Instrumentation-Targetry Synergies for Laser-Driven Systems and Applications

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Science & Technology Facilities Council
Central Laser Facility

Overview

Future Laser-Driven systems

Current Microtarget Production Techniques

Current Microtargetry Characterisation Techniques

LIBRA Targetry

1. Wafer-based microtarget mass production
2. Optical Trapping
3. Electro-static/magnetic Levitation

HiPER

LIBRA-Gemini Experiment

Summary

Future Systems/Applications

Synergies between large programmes.

LIBRA: Laser induced Beams Radiation and their Applications.

- Ion therapy
- Security scanning (large vehicles)

HiPER: Laser-driven fusion reactor technology testbed.

IFE: Target production/handling. Dielectrophoretics techniques of Harding et al. {See for example Z.-M. Bei, et al., Forming concentric double-emulsion droplets using electric fields, Journal of Electrostatics (2009), doi:10.1016/j.elstat.2008.12.013}

XFEL: Colliding liquid droplet targetry?

Repetition rates

Current shot rate on Vulcan (RAL): typically 1 shot per 30 minutes

GEMINI: approaching 1 shot per minute

HiPER: 4a burst mode - 10s full rep rate (6Hz) including some DT shots (T_0 + 7 years)

4b ~10Hz for prolonged period

XFEL: approaching synchrotron rates (kHz)

Underpinning Science

- Scaling issues underpin all aspects of microtarget production, handling and positioning.
- Almost all processes and materials properties behave differently at the micro- to nano- scale compared with the mesoworld.

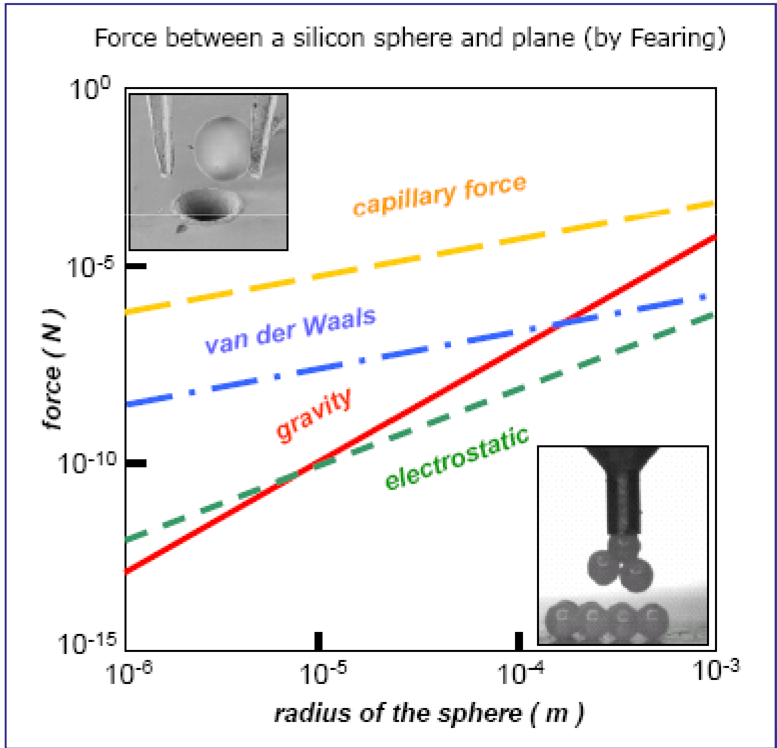

Image courtesy Fearing/Porta (TUD)

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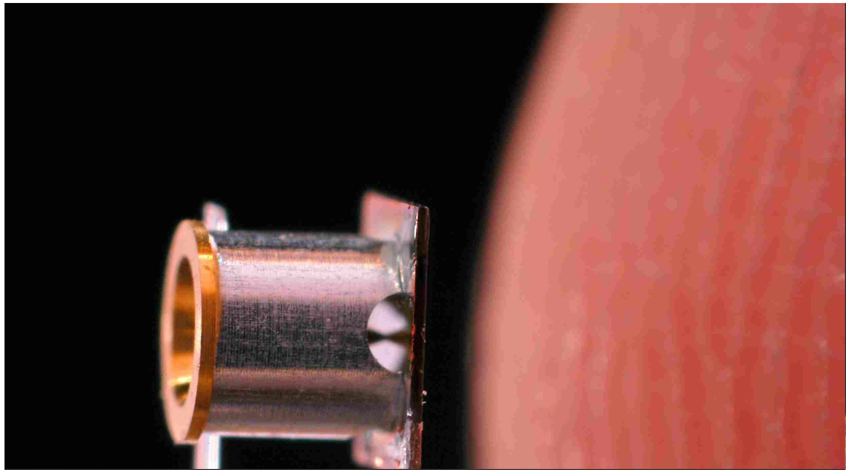
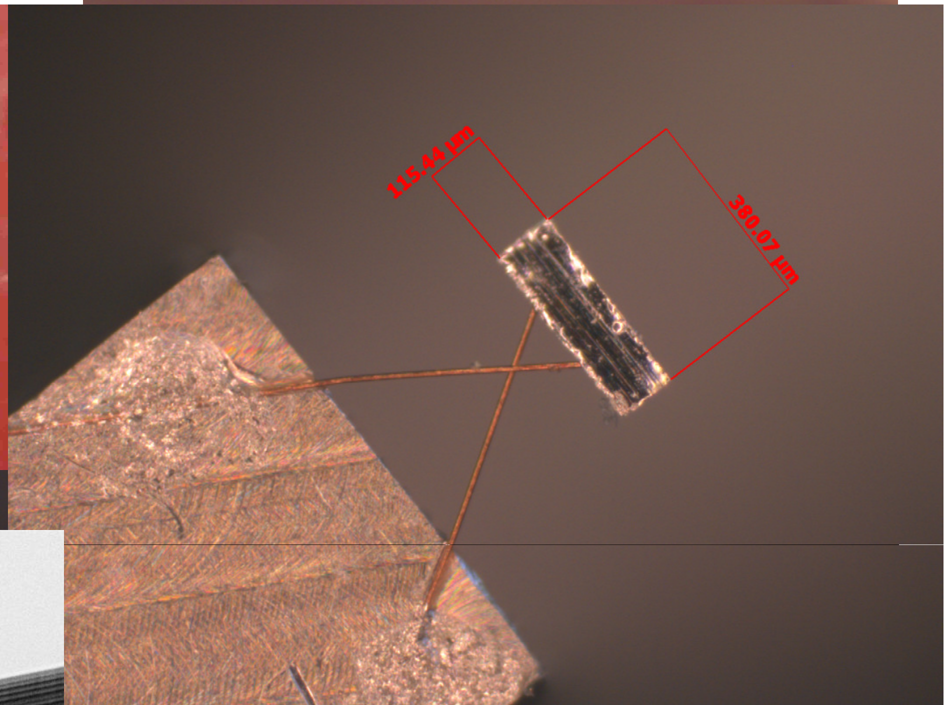
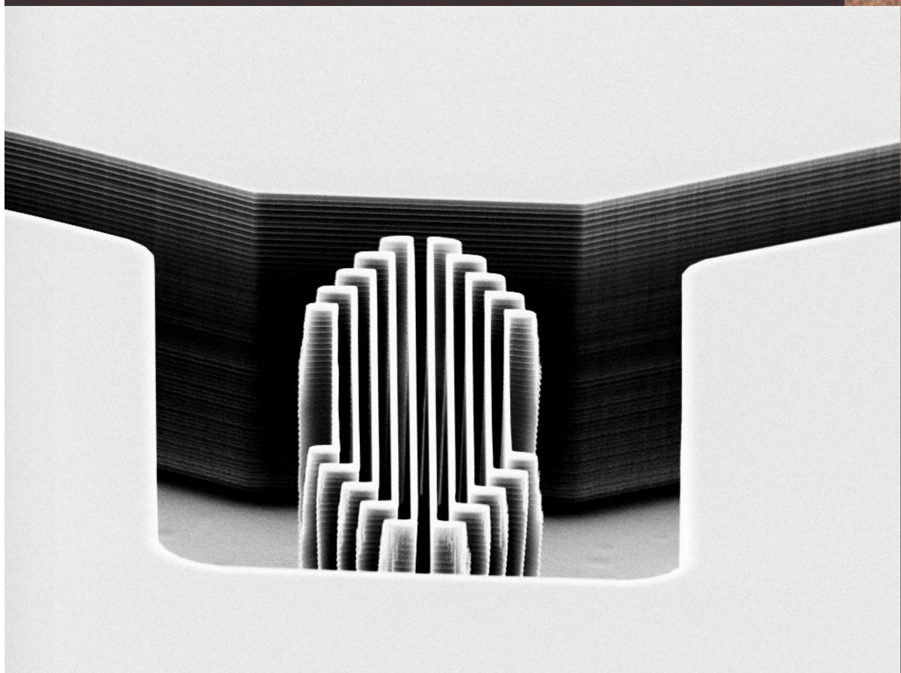
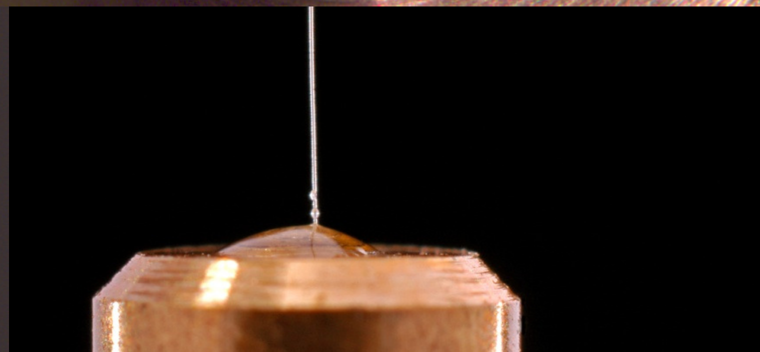
Microtarget designs

