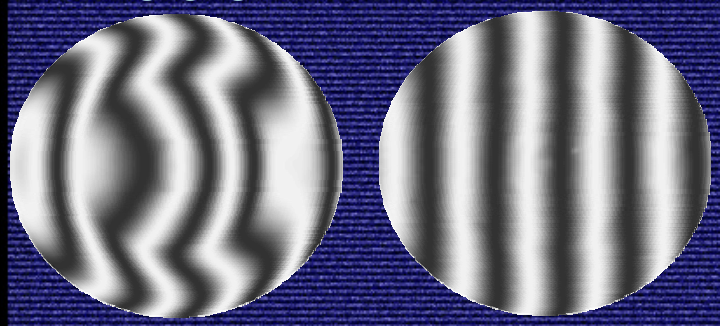
Magneto-Rheological Finishing (MRF) of Large and Lightweight Optics



presented to:

Technology Days in the Government
Mirror Development and Related Technologies
Huntsville, Alabama USA
17-19 August 2004

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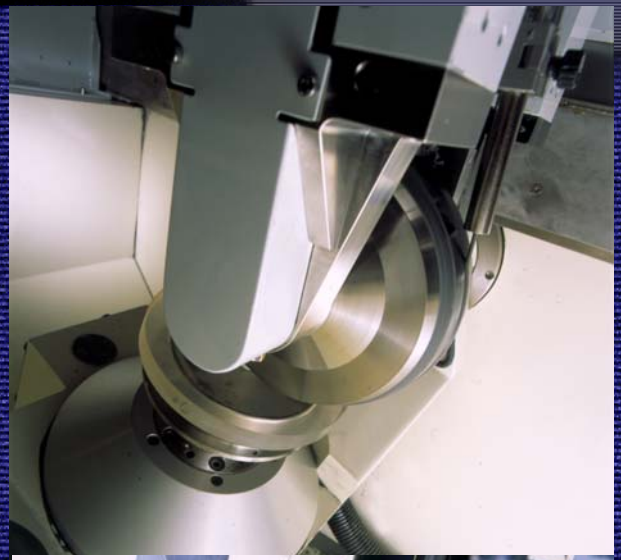
Family of MRF Machines

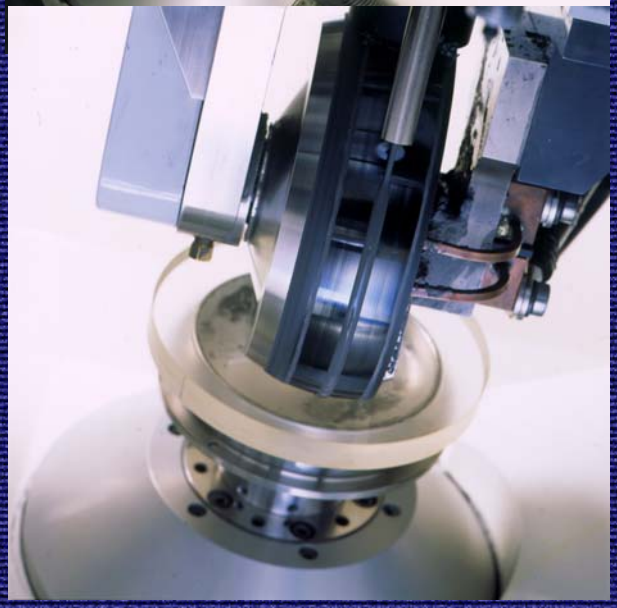
- **Q22-XE – Up to 80 mm in diameter.**
- **Q22-X - Up to 200 mm in diameter.**
- **Q22-Y - Raster tool path, up to 200 mm in size.**
- **Q22-400X - Up to 400 mm in diameter.**
- **Q22-750P2 - Plano optics up to 750 mm x 1000 mm in size.**

- **The next-generation, meter-class machine is being built to finish free-form optics**
  - **Q22-950F – Meter class freeform optics**
  - **Q22-xxxxF – Multi-meters (1-4 m) freeform optics**

- **SSI -- Subaperture Stitching Interferometer (SSI) for high precision metrology.**

