LASER BEES

A Concept for Asteroid Deflection & Hazard Mitigation

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frontier research on visionary space systems

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CONTENTS

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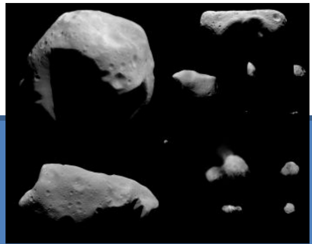
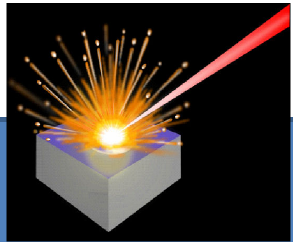
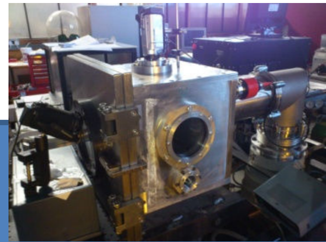


Asteroids Risk



Laser Ablation

Modelling Technique



Experiment

Results & Conclusion

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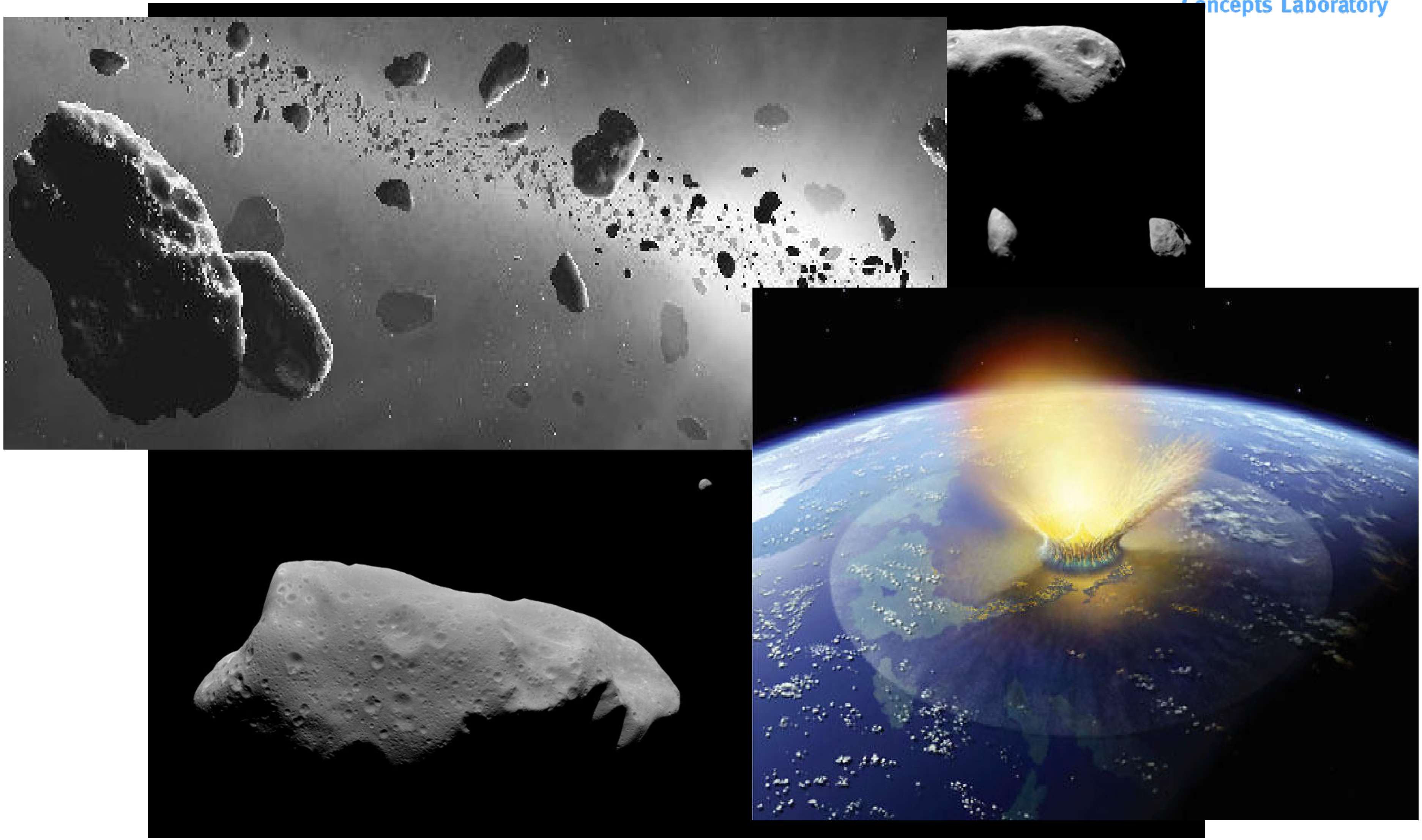
ASTEROIDS



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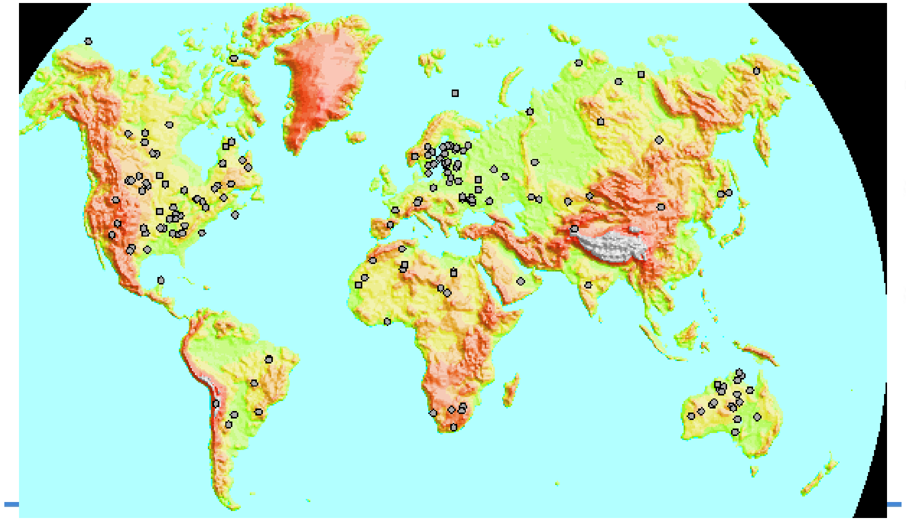
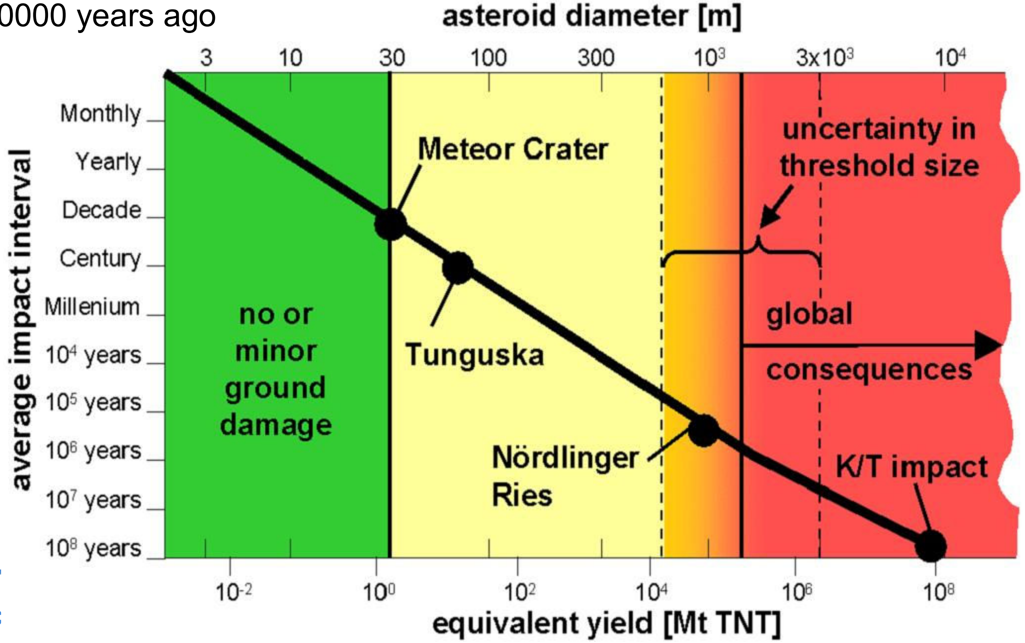
[Alvarz L et al, 1980]

ASTEROIDS

- Asteroid 99942 Apophis, non-negligible impact risk, 2039
- Asteroid YU55 passes in-between the Earth's-Moon orbit, 2011
- Asteroid 2002 MN missed the Earth by only 120000 km, 2002
- Ground Impact, New Guinea, 1994
- Ground Impact, Grand Teton Park, USA, 1972
- Ground Impact, Pribram, Czechoslovakia, 1959
- Ground Impact, Sikhote-Alin, Russia, 1947
- Ground Impact, Curaca Crater, Brazil 1930
- Air Impact, Tunguska, Russia 1908
- Ground impact, Arizona, Barringer Meteorite Crater, 50000 years ago





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DEFLECTION METHODS

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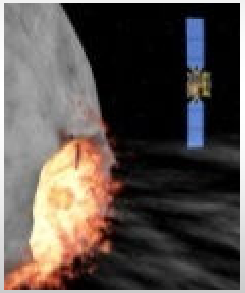
Methods of asteroid mitigation and deflection have therefore been addressed by numerous authors [Melosh, 1994; Conway 2001, Gritznes & Kahle 2004 Sanchez, Vasile et al, 2009; Yeomans, Bhaskaran et al 2009*;* Love 2005; Scheeres & Schweickart, 2004]

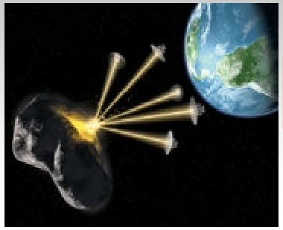


Kinematic Impactor(s)

Nuclear Blast

Impulsive Methods

Low Thrust Methods

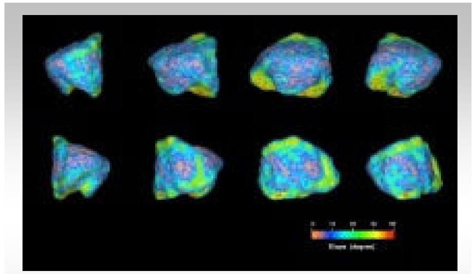


Mass Drivers

Surface Ablation

Low Thrust propulsion

Gravity Tractor(s)



Paint & the Yarkovsky Effect

Passive Methods

The overall performance depends on how the deflection method interacts with the asteroid, the response time, the mission complexity and the technology readiness

WHY SURFACE ABLATION?

Analysis from a multi-criteria quantitative comparison [Sanchez at al, 2009]

Compared kinematic impactor, nuclear detonation, mass drivers, low thrust tug, ablation and the gravity tractor

Relative to the miss distance at Earth, the warning time, the total mass into orbit and the technology readiness levels

Ablation was shown to be, theoretically, a promising technique

No fragmentation of the asteroid

No need to physically attach and/or land on the surface

Energy source is freely available and external from the Sun

Ablated material is the asteroid itself

A high rate of controllable deflection can be achieved.

Both with a relatively low mass into space and a short warning time

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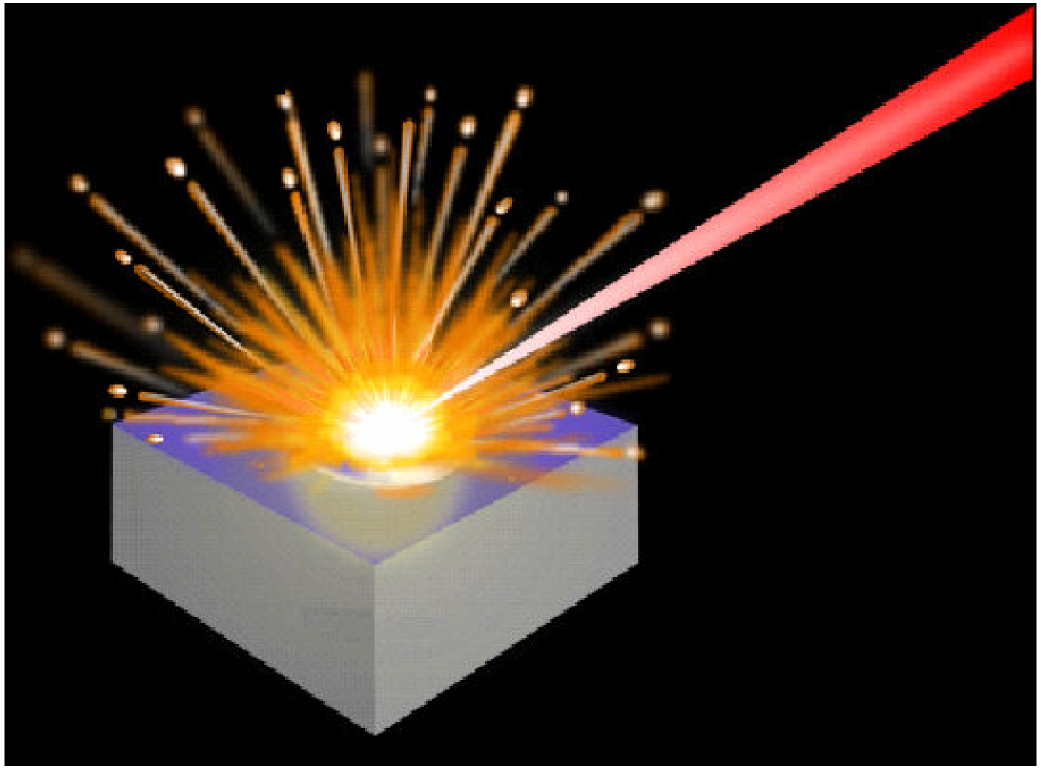
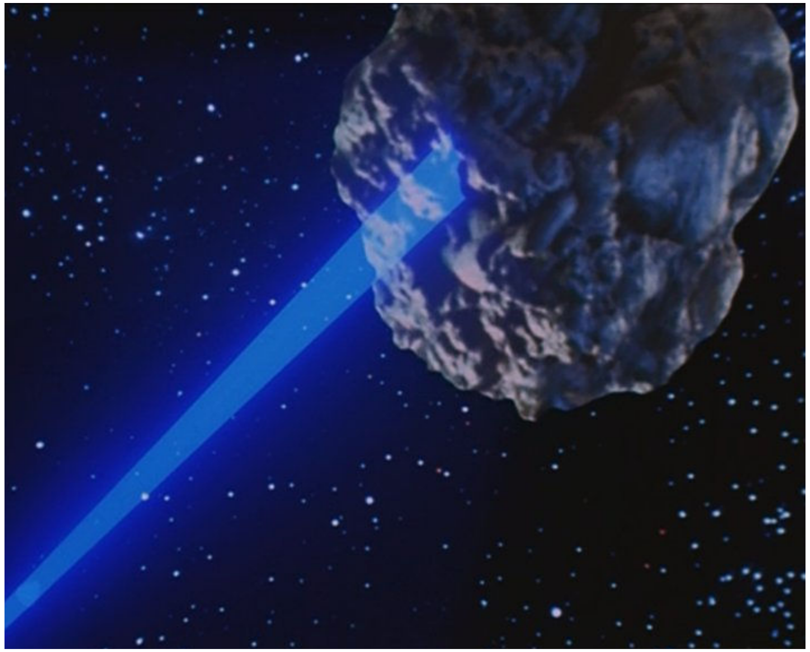
ABLATION

Ablation is achieved by irradiating the surface by light – direct solar radiation or laser – source . The resulting heat sublimates the surface, transforming it directly from a solid to a gas.





An ejecta cloud of the ablated material forms. This acts against the asteroid, providing a continually controlled low thrust

ABLATION, PREVIOUS WORK

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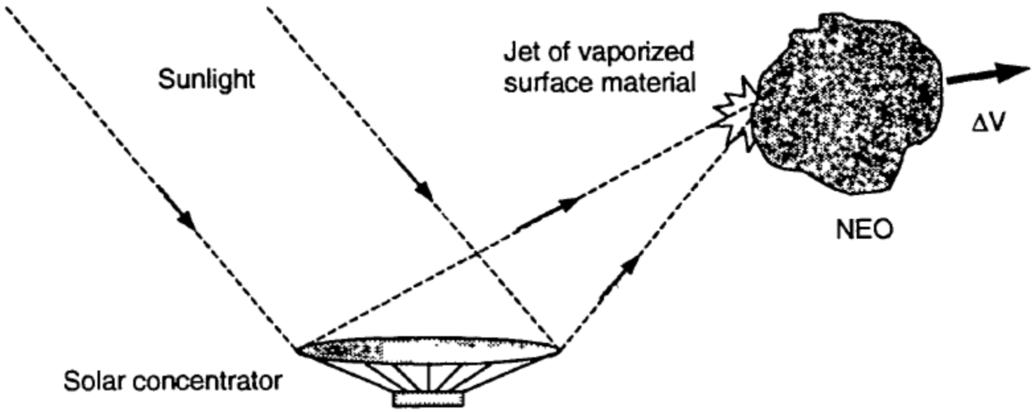
1. Melosh & Nemchomov, 1993, 1994

A large, single mirror – solar concentrator - mounted onto a single spacecraft

To collect, direct and concentrate solar light onto a small area of the asteroid



Technique requires a 1~10 km diameter mirror; Significant space structure

Becomes susceptible to the deposition of ejecta

Operates in close proximity to the asteroid, under an irregular gravity field

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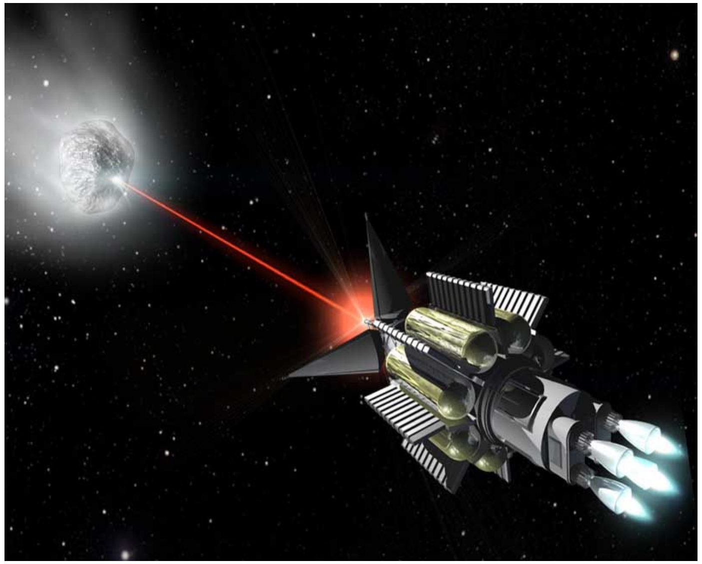
ABLATION, PREVIOUS WORK

<u>2. Campbell, Phipps et al, 1992, 1997; Park & Mazanek, 2005</u>

Sublimate the asteroid with a high power, mega watt, laser

Powered by a nuclear rector



Develop a large nuclear reactor for space applications

Significant legal ramifications of operating a nuclear reactor in space

Difficulties of manoeuvring and operating large structure

ABLATION, PREVIOUS WORK

ALTERNATIVE METHOD: [Vasile & Maddock, 2009, 2010; Sanchez, 2009]

- Fractionate the monolithic spacecraft into a number of identical units
- Swarm of small scale spacecraft, flying in formation about the asteroid
- Each equipped with a small solar concentrator [known as Mirror Bees]

Each spacecraft simultaneously collects and focuses solar radiation directly onto the asteroid's surface

By superimposing their light beams the required surface power density can be achieved, successfully ablating a small portion of the asteroid's surface

Swarm configuration is taken to be:

- A lighter, more adaptable concept
- Increased redundancy by design
- Scaleable

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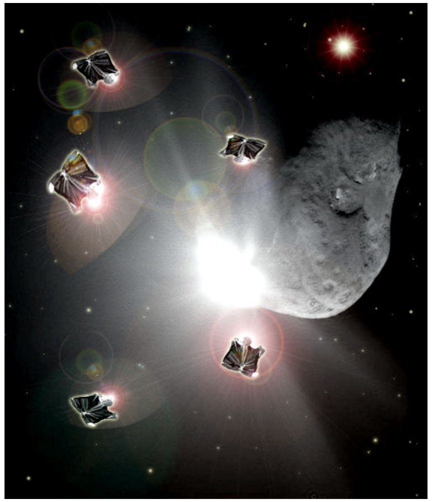
ABLATION, PREVIOUS WORK



However each MIRROR BEE spacecraft still needs to be placed in close proximity to the asteroid

Technique is highly susceptible to the deposition and contamination of the ablated ejecta.

To increase the distance between the asteroid and spacecraft (~1 to 4 km)

- Use a swarm of spacecraft
- Each equipped with a small solar collector and a laser
- A collimated laser beam can propagate over extended distance, without the loss of energy

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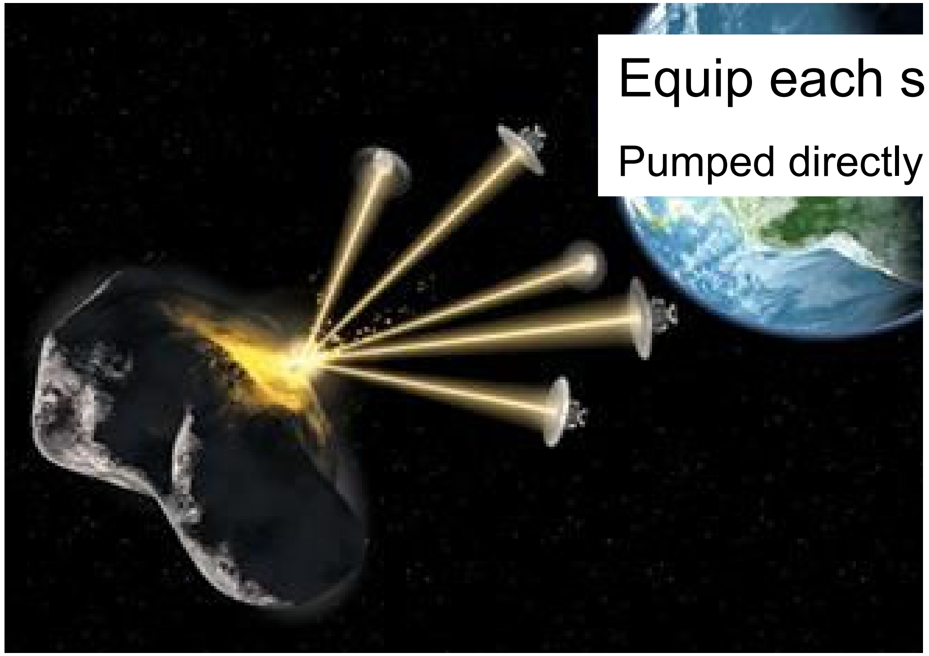
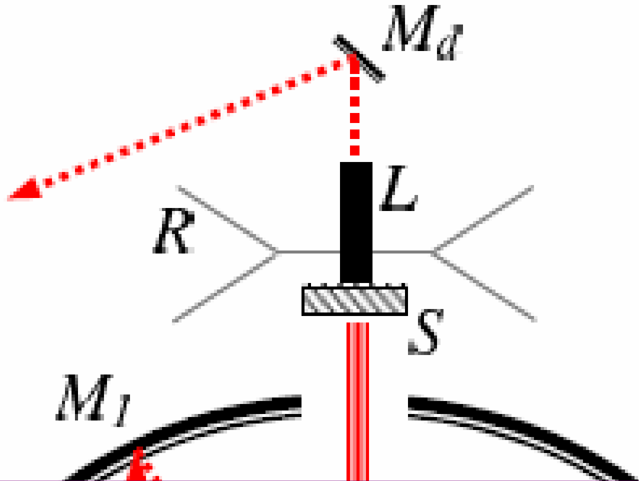
LASER BEES



Equip each spacecraft with a identical kilo-watt laser

Pumped directly or in-directly from the Sun (via solar concentrators)



However, within the vicinity of the ejecta plume, any exposed surface(s) will be subjected to the contaminating effects of the condensing ejecta

M_d – Steering Mirror

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LASER BEES, OPEN QUESTION

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- **Physical formation and evolution of the ejecta plume**
  1. Is it similar to the formation of the rocket exhaust in rocket propulsion?
  2. Is there uniform dispersion of the ejecta over the given hemisphere?
  3. Is a constrained plume of ejecta more plausible?
  4. What particles are contained within the ejecta?
     A. Only hot gas? Any solid particles?
- **Ablation response for different material**
  1. What is the difference between dense and porous material?
- **Sensitivity of contamination and degradation of the ejecta**
  1. What is the actual degradation rates of the exposed surface? $f(r, \theta)$
  2. What are the physical properties of the condensed material?
  3. Does all the ejected material immediately stick?
  4. Is there any attenuation of the laser beam?

