Thermally Managed Z-scan Measurements of Amorphous TiO_2 Films

Christopher C. Evans

J.D.B. Bradley, F. Parsy, K.C. Phillips, R. Senaratne,
E. Marti and Eric Mazur

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Outline

Introduction: amorphous TiO_2 films

Standard z-scan

Thermally managed z-scan

Conclusions and Discussion

Introduction

Titanium Dioxide

Wide Bandgap:

3.2 eV (387 nm)

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High index:

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Nonresonant (ultrafast) nonlinearity

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Titanium Dioxide

Wide Bandgap:

3.2 eV (387 nm)

High index:

2.5

Excellent for 800 nm:

Nonresonant (ultrafast) nonlinearity

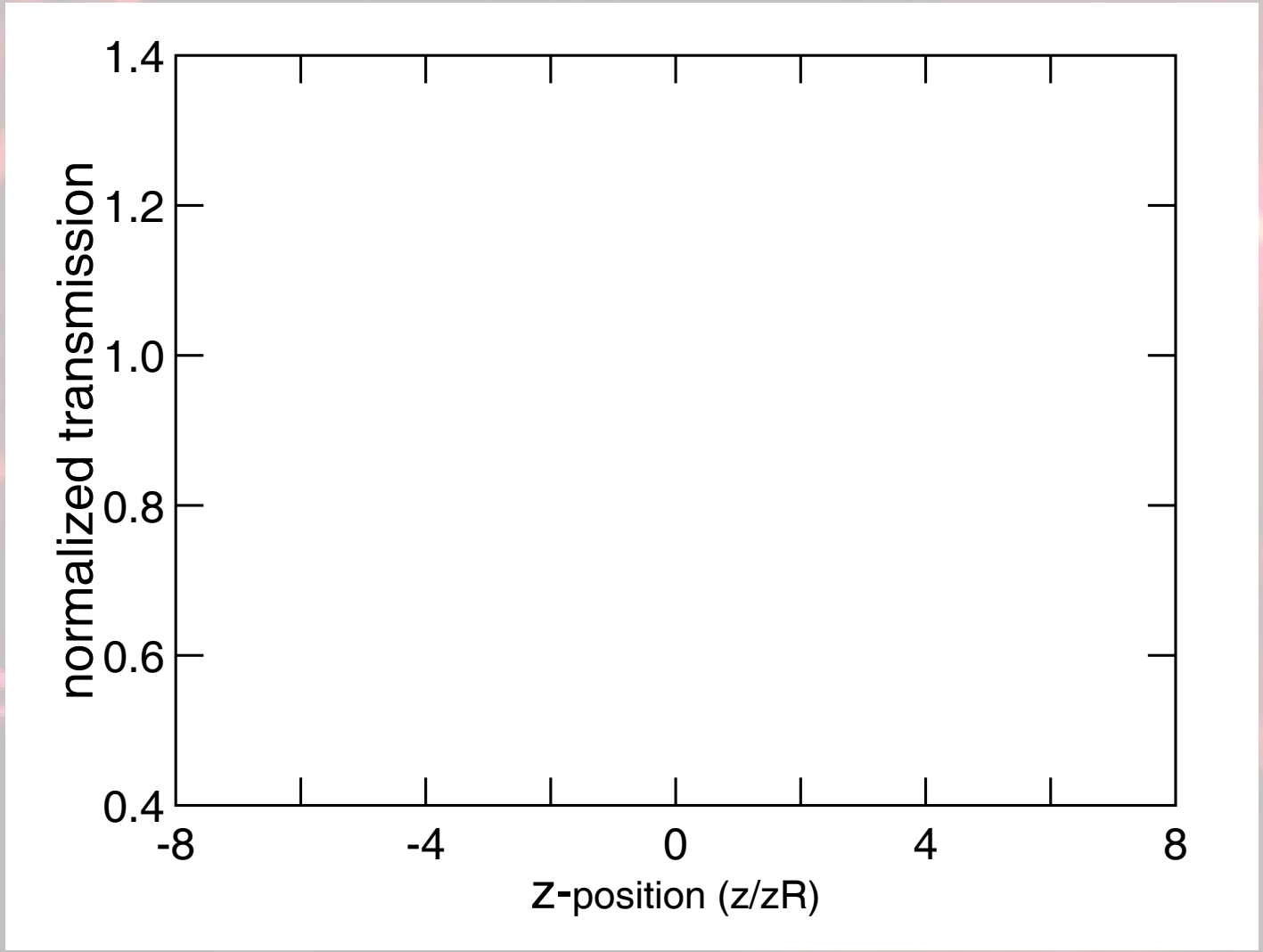
Low two-photon absorption

Introduction

What is the nonlinearity for TiO_2 near 800 nm?

Introduction

Z-Scan of Bulk Rutile



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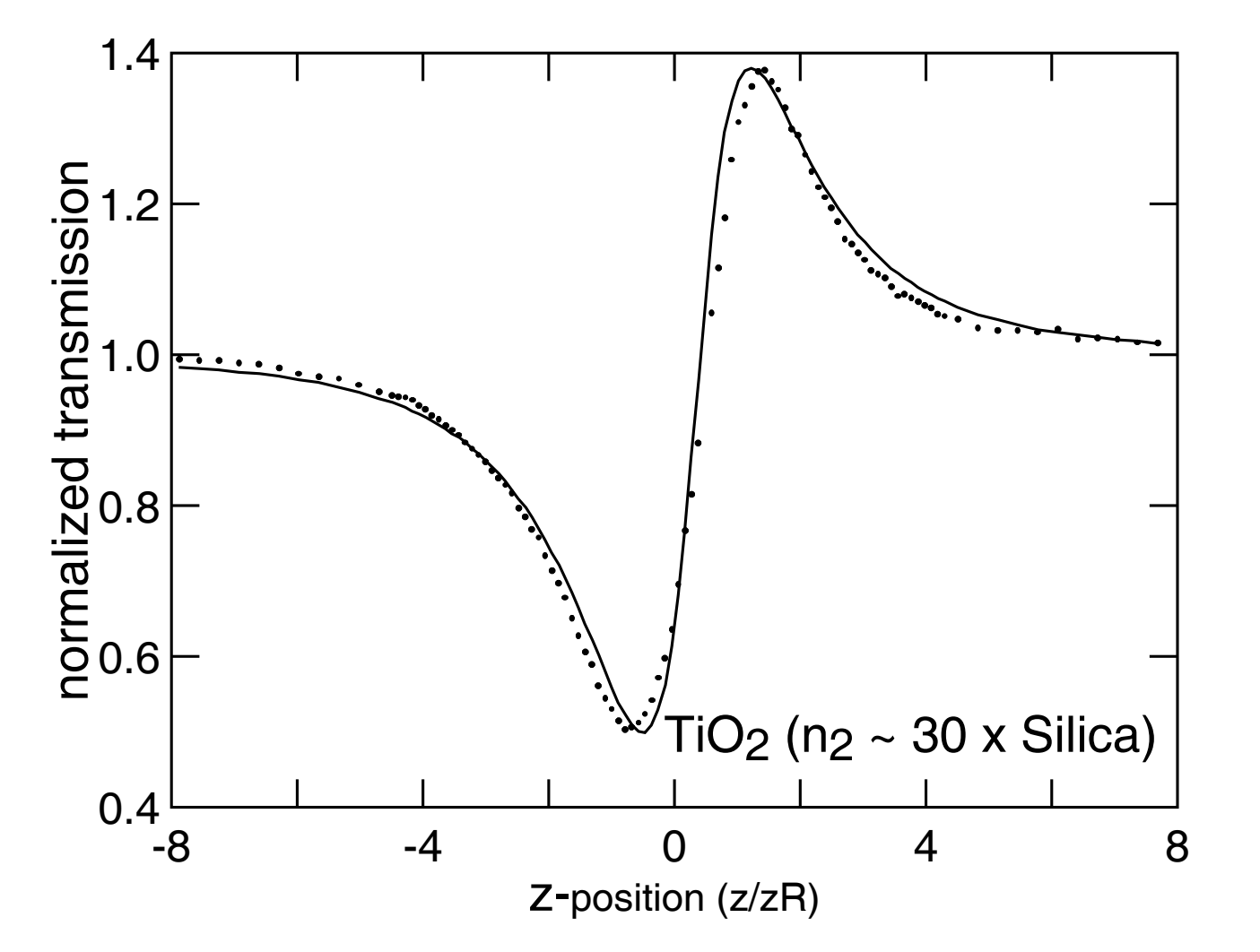
Z-Scan of Bulk Rutile



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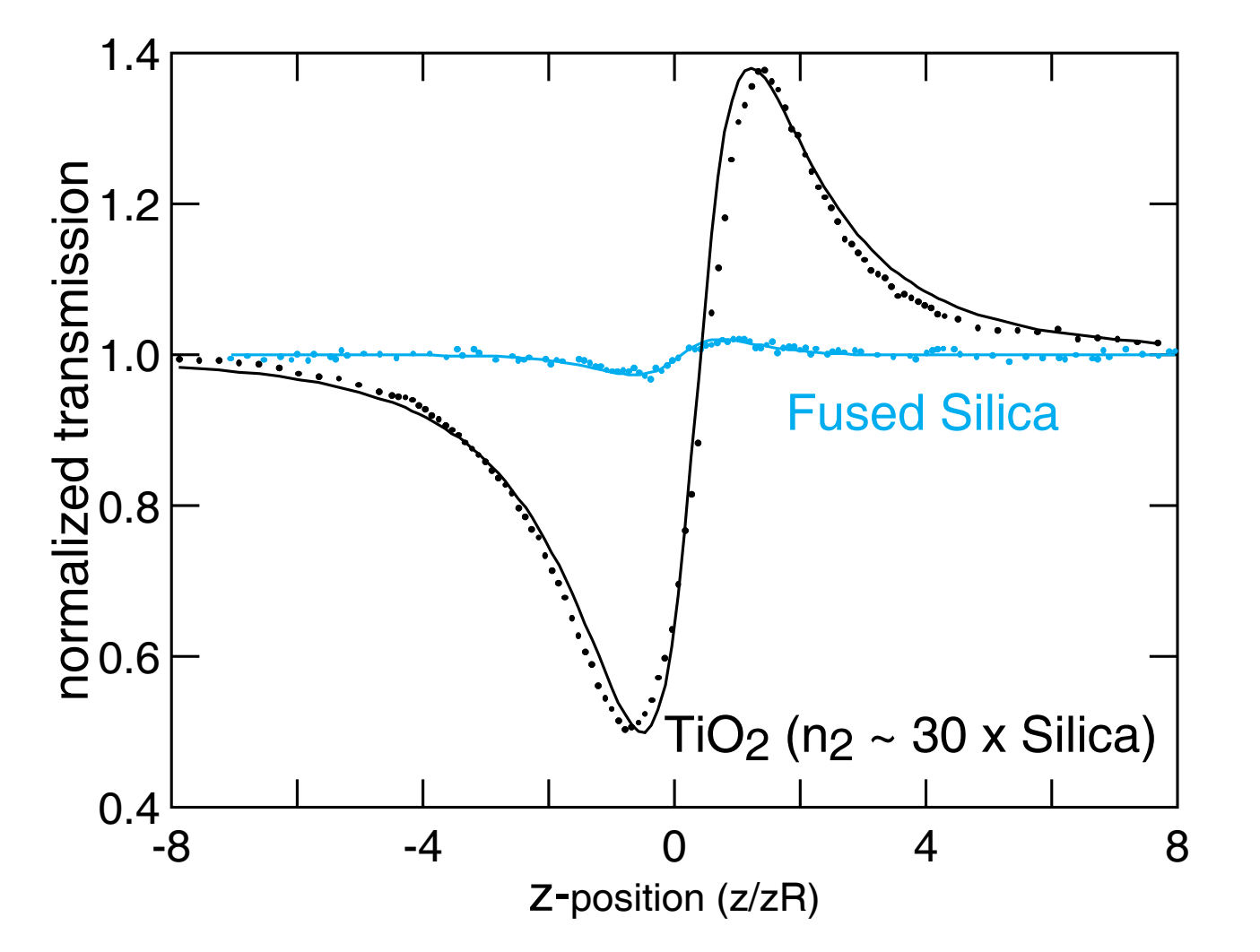
Z-Scan of Bulk Rutile



Introduction

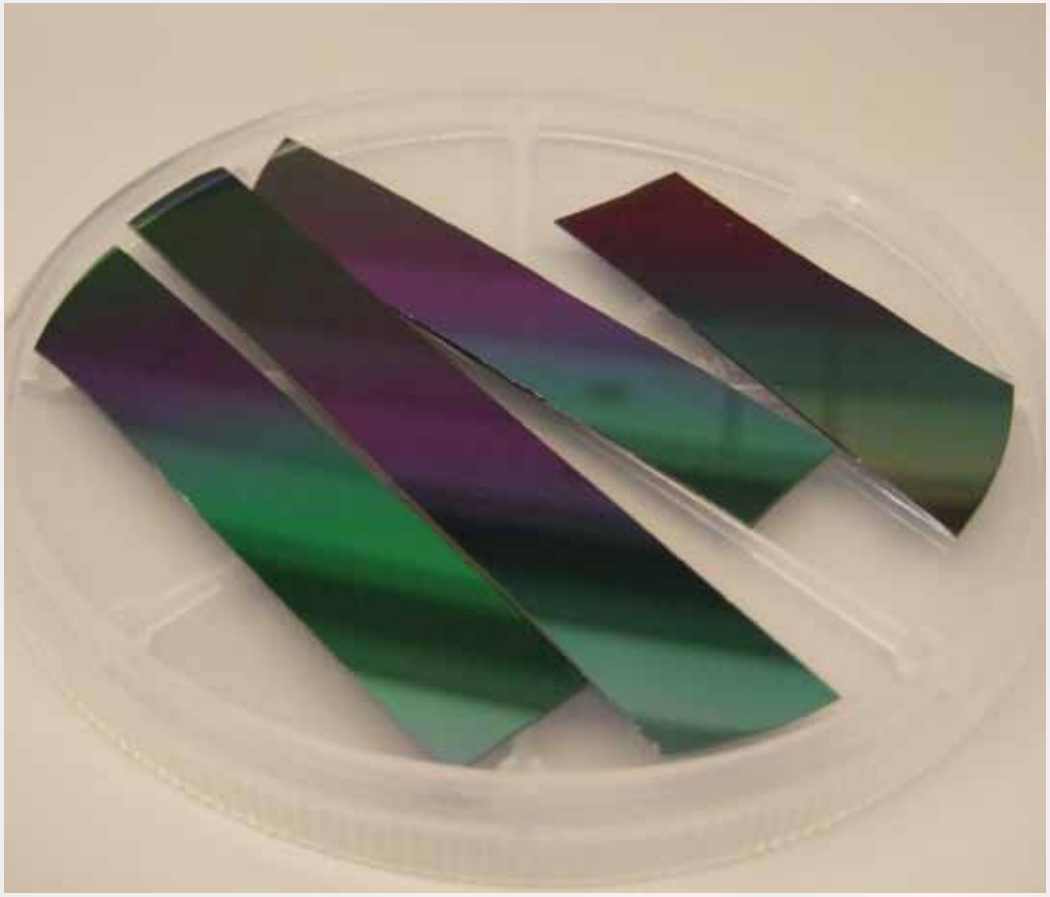
How should we optimize our thin films?

