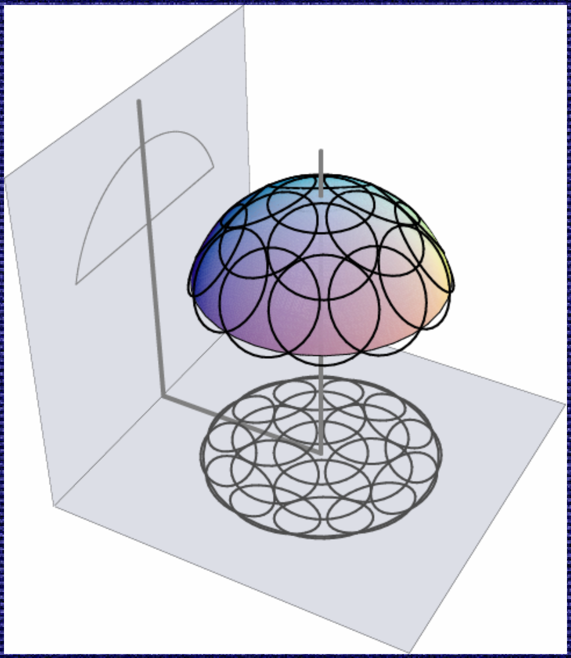
Sub-aperture Approaches to Finishing and Metrology

presented to:

Brookhaven National Laboratory



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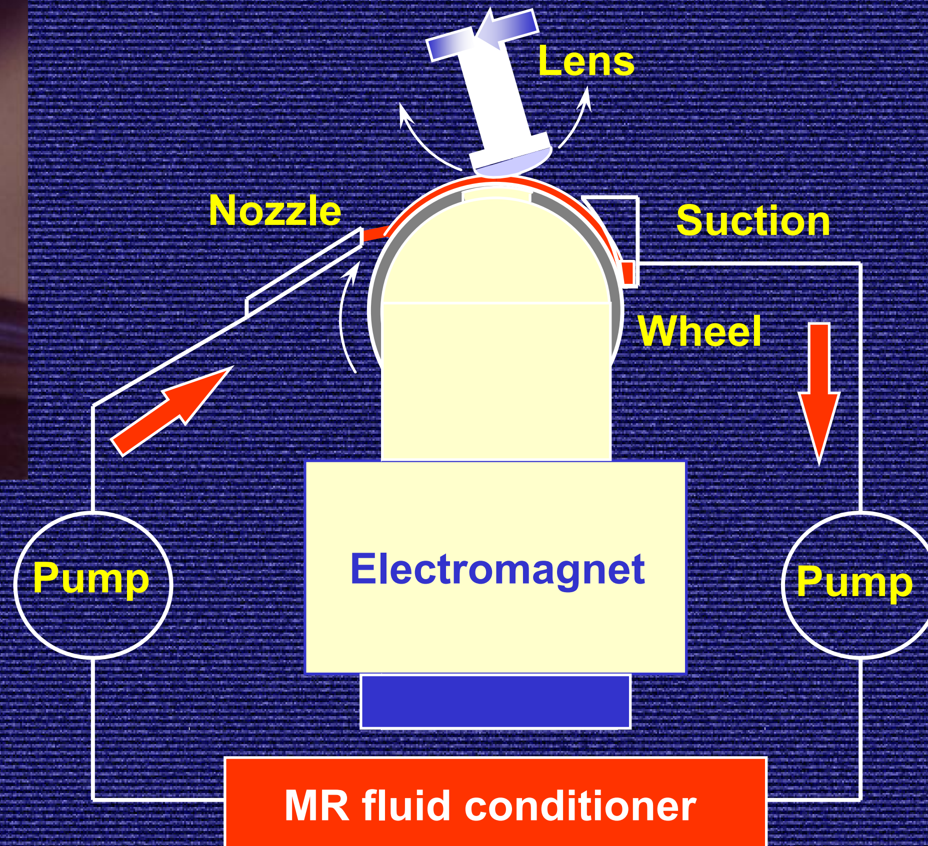
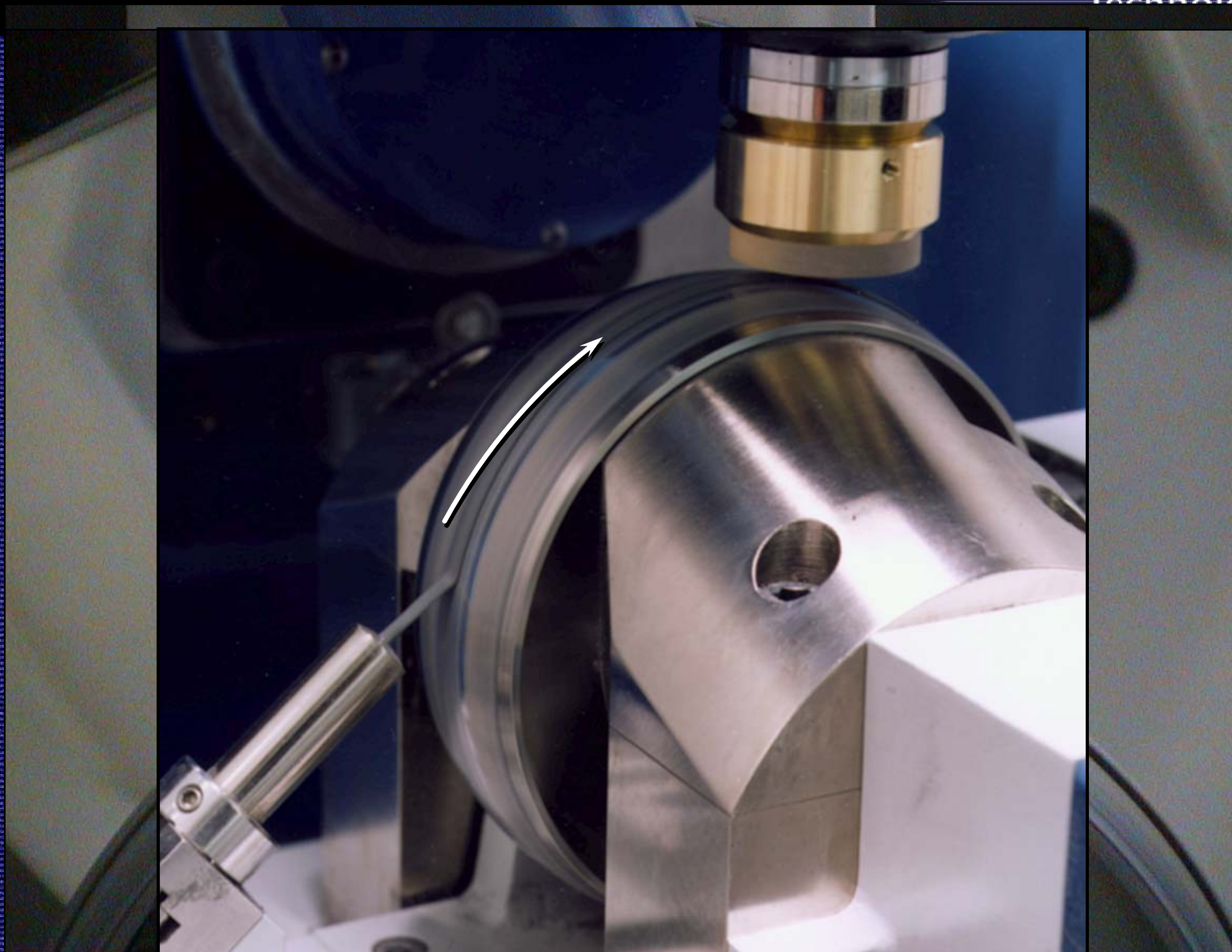
Outline

- ❖ Overview of Magnetorheological Finishing (MRF)
- ❖ MRF Applications
- ❖ Jet Finishing
- ❖ Subaperture Stitching Interferometer (SSI)
- ❖ SSI Applications
- ❖ Conclusions

Magnetorheological Finishing (MRF)

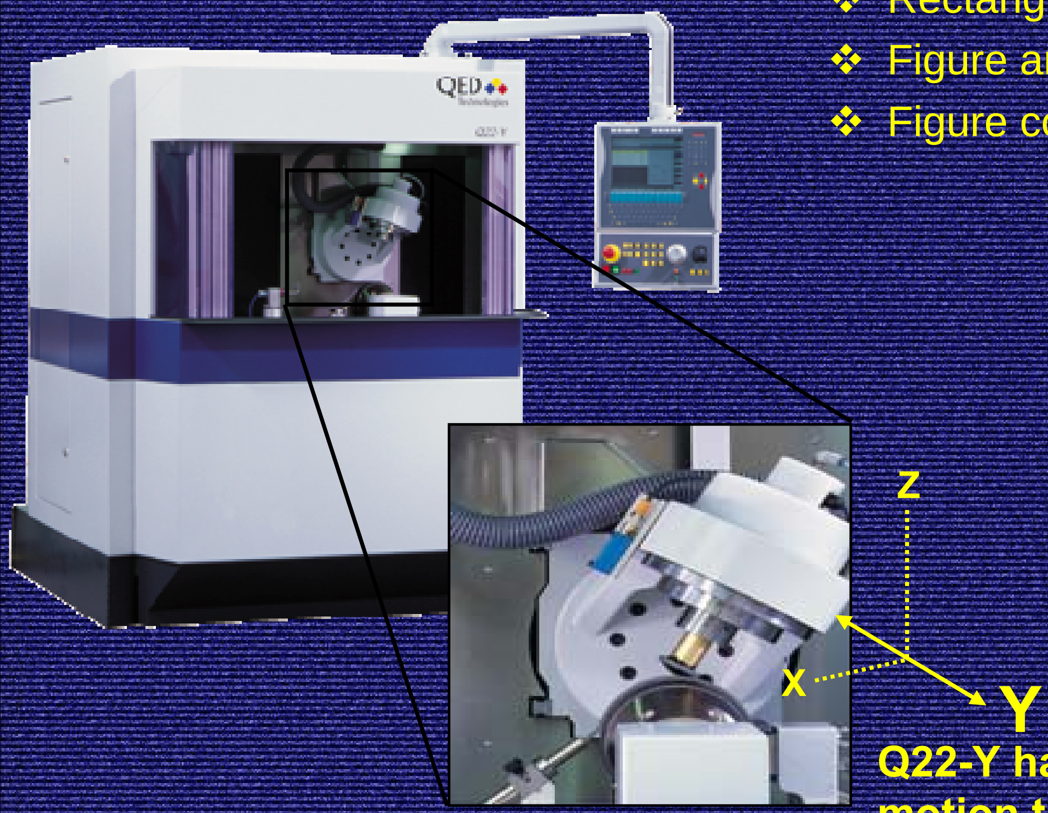
How it works

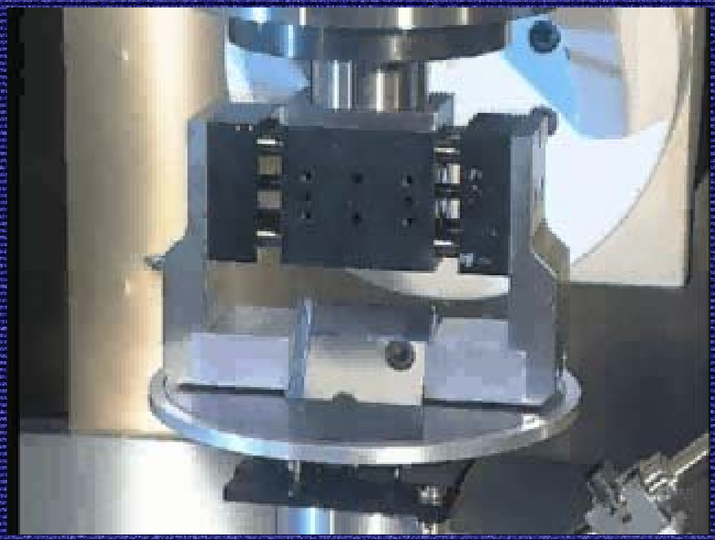




Q22-Y Raster MRF System

- ❖ Various applications for non-round optics are enabled by rastering (e.g. cylinders, prisms, free-forms…)
- ❖ The Q22-Y has all of the capabilities of the Q22-X plus the ability to polish:
  - ❖ Rectangular aperture optics
  - ❖ Figure and angle correction on prisms
  - ❖ Figure correction on cylindrical optics





Q22-Y has additional axis of motion to allow raster polishing

MRF – Breakthrough Technology

QED Technologies

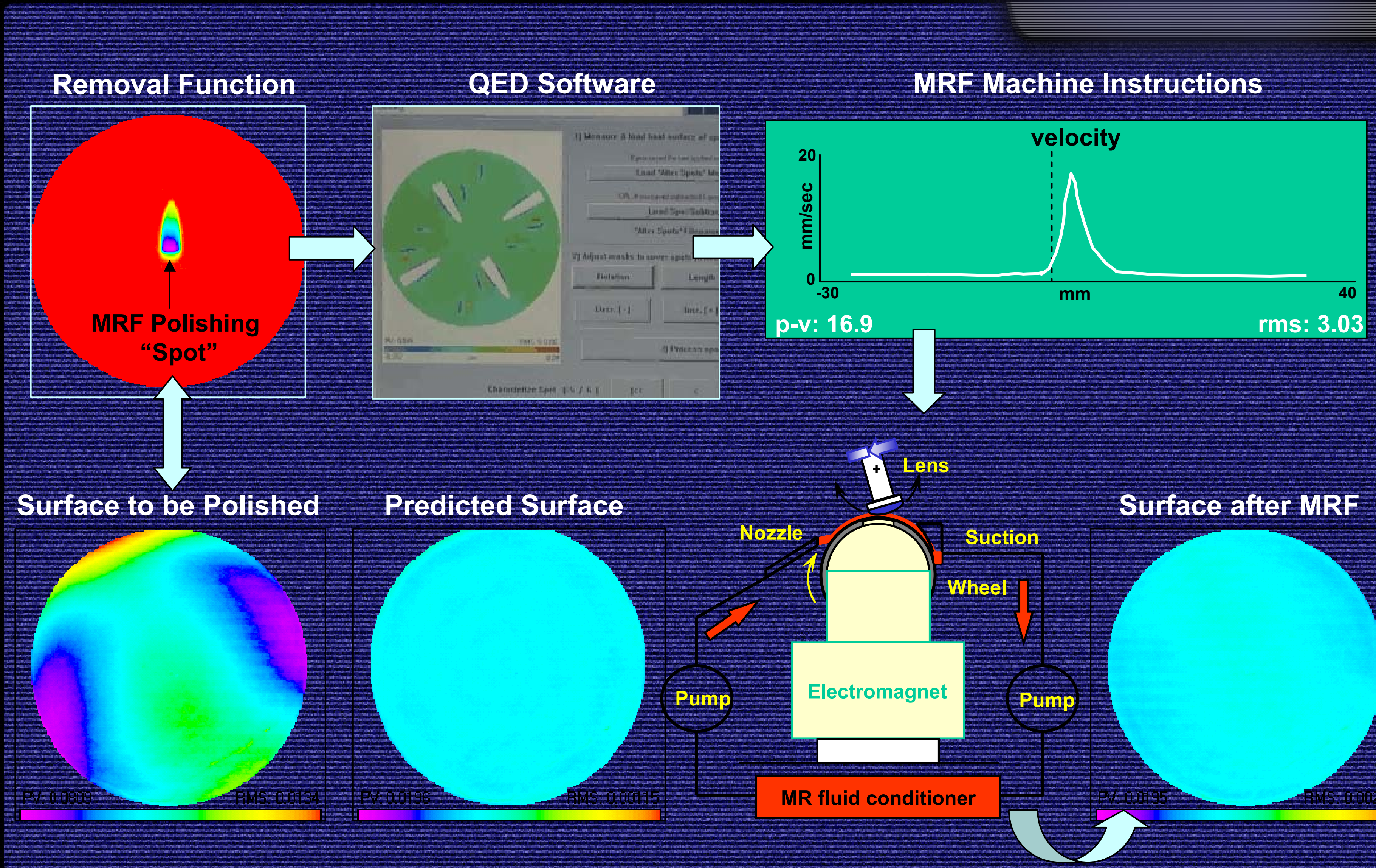
The MRF polishing tool:

- never dulls or changes
- is interferometrically characterized
- is easily adjusted
- conforms to part shape - works on complex shapes (flat, sphere, asphere, cylinder…)
- has high removal rates
- Has a removal based on shear stress so applies very low normal load on abrasive, improving surface integrity
- Is very deterministic, leading to high convergence rate

- These attributes lead to a production oriented, deterministic, computer controlled polishing and figuring technique.
- Production proven: more than 100 machines worldwide

MRF Process Flow Diagram

$$removal(x,y) = dwell(x,y) \otimes spot(x,y)$$



QED MRF Product Line

100+ machines in use, many flavors…

- **Q22-XE – Up to 80 mm in diameter**
- **Q22-X – Up to 200 mm in diameter**
- **Q22-Y – Q22-X + Raster tool path**
- **Q22-400X – Up to 400 mm in diameter**
- **Q22-750P2 – Plano optics up to 750 mm x1000 mm in size**
- **Q22-950F – Free-form optics up to ~ 950 x 1,250mm**

