EPSRC Centre for innovative manufacturing in ultra precision

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Cranfield UNIVERSITY

Some in-process measurement challenges for ultra precision production

Professor Paul Shore, FREng

.ac.uk

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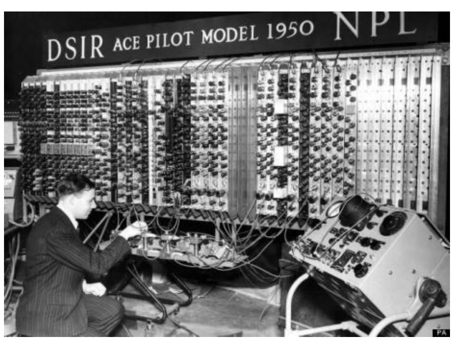
Some things have got bigger!

Some things have got faster!



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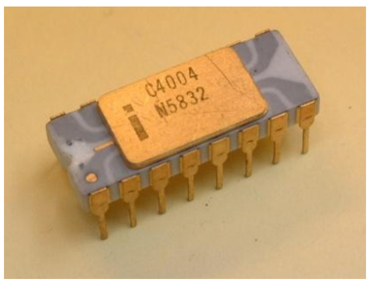
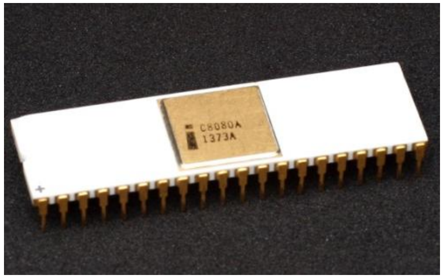
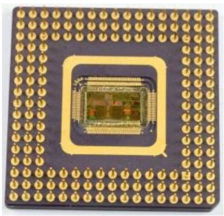
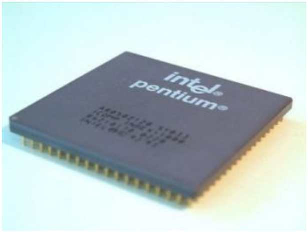
Some things have got "smarter"!

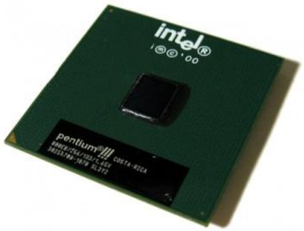
One critical thing has got smaller!

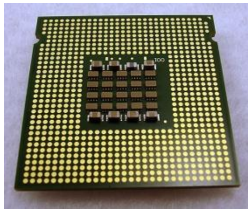





0.01mm 0.006mm 0.003mm 0.001mm

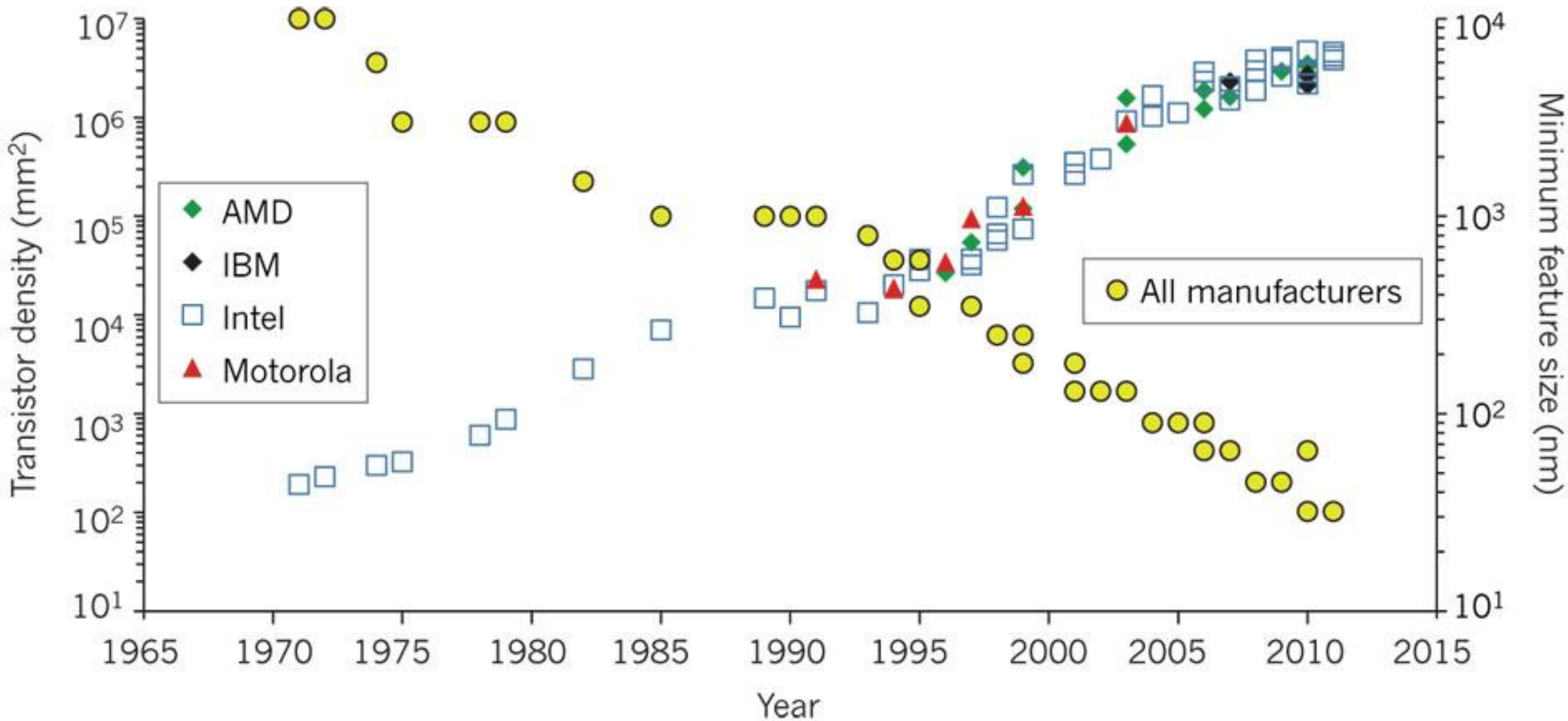





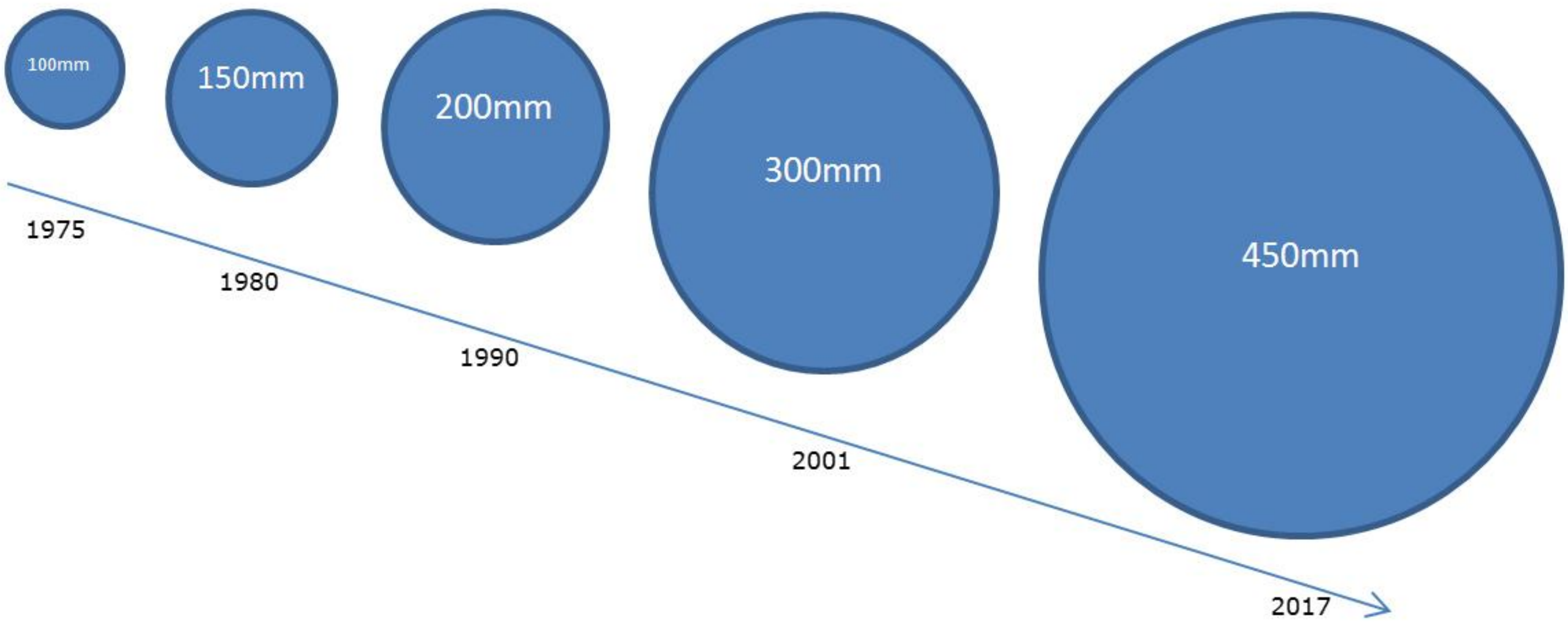


0.0001mm 0.00006mm 0.00003mm 0.00002mm

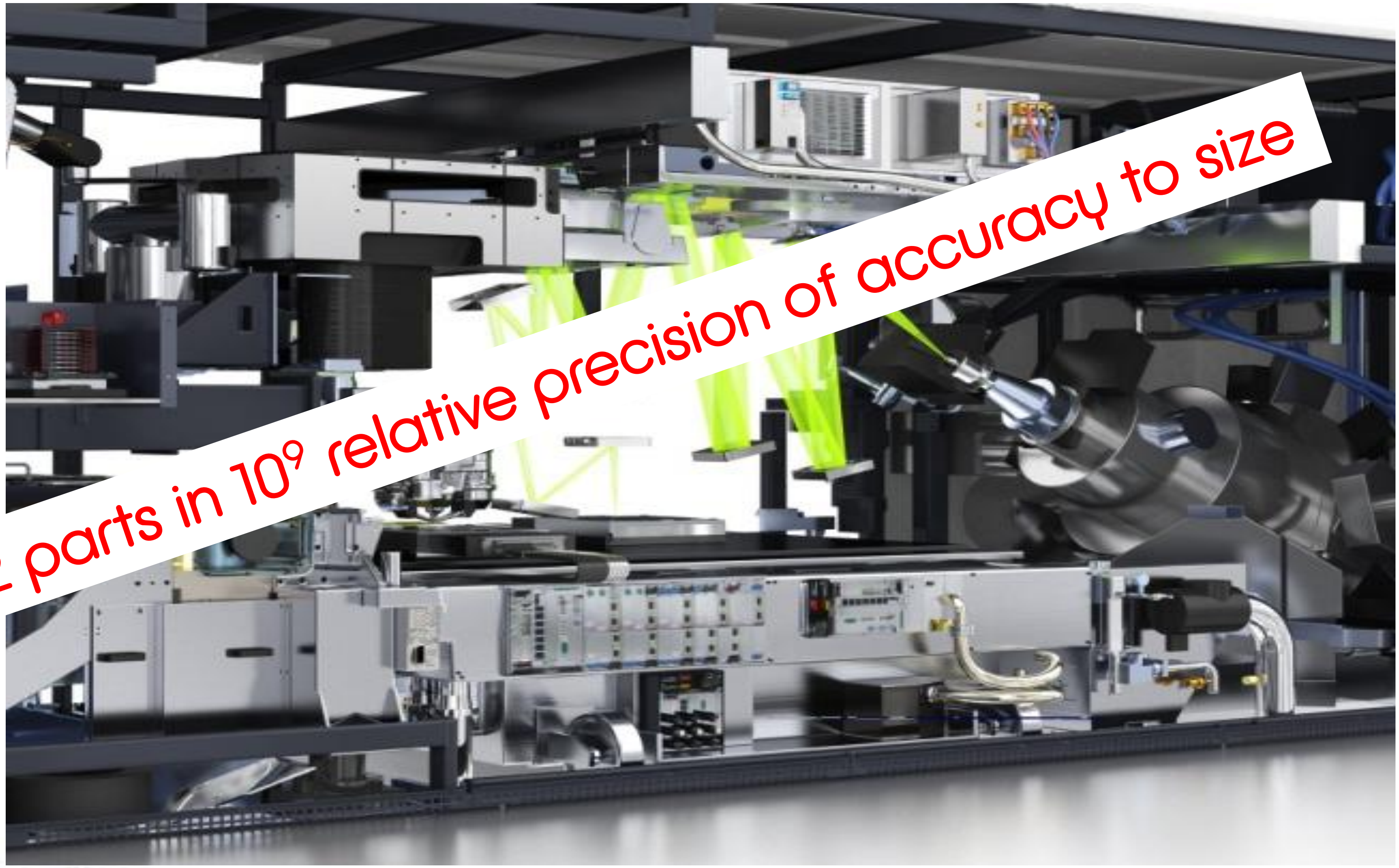
Minimum feature size/areal density
Development of transistors



Silicon wafers getting bigger



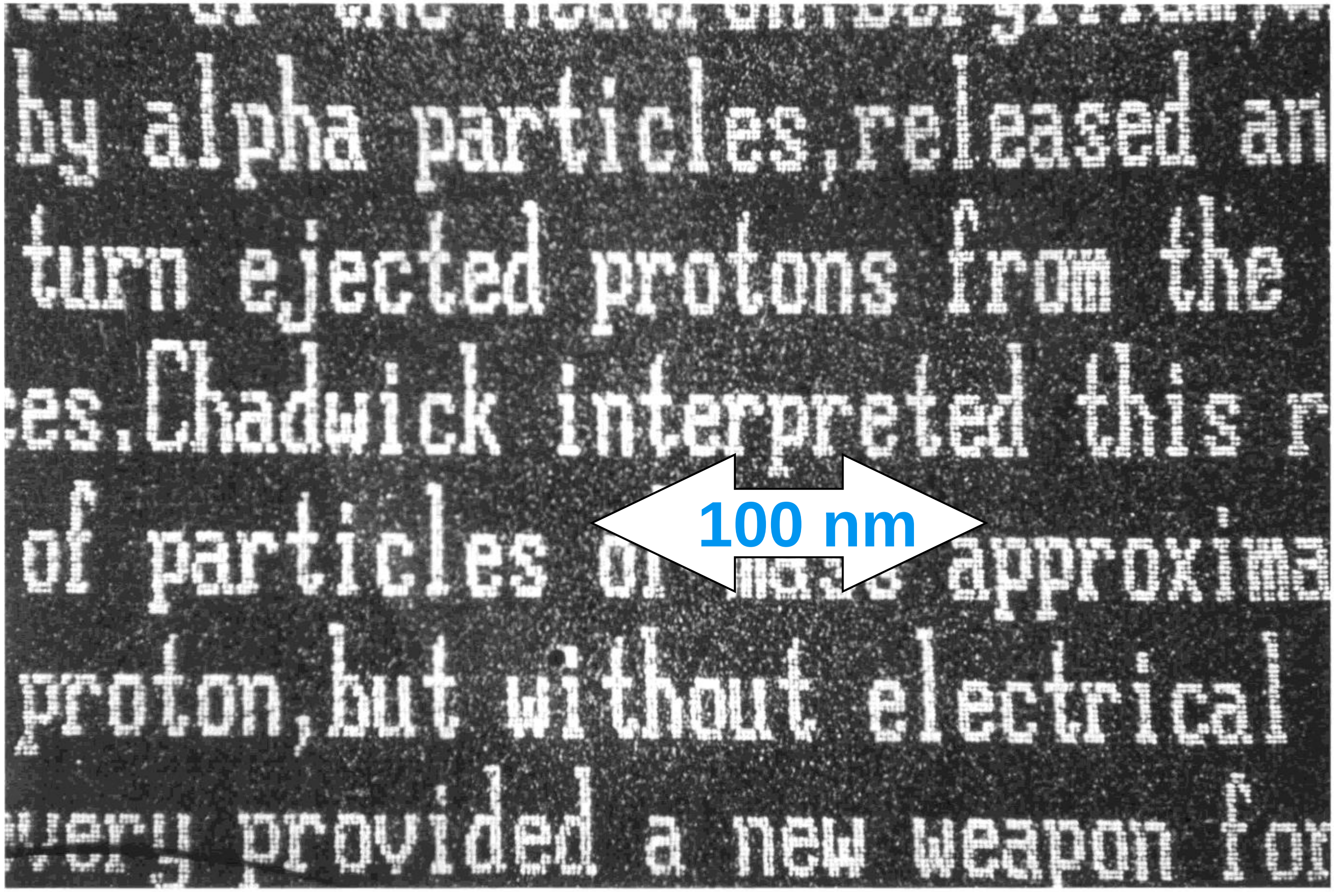
Adherence to Moore's law



ASML **2010:** NXE EUV systems, Resolution: 32 < 20 nm, overlay: 2 nm

Electron beam writing

Encyclopaedia Britannica on the head of a pin



Each letter is made of holes approximately 4nm diameter

C. Humpheys, 1992, University of Cambridge

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Presentation structure

1. Some observations
2. Enabling our future?
3. Drivers of accuracy improvement
4. Power of metrology innovations
5. In process measurement
   - Previous examples
   - New problem
6. Summary

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Energy = enabling our future

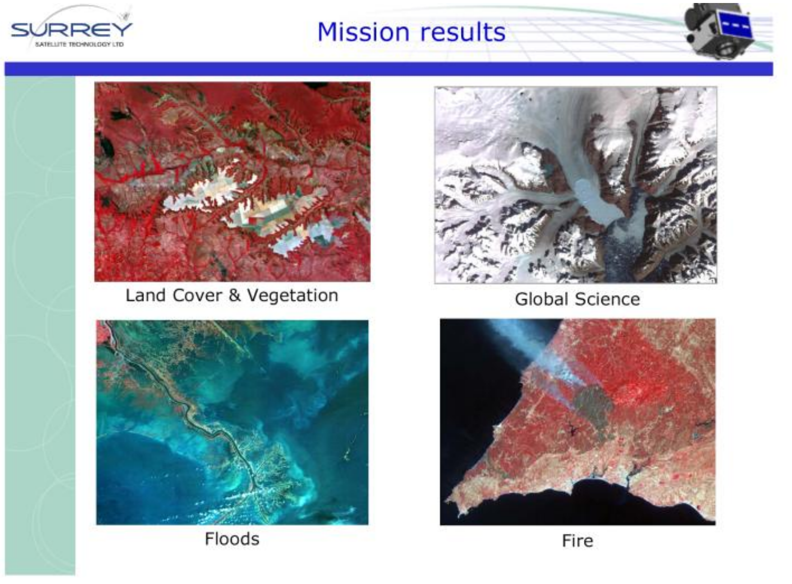
- Wind turbine market will increase and mature
- Solar energy generation will increase and mature

(government drive/environmental pressure)

- People in rapidly growing countries need more energy, and soon

Environment = enabling our future

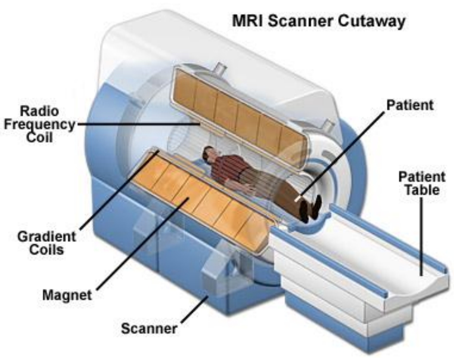
- Flooding seems to be a growing problem
- Drought continues to plague many despite huge technical advancements
- Fires rage in locations near wealthy human dwellings
- Consumption of earths natural resources is not slowing



- Lots of bright / credible scientists say the earth is warming up

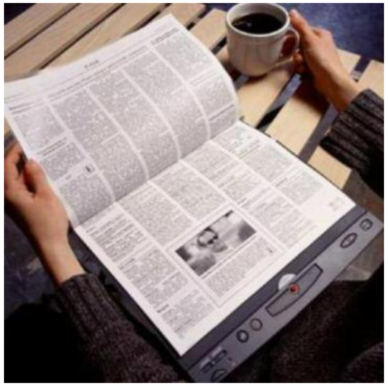
Medical /aging population = enabling our future

- People live longer
- People want to be active longer & will spend money on doing so
- People are more conscious of their appearance
- Younger people are familiar (trust) computer based technologies
- Lots of bright / credible scientists say the protective layers of the earth are waning



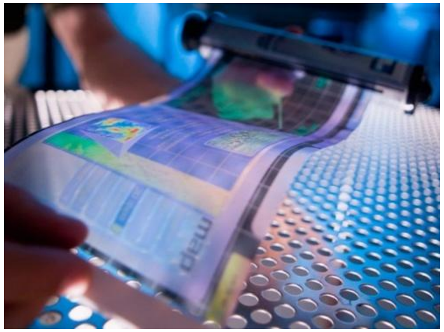
Consumer devices = enabling our future

- Display based products will increase & they will become 2.5D / 3D capable
- Plastic WiFi enabled "newspapers" will emerge



- Hand held communications devices present major opportunities

Computing speeds will need to continue to increase



Presentation structure

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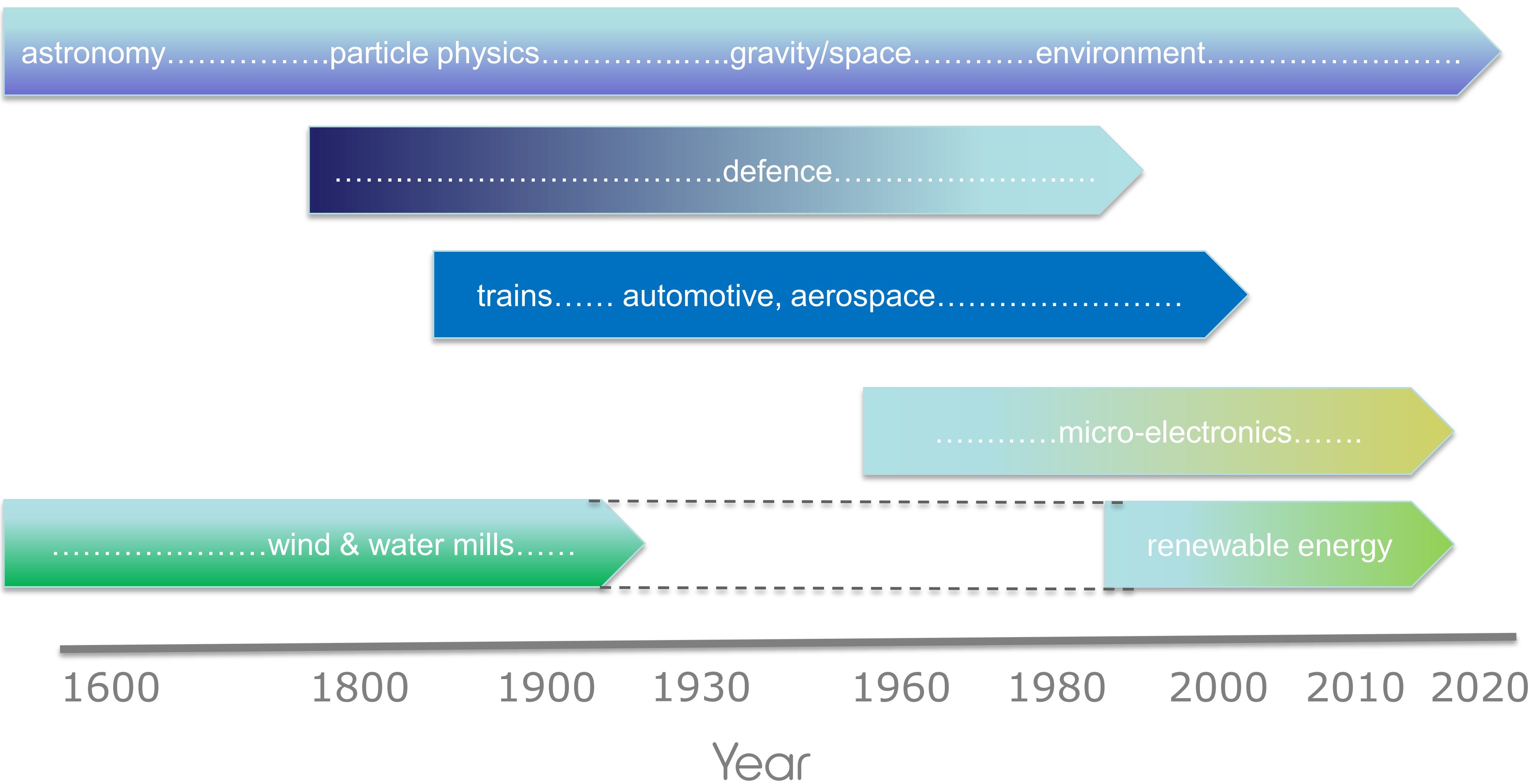
Drivers of manufacturing accuracy capability



Ref, Shore, Morantz, Phil. Trans. Royal Society 2011

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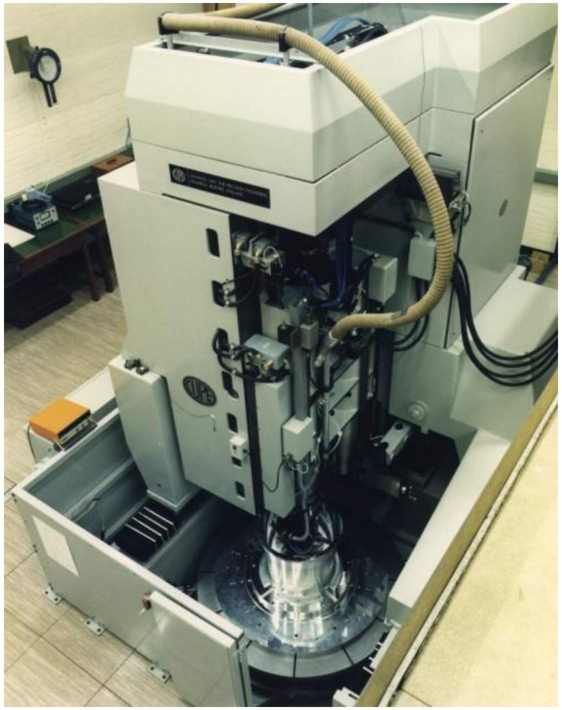
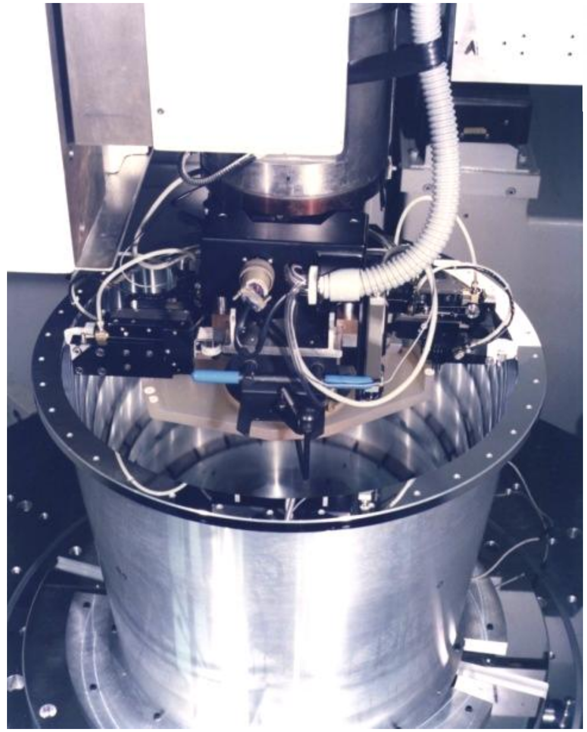
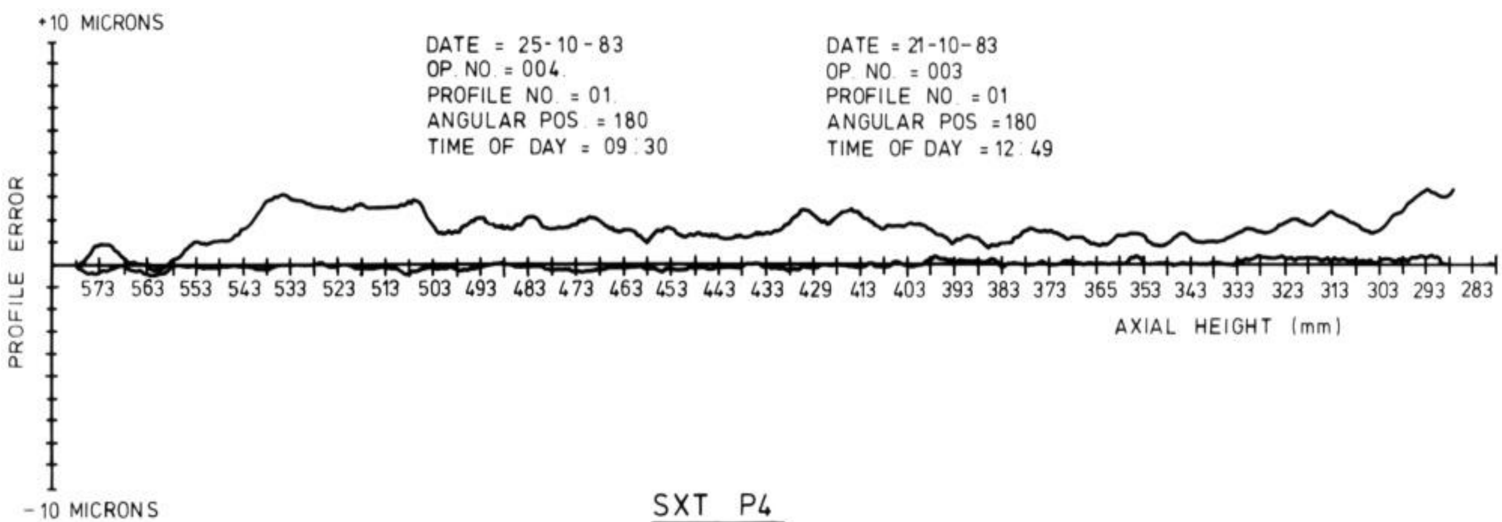


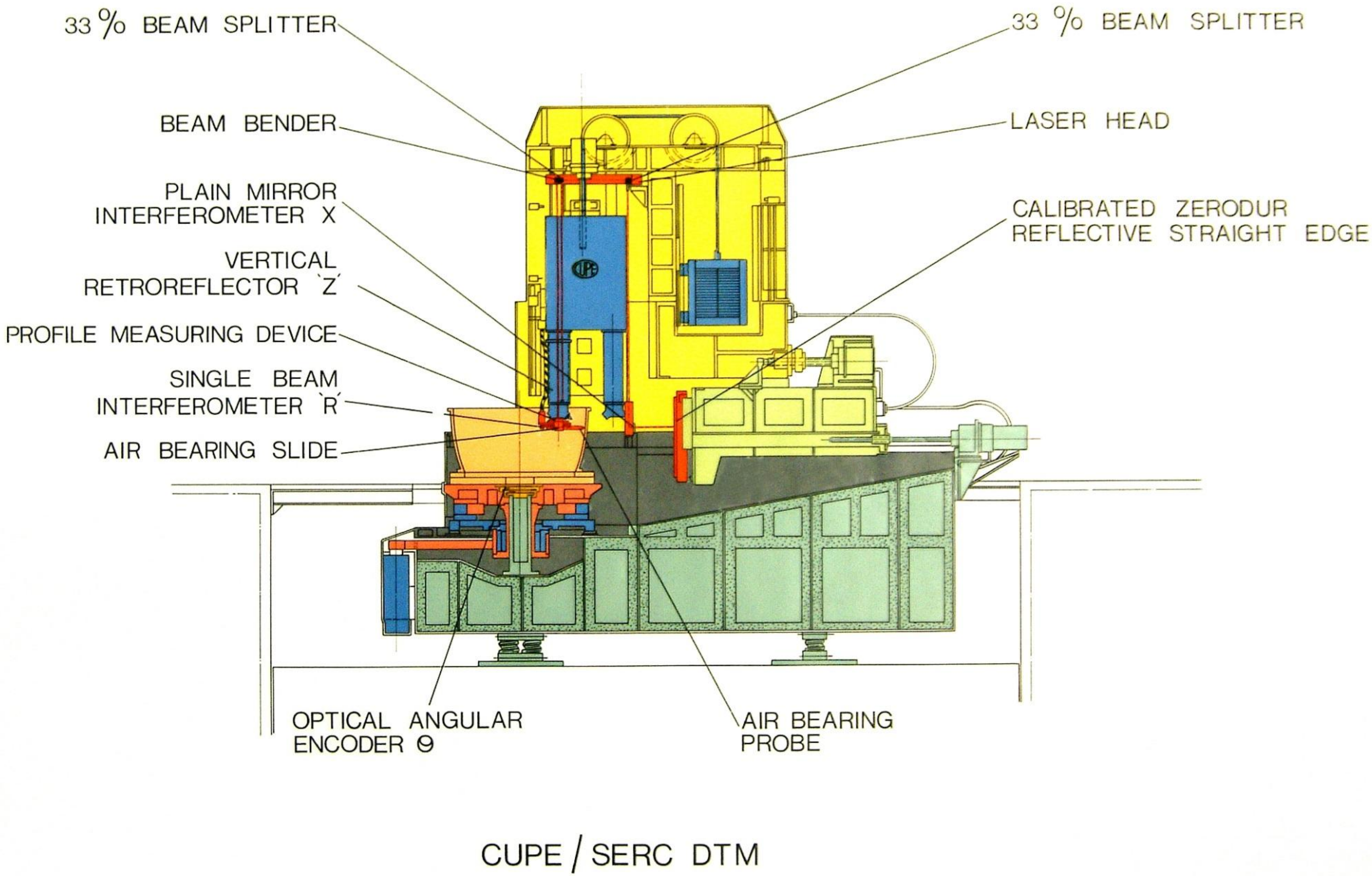


Rosat Space Telescope Mirrors

Large Diamond Turning Machine (1982)



Large Diamond Turning Machine for producing X ray Astronomy Mirrors (1982)



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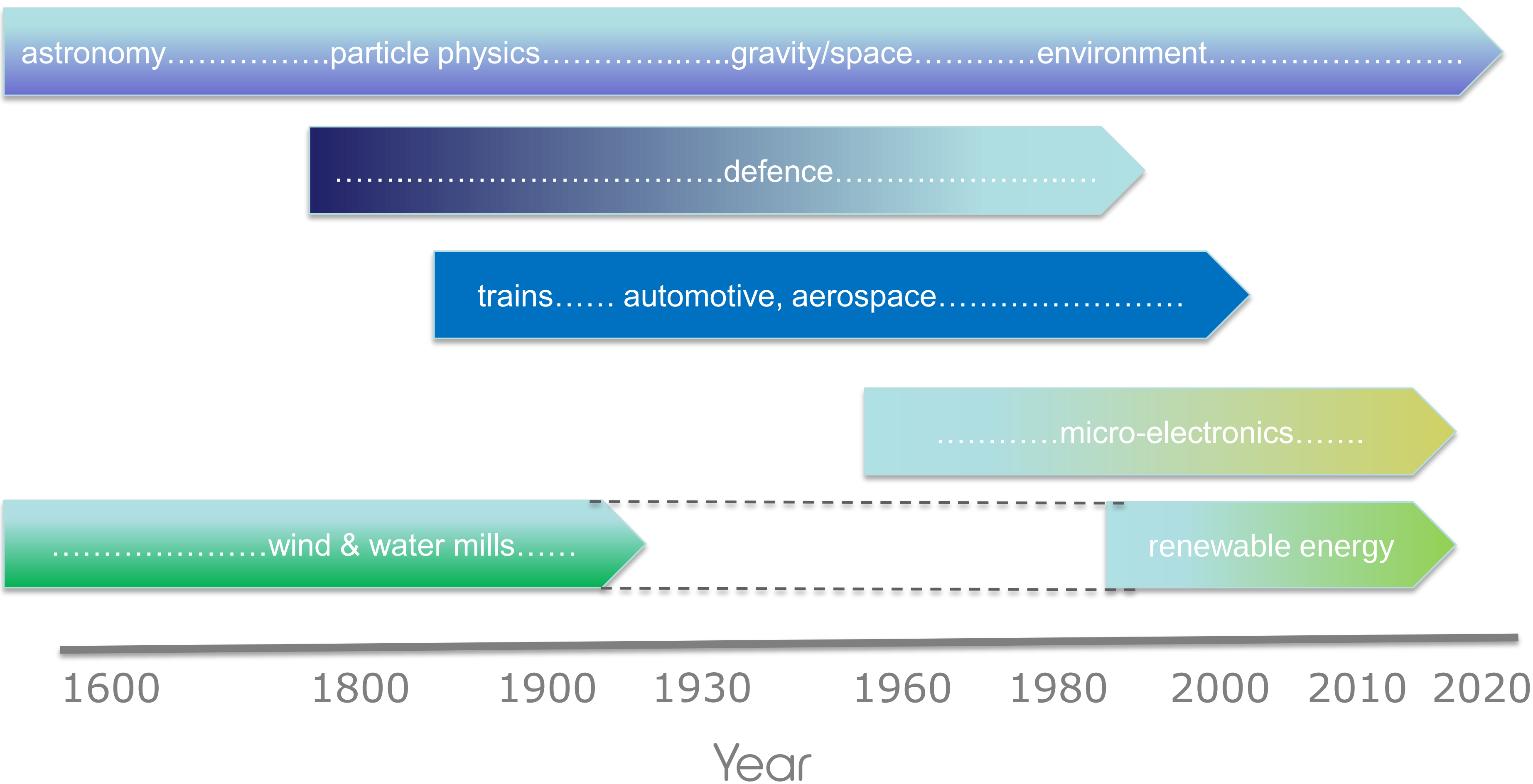
Drivers of manufacturing accuracy capability



Ref, Shore, Morantz, Phil. Trans. Royal Society 2011

Growth in size of commercial wind turbines (height in metres)

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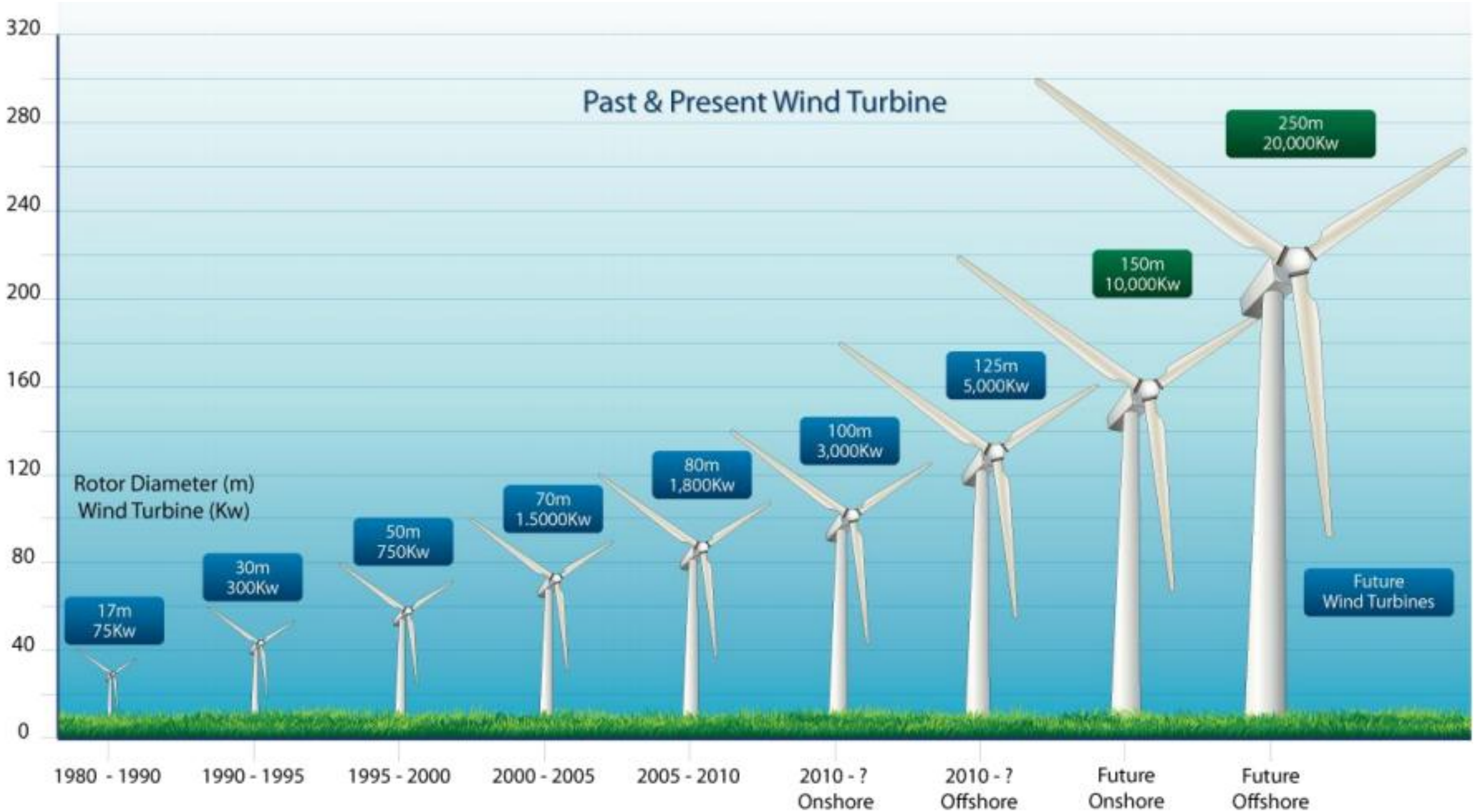

IPCC (2011), "Special report on renewable energy"

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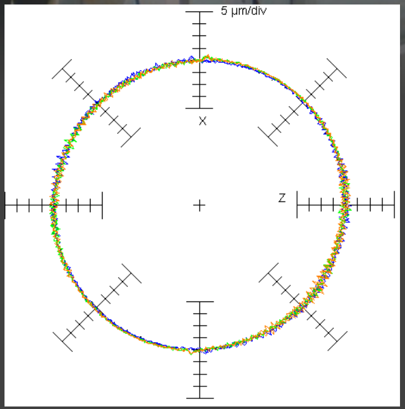
Wind turbine bearing fabrication

KMT Lidköping Vertícal Hard turning/Grinding machine

- Grinding and hard turning in same setup.
- Machine designed for bearing rings.
- Dedicated Man-Machine-Interface.
- Linear motors – ultra precision.
- Hydrostatic slides and workhead.
- In machine probe metrology

Machine weight	145 000 kg
Working range, OD	1 300 – 4 000 mm
Max workpiece weigth	10 000 kg

X-Z slide circular accuracy diagram



Presentation structure

1. Some observations and questions
2. Enabling our future?
3. Drivers of accuracy improvement
4. Power of metrology innovations
5. Precision manufacturing
   i. Current examples
   ii. Future developments
6 Summary

CE Johansson

Carl Edvard Johansson 1864–1943
inventor and metrologist

Combination gauge block set

CE Johansson worked for the Swedish Carl Gustaf arms factory.