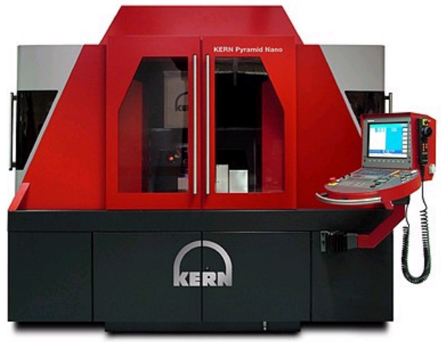








Current Microtargetry Techniques



- Microcomponent manufacture
  - Ultraprecision micromachining
  - (Wafer-based and MEMS techniques)
  - Lithography/etching/electroplating
- Micro-assembly
- Thin film coatings
- Characterisation

- Microtarget placement
  - Insertion
  - Injection (tracking and engagement)

Target Fabrication Diagnostics

1) Target Fabrication already uses a lot of diagnostics ….

except it calls it Characterisation (or metrology).

2) Approximately 1/3 of the cost of a high value target can be characterisation.

3) 30-40 % of characterisation (diagnostics) is in process control/R&D.

Characterisation Techniques in the Target Fabrication Metrology Laboratory

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Introduction

The Target Fabrication Laboratory has been equipped with a range of complimentary techniques that enable the characterisation of high power laser micro targets and a range of other components and optics. The investment has been carefully planned to meet the anticipated trends in high power laser target design and also the needs of programmes such as the Astra Gemini laser which will require high rep-rate targetry.

High Resolution Optical Metrology

The group has a *Zeiss M1m AxioImager* which is a fully motorised microscope with a wide range of magnifications and contrast techniques. Fully linked to image capture and analysis software the microscope has provided images and invaluable data on targets that was not previously available. Also the microscopes ability to produce extended focus, z-stack images and also 3D representation of an image is highly desirable when looking at target characteristics. The group also has a suite of *Zeiss SV11* medium magnification microscopes that are used for micro-assembly and characterisation of larger objects. These are also linked to powerful image capture and analysis software.

Figure 1. An AxioImager Microscope

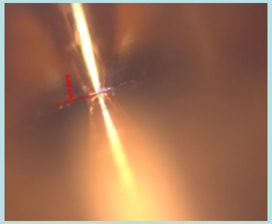

Figure 2. An AFI cone tip under high magnification for analysing a glue joint.

Automated Co-ordinate Measuring Machine (CMM)

An *OGP Smartscope Zip 250* optical co-ordinate measuring machine (CMM) has enabled the characterisation of a large number of identical targets to be carried out in a small space of time. Single programmes can be written to be run many times and has improved the productivity of the laboratory. The machine has micron accuracy in *x* and *y* and is also fitted with a laser probe to enhance accuracy in *z* enabling topographical mapping of surfaces with sub micron accuracy.

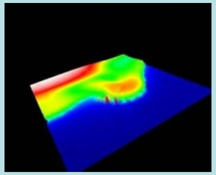

Figure 3. CMM laser probe surface scan of part of a 1p coin, (Blue to white range 150um)

Thin Film Measurement

An *Alpha Step IQ* surface profiler is operated by the Target Fabrication Group. The profiler can measure step heights to below 50nm and has a low contact force (to ensure samples are not damaged). The *Alpha Step* has a range of measurement modes including step height, roughness and form measurement. A typical readout is shown in figure 5.
The system can measure a number of pre-located sites to give a complete picture of, for example a material deposition profile across a substrate.

Figure 4. the Alpha Step IQ surface profiler

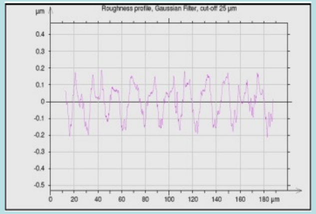

Figure 5. A typical trace from the ASIQ

Scanning Electron Microscopy

A *Topcon SM200* Scanning Electron Microscope fitted with a *Röntec Quantax QX2* Energy Dispersive X-ray Spectrometer (giving elemental analysis) and secondary electron detection is housed in the Target Fabrication Laboratory. This is providing highly informative characterisation data from 5nm resolution images and the x-ray elemental analysis giving is extensive insights into the production processes of microtargets. It is also proving to be an invaluable analysis tool in understanding the processes of thin film deposition. The machine is becoming increasingly accessed by other departments at RAL.

Figure 6. The Topcon SEM

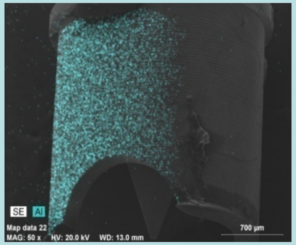

Figure 7. A elemental map showing an Aluminium tube around an AFI cone

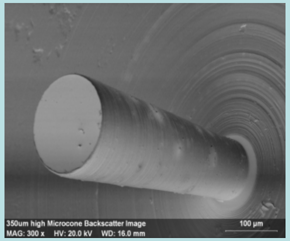

Figure 8. A backscatter SEM image of a hand turned micro-cone, showing machining marks and contamination

White Light Interferometry

A *Veeco Wyko NT9300* white light interferometer is located in the Target Fabrication metrology cleanroom. This system is fully motorised and automated and allows the characterisation of surfaces with a sub nm accuracy. A motorised *x-y* stage, with motorised tip and tilt function, integrated with powerful software allows for the stitching of wafers to allow full characterisation area of up to 200mm

Film analysis software allows for resist layers to be non-destructively characterised and films of down to 1um can be accurately measured. Step heights and surface roughness values can be measured in the nm regime.

Figure 9. The Wyko NT9300 Interferometer

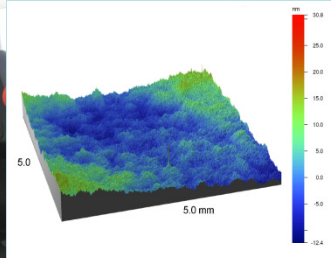

Figure 10. A high resolution scan of the surface of a microscope cover slip

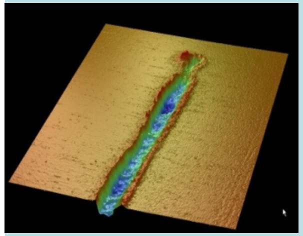

Figure 11. A high resolution scan of a laser etched groove

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LIBRA

Target Stream Motivation

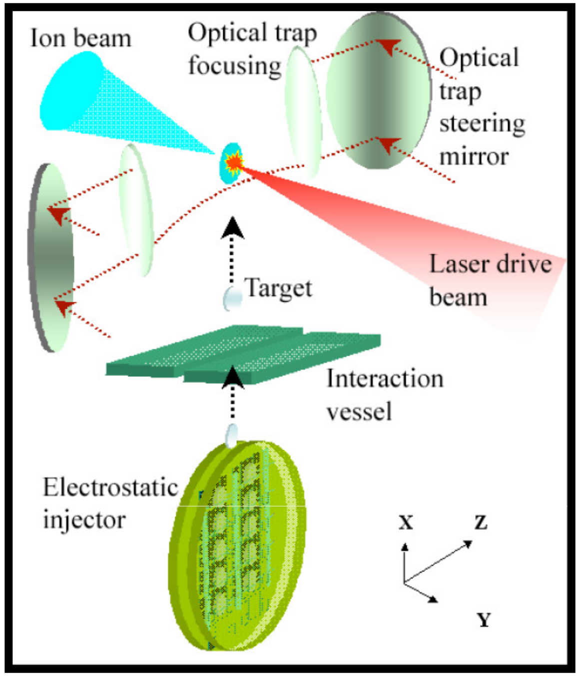
- Develop the capability to produce microtargets (including novel types) and deliver them to the interaction point in a manner suitable for LIBRA applications.

- Baseline target: 10μm diameter, 50 nm thick Si_3N_4 disc which needs to be placed with a final accuracy of ~1 um at a maximum repetition rate of 1Hz.

- Initial approach: develop and integrate three main complimentary technologies; (1) wafer-based mass production, (2) electro-static/magnetic levitation and (3) optical trapping.

