Compact ultra precision micromachining system for rapid fabrication of millimetre scale parts

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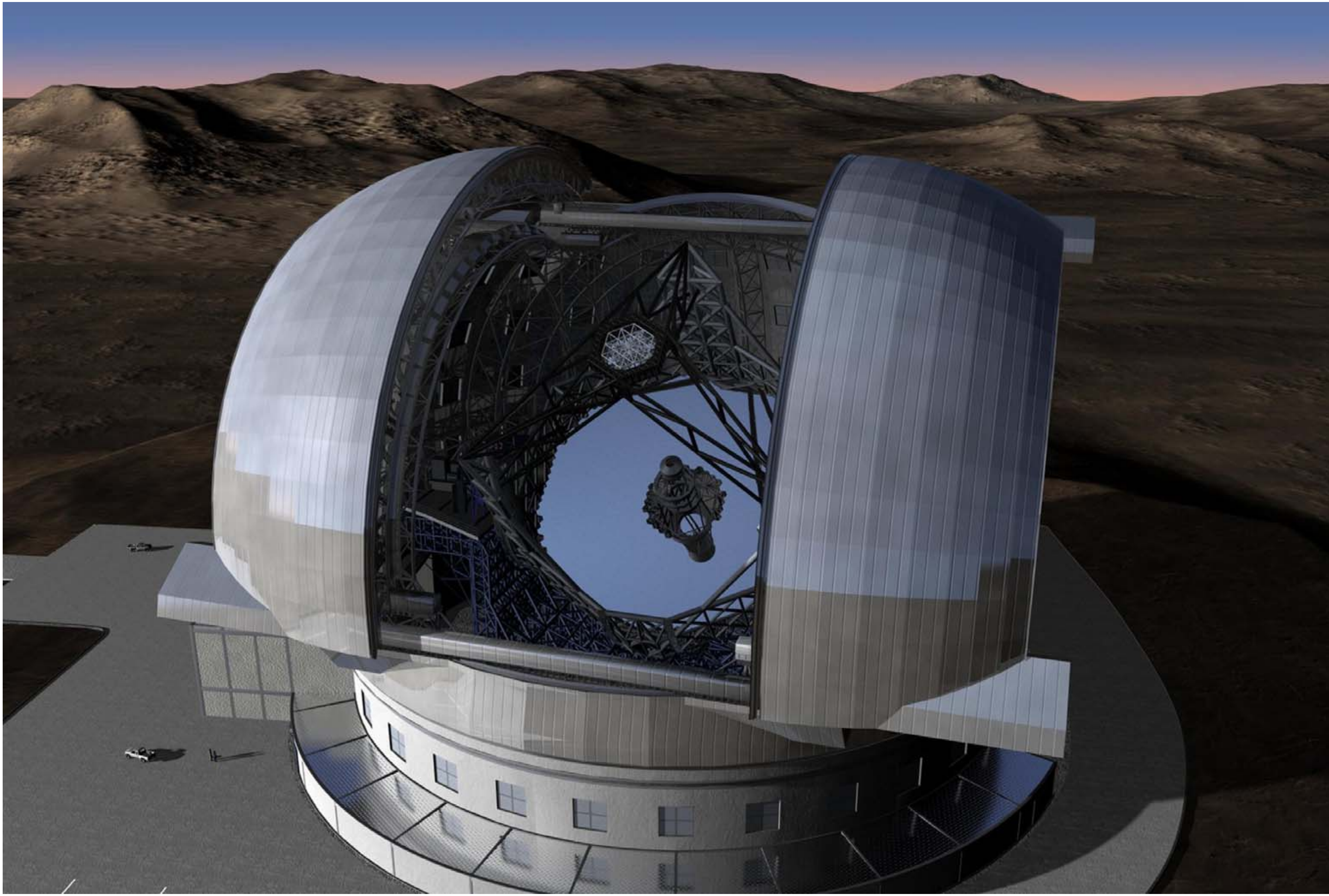
Using diamond machining at nanometre scales of accuracy

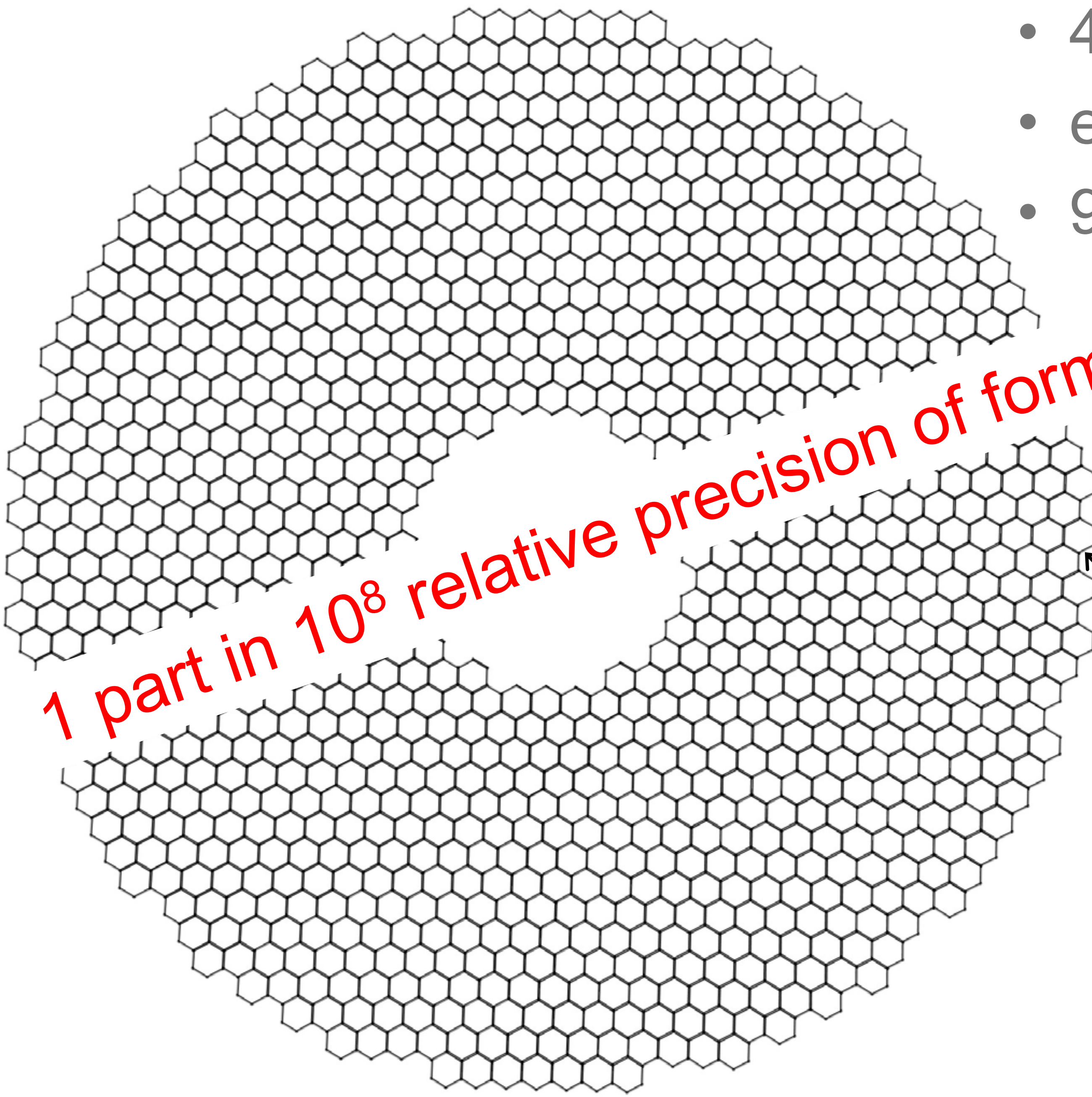
Paul Morantz
David Allen
Paul Shore
Roger Read

ESO E-ELT



Primary mirror

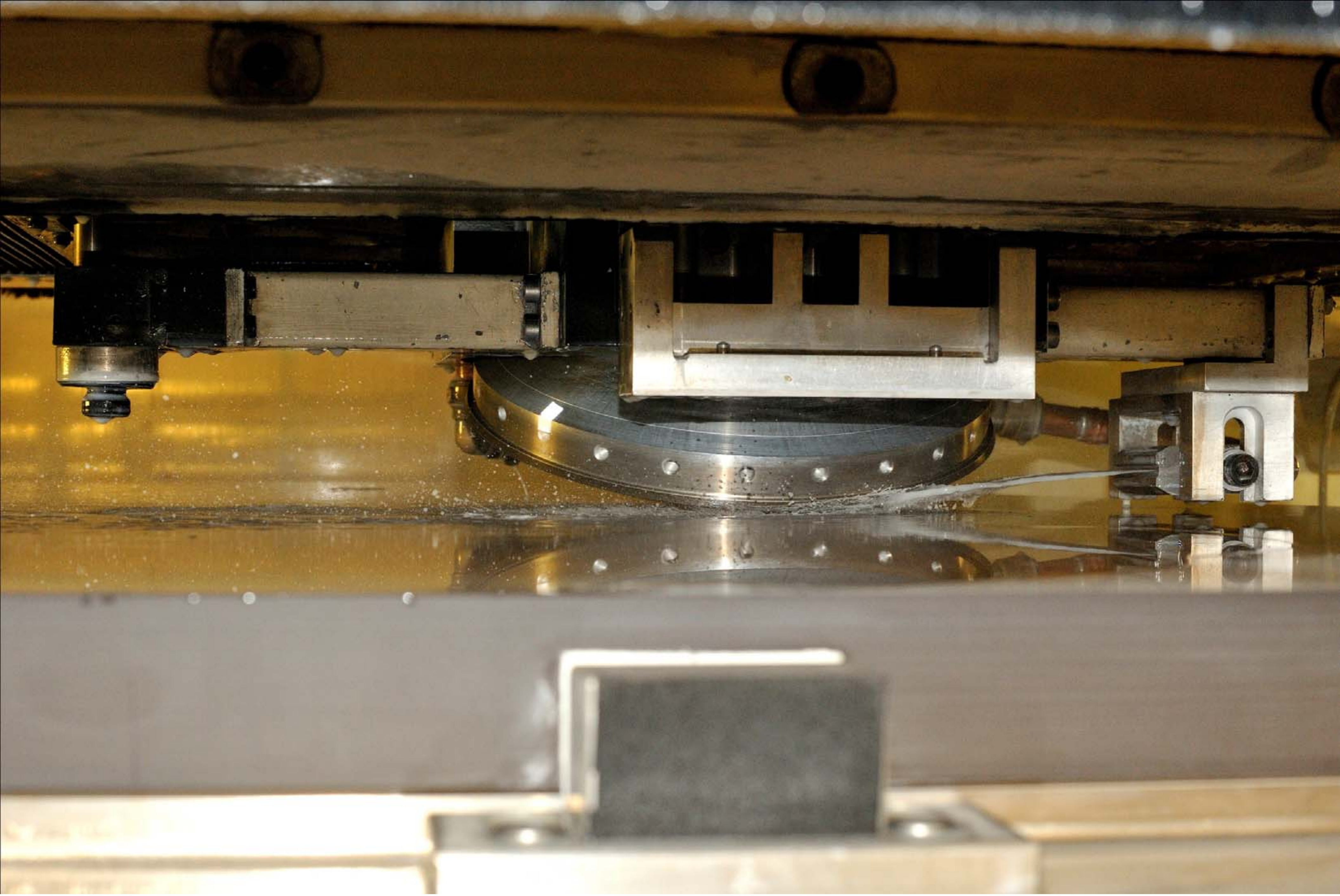
- 42m diameter
- ellipsoidal form
- 984 segme 5m



1 part in 10^8 relative precision of form accuracy to size

Prototype Segment 1

Box machine grinding 1st ESO segment



Box machine grinding 1^{st} ESO segment

1st ESO segment in ground condition

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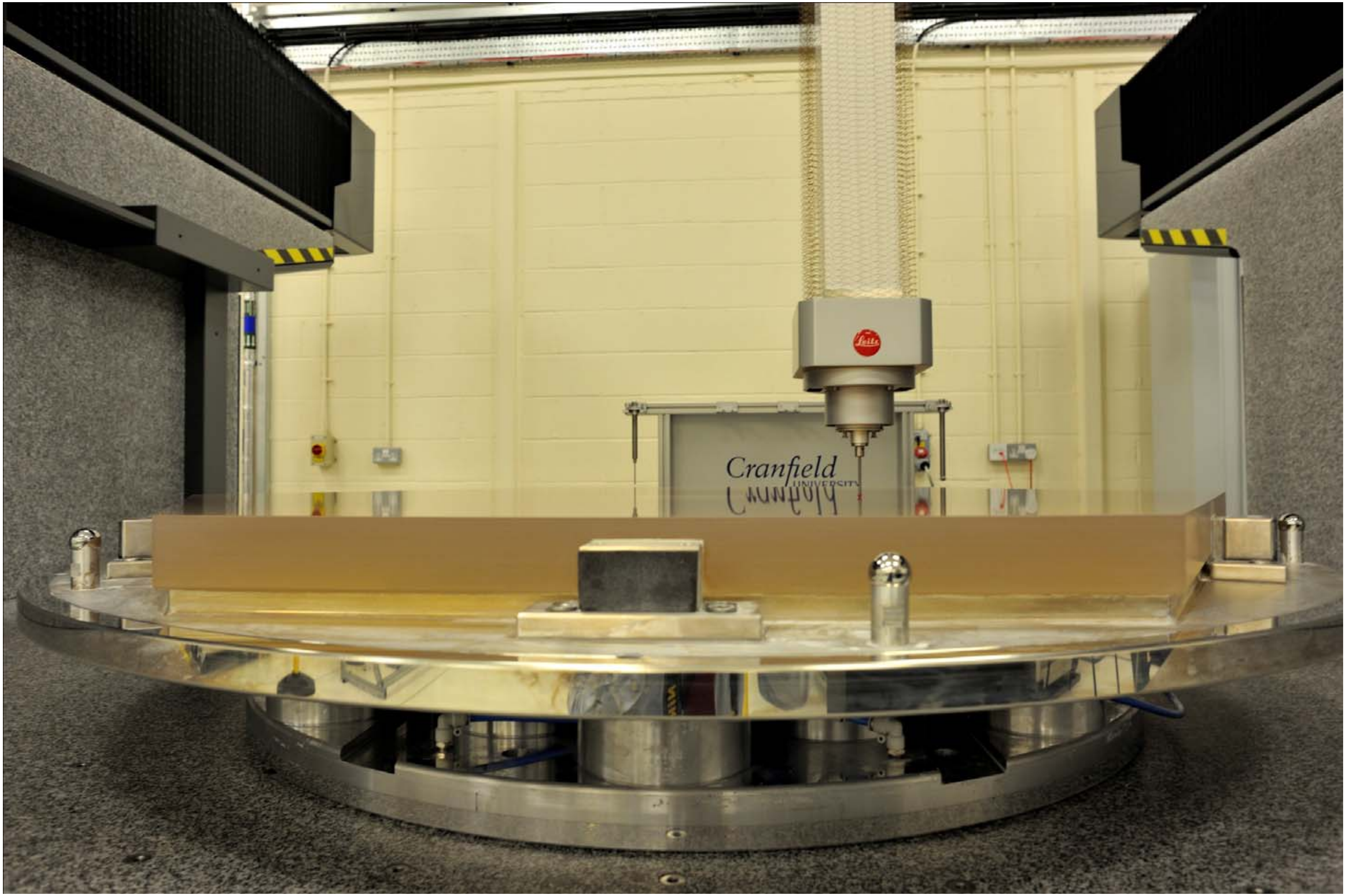

