Actively Cooled Silicon Lightweight Mirrors for Far Infrared and Submillimeter Optical Systems
Contract No. NNM04AA91C4

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Contributors and Acknowledgements

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  - ⇒ Jeff Kegley
  - ⇒ Harlan Haight
  - ⇒ John Tucker
  - ⇒ Ernest “Ernie” Wright
  - ⇒ William “Bill” Hogue

- **THANK YOU!!!**

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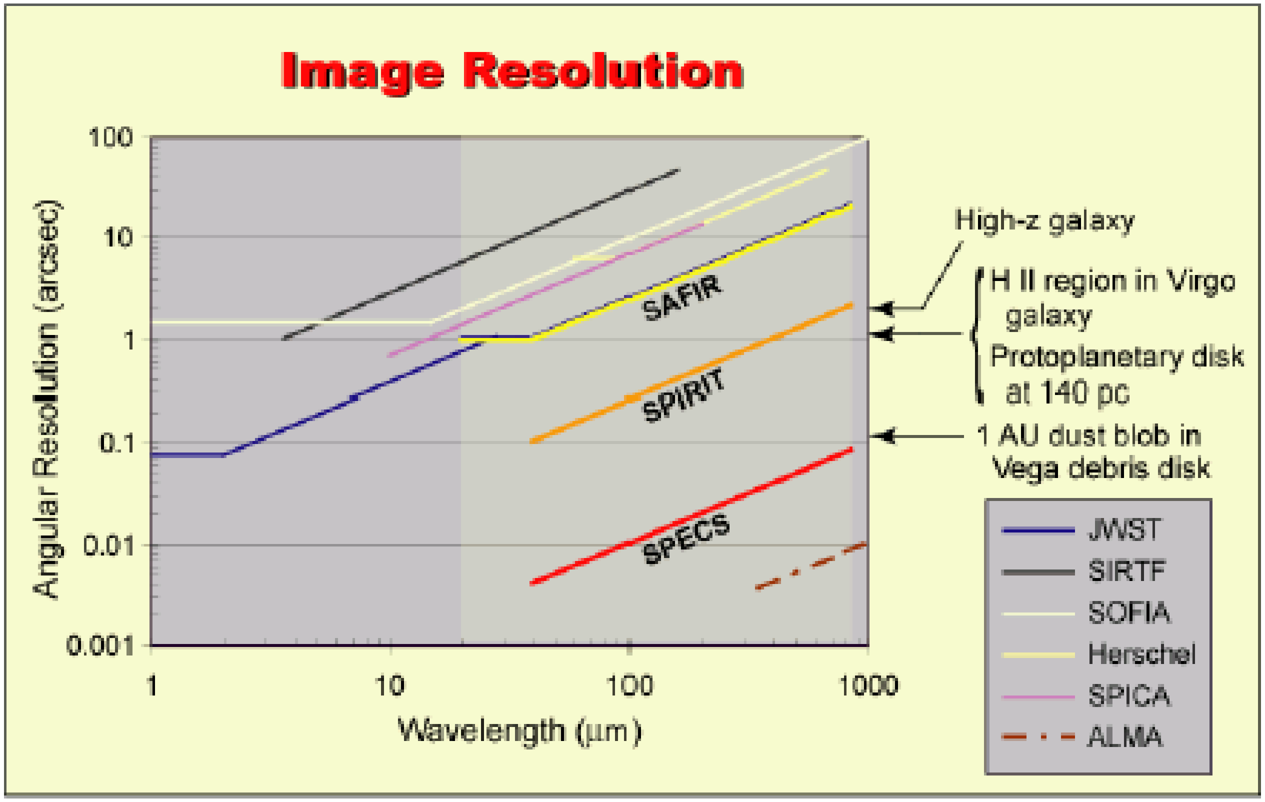
Outline

- NASA Cryogenic Mirror Needs
- Phase I Objectives
- What is SLMS™?
- Manufacturing Process
- SLMS™ Past Cryo Performance
- Phase I Hardware
- Experimental Set-Up
- Phase I Results
- Phase II Project