- Assess feasibility of alternative production and placement techniques.

Target Delivery Original Concept

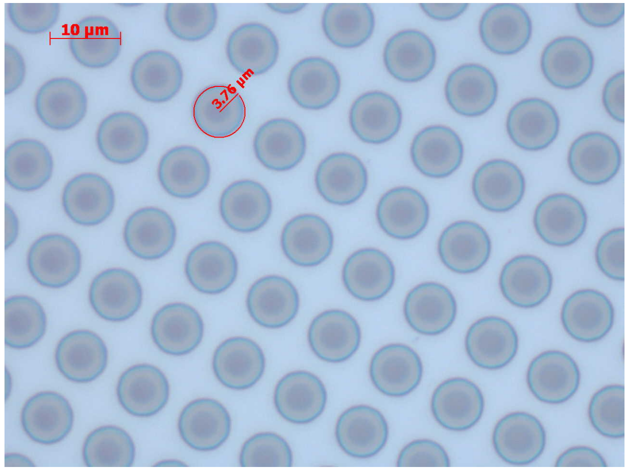


Original design concept for target delivery, optical trapping and target irradiation to produce ion-beams

It was anticipated from the start of LIBRA that the Targetry workpackages would evolve, especially their integration as a whole.

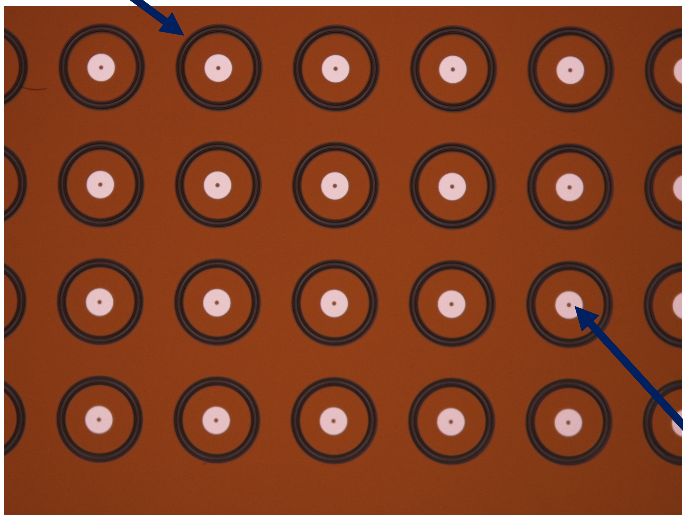
The evolution would be synergistic with the LIBRA project and other programmes.

1. Wafer-based microtarget mass production



Wafer Populated with ~6μm diameter microdiscs (detail)

Double Trench to prevent droplet spread



Disk target (10um diameter)

Double trench design for microsyringe release studies

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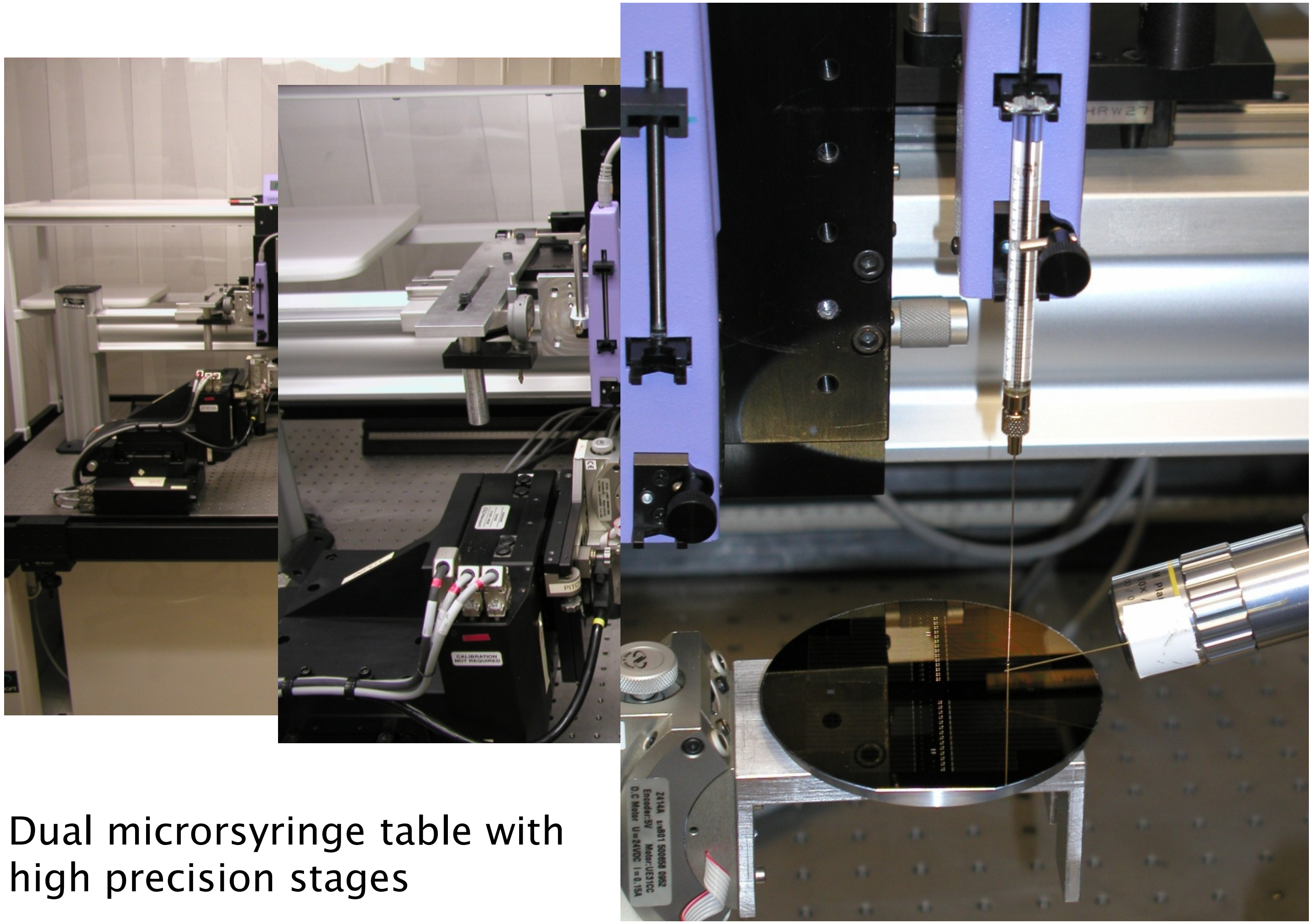
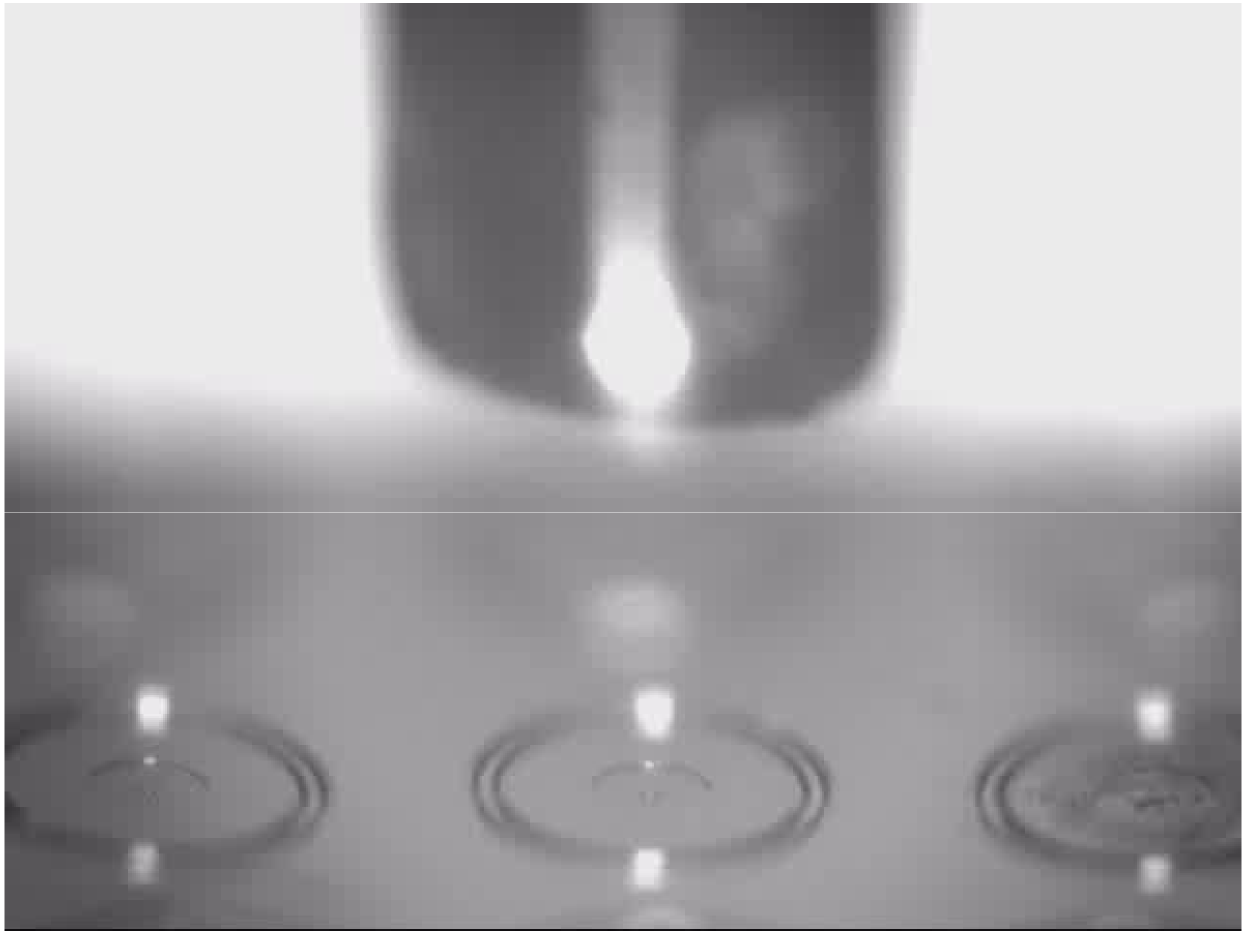
Microdisc-in-Droplet Transport