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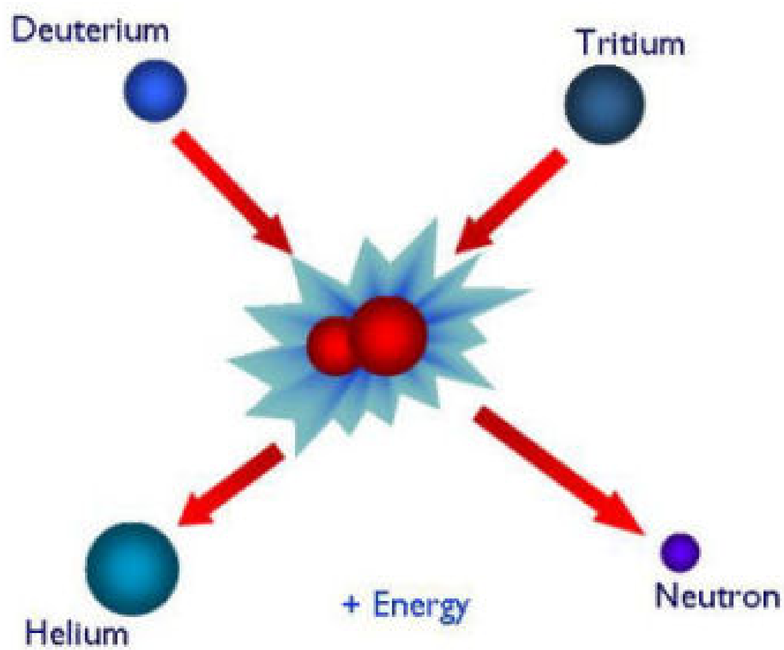
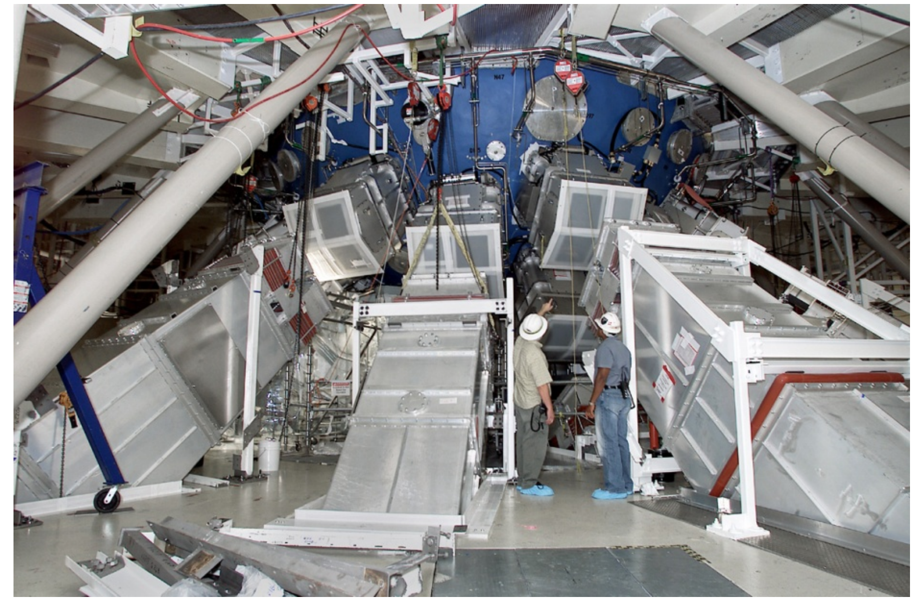
Fusion Energy Research - HiPER





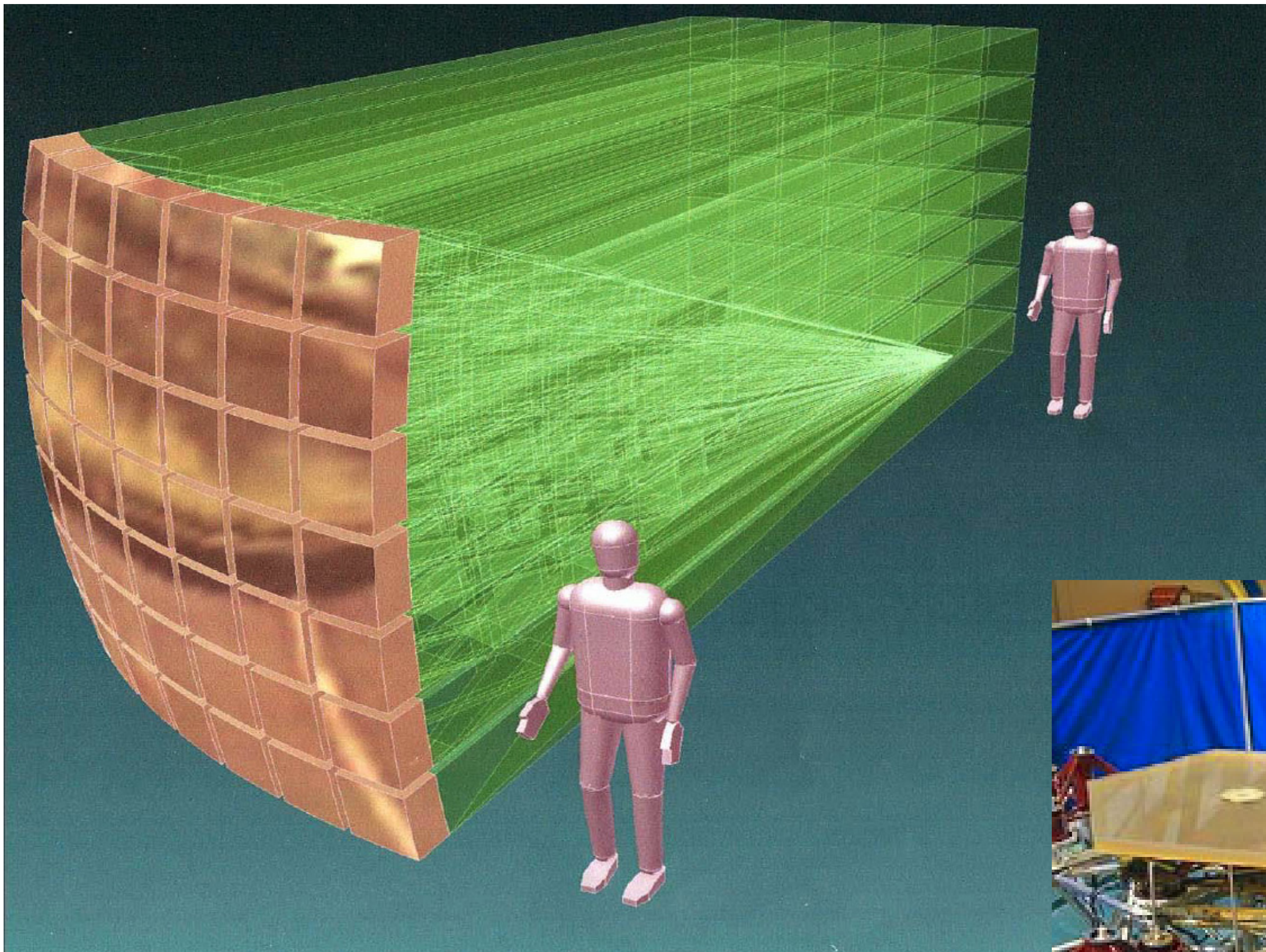
National Ignition Facility, LLNL, USA

Laser Mega Joule, CEA, France

HiPER, Rutherford Appleton, UK

Focusing the high power laser beams

Use similar approach to the large area optical telescope community



Ref, HiPer project

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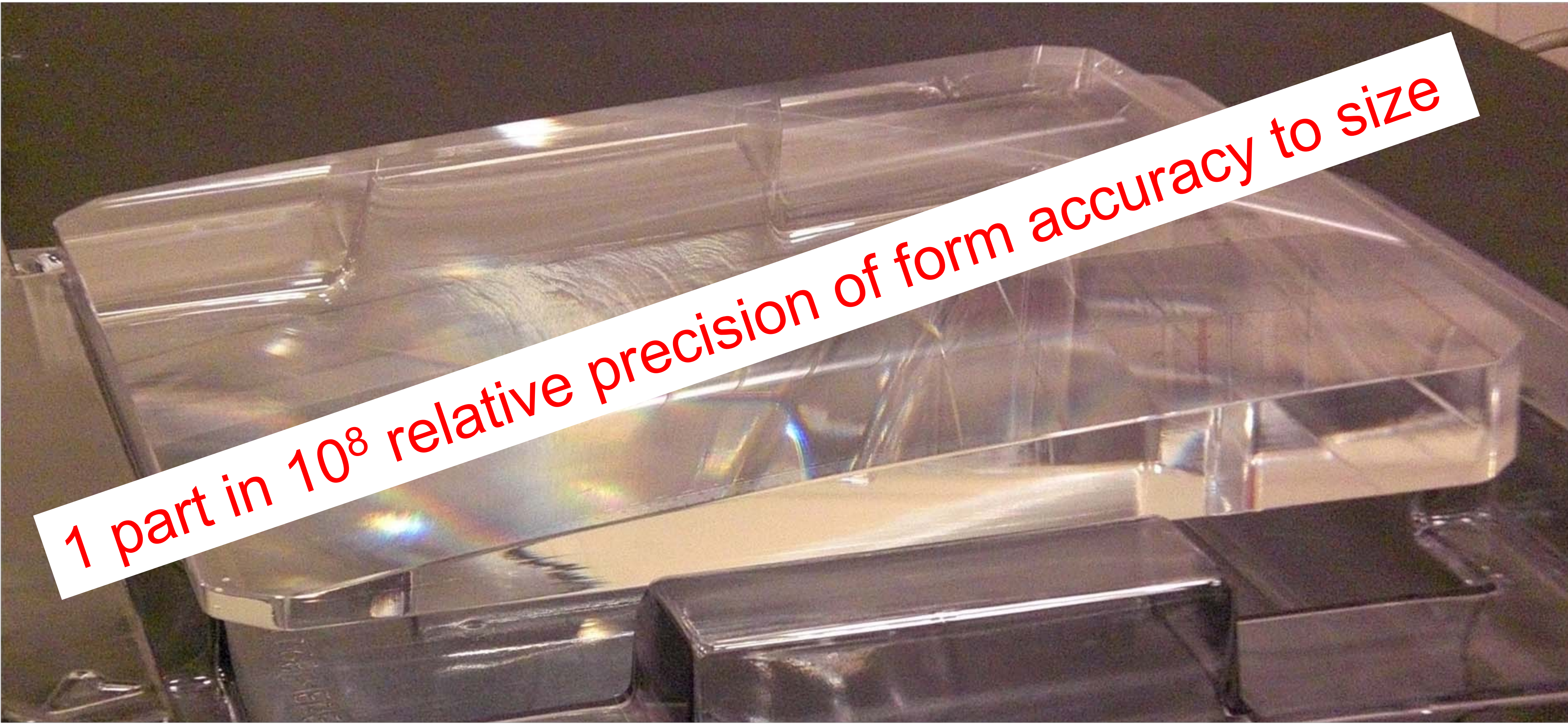
Focusing lens off axis aspheric “wedge” optic
(700mm with form accuracy < 30nm RMS)



Today’s main “wear” component in
Fusion Energy Research

Wbsjpvt!ubshfut

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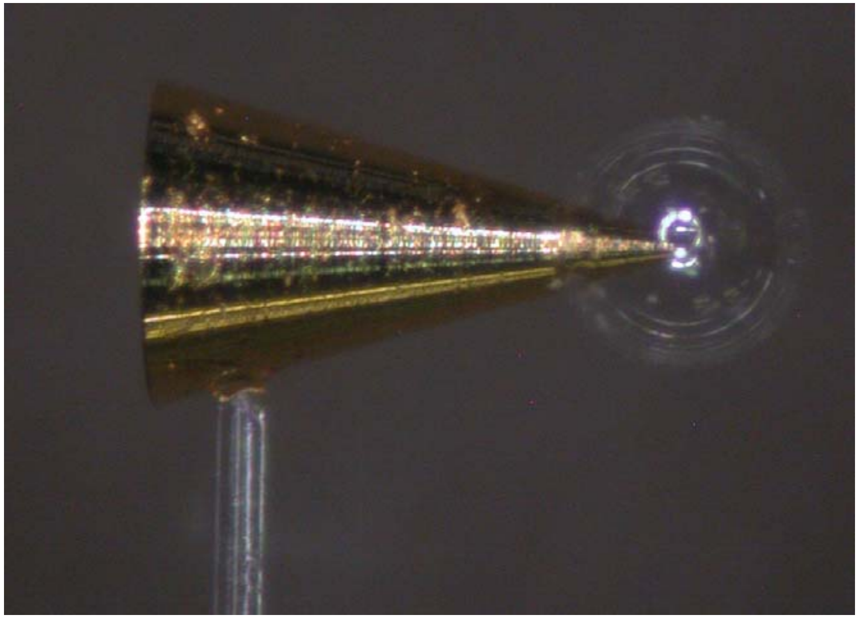

