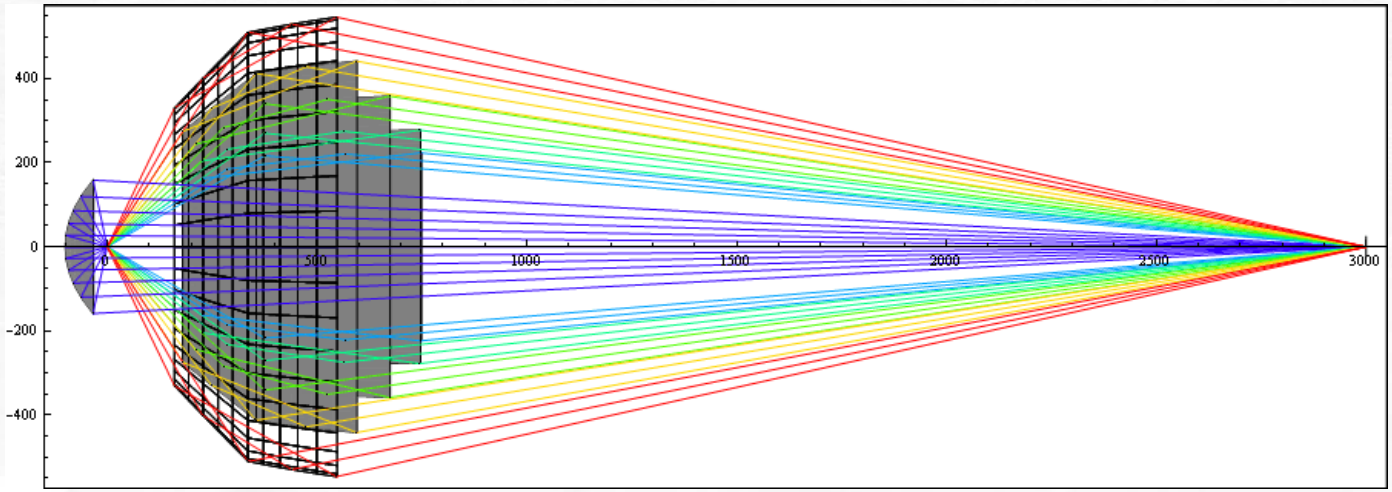
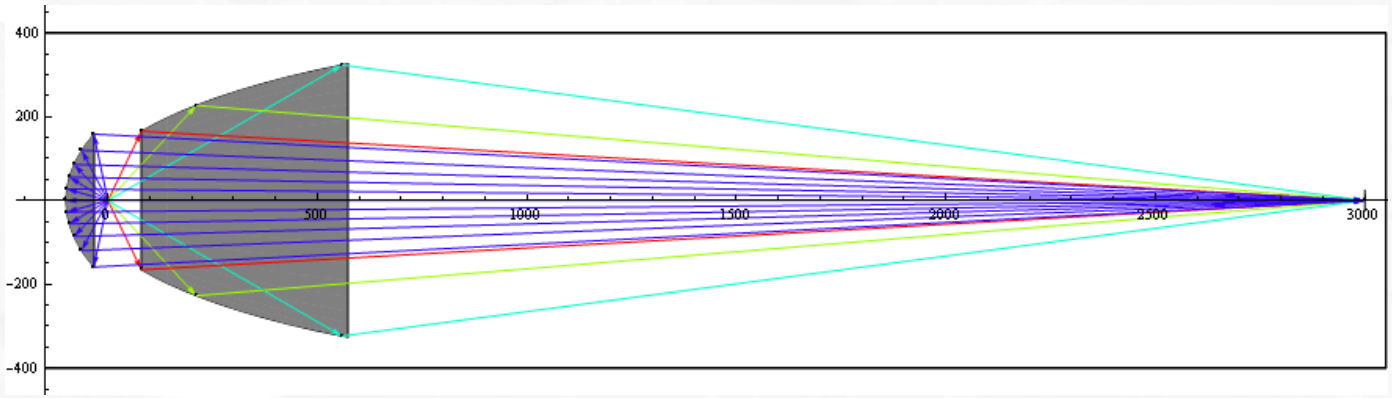
High Etendue Collection

- Grazing incidence collector: 2.7 steradians
- Near normal incidence collector: 5.0 steradians
- Duel hemisphere collector:*** 7.7 steradians