Johansson was concerned that components of their rifles were not "interchangeable".

His combination gauge block set, which he patented, enabled effective calibration of inspection gauges and testers.

Henry Ford

Henry Ford employed CE Johansson

Ford realised the concept of "inter-changeability" proposed by Leland at Cadillac to produce high quality cars would allow others to employ a new production concept to make affordable automobiles.

Production-line assembly

Mass production assembly is enabled through effective inspection of components prior to assembly.

Johansson Slip gauges were in practice the mechanism by which inspection could be achieved in factories.

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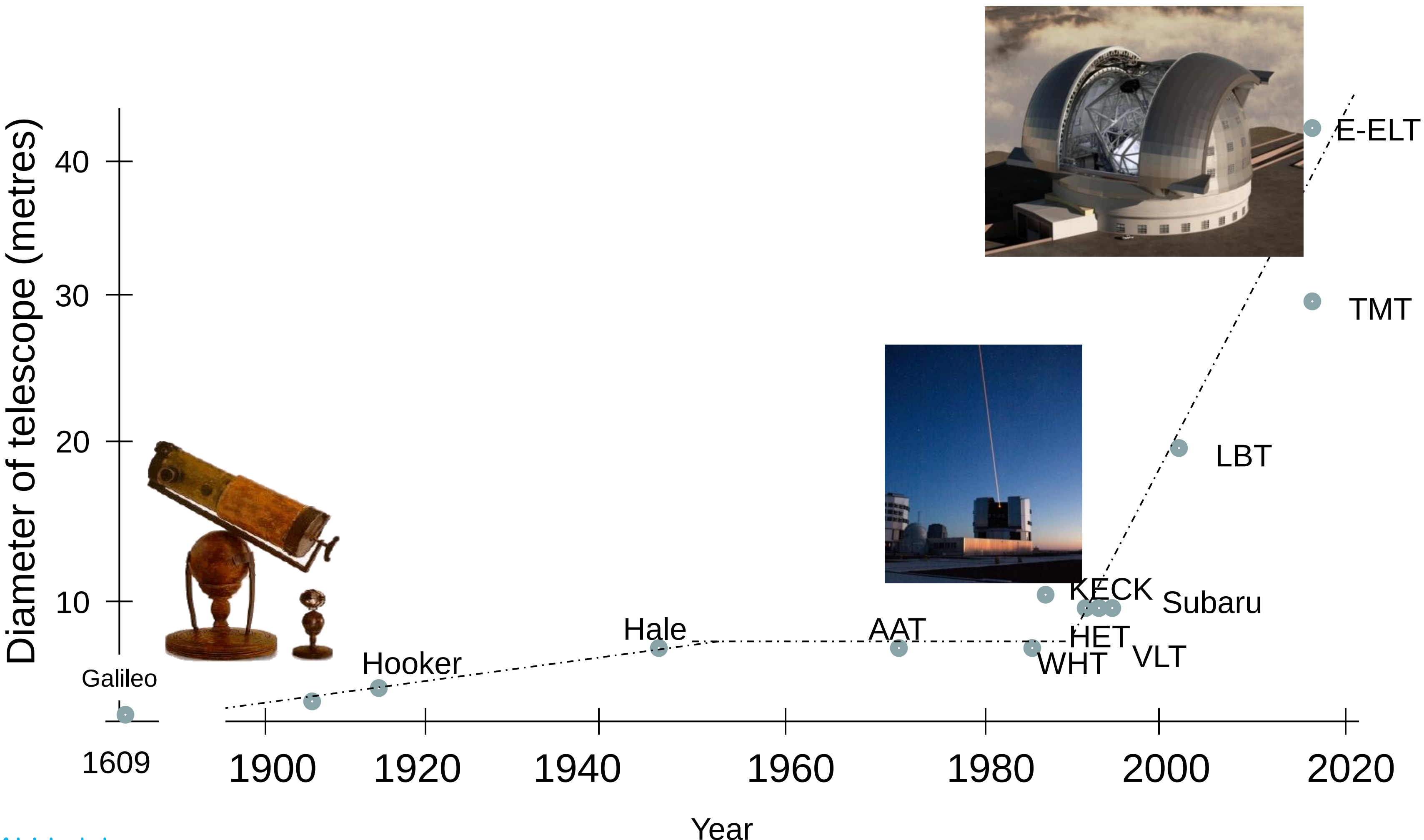
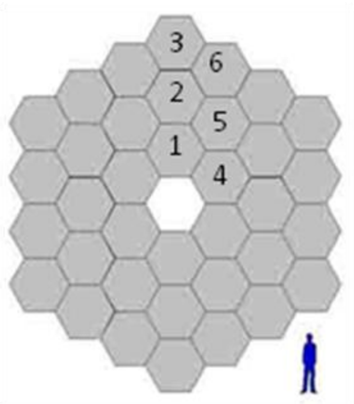
Astronomy: driver of Precision Manufacture

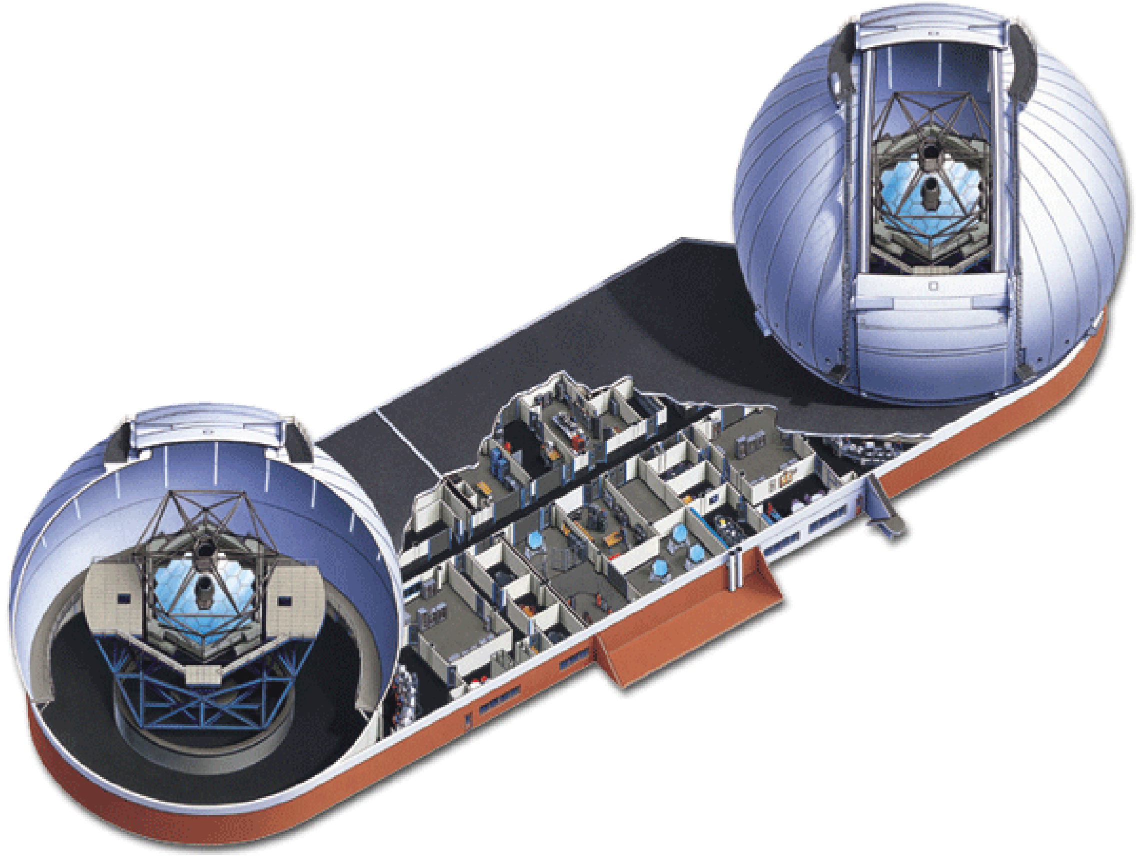


Keck telescopes from 1990's

Active segmented mirror technology



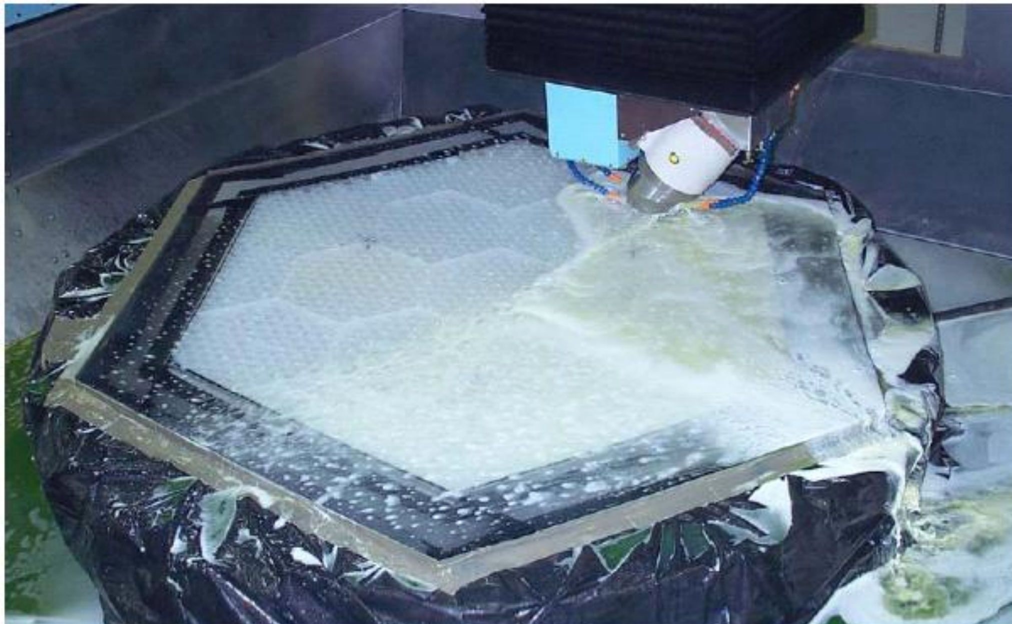
36 mirror segments



Mirror Segment Production Rate

1 mirror segment each month

Aspheric Generation



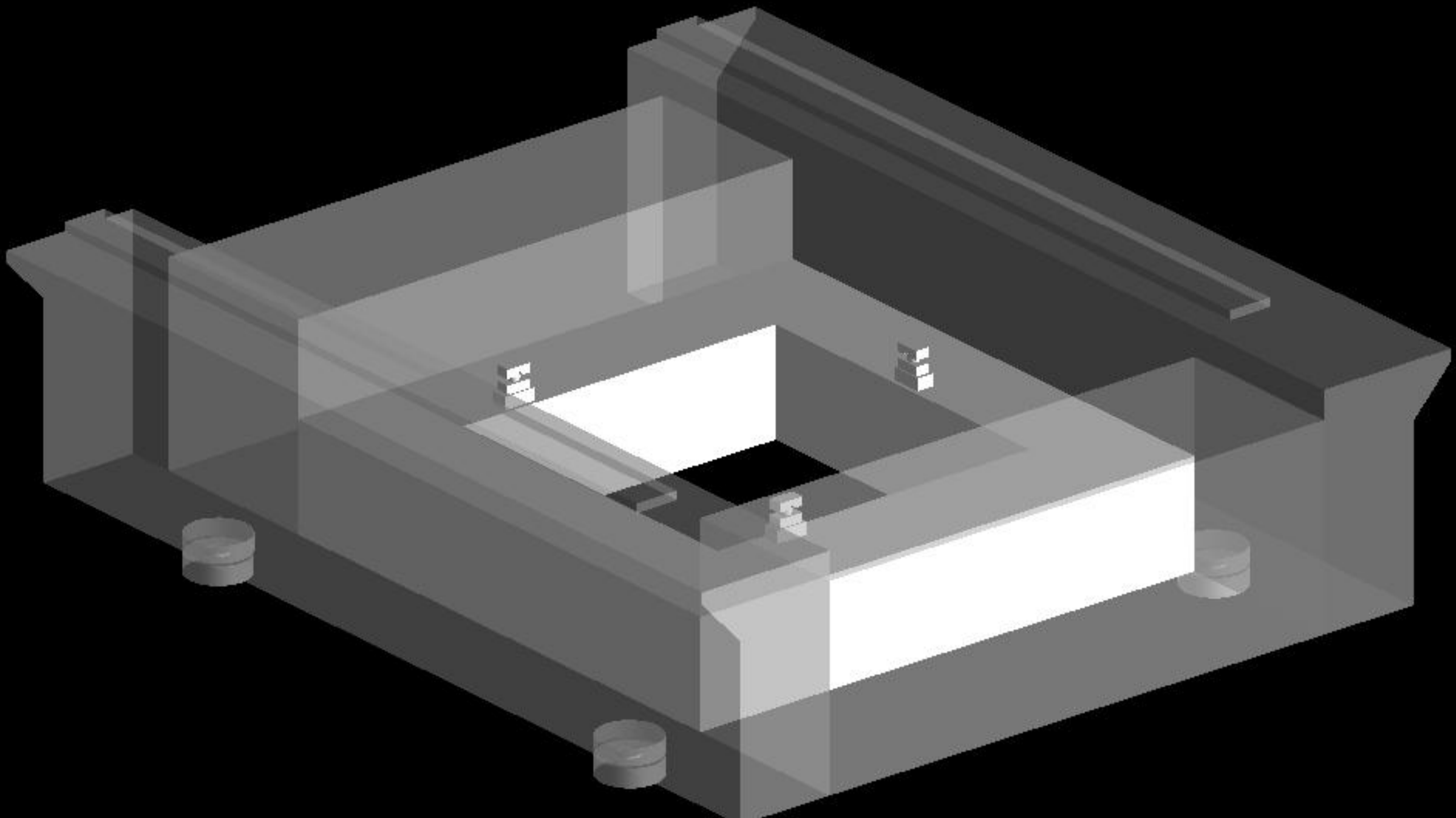
Off-Axis Generation Machine (OAG) used to impart final asphere onto AMSD mirror

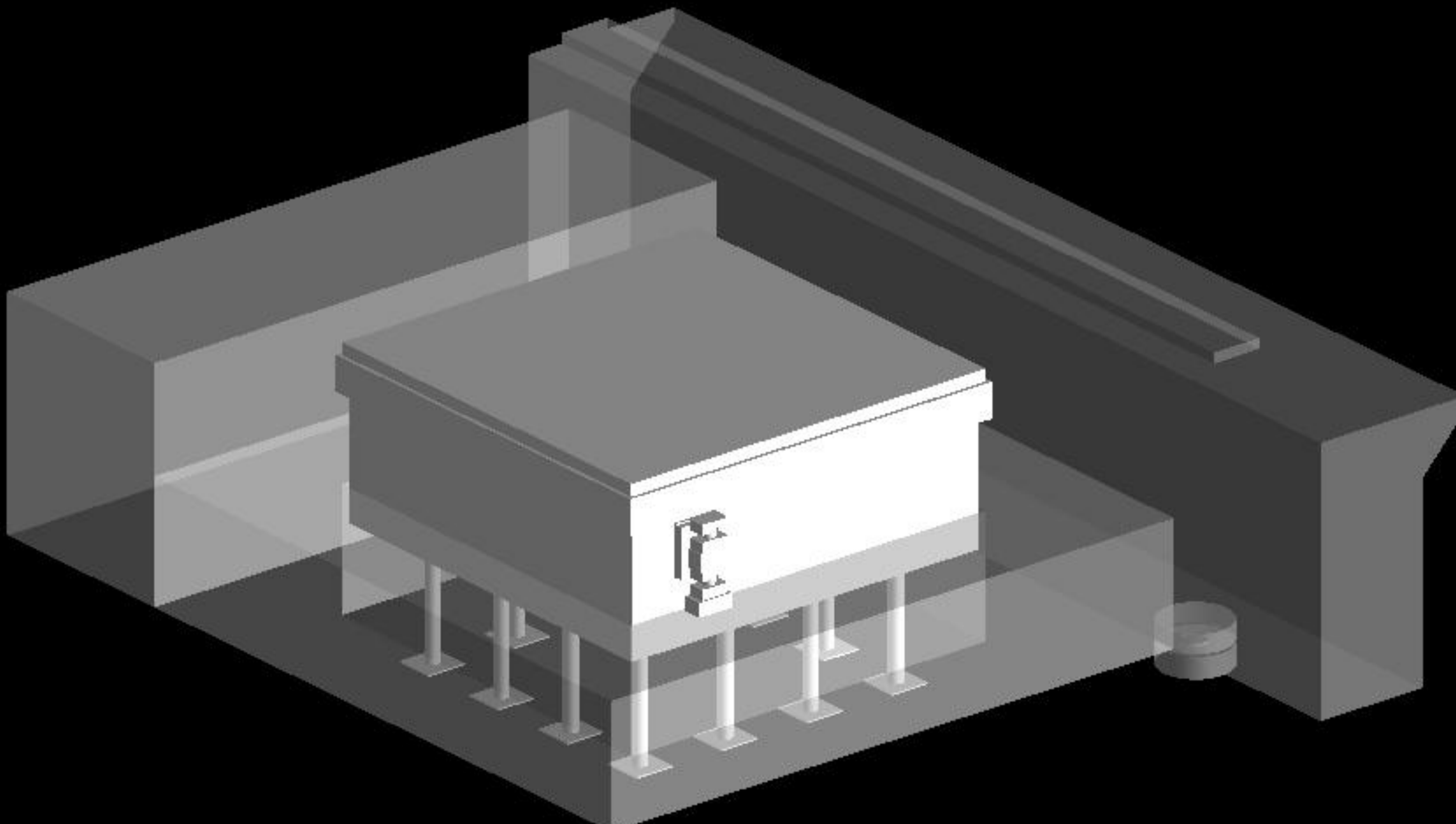
10 micron P-V surface generated

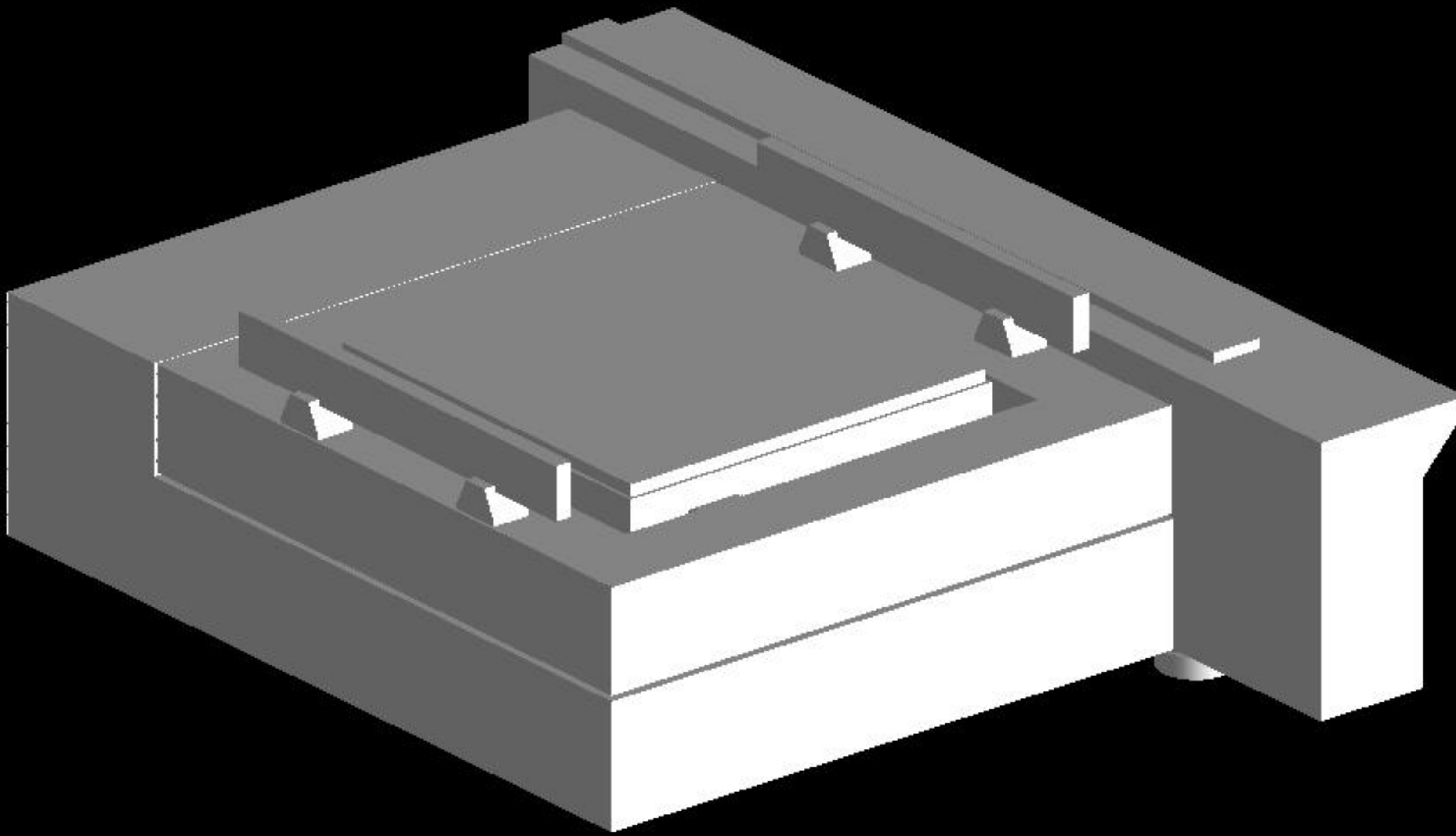
Off Axis Grinding & Co-ordinate Measuring machine

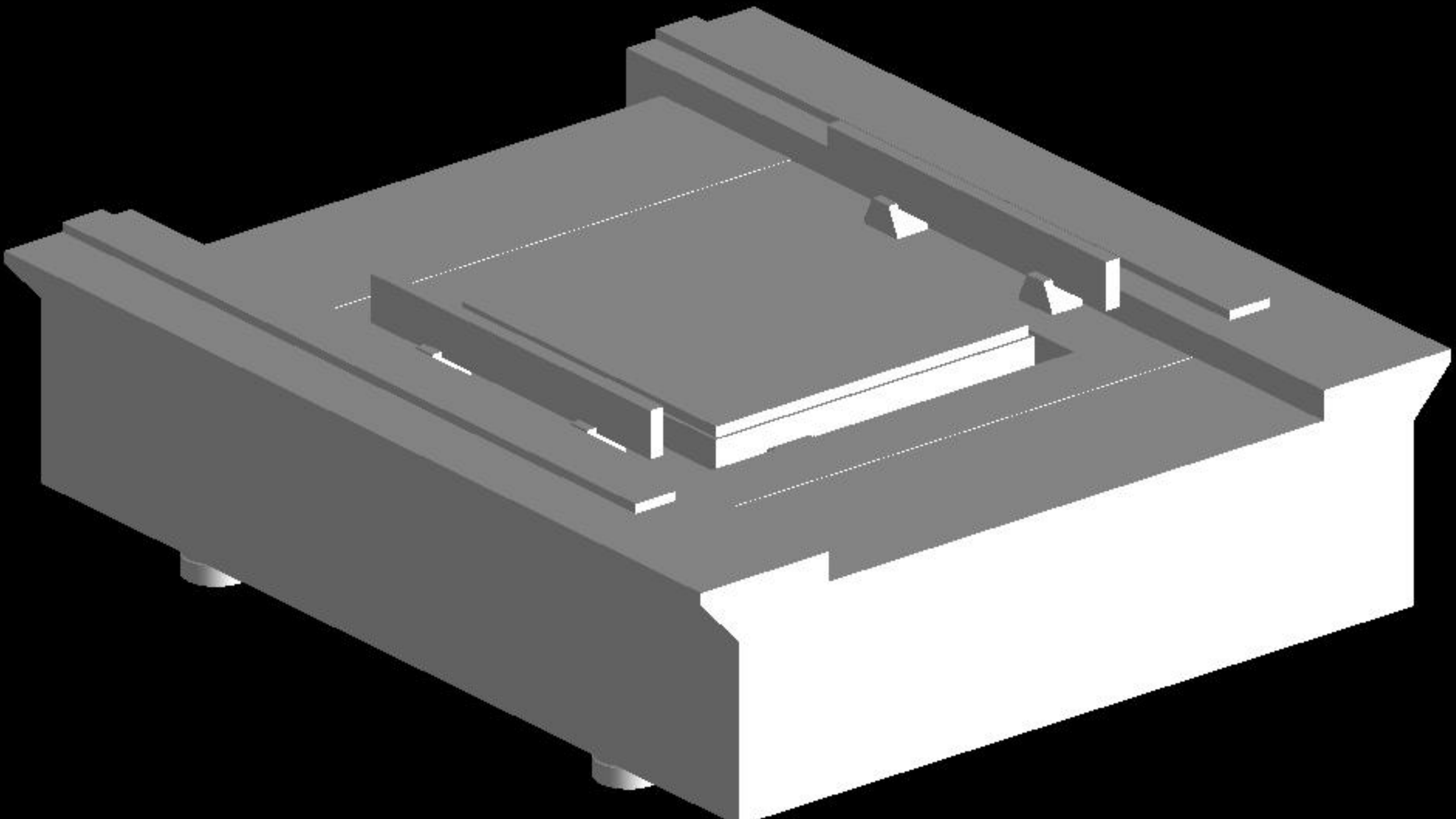
Year 1990

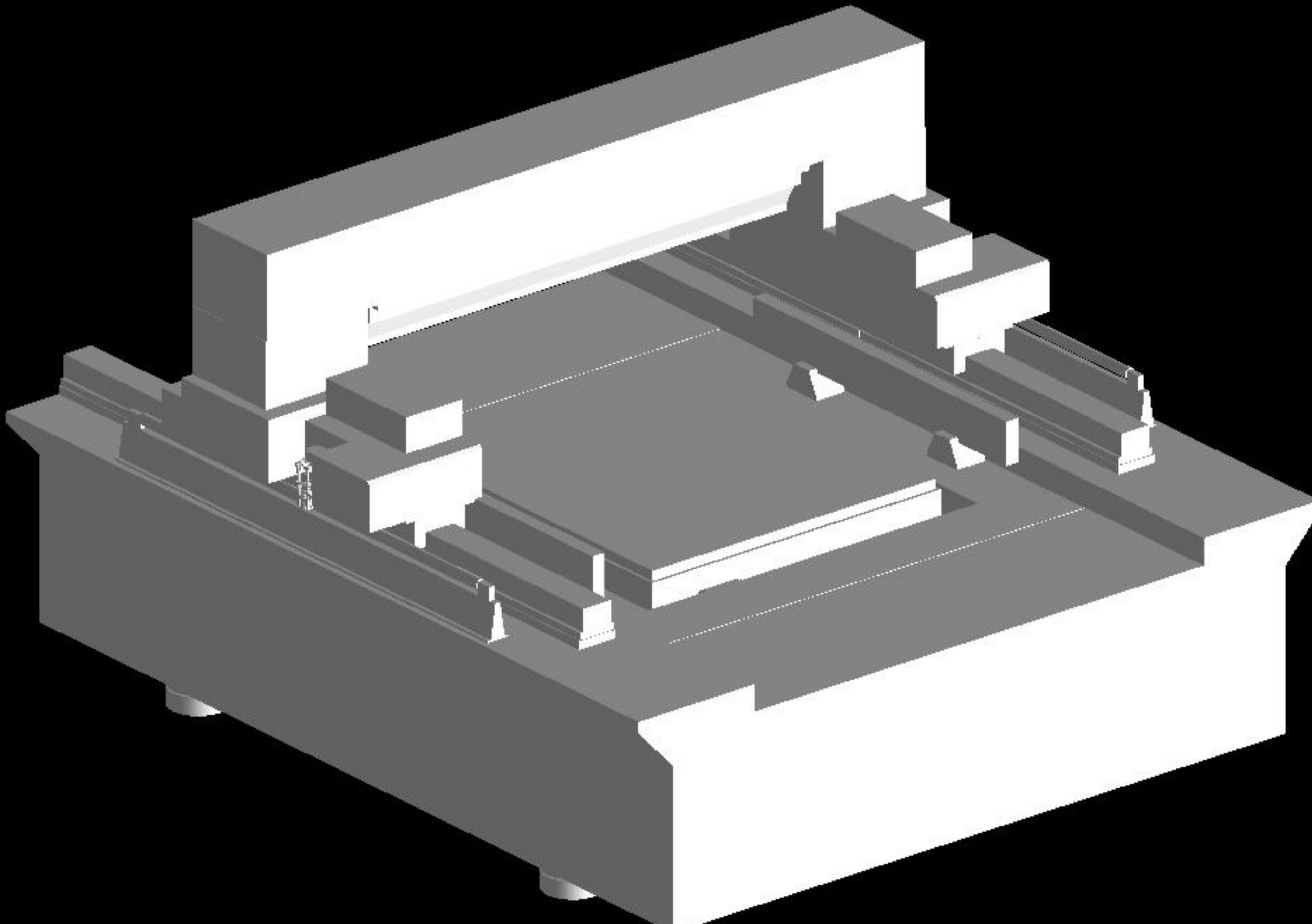
Off-axis grinding machine - Eastman Kodak