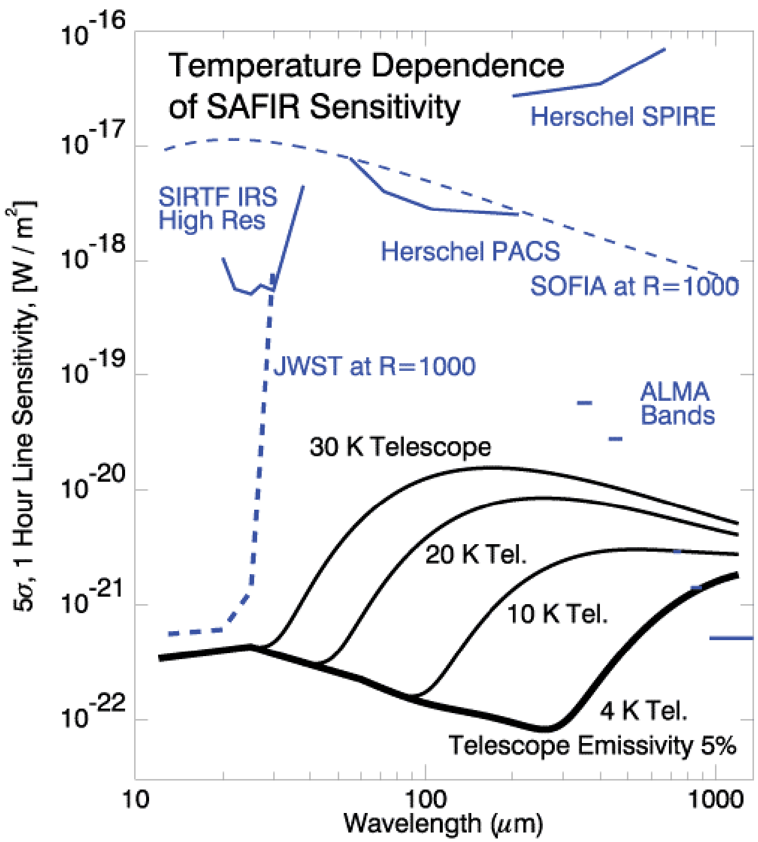
NASA Cryogenic Mirror Needs

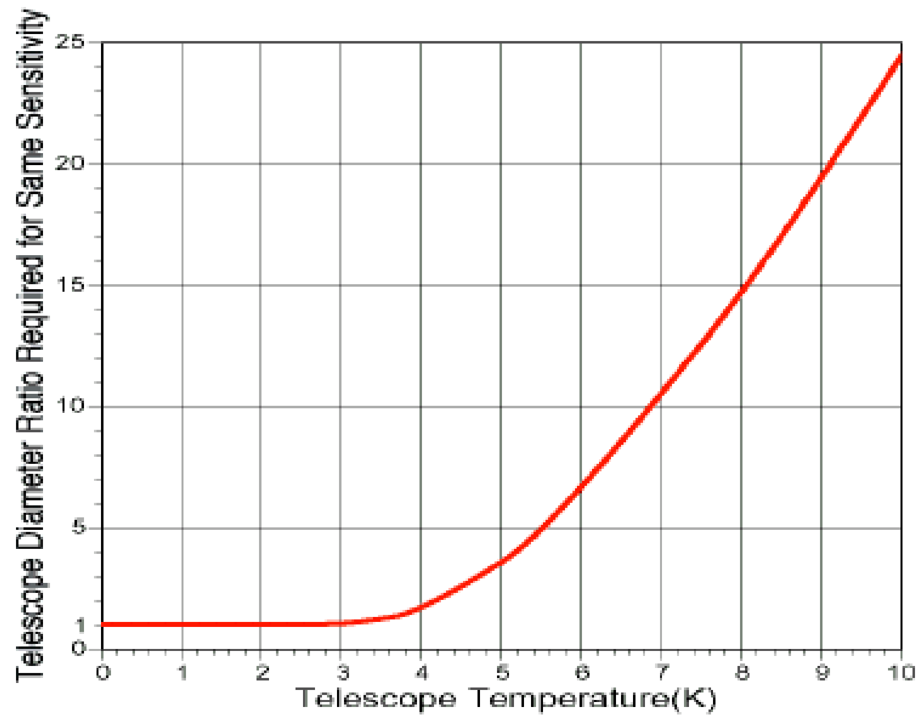
- Future FIR/SMM Missions (20-800 μm bandwidth) Require Optics With:
  - ⇒ 10-25 m, areal density <5 kg/m^2, surface figure specification=λ/14 at 20 μm.
- An order of magnitude improvement in angular resolution above JWST, SIRTF, SPICA, SOPHIA and Herschel (current technologies) is required to resolve extragalactic source confusion, the individual sources of interest, and achieve the science goals of NASA's Origins and SEU themes.



NASA Needs continued

- Performance Premium for Operation at 4 Kelvin
- Point Source Sensitivity More Dependent on Temperature than Aperture at 200 μm
- 4 Kelvin Requires Active Cooling





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Phase I Objectives

- Demonstrate 2 different methods for actively cooling 5-7.5 kg/m^2 areal density Silicon Lightweight Mirrors (SLMS™) technology for future NASA far infrared and sub-millimeter missions.
- Direct internal cooling will be demonstrated by directly flowing liquid nitrogen through the continuous open cell core of the SLMS™.
- Indirect external cooling will be demonstrated by flowing liquid nitrogen through a CTE matched C/SiC manifold that is bonded to the SLMS™. Simulates other types of external Cooling:
  - ⇒ Radiative Cooling Using a Cold Plate
  - ⇒ Active Cooling By Conduction Using an Attached Cooler
- Helium Testing to 4 Kelvin to be Performed

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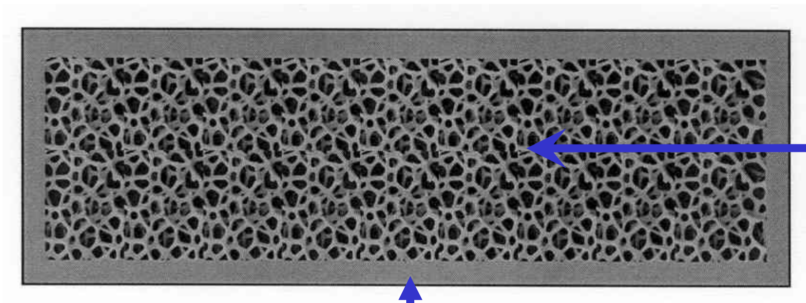
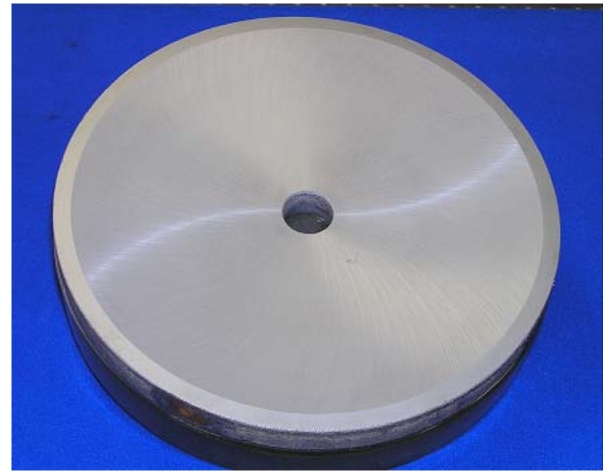
Silicon & Silicon Carbide Lightweight Mirror Systems SLMS™ & SiC-SLMS™

- **Foam Core Optics with a Continuous Shell**

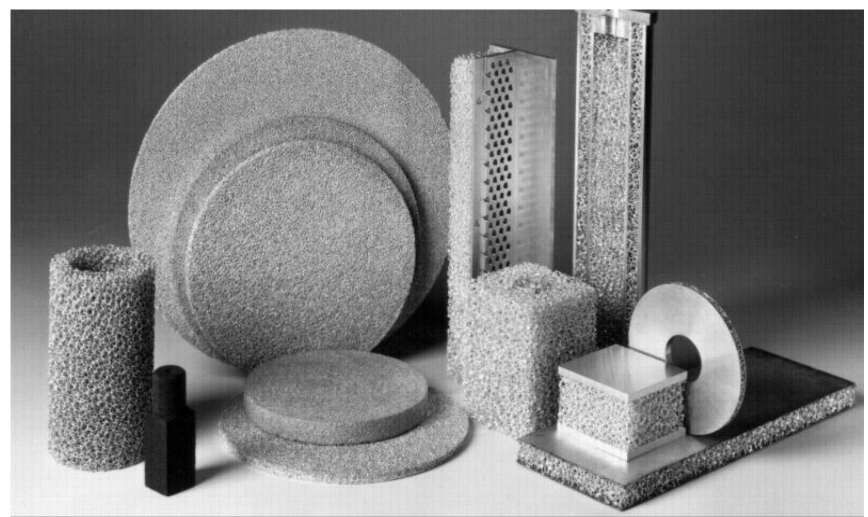


Silicon or Silicon Carbide Foam

Polycrystalline Silicon or Beta-Silicon Carbide Closeout 0.25-1.27 mm typical (0.01-0.05 inch)



- **Foam is Open-Cell, 70-95% Porosity**
- **Pore Size: 0.40 - 4.0 per mm (10-100 per inch)**
- **1500-2000 ft^2 surface area/ft^3**
- **CNC machined to virtually any shape to ± 50 μm (0.002 inch)**



