Atmospheric Pressure Plasma Technology For Ultra-Precision Engineering Of Optics For Applications In Aerospace, Defence And Science

Adam Bennett

Adam Bennett

- Military Officer
- First Degree Physics
- Post Graduate Masters Nanotechnology: First Class Equivalent – Highest Grade On The Programme
- Post Graduate Certificate Ultra Precision Engineering
- PhD in Ultra Precision Engineering: Plasma (submission April 2018)

Aim

Applications

Background

Plasma Figuring Machines

Microwave Induced Plasma Systems

Characterisation Method Developed

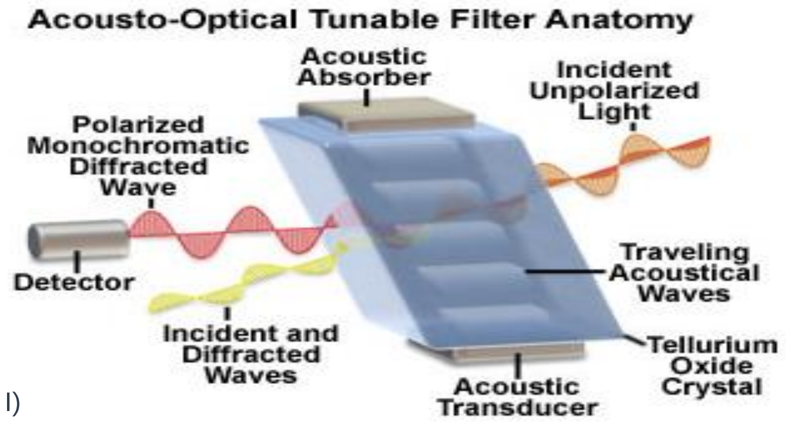
Plasma Processing of Optics

Aim

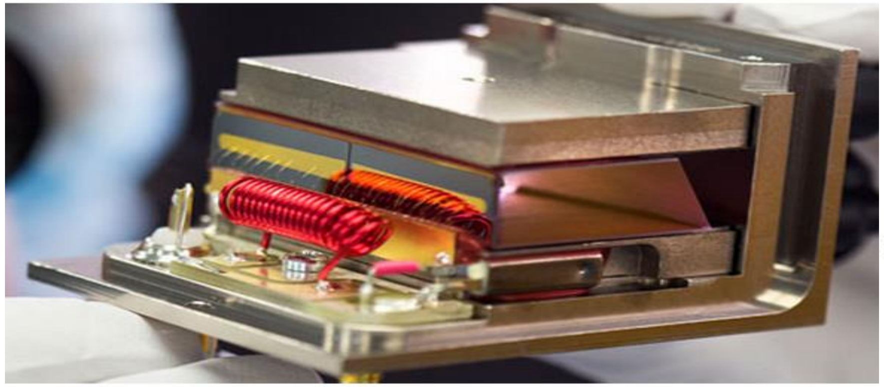
Microwave Plasma Energy Beam	Material Removal Rate of $0.1 mm^3/min$
100mm by 100mm Optics	Form accuracy < 10nm RMS
Crystal Quartz	Surface texture < 1nm RMS

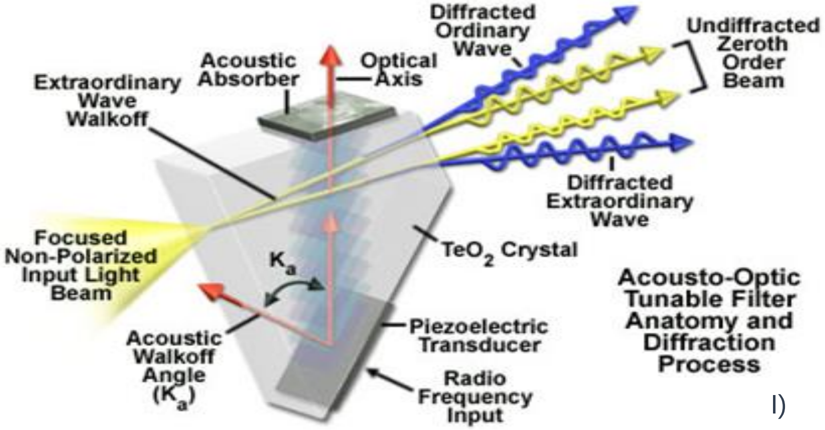
Applications

Acousto-Optics: Beam Deflectors, Frequency Shifters, Modulators, Q Switches



I)


II)



I)

I) T. Fellers, M. Davidson, 2009, Acousto-Optic Tunable Filters, Report for the National High Magnetic Field Laboratory, USA

II) Acousto-Optic, http://goochandhousego.com/capabilities/acousto-optic-capabilities, 21/04/2015

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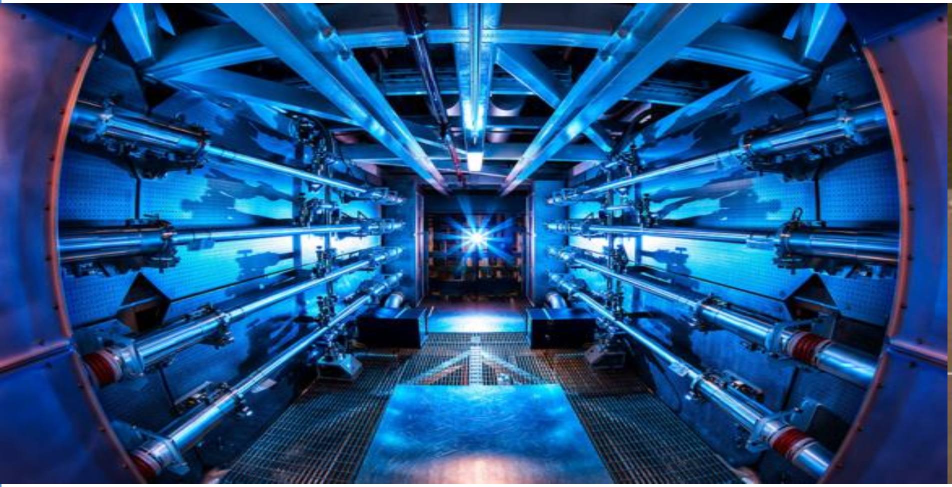
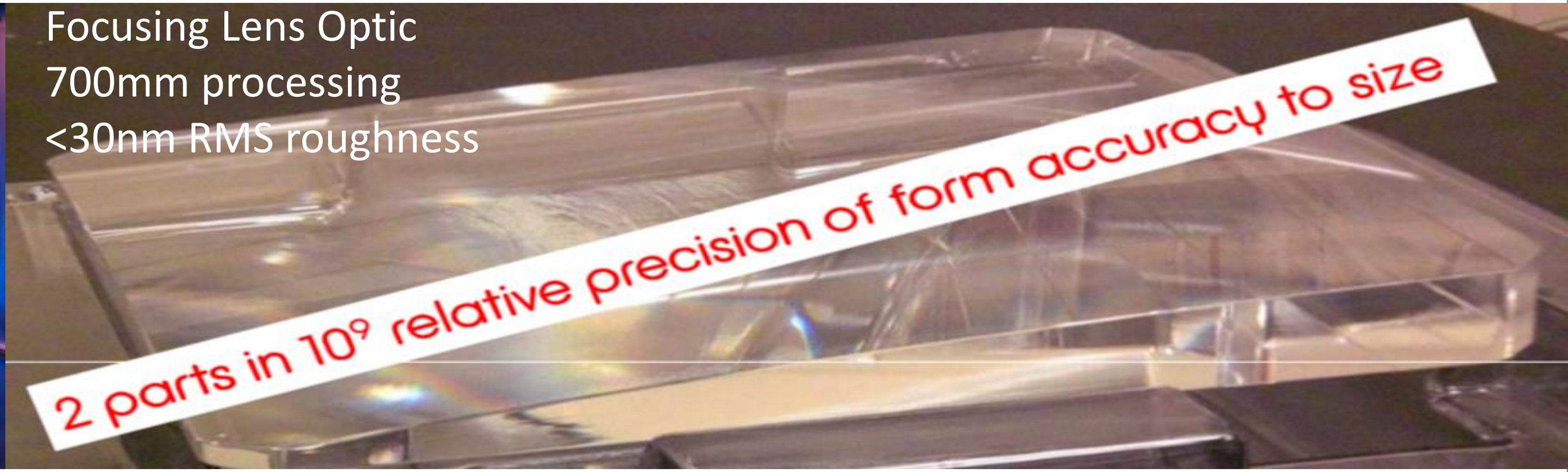
Other Applications

Fusion Energy Research: Using Metre Scale Optics to Focus High Power Laser Beams





III) Cold Fusion, http://phys.org/news/2013-08-laser-fusion-yields-energy.html, 21/04/2015

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Ultra Precision Surface Processing Route for Large Optics

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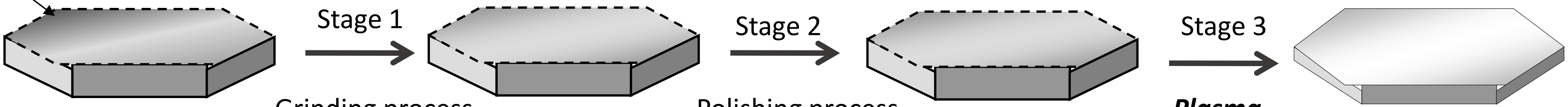
Metre scale optical component

Surface roughness < 1 nm RMS

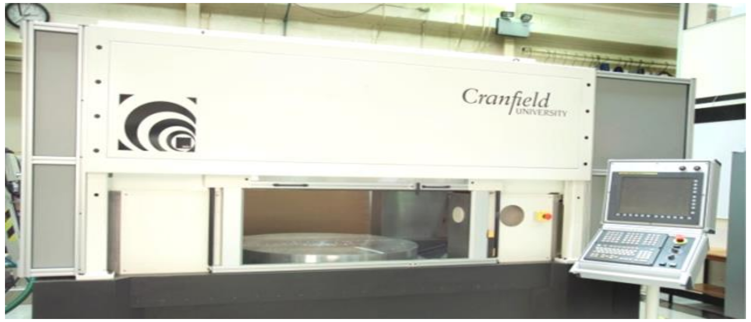


Grinding process

Polishing process

Plasma process

1 mm form accuracy → 1 µm form accuracy → 300nm form accuracy → 10 nm form accuracy



BoX
(Ultra precision grinding)

Polishing machine
(Robot)

Helios1200
(Plasma figuring machine)

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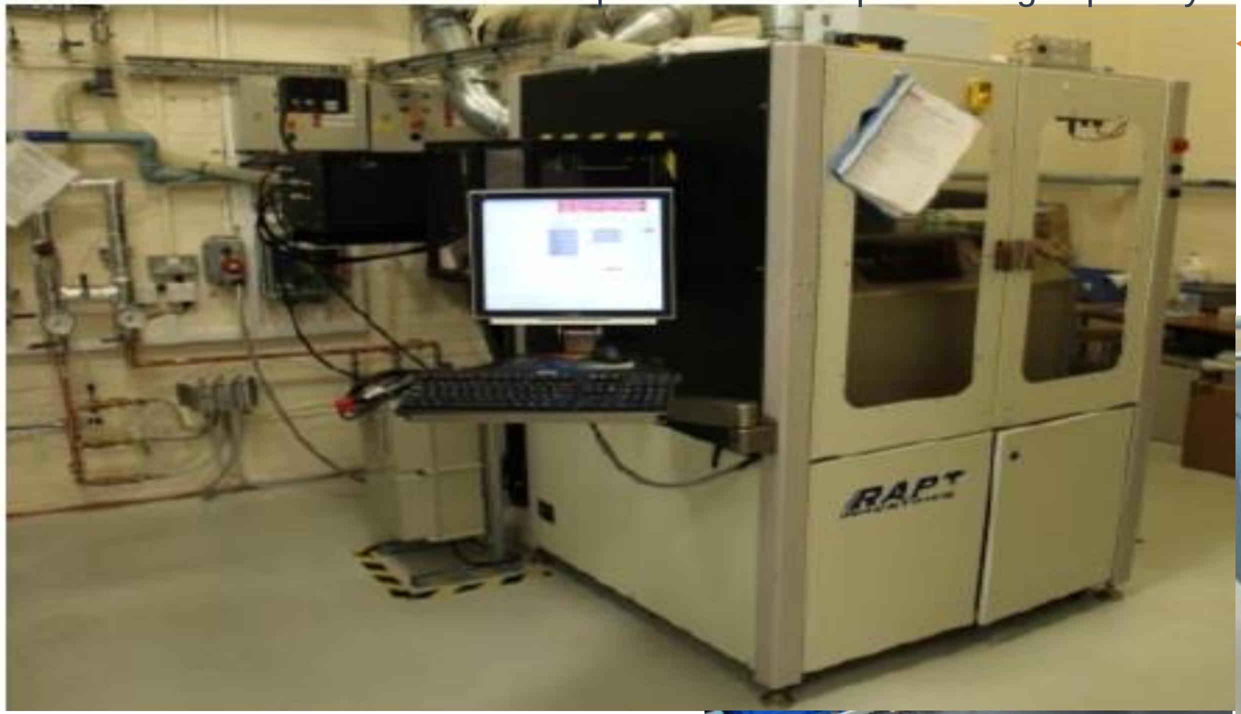
Plasma Figuring Machines at Cranfield University

RAP Plasma Figuring Machine

300mm x 300mm optical substrate processing capability

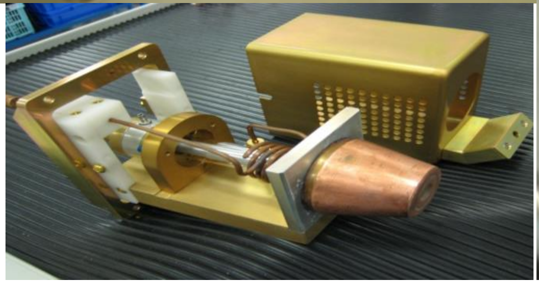


Atmospheric Pressure Plasma Figuring

Helios Plasma Figuring Machine

1200mm x 1200mm optical substrate processing capability

Both plasma figuring machines currently employ an Inductively Coupled Plasma torch



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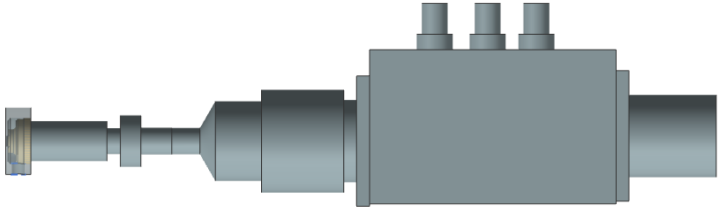
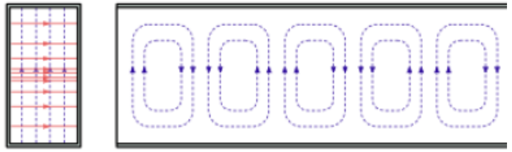
Microwave Induced Plasma Systems

Coaxial Electrode System





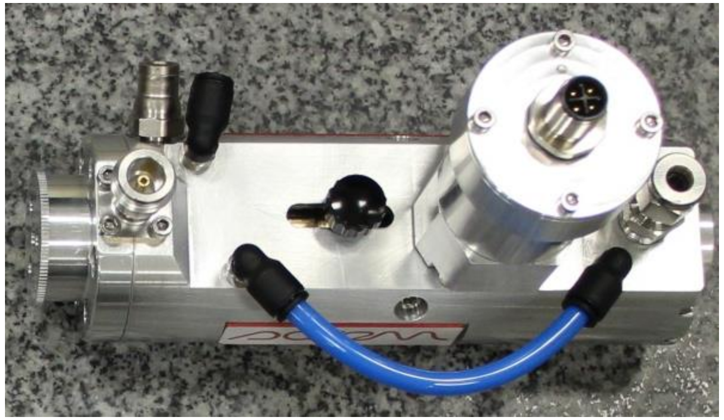
E field
H field

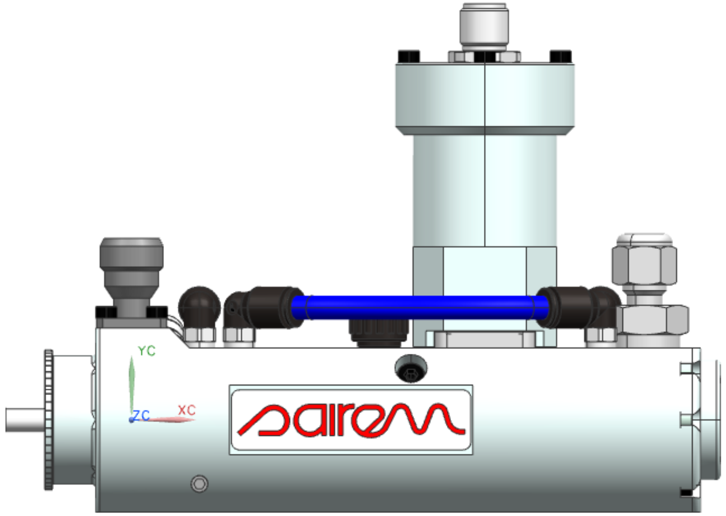
TE$_{10}$

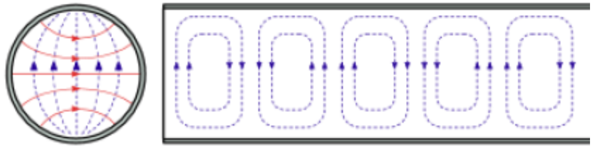
TE f = TM f

$$f_{mnl} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$

Surface Wave Launcher System







TE$_{11}$

$$f_{mnp} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}} \cdot \sqrt{\left(\frac{X'_{mn}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2}$$

