Absorption Studies in Sapphire Crystals and Optical Coatings

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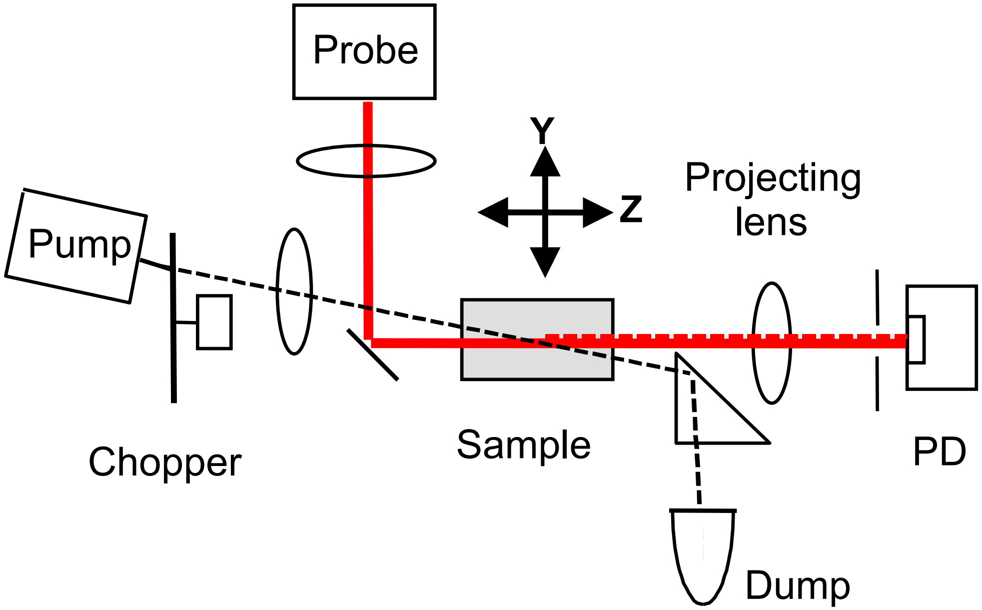
Lasers and Optics Working Group

LIGO LSC meeting, LLO 3/18/03

Photothermal Common-Path Interferometry

- diffraction regime of cross-beam cw thermal lensing -



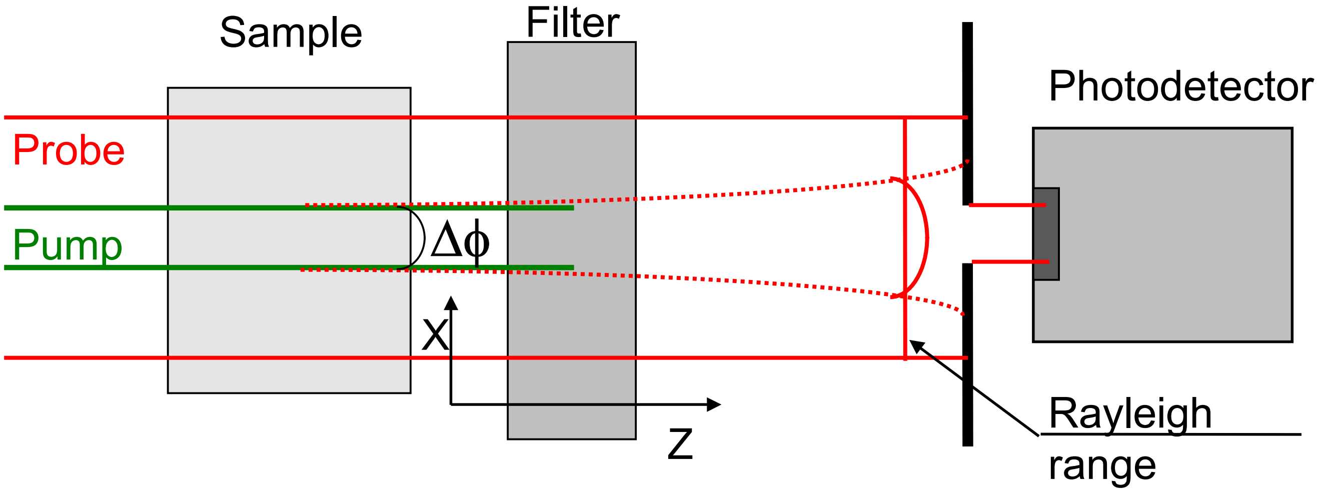
Pump waist	50 µ	Chopping frequency	380 Hz (10Hz- 2 kHz)
Probe waist	120 µ	Crossing angle	1° - 20°(in air)
Pump power	5 W	Probe power	0.5 mW

- **ac-component of probe distortion is detected by photodiode + lock-in**
- **absorption coefficient $<10^{-7}$ cm^{-1} (~10 ppb coating) can be detected with 5 W pump power**
- **crossed beams help to avoid false signals from optics and surfaces of the sample**

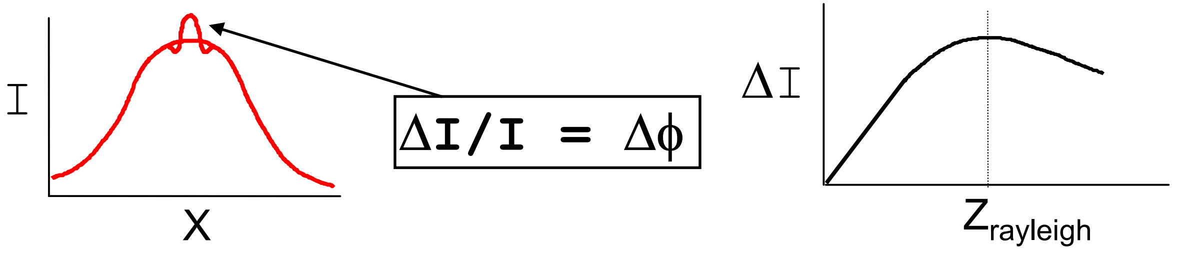
Photothermal Common-Path Interferometry

for optical loss measurements

‘Self-interference’ of probe in the near field



Interferometric sensitivity: 0.1 ppm/cm with 4 W of pump

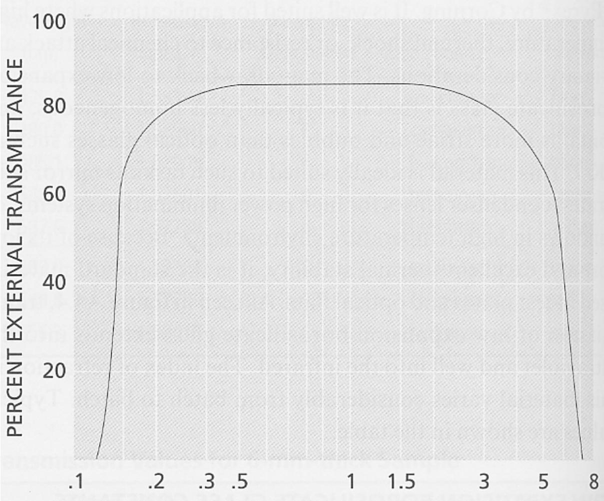


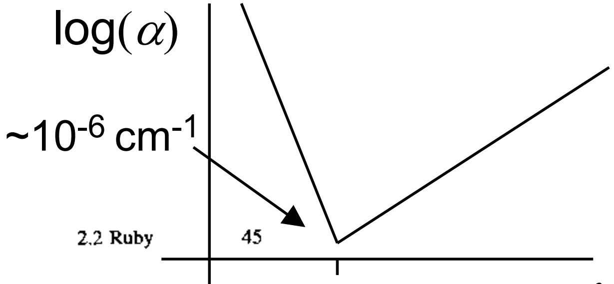
$\Delta I / I = \Delta\phi$

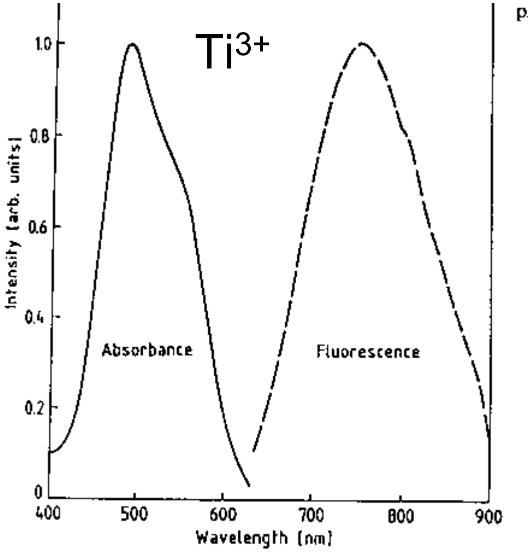
Study of absorption in sapphire

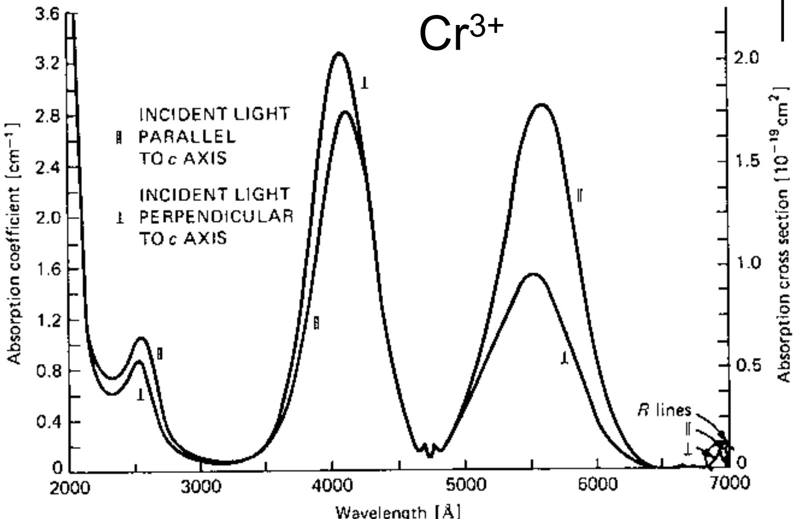
- Intrinsic
  - conduction to valence band in UV
  - multiphonon in mid-IR
  - only cure is different material
    expectation and existence proofs indicate this isn't the problem

- Extrinsic
  - native defects
    vacancies, antisites, interstitials,
  - impurities
    e.g. transition metals: Cr, Ti, Fe, …



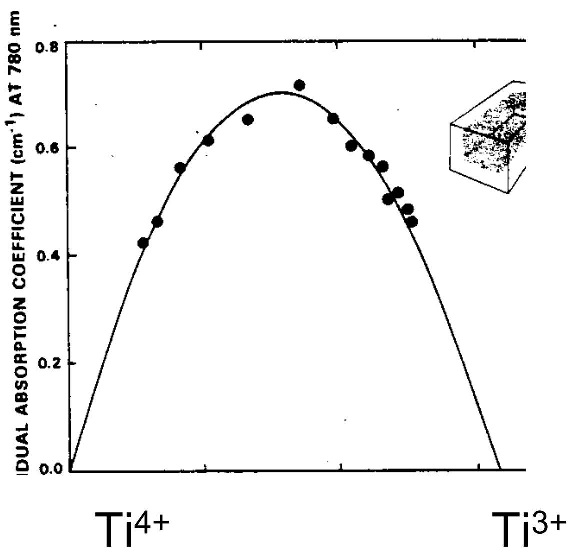






Characteristics of absorbing species

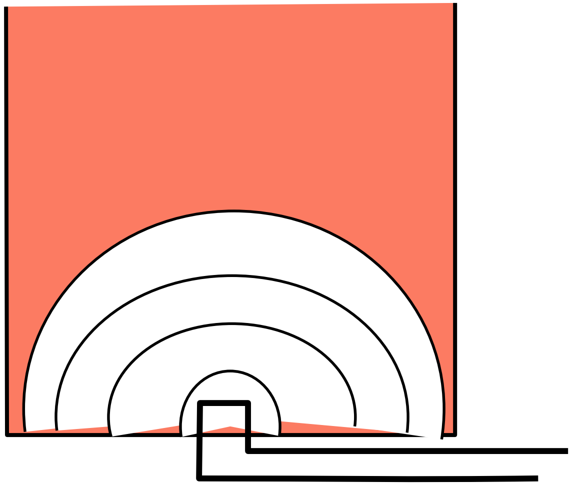
- Allowed transitions
  - large cross sections $\Rightarrow$ ppm concentrations significant
- Broad spectral features
  - identification difficult
  - off “resonant” absorption significant
  - sum of several species can contribute to absorption at given λ
- Redox state important
  - e.g. $\alpha[\mathrm{Ti}^{3+}] \neq \alpha[\mathrm{Ti}^{4+}]$
  - annealing alters absorption without altering impurity concentrations
- Impurities do not necessarily act independently
  - $\mathrm{Al} : \mathrm{Al} : \mathrm{Ti}^{3+} : \mathrm{Ti}^{4+} : \mathrm{Al} : \mathrm{Al} \neq \mathrm{Al} : \mathrm{Ti}^{3+} : \mathrm{Al} : \mathrm{Al} : \mathrm{Ti}^{4+}$
  - absorption spectra at high concentrations not always same as low
    - complicates correlations to known spectra



$$\Rightarrow \alpha_{IR} \propto [\mathrm{Ti}^{3+}][\mathrm{Ti}^{4+}]$$

Growth of sapphire at Crystal Systems, Inc. by the HEM process

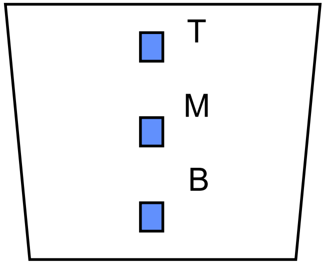
- Heat Exchanger Method
  - He-gas cools bucket of melt
  - solidification outwards from bottom