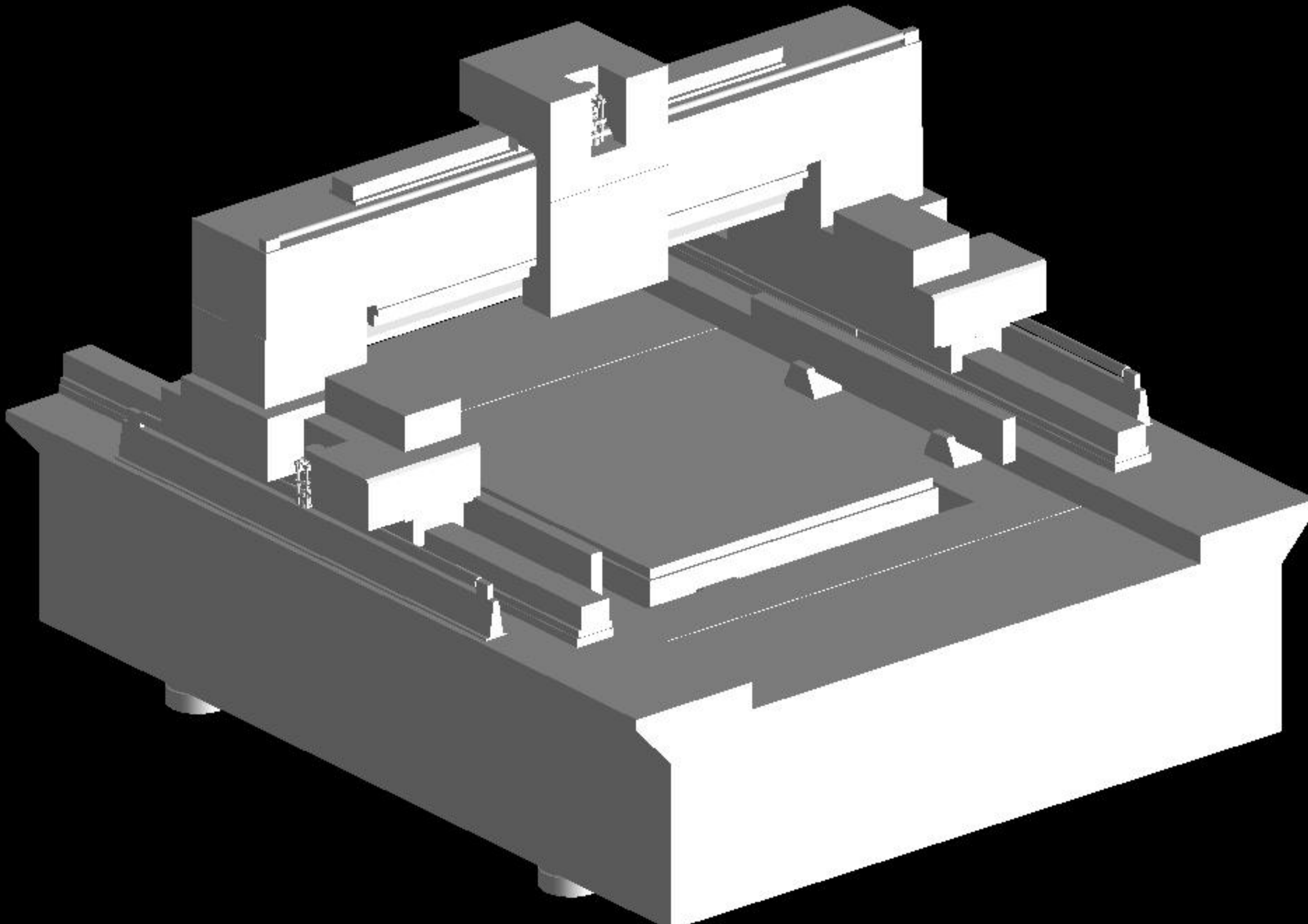


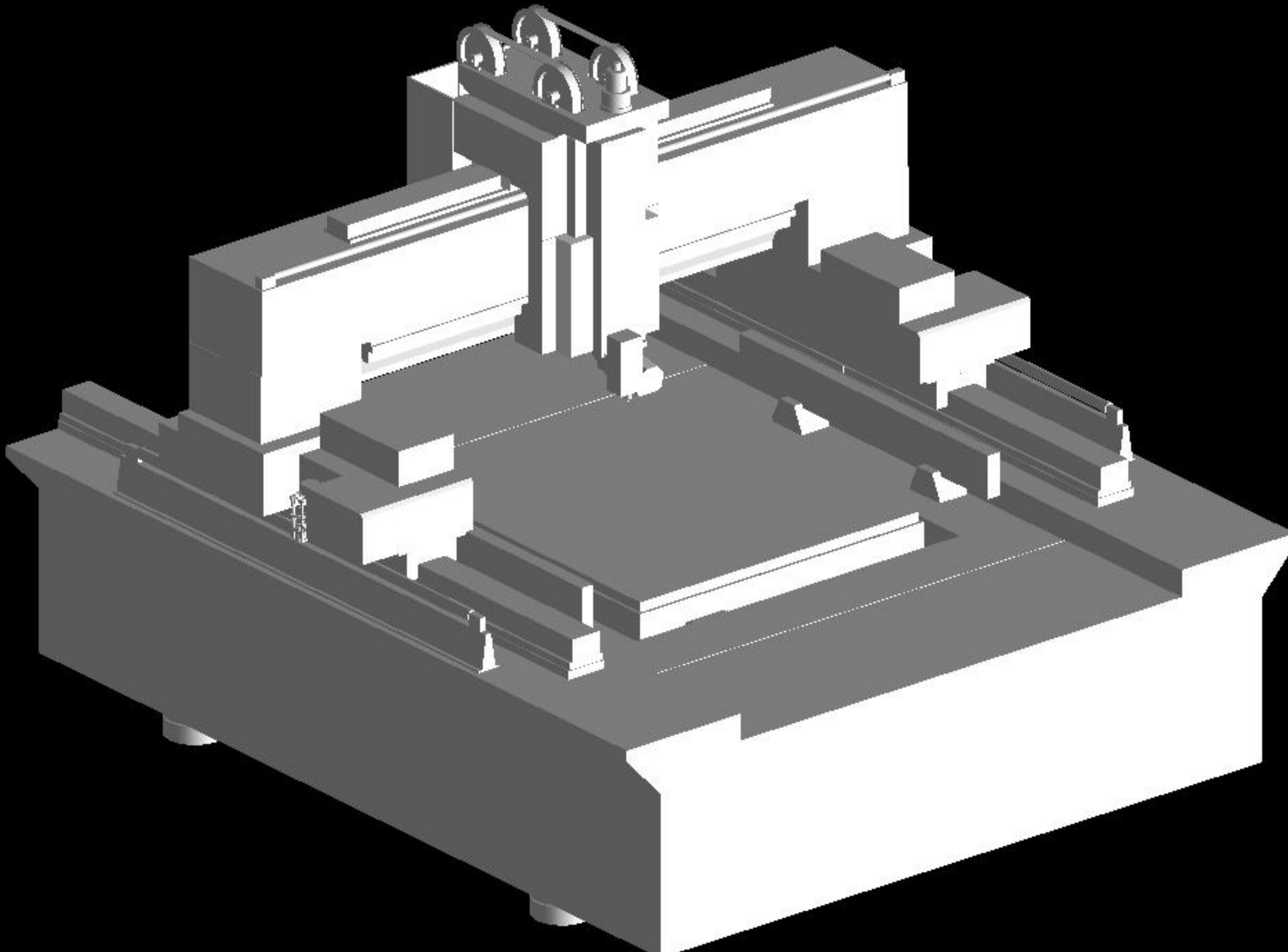


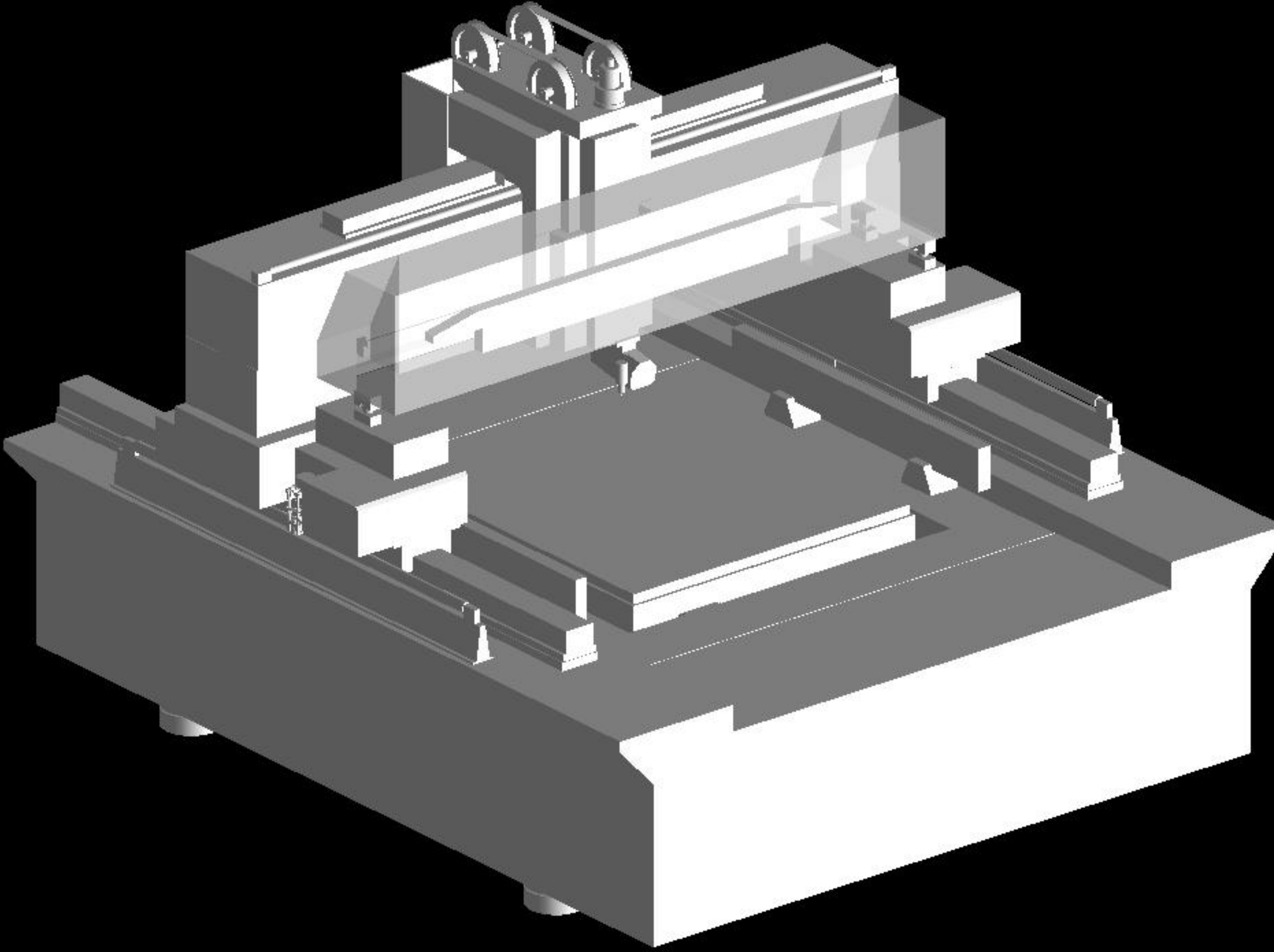




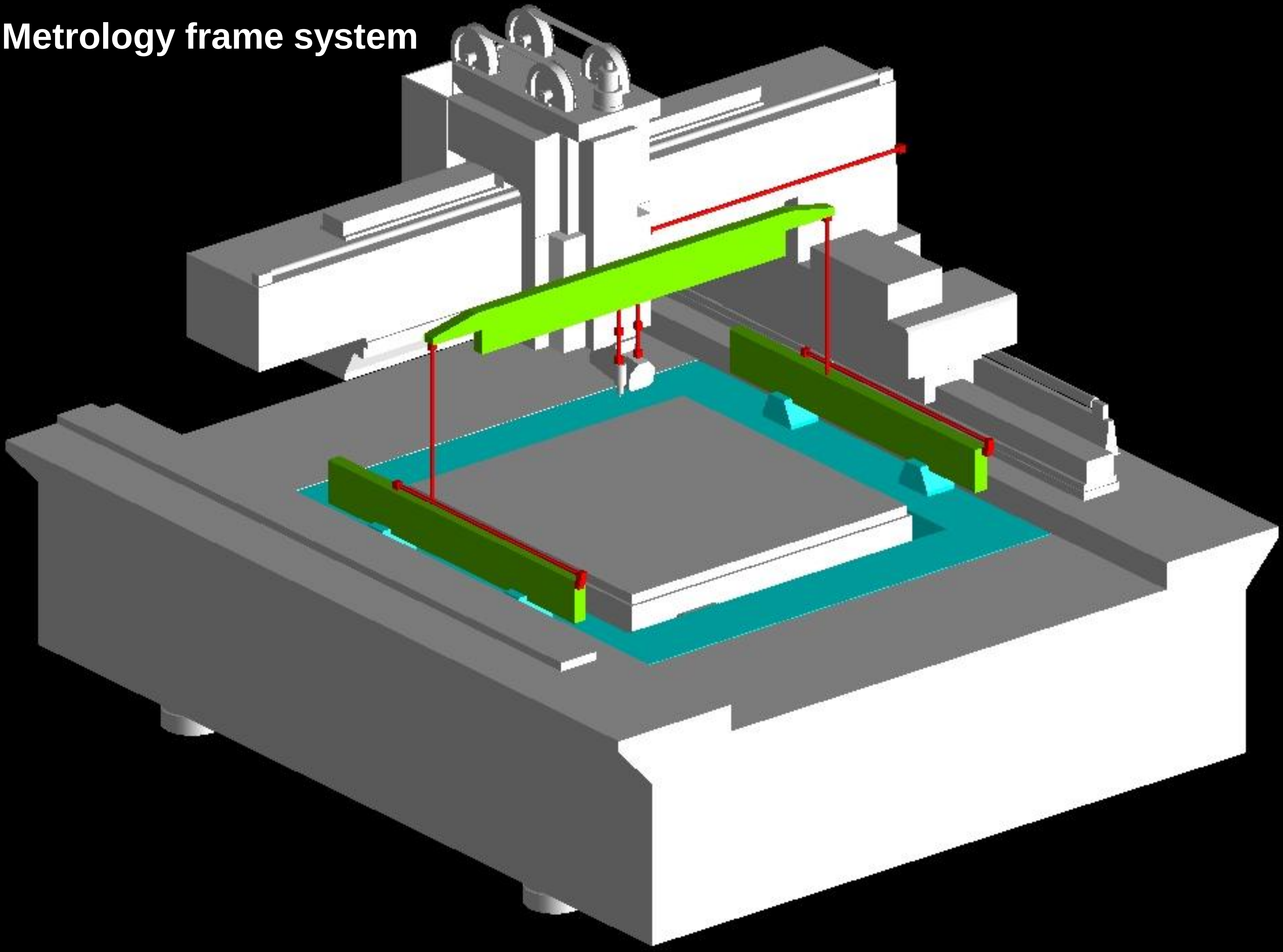


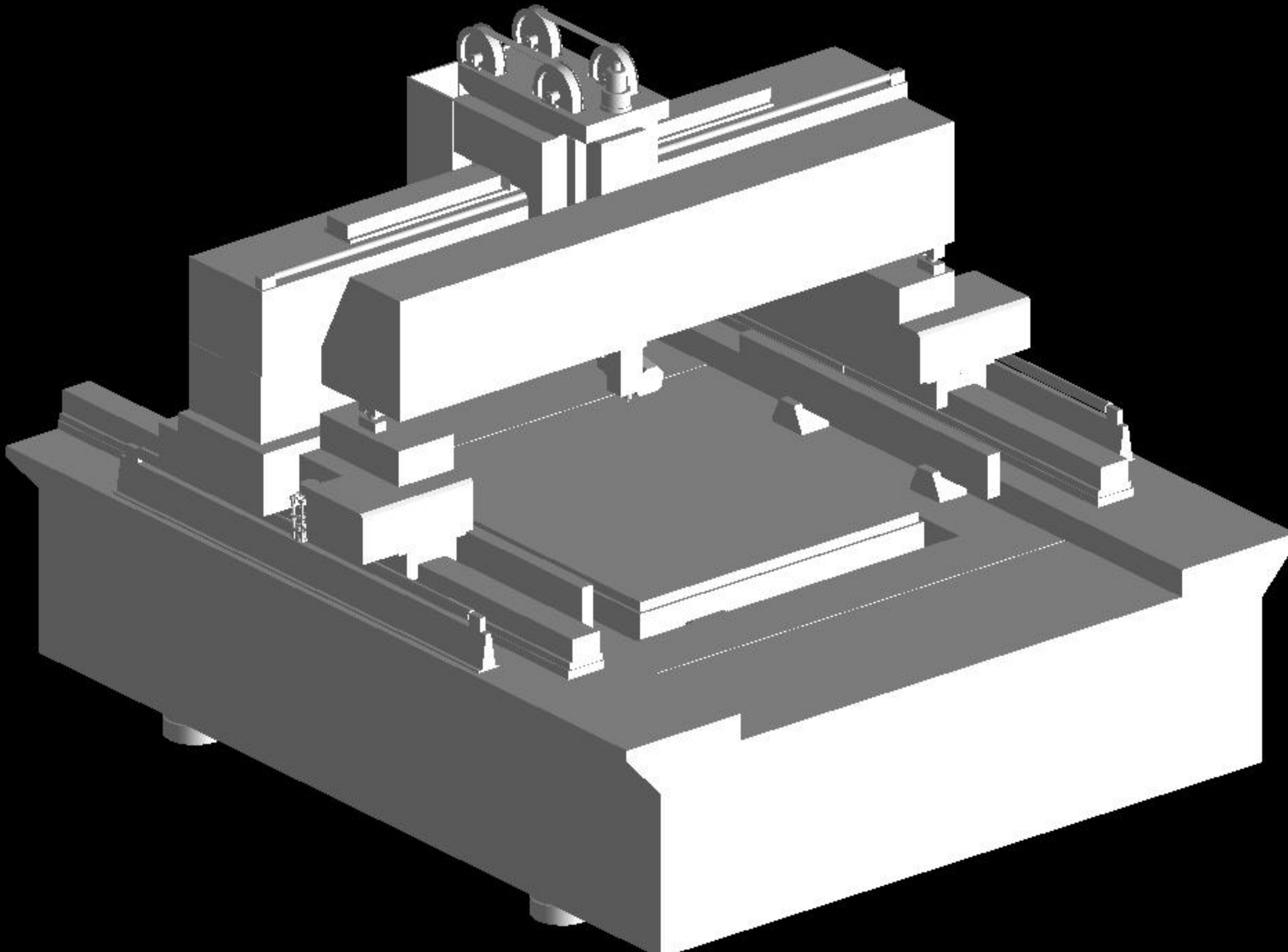






Metrology frame system





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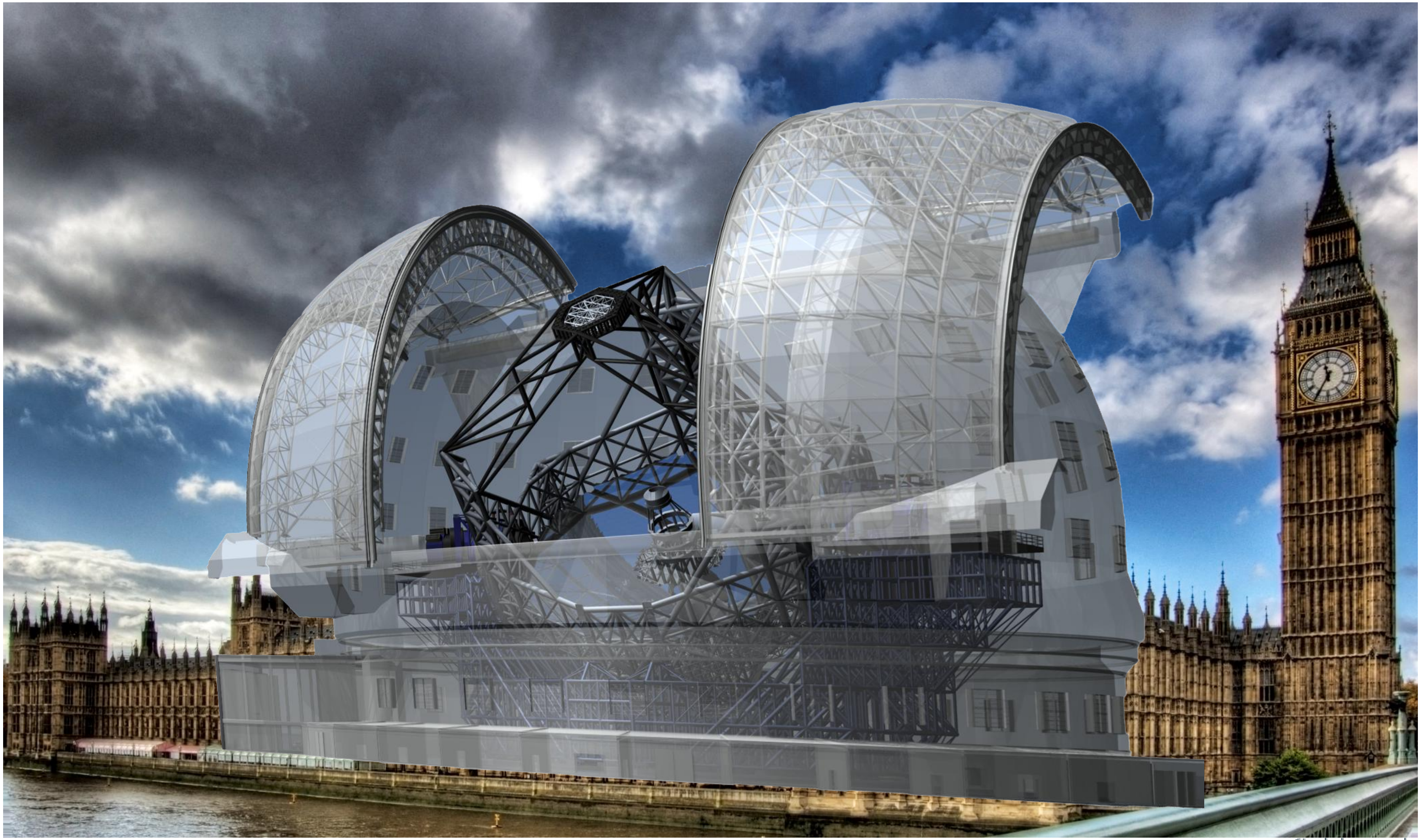
Next generation ground-based telescope



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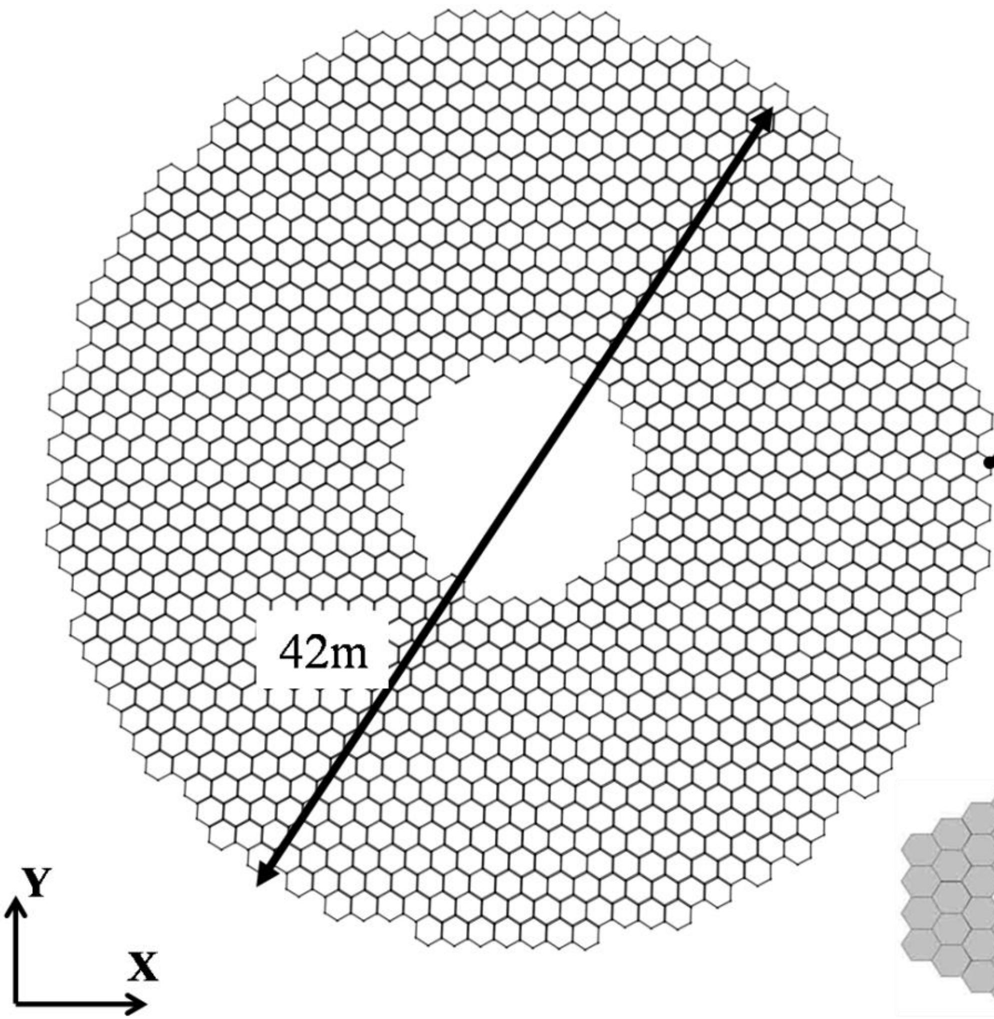
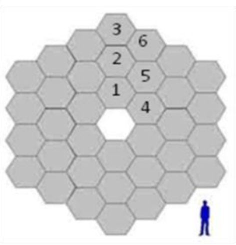
ELT M1 - Primary mirror

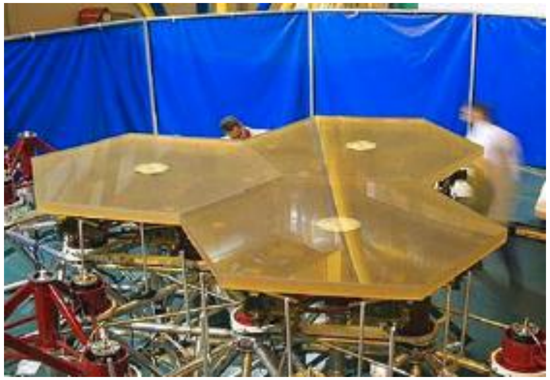


~800 mirror segments of 1.45 metre scale (across corners)

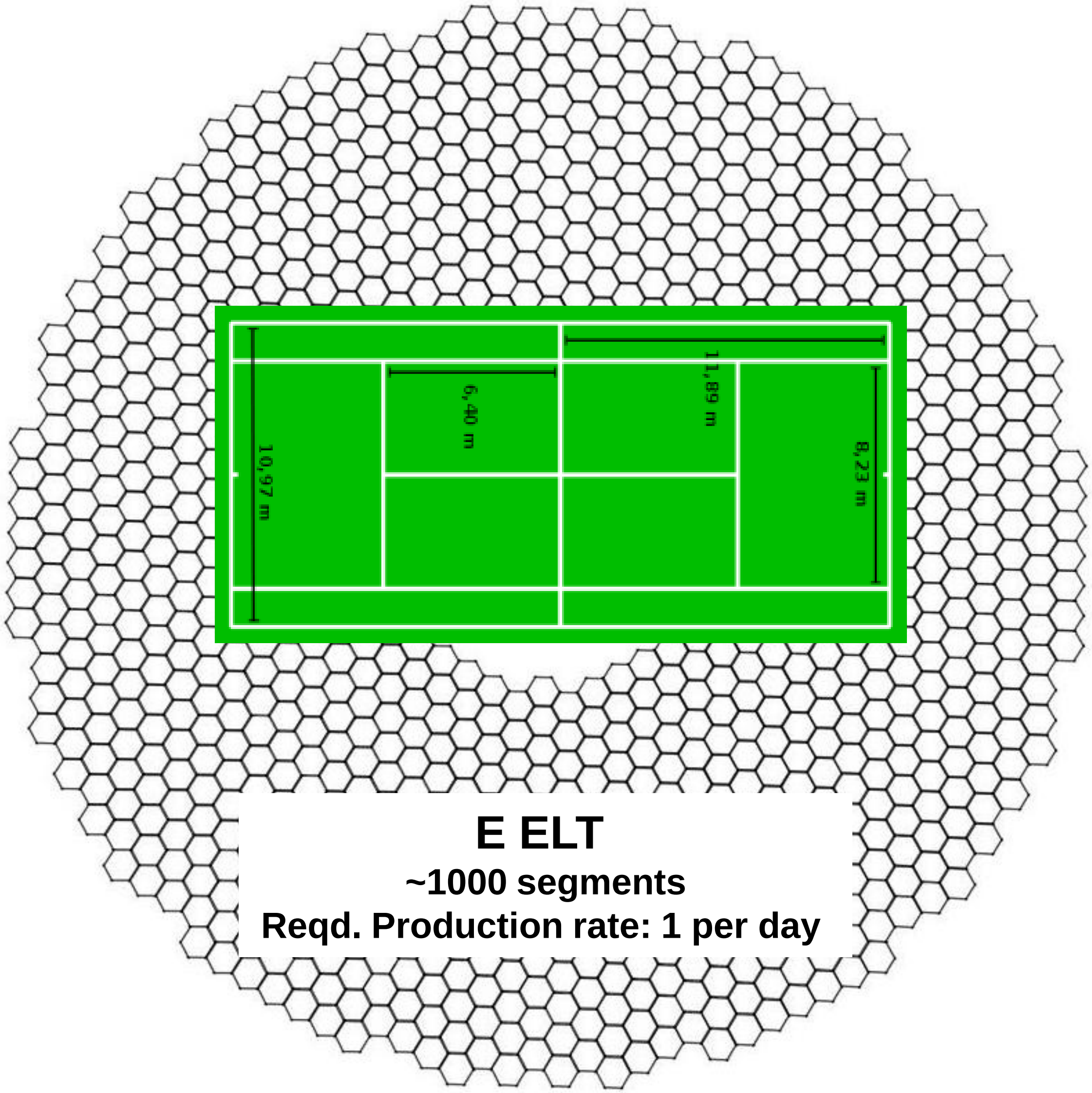
At Keck production rate of 1 per month it would take 66 years to produce the ELT segments

Keck





Astronomy: driver of production & precision



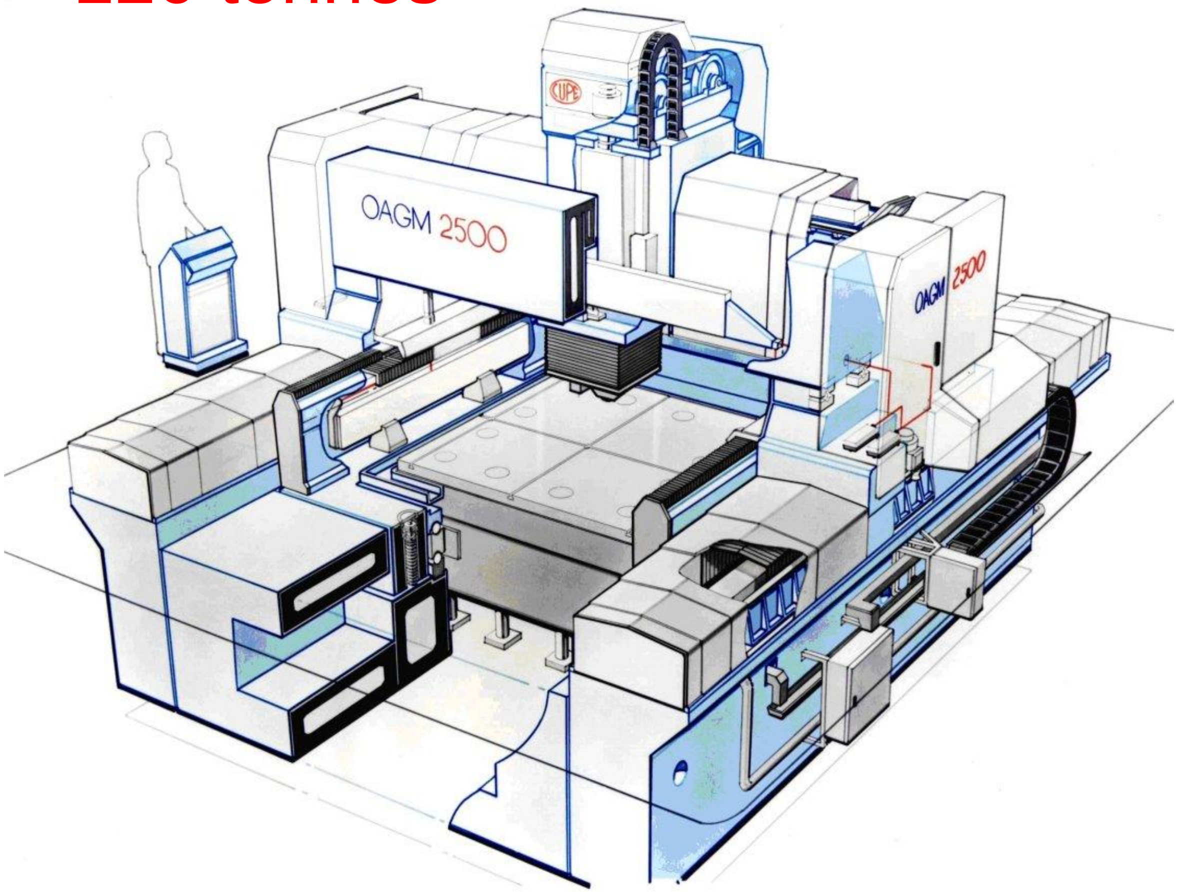
E ELT

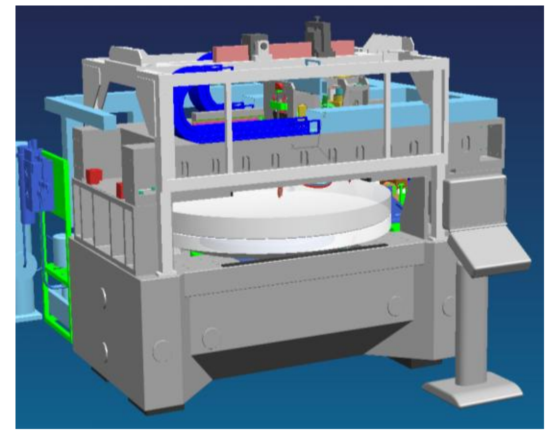
~1000 segments

Reqd. Production rate: 1 per day

Machine size comparison

OAGM 2500
2.5m capacity
120 tonnes





BoX® Grinder
2.1m capacity
15 tonnes

ESO ELT mirror segment

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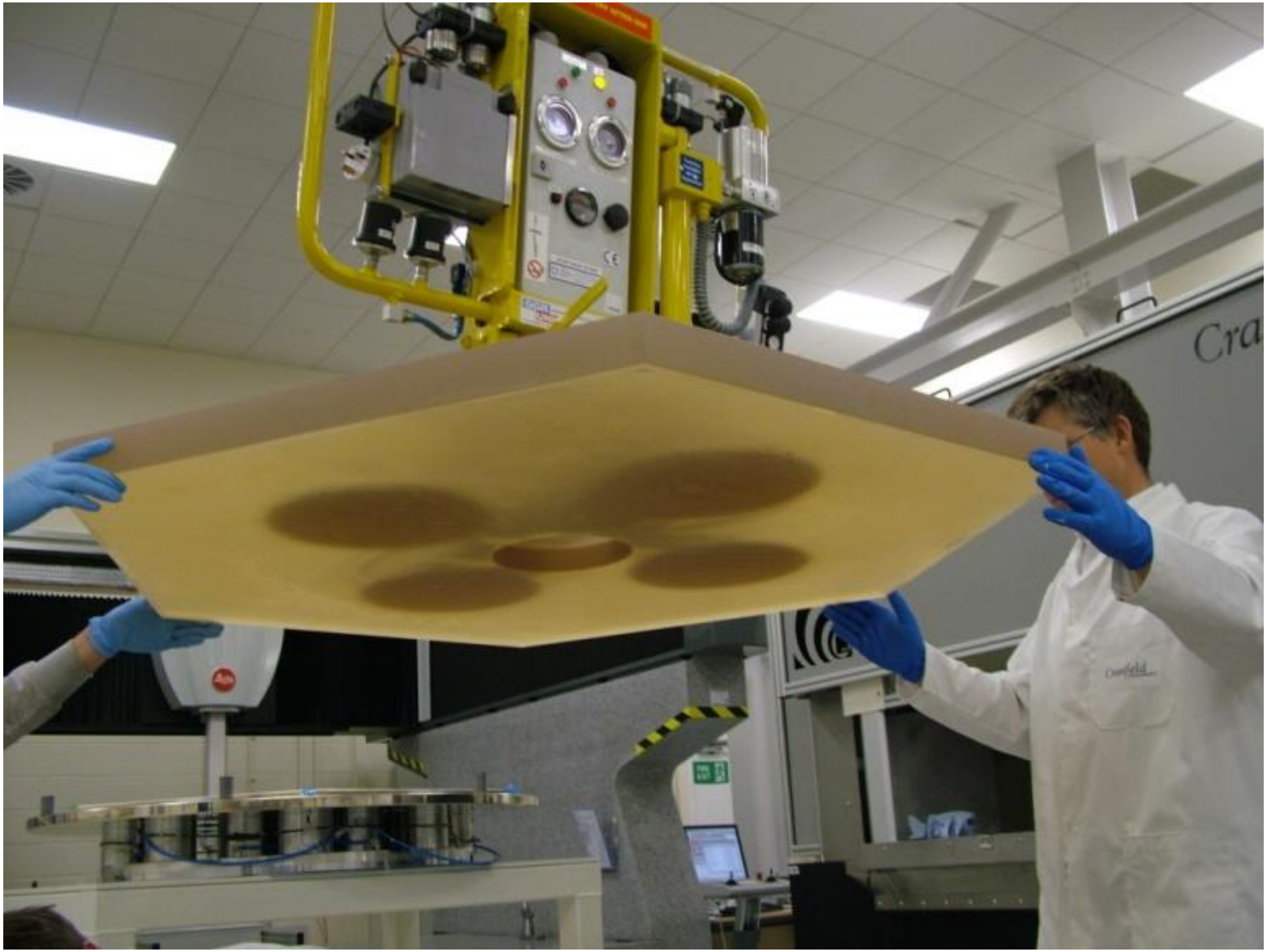

Segment SPN01 surface geometry

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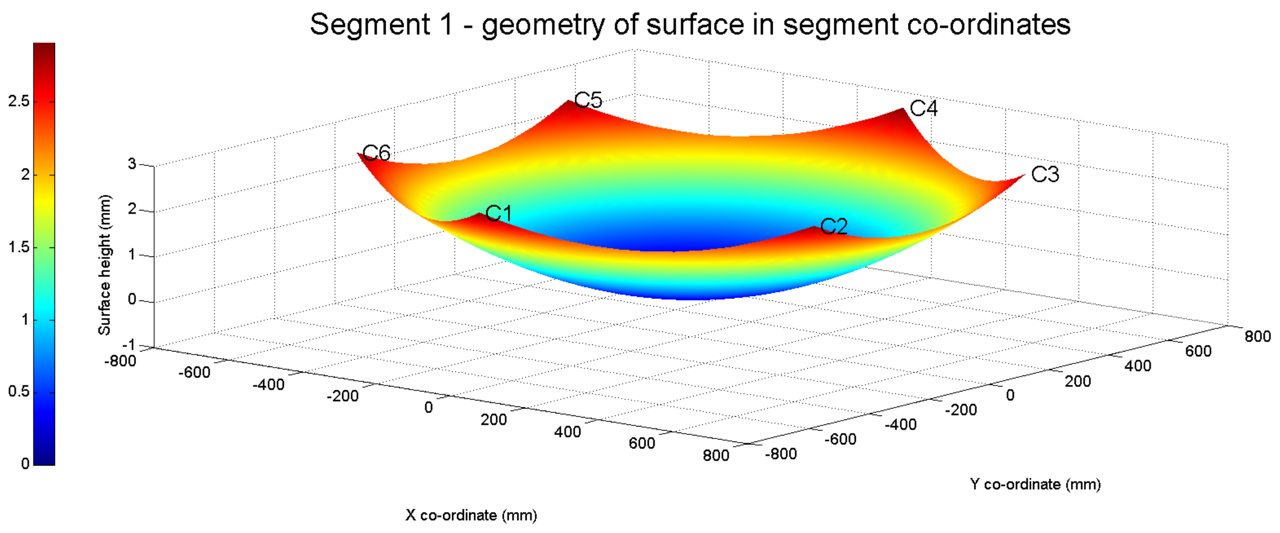
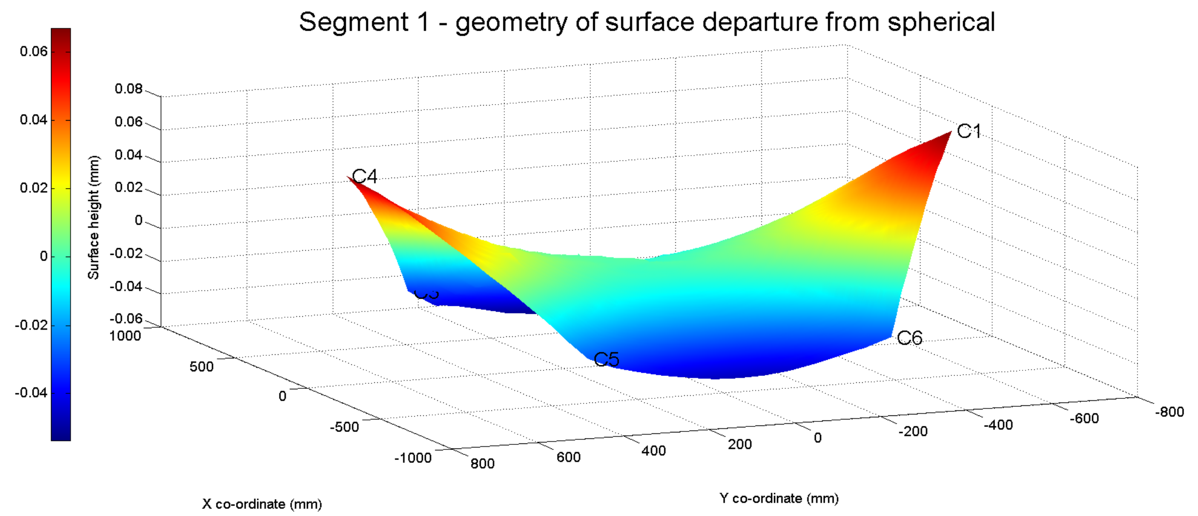


Ellipsoidal form,
~ 3mm sag

Spherical departure ~ 150 microns



BoX® Ultra Precision Machine 1600

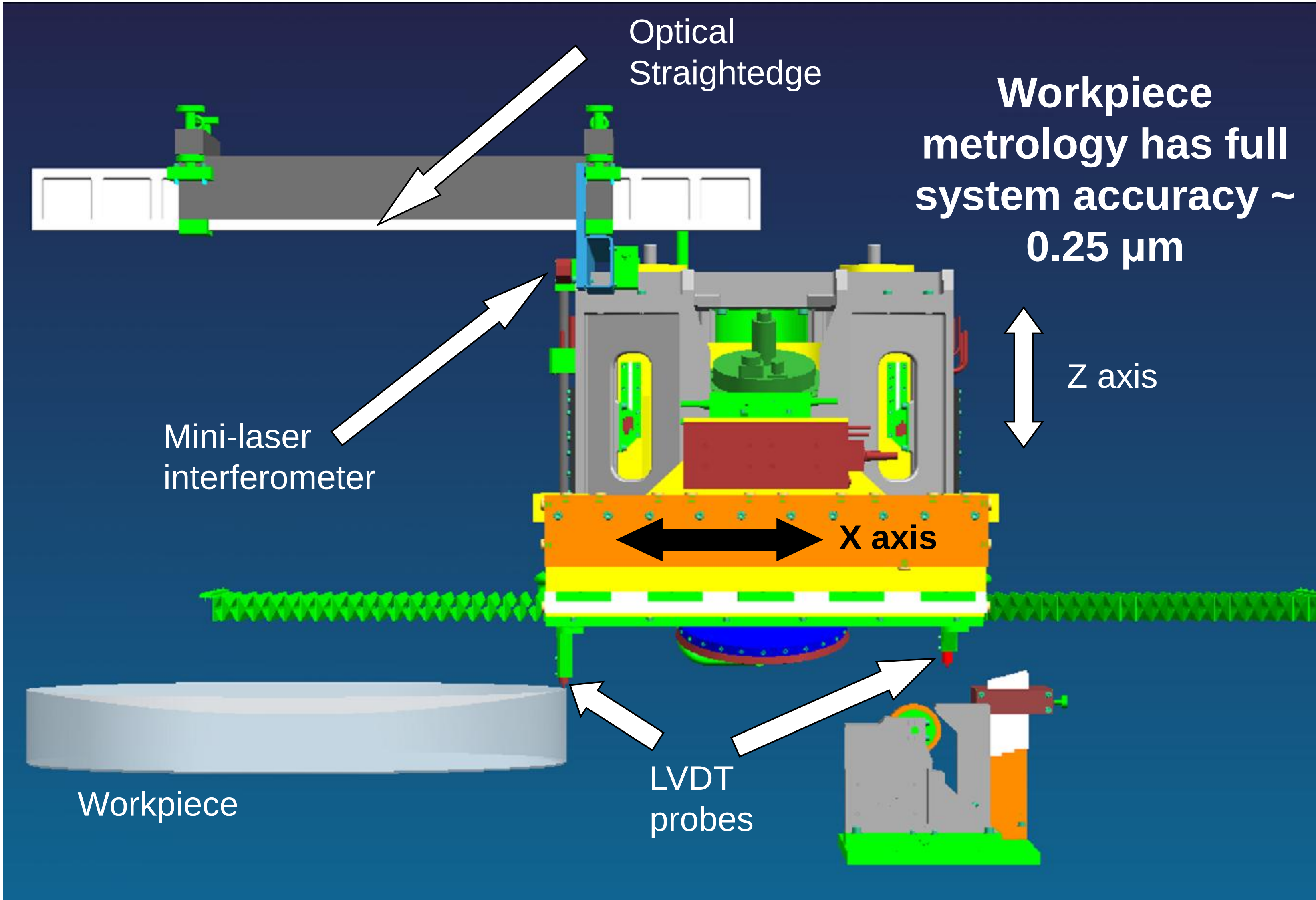
Rapid grinding and measuring system for free-form optics

BoX® 1600 performance

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

Processing rate
Grind time: 20 hours
(10 hours per m^2)
Measurement time: ~ 4 hours
Load time: 1 hour

In machine metrology



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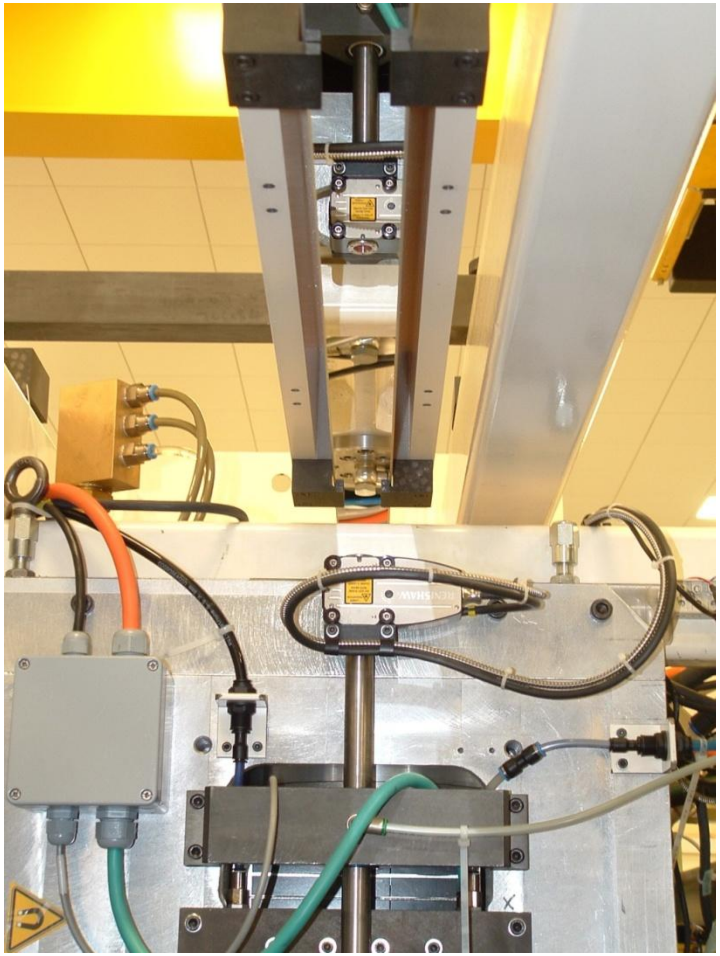
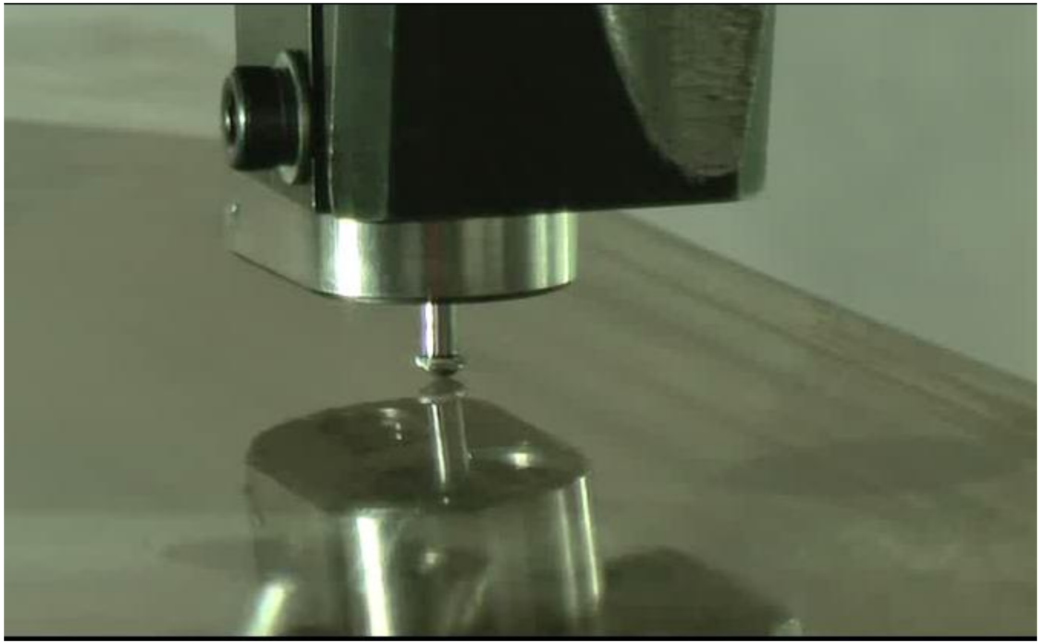
BoX® Ultra Precision Machine 1600



In-situ post grinding measurement using laser based metrology frame



BoX® Mirror segment (1)

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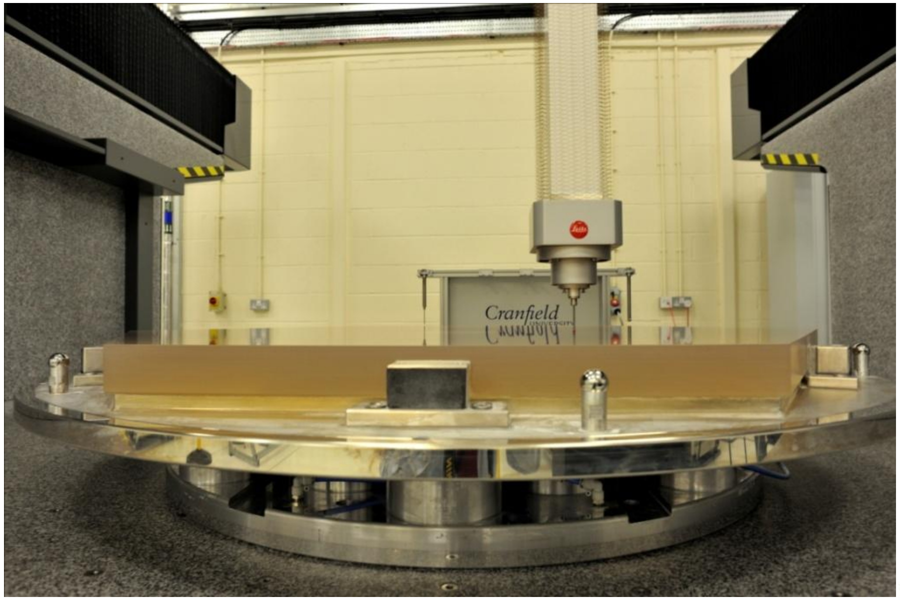
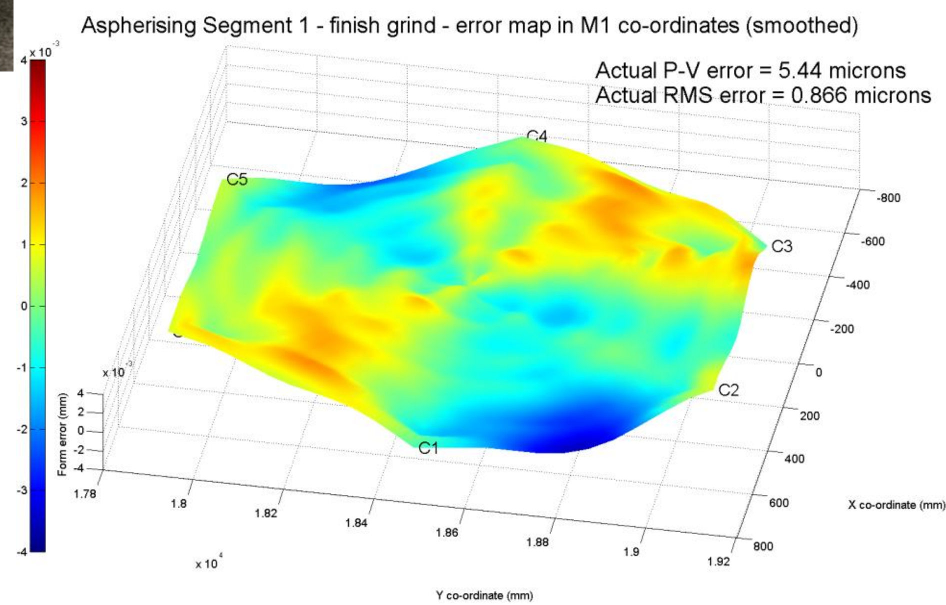


Results:

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

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



On machine metrology in support of manufacture

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- The 'spheres' were made at Cranfield
- Three metrology techniques were used at Cranfield in support of the diamond turning
- On-machine profilometery (1) was eclipsed by:
  - (2) Interferometry
  - (3) CMM Scanning

