Advanced Large Area Deposition using Focused Beam Sources

Surface Optics Corp

SCCAVS May 15, 2012

Michael L. Fulton

Presentation Outline

- Introduction: Including a biographical synopsis
- Coating Processes: PVD and energetic (IAD)
- 3.3 Meter Diameter Chamber
- Kepler Primary Mirror Coating
- Next Generation Large Chamber
- Filtered Cathodic Arc

Brief Biography

- Optical Coating Laboratory Inc. (OCLI): 1973 to 1989
  - Process Engineering; First end-Hall ion source in production
- PSI Max Optics Inc. 1989 to 1990
  - Developed DWDM coating system—OCA / Corning Prototype
- Boeing High Technology Center: 1990 to 1993
  - World Record Space Solar Cell; IAD Development
- Avimo Singapore Ltd. 1993 to 1997
  - Filter Cathodic Arc; IAD; Night Vision; Center of Excellence
- ZC&R Coatings for Optics Inc. 1997 to 2000
  - High Out Put IAD; IFCAD; Space Station Window Program
- Rockwell Science Center 2000 to 2003
  - Laser Eye Protection; Mars Reconnaissance Orbiter
- Ion Beam Optics Inc. 2003 to 2010
  - SBIR Phase II Radiation Hardening of Space Solar Cell Covers
- Surface Optics Corp. 2010 to Present
  - Kepler Primary Mirror; Band Pass Filters for Hyperspectral Imaging; Membrane filters for Space Antennaes

SOC Chambers for Vacuum Deposited Coatings

Small R&D chamber (0.6 meter) For Coating Development

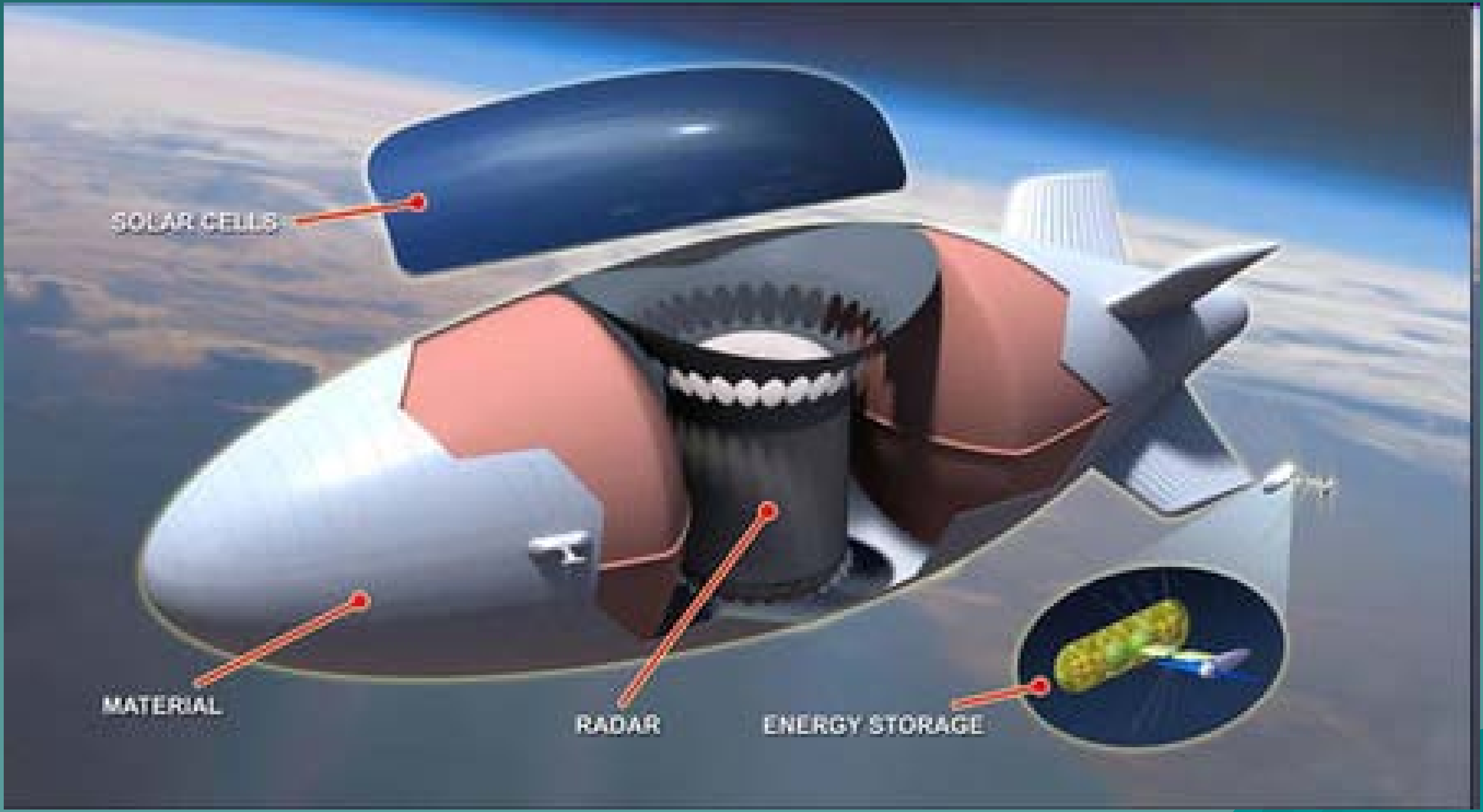
5 meter (roll-to-roll, e-beam IAD)

1.2 meter (Optical Monitoring, planetary)

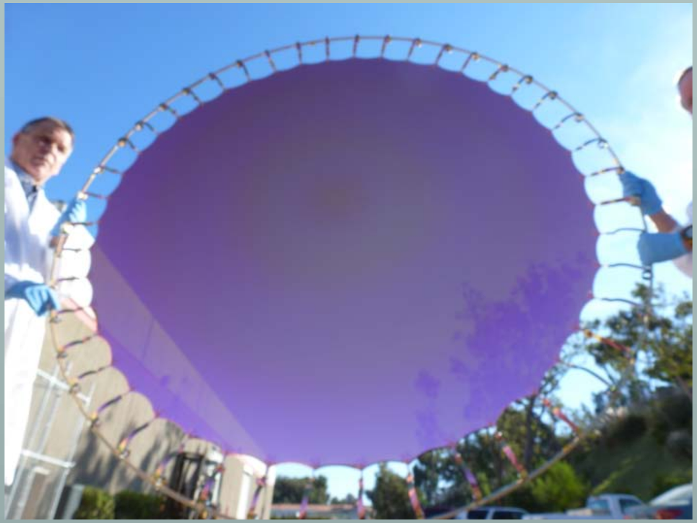
1.8 meter (roll-to-roll, or motion Controlled e-beam IAD)

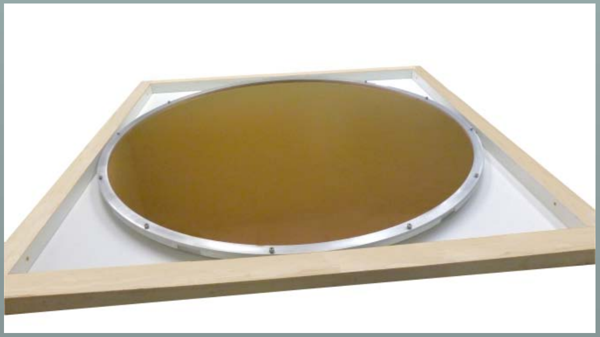
3.3 meter (motion controlled e-beam IAD)

ISIS Surveillance Blimp Program: Thermal Control Coating



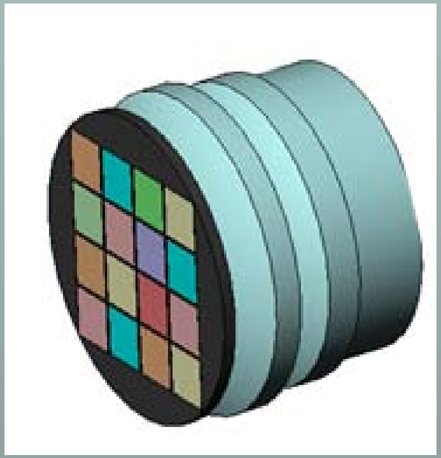
Membrane Coatings



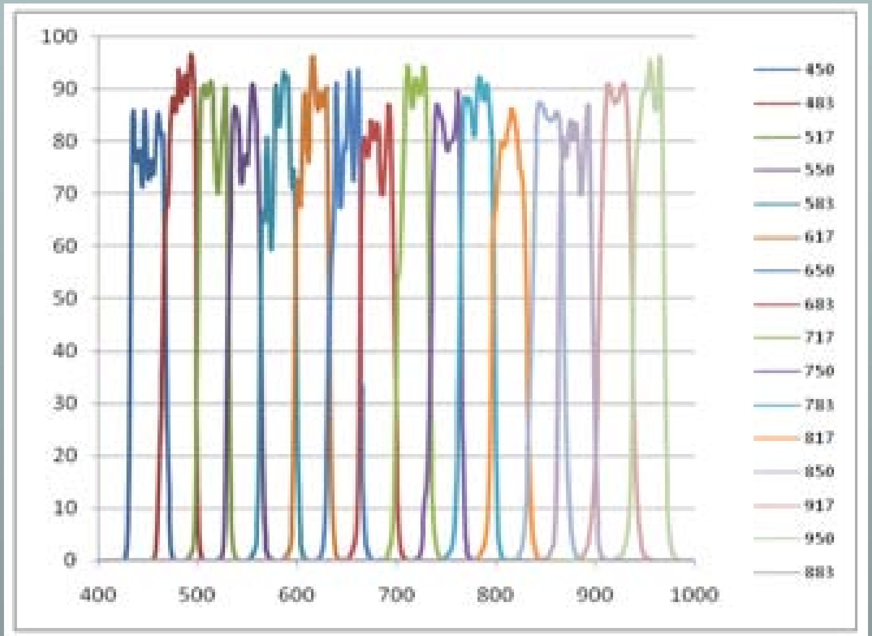


Macro Filter Array for Hyperspectral Cameras

- *Mosaic of narrow bandpass filters*
- *Vacuum deposit bandpass filters on wafer substrate*
- *Dice to size*
- *Assemble into mosaic filter array*



Optical Filter Array,
16-Bands



Filter Response Data

High-Energy Deposition Techniques Offer Advantages

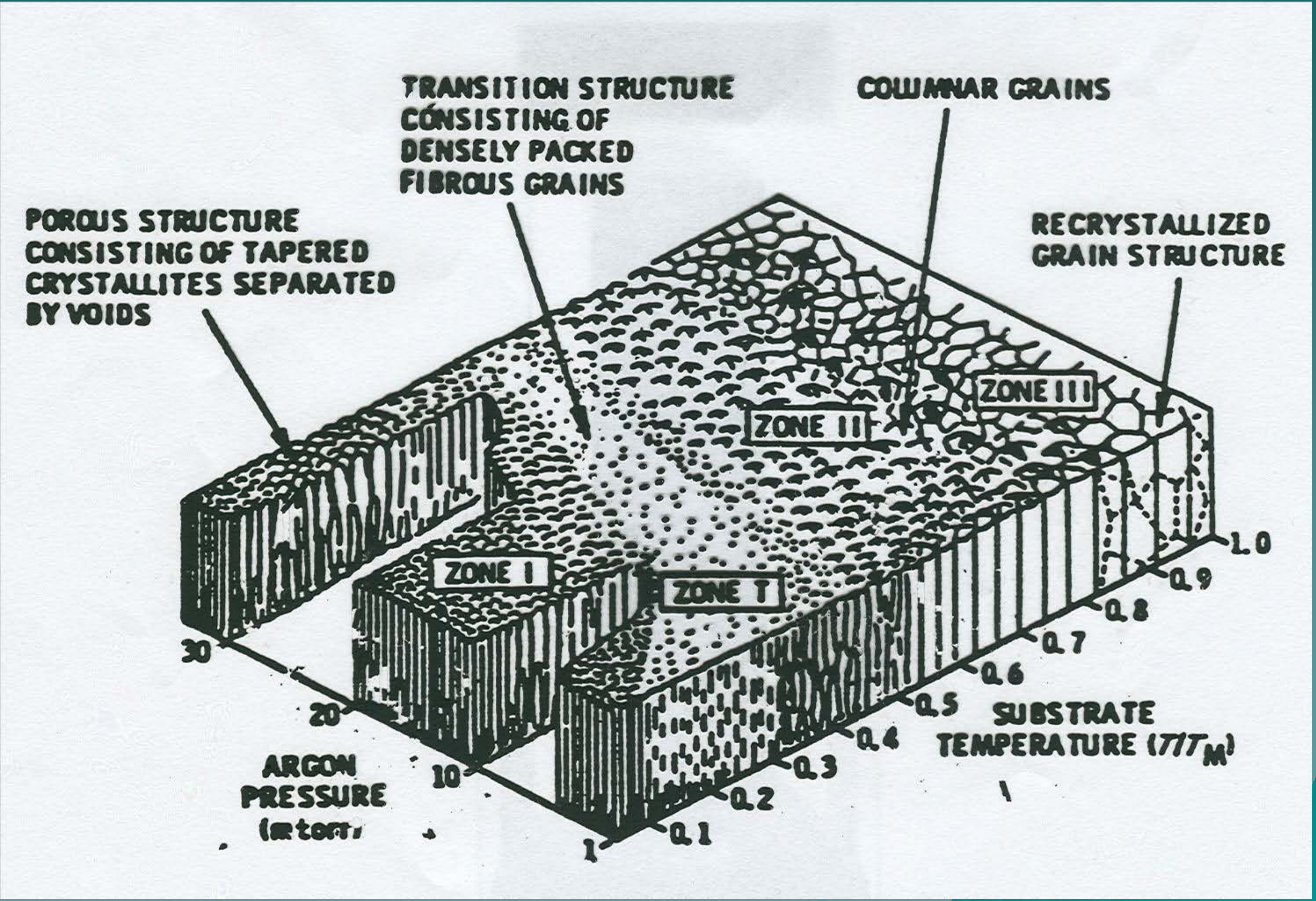
- Ion Assisted Deposition (IAD) e-beam / thermal
- Plasma Assisted Deposition (PAD) Technology
- Magnetron Sputtering

- Improve the physical qualities of optical coatings:
  - Densify microstructure
  - Reduce defect density
  - Produce stiochiometrically correct compositions with stable optical properties
    - Index
    - Low k values

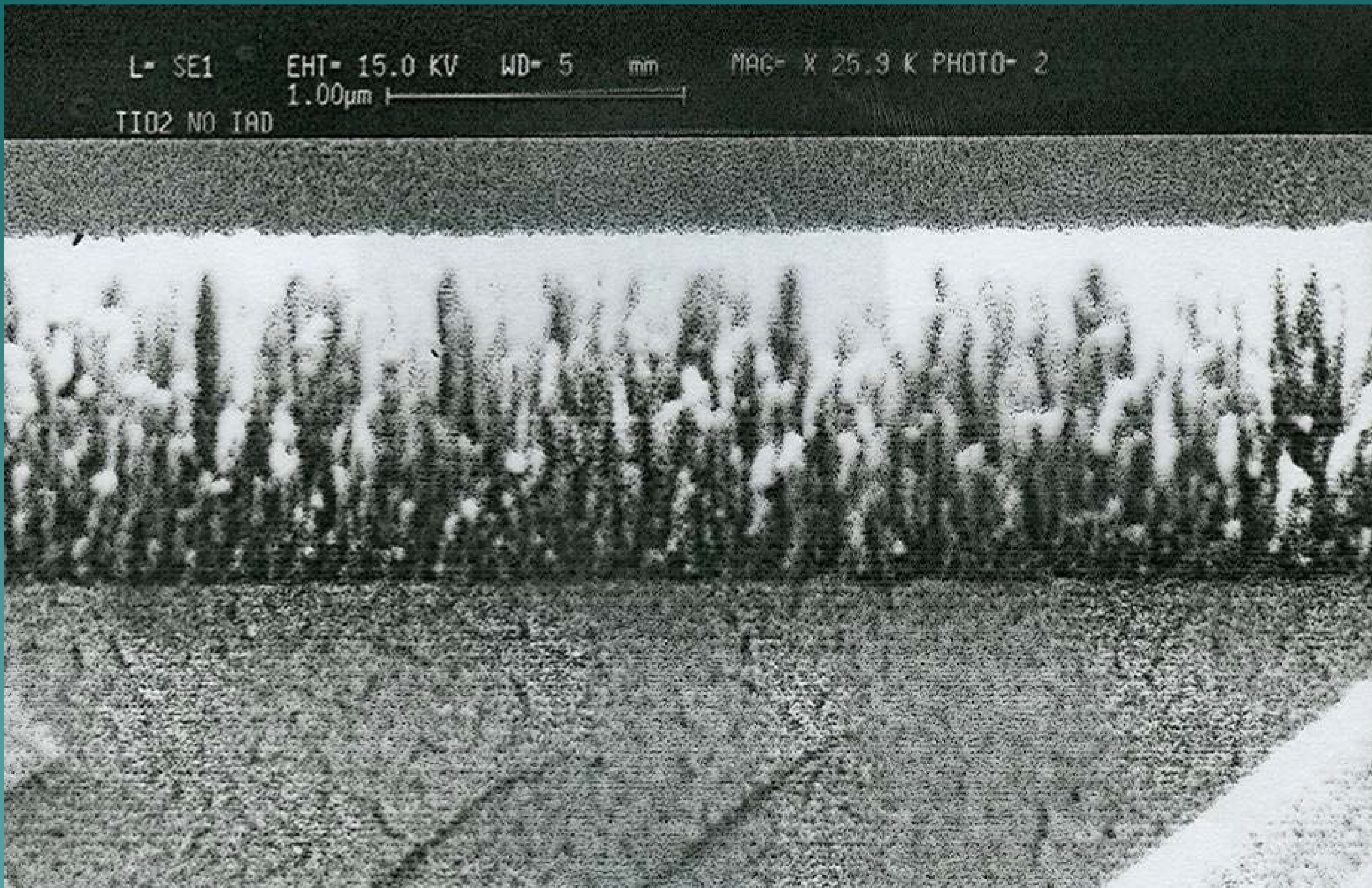
SainTech Source: Ion-Assisted-Deposition (IAD)

Ion Beam in Ion-Assisted-Deposition (IAD)

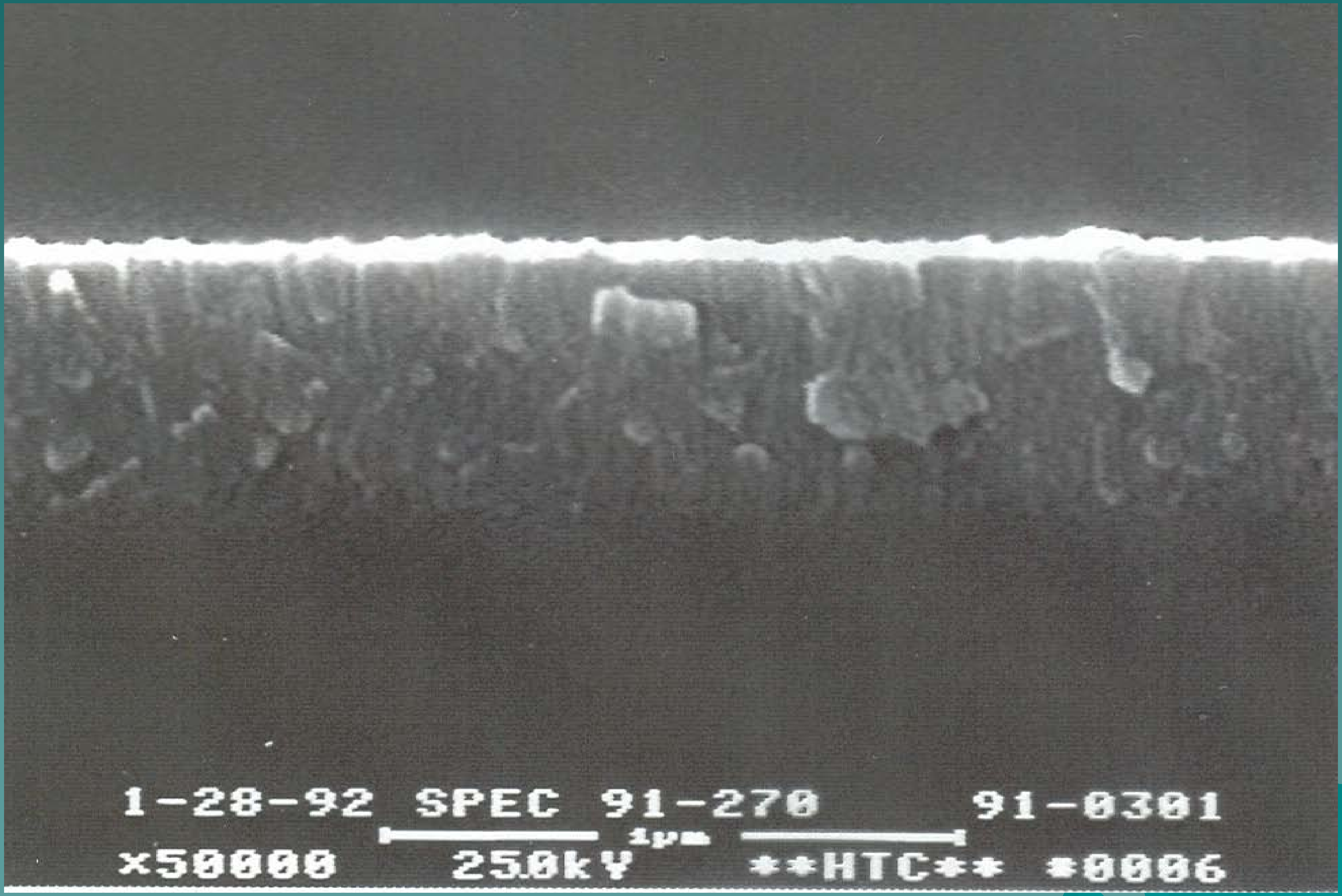
Thornton Film Growth Model (1974)



TiO_2 PVD Film Deposited at 300º C.