Can we ensure the maximum survivability of the system to maximise the achievable deflection of the technique ?

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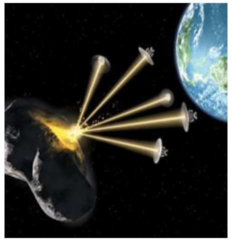
ABLATION EXPERIMENTS



A series of laser ablation experiments using a 90 W continuous-wave laser has been performed

Investigate the development of the ejecta plume – mass flow rate, velocity and divergence – and the potential for contamination.

Calibrate and validate the development of numerical models and existing theory

[Vasile & Maddock, 2010; Sanchez et al, 2009]

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MODELLING TECHNIQUE

Current assumptions in the numerical method must be verified

Ejecta depends on the available energy & efficiency of the ablation process

[Vasile & Maddock, 2010; Phipps 2010; Sanchez, 2009; Kahle 2006]

Plume profile is similar to a rocket exhaust

Standard methods of rocket propulsion

Uniformly expanded gas of ejecta; No solid particles

No ionization of the gas; Constant scatter factor

Assumed a spherical, dense, homogenous body

Forsterite (Mg2Si04) is typically used

Asteroid has an infinite heat sink

Constant internal temperature during sublimation

Ejected particles will immediately condense and stick

Assumptions on the degradation and attenuation

MODELLING TECHNIQUE

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The sublimation process is modelled on the energy balance equations [Vasile & Maddock, 2009, 2010; Sanchez, 2009]

Combines the absorption of the laser beam P_{IN}, the heat losses of conduction Q_{COND} and radiation Q_{RAD} respectively and the sublimation enthalpy of the target material E_v

$$\frac{dm}{dt} = \frac{1}{E_v}\left(P_{IN} - Q_{RAD} - Q_{COND}\right)$$

$$Q_{RAD} = \sigma_{SB}\varepsilon A_{SPOT}\left(T_{SUB}^4 - T_{amb}^4\right)$$

Assumes a black body

$$Q_{COND} = \left(T_{SUB} - T_0\right)A_{SPOT}\sqrt{\frac{c_A\rho_A\kappa}{\pi t}}$$

Assumes an infinite heat sink

MODELLING TECHNIQUE

Average velocity of the gaseous ejecta is calculated from Maxwell's distribution
Assuming the behaviour of a ideal gas

$$\bar{v} = \sqrt{\frac{8kT_{sub}}{\pi M_a}}$$

Force and acceleration acting on the asteroid:

$$F_{SUB} = \boxed{\lambda} \bar{v} \dot{m}_{\exp}$$

$$a = \frac{F_{SUB}}{M_A}$$

Assumes a constant scatter factor

Account for the dispersion of the ejecta plume

Considered to distribute uniformly over a half sphere

Conservative assumption

MODELLING TECHNIQUE

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Density of the ejecta plume

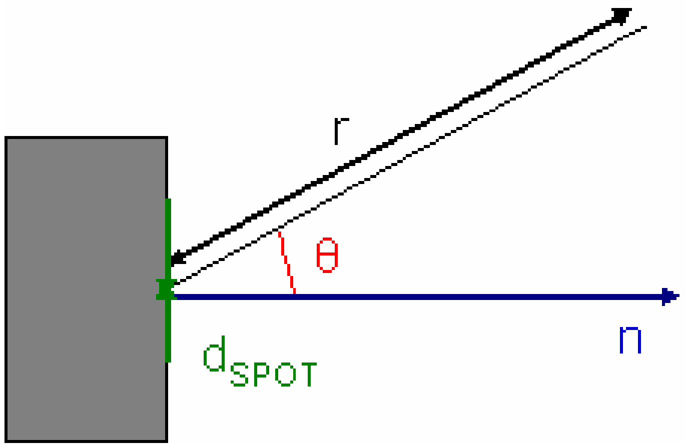
Function of distance, *r*, from the spot and angle, *θ*, from the centre line

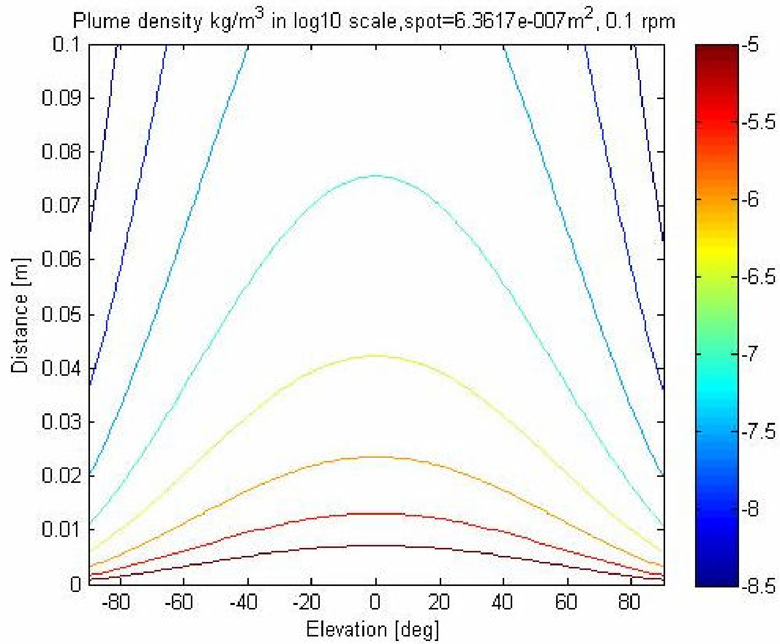
[Kahle et al, 2006]

$$\rho(r,\theta) = \rho^* A_P \frac{d_{SPOT}^2}{\left(2r + d_{SPOT}^2\right)^2}\left[\cos\left(\frac{\pi\theta}{2\theta_{MAX}}\right)\right]^{\frac{2}{k-1}}$$

Density at the nozzle:

$$\rho^* = \frac{\dot{m}_{\exp}}{A_{SPOT}\,\bar{v}}$$





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MODELLING TECHNIQUE

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Contamination and degradation [Kahle et al, 2006]

Will occur to any exposed surface located within the ejecta volume

Assumed that all particles – gas – will re-condense and stick

Variation in ejecta thickness – surface growth - is given by:

$$\frac{dh}{dt} = \frac{2\bar{v}\rho}{\rho_{layer}} \cos(\psi_{vf})$$

ψ_{vf} is the view angle
ρ – Density of the ejecta
ρ_{layer} - Layer density. This is assumed to be 1000 kg/m^3
η - Absorption coefficient (silica, at 800 nm, ~ 10^6/m)

The degradation factor, τ,
Beer-Lambert-Bougier law

$$\tau = e^{-2\eta h_{END}}$$

MISSION CASE

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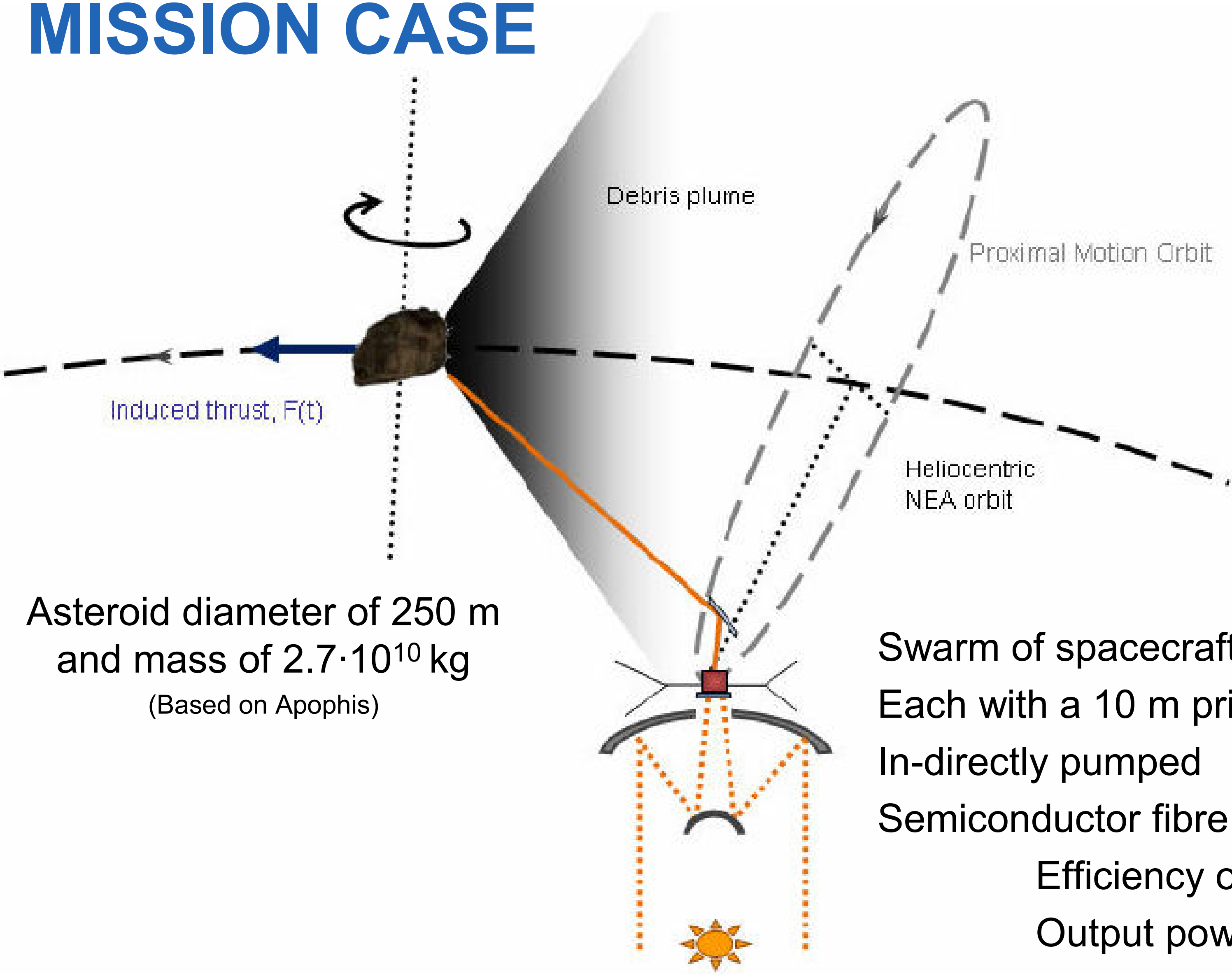

Asteroid diameter of 250 m
and mass of $2.7 \cdot 10^{10}$ kg
(Based on Apophis)

Swarm of spacecraft
Each with a 10 m primary concentrator
In-directly pumped
Semiconductor fibre laser,
Efficiency of 60 %
Output power 22 kW

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MISSION CASE

Not accounting for degradation

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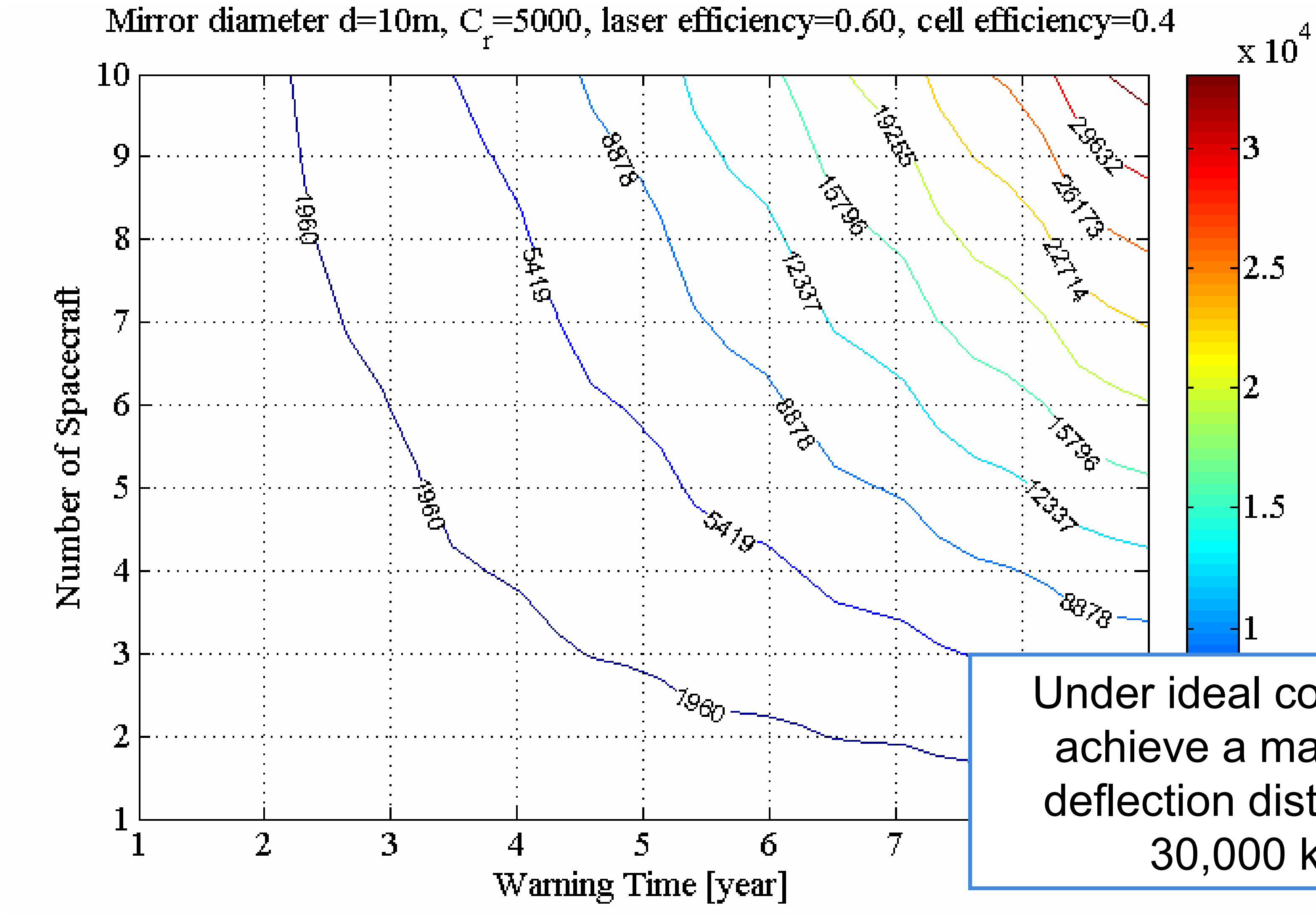

Under ideal conditions achieve a maximum deflection distance of 30,000 km

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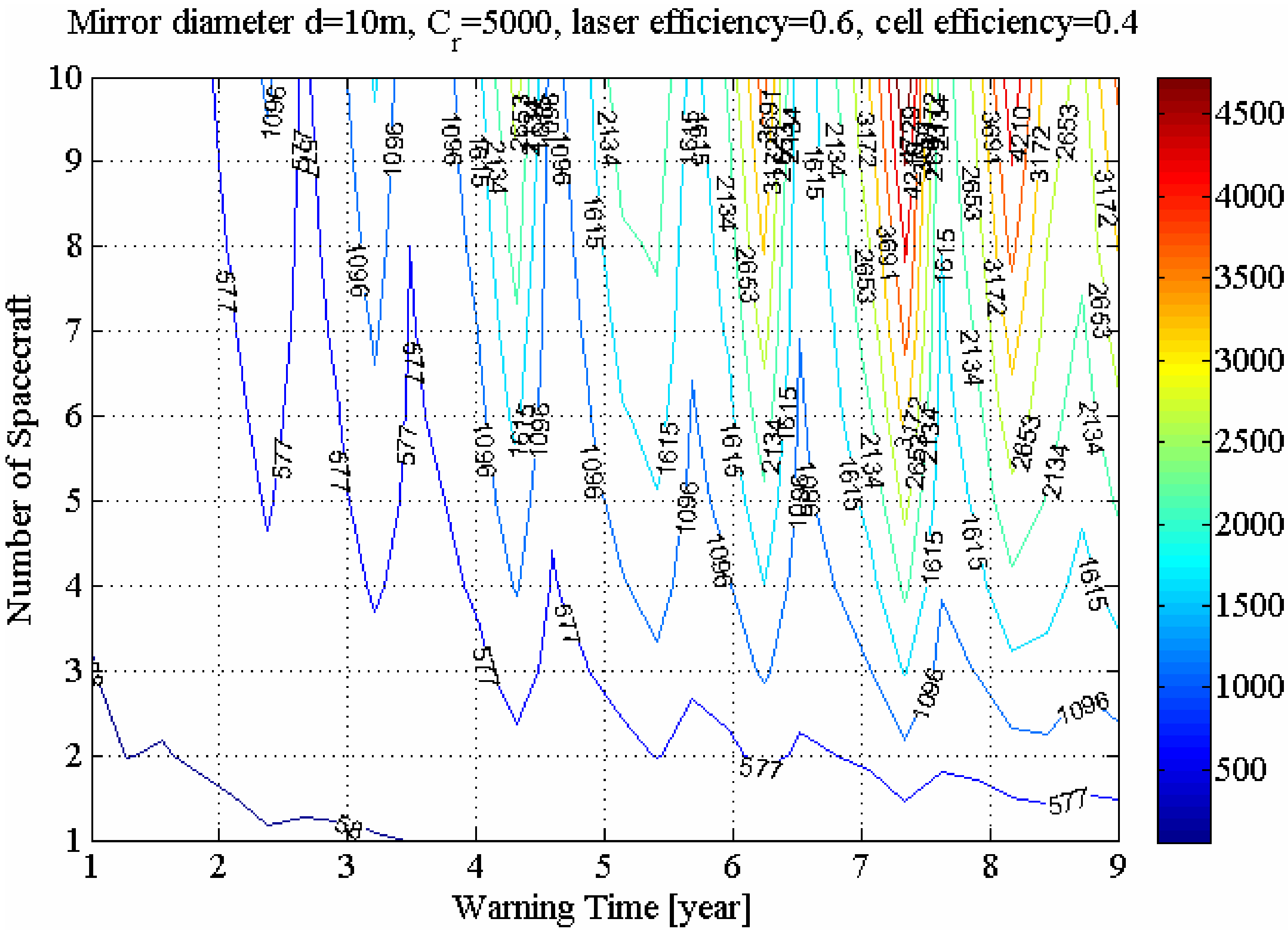
MISSION CASE

Assuming the parameters, given in Kahle

Condensed ejecta density of 1000 kg/m^3

Absorbitivity of 10^6 m^{-1}



Reduction in performance of 85 %

Almost immediate saturation of the exposed optics

Achievable miss distance reduces to 4500 km

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OBJECTIVES

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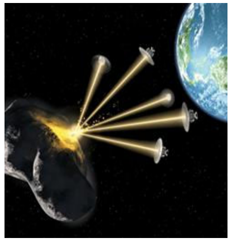

Performed a series of ablation experiments using a 90 W continuous-wave laser

Investigated the development of the ejecta plume – mass flow rate, velocity and divergence – and potential for contamination.

Calibrate and validate the development of numerical models and existing theory

[Vasile & Maddock, 2010; Sanchez et al, 2009]

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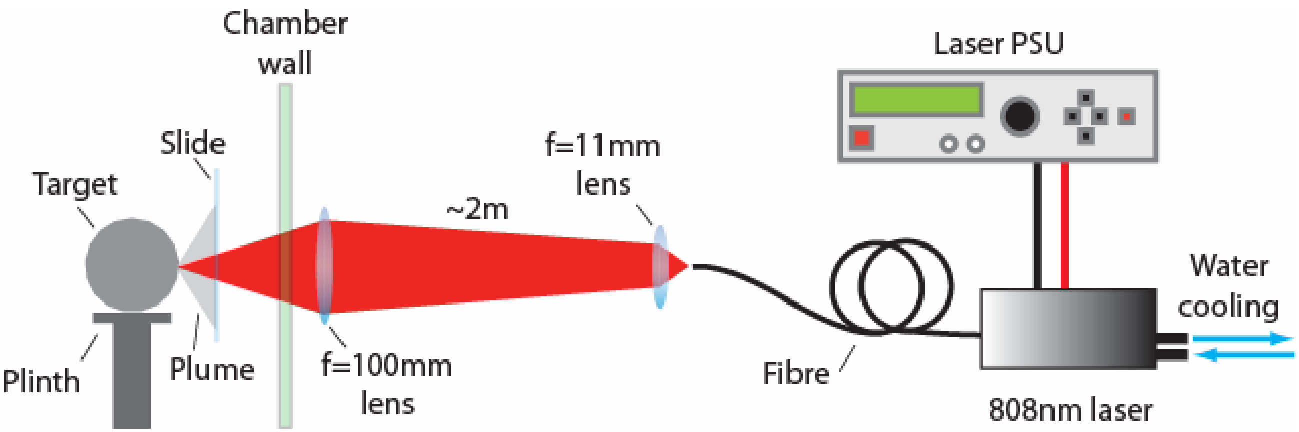
THE LASER

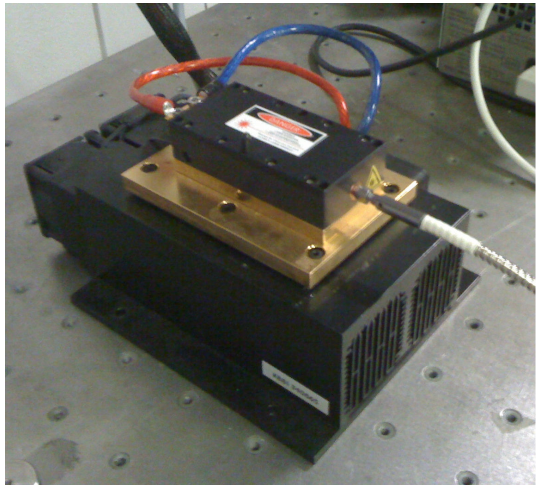
A 90 W continuous wave laser

(LIMO 90-F2000-DL808)

Fibre-coupled semiconductor

Operating at 808 nm





Horizontally mounted and cooled by a recirculation chiller at 15 ^{o}C

After focusing, it provided an approximate spot diameter of 0.5 mm

After losses provides 30 kW/cm^2, surface power density, at the focus

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EXPERIMENT SEQUENCE

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- Initial ablation experiments first occurred under a nitrogen purge environment
  - Transparent test chamber
  - Reduce the occurrence of atmospheric combustion to negligible levels. Any innate material combustion still occurred.
  - Tested and refined the proposed methodologies and techniques
    - Either measured, calculated or inferred quantities

- Developed and integrated the vacuum chamber system
  - Allowed for maximum expansion of the plume
  - Eliminating particle drag caused by an atmosphere

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THE EXPERIMENT

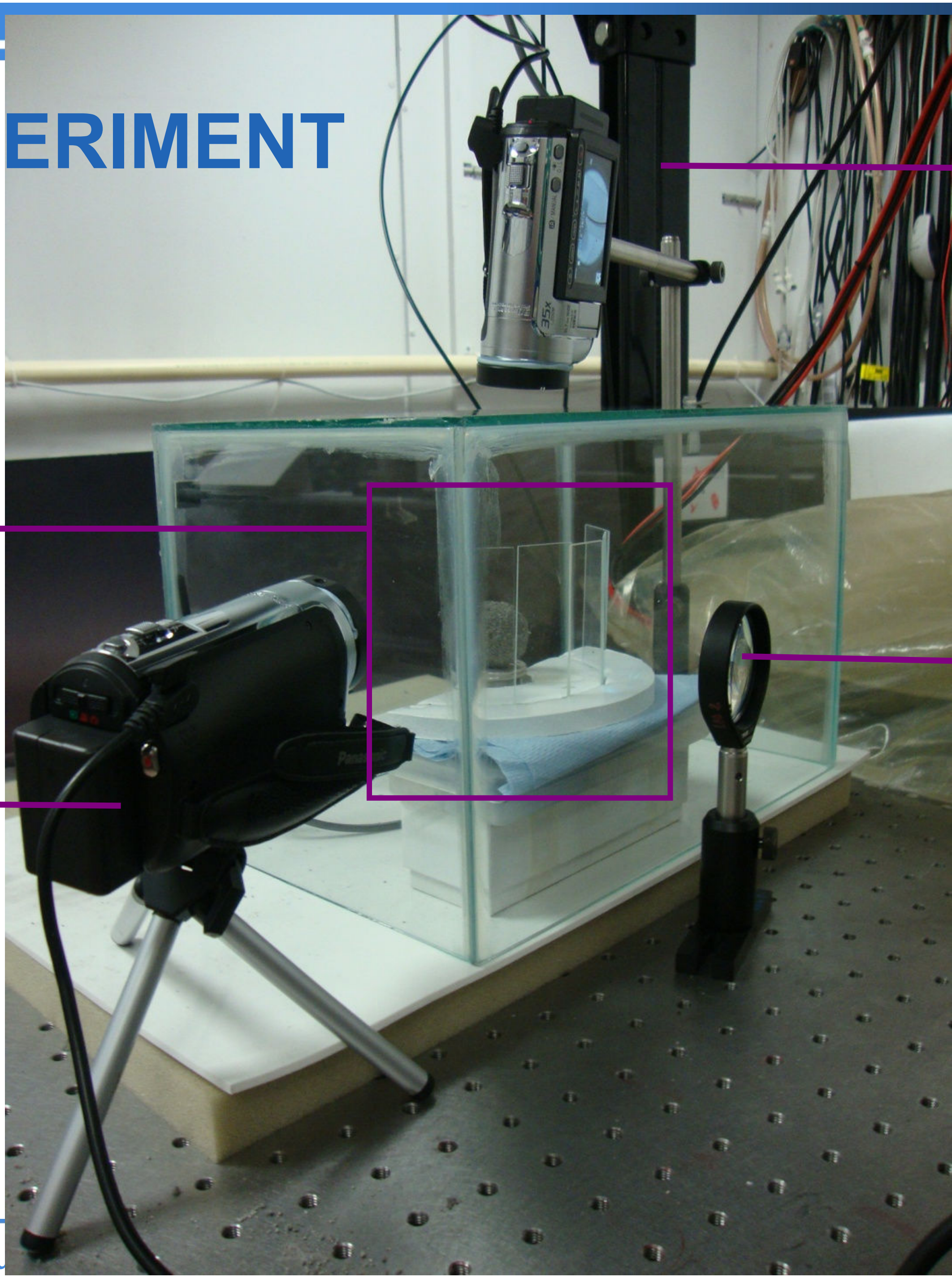
Ejecta is collected on microscope slides.