Design Flexibility with Large Manufacturing Basis

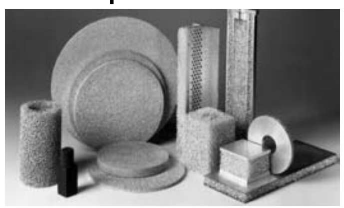
SLMS™ Manufacturing Process

Task: Optical and Mechanical Design

Task: Generate RVC Raw Material – Visual Inspect
Net Shape Machine – Visual Inspect
Infiltrate Foam – Confirm density
Close-Out Foam – Visual and Weight

RVC Foam

Net Shape Si or SiC Foam



SiC clad SiC Foam

Silicon Encapsulated

Task: Visual, Dimensional, Hermetic Inspections

Task: Rough Grind to Near Net

Task: Fine Grind or SPDT

Task: Addition of Cladding for Specific Applications

Optional

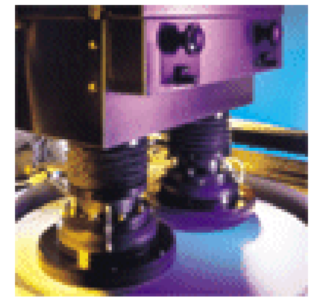
Task: Hermetic, Acoustic Inspect

Task: Polish

Task: Coat

Task: Metrology

Deliver



Cost Less Than Beryllium – Polishes Like Glass – ISO9001 Processes

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SLMS™ Passive Cryogenic Performance

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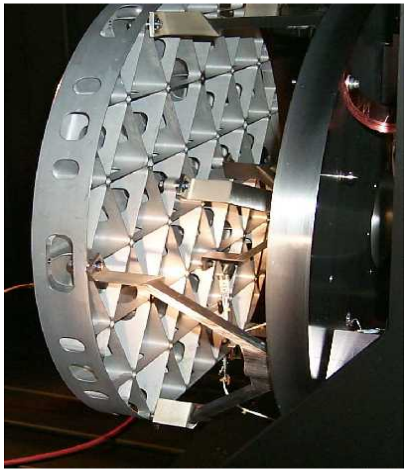
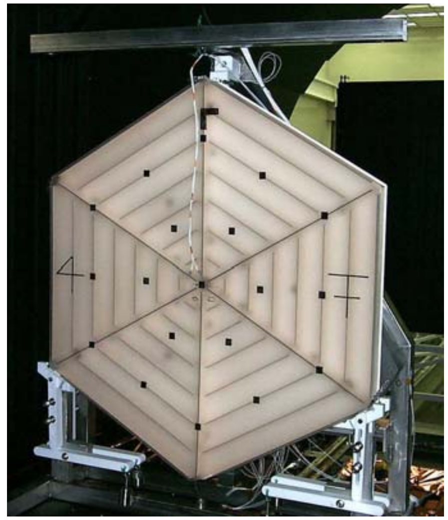
How Do SLMS™ Compare to Lightweight Be, SiC and Glass Mirrors at Cryo?

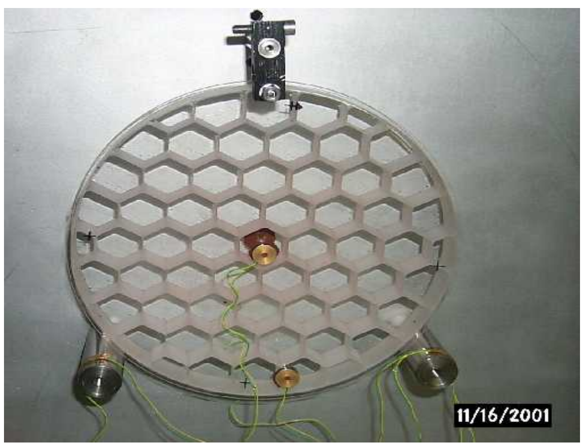


Ball Be SBMD

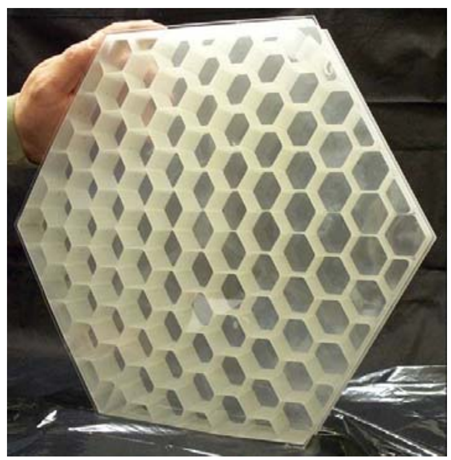


COI Zerodur/Comp NMSD

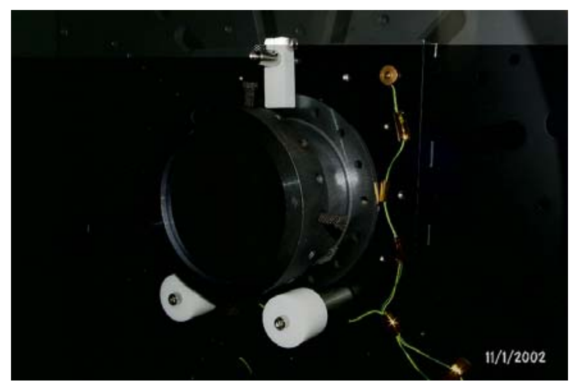
Xinetics SiC, IABG C/SiC, & Goodrich Joined-Be



Kodak Subscale SiO2



Kodak Subscale ULE



Schafer SLMS™

Data Courtesy of NASA and UAH, SPIE 2003

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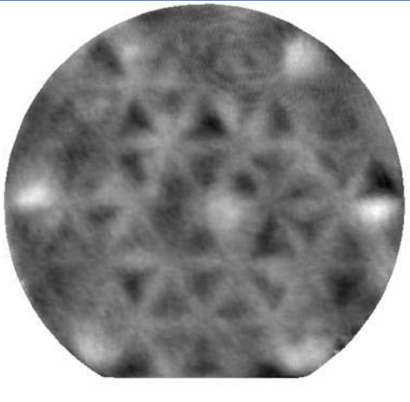
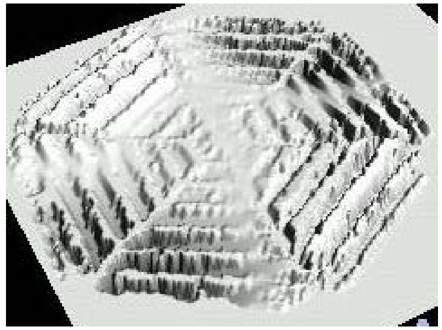
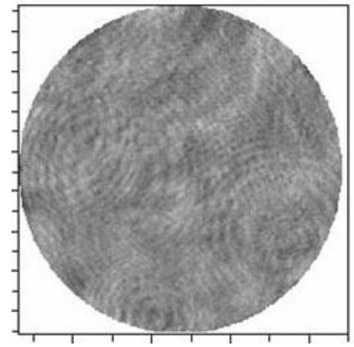
Cryogenic Performance – 27 Kelvin