TiO_2 IAD Film Deposited at 50º C.

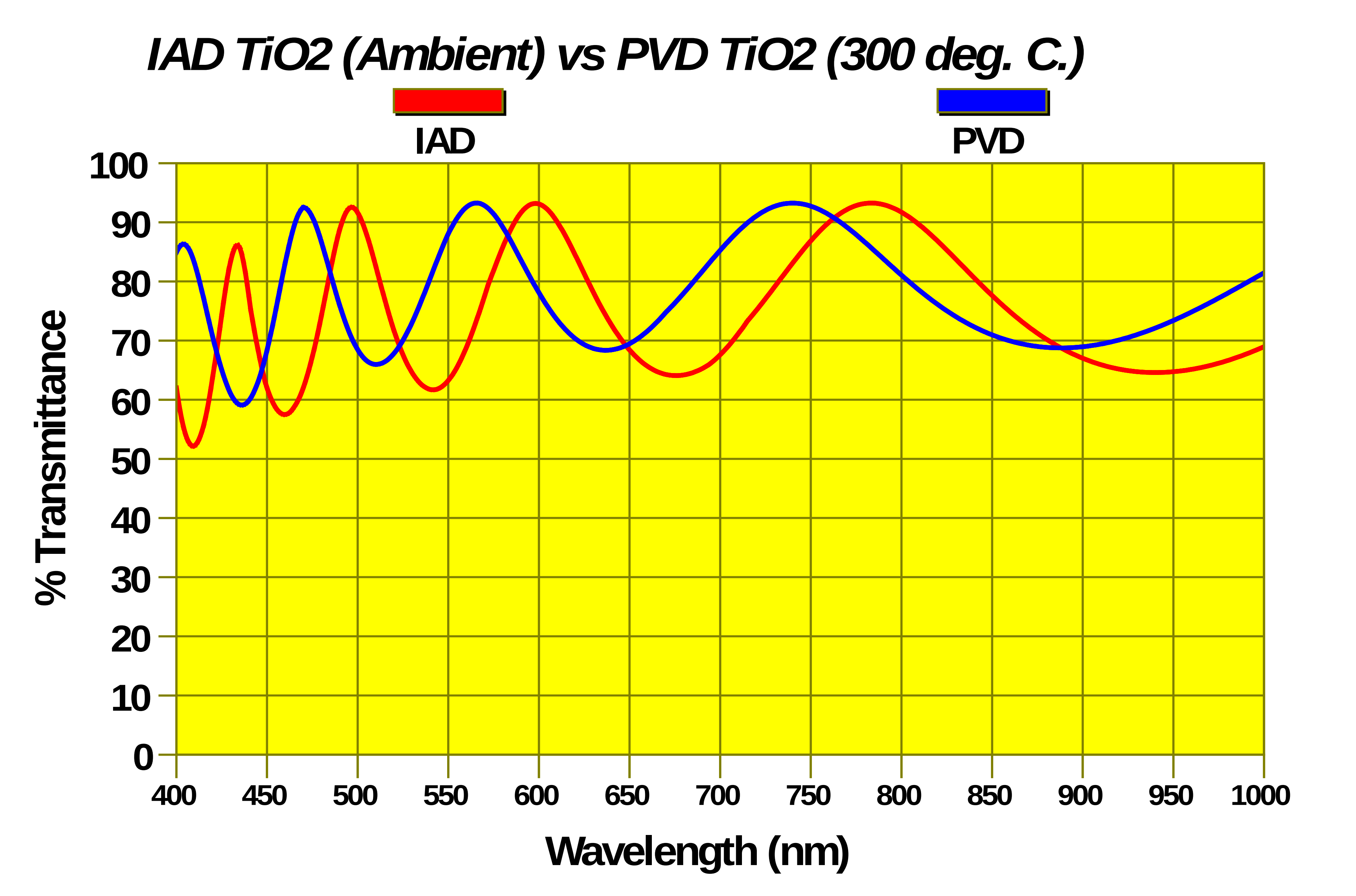


TiO_2 Optical Constants using IAD

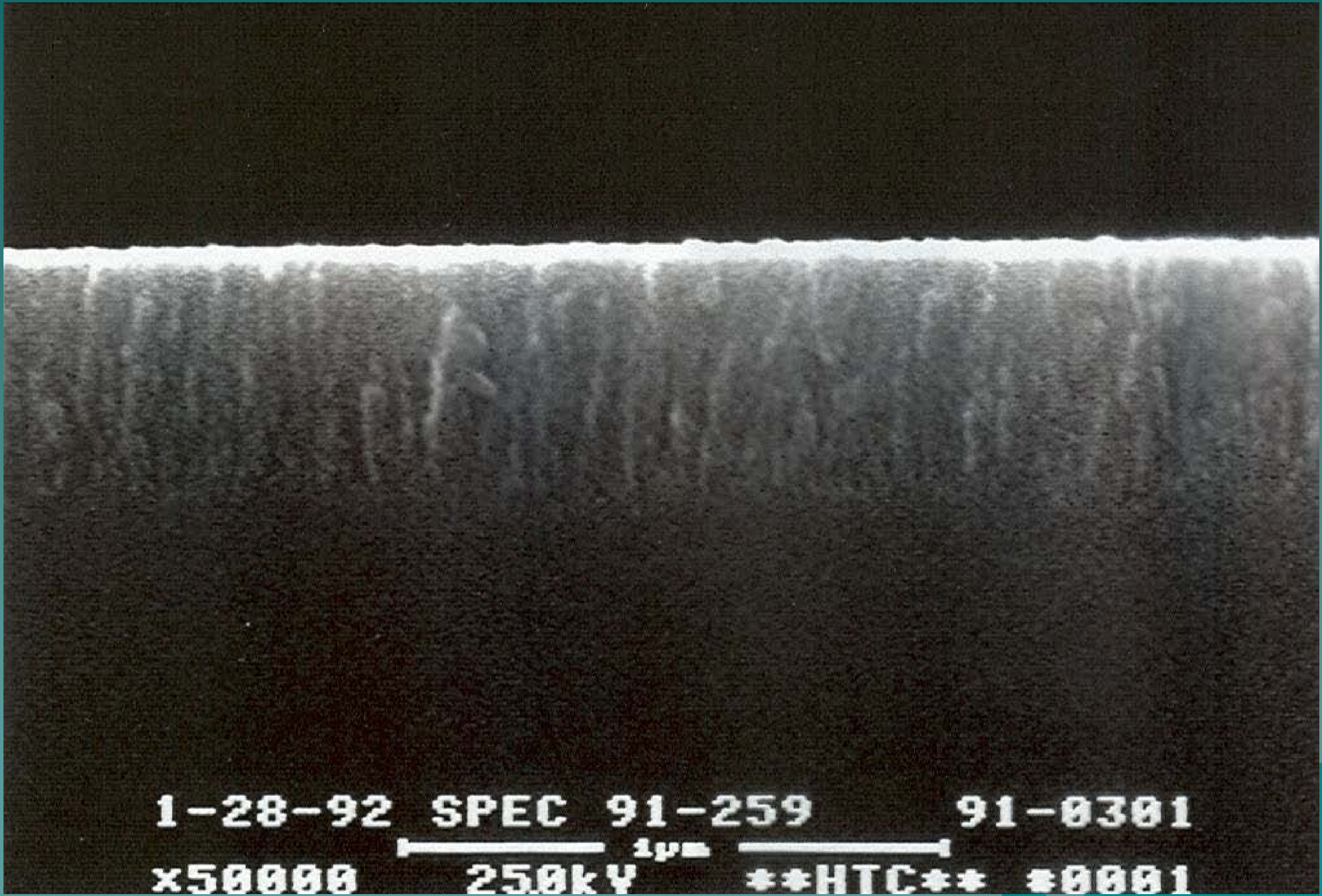
λ (nm)	n	k
300	2.85	.003
400	2.76	.005
500	2.55	.0003
600	2.47	
700	2.42	
800	2.41	
1000	2.40	

- PVD Process = 2.35 @ 500nm

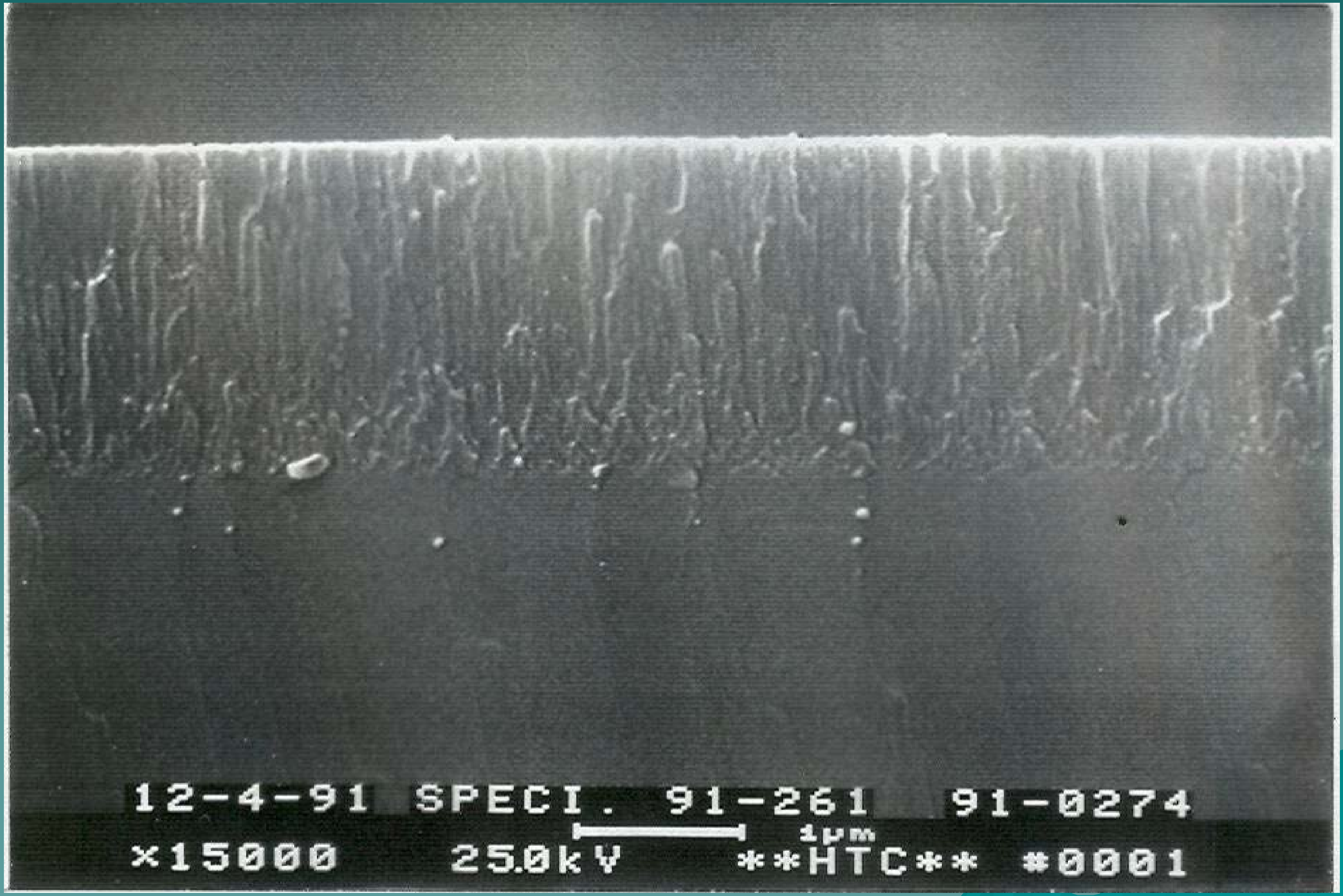
TiO_2 Optical Constants using IAD



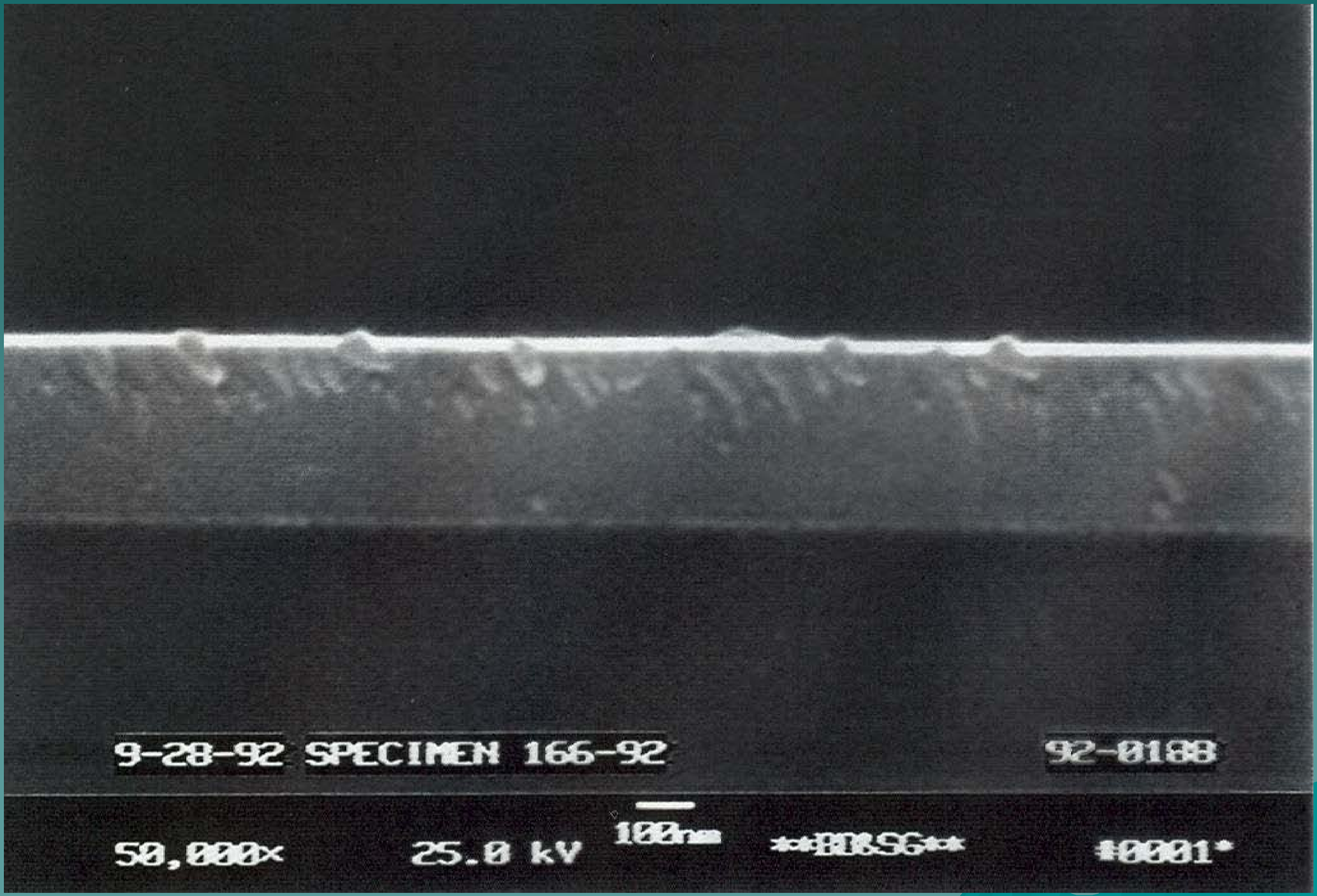
SiO_2 IAD Film Deposited at 50º C.



Al_2O_3 IAD Film Deposited at 50º C.



Si_3N_4 IAD Film Deposited at 50º C.



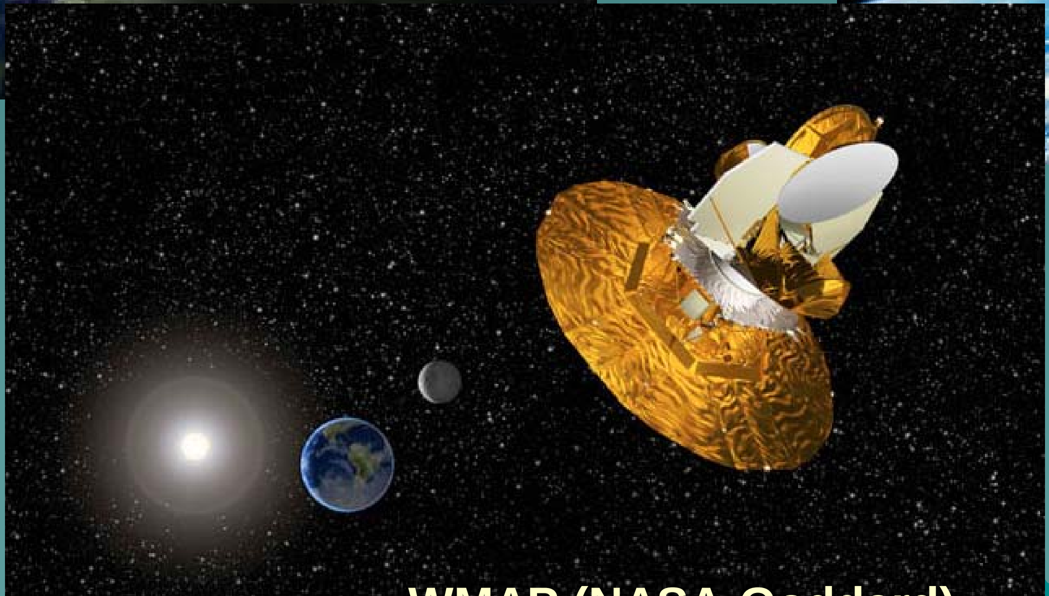
Ion Assisted Deposition Summary

- Temperature: Second Order Effect
- Mechanical Properties: Improved Adhesion & Durability
- Optical Performance: Refractive Index Stability
- Manufacturing: Repeatability
- Temperature Sensitive Substrates
- Pulsed IAD: Fluoride Deposition at
  Ambient Substrate Temperature

SOC Heritage…Spaceflight Reflectors

CloudSat (JPL)

