Rapid fabrication of advanced optics
1 foot^2 per hour

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www.loxhamprecision.com

Cranfield UNIVERSITY

Established Royal Air Force Base Cranfield in 1937

Revised as the UK's College of Aeronautics in 1946

Broadened activity and renamed Cranfield Institute of Technology in 1969

Rebranded as Cranfield University in 1996

Turnover of £170 million per annum

2500 staff : 2500 PhD/MSc students

Manage the UK’s Military Defence Academy

Retain Aircraft design/build accreditation

Own and operate a Grade 3 Airfield

Strategic partners to: Rolls Royce, BAe Systems, Boeing, Airbus Defence and Space

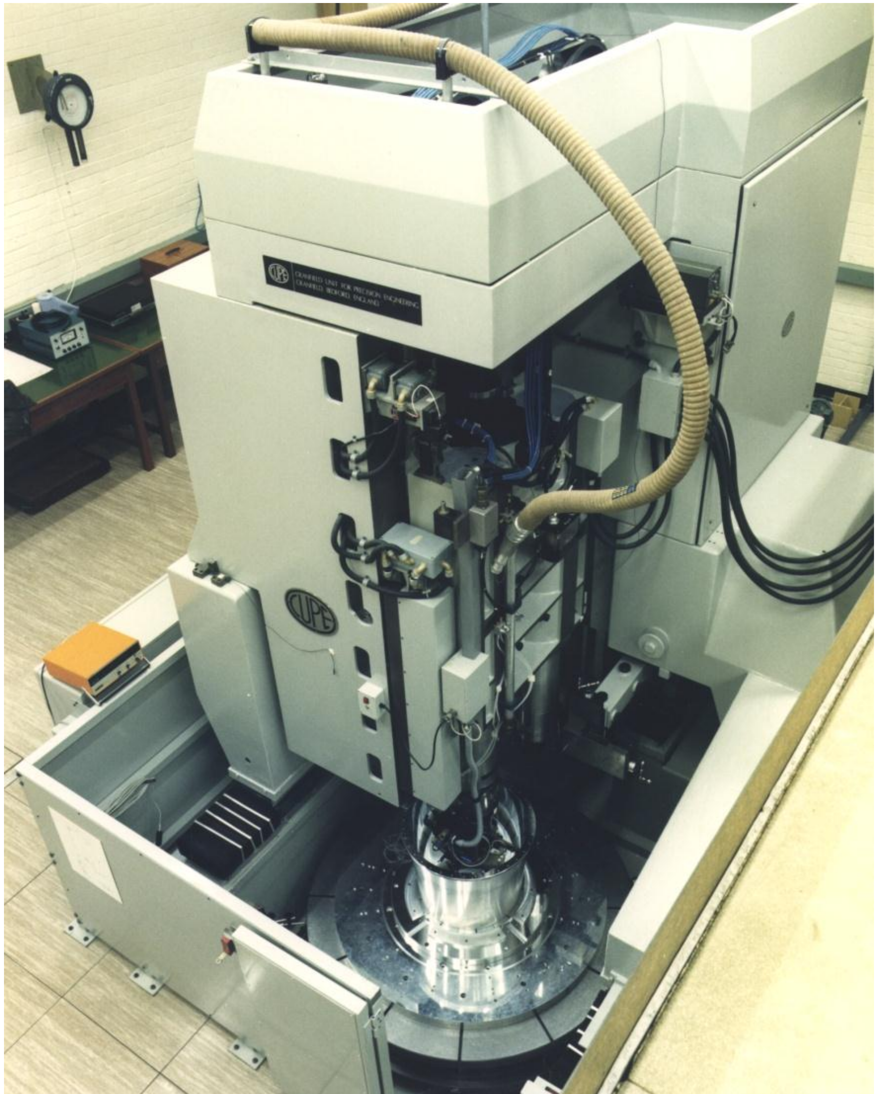
Approved supplier for ESA, NASA, ESO and NPL programmes

Talk structure

1. Cranfield previous mirror activities
2. 1 foot^2 per hour
3. Rapid freeform process chain
4. Freeform surface grinding
5. Reactive atom plasma surface figuring
6. Summary

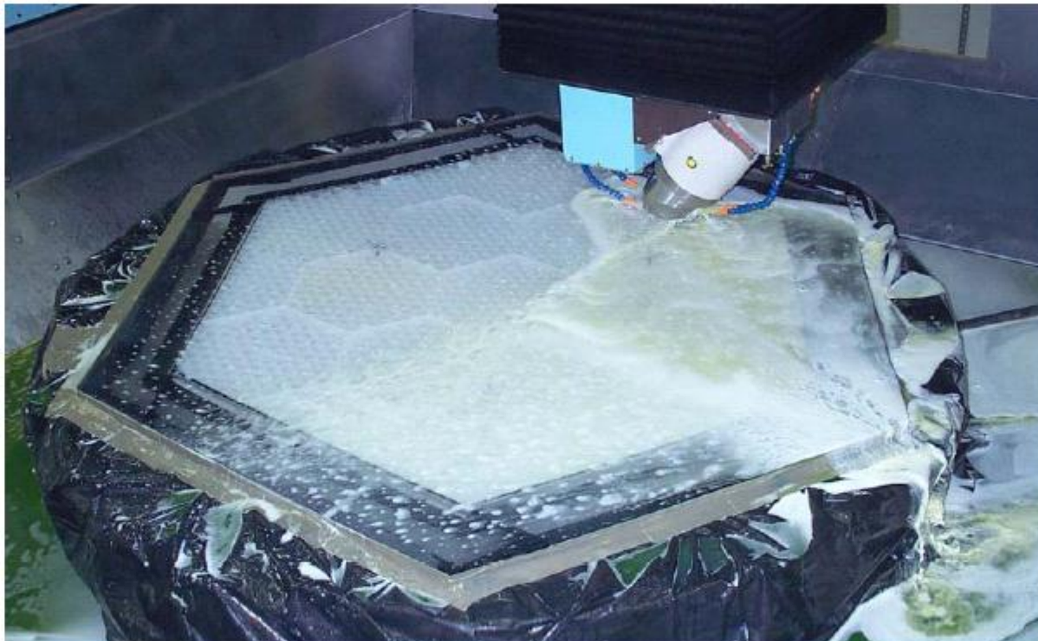
Large Diamond Turning Machine for producing

X ray Astronomy Mirrors




OAGM 2500
CUPE

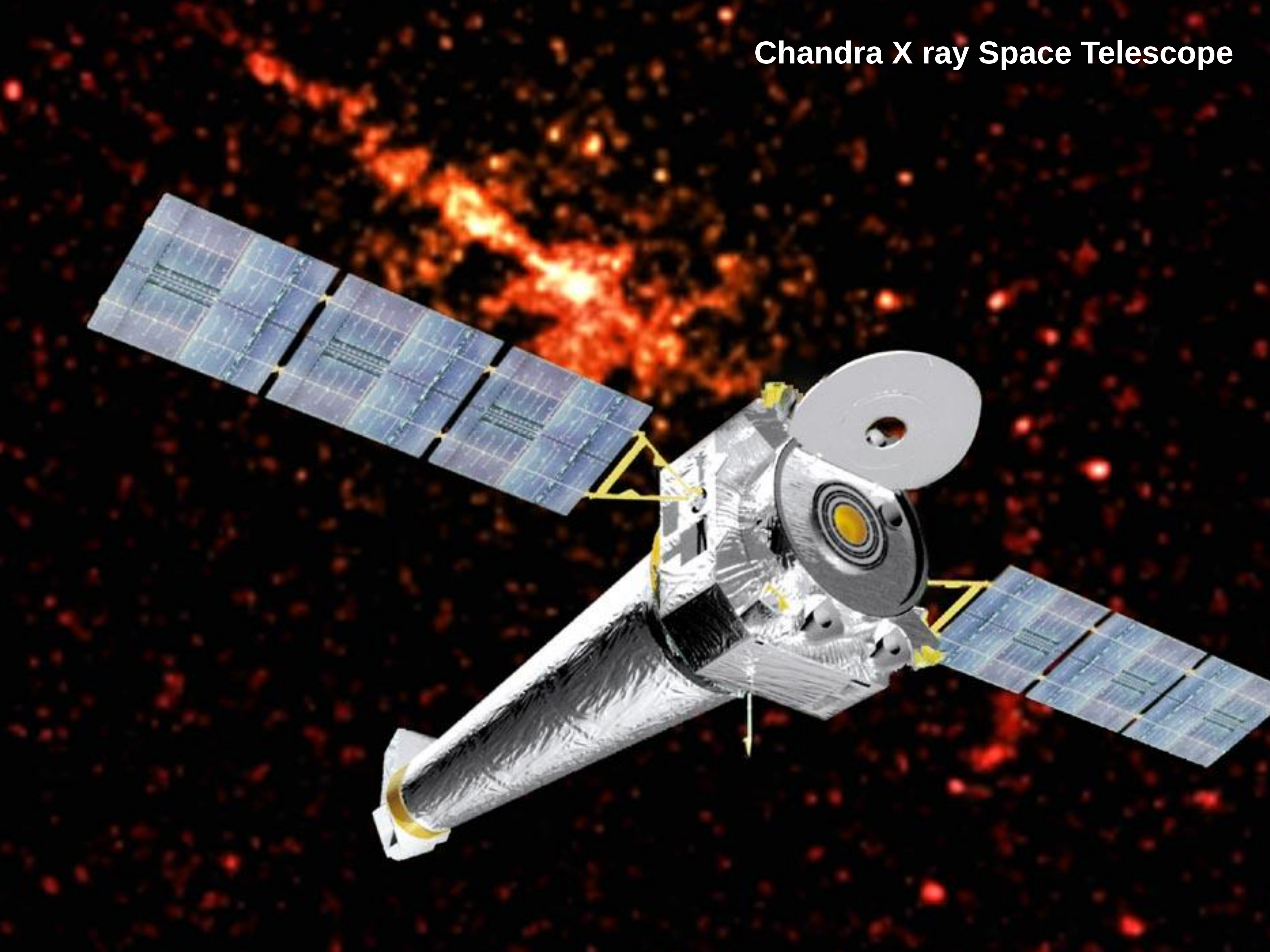
Aspheric Generation



Off-Axis Generation Machine (OAG) used to impart final asphere onto AMSD mirror

10 micron P-V surface generated

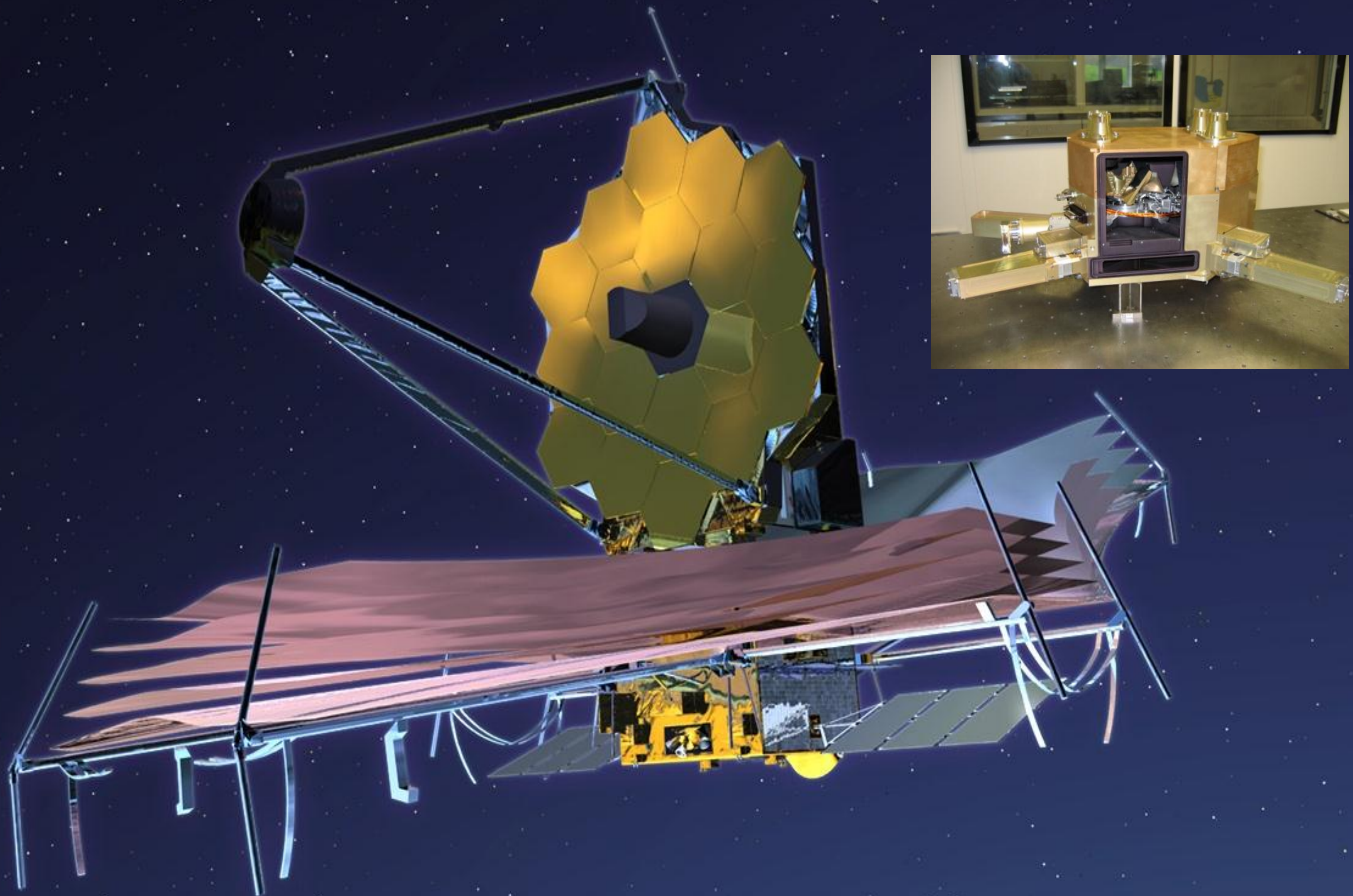
Chandra X ray Space Telescope



CUPE CIDI measuring machines made for Hughes Danbury for the “Chandra” X ray space telescope