- Starting materials
  - typically “craquelle” sapphire
  - ppm levels of some transition metals
  - purity ↑ ⇒ $ ↑↑
- Segregation
  - impurities rejected ($k < 1$) into melt
  - segregate into outer regions of crystal (last to crystallize)
  - can expect different behavior top/middle/bottom of boule
  - can remelt outer portion to concentrate impurities
    remelt inner portion to reduce impurity concentration
  - opposite argument for $k > 1$ impurities
- LIGO target - 10 to 20 ppm/cm at 1064 nm
- Typical CSI “Hemex white” 40 to 60 ppm/cm

Collaborative studies with CSI

- **Experimental design**
  - **anticipated mechanisms: impurity concentration, intrinsic defects, redox state**
  - **two main control methods: growth and annealing**
- **Growth Studies**
  - **~ 30 CSI White, 1 cm cubes**
  - **primarily expected to influence impurity concentration**
  - **starting materials**
    - **virgin material from 5 different vendors/purity**
    - **re-melted boules**
  - **samples cut from top/middle/bottom of boule**
    - **explore impurity segregation effects**
  - **no strong correlation found**

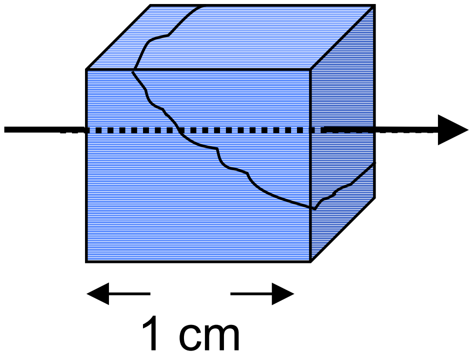


- **Annealing Studies**
  - **2.5 cm dia x 1 cm thick a-axis CSI Hemex White**
  - **primarily influence redox state, intrinsic defects (e.g. Oxygen vacancies)**
  - **parameters: time, temperature, reducing (H_2) or oxidizing (air, O_2)**
  - **furnace design**
    accidental introduction of impurities, especially near surface

Compositional analysis by GDMS: ppms of everything

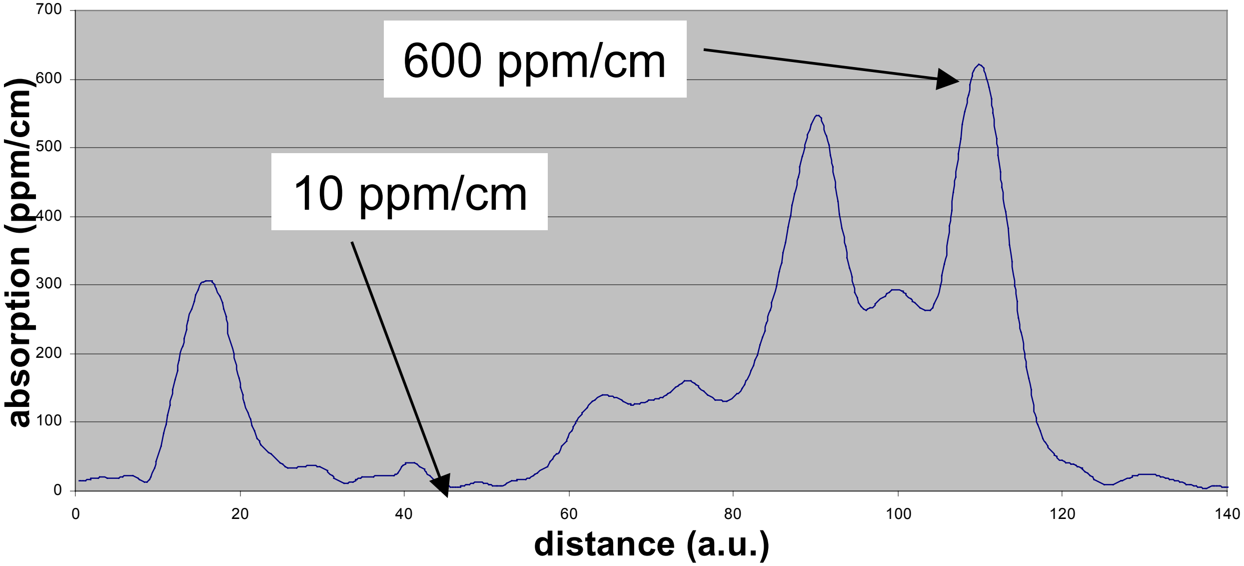
	LIGO #1T Sample #10 ppmw	LIGO #1M Sample #11 ppmw	LIGO #1B Sample #12 ppmw	LIGO #2T Sample #07 ppmw	LIGO #2M Sample #08 ppmw	LIGO #2B Sample #09 ppmw	LIGO #3T Sample #04 ppmw	LIGO #3M Sample #05 ppmw	LIGO #3B Sample #06 ppmw	LIGO #4T Sample #01 ppmw	LIGO #4M Sample #02 ppmw	LIGO #4B Sample #03 ppmw	LIGO #5T Sample #13 ppmw
Li	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Be	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
O	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major
F	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na	0.21	0.42	0.40	0.25	0.75	0.35	0.36	0.44	0.81	0.82	3.2	0.95	0.20
Mg	0.16	0.27	0.30	0.22	0.29	0.18	0.19	0.25	0.25	0.53	0.39	0.20	0.15
Al	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major	Major
Si	12	8.5	10	8.5	7.5	9.5	4.2	5.9	9.5	10	15	8.5	15
P	0.1	0.053	0.20	0.11	0.11	0.11	0.1	0.15	0.15	0.21	0.19	0.1	0.045
S	1.1	1.5	1.8	0.79	1.2	1.6	1.5	1.5	0.21	1.5	1.8	1.1	0.88
Cl	1.2	5.5	4.2	1.5	2.5	2.5	2.6	2.9	3.1	4.7	6.0	1.0	2.5
K	0.29	0.25	0.39	0.33	0.33	0.35	0.23	0.35	0.33	1.1	1.2	0.40	0.25
Ca	1.1	1.2	1.1	1.1	1.1	1.5	1.2	0.63	0.75	1.7	1.4	0.75	0.80
Ti	0.37	0.11	0.45	0.12	0.36	0.45	0.089	0.39	0.27	0.22	0.14	0.12	0.11
V	0.10	0.037	0.026	0.12	0.23	0.37	0.026	0.021	0.04	0.11	0.086	0.095	0.056
*Cr	2.5	1.1	1.5	1.2	1.1	1.5	1.0	1.4	1.4	1.3	1.0	1.1	1.0
Mn	0.10	0.088	0.065	0.021	0.083	0.15	0.033	0.055	0.068	0.073	0.065	0.03	0.034
*Fe	2.5	2.2	5.5	1.8	1.4	1.5	2.1	1.8	1.8	1.5	1.3	1.5	2.7
Co	0.10	0.018	0.02	0.02	0.01	0.012	0.01	0.018	0.06	0.01	0.01	0.01	0.01
Ni	0.46	0.025	0.23	0.11	0.11	0.067	0.066	0.17	0.28	0.074	0.025	0.060	0.045
Cu	0.23	0.11	0.15	0.31	0.24	0.20	0.38	0.20	0.22	0.096	0.19	0.30	0.10
Zn	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ga	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
As	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zr	0.14	0.02	0.15	0.12	0.050	0.22	0.048	0.13	0.15	0.38	0.12	0.14	0.045
Nb	0.027	0.13	0.11	0.047	0.037	0.041	0.065	0.092	0.025	0.019	0.045	0.045	0.021
Mo	0.25	0.24	0.24	0.18	0.37	0.29	0.29	0.29	0.15	0.18	0.26	0.29	0.15
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sn	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ba	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
La	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ce	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Hf	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
W	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2
Pb	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Bi	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Low optical loss existence proof (Rosetta sapphire)

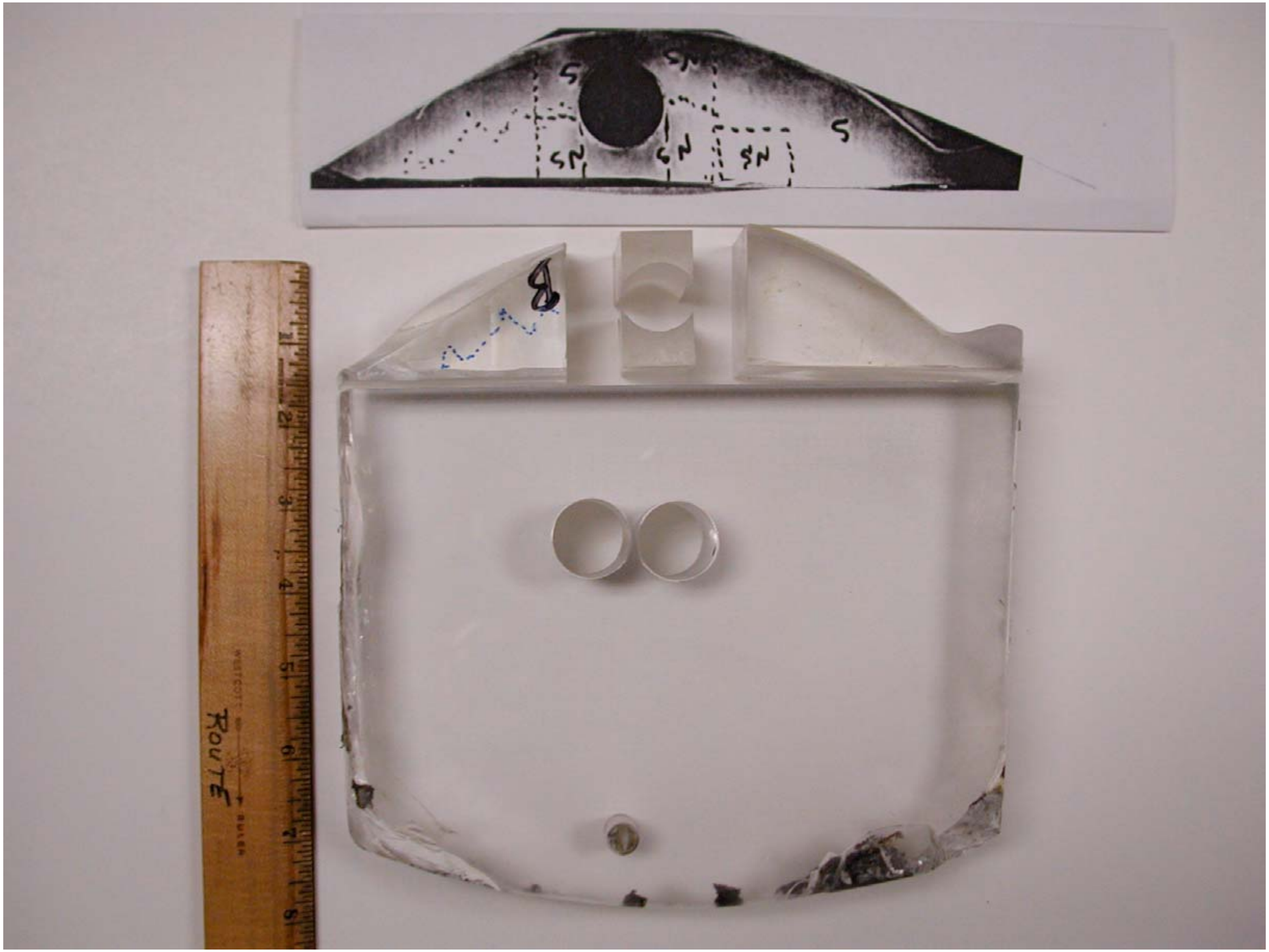


- Single 1 cm sample
  - region with 10 ppm/cm
  - region with 600 ppm/cm
  - abrupt boundary between
- Preparation unexceptional
- Mechanism not yet clear
  - not typical of normal impurity segregation
  - specimen should be useful for “self-normalizing” measurements

Sapphire cube 8T: IR scan across the scatter boundary (10 mm-long sample)



Parent slab from which 8-T was taken



GDMS Studies on HEM Sapphire 8-T

(Measurements by Shiva Technologies, Inc.)