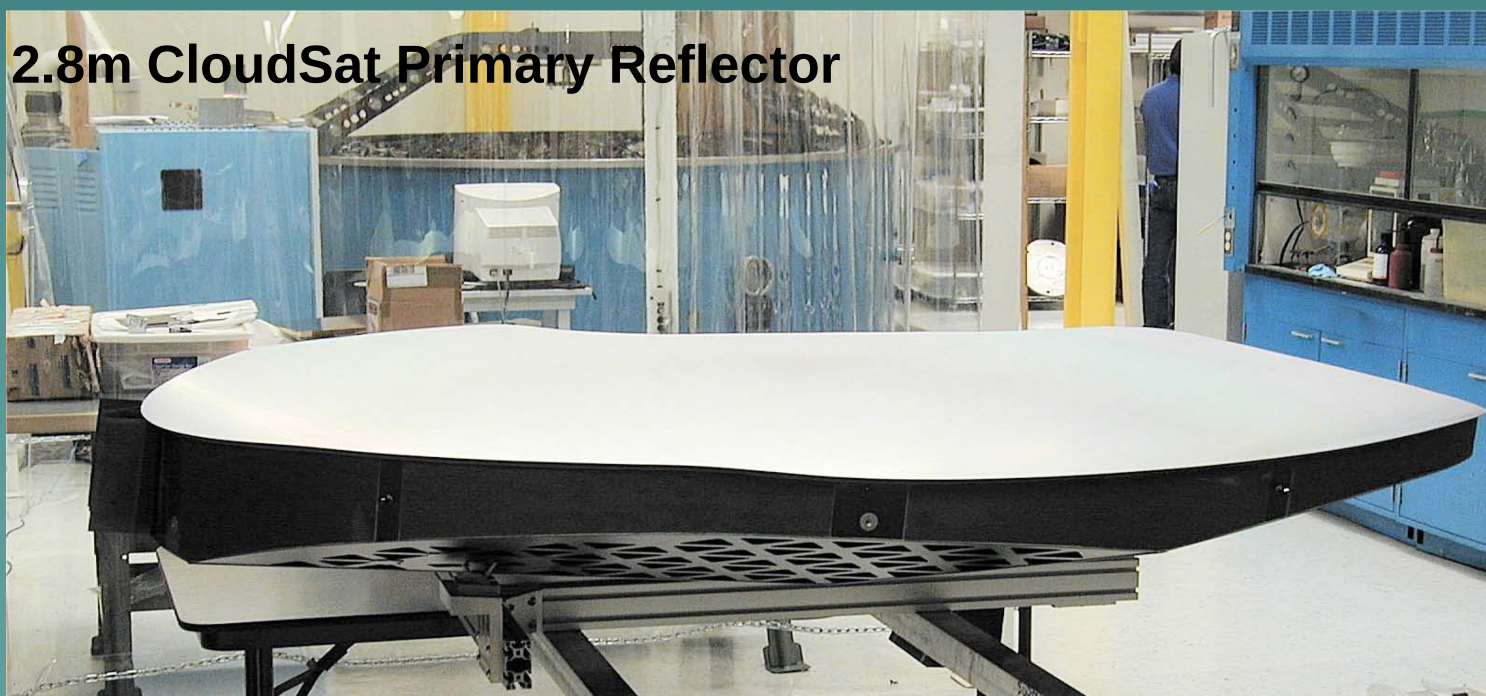
Commercial Telecom Satellite (Boeing)



WMAP (NASA-Goddard)

Typical Reflector Requirements

Materials	Aluminum, Silicon Oxide (SiOx or SiO_2)
Thickness	20,000Å +/- 2,000Å
Size	1m < Diameter < 3m

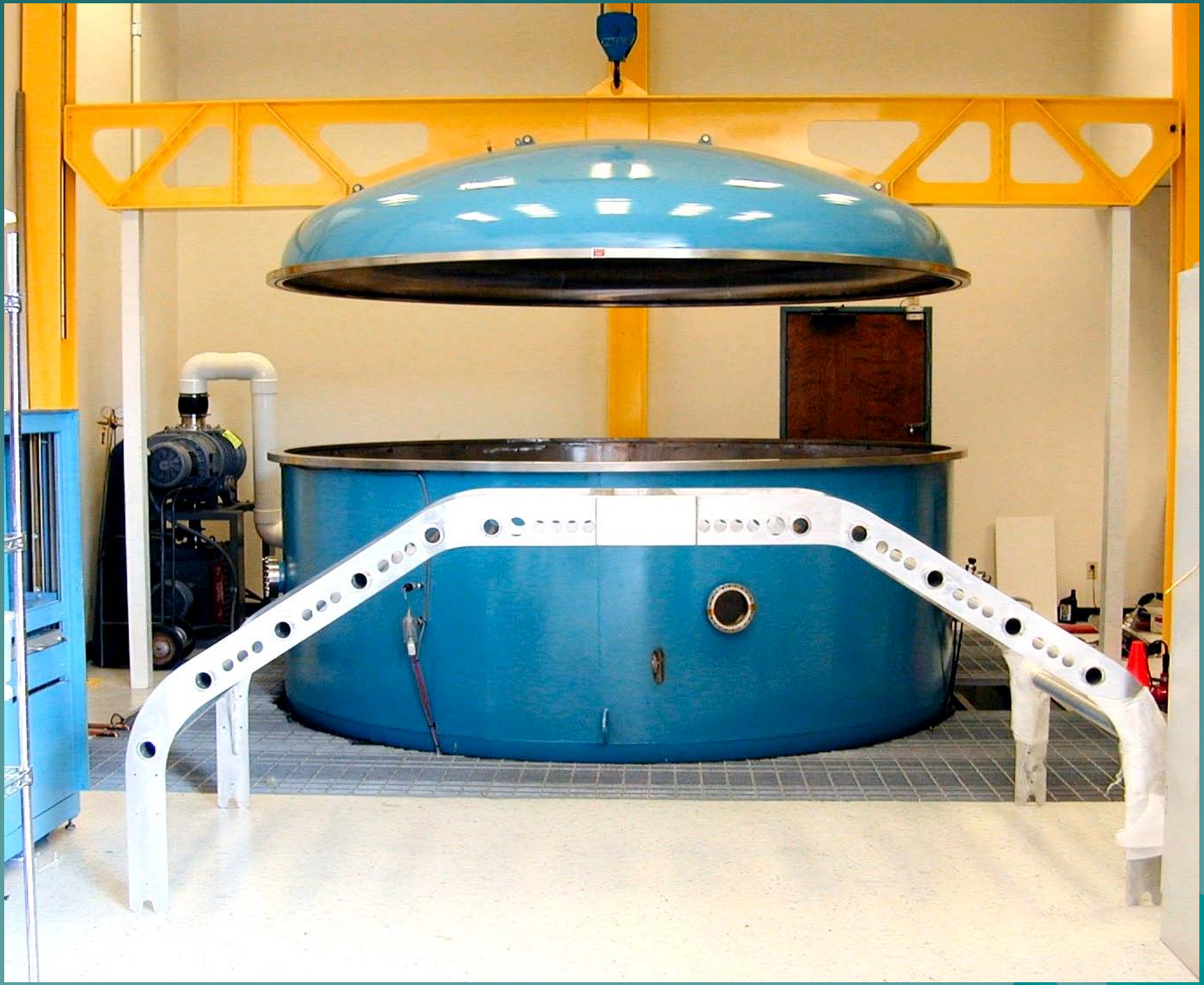


2.8m CloudSat Primary Reflector

CLOUDSAT: CLIMATE SURVAYOR

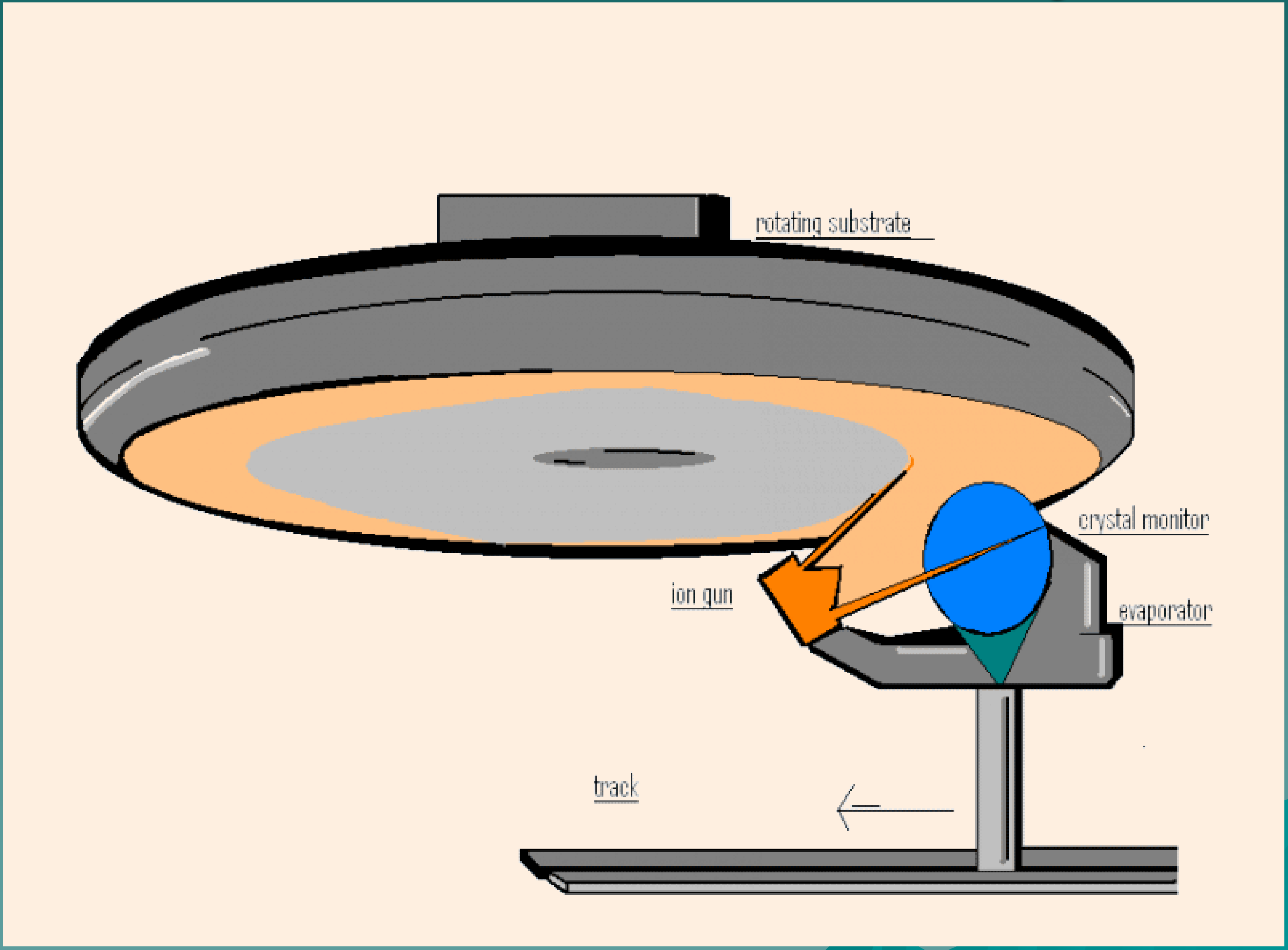
Satellite Program to Monitor Climate and Weather from Space

3.3m Diameter Vacuum Chamber Commissioned (2001)



Fixture Diameter - 120 inches

Animation of motion system



Moving Into Optical Coatings…

- ☑ Improvements in Thickness feedback and control
- ☑ Ion Assisted Deposition (IAD) was added for greater material & process versatility

NASA need: Space Qualified Silver

Reflectance	R > 95%, 360nm to 2,000nm
Stress	Compatible w. lightweight substrate
Space Environment	Radiation, thermal cycling
Ground Environment	Humidity, T/C, cleaning, adhesion
Size (dia.)	Up to 2.5m, or multiple segments up to 1.5m

LLNL Protected Silver Design

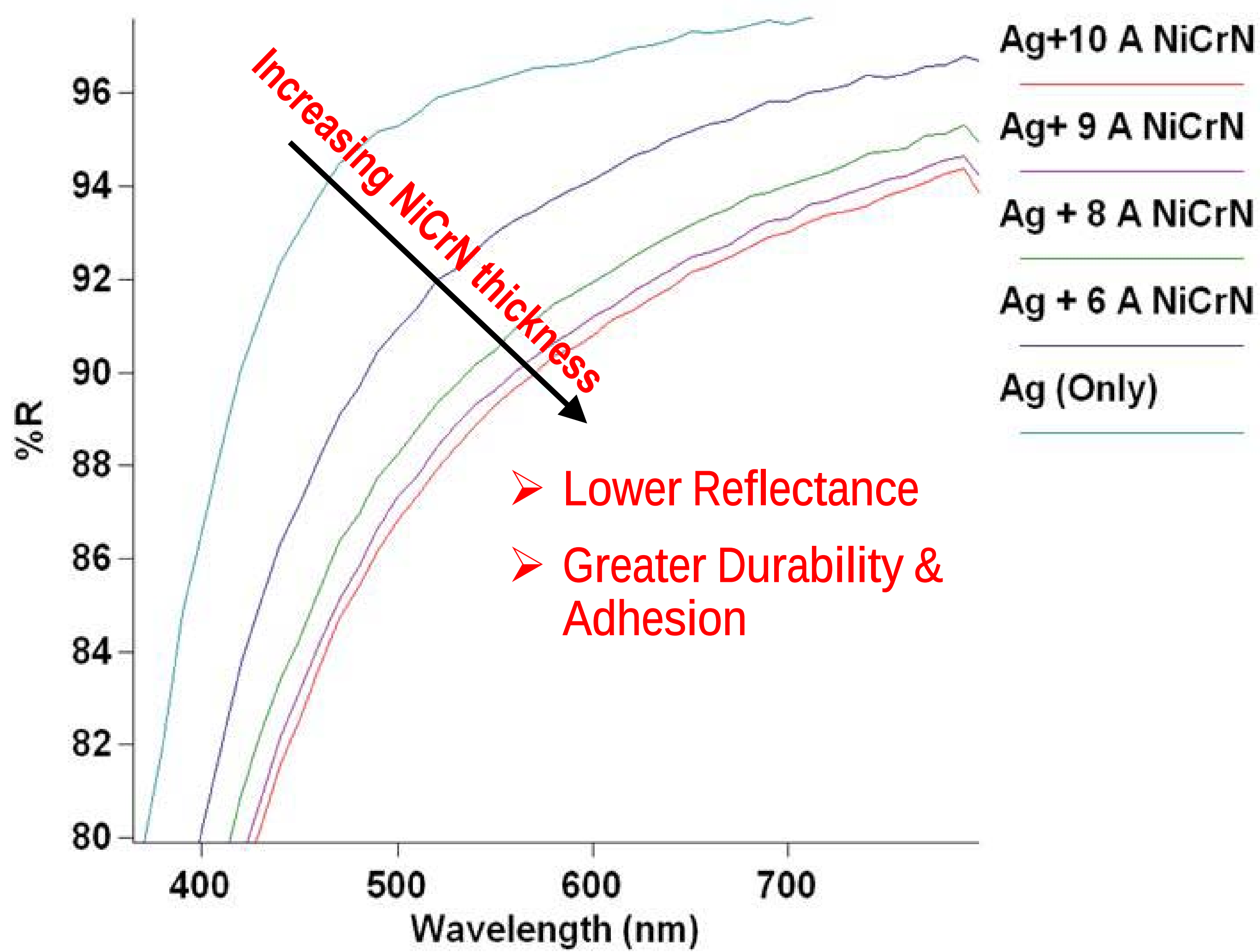
L-Oxide	Reflection Enhancement Layers
H-Oxide	
L-Oxide	
H-Oxide	
L-Oxide	
Si_3N_4	Basic Protected Ag
$Ni\text{-}CrN_x$	
Ag	
$Ni\text{-}CrN_x$	
Substrate	

- Design developed & verified at LLNL.
- LLNL created nitride layers by sputtering NiCr and Si in presence of N+ ions.
- SOC developed process to produce nitride layers by IAD. (SBIR funding)
- NiCrN highly absorbing in blue/UV. Want to apply minimum thickness only.

Why LLNL protection works?

- NiCrNx
  - Prevents Ag from reaction with S+
  - Promotes adhesion between Si_3N_4 and Ag
- Si_3N_4
  - Protects Ag from S+ and other chemical attack
  - Protects Ag from O+ during oxide deposition
- SiO_2/Ta_2O_5 pairs
  - Protect surface from scratching
  - Tailor to enhance reflectance in blue/UV

Effect of NiCrN thickness on Ag reflectance



- Lower Reflectance
- Greater Durability & Adhesion

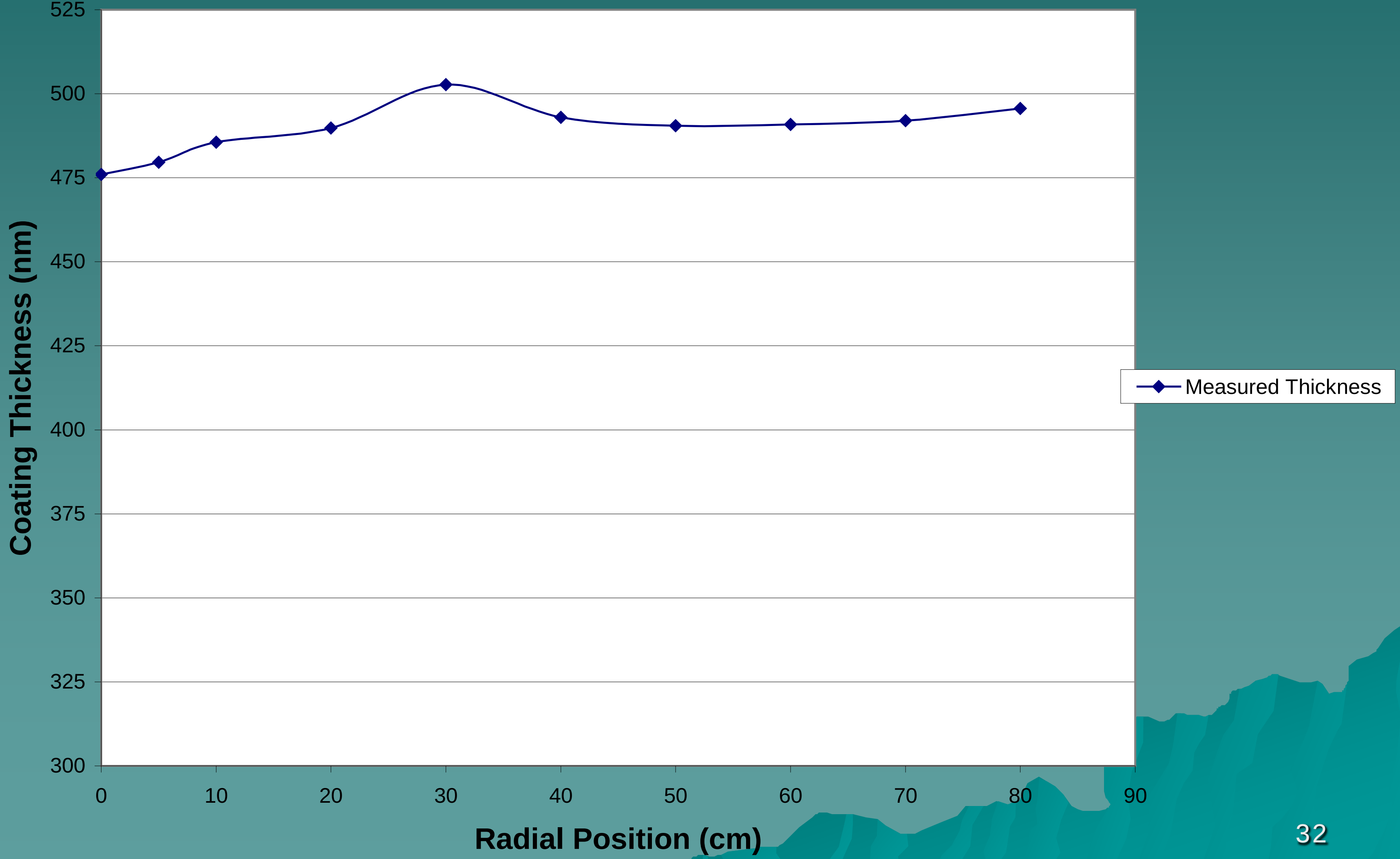
LLNL Processing Challenges for Silver on Large Optics (Kepler)

- Precise deposition of 5Å of NiCrNx difficult over large areas.
- N+ bombardment of NiCr to make NiCrNx removes NiCr (had to compensate by adding extra NiCr to outer radial positions).
- Si_3N_4 easily contaminated with background gas (requires exceptional vacuum). Need for UHV slows cycle time between runs.
- Si_3N_4 has high index that reduces Ag reflectance.

Processing Challenges for Large Optics (Kepler): Uniformity

- Deposition Uniformity of 5Å of NiCrNx difficult over large areas: e-beam / IAD plume control a huge challenge
- Si_3N_4 uniformity was also a challenge; Ag and the dielectrics were less troublesome
- General uniformity constraints: precision of translation stage movement; confinement of e-beam and resistance source plumes; center position sensitivity; and process repeatability.