Ref; CUPE 1991

James Webb Space Telescope - MIRI Instrument Spectrometer Mirrors



JWST MIRI image slicer and re-imaging mirrors

Cranfield
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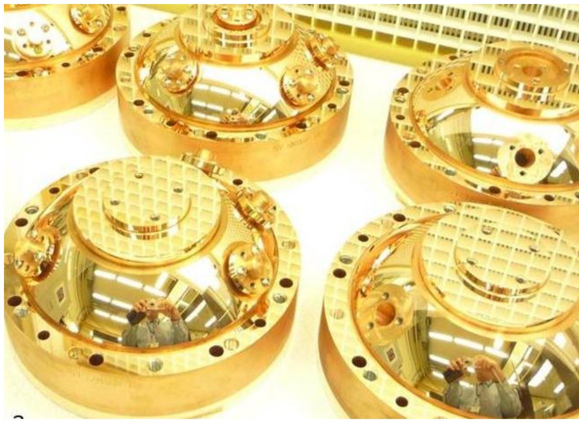
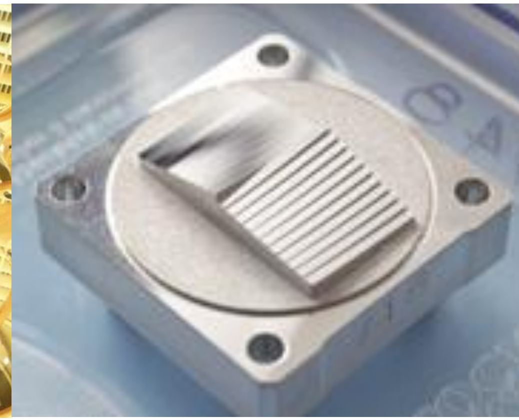
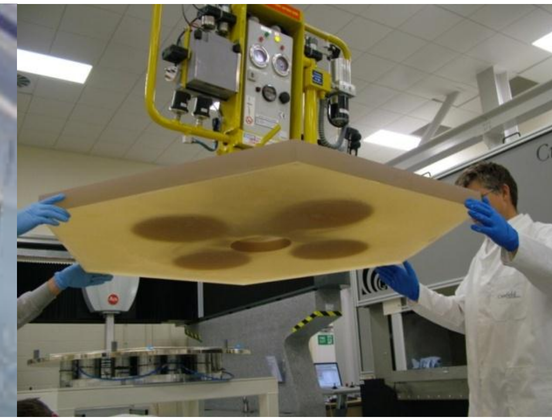
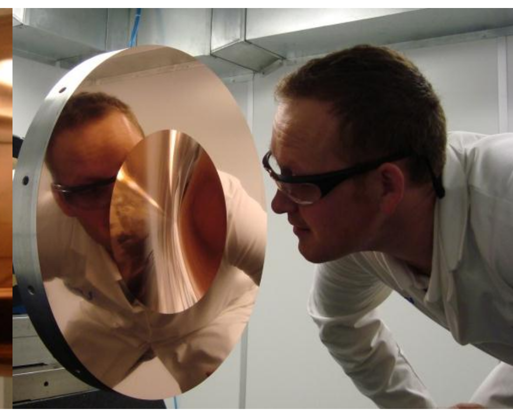






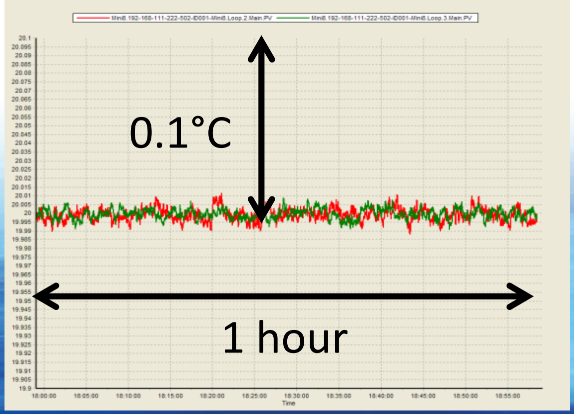


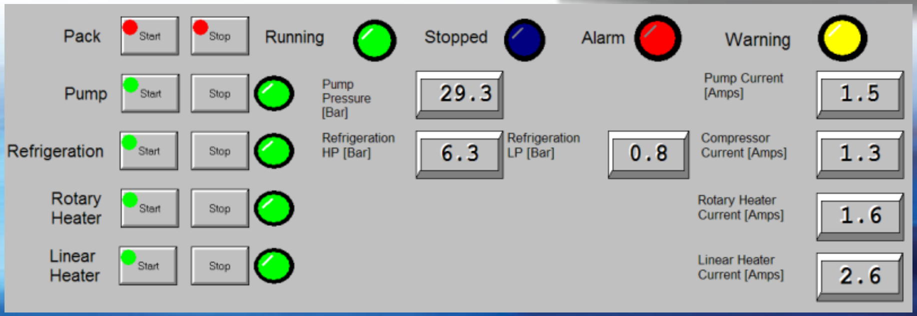
mK Ultra Precision Temperature Controllers

milli Kelvin Controllers

Loxham Precision's ultra precision temperature controllers are based on the most advanced thermal management technologies offering:

- Sub milli-Kelvin resolution control
- Multiple channels
- Matched performance temperature sensors
- High response cooling technology
- Advanced fluid heater technology
- Remote heater and sensor positioning
- Advanced control functions





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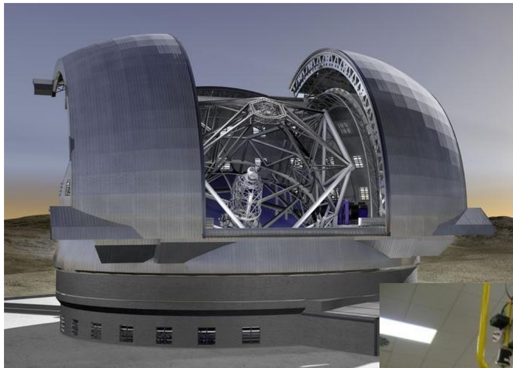
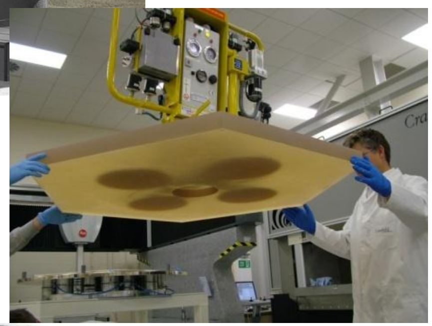
LOXHAM PRECISION

Production rate : 1 $foot^2$ per hour
(1 $metre^2$ per 10 hours)

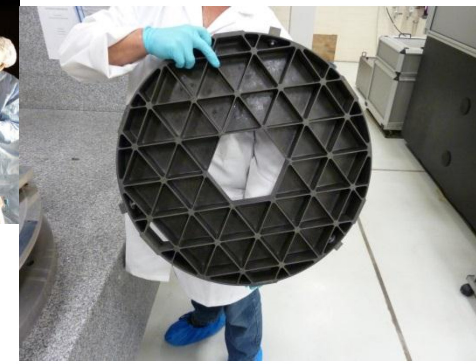
Freeform optics

LOXHAM PRECISION

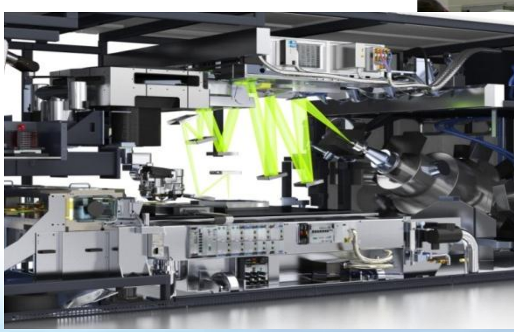




Telescopes - ELT



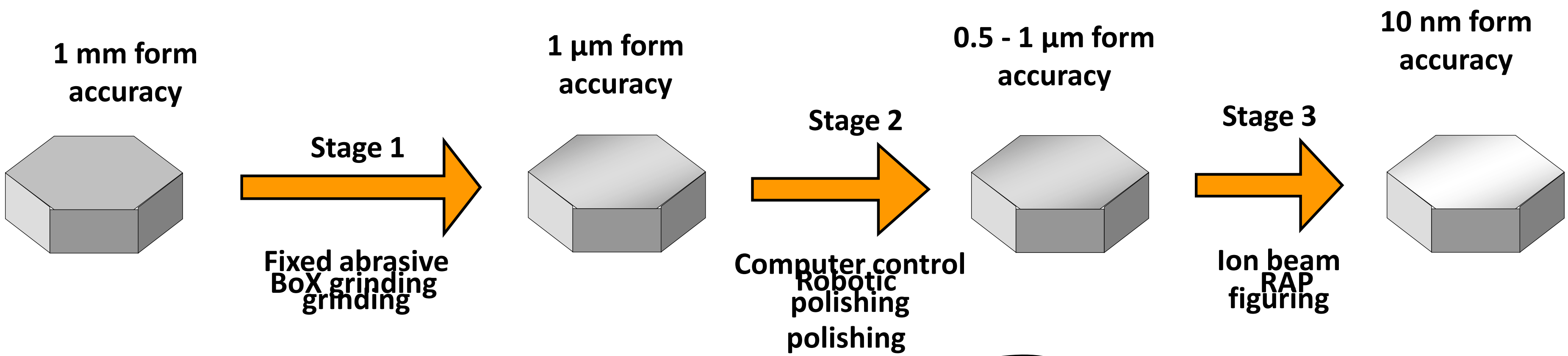
Space – Earth orbiters

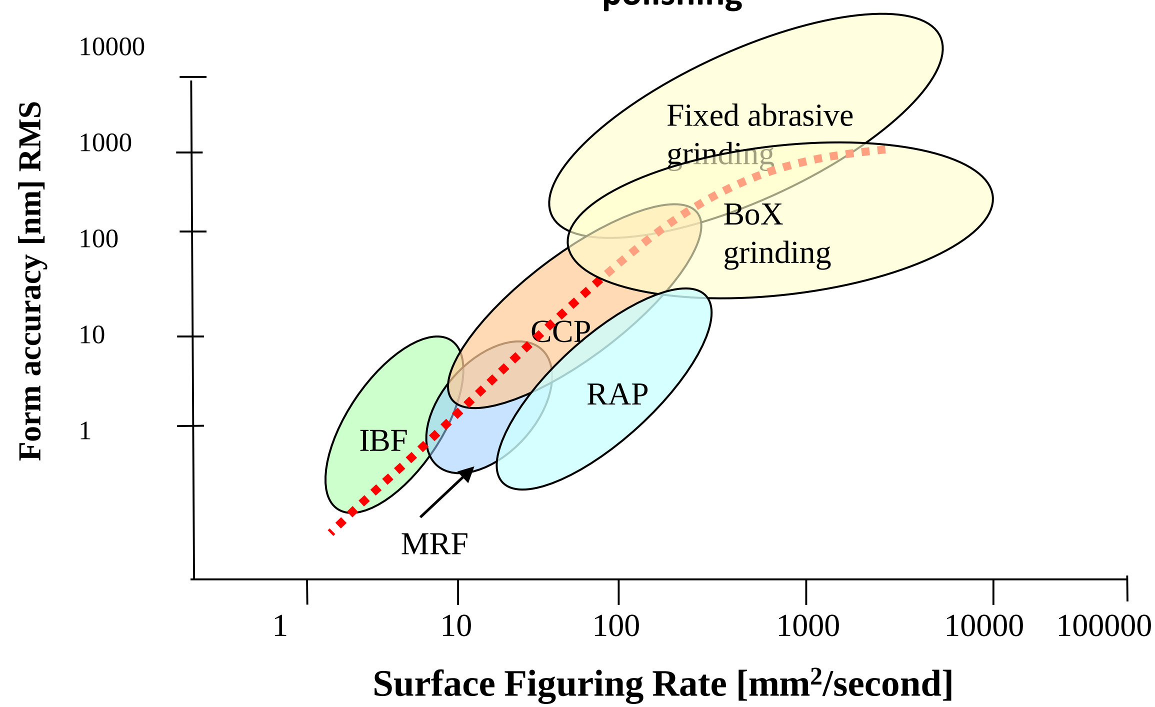


Lithography - EUV microlithography Systems

Fusion – High power laser optics

UPS Project Rapid Process Chain





Rapid Process Chain

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Requirement: 10 hours per 1m^2 (1ft^2 per hour or 1 E-ELT segment per day)

1 mm form accuracy | **1 µm form accuracy** | **0.01- 1 µm form accuracy** | **10 nm form accuracy**

Stage 1 — **BoX grinding**

Stage 2 — **Robotic polishing**

Stage 3 — **RAP**

Grinding:

- Remove min 1mm depth
- Output visible by full aperture interferometry (P-V < 3 um)
- Minimum sub-surface damage

Polishing:

- Remove SSD
- 1 nm RMS roughness
- Form accuracy <0.5 um P-V (as time allows)

Re-active atom plasma:

- Remove min 2 um depth
- Form accuracy 10nm
- Degrade roughness < 2 nm RMS

Freeform surface grinding at 1 foot^2 per hour
(1 metre^2 per 10 hours)

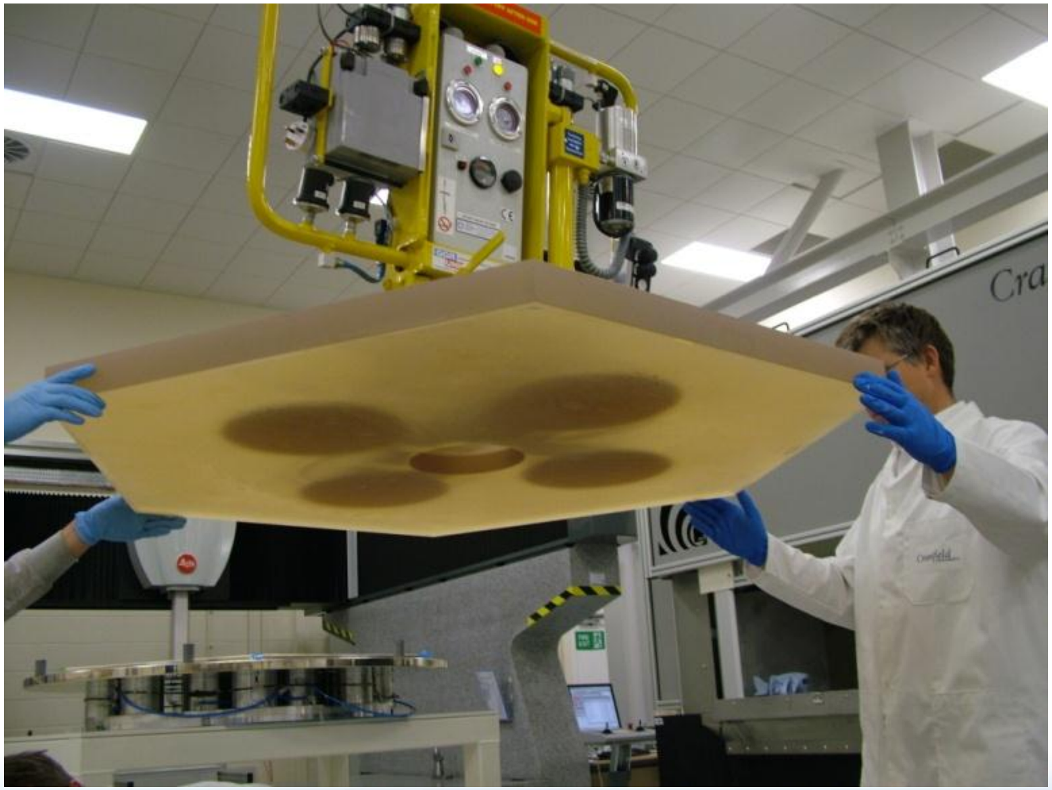
BoX® Freeform grinding/measuring machine

Work-piece quality
Form accuracy: < 1 um RMS
Sub-surface damage: < 5 um
Roughness: 100 - 200 nm
(Zerodur data)

Processing rate
Grind time: 10 hrs/m^2
Measurement time: 4 hrs/m^2
Load/set/unload time: 1 hour