Q22-400X MRF System



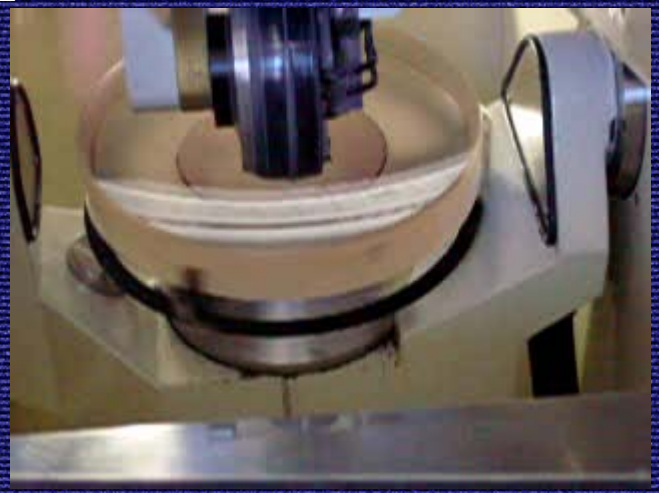


Examples of Polishing on Q22-400x

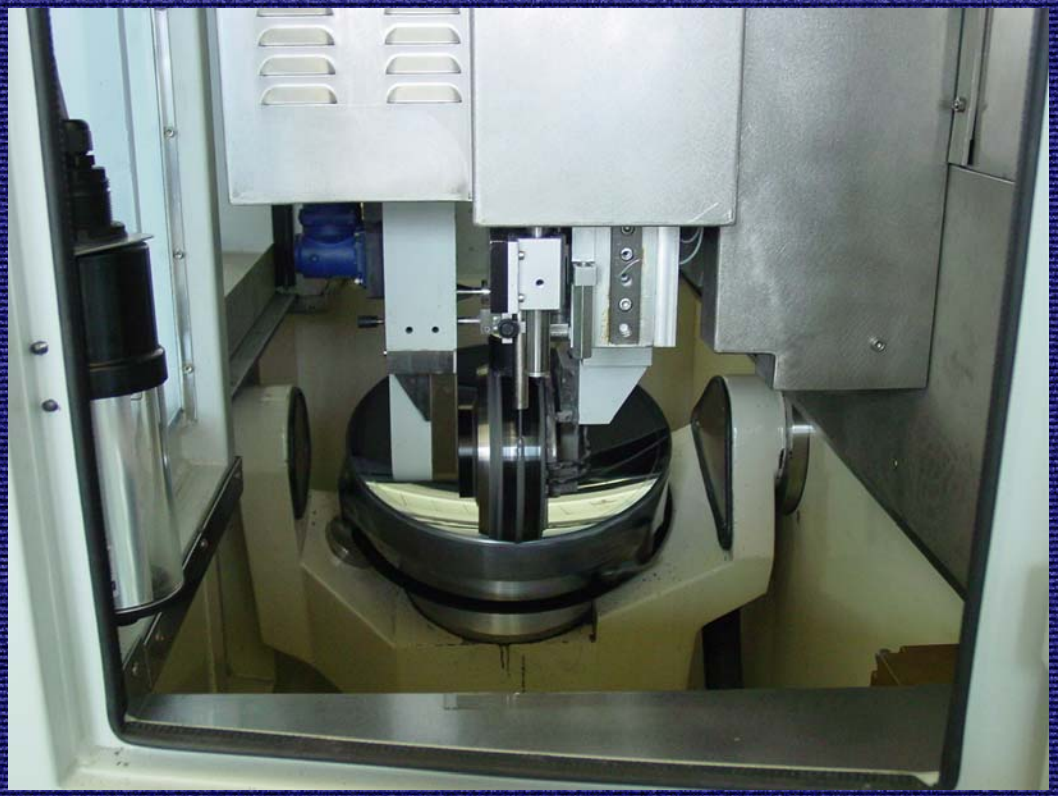
400mm diameter ULE Concave

M

Q22-400x

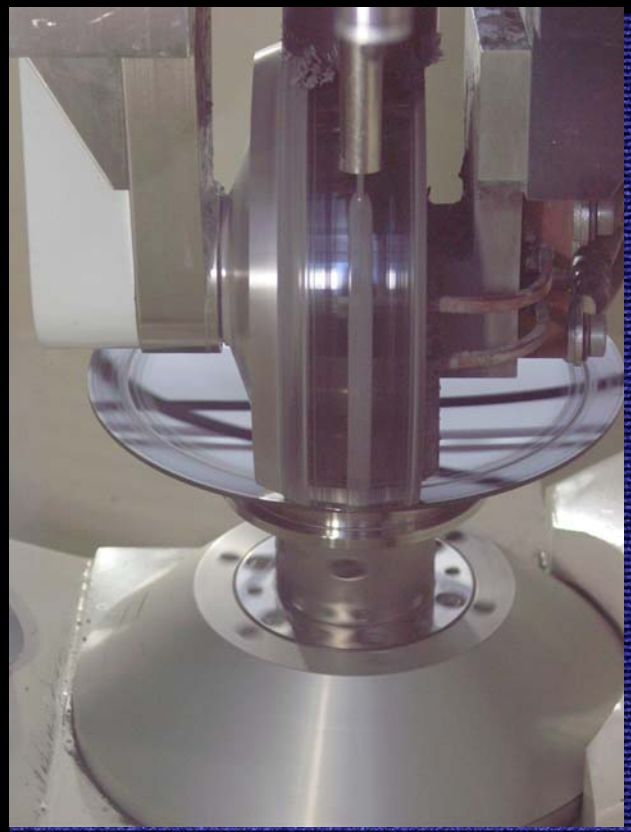


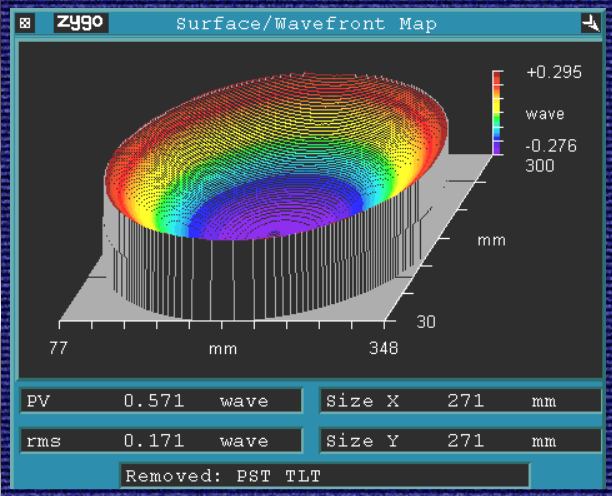
Q22-400x

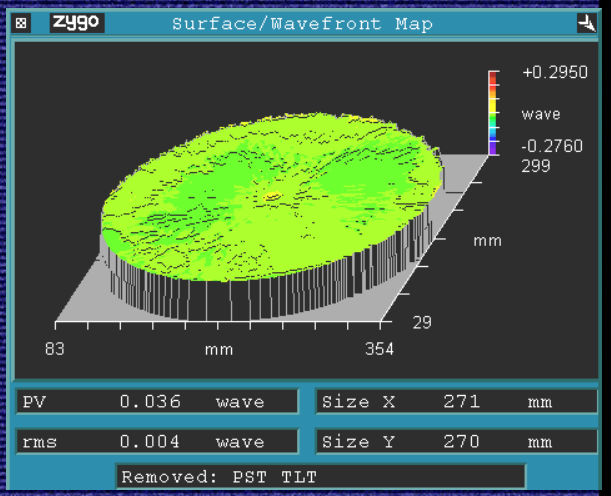


400mm diameter Silicon Concave

300mm SiC Mirror

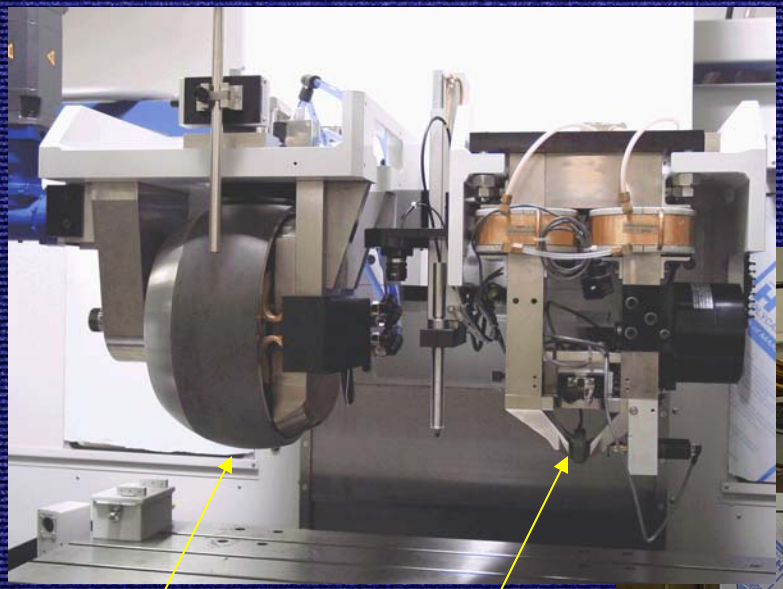






- A 300 mm diameter flat SiC mirror was polished from 0.57λ to 0.04λ P-V (0.17λ to 0.004λ RMS)
- Final roughness was ~ 1.5 nm RMS (20x magnification)