Processing Challenges for Large Optics (Kepler): Uniformity



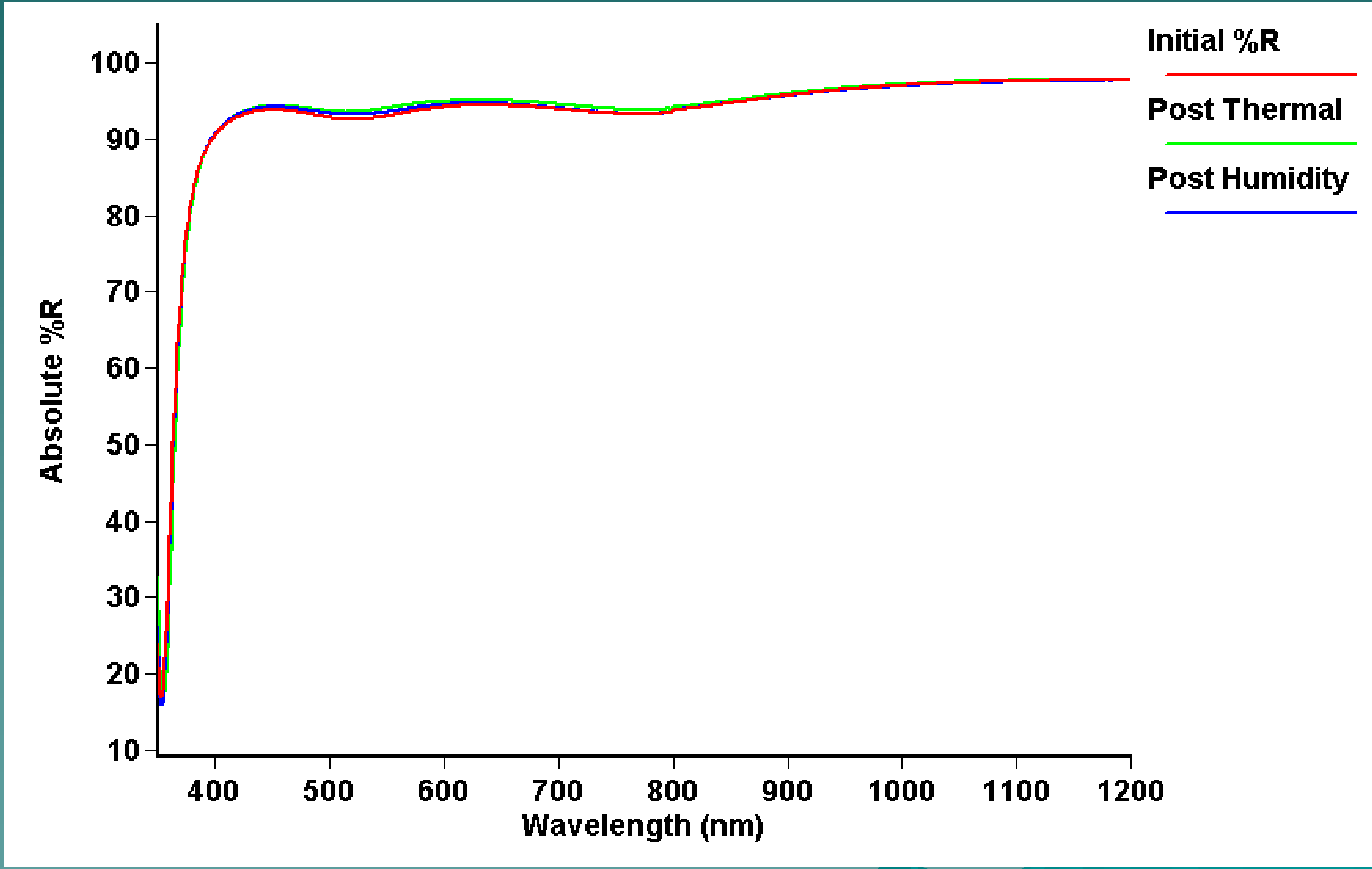
Processing Challenges for Large Optics (Kepler): Durability

- Durability requirements were driven primarily by the terrestrial exposure prior to launch

- The humidity test consisted of a 24-hour exposure at 50°C and 95% RH. The coating was thermally cycled 30 times from -80°C to +35°C and the reflectance was measured before and after each exposure test. Following environmental exposures, the coating passed MIL-13508C adhesion and moderate abrasion tests.

- Protected Ag Coating with Five-Layer HL Interference Coating; Passed Environmental Testing: Next Slide

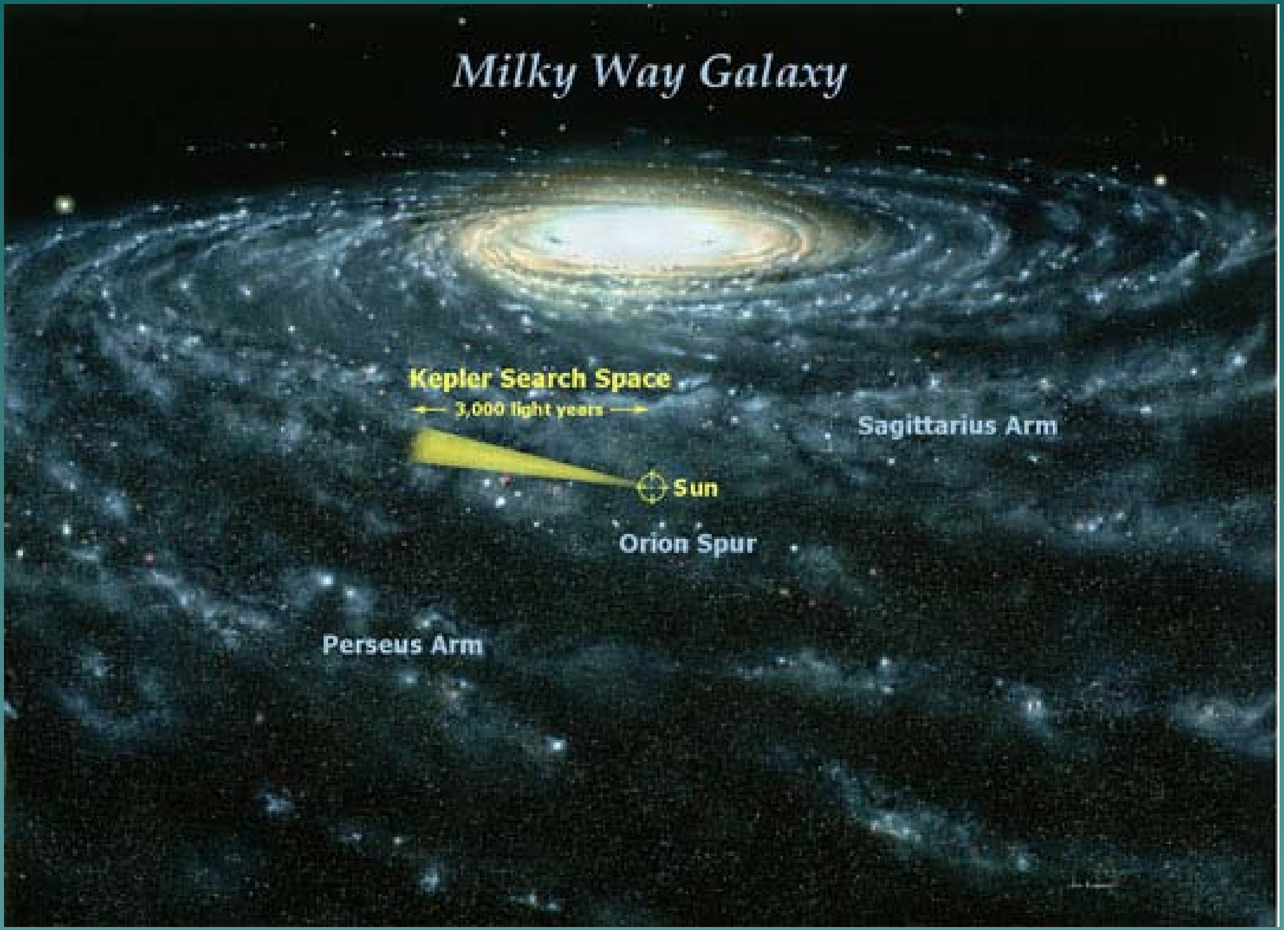
Processing Challenges for Large Optics (Kepler): Durability



Processing Challenges for Large Optics (Kepler): Computer Control Improvements

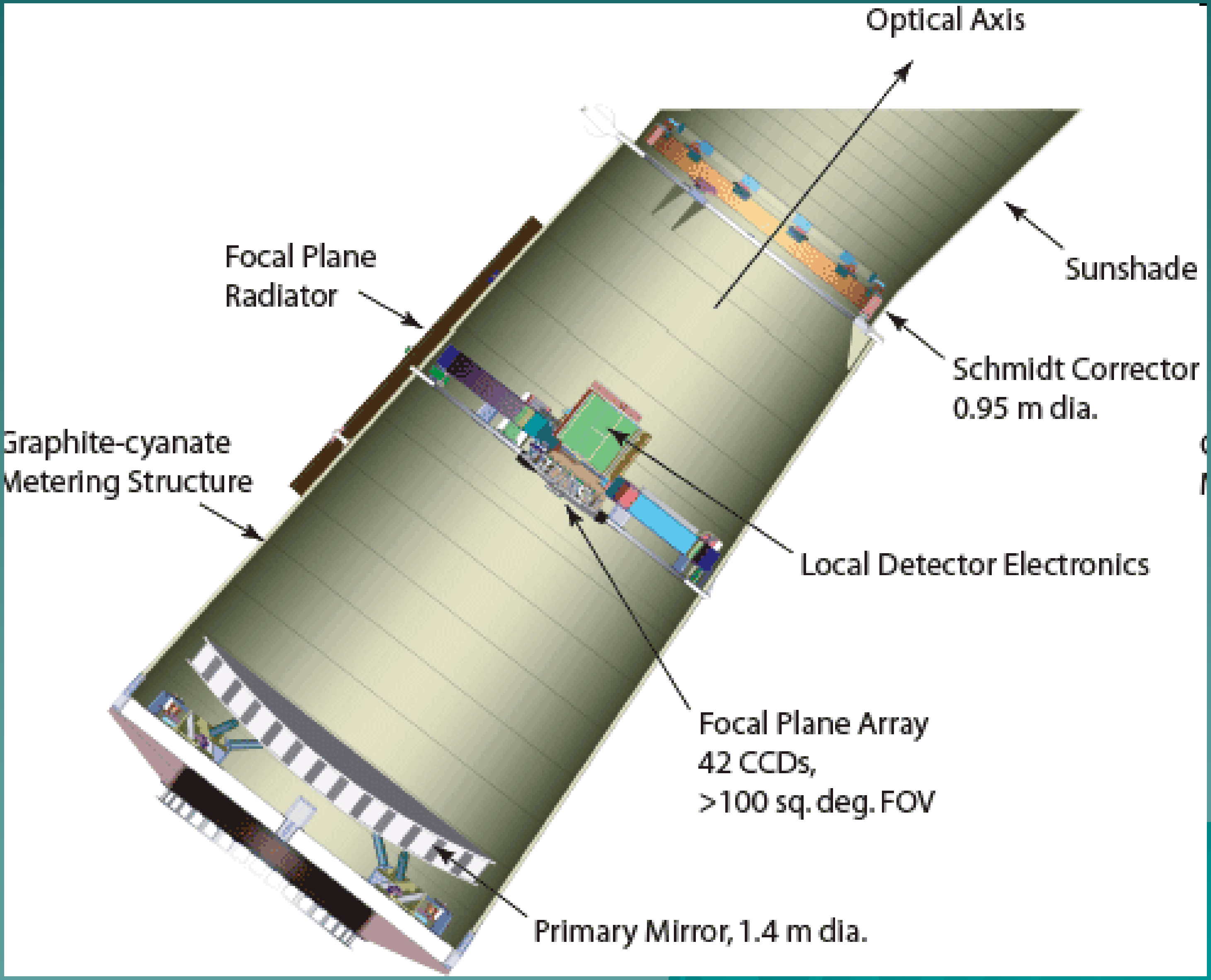
- Old program ran on text files with relevant automation data; new version includes ability to generate text files from an updateable material data base.
- Program allows coating to deposit from the outside to inside (or, visa versa): thin layer rate is more controlable when source is already on.
- Others: Limit switches for home and start positions; run log file has overshoot data; computer control for translation stage stepper motor results in < 1% run-off across part.

Kepler Mission

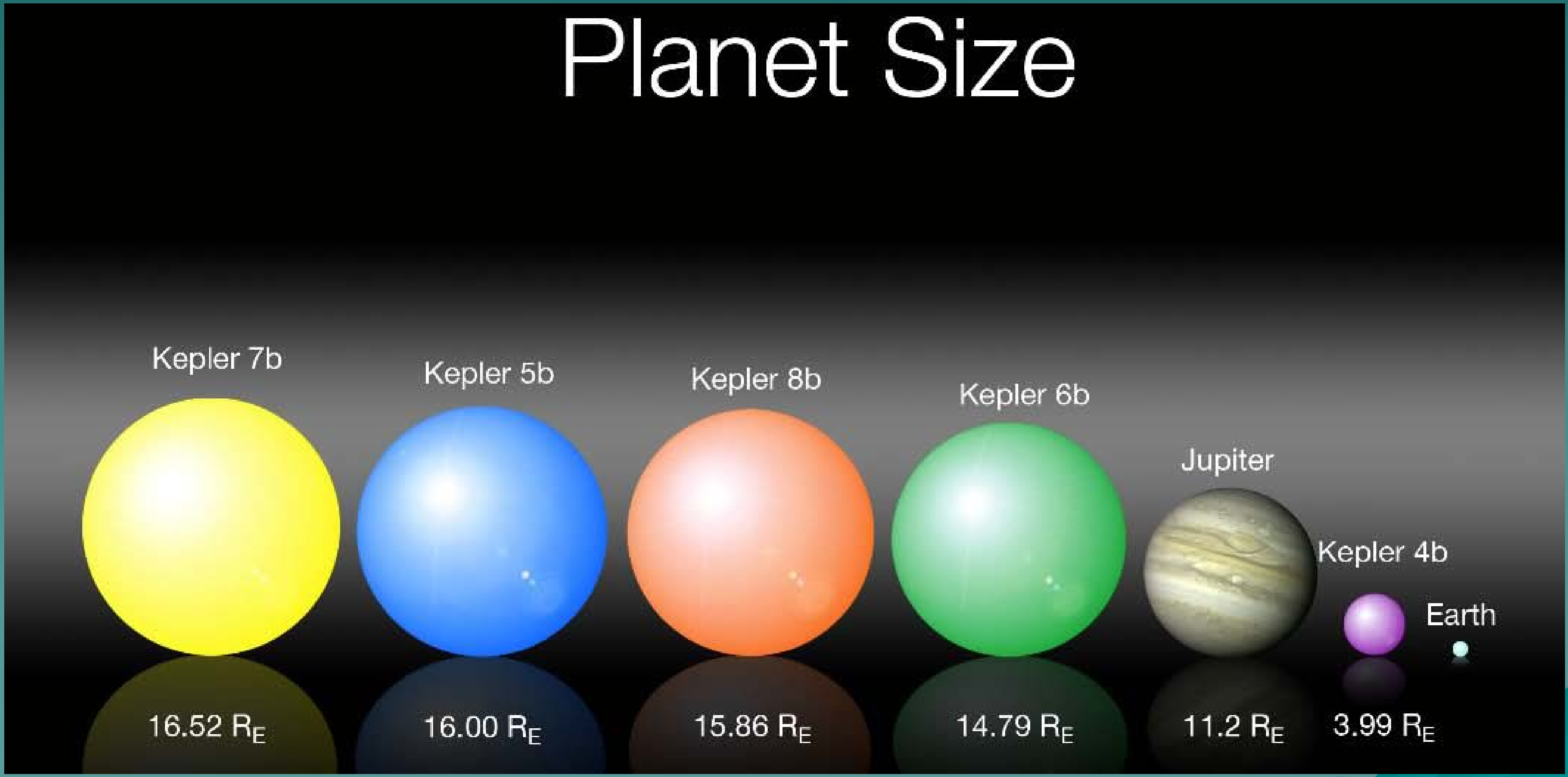


The Milky Way, showing our sun about 25,000 light years from the galaxy's centre. The yellow cone illustrates the region or 'starfield' in which Kepler hunts for habitable planets

Kepler Spacecraft



Discovery of First 5 Planets reported January, 2010

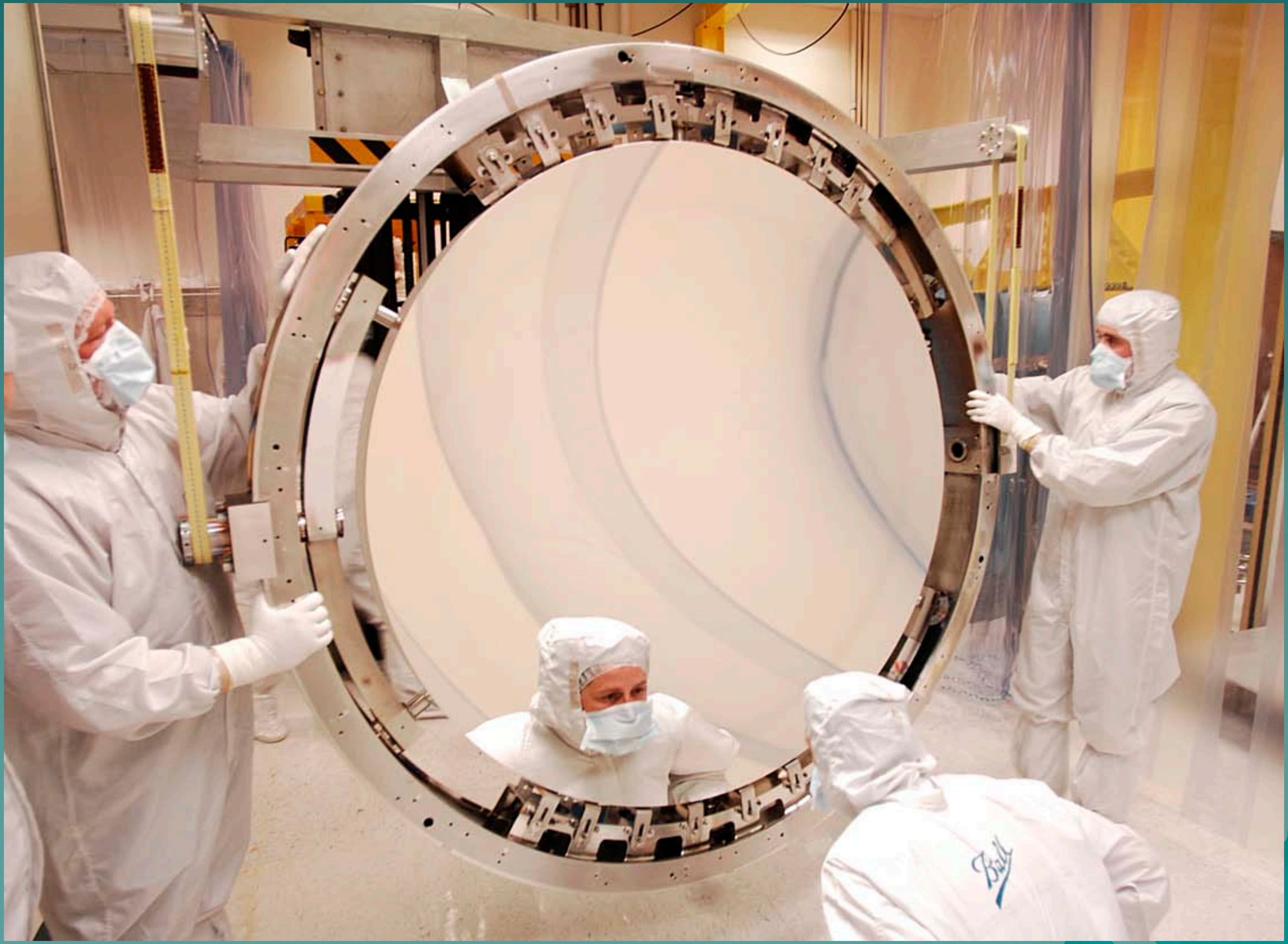


Surface Optics Corporation
Kepler Primary Mirror (1.4 m dia.)