Dual microrsyringe table with
high precision stages

Registration and Containment Tests



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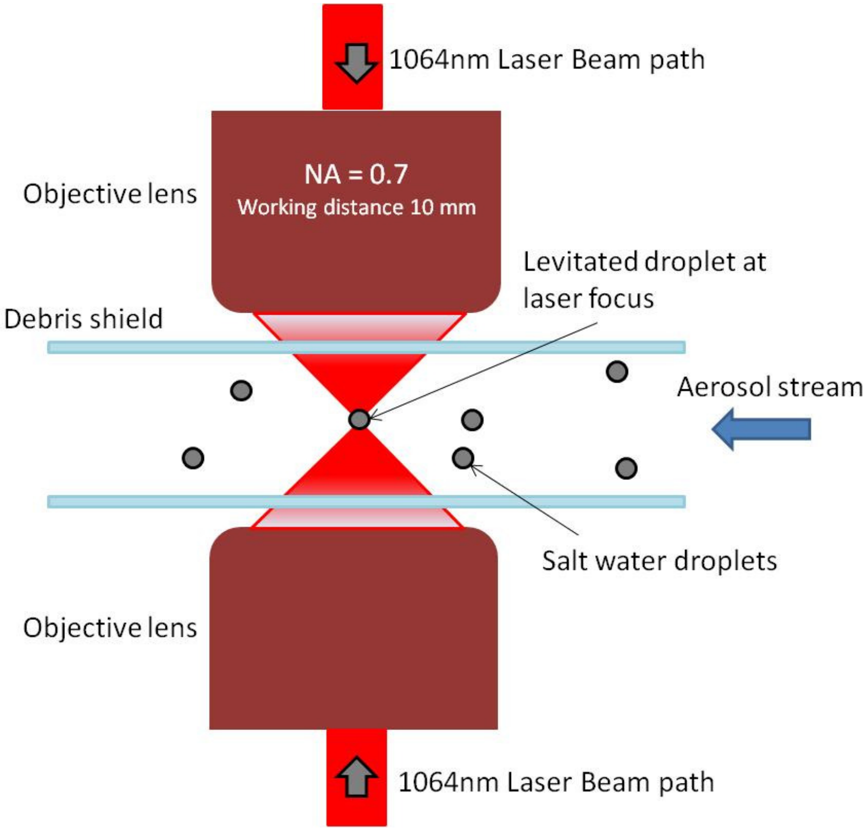
Counter-propagating Optical Traps

- We use two co-axially aligned, counter-propagating, laser beams where optical trapping occurs through a balance of opposed scattering forces



- Objective lenses
  - Working distance 10mm
  - Withstand vacuum environment
  - Good transmission of NIR laser light
- High numerical aperture
  - NA = 0.7
  - Increased positional stability
  - Robust optical trapping

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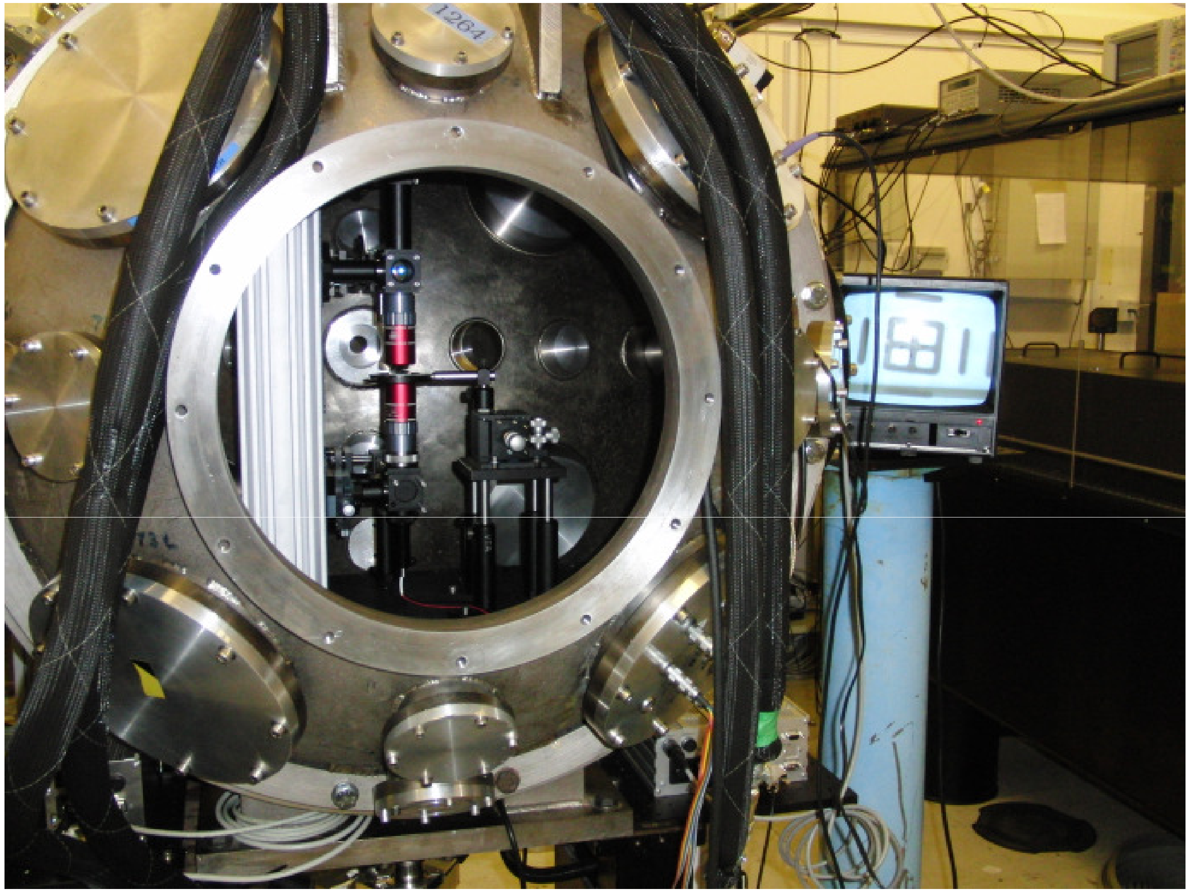
Interaction chamber experiments



Mark 2 kit – November 2009

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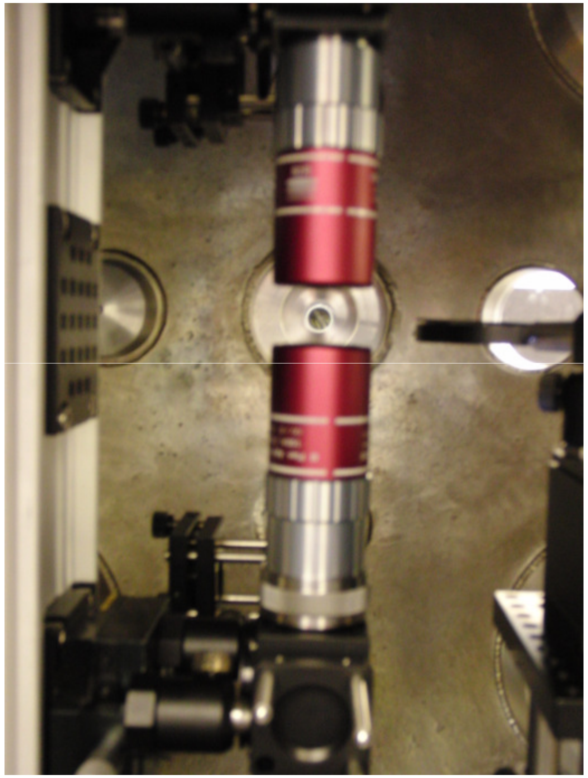
Interaction chamber experiments