Q22-750P2



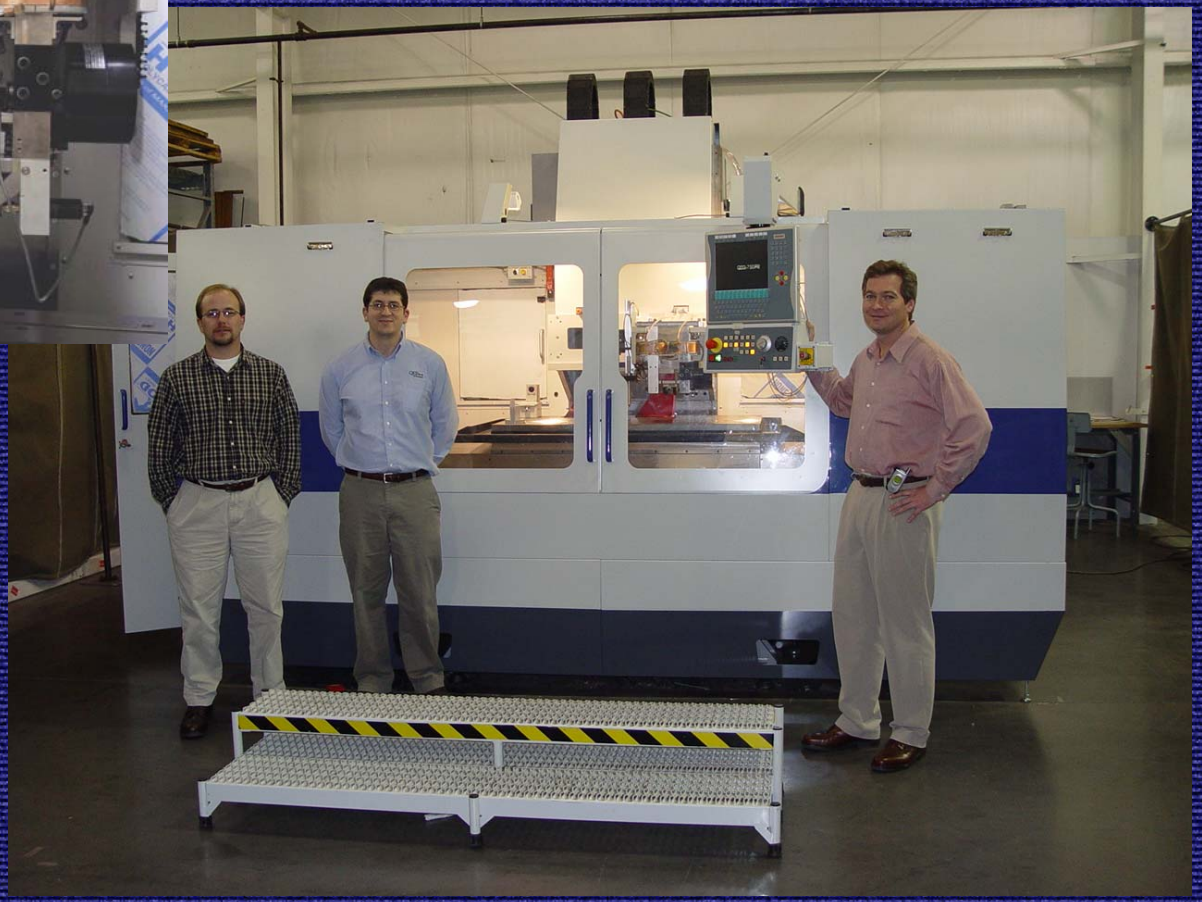
Large Wheel
370 mm diameter

Small Wheel
50 mm diameter

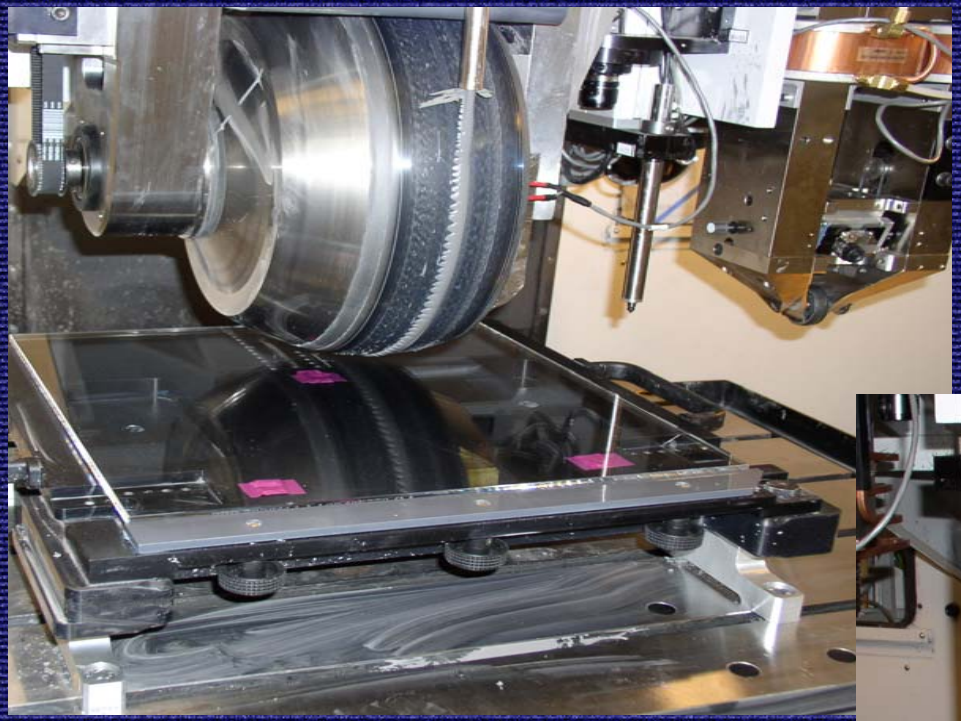
2 MRF "Heads"