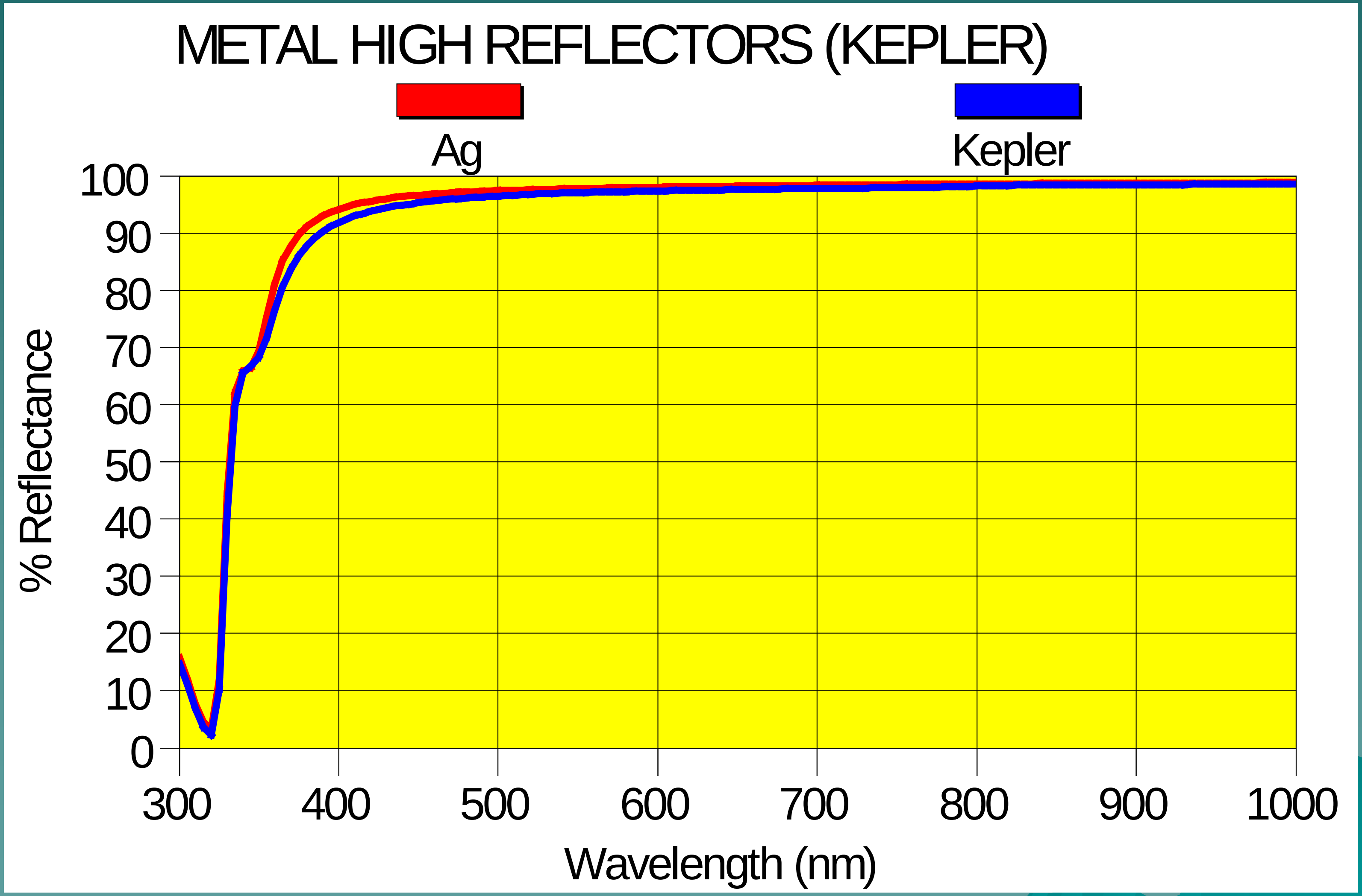
Surface Optics Corporation
Kepler Primary Mirror

Surface Optics Corporation
Kepler Primary Mirror

Surface Optics Corporation
Kepler Primary Mirror

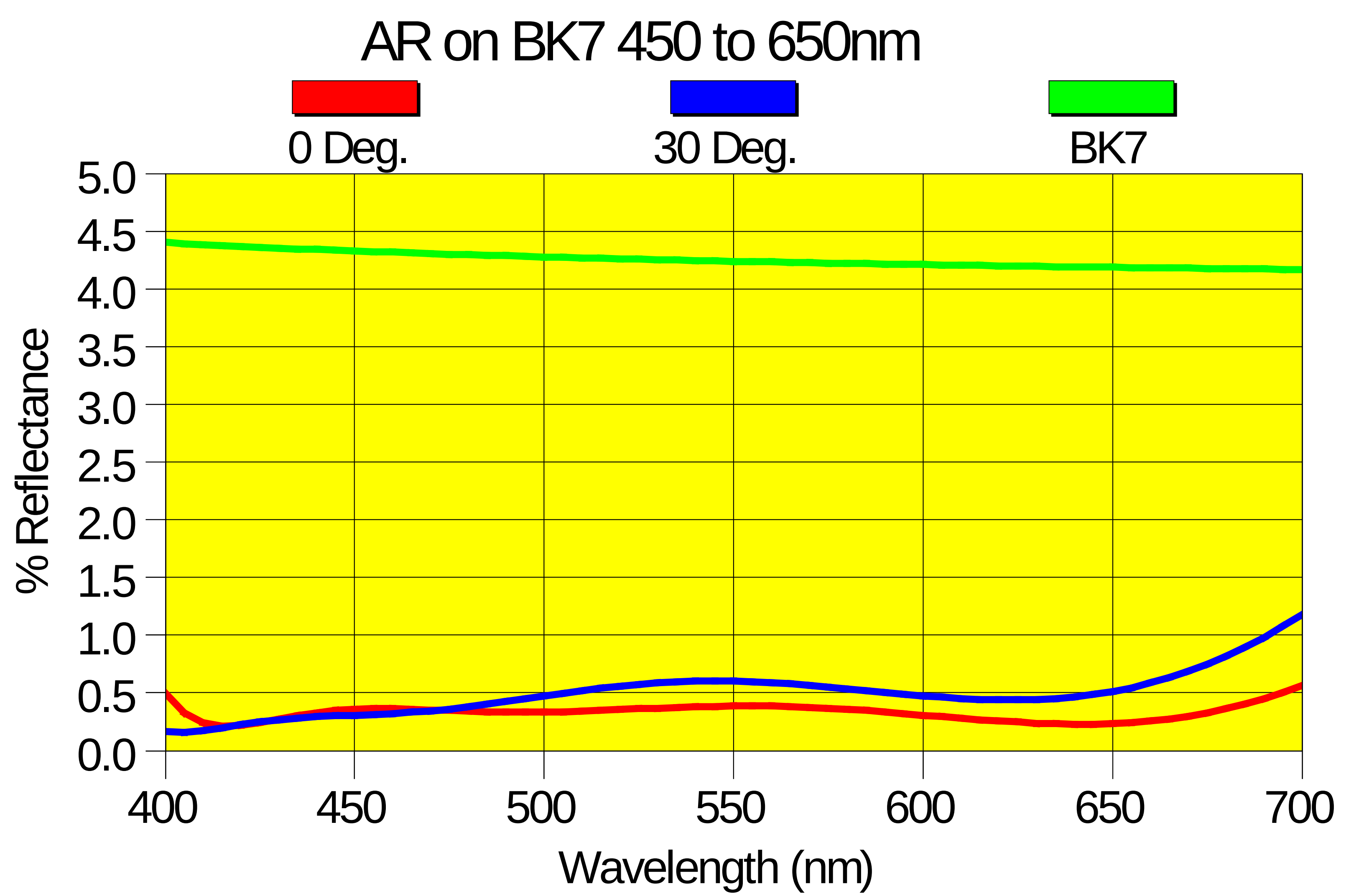


Surface Optics Corporation
Kepler Primary Mirror

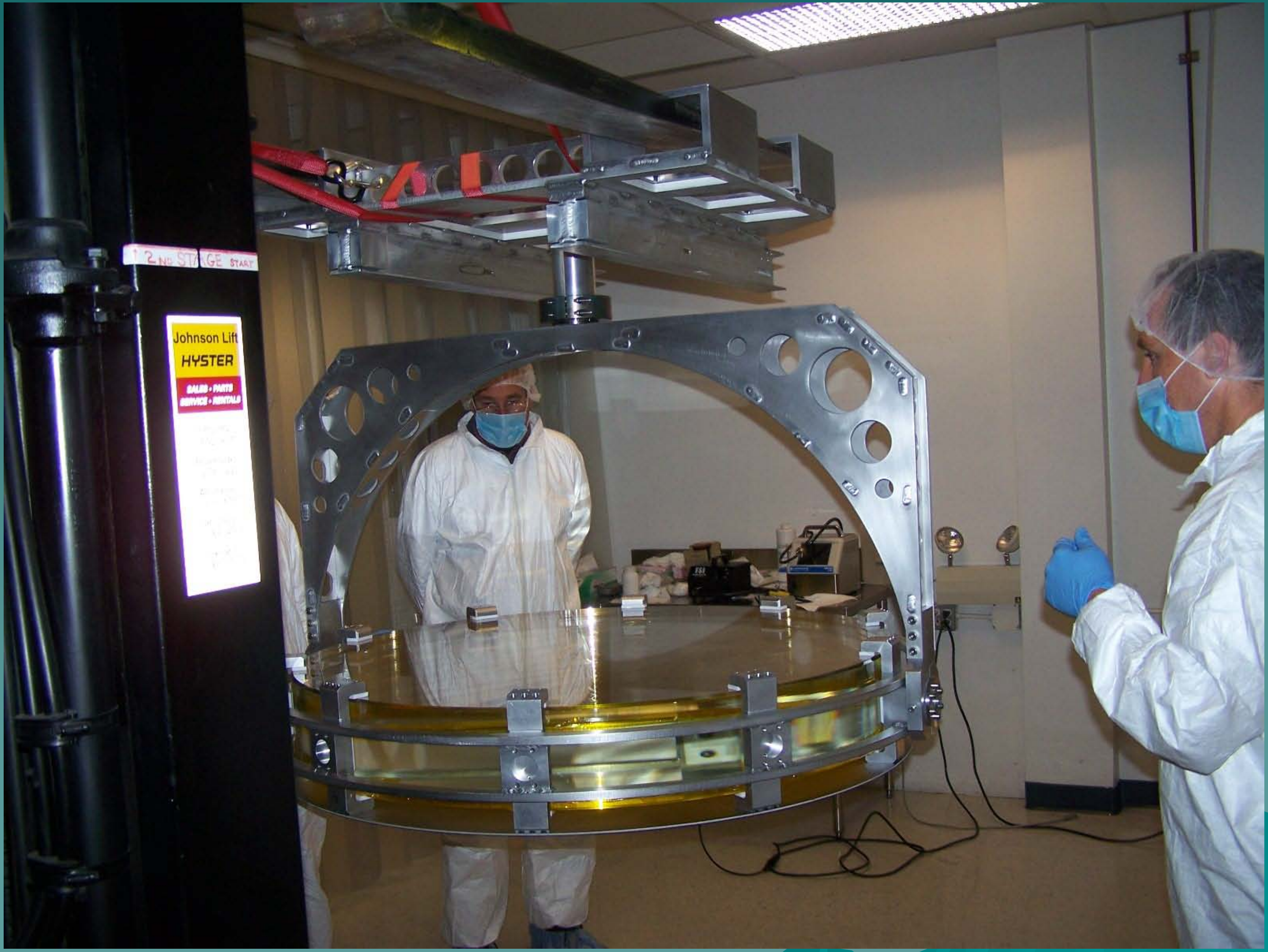


AR Window For NIF at LLNL

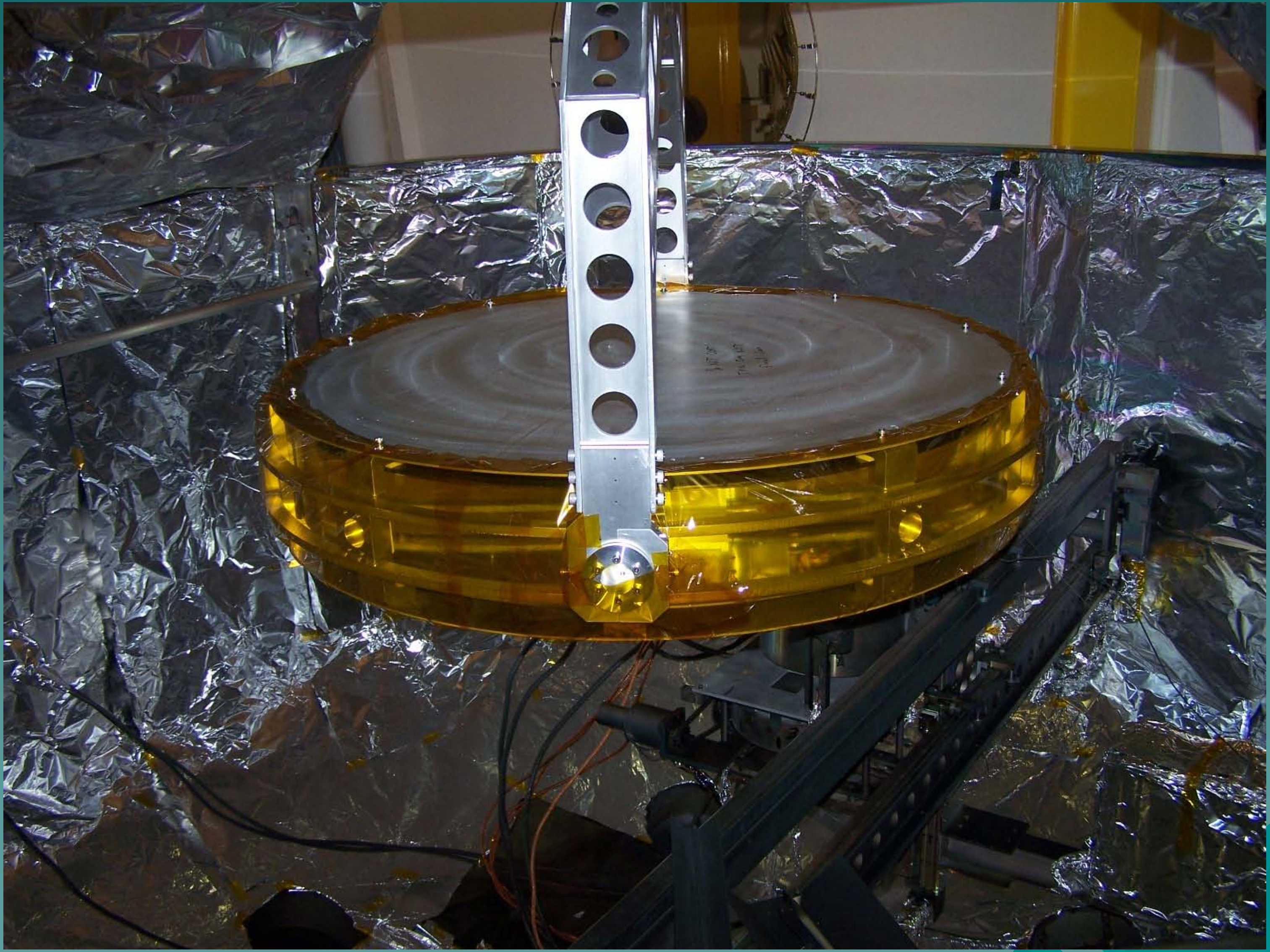
Ta_2O_5 / SiO_2 4 LAYER AR LLNL Completed on 5/27/10



Ta_2O_5 / SiO_2 4 LAYER AR



Ta_2O_5 / SiO_2 4 LAYER AR

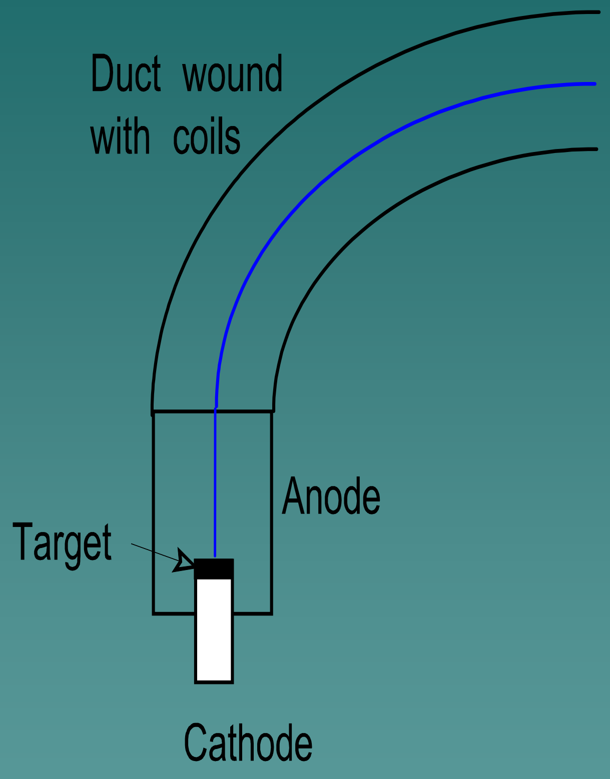


NEW 4-5 Meter Diameter Chamber

- Needed for Coating Larger Diameter Optical Elements (Customer driven requirement)
- Multiple Depositions Platforms
  1. Multiple Sources: E-beam; Thermal; Ion Assisted Deposition; Magnetron Sputtering; Filtered Cathodic Arc
  2. Designed to increase useable deposition area
  3. Designed to increase deposition rate
  4. Designed to coating uniformity

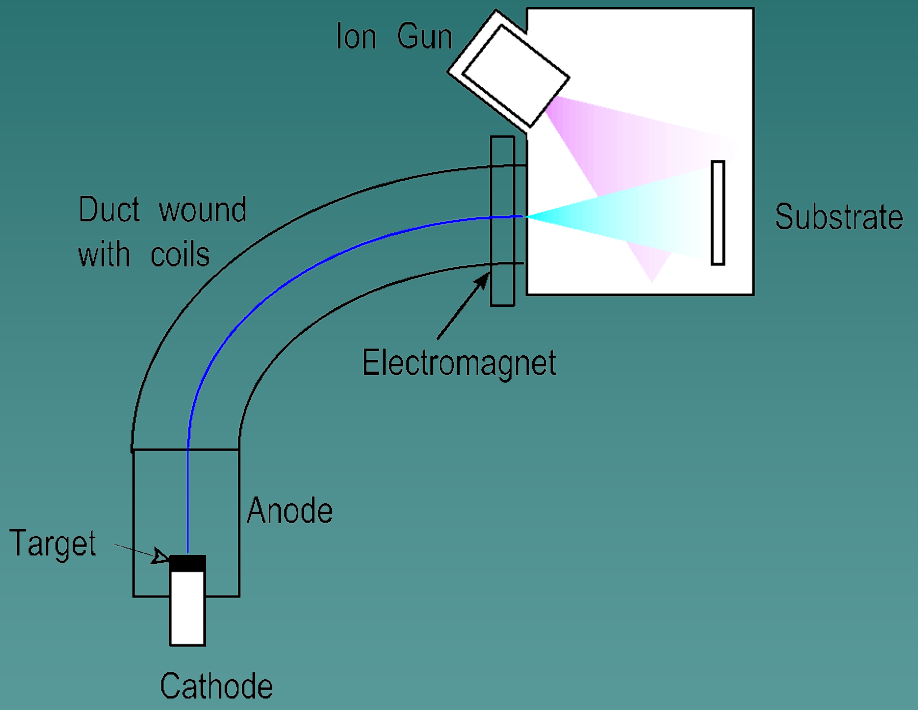
The Filtered Cathodic Arc Process

- A low DC voltage-high current supply is used to generate an arc on a water cooled target.
- The arc vaporizes the target material generating high energy ions, neutral atoms and particles.
- The ions are steered by the magnetic and electrical fields through a curved duct.
- Particles and neutrals are filtered by the non-line -of-sight path.