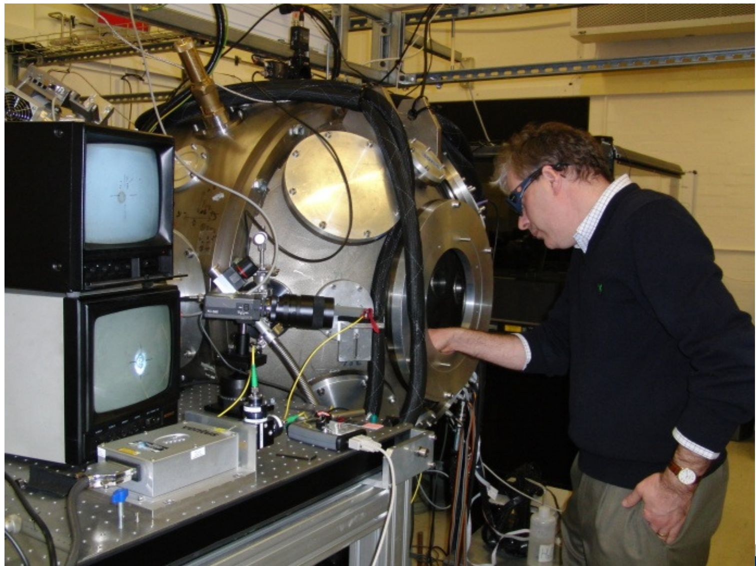
- Centre position on drive laser axis – for future interaction tests
- Vacuum tests 1 x 10^{-3} mbar
- Vacuum feed through of optical fibres into chamber
- Small issues with focal length shortening as pressure lowered – required calibration and correction using z stage
- Currently trap droplets at 1000mbar, seal, then reduce pressure.

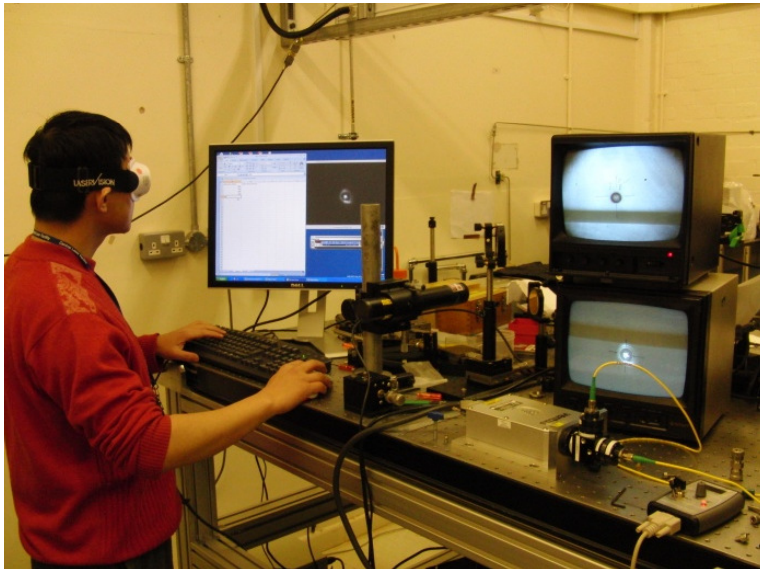


LIBRA

Optical Trapping: Summary

- We can trap and hold liquid droplets in air
  - Loading the trap can be robust
  - Approaching 1 target per second timescales
- We can reduce pressure and retain droplet
  - Lowest pressure around 9 mbar
  - At this point droplet crystallises
- Target positioning
  - To within 1 micron





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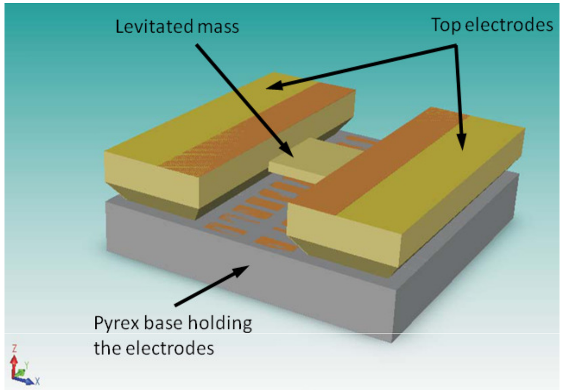
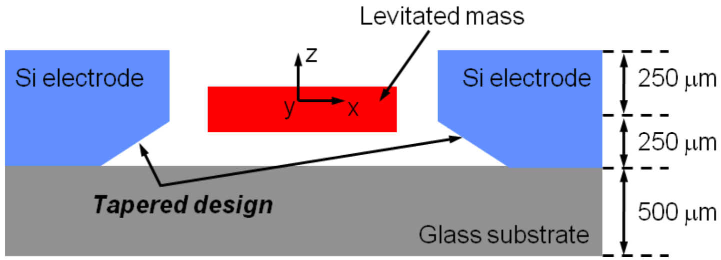
3. Electro-static/magnetic Levitation

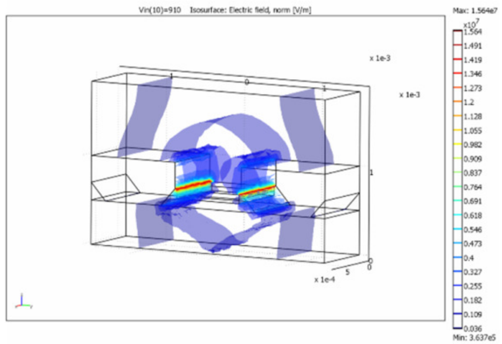
Next talk by Michael Kraft



Schematic drawing of proposed design



Cross-sectional view of
proposed design

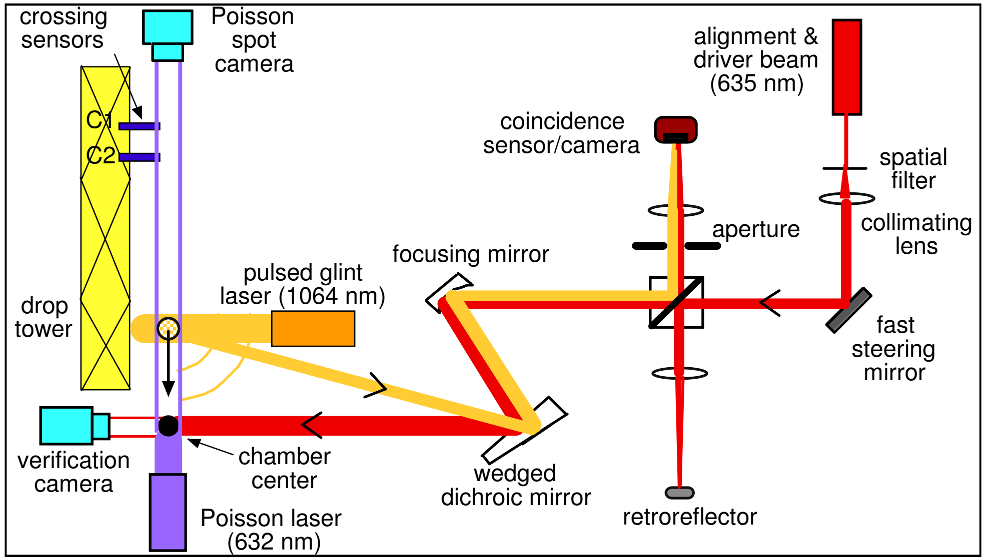


Electrical field lines across
the side Si electrodes

Tracking – an Opportunity for Diagnostics?

- A scheme for microtarget tracking (and stationary optically trapped position sensing) has been proposed.

- It may be more effective to collaborate with the recent HiPER EU tender for microtarget tracking.



Schematic courtesy
General Atomics Inc

HiPER

Two Baseline Target Types

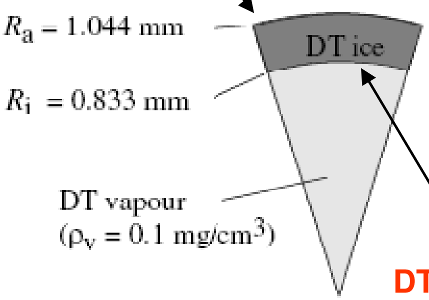
CH shell (3μm thick): 2.040mm ID, 2.046mm OD

Foam + DT (70μm thick) 1.900mm ID, 2.040mm OD

DT Ice layer (120μm thick) 1.660mm ID, 1.900mm OD

Mat	R_{int}(mm)	Dr(mm)	R_{ext}(mm)	r_0
DT	0	830	830	1.e-4
DT	830	120	950	0.253
CH(DT)$_6$	950	70	1020	0.364
CH	1020	3	1023	1.05

CH shell outer roughness ~50nm



DT layer inner roughness ~1μm

CH shell (3μm thick): 2.088mm ID, 2.094mm OD

DT layer (211μm thick): 1.666mm ID, 2.088mm OD

Au Cone: 20μm wall thickness, 5μm tip wall, 20°-30° half angle

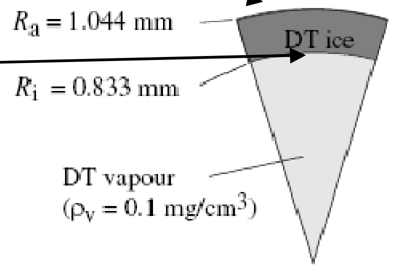
Cone to shell centre separation: 100-150μm

Fuel mass: ~0.6mg

Temperature: 16-19.6K

CH shell outer roughness ~50nm

DT layer inner roughness ~1μm



HiPER Design

A series of Sponsor Requirements have been issued for HiPER shot demonstrations:

- The most demanding is running in “Burst mode” at 5Hz for 100 shots with the first and last shots being high gain DT and those in between not burning (for example HDT).