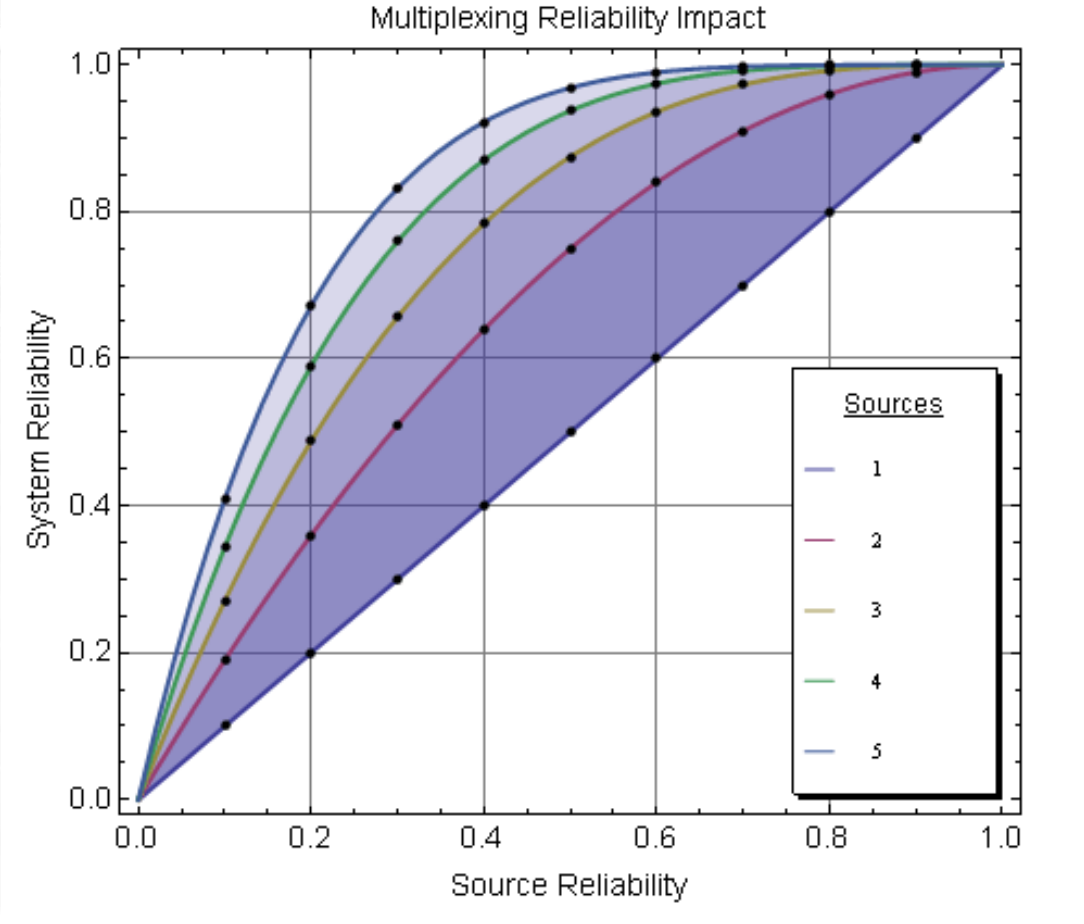




*** P. Silverman, M. Goldstein, "Dual hemispherical collectors," US Patent 7,034,320, April 25, 2006.

Reliability benefit from multiplexing

- System reliability benefits greatly from source multiplexing



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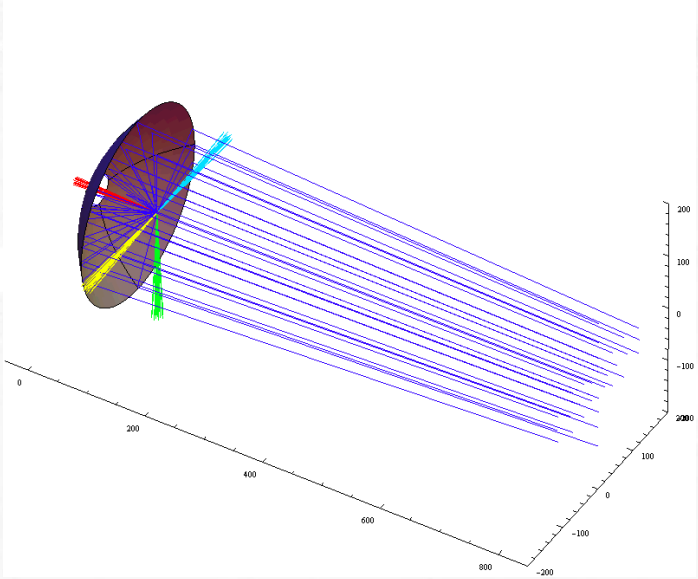
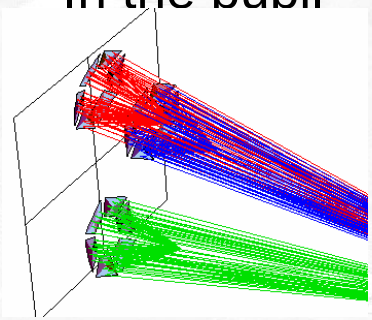
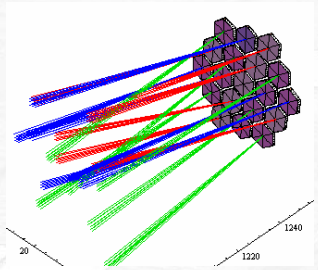
LPP Multiplexing