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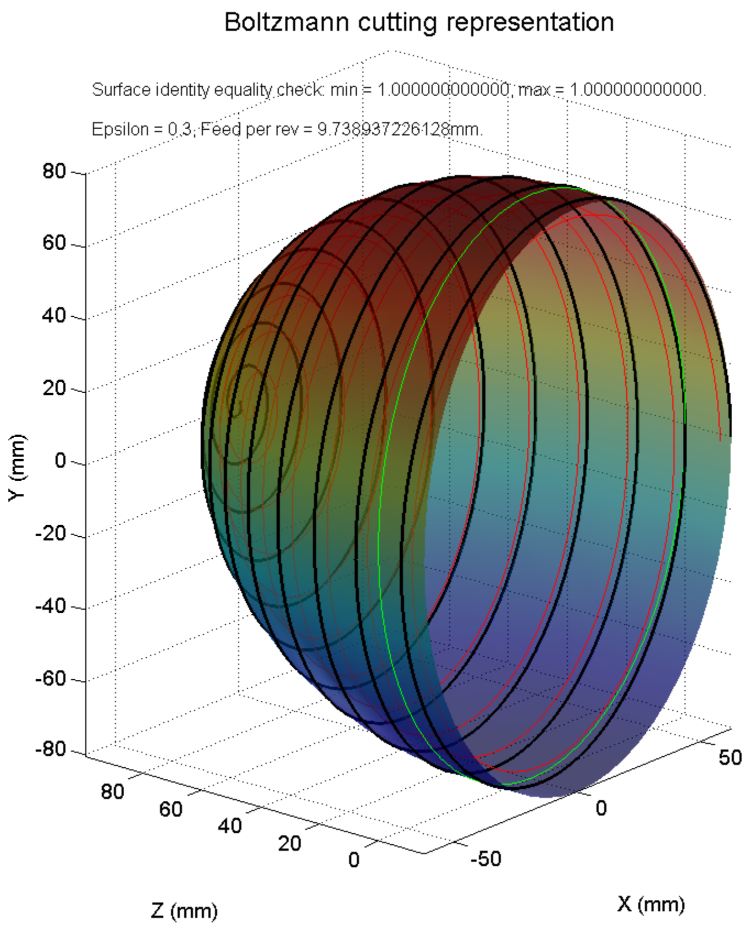
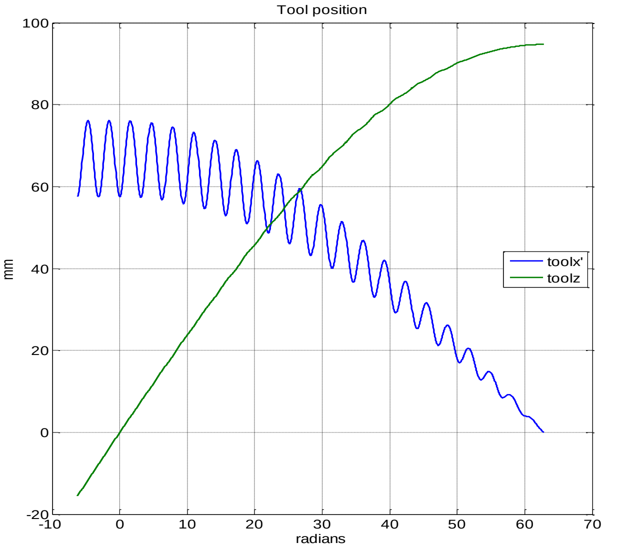
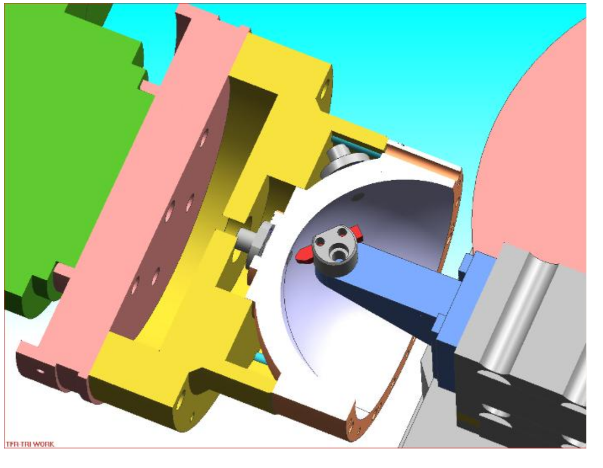
Turning programming

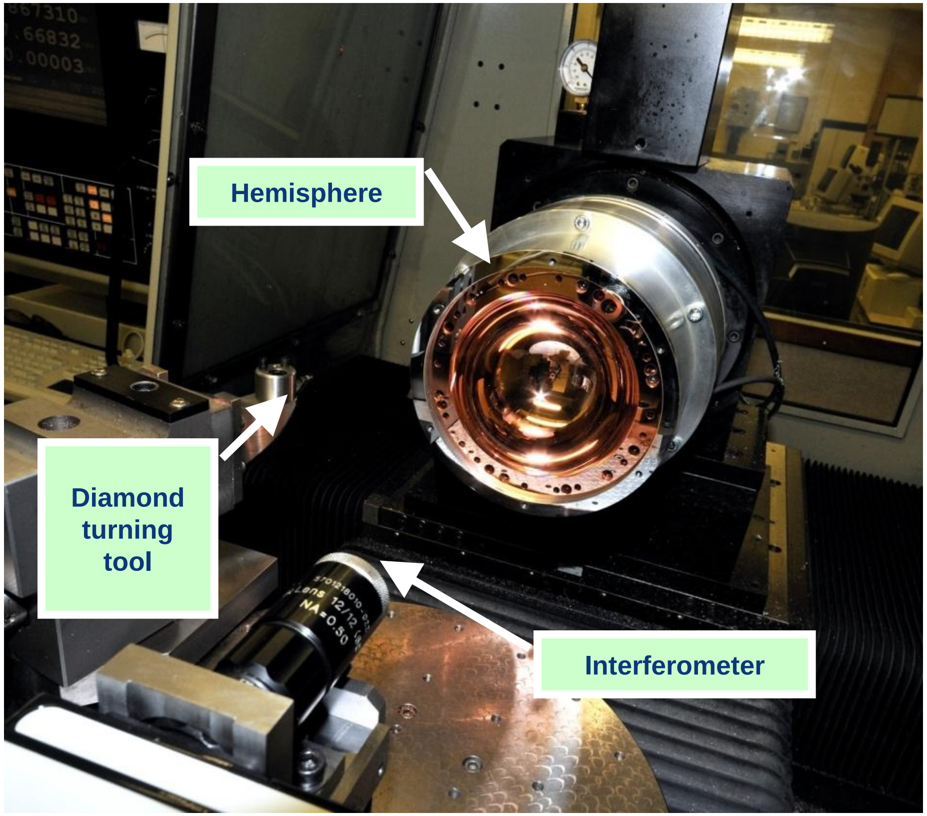


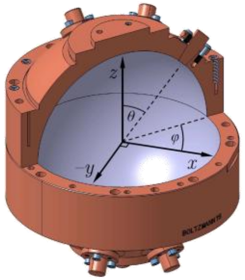


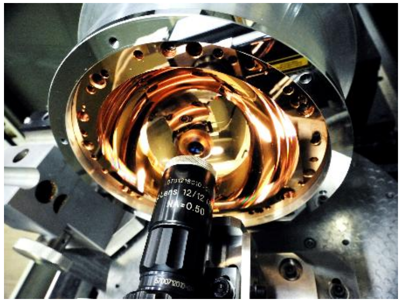
This is a tri-axial ellipsoid, non-rotationally symmetric (freeform) turning, with sub-micron accuracy

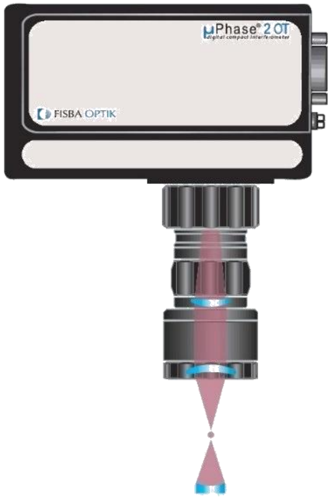


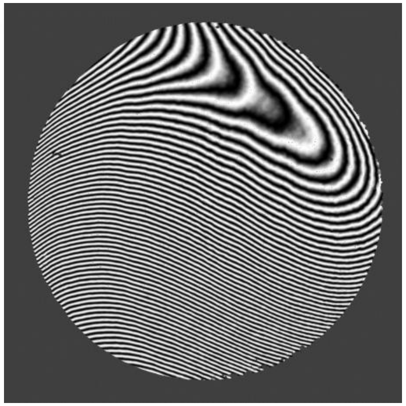
Interferometry

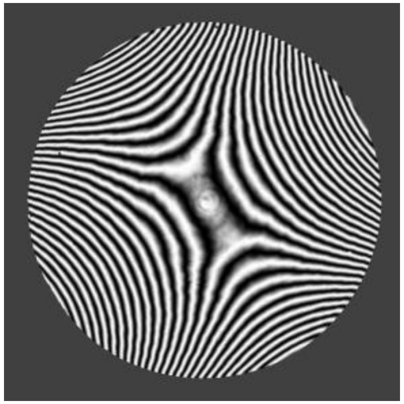


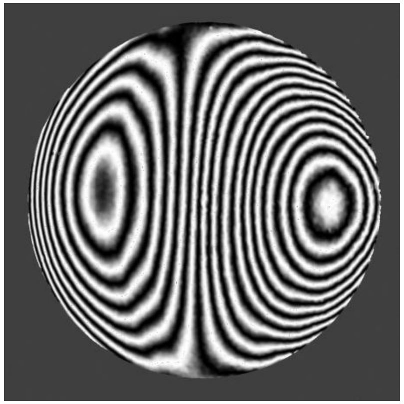






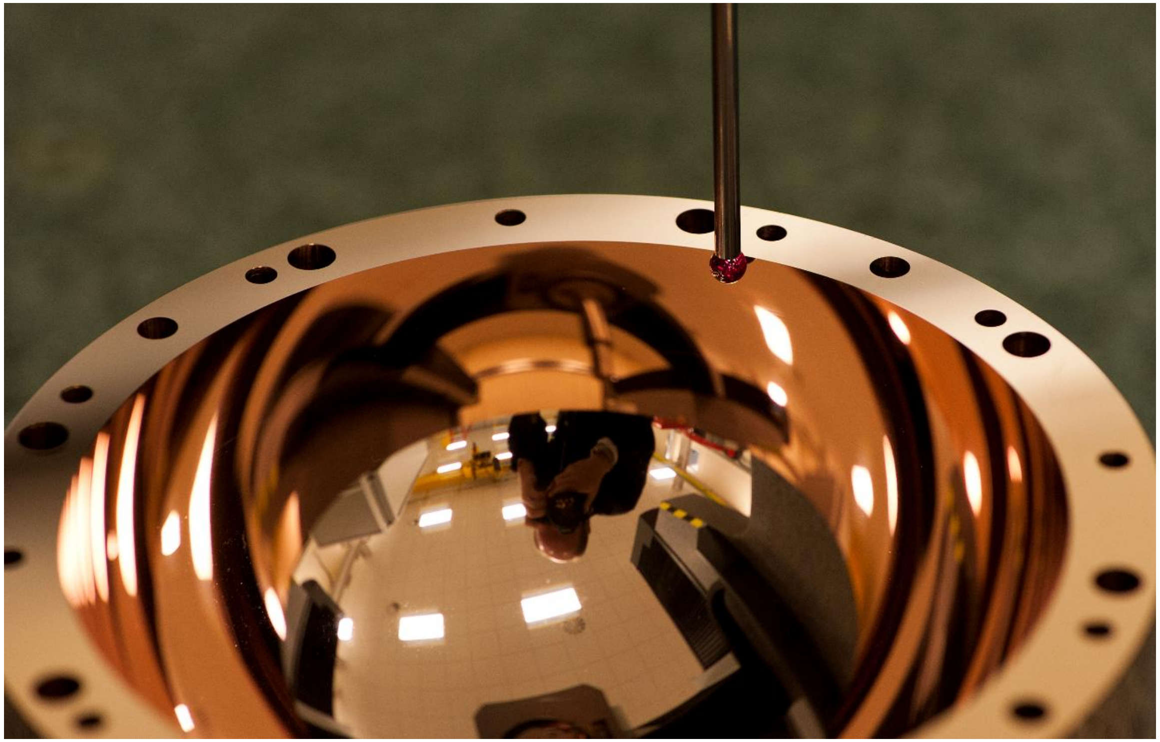


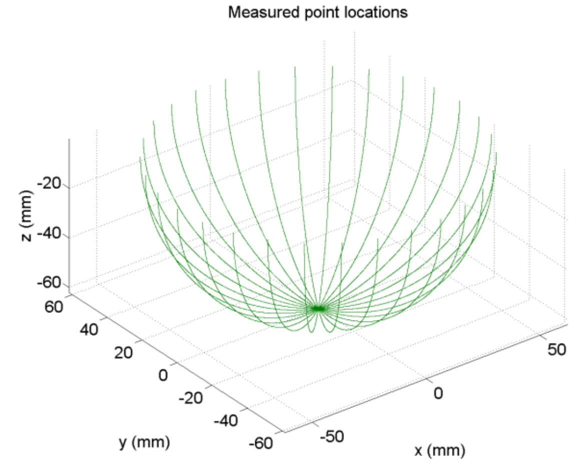


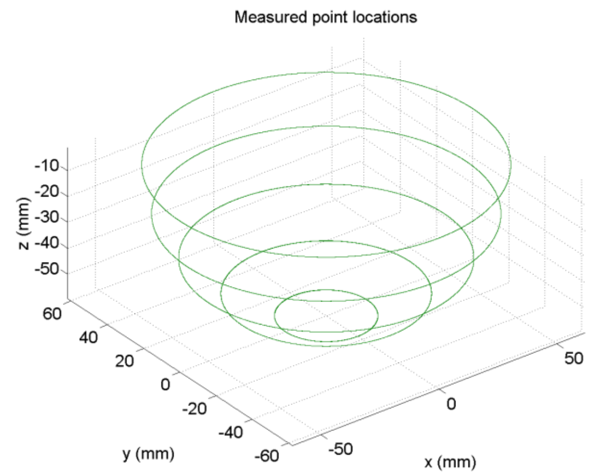


Field of view and fringe spacing limitations require stitching interferometry for full hemisphere metrology

CMM scanning metrology







- Scanning measurements (as for single point ones) will damage the surface
- Final measurement is taken before final machining pass, which removes < 2 μm

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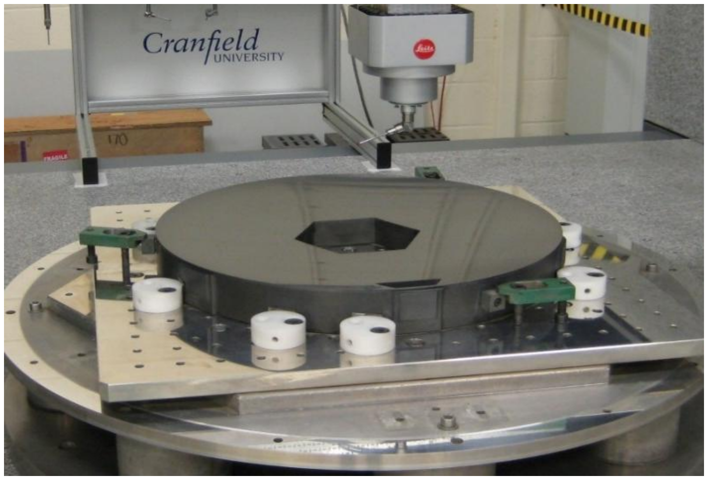
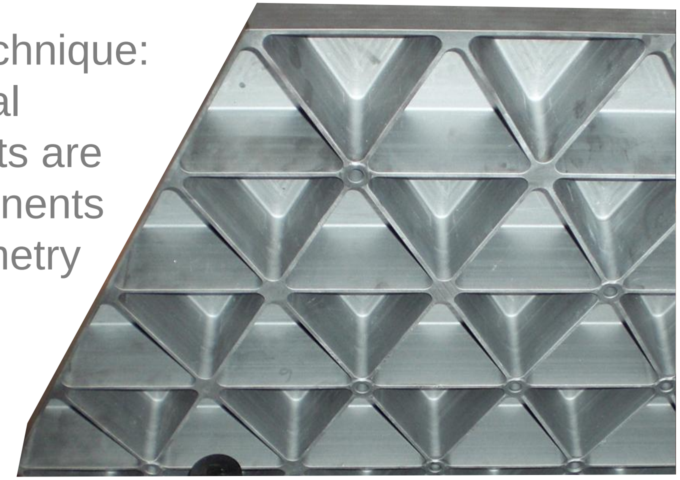
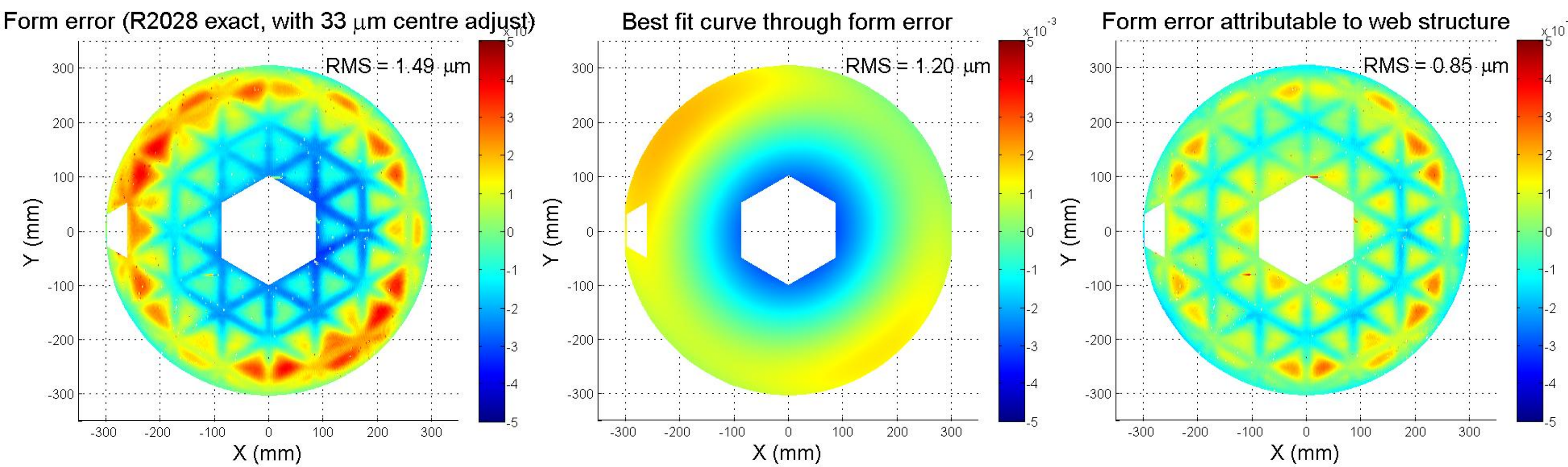
Complex form compensation



Clearer exposition of technique: high (~10^6 points) spatial resolution measurements are valuable also for components unsuitable for interferometry i.e. non-reflective





Presentation structure

1. Some observations
2. Enabling our future?
3. Drivers of accuracy improvement
4. Power of metrology innovations
5. In process measurement
    - Previous examples
    - New problem
6. Summary

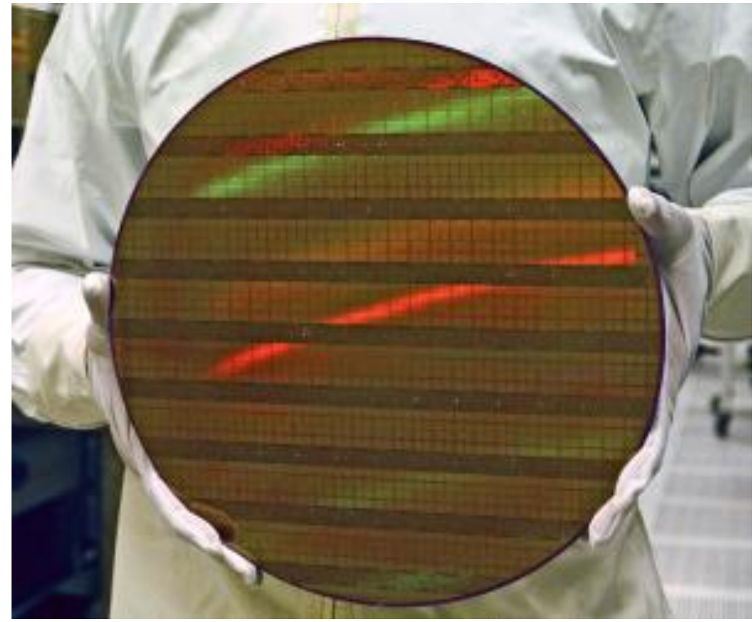
Emerging production

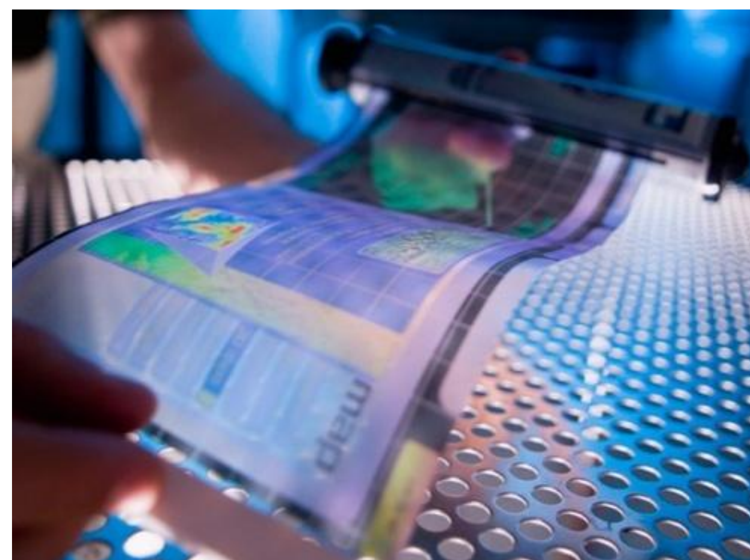
Shifting from processing
stable silicon substrates to films

Shifting from
"step and repeat" operations

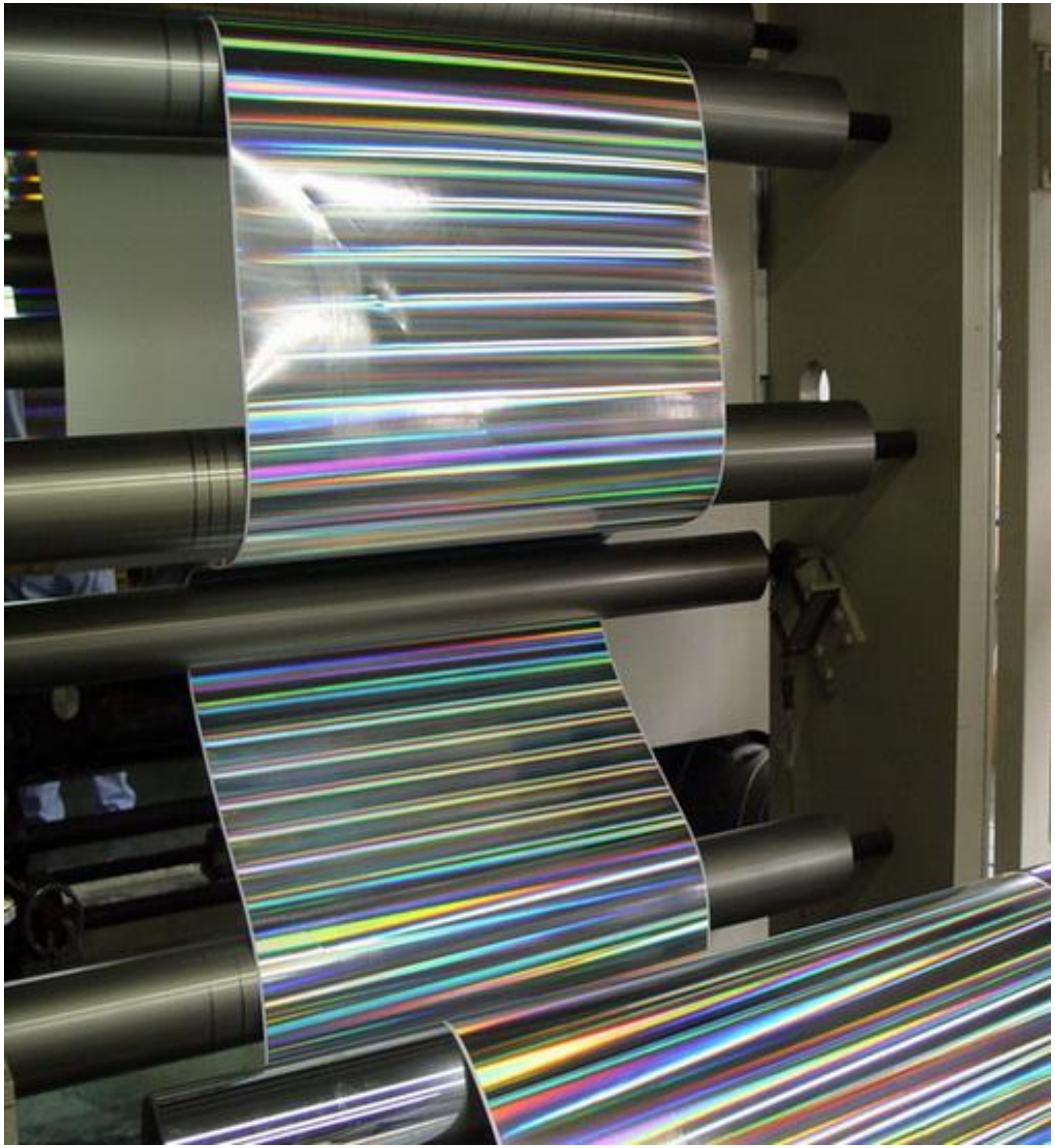
to

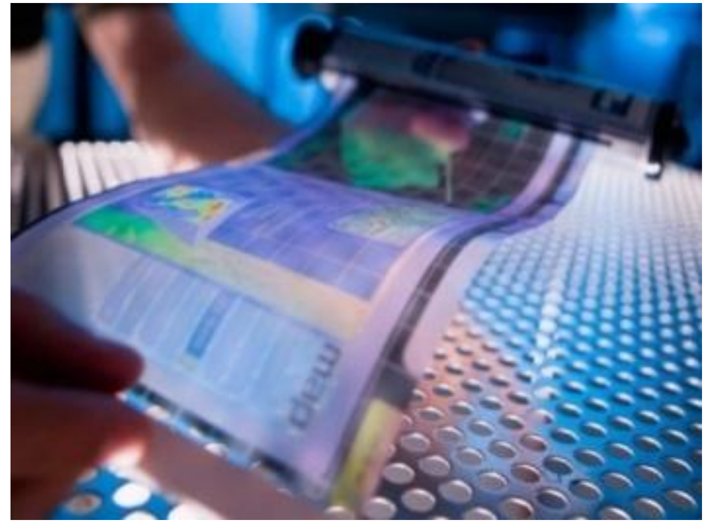
"reel to reel"
continuous processing



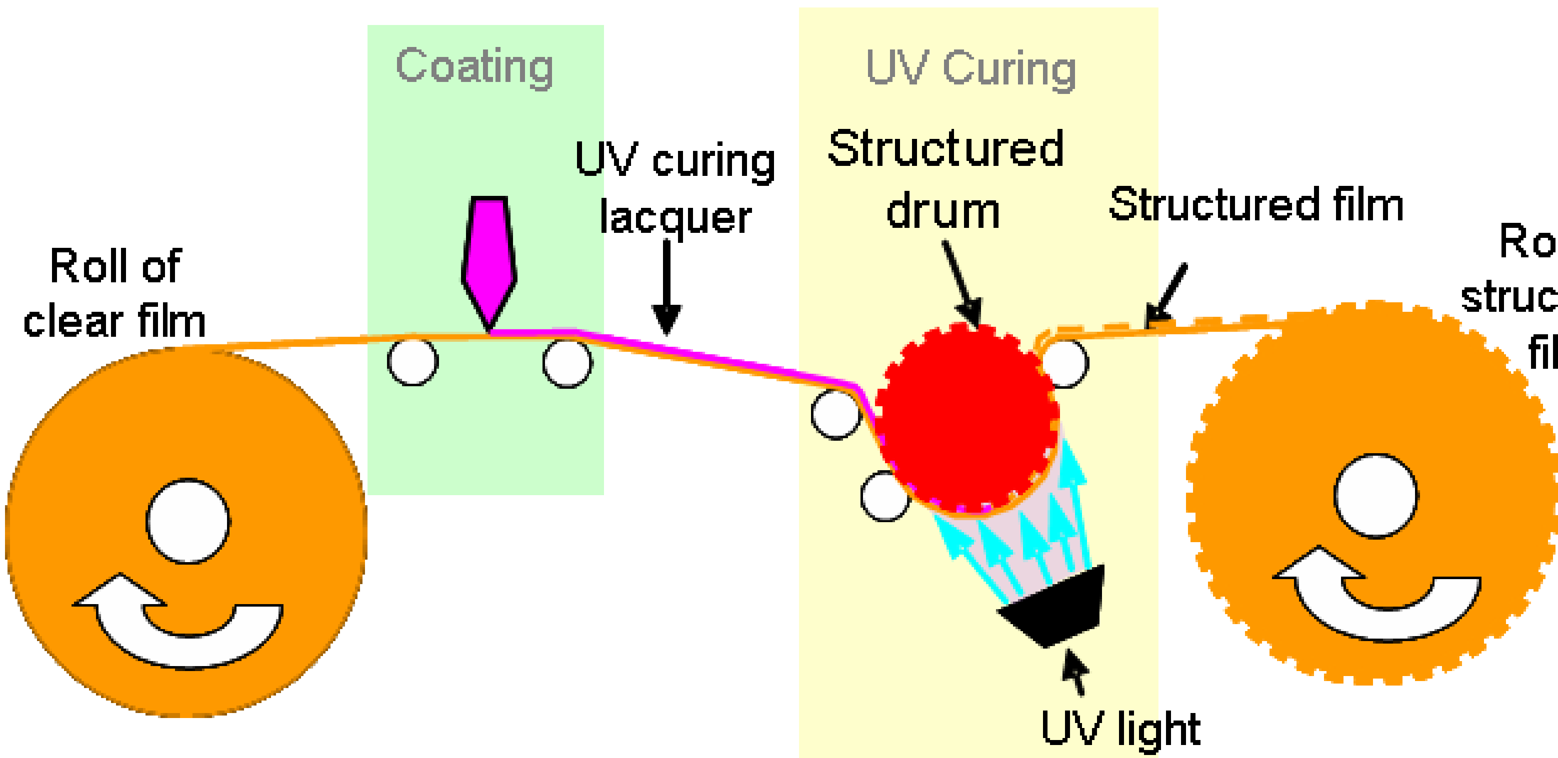


Emerging products

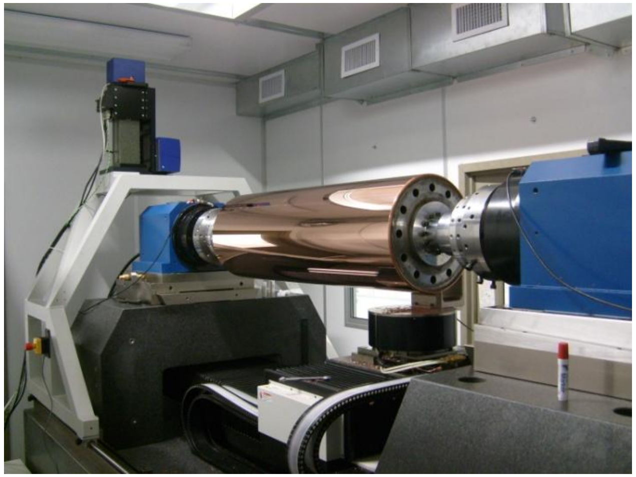




Replicating film from a structured drum



Surface Structuring of mould tools for Reel to Reel fabrication of light handling films



Purpose built facility

Clean room class 10,000

Lab temperature control +/- 1ºC

Enclosure temperature control +/- 0.1ºC

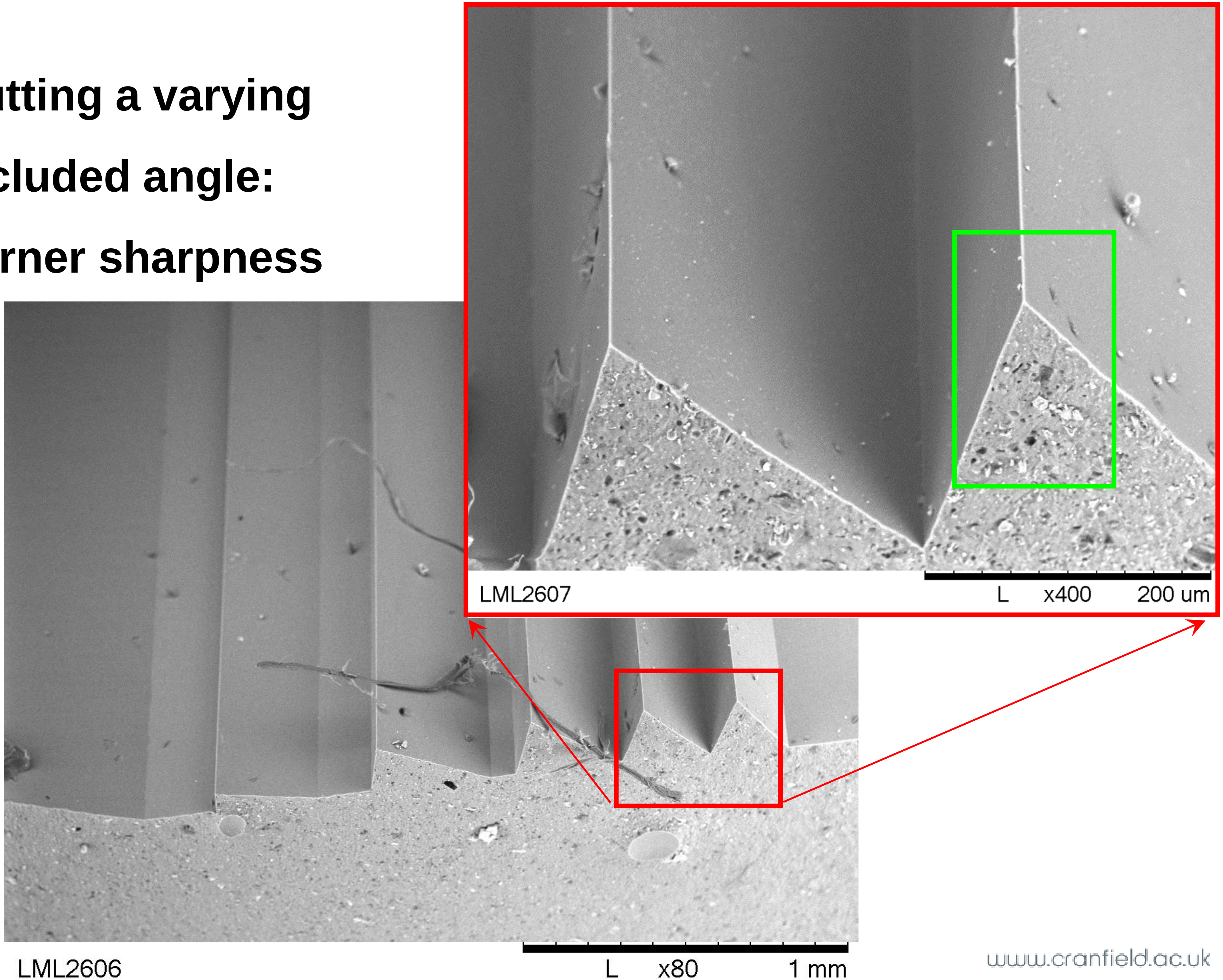
Active vibration isolation

Micro-textured cylindrical mould

NPL National Physical Laboratory

Cranfield UNIVERSITY

Cutting a varying included angle: corner sharpness

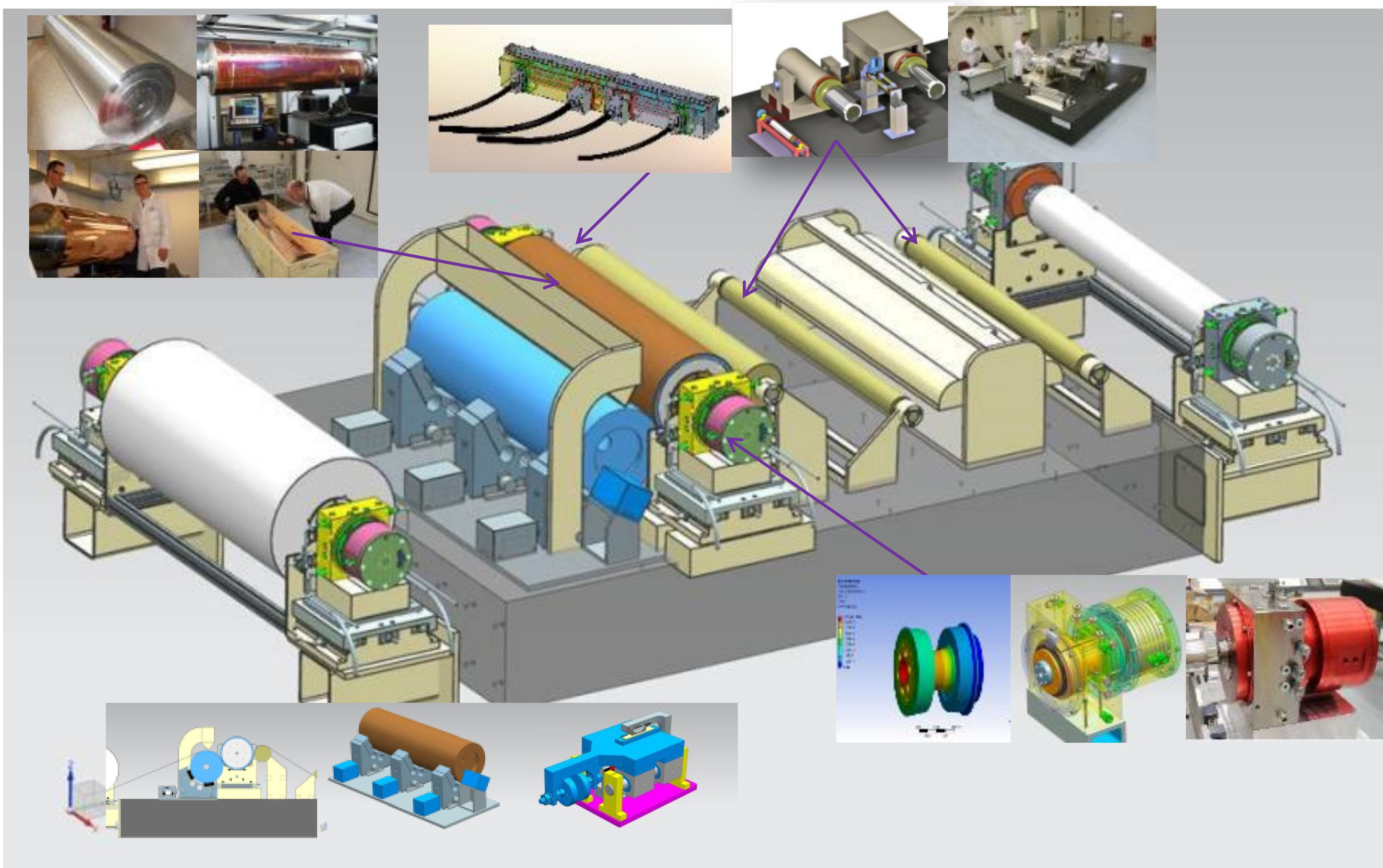


EPSRC Centre for innovative manufacturing in ultra precision

NPL National Physical Laboratory

UNIVERSITY OF CAMBRIDGE

Cranfield UNIVERSITY



Research Aspirations

Create machine technologies to realise an ultra precision Roll to Roll research platform that demonstrates:

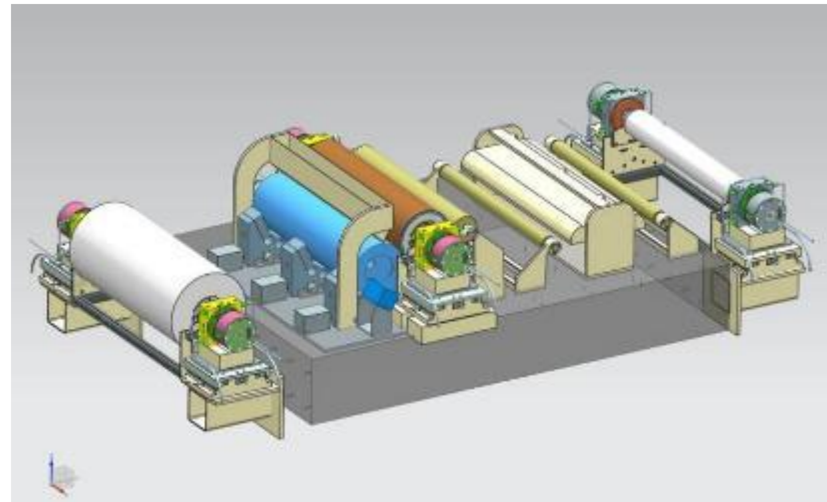
Large width film processing capability at **48”**