	High Loss (α>50 ppm/cm)	**Low Loss** (α<20 ppm/cm)
Element	Concentration	Concentration
	[ppm wt]	[ppm wt]
Na	0.25	0.16
Si	0.31	0.13
Cr	< 0.1	< 0.1
Fe	< 1	< 1
Cu	< 1	< 1
Ti	< 0.05	< 0.05
Y	0.15	0.02
Nb	< 5	< 5
Mo	< 1	< 1
Ta	Binder	Binder

Other Impurity Studies on HEM Sapphire 8-T
(Measurements by S. McGuire, Southern Univ.)

Neutron Activation Analysis of Impurities in CSI Sapphire

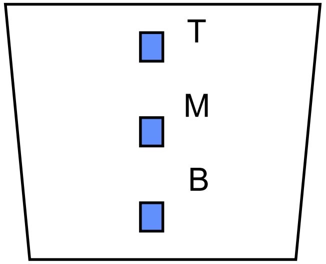
Observed impurity concentrations given in nanogram of impurity per gram of sample.

Element	Relative Concentration by mass ng/g	Observed radionuclide	Halflife	γ - ray energy (keV)	γ - ray intensity (%)
Ti	300± 29	47_{Sc}	3.34 d	159.4	68
Sc	3± 0.20	46_{Sc}	86.6 d	889.1	99.98
Cr	5±1	51_{Cr}	27.7 d	320.2	9.83
Fe	≤1000	59_{Fe}	44.5 d	1099.3	56.5
Mo	1500± 227	99_{Mo}	2.75 d	141.0	90.7
				739.5	12.14
				777.9	4.35

The errors are compounded uncertainties and correspond to one standard deviation.

Collaborative studies with CSI

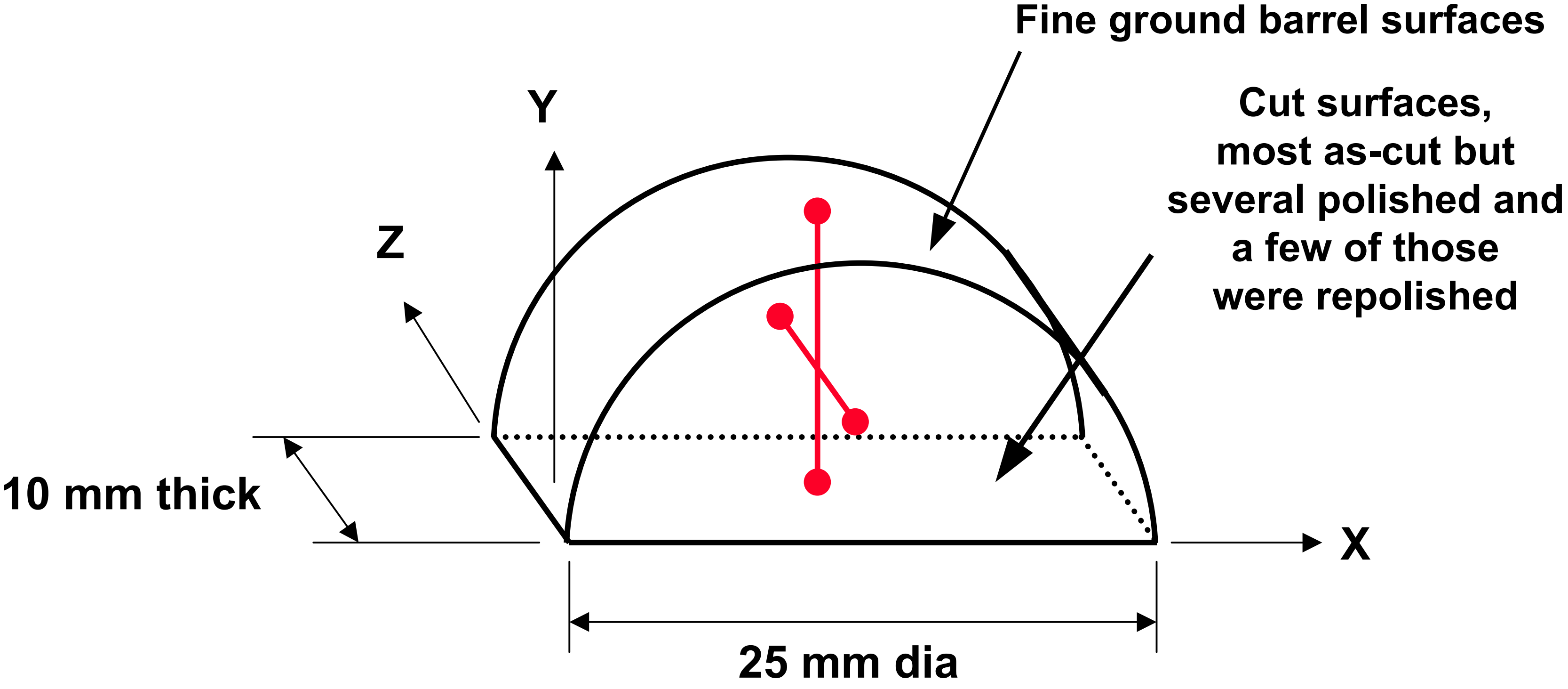
- **Experimental design**
  - **anticipated mechanisms: impurity concentration, intrinsic defects, redox state**
  - **two main control methods: growth and annealing**
- **Growth Studies**
  - **~ 30 CSI White, 1 cm cubes**
  - **primarily expected to influence impurity concentration**
  - **starting materials**
    - **virgin material from 5 different vendors/purity**
    - **re-melted boules**
  - **samples cut from top/middle/bottom of boule**
    - **explore impurity segregation effects**



- **Annealing Studies**
  - **2.5 cm dia x 1 cm thick a-axis CSI Hemex white**
  - **primarily influence redox state, intrinsic defects (e.g. oxygen vacancies)**
  - **parameters: time, temperature, reducing (H_2) or oxidizing (air, O_2)**
  - **furnace design**

    accidental introduction of impurities, especially near surface

Optical loss measurement scheme for sapphire windows

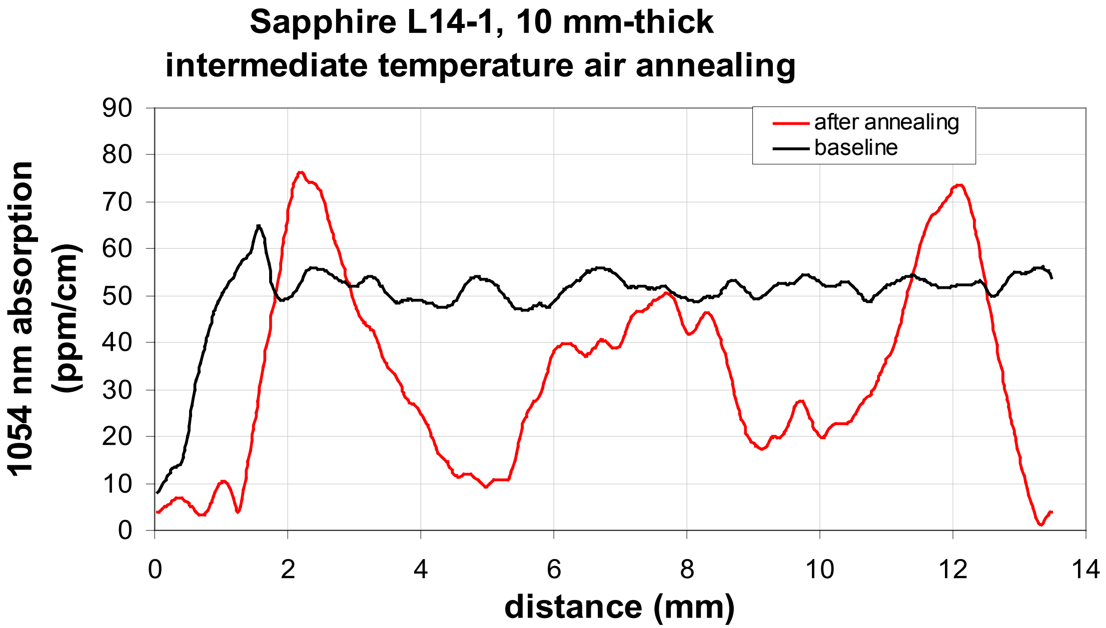


Fine ground barrel surfaces

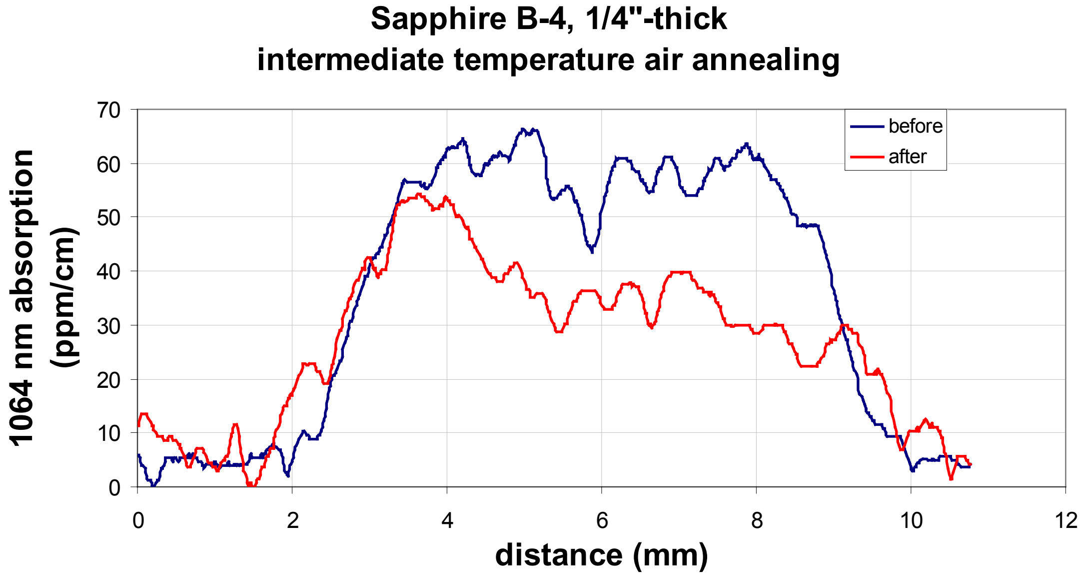
Cut surfaces,
most as-cut but
several polished and
a few of those
were repolished

●—● Locus of intersection of pump and probe beam where absorption in a 100 micron long x 25ϕ micron cylinder is measured during Y- and Z-scans