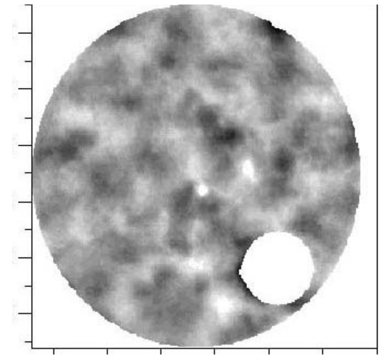
Ball Be SBMD
D=.5m, R=20m,
9.8 kg/m²
17 nm RMS



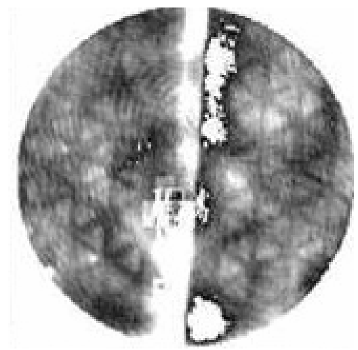
COI Zerodur/Comp NMSD
D=1.6m, R=15m,
11 kg/m²
650 nm RMS



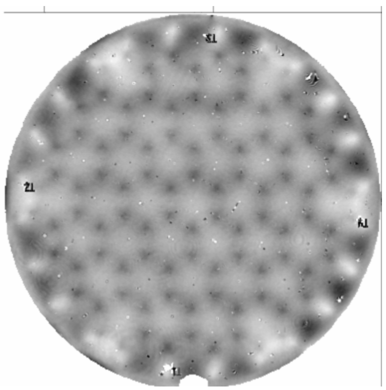
Xinetics SiC, D=.5m, R=20m
22 kg/m², 6.6 nm RMS



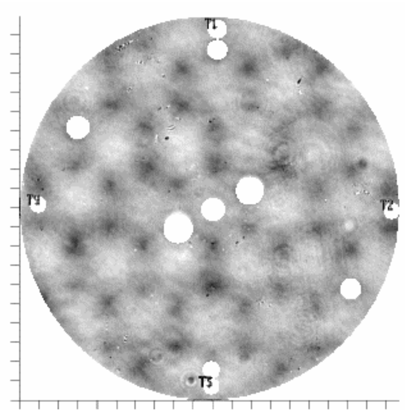
IABG C/SiC
D=.5m, R=20m,
8 kg/m²
31 nm RMS



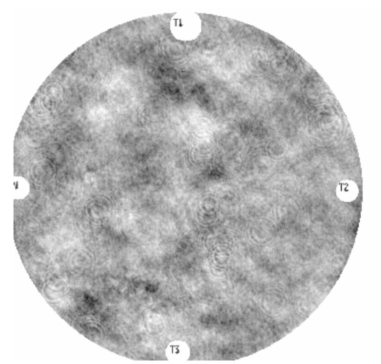
Goodrich Joined-Be
D=.5m, R=20m
15 nm RMS



Kodak Subscale SiO2
D=.23m, R=1.3m
10 kg/m²
17 nm RMS



Kodak Subscale ULE
D=.36m, R=1.2m
10 kg/m²
8.4 nm RMS

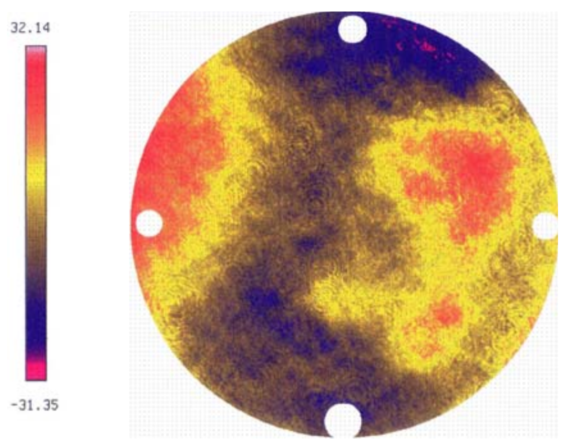


Schafer SLMS™
D=.12m, R=0.6m
9.8 kg/m²
3.7 nm RMS
Lowest Print-Through

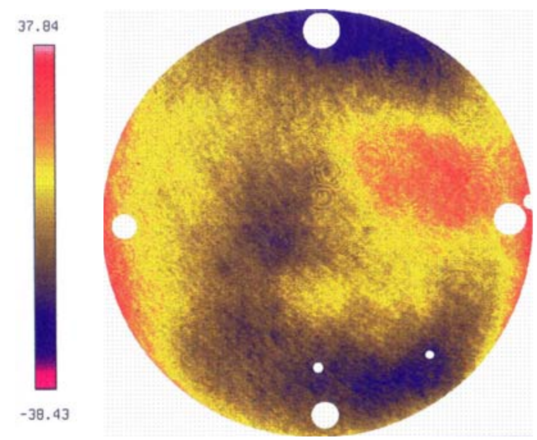
Data Courtesy of NASA and UAH, SPIE 2003

Coated vs Uncoated at Cryo

- **Successfully applied HEL mirror Very Low Absorption (VLA) coatings to SLMS™**
- **5-micron thick, 20-pair dielectric coating, validated at 27 K**
  - ⇒ **Difference of 0.5 nm rms measured after coating**