Multi stage embossing module with **200nm** re-positioning accuracy

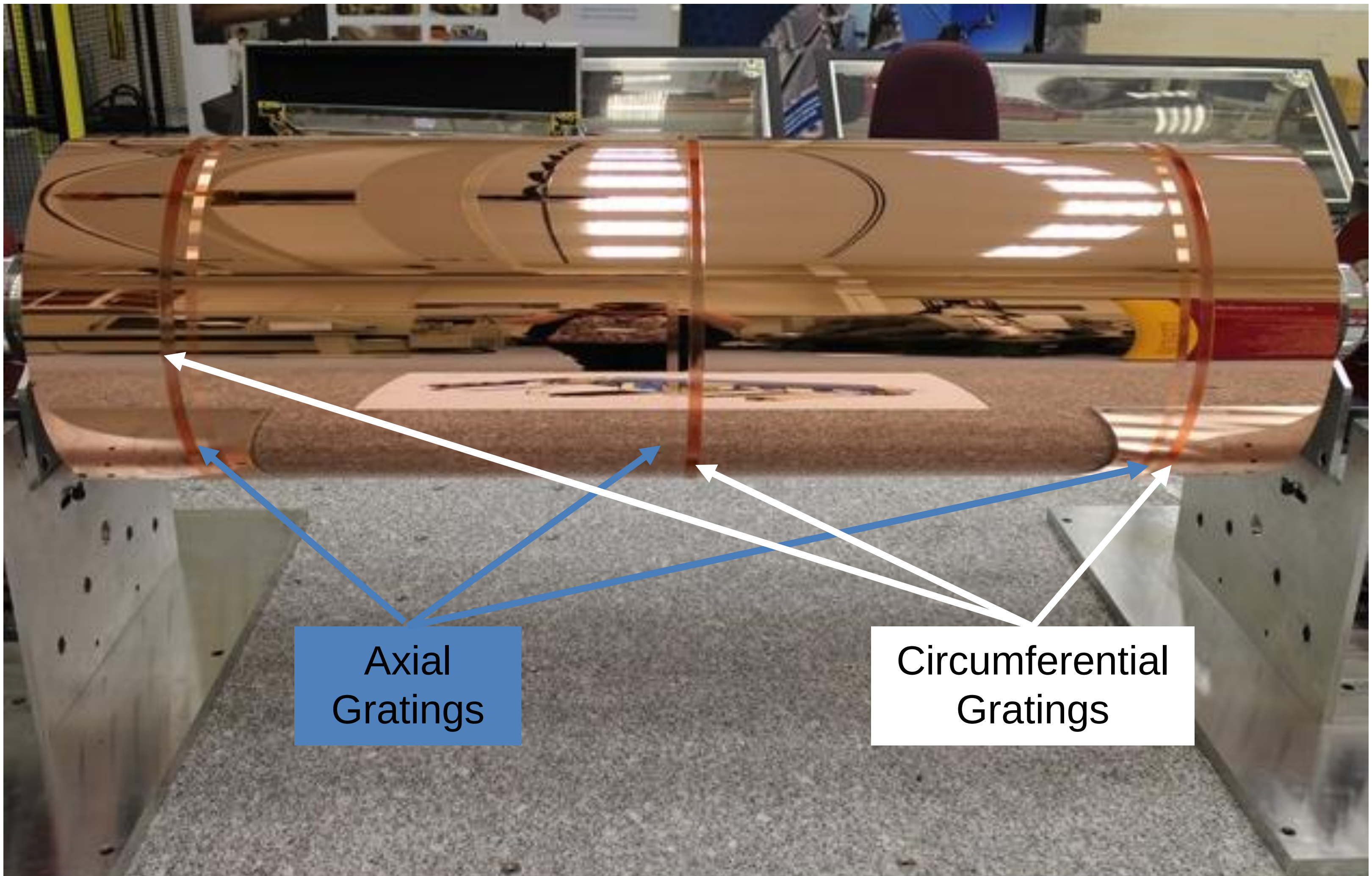
Film alignment measuring at **100nm** accuracy

Precision alignment module for multi film lamination at **500 - 1000nm** with alignment

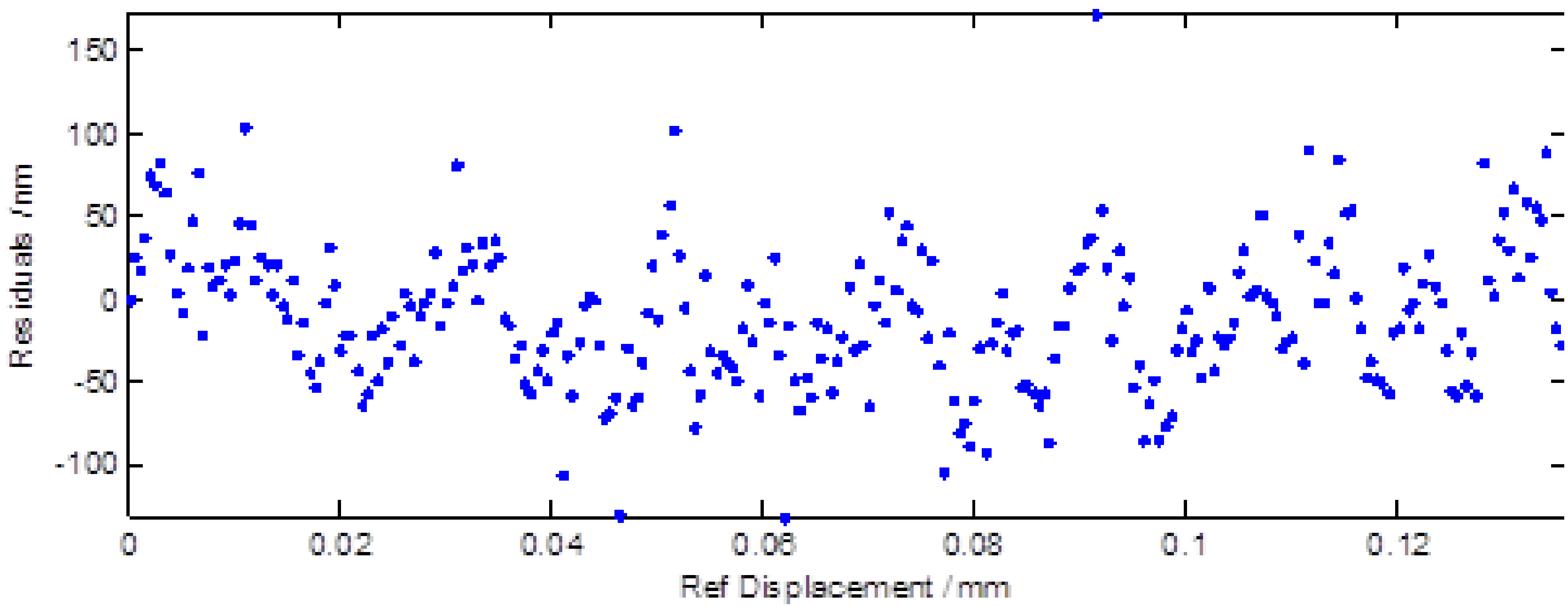
Apply processes:
Lacquer application, embossing, UV/flash cure, inkjet, laser, precision lamination



Instrumenting films prior to processing

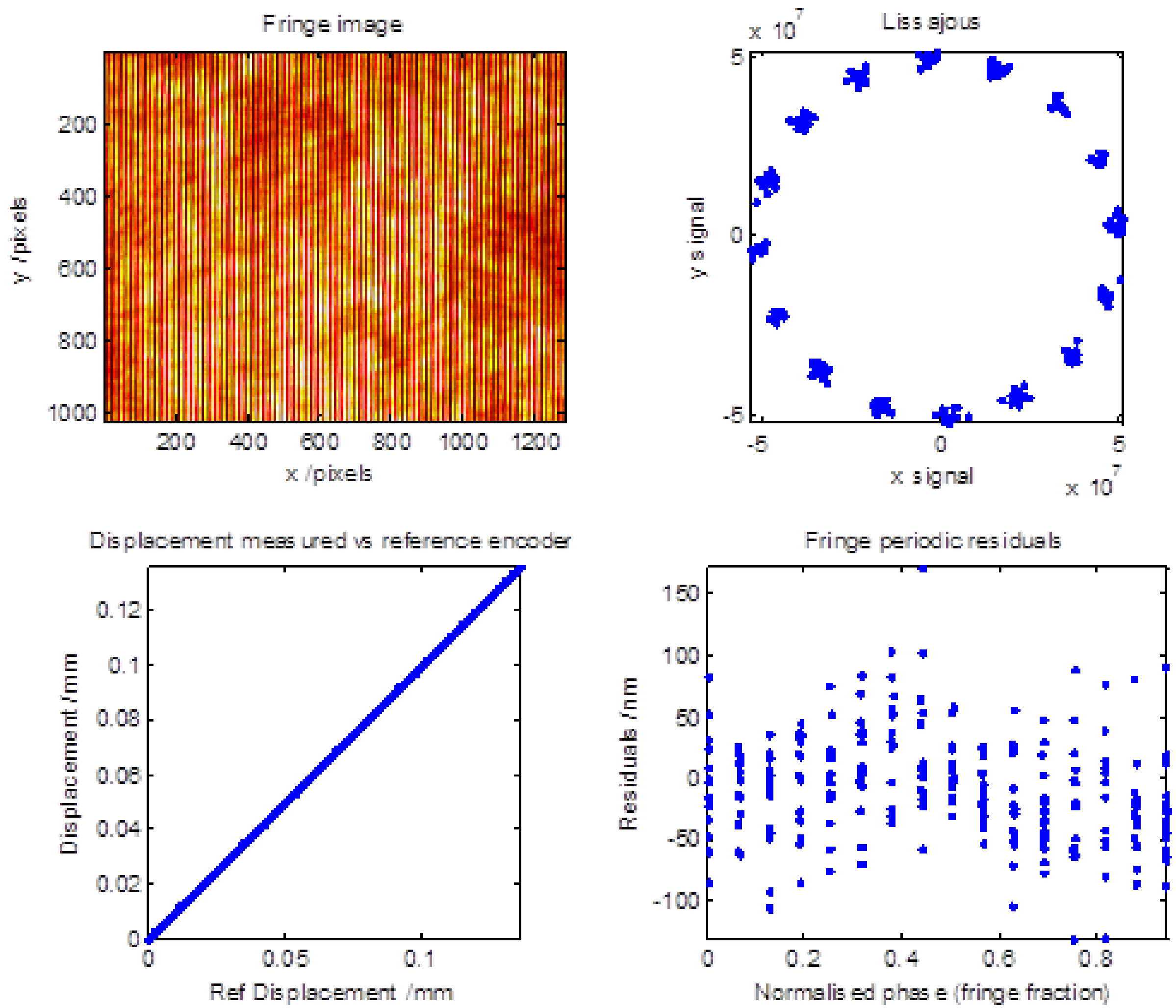


Instrumented plastic film with embossed gratings residual errors



Ref: Chris. Jones, NPL

Measurement performance of embossed gratings



Ref: Chris. Jones

Presentation structure

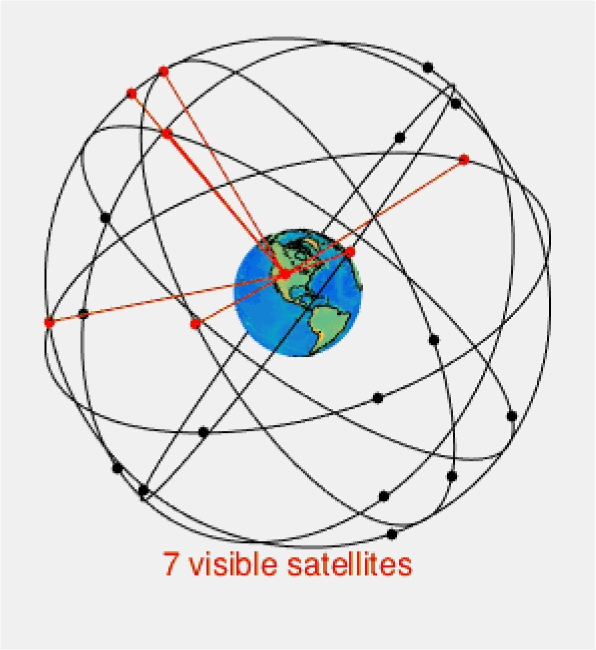
1. Some observations
2. Enabling our future?
3. Drivers of accuracy improvement
4. Power of metrology innovations
5. In process measurement
   - Previous examples
   - New problem
6 Summary

Power of metrology innovation

20 million metres above the earth

GPS provides 3D positioning uncertainty of < **10 metre**

5 parts in 10^7



In the near future,

23 million metres above the earth

Galileo targeting a positioning uncertainty to **0.01 m (1 cm)**

5 parts in 10^{10}

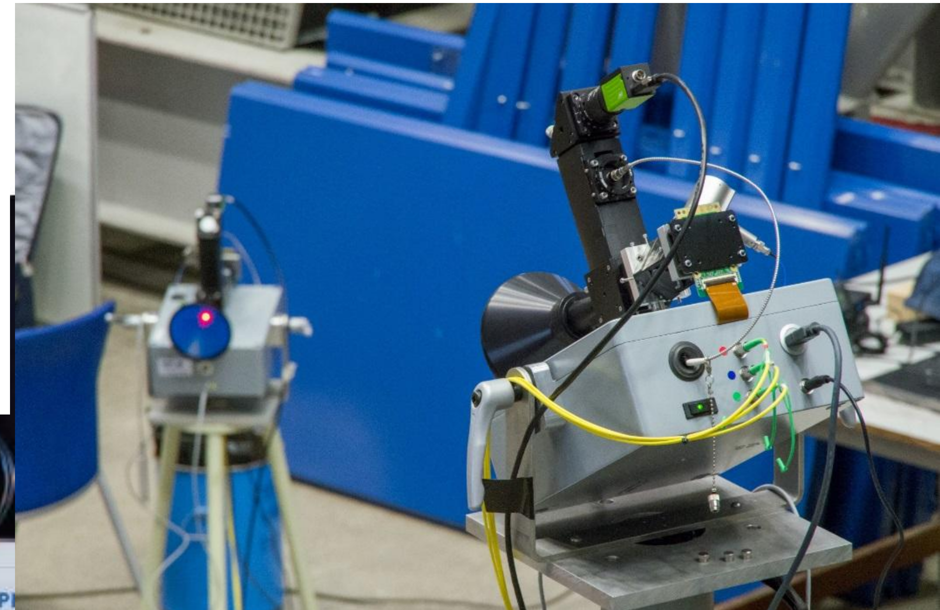
Indoor “GPS” Technology

NPL
National Physical Laboratory

High accuracy measurement complement to GPS / Galileo

Frameless that makes Buildings the measuring machine frames

Able to identify elements and perform measurements on them



NPL National Physical Laboratory

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Acknowledgements

- UK National Measurement system
- EPSRC UPS Basic Technologies
- EPSRC UPS^2 IKC Programme
- EPSRC Ultra Precision Centre
- UK National Measurement System
- Companies and organisations

Microsharp, RAPT, Surrey Satellites, Qioptiq, Loxham, Gooch & Housego, Kodak, RAL, LLNL, LMJ, CP, UK ATC, ESO, ESA, NASA, NPL , Rolls Royce, Lidkoping Machine Tools, SKF, SBC, CERN

The NPL-Cranfield Acoustic Thermometer

Measures the speed of sound in a spherical resonator

BOLTZMANN Primary Thermometer

Most accurate thermometer in human history

Combined microwave and acoustic resonator with quasi-spherical inner surface enabling:

Thermodynamic temperature within ±0.2 mK

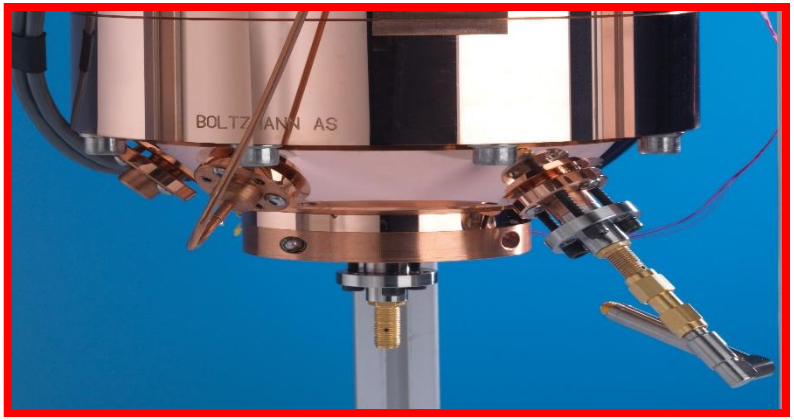
- *From 118 K to 303 K - extendable*

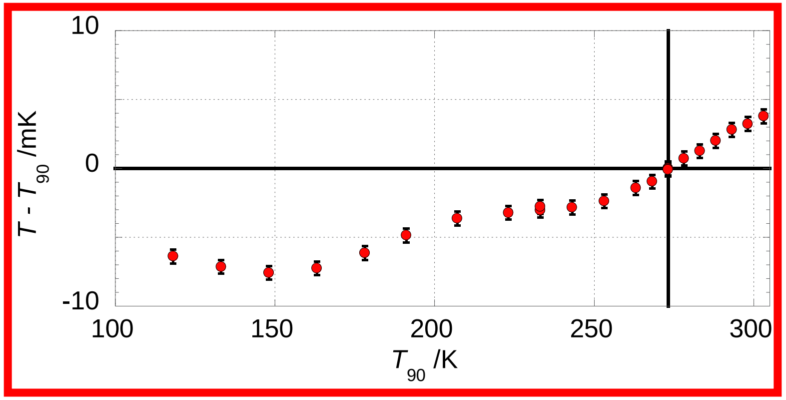
Mode-to-Mode agreement:

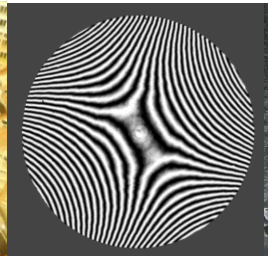
- *Acoustic resonances* u_R < 0.5 ppm (~0.1 mK)
- *Microwave resonances* u_R < 0.1 ppm (~6 nm)
- *Fractional Excess Acoustic half-width* < 10^{-6}

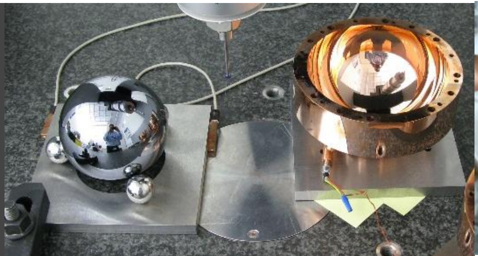
Achieved by:

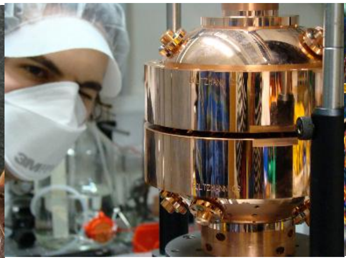
- *Internal surface is trixial-ellipsoid within 1.5 µm performed at Cranfield University*
- Calculation of probe and shape perturbations

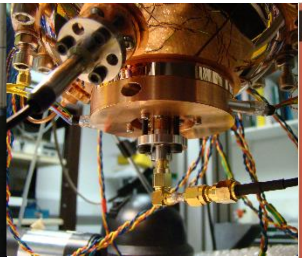


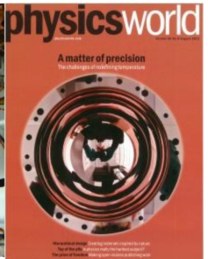




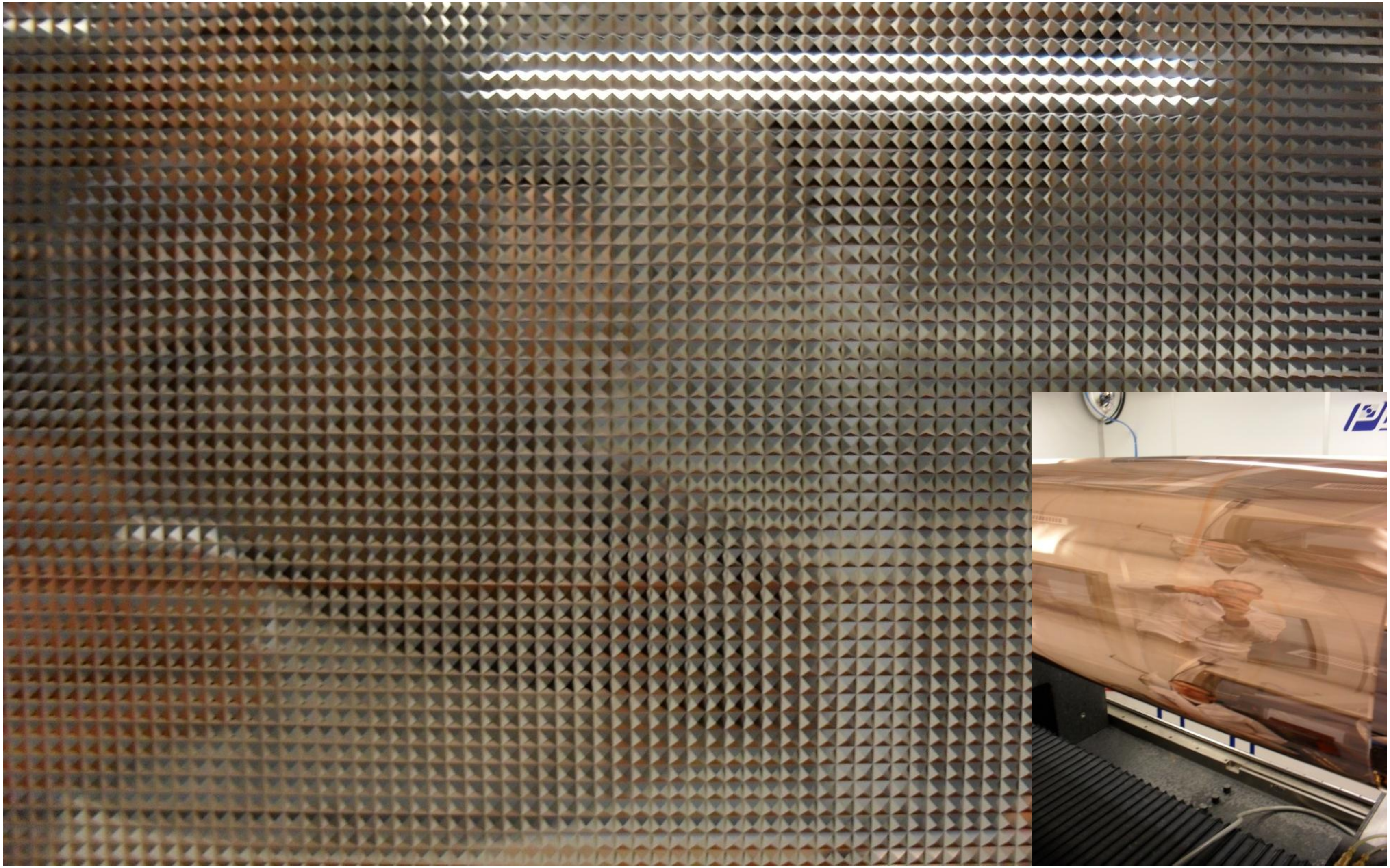








Micro-textured retro-reflecting surfaces



Summary

1) How do product development pathwaths influence manufacturing, manufacturing research and measurement research?

Tend to demand higher relative levels of accuracy, on components of shape complexity with greater scale

Noting: energy is enemy of precision but the driver of production

2) What key technical developments will help secure and establish future successful manufacturing capability?

Processes that can be performed in more "hostile" environments on materials having lower stability levels and more complexity

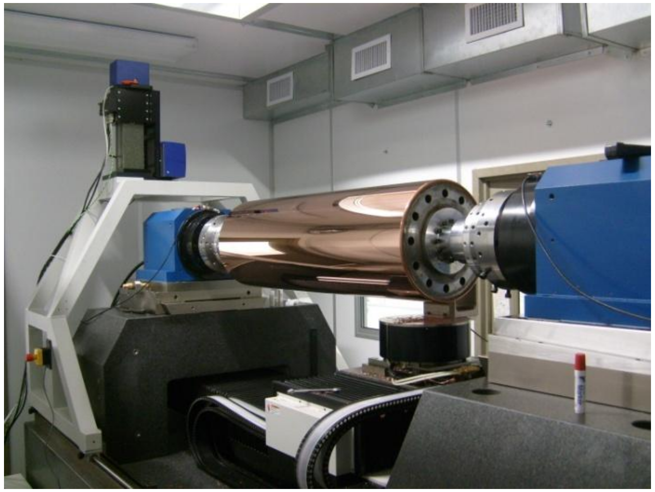
3) What future manufacturing developments will be critical to human-kind's long term prosperity?

Those that enable effective energy production technologies

Precision Engineering at Cranfield

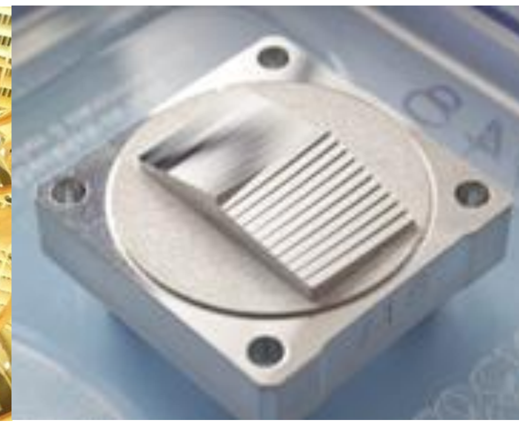
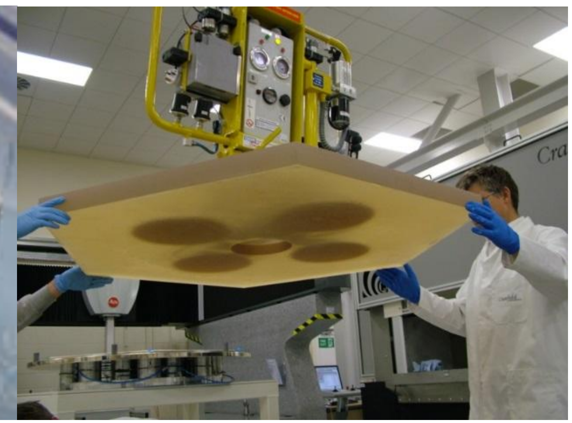
Cranfield UNIVERSITY

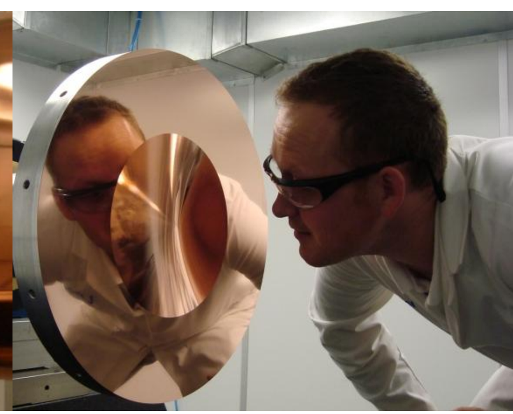
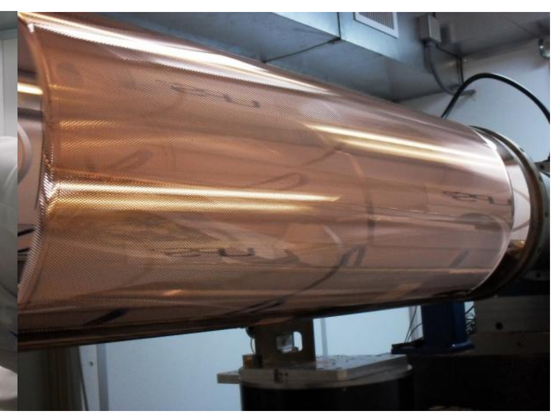
We aim to hold a capability to innovate and build new machine tools, and to operate purposeful ultra precision laboratories that **provide a good place to train precision engineers**.



“marketing”, that we:

- Define temperature
- Make more mirror surfaces for Hubble replacement than anyone else
- Produce mirror segments for ESO’s extremely large telescope
- Operate leading commercial micro-structuring facility supplying “blue chips”

The 11 Principles and Techniques for the Design of High Precision Machines (P.A. McKeown)

1. **Structure:**
   symmetry; dynamic stiff; high damping; secular stability;
   thermal stability; independent of foundation; seismic isolation.
2. **Kinematic/Semi-Kinematic Design:**
   rigid body kinematics; three point support
3. **Abbé Principle (or options)**
4. **"Direct" Displacement Transducers:**
   scale or laser interferometer(s)
5. **Metrology Frames:**
   isolate measuring system from force paths and machine distortion
6. **Bearings:**
   high accuracy; high averaging/low rumble; low
   thermal effects; low limiting friction; high damping

The 11 Principles and Techniques for the Design of High Precision Machines (P.A. McKeown)

7. **Drives/Carriages:**
   through axes of reaction; "non-influencing" couplings and clamps
8. **Thermal Effects:**
   eliminate/minimise thermal inputs and drift;
   stabilisation/compensation
9. **Servo-Drives and Control (CNC):**
   high stiffness/response/bandwidth; zero following errors;
   dynamic position-loop synchronisation
10. **Error Budgeting:**
    (i) geometrical-angular, straightness & orthogonal error motions
    (ii) thermal-loop expansions; deformations
11. **Error Compensation:**
    linear; planar; volumetric; quasi-static and dynamic

common design "tensions"

Rapid dynamically stiff and responsive characteristics

Require low m… …er density
m… …interfaces /
…ings

the "enemy" of precision
is stray energy

High load & power capacit…
with high static stif…

Significant (heavy) structures and large (heat generating) bearings

High vo… …c motional accuracy

Low energy, kinematic designs with athermalising features

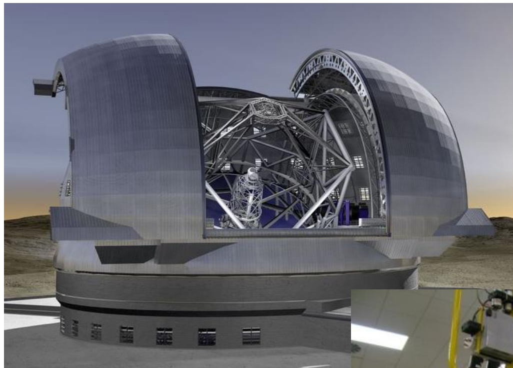
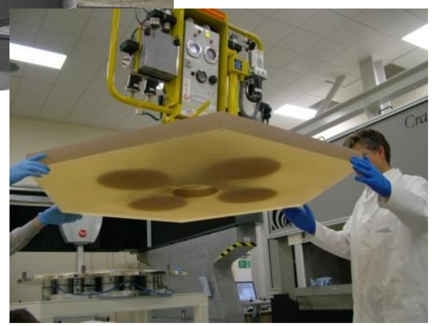
Machine Tool Productivity is significantly associated with power density

Presentation Outline

- Cranfield approaches to design of machine systems
- **Systems thinking through a production chain**
  - Ultra Precision Surfaces at 1 foot^2 per hour
- Integration challenges
  - Domestic appliance sized machine
- Summary

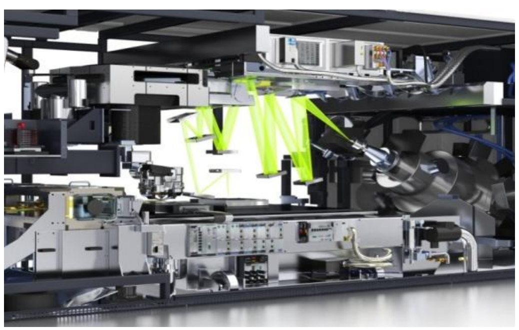
Production of Large Scale Optics

Cranfield UNIVERSITY

Telescopes
- ELT

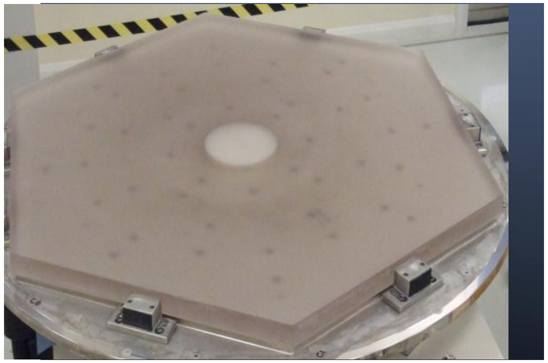

Space – Earth orbiters



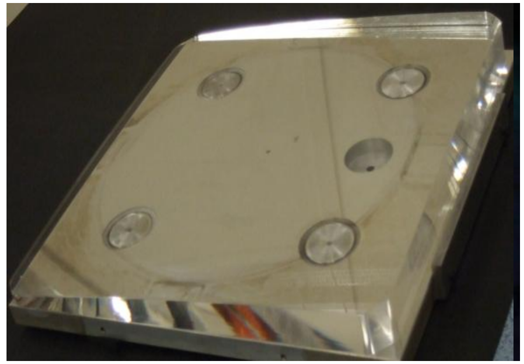

Lithography - EUV microlithography Systems


Fusion – High power laser optics

Demand for Metre Scale Optics



Astronomy: segments up to 2 m diameter for extremely large telescopes primary mirrors.



Laser fusion energy: thousands of optics up to 0.75 m for laser focussing systems.

EUV-lithography: new reflection optics for 13 nm wavelength technology up to metre scale.

Surface qualities

Free form shapes (off axis Ellipsoids / Paraboloids)

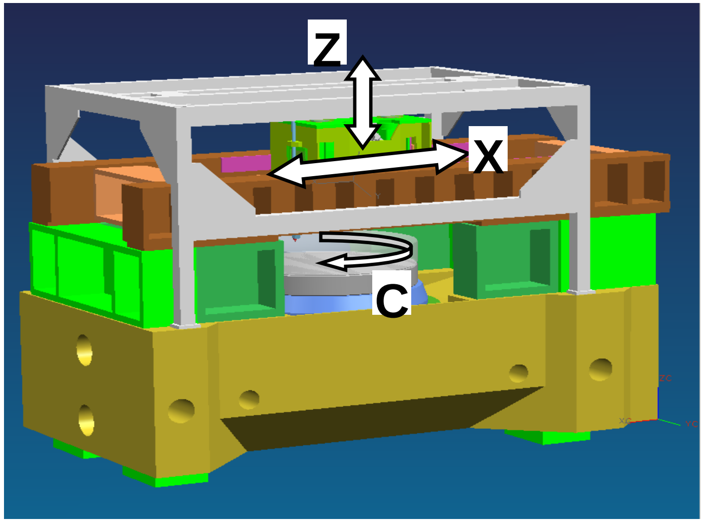
< 1 nm RMS (Sa) surface roughness

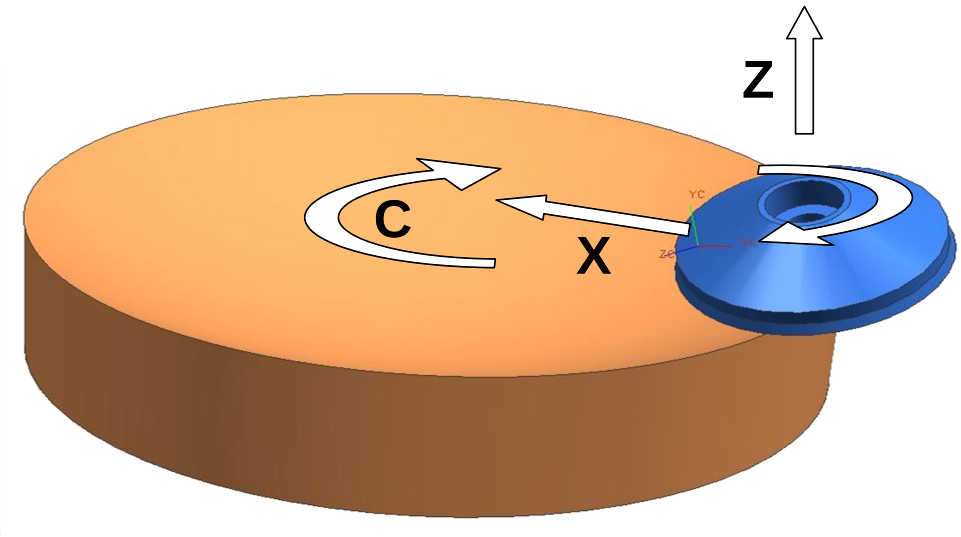
~ 1 – 30 nm RMS form accuracy (including edge regions)

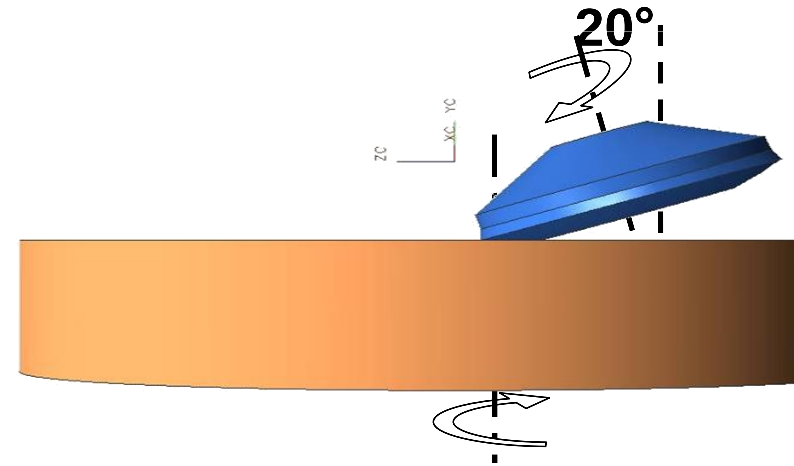
Very limited surface structure (mid-spatial features)

Free of sub surface defects / stresses

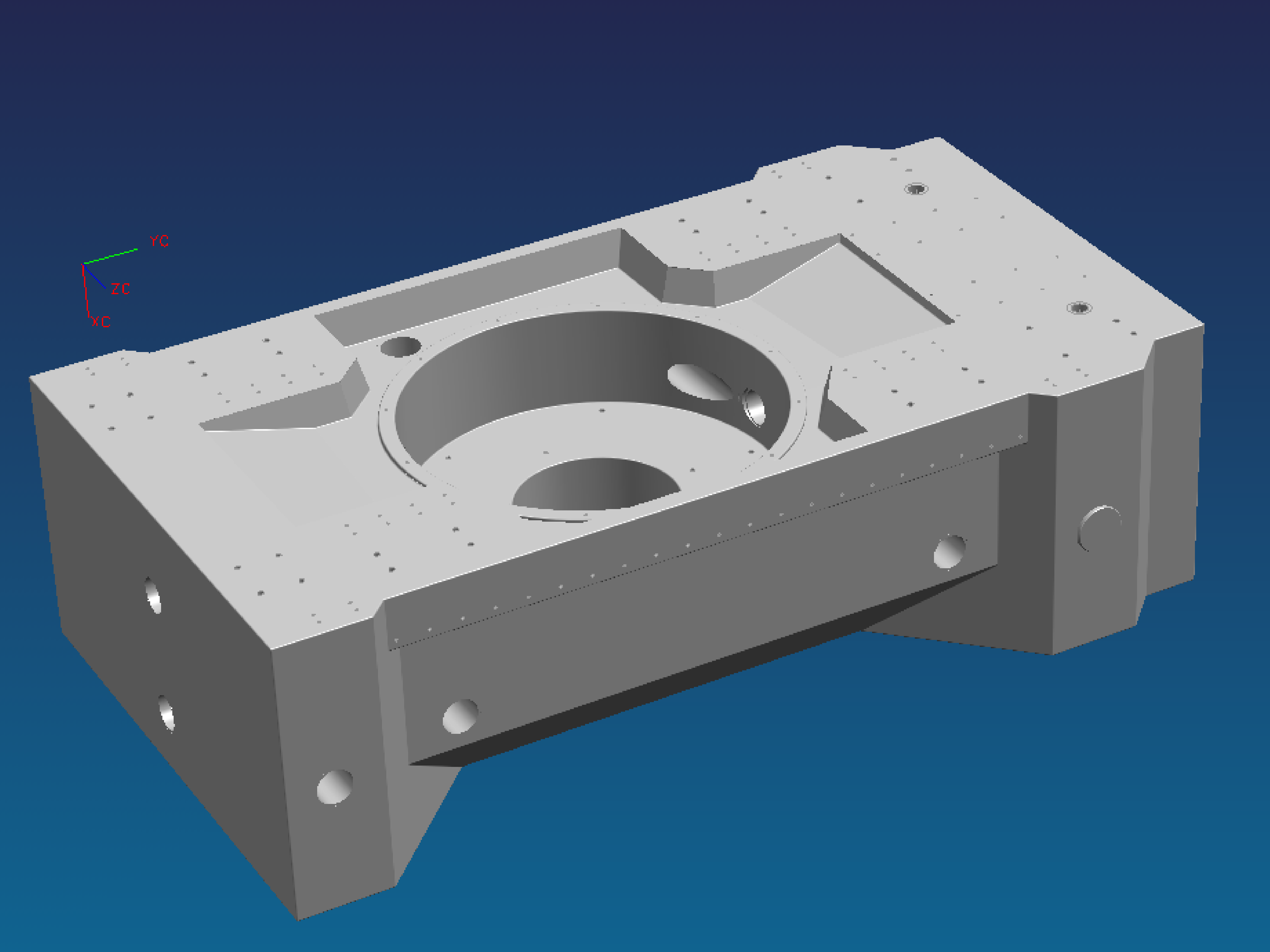
BoX grinding motion

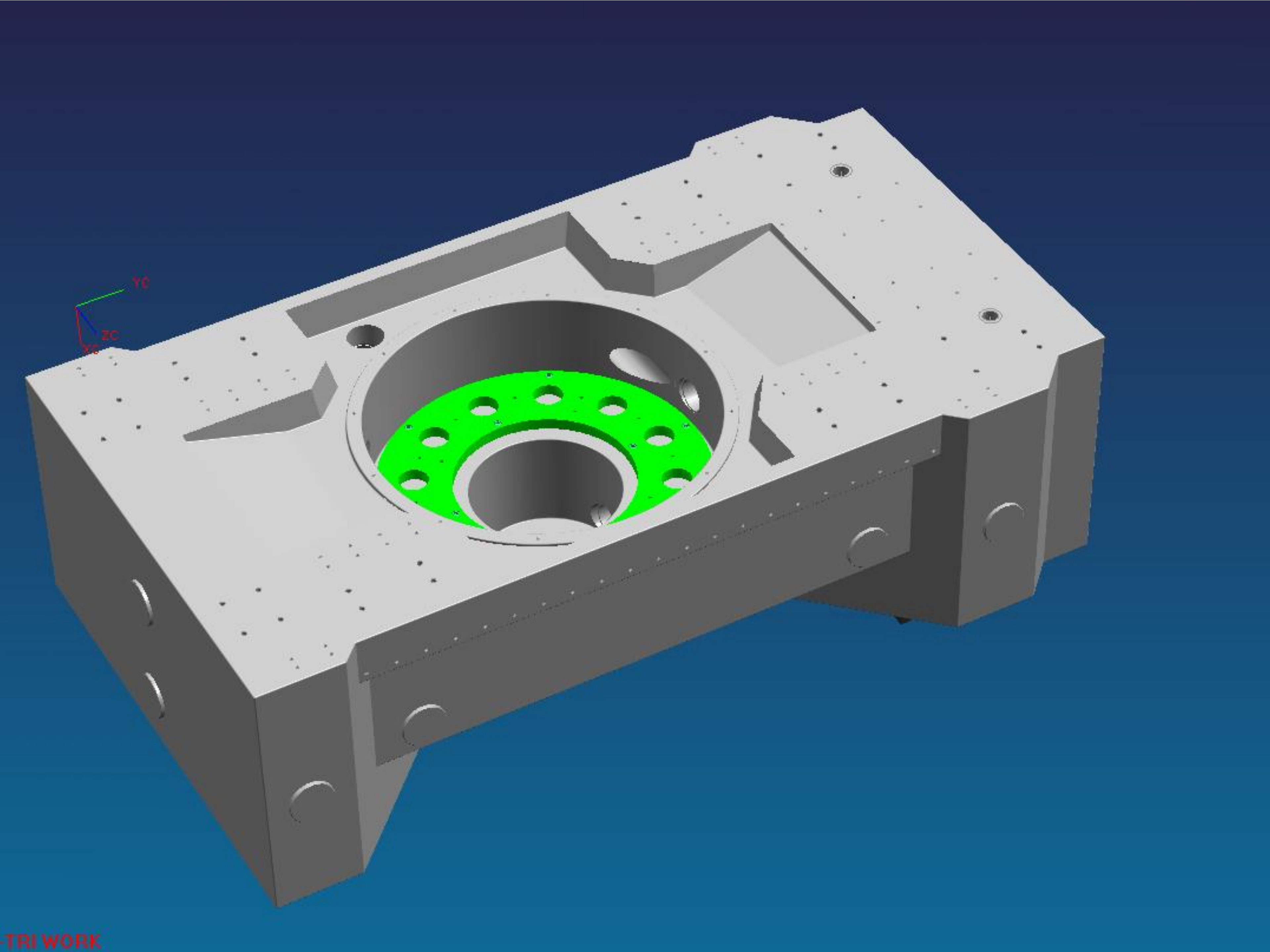


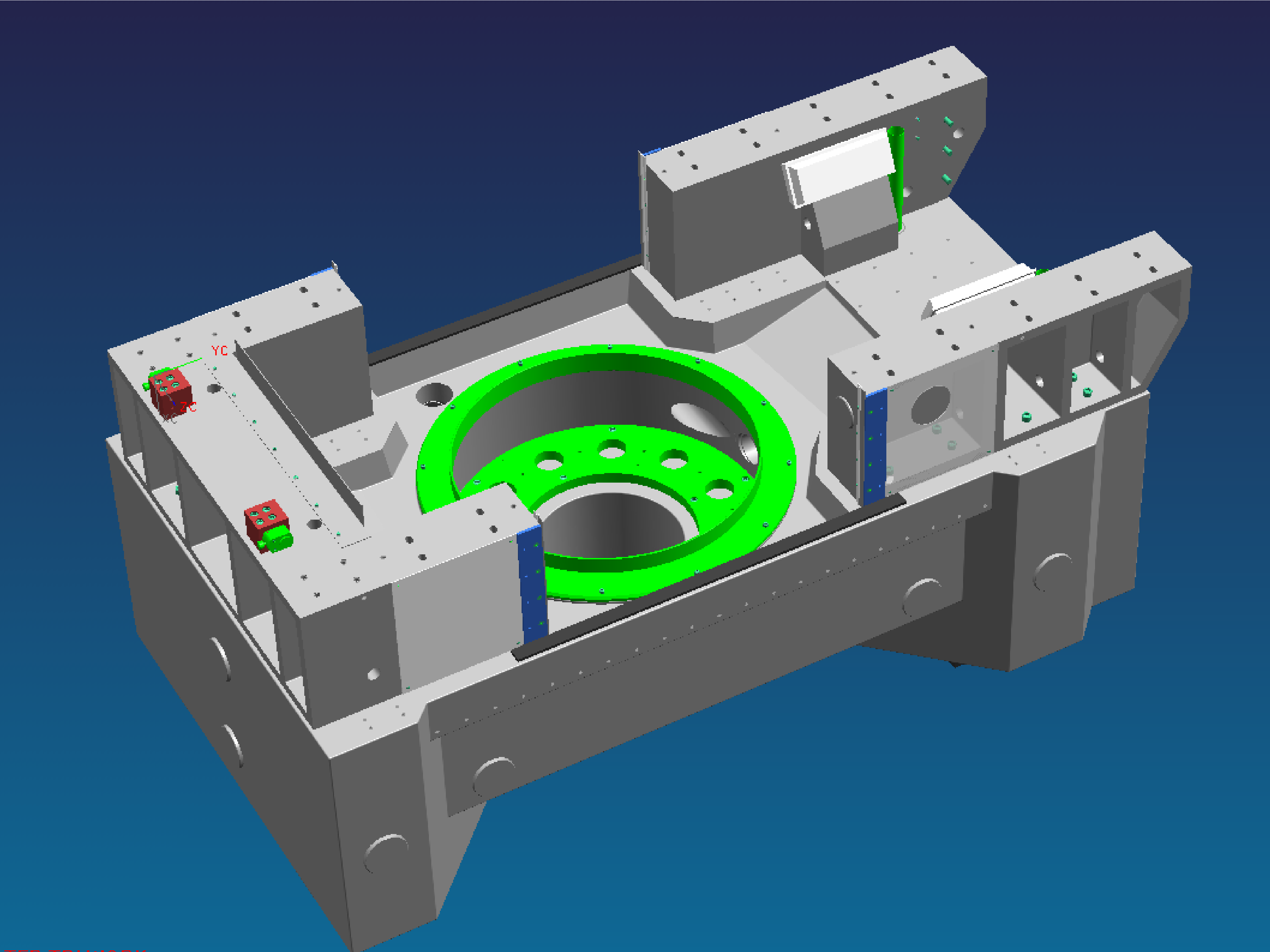




- Free-form grinding capability
- Novel 3 axes configuration
- R-theta grinding mode
- Toroidal shape grinding wheel
- Sophisticated toolpath software