Introduction

Optimization of thin films

Crystalline Phases:

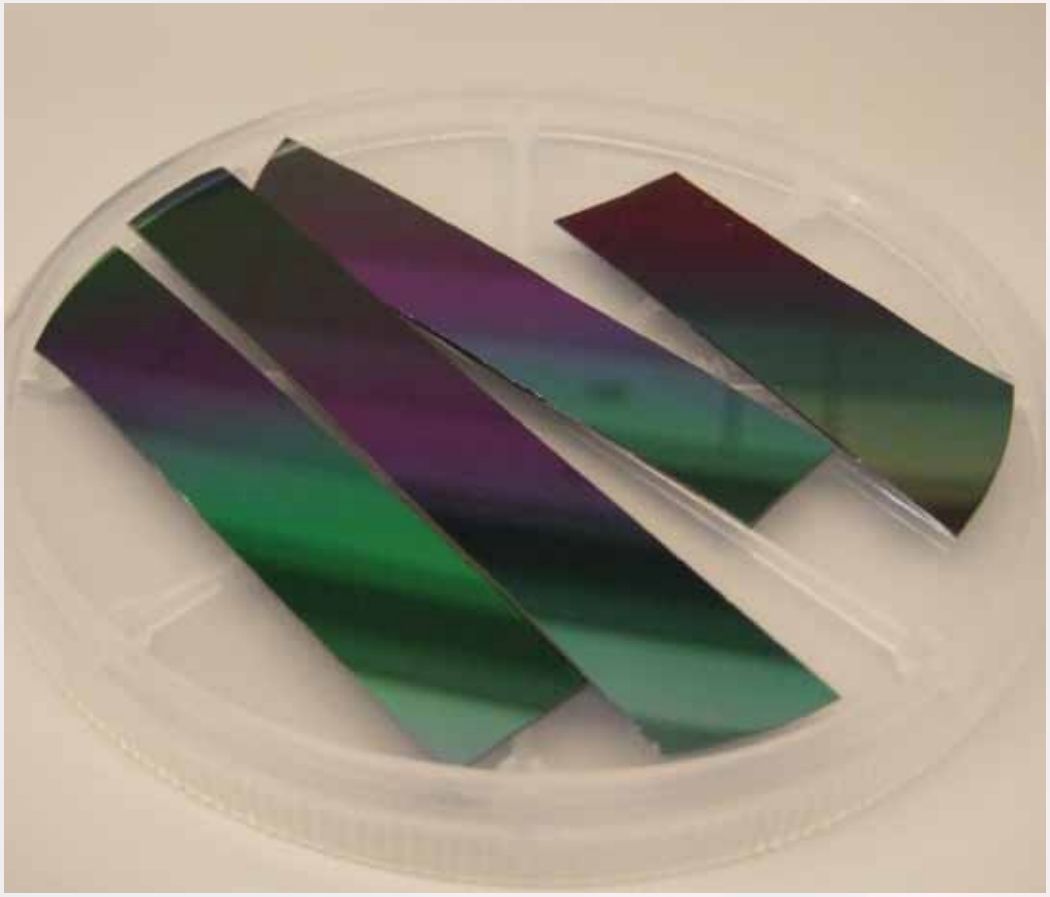
- Amorphous
- Anatase
- Rutile



Introduction

Optimization of thin films

Refractive Index



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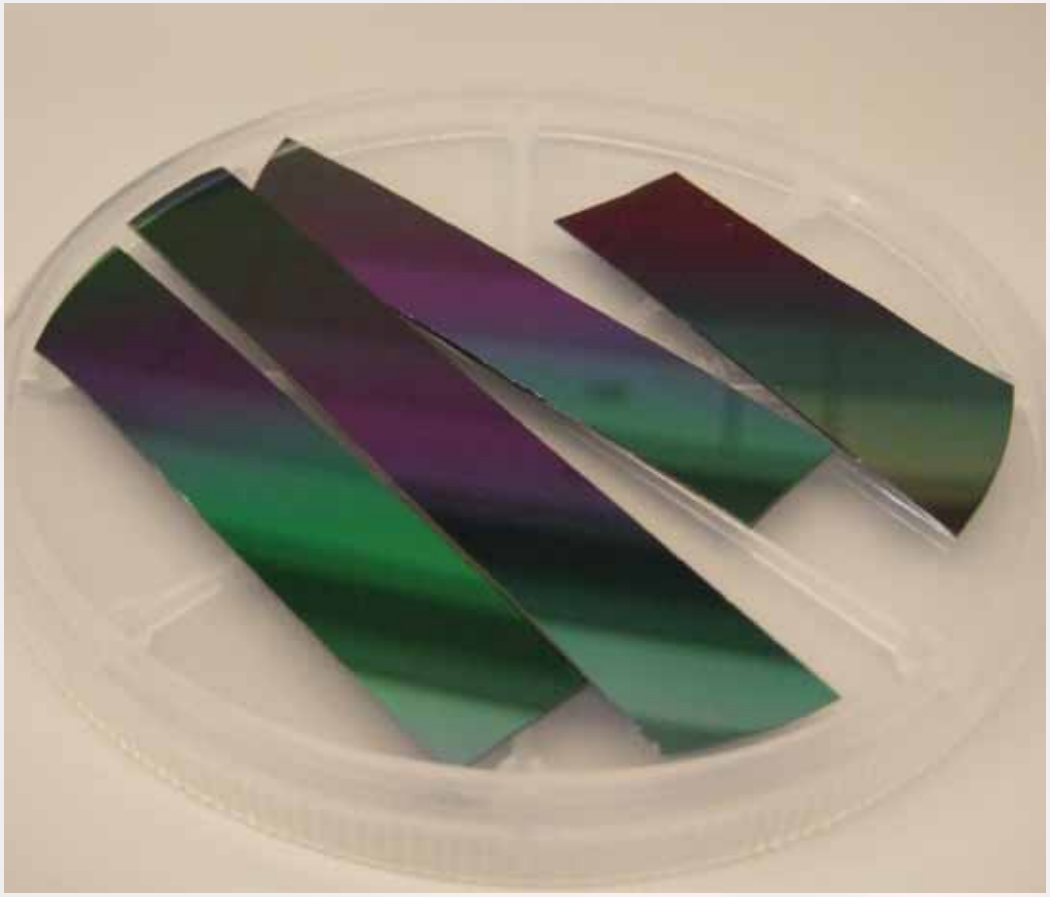
Optimization of thin films

Refractive Index

Amorphous: 2.35

Anatase: 2.45



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Optimization of thin films

Refractive Index

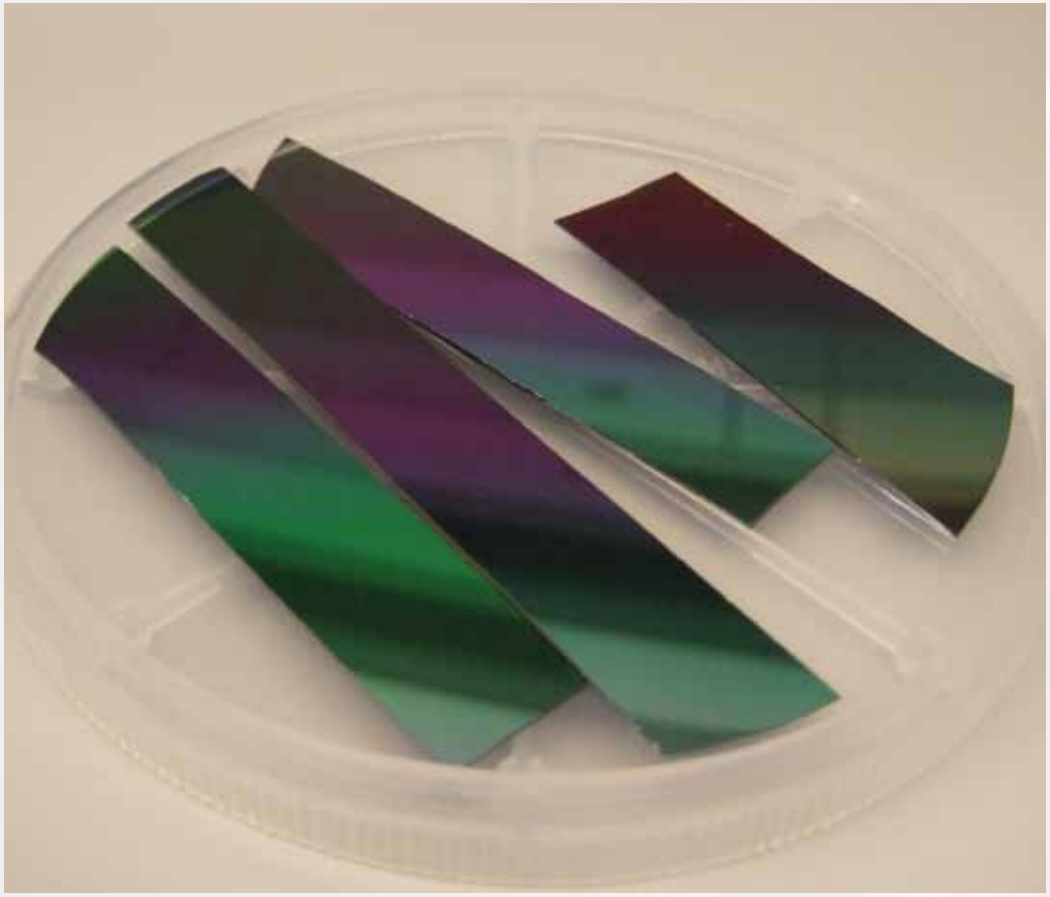
Amorphous: 2.35

Anatase: 2.45

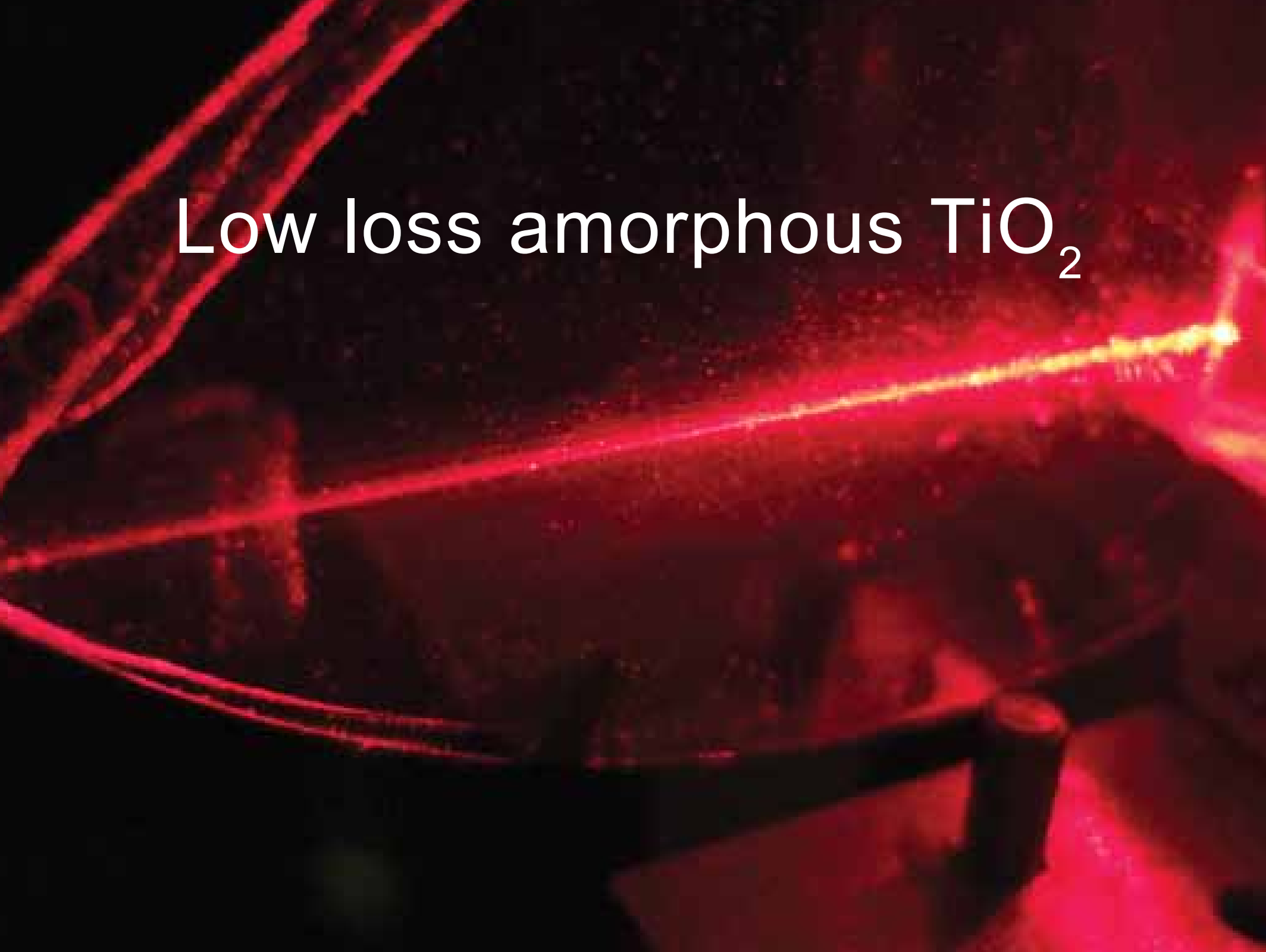
Guiding Losses

Amorphous: 1 dB/cm

Anatase: 5 dB/cm



Low loss amorphous TiO_2



Low loss amorphous TiO_2

Deposition Method: Reactive Sputtering

Thickness: 2.2 micron

Substrate: Fused Silica (500 micron)