Polish apertures up to

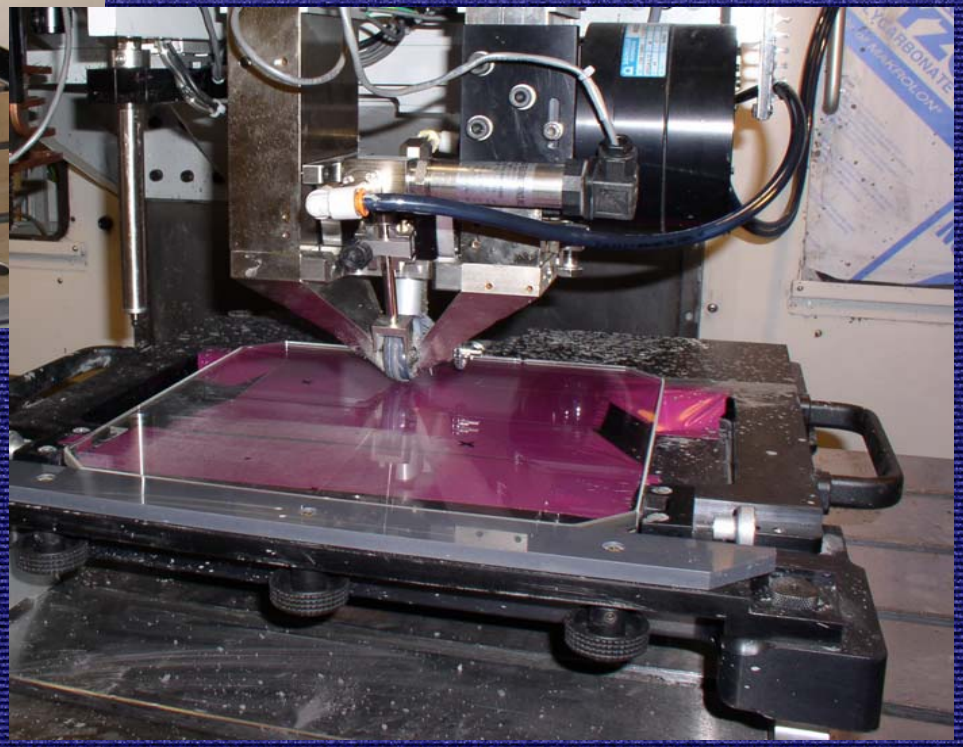
750 x 1000 mm



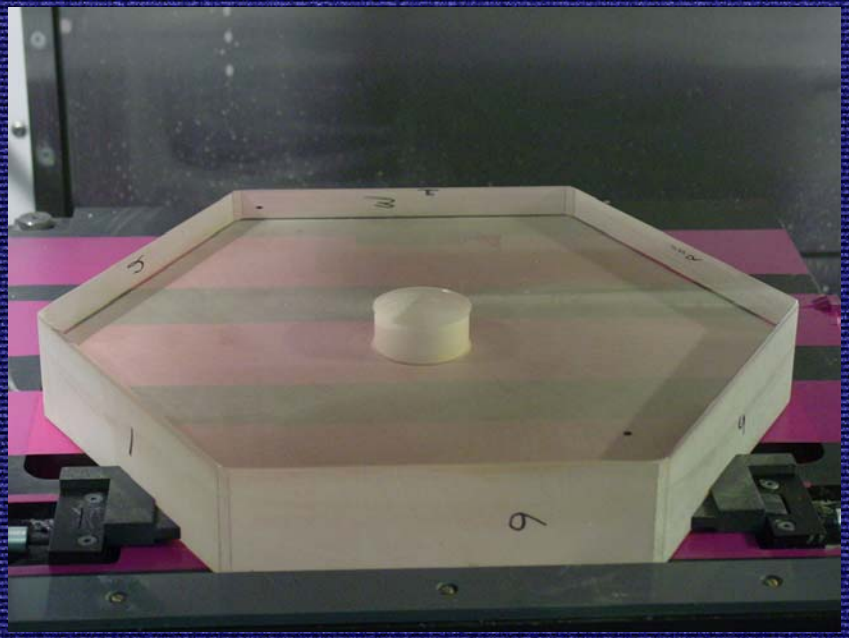
Q22-750P2 Polishing



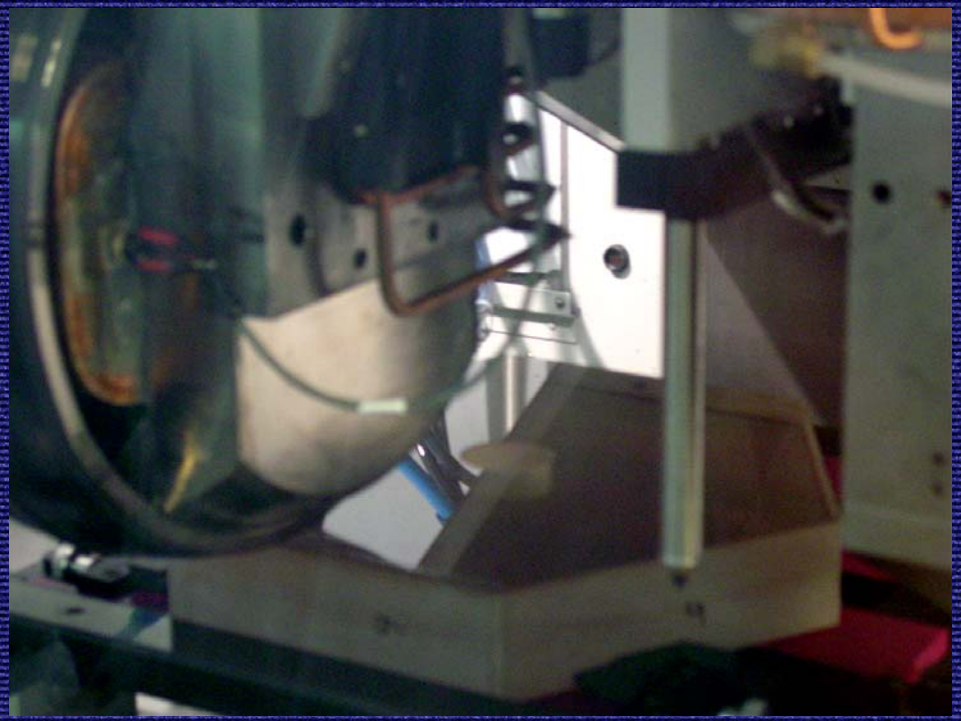
~500 mm diameter FS Plate



Q22-750P2 Polishing

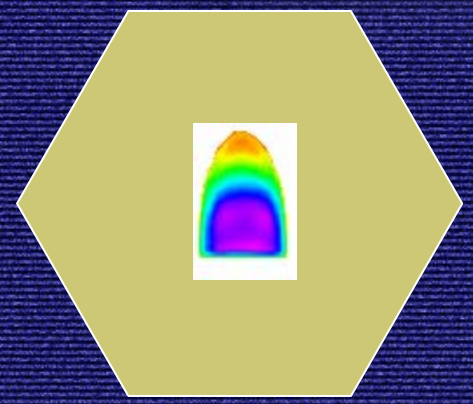


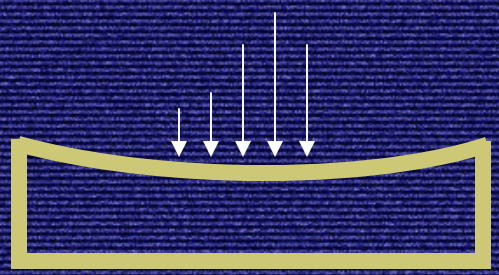
350mm flat-to-flat ULE Plano



Advantages of Using MRF to Finish Lightweight Optics

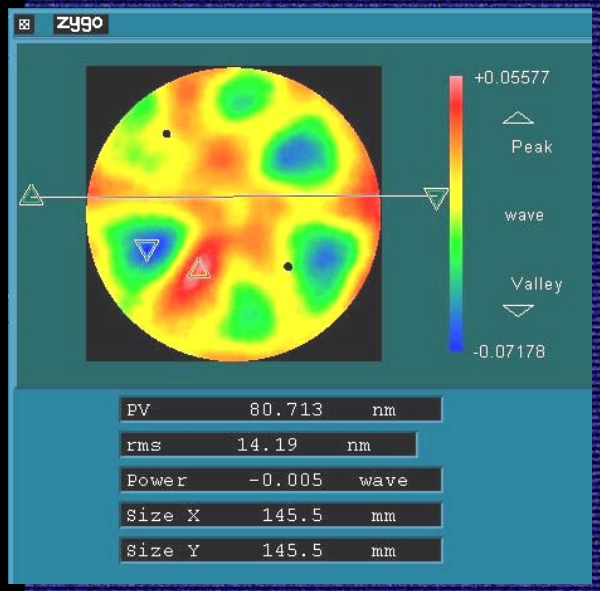
- Contact zone in MRF can be easily tailored depending on the cell size and/or existing quilting
- Low force, while maintaining high MRR