Apparent furnace effects

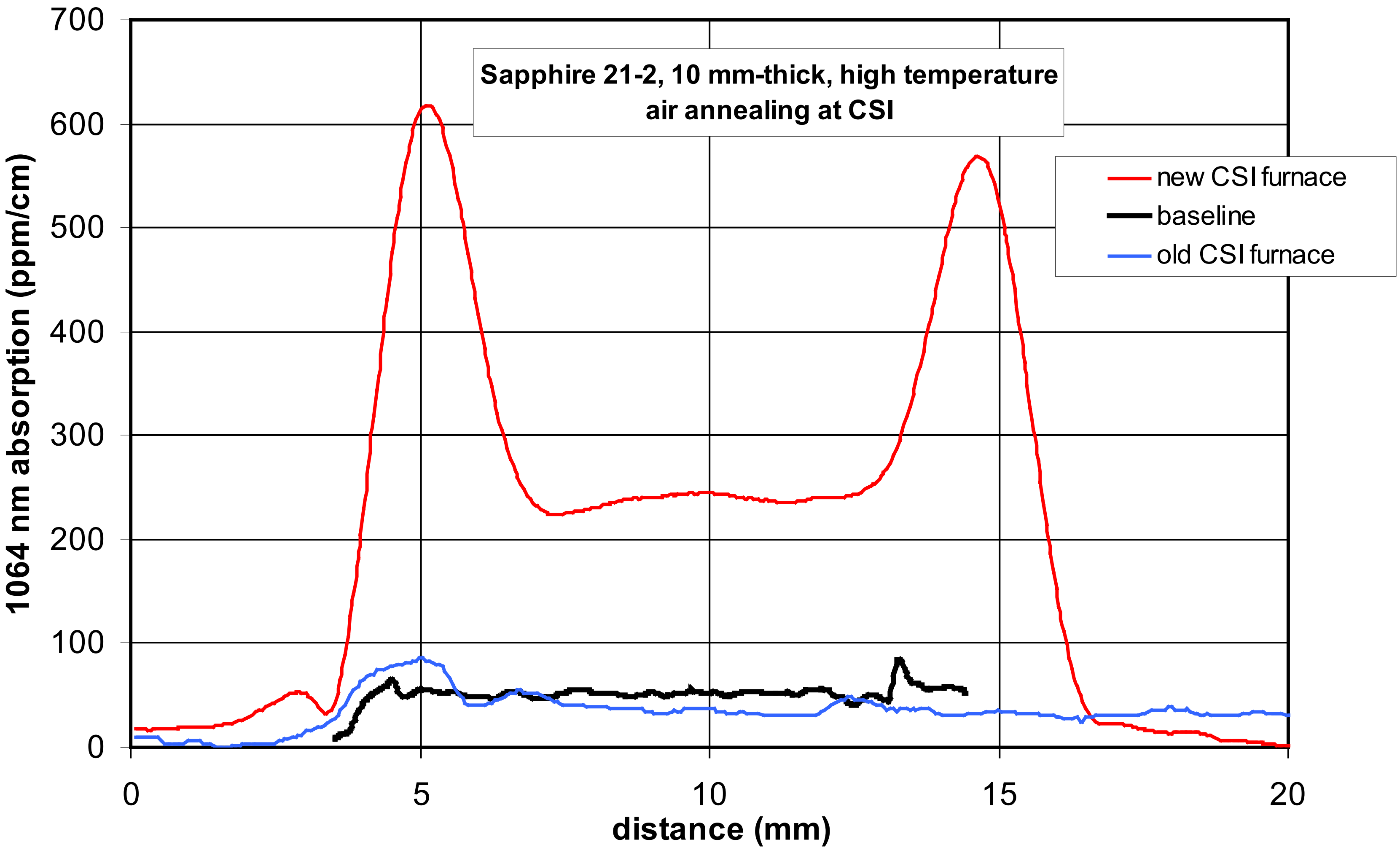


Annealed at CSI



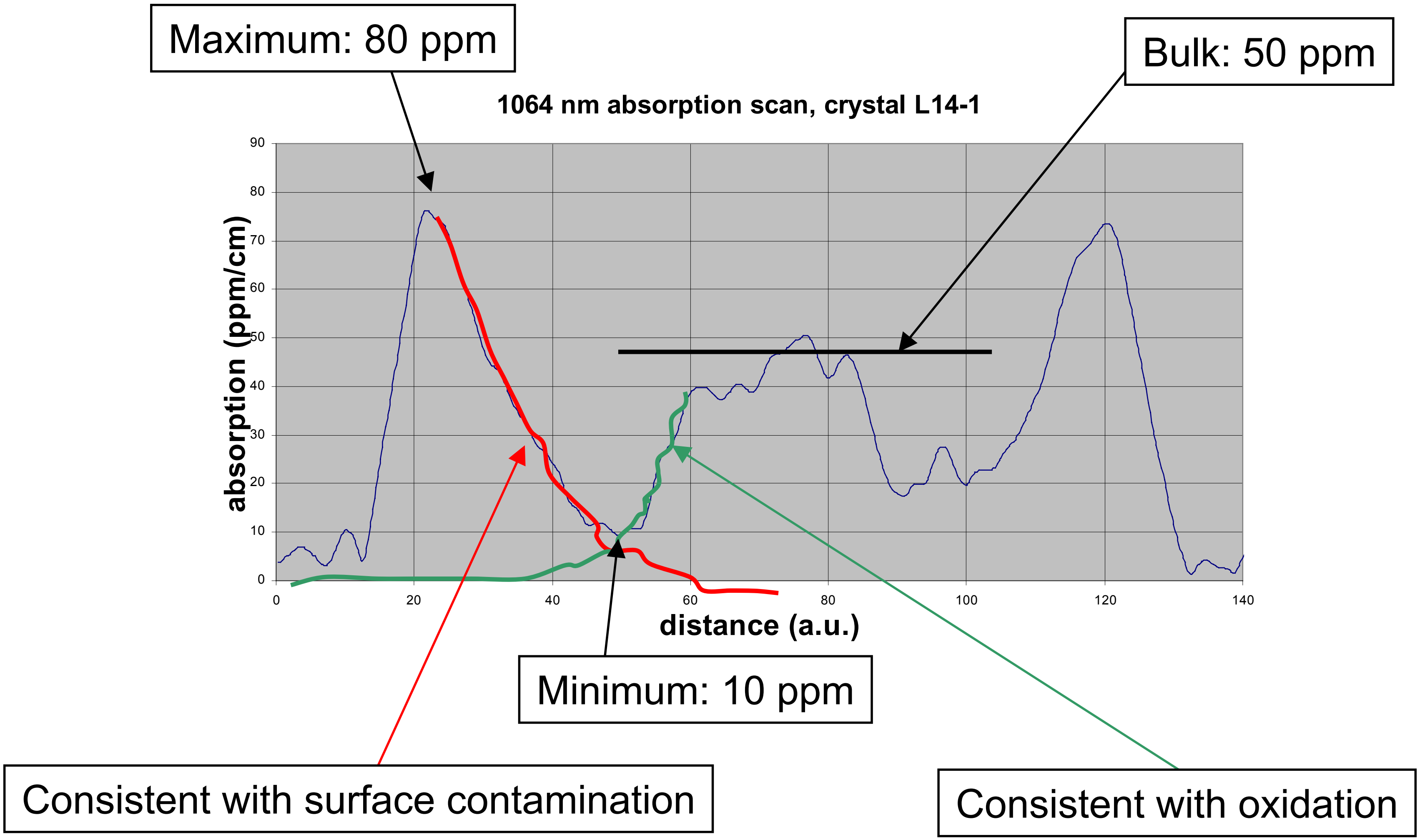
Annealed under similar conditions at Stanford

Apparent furnace effects



Complicated air-annealing behavior

(1064 nm absorption through cross-section of a window)



Maximum: 80 ppm

Bulk: 50 ppm

1064 nm absorption scan, crystal L14-1

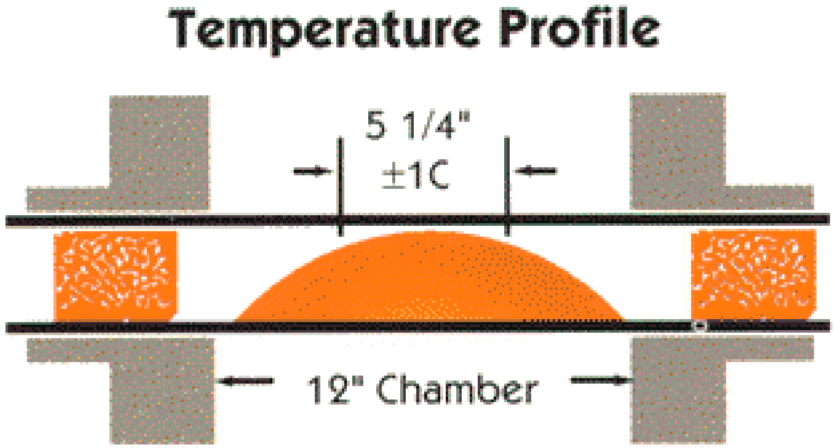
Minimum: 10 ppm

Consistent with surface contamination

Consistent with oxidation

Post-growth heat treatment studies at Stanford

- Controlled atmosphere processing
  - Oxidizing conditions - air or oxygen
  - Inert/reducing conditions - N2 w/wo H2



$MoSi_2$ “Super Kanthal” max. temp. to 1700° C
High density 998 alumina process tube, 3” OD
O-ring sealed fittings at both ends for atmosphere control
Vestibules closed with 998 alumina heat shields

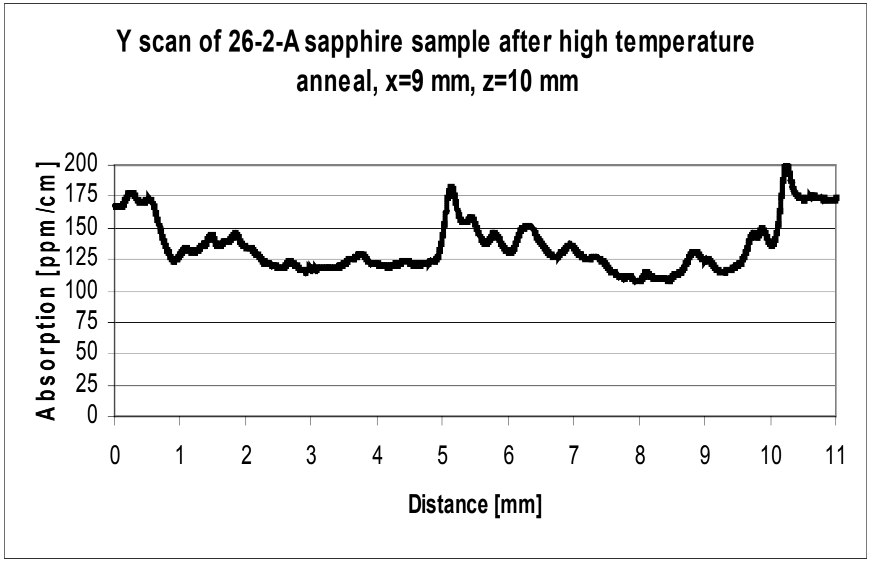
Annealing studies under oxidizing conditions

Crystal	Temperature	α (ppm/cm)					
		514 nm			1064 nm		
		bulk	dip	surface	bulk	dip	surface
Annealed at CSI							
LB-1	Control	850-1300	no	no	50-60	no	no
LB-2	Control	1200-1500	no	no	60-70	no	no
L14-1	Intermediate	1350	300	600	50	10-20	75
L14-2	Intermediate	800	300	2200	75	45	4000
L14O-1	Intermediate	1100	250	700	50-60	20	260
L14O-2	Intermediate	700	250	700	45	25	900
L16-1	High	80-170	no	350	25	no	90
L16-2	High	170	no	500	35	no	140
L16O-1	High	120	no	300	80	no	220
L16O-2	High	200	no	375	90	no	300
L1696-1	High	300	no	450	50	no	140
L1696-2	High	230	no	500	32	no	120
22-1	High				4700	no	<<bulk
22-2	High				4800	no	<<bulk
Annealed at Stanford (Cut surfaces unpolished unless specified)							
B-2-B	Control						
B-2-A	Intermediate	NA	NA	NA	NA	NA	NA
B-4-B	Control	1200	no	1200	60	no	60-70
B-4-A	Intermediate	1100	700-800	900-1200	35	<20	20-100
23-1-A	Control				70/80	no	
"	Intermediate				40/50	20	120
24-1-A	Control				70	no	
"	Intermediate				55/60	40	<50
24-2-A	Control				80	no	
"	Intermediate				50	20/30	75/120
26-2-A	Control				50	no	
"	High				130	125	400/700
27-2-B	Control				52	no	
"	Intermediate				45/50	30	<50
31-2-B	Control				35/40	no	
"	Intermediate				30	20	<30
30-2-B	Control				55/65	no	
"	Intermediate				45/55	20/25	<40