TE f ≠ TM f

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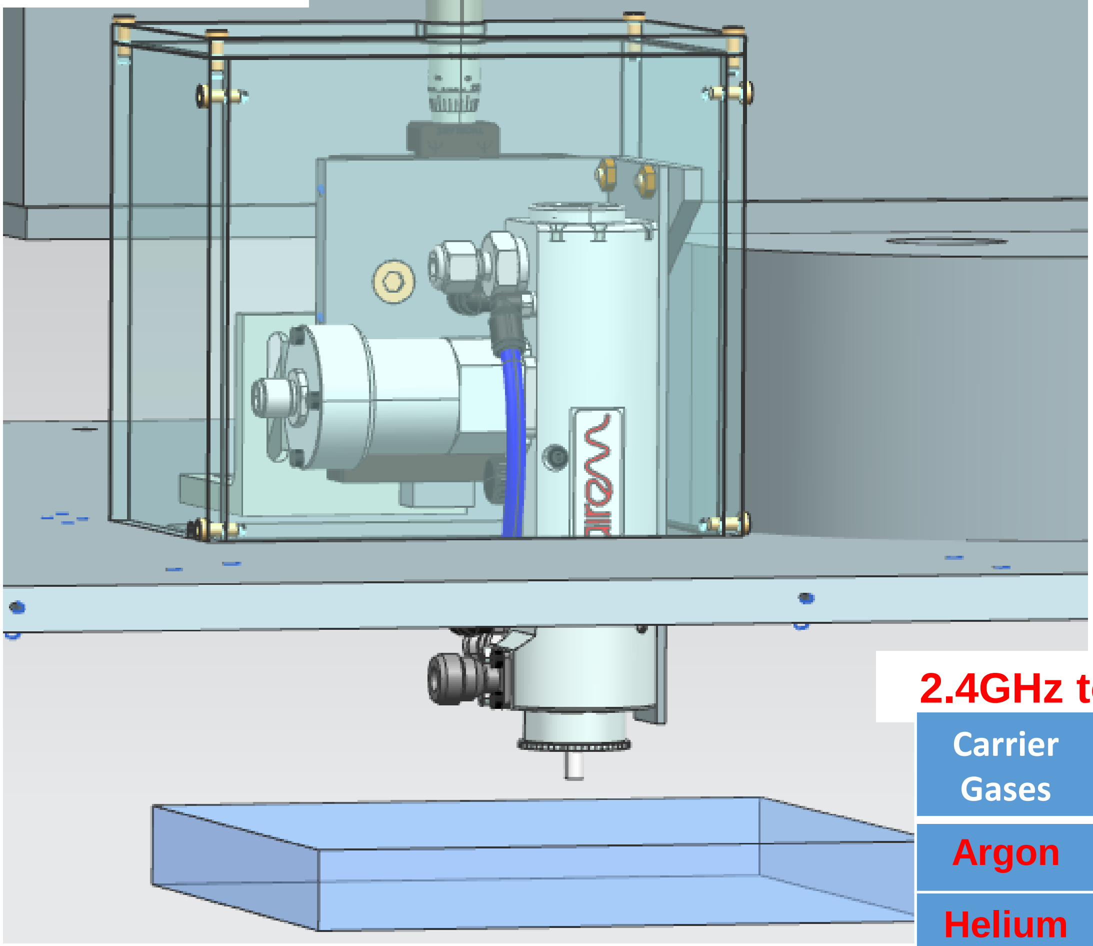
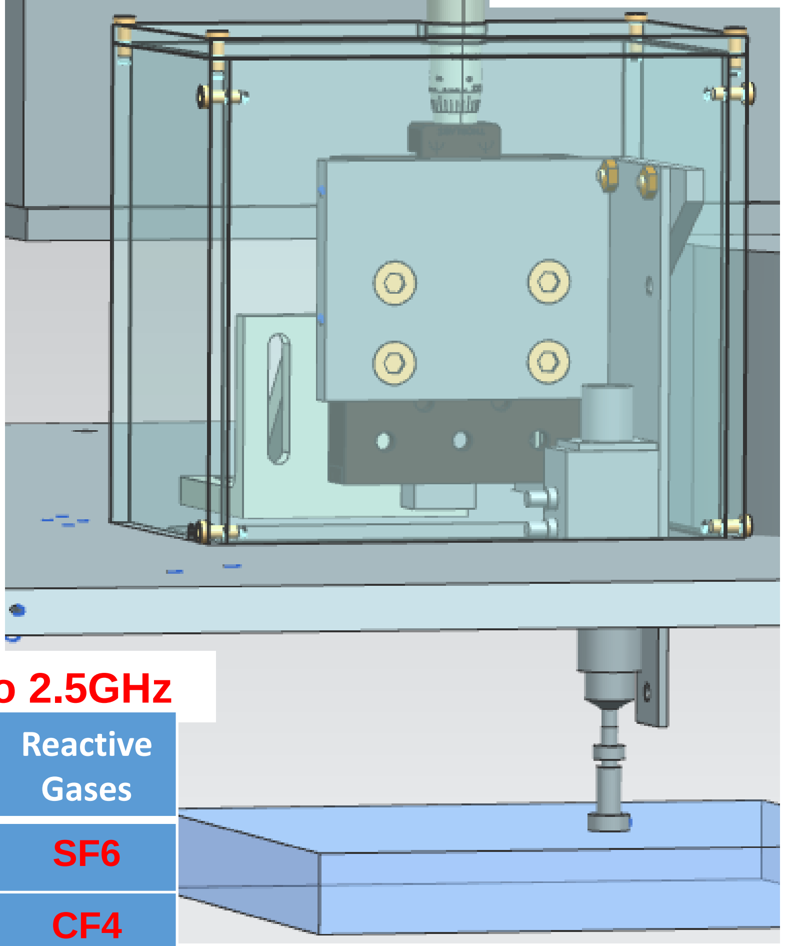
Surface Wave Launcher System

50W to 200W



Coaxial Electrode System

13W to 17W



2.4GHz to 2.5GHz

Carrier Gases	Reactive Gases
Argon	SF6
Helium	CF4

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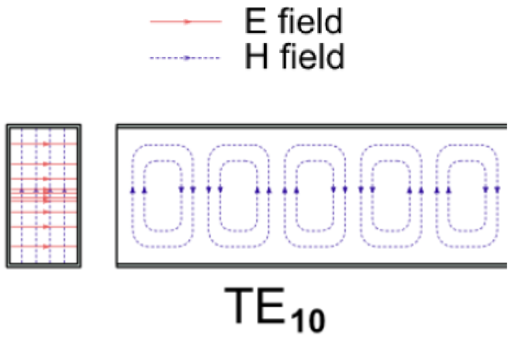
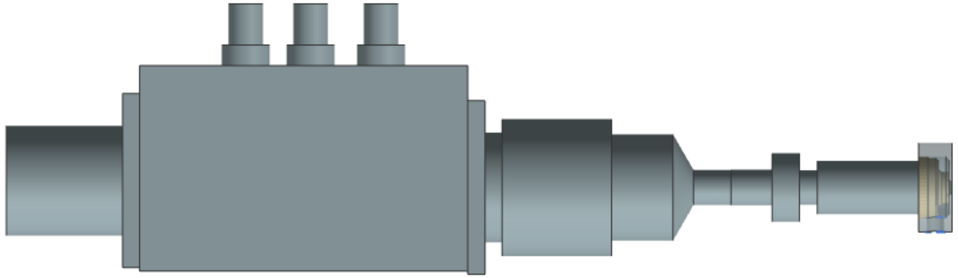
Coaxial Electrode Microwave Induced Plasma Torch

Transverse Electric frequency = Transverse Magnetic frequency

$$f_{mnl} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2}$$





Coaxial Electrode Microwave Induced Plasma Torch

Military Microwave Anechoic Chamber

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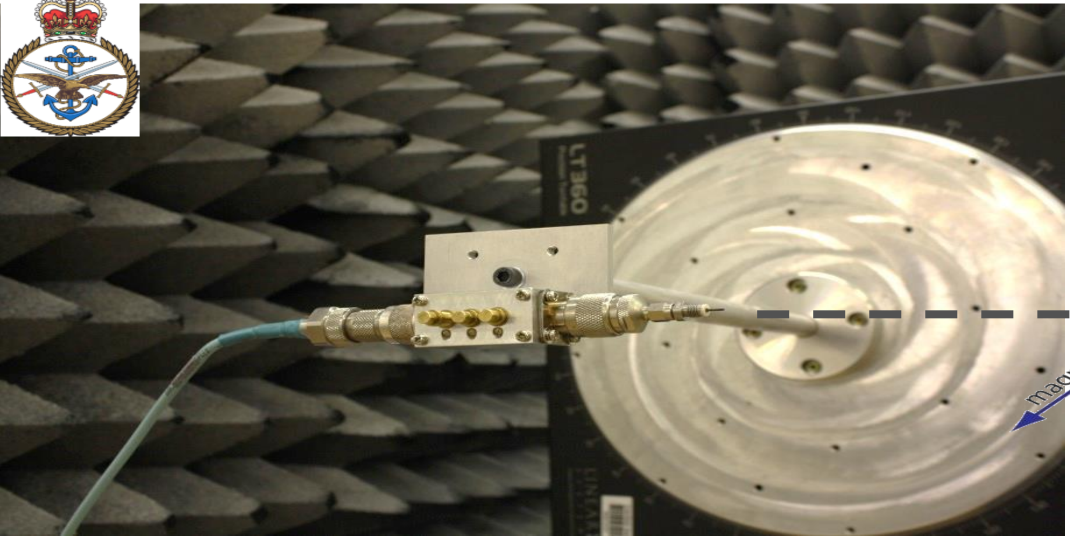
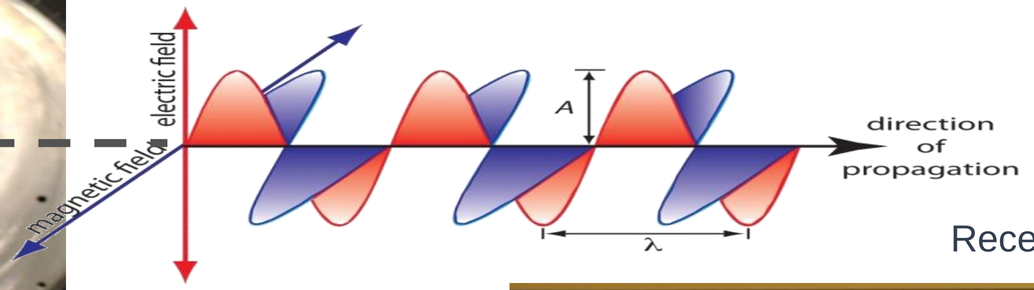
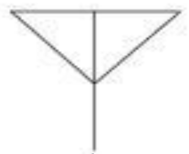
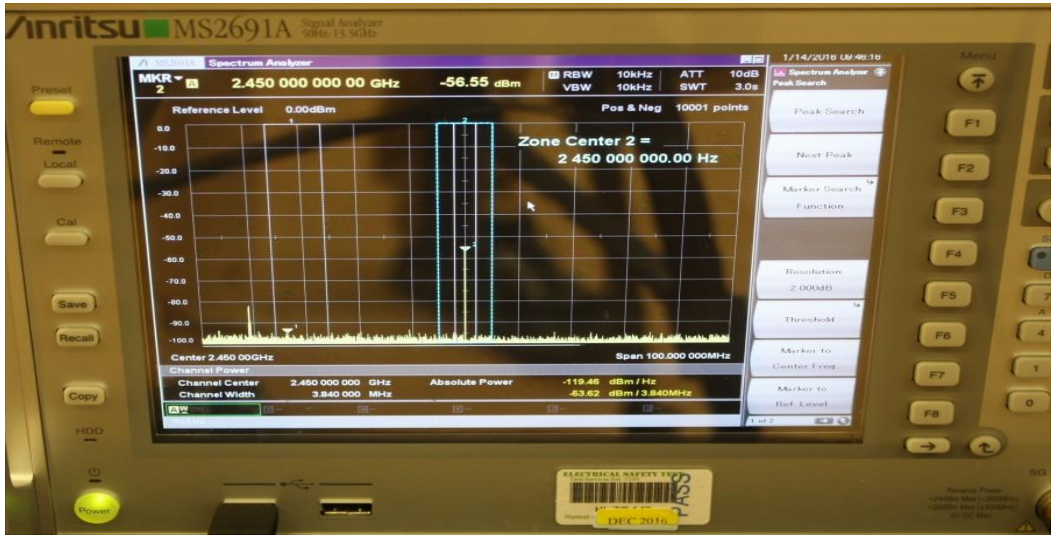


Adtec torch placed into RADAR/MWDAR Anechoic Chamber





Receiving antenna



Anritsu MS461221 spectrum analyser

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Coaxial Electrode Microwave Induced Plasma Torch
Military Microwave Anechoic Chamber

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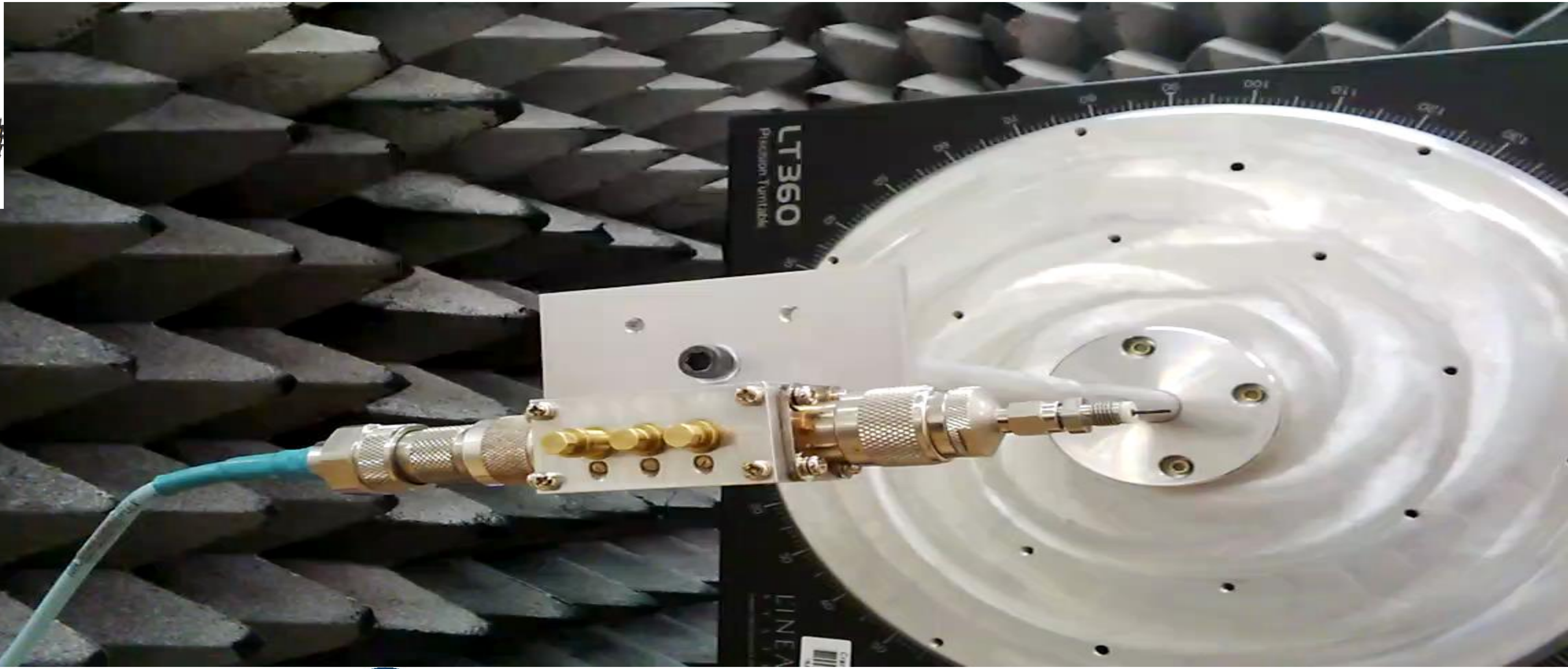

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Coaxial Electrode Microwave Induced Plasma Torch