Guiding Losses: ~1 dB/cm

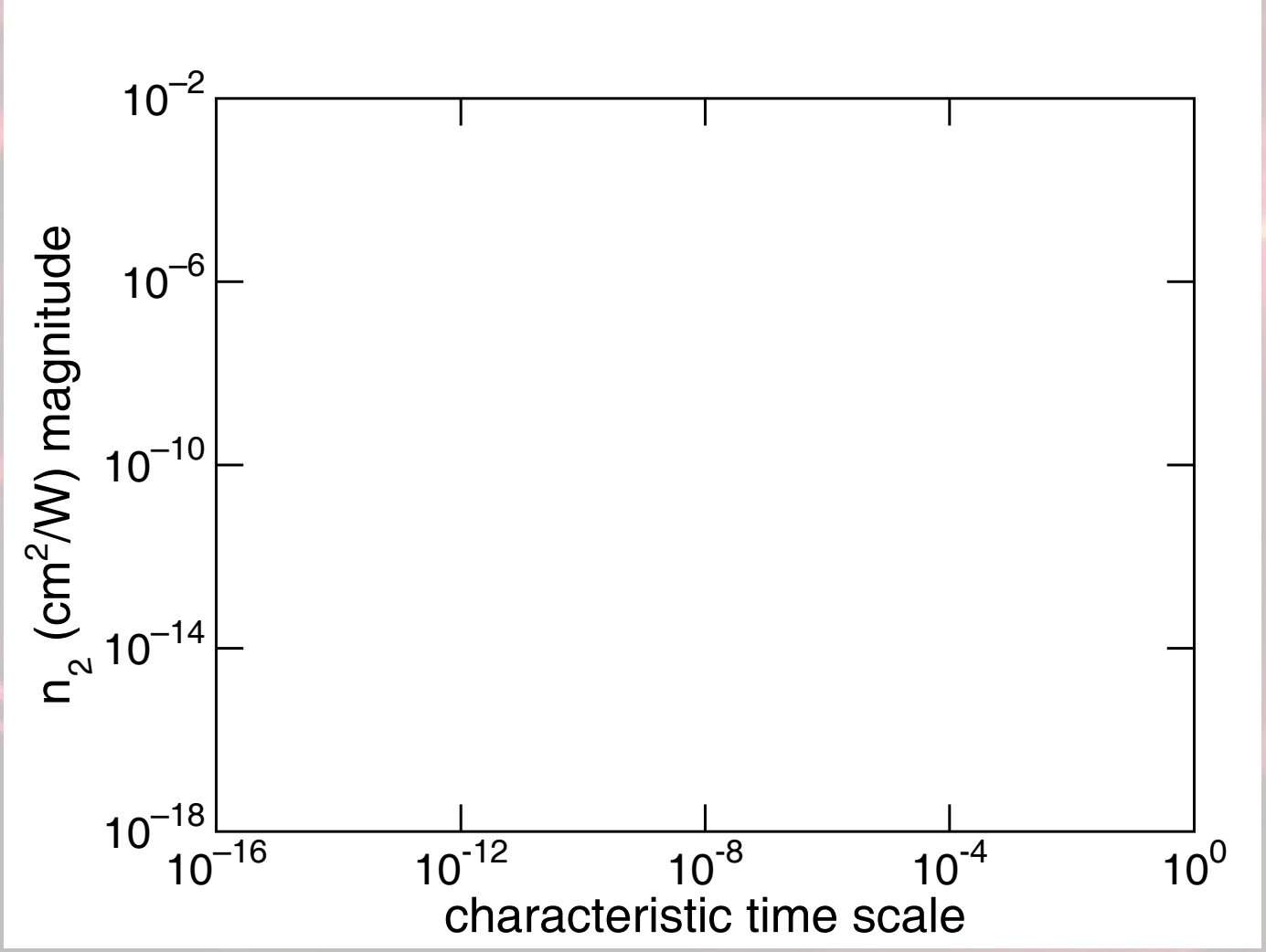
What is the nonlinearity of amorphous TiO_2?

What is the nonlinearity of amorphous TiO_2?

Are there thermal effects?

Introduction

Typical nonlinear time scales



Boyd, R. W. Nonlinear optics. 2nd edn

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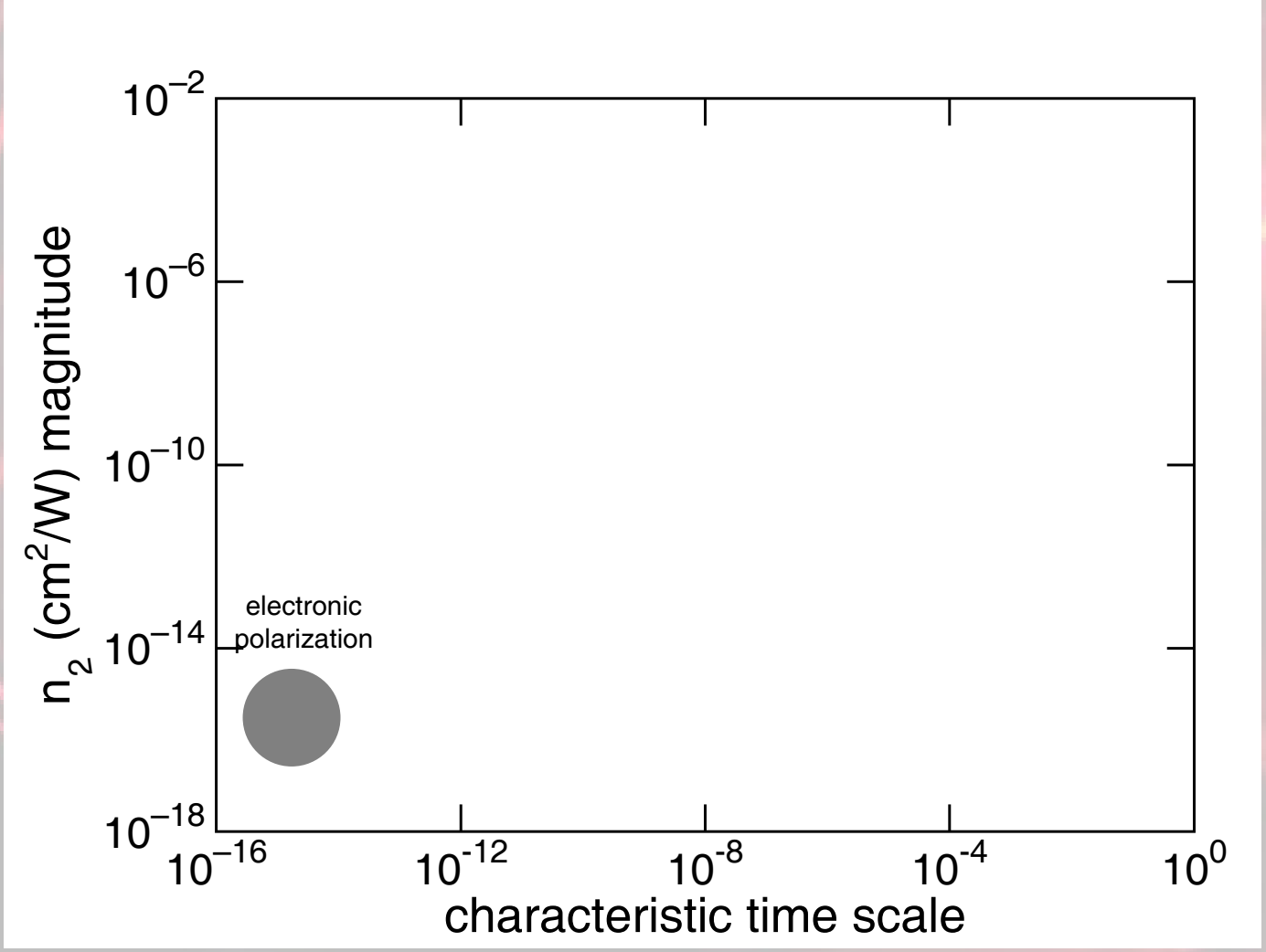

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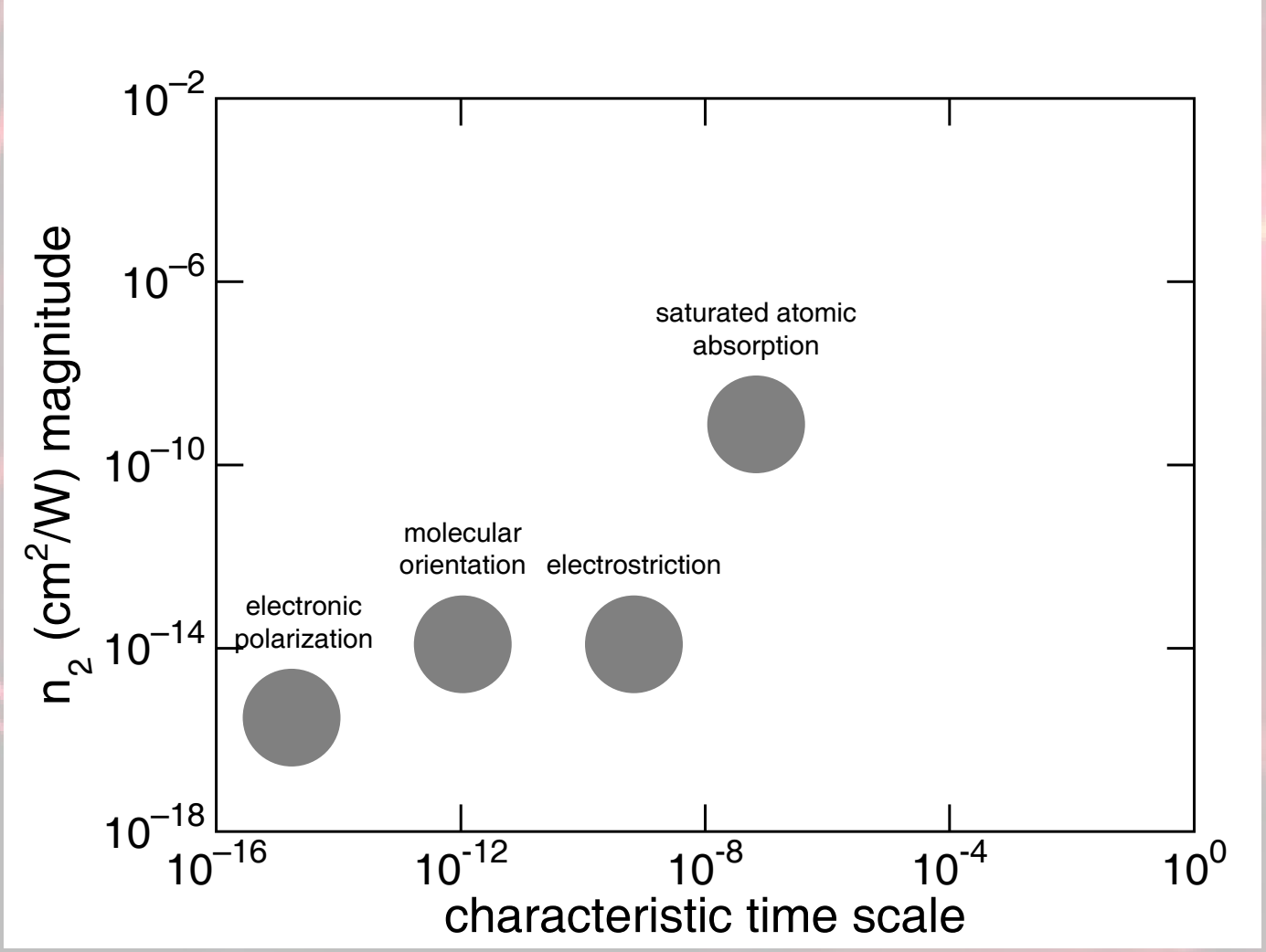

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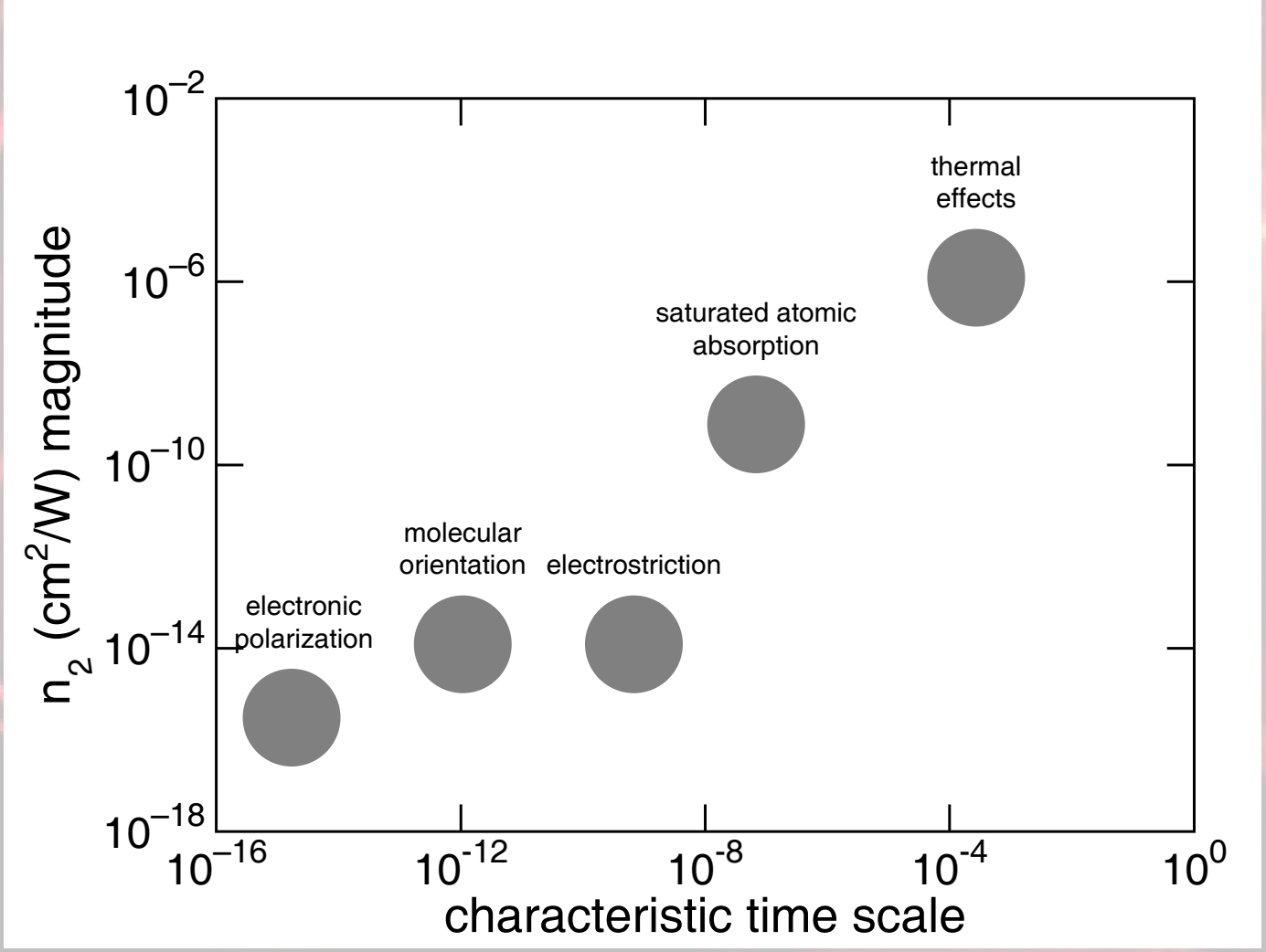