- **The next-generation, meter-class machine is being built to finish free-form optics**
  - **Q22-xxxxF – Multi-meters freeform**

- **SSI – Sub-aperture Stitching Interferometer (SSI) for high precision metrology**

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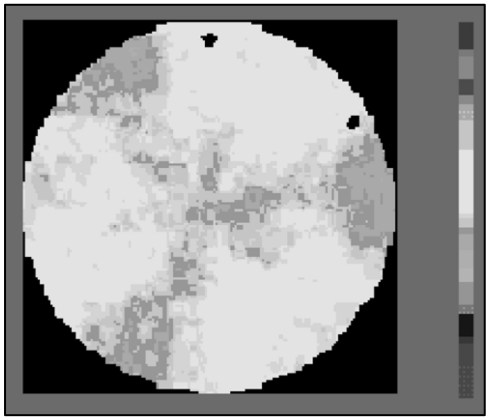
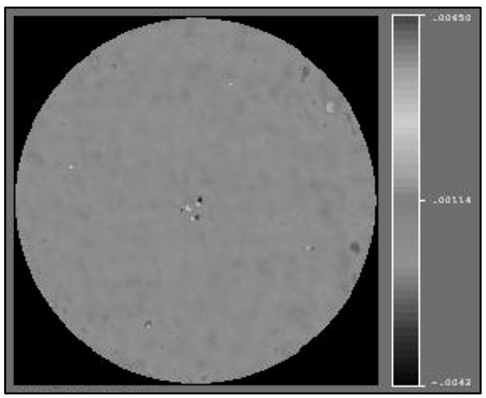
- **MRF Applications**
- Jet Finishing
- Subaperture Stitching Interferometer (SSI)
- SSI Applications
- Conclusions

High Precision

CaF2 Lenses for 157nm Lithography

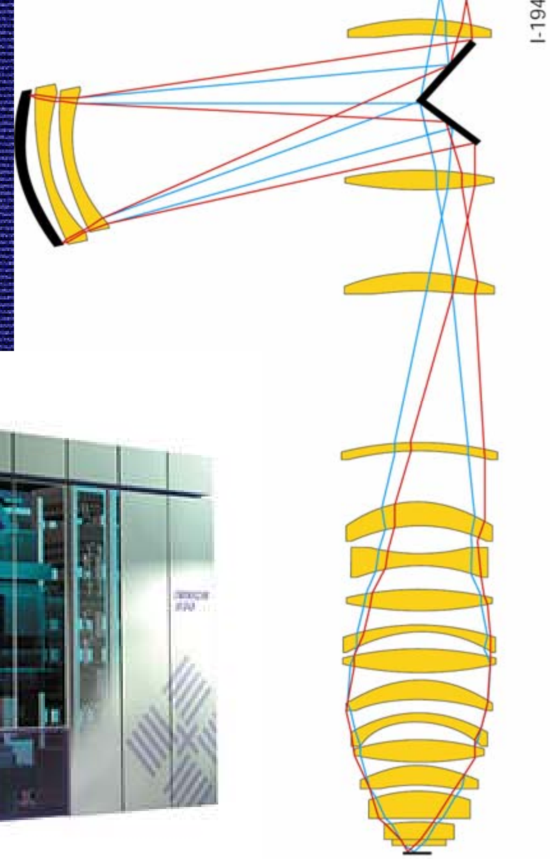


<111> Element
Surface figure: 0.57nm rms



<100> Element
Surface figure: 0.63nm rms

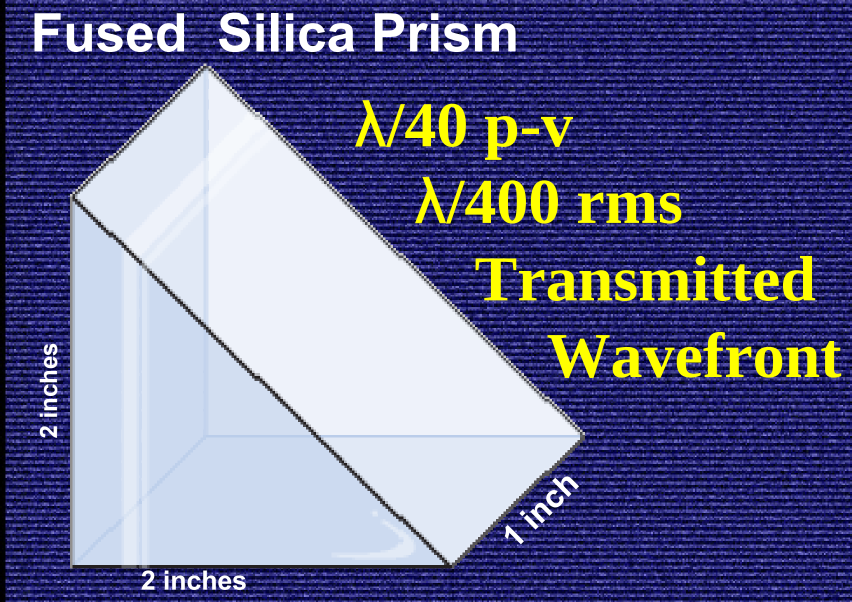
Example of catadioptric lens for TWINSCAN.

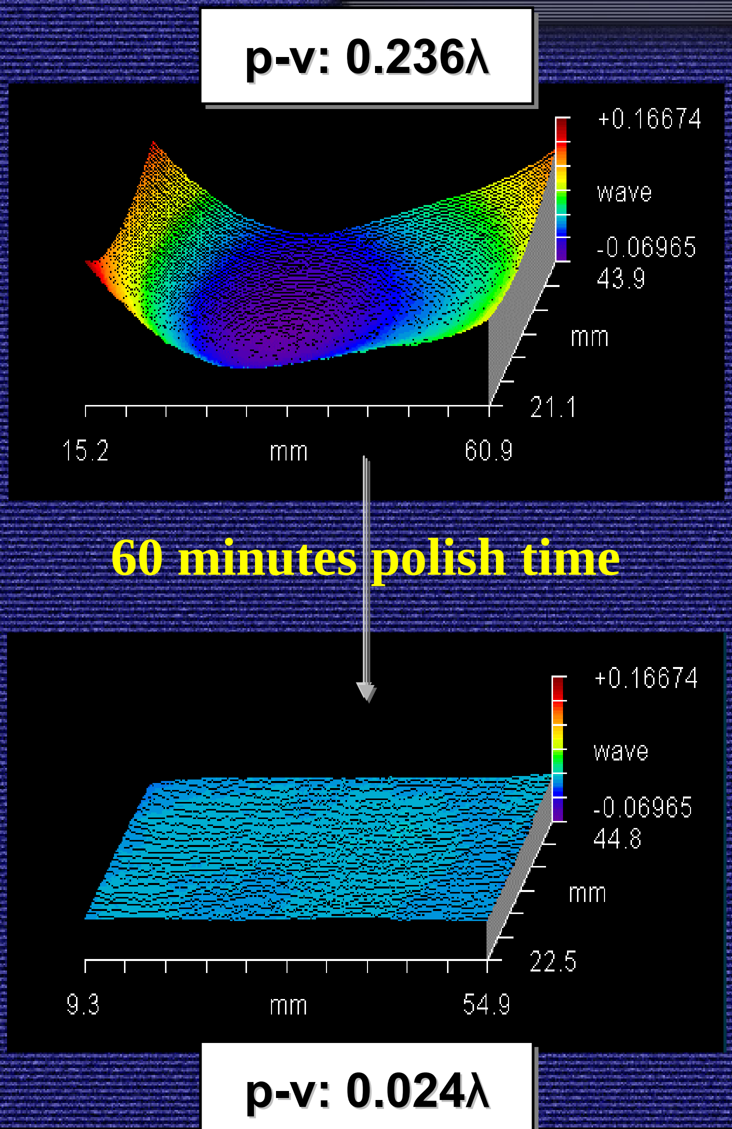


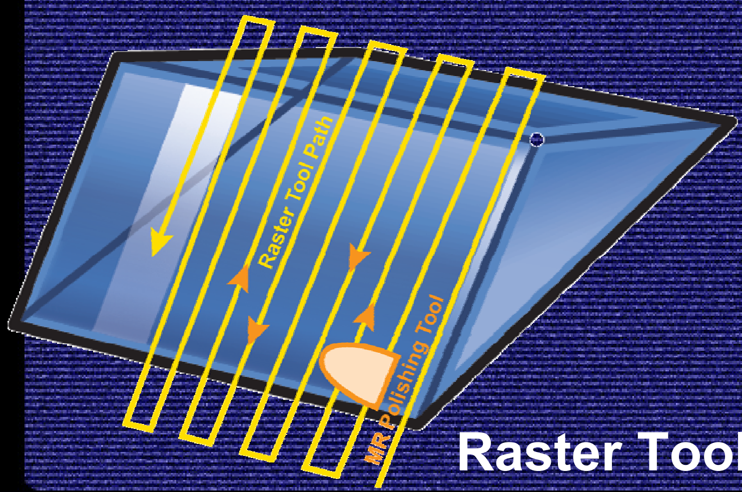
Jan Mulkens (ASML), et al., "Optical lithography solutions for sub-65 nm semiconductor devices", Proc. of SPIE, 5040; pp: 753-762, 2003.

Transmitted Wavefront Correction

Fused Silica Right angle prism



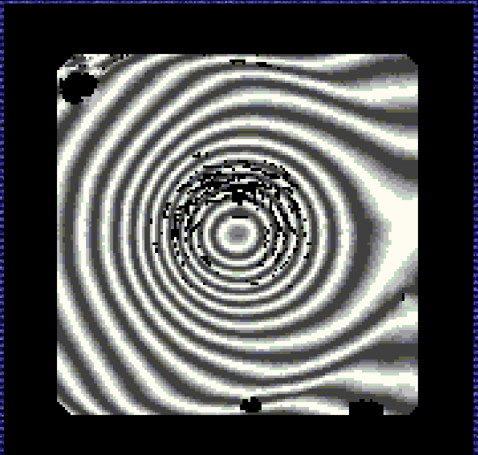


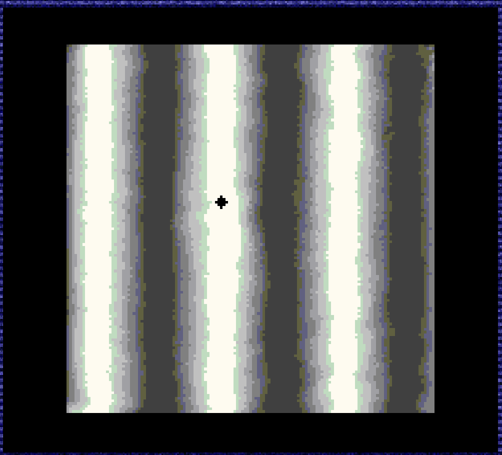


Transmitted Wavefront

Nd:YLF Rods

Original | **After MRF**



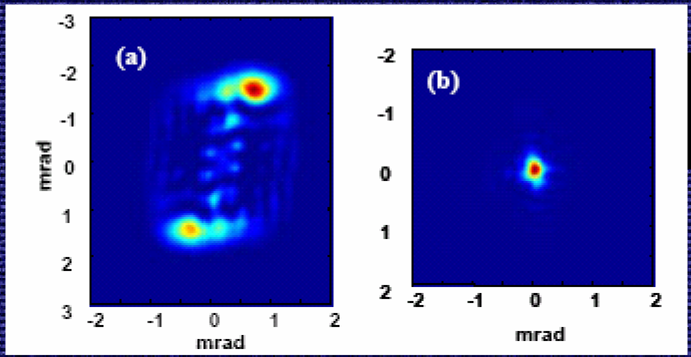


7.85 λ (p-v)
1.59 λ (rms)

0.143 λ (p-v)
0.013 λ (rms)

Central 15×15 mm² region of 25×100 mm Nd:YLF rod (**λ** = 1053 nm)

Surface roughness < 7.0 Å (rms)

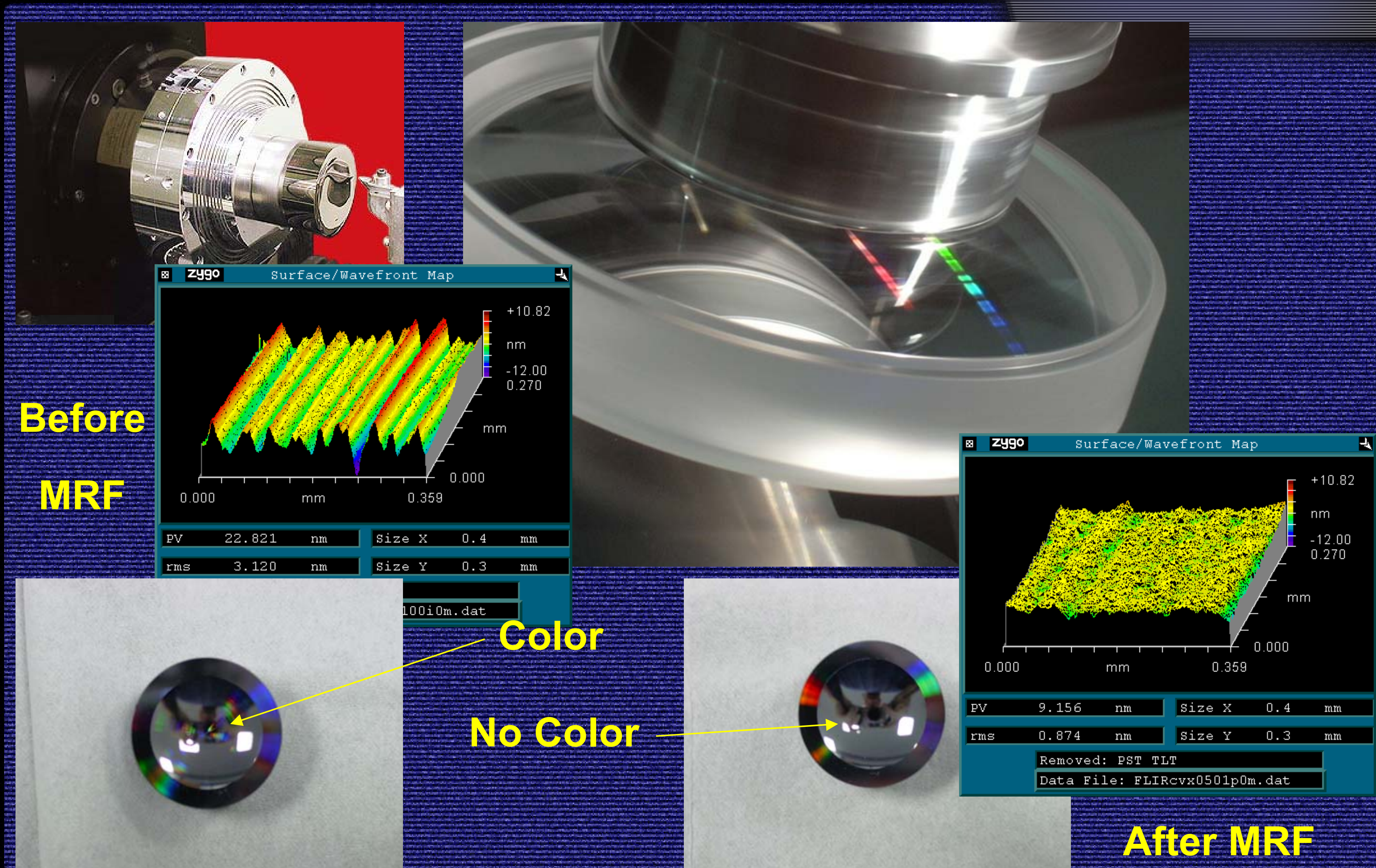


Far Field Measurements

MRF deterministically improves surface figure on a lateral scale down to ~1mm.

High-energy, 5-Hz repetition rate laser amplifier using wavefront corrected Nd:YLF laser rods, by Vincent Bagnoud, Jason Puth, Jonathan D. Zuegel et al.