Uncoated: 10.40 nm rms

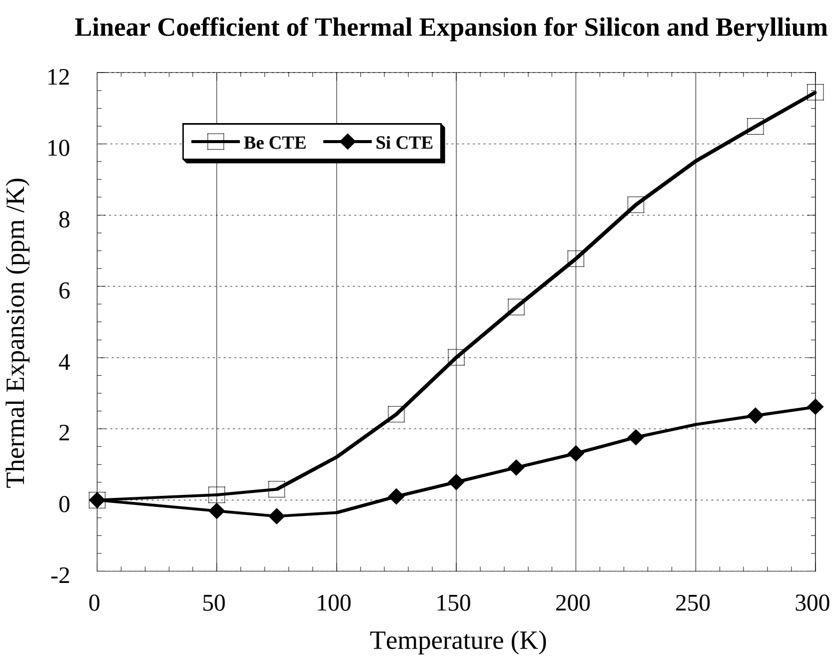


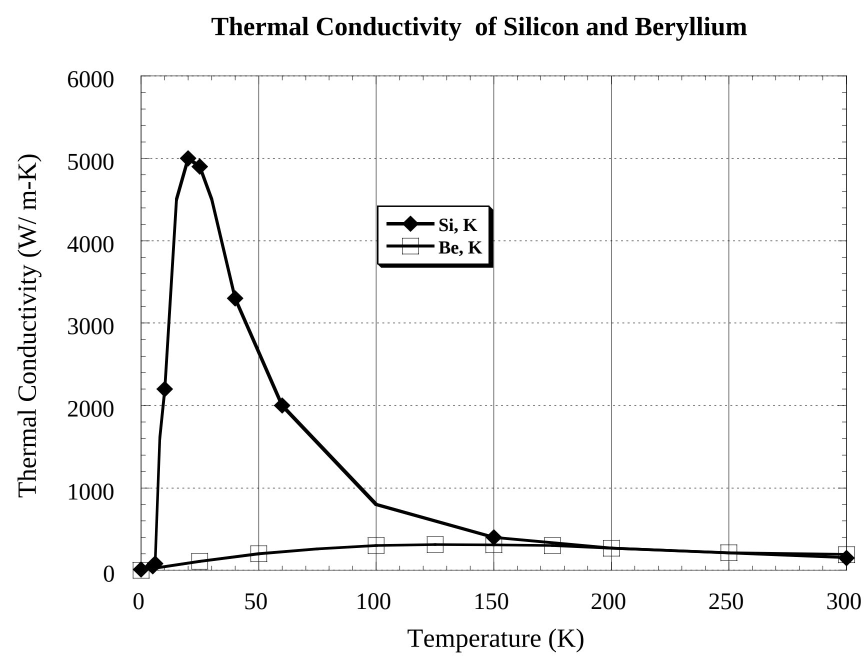
Coated: 10.92 nm rms

Coating Does Not Degrade SLMS™ Figure Performance

Silicon vs Beryllium – Thermal Comparison

	ρ	E	E/ρ	σ_t	σ_t/ρ	α	k	C_p	$D=k/\rho C_p$	α/k	α/D	ν
Room Temperature Property:	**Density**	**Young's Modulus**	**Specific Stiffness**	**Tensile Strength**	**Specific Strength**	**Thermal Expansion**	**Thermal Conductivity**	**Specific Heat**	**Thermal Diffusivity**	**Steady State Distortion**	**Transient Distortion**	**Poisson's Ratio**
Units:	kg/m^3	GPa	$MPa\text{-}m^3/kg$	Mpa	$MPa\text{-}m^3/kg$	$10^{-6}/K$	W/m-K	j/kg-K	$10^{-6}/m^2/s$	μm/W	$s/m^2\text{-}K$	arbitrary
Preferred Value:	**Small**	**Large**	**Large**	**Large**	**Large**	**Small**	**Large**	**Large**	**Large**	**Small**	**Small**	
Beryllium:I-70	1850	287	155	237	0.13	11.3	216	1920	60.81	0.05	0.19	0.25
Silicon SLMS™ Skin	2330	130	56	120	0.05	2.5	148	750	84.69	0.02	0.03	0.24
Beta-SiC-SLMS™ Skin	3210	465	145	470	0.15	2.2	300	640	146.03	0.01	0.02	0.21





Si has superior thermal performance than Be with similar Structural Properties

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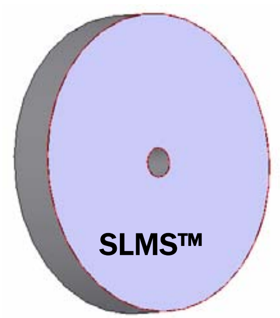
Structural Efficiency Comparison



Mirror	1st frequency	Mass	Areal Density
	(kHz)	(kg)	(kg/m^2)
ULE	1.76	0.98	16.1
Zerodur	1.93	1.12	18.4
Beryllium	3.98	0.81	13.3
SLMS, design A	3.98	0.75	12.3
SLMS, design B	4.29	0.81	13.3
SiCSLMS	5.24	0.81	13.3

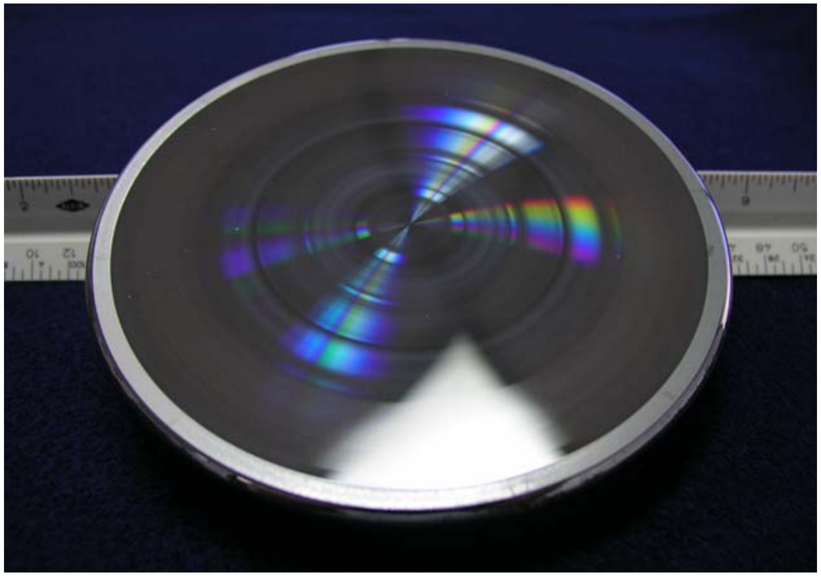
- **SLMS™ same 1st Frequency as Be, at 93% the weight of Be**
- **SLMS™ same weight as Be, at 108% 1st Frequency**
- **SiC-SLMS™ same weight as Be at 131% 1st Frequency**