Directionality of the Microwave Energy being Emitted from the Adtec Electrode

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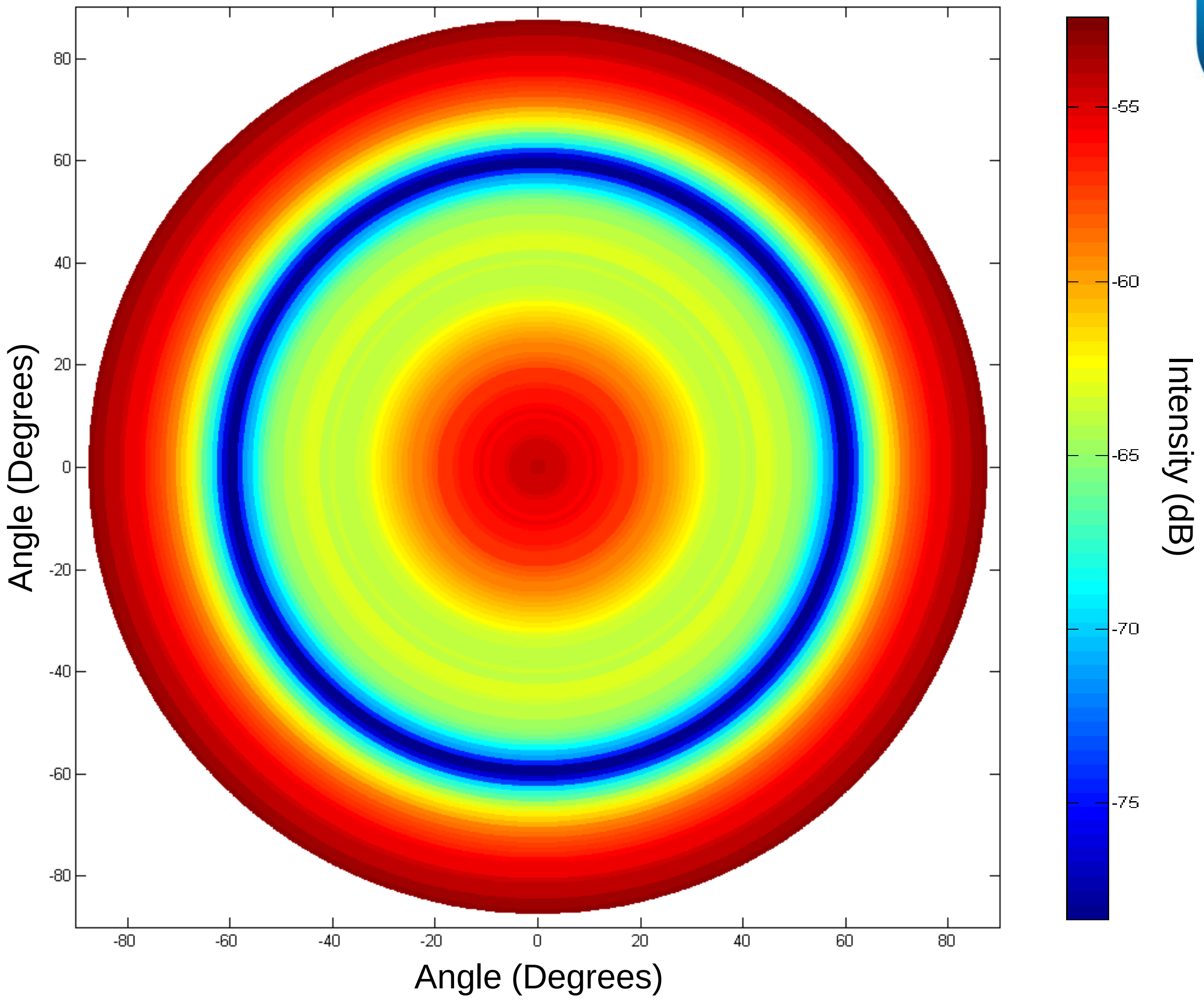

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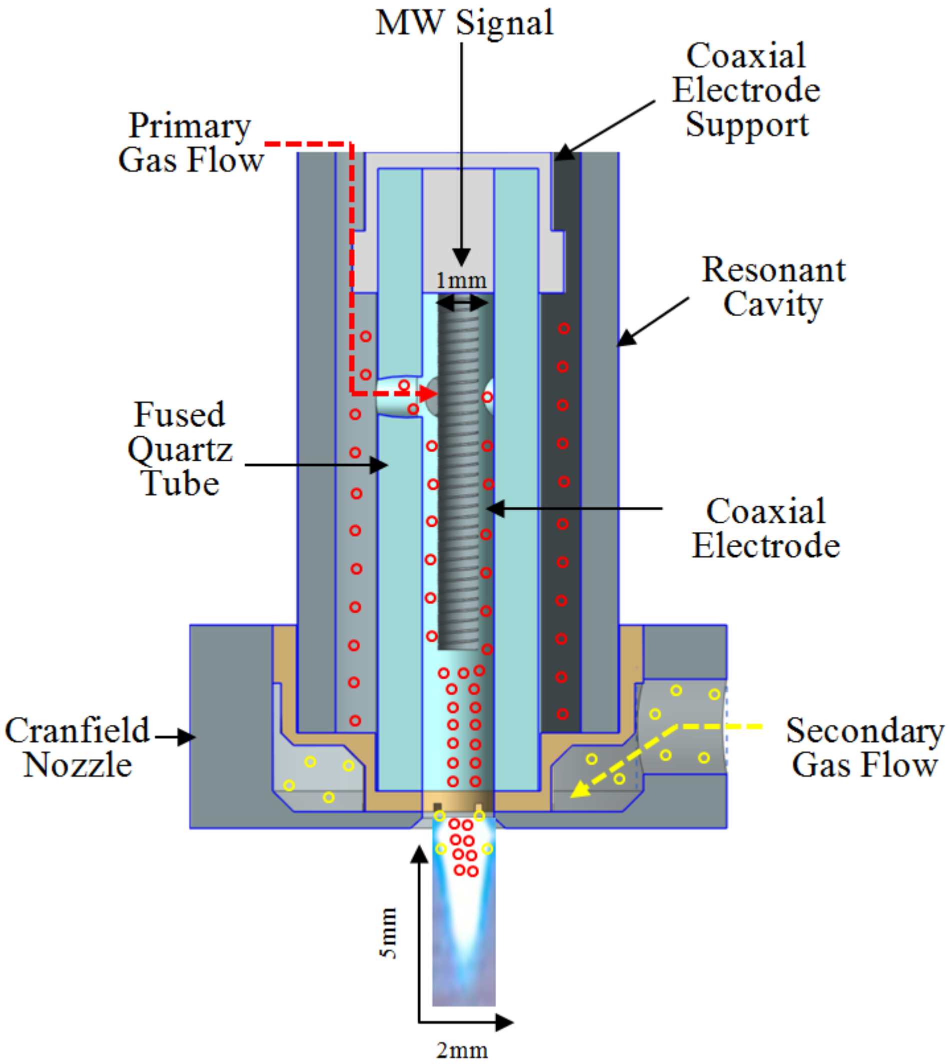
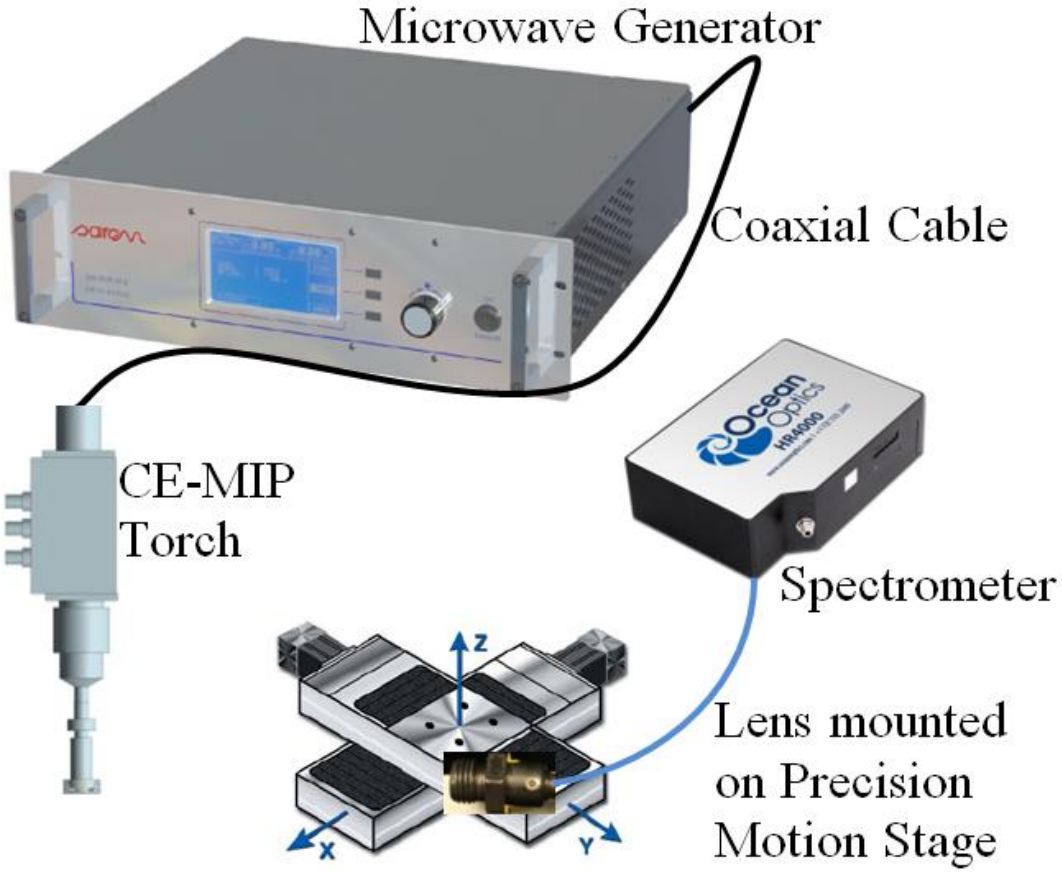
Coaxial Electrode Microwave Induced Plasma Torch Characterisation by Optical Emission Spectroscopy

Experimental Setup





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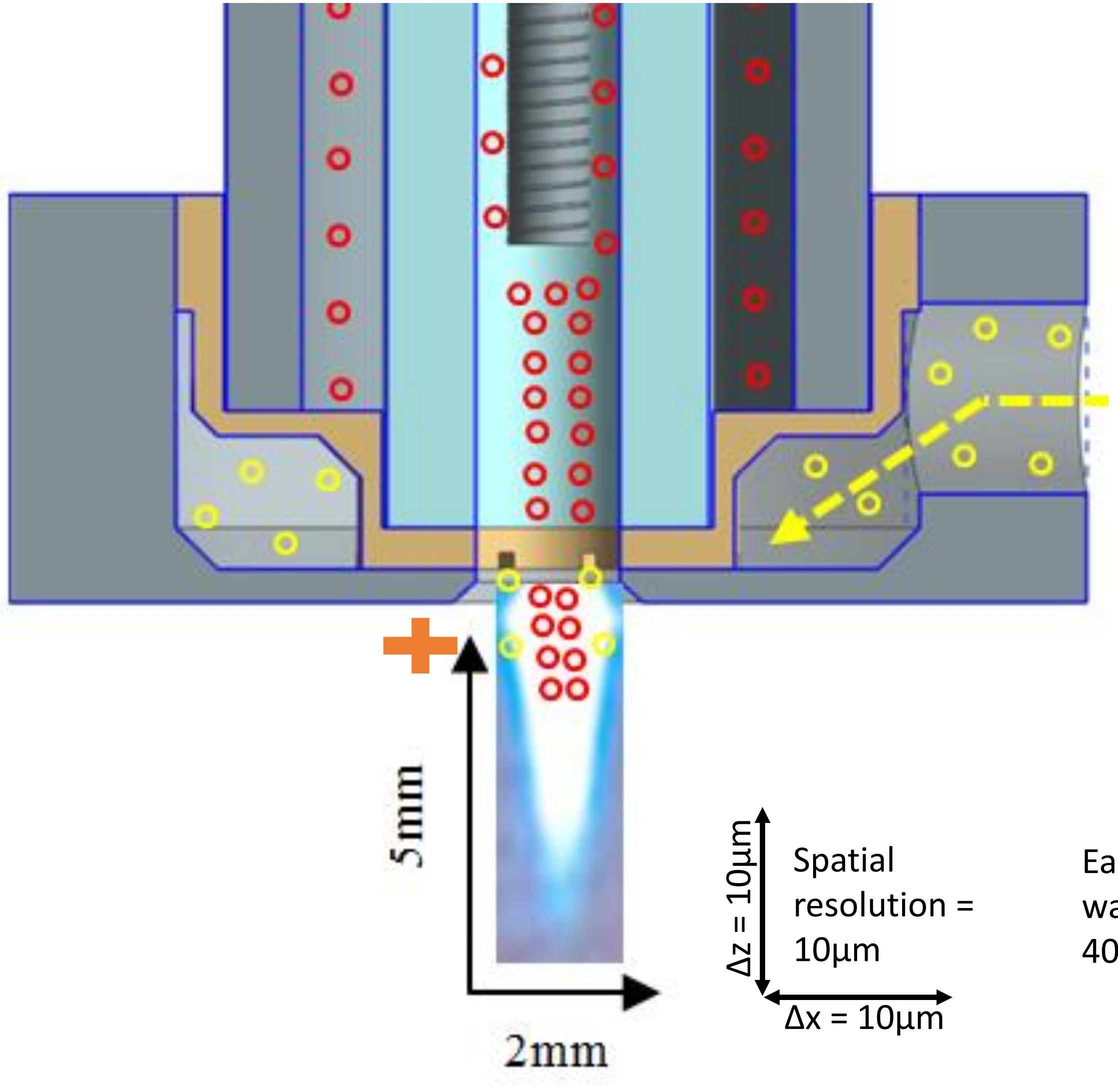
Coaxial Electrode Microwave Induced Plasma Torch

Optical Emission Spectroscopy

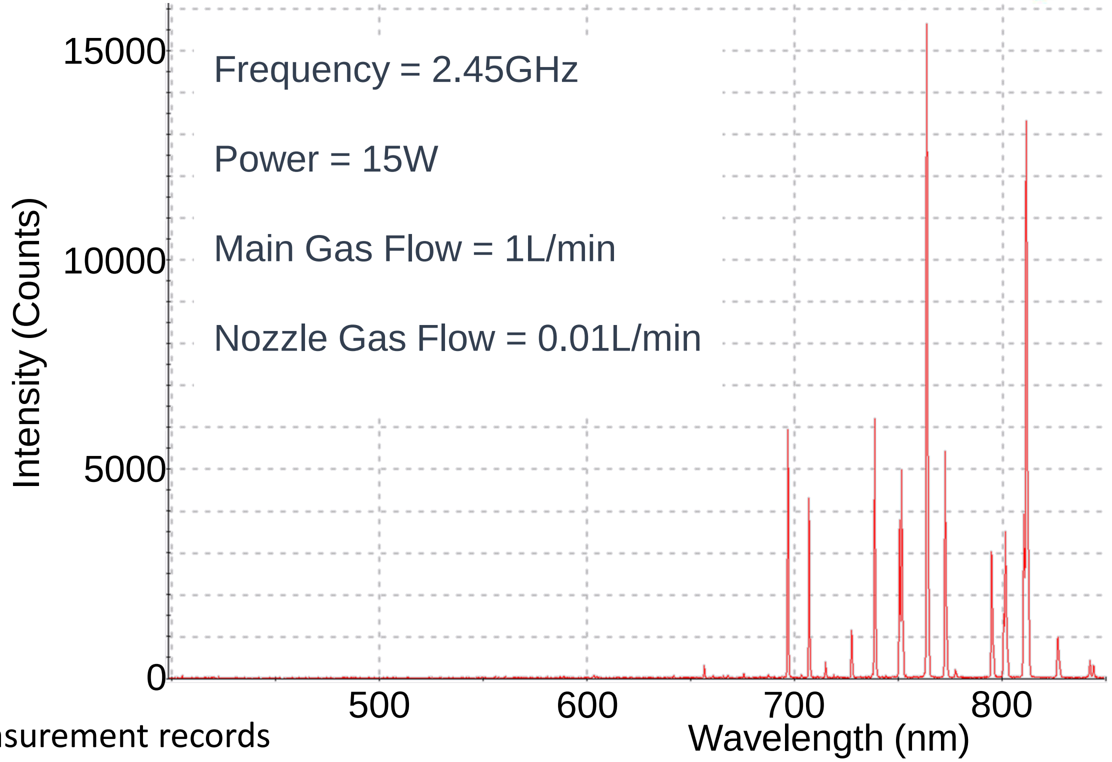


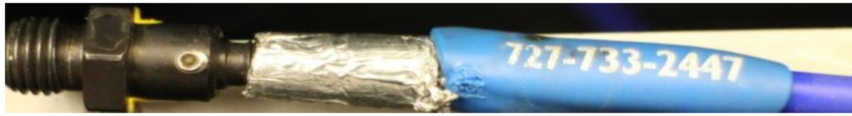
Δz = 10µm

Spatial resolution = 10µm

Δx = 10µm

Each measurement records wavelengths from 400nm to 850nm





Lens Connected To Spectrometer

Coaxial Electrode Microwave Induced Plasma Torch

Optical Emission Spectroscopy Results

Power = 15W; Frequency = 2.45GHz;

Main Gas Flow = 1L/min; Nozzle Gas Flow = 0.01L/min

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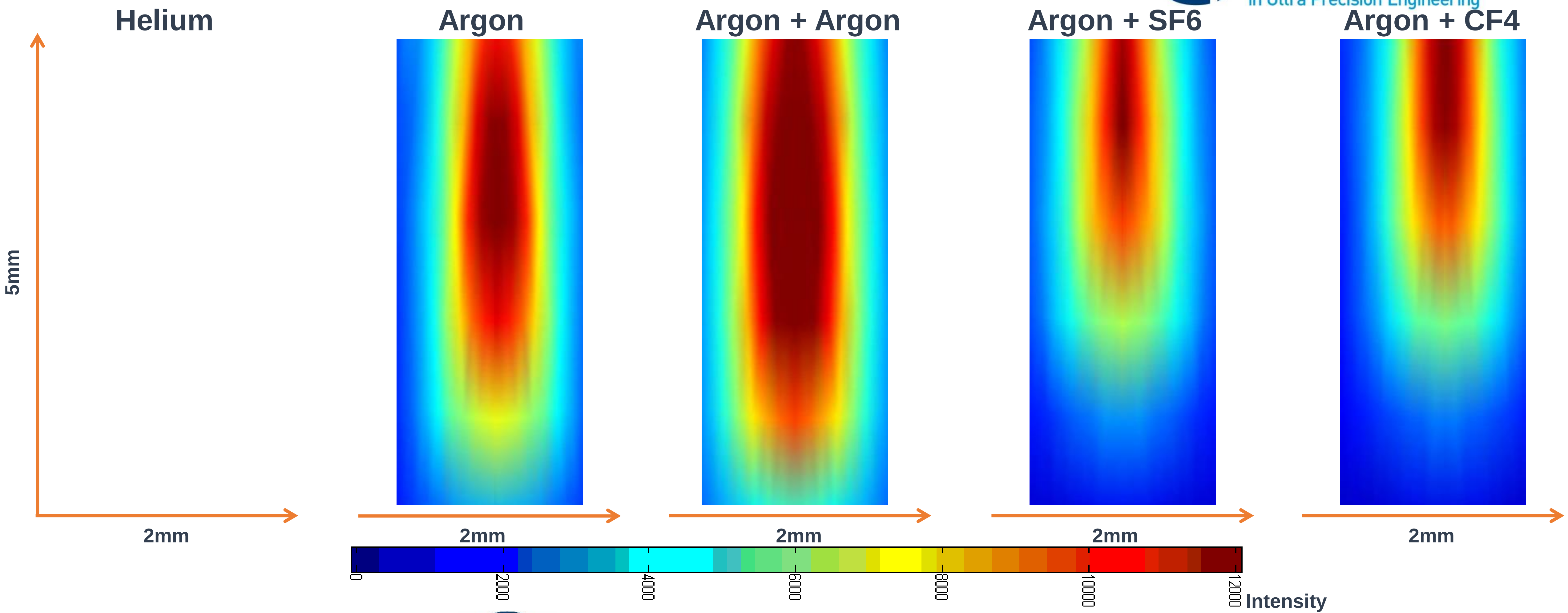