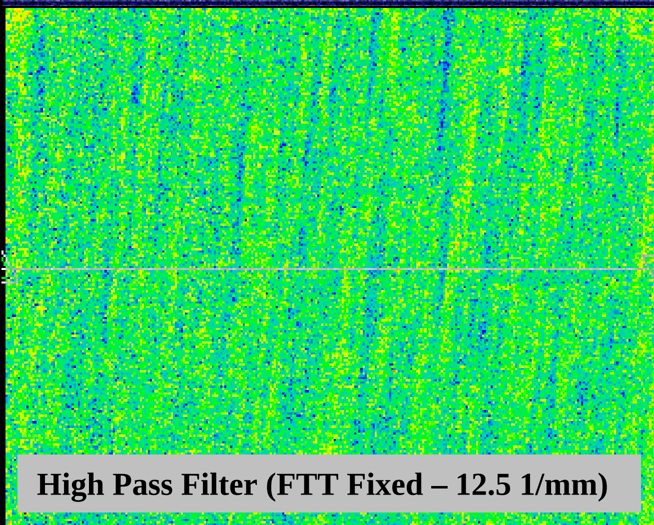
Improve SPDT surfaces

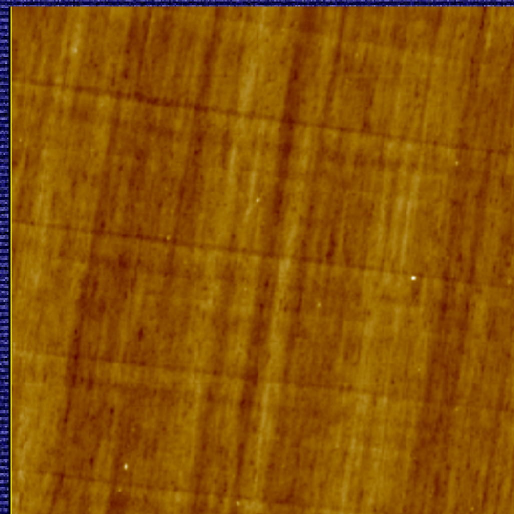


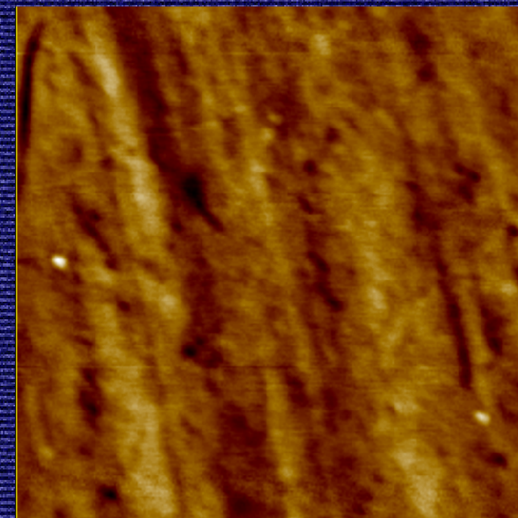
Roughness

Cerium oxide or diamond based fluids

New-View 5000 359 x 270 µm	AFM 10 x 10 µm	AFM 1 x 1 µm







Rmax	44.692	Å
Ra	2.829	Å
Rq	3.575	Å

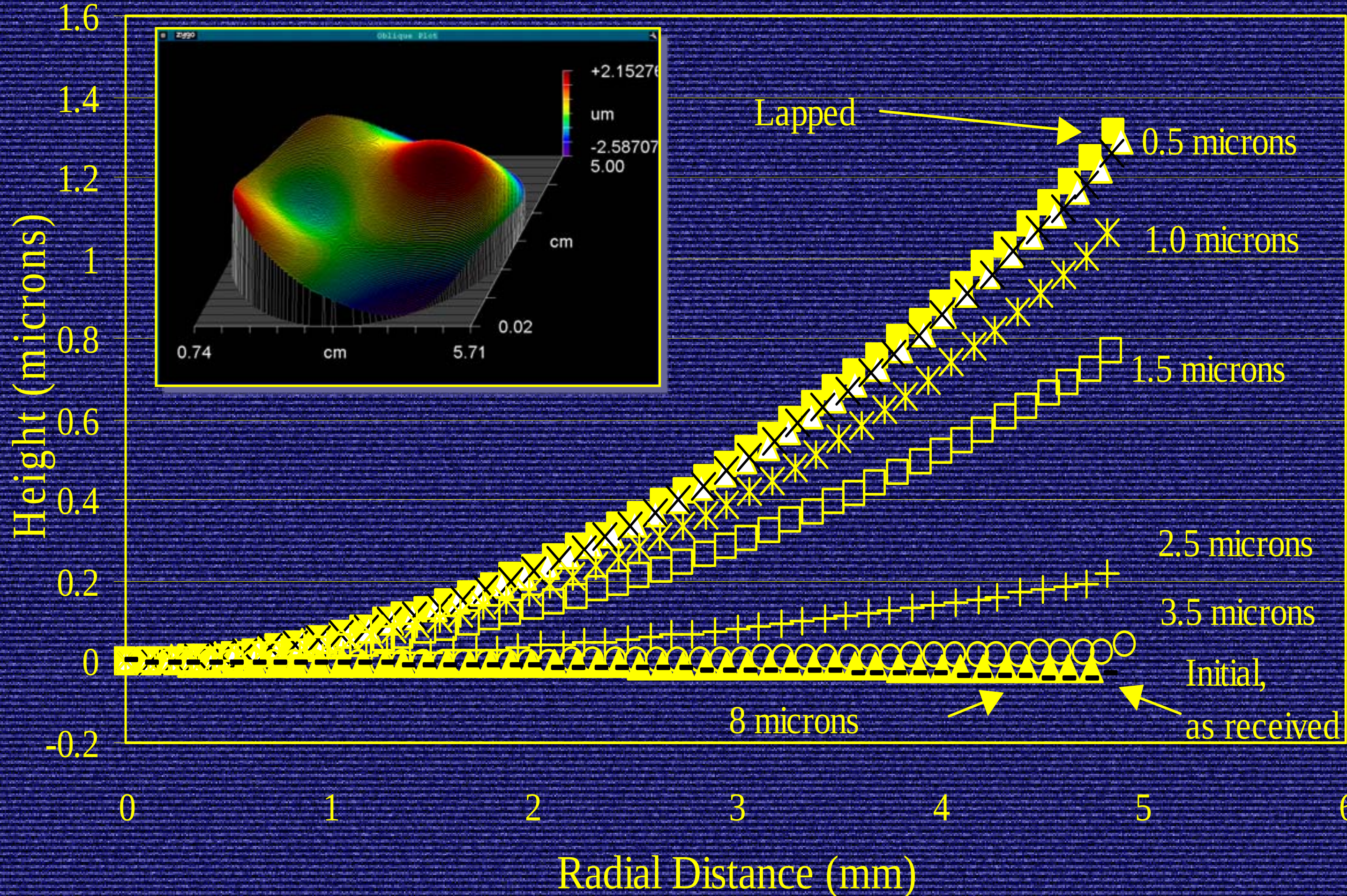
Rms (Rq)	0.347	nm
Ra	0.277	nm
Rmax	5.718	nm

Img. Rms (Rq)	0.176	nm
Img. Ra	0.136	nm
Img. Rmax	1.884	nm

Fused silica - round flat, 0.5µm DC-run polishing

Improvements in Surface Integrity

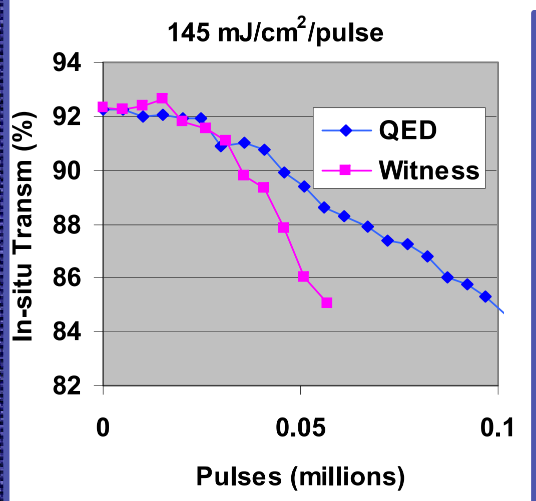
Residual stress removal

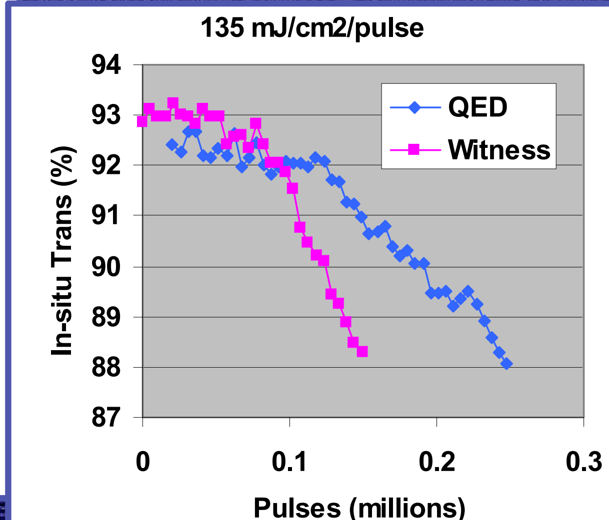


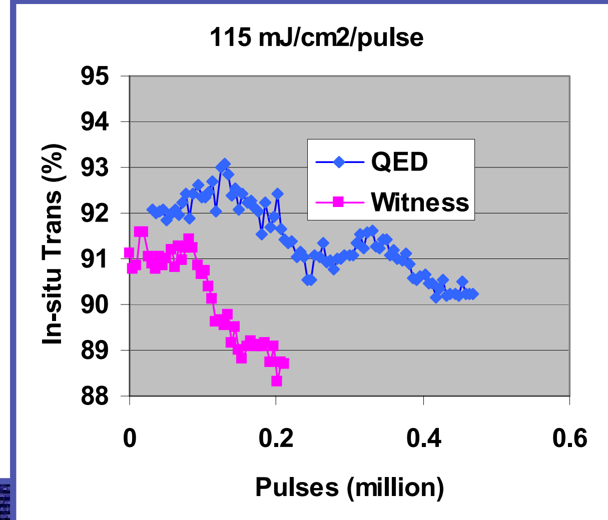
From: "Magnetorheological Finishing (MRF) to Relieve Residual Stress and Subsurface Damage on Silicon Wafers", by Steven R. Arrasmith, Stephen D. Jacobs, John C. Lambropoulos, Alexander Maltsev, Donald Golini and William I. Kordonski.

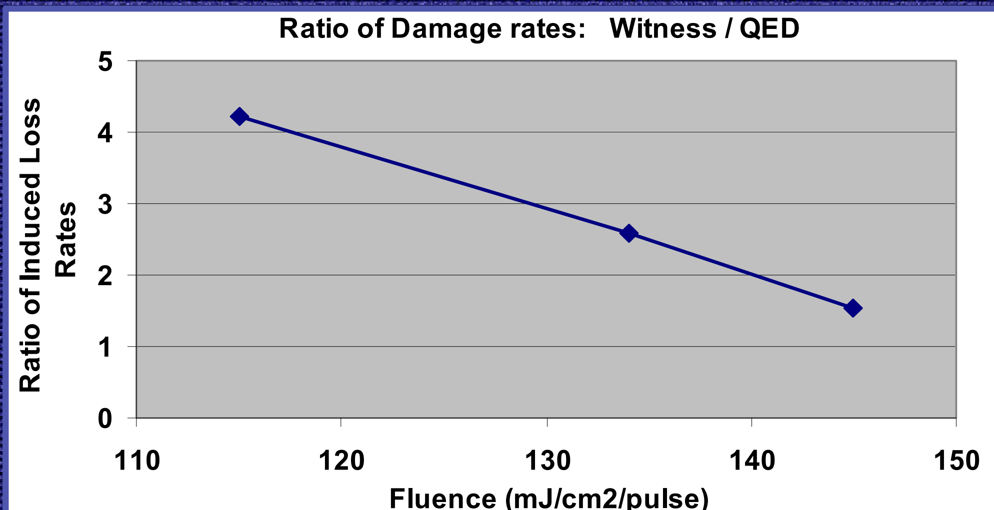
MIT Lincoln Lab

157 nm Laser Damage Study on CaF2

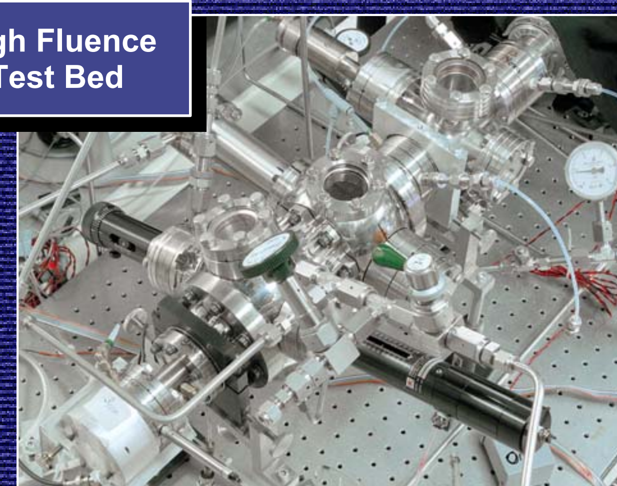




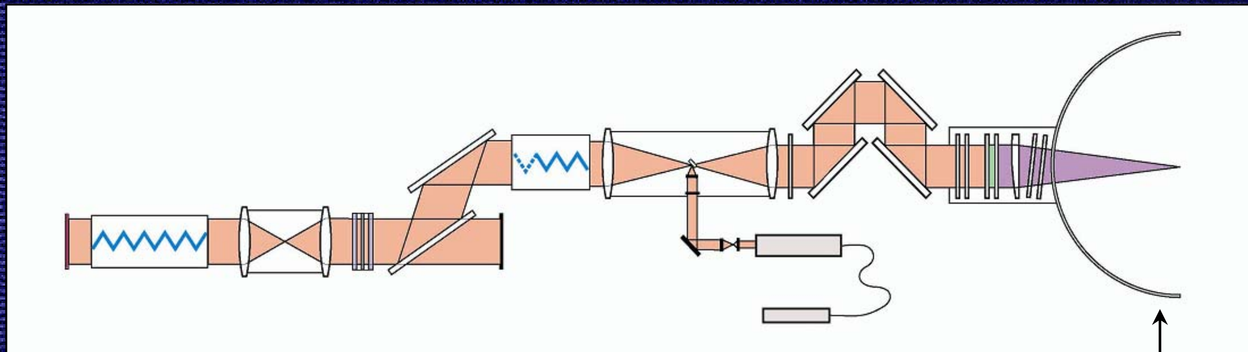


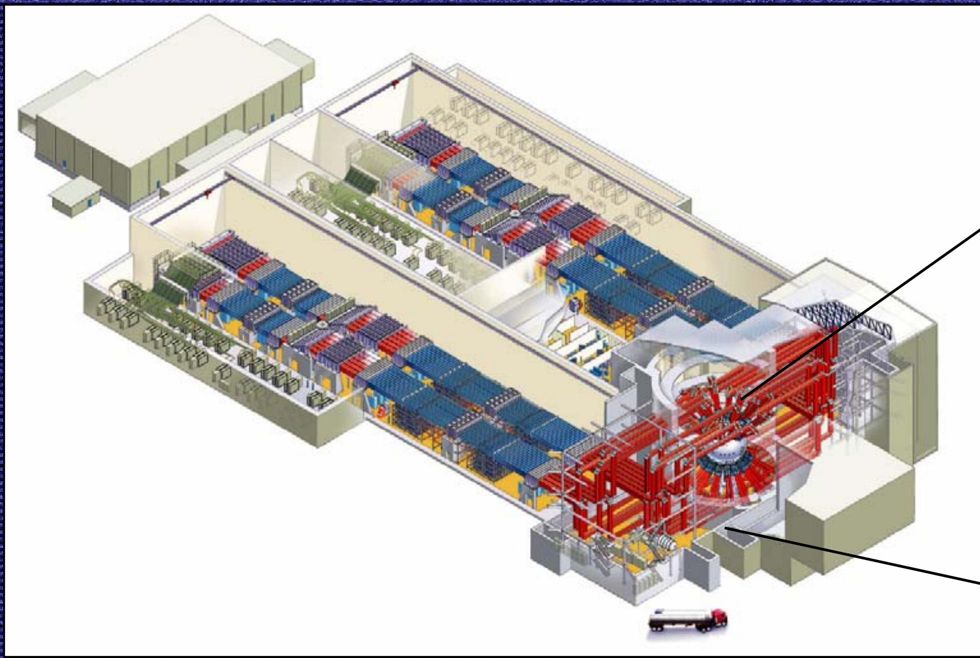


High Fluence Test Bed



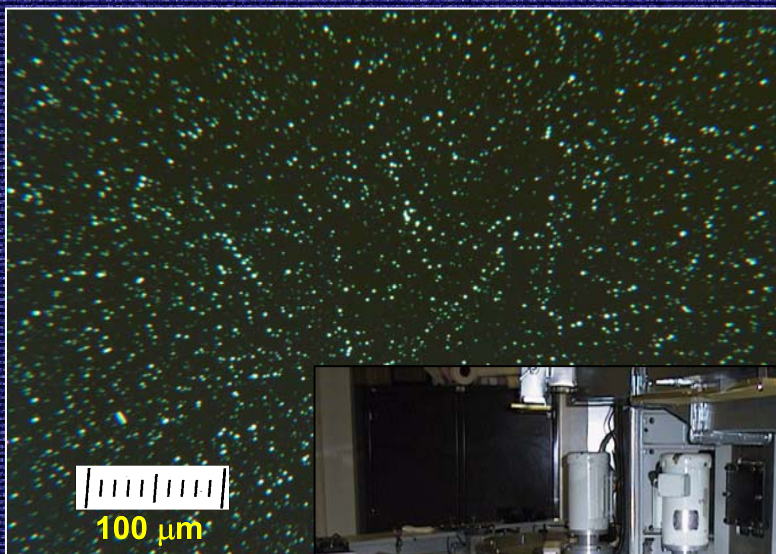
Improvements in Surface Integrity
National Ignition Facility (NIF) at LLNL