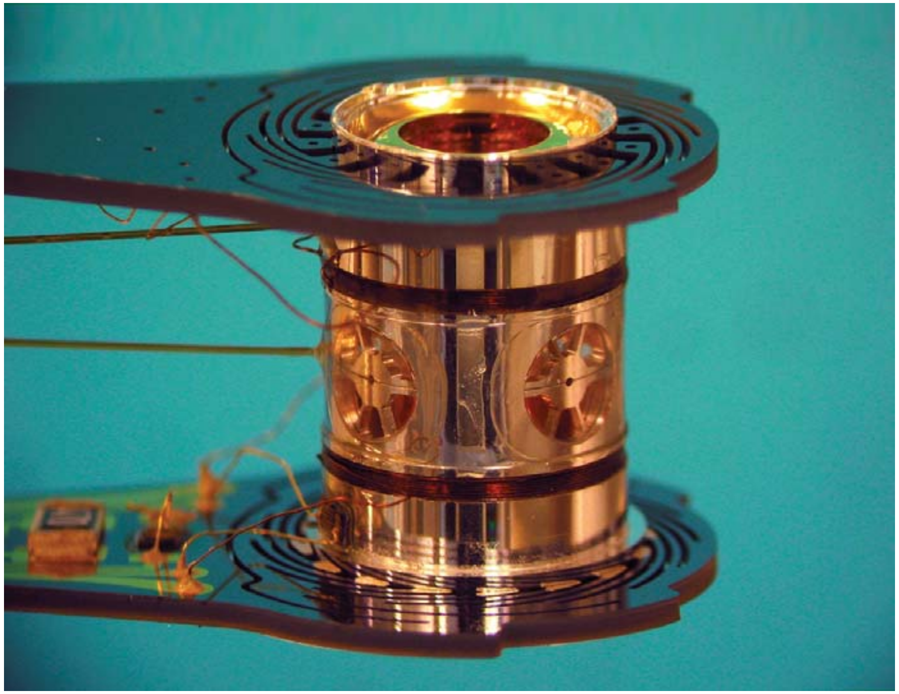

- How to make them?

Refs: *lasers.llnl.gov, stfc.ac.uk*

Diamond turning set up

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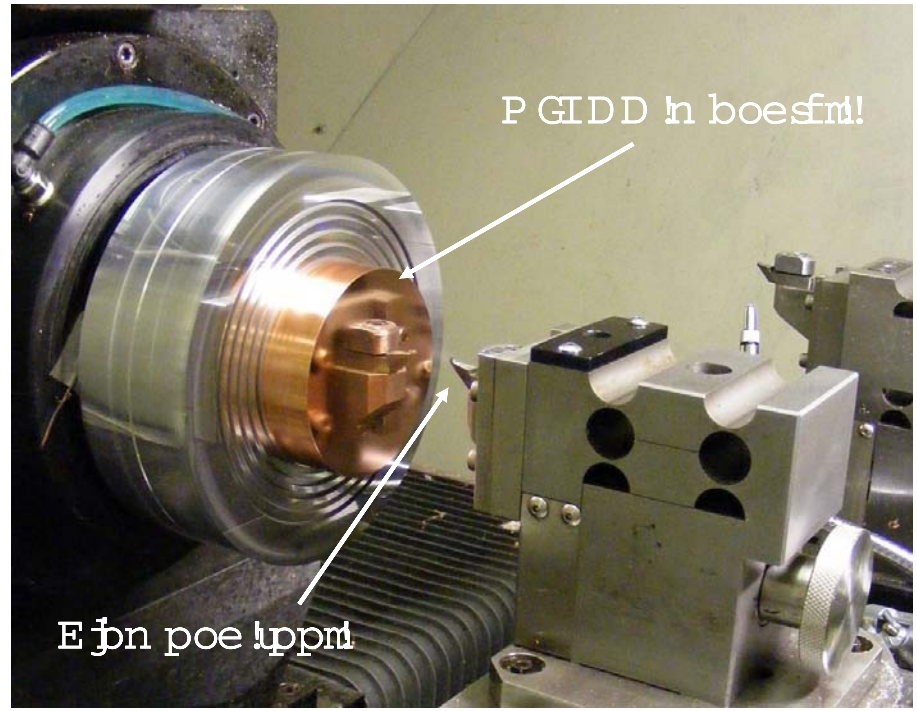

Moore 350 Ultra-precision lathe:

- aerostatic spindle (up to 6000 rpm)
- hydrostatic guide-ways (X & Z axis)
- Temperature controlled environment (±0.1°C)

Fabrication of Micro-Structured Surfaces by SPDT: RAL target mandrel requirement

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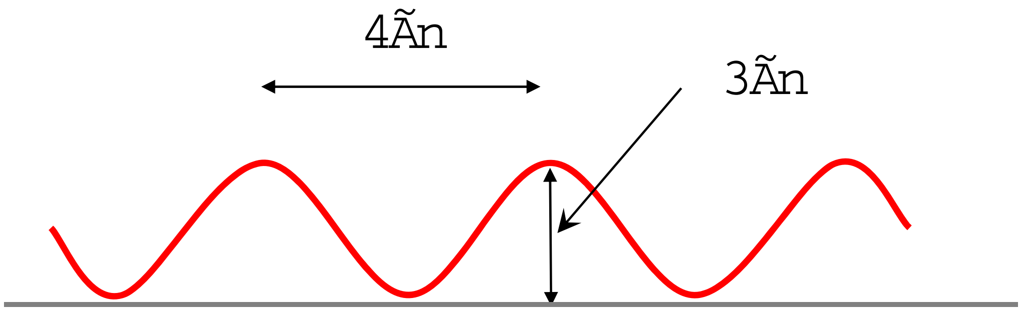
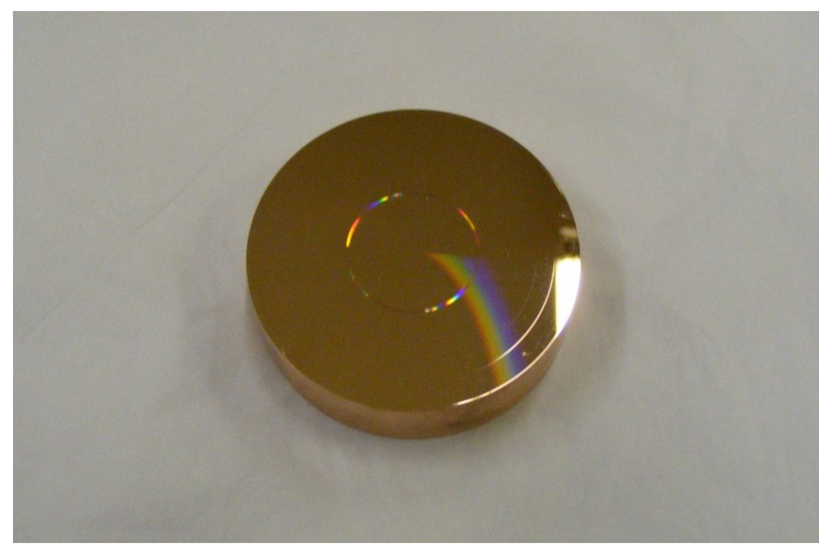


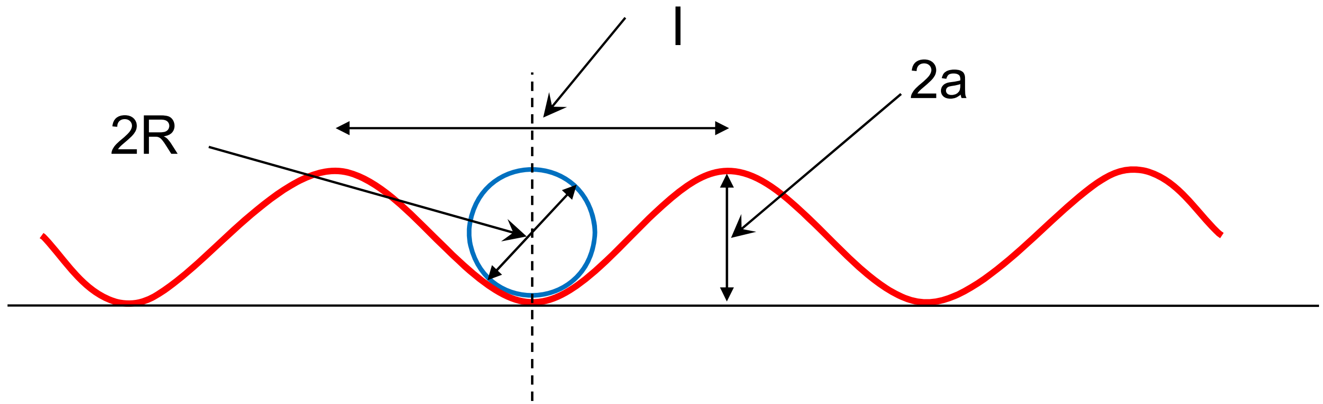
A sinusoidal pattern extending from the edge of an Oxygen-Free High Conductivity Copper disk 13mm inwards. Roughness requirement: 25nm RMS

The OFHCC disks were then used by RAL as mandrels to replicate the sinusoidal pattern using coating techniques to produce thin foil targets for high power laser experimentation



The size of the sinusoidal pattern is very challenging!

Diamond tools: geometry & size



a= 1µm

l= 3 µm

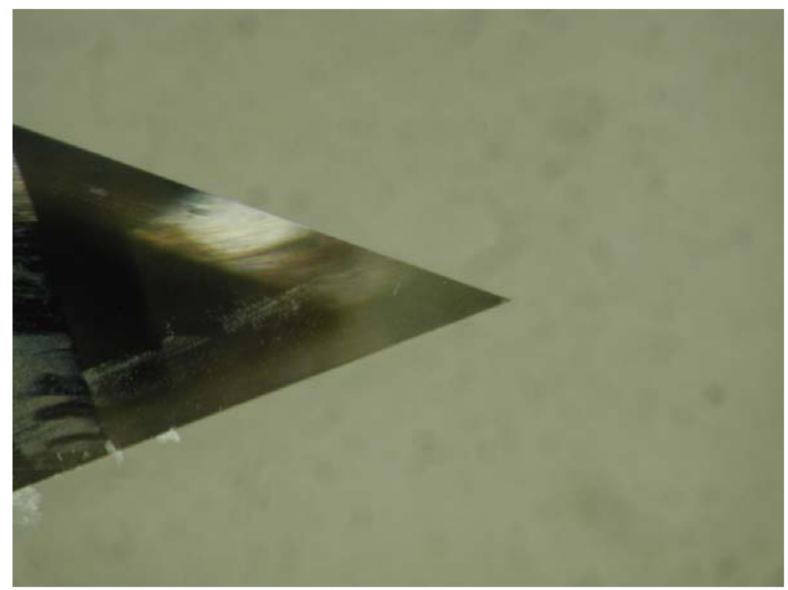
Tool geometry and size are critical!

Max. tool radius size:

$$z = a\left(1 - \cos\frac{2\pi x}{l}\right)$$

$$\frac{d^2 z}{dx^2} = kN \qquad k = \frac{1}{R}$$

For a= 1 and l= 3 then R ≈ 228nm Max



Tools were supplied with a sharp edge point (no nominal radius)!

Results: Replication process in gold (RAL)

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Veeco

3-Dimensional Interactive Display

Date: 08/29/2008
Time: 13:47:43

Surface Stats:

Ra: 668.16 nm

Rq: 773.65 nm

Rt: 5.11 um

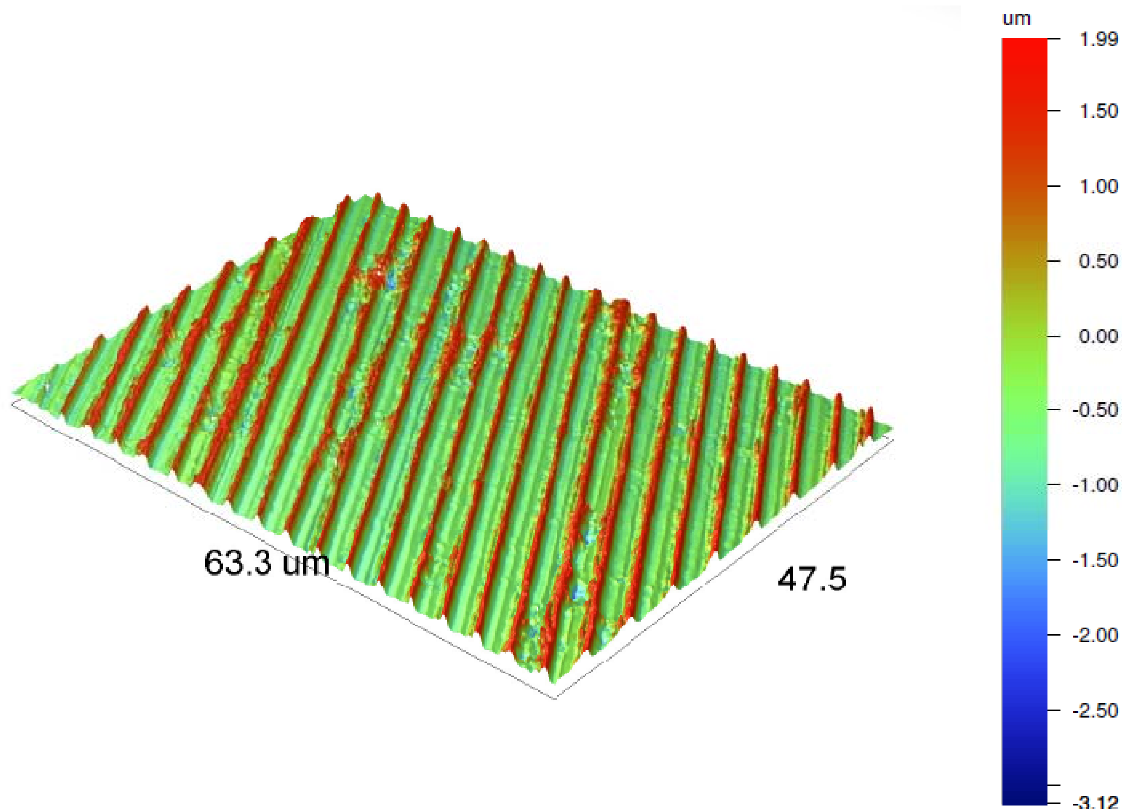
Measurement Info:

Magnification: 100.04

Measurement Mode: VSI

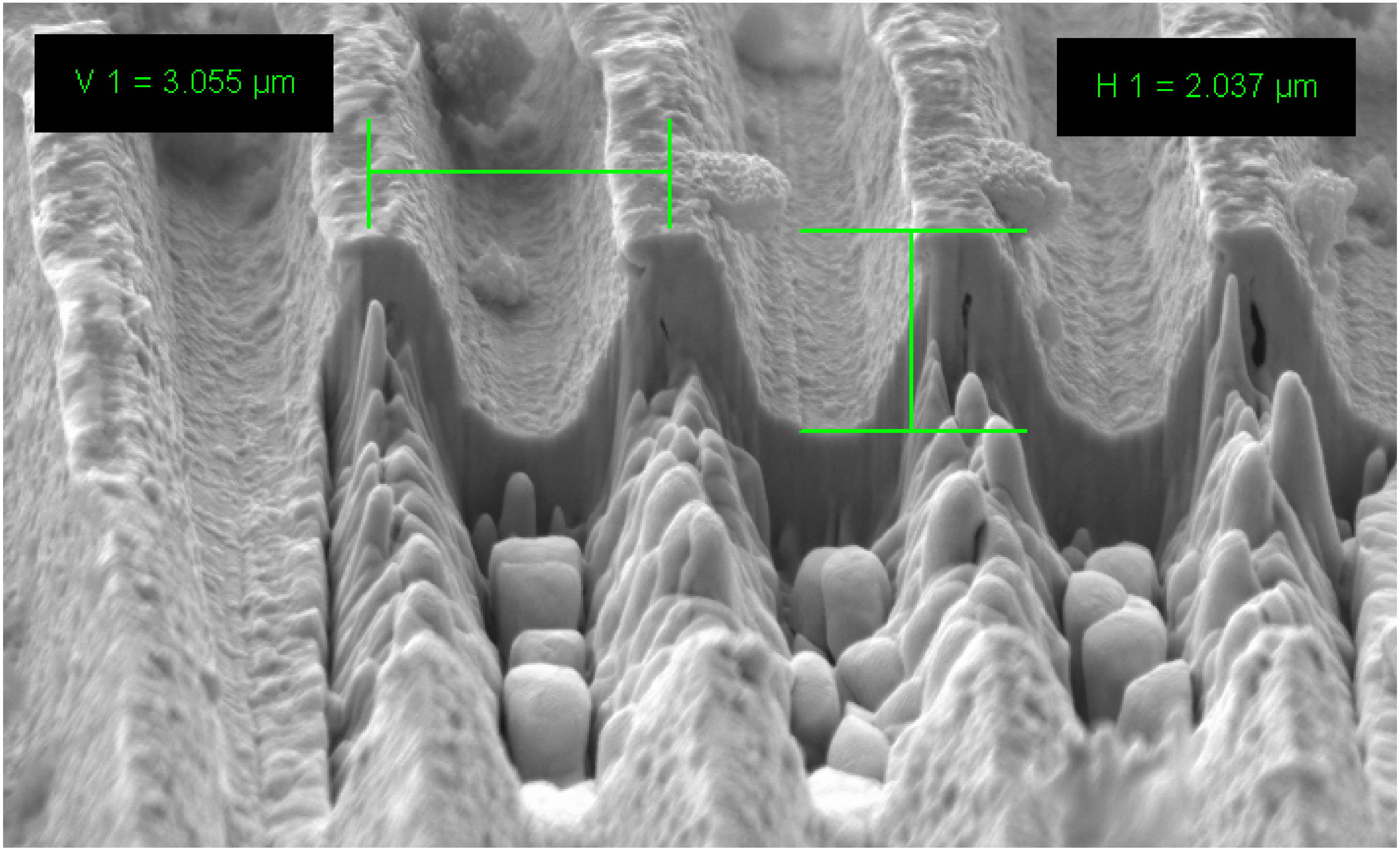
Sampling: 98.96 nm

Array Size: 640 X 480



Title: Gold Plated Part
Note: Edge of Sample

SEM micrograph of target cross-section



Further work alternatives: Tool design and fabrication

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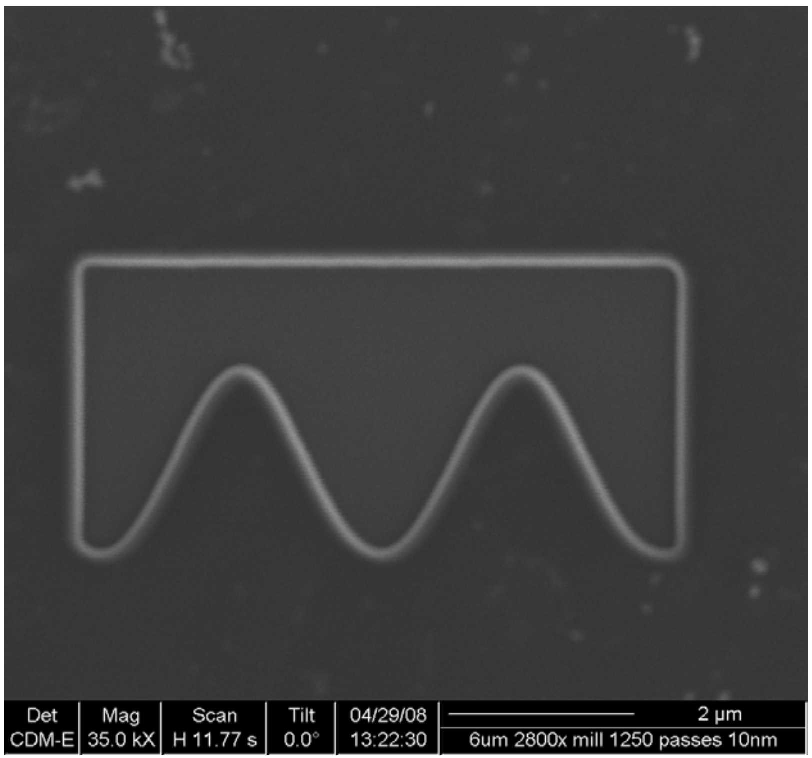
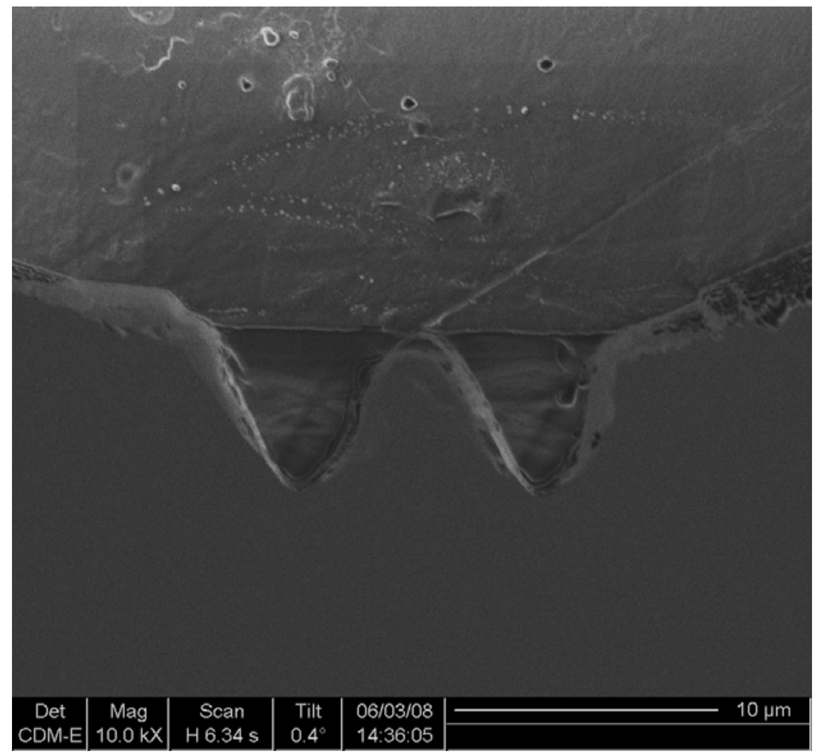
Cranfield sinusoidal FIB prototype diamond tool

a= 2μm, l= 3μm





Bmfo!E-!Fwbot!S-!3119/!

Boltzmann ellipsoids

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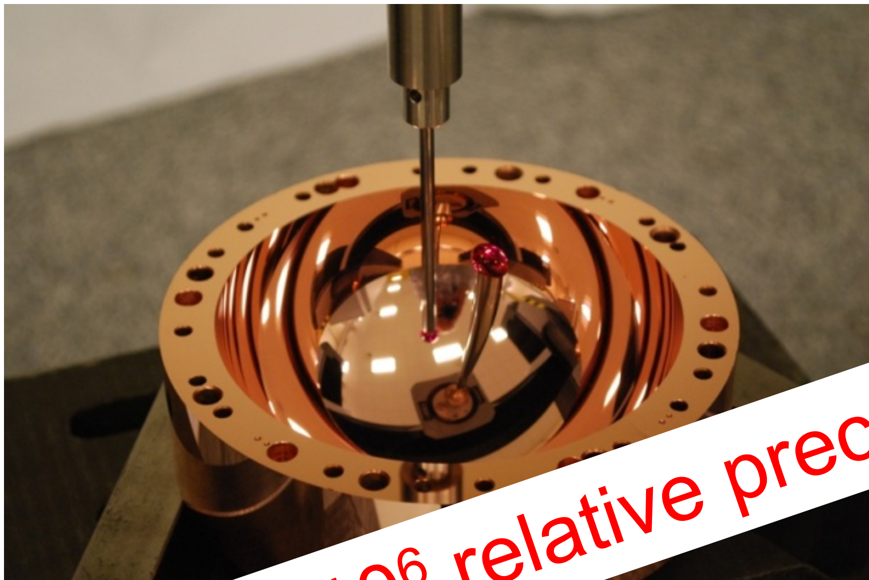

1 part in 10^6 relative precision of form accuracy to size

- Tri-axial ellipsoid internal form, characterised to ~1nm uncertainty on mean radius

Various targets

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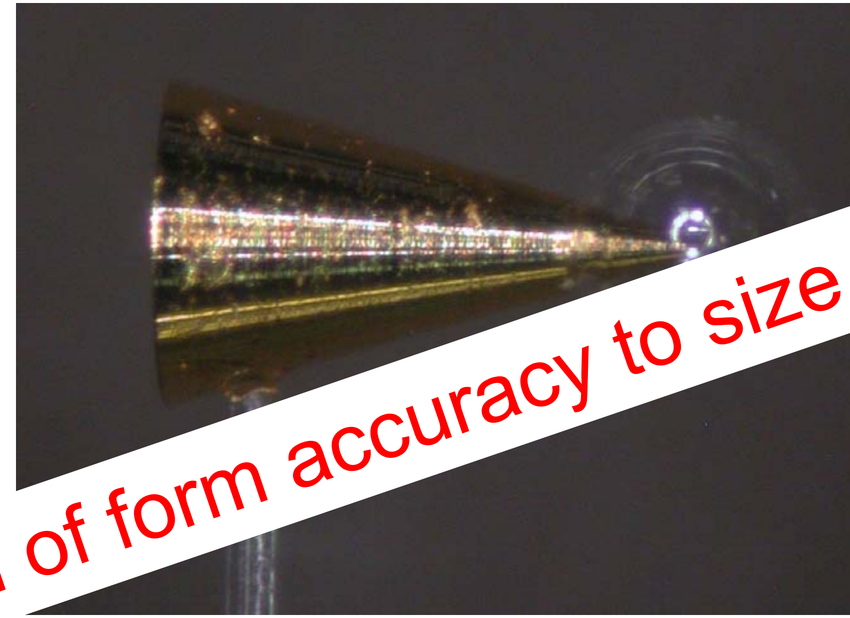
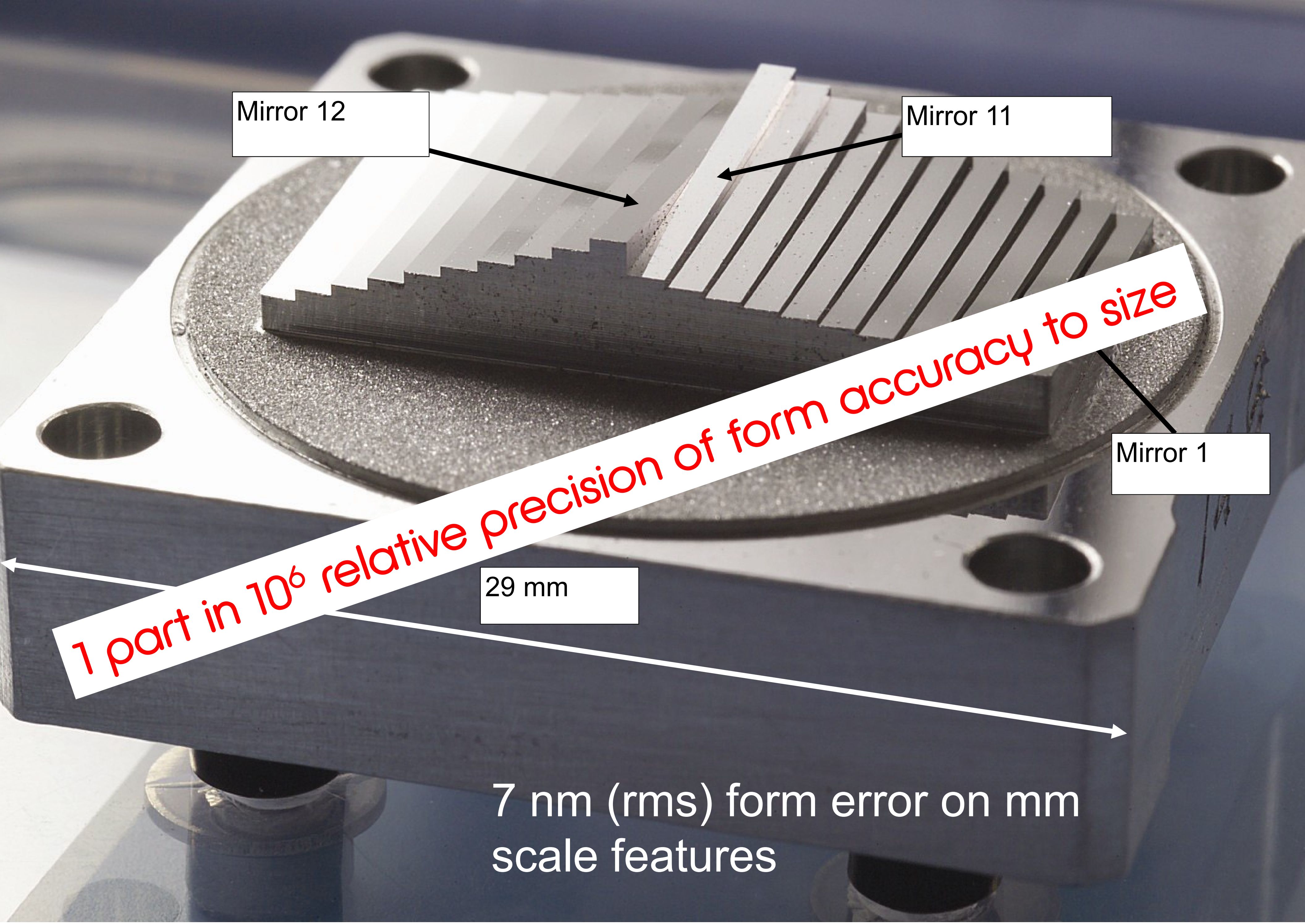


1 part in 10? relative precision of form accuracy to size

- How to make them?