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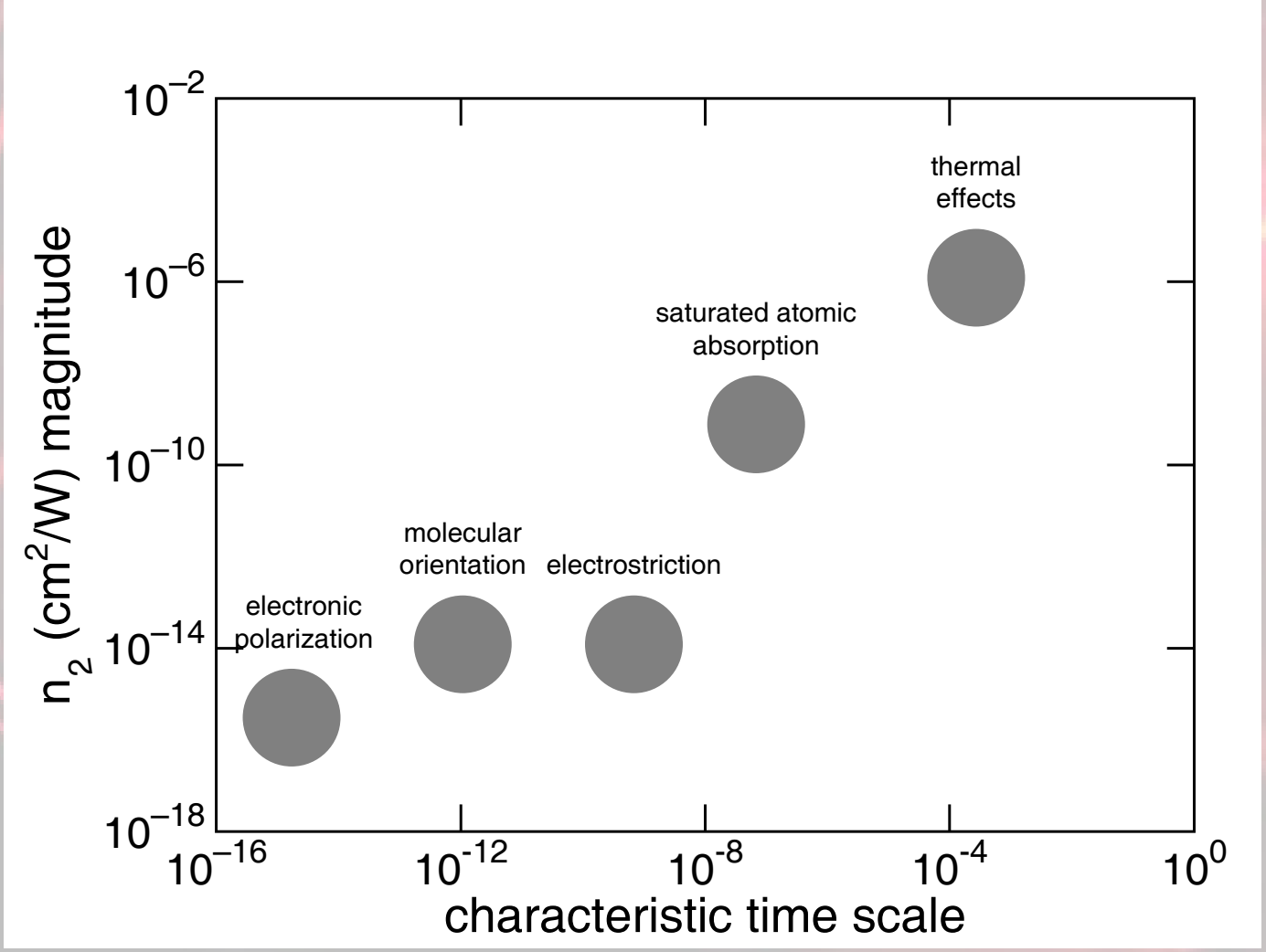
Introduction

Laser Specifications

Type:	Amplified Ti:Sapphire (CPA)
Center λ:	800 nm
Pulse Duration:	100 fs
Repetition Rate:	10kHz - 250kHz

Introduction

Typical nonlinear time scales



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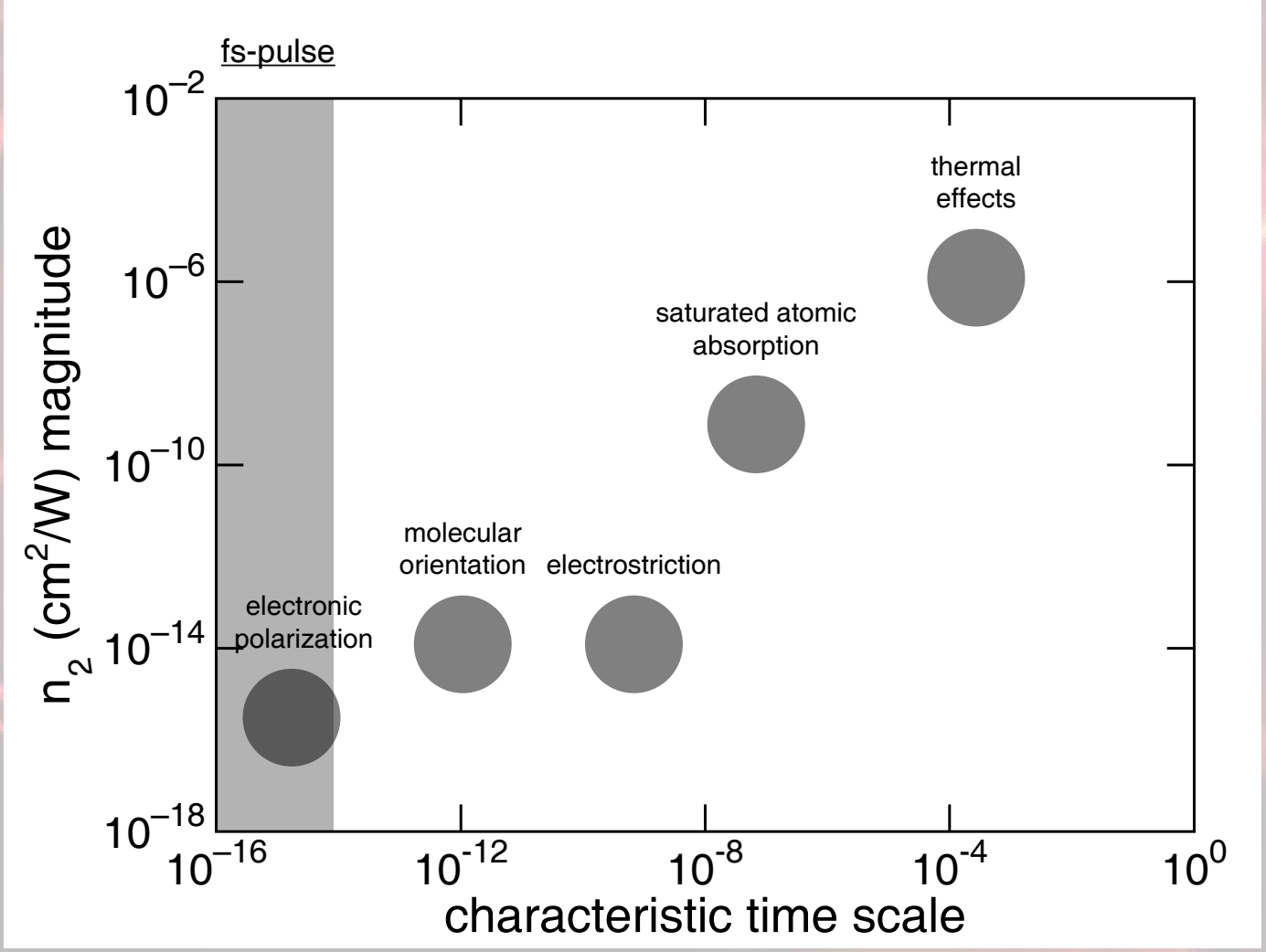

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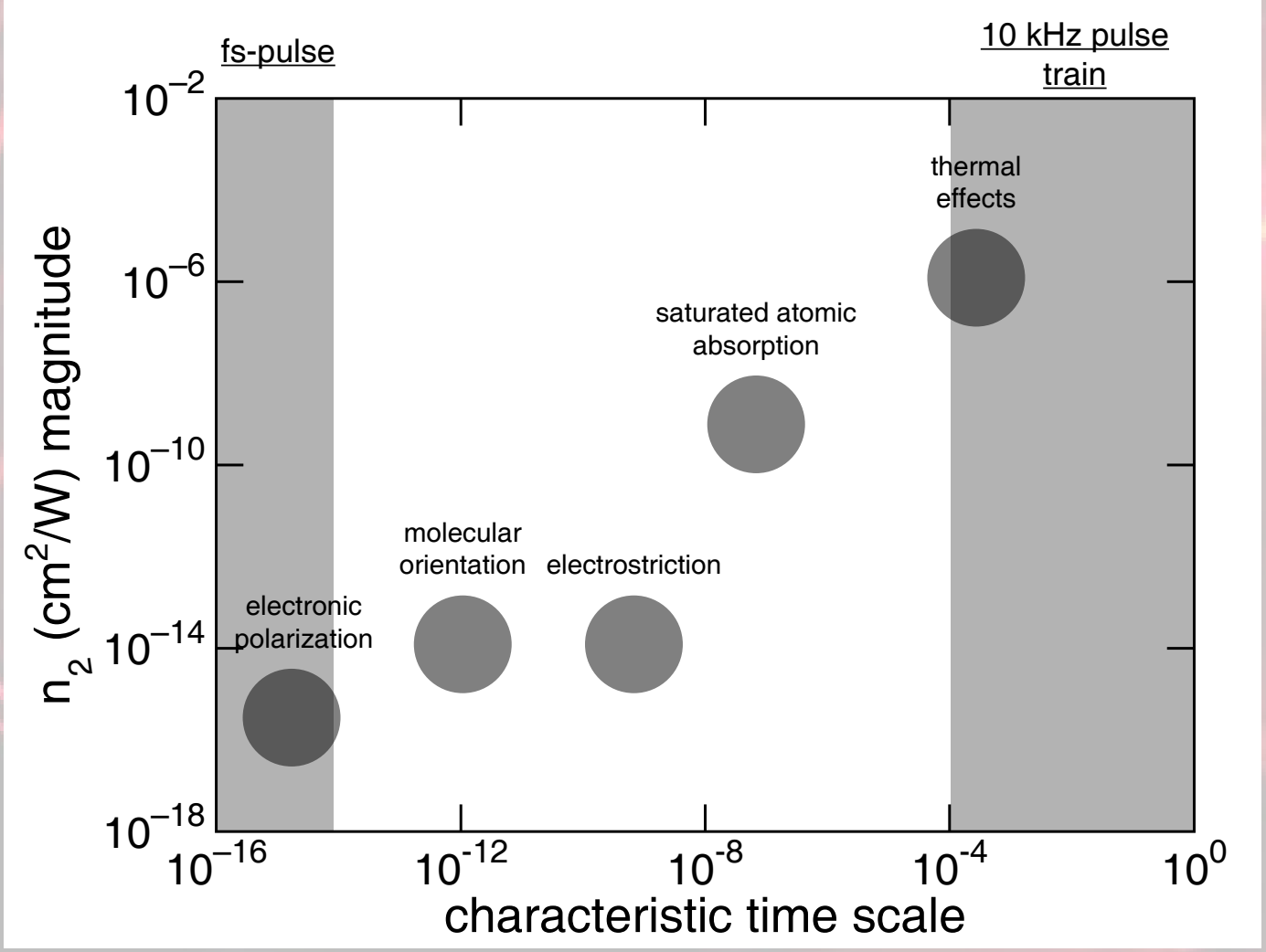