Annealing at high temperatures under oxidizing conditions

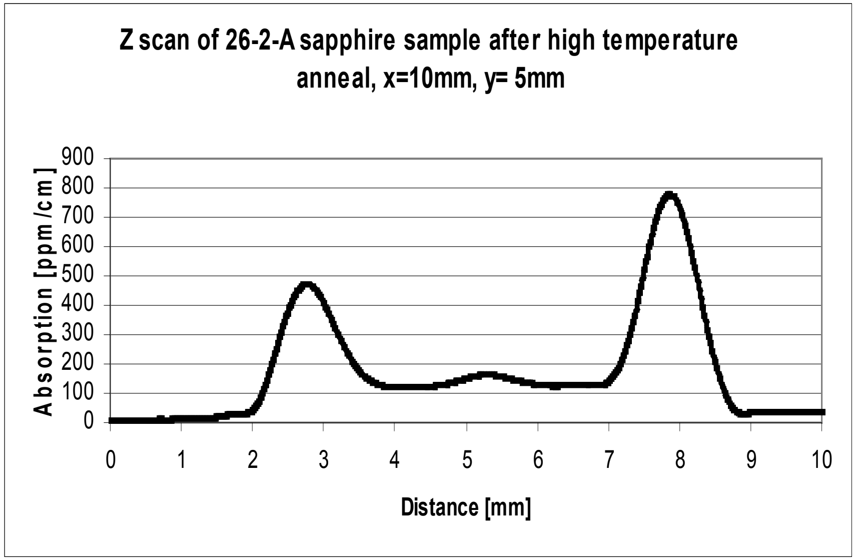
Y-Scan

Fine-Ground **Fine Ground**



Z-Scan

Polished Face **Polished Face**



Consistent trends under oxidizing anneals

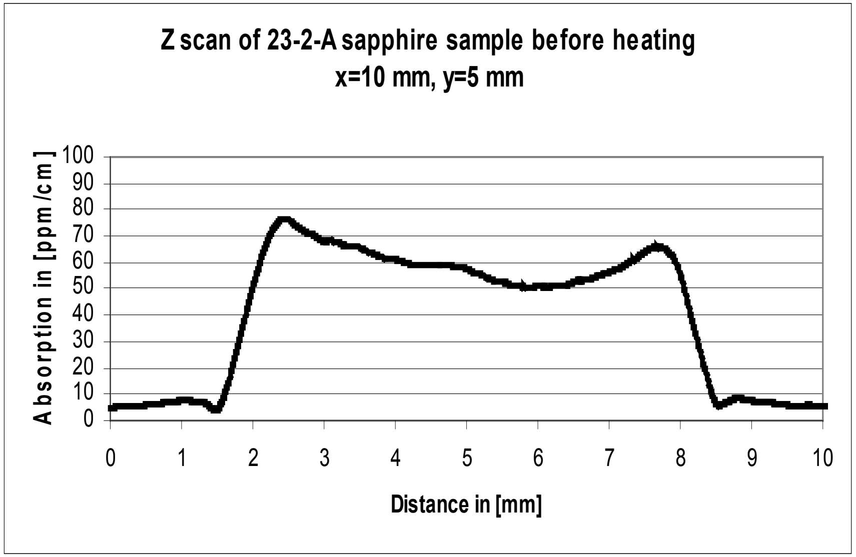
- As grown
  - Unclear correlation with starting material or furnace
    - Question of impurities, native defects and process contamination unresolved
  - No strong correlation with position in boule or use of re-melted feedstock
    - “Rosetta” sapphire indicates melt segregation operative during growth
    - Difficult to understand as simple impurity segregation
- After oxidizing anneals
  - Intermediate temperature annealing reduces bulk absorption at 1064 nm and reduces fluorescence (due to Ti^{3+}), but increases scatter
  - High temperature annealing increases bulk absorption and increases scatter
  - Surface kinetics and/or surface contamination influences outcome
    - Two diffusion “waves”: one reduces loss, one increases it
    - Rough surfaces enhance effect
- Oxidizing anneals do not appear to be the best route to low loss material

Previous annealing studies under inert/reducing conditions

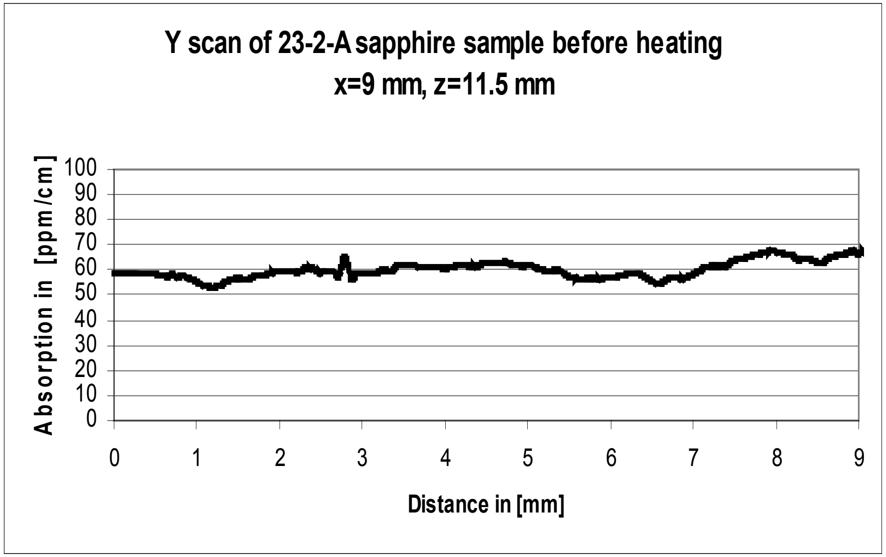
ID	Temperature	Time	Heat/Cool	Gas Flow	Before HT	After HT
---------	---------	---------	---------	---------	---------	---------
23-2-A	Low	Intermediate	200 C/hr	0.4 CFH	50-75	32-40
25-2-A	Low	Intermediate	200 C/hr	0.3 CFH	40-50	Cont.
25-2-A	Low	Long	200 C/hr	0.2 CFH	Cont.	25-35
27-2-A	Low	Long	200 C/hr	0.2 CFH	50	37-40
24-2-B	Low	Short	200 C/hr	0.2 CFH		
24-2-B	Low	Intermediate	200 C/hr	0.2 CFH	80-100	70-95
23-1-B	Low	Intermediate	200/800	0.2 CFH	70-80	30-40
23-2-B	High	Short	200 C/hr	0.2 CFH	60-75	NA
23-2-B	High	Intermediate	200 C/hr	0.2 CFH	NA	40-55
23-2-B	Intermediate	Short	200 C/hr	< 0.2 CFH	40-55	NA
23-2-B	Intermediate	Intermediate	200 C/hr	< 0.2 CFH	NA	50-65
30-1-B	Intermediate	Long	200 C/hr	0.2 CFH	55-65	35-40
27-1-B	Intermediate	Long	200 C/hr	0.2 CFH	50-55	30-35
25-1-A	Intermediate	Short	200 C/hr	0.2 CFH	40	25-30
	Intermediate	Short	200 C/hr	0.2 CFH	25-30	25-30
24-1-A	Intermediate	Short	200 C/hr	0.2 CFH	50-60	50-60
LH12-S-1-A	Low	Short	200 C/hr	0.2 CFH	40-50	28-30
LH12-S-1-A	Low	Short	200 C/hr	0.2 CFH	28-30	28-30
LH12-S-1-A	Intermediate	Short	200 C/hr	0.2 CFH	28-30	25-30
LH12-S-1-B	Low	Short	200 C/hr	0.2 CFH	40-55	32-42

Annealing at intermediate temperatures under reducing conditions using moderate heating and cooling rates

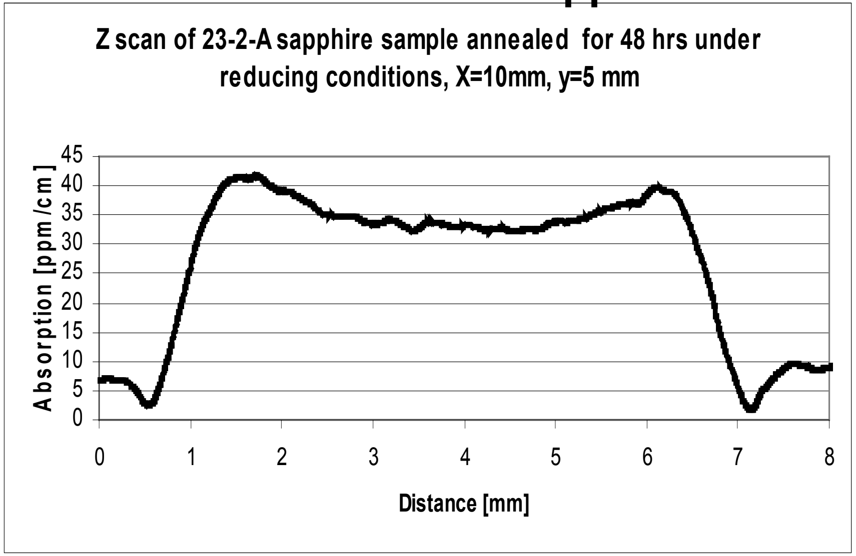
Z-scan Before - 55/65 ppm/cm



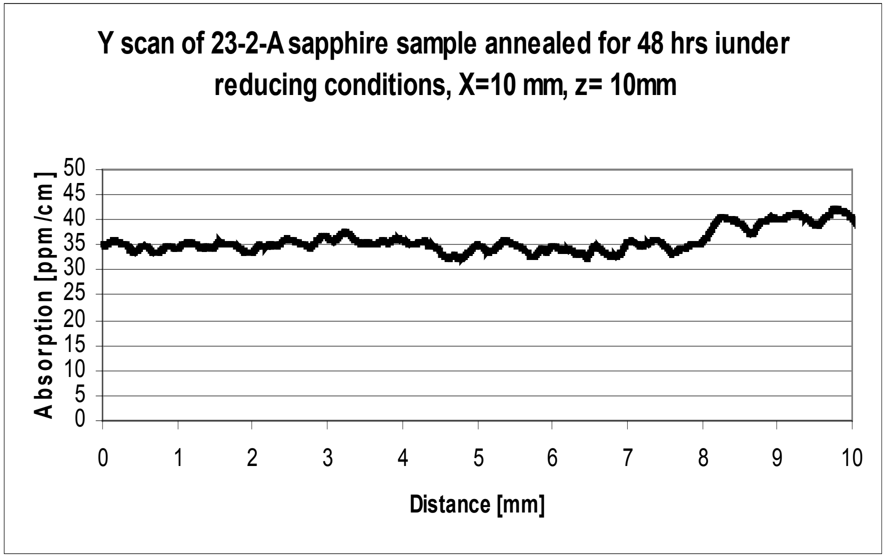
Y-scan Before - 55/65 ppm/cm



Z-scan After - 35/40 ppm/cm



Y-scan After - 35/40 ppm/cm



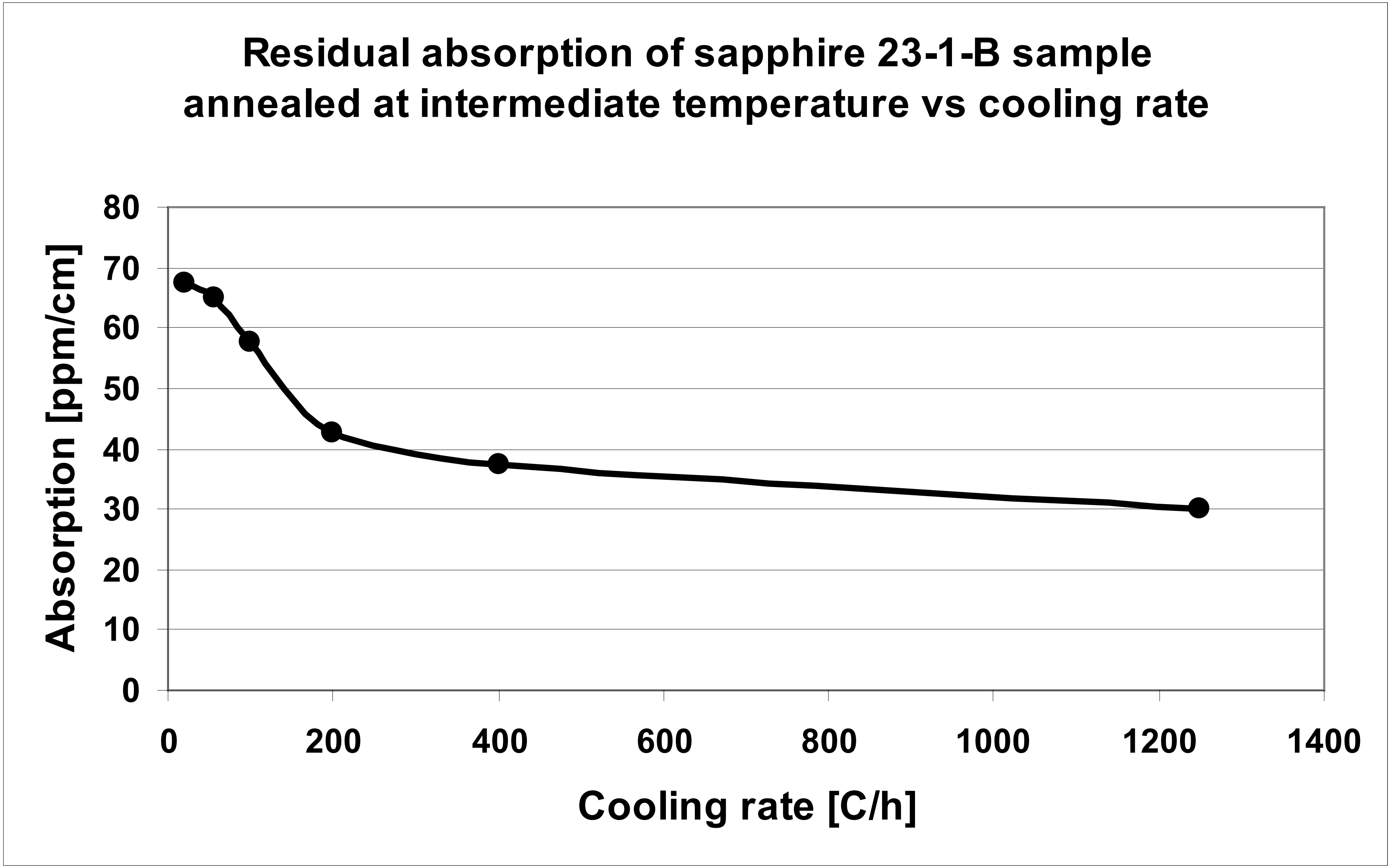
Recent annealing studies under inert/reducing conditions