- → Conformal nature and shear mode of removal make MRF insensitive to small changes in distance between workpiece and wheel surface.



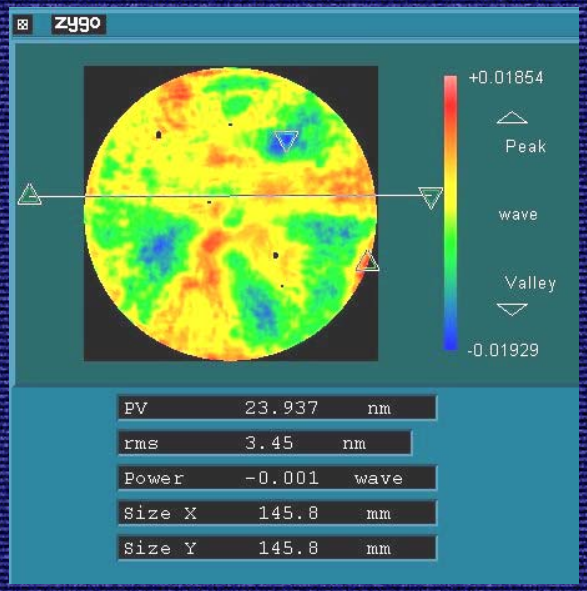


MRF Quilt Pattern Removal

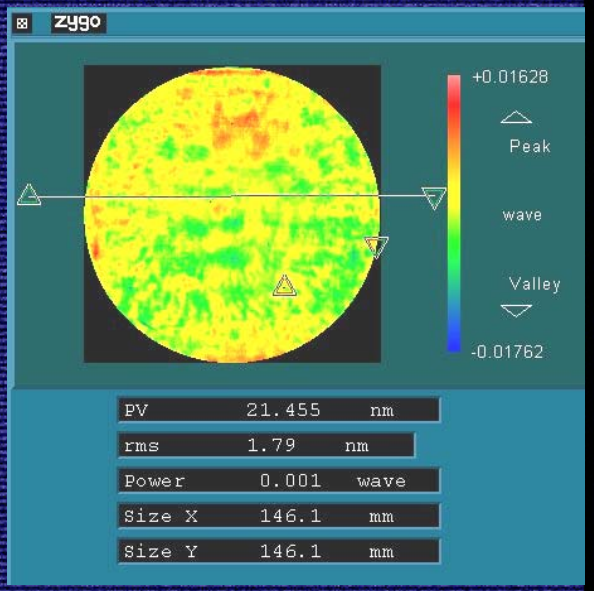
Initial



1st Iteration



2nd Iteration



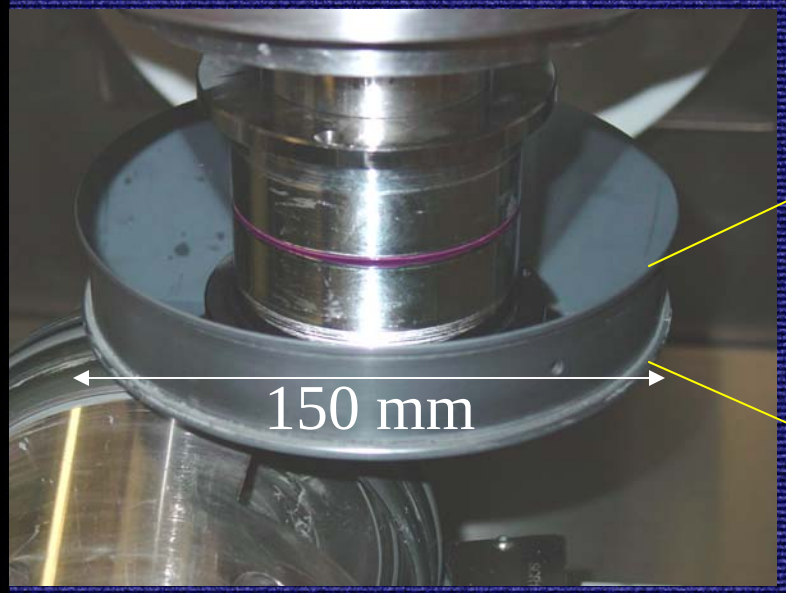
Subset of cryogenic quilting error printed into a part using MRF to simulate figure correction of lightweight optic

Provided by NASA MSFC

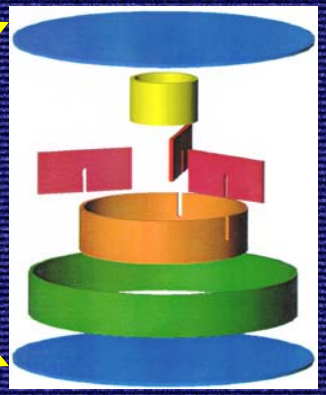
- > 4x improvement after 1 iteration with MRF
- Initial = 14.2 nm RMS
- Final = 3.5 nm RMS