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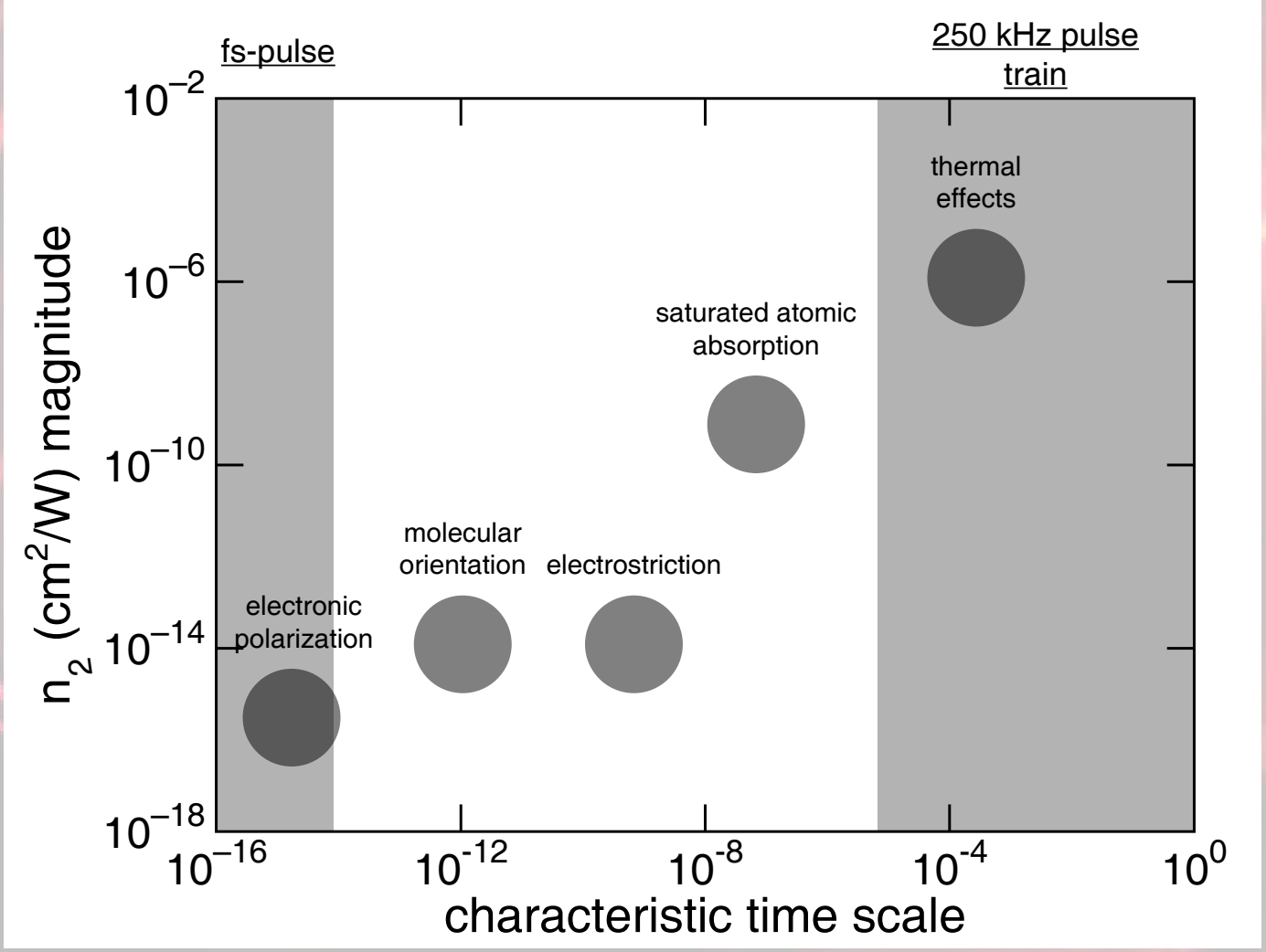

Boyd, R. W. Nonlinear optics. 2nd edn

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Standard z-scan

<u>Laser Parameters</u>

w0 (measured): 37 micron

Standard z-scan

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w0 (measured):	37 micron
zR (from fitting):	2.1 mm
Approximate M^2:	1.8

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w0 (measured):	37 micron
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Repetition Rate:	10 kHz
Pulse Duration:	100 fs

Standard z-scan

Laser Parameters

w0 (measured):	37 micron
zR (from fitting):	2.1 mm
Approximate M^2:	1.8
Repetition Rate:	10 kHz
Pulse Duration:	100 fs
Max Power:	18 mW
Max Fluence:	0.08 J/cm^2
S parameter:	0.016

Standard z-scan

What power should we use?

Standard z-scan

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Reported Damage Threshold: 0.55 J/cm^2

Yao, J. et al. Thin Solid Films 516, 1237-1241 (2008).

Standard z-scan

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Reported Damage Threshold: 0.55 J/cm^2

Our Maximum Fluence: 0.08 J/cm^2

Yao, J. et al. Thin Solid Films 516, 1237-1241 (2008).

Standard z-scan

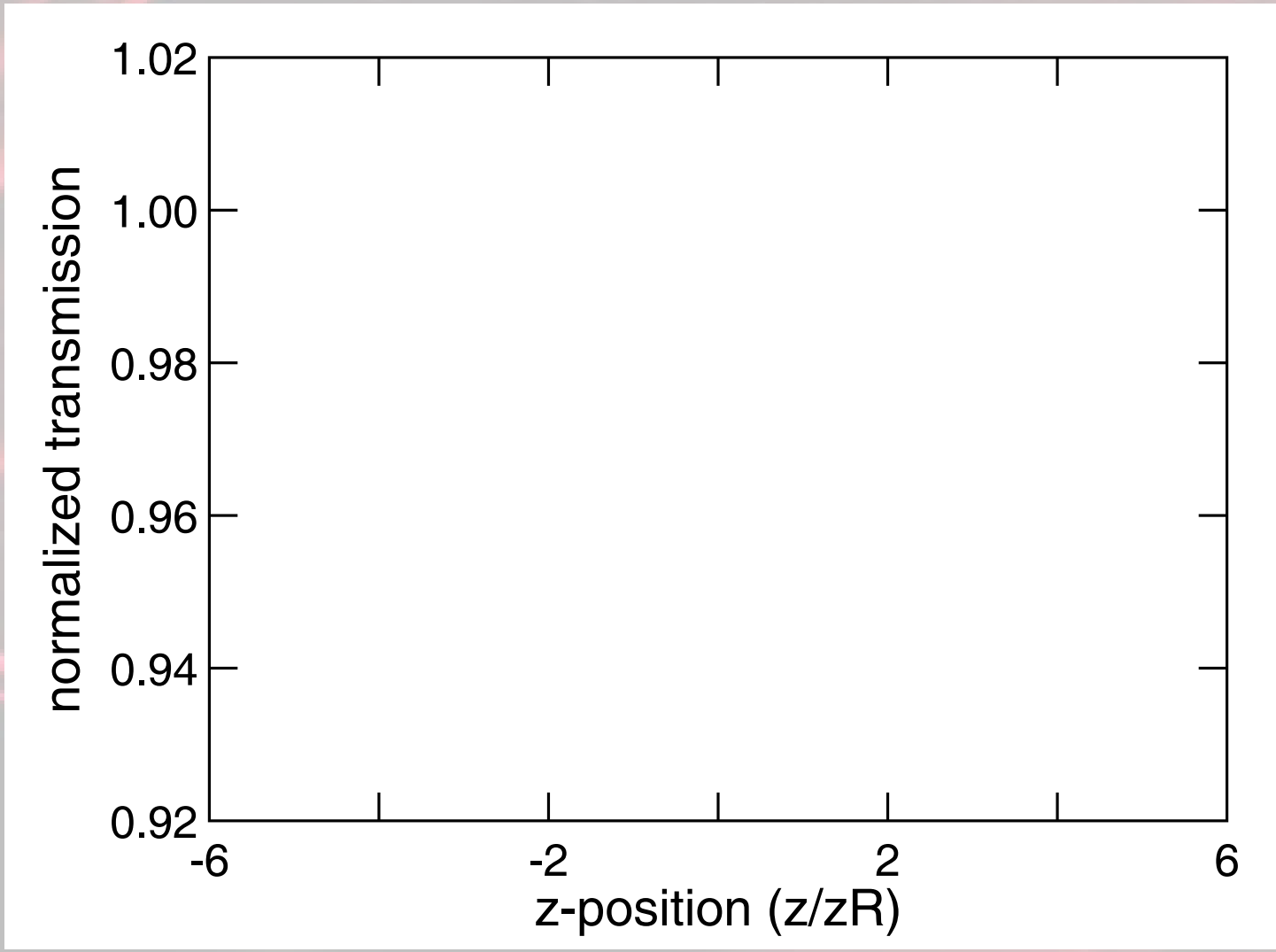
What power should we use?

Reported Damage Threshold:	0.55 J/cm^2
Our Maximum Fluence:	0.08 J/cm^2
Low Power Used:	0.002 J/cm^2

Yao, J. et al. Thin Solid Films 516, 1237-1241 (2008).

Standard z-scan

Open Aperture



Standard z-scan

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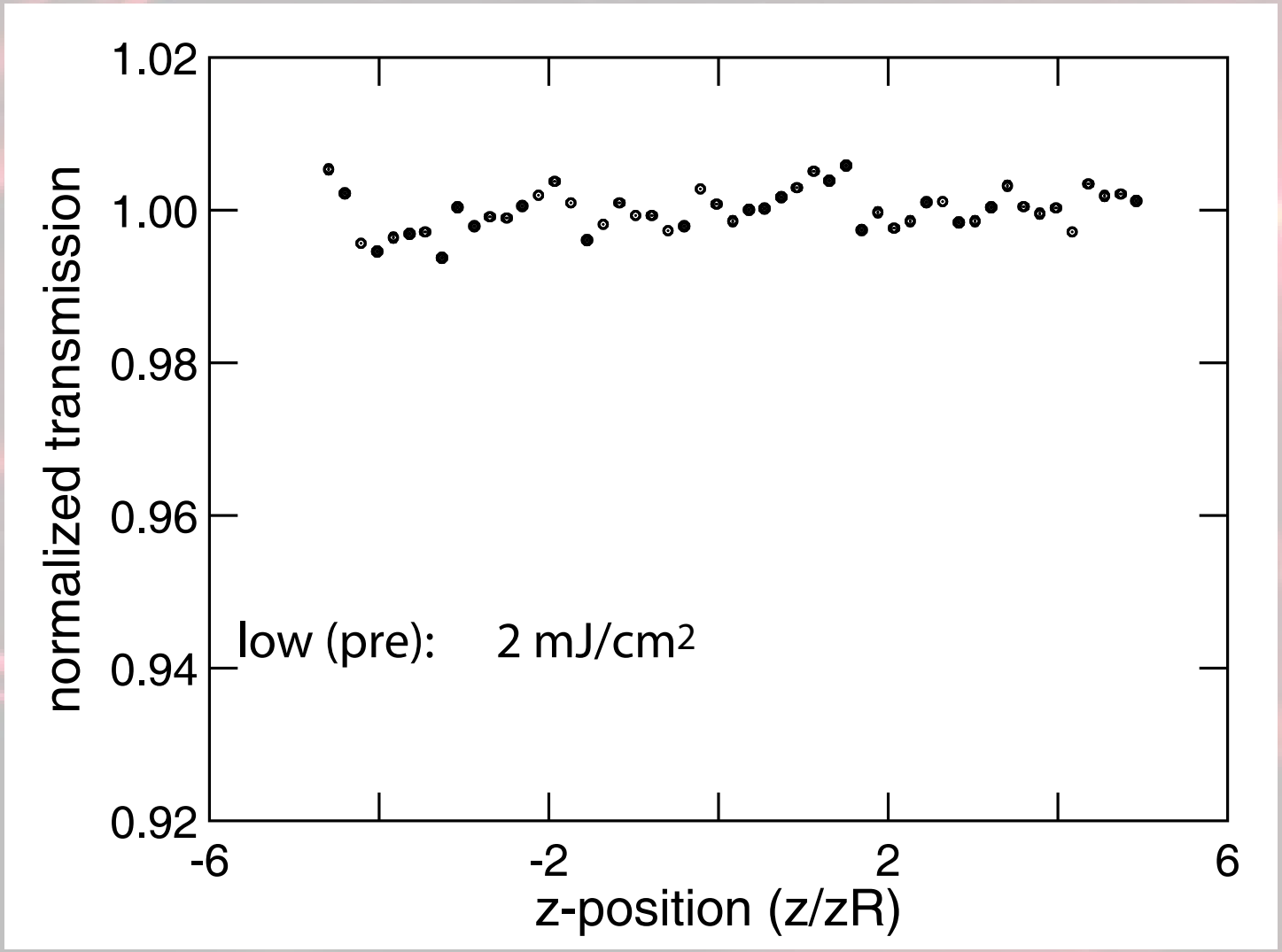

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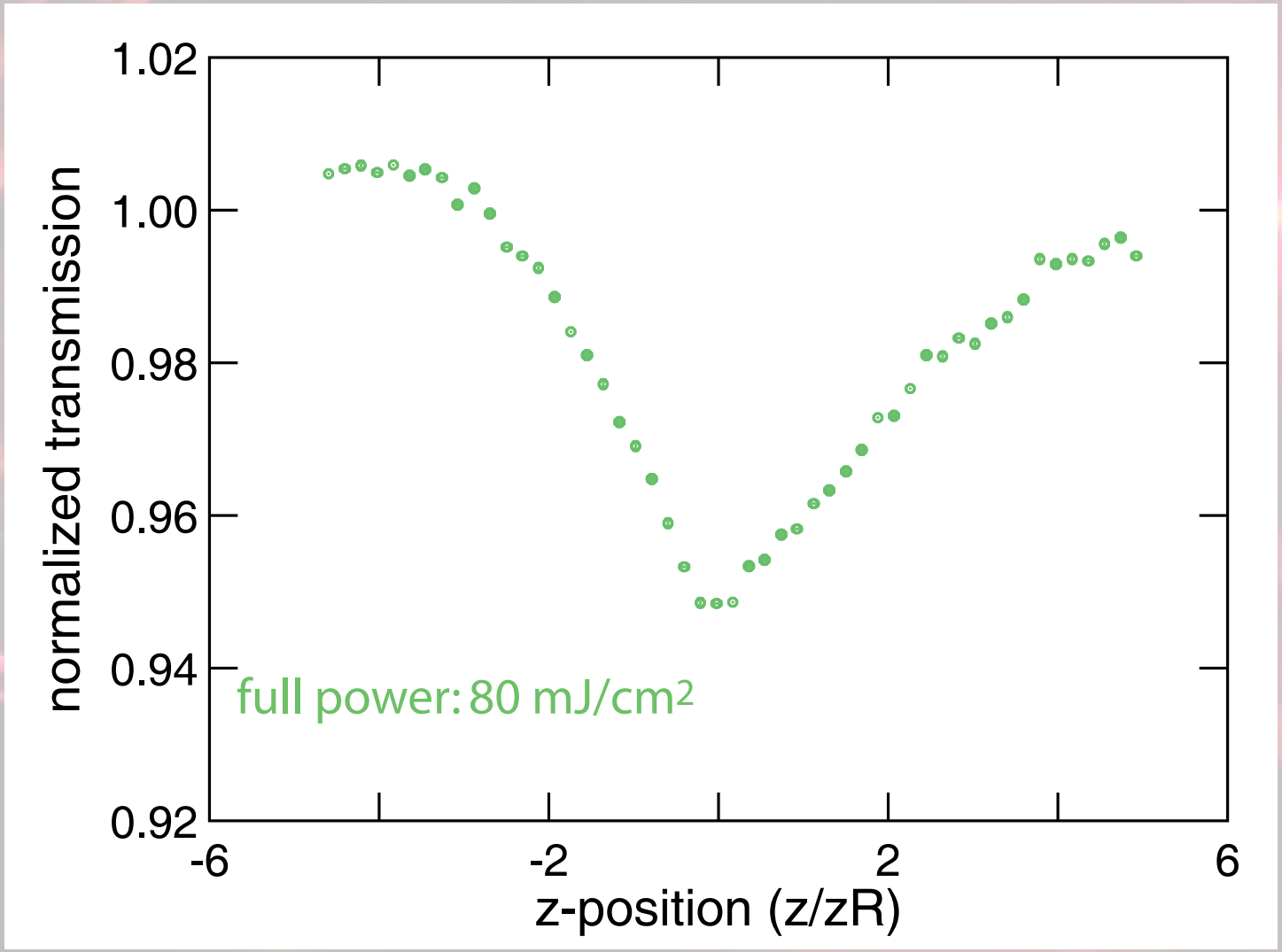