Measure the deposited mass of the ejecta

Measure the affect of contamination and degradation

High resolution cameras

Used a thermocouple **measure the temperature of the target material during ablation**



High resolution cameras

Measure the divergence and formation of the ejecta plume

Measure the ablation time

Focusing Optics

Laser off screen

Measured the mass of the target material before and after. Enabling the mass flow rate of ablation to be determined

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THE EXPERIMENT

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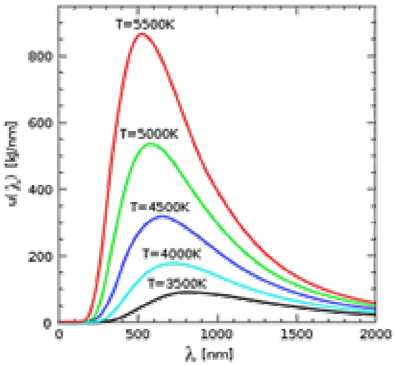


Used a spectrometer to **measure the spectra** – wavelength vs intensity - **of the ablated spot**

Temperature of the spot was then inferred from the Wein displacement law

$$\lambda_{PEAK} T_{SUB} = 2.898 * 10^{-3}$$

$$\bar{v} = \sqrt{\frac{8kT_{sub}}{\pi M_a}}$$

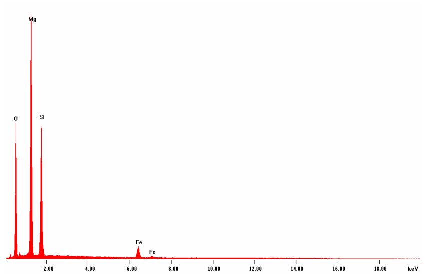
Used a microscope to **measure the height of the collected ejecta** on the slides and the **diameter of the ablated hole**

Measured the depth of the ablation hole

$$\eta_{EXP} = \frac{a_b}{h_{EXP}}$$

Measured the transmittance/absorption of the ablated slides

Calculated the absorbance per unit length, η, of the ejecta



Used a **Scanning Electron Microscope to study the composition of the plume**

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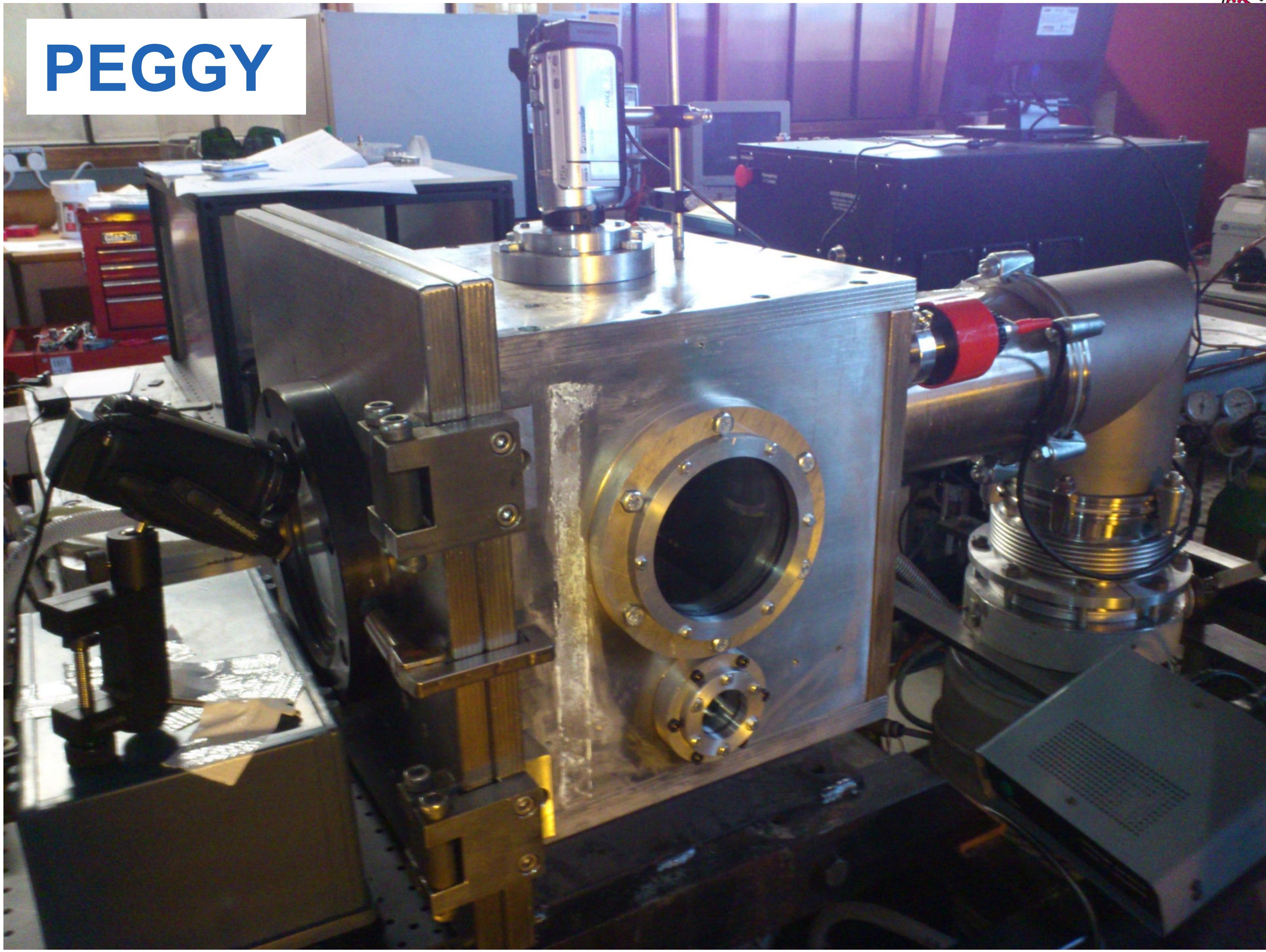
PEGGY



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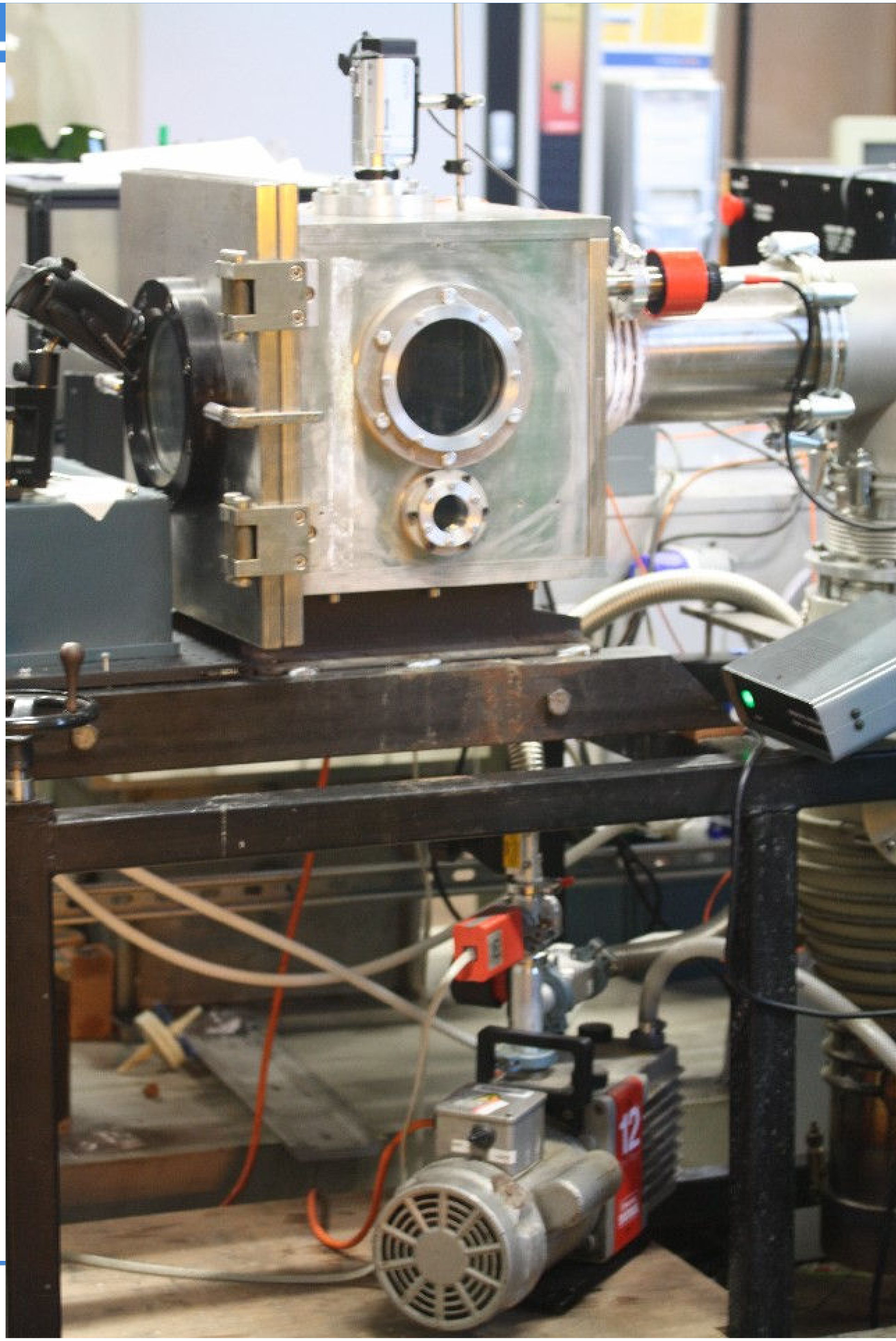

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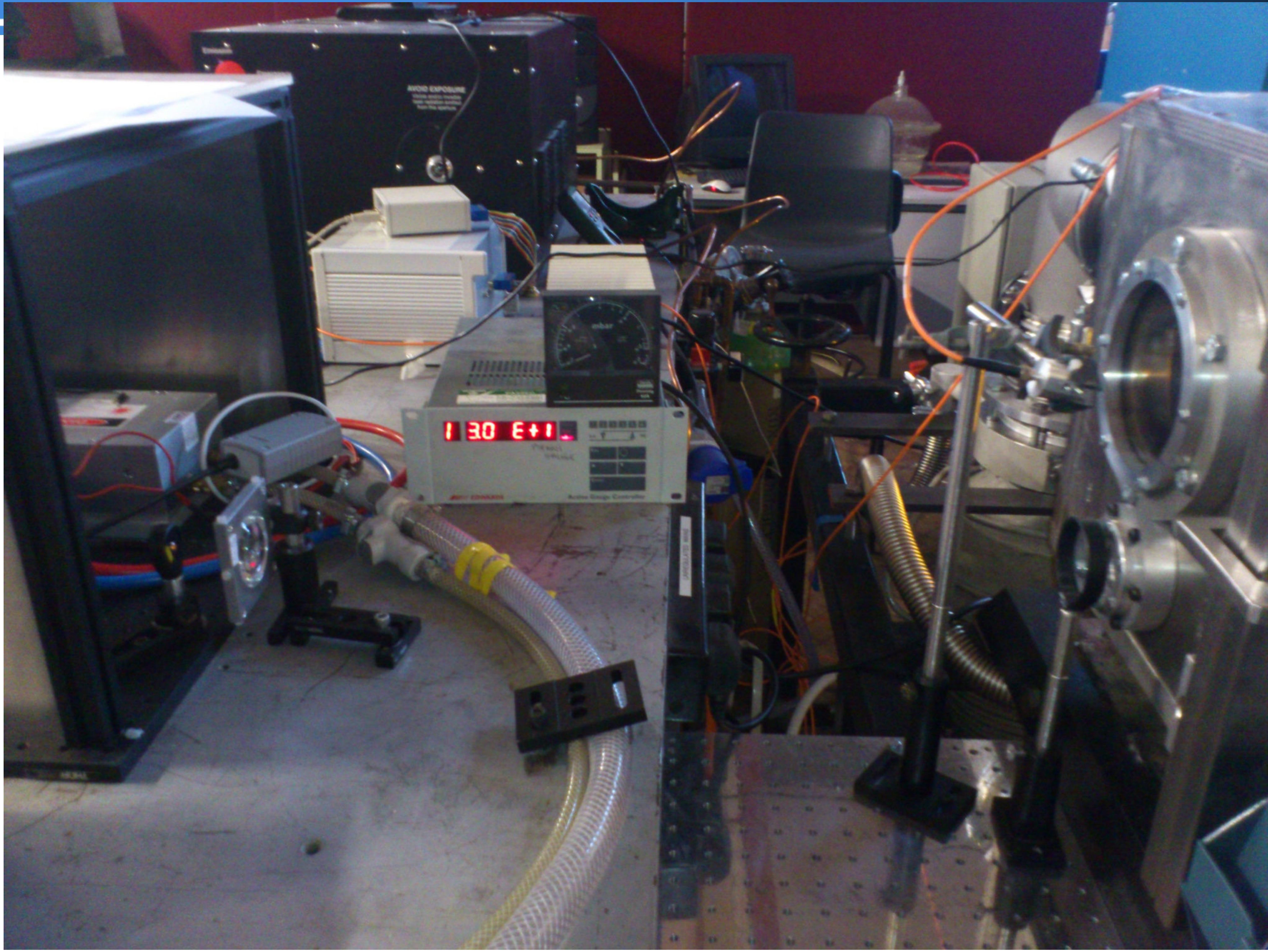

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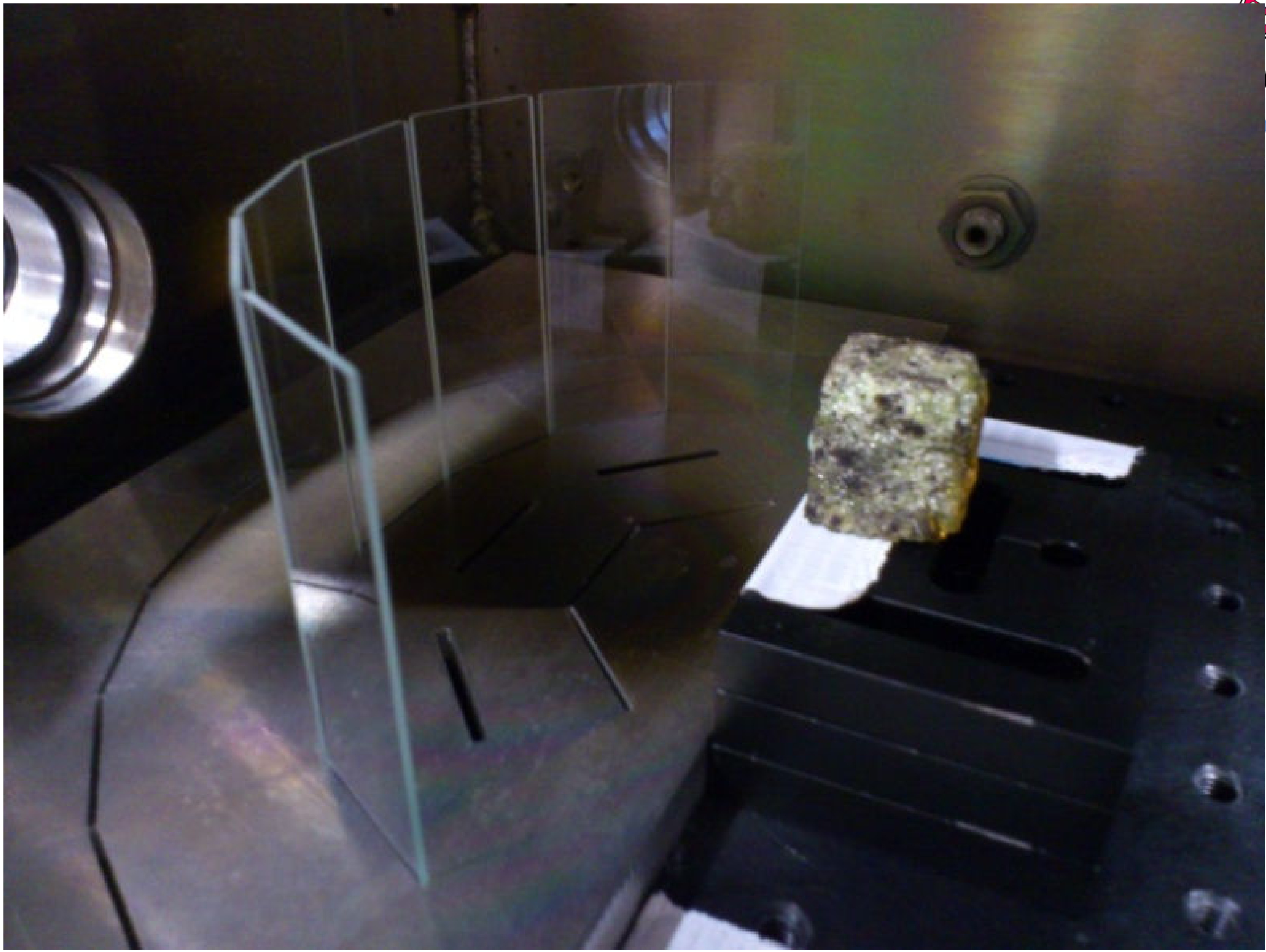

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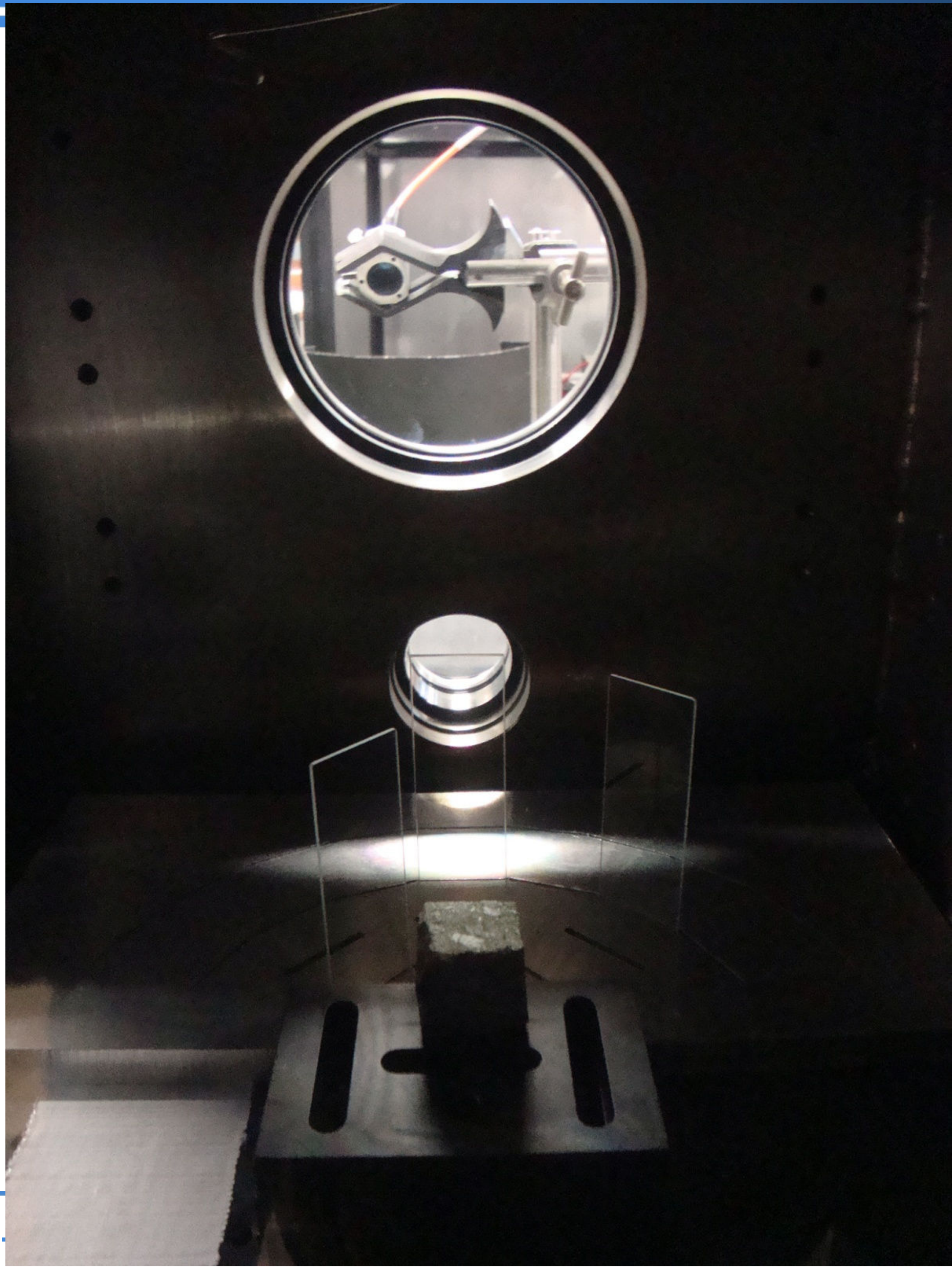

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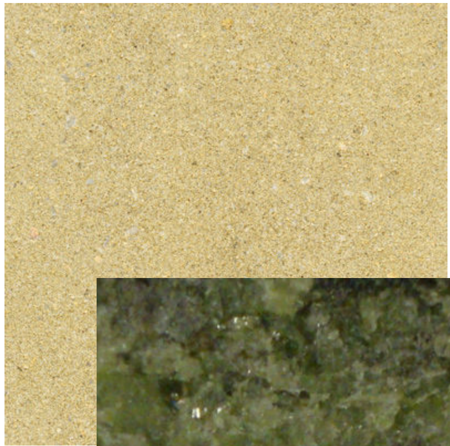
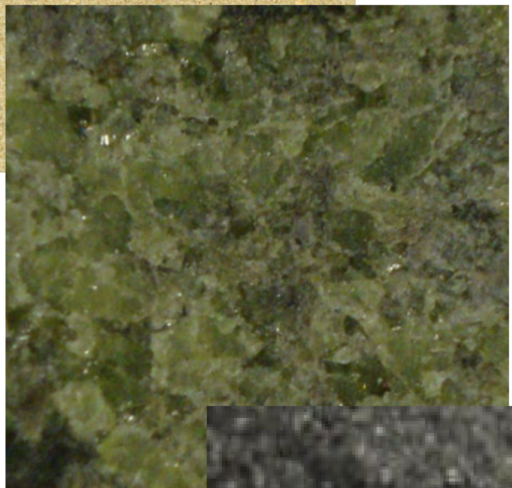
TARGET MATERIAL



Sandstone

Represent a rocky, dense asteroid

Bulk density: 2250-2670 kg/m^3



Olivine, magnesium iron silicate $(MgFe)_2SiO_4$

Represent a rocky, dense, S-type asteroid

Bulk density – 3500 kg/m^3

Fabricated a composite mixture

Represent a highly porous, rubble pile asteroid

Expanded perlite, sand, fly ash and water

Bulk density ~ 400 kg/m^3

Bulk porosity ~ 80 %

[Housen, 2004, Housen & Holsapple 2003]