Refs: *lasers.llnl.gov, stfc.ac.uk*


Mirror 12
Mirror 11
Mirror 1
29 mm
1 part in 10^6 relative precision of form accuracy to size
7 nm (rms) form error on mm scale features

Ultra-precision diamond turning

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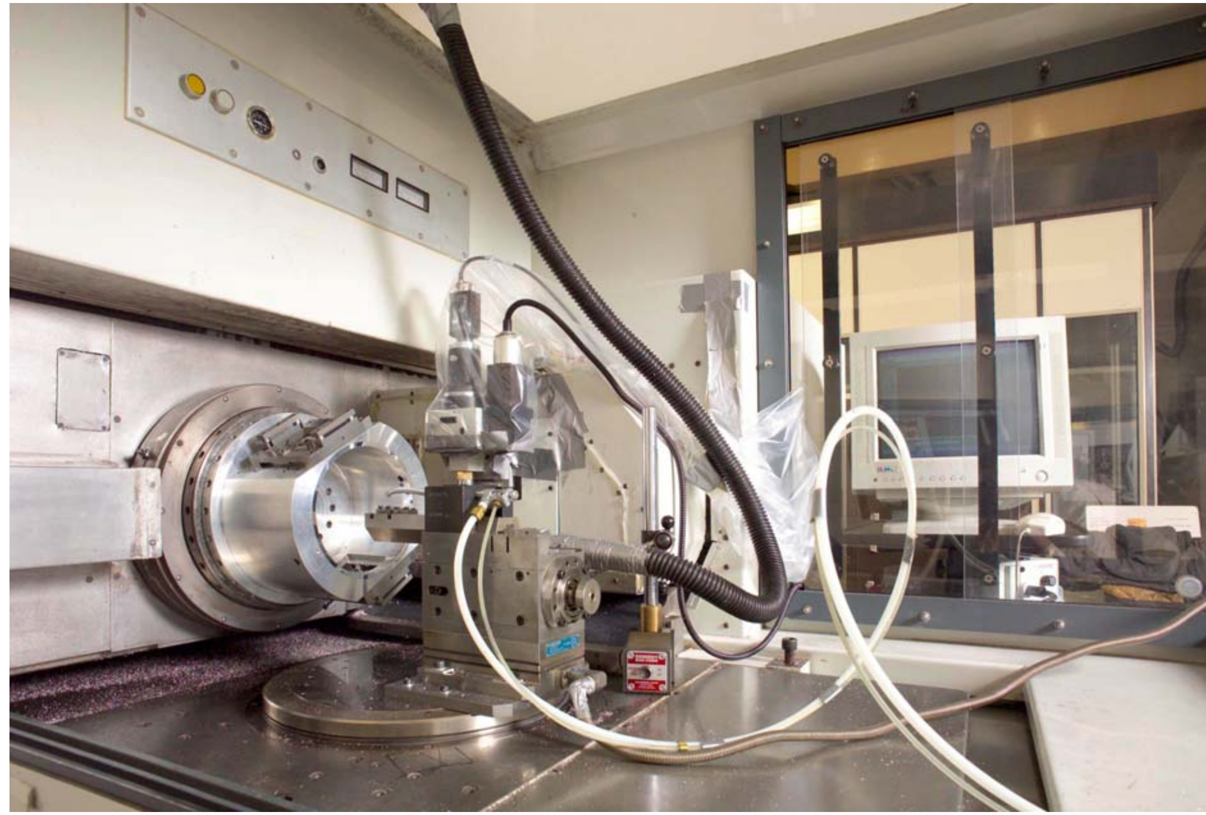

- nm resolution positioning
- 0.001°C resolution temperature control with 0.01°C accuracy under dynamic load
- ~ 100 nm p-v form capability on 200mm size parts
- Machine footprint ~ 10 m^2

‘Rough’ precision pre-machining of components for subsequent SPDT

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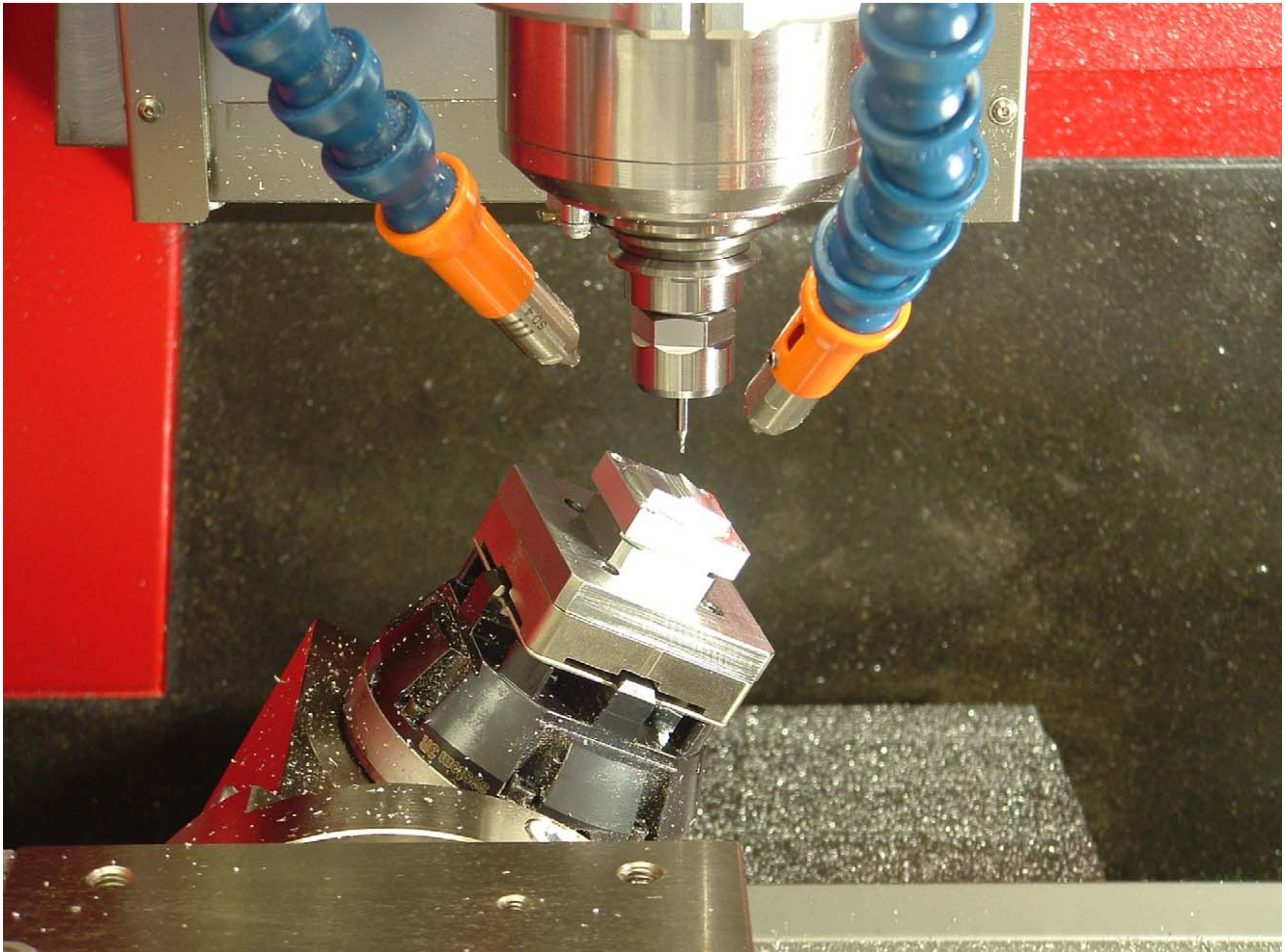
‘Rough’ precision pre-machining of components for subsequent SPDT



Performance deficits of conventional micro-milling machines for target fabrication

- Surface finish
- Accuracy
- Speed of production
- Cost of ownership

Innovation for surface finish

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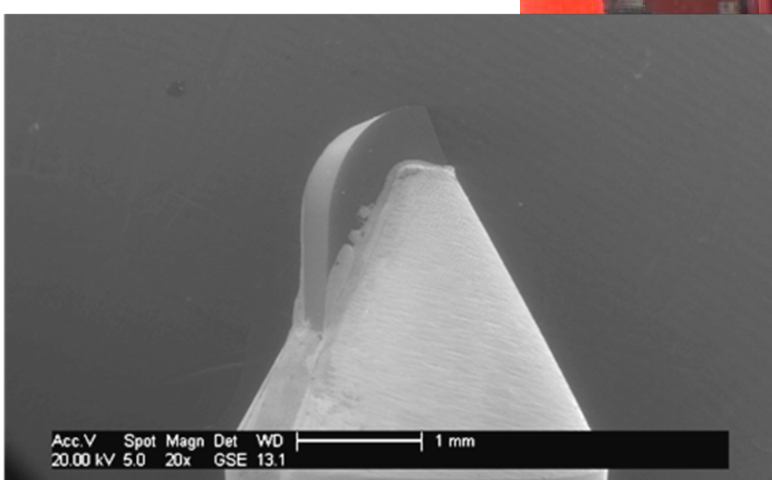
High speed air bearing spindles will be an innovative feature

Westwind spindle testing with single point diamond tooling



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Test results

Measured surface roughness (Ra)

	285k spindle		160k spindle	
	Aluminium	Brass	Aluminium	Brass
Ra across (nm)	13-24	11-44	13-31	5-24
Ra along (nm)	4-15	7-36	3-17	2-10

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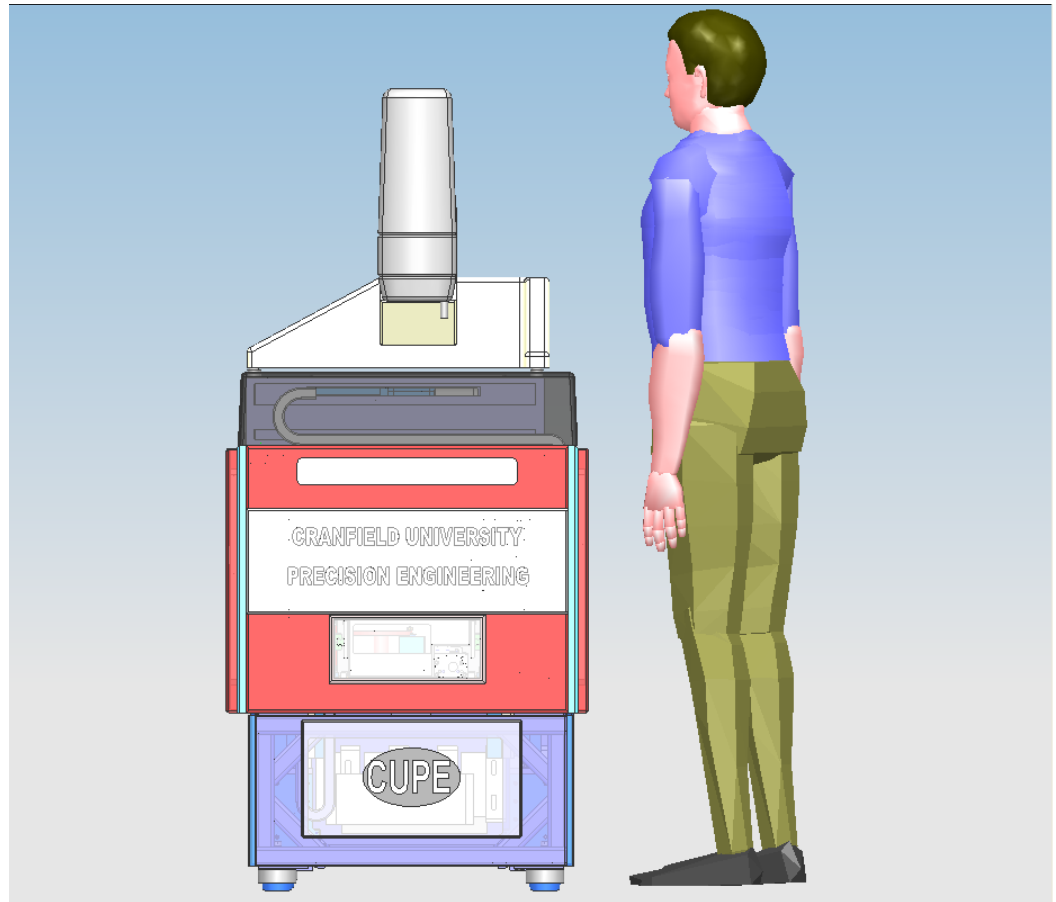
Performance characteristics of two CNC precision machining centre (Photographs courtesy of Kern, Germany)

	Kern Evo	Kern Pyramid Nano
Positioning scatter (Ps) according to VDI/DGQ 3441	±0.5µm	±0.3µm
Minimum space requirement	2.80 x 2.50 x 2.20 m^3	2.85 x 3.58 x 3.14 m^3
Footprint area	7.0 m^2	10.203 m^2
Weight	3 tonnes	~ 8 tonnes

The more precise the machine; the larger the footprint!