EELT Mirror segment

LOXHAM PRECISION

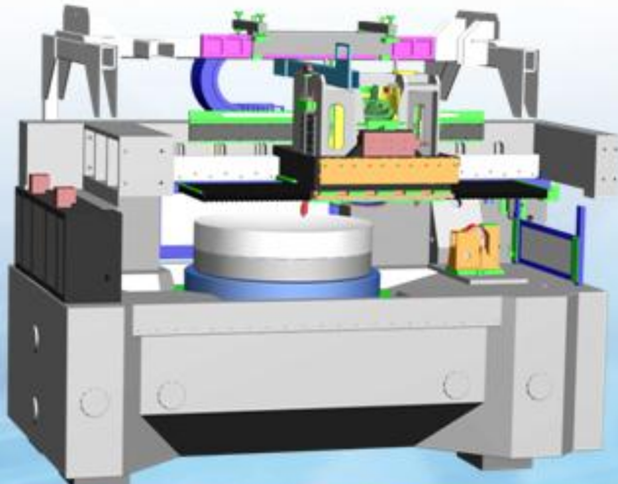


Watch Youtube video

Search “Loxham Precision”

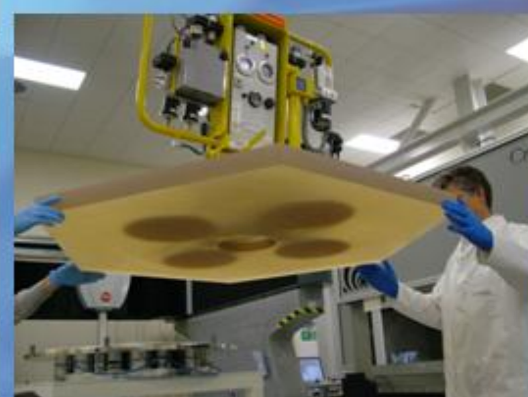
https://www.youtube.com/watch?v=TBvFTmYzUYQ

BoX® Ultra Precision 1600
Freeform grinding & measuring machine



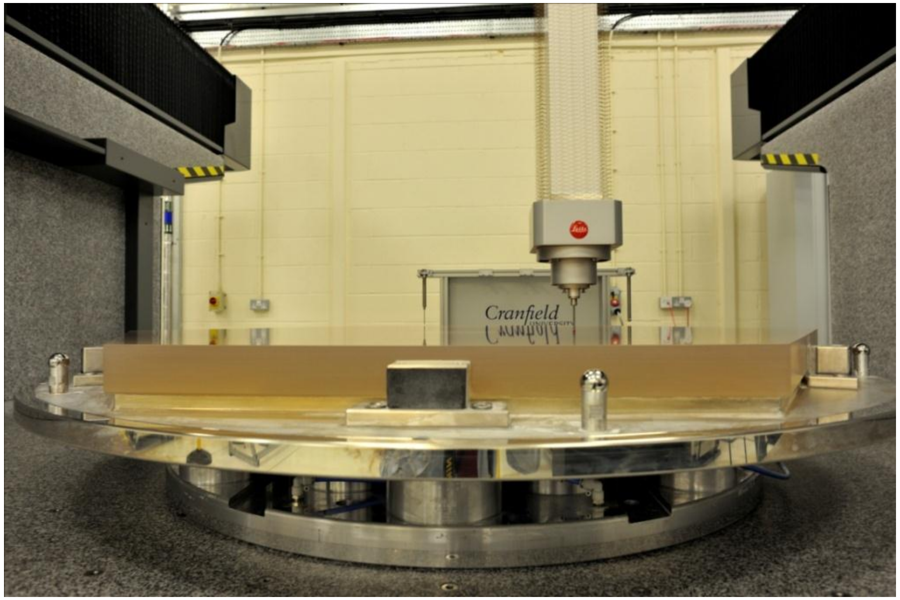
Deterministic ultra precision production technology to rapidly grind large optics of complex shape

- Proven freeform surface generation
- Unrivalled form accuracy capability
- Rapid processing rates
- Reduced levels of sub-surface damage
- Low cost of ownership



BoX® EELT Mirror segment (1)

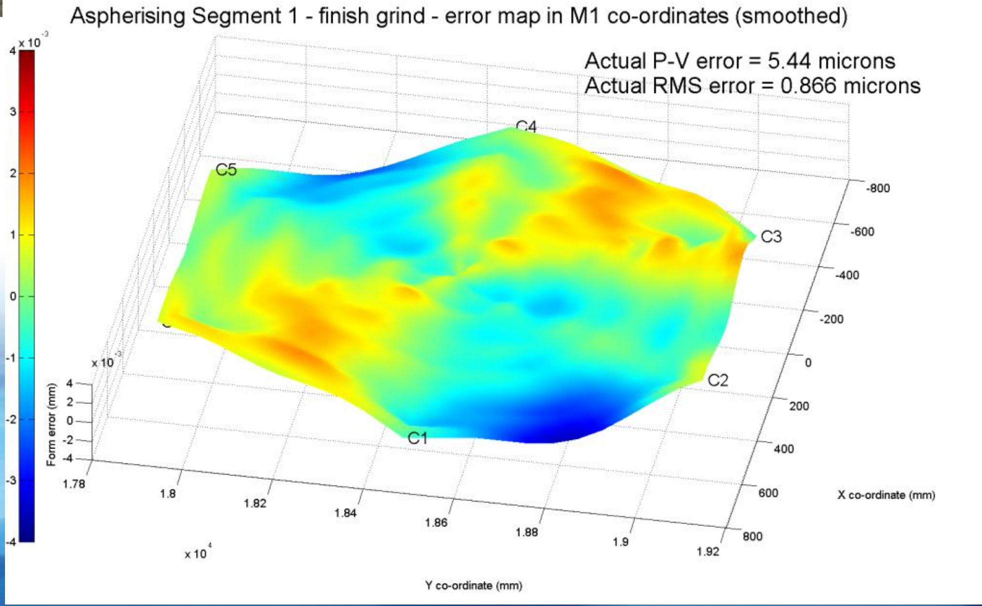
LOXHAM PRECISION



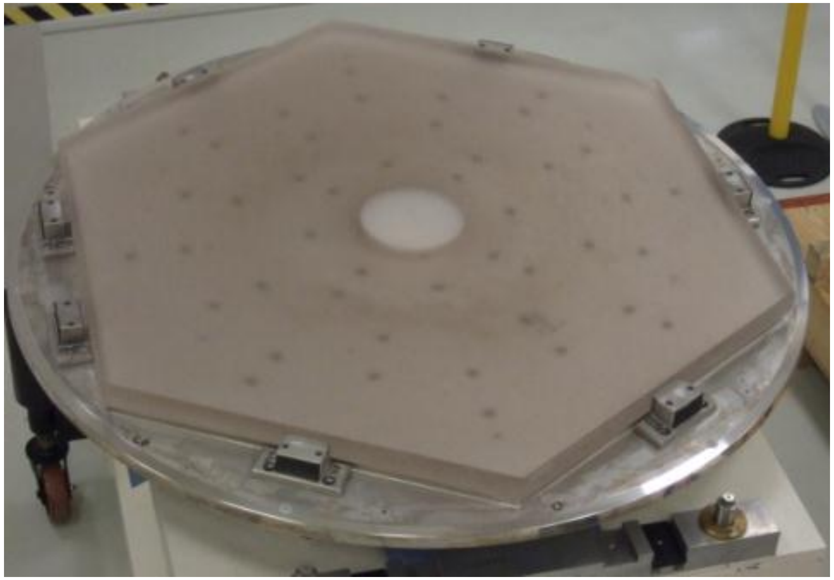
Results:

- Surface map (CMM)
- RMS < 1 µm,   P-V < 5.5 µm
- No visible edge chipping
- No attributable cavity effect

- ELT segment SPN01 (15:15)
- Material – Zerodur
- 580,000 measurement points
- Data to within 0.5mm of edge

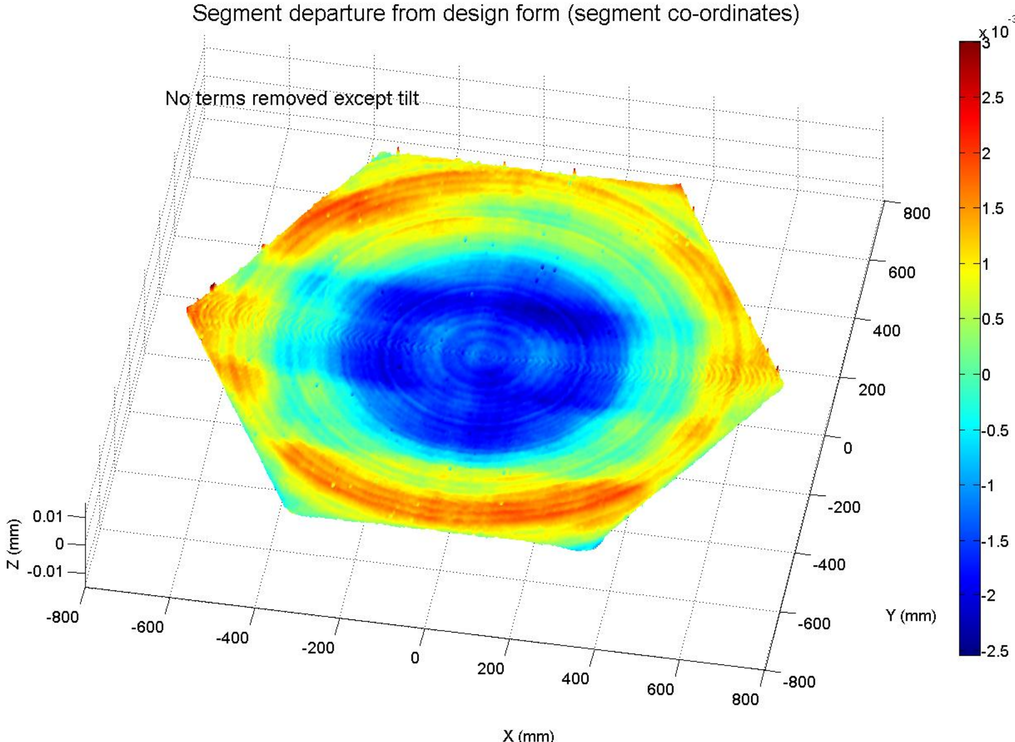


BoX® EELT Mirror segment (2)



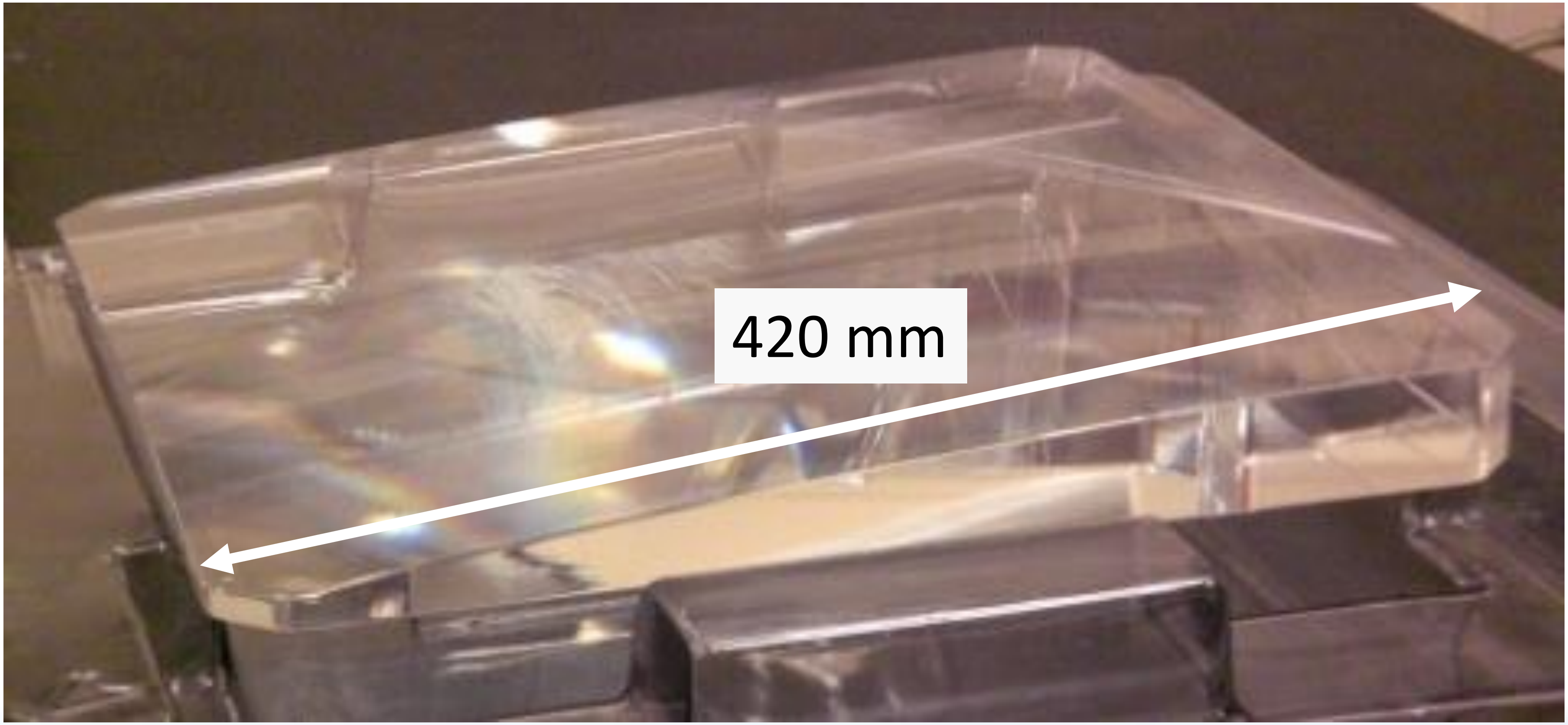
Results:

- Surface map (CMM)
- 580,000 measurement points
- RMS < 0.6 µm
- PV < 4.5 µm



- ELT segment SPN04 (16:15)
- Material – ULE
- Grinding cycle 20 hours
- Max MMR 187.5mm^3/sec

BoX® NiF Wedge Optic Lenses



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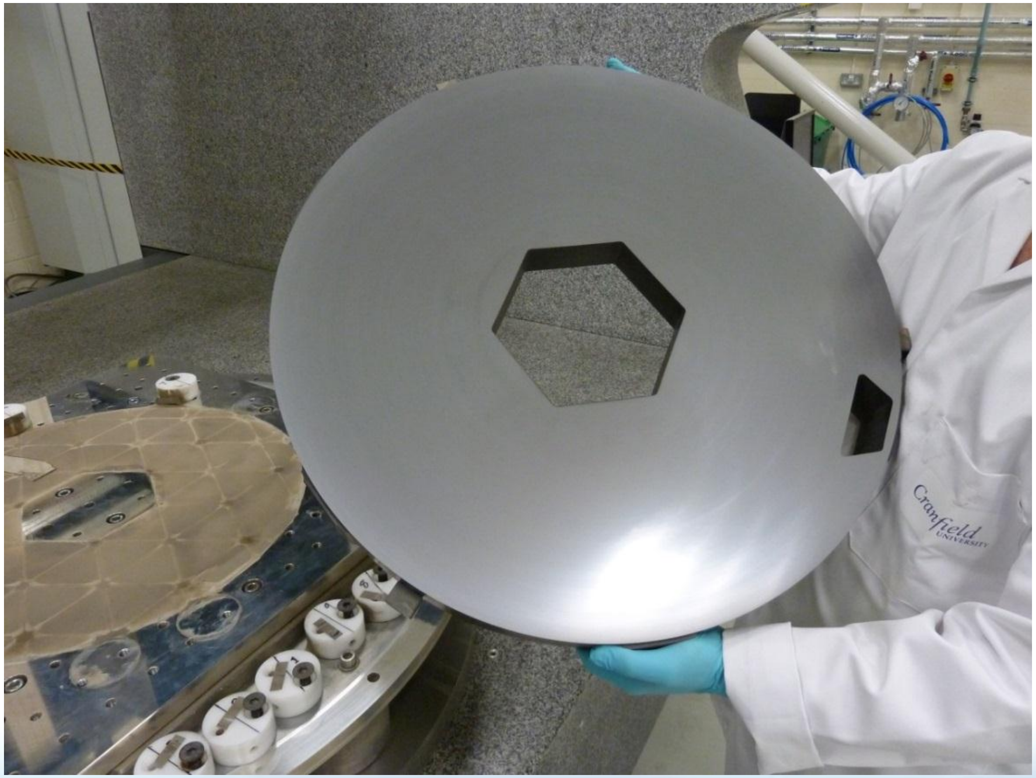
BoX® Adaptive grinding of lightweight mirror structures