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THE EXPERIMENT

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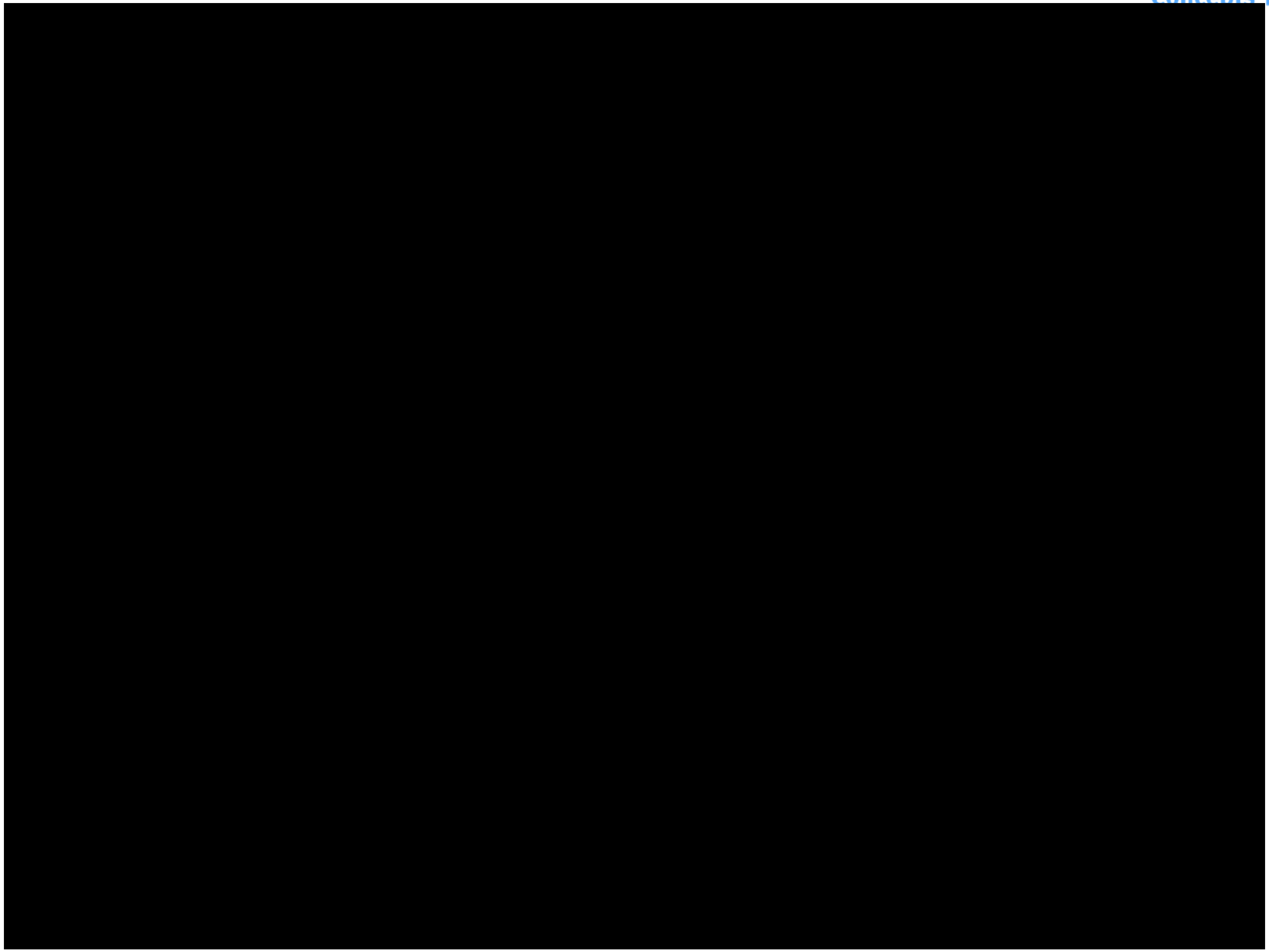

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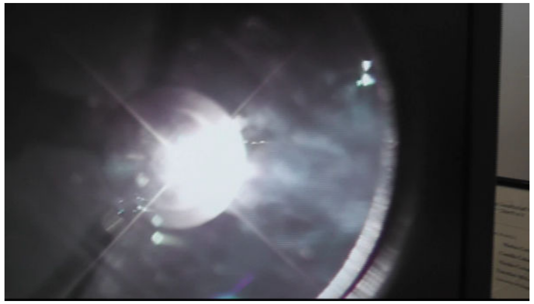
NITROGEN PURGE

Small, and extended rocket plume

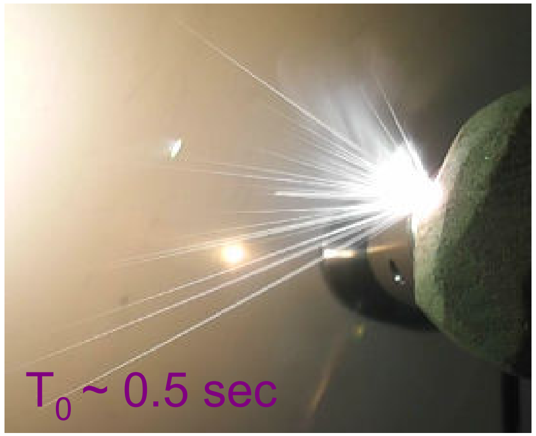
Similar mass flow rate, compared to the model

Variation in cone angle and ejecta distribution

- Ablation process included solid ejecta particles
- Subjected to the volumetric removal of material
- Resulted in the laser tunnelling into the subsurface
- Technique is sensitive to the focal point of the laser



Subjected to the structure and composition of the target material



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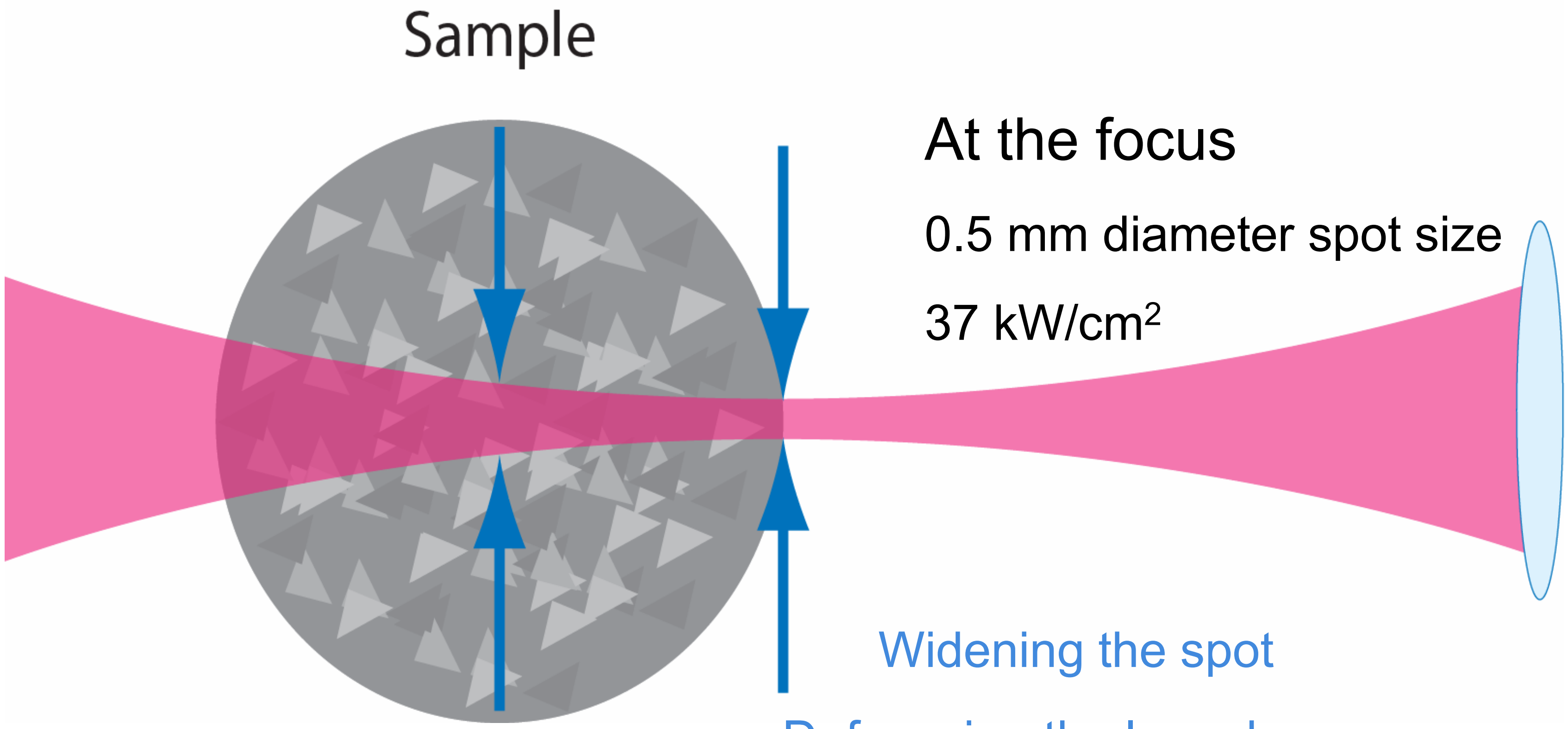
NITROGEN PURGE



At the focus

0.5 mm diameter spot size

37 kW/cm^2

Widening the spot

Defocusing the laser beam

5 mm behind the initial focus

2.4 mm diameter, spot size

1.98 kW/cm^2

Adaptive Optics

Collimated Beam

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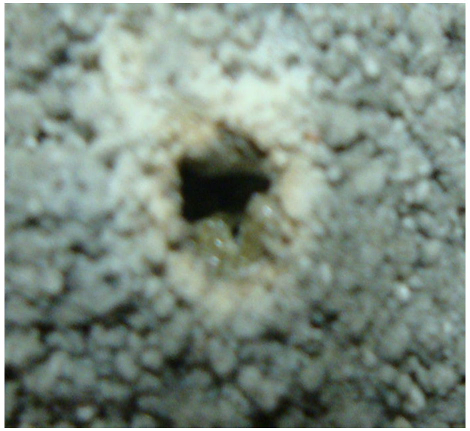
NITROGEN PURGE

Sandstone



Composite Porous

Local depositions in and around the ablation volume

- White residual was deposited around the ablation rim
- Within the ablation volume a semi-melted glassy material is created

These depositions do not contribute to the formation of the ejecta plume

Ablation hole was larger that the spot size diameter

- Original illumination 0.5 mm (assumed constant in model)
  - Sandstone – 1.83 mm
  - Porous – 2 mm

Volumetric heating of the target material

- Leads to increased ablation for a lower energy input

No observable attenuation of the laser beam

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VACUUM

Small & extended rocket plume. Little ejecta

At 3, 7 and 10 cm away from the spot:

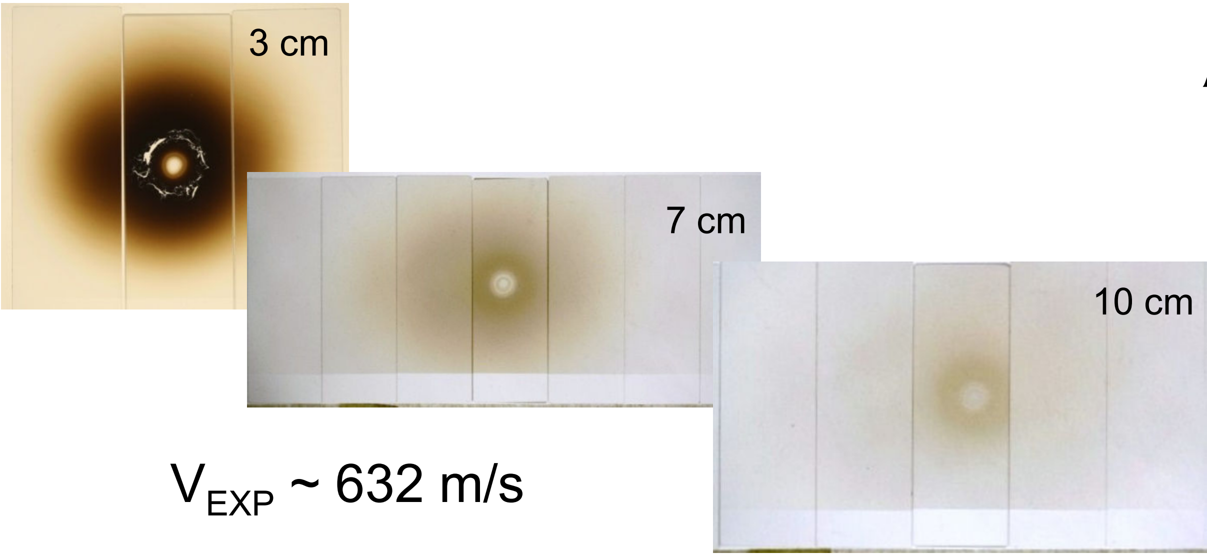
- Measured the deposited mass/area, $(\Delta m/A)_{SLIDES}$
- Measured the height of the ejecta, Δh_{EXP}

From this the density of the deposited material can be calculated $\rho_{EXP}(r,\theta)$

Derive the expected collection rate of ejecta on each slide

$$\rho_{l,EXP}(r,\theta) = \frac{\left(\frac{\Delta m(r,\theta)}{A}\right)_{SLIDES}}{\Delta h_{EXP}}$$

$$\frac{1}{A}\frac{dm}{dt} = 2\rho(r,\theta)\overline{v}$$



Measured the transmittance of the slides

V_{EXP} ~ 632 m/s

Tsub ~ 4747 K

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MASS FLOW RATE, SAMPLE

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Surface illumination of either a 43 W or 62 W laser beam

43 W

Theory: $2.59 \cdot 10^{-8}$ kg/s

Exp: $2.40 \cdot 10^{-8}$ kg/s (-7 %)
Exp: $3.90 \cdot 10^{-8}$ kg/s (+50 %)
Exp: $2.12 \cdot 10^{-8}$ kg/s (-18 %)

62 W

Theory: $3.17 \cdot 10^{-8}$ kg/s

Exp: $4.63 \cdot 10^{-8}$ kg/s (+25 %)
Exp: $3.07 \cdot 10^{-8}$ kg/s (-17 %)
Exp: $5.65 \cdot 10^{-8}$ kg/s (+52 %)
Exp: $4.43 \cdot 10^{-8}$ kg/s (20 %)
Exp: $3.28 \cdot 10^{-8}$ kg/s (-12 %)

Variations are considered to be caused by local variations in the rock sample

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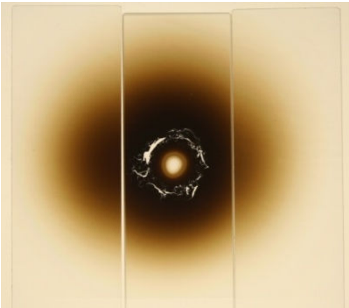
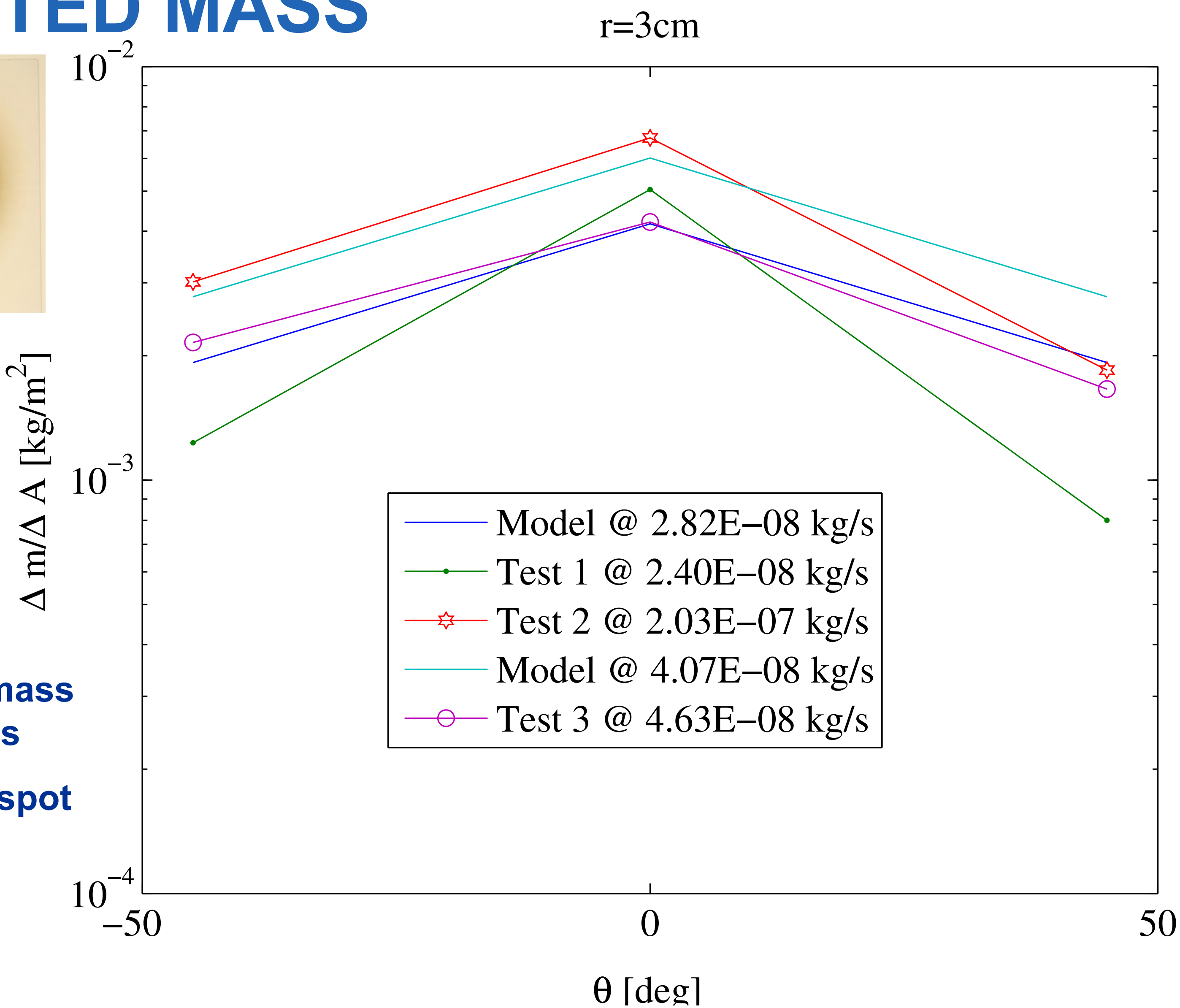
DEPOSITED MASS





Accumulated mass on the slides

3 cm from the spot

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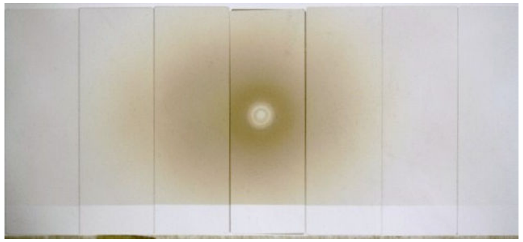
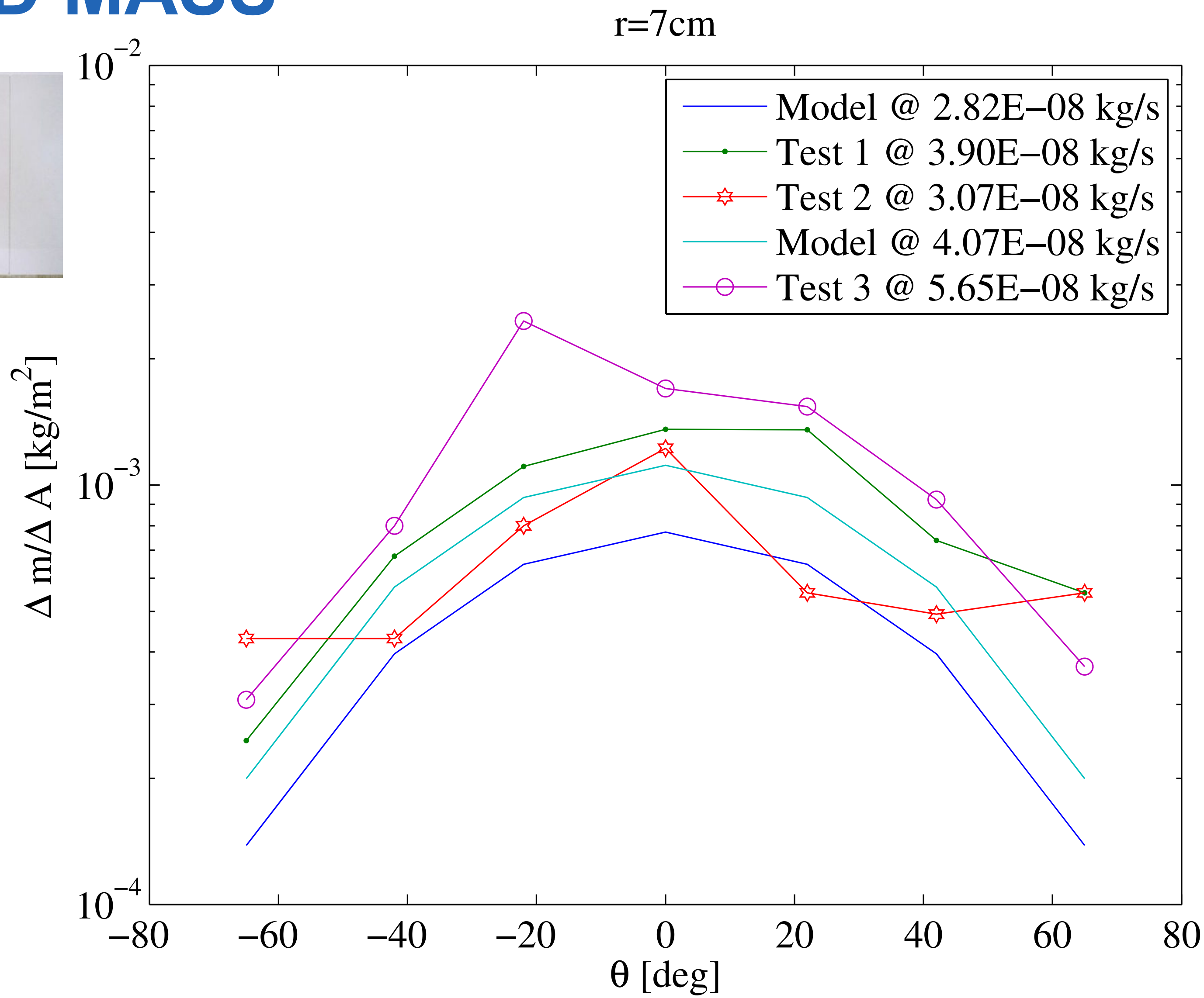
DEPOSITED MASS