YC
ZC
XC


YC
ZC
TRI WORK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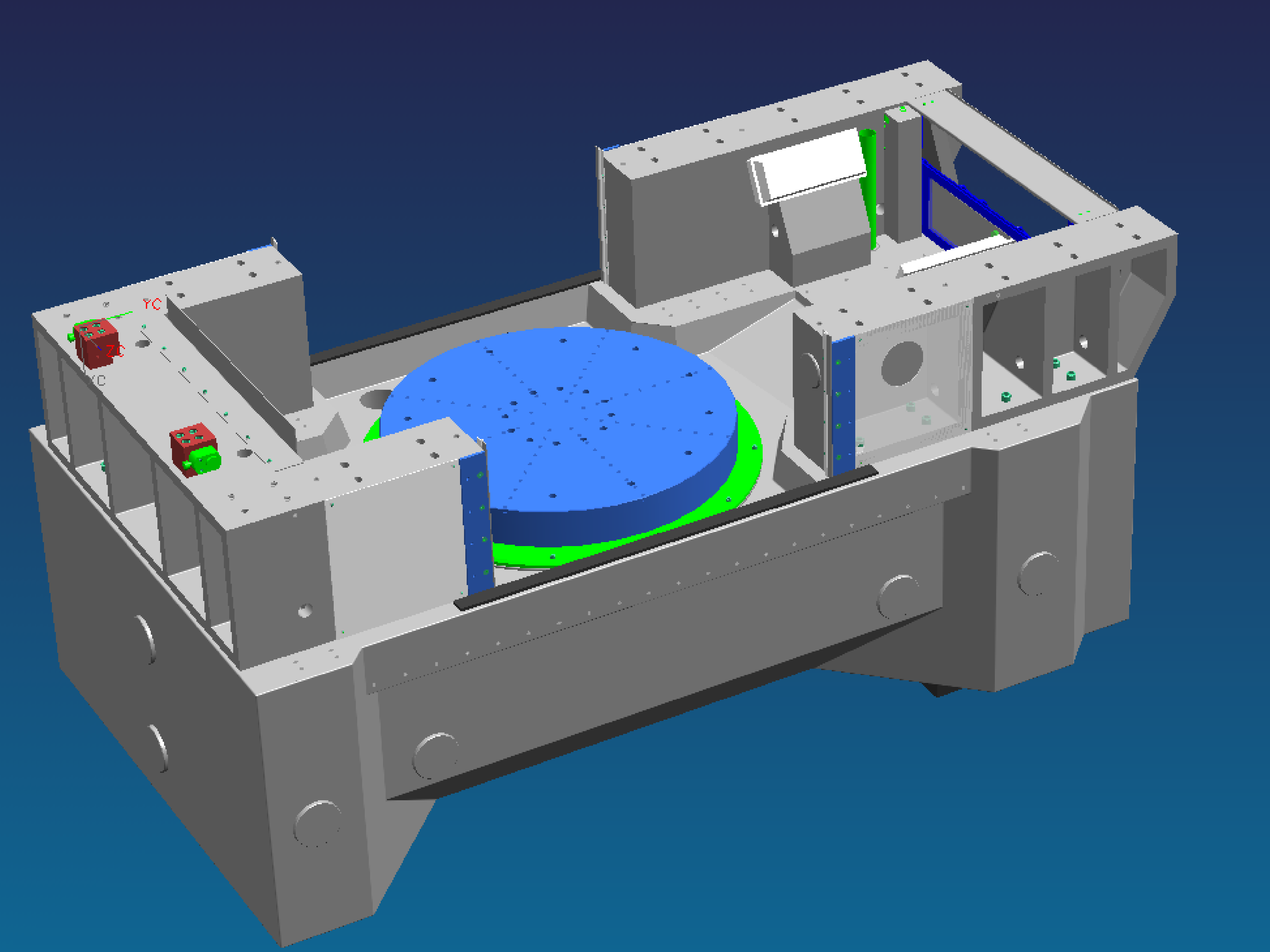
ZC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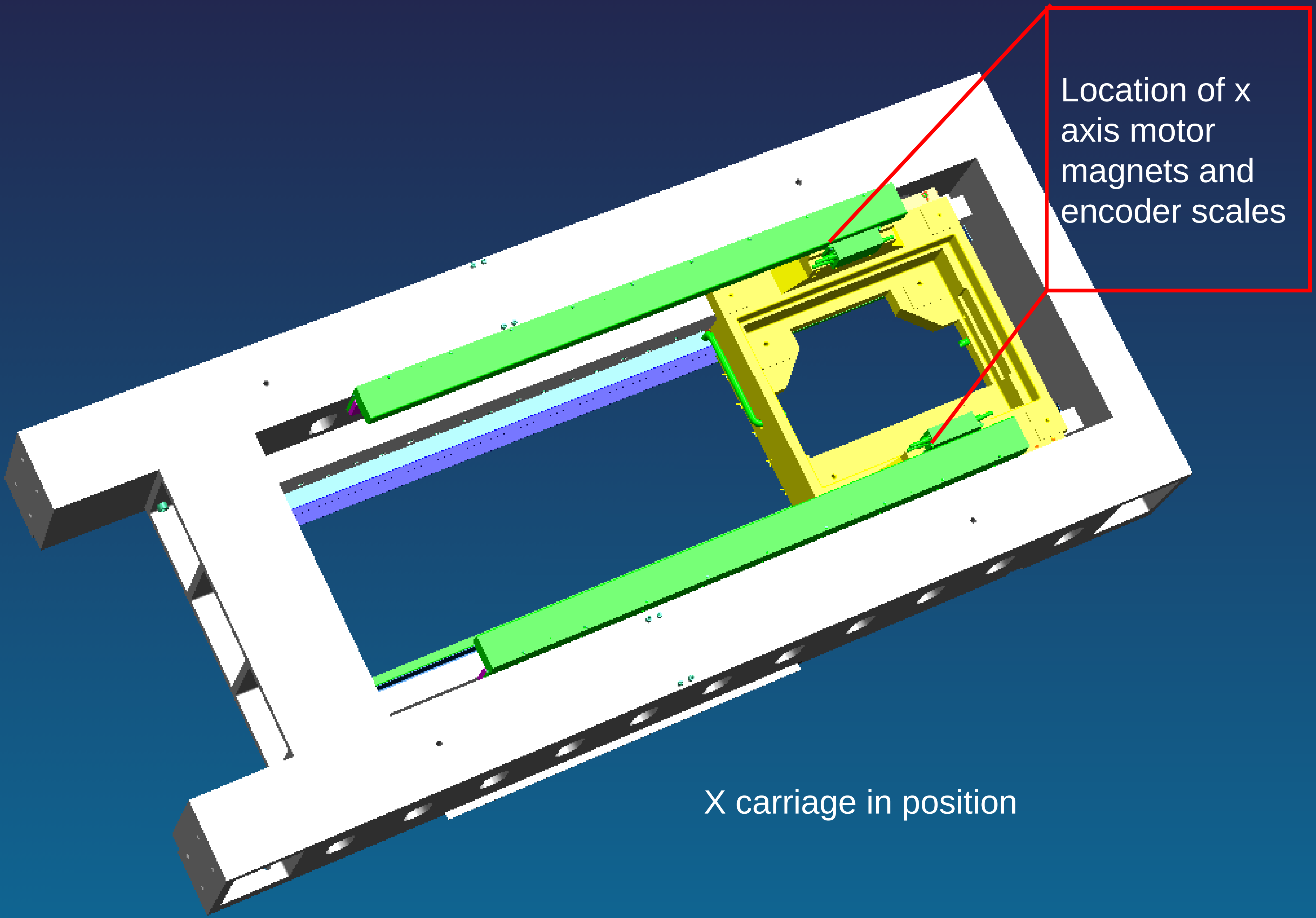
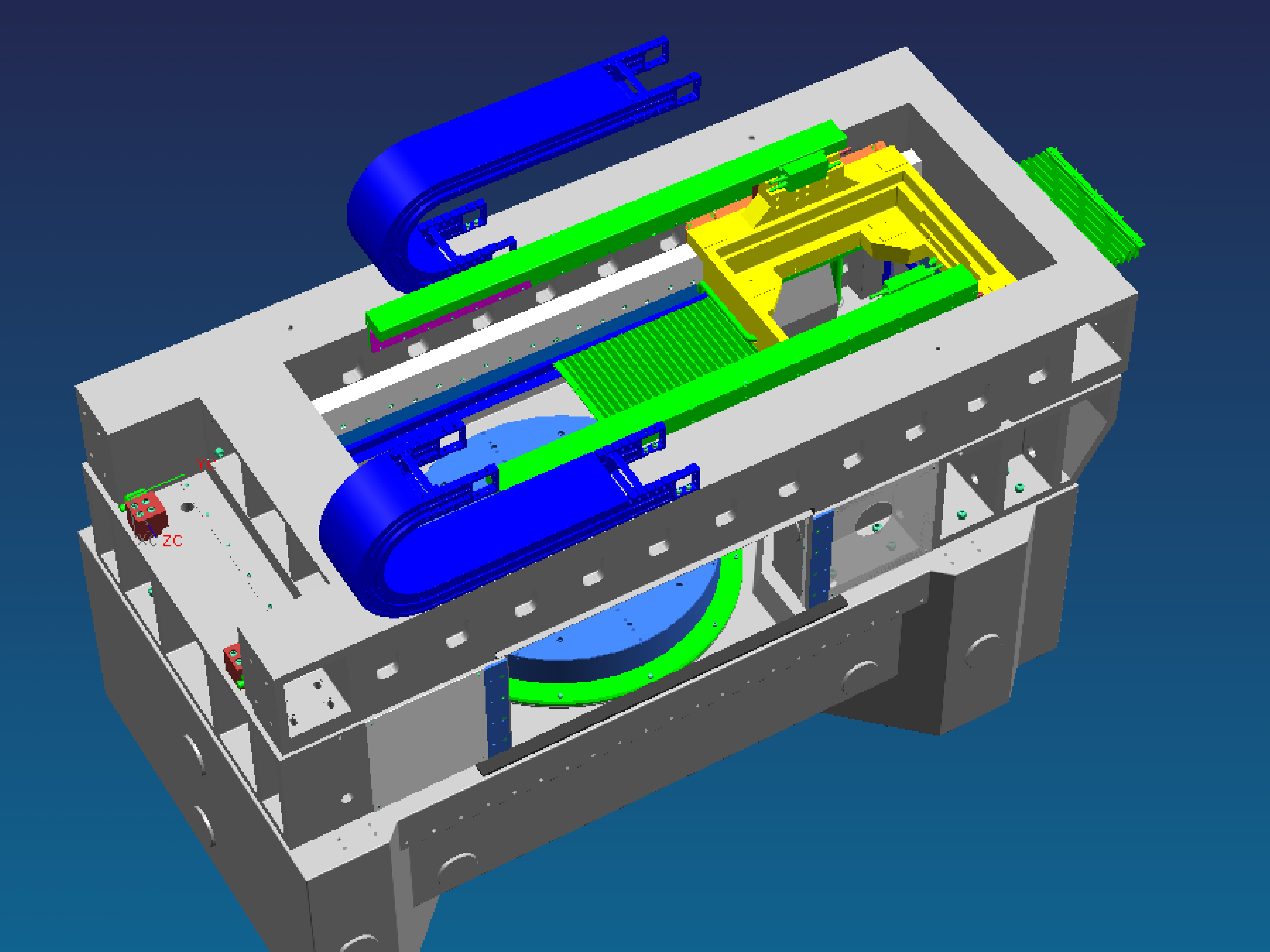


X carriage in position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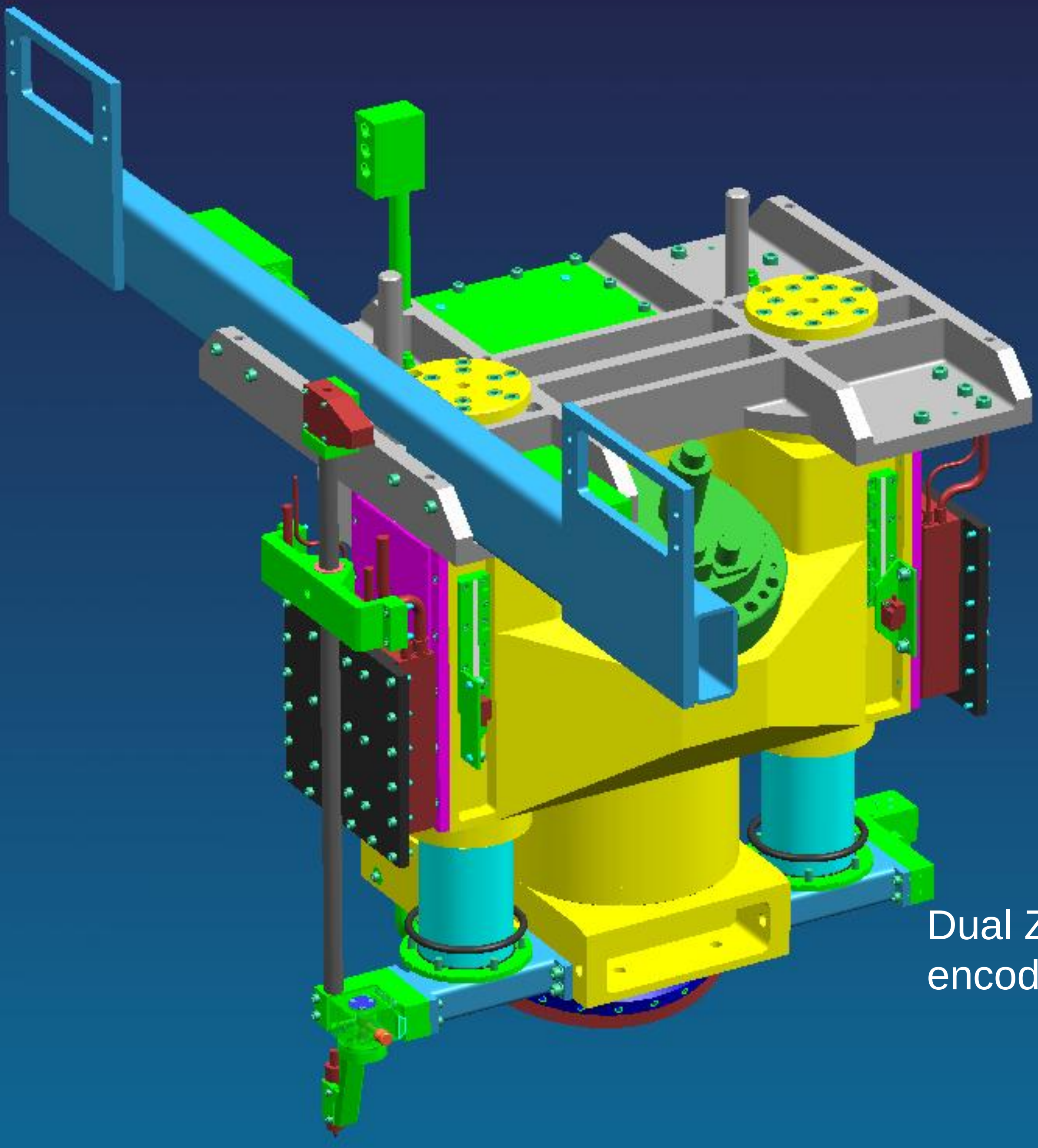
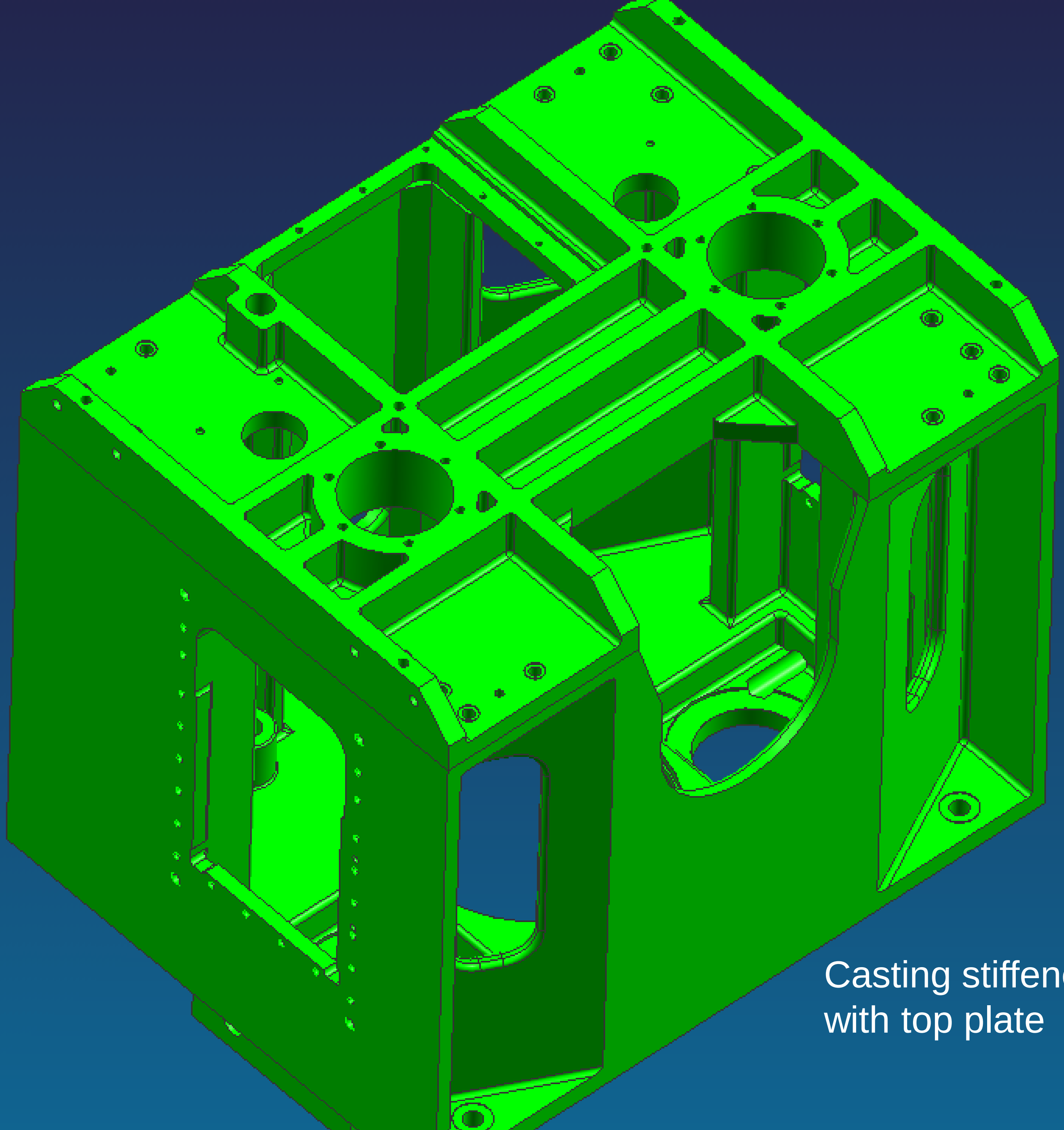
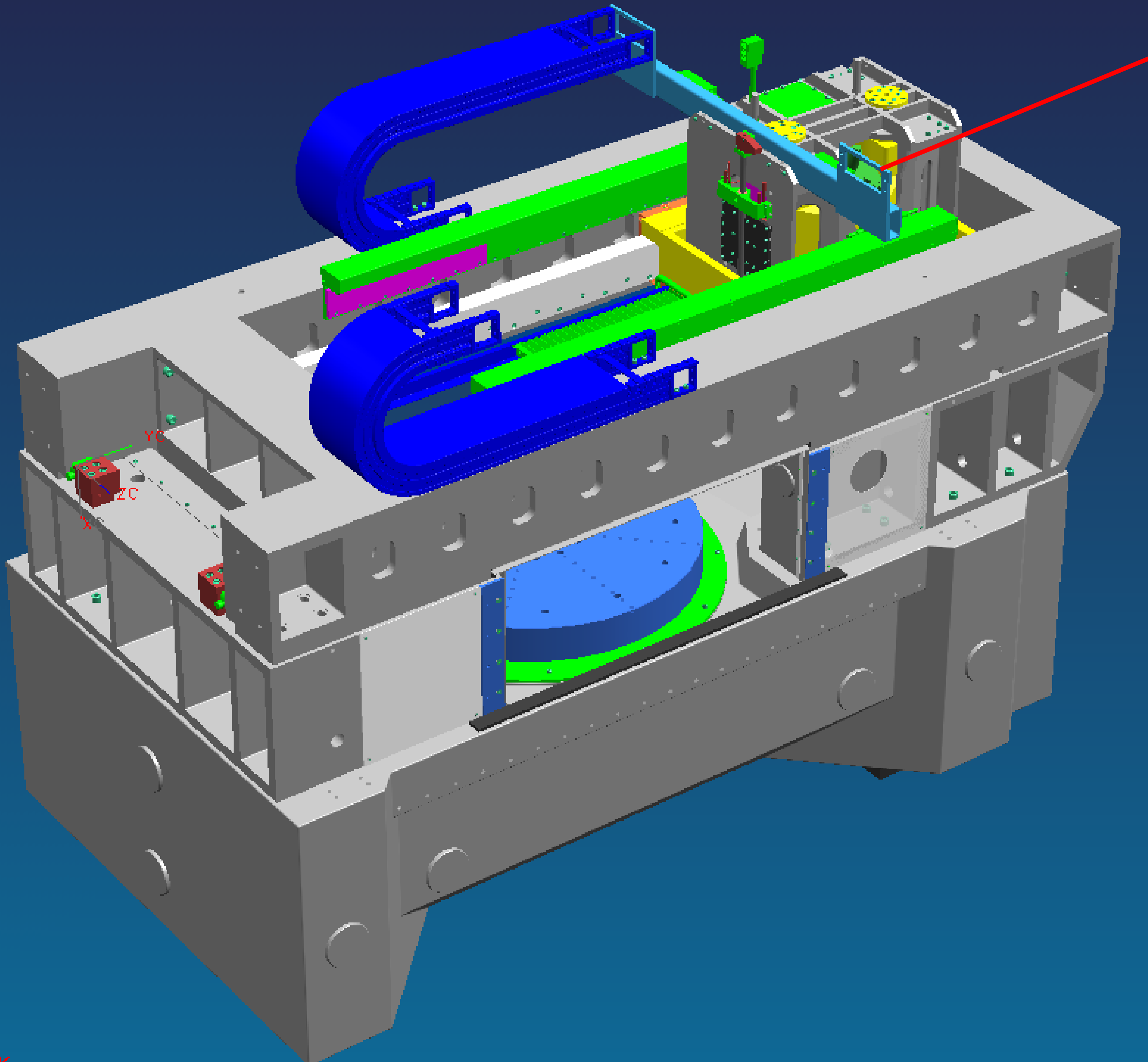


Dual Z axis motor and
encoder configuration

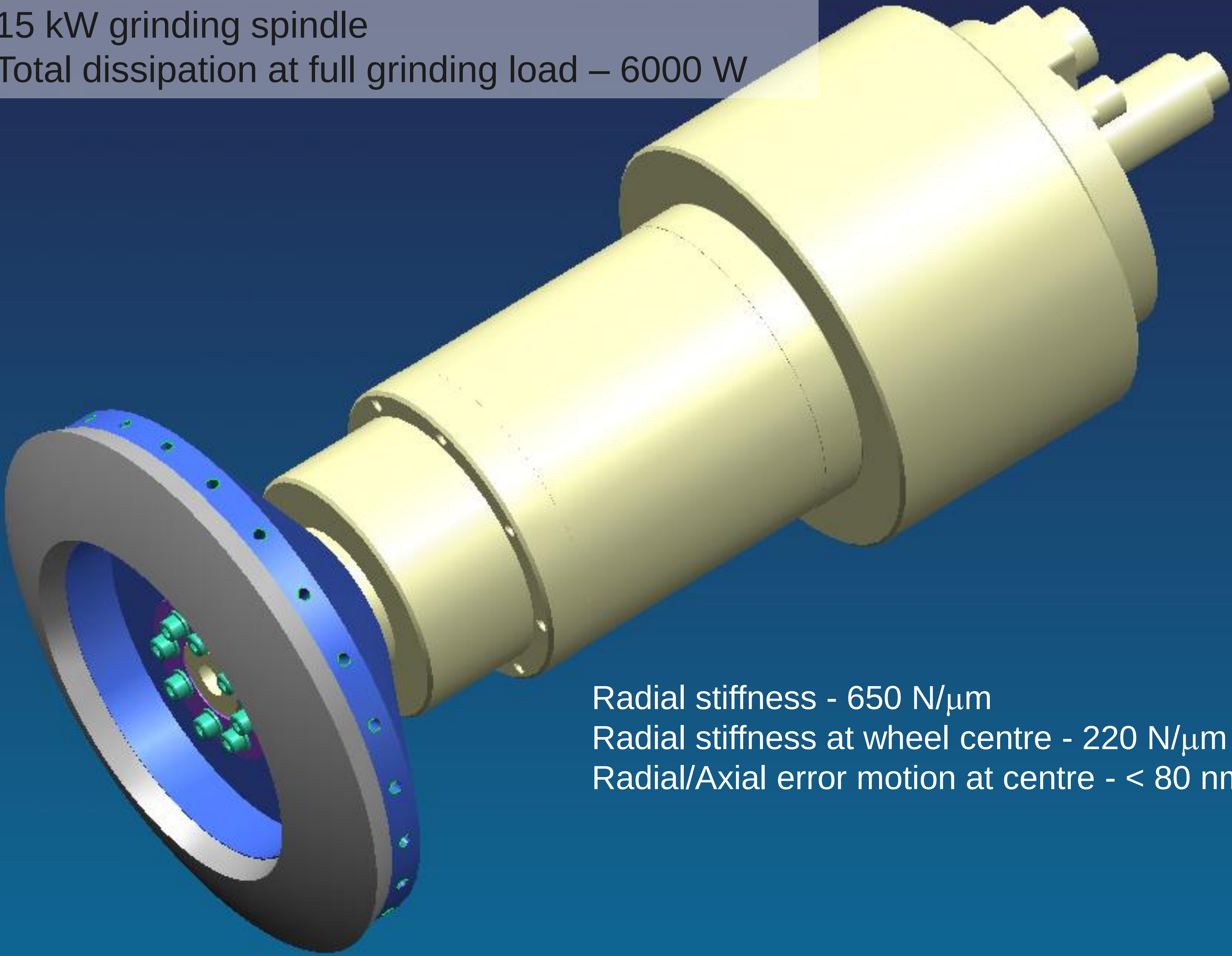


Casting stiffened
with top plate

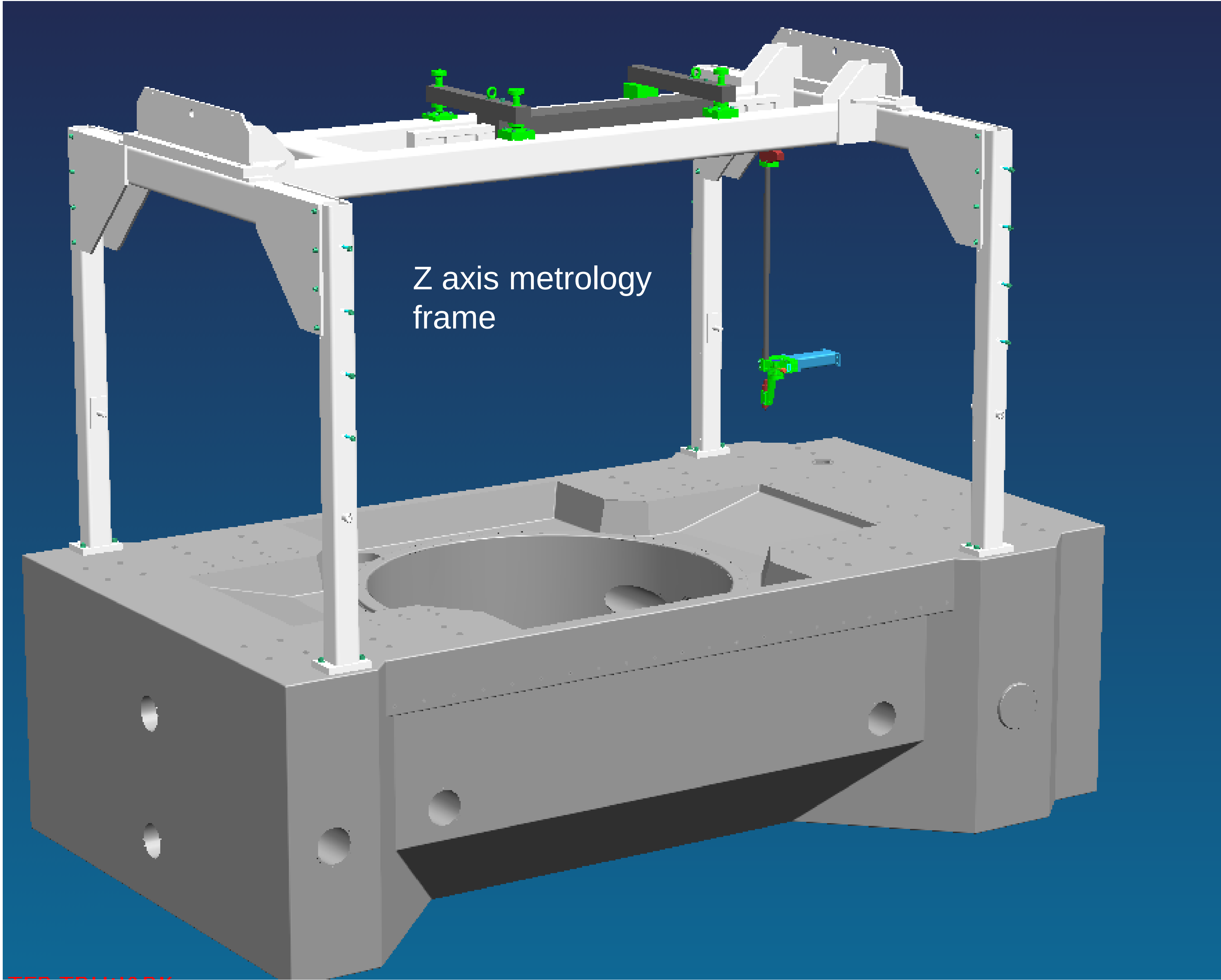


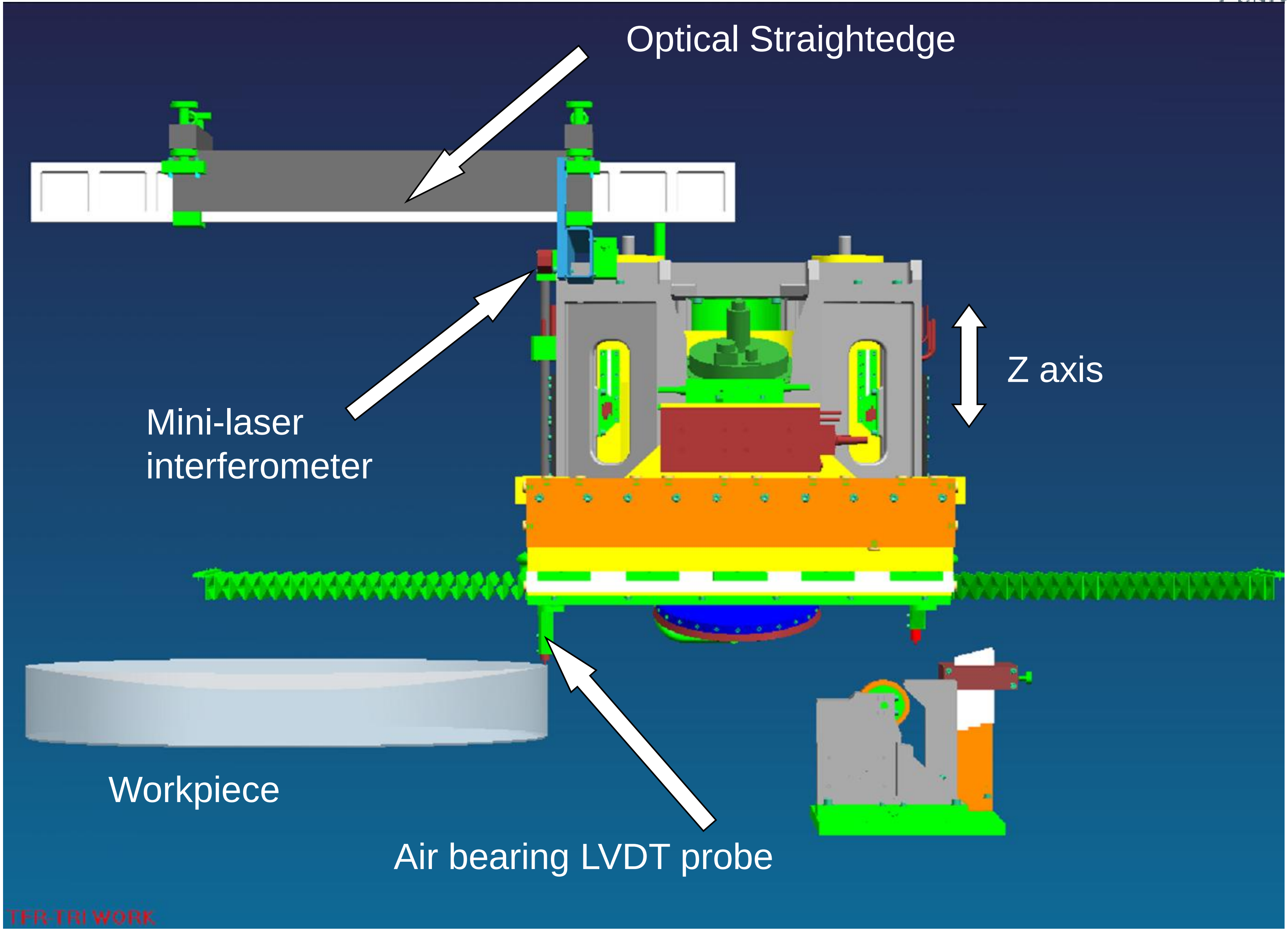
Z carriage in position

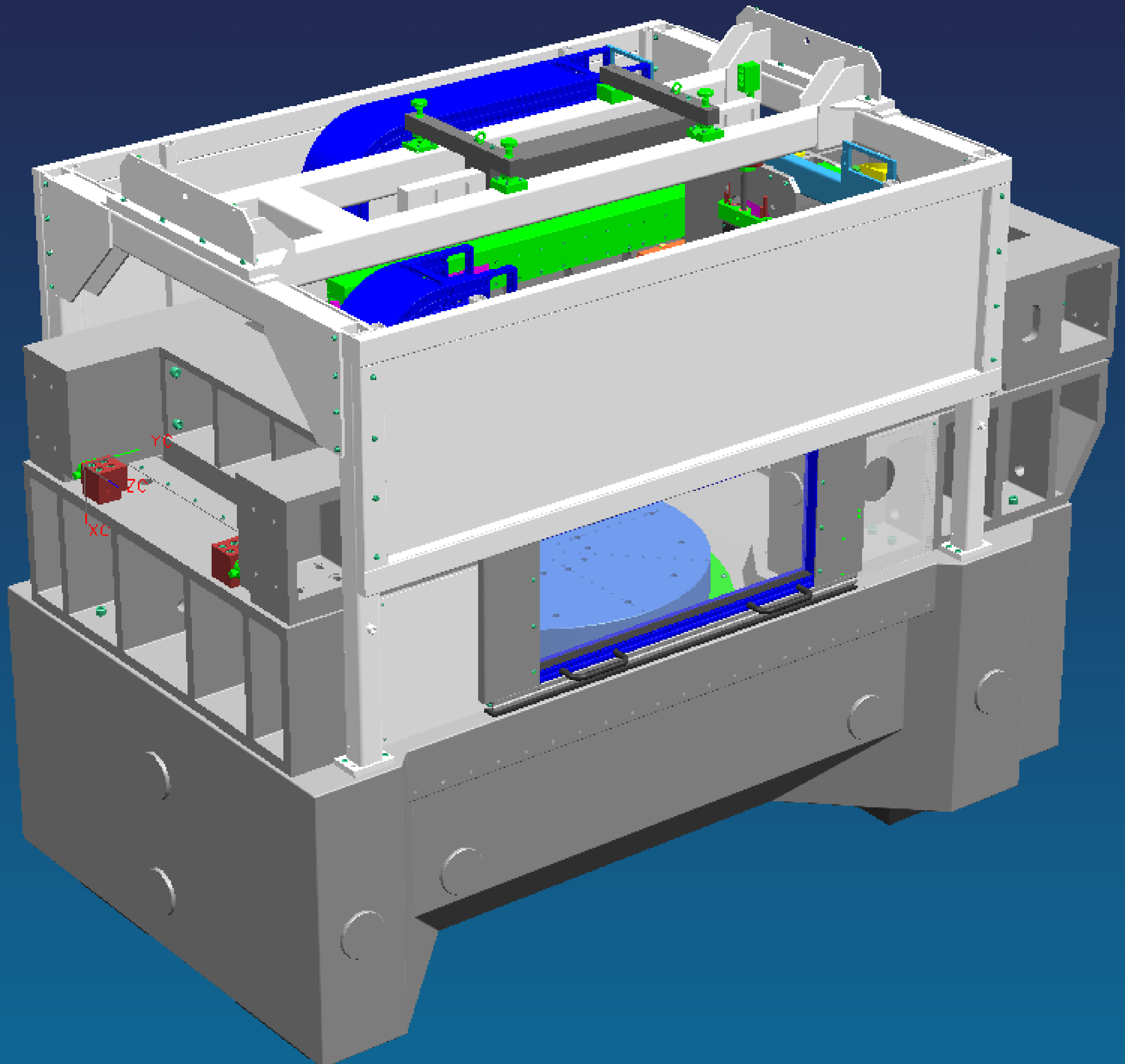
15 kW grinding spindle
Total dissipation at full grinding load – 6000 W