Stiffer than Be at Same Mass; Lighter at Same Stiffness

Phase I Hardware

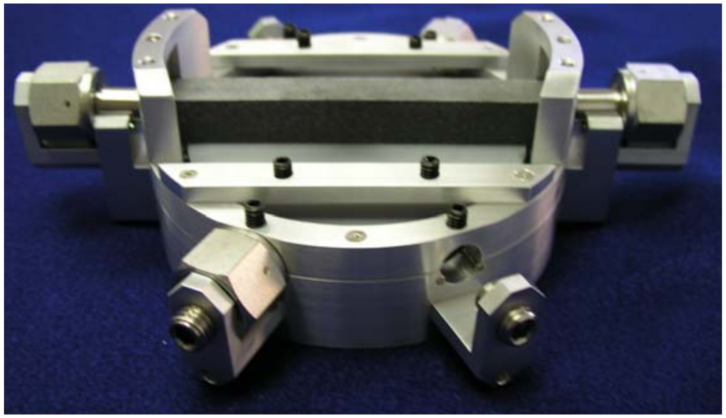
Invar Swagelok® butt weld VCR glands
for cryo-fluid delivery and bond fixture

SURROGATE



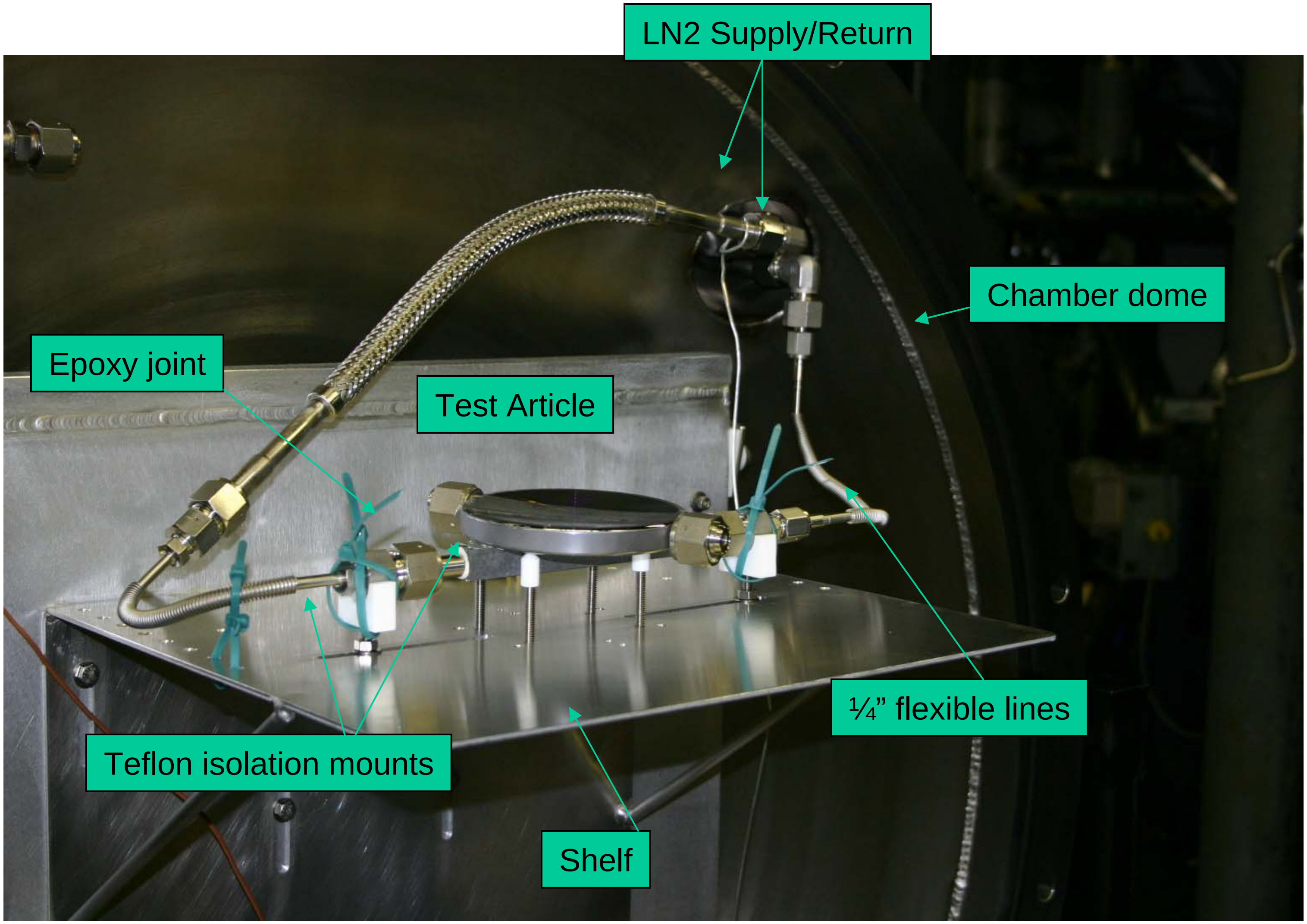
Cryogenic Far Infrared Submillimeter Mirror
C-FISMM was Single Point Diamond Turned