- Perform 2nd iteration with MRF
- Quilting pattern removed
- Final = 1.8 nm RMS

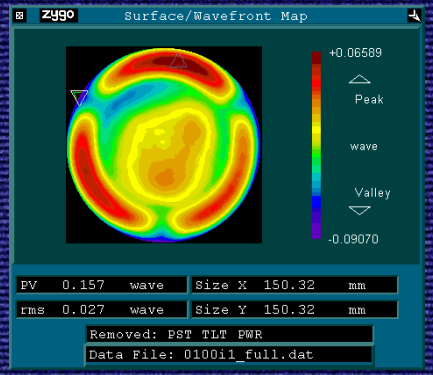
McCarter Frit-bonded Single Crystal Light-Weight Silicon Mirror



Lightweight Design



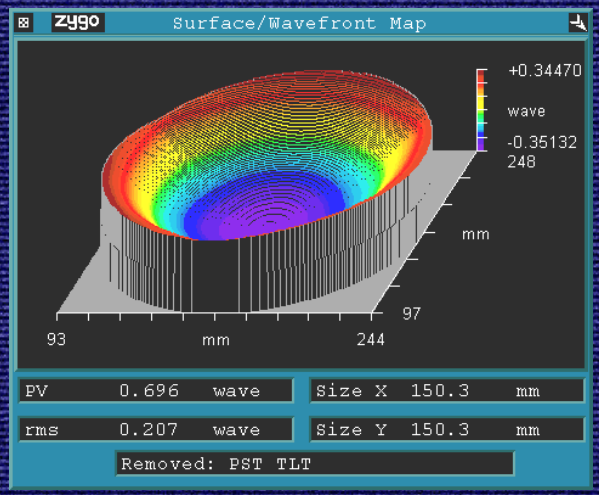
Quilt Error



- Areal Density = 25 kg/m^2
- Polished on Q22-X (rotational mode), 150 mm diameter wheel
- Diamond MR fluid
- Initial and final roughness ~ 0.25 nm rms

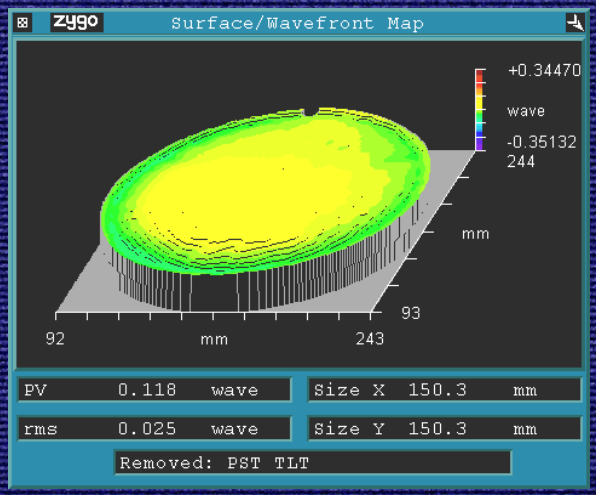
MRF Correction of McCarter Frit-bonded Single Crystal Light-Weight Silicon Lightweight Mirror

Initial Figure



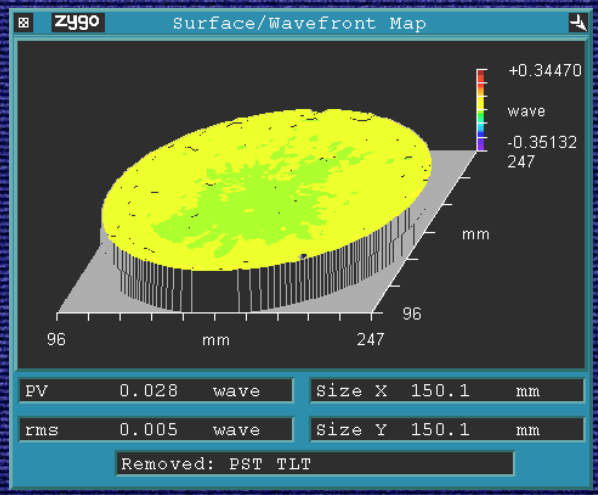
0.207 λ RMS

After 1 iteration

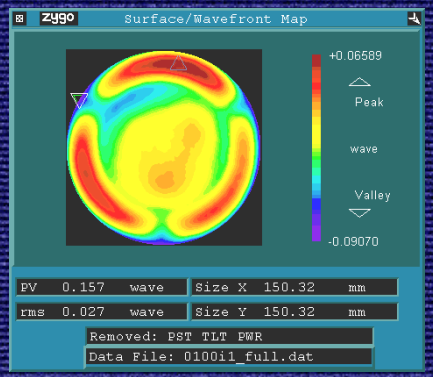


0.025 λ RMS

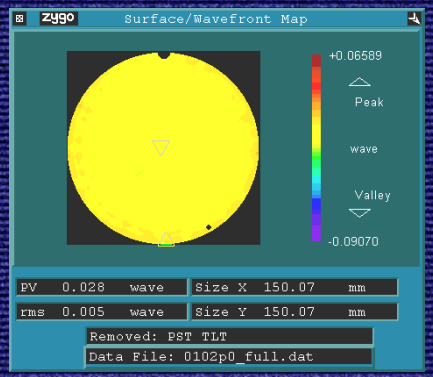
After 2 iterations



0.005 λ RMS

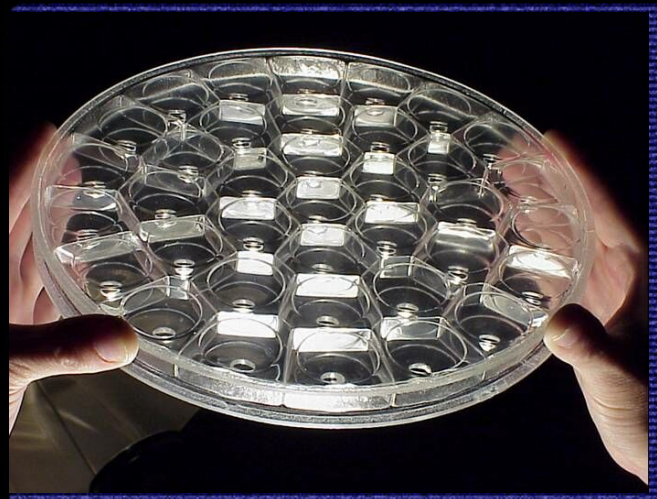


Initial figure (with "power" removed) shows "print through" of support structure.