ID	Soak Temp.	Heat/Cool Rate	Absortpion Before HT	Absortpion After HT	Comments	Gas
27-2-A	Intermediate	200 C/hr	50	37-40		H2/N2
24-2-B	Low	200 C/hr	80-100	70-95		H2/N2
30-1-B	Intermediate	200 C/hr	55-65	35-40		H2/N2
27-1-B	Intermediate	200 C/hr	50-55	30-35		H2/N2
25-1-A	Intermediate	200 C/hr	40	25-30	As-received	H2/N2
24-1-A	Intermediate	200 C/hr	50-60	50-60	Prev. O2 anneal	H2/N2
LH12-S-1-A	Intemediate	200 C/hr	40-50	28-30		H2/N2
LH12-S-1-A	Intermediate	200 C/hr	28-30	28-30		H2/N2
LH12-S-1-A	Intermediate	200 C/hr	28-30	25-28		H2/N2
LH12-S-1-B	Intermediate	200 C/hr	37-45	32-37		N2
LH12-S-1-B	Intermediate	200 C/hr	32-37	32-37		N2
LH12-S-1-B	Intermediate	200 C/hr	32-37	22-27		N2
23-1-B	Intermediate	200/800	70-80	30-40		H2/N2
23-1-B	Intermediate	20 C/hr	30-40	~65	Slow cool	N2
23-1-B	Intermediate	55 C/hr	~65	~65	Slow cool	N2
23-1-B	Intermediate	100 C/hr	~65	55-60		N2
23-1-B	Intermediate	200 C/hr	55-60	40-45		N2
23-1-B	Intermediate	400 C/hr	40-45	35-40		N2
23-1-B	Intermediate	>1250 C/hr	35-40	30	Power-off cool	N2
23-1-B	Intermediate	20 C/hr	30	65-70	Slow cool	H2/N2

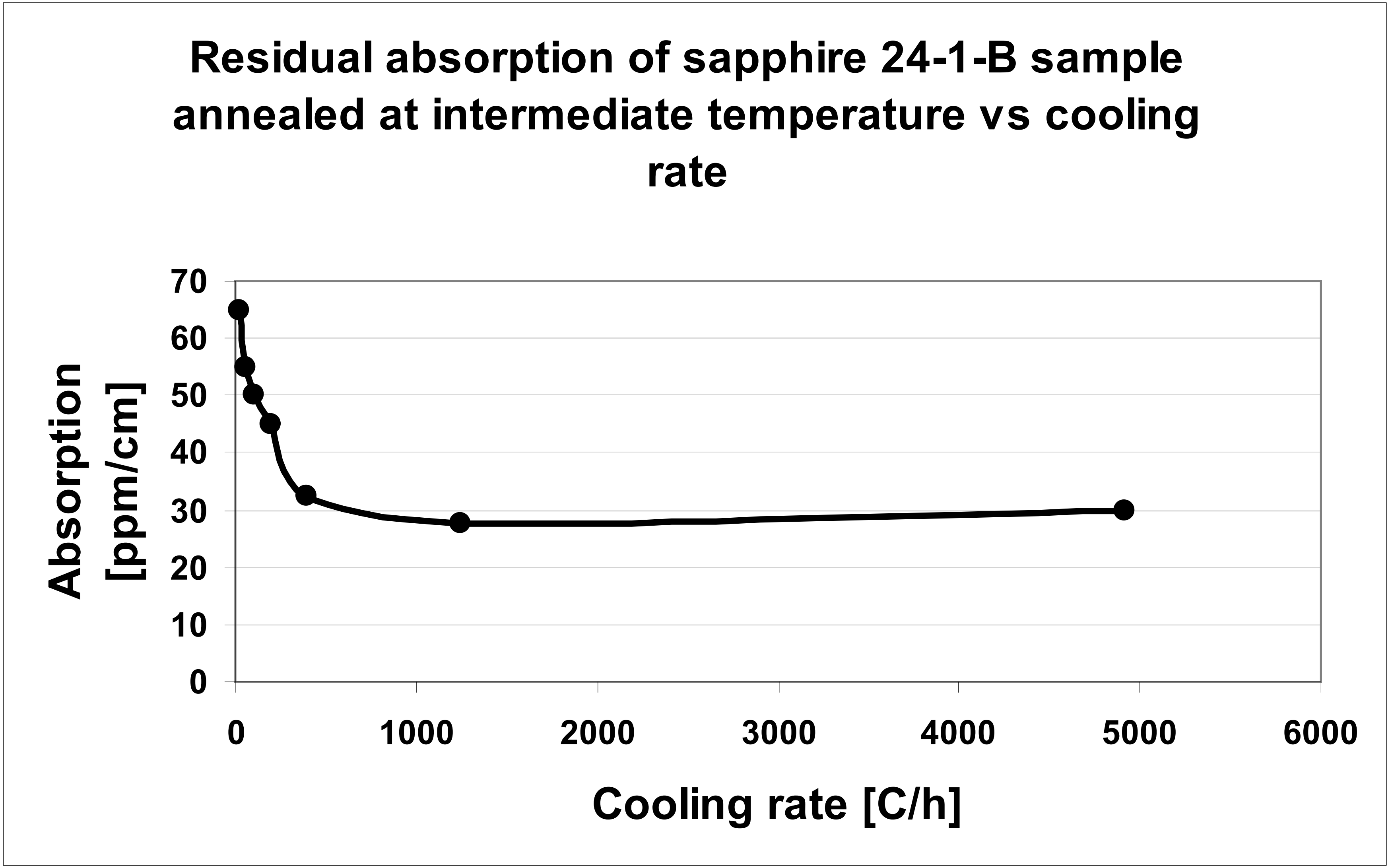
Recent annealing studies under inert/reducing conditions

ID	Soak Temp.	Heat/Cool Rate	Absortpion Before HT	Absortpion After HT	Comments	Gas
24-1-B	Low	200 C/hr	~60	~45		N2
24-1-B	Intermediate	200 C/hr	~45	~45		N2
24-1-B	Intermediate	20 C/hr	~45	~65	Slow cool	N2
24-1-B	Intermediate	55 C/hr	~65	~55	Slow cool	N2
24-1-B	Intermediate	100 C/hr	~55	50		N2
24-1-B	Intermediate	200 C/hr	50	40-45		N2
24-1-B	Intermediate	400 C/hr	40-45	30-35		N2
24-1-B	Intermediate	>1250 C/hr	30-35	25-30	Power-off cool	N2
24-1-B	Intermediate	20 C/hr	25-30	55	Slow cool	H2/N2
24-1-B	Intermediate	4920 C/hr	55	30	Forced cool	H2/N2
30-2-A	Low	1250 C/hr	50-55	50-55	Power-off cool	H2/N2
30-2-A	High	2700 C/hr	53	26	Power-off cool	H2/N2
30-1-A	Low	880 C/hr	42-45	42-45	Power-off cool	H2/N2
30-1-A	High	2700 C/hr	42-45	20-25	Power-off cool	H2/N2
30-1-A	Intermediate	5100 C/hr	20-25	21	Forced cool	H2/N2
30-1-A	Intermediate	4920 C/hr	21	18-20	Forced cool	H2/N2
31-1-A	Low	780 C/hr	85	85	Power-off cool	H2/N2
31-1-A	High	2700 C/hr	85	30-40	Power-off cool	H2/N2
31-2-A	Intermediate	2000 C/hr	35	22-24	Power-off cool	H2/N2

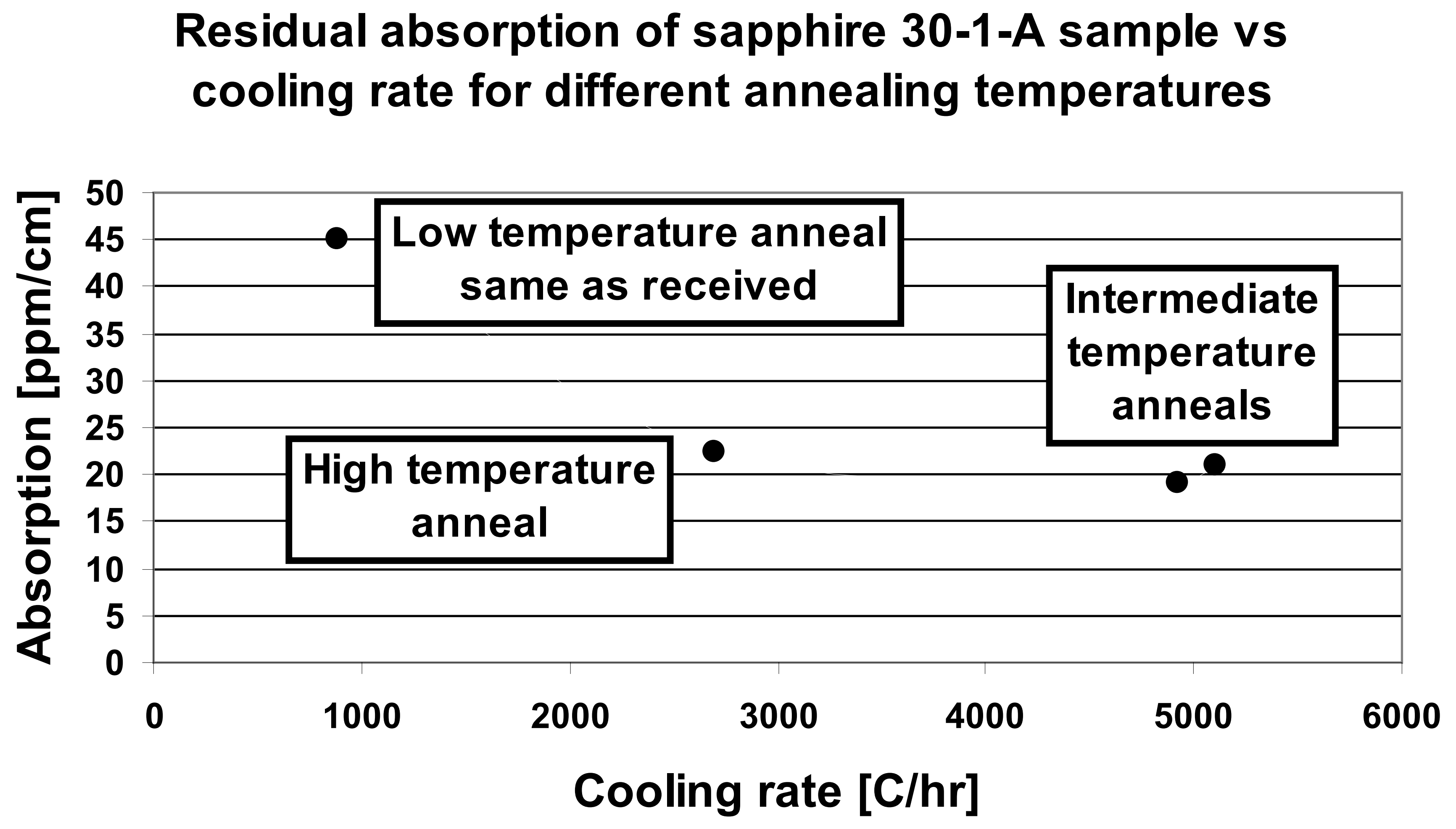
Observed trends under inert/reducing conditions