C/SiC External Manifold



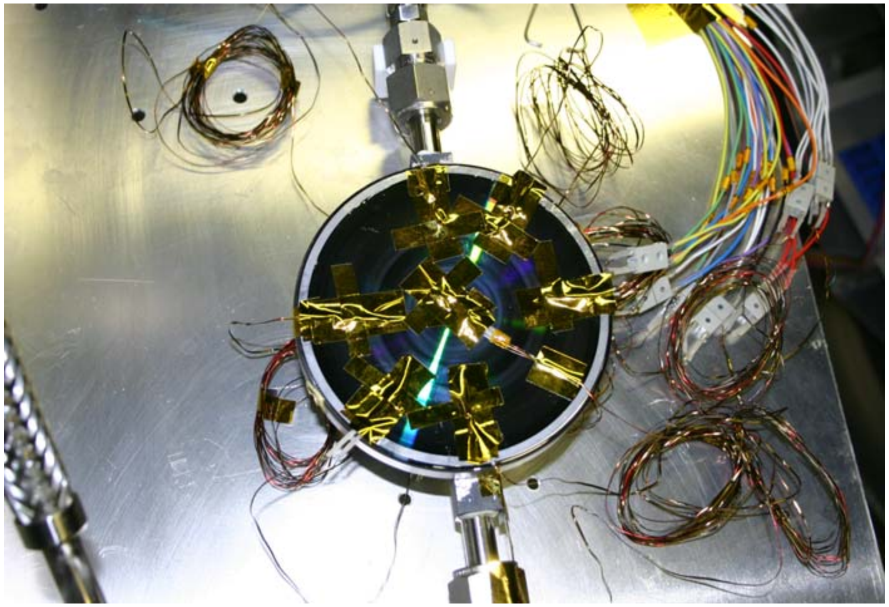
Assembly Check

Test Assembly



4-Foot Vacuum-Ambient Chamber Pumped Down to 10^{-3} Torr for Testing

Schafer Setup for External and Internal Cooling



External Flow: Mon 19 July 2004
No Insulation

N

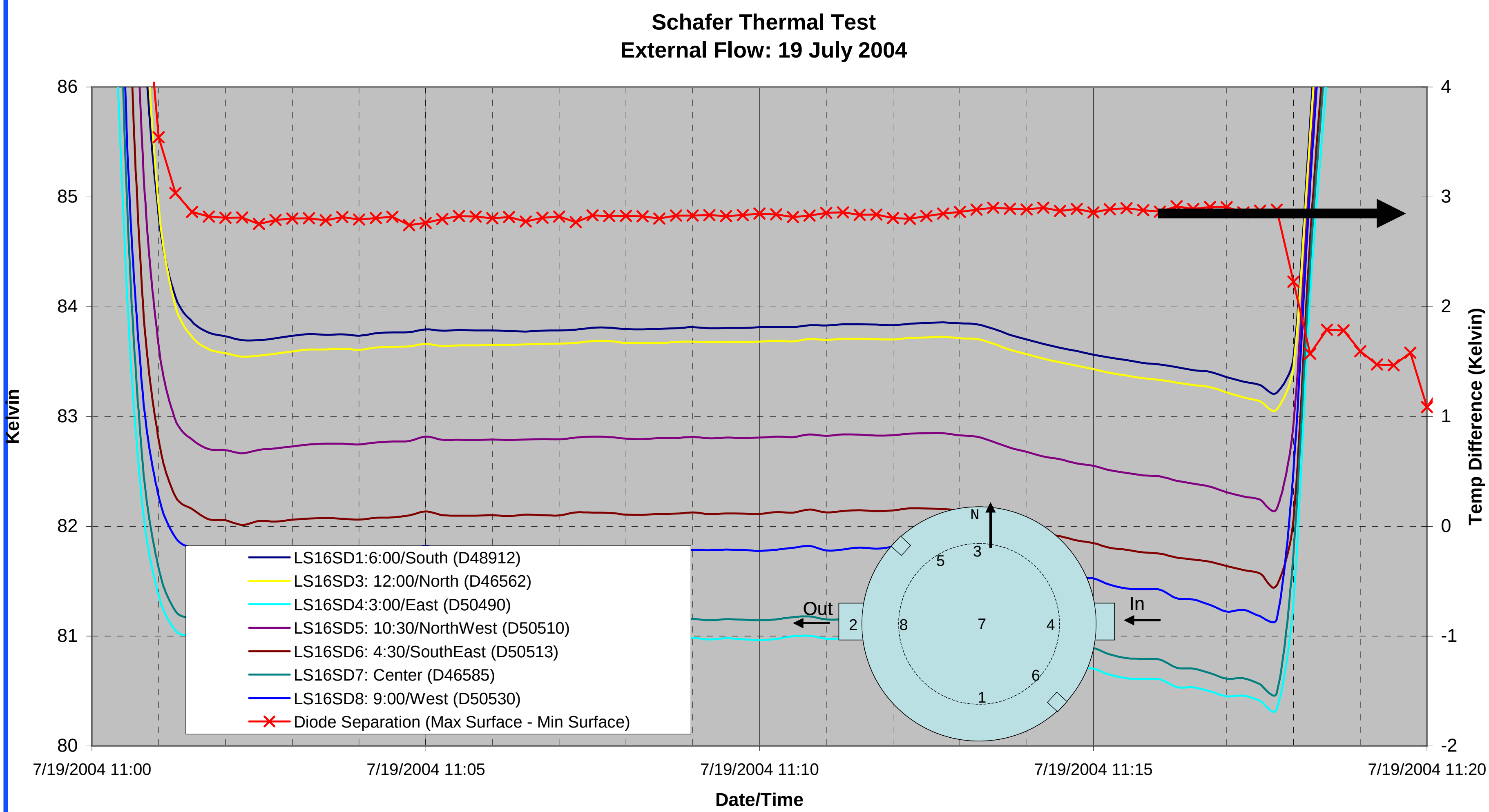
Internal Flow: Tues 20 July & Wed 21 July 2004
No Insulation

N

No picture available. Diode LS16SD8 was remounted and a multi-layer insulation blanket was placed over the entire test setup.