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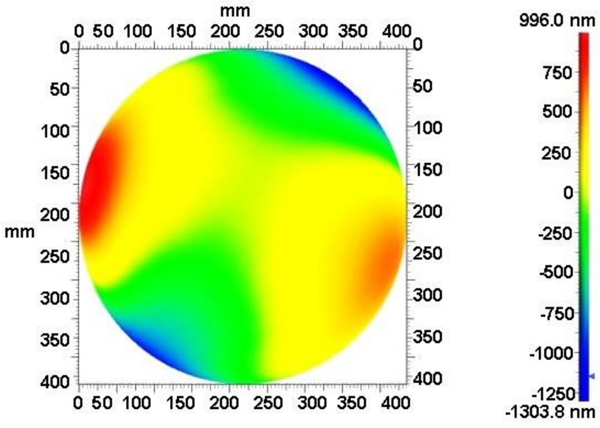
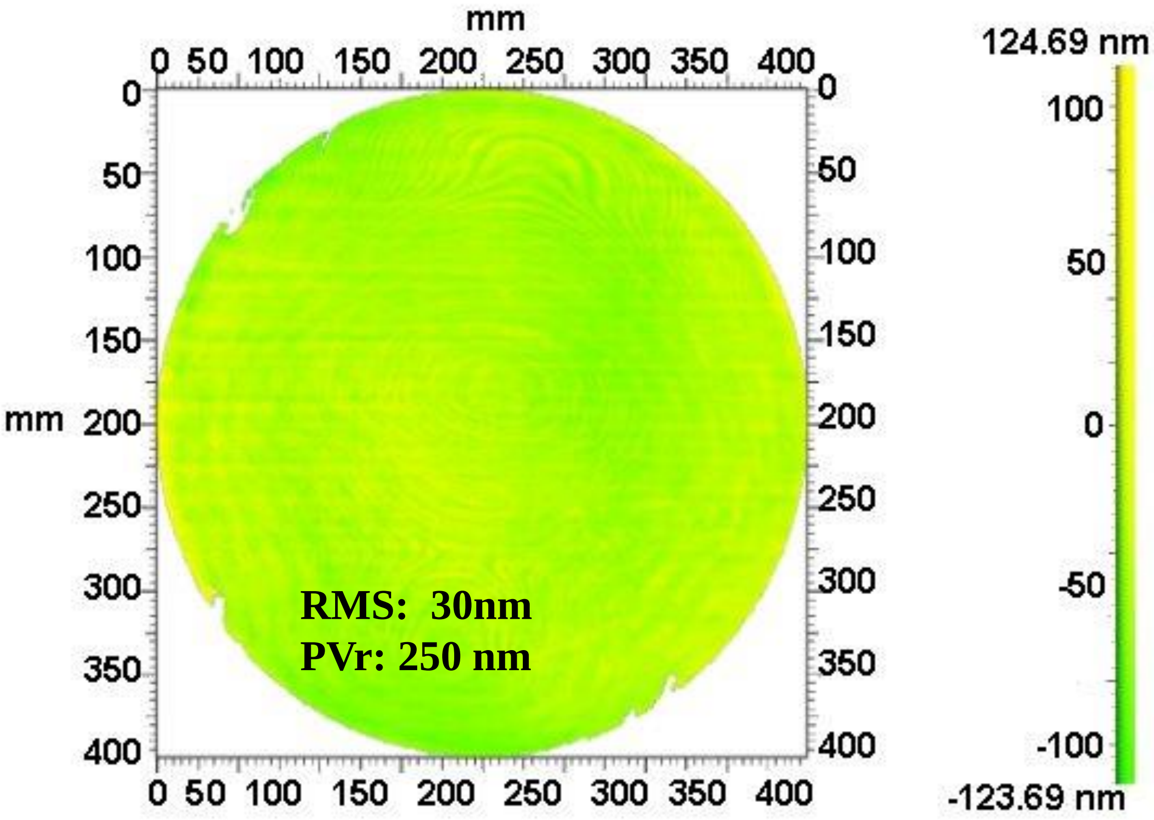
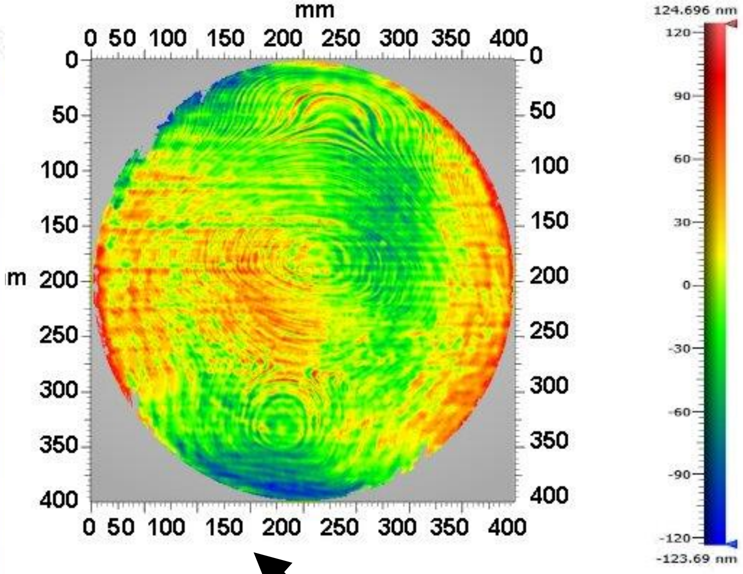
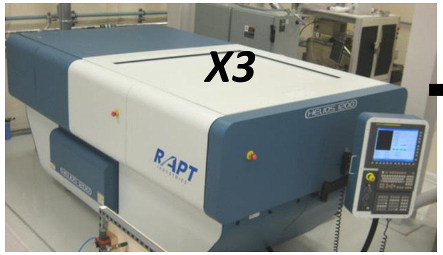
Previous Plasma Processing Results

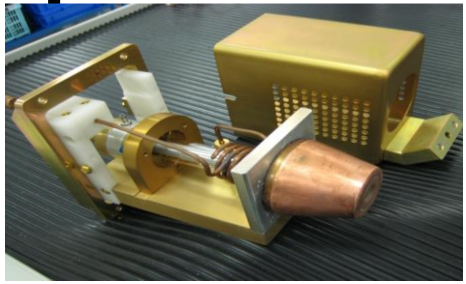


Initial figure error









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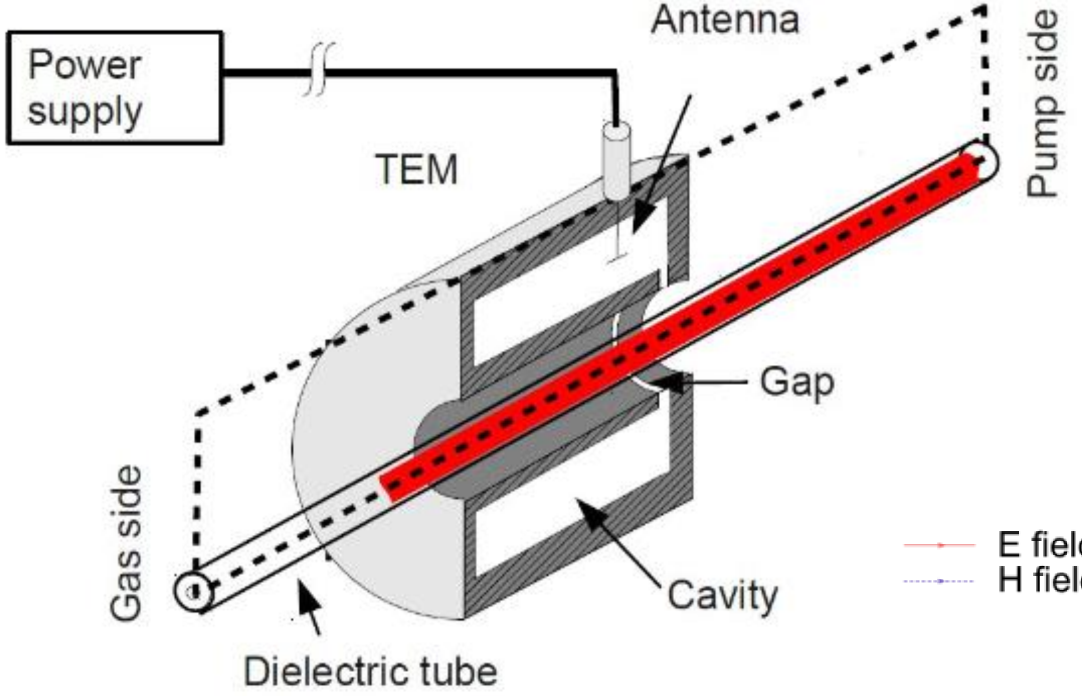
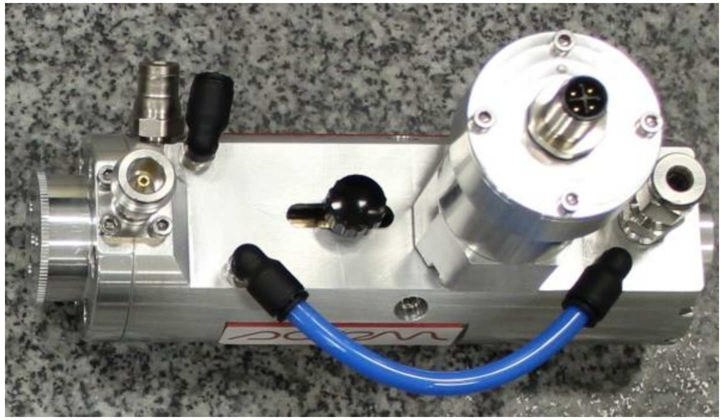
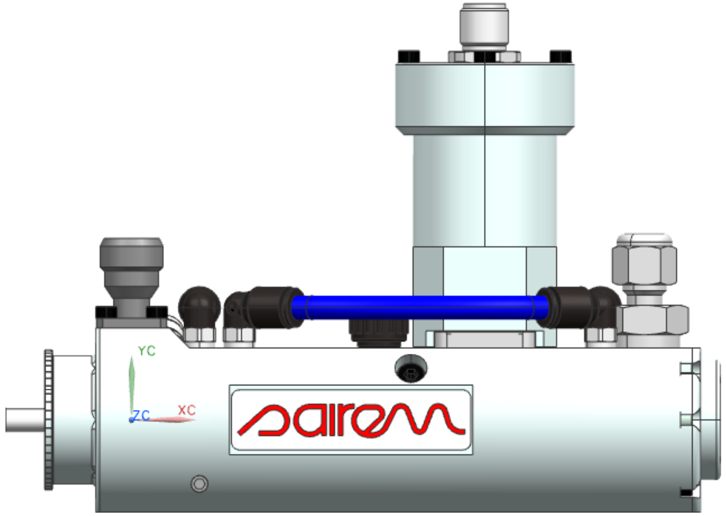
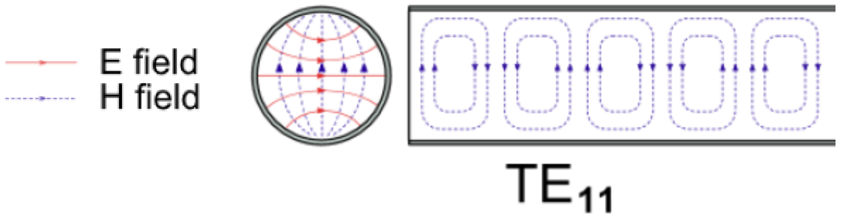
Surface Wave Launched Microwave Induced Plasma Torch









$$f_{mnp} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}} \cdot \sqrt{\left(\frac{X'_{mn}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2}$$

TE f ≠ TM f

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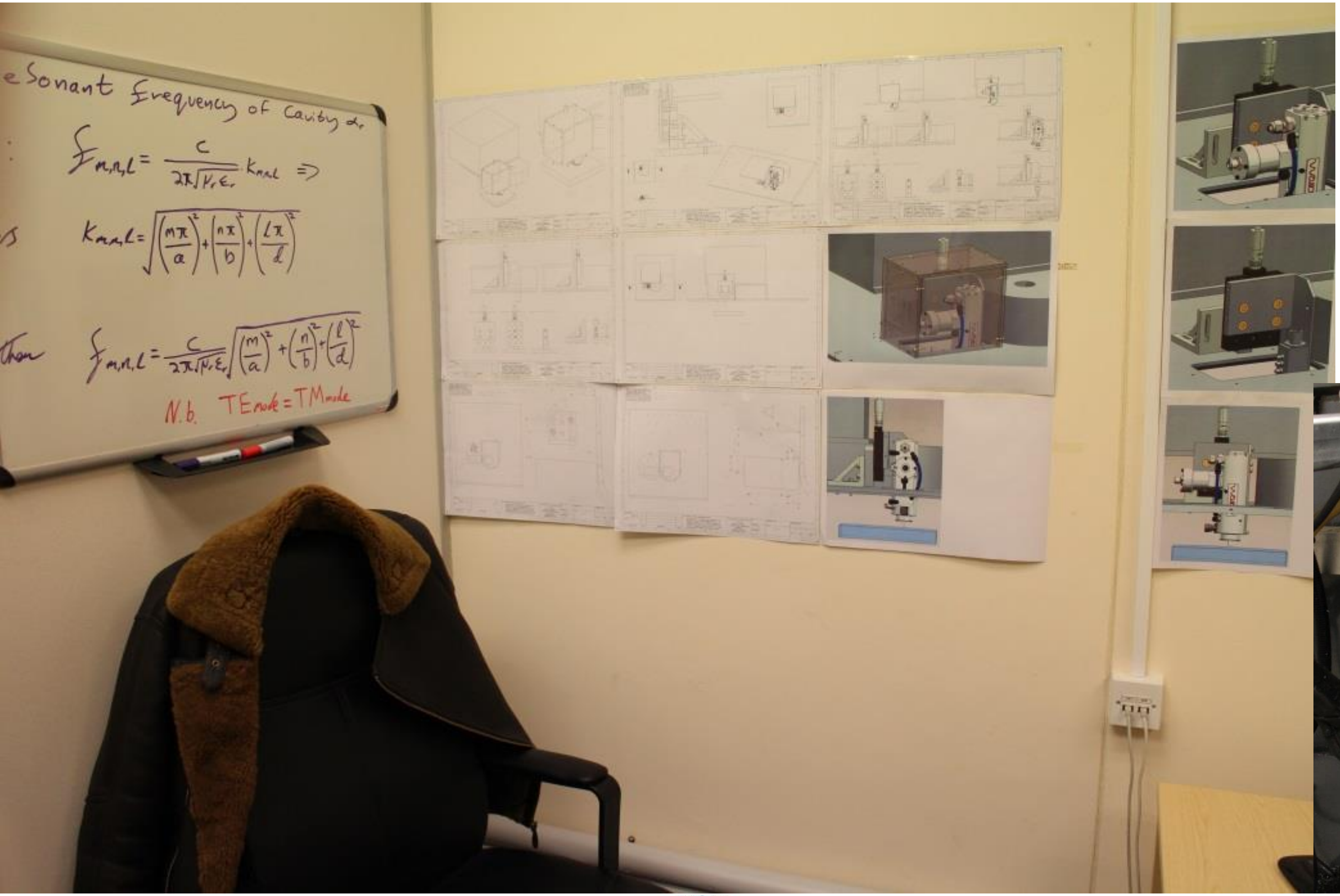
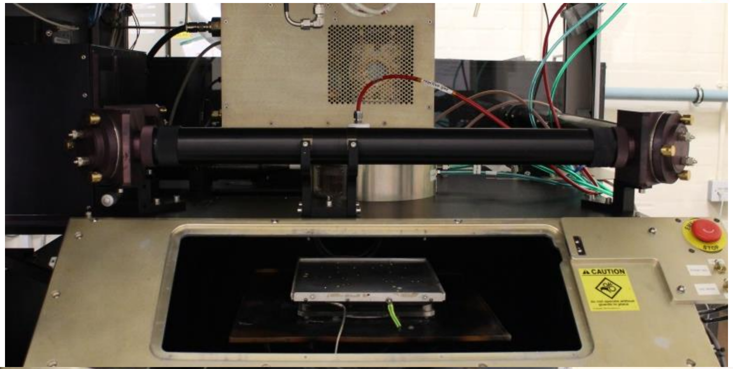
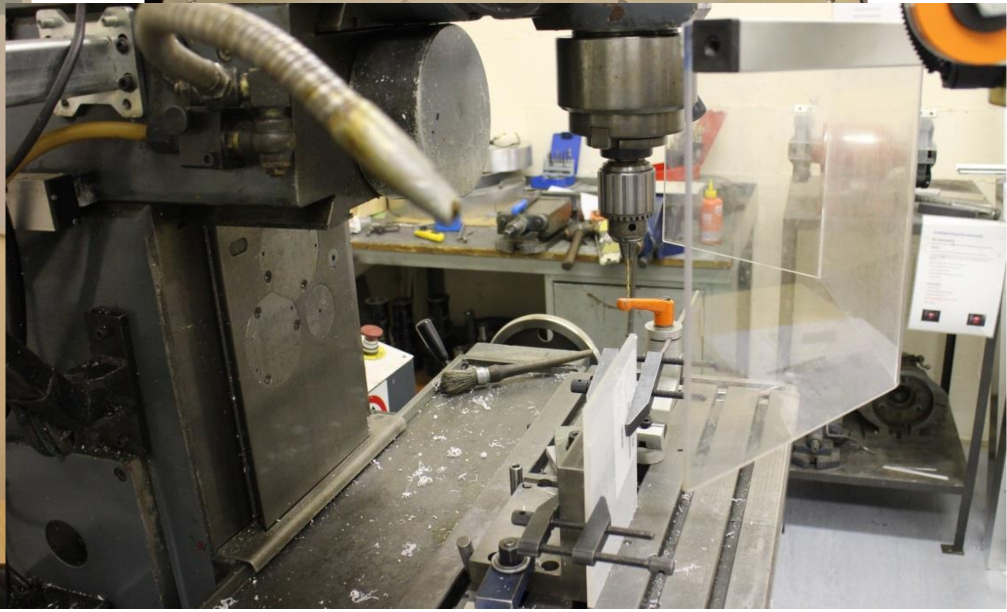
Microwave Plasma System & Enclosure Installation