Accumulated mass on the slides

7 cm from the spot

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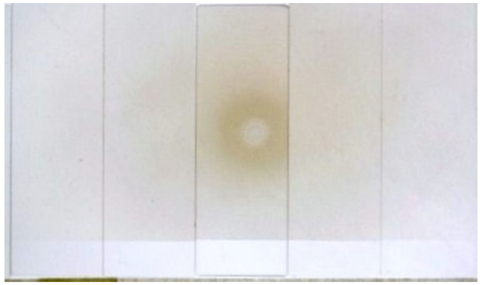
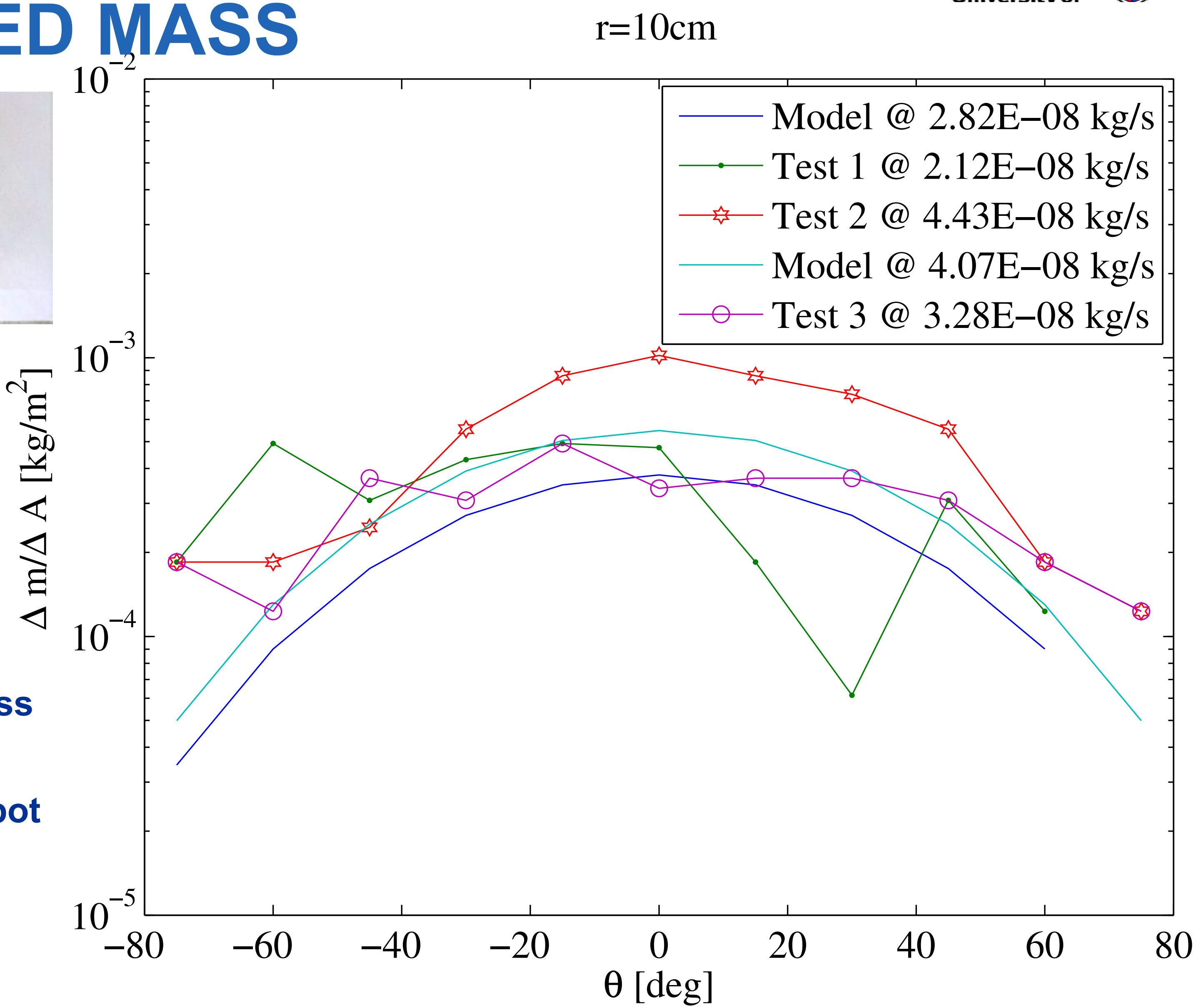
DEPOSITED MASS





Accumulated mass on the slides

10 cm from the spot

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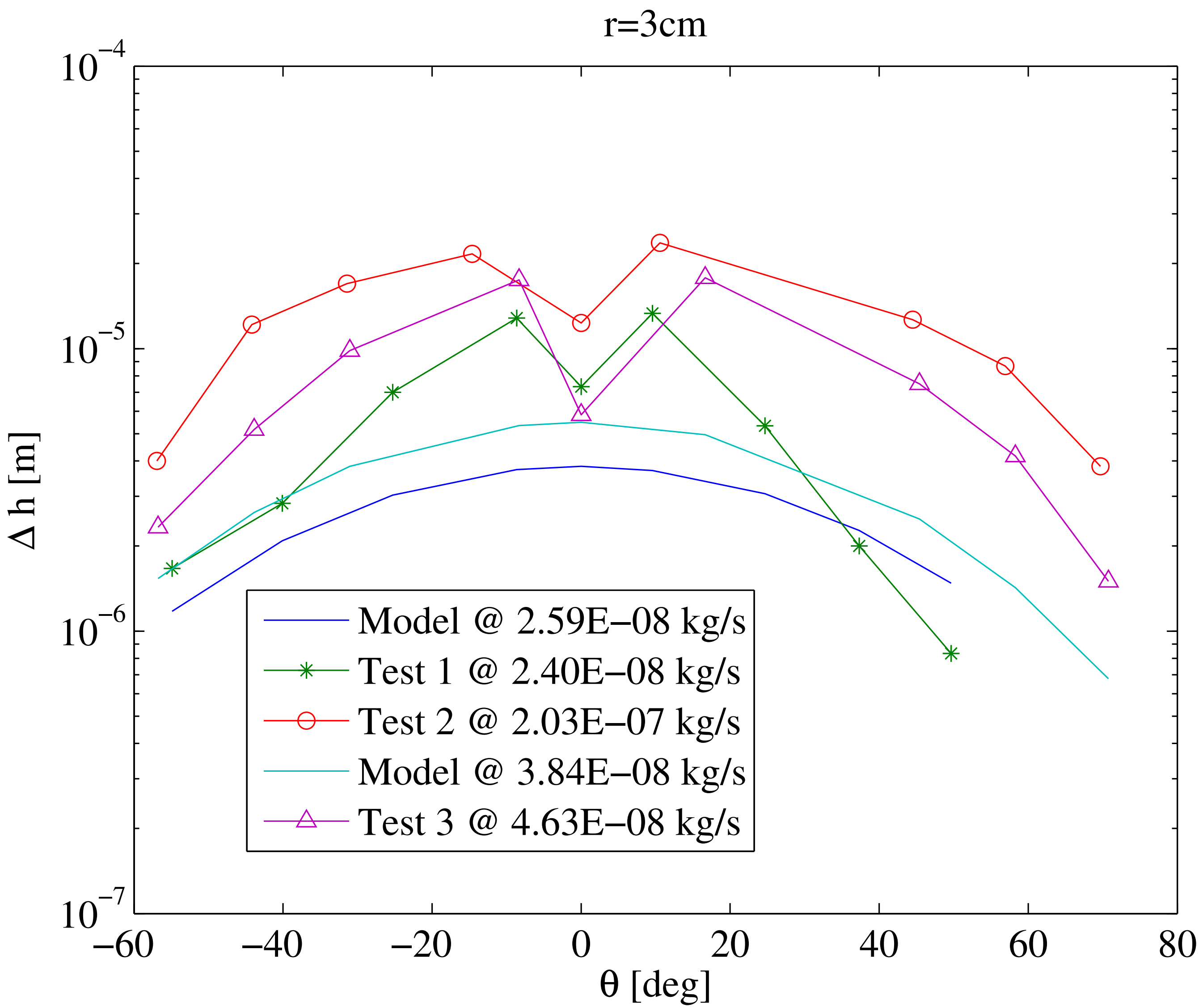
THICKNESS, DEPOSITED MATERIAL



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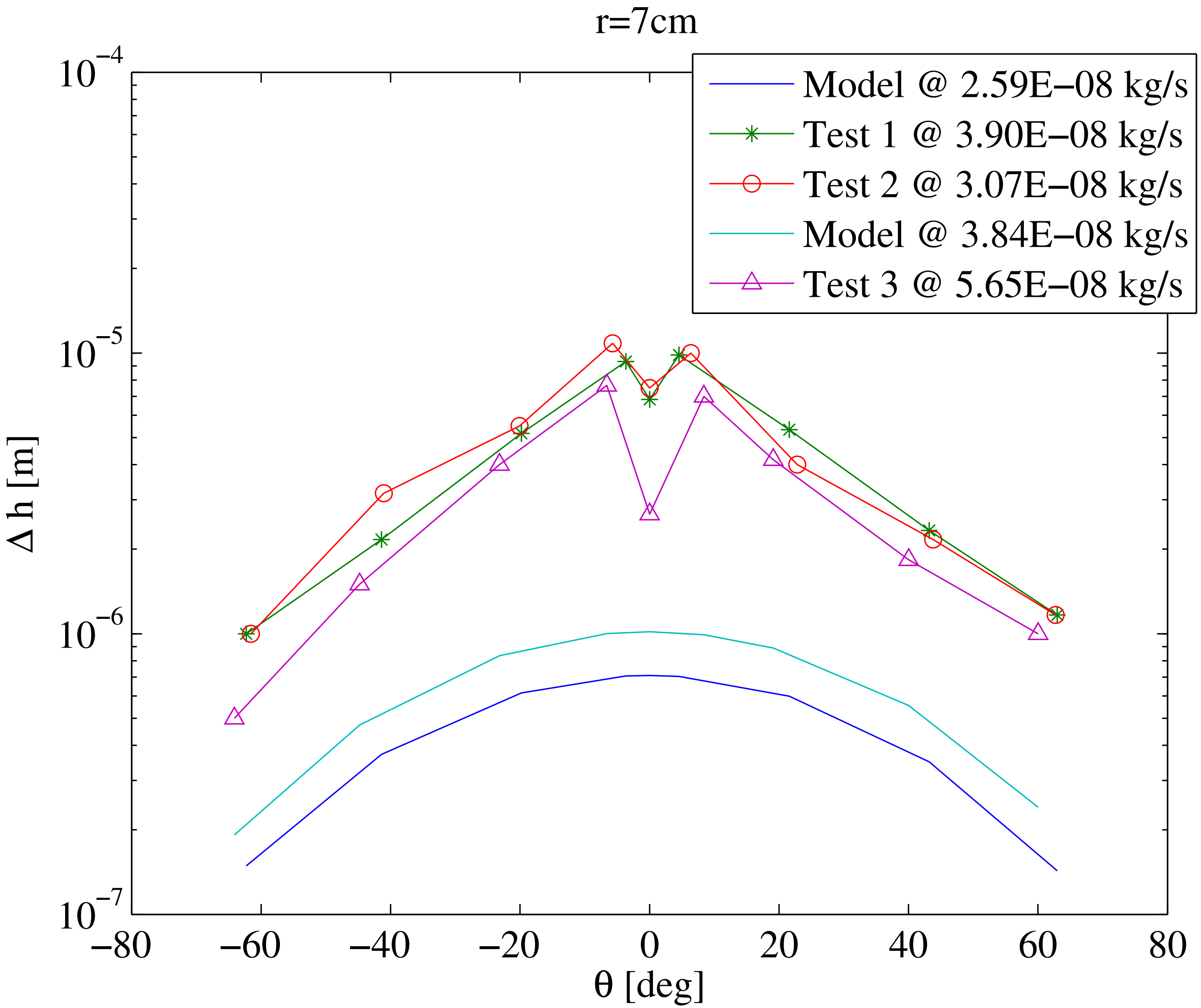
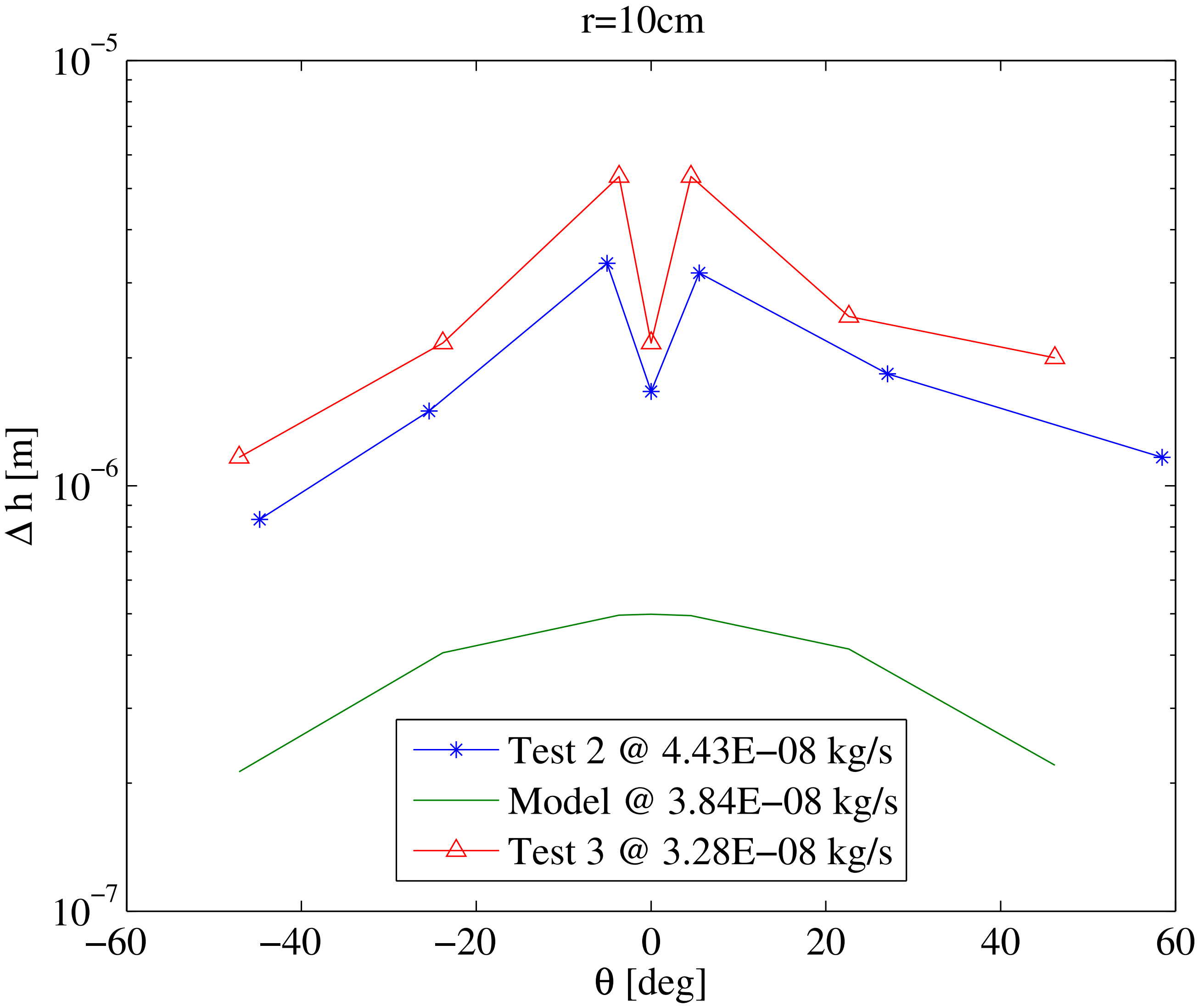
THICKNESS, DEPOSITED MATERIAL



THICKNESS, DEPOSITED MATERIAL



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THICKNESS, DEPOSITED MATERIAL

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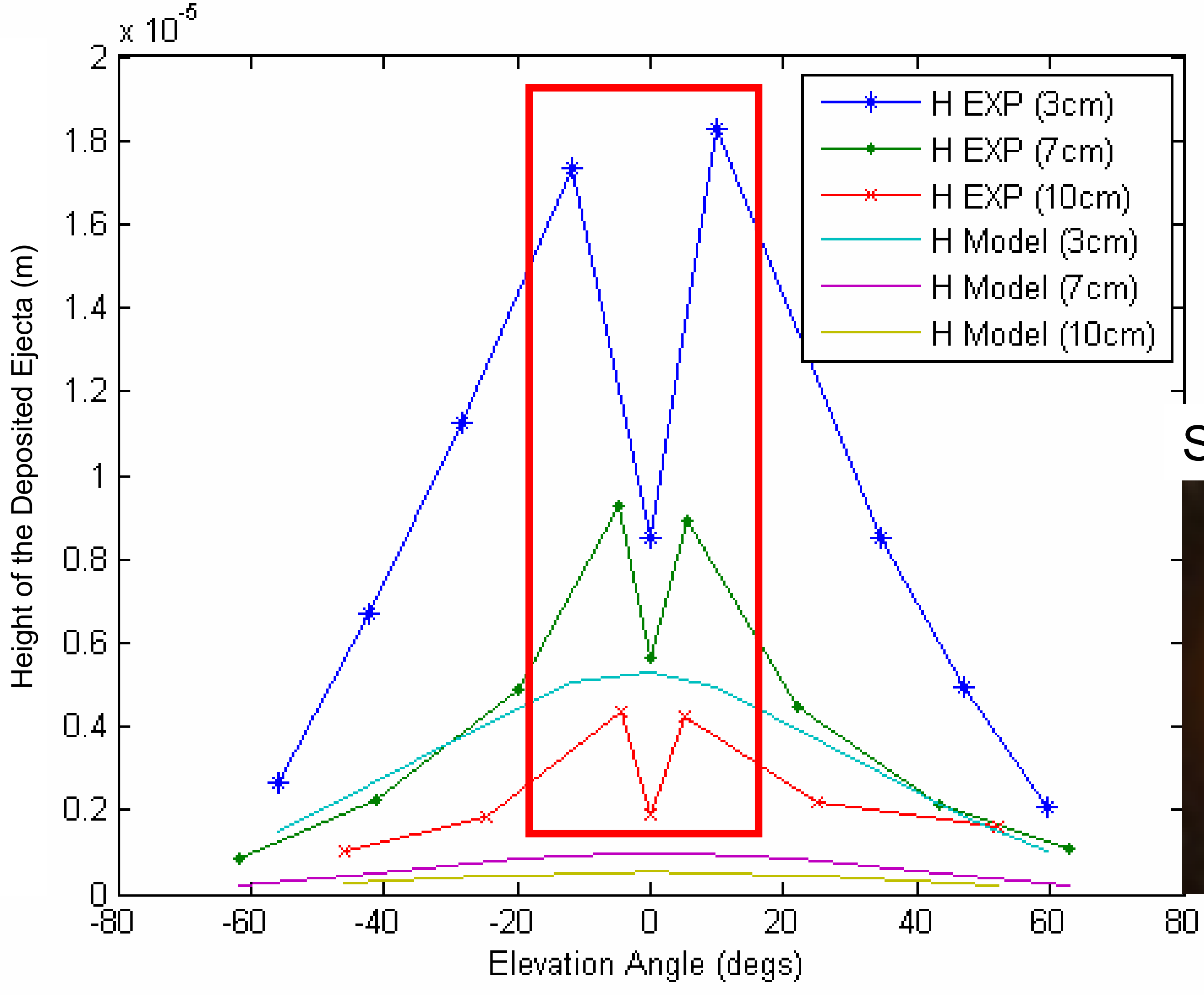

Self cleaning action

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TRANSMITTANCE ACROSS SLIDES

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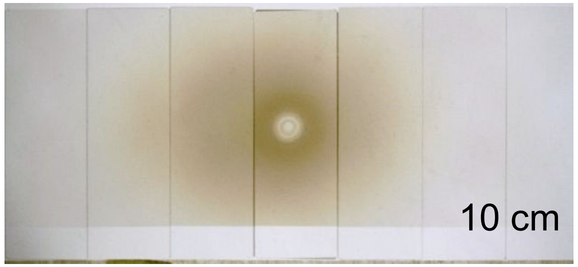