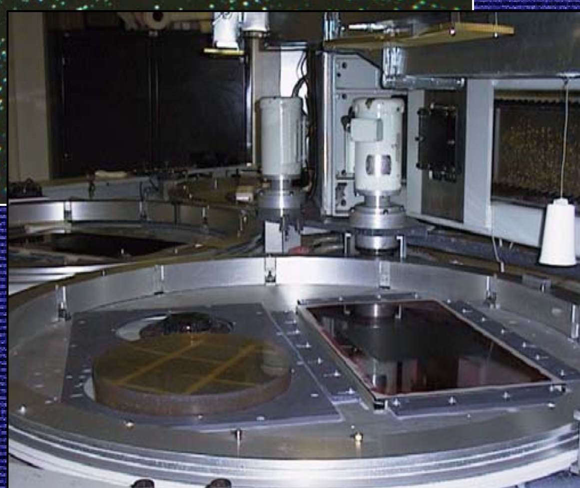




MRF polished and etched parts

Highest quality conventional polish



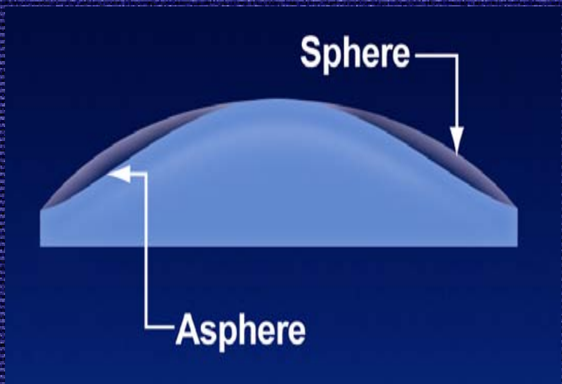


MRF polished part

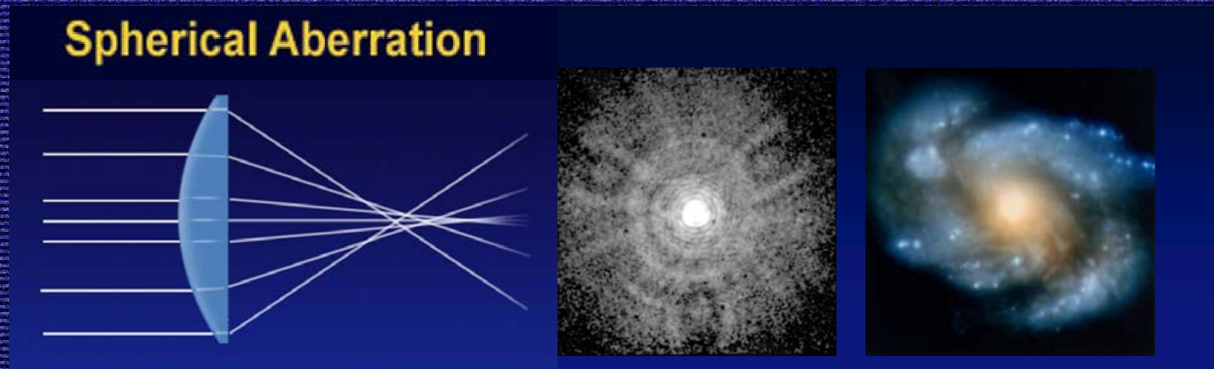
Dark-field microscopy of etched MRF surfaces shows a near-absence of the sub-surface damage normally associated with conventional finishing

Aspheres

Spherical vs. Aspheric Optics



Aspheric optics provide performance advantages.



Pictures from the Hubble Space Telescope

MRF's Unique Attributes

MRF's unique attributes…

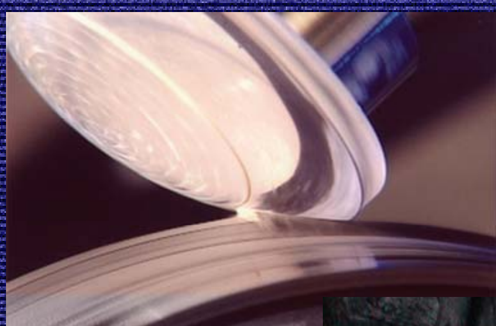
MR Fluid properties are Precisely Controlled.

MRF tool is Subaperture.

therefore

MRF is Deterministic.

Lead to a unique asphere manufacturing capability



MRF Asphere Manufacturing:

1. **"Mild" aspheres – Aspherize from a best fit sphere and figure correct**

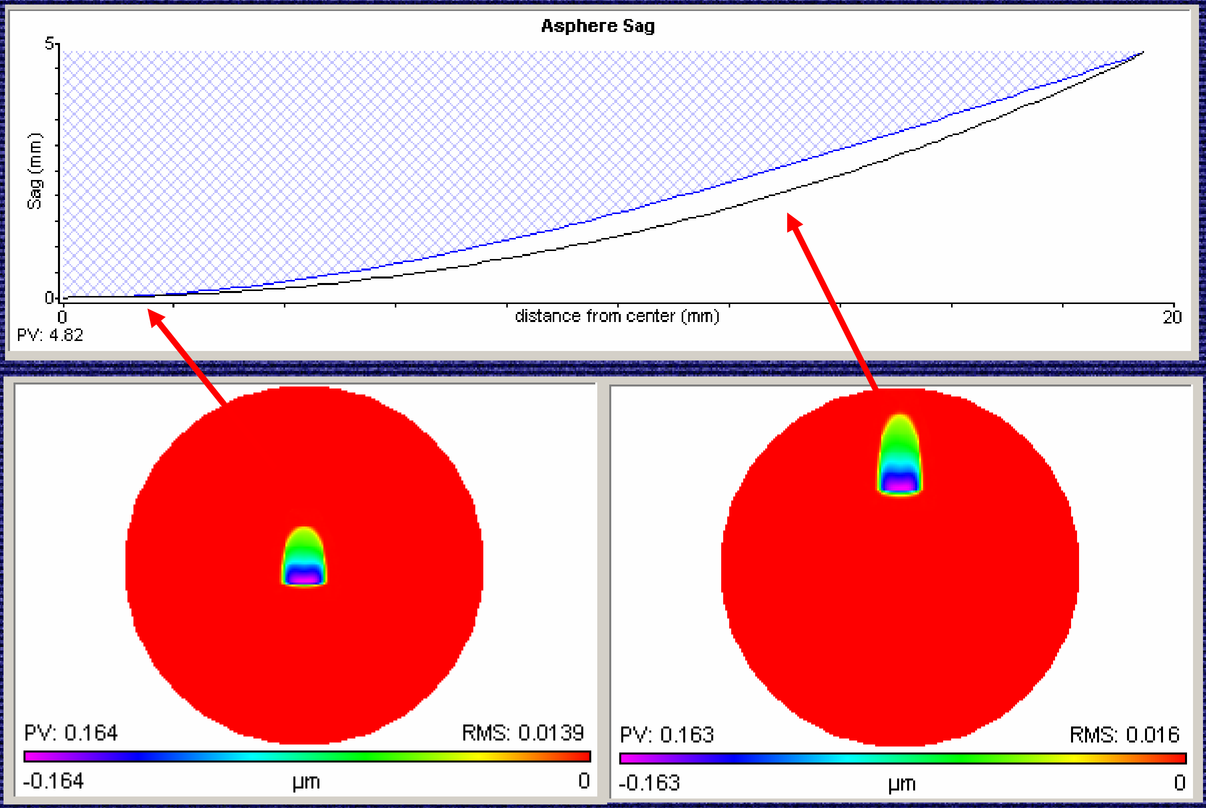
or

2. **"Wild" aspheres – MRF figure correction following:**
   - **Diamond turning to aspheric**
   - **Ground aspheric shape**
     - **Intermediate pre-polish step**
     - **Direct from grind (in some cases)**

Aspherizing from Best Fit Sphere

Asphere polishing with MRF

- **Spot shape = *F* (local curvature)**
- **Impossible for conventional pads**
- **Algorithms to “morph” spot**



MRF Aspherizing - “mild” aspheres

Complete Asphere Manufacturing

- **MRF “aspherizes” or polishes in the aspheric shape from a best fit sphere**
- **MRF then figure corrects the optic**

Deviation from asphere

P-V λ/10, rms λ/60

(over the 64 mm CA *in reflection)*

Before

- Hyperbola (conic constant = -1.355)
- OD 70 mm, CA 64 mm
- Convex base radius, R = 272.539 mm
- Best-fit radius = 274.059 mm (at an aperture of 70 mm)
- Aspheric departure = 3.1 µm (from best-fit sphere)

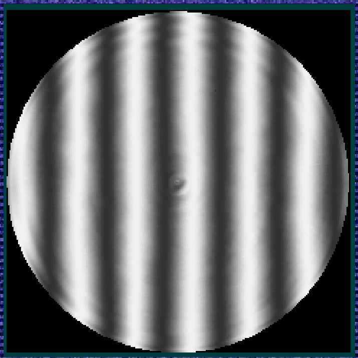
Results after 3 iterations

- (1) Shaping: 70 min
- (2) Figure corrections: 20 min and 5 min

MRF Aspherizing - “mild” aspheres

BK7 Aspheres produced with MRF

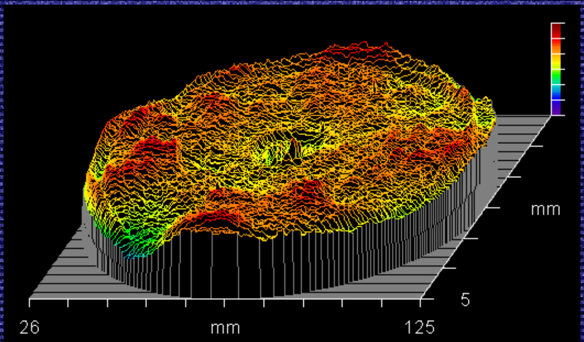
MRF aspherizes and then figure corrects

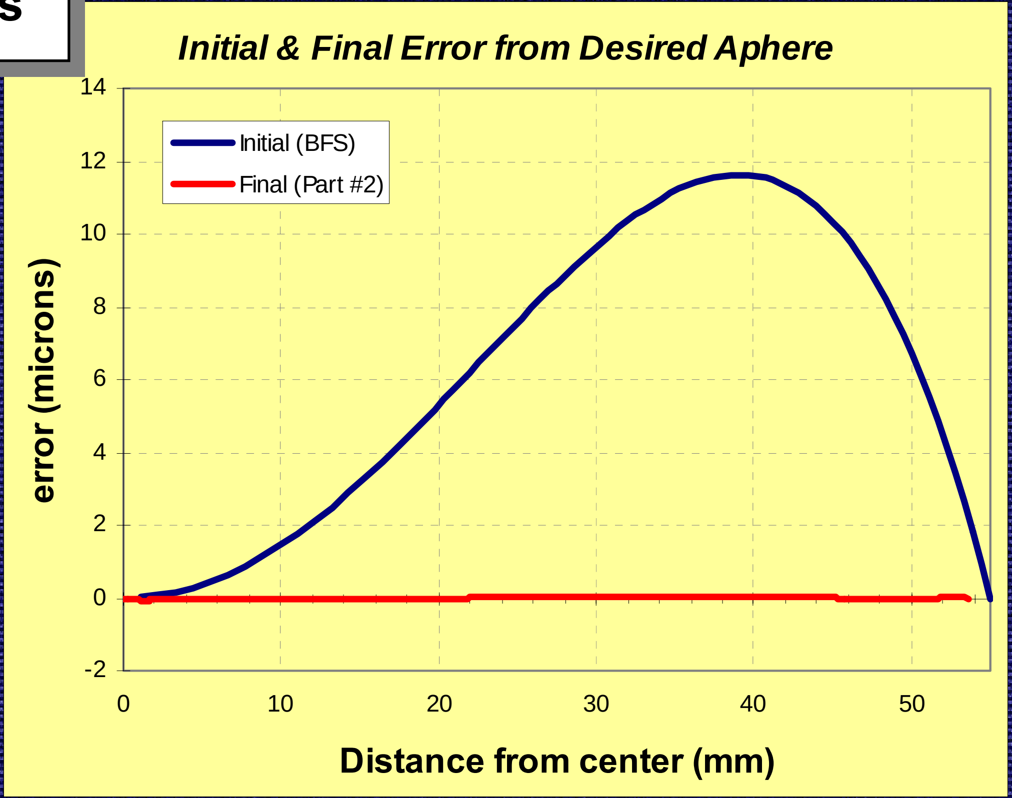


Trial #1

0.185λ p-v

0.015λ rms





- **Aspheres are 110 mm diameter with 11 microns of departure.**
- **Total run time was ~5 hours per lens.**

Large Optics

❖ **Optics getting larger and larger**
- Size and/or number of segments increasing

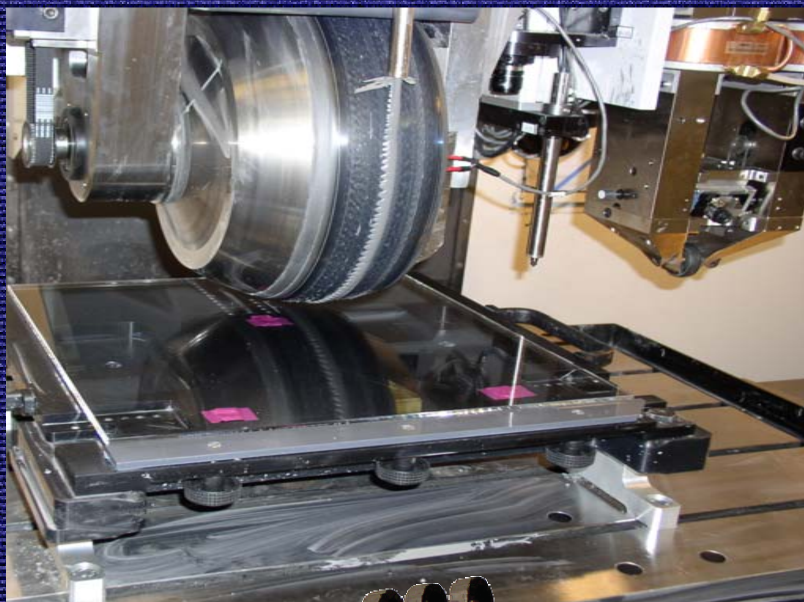
❖ **Manufacturing time decreasing**
- From month(s)/m^2 to day(s)/m^2

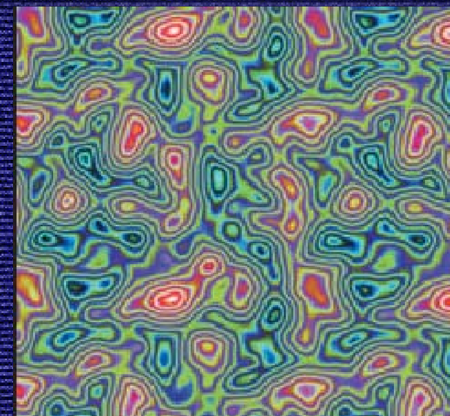
❖ **Increasing light-weighted structures**
- From 100's kg/m^2 to <10 kg/m^2
- Decreasing face sheet thickness
- New materials (e.g. SiC, Be, porous Si etc.)

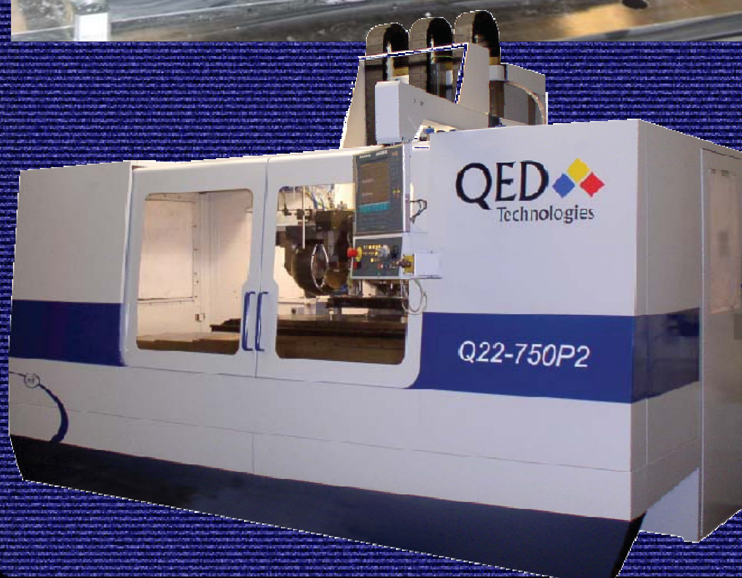
❖ **Specifications tightening**
- Figure, mid-spatial frequency and roughness
- Edge exclusion going to zero (for segment design)
- More challenging shapes: aspheres, off-axis etc.