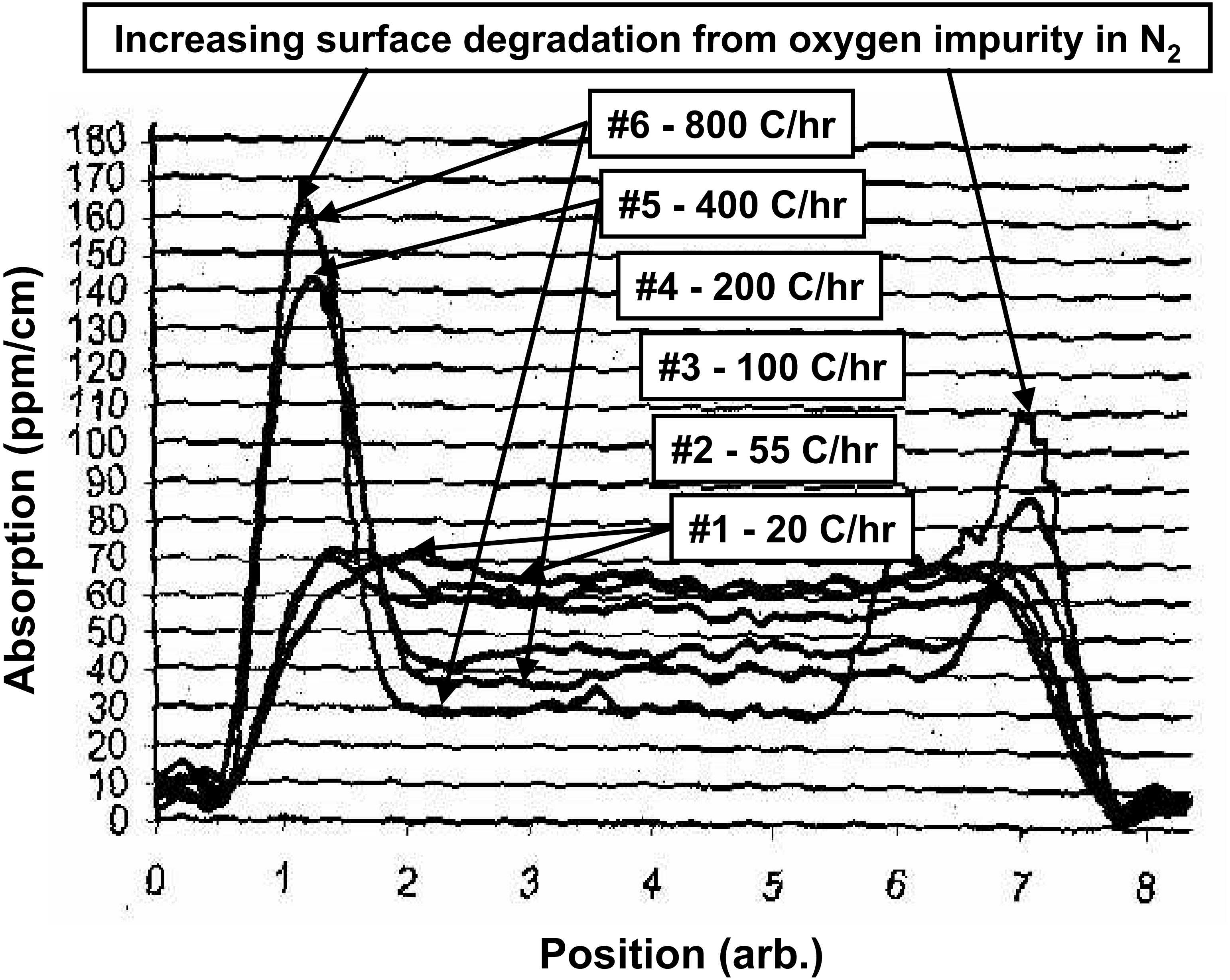
Observed trends under inert/reducing conditions



Observed trends under inert/reducing conditions



Sequential z-scans of 23-1-B heated to intermediate temperatures in N2 and cooled at rates shown



Increasing surface degradation from oxygen impurity in N_2

#6 - 800 C/hr

#5 - 400 C/hr

#4 - 200 C/hr

#3 - 100 C/hr

#2 - 55 C/hr

#1 - 20 C/hr

Sapphire Summary

- **Status**:
  - **40-60 ppm/cm at 1064 nm in large volumes from CSI**
  - **Heat treatment (annealing) can strongly influence optical losses**
  - **Oxidizing anneals irreversibly increase bulk absorption and scatter**
  - **Reducing anneals reversibly lower absorption without causing scatter**

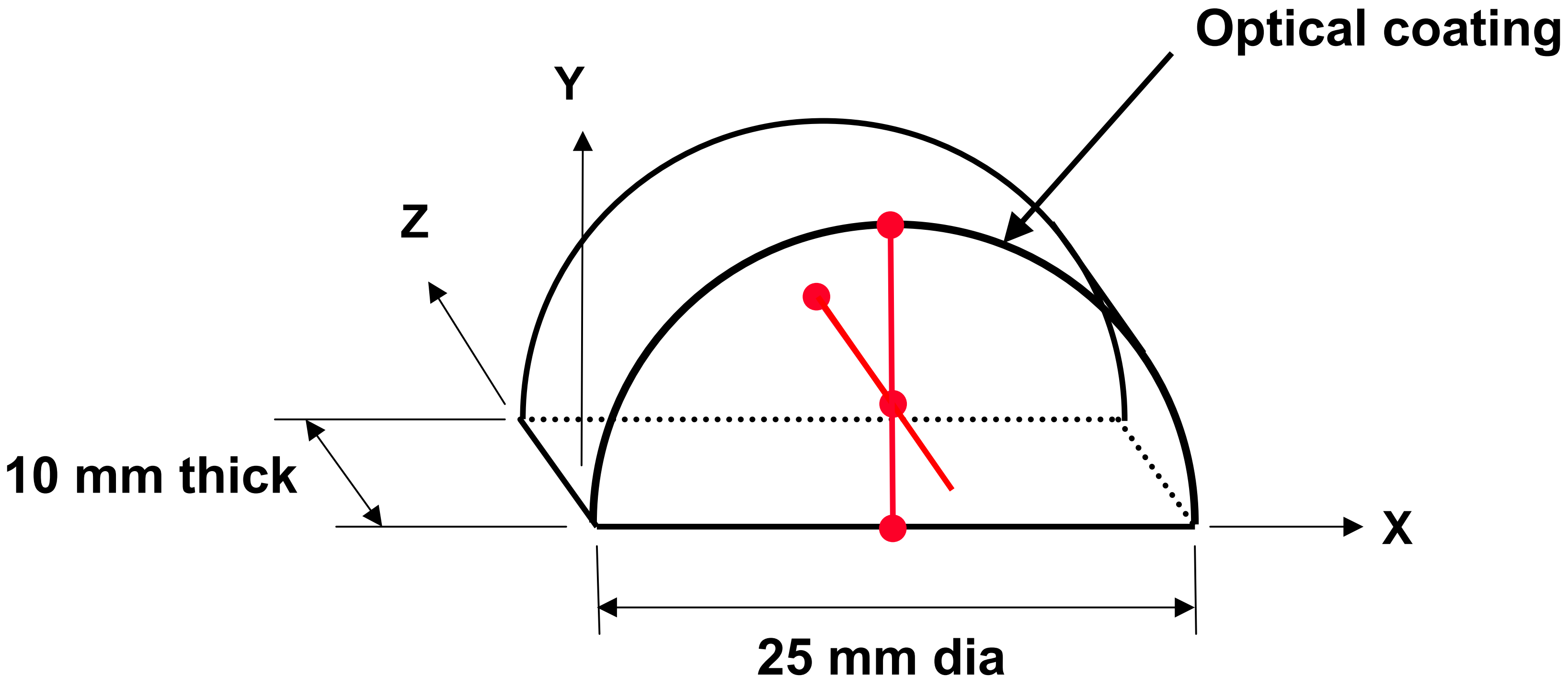
    Annealing at intermediate temperatures in H2/N2 yields >50% reductions
    - **25-30 pm/cm achieved with passive cooling at rates of >200º C/hr**
    - **20 ppm/cm achieved with forced cooling at rates of >400º C/hr**
  - **Cooling kinetics of the annealing process are controlling variables**
- **Current thinking:**
  - **At least two extrinsic defect species (eg. Ti^{3+}:Ti^{4+} complex plus other(s))**
  - **Point defect equilibrium most important factor in current CSI material**
    - **Metastable state resulting from rapid cooling from high temp is beneficial**
  - **Low loss 8-T “Rosetta” at 10 ppm/cm suggests extrinsic defects still present and responsible for the 20 ppm/cm floor in optical absorption**
- **Next steps**:
  - **Continue study of processing kinetics in larger size samples**

    How fast can large sapphire windows be cooled?
  - **Complete chemical analysis of low-loss regions of 8-T and both matrix phase and scattering centers in high loss regions**
  - **Refine list of “suspects” and design purposeful doping studies to evaluate**

Optical coating loss study

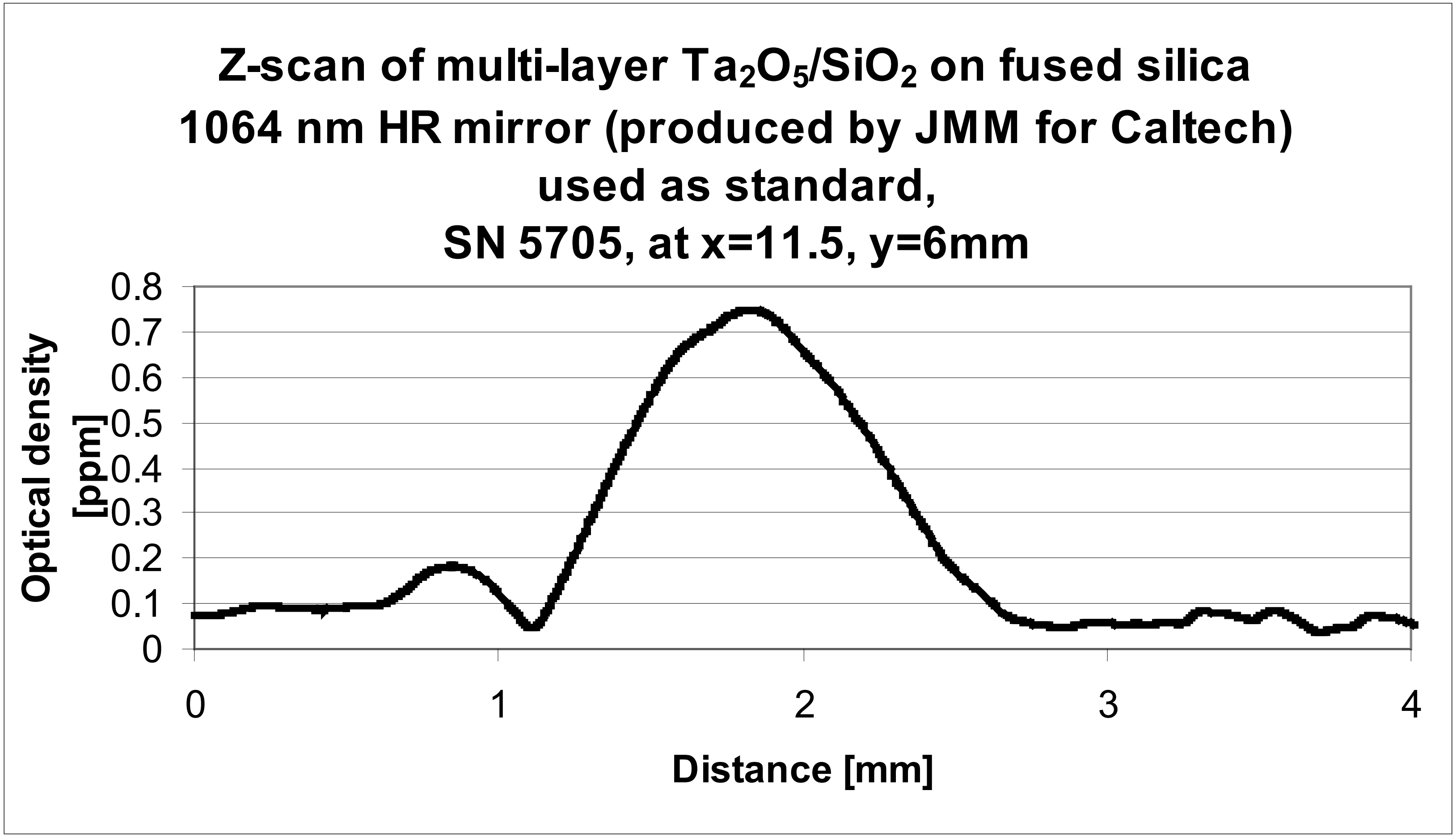
- High reflecting MLD coatings on 1" dia GO fused silica. Multiple λ/4 layers designed for T = 70 ppm (~30-60 layers).
  - Ta_2O_5 / SiO_2 (Annealed from 250 - 500 °C)
  - Nb_2O_5 / SiO_2 (Annealed from 300 - 500 °C)
  - ZrO_2 / SiO_2 (Annealed from 300 - 400 °C)
  - Ta_2O_5 / Al_2O_3 (Annealed from 300 - 400 °C)
- Partially reflecting MLD coatings on 1" dia fused silica. (30 λ/4 layers).
  - SiO2/Al2O3 (Annealed, R = 60 to 80%)
- Specimens from other vendors
  - Newport M/FS 79% ND filter (~19.4 ±0.5% loss) used for calibration (measured by direct insertion loss minus reflection)
  - REO (PL/PL) HR = 0.22 ppm
  - SMA (PL/PL) HR = 0.72 ppm, SMA (Curve) HR =1.1 ppm
  - Wave Precision (PL/PL) HR = 1.7 ppm