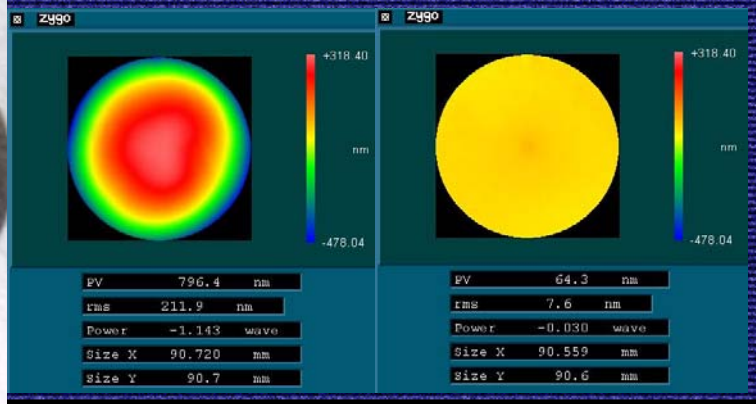


Final figure shows no "print through" of support structure.

Other Lightweight Mirrors

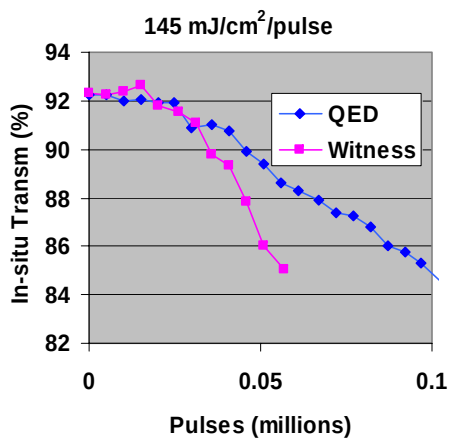


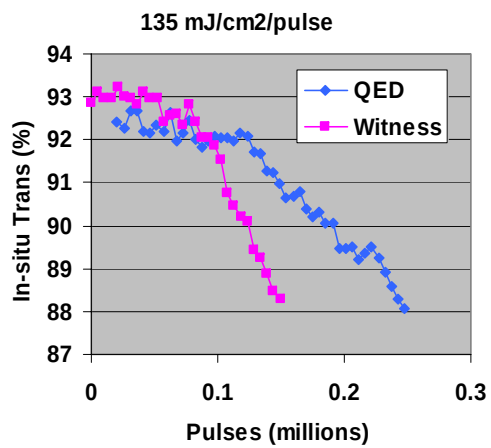
- Hextek Gas Fusion™ Borosilicate 15 kg/m^2 mirror blank
- Correct cryo-quilting
- Better than 50% improvement in 1 hour of polishing
  - Performance limited by clocking error
- Results discussed in previous talk

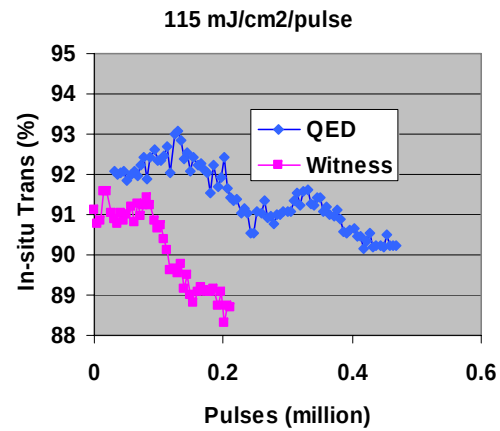


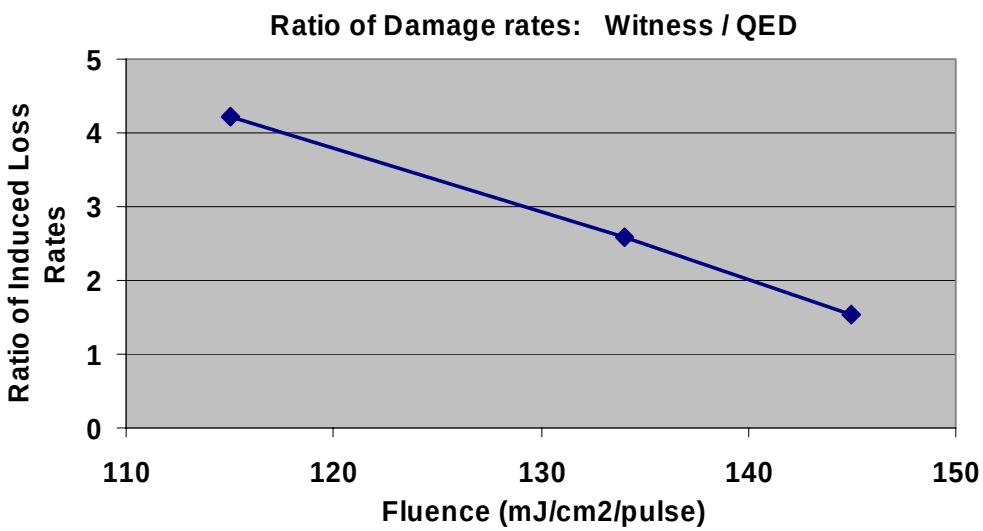
- CoorsTek lightweight SiC mirror
- 20 kg/m^2
- Initial = 212 nm RMS
- Final = 8 nm RMS