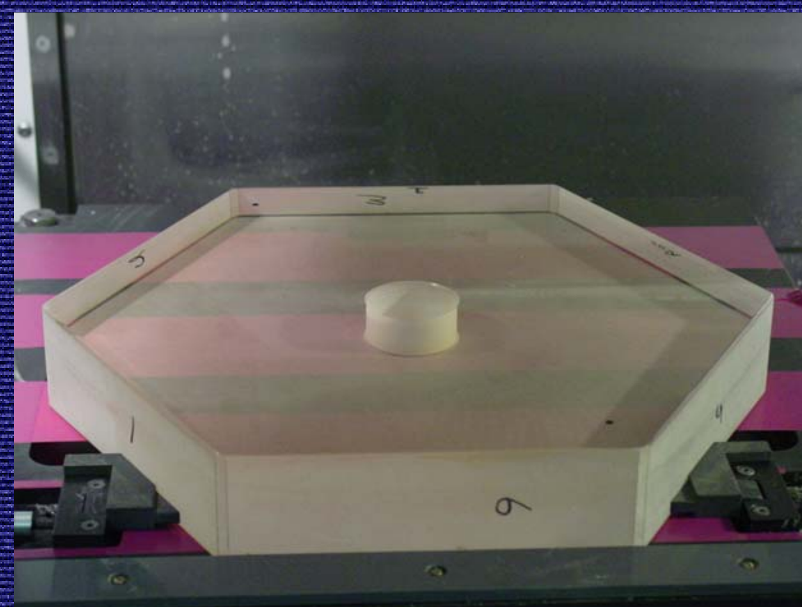
❖ **Costs decreasing**

Q22-750P2 Polishing





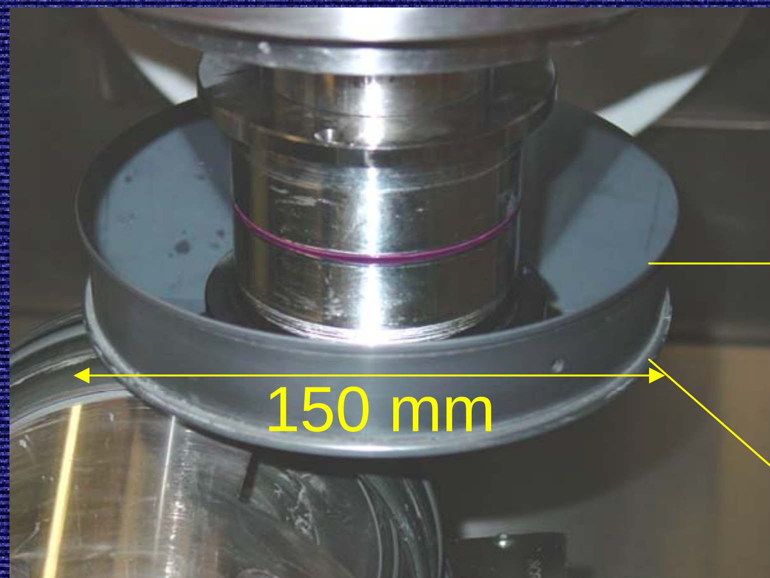


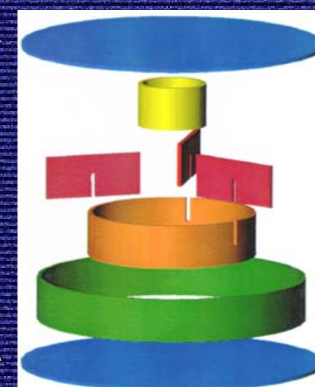


Light-weighted optics

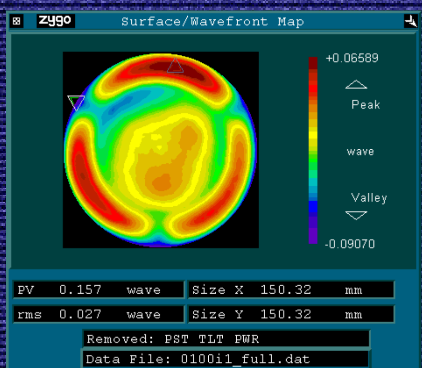
MRF Fixing quilting errors

McCarter Light-Weight Si Mirror
Areal Density = 25 kg/m^2

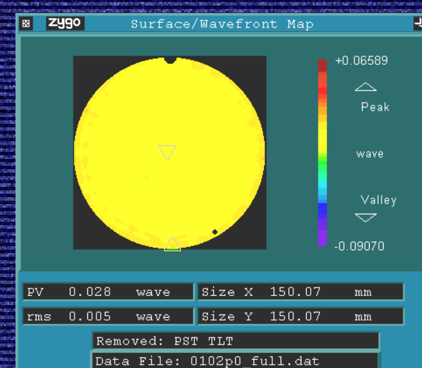




Quilt Error



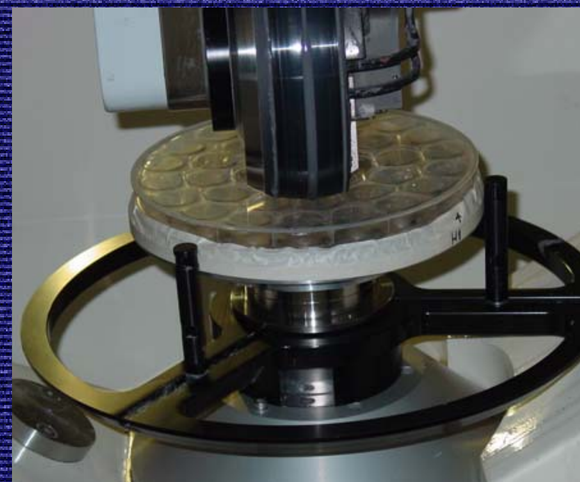
Initial figure (with "power" removed) shows "print through" of support structure.

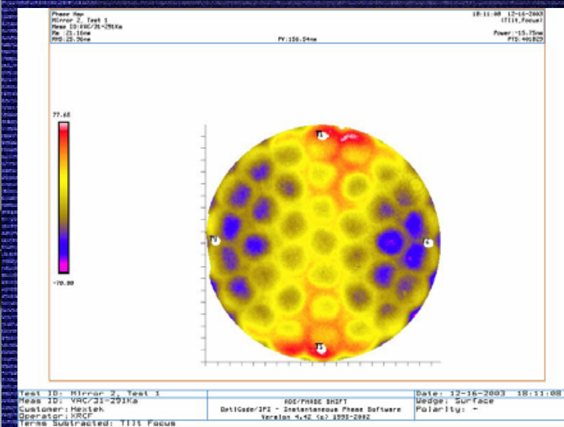


Final figure shows no "print through" of support structure.

Light-weighted optics

MRF Fixing quilting errors – Add'l examples





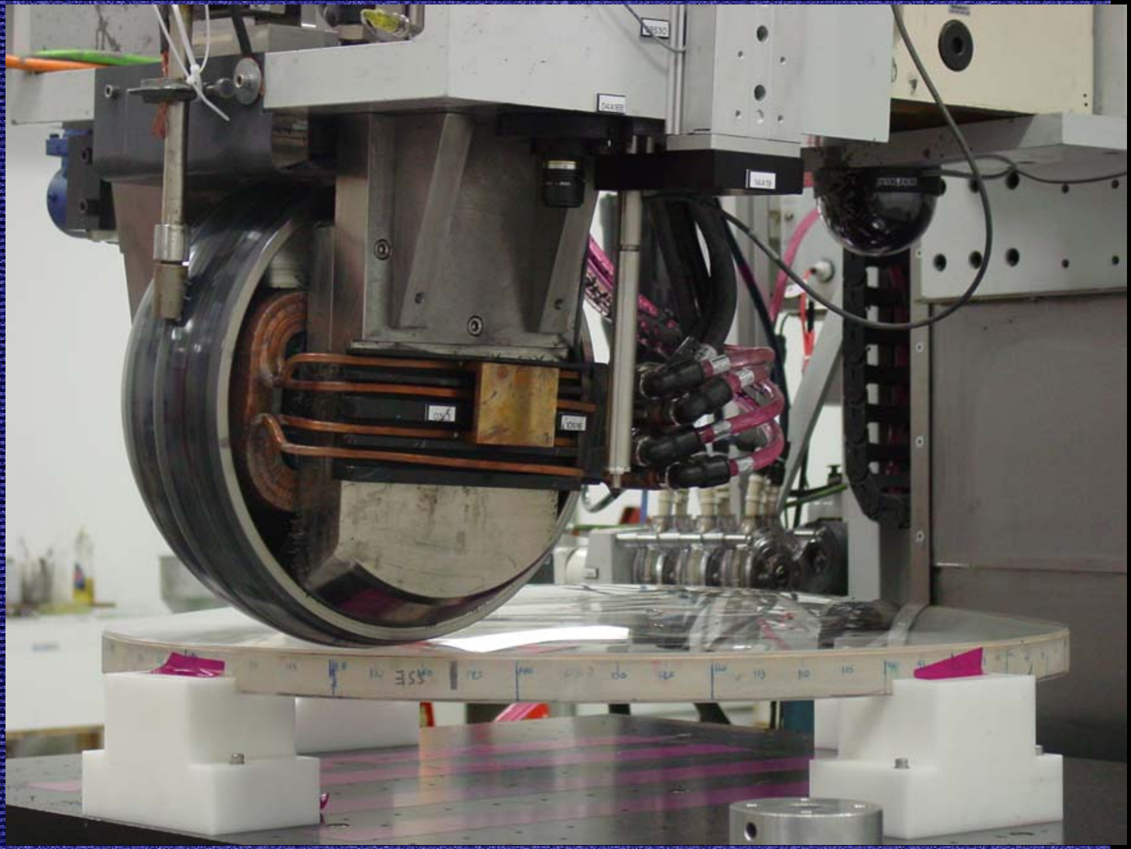
Hextek Gas Fusion™ Borosilicate 15 kg/m^2 mirror blank

Correct cryo-quilting

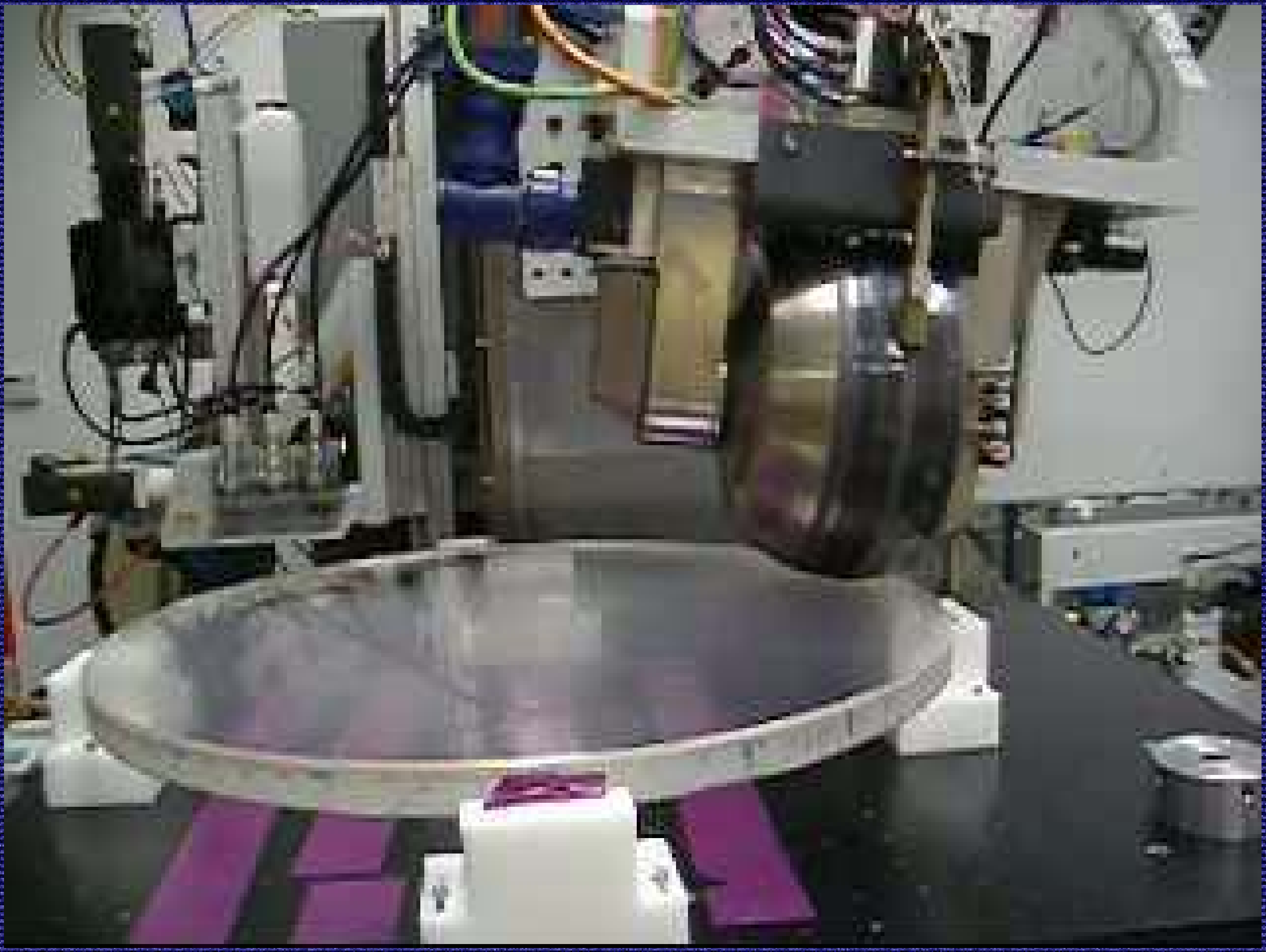
CoorsTek lightweight SiC mirror 20 kg/m^2

Q22-950F Large Asphere Polishing

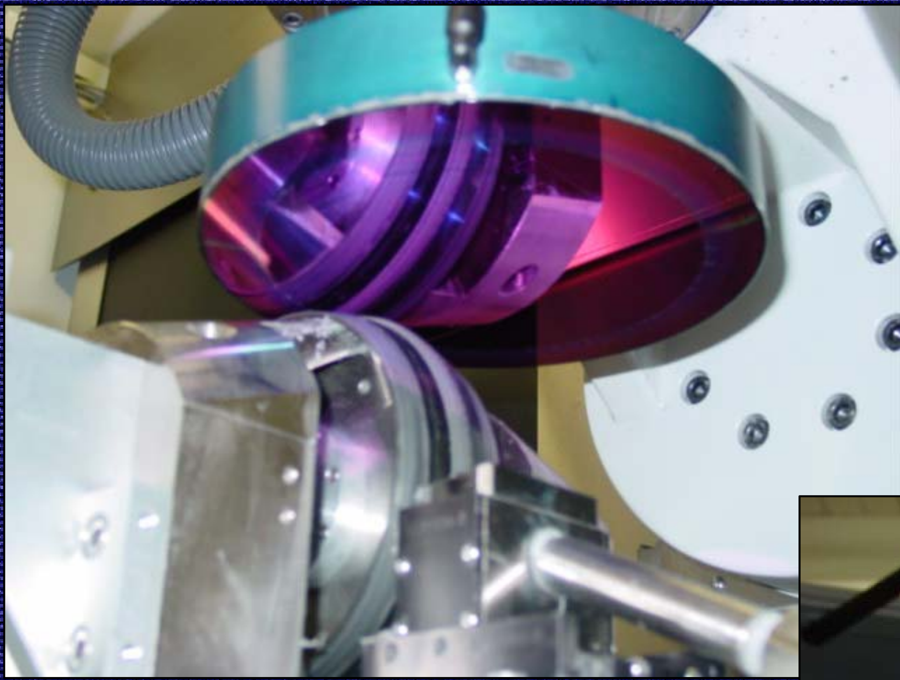
- Asphere ~ 1,300 um (1.3mm!) of departure from BFS
- Fused Silica
- 840mm in diameter