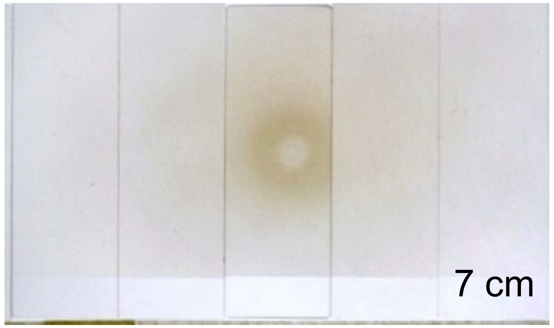

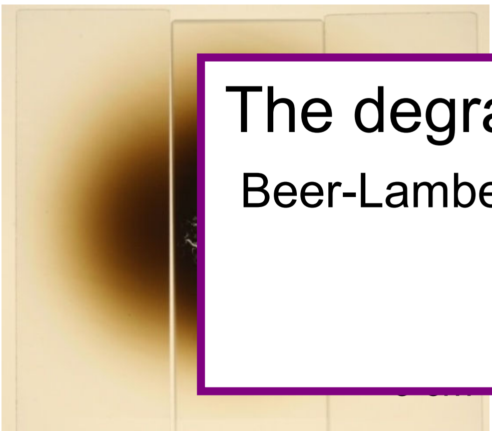

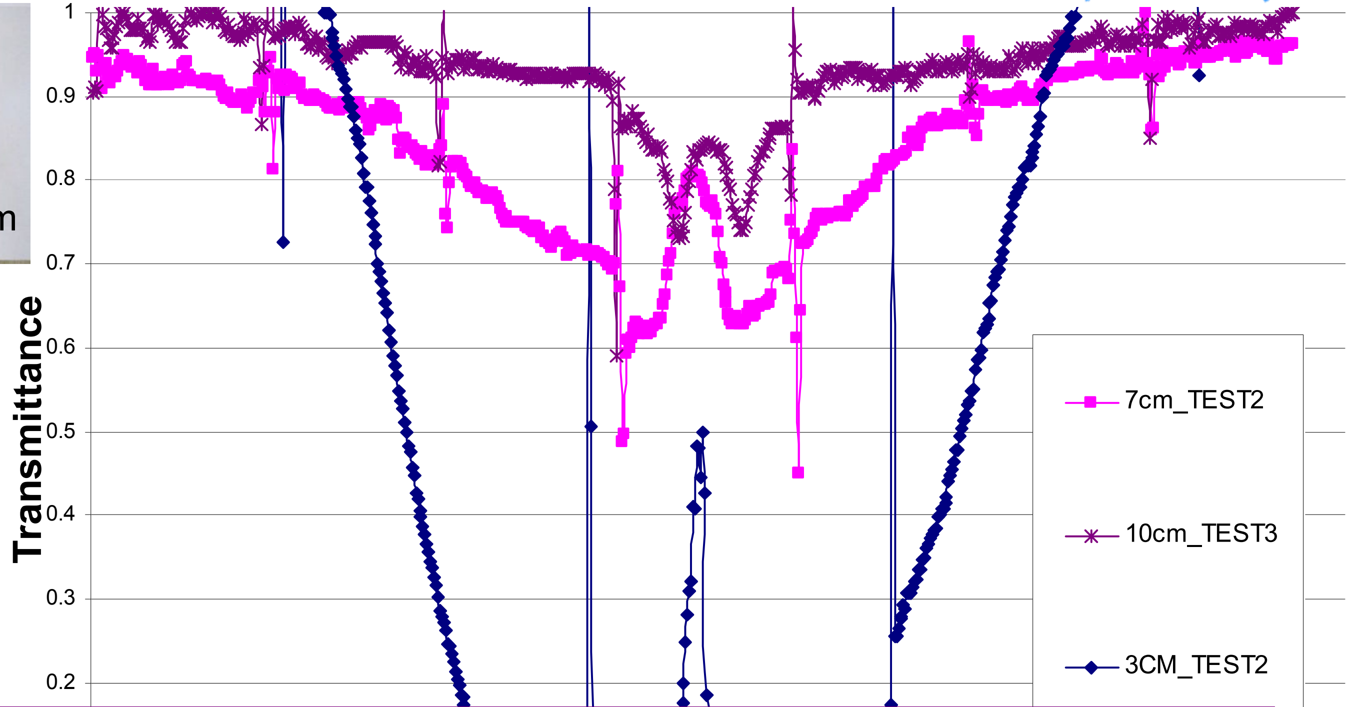

The degradation factor, τ,

Beer-Lambert-Bougier law

$$\tau = e^{-2\eta h_{EXP}}$$

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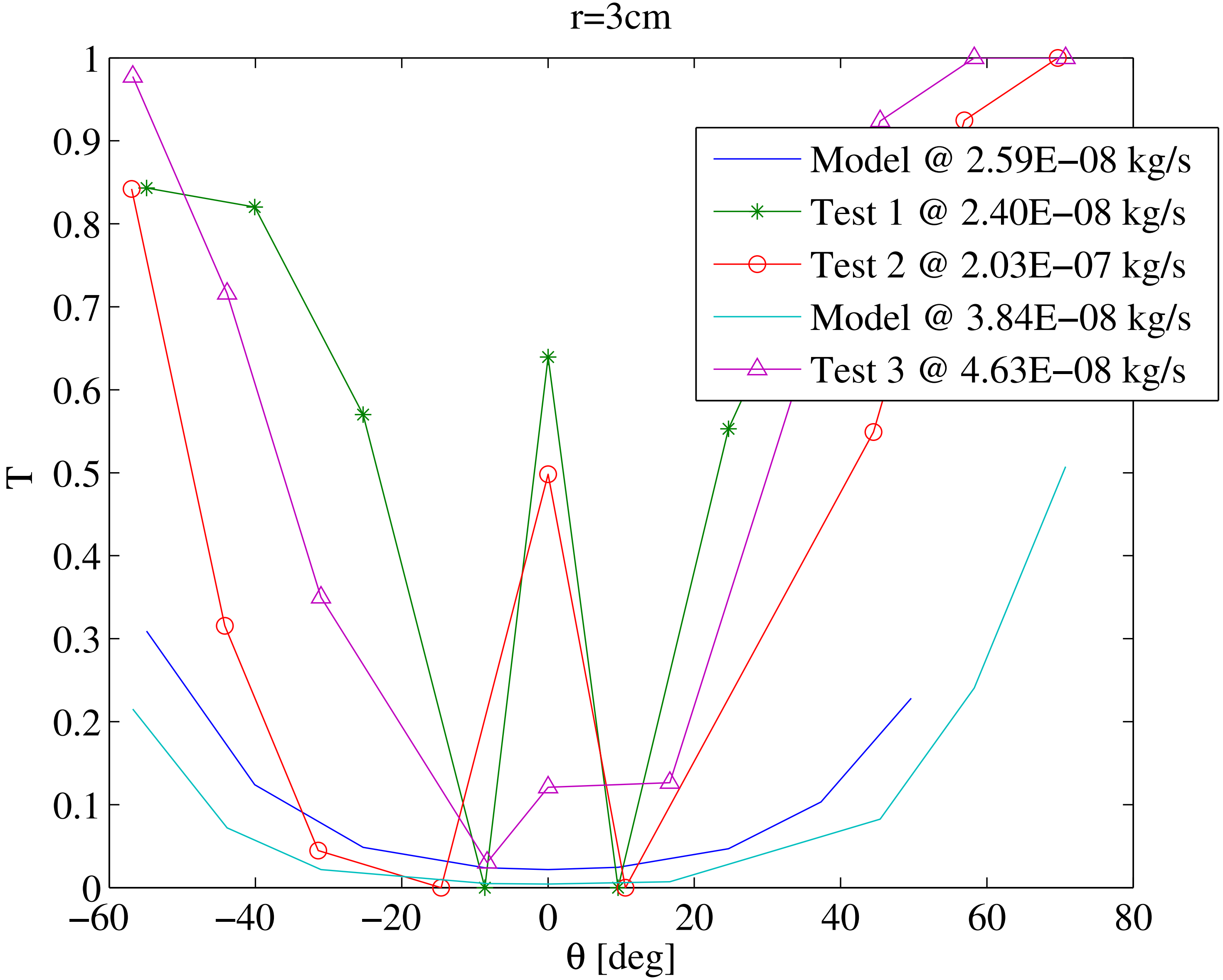
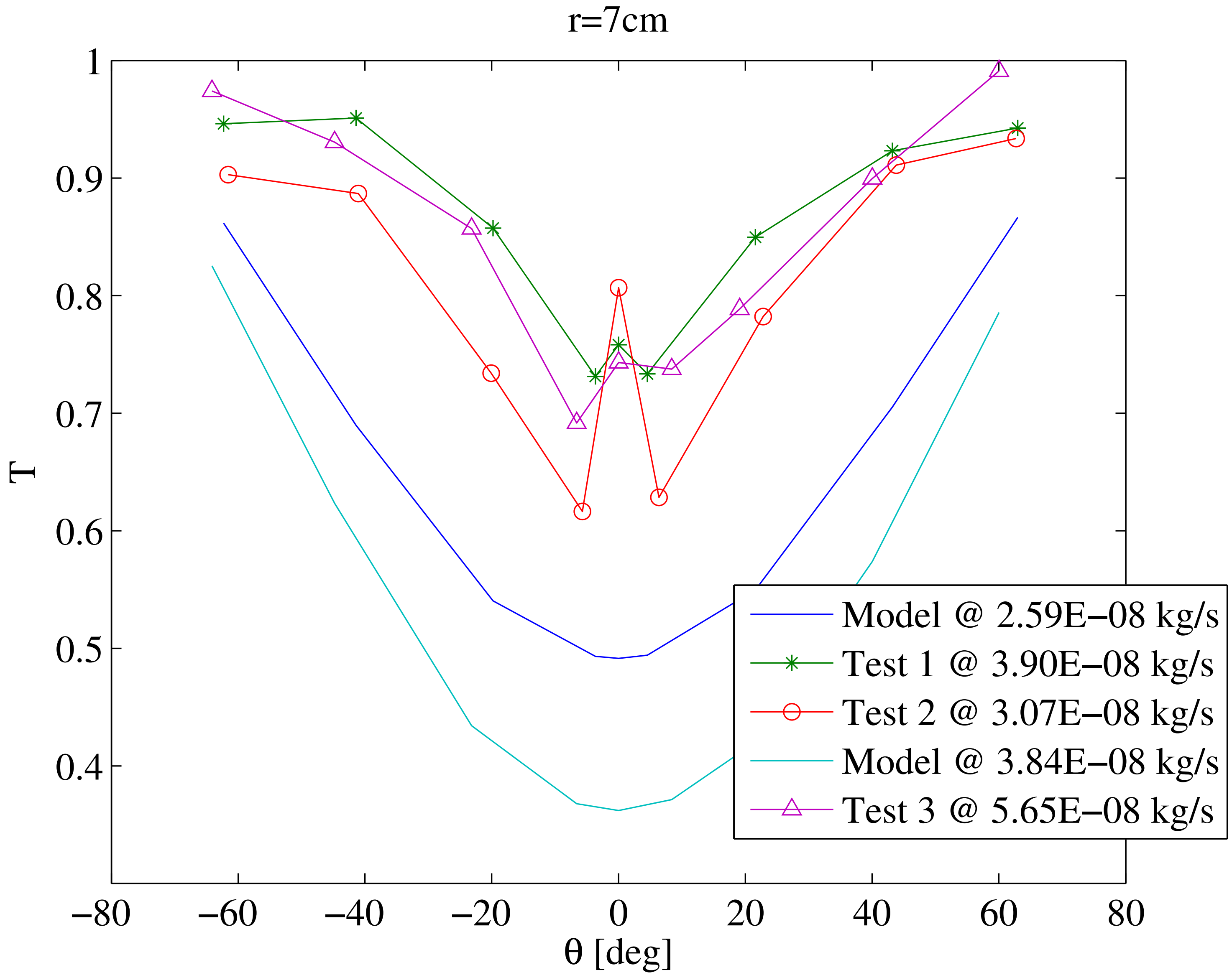
DEGRADATION FACTOR



DEGRADATION FACTOR



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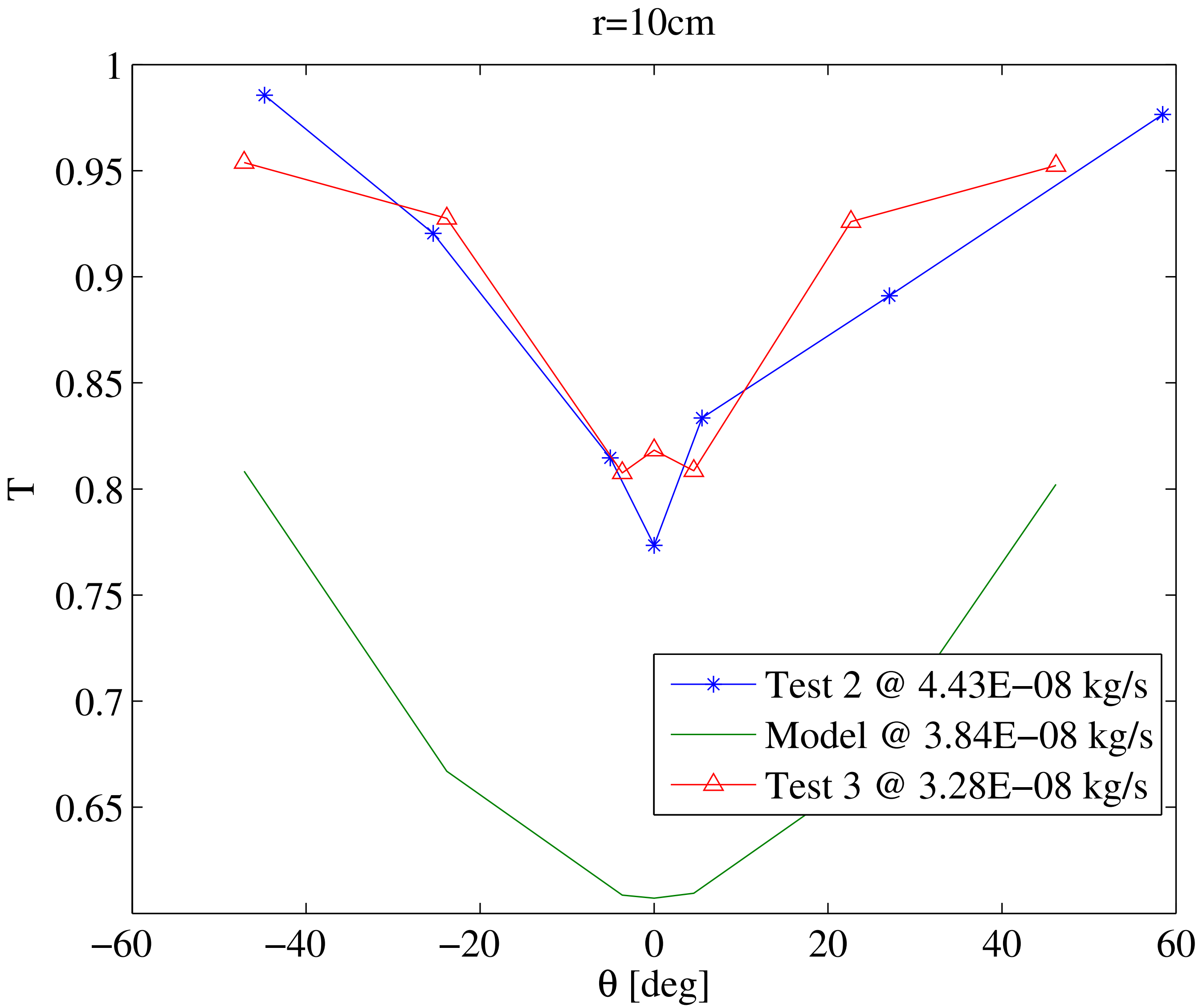
DEGRADATION FACTOR



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COMPARISON

- Model predicts significantly greater degradation that observed
  - Expected to be higher at lower angles; plume density is larger.

- HOWEVER, instead, the experimentally measured thickness is much higher
  - BUT with equal mass per unit area

- Density of the deposited ejecta is much lower than assumed
  - Model: 1000 kg/m^3 with an assumed absorptivity of 10^6 m^{-1}
  - Experiment:
    - At 7 and 10 cm away

Reasonable to assume that at 3 cm the plume is very focused

Expansion leads to a more distributed layer of material at 7 and 10 cm

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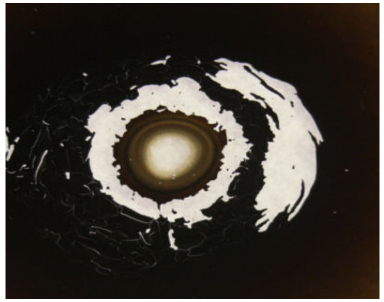
COMPARISON



Experiment had a correlated mass flow and deposition rate

However, the model assumed:

- An incorrect growth of the deposited material
- An incorrect density of the ejected material
- An incorrect absorptivity
- That all the material bonded with the slides

Represents an inaccuracy within the modelling technique

Experiment also demonstrated

- Variation in cone angle & dispersion geometry
- Variation in distribution of ejecta
- Ablation includes the ejection of solid particles f(material)
- Subject to the volumetric removal of material & material phase change
- Subject to the depth of focus of the laser

LASER BEES, OPEN QUESTION

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- **Physical formation and evolution of the ejecta plume**
  1. Is it similar to the formation of the rocket exhaust in rocket propulsion?
  2. Is there uniform dispersion of the ejecta over the given hemisphere?
  3. Is a constrained plume of ejecta more plausible?
  4. What particles are contained within the ejecta?
     A. Only hot gas? Any solid particles?

  Function of the target material and composition

- **Ablation response for different material**
  1. What is the difference between dense and porous material?

  Partially Captured

- **Sensitivity of contamination and degradation of the ejecta**
  1. What is the actual degradation rates of the exposed surface? $f(r, \theta)$
  2. What are the physical properties of the condensed material? — **Absorptivity & density**
  3. Does all the ejected material immediately stick? — **No**
  4. Is there any attenuation of the laser beam? — **No**

Can we ensure the maximum survivability of the system to maximise the achievable deflection of the technique ?

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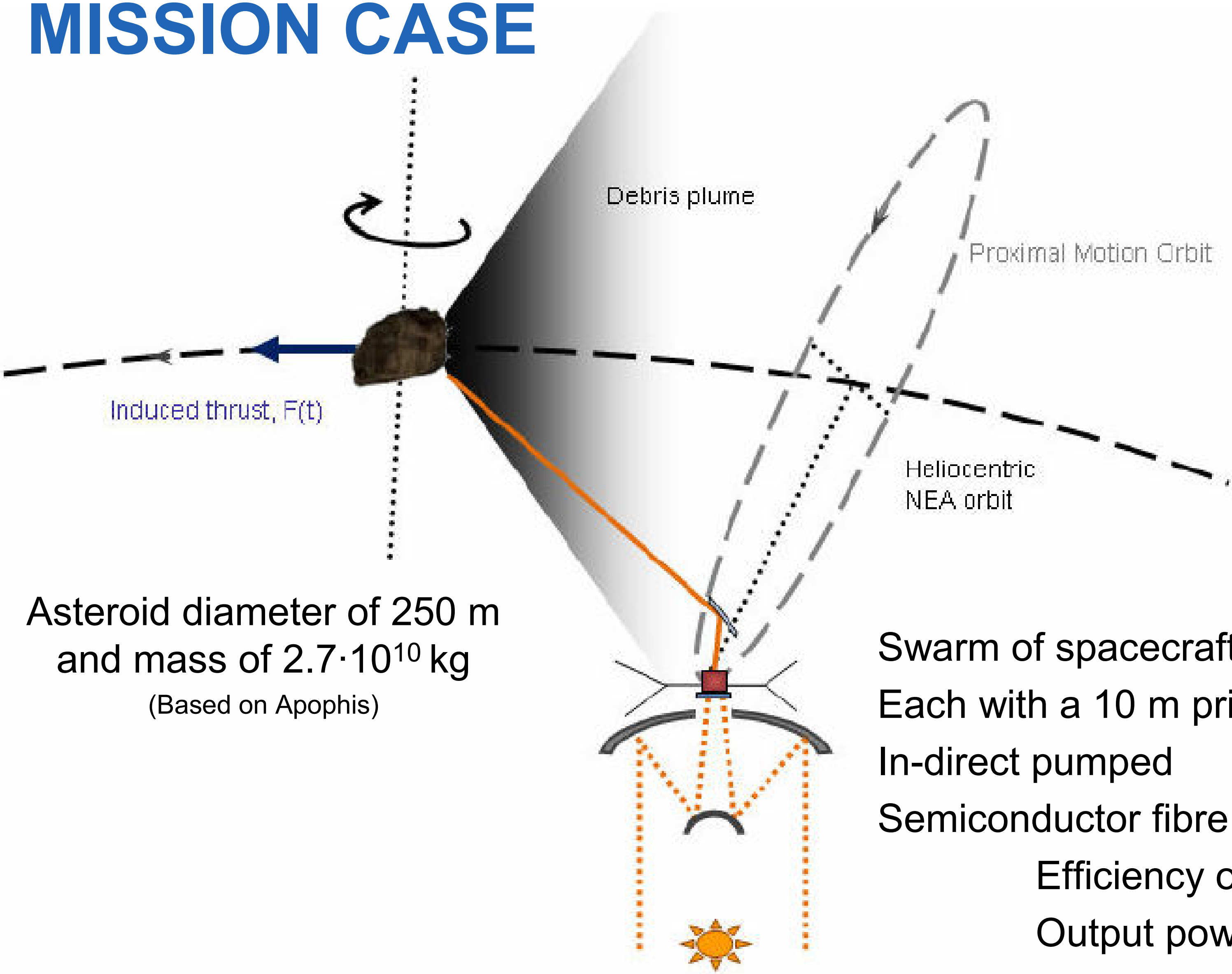
MISSION CASE



Asteroid diameter of 250 m and mass of $2.7 \cdot 10^{10}$ kg

(Based on Apophis)

Swarm of spacecraft

Each with a 10 m primary concentrator

In-direct pumped

Semiconductor fibre laser,

Efficiency of 60 %

Output power 22 kW

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MISSION CASE

Not accounting for degradation

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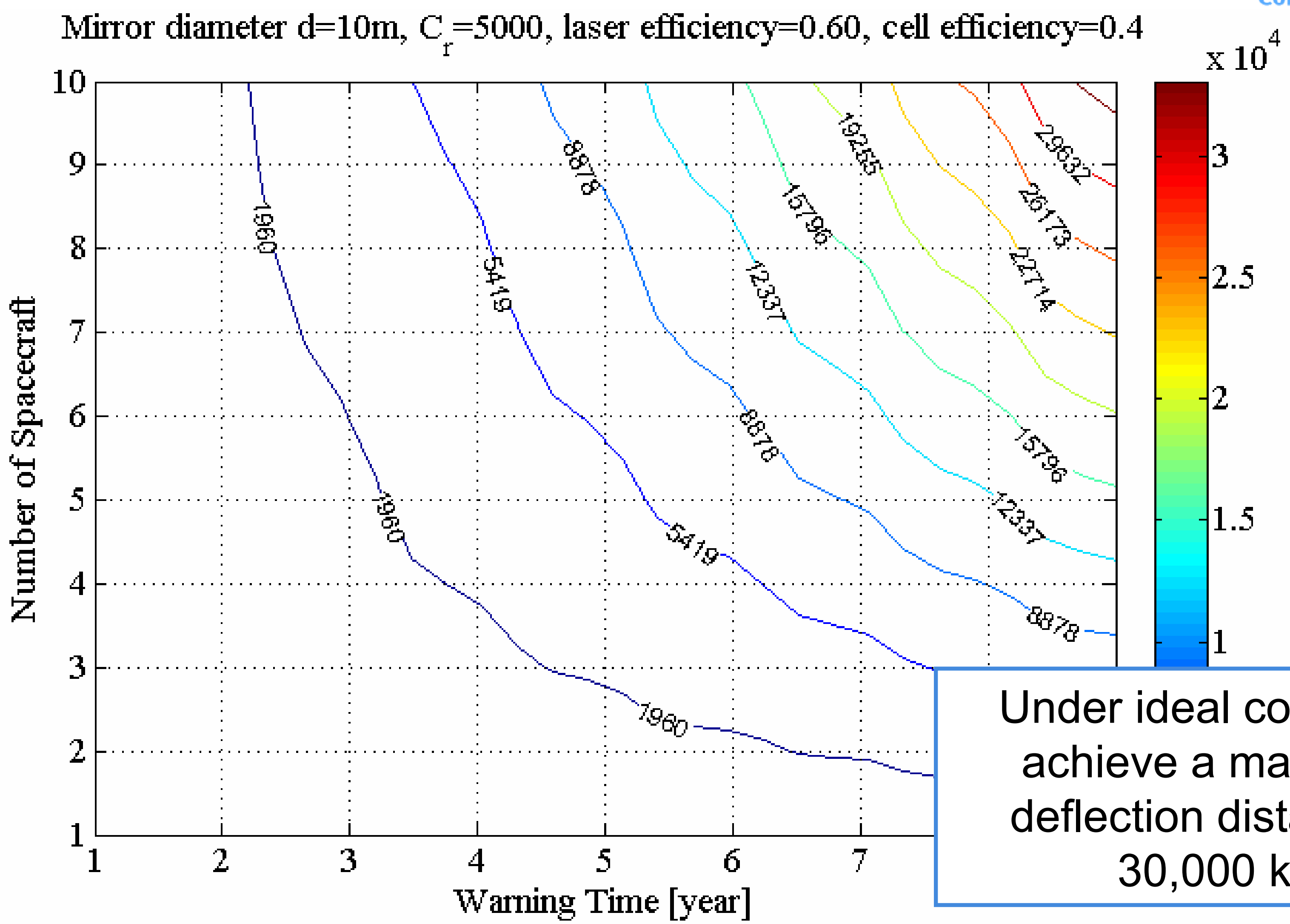

Under ideal conditions achieve a maximum deflection distance of 30,000 km

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MISSION CASE

Assuming the parameters, given in Kahle

Condensed ejecta density of 1000 kg/m^3

Absorbitivity of 10^6 m^{-1}

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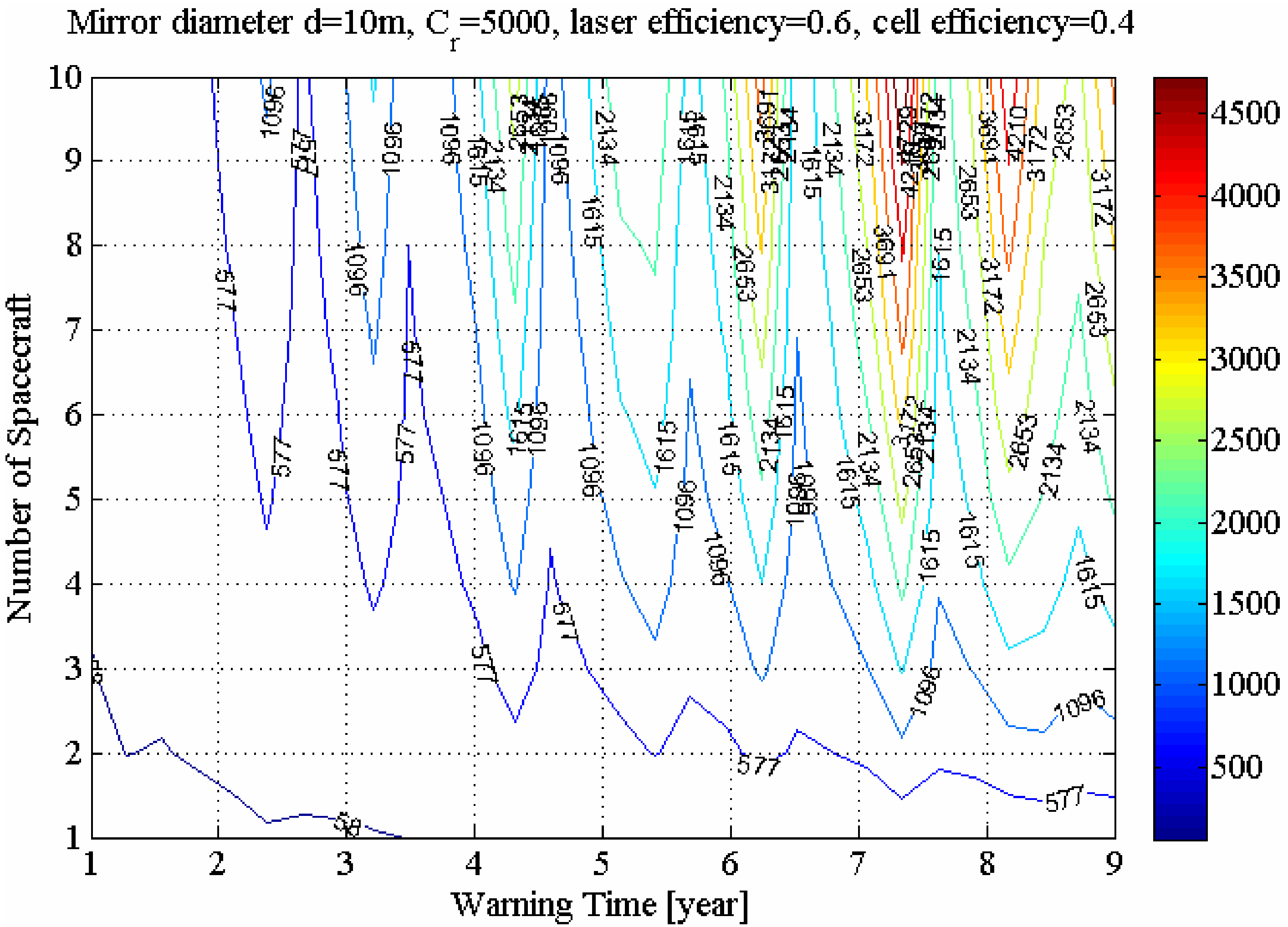