Cost of ownership – speed of production

Project objective



To design and develop a cost-effective, multi-axis, compact ultra precision micromachining system capable of diamond turning, fly cutting, milling and super-abrasive machining. This machine will be capable of producing component parts of <50mm^3 having nanometre surface roughness and commensurate size/form accuracy. It will incorporate novel air bearing technologies within key machine sub-systems.

Commercial exploitation of synergy between precision engineering and microengineering

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A NEW NOVEL AND COMPACT ULTRA HIGH PRECISION 5-AXIS TOP-LOADING CNC MICROMACHINING FACILITY

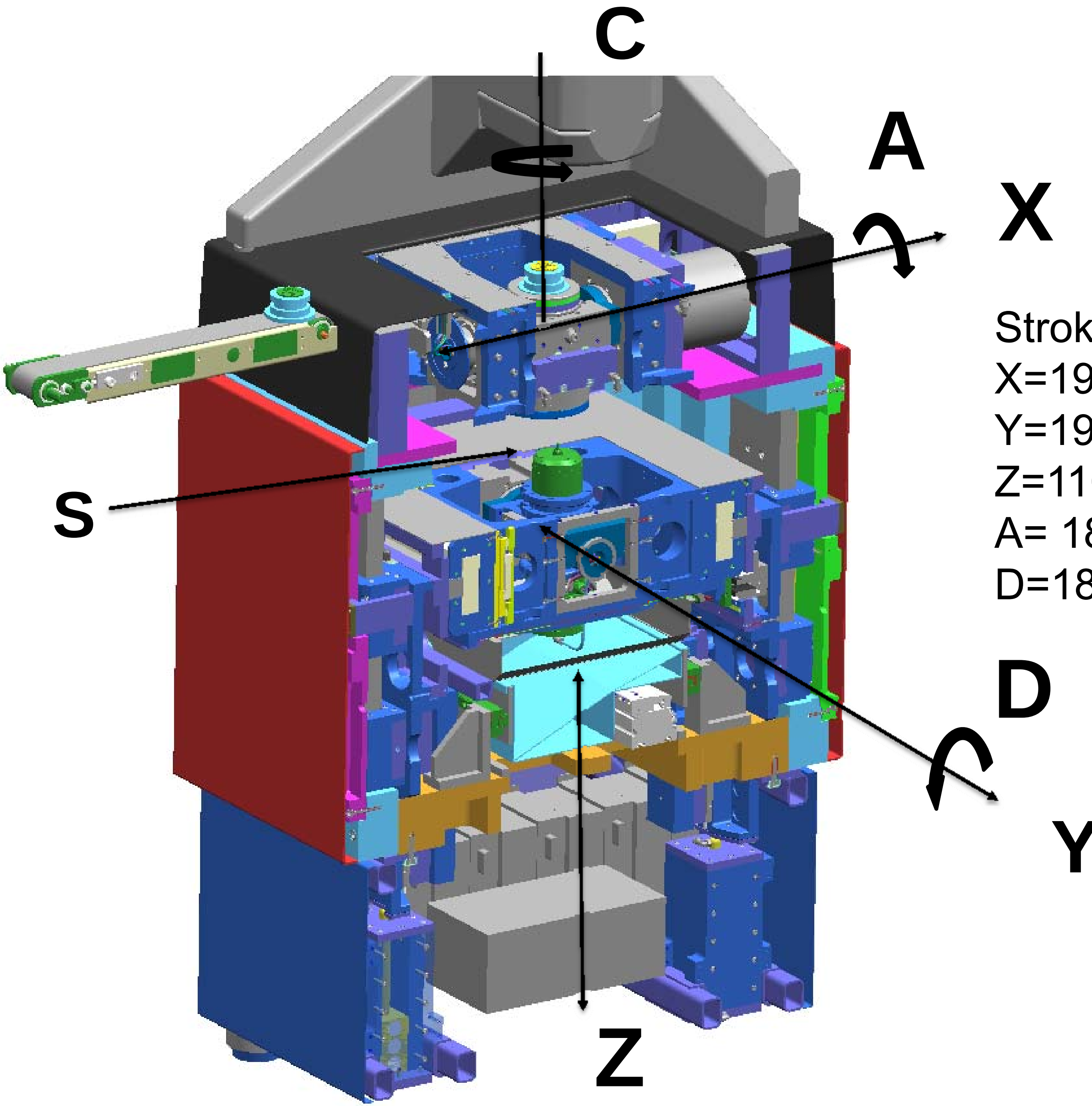
DESIGNED BY CRANFIELD UNIVERSITY PRECISION ENGINEERING CENTRE

Offers:-

- 5 axes micro machining capability of complex shapes in a variety of hard and soft materials
- Single point diamond turning.
- Diamond milling drilling and grinding
- CMM head with optical capability (for *in situ* metrology)
- Error compensation
- Porous ceramic linear air bearing technology (Developed at Cranfield University)
- 1nm resolution linear and ~10 nano-radians rotary motions on all axes.

- Maximum component capacity 50 x 50 x 50mm^3.

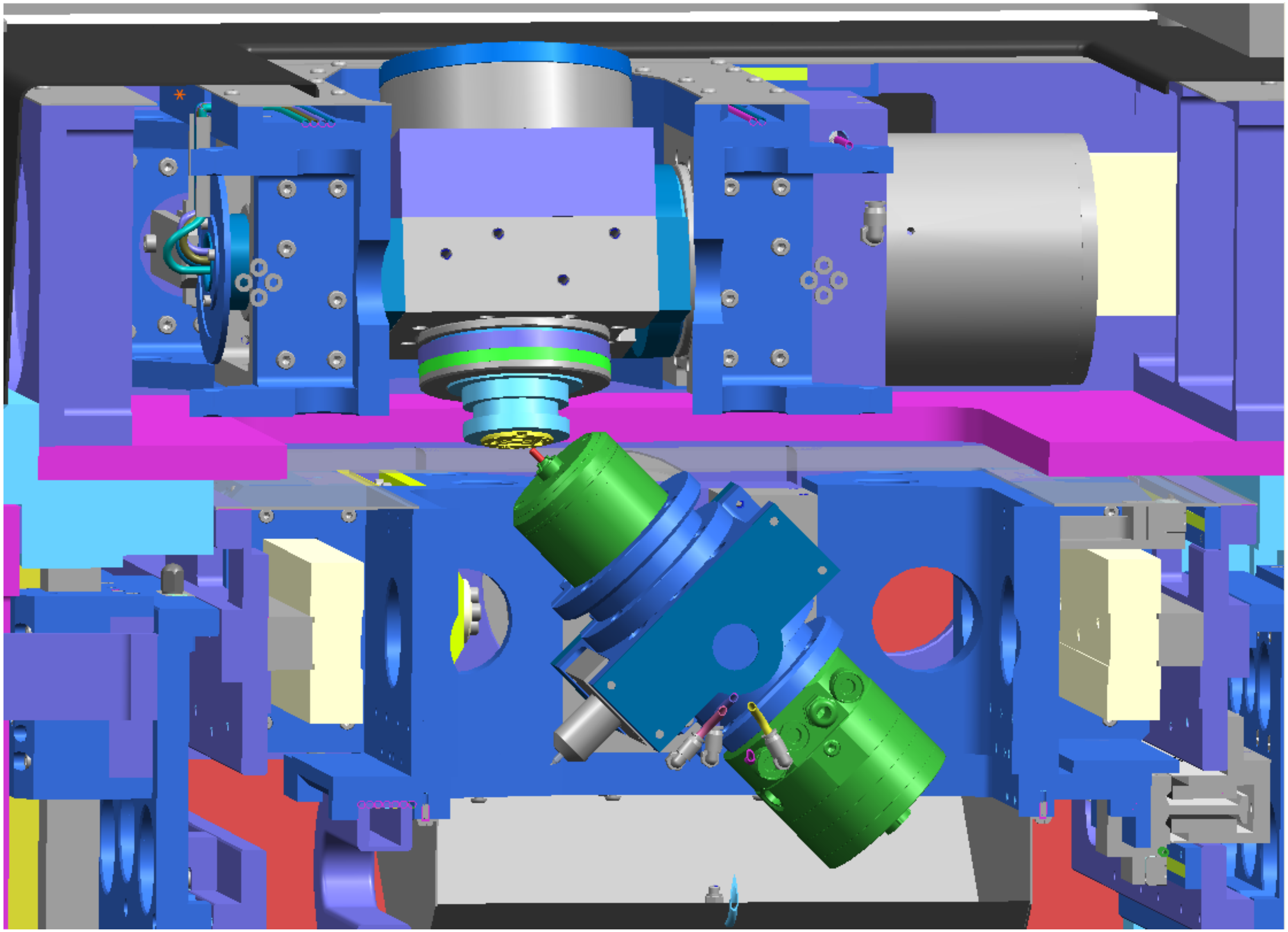
What is inside the new machine?



Strokes
X=190mm
Y=190mm
Z=110mm
A= 180 deg
D=180 deg

Axes
Strokes
Capacity

What is inside the new machine?



What is inside the new machine?

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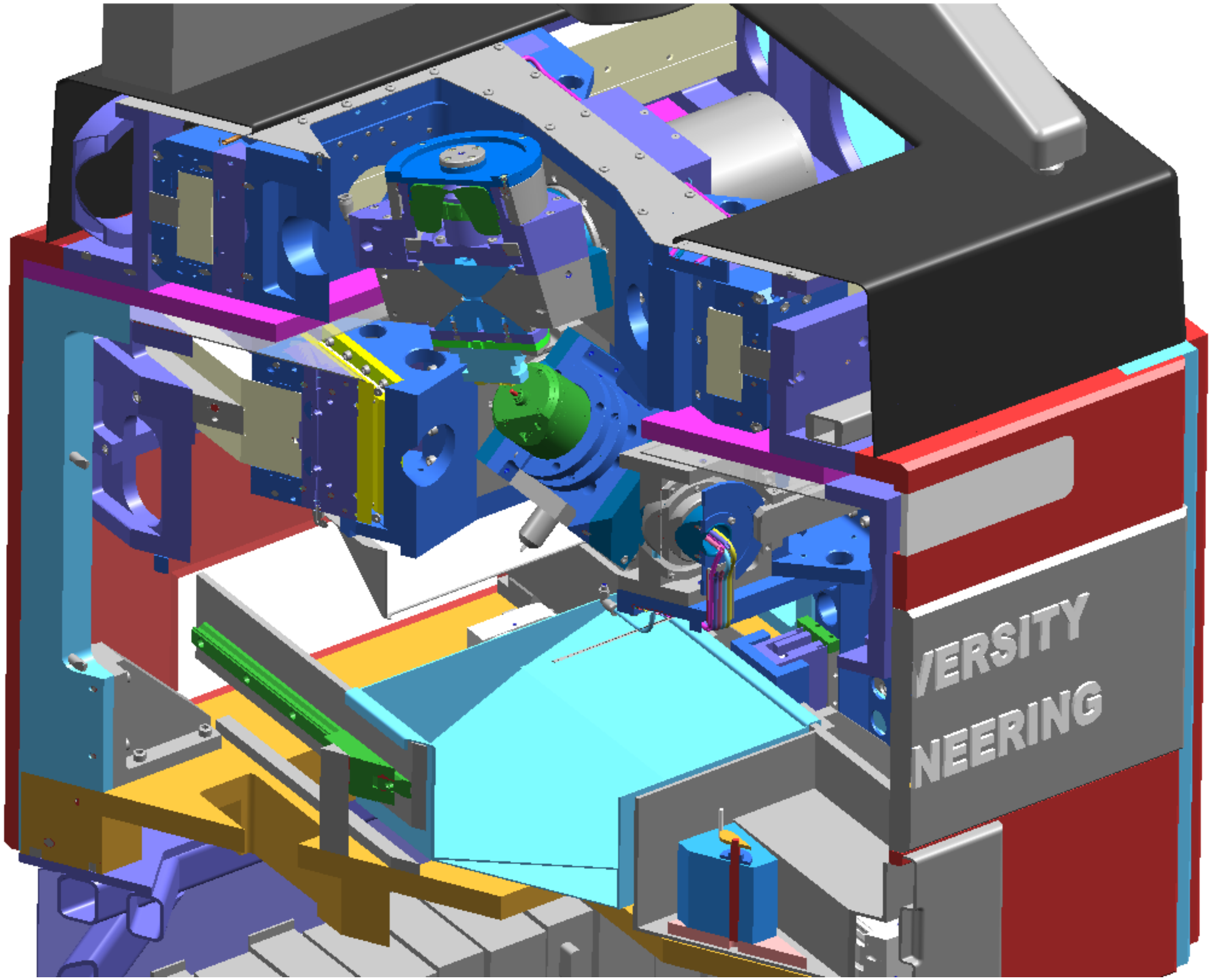
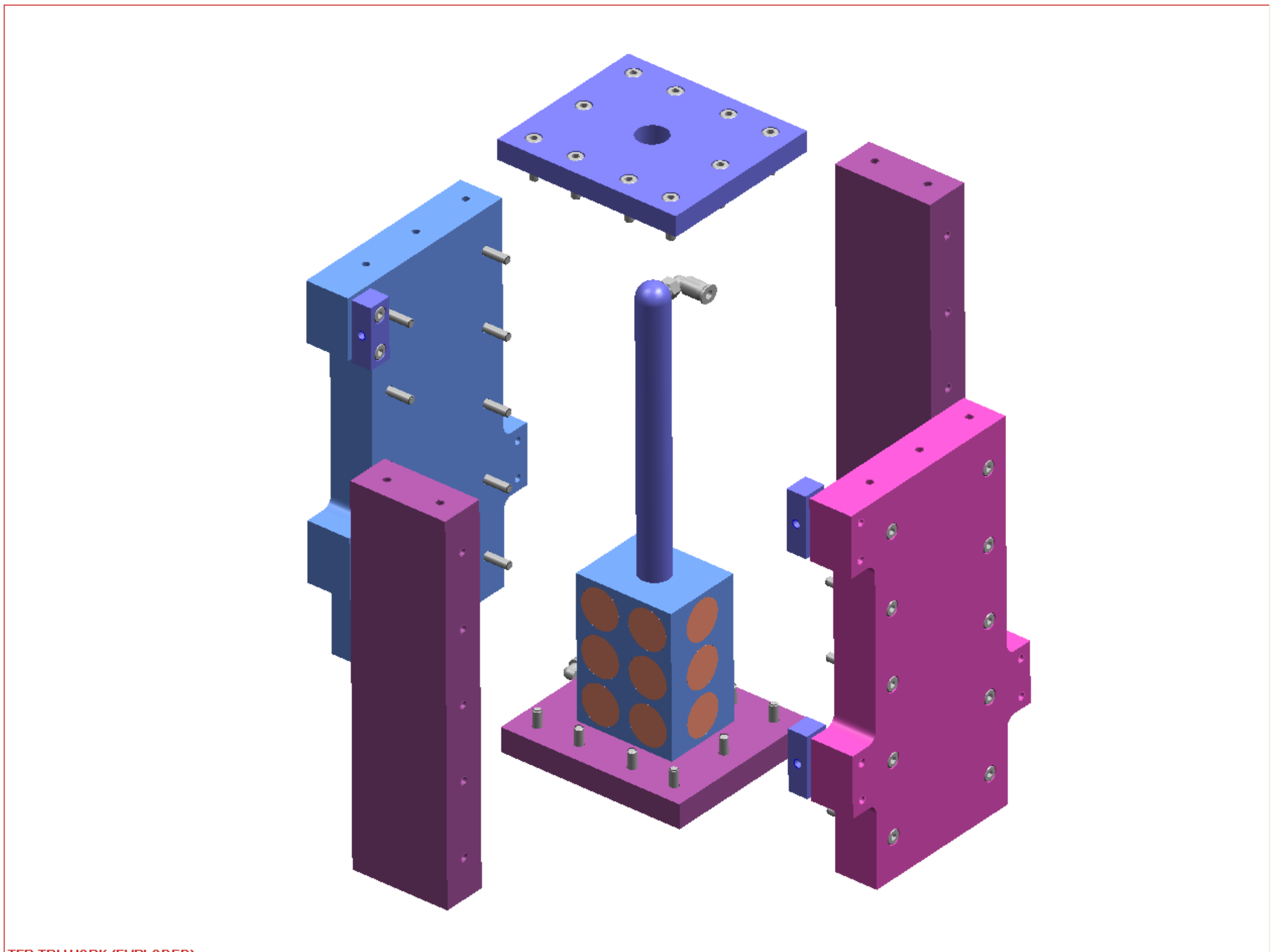