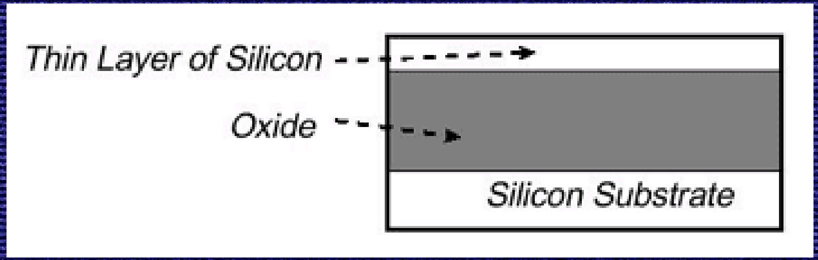


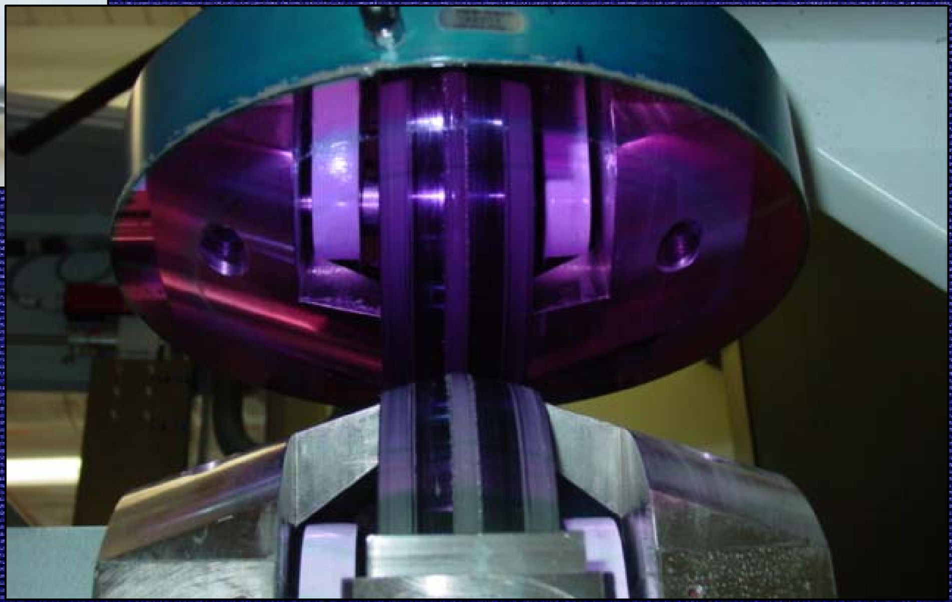
Asphere Polishing Video



SOI Wafer

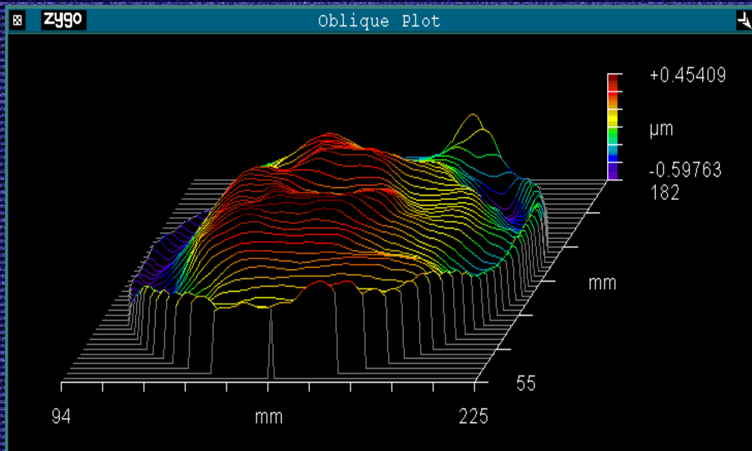






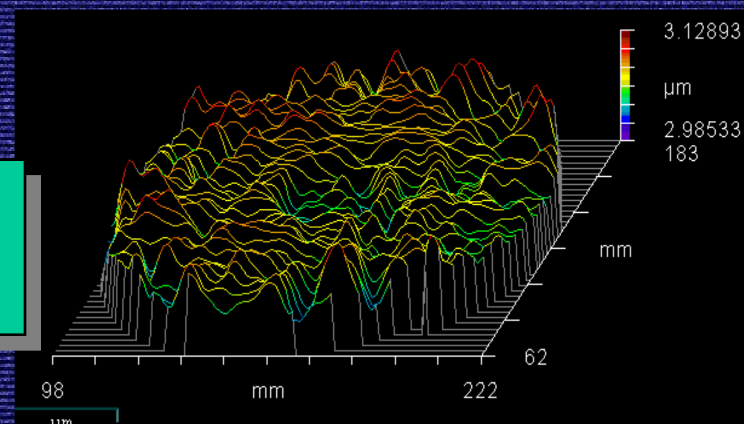
Thick film 150mm SOI wafer

Initial Condition



Thickness: 5.36 µm with TTV of 1.131 µm

2 MRF Corrections

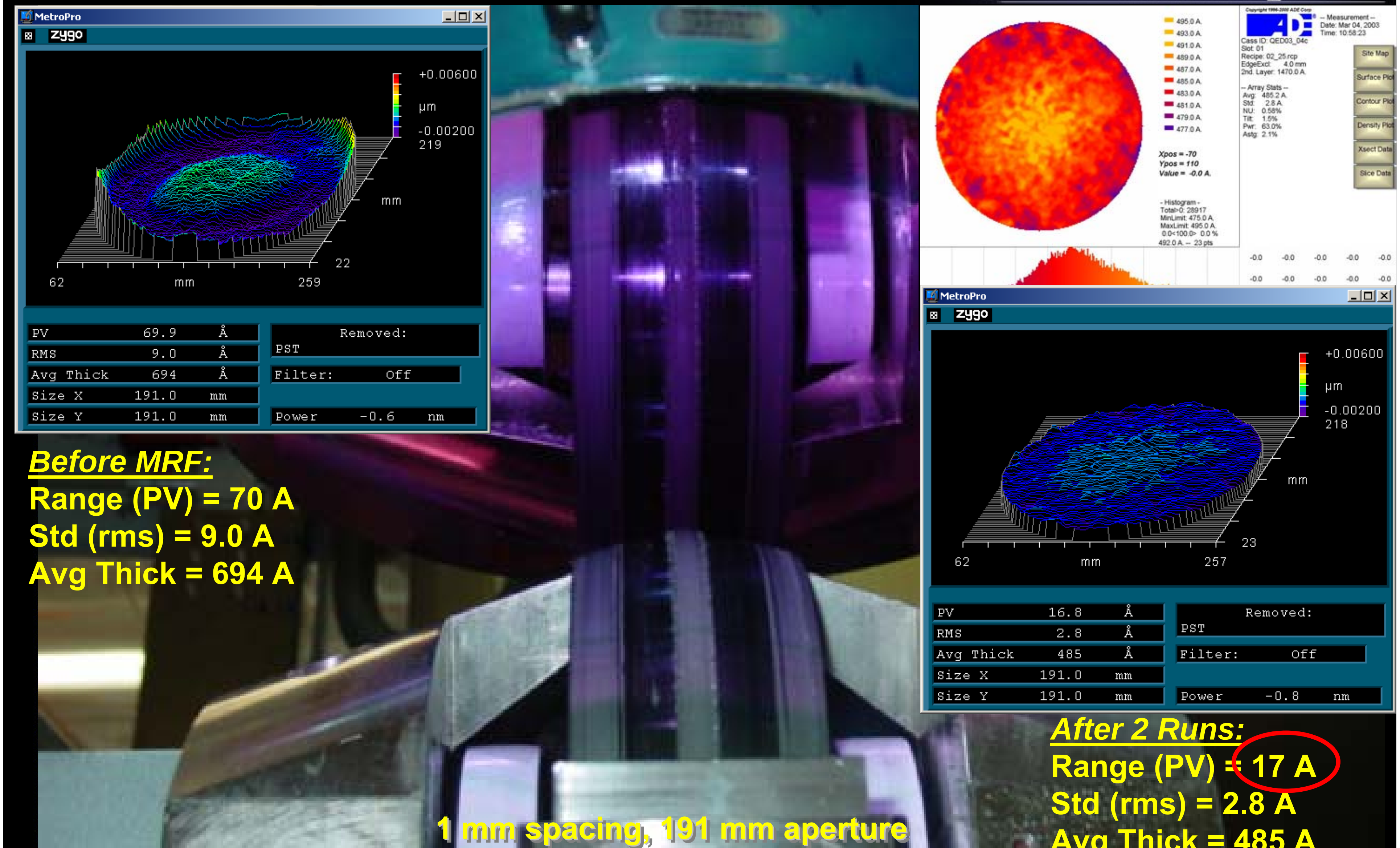


Measured over 130 mm

Thickness: 3.07 µm with TTV of 0.144 µm

Thin film 200mm SOI Wafer

Thickness variation



Before MRF:

Range (PV) = 70 A

Std (rms) = 9.0 A

Avg Thick = 694 A

After 2 Runs:

Range (PV) = 17 A

Std (rms) = 2.8 A

Avg Thick = 485 A

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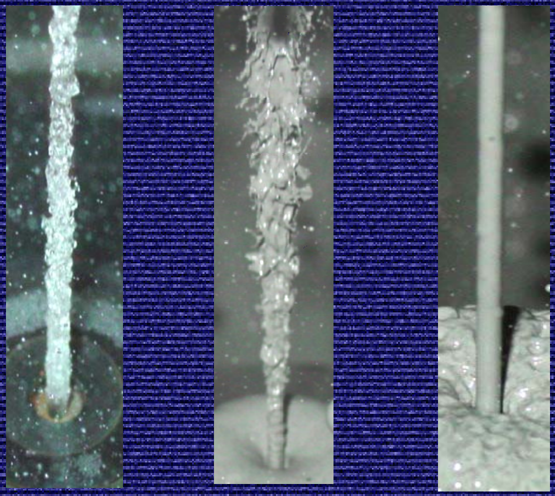
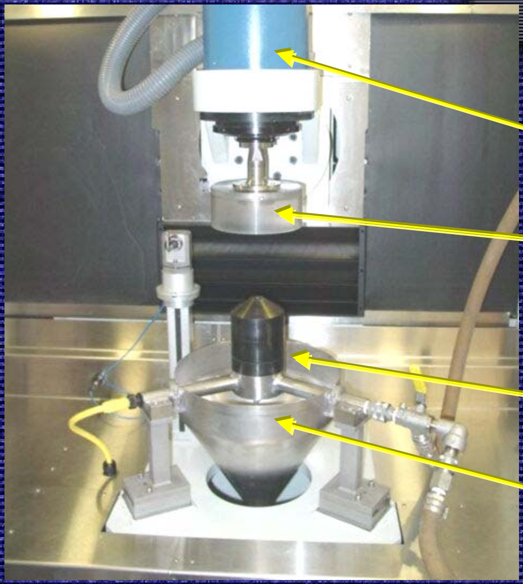
- ❖ SSI Applications
- ❖ Conclusions

MR Jet Polishing

- For special geometries
- Jet of MR fluid
- Polish steep/deep concave surfaces
- Polish magnetic materials
- Stable spot over large range of standoff distances
- Same shear-based removal process

MR Jet™ Prototype



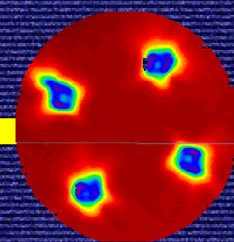


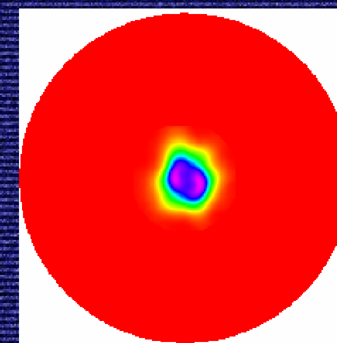
- A fluid jet can be stabilized by using a magnetorheological fluid and a magnetic field
- This stabilized jet gives significant advantages in finishing complex shapes
- Contained in the CNC machine with stable delivery system, MR Jet is used for polishing challenging shapes to high precision

MR Jet Removal Function Stability

Magnet Off

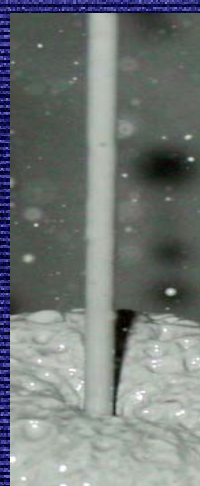
Non-deterministic

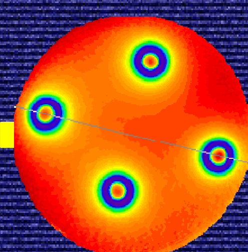


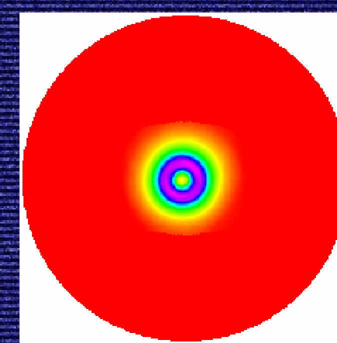


Magnet On

Deterministic

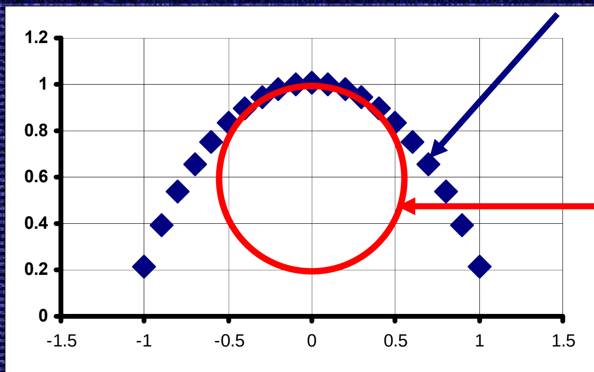






- Stability provided by MR Jet enables *deterministic finishing* at large stand-off distances

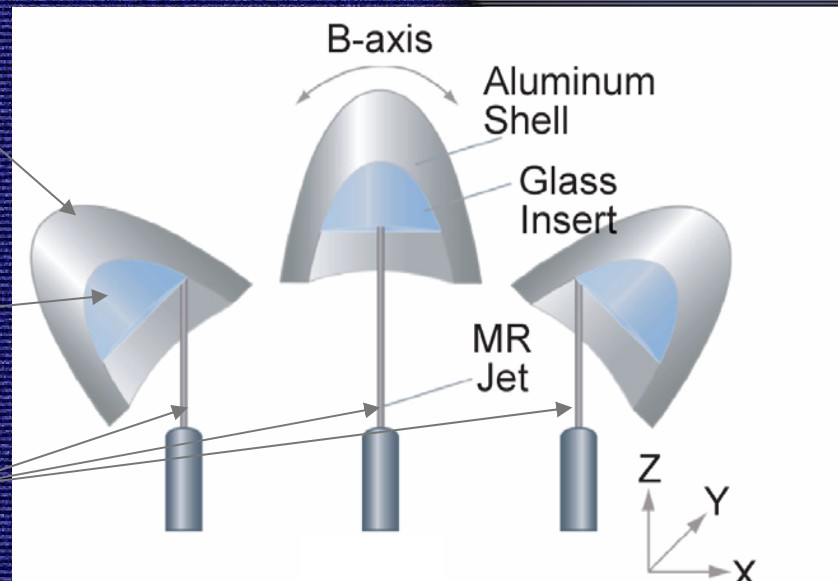
Polishing *Inside* an Ogive Dome

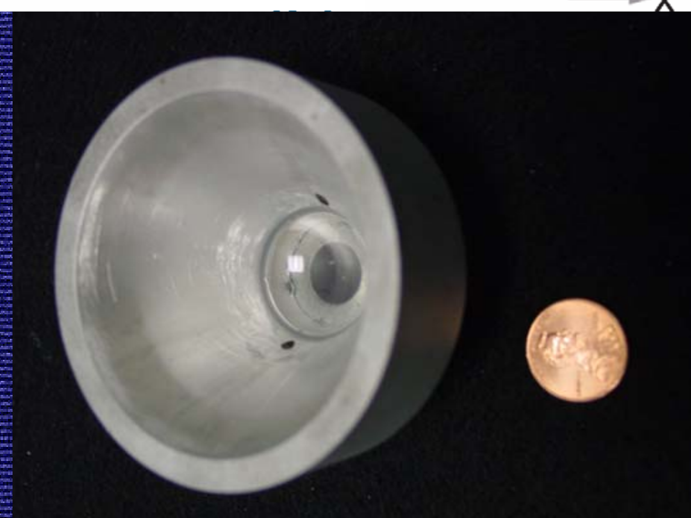


Aluminum
"dummy" ogive

BK-7
Insert

MR Jet





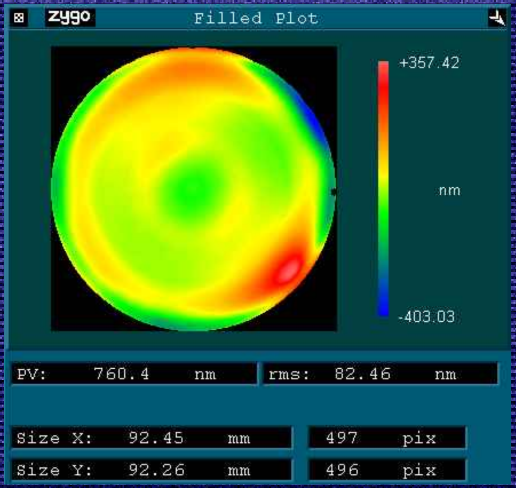
- **Concave sphere in tip of aluminum "dummy" ogive**
- **R = -20 mm, Dia. = 25 mm**
- **~49 mm sag, ~60 mm diameter**
- **Normal incidence between part and jet is maintained**