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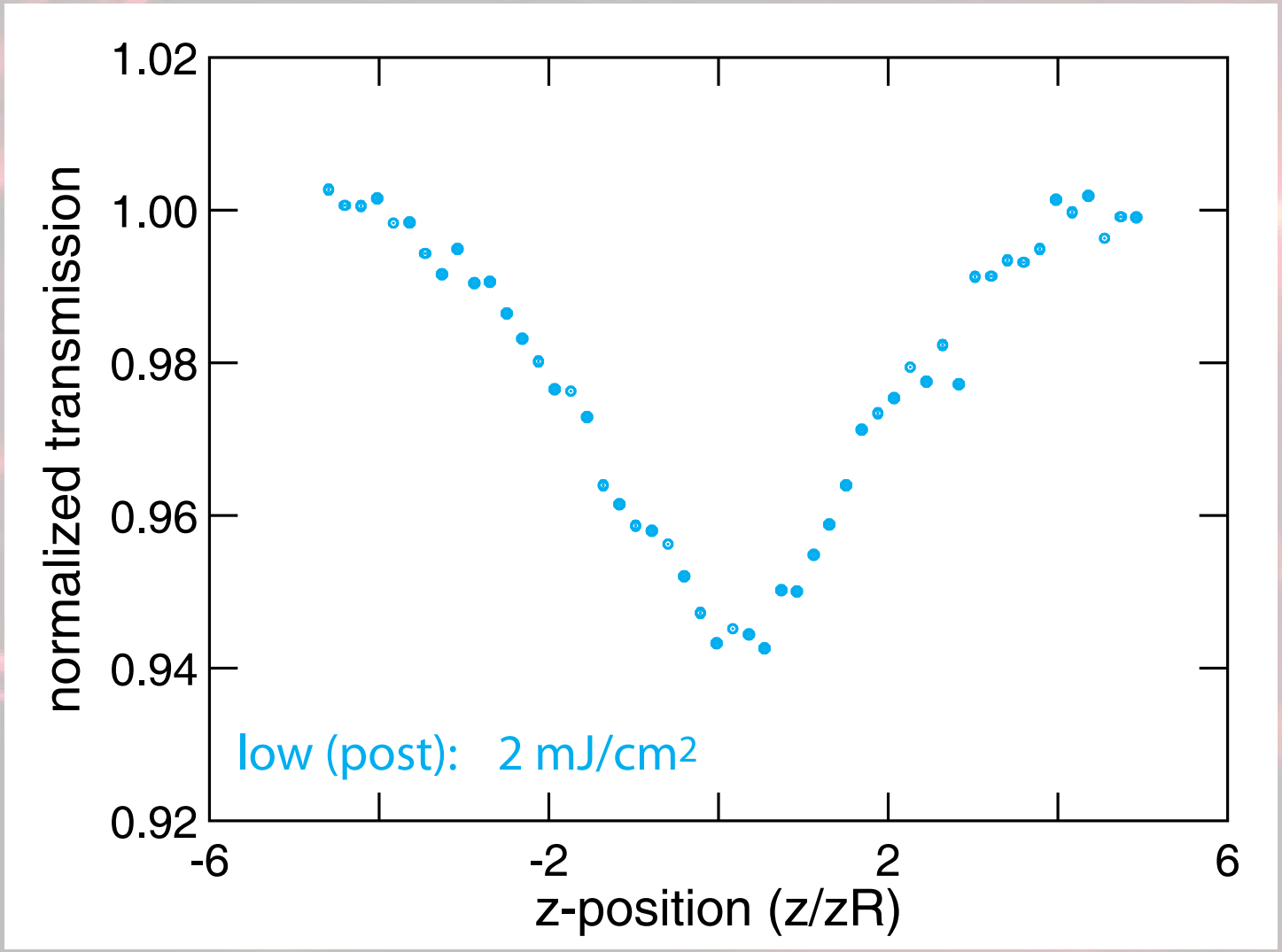
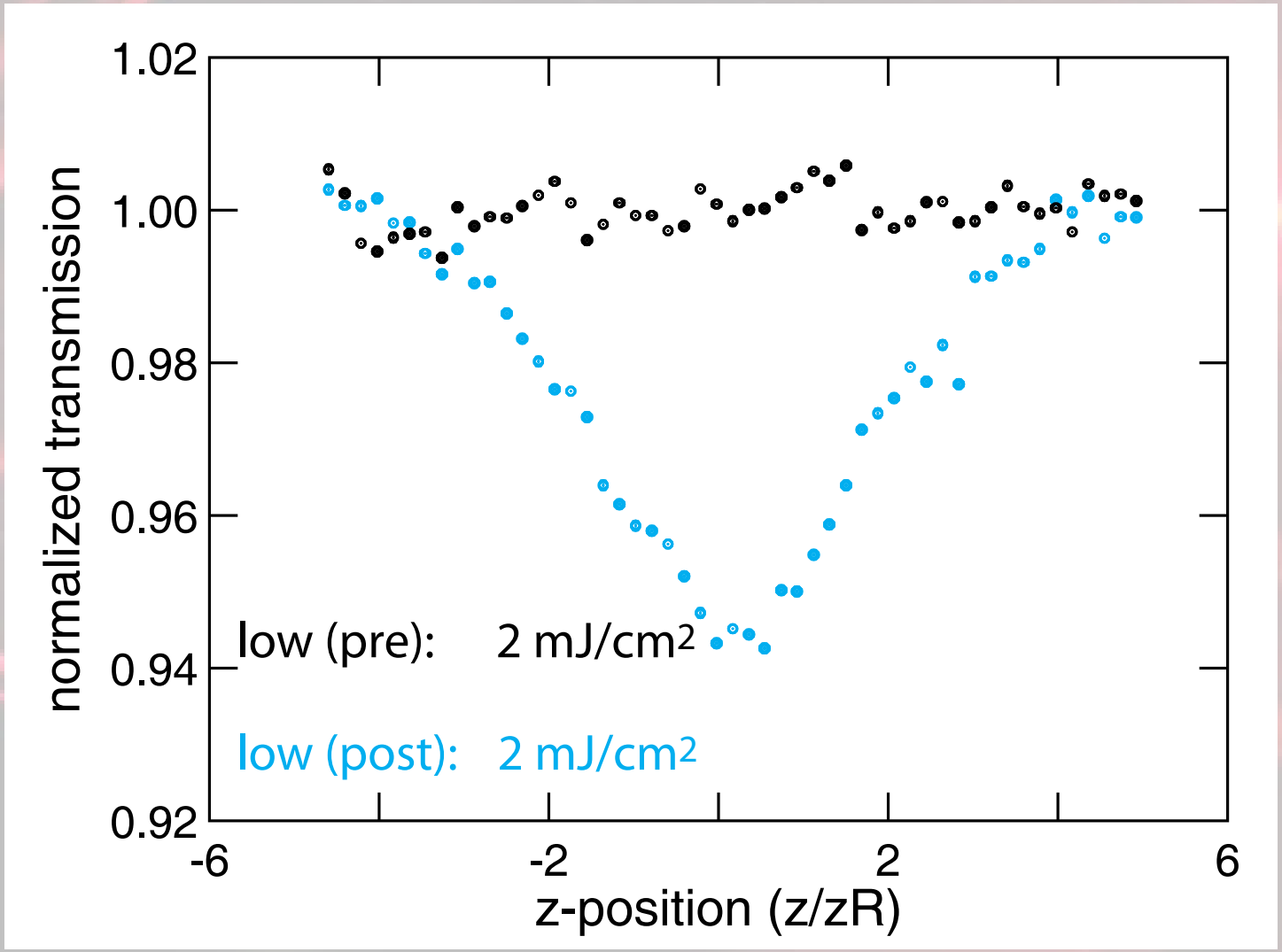
Open Aperture



Standard z-scan

Sample has been changed

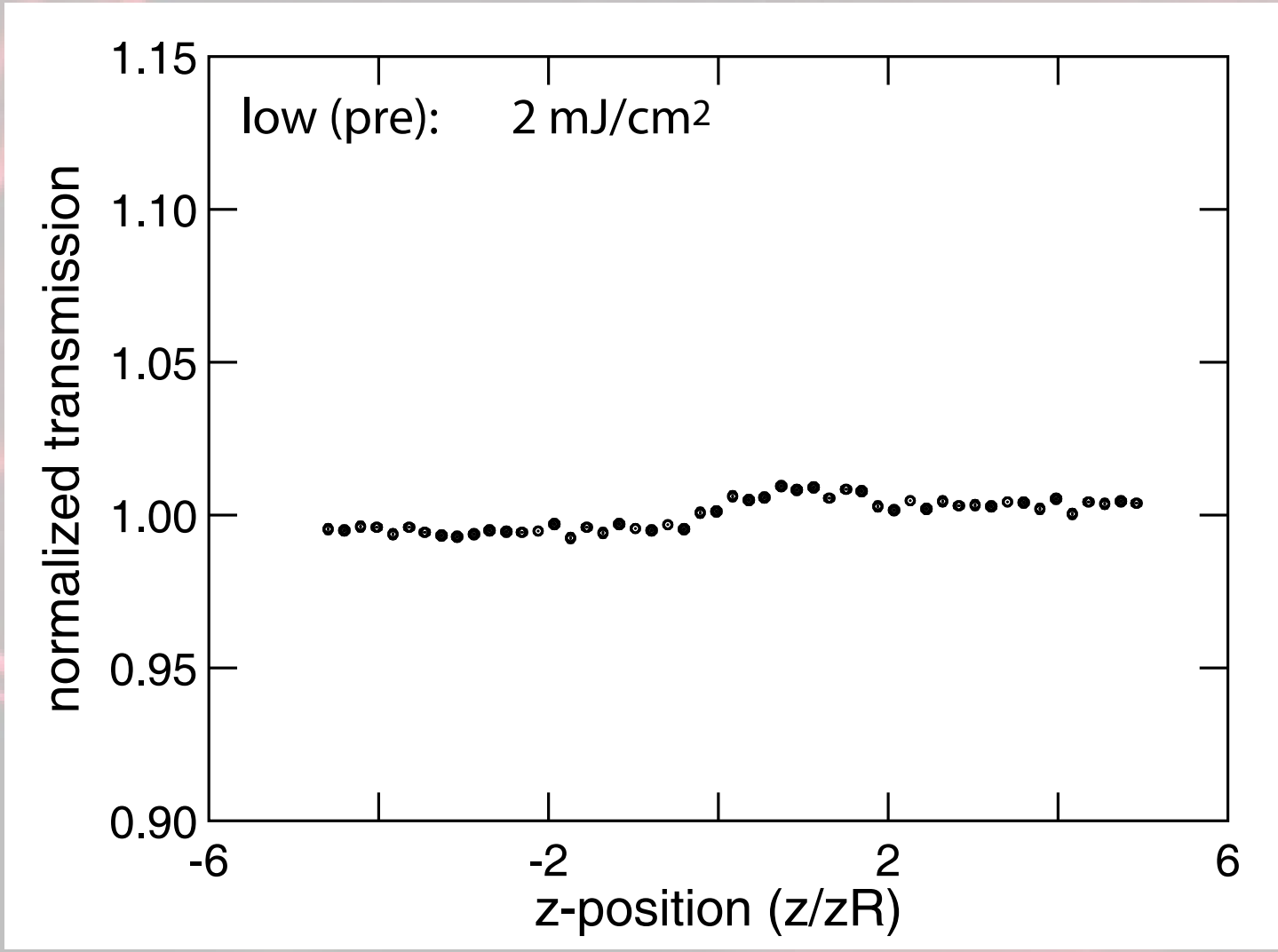


Standard z-scan

What about the closed aperture?