Frictionless counter-balance cylinder for Z-axis.
18 air bearings per assembly.
2 assemblies required per machine; total 36.



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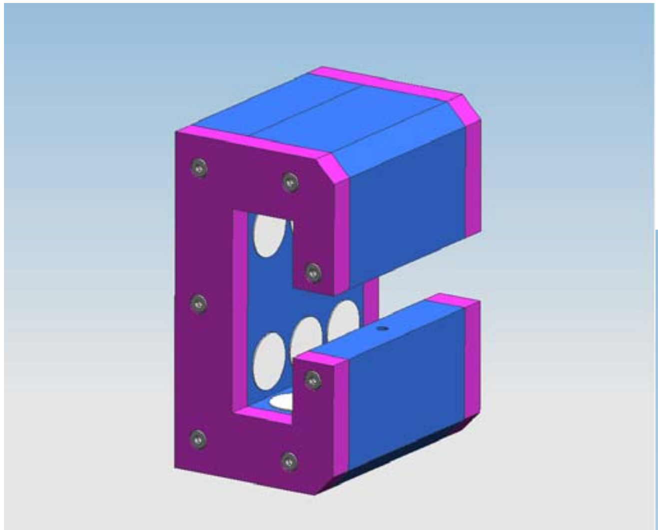
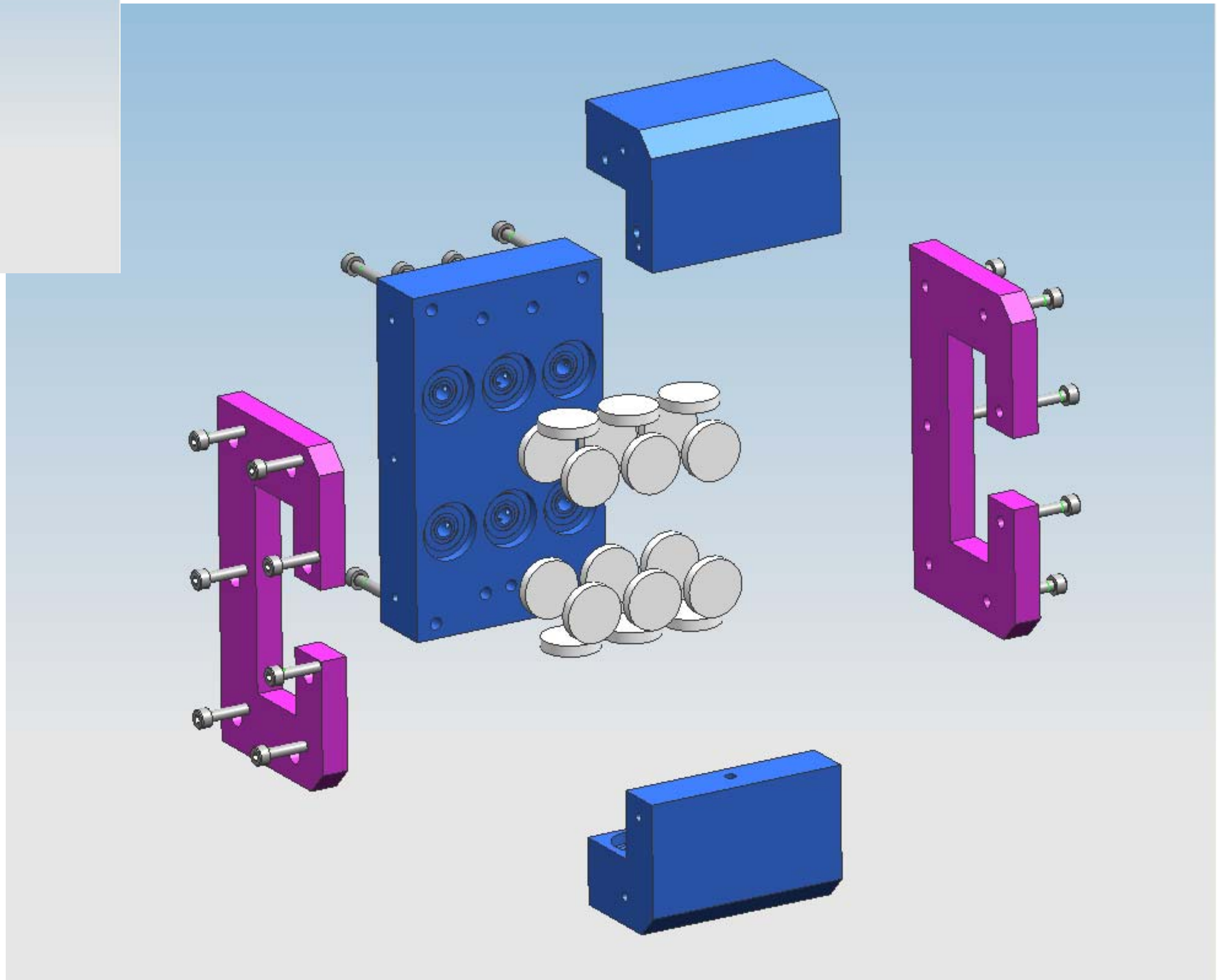
Porous ceramic linear bearing





CERAMIC BEARING ASSEMBLIES

- New size: 20mm diameter by 4mm finished size.
- New tooling required.
- Total requirement : 252 per machine.

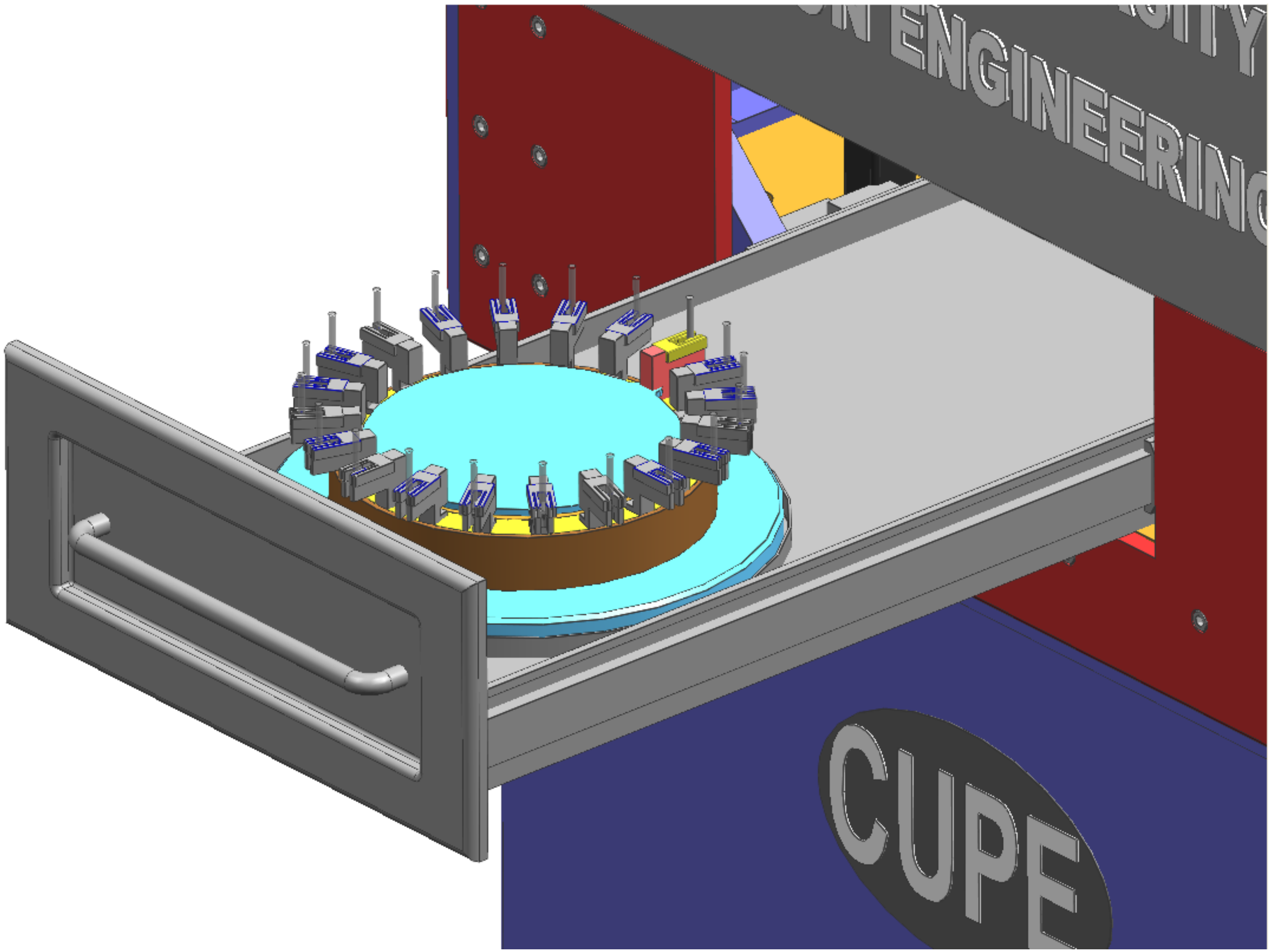
Assumptions are:

- Ceramic biscuits will be bonded into various aluminium carriers and finish- ground as an assembly.
- The intention is for the bearings to run on hard-anodised rails

DIRECT DRIVE

- High force/torque motors and nearly co-located sub-nanometre resolution encoders

- The combination gives highest dynamic accuracy and stiffness



Tool holders inserted into carousel

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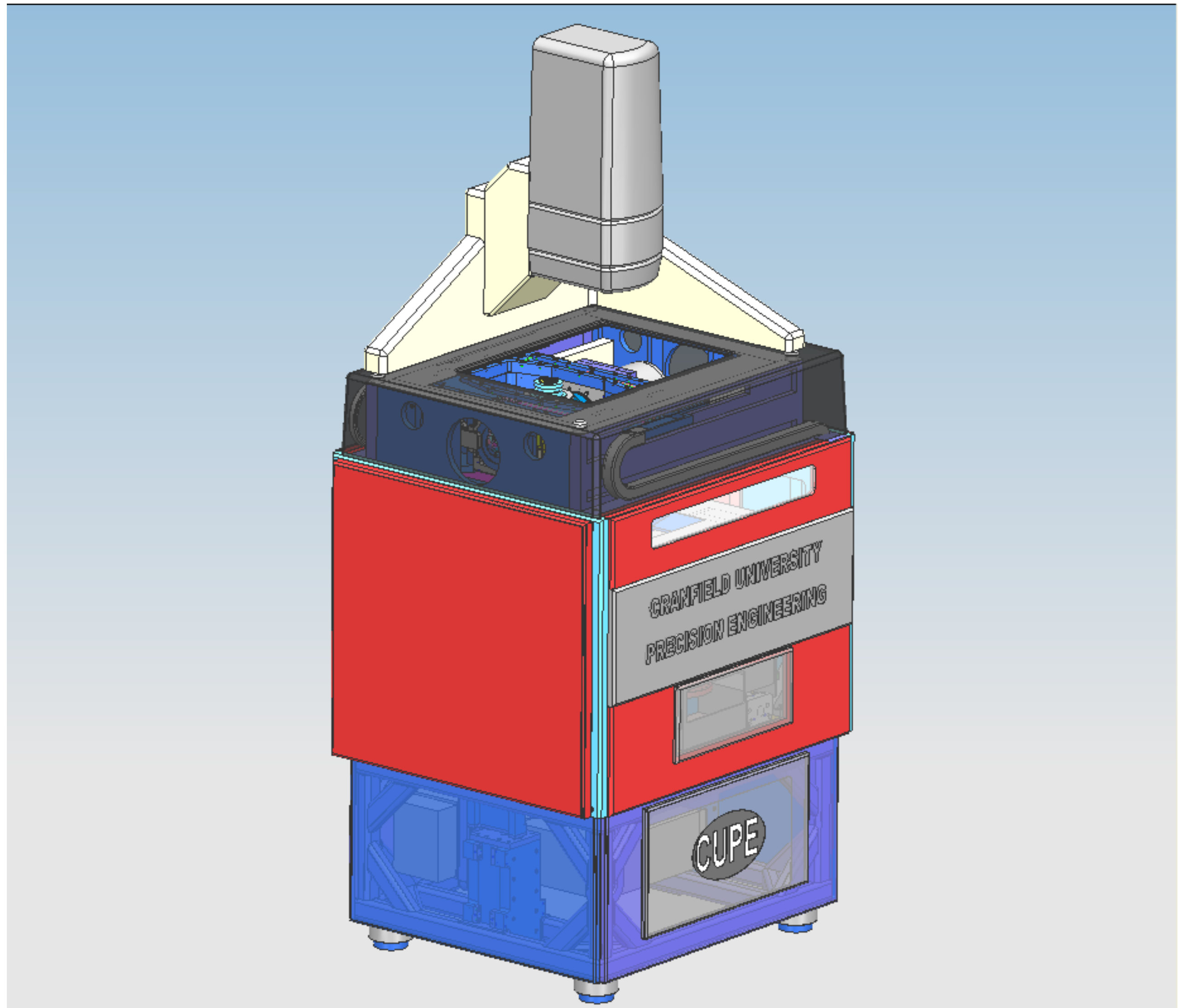
On-line smart inspection and metrology