LOXHAM PRECISION

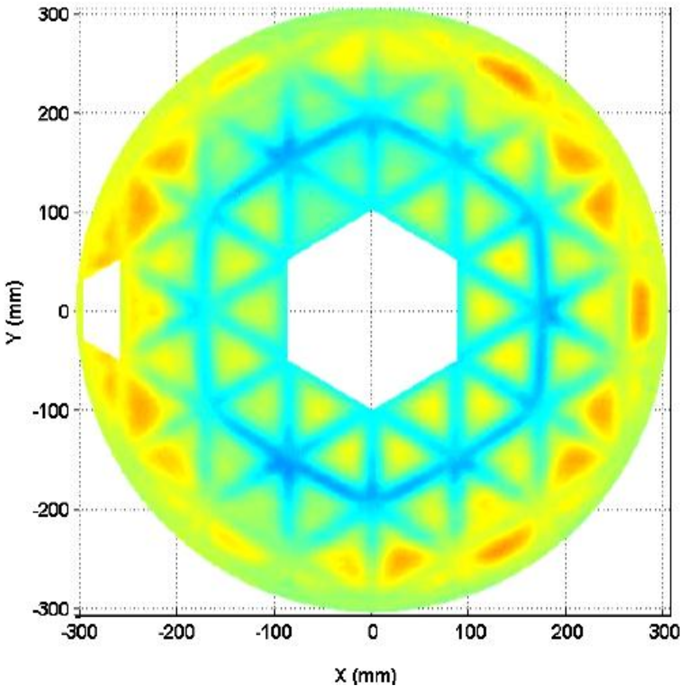


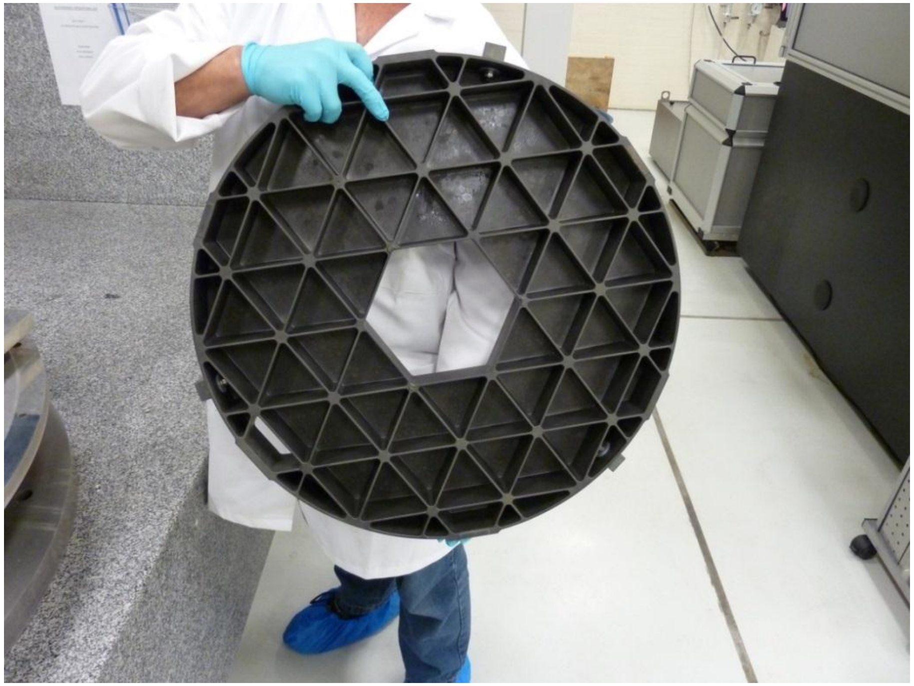
Thinned from 6mm
to 1.3 mm shell thickness

Grinding time: 16 hours
Measurement time: 4 hours

Form accuracy : 0.48um RMS
SSD : 5um
Roughness:0.15um RMS

BoX® Adaptive grinding of lightweight mirror structures





0.4um RMS, 4.6 um P-V
(before error correction)

Robotic polishing

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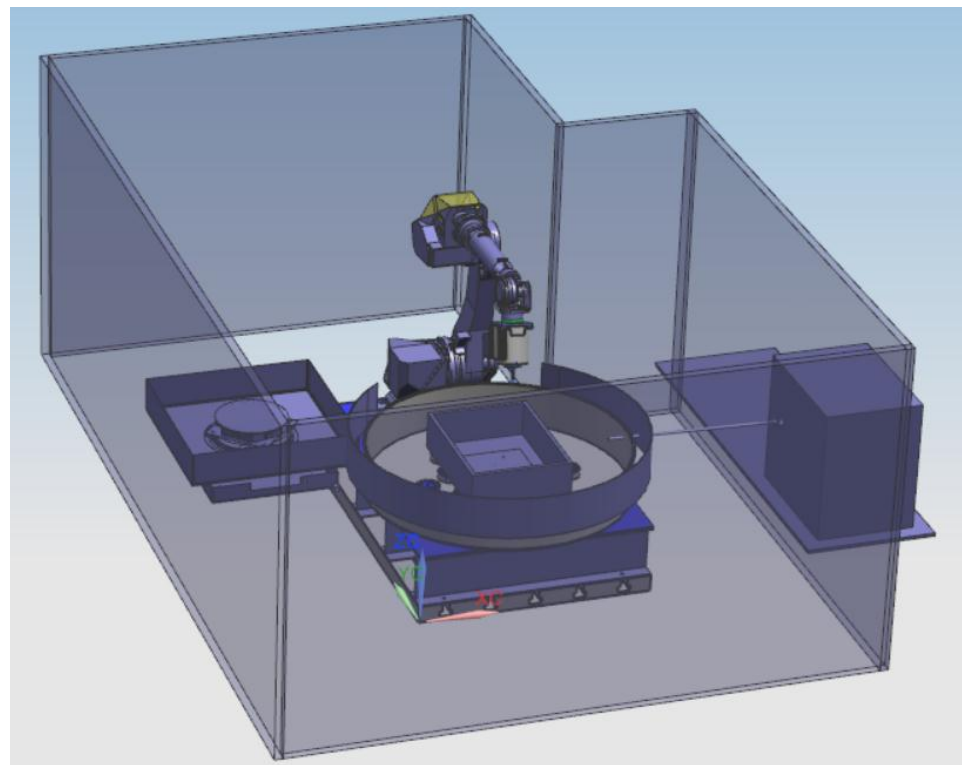
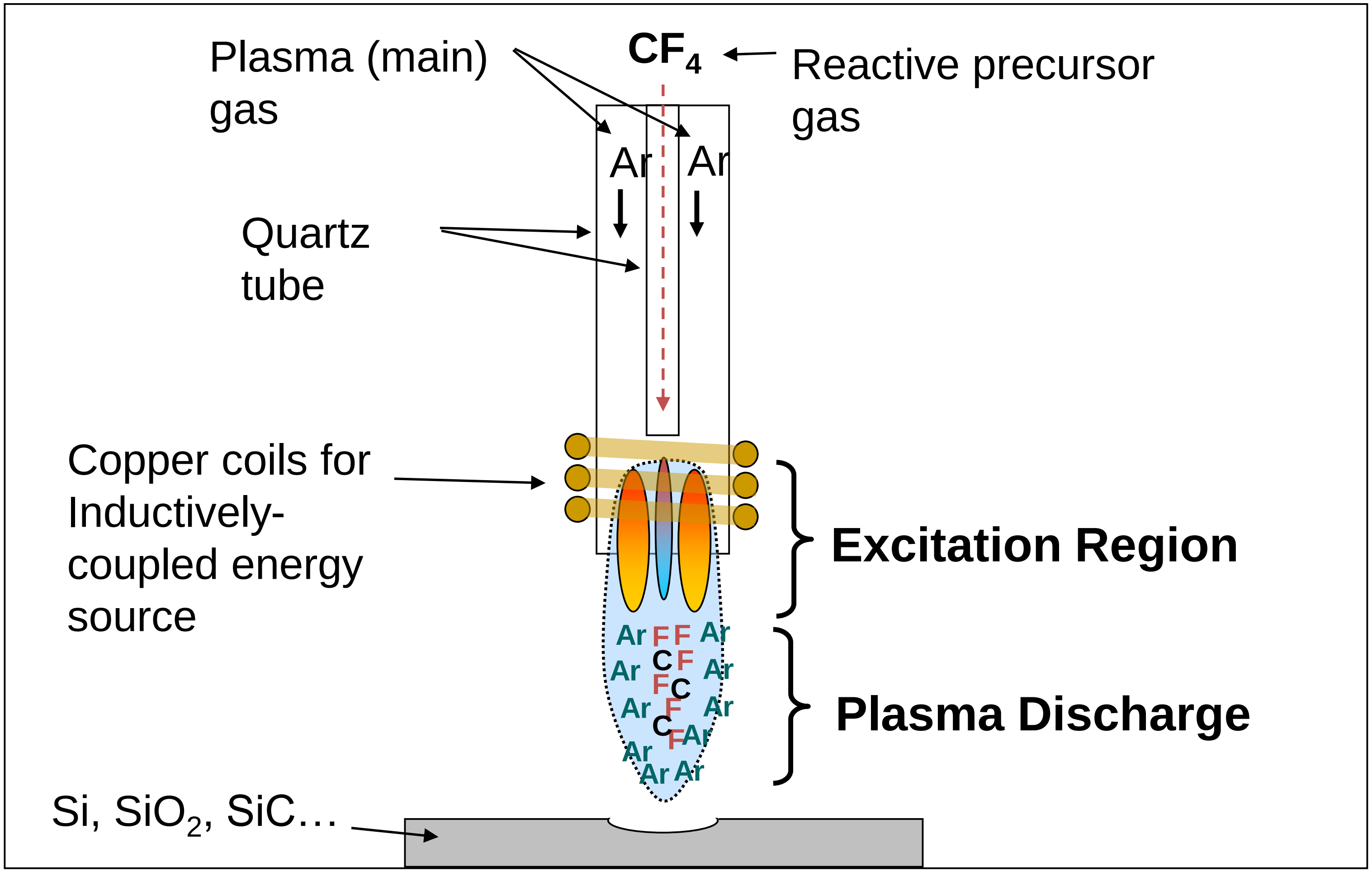


Reactive Atom Plasma (RAP) Processing: A New Tool for the Rapid Shaping and Smoothing of Optical Materials

Dr. Peter S. Fiske
Dr. Jeff Carr
Dr. Andrew Chang
Dr. Jude Kelley

RAPT Industries
Livermore, California



Courtesy ***Carr***

Reactive Atom Plasma Figuring
Helios 1200

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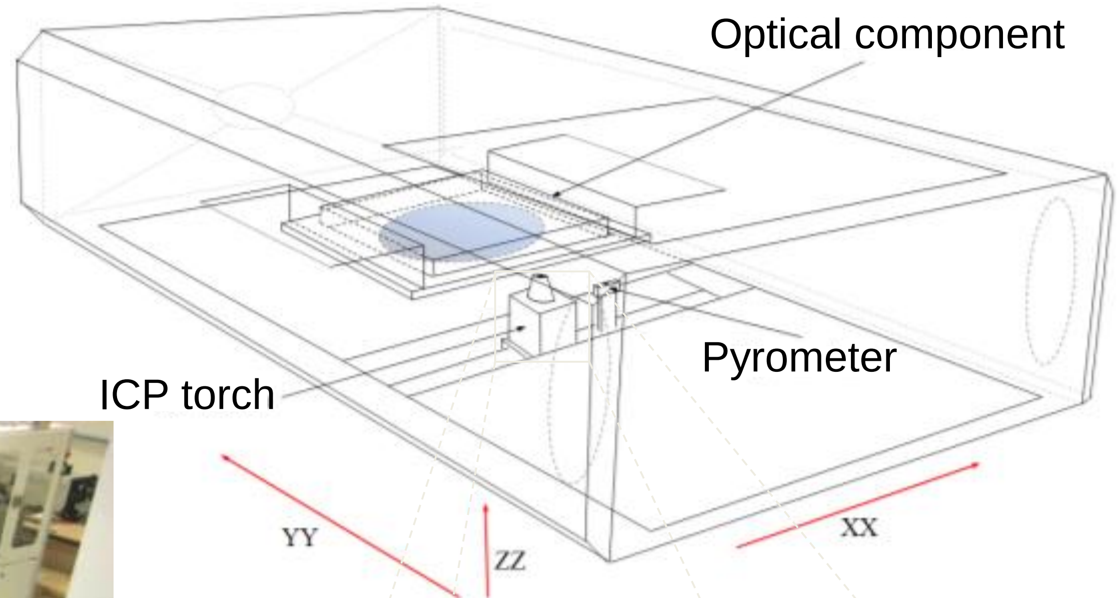
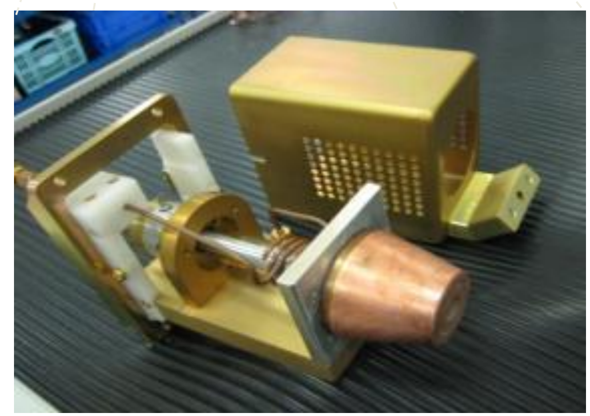


Chamber for 1.2 m optical component



Iterative figuring procedure

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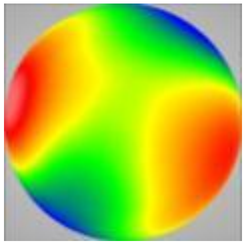
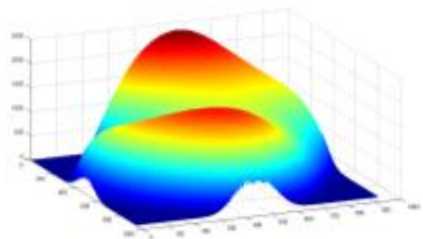