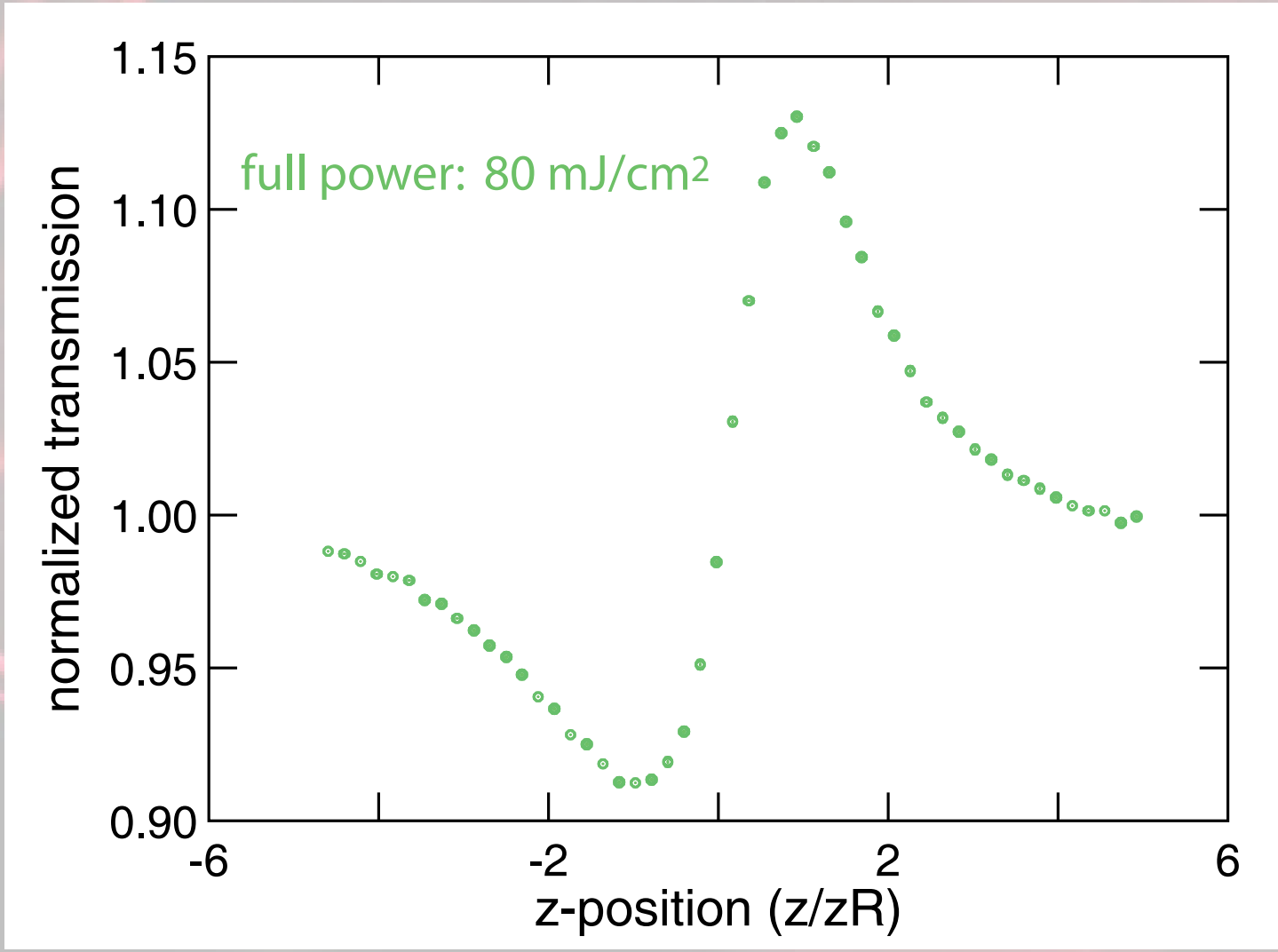
Standard z-scan

Closed Aperture (CA/OA)



Standard z-scan

Closed Aperture (CA/OA)



Standard z-scan

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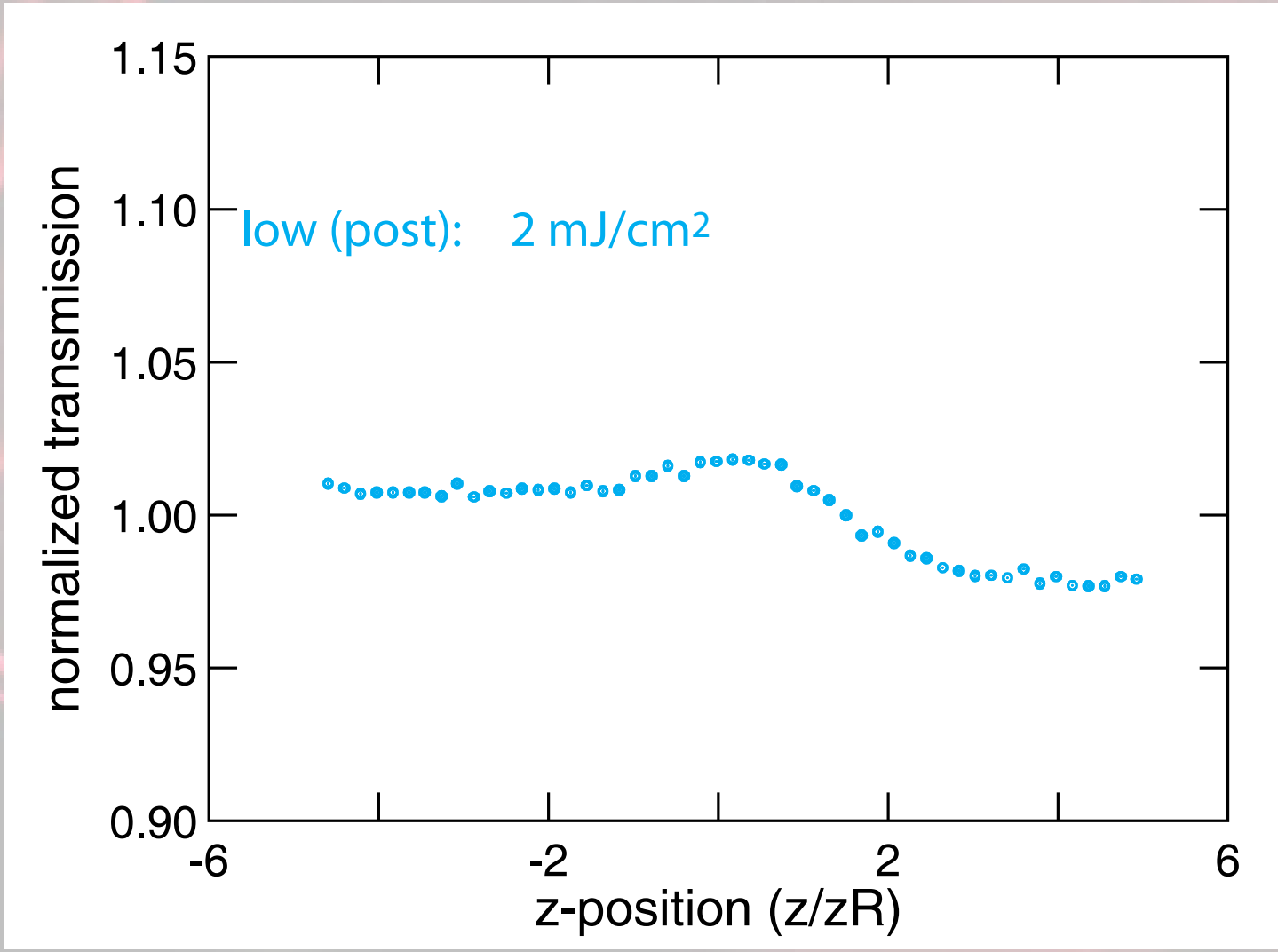
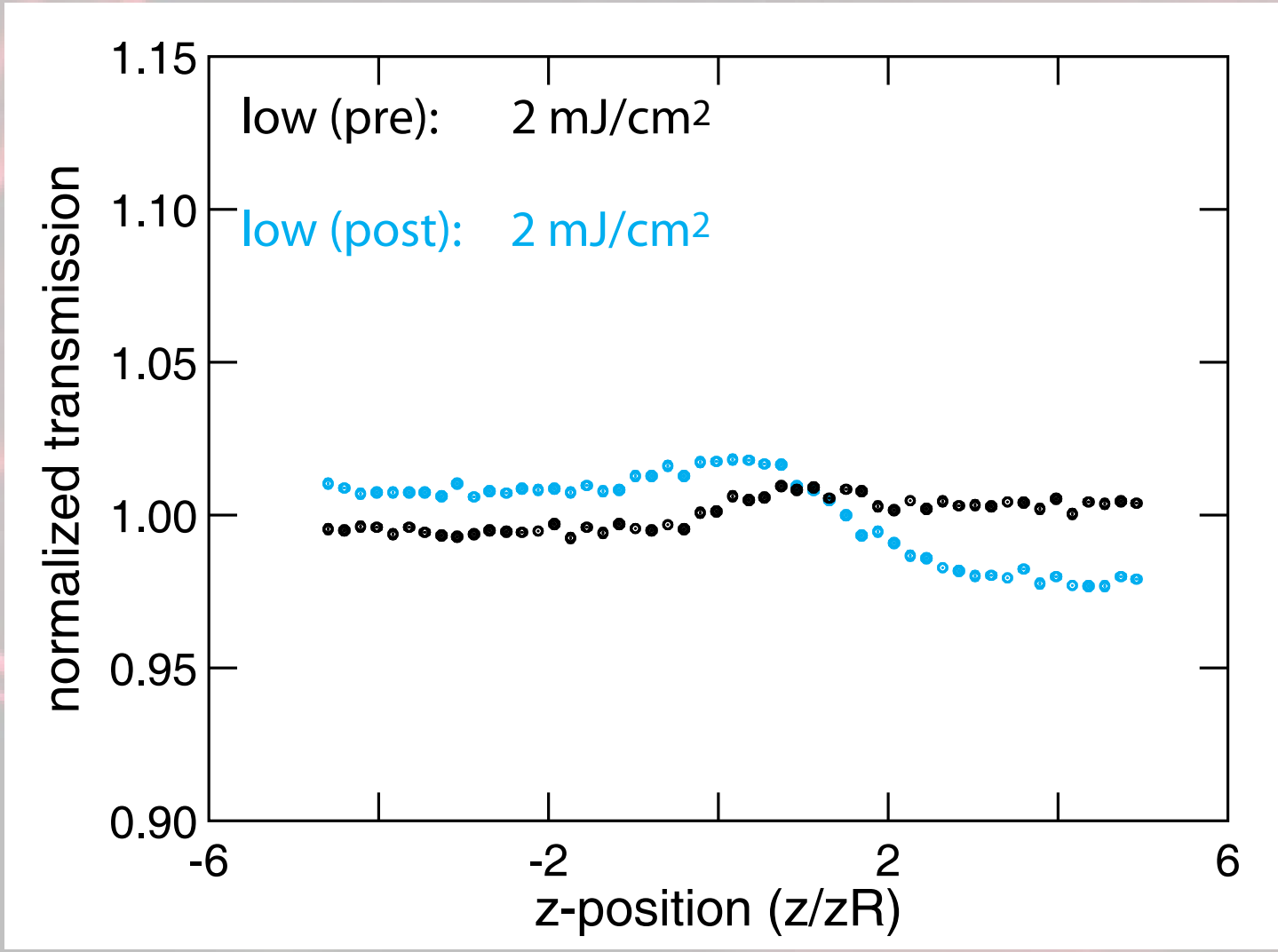


Standard z-scan

Sample has been changed

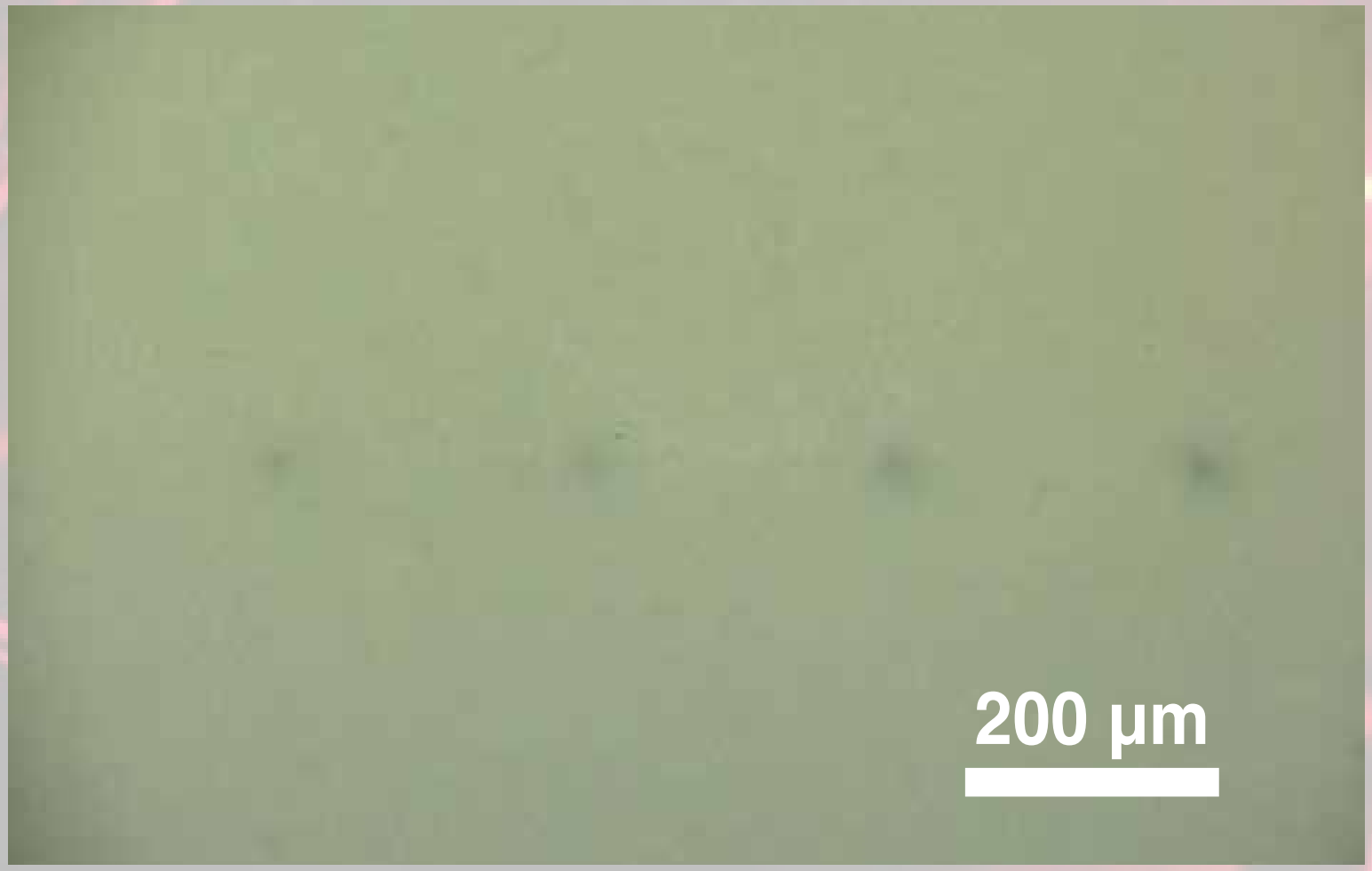


Standard z-scan

What does the sample look like after?