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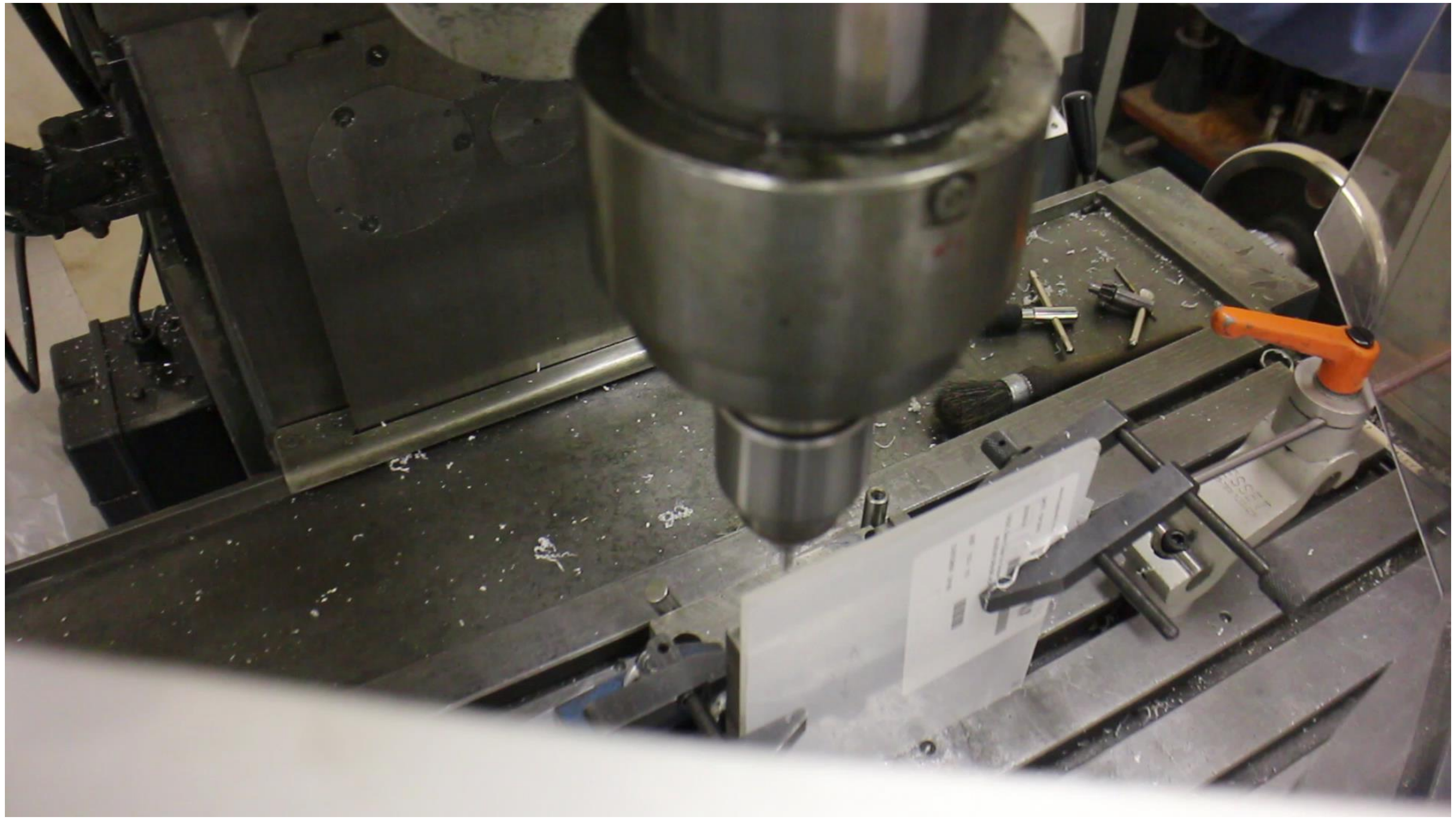

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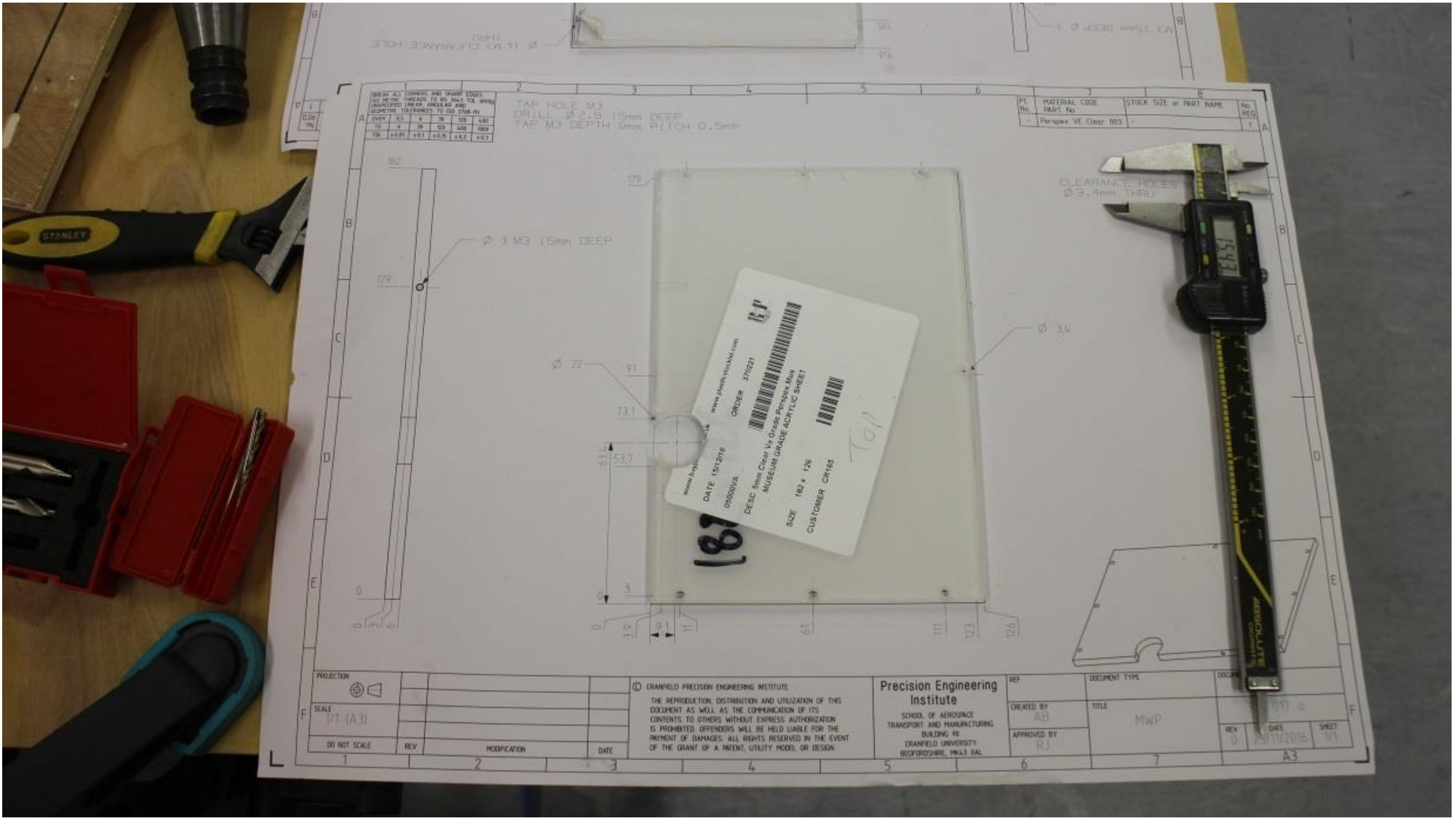

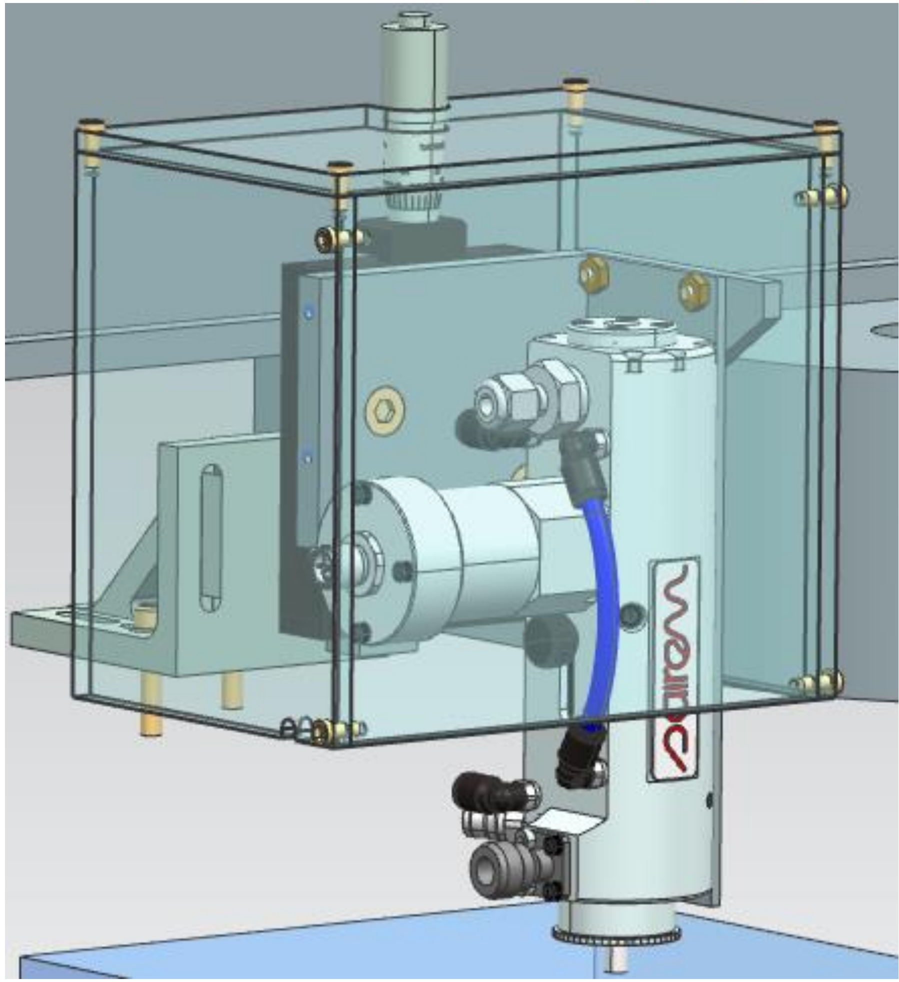

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Microwave Plasma System & Enclosure Installation

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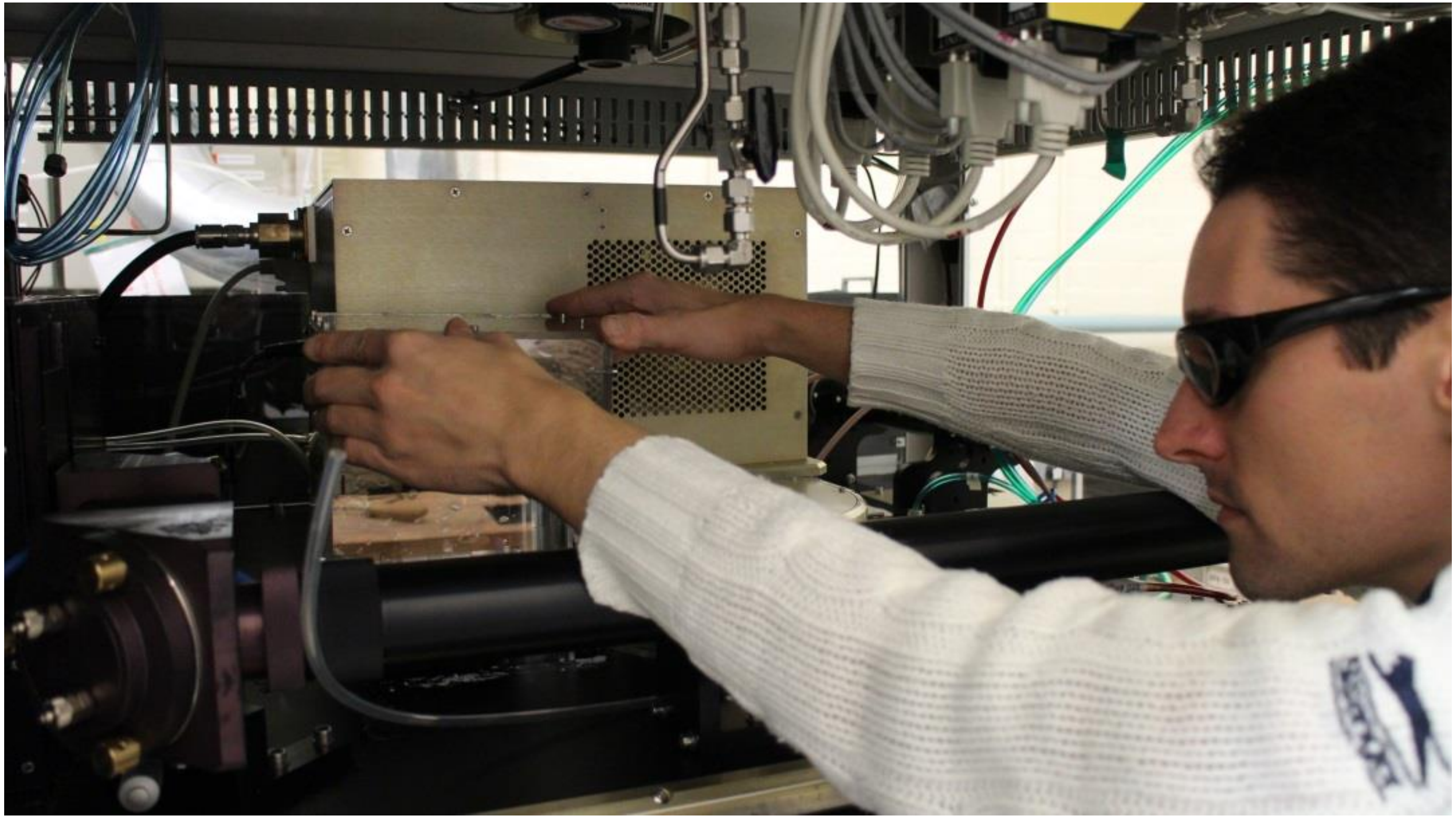