- This series poses a range of challenges for Targetry.

In continuous operation at 6Hz one **IFE reactor** would require:

518 400 fuel capsules per day

189 345 600 fuel capsules per year

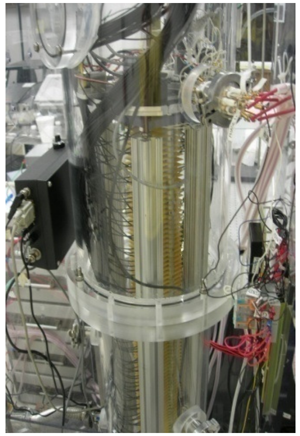
It is essential to remember that any technologies used for HiPER may need to be scaled up to meet IFE production numbers.

GA: Target injection, tracking and engagement

- Apply direct drive injection techniques to HiPER
  - Spherical targets (shock-ignition)
  - Gas gun, mechanical, coil gun, electro-static accelerator
- Develop injector for cone and shell FI targets
  - Prime concepts: Gas gun, and induction accelerator with sabots
- Apply developments in in-flight steering to improve placement accuracy
  - Potential for HiPER to not need beam steering for burst mode
    - 10 µm placement demonstrated at low velocity and 0.5 m stand-off
  - May be possible for burst mode (short stand-off, modest number of shots)

*From HAPL and FTF programs and in collaboration with UCSD

Gas Gun*

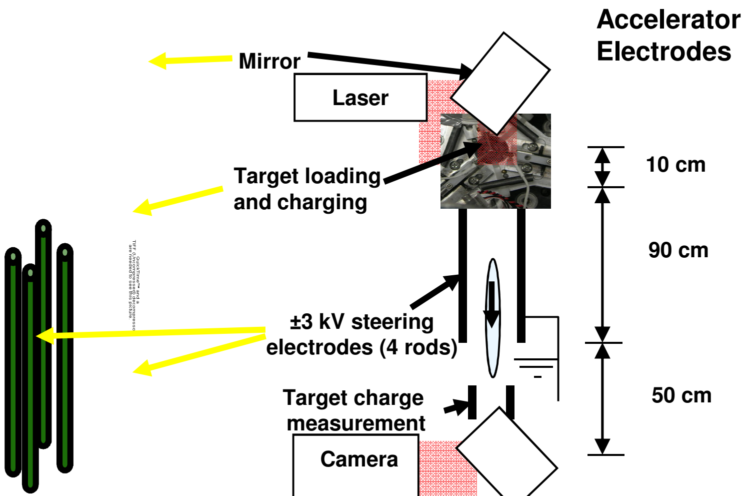


Electrostatic Accelerator*

Demonstrated

Gas Gun: ≥400m/s, 10 mm accuracy at 17m

Mechanical: ≥75m/s, 4mm accuracy at 17m

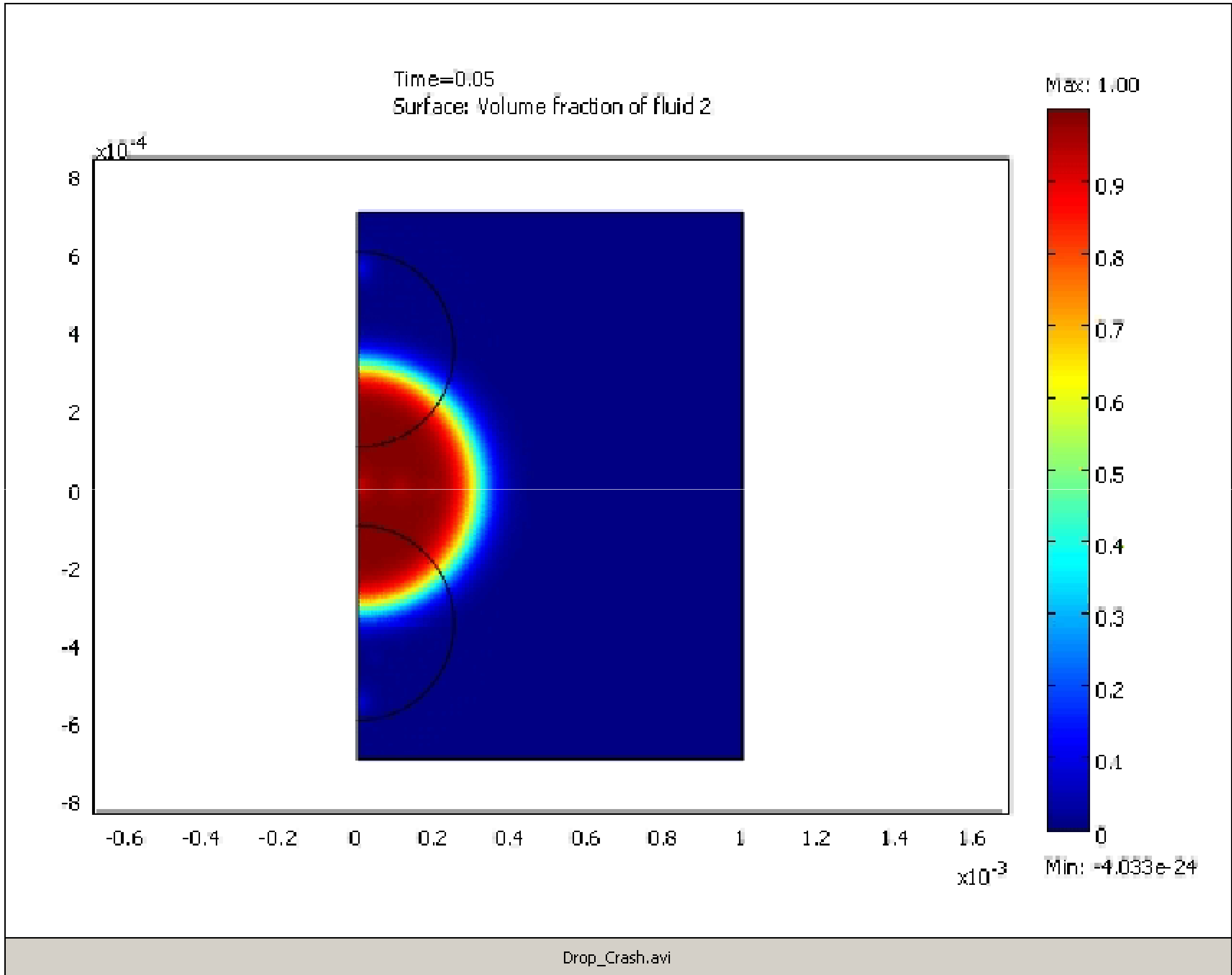


In-Flight Target Steering Demo*

Alternative Techniques: Colliding Droplets

- Colliding droplet technology suggested as alternative technique for microtarget production
- Initial modelling (Gabriel Schaumann) showed promise
- Collaboration with Yannis Hardalupas at IC {See, for example, Hardalupas,Y., Whitelaw,J.H., Interaction between sprays from multiple coaxial airblast atomizers, Transactions of the ASME Journal of Fluids Engineering, 1996, Vol: 118, Pages: 762 - 771, ISSN: 0098-2202}
- Hardware being built at RAL (Chris Spindloe)