Reduction in performance of 85 %

Almost immediate saturation of the exposed optics

Achievable miss distance reduces to 4500 km

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MISSION CASE

Using the experimental data

OLIVINE

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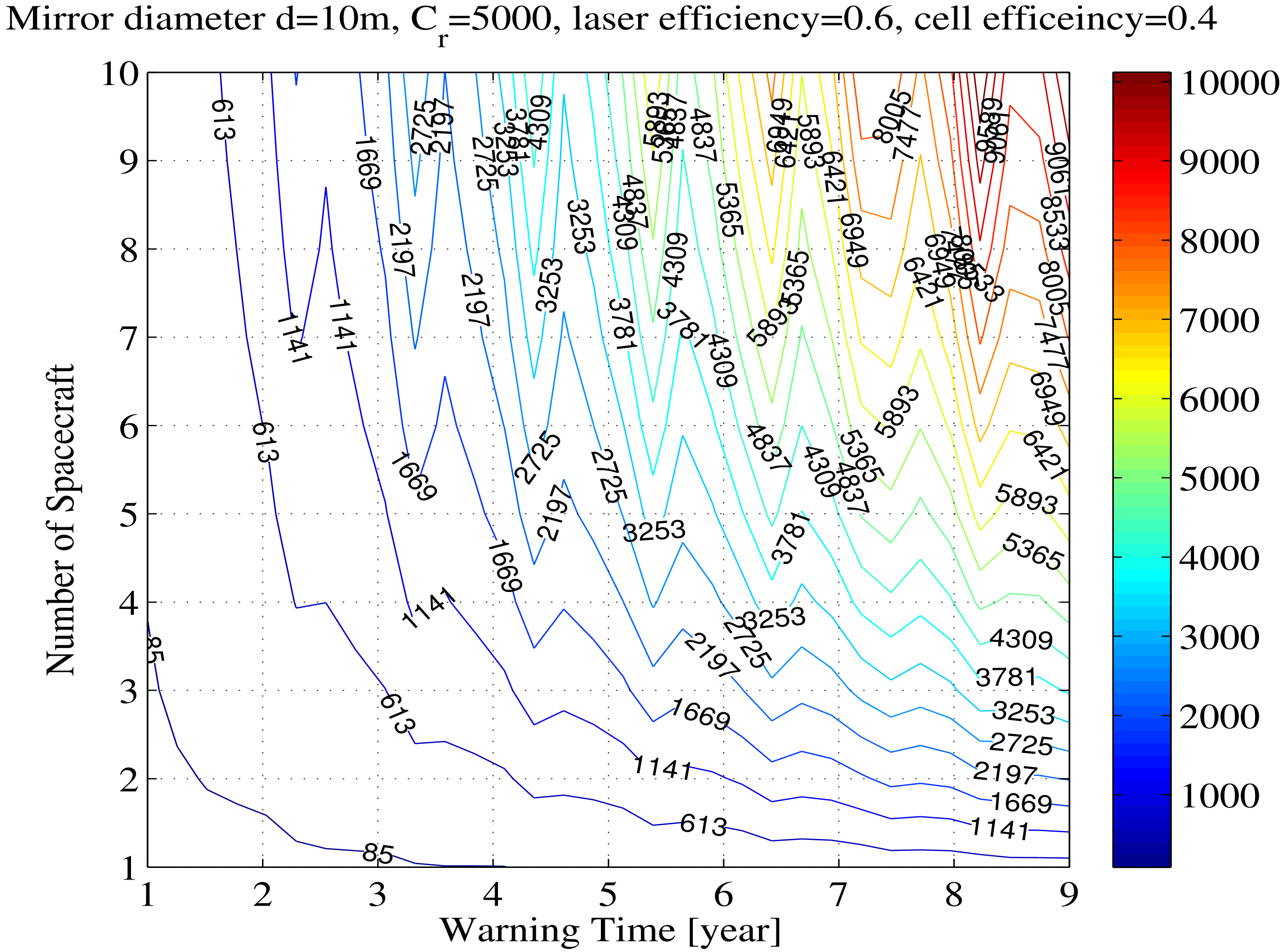
Deposited ejecta density of 250 kg/m³ and an absorbitivity of $5 \cdot 10^4$ m⁻¹



Compared to Kahle

Over double the achievable deflection distance

There is an effect, but its affect is not as significant

Reduction of 67 % compared to the nominal case

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MISSION EXTENSION

Experiment also demonstrated that laser ablation can be used for a wide range of space-based missions. Once a plume of ejecta has been formed:

In-situ Spectra Analysis
Collection & Sample Return
Resource Extraction
Resource Exploitation
Capture & Control

Contactless method

No requirement to land and attach to the asteroid

No complex landing operations

No fragmentation of the asteroid

Durability and diversity of a space-based laser system

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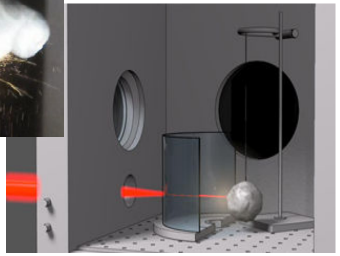
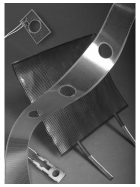
DEVELOPMENT, FUTURE WORK

However a number of questions still remain unanswered. This includes:



- Ablation experiment on a pendulum, rather than static sample
- Ablation from a highly angled laser beam
- Ablation of a pulsed laser beam, assess higher energy ablation
- Ablation of inhomogeneous, irregular rotating samples, affect of porosity
- Using a thermal and high speed camera
  - Identification of the ejecta plume and measuring the velocity of the ejecta
  - Spot, slide and target material temperature profile during ablation f(t)
  - Efficiency of the self cleaning action
- Effect of slide heating in the contamination of the deposited ejecta
- Assess the composition and distribution of the ejecta
  - AFM for global topography and SEM for composition
- Measure the deposition of ejecta *in-situ* as a function of time
- Experiments with *in-situ* measuring of the mass flow, relative to the depth of focus
- Measure the force directly imparted onto the asteroid during ablation
- Enhanced quality – reduced pressure - of the vacuum chamber



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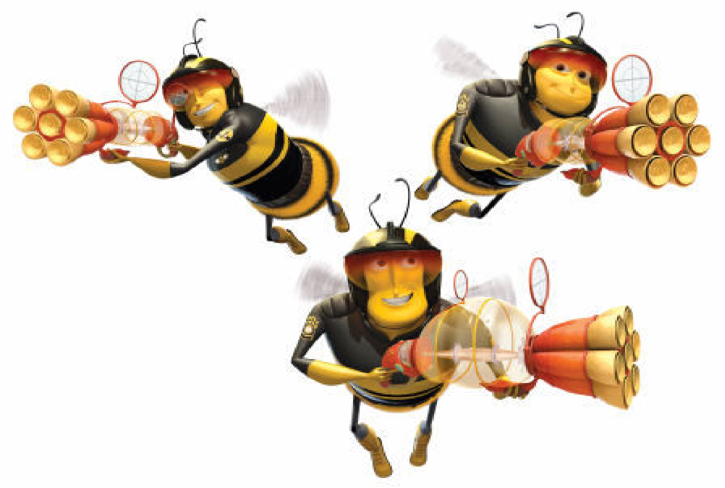
Thank you for your time & the continued support of The Planetary Society.



Questions Please

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References

Conway, B.A “Near-optimal deflection of Earth-approaching asteroids”. *J.Guidance, Control and Dynamics* 24 (5), 1035–1037, 2001

Gritzner, C., Kahle, RMitigation technologies and their requirements, in: Belton, M.,Morgan, T., Samarainha, N., Yeomans, D. (Eds.), Mitigation of Hazardous Comets and Asteroid. Cambridge University Press, Cambridge, pp. 167–200, 2004

Housen “Collisional Fragmentation of Rotating Bodies”, Lunar and Planetary Science XXXV, No 1826, 2004

Housen K.R, Holsapple K “Impact Cratering On Porous Asteroids”. Academic Press, Icarus 163. Pg 102-119, 2003

Kahle R, Kuhrt E, Hahn G, Knolenberg J “Physical Limits of Solar Collectors in Deflecting Earth-threatening Asteroids” Advanced Science and Technology, Vol 10, pg 256-263, 2006

Melosh, H.J., Nemchinov, I.V., Zetzer, Y.I. Non-nuclear strategies for deflecting comets and asteroids, in: Gehrels, T. (Ed.), Hazards due to Comets and Asteroids. University of Arizona Press, Tucson, AZ, pp. 1111–1132, 1994

Phipps C, Birkan M, Bohn W et al “Review: Laser Ablation Propulsion”, Journal of Propulsion and Power, Vol 26, No 4, 2010

Sanchez, J.P., Colombo, C., Vasile, M., et al “Multicriteria comparison among several mitigation strategies for dangerous Near-Earth objects”. *J. Guid. Control Dynam.* 32, 121–141, 2009.

Vasile M, Maddock C “On the Deflection of Asteroids with Mirrors”, *Journal Celestial Mechanical Dynamics*, Vol 107, pg 265-284, 2010

Vasile M., Maddock C., Radice G., McInnes C “NEO Deflection though a Multi-Mirror System”, ESA Call for Proposals: Encounter 2029, Final Report for Ariadna Study Contract 08/4301, Technical officer: Summerer L., March 2009.

Alvarz L et al, Extraterrestrial Cuase for the Cretaceous-Tertiary Extinction, Science 6, Vol 208, no 4448, 1980

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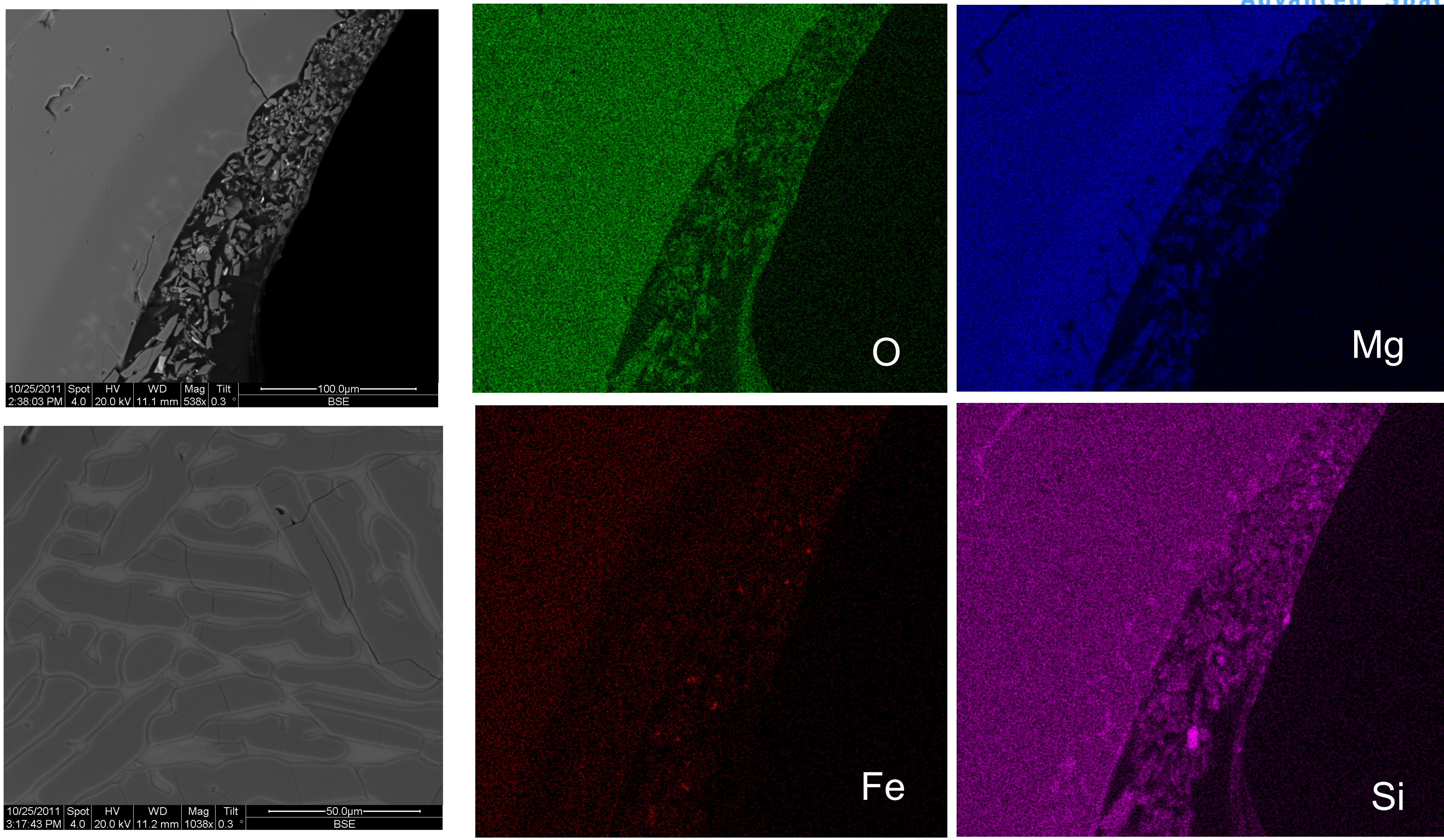
BACK-UP MATERIAL

SEM – TARGET MATERIAL



Re-crystallisation around ablation hole rim

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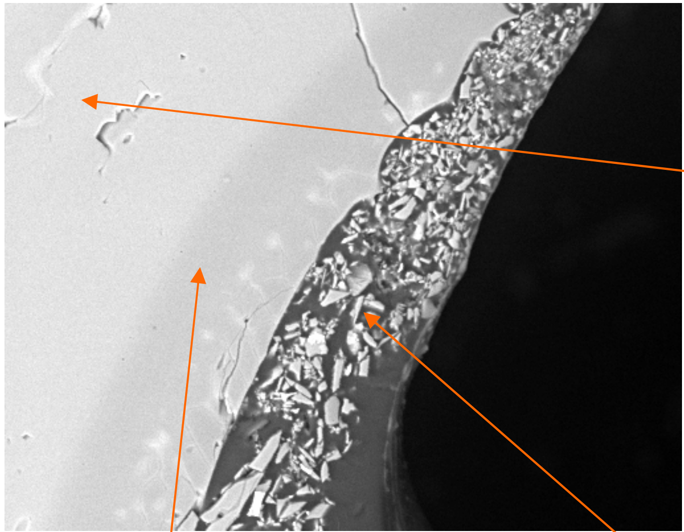
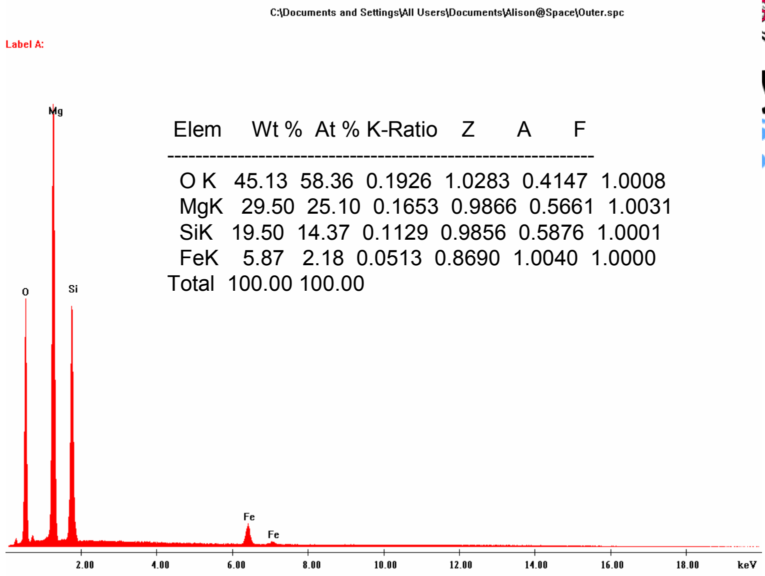
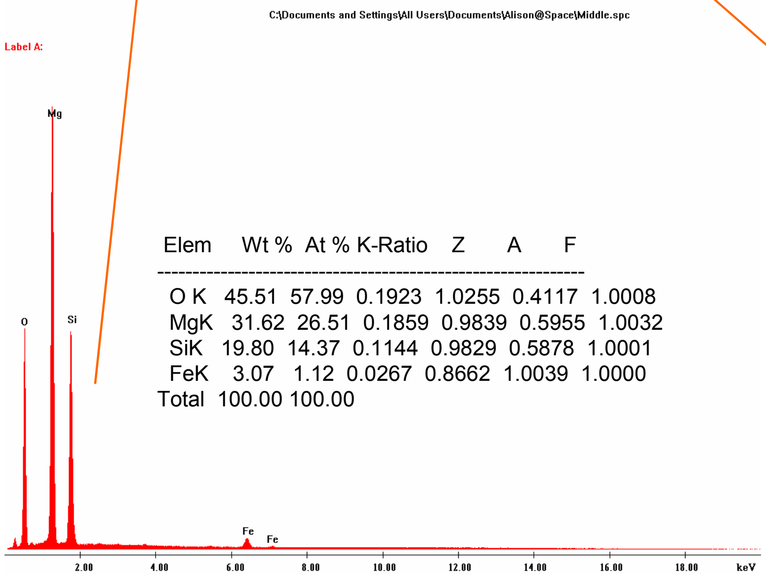
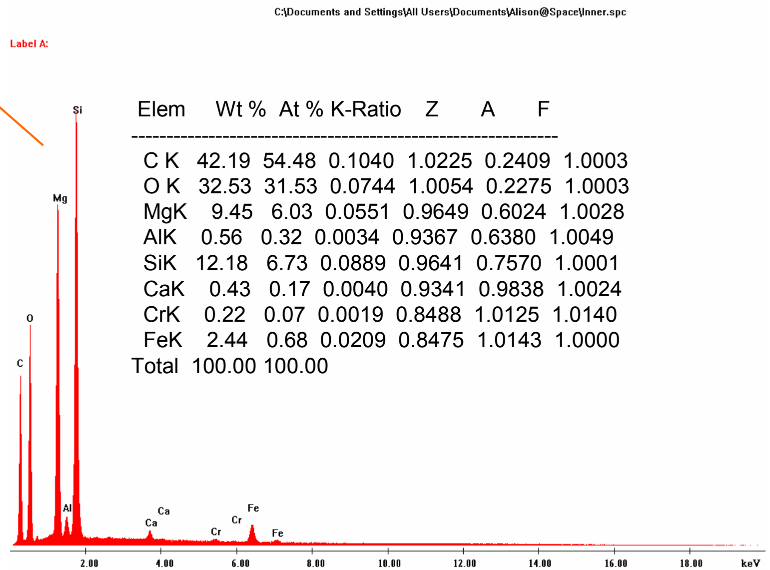




Elem	Wt %	At %	K-Ratio	Z	A	F
O K	45.13	58.36	0.1926	1.0283	0.4147	1.0008
MgK	29.50	25.10	0.1653	0.9866	0.5661	1.0031
SiK	19.50	14.37	0.1129	0.9856	0.5876	1.0001
FeK	5.87	2.18	0.0513	0.8690	1.0040	1.0000
Total	100.00	100.00				



Elem	Wt %	At %	K-Ratio	Z	A	F
O K	45.51	57.99	0.1923	1.0255	0.4117	1.0008
MgK	31.62	26.51	0.1859	0.9839	0.5955	1.0032
SiK	19.80	14.37	0.1144	0.9829	0.5878	1.0001
FeK	3.07	1.12	0.0267	0.8662	1.0039	1.0000
Total	100.00	100.00				



Elem	Wt %	At %	K-Ratio	Z	A	F
C K	42.19	54.48	0.1040	1.0225	0.2409	1.0003
O K	32.53	31.53	0.0744	1.0054	0.2275	1.0003
MgK	9.45	6.03	0.0551	0.9649	0.6024	1.0028
AlK	0.56	0.32	0.0034	0.9367	0.6380	1.0049
SiK	12.18	6.73	0.0889	0.9641	0.7570	1.0001
CaK	0.43	0.17	0.0040	0.9341	0.9838	1.0024
CrK	0.22	0.07	0.0019	0.8488	1.0125	1.0140
FeK	2.44	0.68	0.0209	0.8475	1.0143	1.0000
Total	100.00	100.00				

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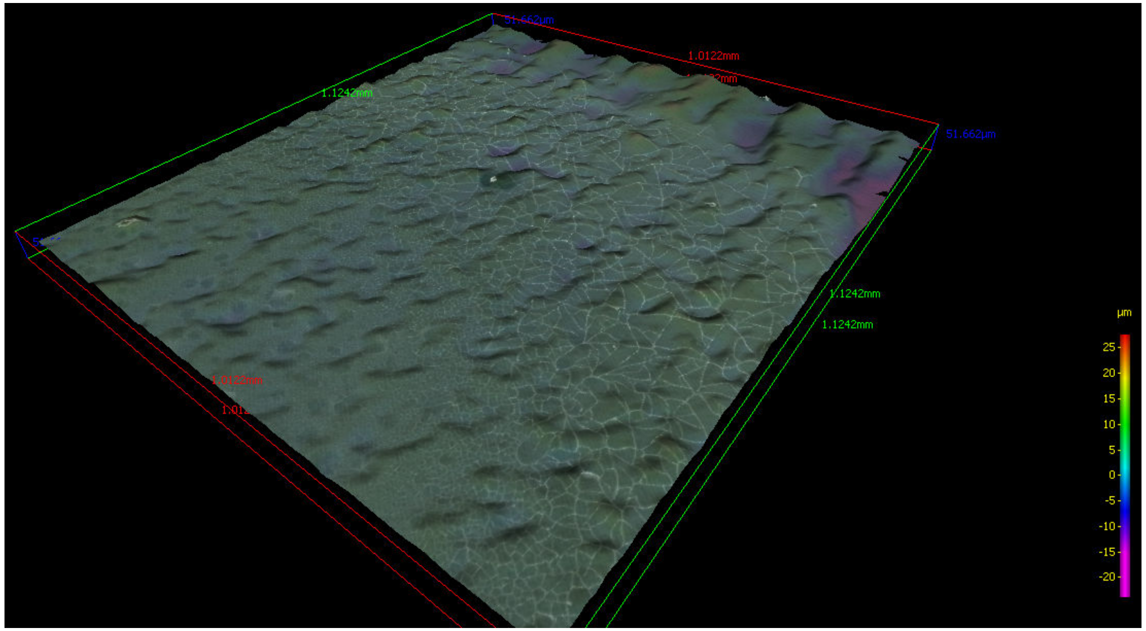
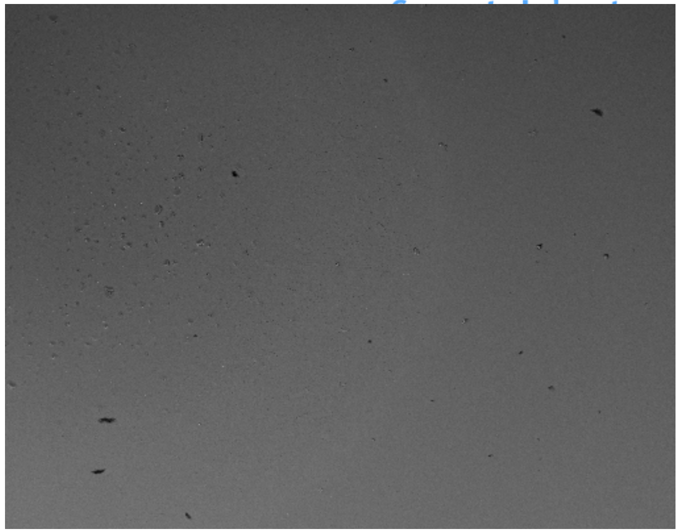
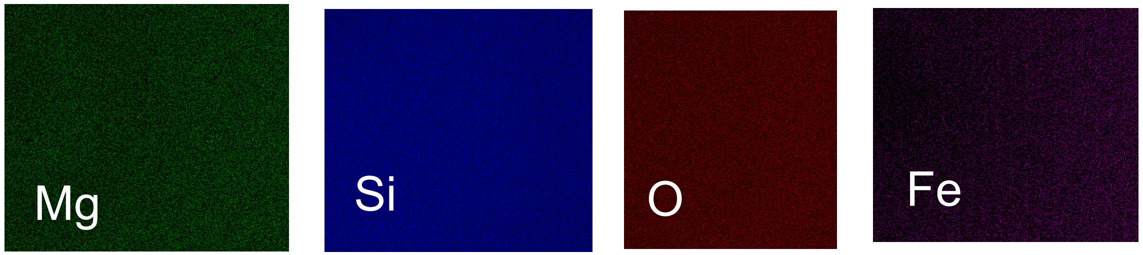
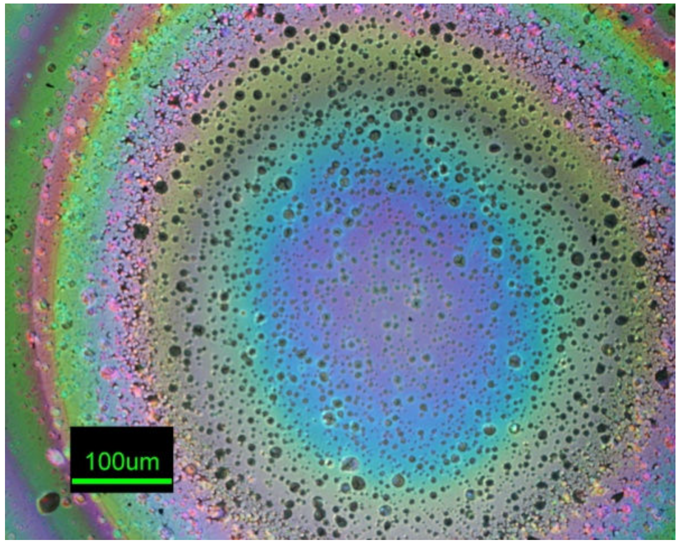
SEM – DEPOSITED EJECTA