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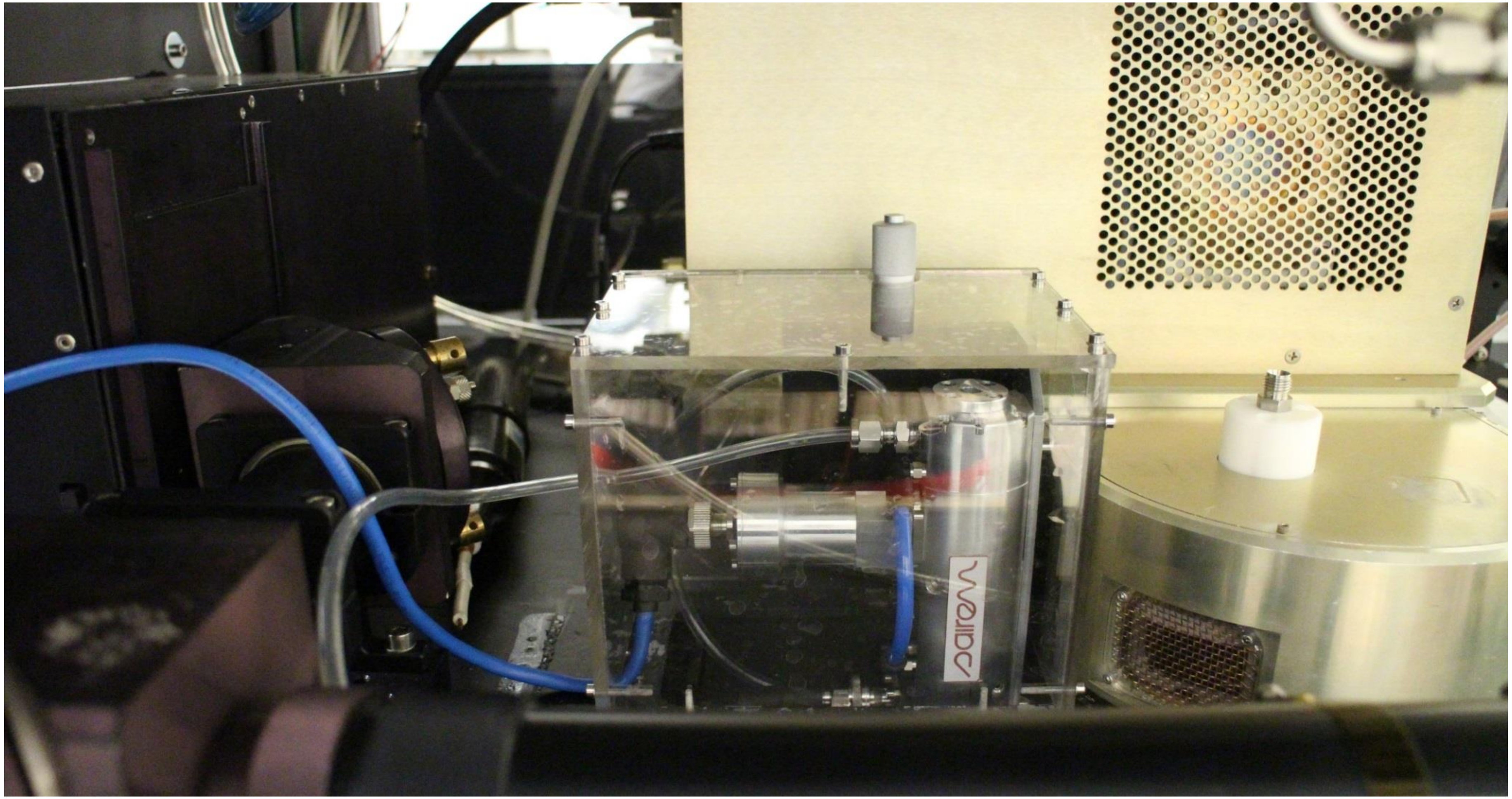
Microwave Plasma System & Enclosure Installation

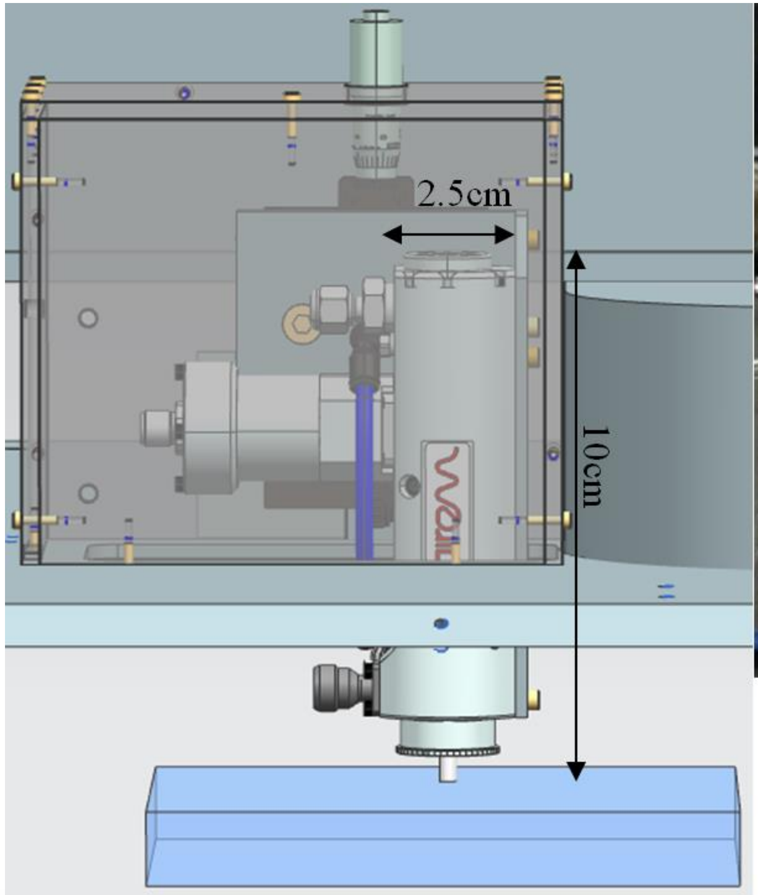


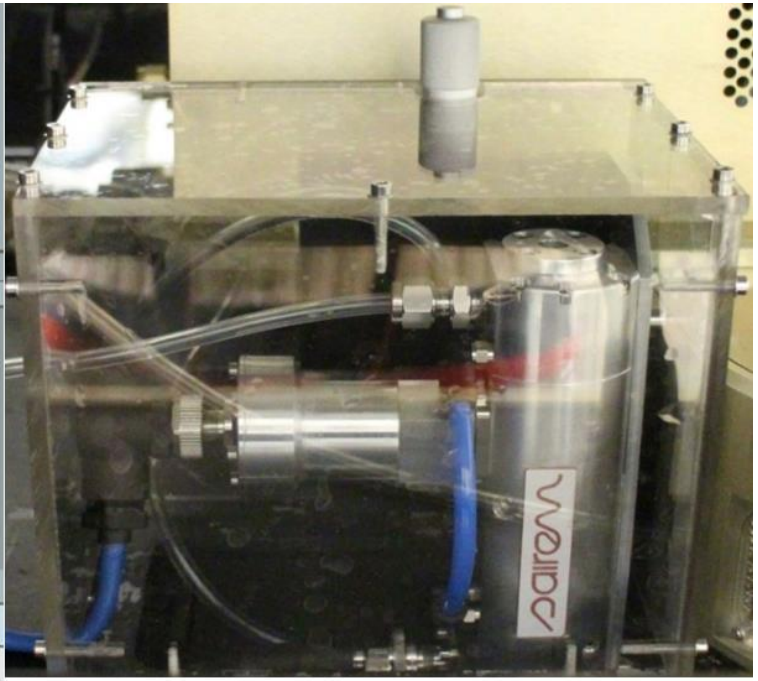
Plasma Processing

The Surface Wave Launcher Microwave Induced Plasma torch was placed into a bespoke enclosure within a Plasma Figuring machine.

Contains all UV(UV-A, UV-B, UV-C); radio-waves; micro-waves; and reactive atoms.

Enables rapid processing at atmospheric pressure.





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Plasma Processing

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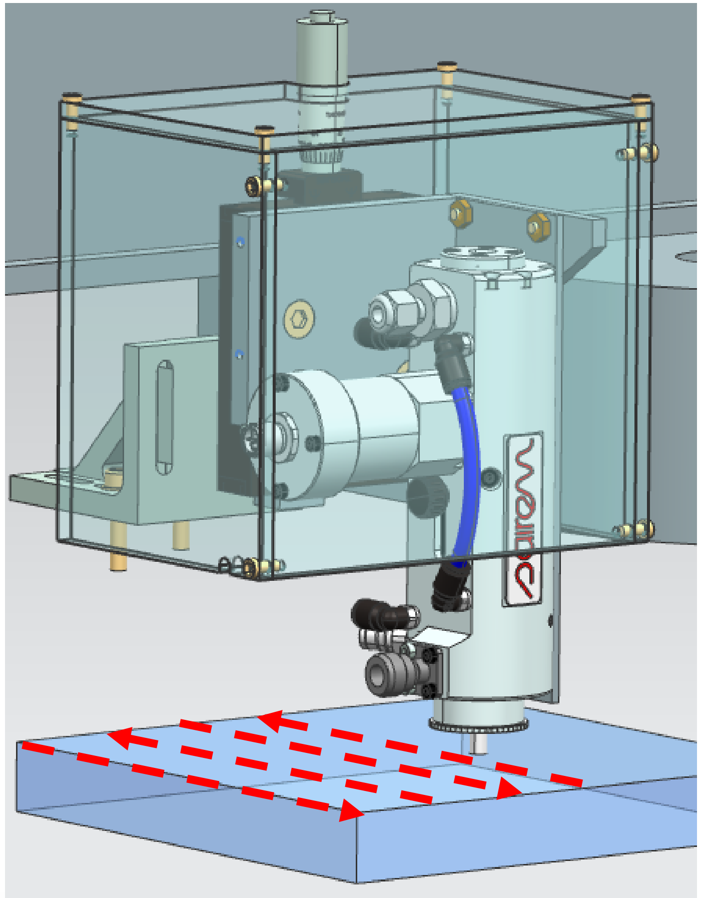
Contains all UV(UV-A, UV-B, UV-C); radio-waves; micro-waves; and reactive atoms.

Enables rapid processing at atmospheric pressure.

Tool path: the route the torch moves with respect to the optic

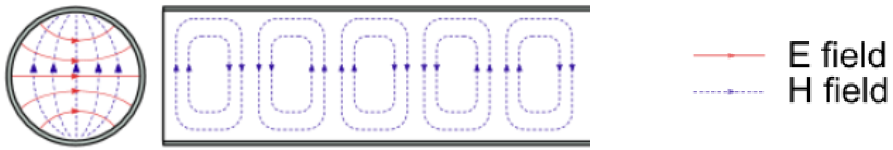


Frequency = 2.4GHz to 2.5GHz

Power = 100W to 200W

Main Gas Flow = 4L/min to 10L/min

Main Gas : Reactive Gas = 99.5% : 0.5% to 96% : 4%



TE_{11}

$$f_{mnp} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}} \cdot \sqrt{\left(\frac{X'_{mn}}{R}\right)^2 + \left(\frac{p\pi}{L}\right)^2}$$

TE f ≠ TM f

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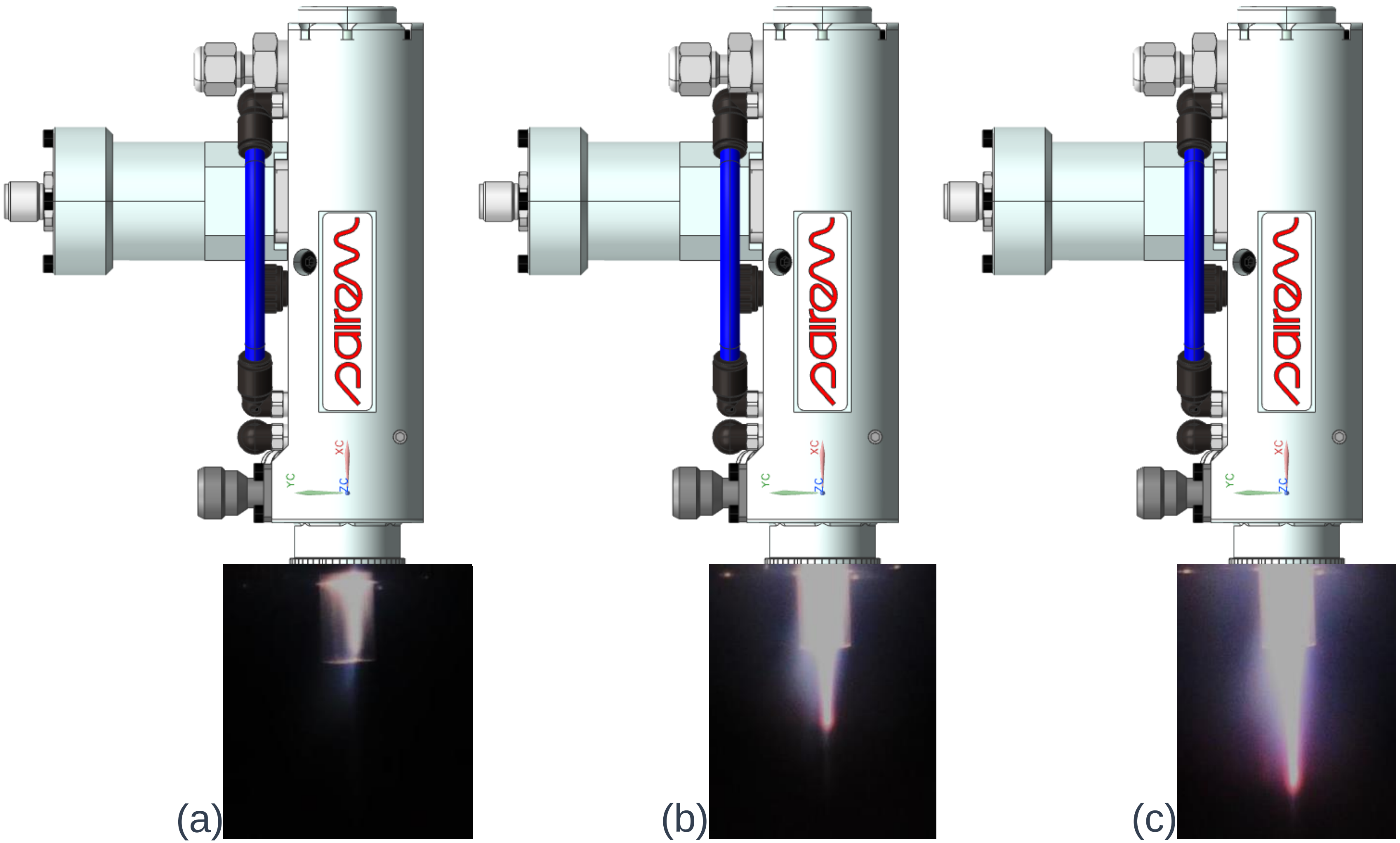
Plasma Processing



Plasma Jets:

(a) 25W 5L/min Ar;

(b) 100W 5L/min Ar;

(c) 200W 5L/min Ar.