Colliding Droplets - Modelling



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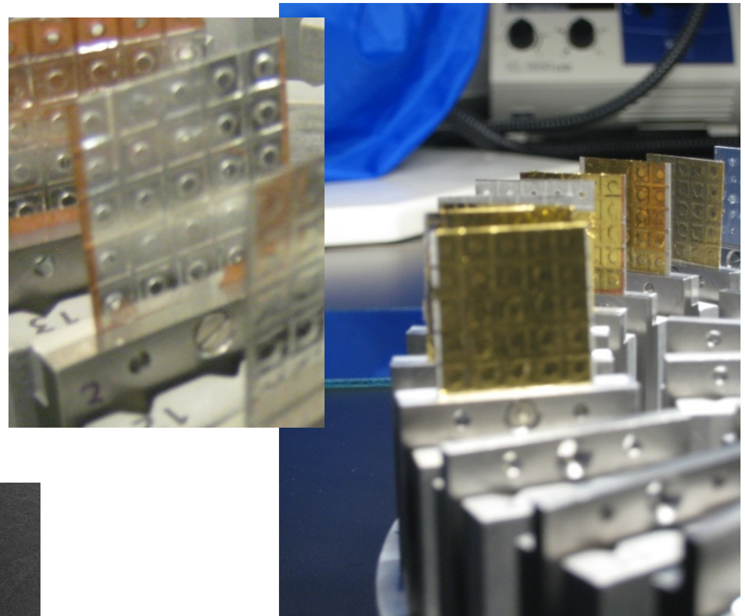
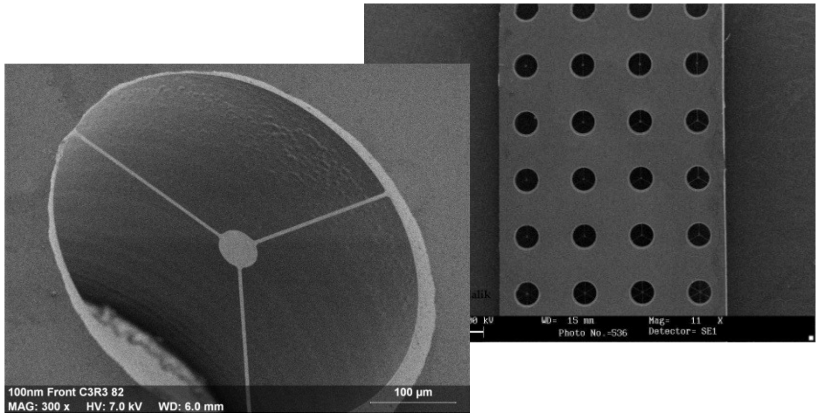
LIBRA-Gemini Expt: High Rep Rate

Foil Array Targets: Flexible, rapid delivery of target arrays at a low cost planar targets limited by size and complexity



MEMS Produced Targets:
2-D targets. High cost,
long lead-time items.



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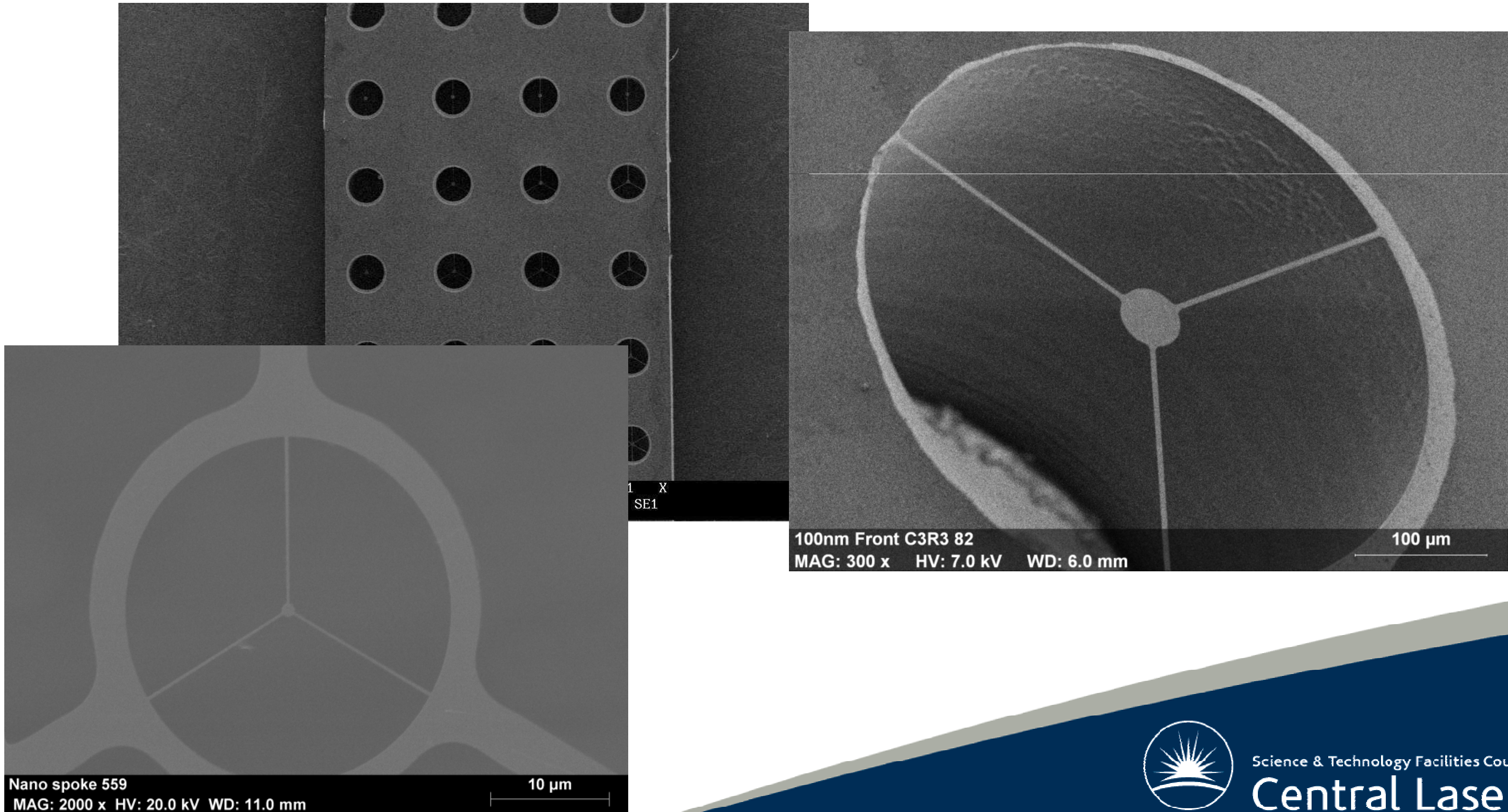
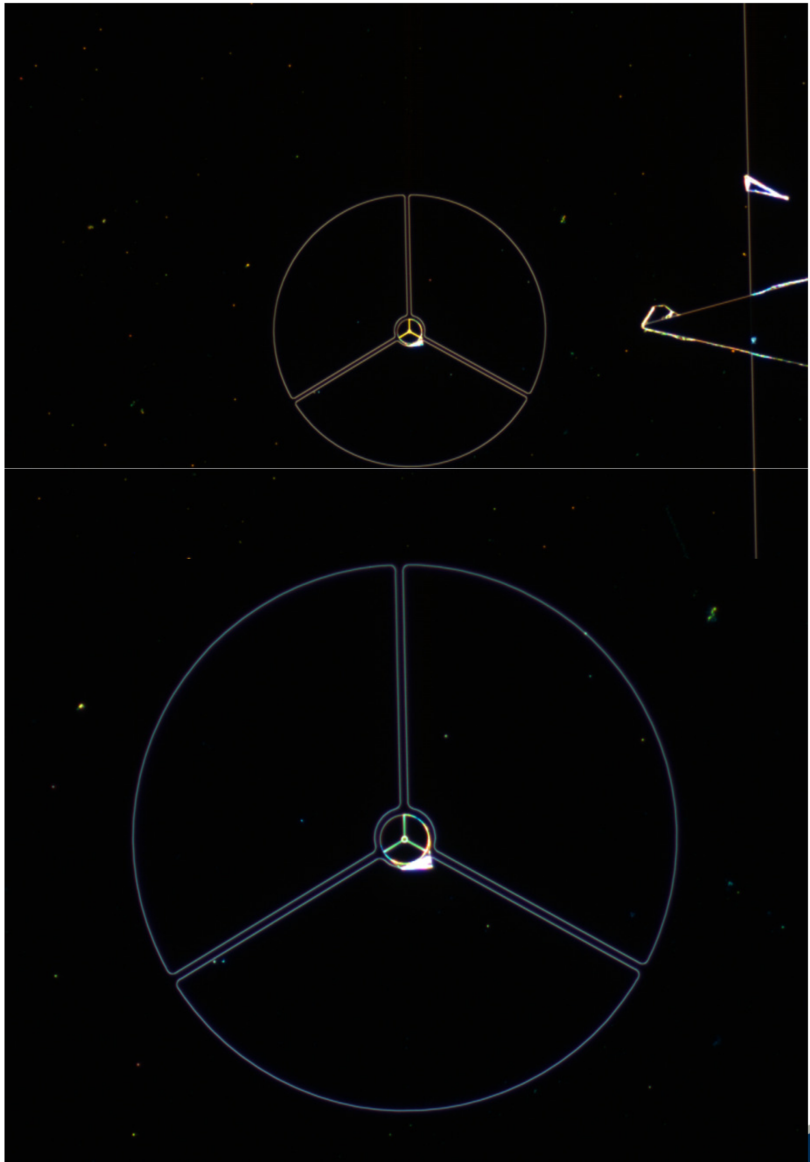
MEMS Manufacture