Ablated material is chemically identical to the target material

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SPECTRA ANALYSIS Ablation Spot - Alignment

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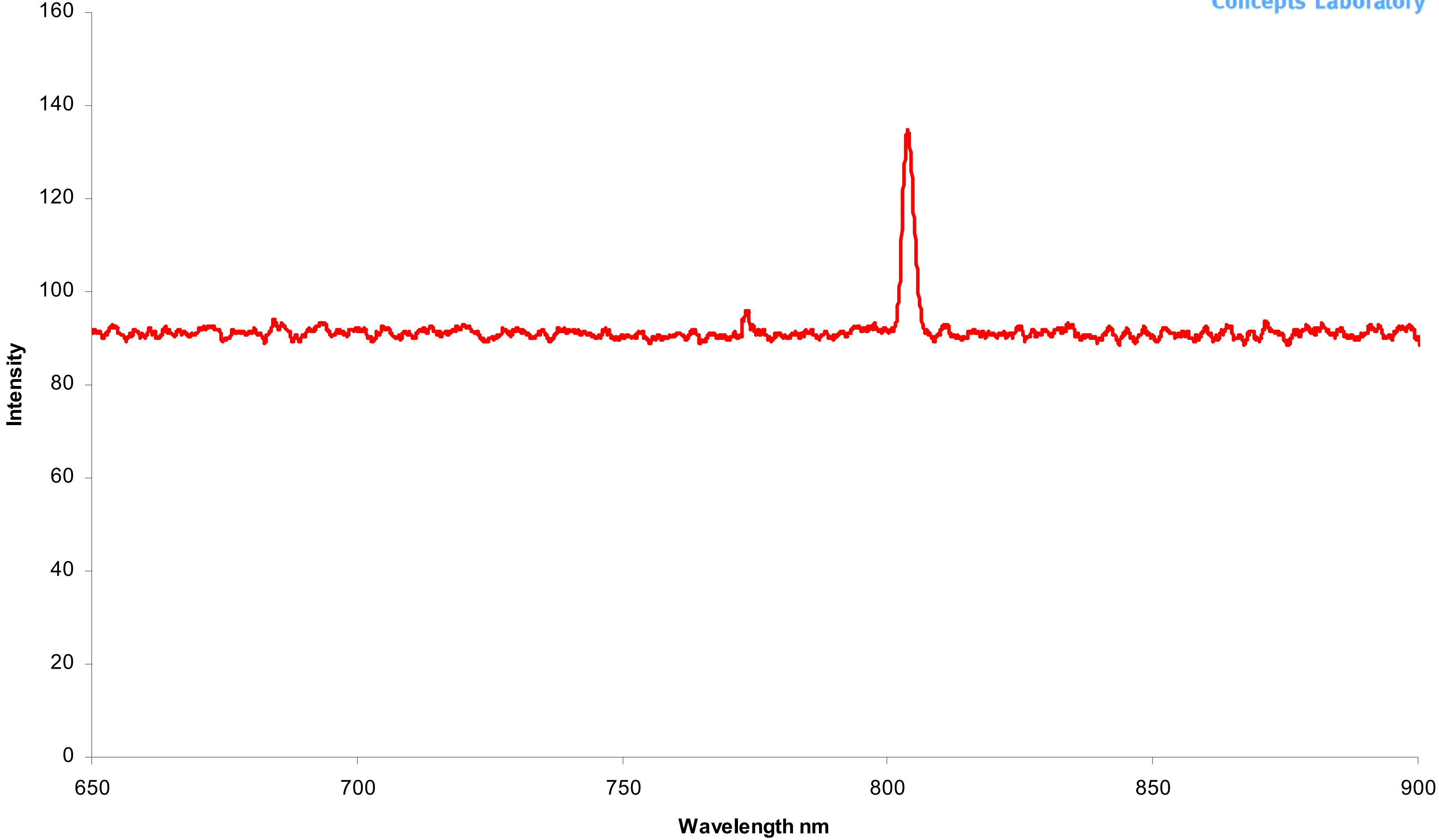
Advanced Space Concepts Laboratory



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SPECTRA ANALYSIS

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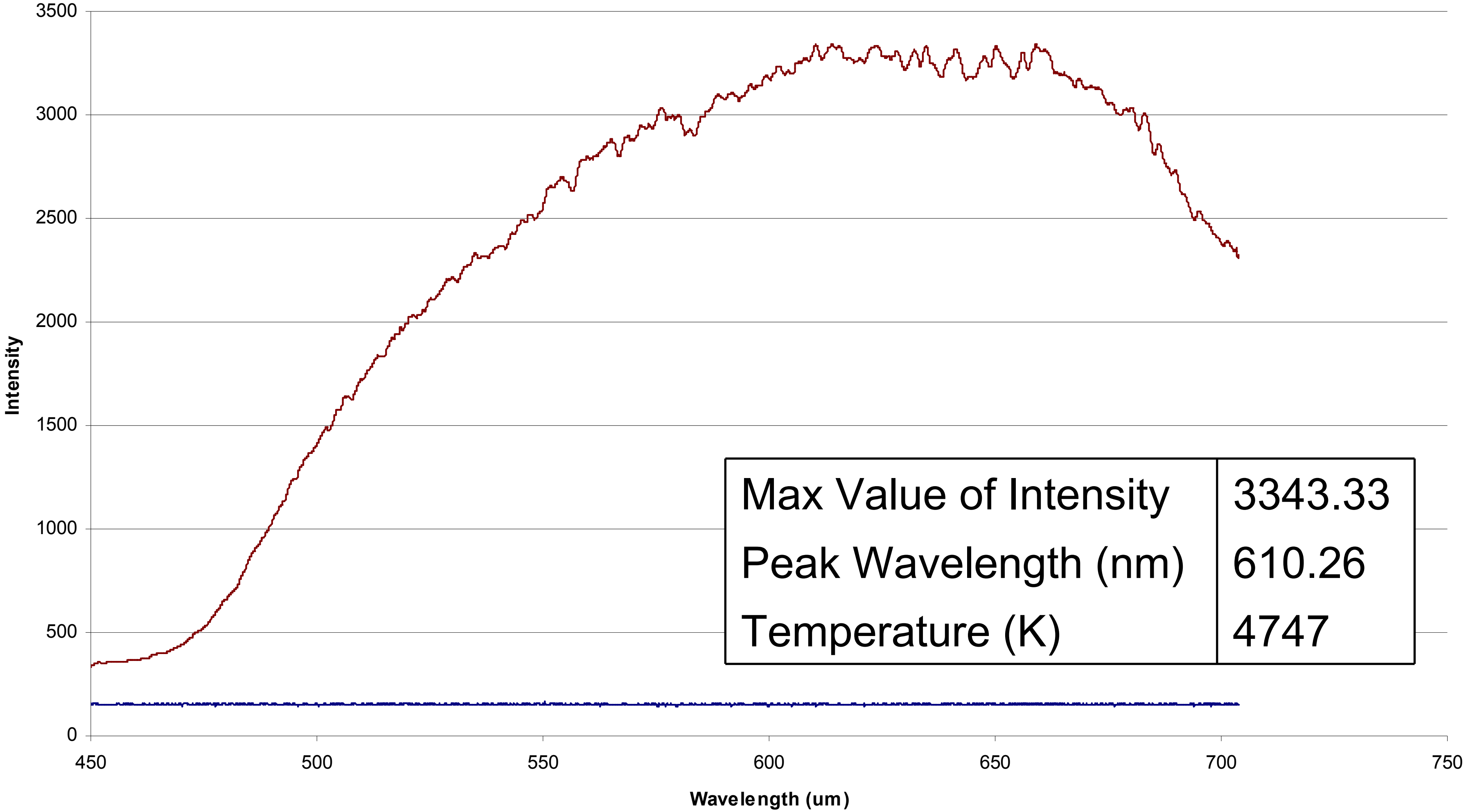

Max Value of Intensity	3343.33
Peak Wavelength (nm)	610.26
Temperature (K)	4747

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METEORITES

Spectra bands show that ordinary Choridities have similar mineralogy to S-type asteroids.

Bensour [LL]

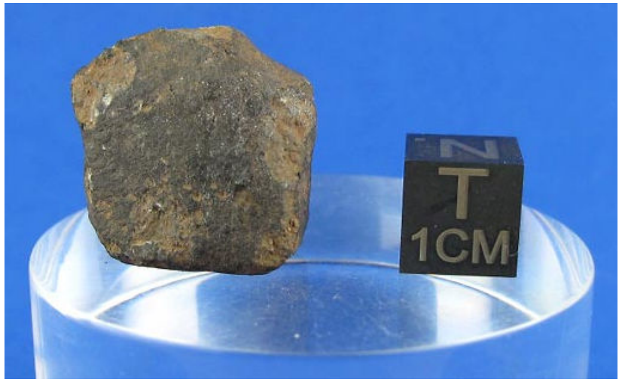
Recovered from a 2002 fall, Morocaan-Algerian

Negligible terrestrial alteration

Low iron, olivine, magnesium silicate [foresterite]

Porosity ~ 10 %

To represent a C-type a carbonaceous choridrite meteorite, Allende, was selected



Allende is a meteorite from a very rate, witness fall

The carbonaceous choridrite is rich in carbon, and contains microscopic diamonds

Approximately 46 billion years old

METEORITES

To represent an M-type asteroid, the meteorite Thuathe was selected

THUATHE

Witnessed fall July 21, 2002, Lesotho

H4/5 Ordinary Chondrite

High iron content

Each meteorite ideally needs to be sourced from a witness fall (freshly fallen stone), with limited weathering and fusion crust.

Ablation has to occur onto the meteorites surface, not the fusion crust.

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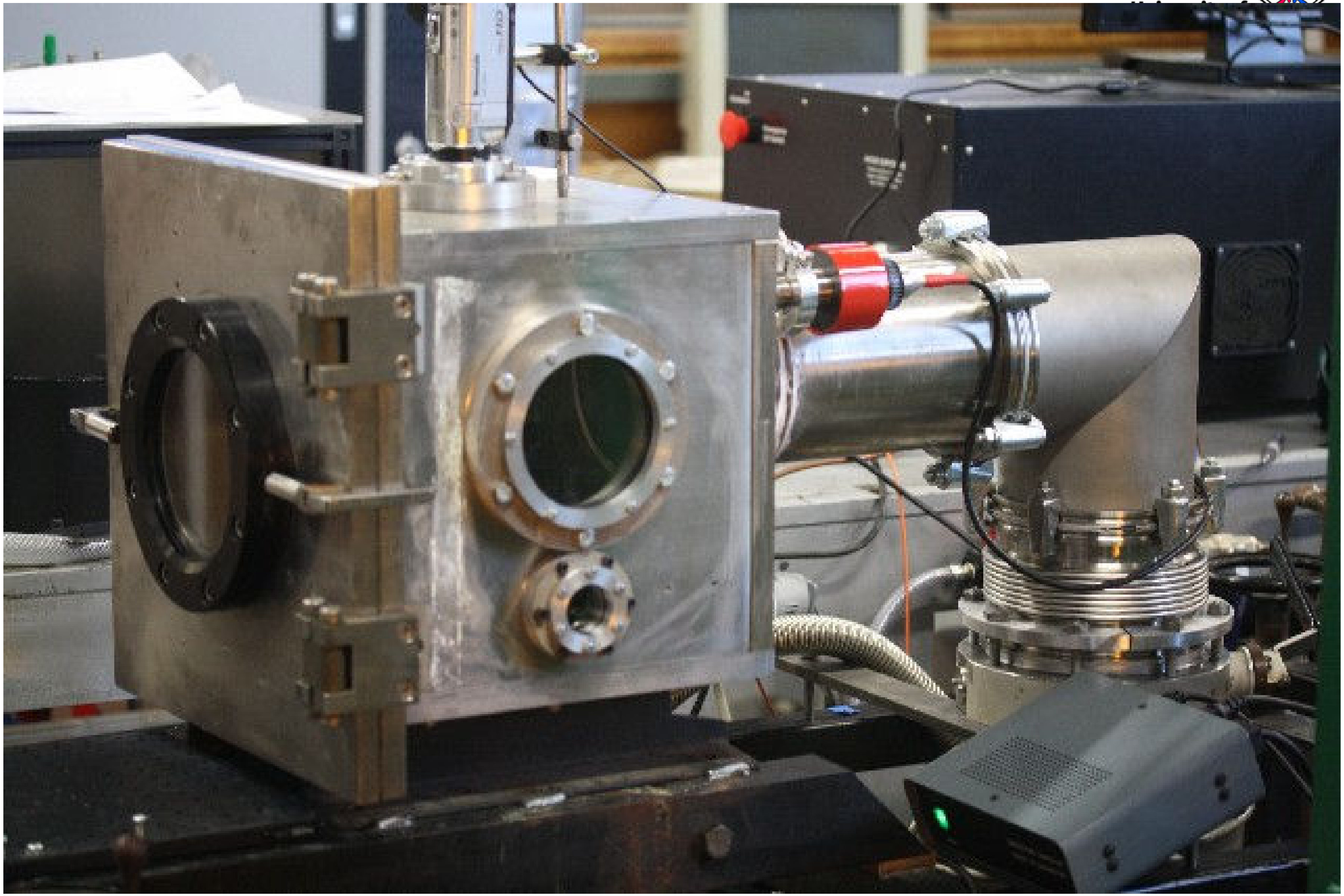

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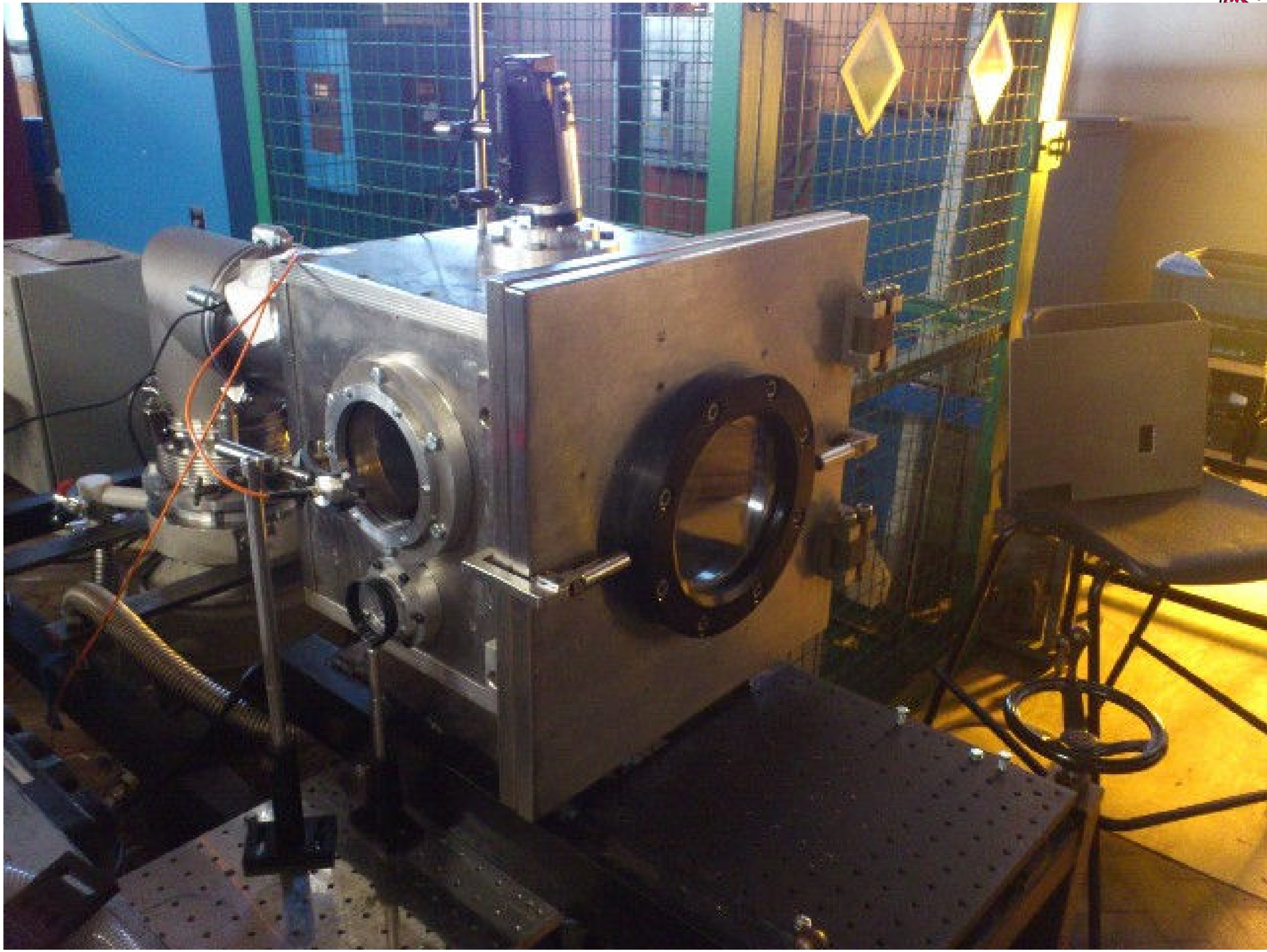

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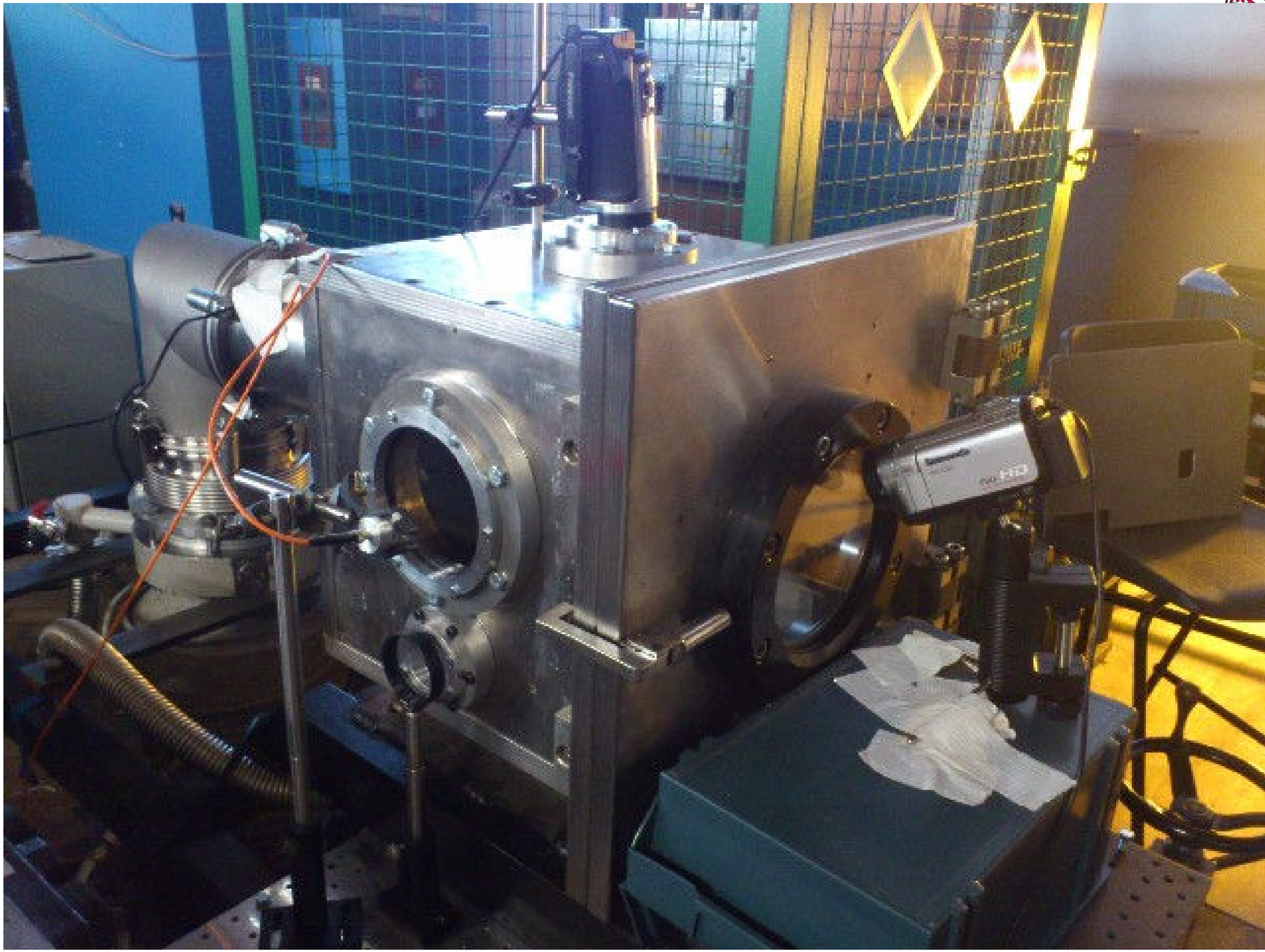

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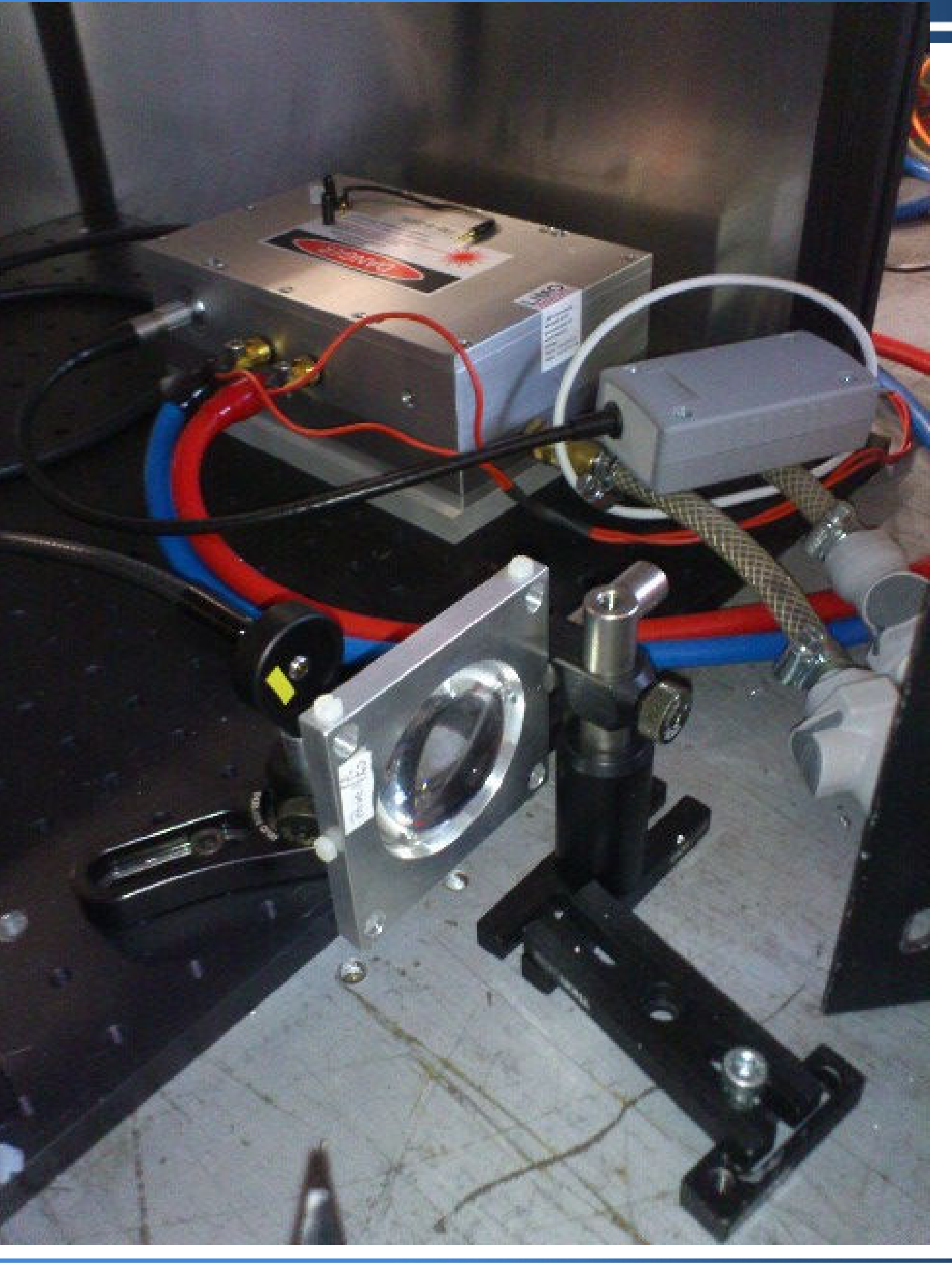

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