Ion-Assisted-Deposition (IAD)

- The plasma beam is scanned at the exit of the duct by an electromagnet.
- Ions can be accelerated by a substrate bias, permitting well adhered coatings
- Deposition rate ~ 5 nm/s per in^2 for carbon
- The addition of an End-Hall Ion Source to the Arc Process positively modifies the thin-film properties, increasing adhesion and converting the evaporation material to an oxide, nitride, etc.
- Ambient Temperature Depositions



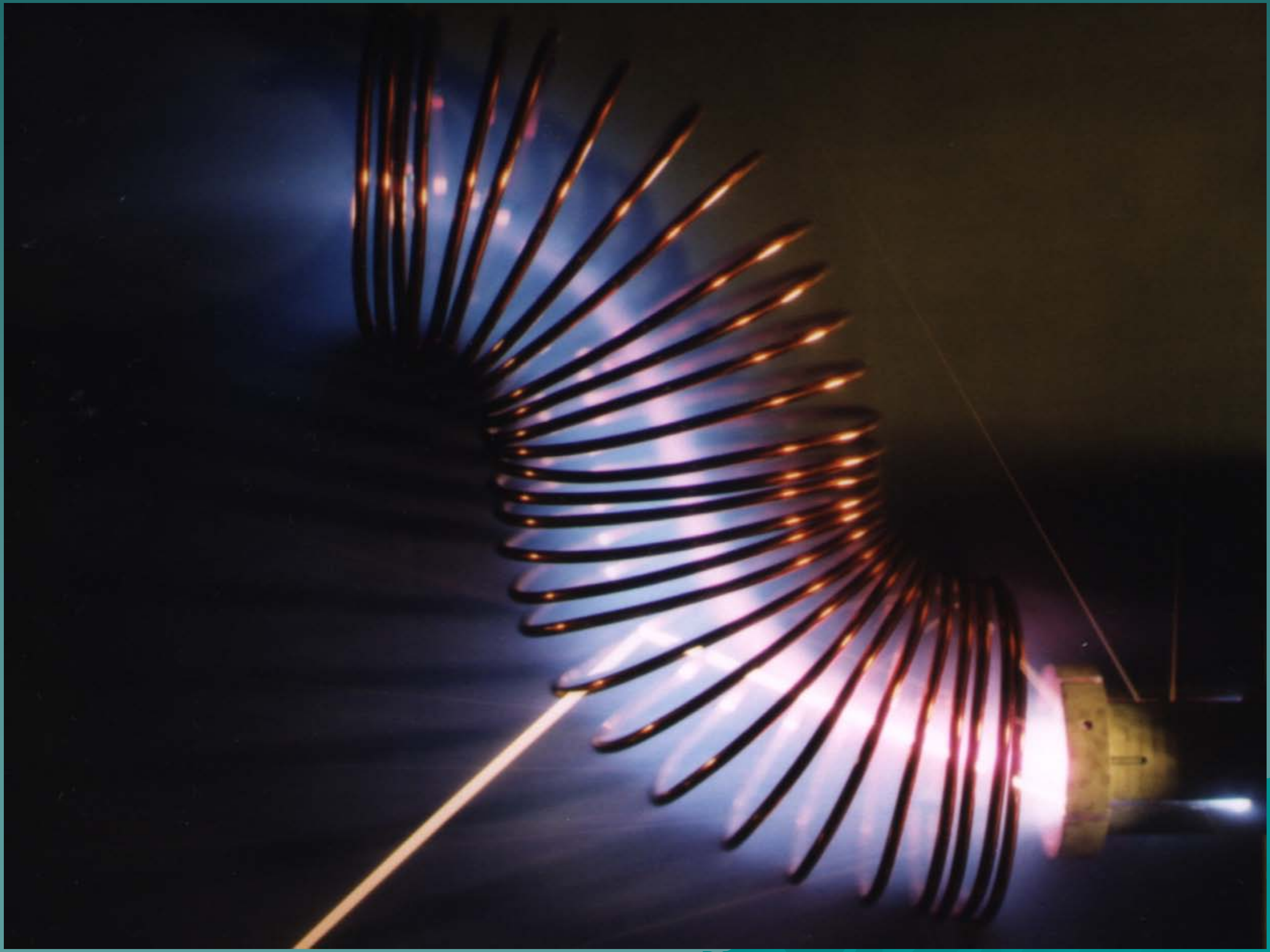
Freestanding 90° filter (A. Anders)

- Freestanding coil ⇒
  - High current required (e.g. arc current in series)
  - Openings allow macroparticles to leave the filter volume

From: A. Anders, *Surf. & Coat. Technol.* 93 (1997) 158-167

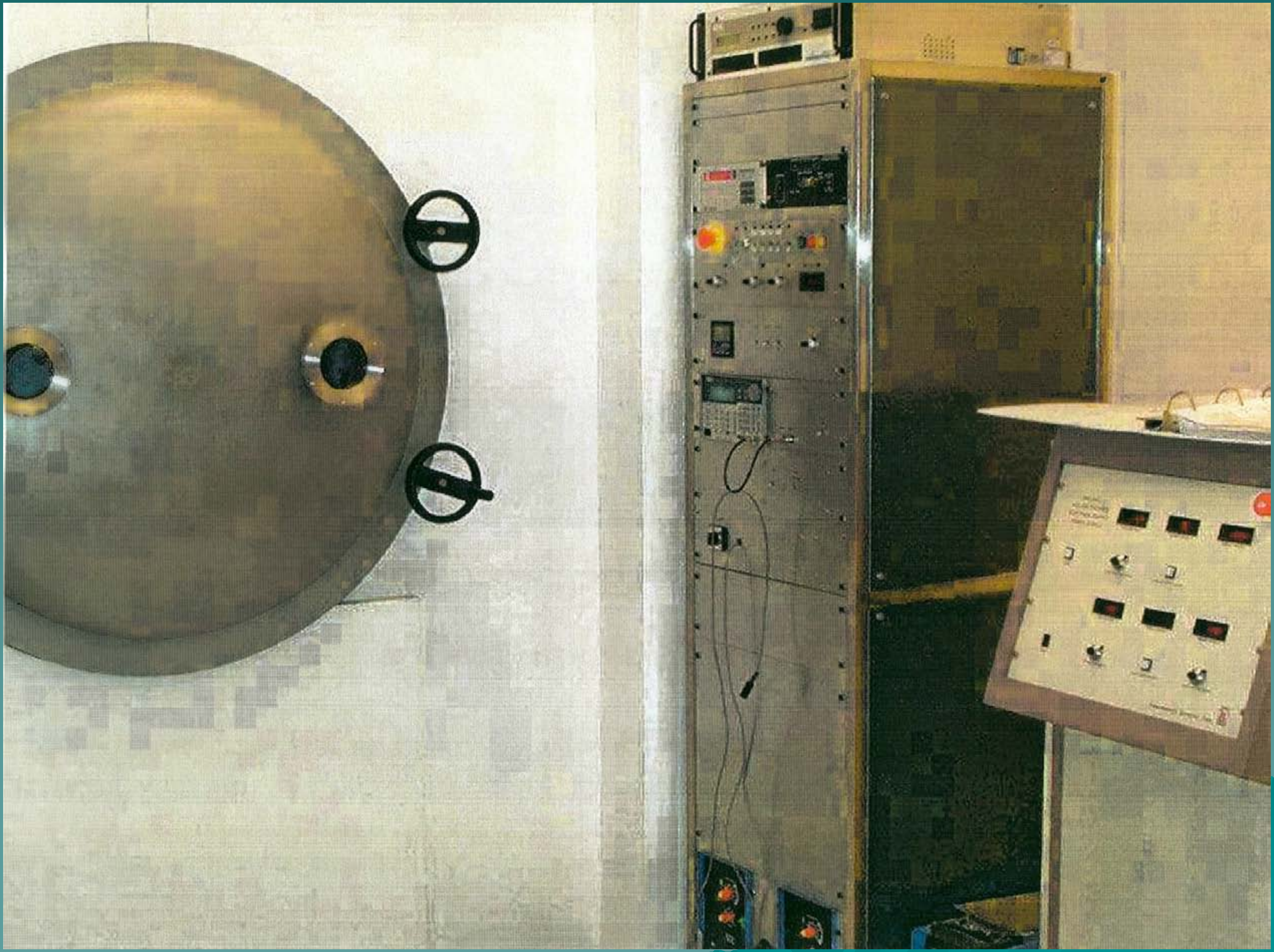
Freestanding S-filter (A. Anders)

- Here: arc source is operated with graphite cathode

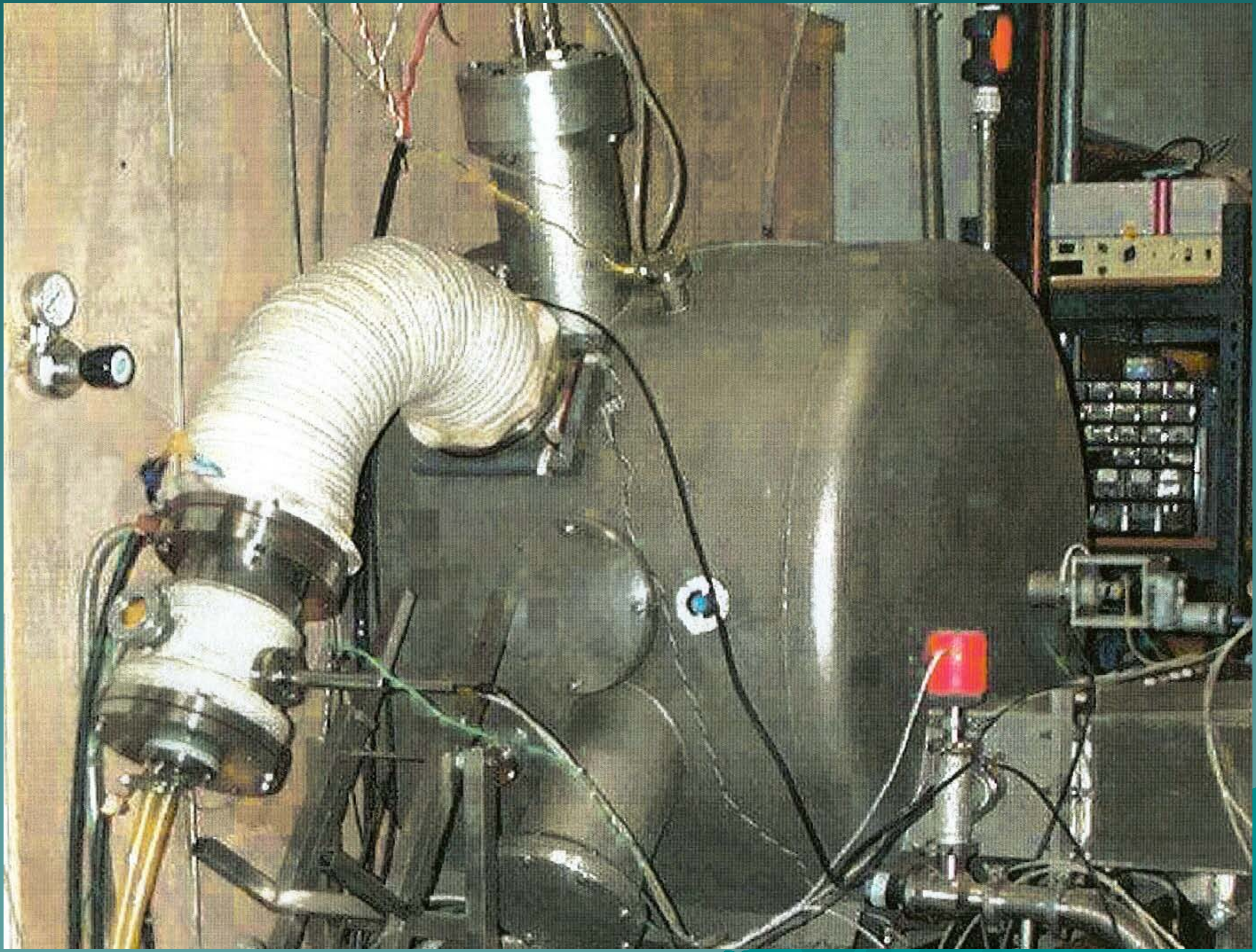


Ion-Assisted Filter Cathodic Arc Deposition (IFCAD)

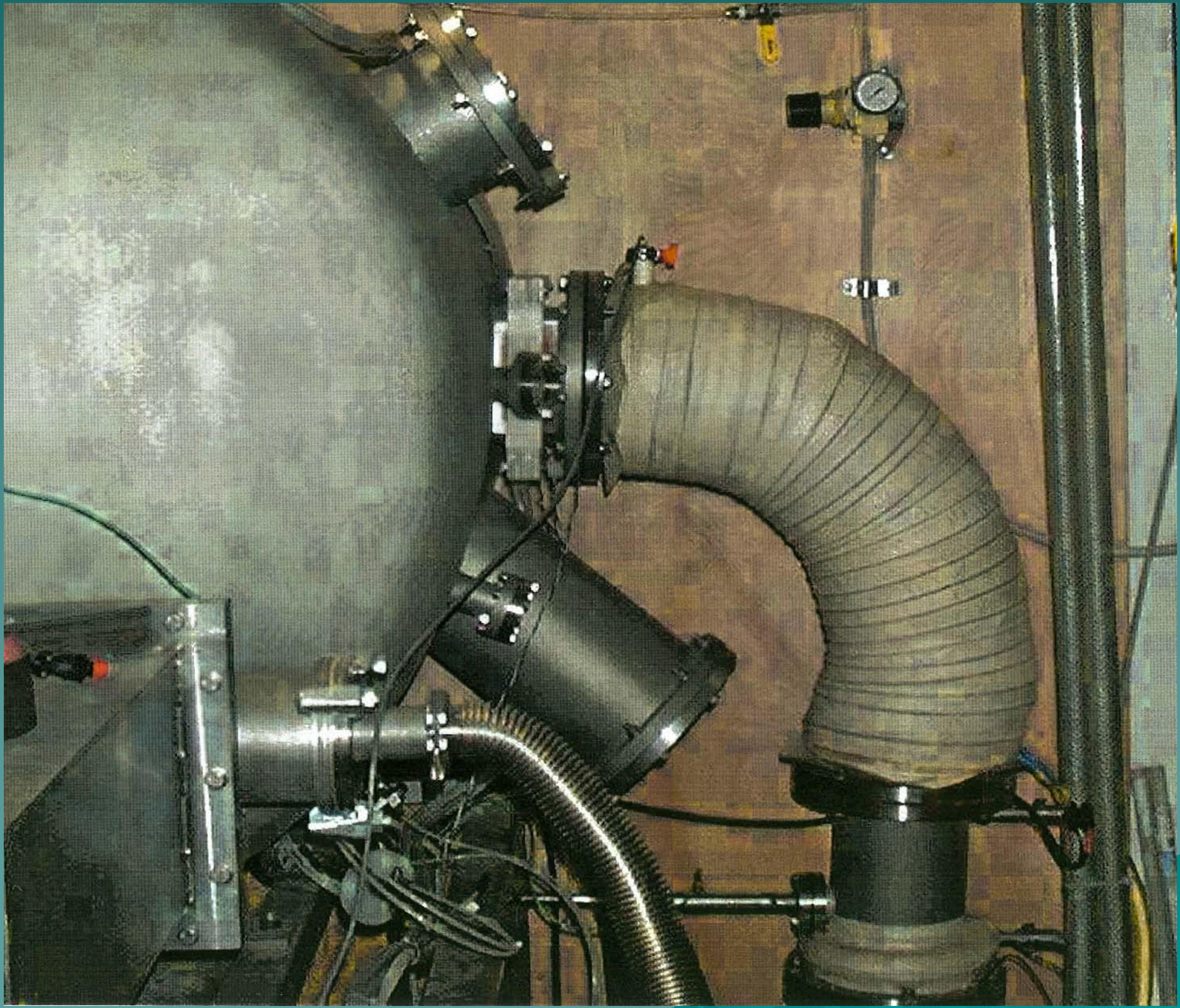
IFCAD: Front of Chamber with Control Panel



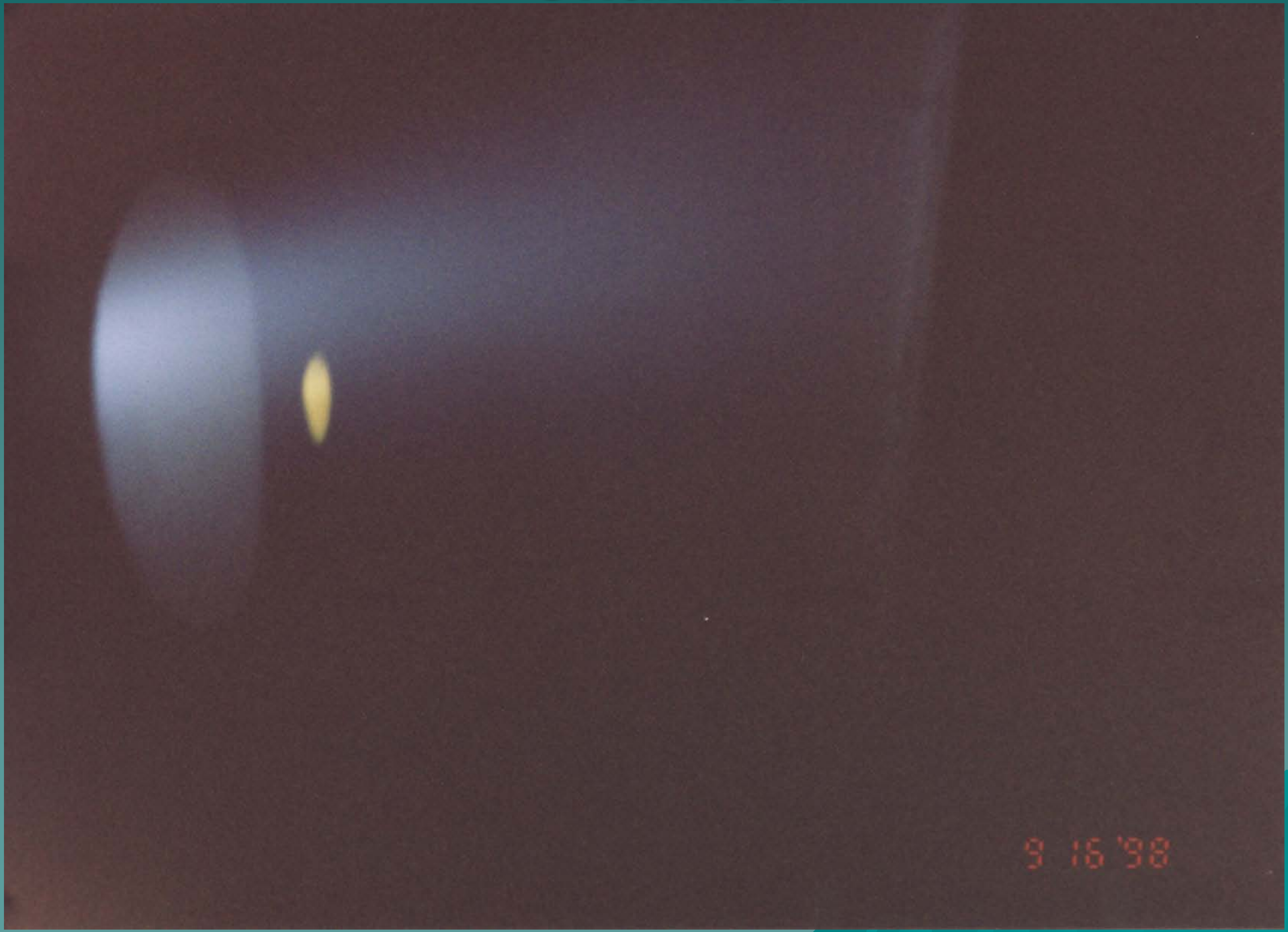
IFCAD: Metal Arc Source with IAD Source: Movie