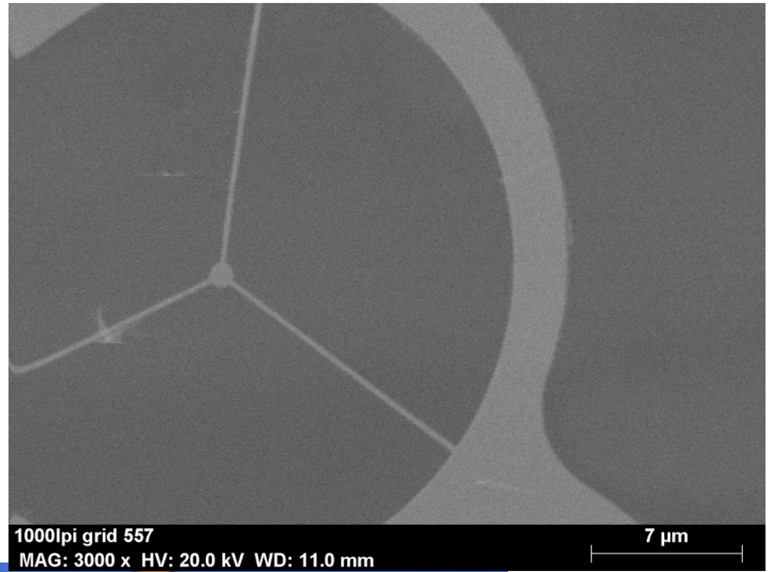
Ultra-thin membrane targets – 32um diameter, 40nm thick SiN membranes supported on 1µm wide, 40nm thick arms over hole etched through 400µm thick silicon. {See C Strangio et al., Production of multi-MeV per nucleon ions in the Controlled Amount of Matter mode (CAM by using causally isolated targets, Proc 29th ECLIM, 2006}

Nano Targets – 32um outer diameter, inner target 1um diameter.



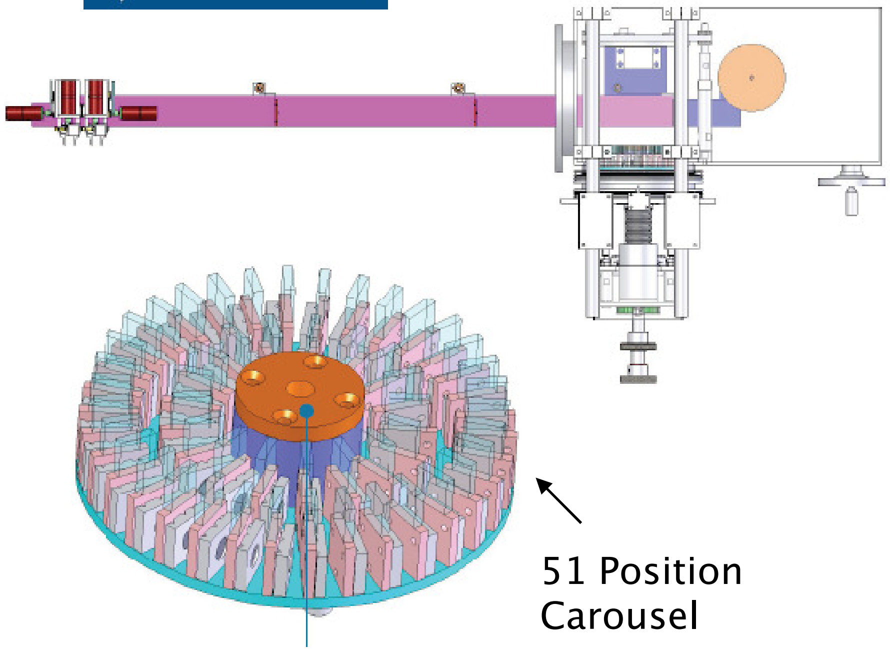
Silicon Nitride Nanospoke Targets

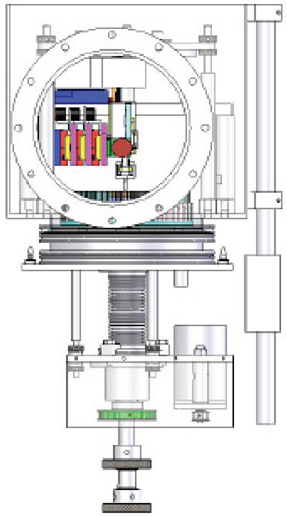


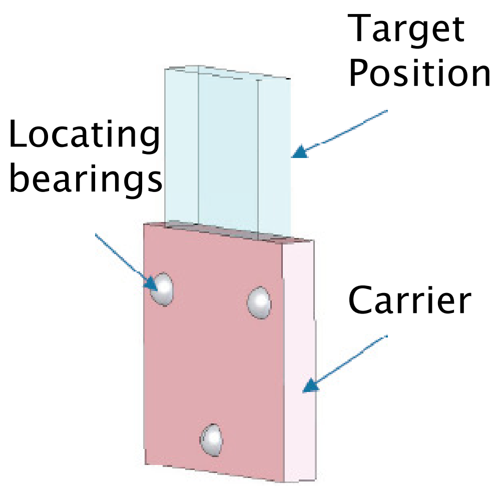


Target Inserter

GENERAL ATOMICS







Telescopic cable reel arm with gripper to position target holder. Targets stored and picked from a carousel with 51 positions.

Hexapod on target positioner and metrology station

Quality Control

Acceptable failure levels in Targetry for **industrial** applications.

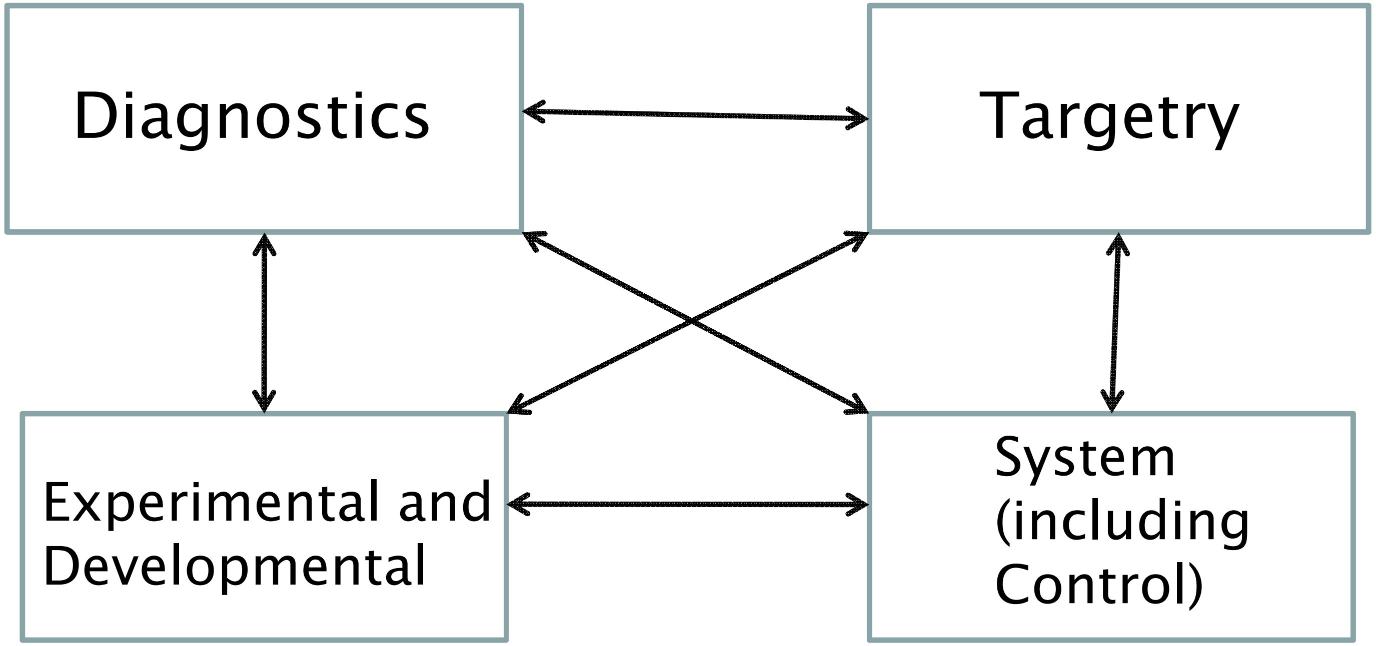
- 4σ (0.62% defective)?

Acceptable failure levels in Targetry for **medical** applications.

- 6σ (0.00034% defective)?

Stating the Obvious

Laser-Driven Applications and Systems



Introduce standards ?
ISO9001 ??

Impact of Diagnostics on Targetry

(1) Optimisation of Target production and placement (to ensure system delivery).

(2) Embedded within Control Loop to maintain system in optimised state.

Summary

For future laser-driven systems/applications microtarget production and characterisation techniques will have to be very different from current techniques largely because of much higher repetition rates.

Much more automation will be required.

Major impact of diagnostics on Targetry will be (1) Targetry optimisation, (2) in control loop.