Error map



Edge extension

De-convolution
(modified)

CNC-code generation with optimized tool-path and thermal adaption

RAP process

Interferometric measurement

Final form accuracy down to λ/30 rms

RAP process capability

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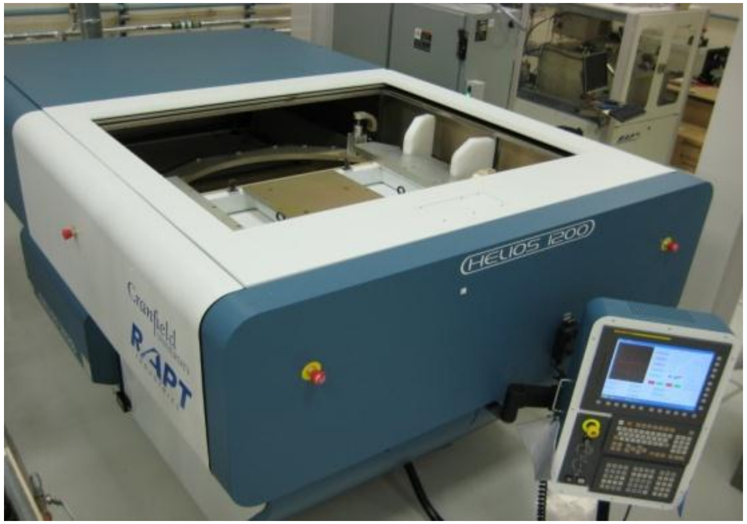
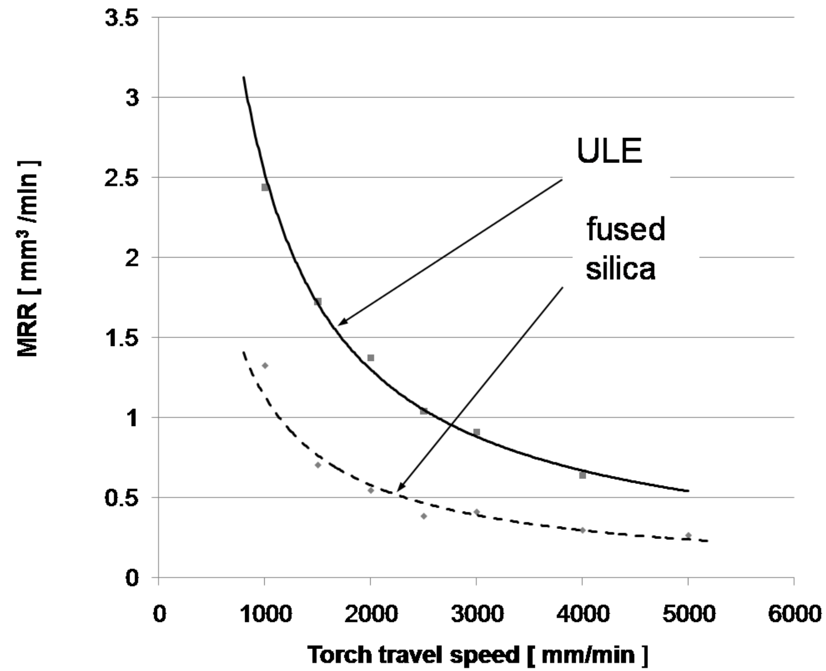


- 1.2 m capacity
- 3 axes CNC through Fanuc 30i
- Low cost operation
- Compact machine size

Processed materials:

- Fused silica
- ULE
- SiC
- Silicon
- Borosilicate

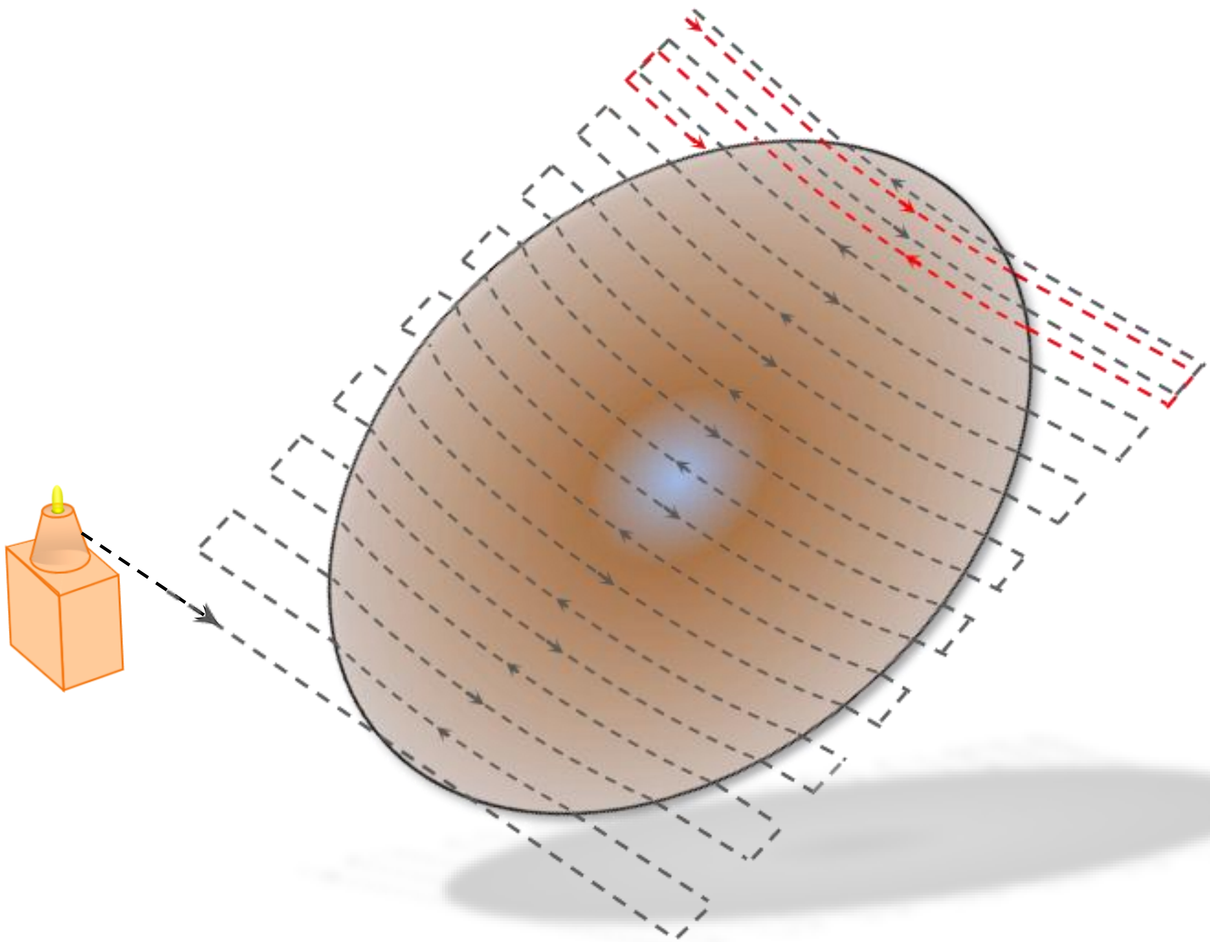


Refs

1: Jourdain et al., (2011). “Fast 3D Figuring of Large Optical Surfaces Using Reactive Atom Plasma (RAP) Processing”, 2nd EOS Conference on Manufacturing of Optical Components, Munich (D), May 2011.

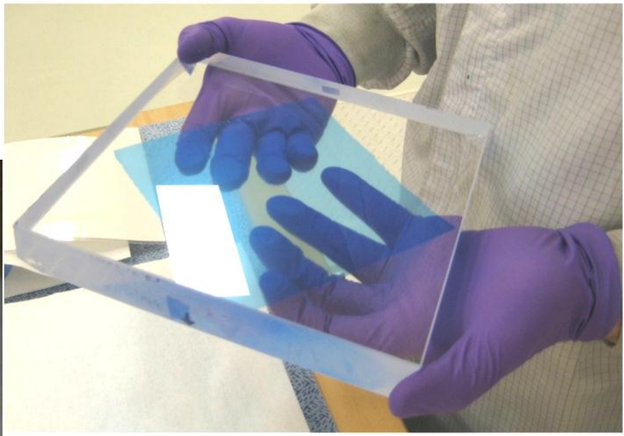
2: Castelli et al., (2010). “Initial Strategies for 3D RAP Processing of Optical Surfaces Based on a Temperature Adaptation Approach” 36th Matador Conference, Manchester, section:18, pp 569-572 , July 2010

Tool-path algorithm



RAP figuring process

0.5 um depth of cut



Fused Silica

RAP figuring process
0.5 um depth of cut

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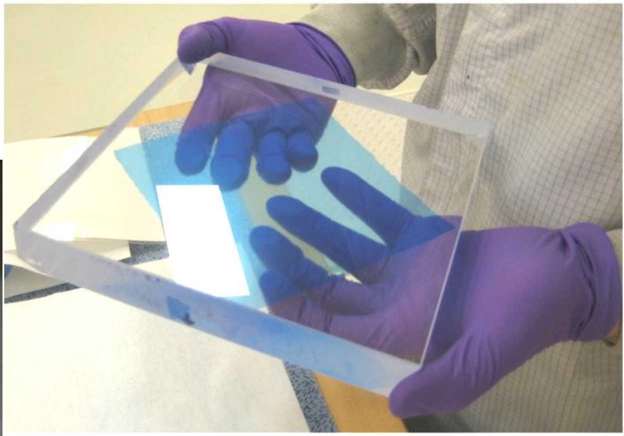

Fused Silica

RAP figuring capability

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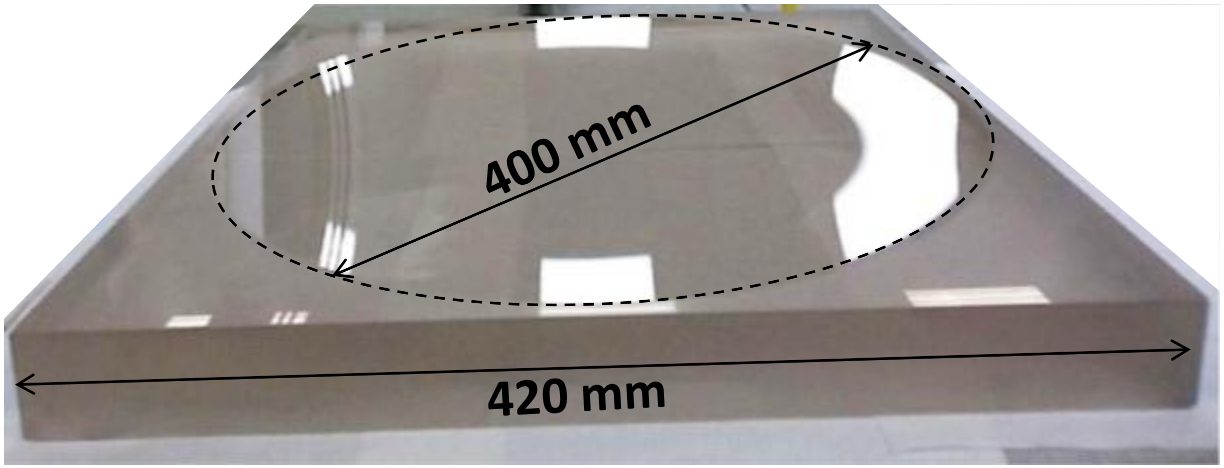

420mm x 420mm x 40mm ULE substrate

- Concave spherical geometry – 3 m ROC.
- 400 mm clear aperture.
- Ground on BoX to ~2.2 μm PV form accuracy.
- Polished to 2.4 μm PV form accuracy.

Large scale figuring results: optic #001/1

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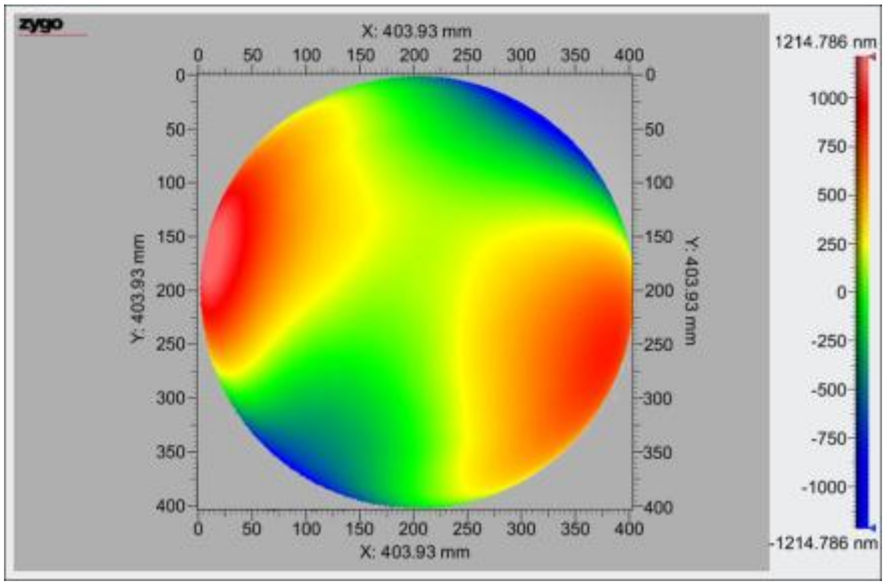
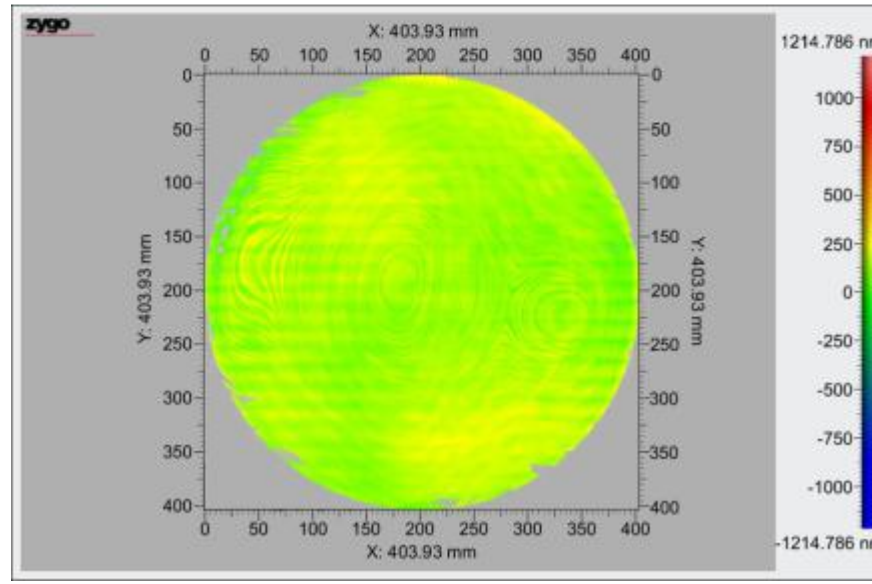
Initial figure error



PV: 2.4 µm PVr: 2.3 µm RMS: 373 nm

Residual figure error



PV: 450 nm PVr: 282 µm RMS: 45 nm

- Mean processing time: 51 min - three iterations → **total processing time 2.5 hours**
- Residual figure error: 43 nm rms
- 89% overall convergence