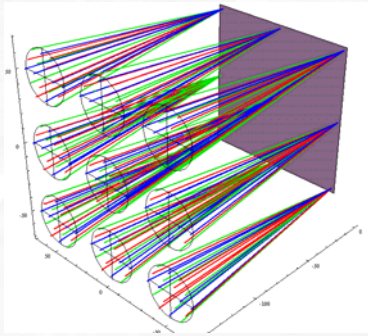
- Temporal Multiplexing
  - Multiple pump sources
  - Increases power
  - Increases reliability
  - The collector becomes the weakest link…



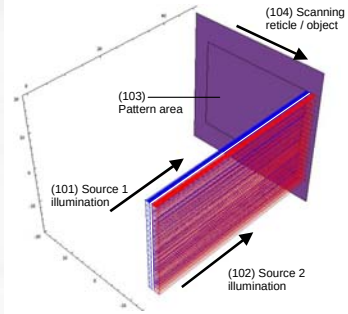
- Interleaving (etendue limited)***
  - In the pupil







  - At the reticle (scan integration)

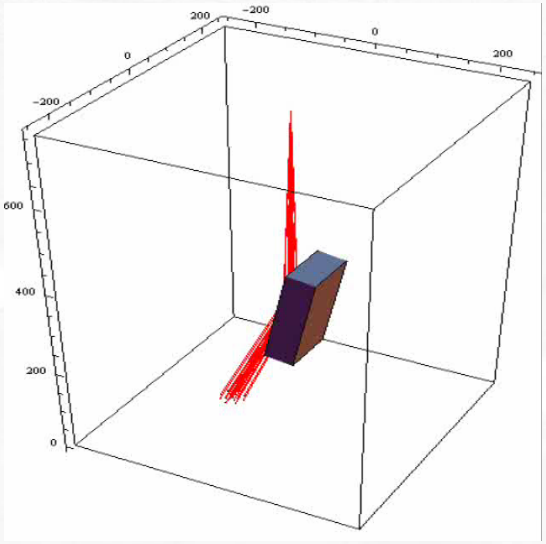


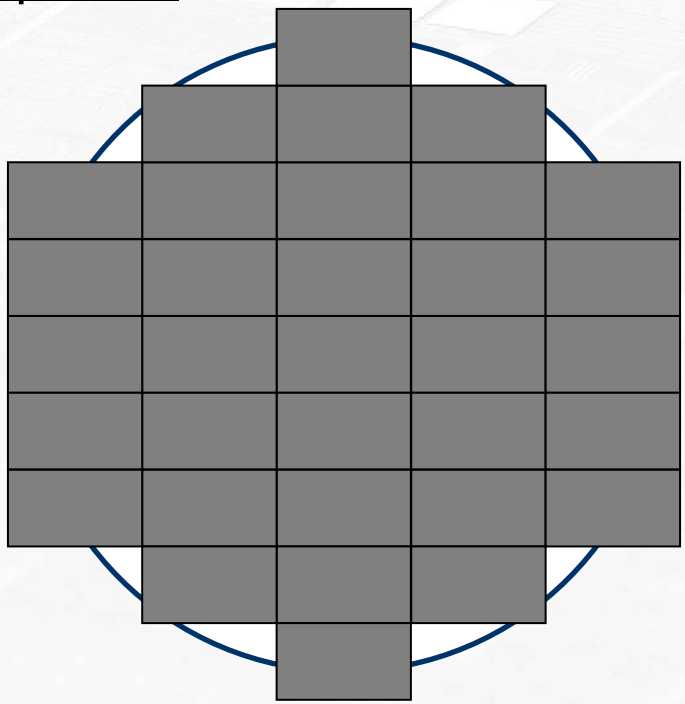
*** M. Goldstein, P. Silverman, "Extreme Ultra-Violet Source Multiplexing," 2006 EUV Source Workshop.

DPP Temporal Multiplexing

- A fold mirror (R≈85%) can be rotated for temporal multiplexing
- The source is switched between an integer number of exposure fields
- Burst operation of tens to hundreds of milliseconds per source
- Mirror rotation and alignment also needed in tens to hundreds of mS

Conceptual Approach





***** M. Goldstein, P. Silverman, "Source Multiplexing in Lithography," US Patents 7002164, 7183565, 7279693, January 2003.**

Radiometric Improvement Opportunities

- Illuminator design:
  - Eliminating reflections: 2.0× to 3.0×
- Increasing Etendue:
  - 0.35NA: 1.5× to 2.0×
- Multiplexing
  - LPP or DPP: 1.0× to 2.5×
    (one to three sources)

- Recommended target: ~3× to ~15× improvement
- Considerable development is needed to realize this opportunity.
- However, significantly less effort is needed then would be required to realize an equivalent source improvement.

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Conclusion

- There has been a multiyear and multi hundred million dollar effort to improve source power and reliability
- The current roadmap is at very high risk of missing the required timeline for delivery of beta and HVM sources
- Early full field tools are relatively inefficient and an illuminator design with ~3× greater transmission was presented.
- High collection and ultra-high efficiency illumination systems should be developed for HVM EUV lithography
- Multiplexing is an option for increased power and reliability

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