Dome Polish – MR Jet

Glass Dome

Concave surface in SSI

Glass dome prior to MR Jet

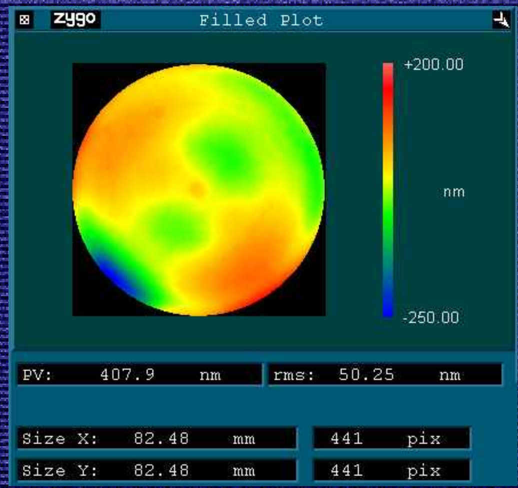


Example of conventionally polished concave surface measured in reflection

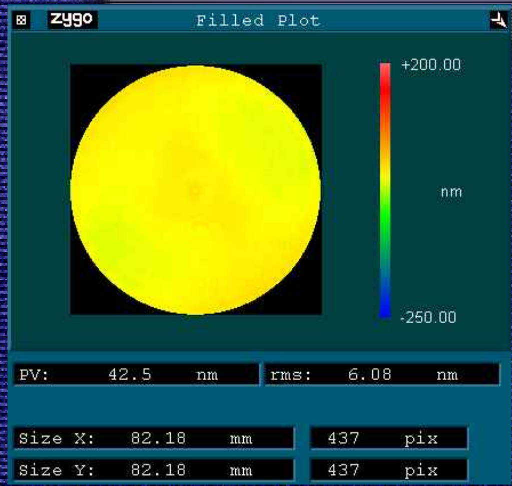
- **97 mm diameter, 2.5 mm thick Fused Silica dome**
- **Measured in reflection in SSI**
- **Concave surface polished with MR Jet**
- **Initial surface error > 1 wave error over full aperture**

FS Dome Polish – MR Jet Results

97 mm OD, 2.5 mm thick fused silica dome in MR Jet Machine



Initial
408 nm P-V
50.3 nm RMS



Final
42.5 nm P-V
6.1 nm RMS

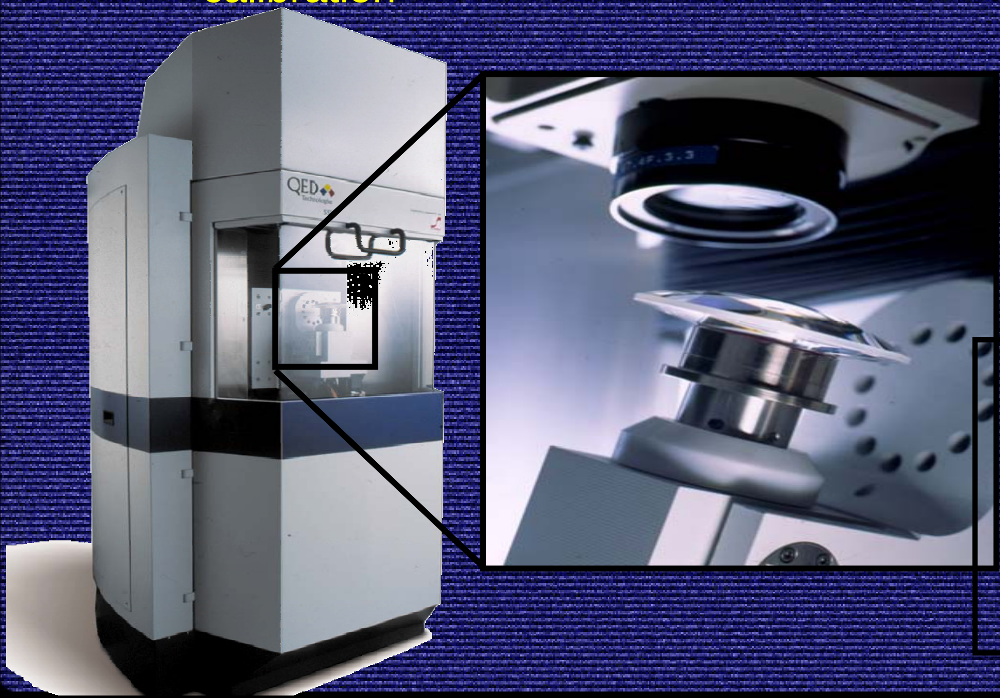
- **Improved figure error from 408 nm P-V (50.2 nm RMS) to 42.5 nm P-V (6.1 nm RMS)**
- **MR Jet was able to polish this high aspect ratio dome to high precision**
- **This technique provides an opportunity to correct the concave surface of a dome, and other challenging shapes, to high precision**
- **Future applications will include more aerodynamic conformal shapes**

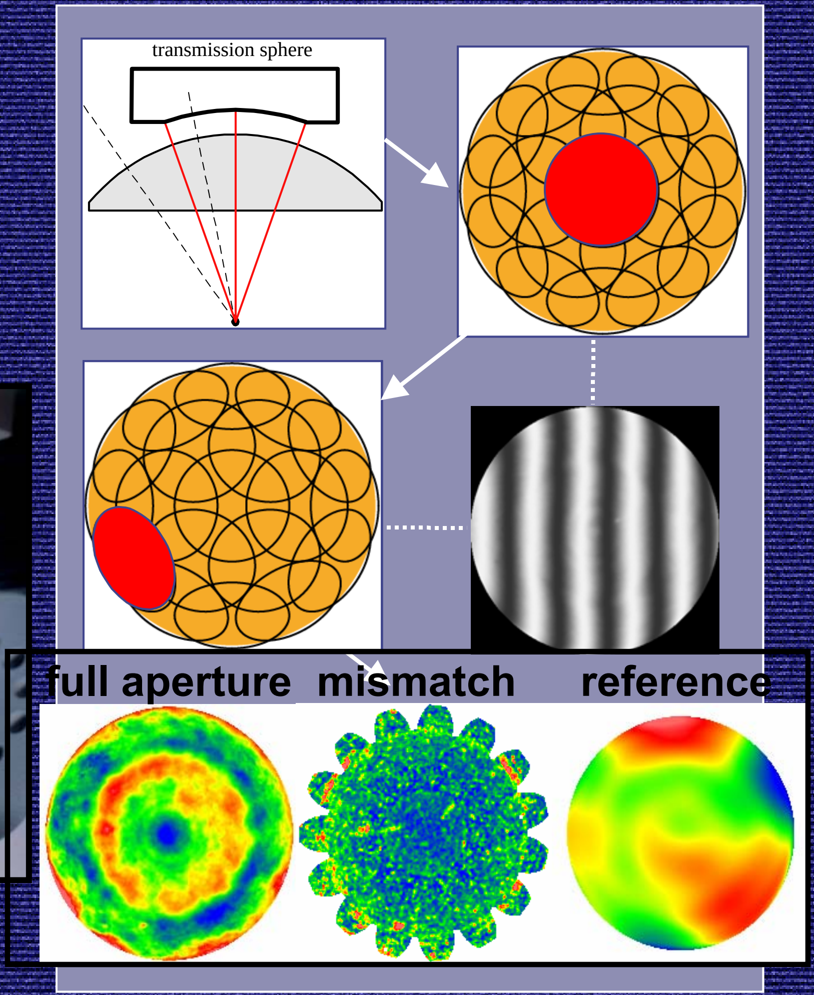
Outline

- ❖ Overview of Magnetorheological Finishing (MRF)
- ❖ MRF Applications
- ❖ Jet Finishing
- ❖ **Subaperture Stitching Interferometer (SSI)**
- ❖ SSI Applications
- ❖ Conclusions

Innovative Metrology: SSI

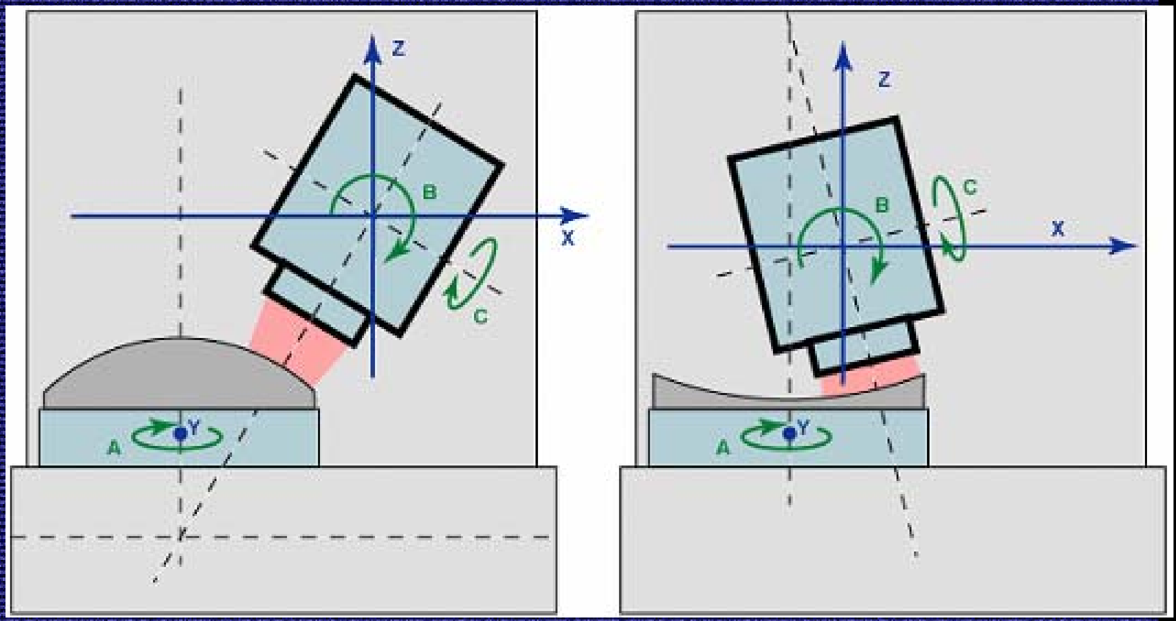
- ❖ **Full aperture measurement of large NA & CA parts**
- ❖ **Completely Automatic**
  - Auto-Positioning, nulling, & radius testing
- ❖ **Intuitive & Easy to Operate**
  - ❖ Reference wave, distortion, pixel scale calibration





Large Aperture Metrology

Large aperture lens mounted in QED's SSI.



Schematic representations of a six-axis platform for performing stitching interferometry on large aperture convex and concave parts.

Outline

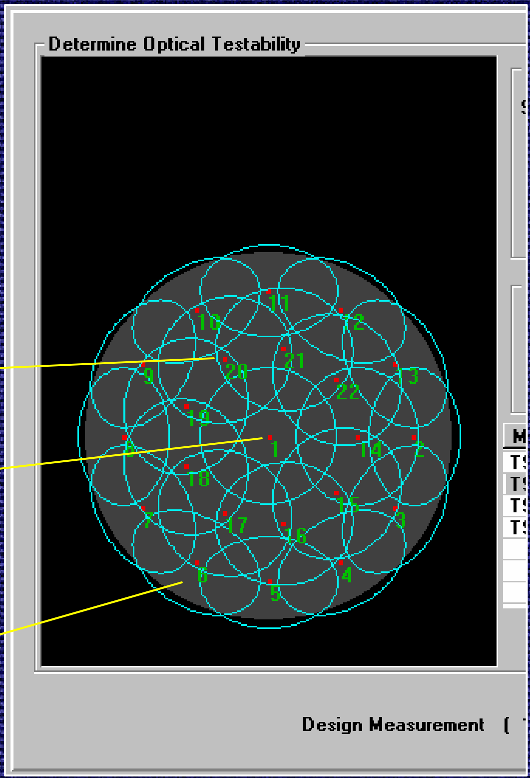
- ❖ Overview of Magnetorheological Finishing (MRF)
- ❖ MRF Applications
- ❖ Jet Finishing
- ❖ Subaperture Stitching Interferometer (SSI)
- ❖ **SSI Applications**
- ❖ Conclusions

Stitching a Large AlON Dome
Lattice & Motions

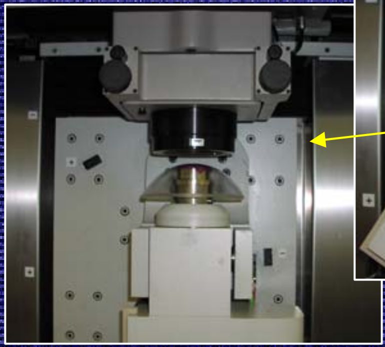
Aperture – 148.34 mm (5.84")
Radius – 82.55 mm (3.25")
CT – 3.04 mm (0.12")
Sag – 50.39 mm (1.984")

F/0.55

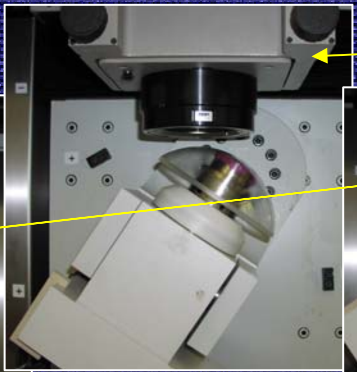
Objective - Zygo 4" f/1.5
Subaperture = 55.1 mm
Required 25 subapertures –
(4 center, 9 inner, 12 outer)



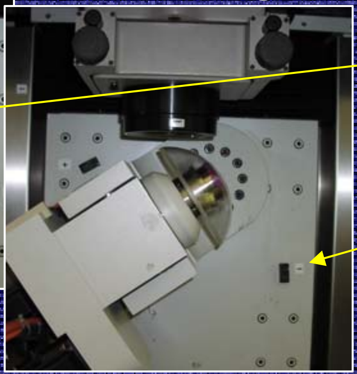
Center



Inner Ring



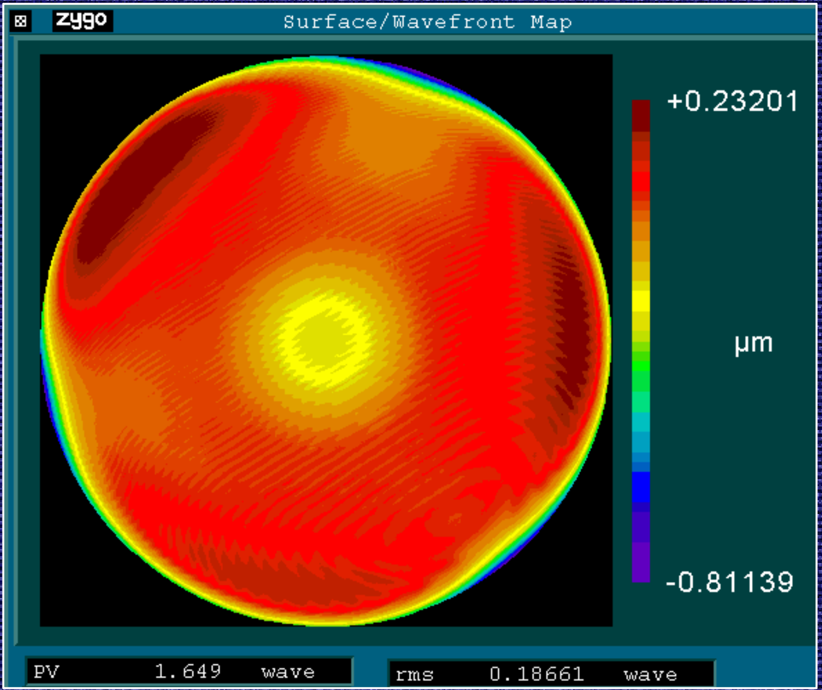
Outer Ring



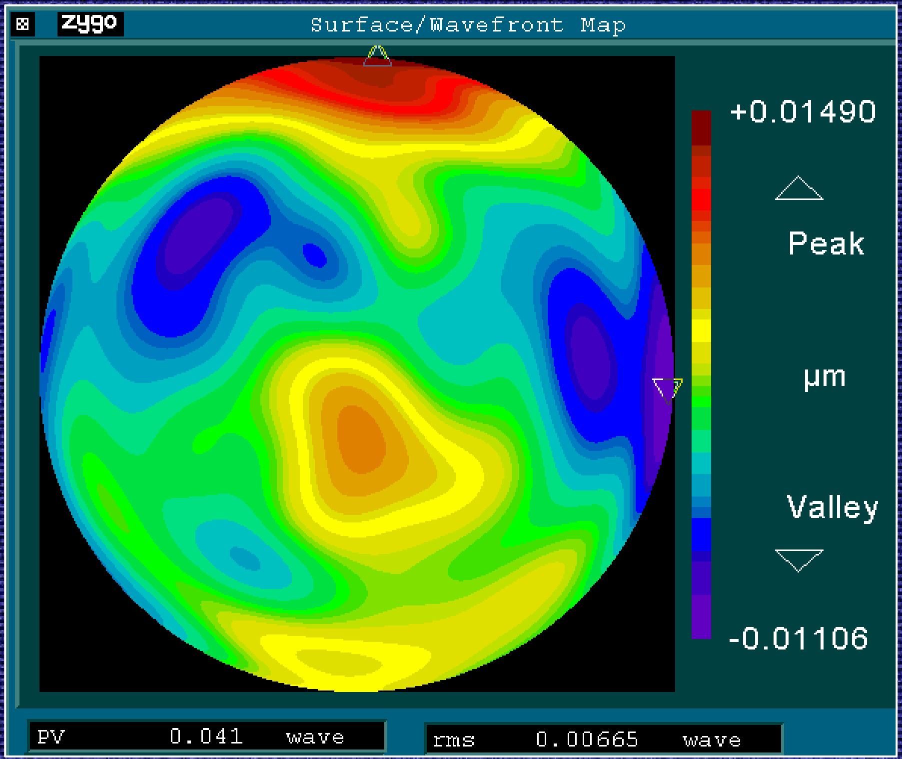
Stitching a Large AlON Dome

Results

Full Aperture Stitched Result



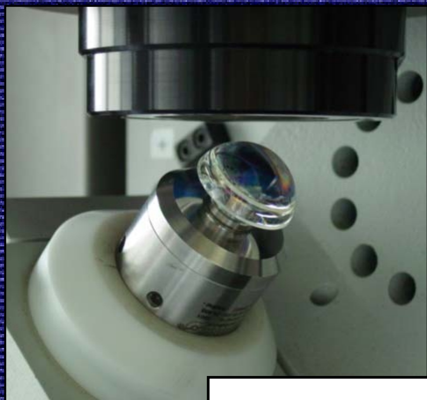
Reference Wave Error



Radius: 82.6 mm
Surface:
PV – 1.649 λ (@ 633nm)
Rms – 0.187 λ (@ 633nm)
Total measurement time:
12 minutes!!