Large scale figuring results: optic #001/2

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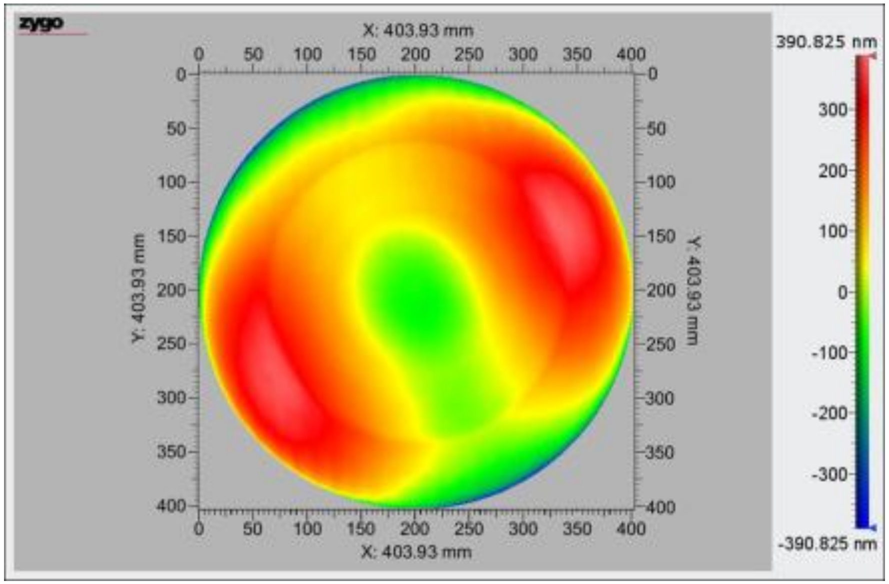
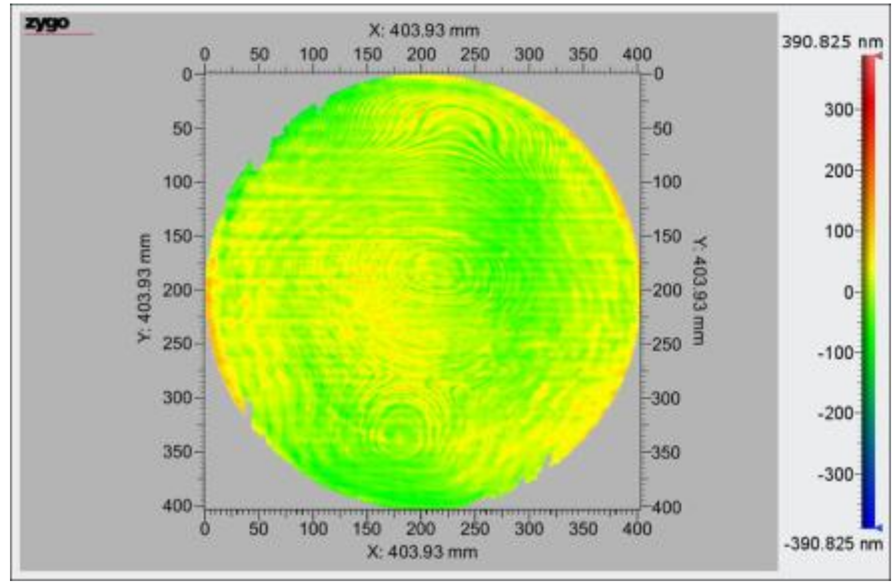
Initial figure error



PV: 780 nm PVr: 723 nm RMS: 137 nm

Residual figure error

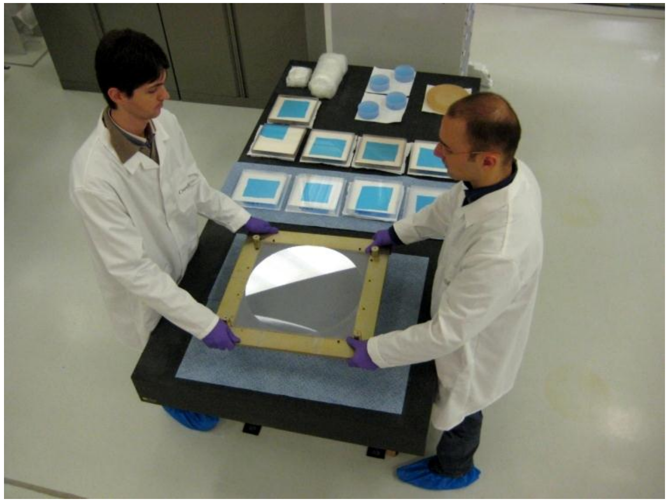


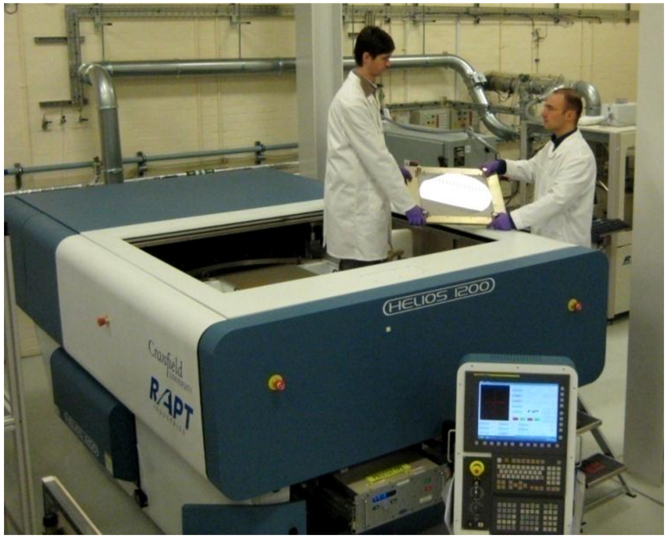
PV: 350 nm PVr: 230 nm RMS: 31nm

- Mean processing time: 49 min – two iterations → **total processing time 1.5 hours**
- Residual figure error: 31 nm rms
- 77% overall convergence

RAP processing rate

- Removal depth of 1µm
- 420 mm x 420mm surface
- 2 iteration process
- Average MMR 1.5 mm^3/min
- Figuring time ~ 3 hours
- x10 times faster than IBF





Reactive plasma summary

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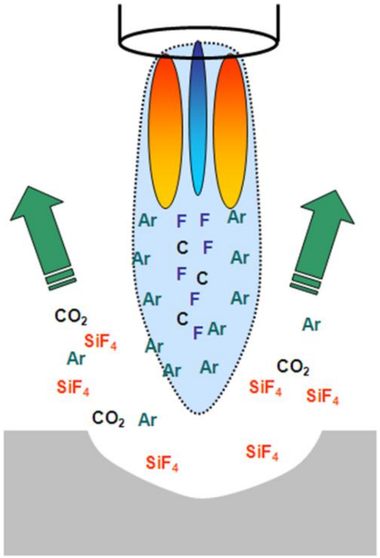
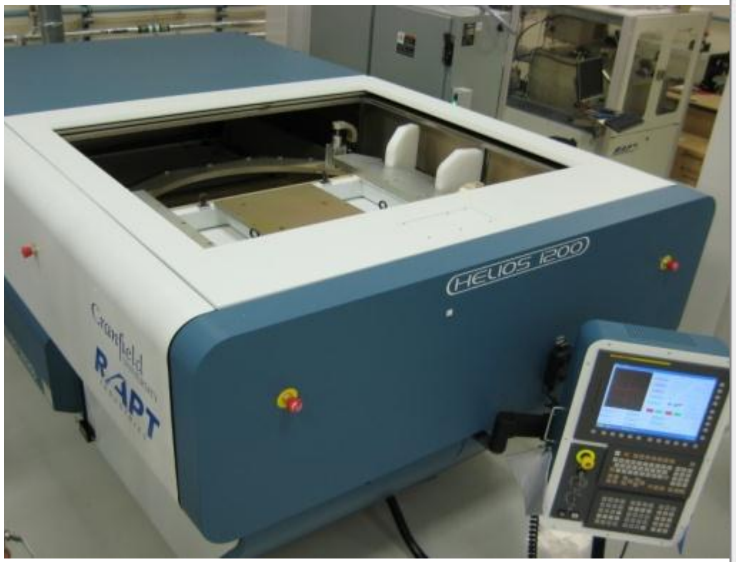
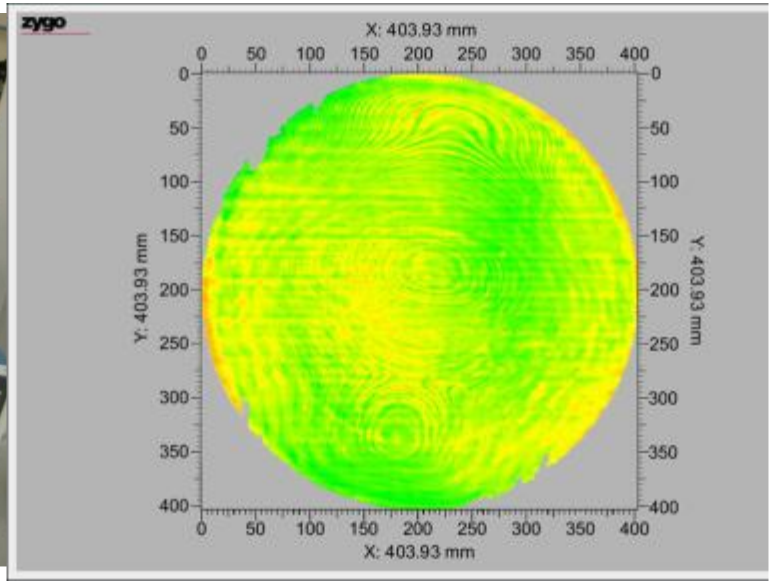






Processed materials:

- Fused silica
- ULE
- SiC
- Silicon
- Borosilicate

RAPT Machine

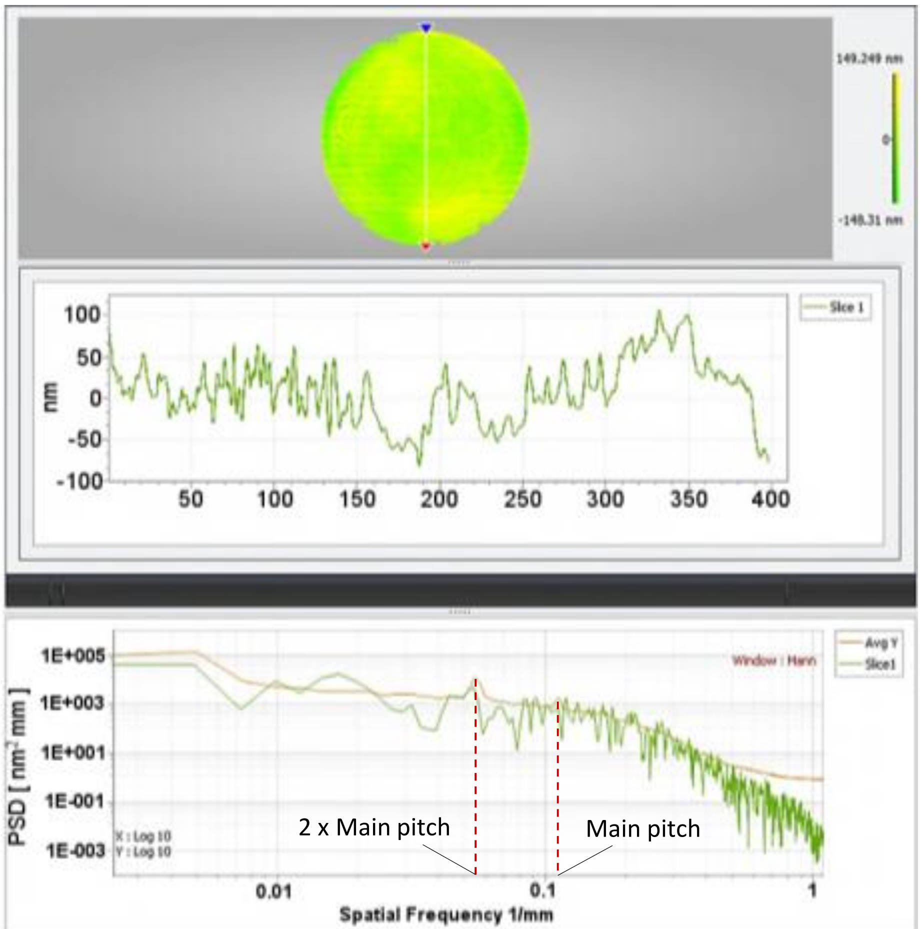
- 1.2 m capacity
- 3 axes CNC through Fanuc 30i
- Low cost operation
- Compact machine size

Processing capability

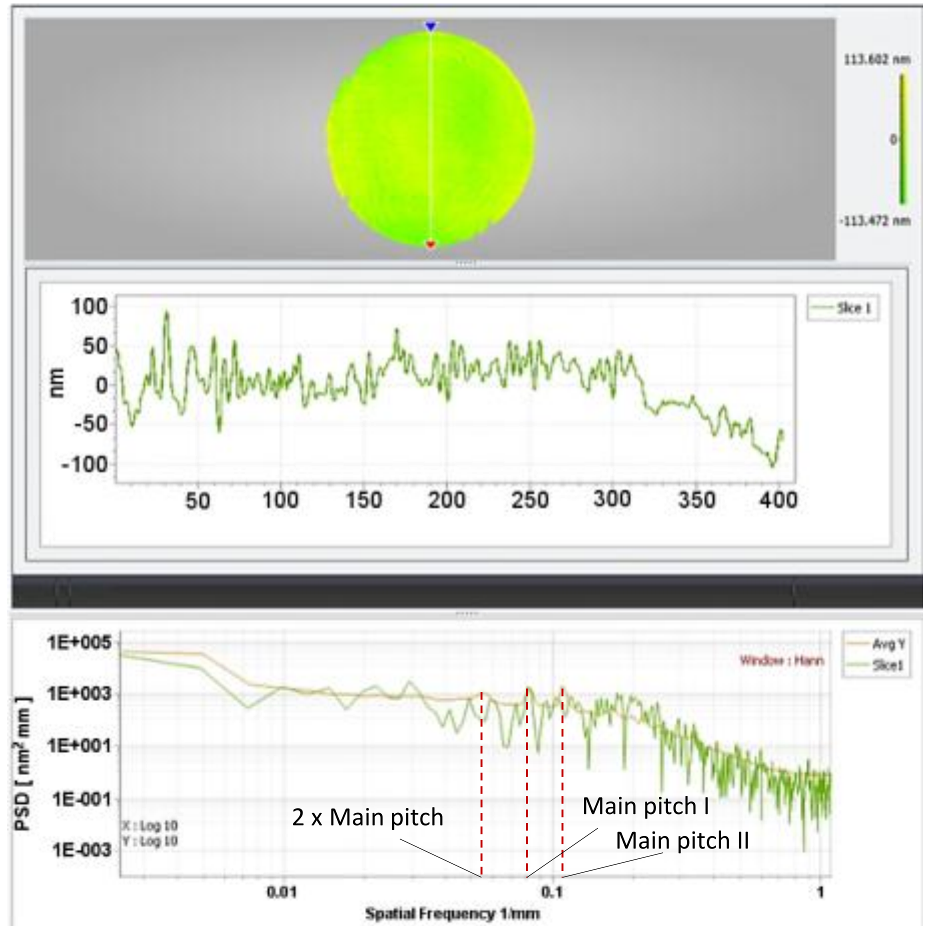
- < 30nm RMS
- 10 hours per metre^2
- 400mm mirror in 2 hours