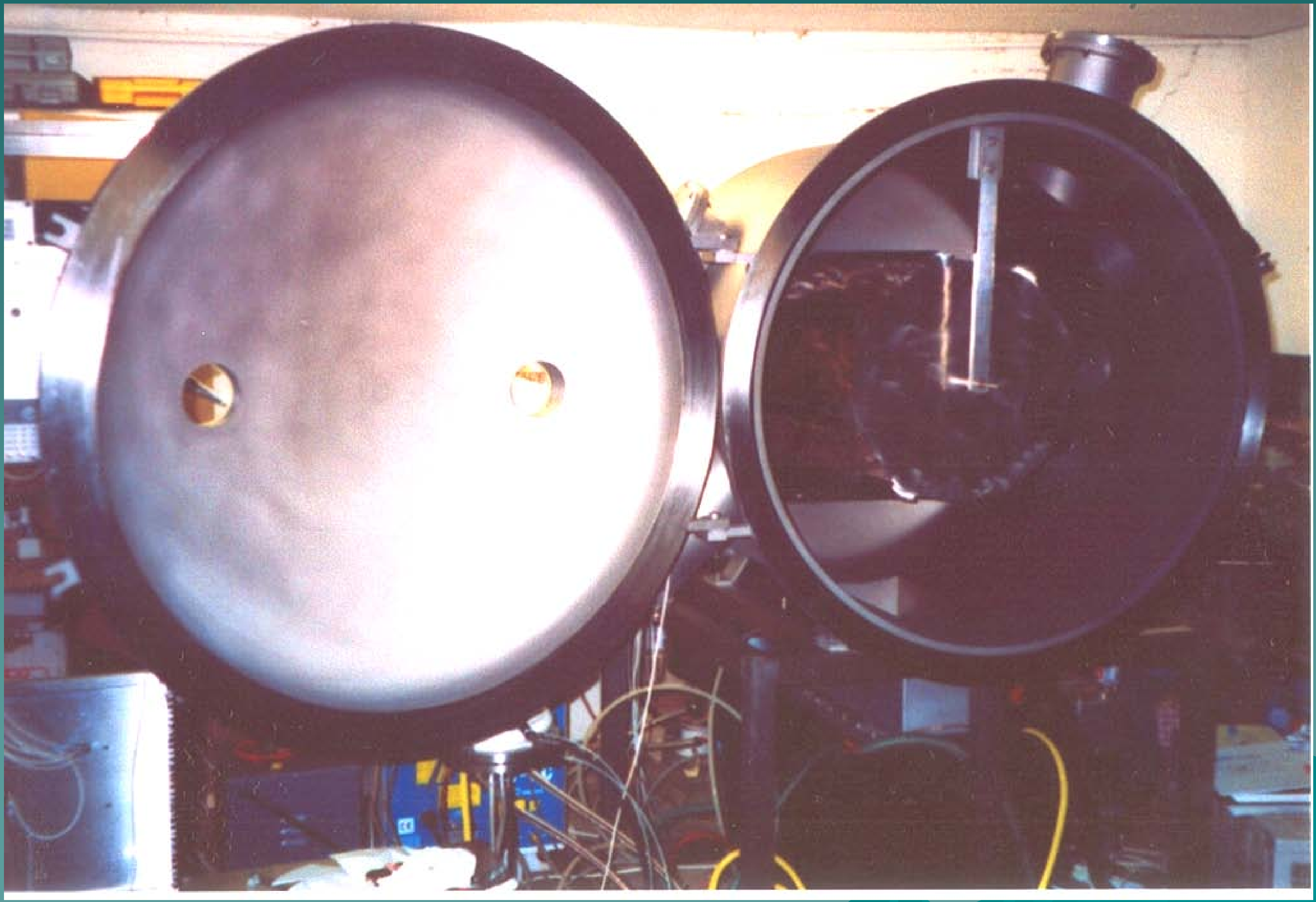
IFCAD: Carbon Source Attached to Chamber



IFCAD: Carbon Ion Beam Entering Chamber



IFCAD: Chamber with Door Open: Drum View

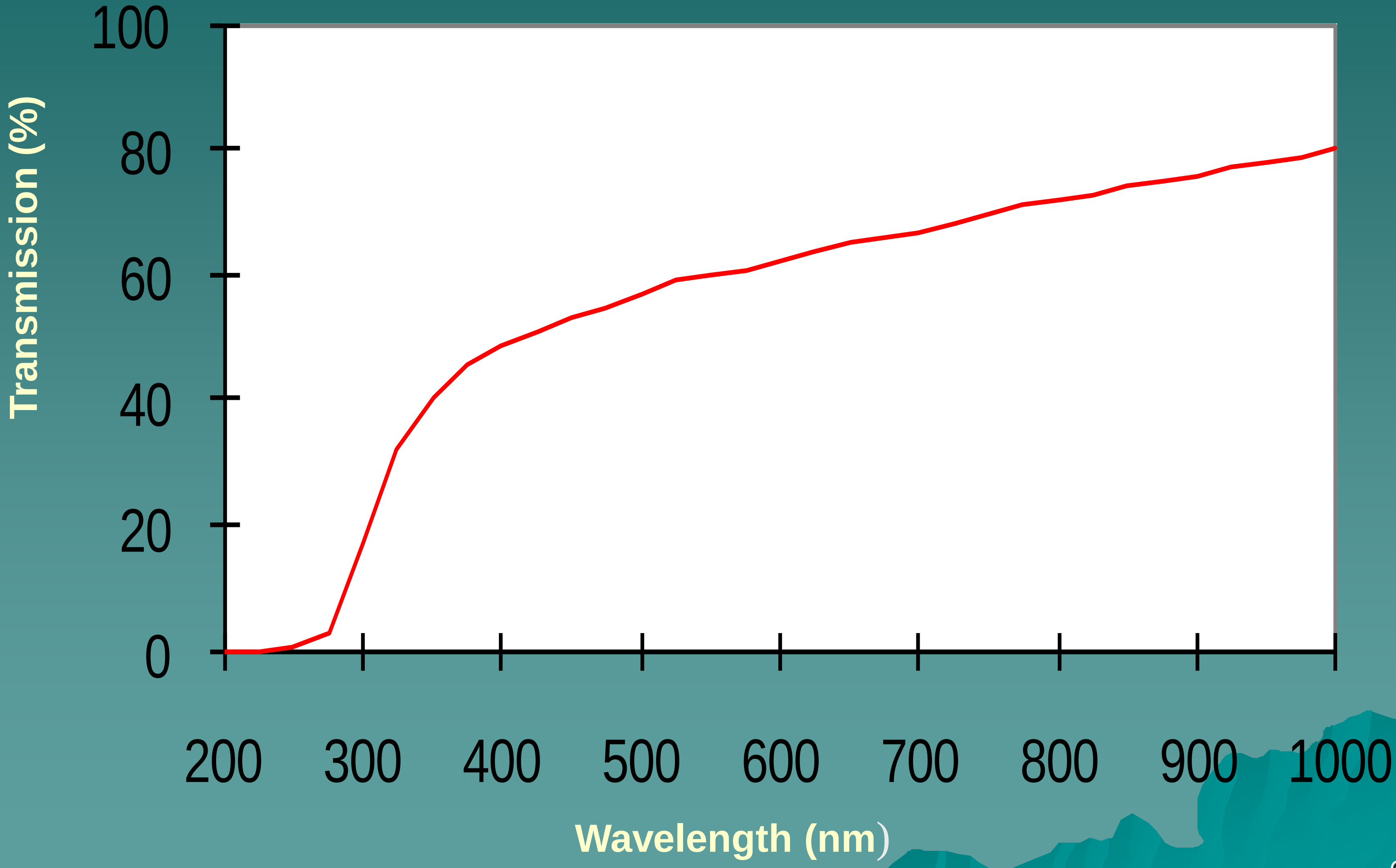


Amorphous-DLC Properties

Property	Nat. Diamond	CVD DLC	DLC (a:CH)	FCA (t:aC)
Hardness GPa	100	80 - 100	10 - 50	70 - 100
Density g/cm^3	3.5	3.2 – 3.4	1.7 – 2.2	3.0 – 3.3
Friction Coeff.	0.1	0.1 (polished)	0.1	0.1
Film Roughness	N/A	3μm	Optically Smooth	Optically Smooth
Adhesion	N/A	Low	Moderate	High
Process T ºC	N/A	>600	20 – 325	20 - 150
Structure	Crystalline Sp3	Crystalline Sp3	Amorphous mostly Sp2	Amorphous mostly Sp3
Reactive Gas	N/A	Yes	Yes	None
Transform T ºC	N/A	>600	250 – 350	>500

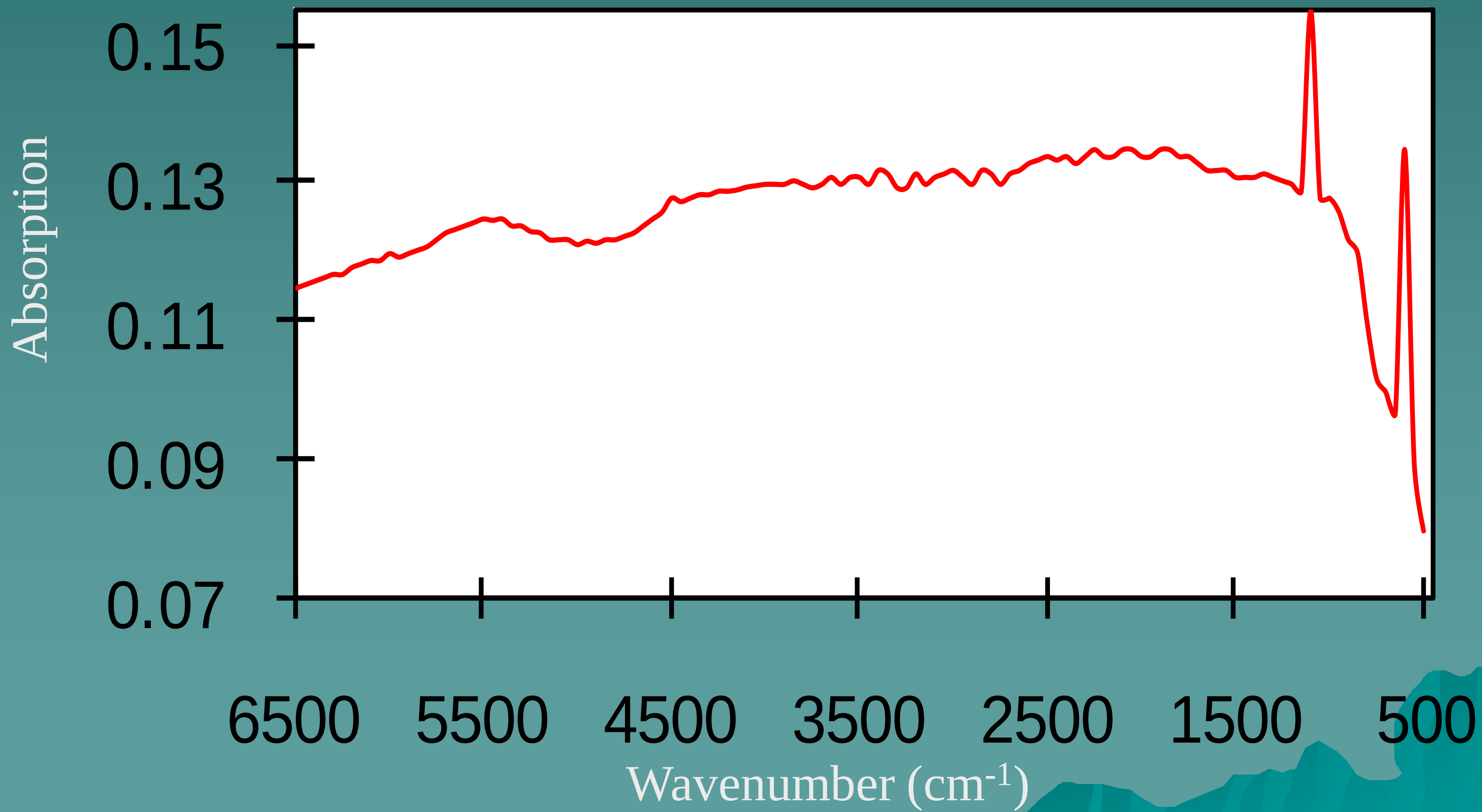
Optical Performance

- A-DLC (single layer) exhibits a sharp cut-off in the UV



IR Performance

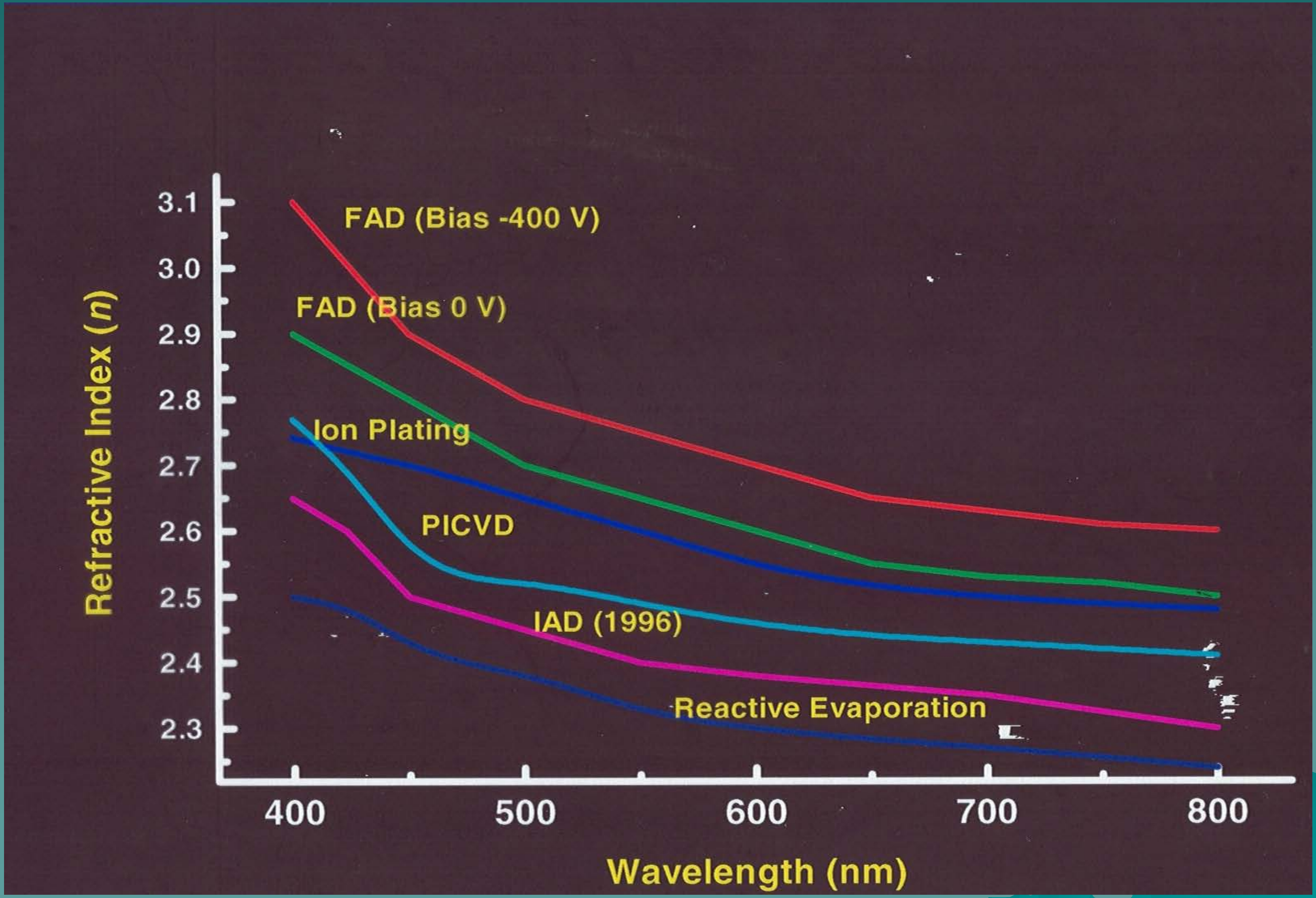
- A-DLC films are highly transparent in the long wavelength region (1.5µm to 20µm) without any absorption peaks caused by C-H bonds (no hydrogen required during deposition)



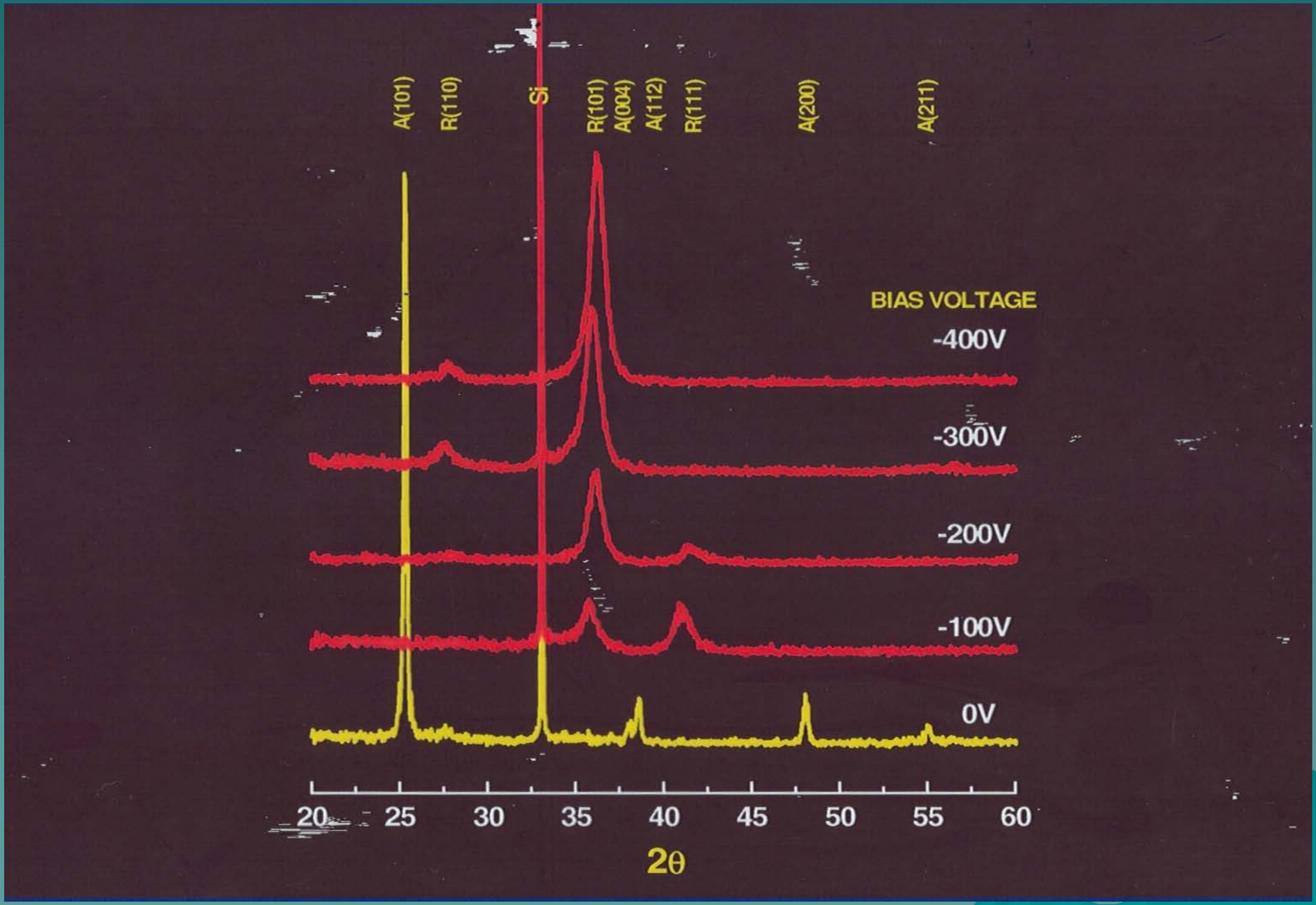
Other IFCAD Materials

•Al_2O_3	clear film of high hardness
•Ta_2O_5	optical coating material (2.1n)
•TiO_2	high index optical coating material (>2.6 n)
•AlN	purple decorative film
•TiN	hard reddish gold wear resistant film
•TiCN	dark gray and hard wearing
•CrN	dull gray with low coefficient of friction
•ZrN	brass colored film with good corrosion resistance
•ITO	transparent conductive thin-film
•C_3N_3	material exhibiting extreme hardness (potentially)

TiO_2: Produced by Energetic Processes (P. Martin)



TiO_2: X-Ray Diffraction vs Substrate Bias Voltage (P. Martin)