Optical loss measurement scheme for optical coatings

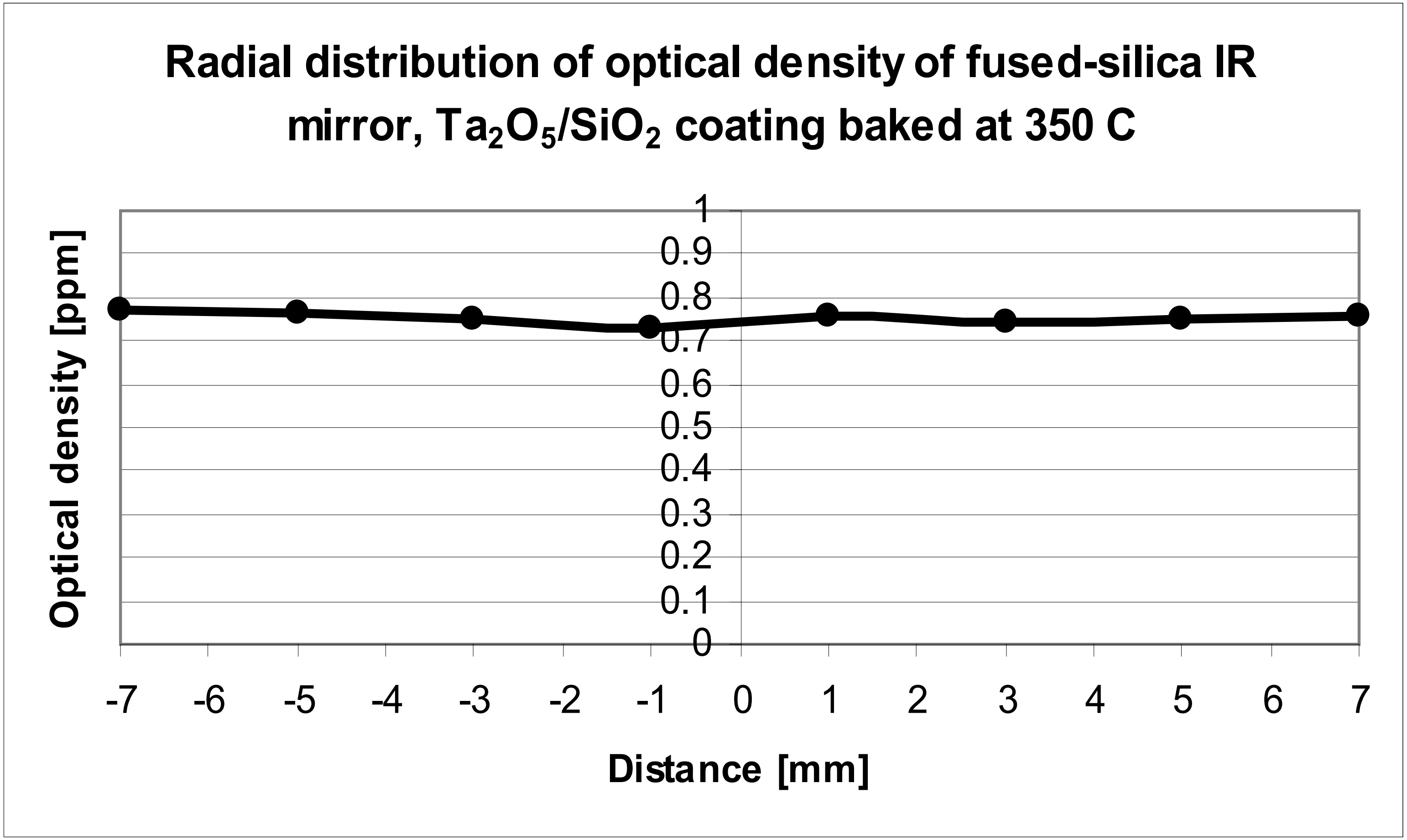


Locus of intersection of pump and probe beam where absorption in a 100 x 25ϕ micron cylinder is measured during Y- and Z-scans

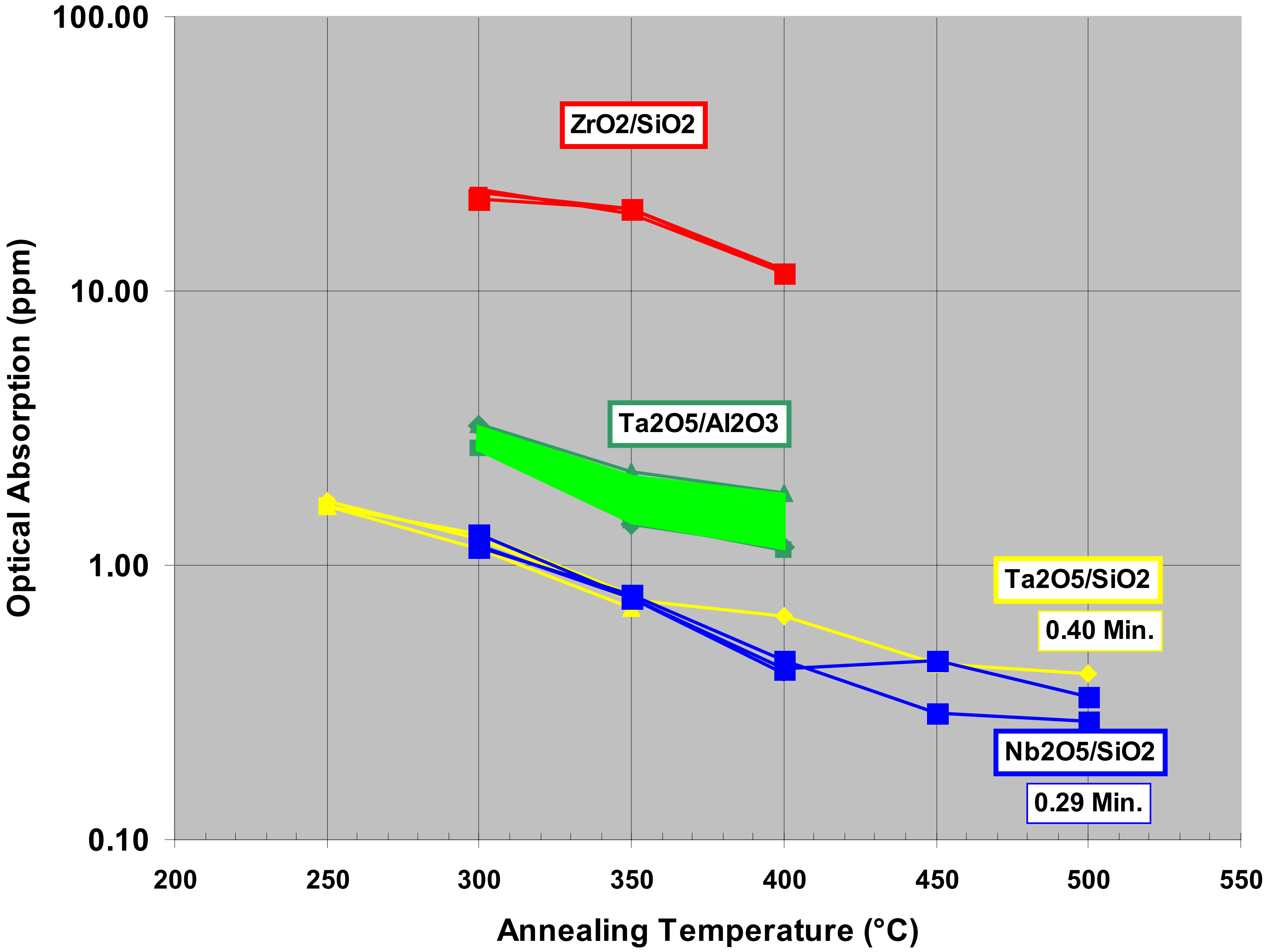
Z-scan to locate optical coating



Y-scan to measure radial uniformity of coating absorption

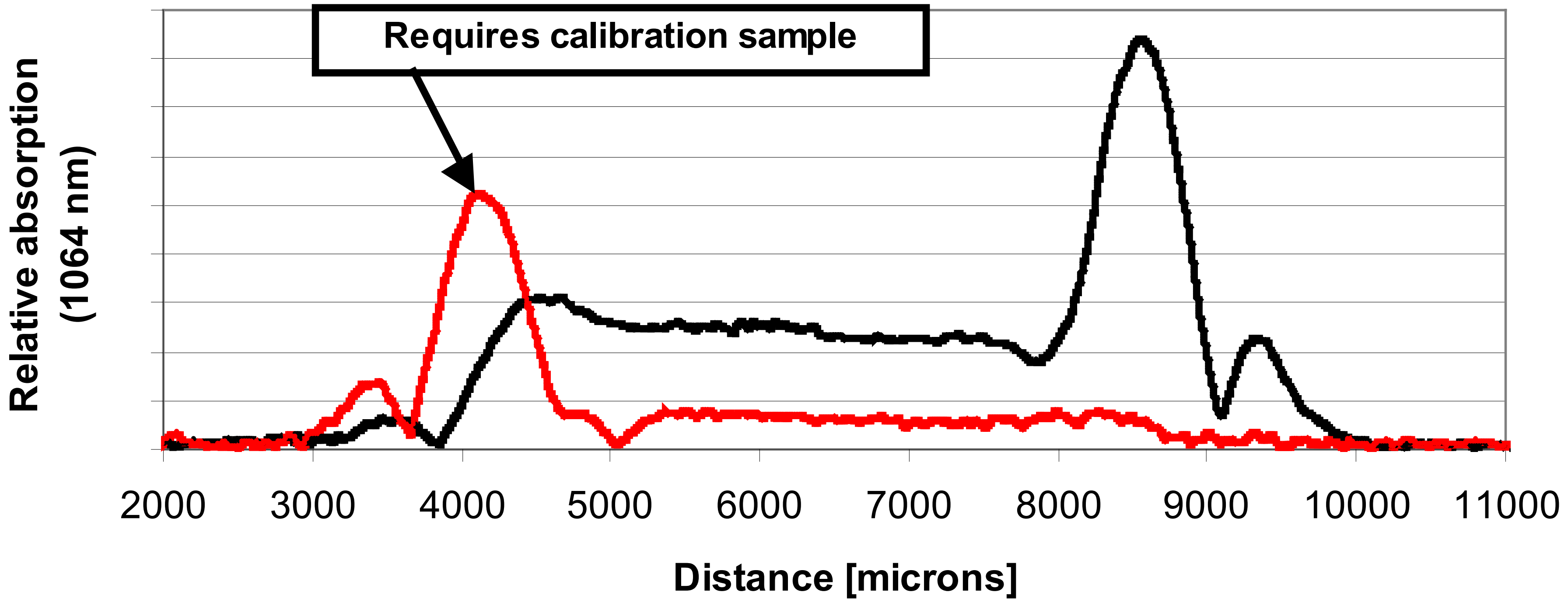


Dependence on materials and annealing temperature of optical loss in high reflectivity multilayer coatings



Coating loss studies on partially reflecting films

Z scans of FSIRM S/N8137 (30 layers of SiO2/Al2O3), for regular (front surface) and reverse (rear surface) geometry



Requires calibration sample

Current coating loss estimates based on Newport metal-coated neutral density filter*

		Partially-reflecting multilayers of SiO2 and Al2O3			(3/12/03)
		COATINGS BY MLD			
Serial No.	Substrate	Coating Design	Configuration	PCI Loss (PPM)	Notes
8132	PL/PL	SiO2/Al2O3	Front Illuminated	1.75 - 2.0	R = 0.70 to 0.77 (30 layers)
8137	PL/PL	(Partial Reflectors)	Front Illuminated	1.8 - 2.2	R = 0.68 to 0.75 (30 layers)
8178	PL/PL	"	Front Illuminated	1.7 - 1.8	R = 0.77 to 0.80 (30 layers)
8211	PL/PL	"	Front Illuminated	1.8 - 2.0	R = 0.62 to 0.79 (30 layers)
	MISC. COATINGS BY OTHER VENDORS				
REO (HR+AR)	PL/PL	Ta2O5/SiO2 *	Front Illuminated	HR = 0.22	
			Front Illuminated	AR = ~3.6	Requires standard for calibration
SMA (HR Ref. 01044/11)	Curve	Ta2O5/SiO2 *	Front Illuminated	HR = 1.1	0.95 by SMA
Wave Precision (GO 5703)	PL/PL	Ta2O5/Al2O3 *	Front Illuminated	HR = 1.7	
HR/AR - Ref. E000718/7			Front Illuminated	AR = ~2.4	Requires standard for calibration
Newport M/FS ND filter	FSQ-ND01 (79%)	Metal Coated FS PL/PL	Front Illuminated	18% **	Used as Primary Standard
SMA (HR Ref. 01045/12, GO	PL/PL	Ta2O5/SiO2 *	Front Illuminated	HR = 0.72	1.2 by SMA, used as Secondary Standard
		* Structure of coating unknown		** Loss determined by photometric methods	

* Newly-designed coating reference standard will have only half the front surface coated to allow self-referencing between adjacent coated and non-coated surfaces