PSD Analysis

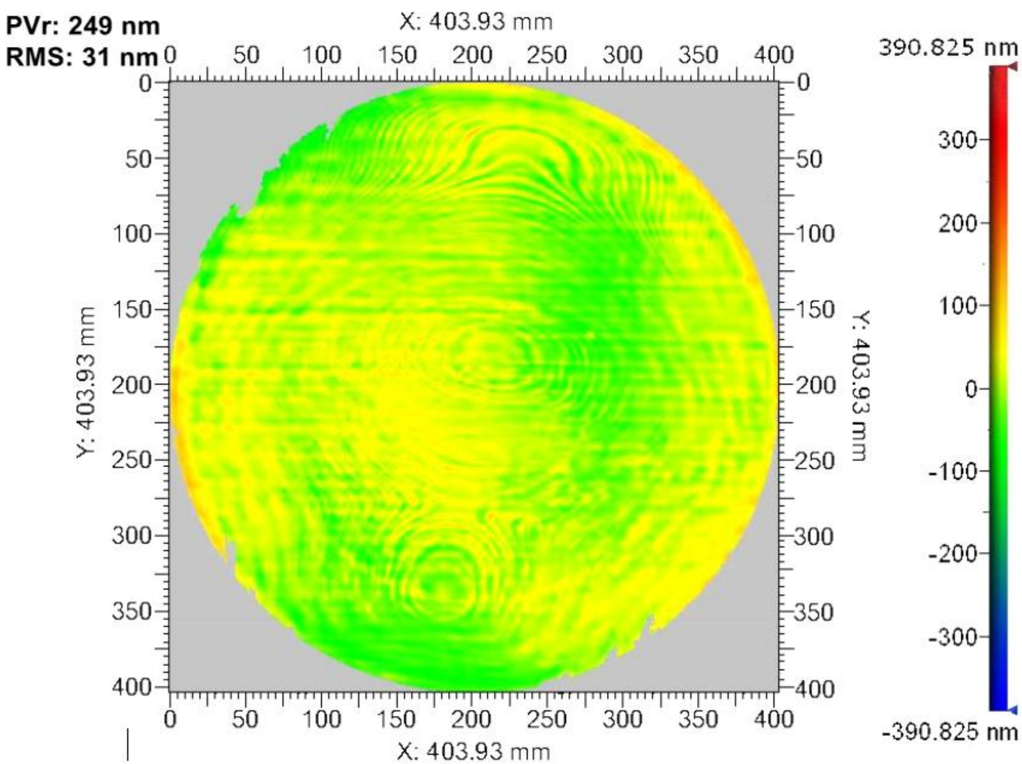
AFTER FIRST FIGURE CORRECTION



AFTER SECOND FIGURE CORRECTION



Present research focus



Reduce the MSF structures

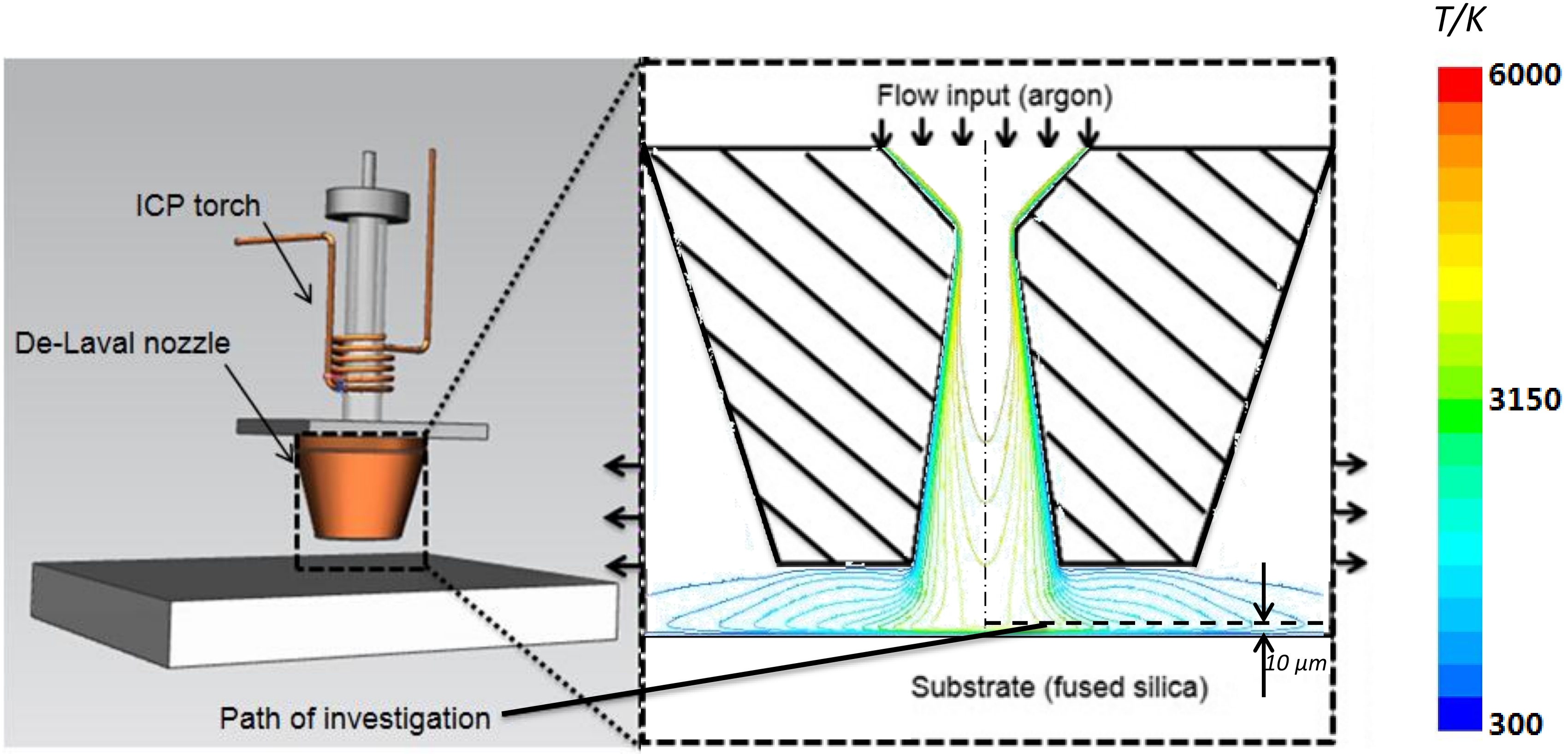
*(Results carried out by **Castelli** [12])*

Ref:

[12] Castelli M. Advances in Optical Surface Figuring by Reactive Atom Plasma(PhD thesis), Cranfield University, 2013.

Thermo-chemical CFD simulation

Temperature distribution



Overview of the CFD investigation.
3D drawing of the plasma figuring torch (left);
2D CFD simulation illustration of flow temperature in the nozzle (right).

Summary

- Freeform grinding $1ft^2$ per hour is doable
- Error correction enables <1 um RMS form (Even for thin LW substrates)
- Plasma processing is promising to alleviate bottle-neck surface figuring process stage
- Plasma figuring at $1ft^2$ per hour to 30nm RMS is already doable
- Plasma figuring at $1ft^2$ per hour to 10nm RMS is our next milestone

Acknowledgements

UK's Engineering and Physical Sciences Research Council

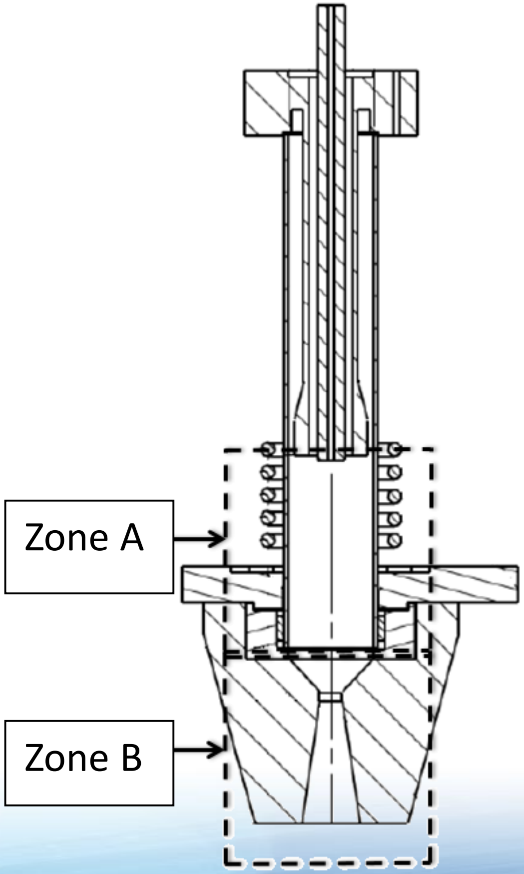
UK's Astronomy Technology Centre

McKeown Precision Engineering Foundation

Collaborators: Qioptiq Ltd, G&H plc, Airbus Space and Defence, SSTL, ESO, ESA, Fanuc, RAPT Industries, University of Cambridge, Cranfield Precision, Optic Glyndwr, UCL, Zeeko, Aerotech

CFD simulation

Model set-up



Schematic diagram of calculation areas (Picture from Jourdain)

Domains: (Zone B)

Based on the ICP torch and De-Laval nozzle made by RAPT

Assumptions:

1. A one-fluid model;
2. In local thermal equilibrium (LTE);
3. Negligible EM field calculations and chemical equilibrium;
4. Thermally expansible and mechanically incompressible;
5. Fluid: axisymmetric, uniform, steady and turbulent plasma with negligible viscous dissipation.

Boundary conditions:

Stage	Parameter	Input value
Inlet	Velocity	25.76 m/s (from calculation)
	Temperature	6000K (based on [8])
	Pressure	101280pa (from calculation)
Wall	Temperature	350K (from estimation)
Outlet	Pressure	101325pa (room pressure)
	Temperature	300K (room temperature)

μ4 diamond machining system

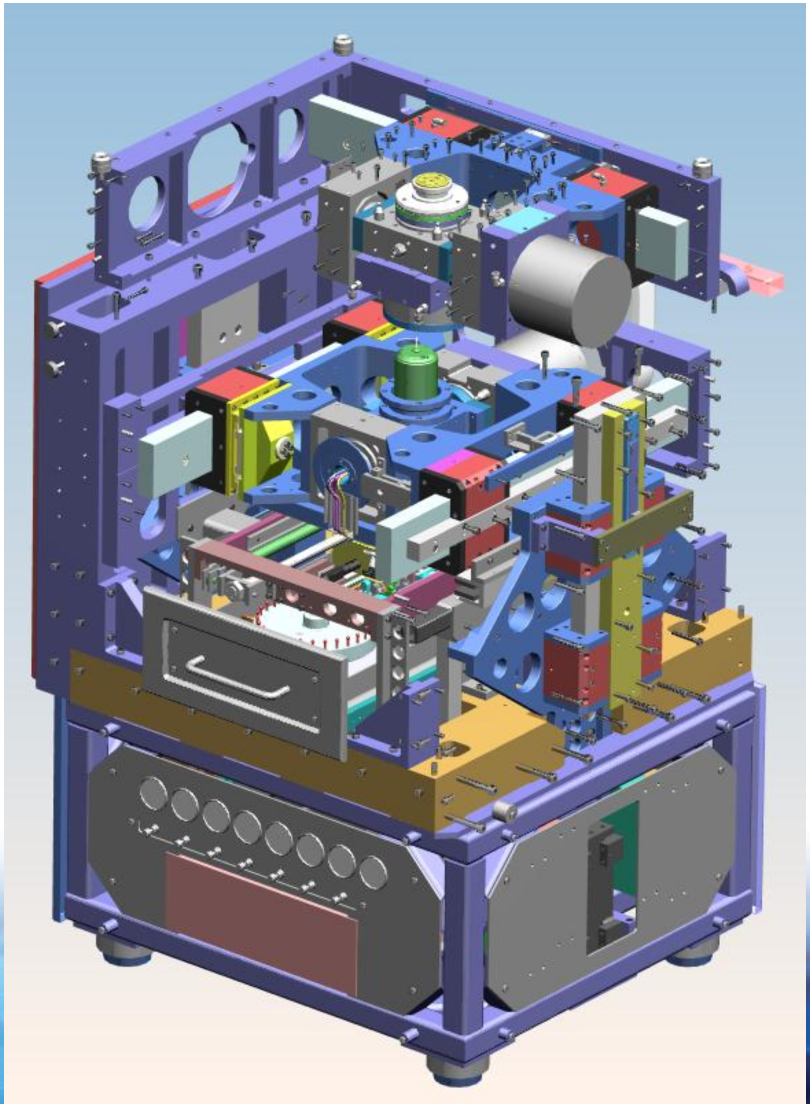
LOXHAM PRECISION

Fully automated & integrated:

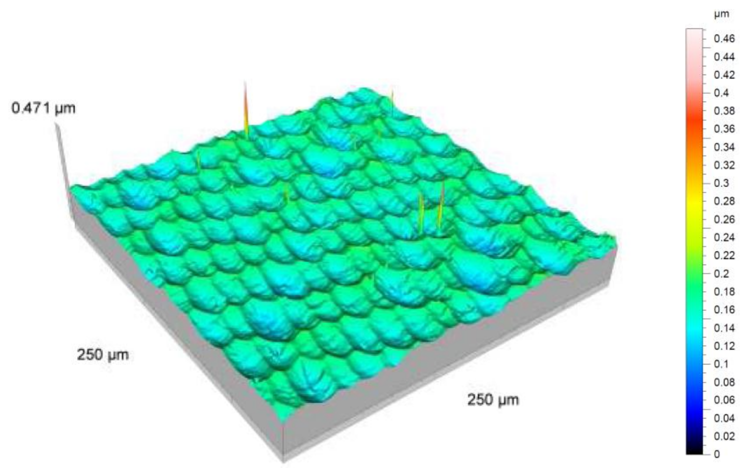
- 4 axis diamond turning
- 5 axis diamond milling
- Tool loading
- Workpiece loading

Machine size and supply

- 0.6m x 0.6m x 1.0m, portable
- Fully integrated control electronics
- single-phase supply "plug-and-play"
- chilled water and compressed air