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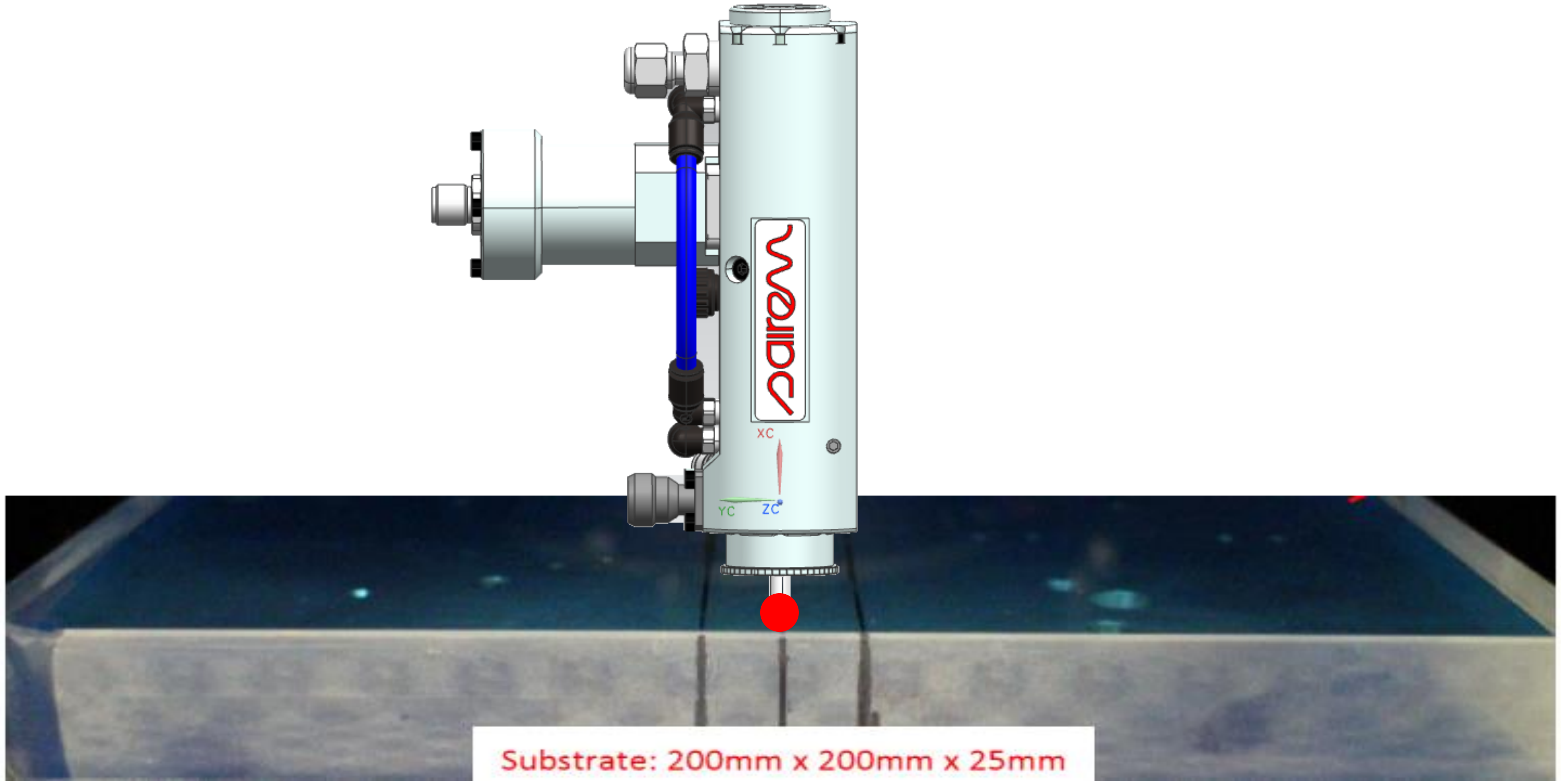
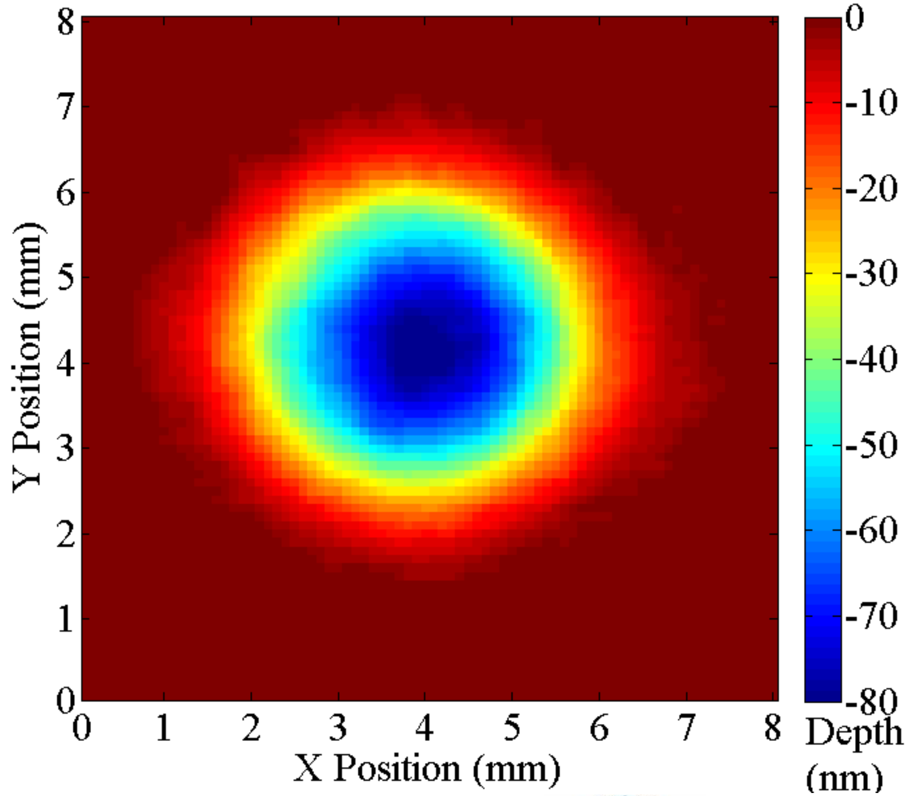
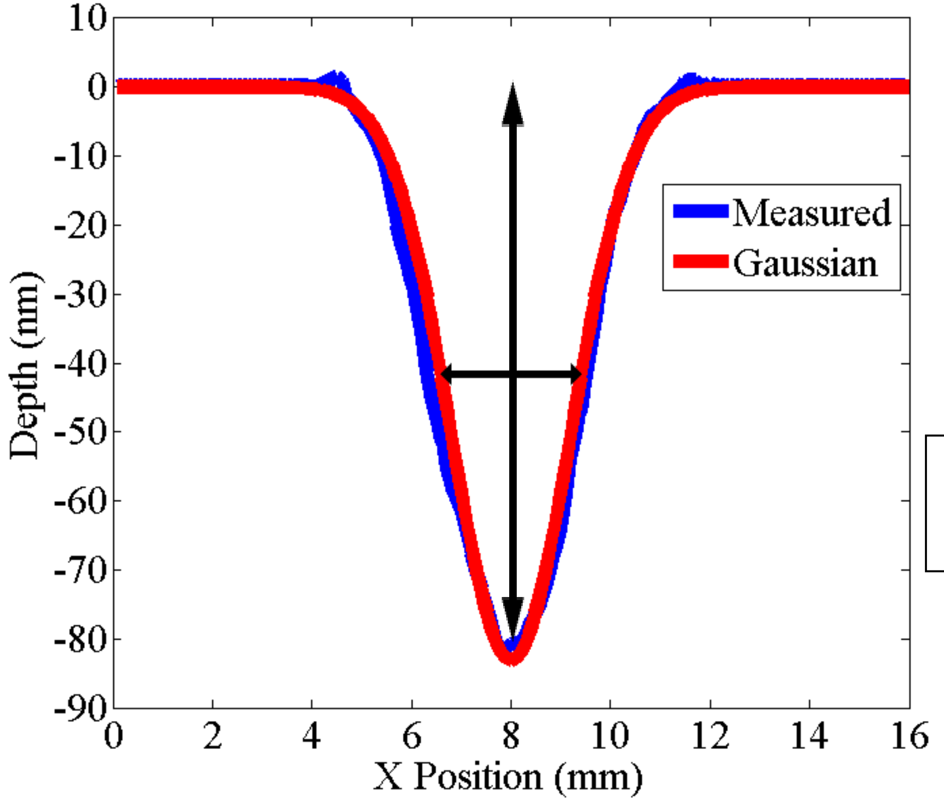
Plasma Processing
Stationary Dwell – Material Removal



Plasma Processing
Stationary Dwell – Material Removal

Power = 100W, Frequency = 2.45GHz, Main Gas Flow = Argon @ 5L/min,
Reactive Gas Flow = 10% CF_4 in Argon @ 0.5L/min, Stand-Off Distance = 10mm, Dwell Time = 10s
Optical Substrate = ULE





FWHM = 2mm

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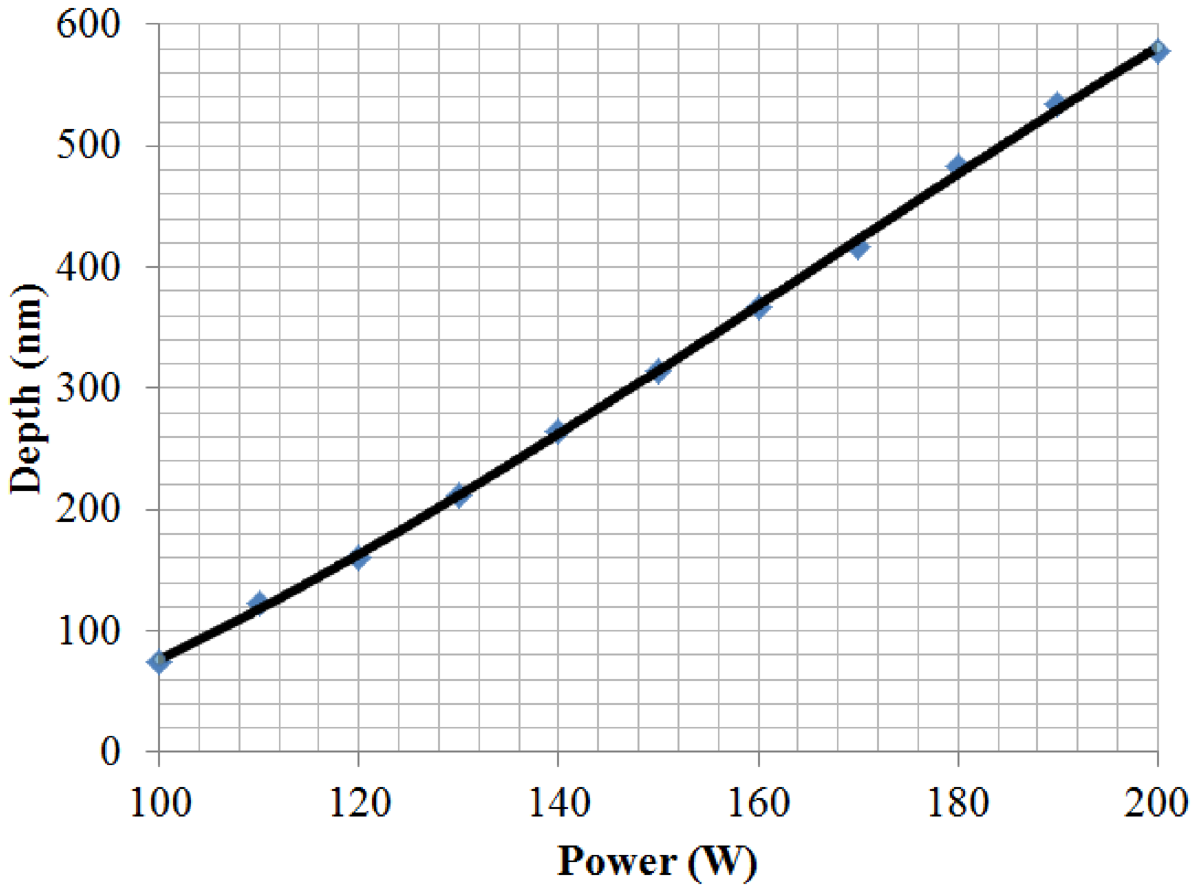
Plasma Processing
Stationary Dwell – Material Removal

Power effect on maximum depth



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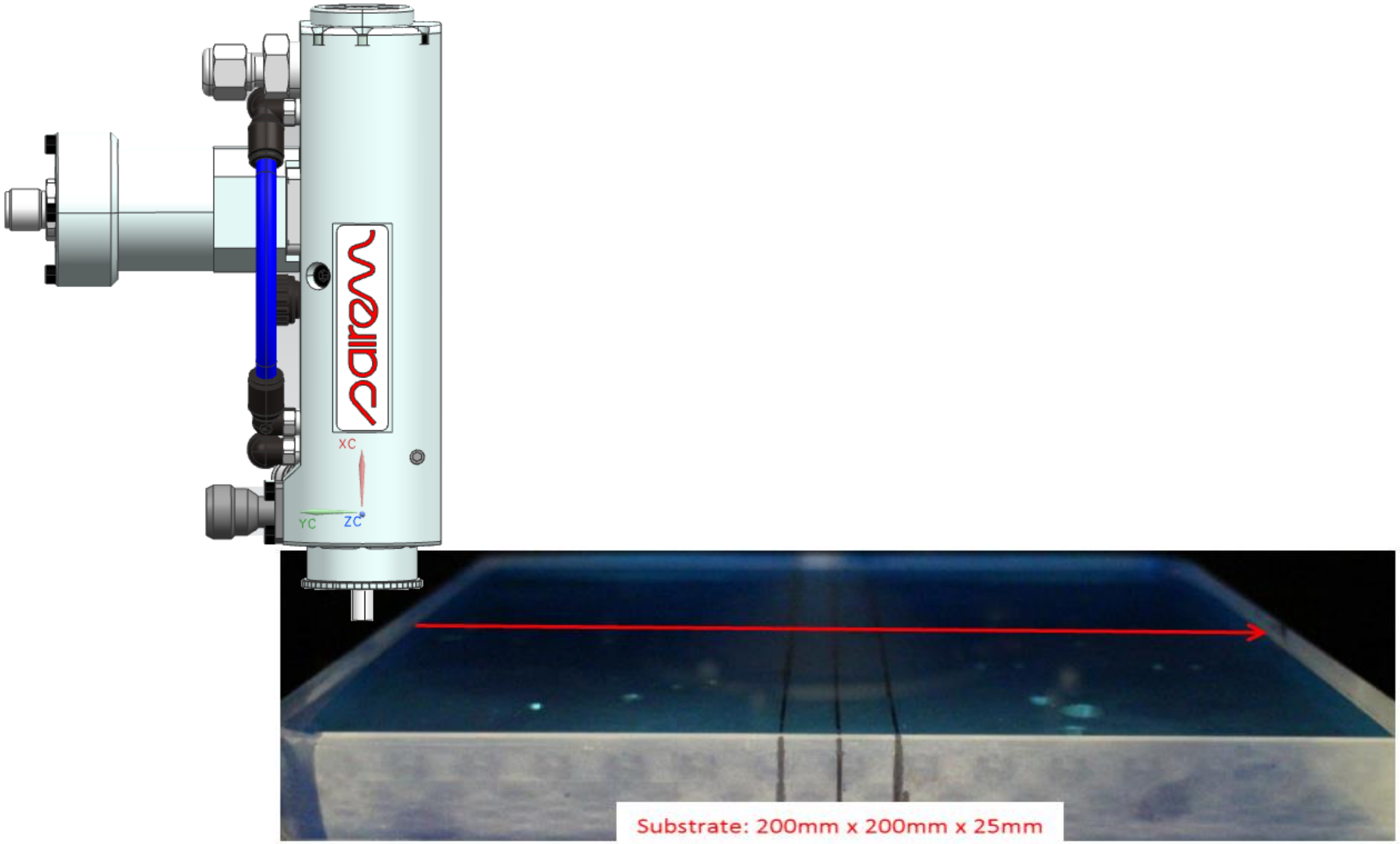
Plasma Processing
Single Trench – Material Removal



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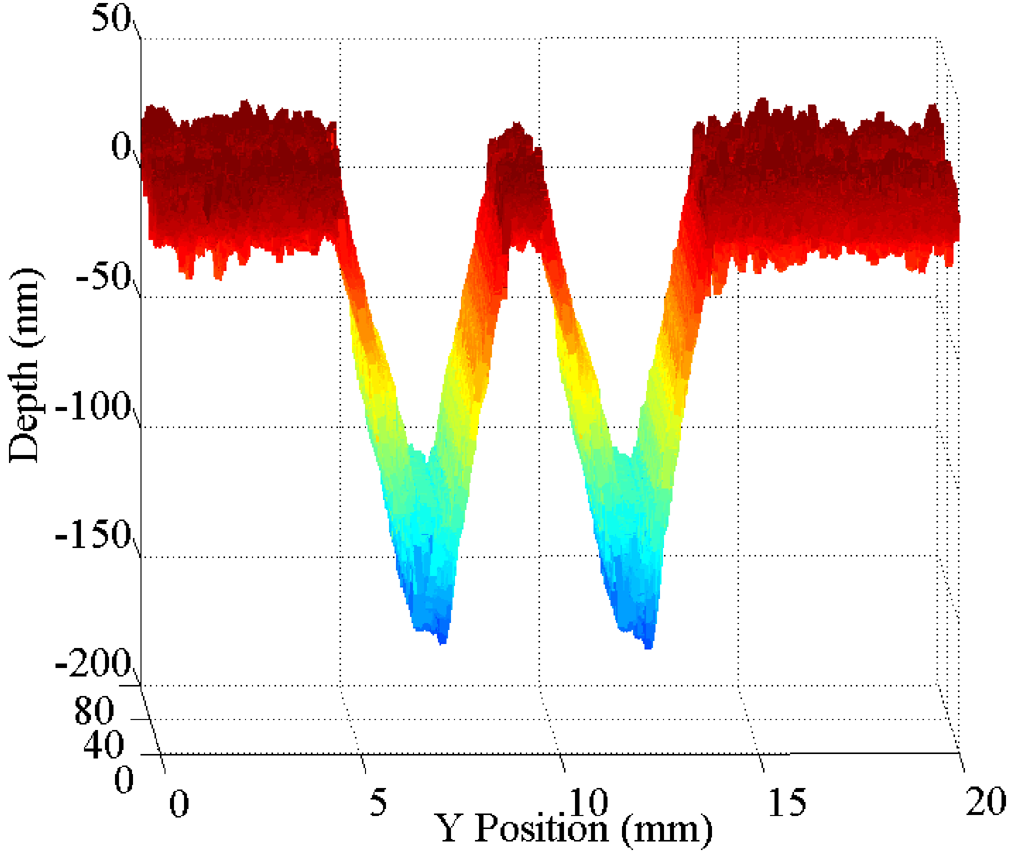
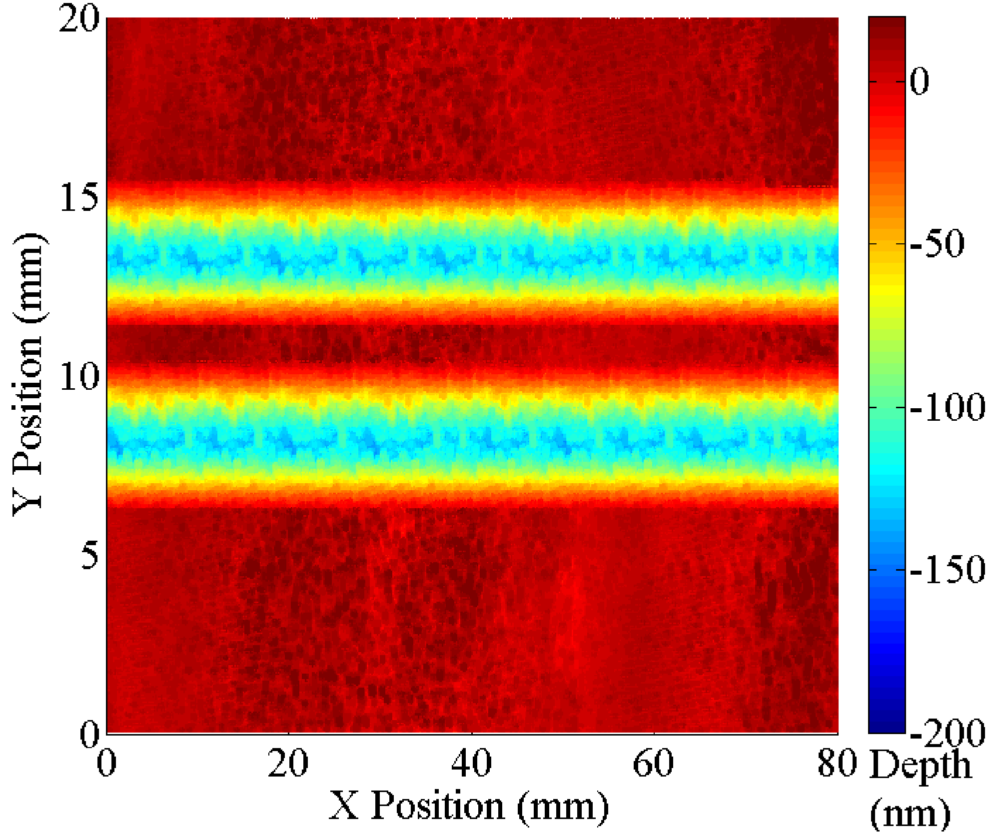
Plasma Processing
Single Trench – Material Removal