Out-of-Plane, Double-Bend Filter

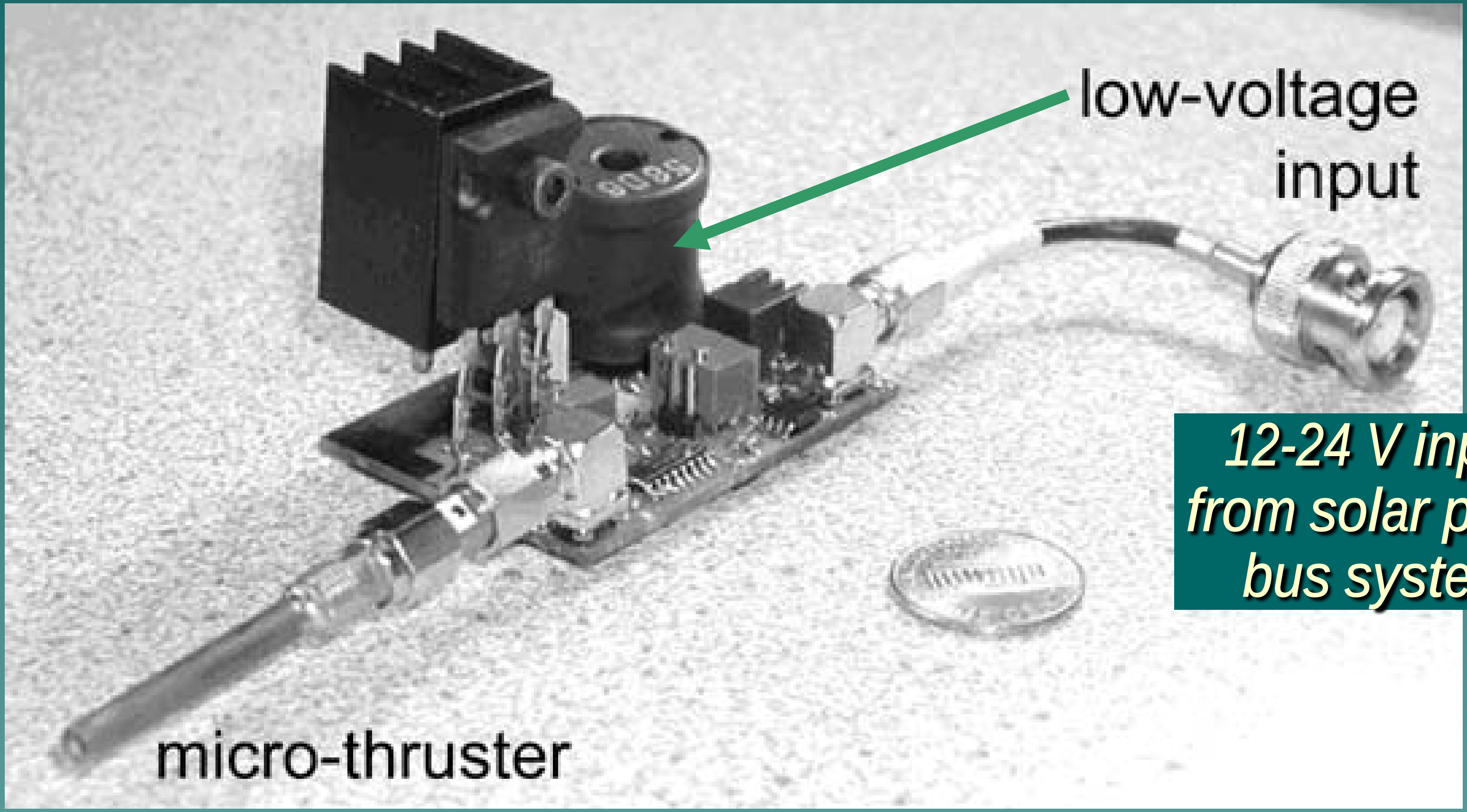
- Out-of-plane S-filter from Nanyang Technical University
- Commercial version:
  - Hard Disk Drives
  - Reading Heads:
  - Samples
- Nanofilm Technologies International Pte. Ltd.

Future Outlook for Space-Based Deposition Technology

- Lunar-Mars Proposal (January 14, 2004) CHANGED
- Moon used as a Temporary Stop for Voyages to Mars
- Lightweight Deployable Structures for Space Power
- Space-Based Depositions for Large Area Telescopes
- Lunar Vacuum: 5.0 X 10^{-13} Torr
- Low Earth Orbit: Not Suitable for Metal Film Depositions
- (LEO) Atomic Oxygen Fluence: 2.3 X 10^{20} atoms/cm^2
- Filtered Cathodic Arc: Simple Process for High Quality Thin-Film Deposition

Light-Weight Pulsed CA Source

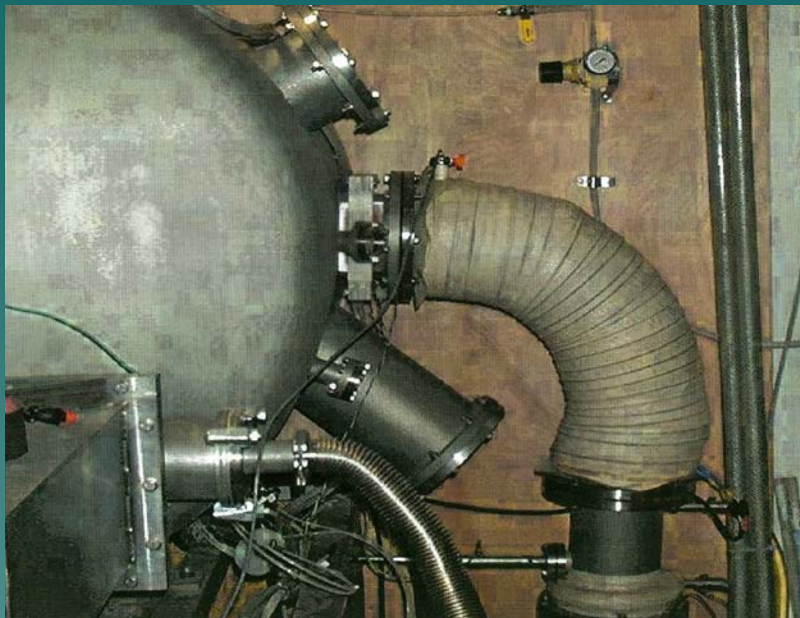
Use of low voltage and inductive energy storage

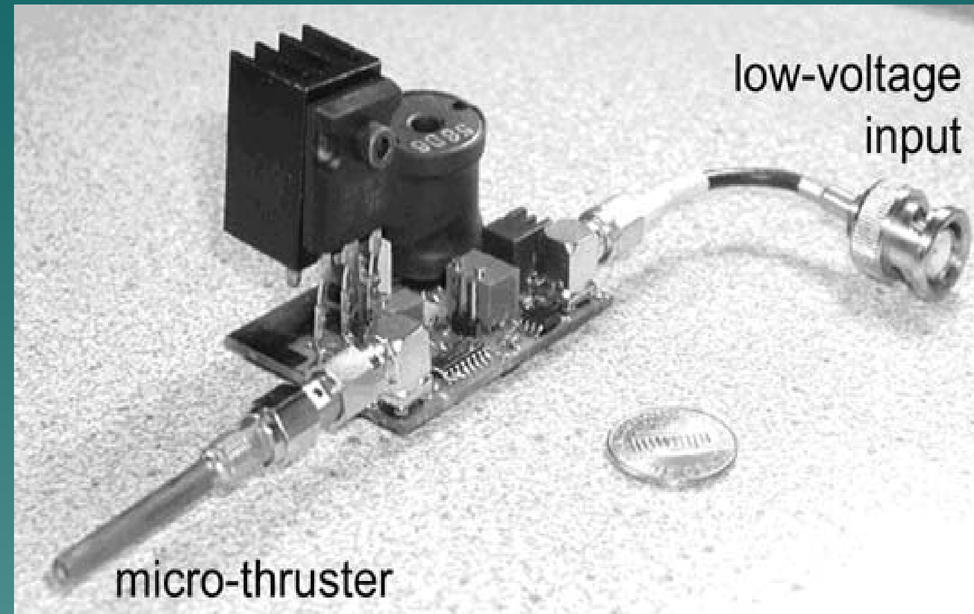


12-24 V input from solar panel bus system

PULSED **cathodic arc can readily be miniaturized, for example as "microthruster," used to correct the orbit of satellites**

Weight Reduction of the Deposition System





~ 500 kg → **~ 100 g**

- ***Weight of arc source, filter, and power supply < 300 g (!)***
- ***Vacuum is "free"***
- ***Cathodic arc does not need any process gas***

Future Work on Space-Based FCAD Technology

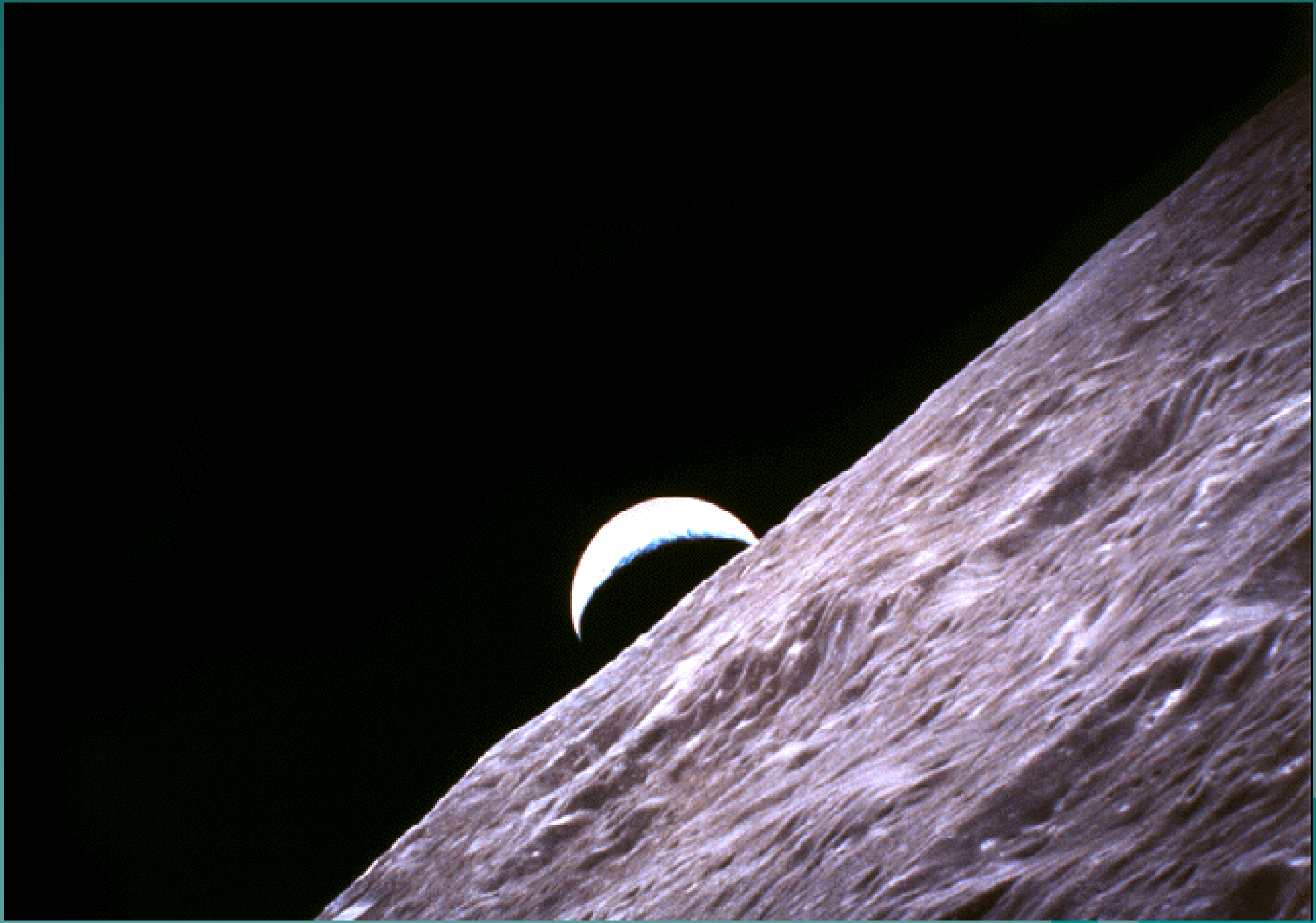
- No Free Lunch: the price of miniaturization is relatively slow deposition speed for large areas. **This is OK!**

- Robotic Control Design for In-Vacuum Large Area Terrestrial Depositions—time of deposition is not a critical. **Vacuum is Free in Space.**

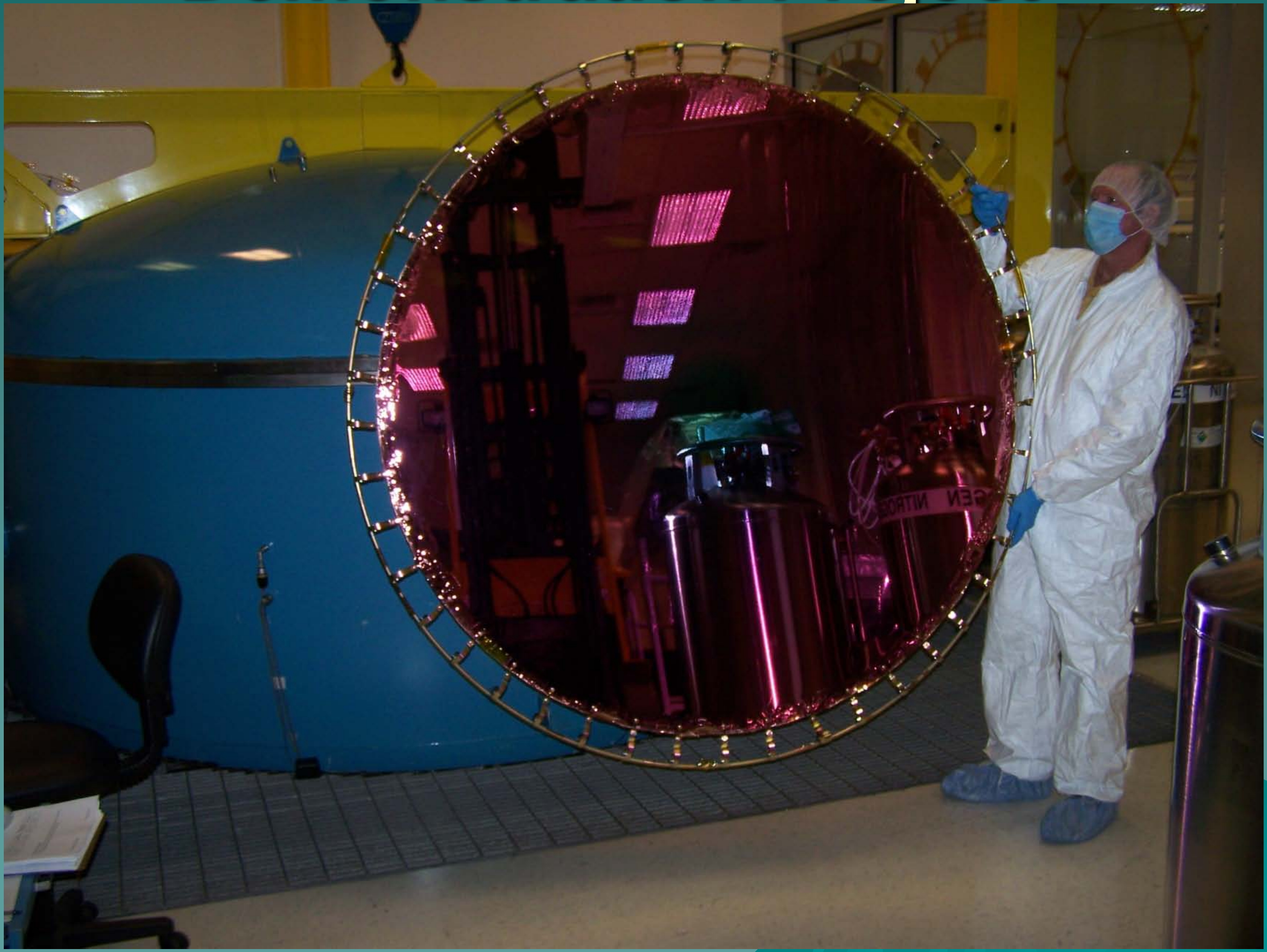
- Design and Testing of miniaturized FCA source with continuous source material feed: Teaming with LBNL to develop this enabling technology for future space missions.

- NASA had announced plans to send man missions to the far side of the moon: this technology could play a vital part in the future of space exploration.

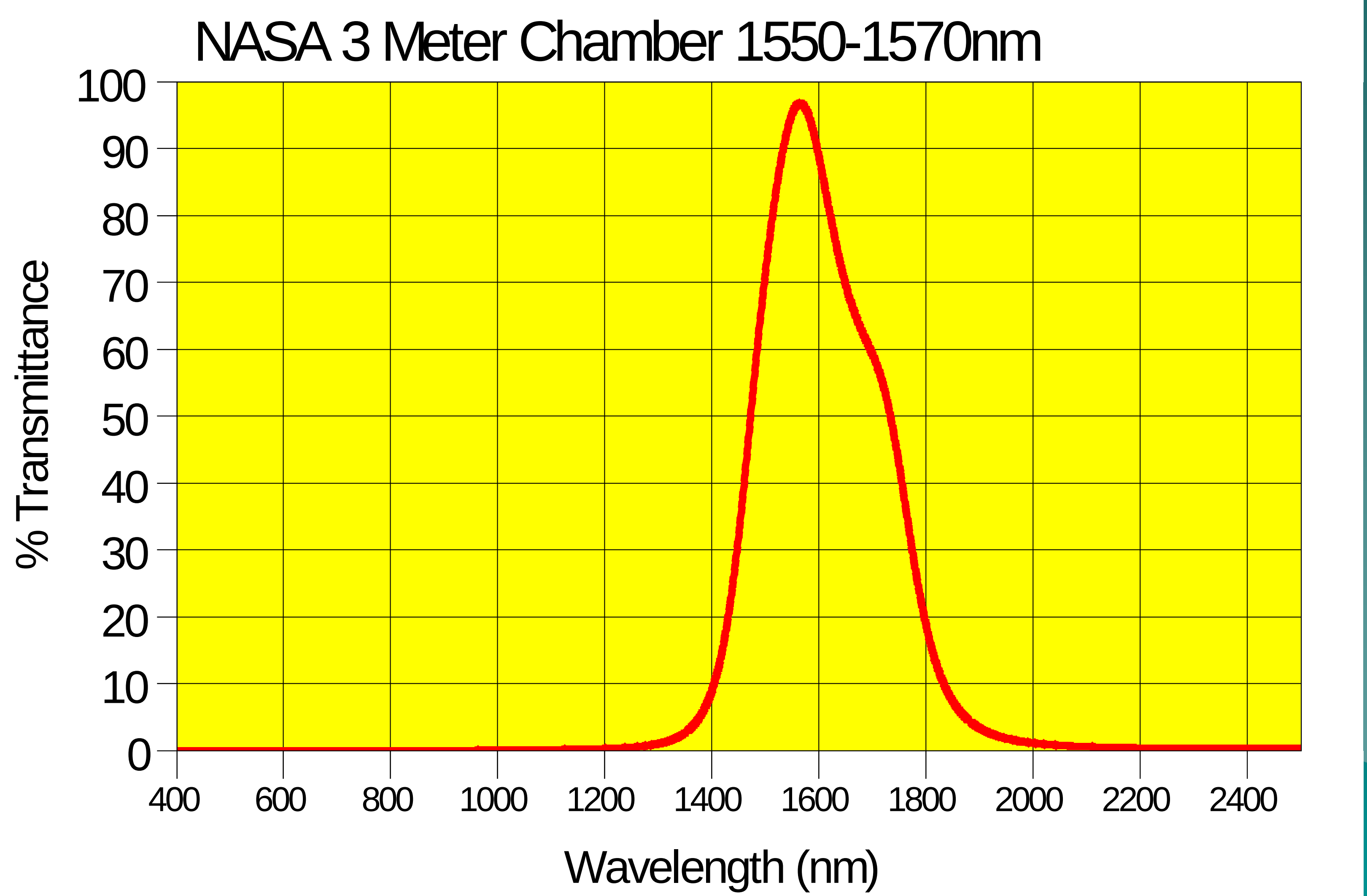
Technology will be best used on the Lunar Surface



Mars Laser Communications Demonstration Project



Mars Laser Communications Demonstration Project



Large Area Reflector on Polymeric Substrates

Thirty Meter Telescope Project

Surface Optics Corp: Future Work

- SOC is continually developing coating capabilities for advanced optical coatings on temperature-sensitive substrates and large scale optical applications.
- Uniformity across large area substrates is being improved by upgrades in the computer control and thickness monitoring system for the translating deposition platform.
- Plans to Build an Even Larger Chamber (4-5 meter) with more Powerful Deposition Capability: incorporating FCA and Sputtering
- SOC is working to improve the polymeric coating process for new flexible space power systems.

Surface Optics Corp.

Thank you for your attention!

More information available at:
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