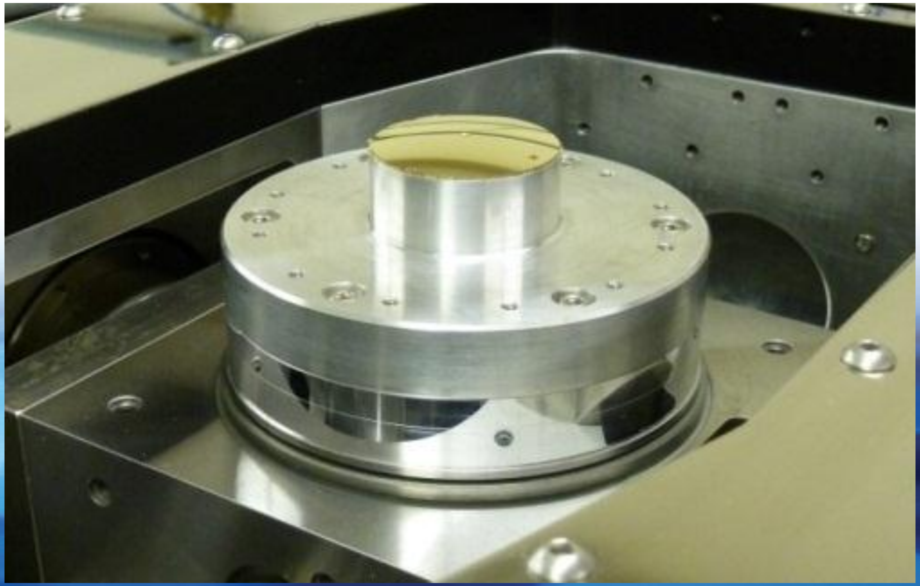


µ4 diamond machining system

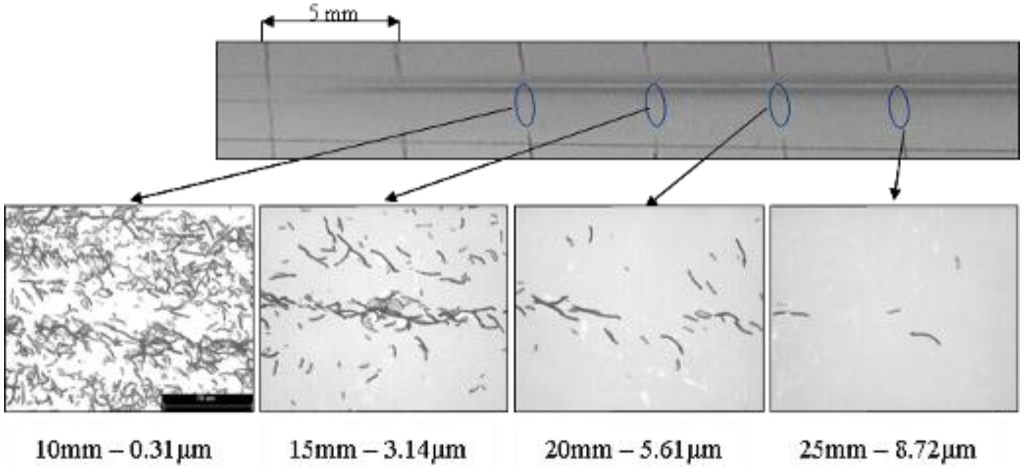


Tests in brass

Roughness: 3nm Ra, 6nm Sa



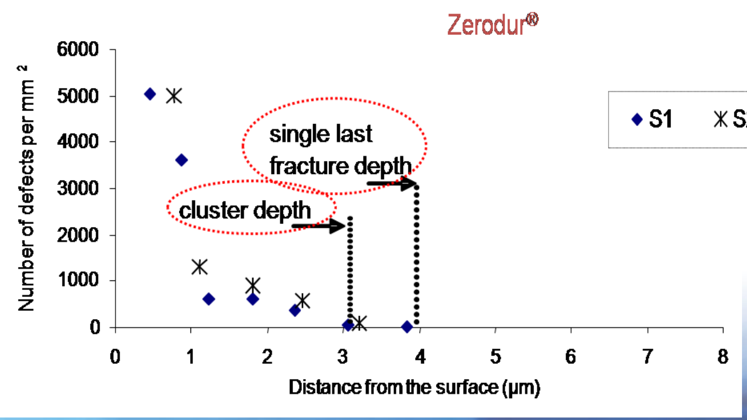
BoX® Induced Sub-surface Damage



Evaluation technique:

- Polished tapered grooves
- Etched HF, target removal 1µm
- Groove depth - contact profilometery
- Crack observation using optical microscope

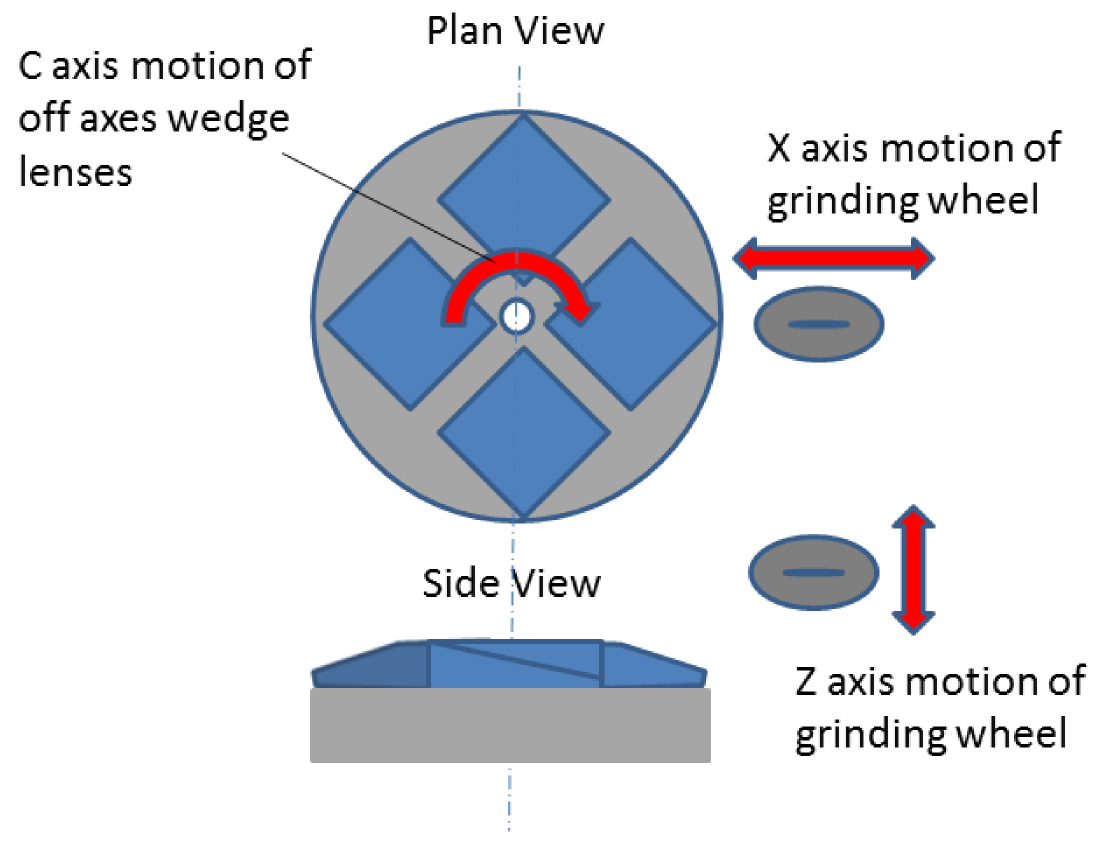
Grinding Conditions	*Cluster depth (µm)*		*Last fracture depth(µm)*	
	Zerodur®	*ULE®*	*Zerodur®*	*ULE®*
Rough cut (D76)	*5*	*8.5*	*8*	*18.5*
Semi-finish cut (D46)	*4*	*4.5*	*7.5*	*9*
Finish cut (D25)	*3*	*4*	*4*	*8*



Ref: Tonnellier, T. et al. 2008, Sub-surface damage issues for effective fabrication of large optics, Proc of SPIE Vol. 7018, pg 701836-1 to 701836-10

BoX® NiF Wedge Optic Lenses

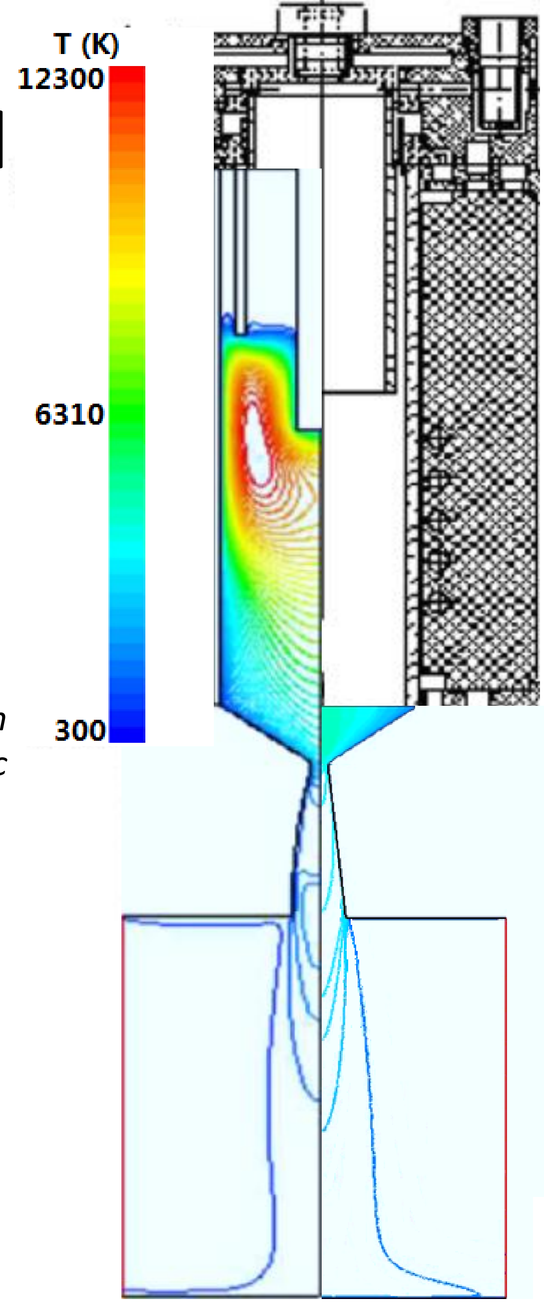
LOXHAM PRECISION



4 off lenses ground
Grinding time: 8 hours
Form accuracy : 1um RMS
SSD : 10 um
Last fracture depth

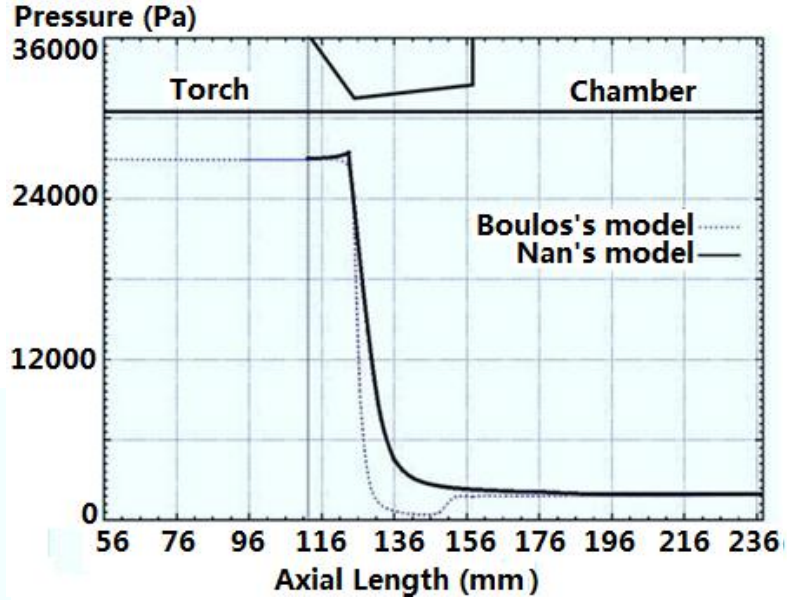
Background

ICP modelling



Temperature distribution in ICP torch with supersonic nozzle [15]

Temperature distribution from a repeated trial of the validation



Axial profile of the pressure along the centreline in [15] and in the repeated trial

μ4 diamond machining system

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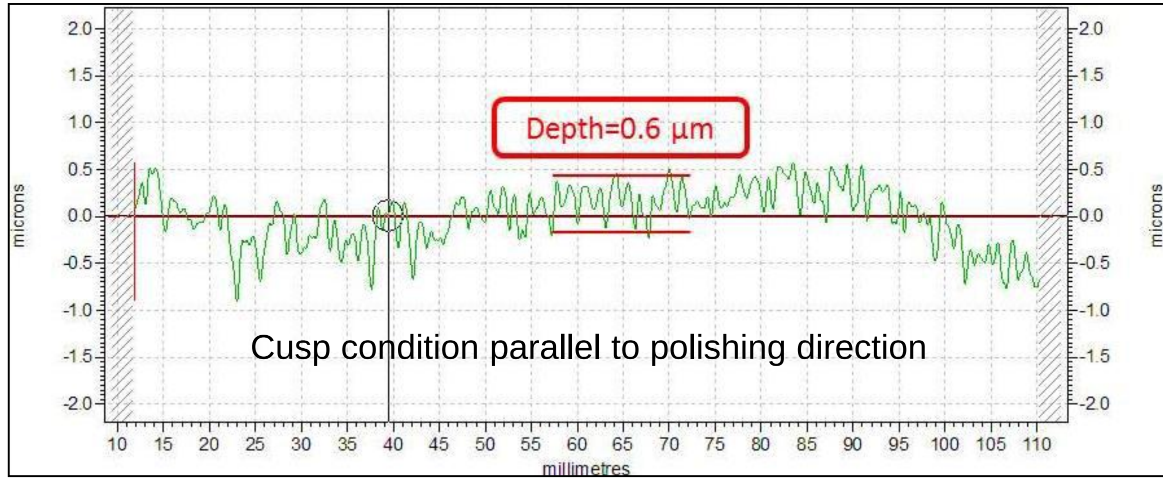
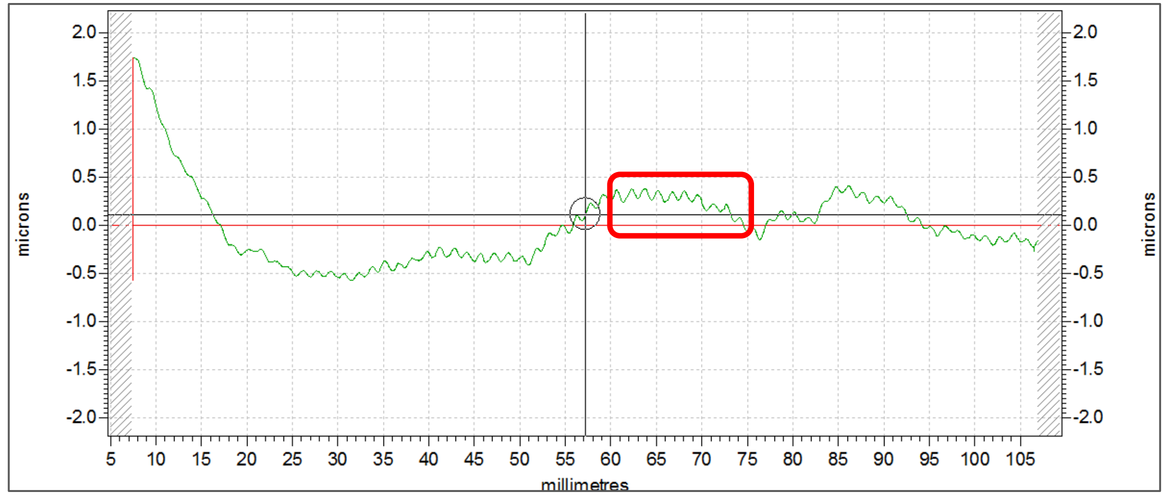
- chilled water

before polishing



after 4 polishing runs



after 9 polishing runs