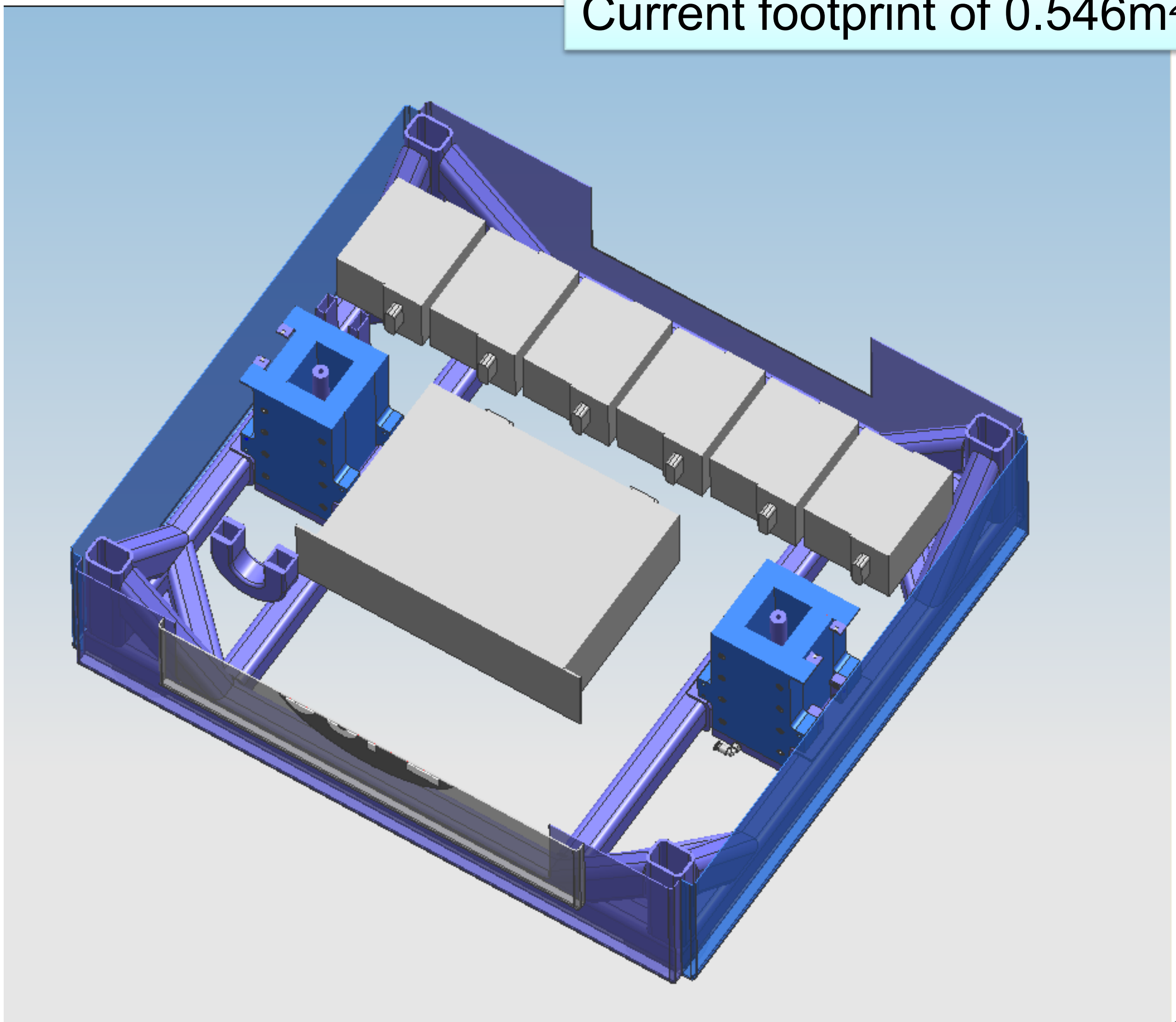
- Coordinate Measuring Machine (CMM) head with optical capability. (for *in situ* metrology).
- Error compensation.



Miniaturised electrical and electronic control modules

- The design is trying to create as large a volume as possible for housing electrical and electronic control modules.
- Normally, stand-alone power/control units are utilised.
- Miniaturisation is required so that the small footprint machine design dimensional specification can be met.
- Some modules have been identified and are shown positioned in the machine base opposite.

Current footprint of 0.546m^2



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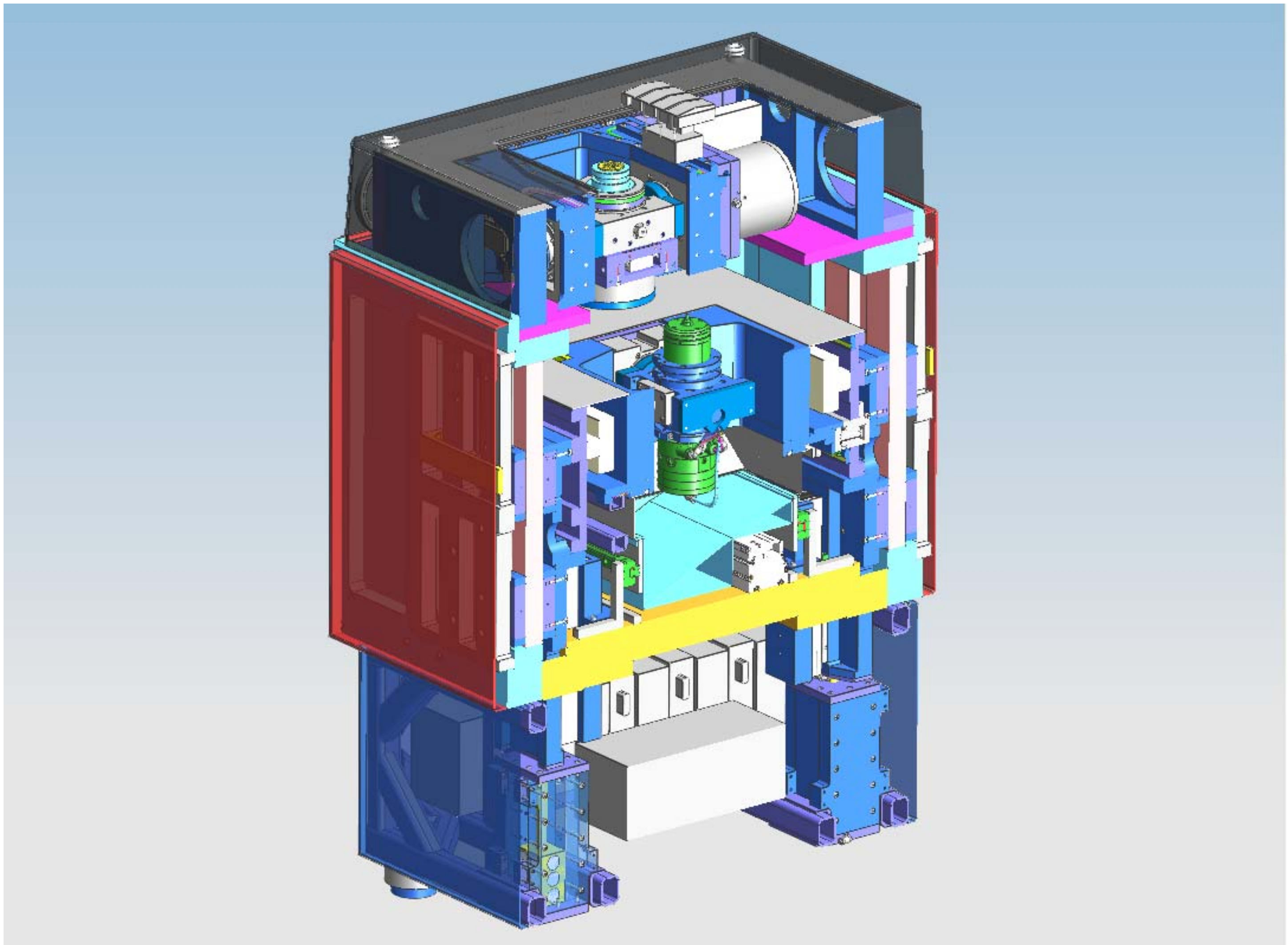
Design of ultra precision machine with higher machining performance, small footprint and reduced environmental impact



Integ Micro Platform 4 742 x 645 x 1060 mm

Performance advantages of novel micro-milling machine for target fabrication

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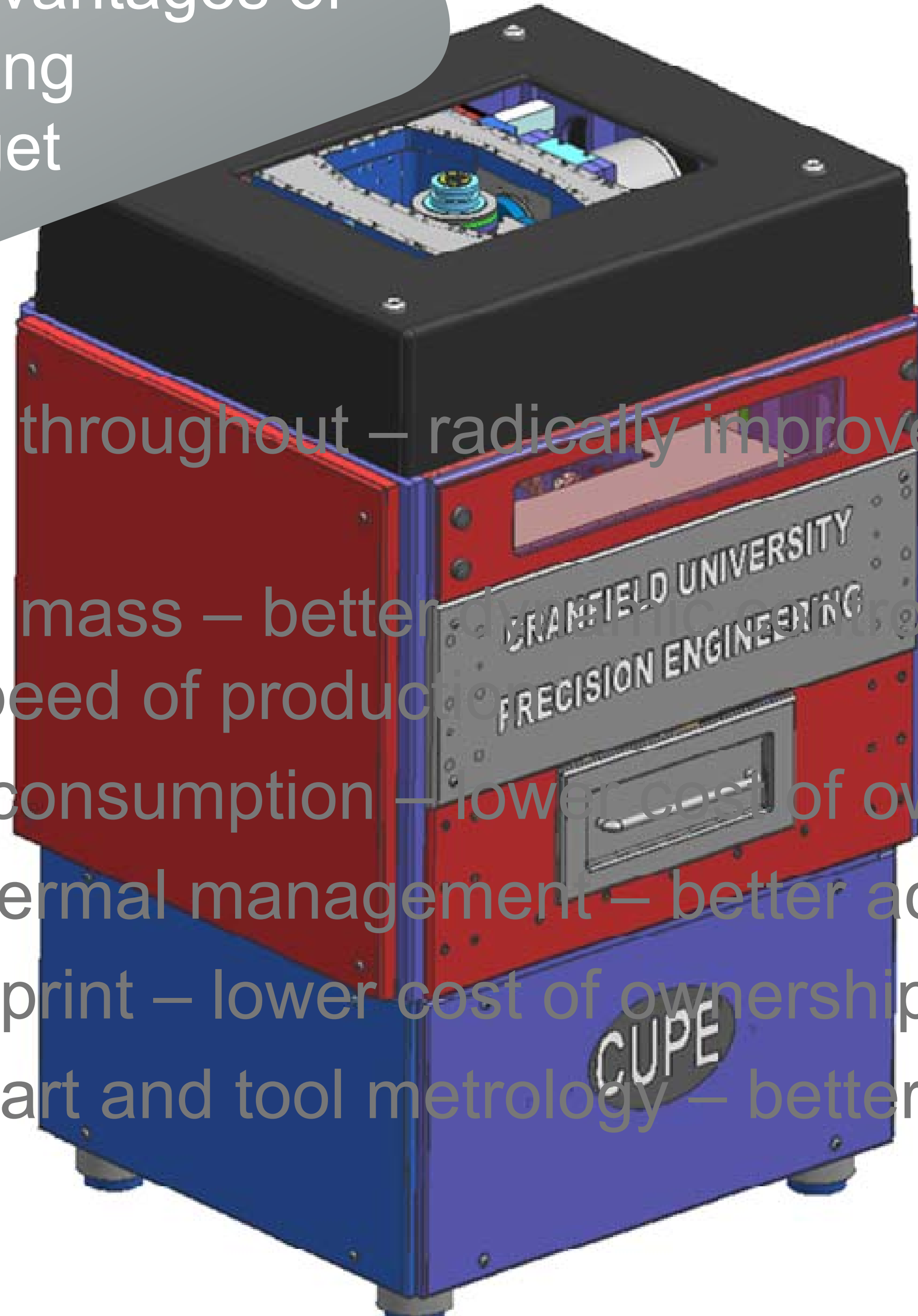

- Air bearings throughout – radically improved surface finish
- Low moving mass – better dynamic control for improved speed of production
- Low power consumption – lower cost of ownership
- Improved thermal management – better accuracy
- Smaller footprint – lower cost of ownership
- Integrated part and tool metrology – better accuracy