Relative Damage Rates – CaF_2





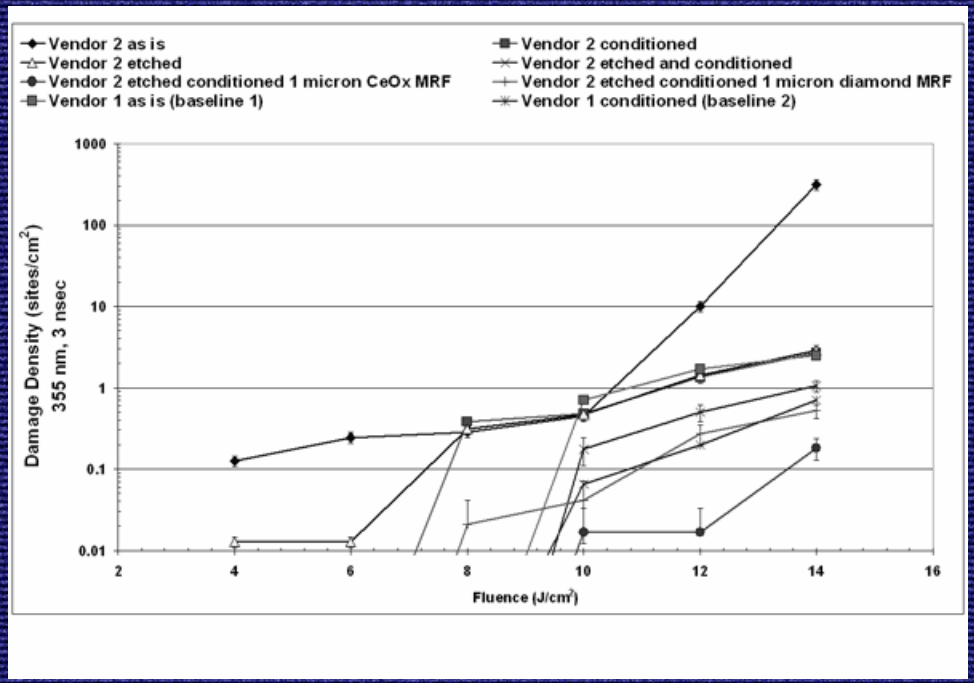




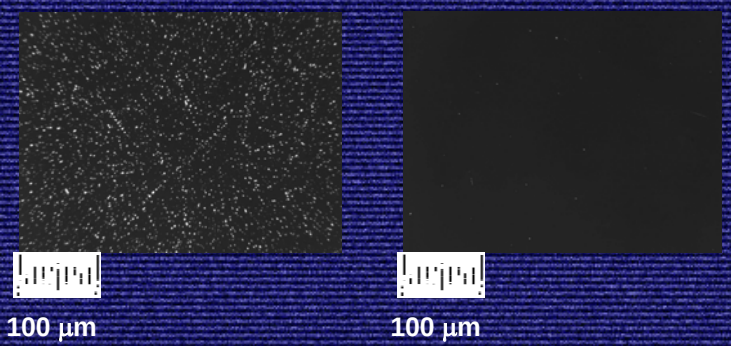
MRF-polished samples damage slower than conventionally polished samples

Acknowledgement
V. Liberman
MIT Lincoln Laboratory

MRF Removes Sub-Surface Damage - FS



Conventional Polish | **Processed with MRF**

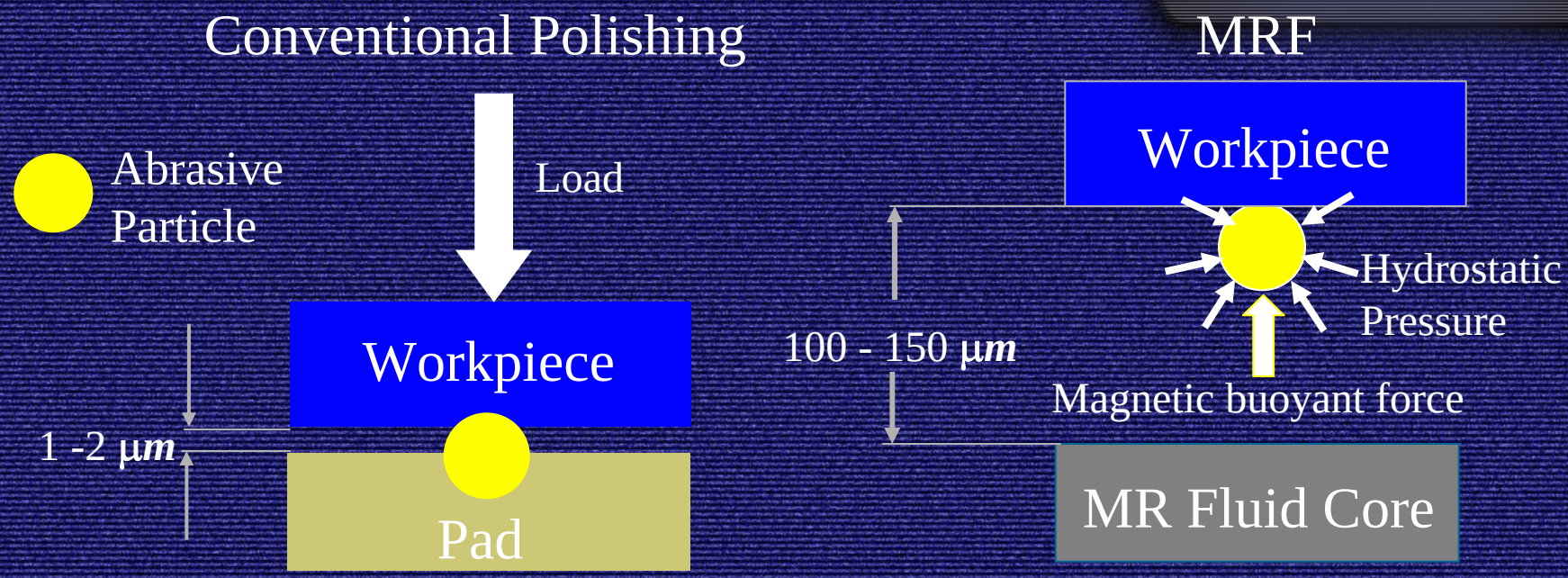


Dark Field Microscopy after Etch

- **The MRF processed surface has significantly fewer damage sites at higher fluence after 3 ns pulse with wavelength = 355 nm[1]**
- **Dark field microscopy clearly illustrates that advantages to using MRF to remove sub-surface damage**

[1]J.A. Menapace, B. Penetrante, D. Golini, A. Stromba, P.E. Miller, T. Parham, M. Nichols and J. Peterson, "Combined Advanced Finishing and UV-Laser Conditioning for Producing UV Damage Resistant Fused Silica Optics", Laser Induced Damage in Optical Materials: 2001, Exarhos, Guenther, Lewis, Soileau, Stolz eds, Proceedings of SPIE 4679: 56-68 (2002).

Forces Acting in Polishing



An abrasive particle is embedded in the rigid pad, which supports the particle load. The normal force (~0.01 N) is significant to cause the surface indentation and scratching.

Because particle/surface contact area is very small the hydrostatic pressure results in insignificant normal force (~10^{-7} N). The buoyant force (~10^{-9} N) is also too small to cause appreciable surface indentation.

MRF Conclusions

- MRF deterministic polishing process
  - High material removal rate
  - Excellent convergence rate
  - Can improve roughness on most materials
- Including MRF in manufacturing process improves resistance to laser damage
- Process scalable to larger size optics
  - MRF machines for up to meter class optics already available
  - 1-4 meters currently being engineered
- For light-weighted optics:
  - Unique MRF attributes give it the ability to polish lightweight mirrors without inducing quilting and can fix existing errors such as quilting patterns

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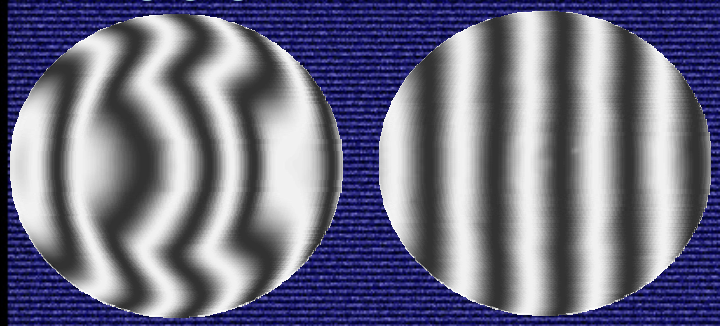

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