Radial stiffness - 650 N/μm
Radial stiffness at wheel centre - 220 N/μm
Radial/Axial error motion at centre - < 80 nm

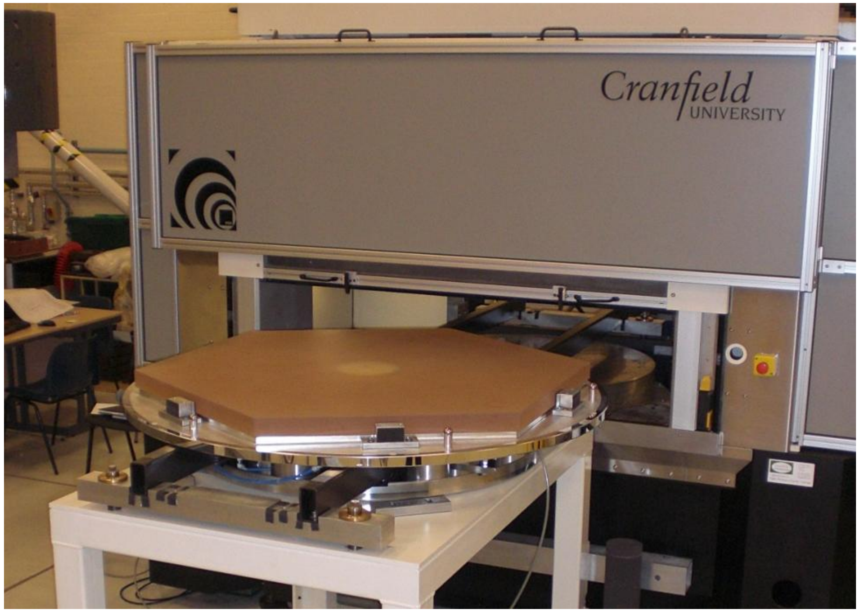

Z axis metrology
frame


Optical Straightedge
Mini-laser interferometer
Z axis
Workpiece
Air bearing LVDT probe
TFR-TRI WORK


YC
ZC
XC

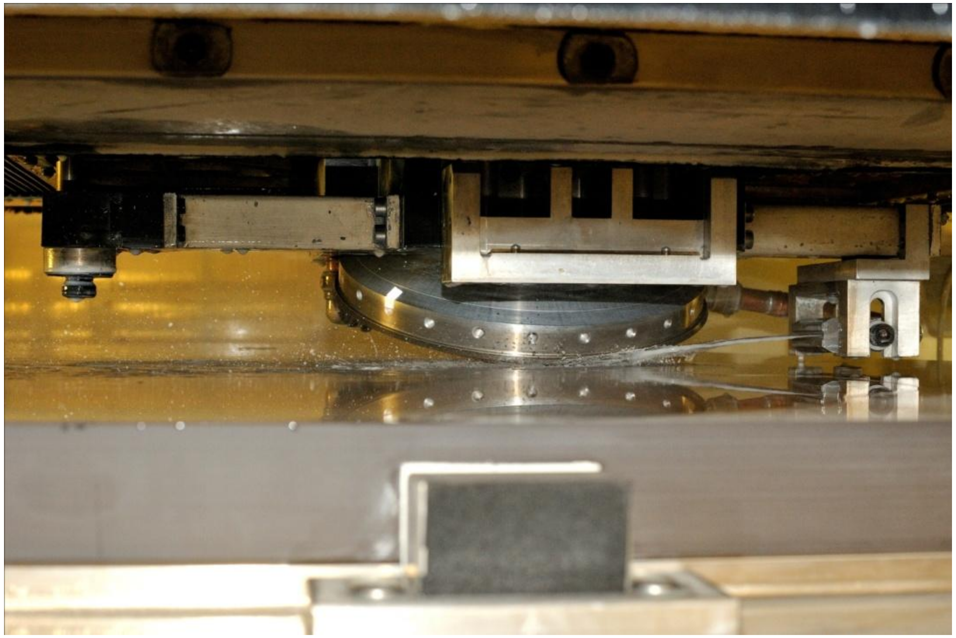
BoX® Mirror segment processing

Cranfield UNIVERSITY



Segment fixture

- Transportation
- Metrology
- Loading
- Grinding
- Location using master spheres

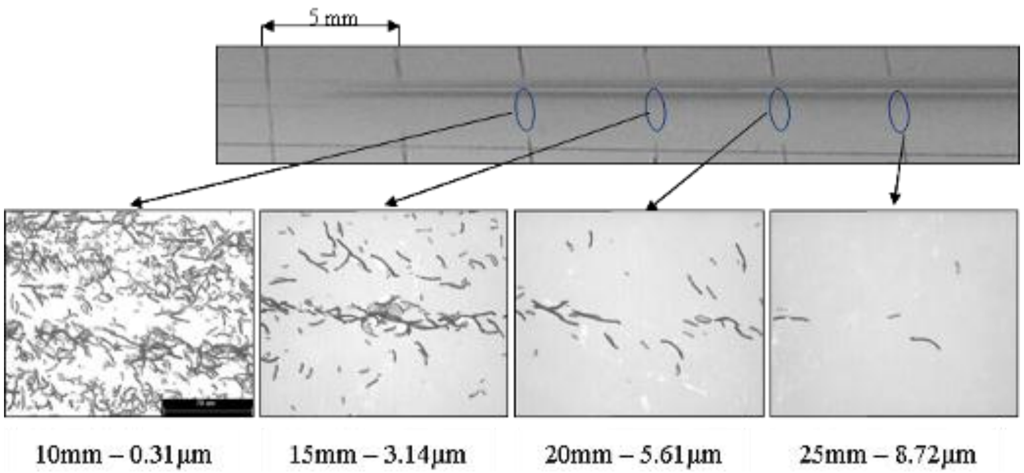


Grinding

- 200 mm^3/second MMR
- 90% material removed in 1 hour
- 2 finish grinds
    - Each 50um depth of cut
    - 2^{nd} using form error compensation

BoX® Induced Sub-surface Damage

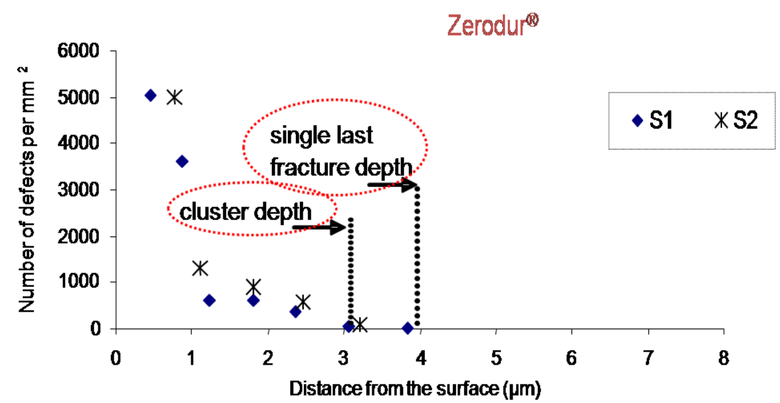
Cranfield UNIVERSITY



Evaluation technique:

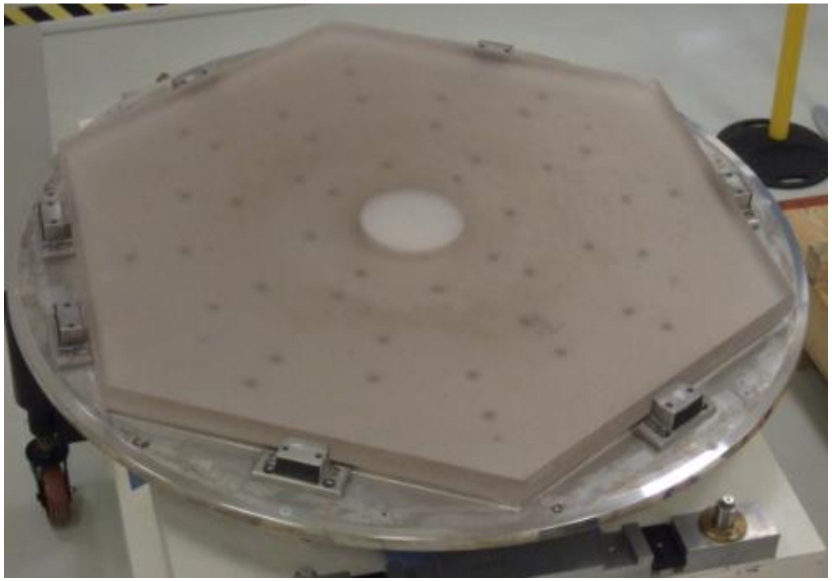
- Polished tapered grooves
- Etched HF, target removal 1µm
- Groove depth - contact profilometery
- Crack observation using optical microscope

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

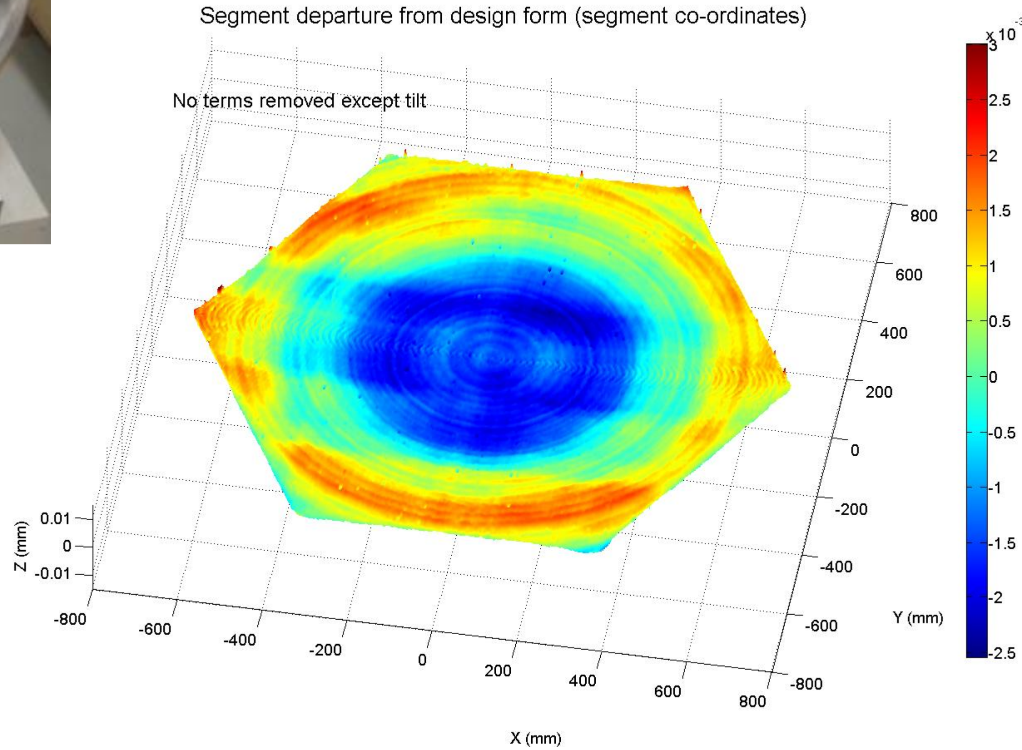
BoX® Mirror segment (2)



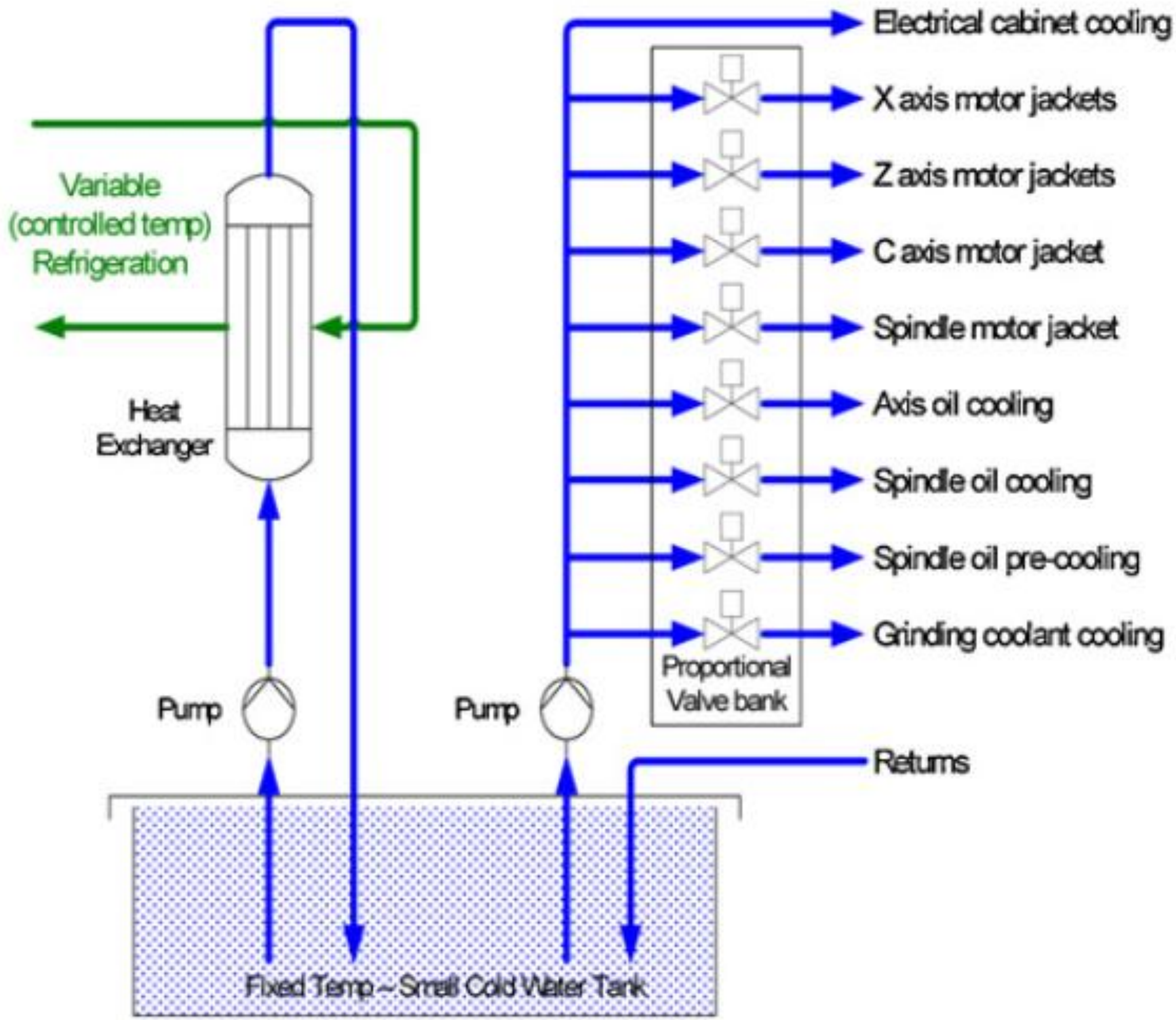
- ELT segment SPN04 (16:15)
- Material – ULE
- Grinding cycle 20 hours
- Max MMR 187.5mm^3/sec

Results:

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

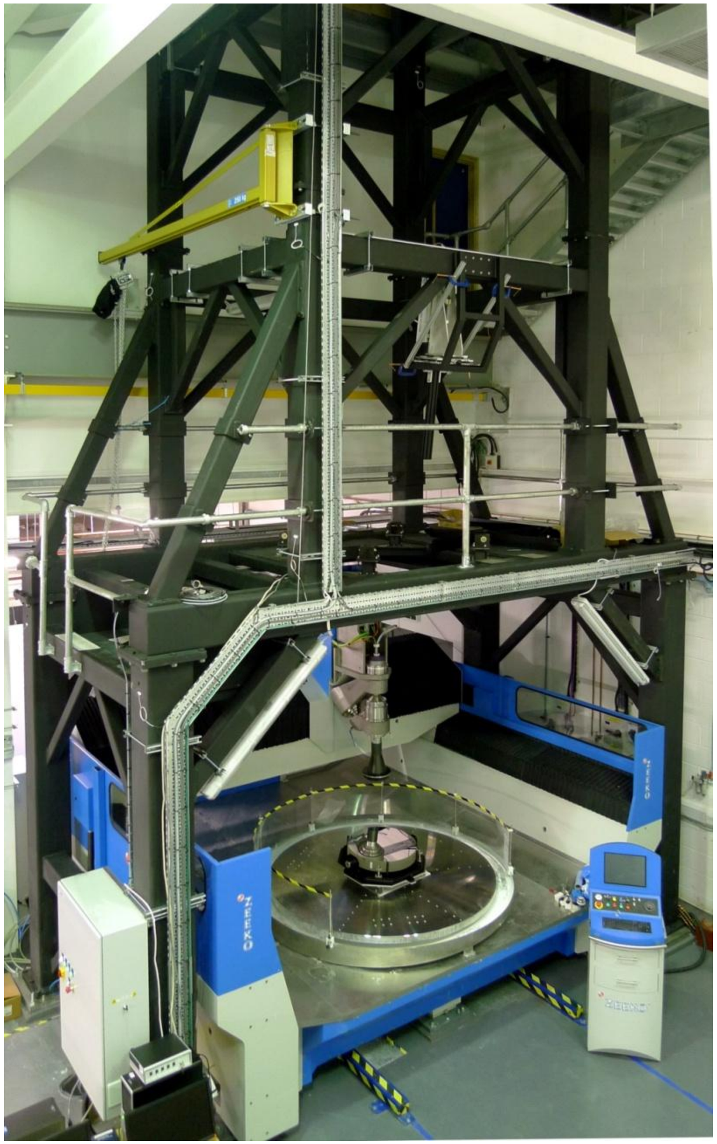


Box temperature control facility



Optical test tower over polishing system

Cranfield UNIVERSITY



Free abrasive polishing technology

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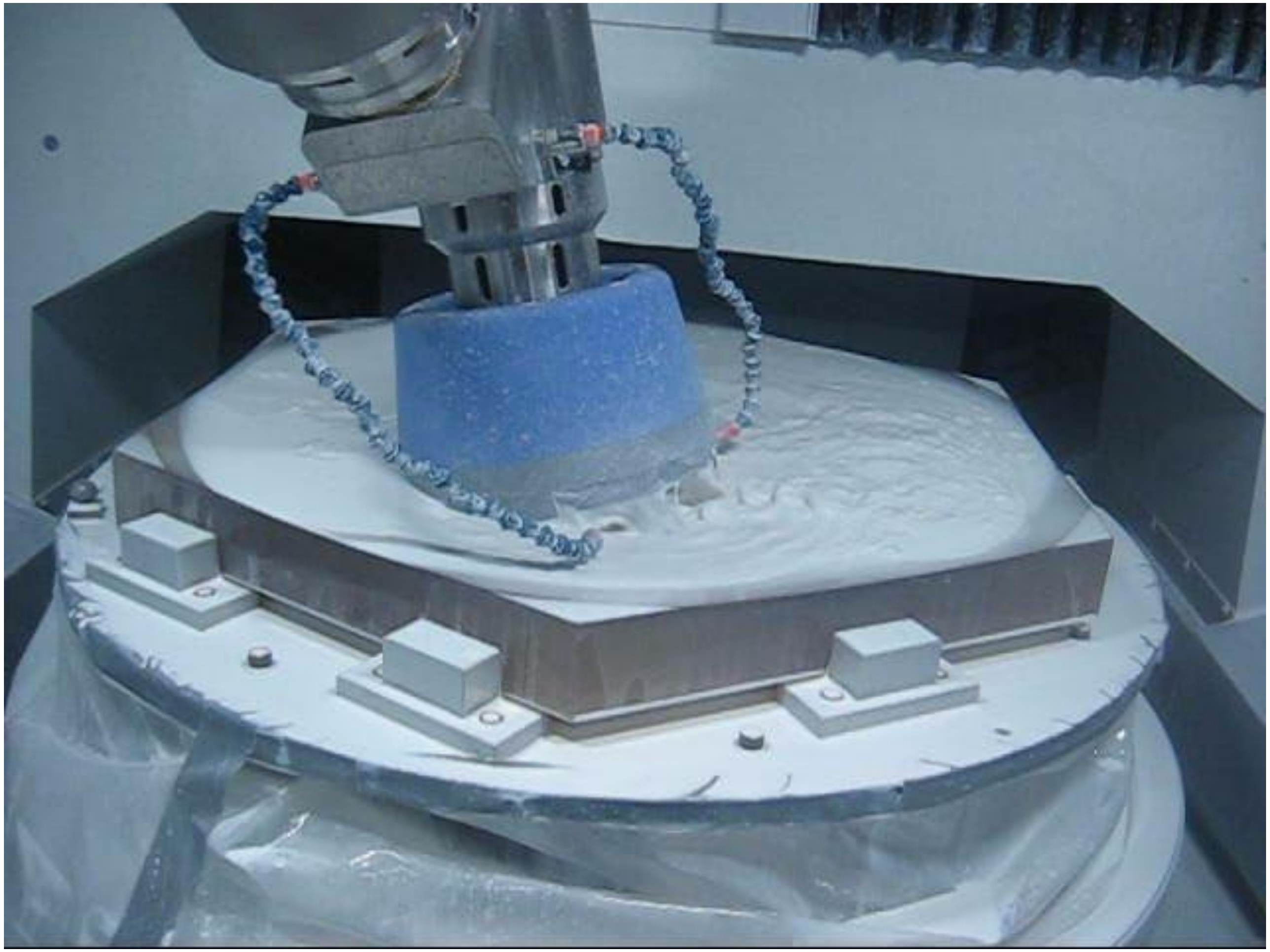

Source: David Walker, University of Wales Professor of Optics at Glyndwr University Professorial Research Associate, University College London, Research Director, Zeeko Ltd

Zeeko 1600 with OpTIC optical test tower

Cranfield UNIVERSITY

- Segment radius of curvature 84m
- Test tower 10m
- Folded path using spherical mirror
- 45˚ fold mirror near intermediate focus (central obscuration)
- Focus relayed to interferometer by pair of aspheric lenses
- Spherical aberration corrected by aspheric plate off-axis and a pair of cylindrical lenses.
- Option for final residual aberrations to be corrected by CGH
- Located over polishing machine

Acknowledgement: Dr John Mitchell, Ultra Precision and Structured Surfaces (UPS2)

Master spherical segment (MSS)

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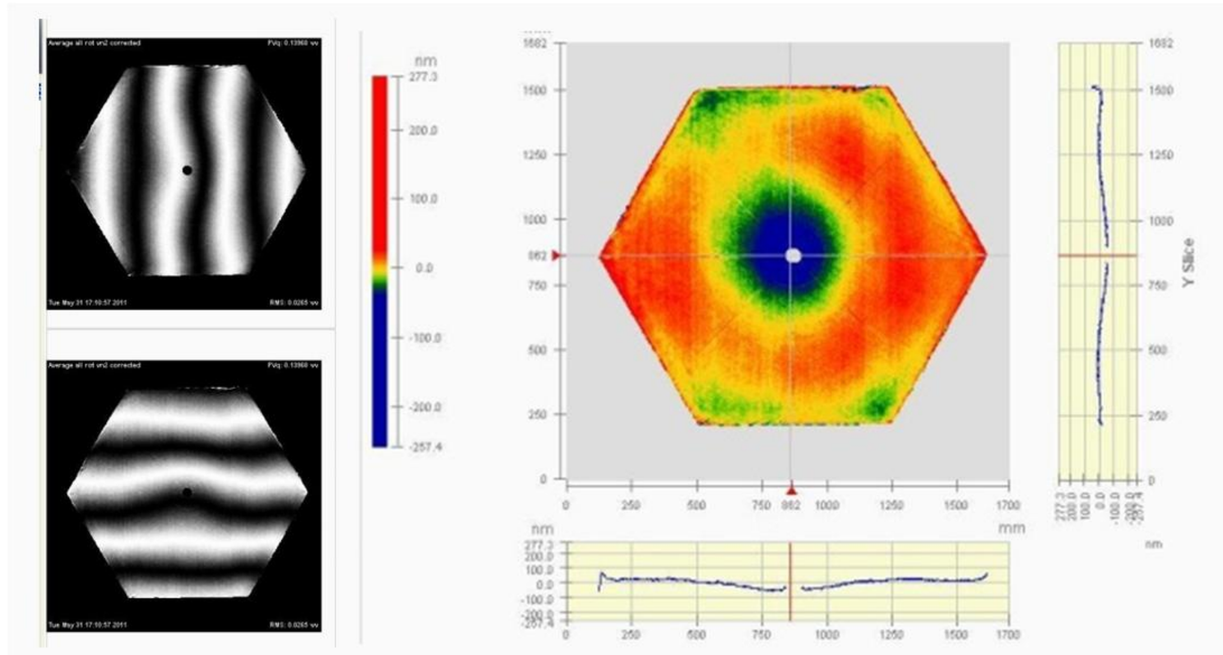

- 1.490 m across corners
- 200 mm thickness
- Spherical form 84 m ROC

- Composite measurements constructed from lateral and rotational shears
- Form 16.8 nm ± 2nm RMS
- Mid spatial frequencies < 5nm RMS

Source: David Walker, University of Wales Professor of Optics at Glyndwr University , Professorial Research Associate, University College London, Research Director, Zeeko Ltd

Reactive Atom Plasma Figuring

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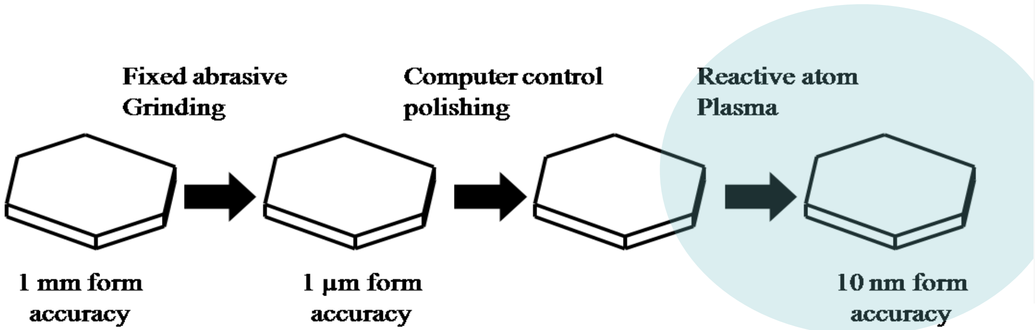
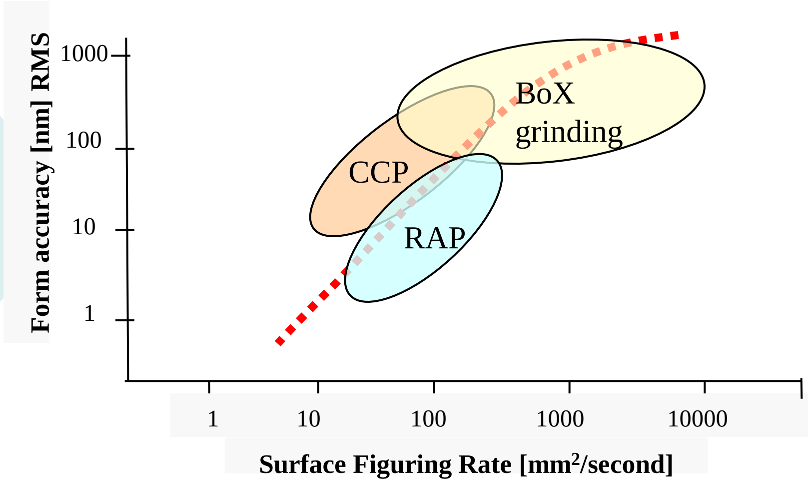
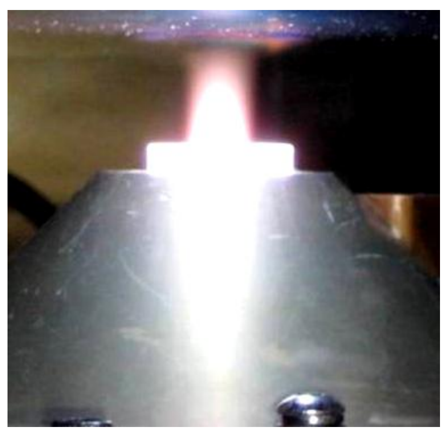
Research initiative – processing metre scale *freeform* optical surfaces



Final figure correction



RAP technology for the final figuring of large metre scale optics



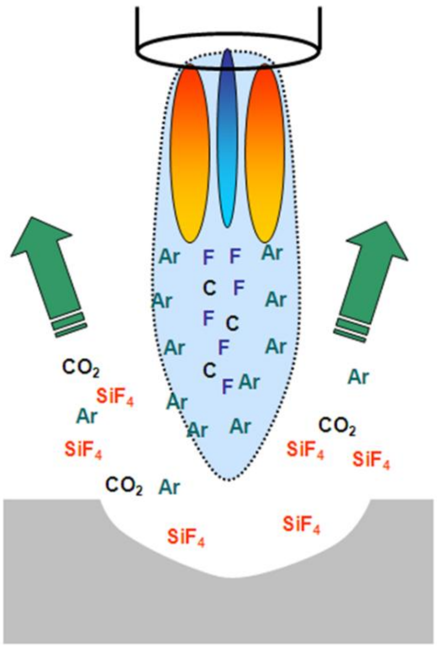
Figuring requirement:

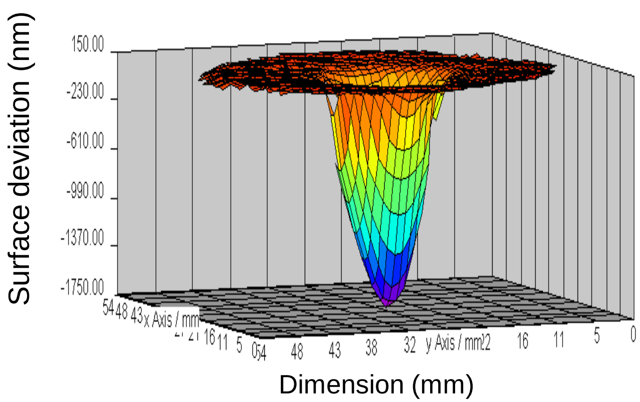
- 1 Segment per day
- Form accuracy < 20 nm RMS
- Surface roughness < 1 nm RMS
- Removal of process signatures

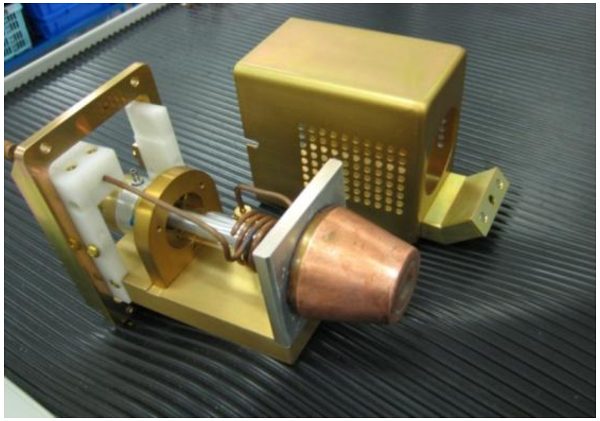
RAP technology

Rapid nanometer dexterity surface process for figure correction of ultra precision metre-scale optics. Technology employs inductively Coupled Plasma Torch.

- Dry etch process – fluorine based gas
- Atmospheric pressure processing
- Gaussian beam distribution
- Dwell time based raster figuring algorithm
- No induced SSD







Helios 1200 RAP figuring facility

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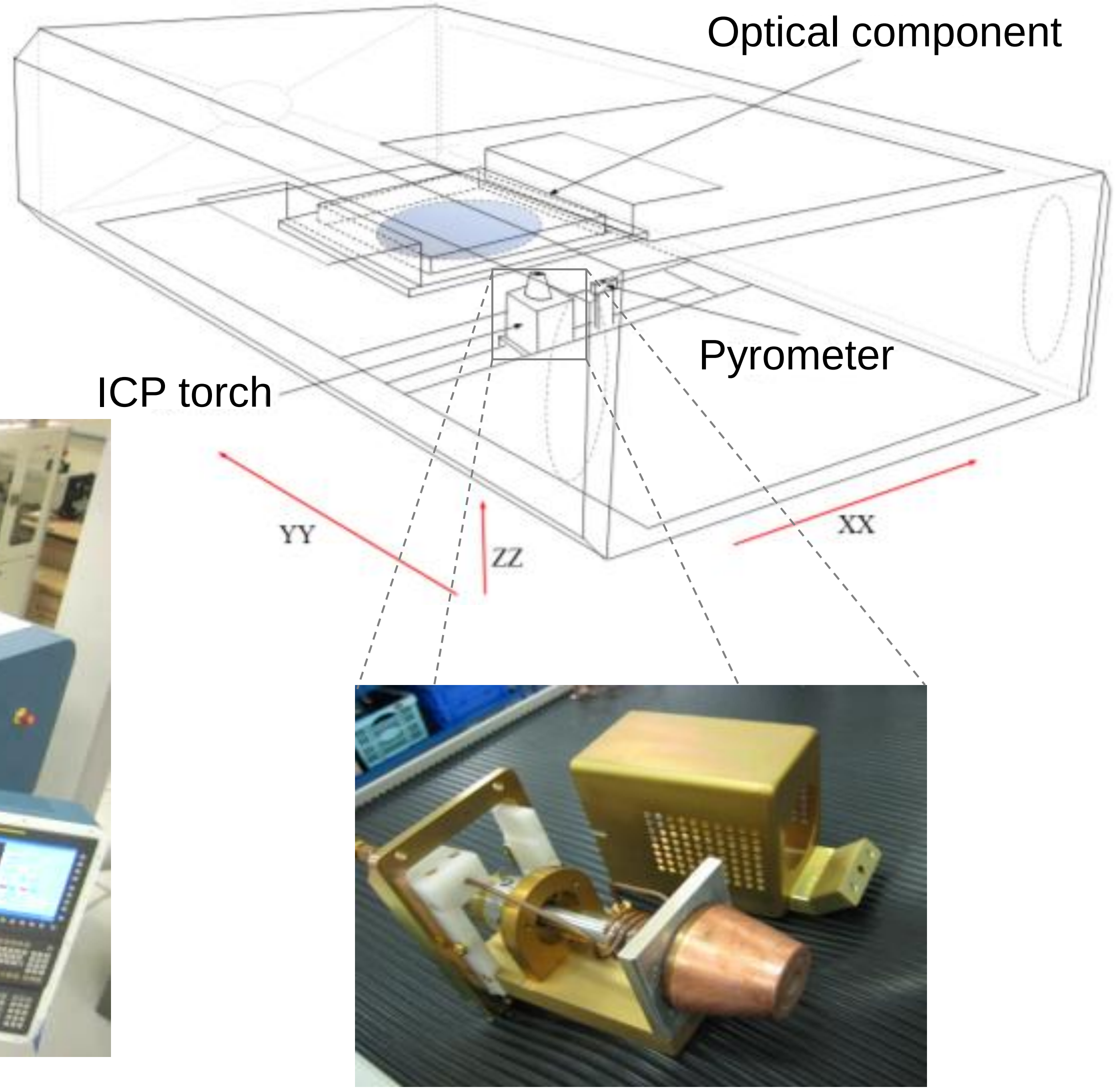
Chamber for 1.2 m optical component



RAP process capability

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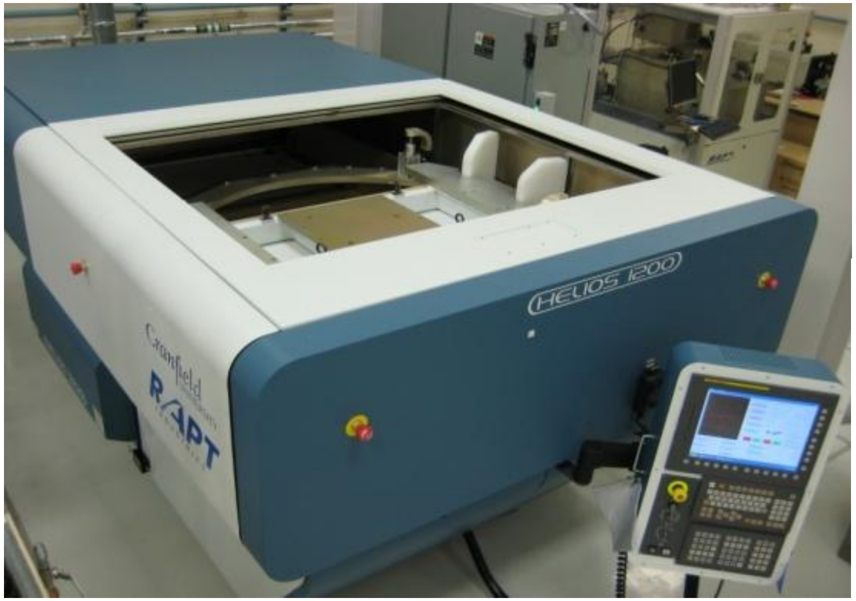
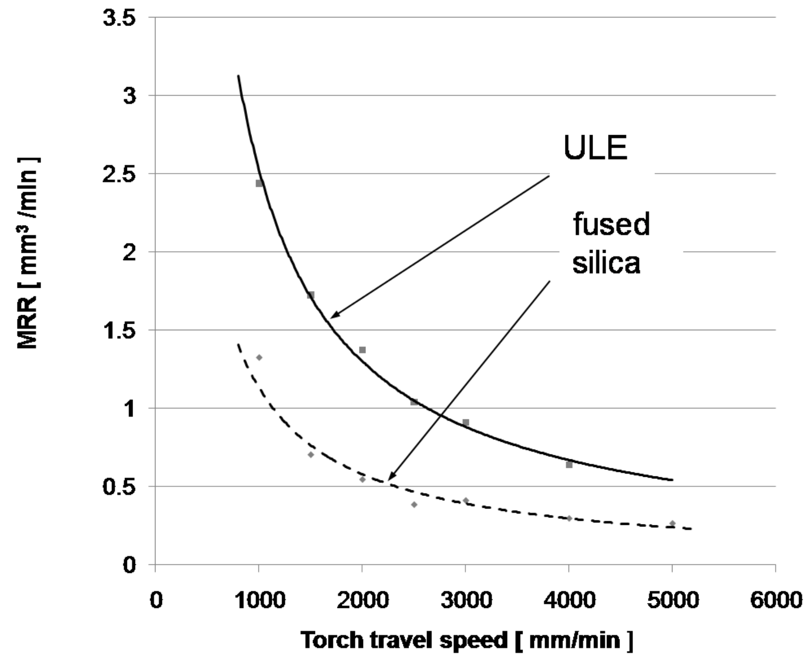


- 1.2 m capacity
- 3 axes CNC through Fanuc 30i
- Low cost operation
- Compact machine size

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

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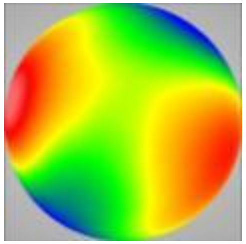
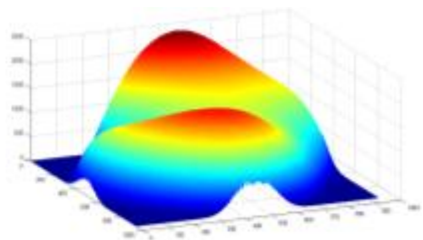
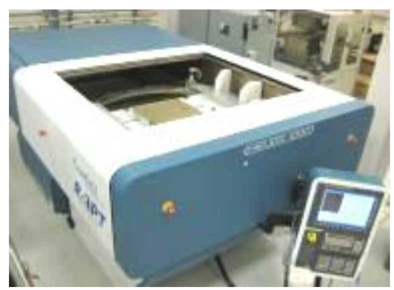
The iterative figuring procedure


Error map


Edge extension


De-convolution (modified)

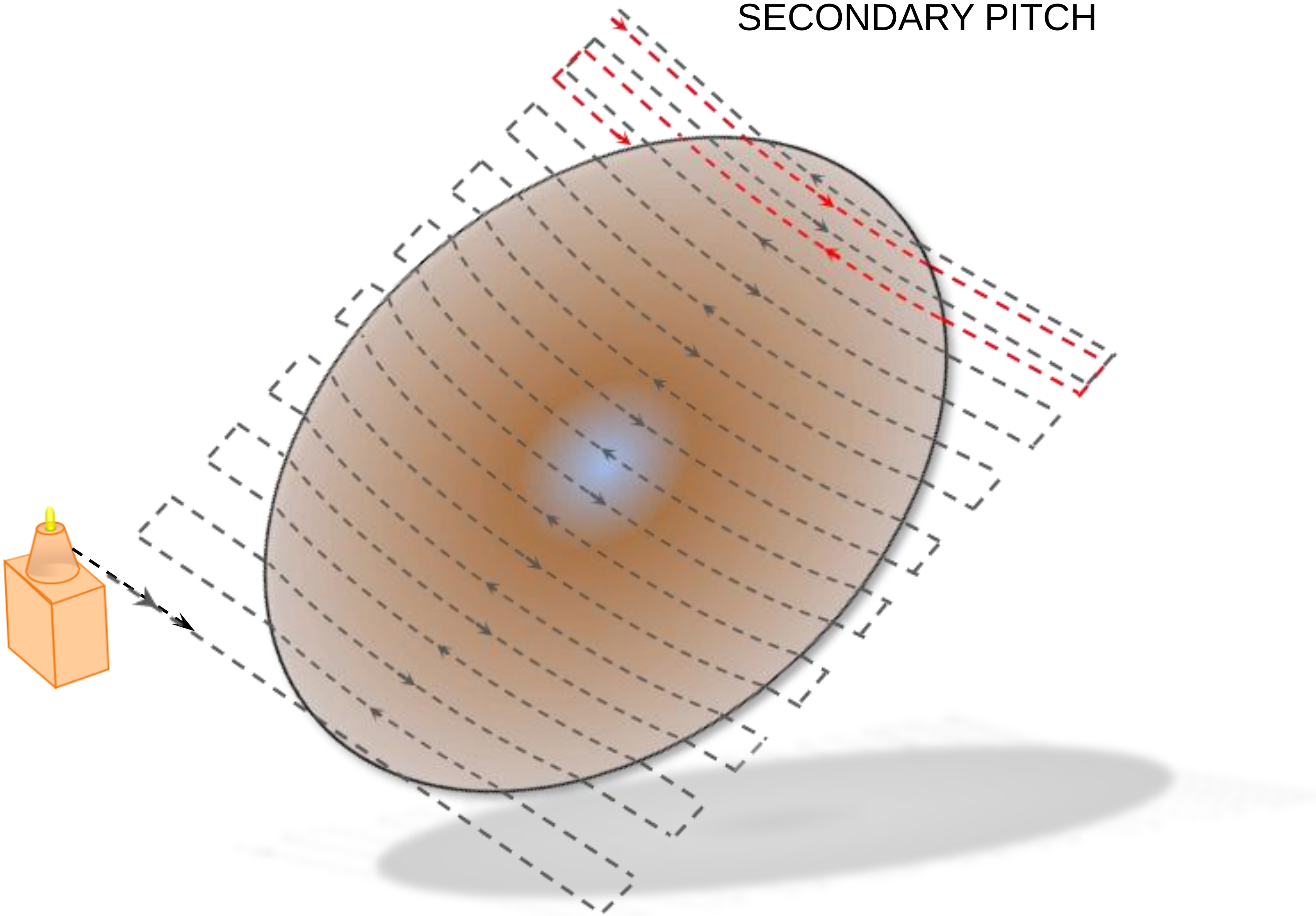
CNC-code generation with optimized tool-path and thermal adaption