Internal Flow with MLI Insulating Blanket: Thurs 22 July 2004

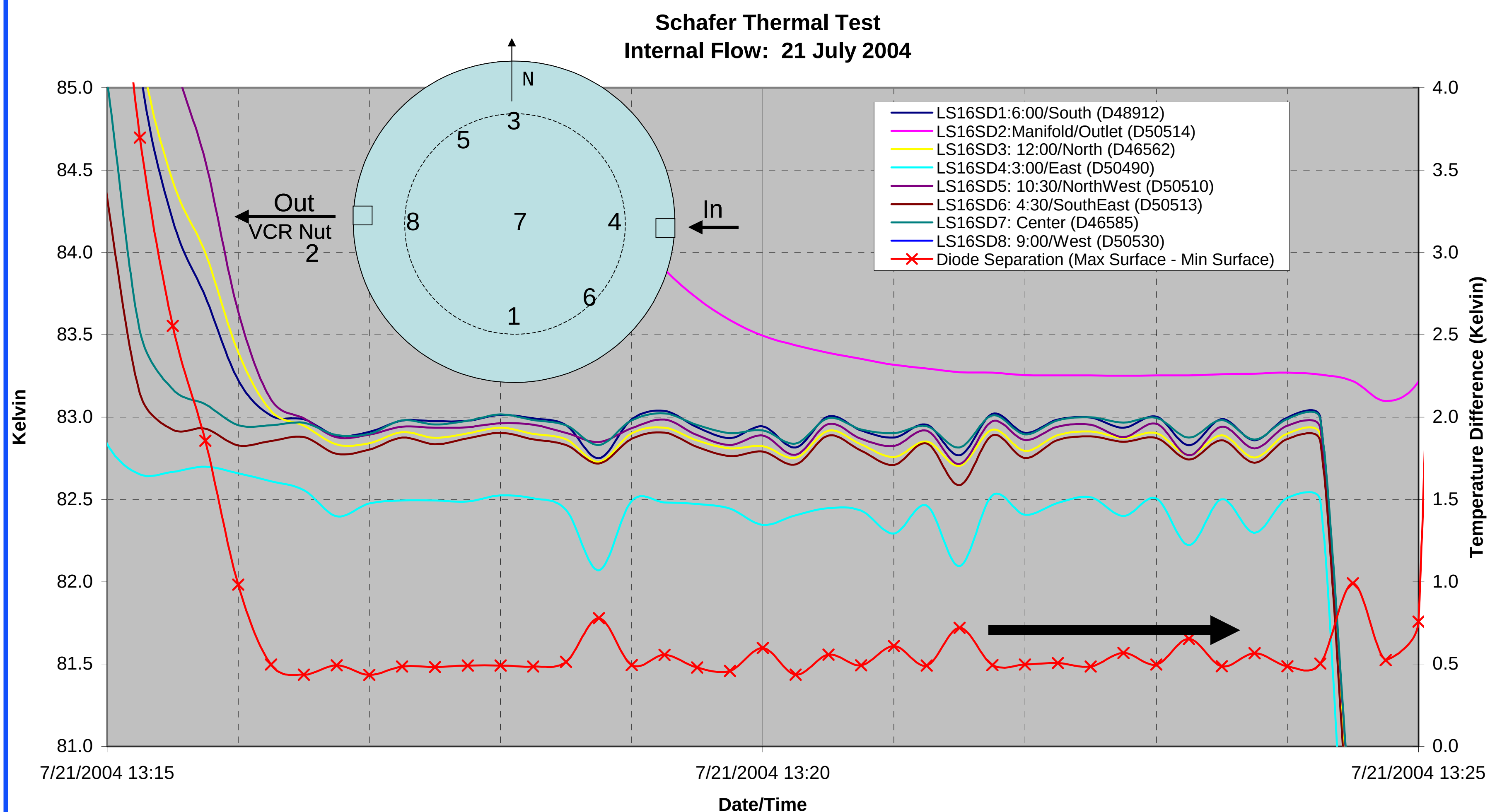
External Flow – No Mirror Insulation



Note: The manifold diode (LS16SD2) detached during cooldown. Not included in difference calculation.

Mirror Reaches Steady State @ 82.4 ± 1.45 Kelvin in <4 minutes

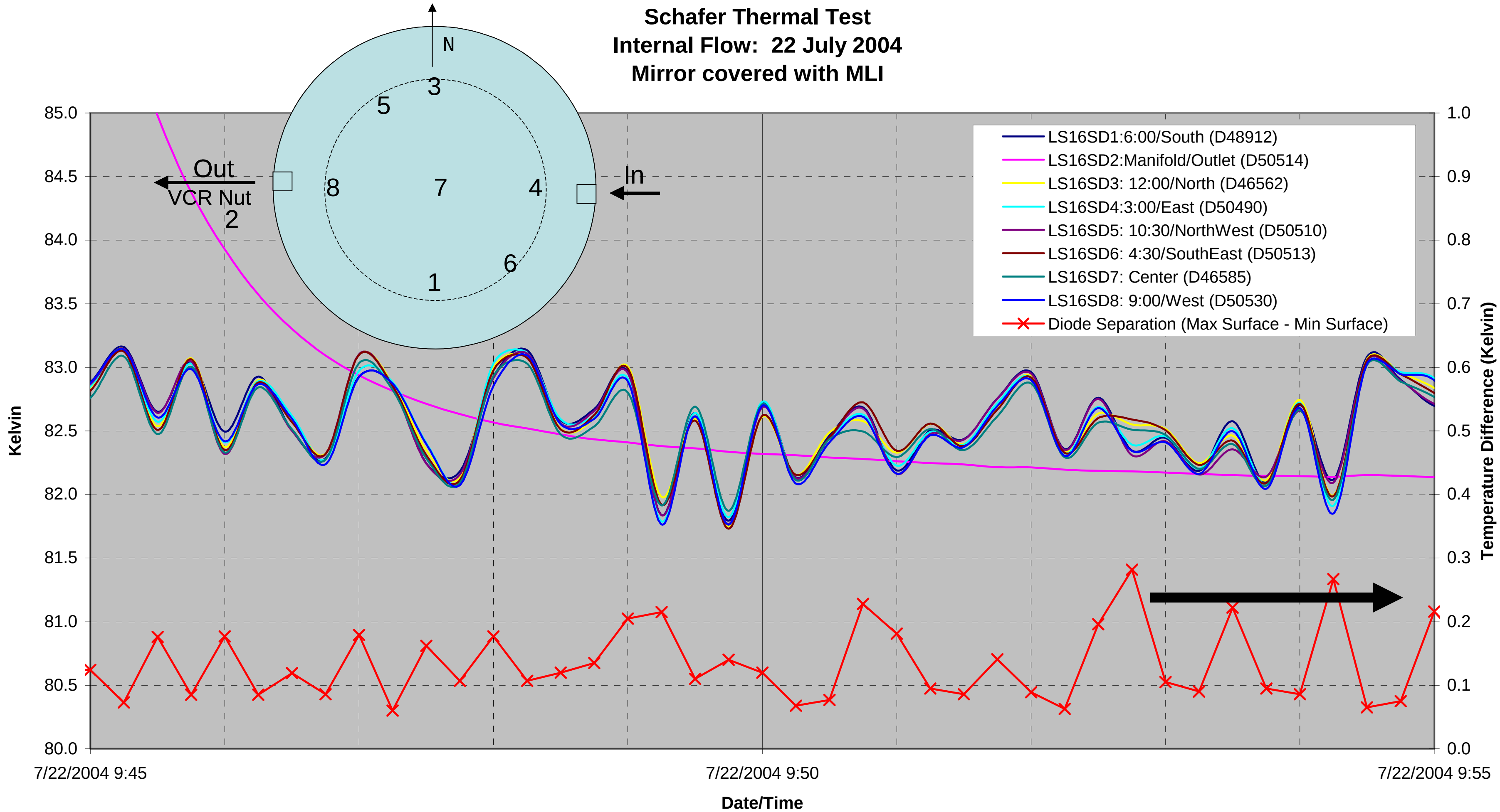
Internal Flow – No Mirror Insulation



Notes: The outlet diode (LS16SD8) detached during cooldown; not included in difference calculation.
LS16SD2 was mounted to the SS VCR nut; not included in difference calculation.

Mirror Reaches Steady State @ 82.75 ± 0.25 Kelvin in <4 minutes

Internal Flow – Insulated Mirror



Notes: LS16SD2 was mounted to the SS VCR nut; not included in difference calculation.

Mirror Reaches Steady State @ 82.75 ± 0.075 Kelvin

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Phase II Project

- Build 0.5 m Actively Cooled SLMS™ with ROC = 5 m
- Cryotest at Ball
- Cryotest at NASA MSFC in Small or Large Chamber
- Continue Technology Maturation