MRF/SSI Hemisphere Demonstration

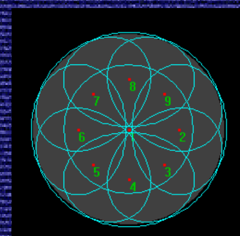
QED Technologies



- **Polished on the Q22-Y**
  - → 7 minute polishing run
  - → from λ/20 to λ/30
- **Measured on the SSI**
  - → live on the exhibit hall floor

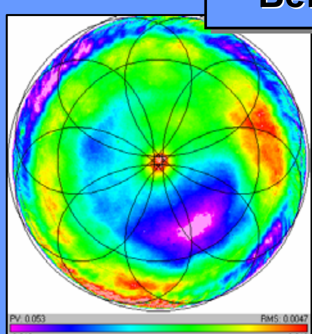
Full aperture: 42.6 mm
RC: 21.6 mm R/#: 0.51

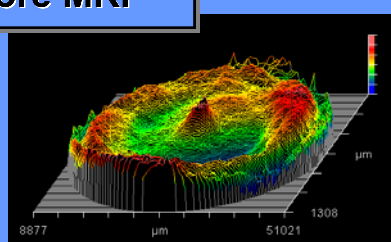
Zygo 6" Verifire AT
4"/0.75 transmission sphere



Lattice design

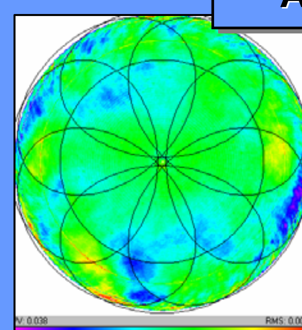
Before MRF

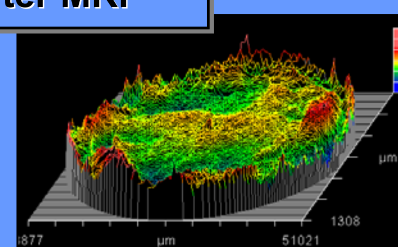




PV = 0.046 waves
RMS = 0.007 waves

After MRF





PV = 0.031 waves
RMS = 0.003 waves

SSI measurement process

Specify surface to test

Select transmission sphere and define lattice

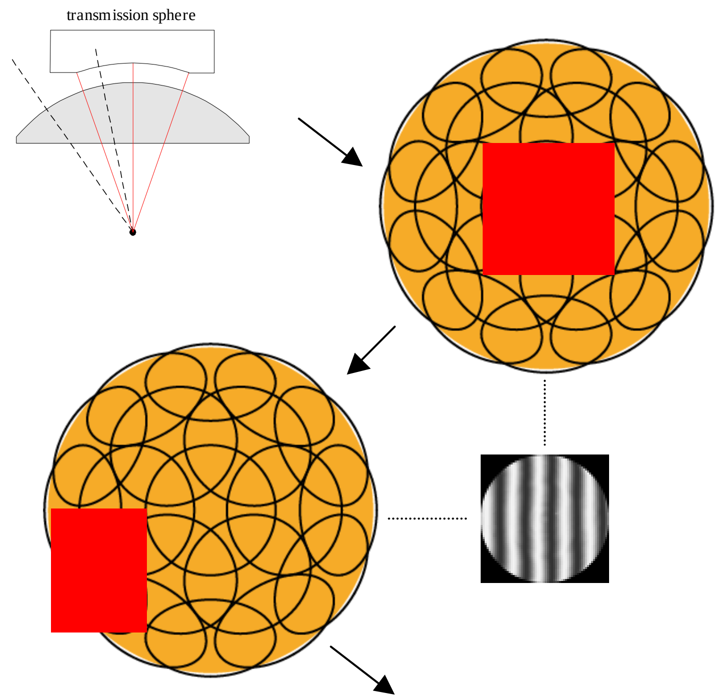
Locate central null

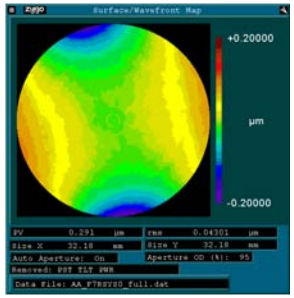
Move to lattice position

Auto-null

Measure

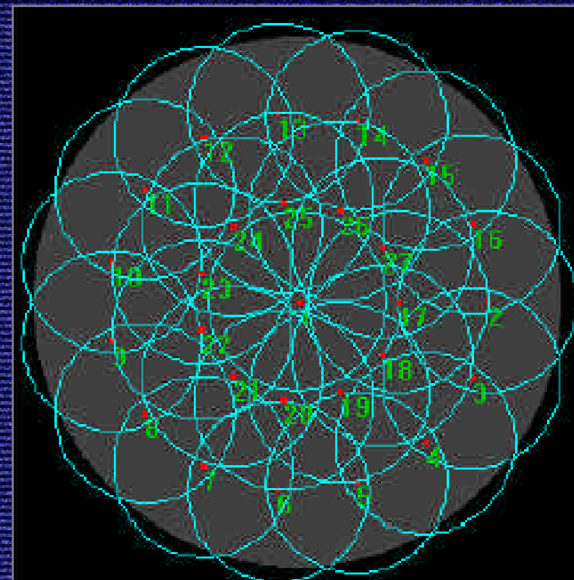
Stitch





Full-aperture map

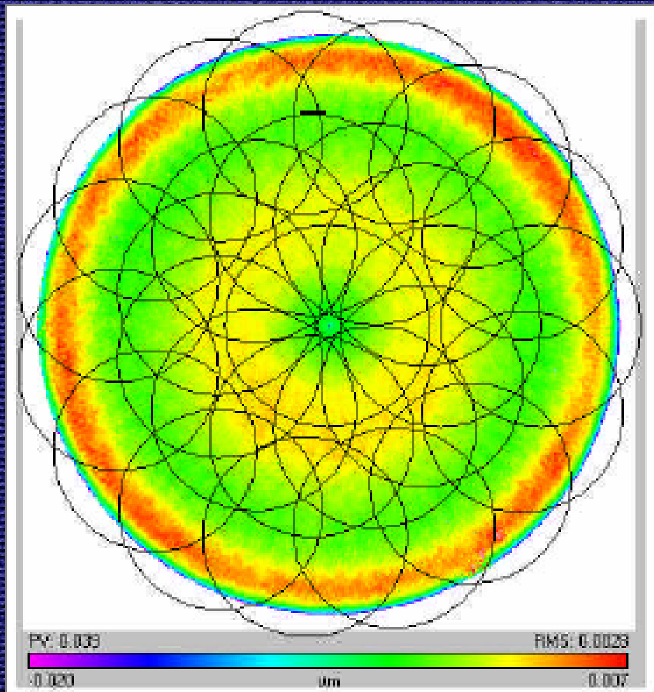
Measuring High Precision Spheres

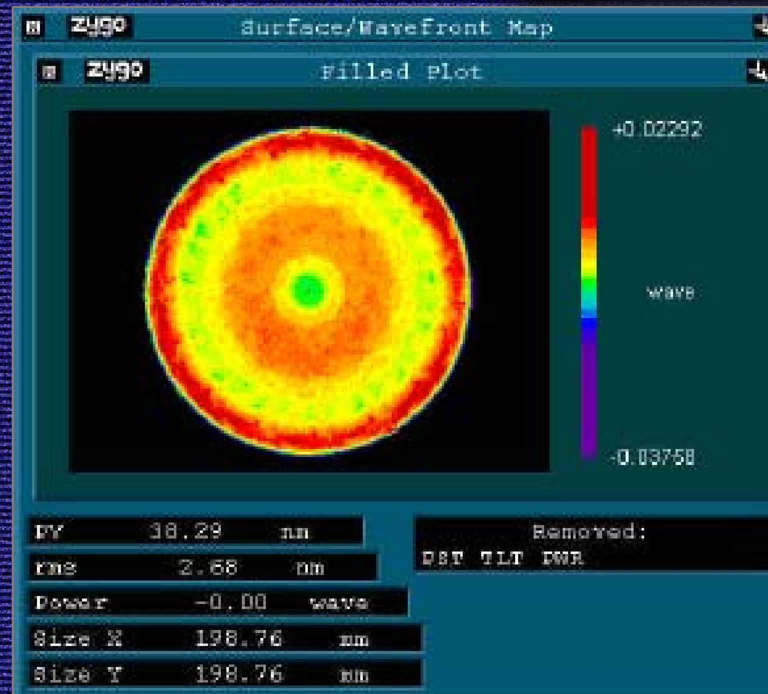


Aperture: 200 mm (8.0")
Radius: 500 mm (19.7")
CT: 34 mm (1.3")

Objective: Zygo 4" f/7.2
Subaperture: 69.4 mm
Extension Factor: 2.95
Required subapertures: 30
(4 center, 11 inner, 15 outer)

The Stitched Result

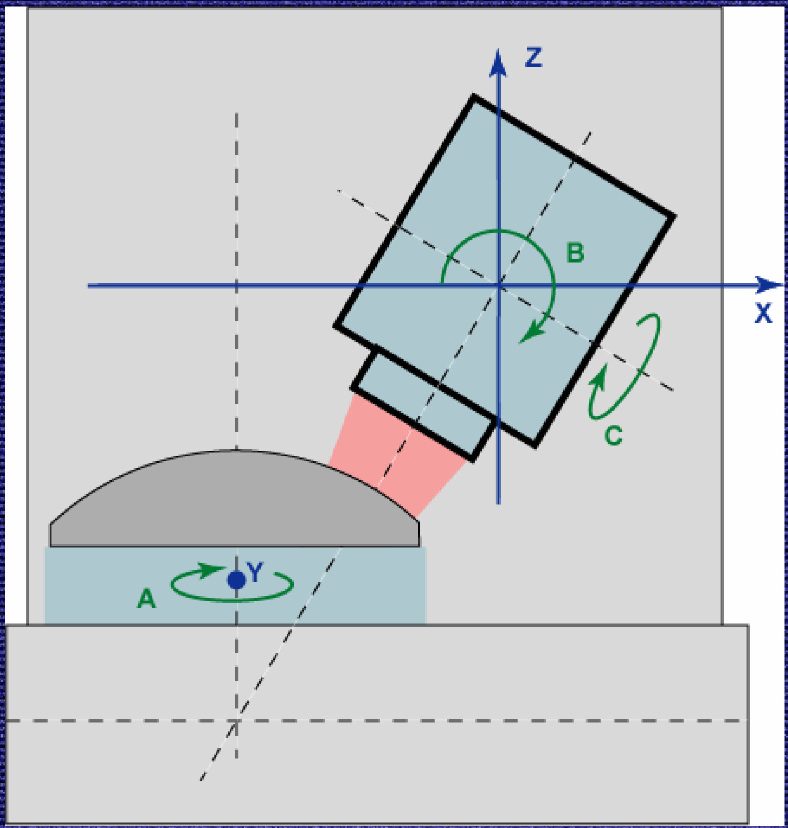




Radius:	499.9765 mm
Surface:	PV = 0.060 λ (@ 633nm)
	RMS = 0.004 λ (@ 633nm)
Total measurement time:	25 minutes!!

Summary

- Boosted testable aperture sizes (i.e. cost-effective reference optics)
- Boosted testable aspheric departure (can obviate need for nulls)
- Boosted accuracy (from thorough, automated calibration of reference wave, distortion, retrace, etc.)
- Boosted resolution
- Reduced non-common air path for long-radius concaves



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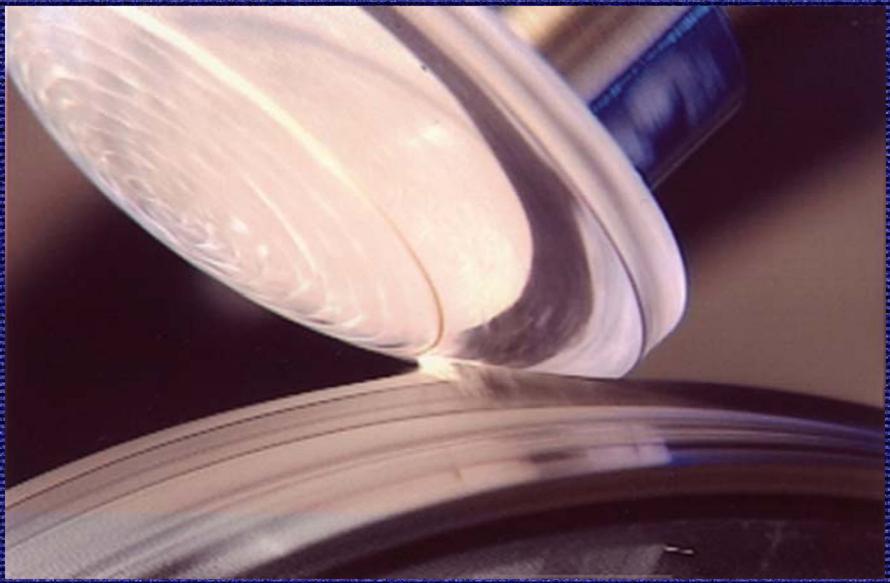
- ❖ Subaperture Stitching Interferometer (SSI)
- ❖ SSI Applications
- ❖ **Conclusions**

Conclusions

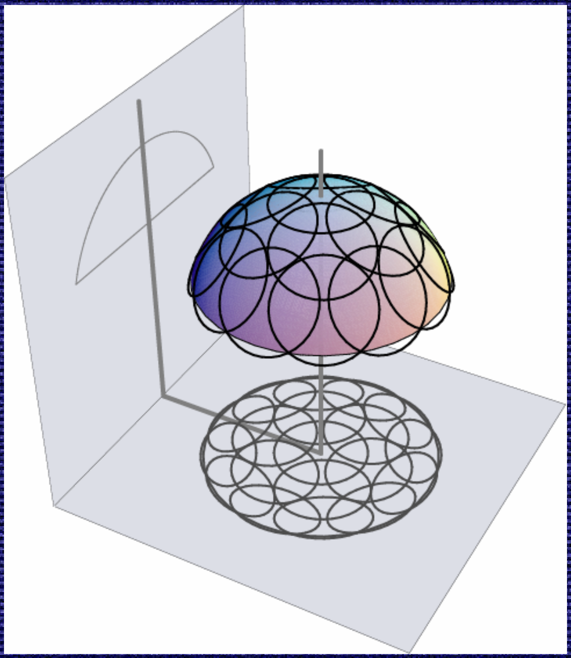
- **MRF:**
  - Shaping - high precision figure correction
    - From real small to real large optics
  - Improve surface integrity
  - Thickness control – substrates, or thin/thick films
- **Jet Finishing:**
  - For difficult geometries
  - Or new materials
- **SSI:**
  - Metrology solution for small to large optics
  - Including hemispheres and other high NA parts

Sub-aperture Approaches to Finishing and Metrology



presented to:

Brookhaven National Laboratory



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