RAP process

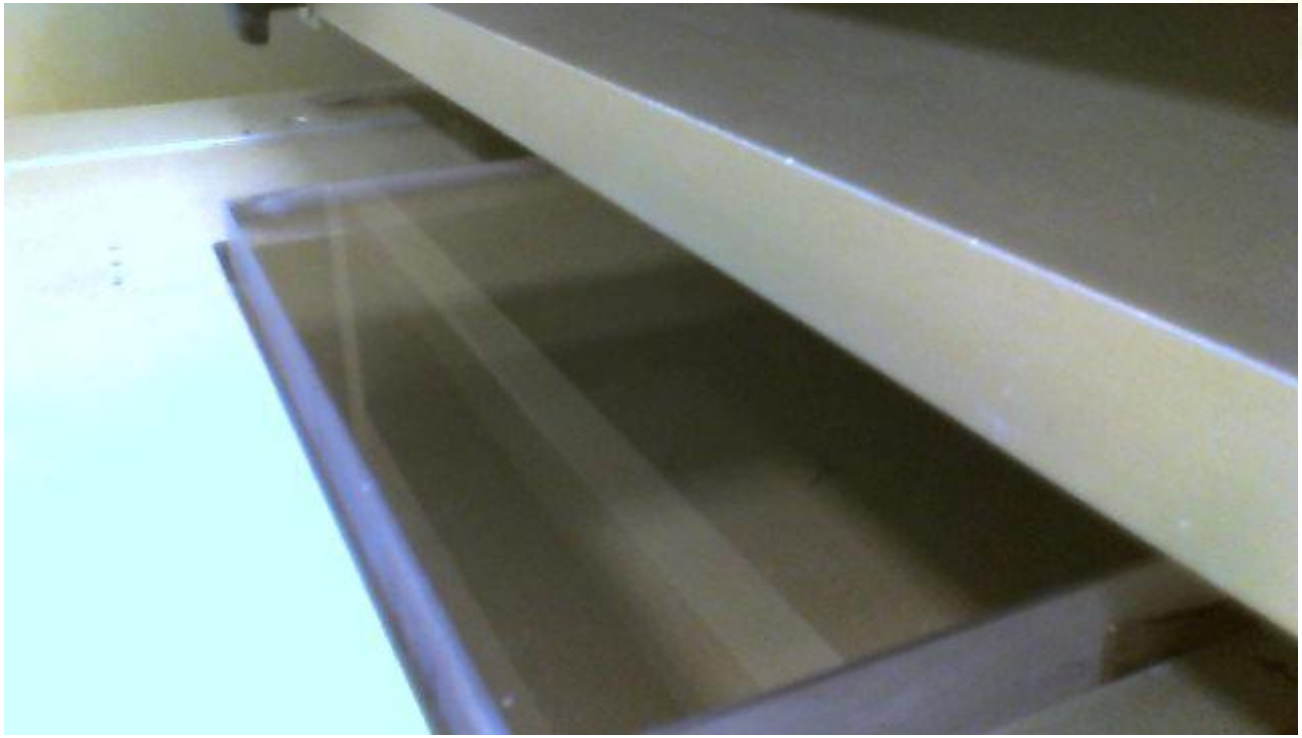

Interferometric measurement

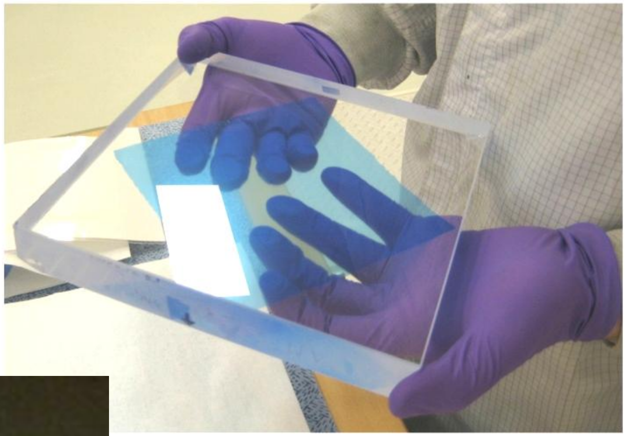
Final form accuracy down to λ/30 rms

Tool-path algorithm

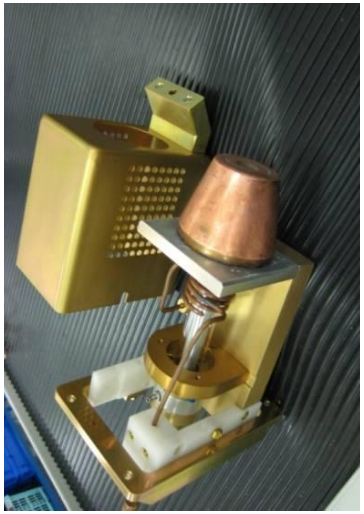


RAP figuring process

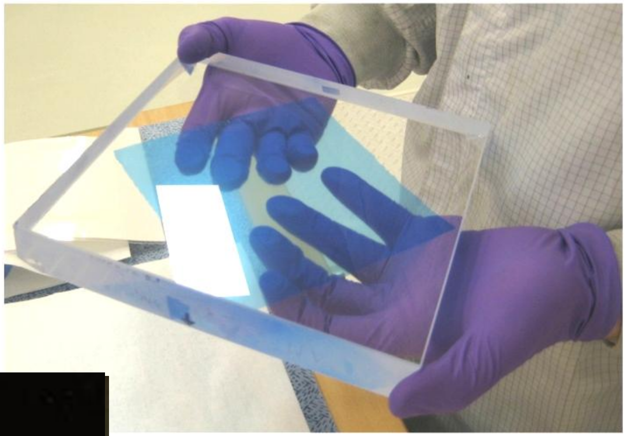




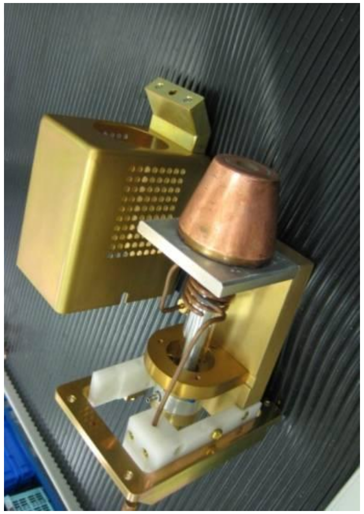
Fused Silica



RAP figuring process



Fused Silica



RAP figuring capability

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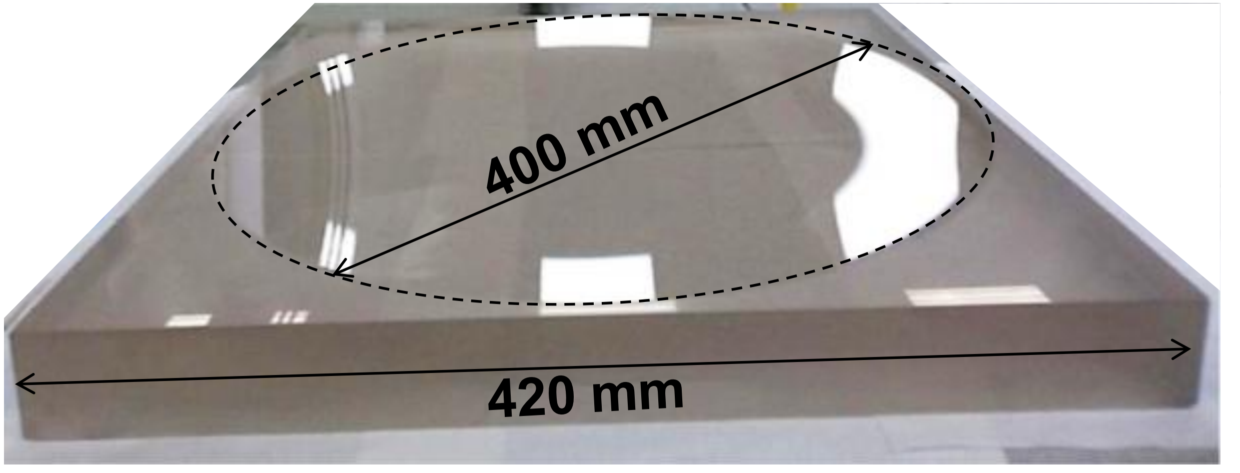
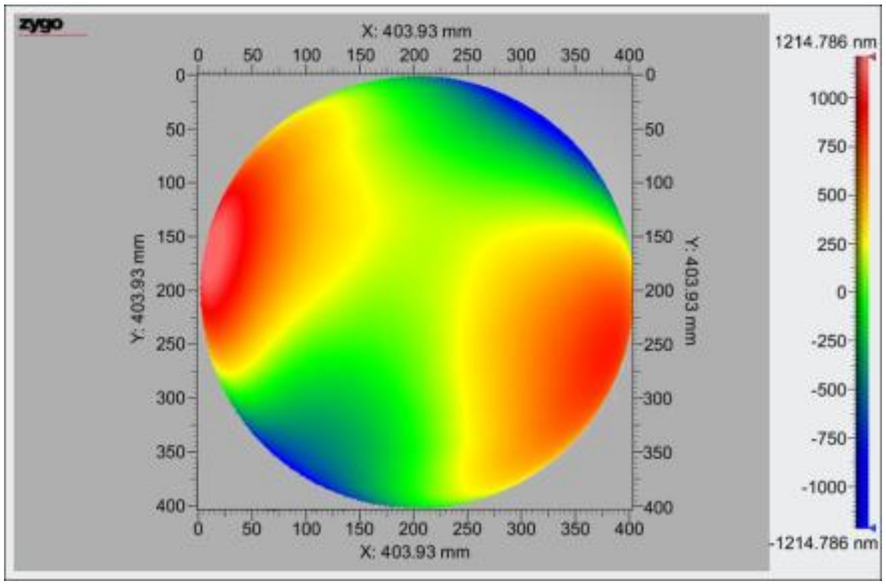


420mm x 420mm x 40mm ULE substrate

- 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.

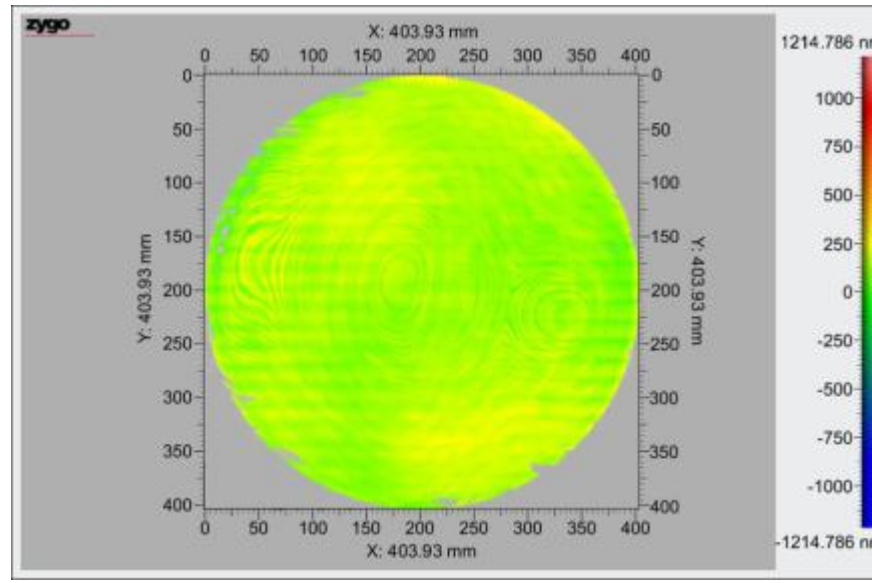
Large scale figuring results: optic #001/1

Initial figure error



PV: 2.4 µm PVr: 2.3 µm RMS: 373 nm

Residual figure error

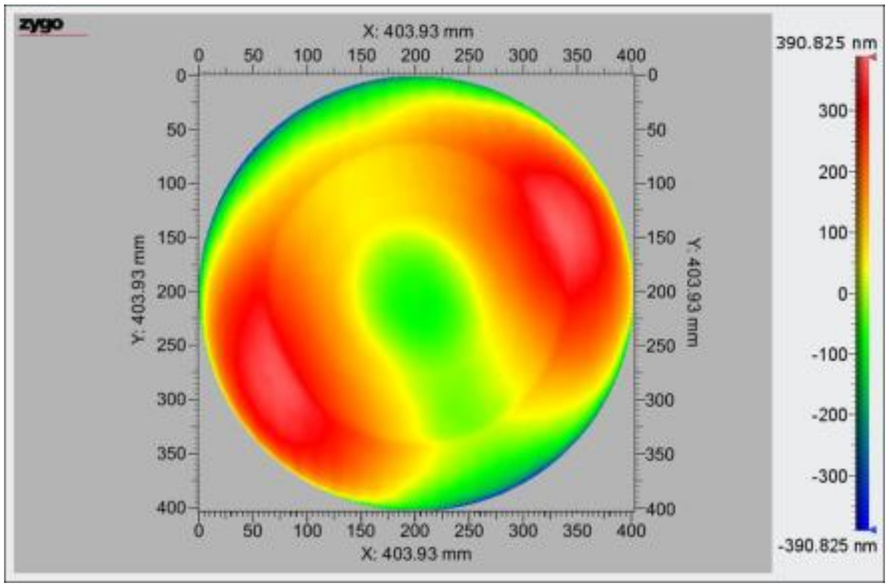


PV: 450 nm PVr: 282 µm RMS: 45 nm

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

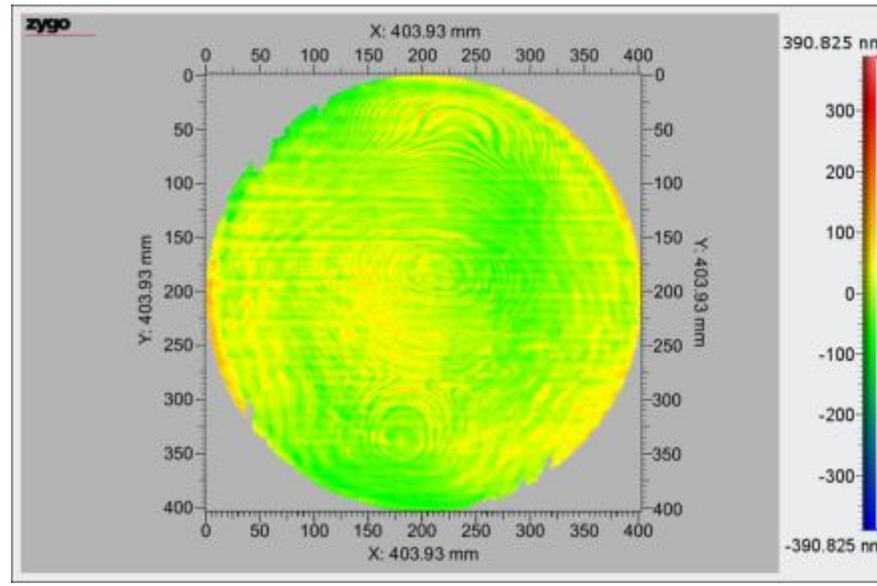
Large scale figuring results: optic #001/2

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

PSD Analysis

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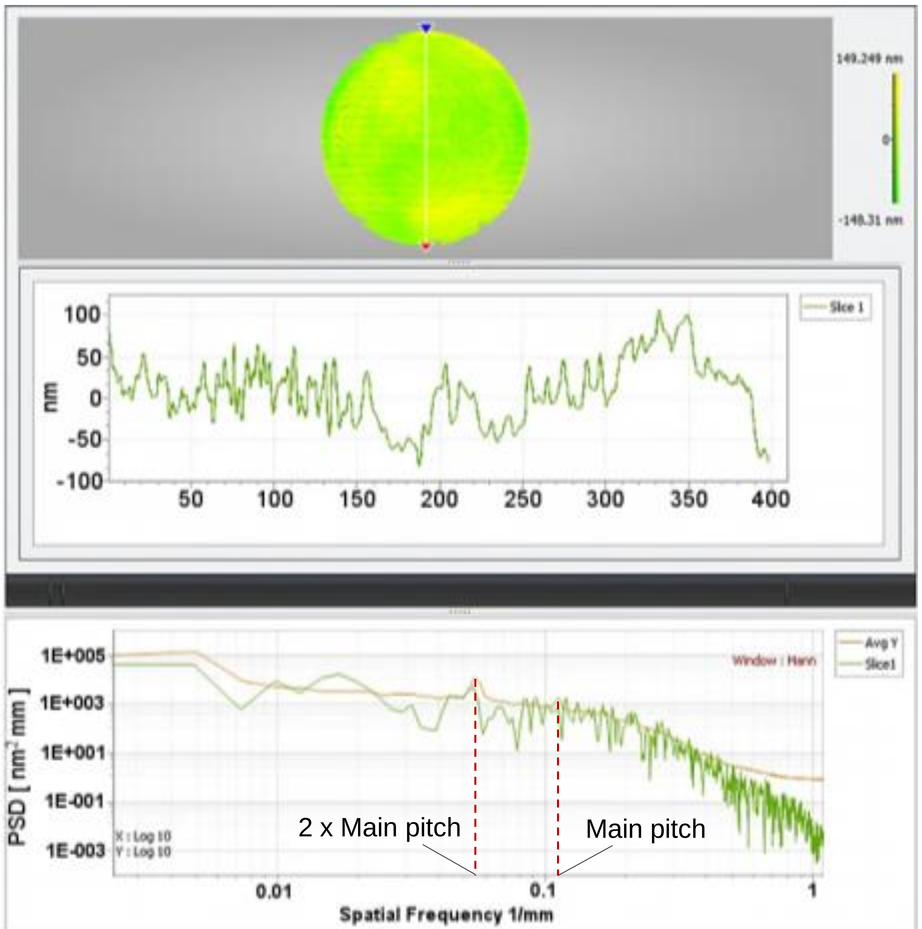
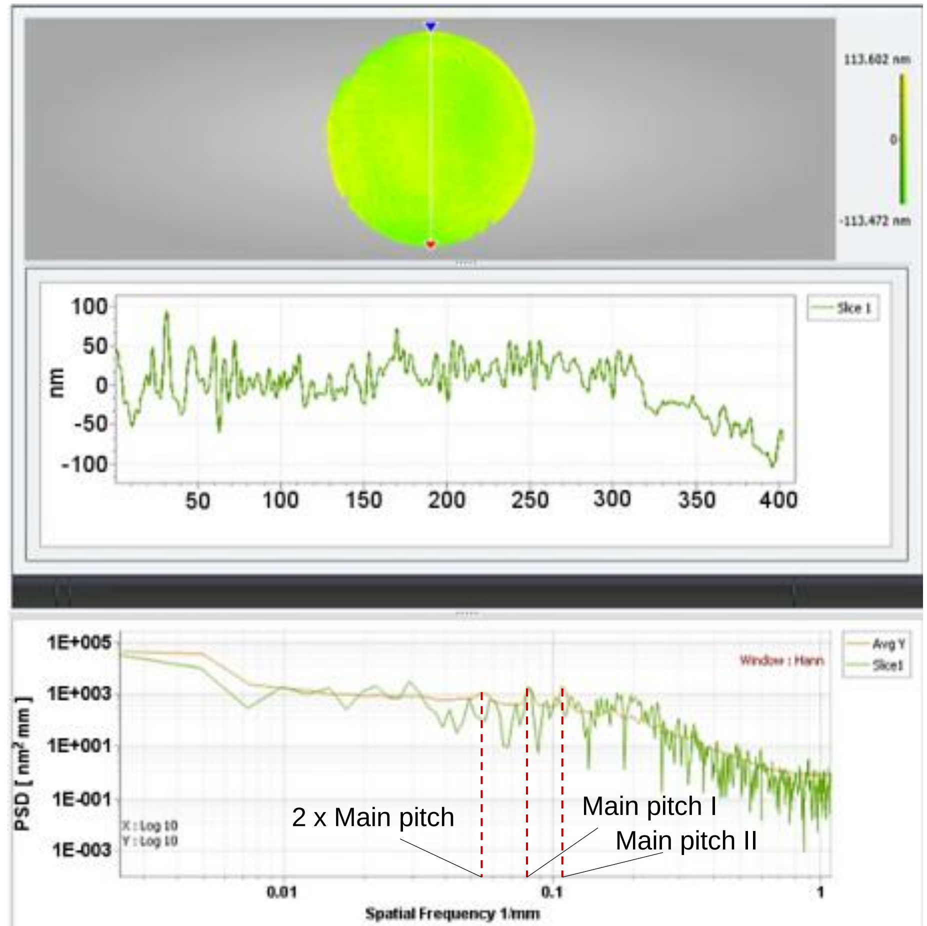
AFTER FIRST FIGURE CORRECTION

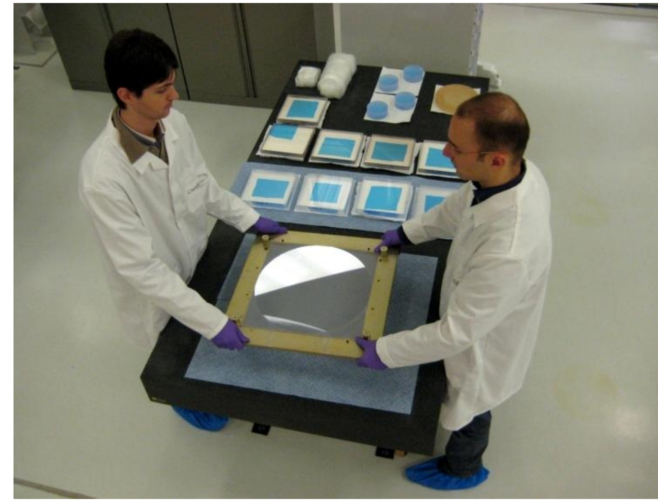


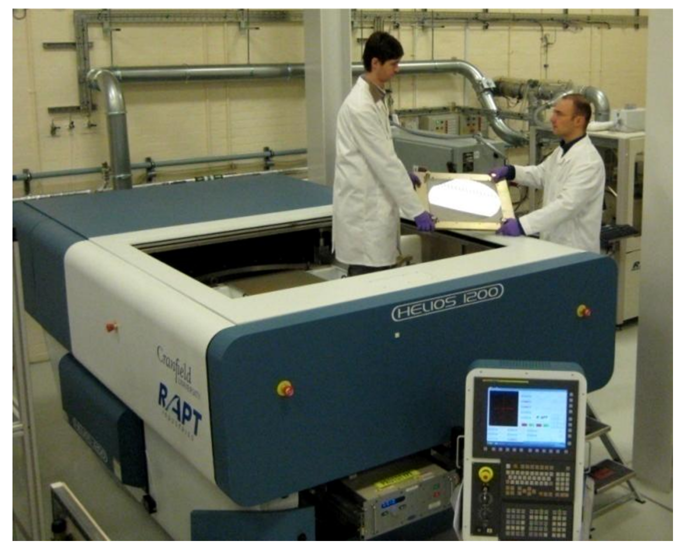
AFTER SECOND FIGURE CORRECTION



National Ignition Facility focussing lens

- 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





RAP figuring results: summary

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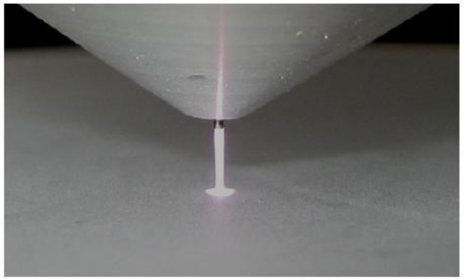
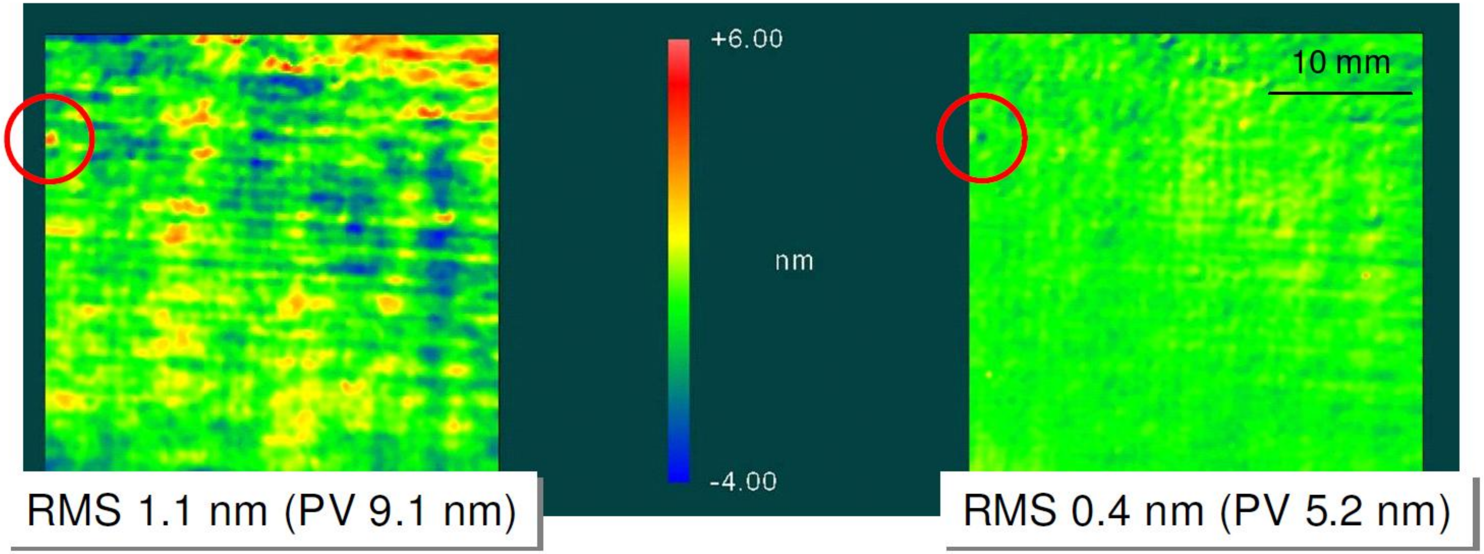
Evaluated aspect	100 mm Ø	150 mm Ø	400 mm Ø
Mean figuring time [min/iteration]	**12**	**7**	**50**
Overall convergence [%]	89	76	92
Figure error in RMS [nm] **Initial** **Final**	 **169** **18**	 **95** **23**	 **373** **31**
Figure error in PV [nm] Initial Final	 656 129	 504 183	 2400 230

Fine tool corrections

MSFR correction on aspheric fused silica lens



FWHM:	~ 0.65 mm
Removal rate:	~ 50 nm/s
Volume remov. rate:	~ 0.0015 mm^3/min
DC removal :	~ 8 nm



Differential Absorption LIDAR "DIAL"

NPL National Physical Laboratory Instrumentation

Mobile airborne pollution measurement

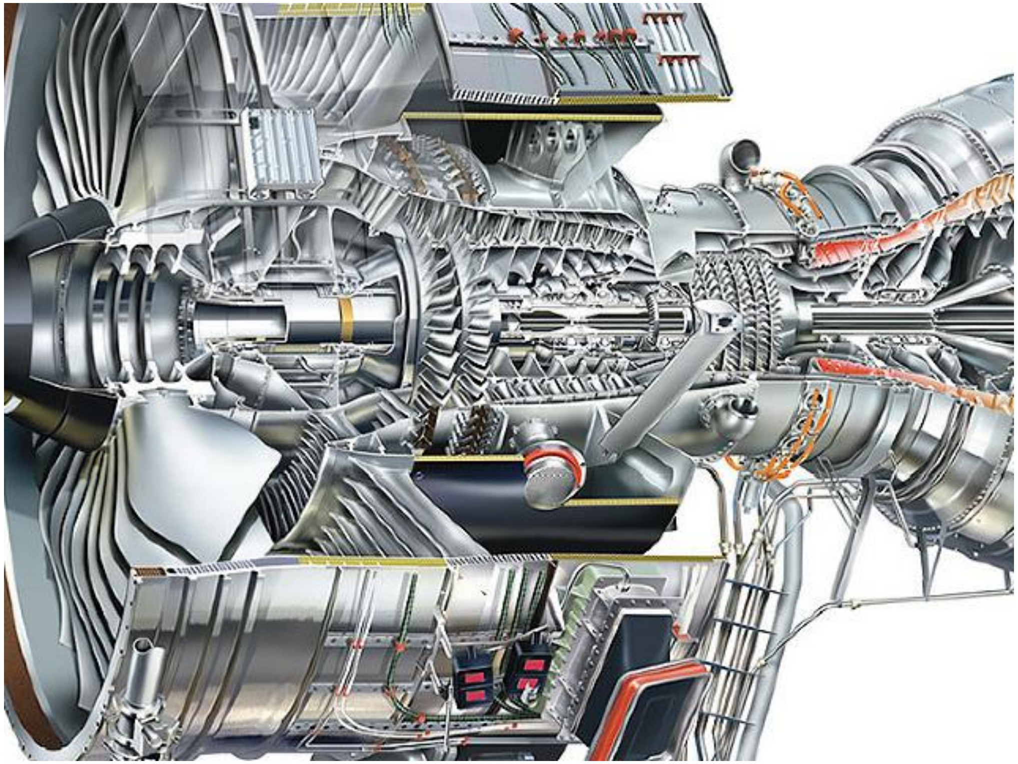
- *Remote sensing system providing rapid, accurate measurements of airborne atmospheric pollutants*
- *Completely self-contained laboratory carrying a suite of measurement devices to monitor meteorological parameters and ambient gas concentrations*
- Used across the World to offer service

Achieved using absorption in UV-VIS-NIR spectral regions including: SO2, NO2, NO, ozone, benzene, toluene, xylene and higher aromatics, alkanes, alkenes, petroleum and diesel vapours, HCl, N2O, HF and H2S

Complex shape component processing

Technology Strand to Develop Effective Manufacturing.

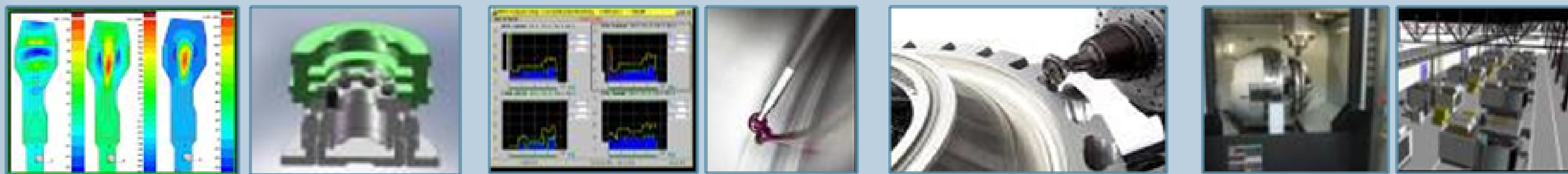
Ref, Rolls Royce



High Performance Disc Machining

A system of technology strands for a modern and competitive Method of Manufacture – technology demonstration for the Washington Disc Facility

Modelling | Monitoring | Integration | Green Button



Distortion | Fixtures | Process | In Cycle | Mill-turn, deburr | Less setup | Less Ops

- Operations down 40%
- Hours down 50%
- Productivity up 100%
- Quality up 15% (RFT)
- Underpins new factory investment

Fan Disc

HPDM will halve the current value added time, double the productivity at zero consumable cost difference and achieve 6-sigma process capability

Rolls-Royce

Marine Robotised Propeller Finishing

A robotised approach to replace a time-served, manual process

Current Method

Capture process

KPV & Development

Force control & OLP

System Validation

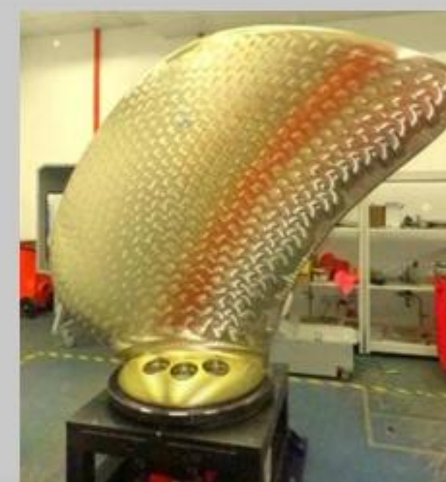
Auto tool changer

Implementation

Automated Polishing

- **50% cycle time reduction**
- **Improved productivity**
- **Consistent quality**
- **Product configurable**
- **HSE benefits**

Propeller Blade

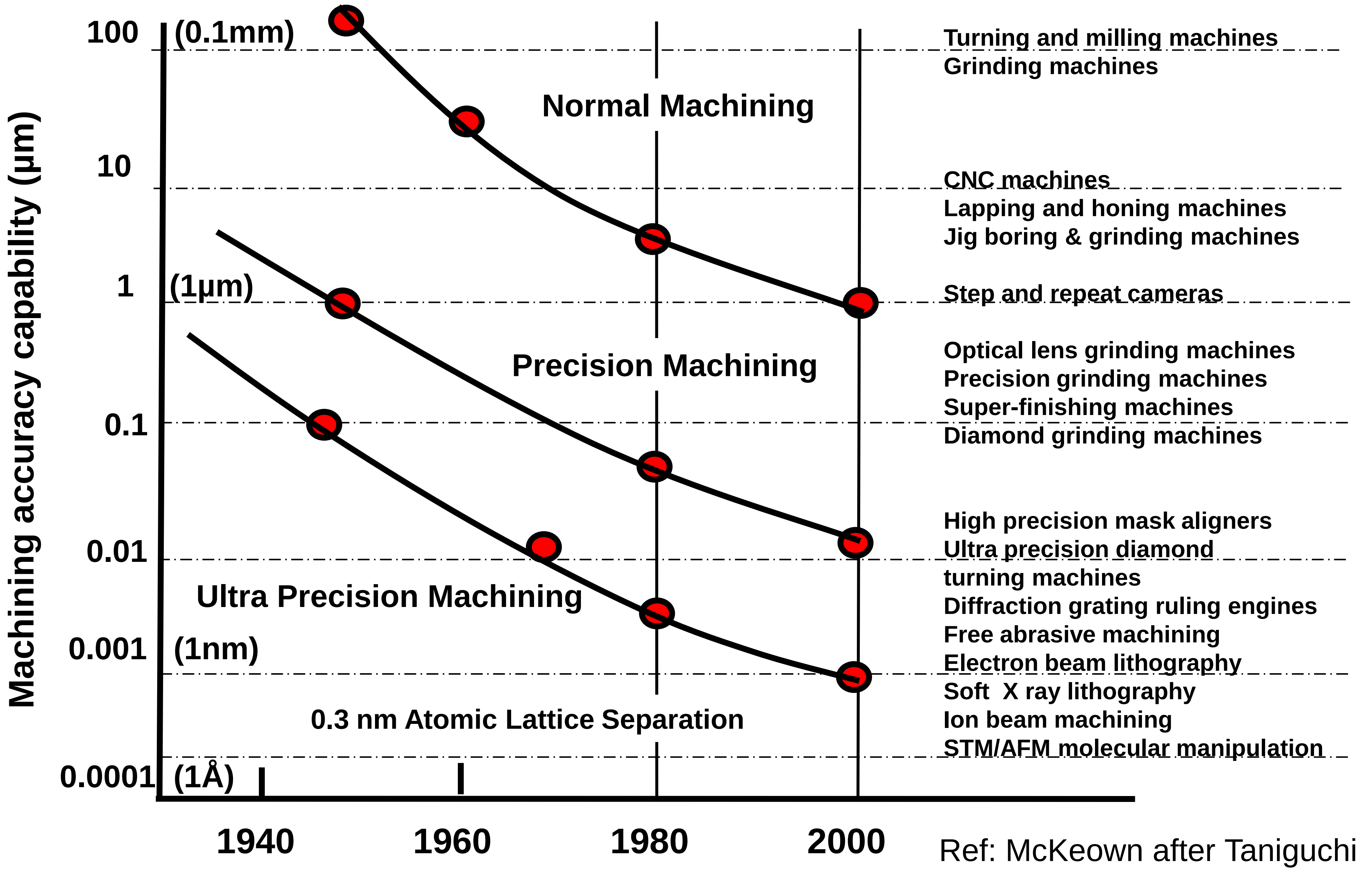


In production and winner of the 2012 Manufacturing Excellence 'Sir Henry Royce Award'

Rolls-Royce

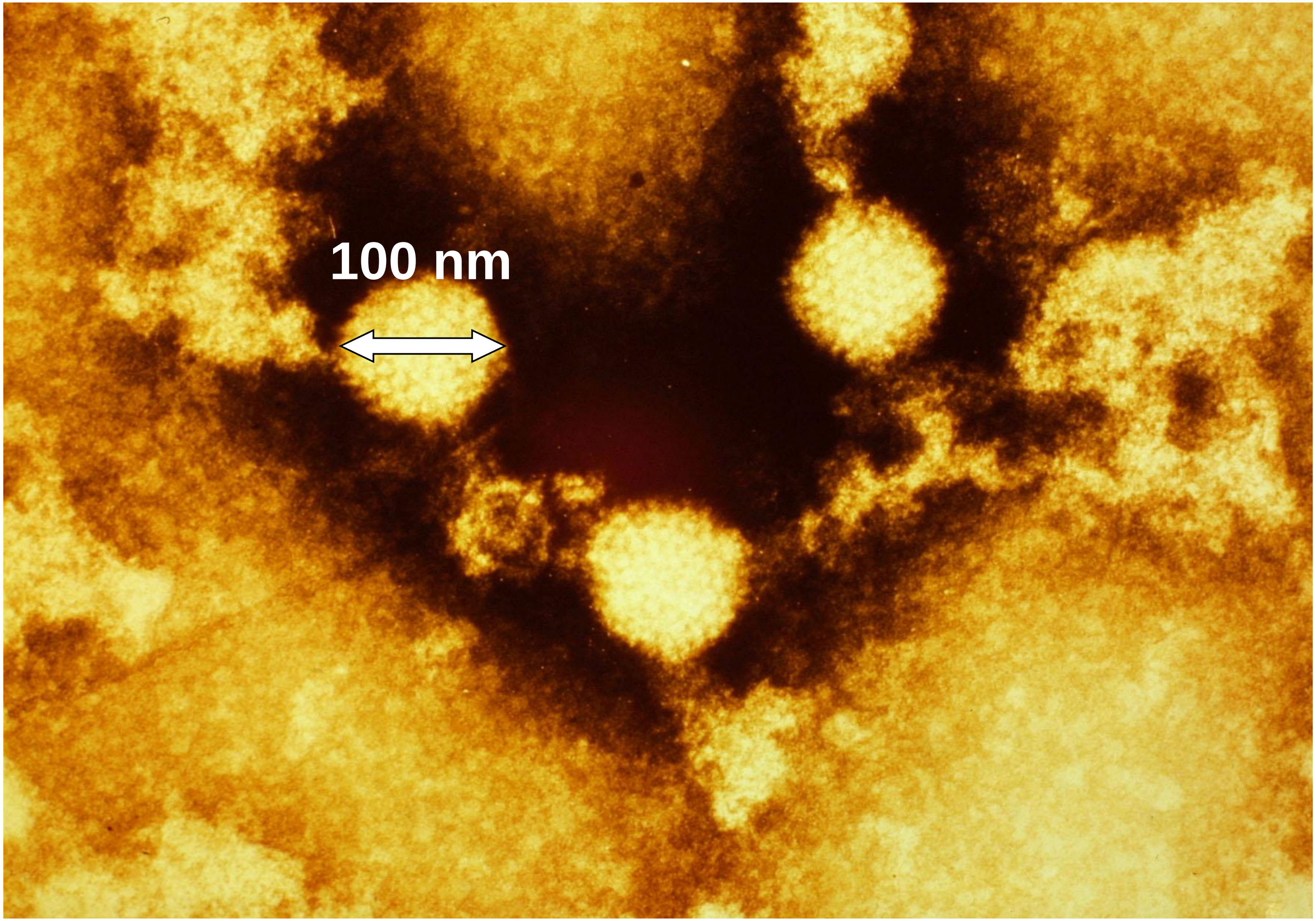
On the Basic Concept of 'Nano-Technology'

N. Taniguchi, Proc. Conf. Prod. Eng. Tokyo, Part II, JSPE, 1974

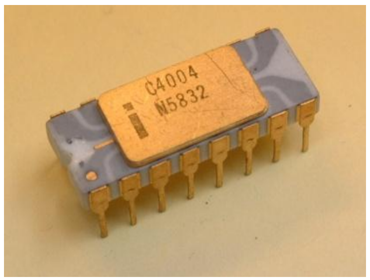


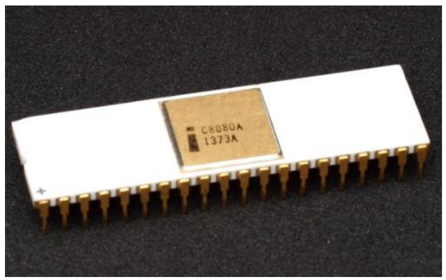
Ref: McKeown after Taniguchi

SEM image of the cold virus

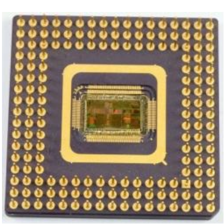


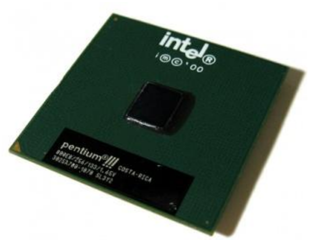
One critical thing has got smaller!

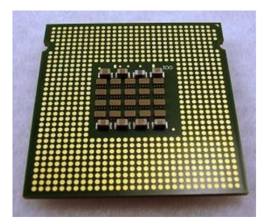





0.01mm 0.006mm 0.003mm 0.001mm





0.0001mm 0.00006mm 0.00003mm 0.00002mm

"measure what is measurable
make measurable what is not"

Maxim ascribed to Galileo Galilei

EXCELLENCE
IN SCIENCE

THE ROYAL SOCIETY

Micro-textured "Scotchlite" material by 3M

Ref: www.3M.scotchlite