Power = 150W, Frequency = 2.45GHz, Main Gas Flow = Argon @ 5L/min,
Reactive Gas Flow = 10% CF_4 in Argon @ 0.5L/min, Stand-Off Distance = 10mm, Optical Substrate = ULE



FWHM = 2mm

Torch Speed = 10mm/min



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AD-TEC Plasma Technology co., ltd. · Cranfield University · The University of Nottingham (United Kingdom · China · Malaysia) · University of Cambridge · Gooch & Housego (Enabling Photonic Technologies)

Surface Wave Launched Microwave Induced Plasma Torch Characterisation by Optical Emission Spectroscopy

Experimental Setup

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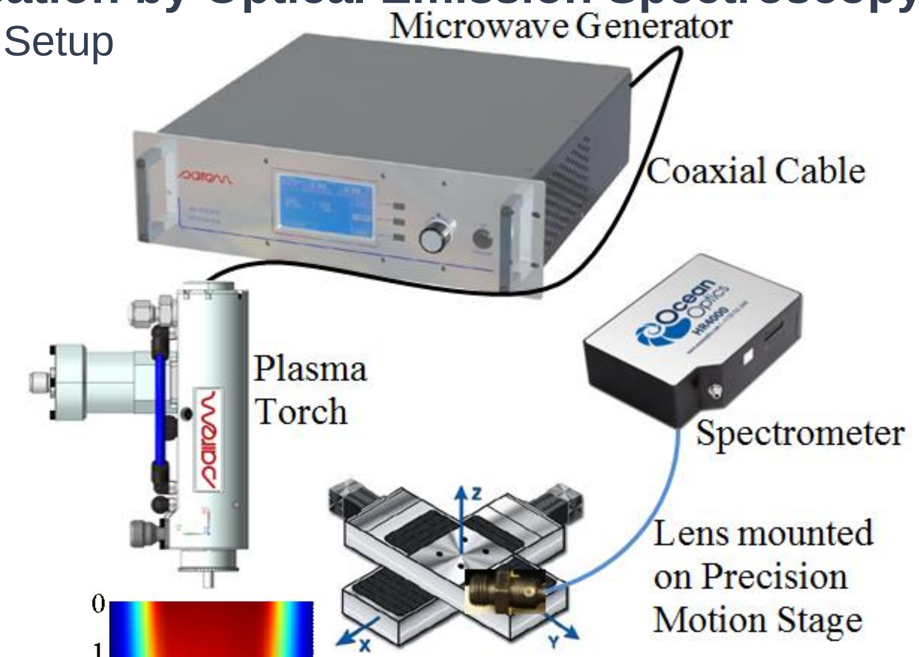

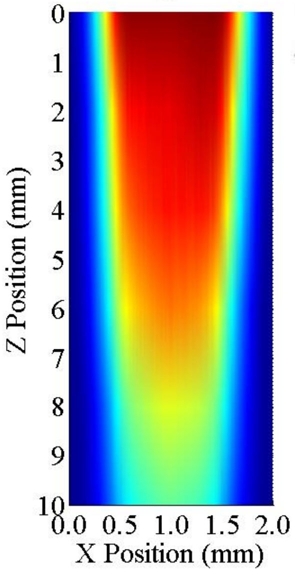

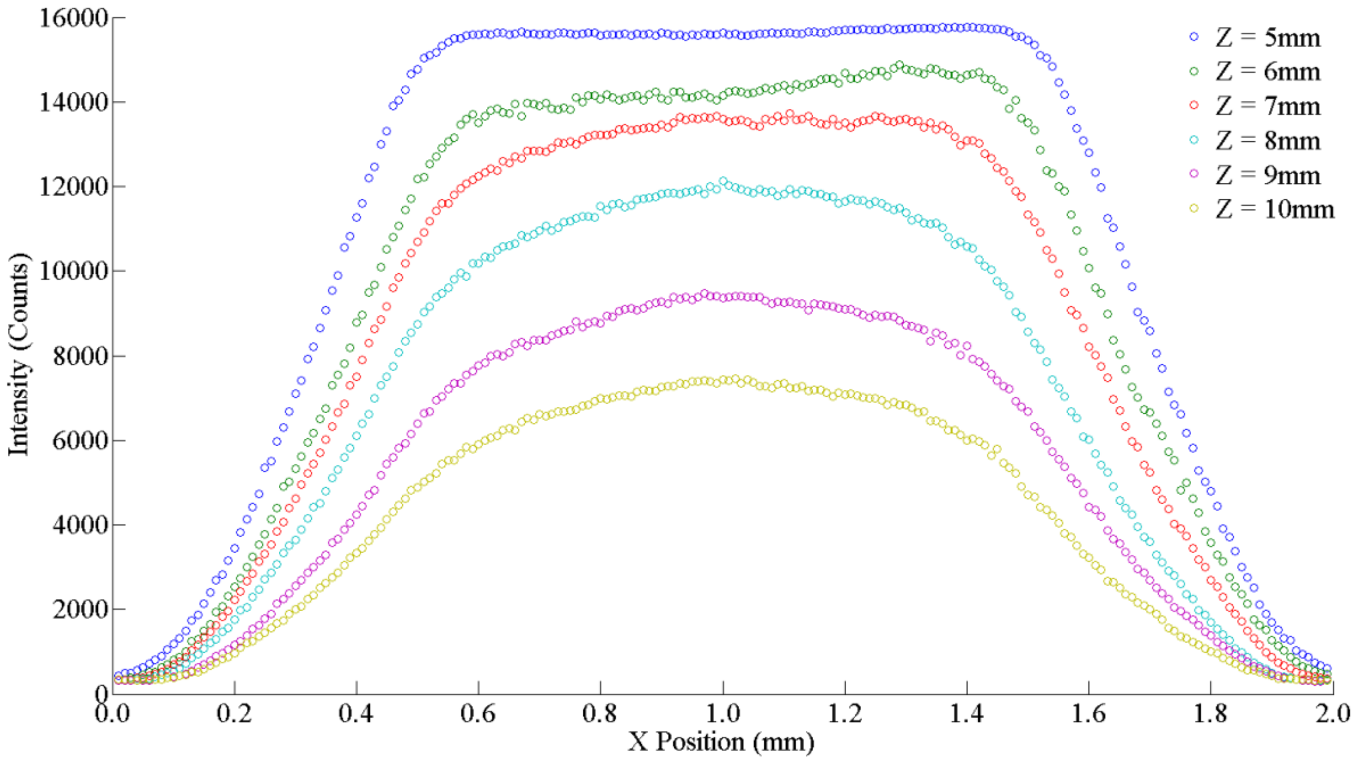

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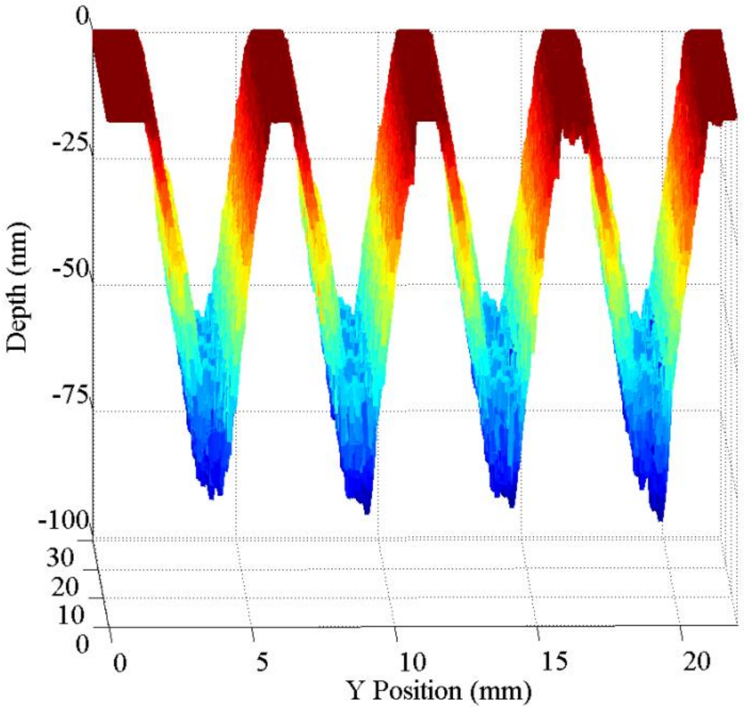
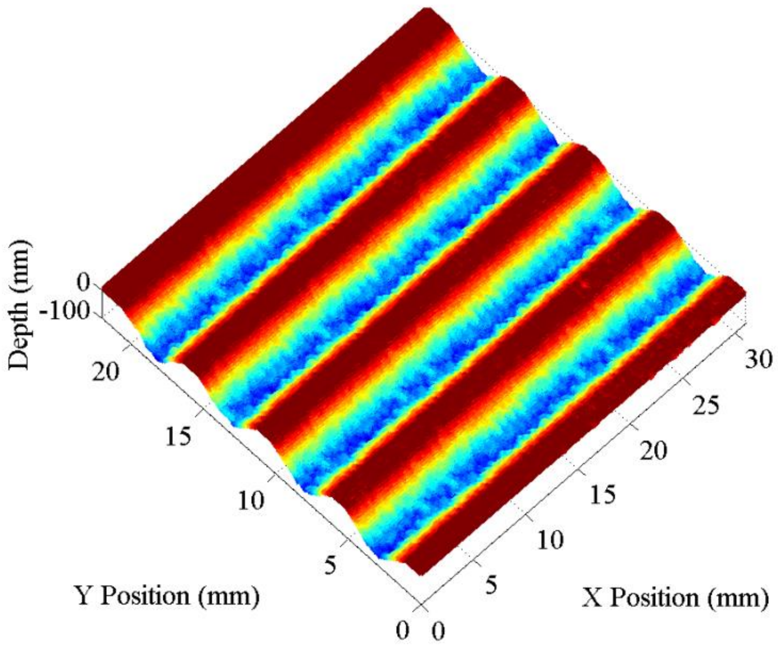
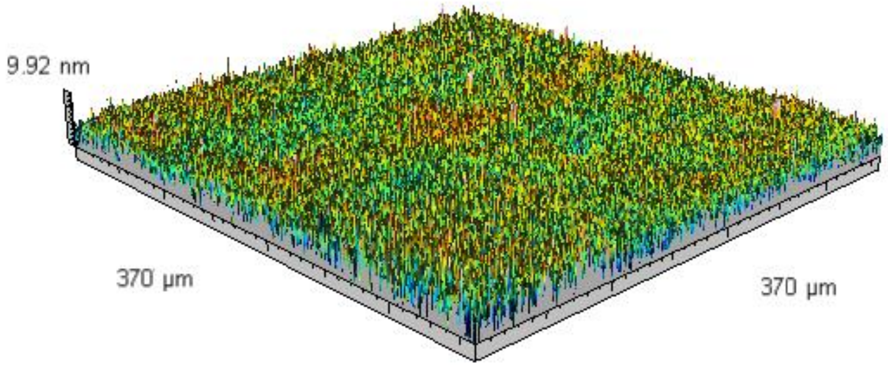
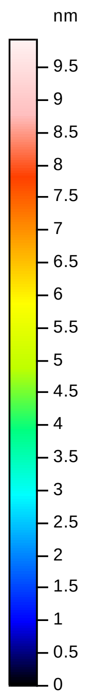
Plasma Processing
Surface Figuring – Material Removal – Crystal Quartz



Form Correction Capability







Surface Roughness

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Plasma Processing
Stationary Dwell – Material Deposition

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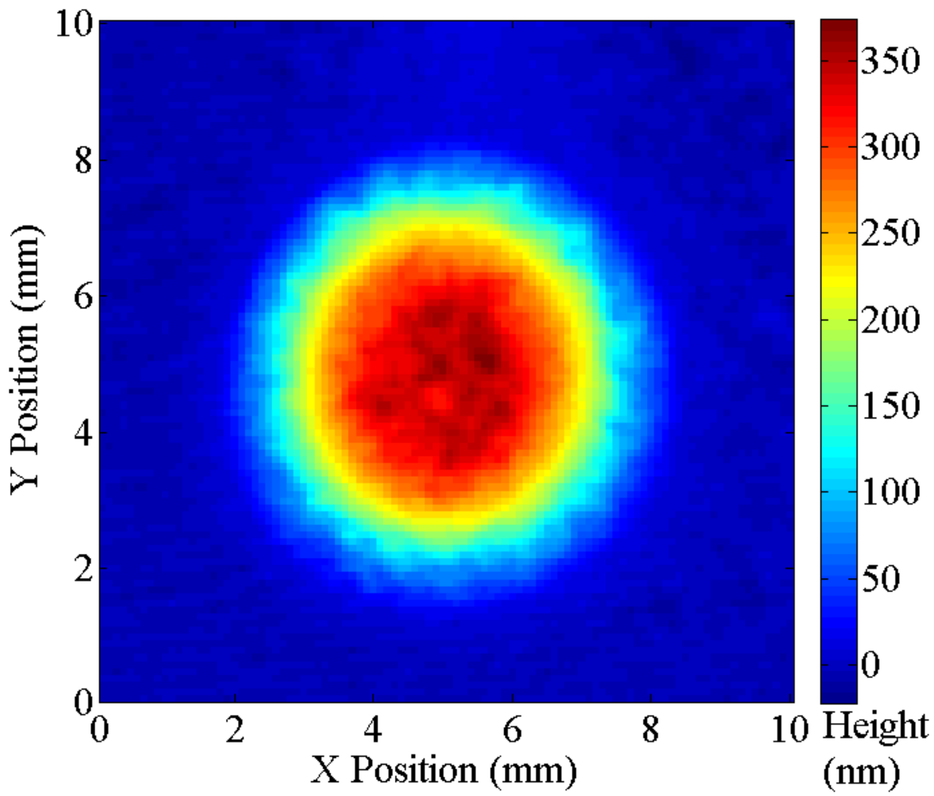

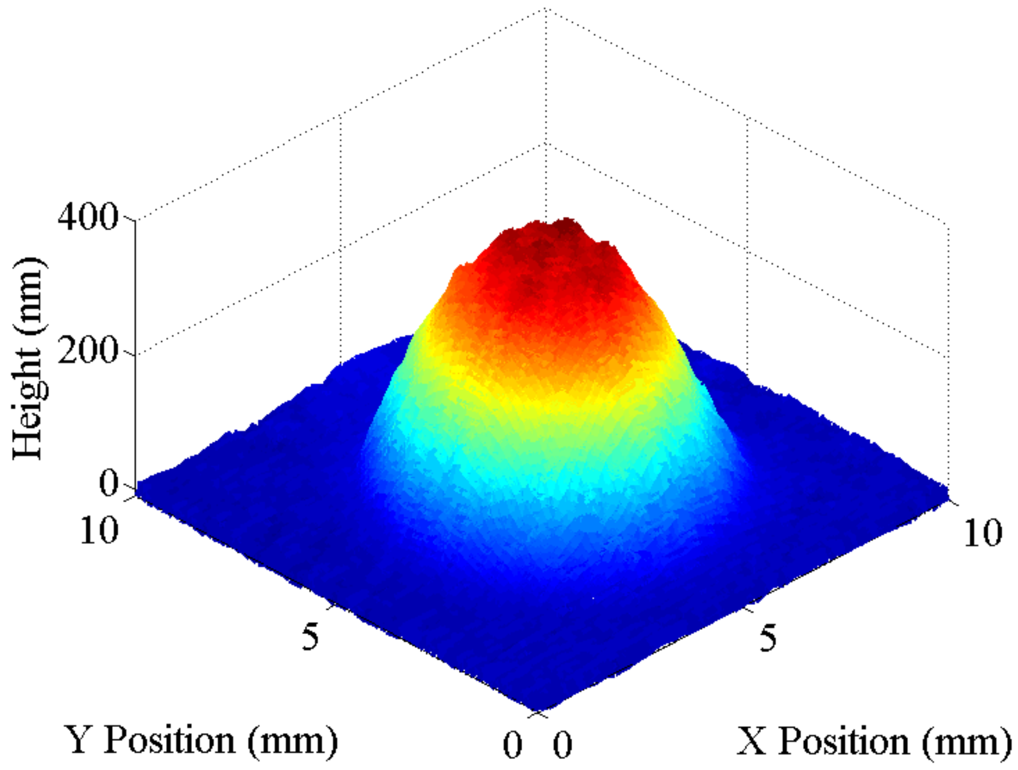

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Summary

Novel Microwave Spectrum & Optical Emission Spectroscopy techniques developed to characterise plasma torches.

New microwave plasma system has been commissioned and installed into the plasma figuring machine.

Stable material removal on the surface of optics has been demonstrated.

Full Design Of Experiments conducted to optimise the parameters.

Entire surface of Crystal Quartz substrates have been processed.

Deposition has also been demonstrated!

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Acknowledgements

Cranfield University EPSRC Centre for Innovative Manufacturing in Ultra Precision {EP/I033491/1}: Plasma Figuring Laboratory

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Gooch & Housego: Project Funding

ADTEC: Technical Support & Pioneering Microwave Plasma System Loan

Defence Academy: Military Grade Microwave Characterisation

Adam Bennett

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