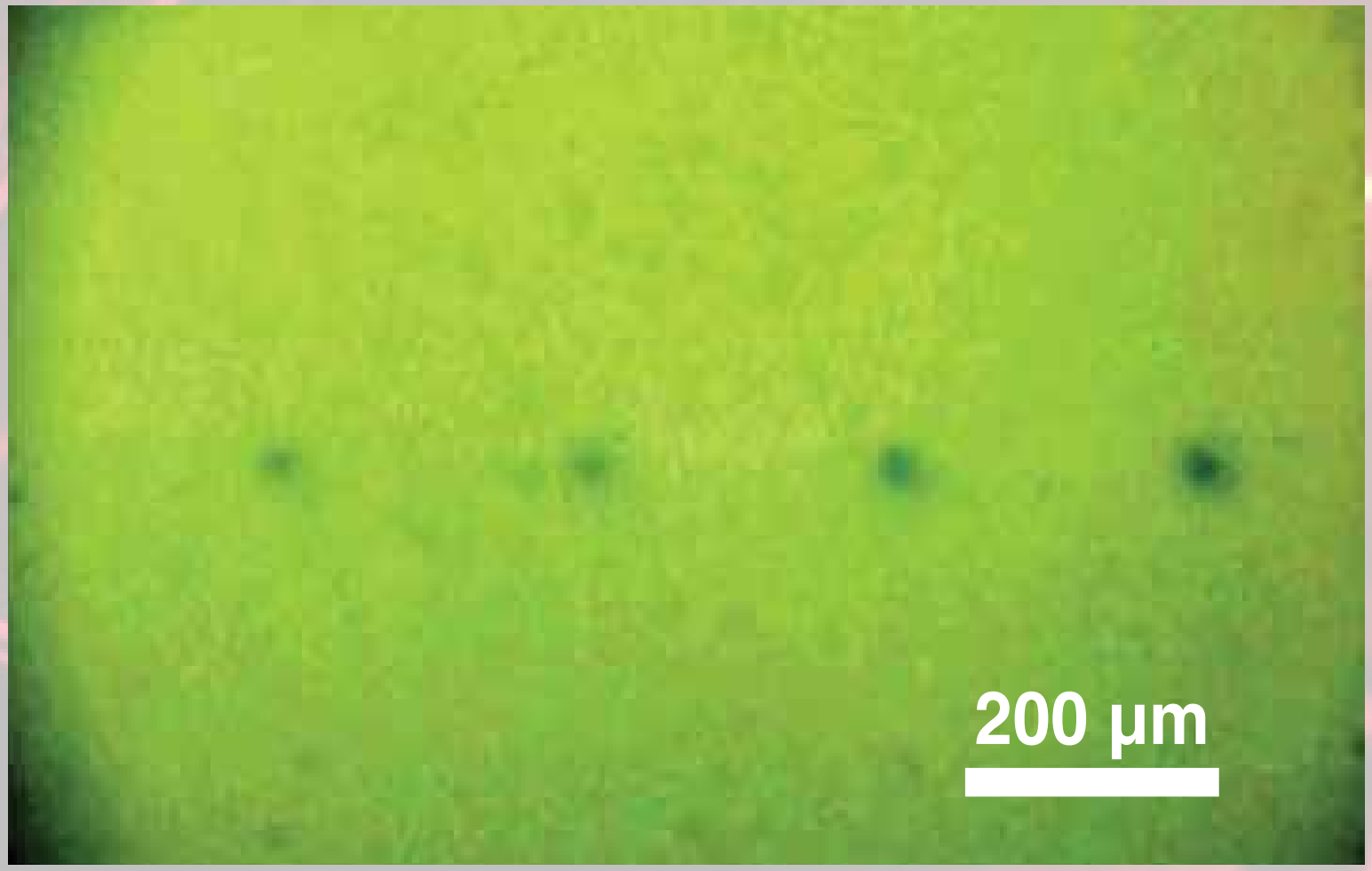
Standard z-scan

Optical microscopy



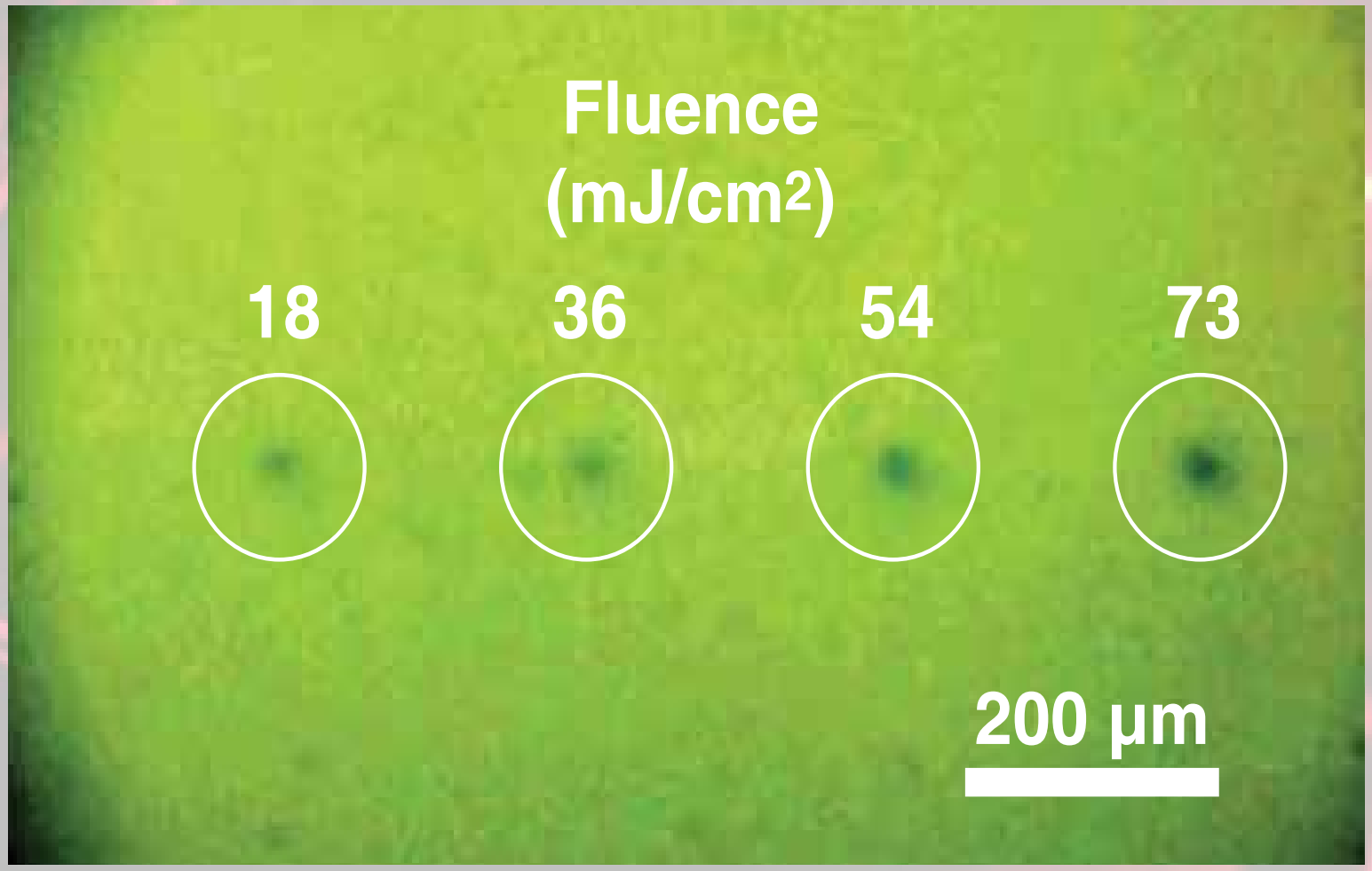
Standard z-scan

Optical microscopy (enhanced)

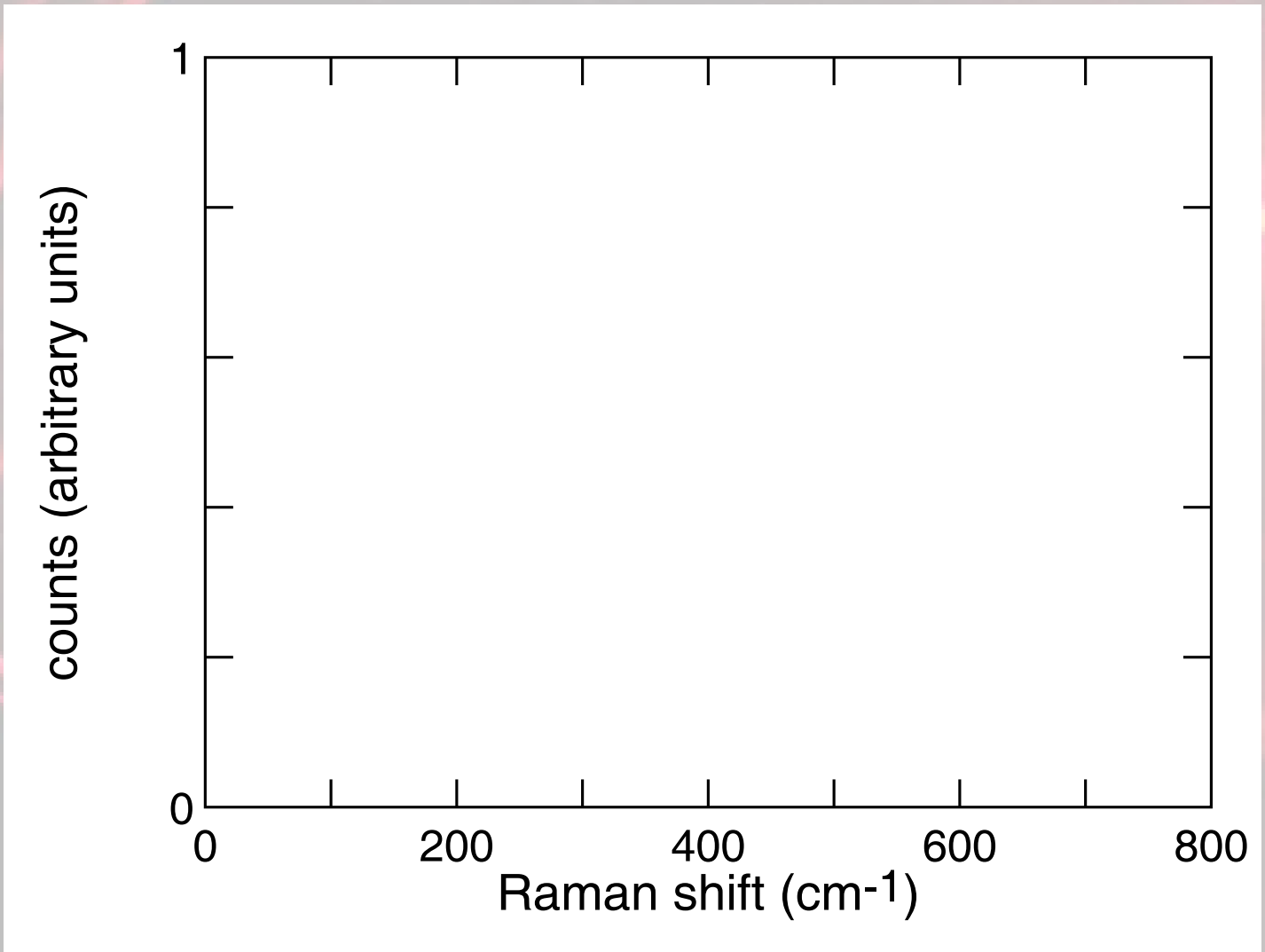


Standard z-scan

Optical microscopy (enhanced)

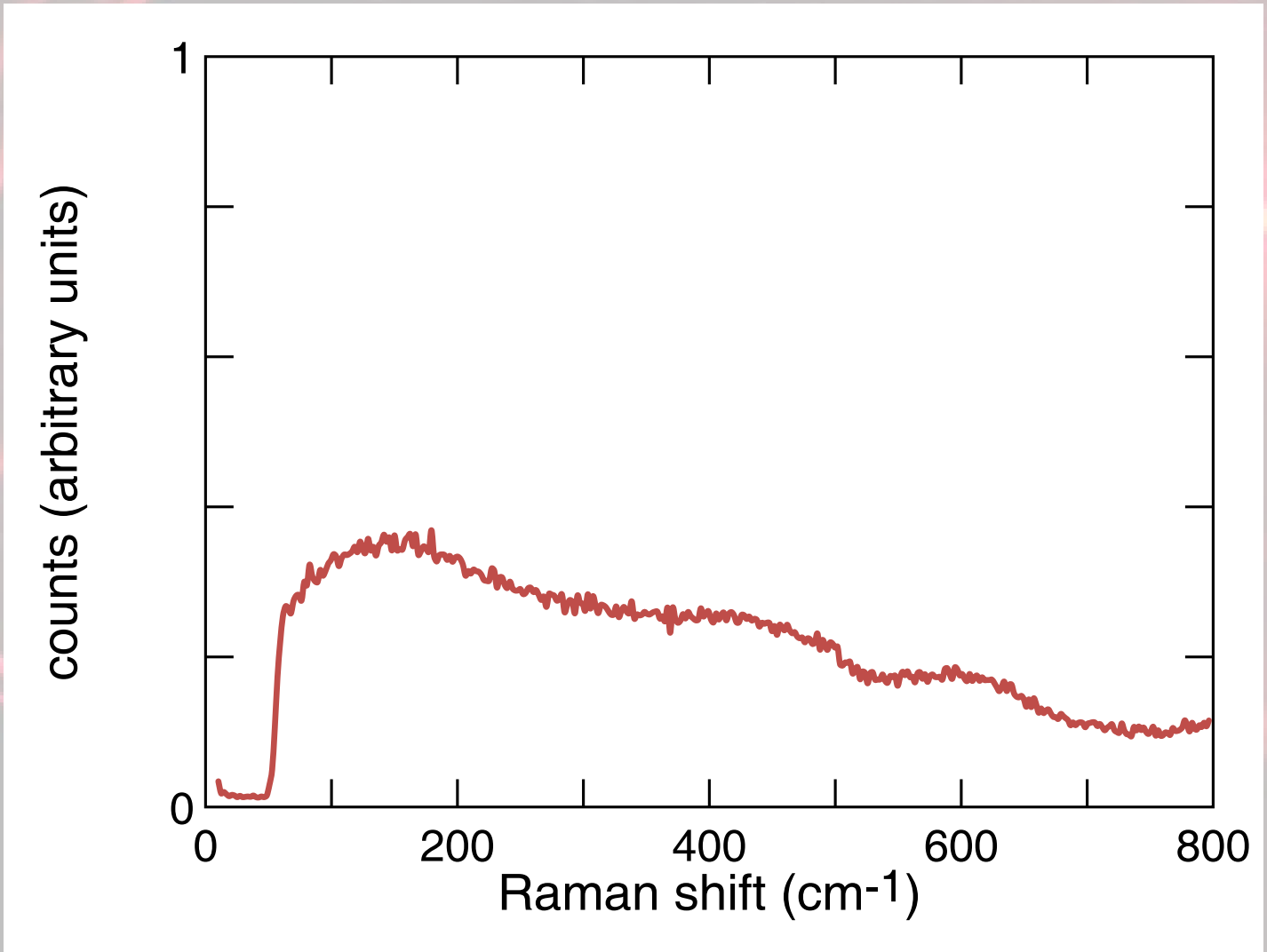


Standard z-scan



Standard z-scan

No Peaks

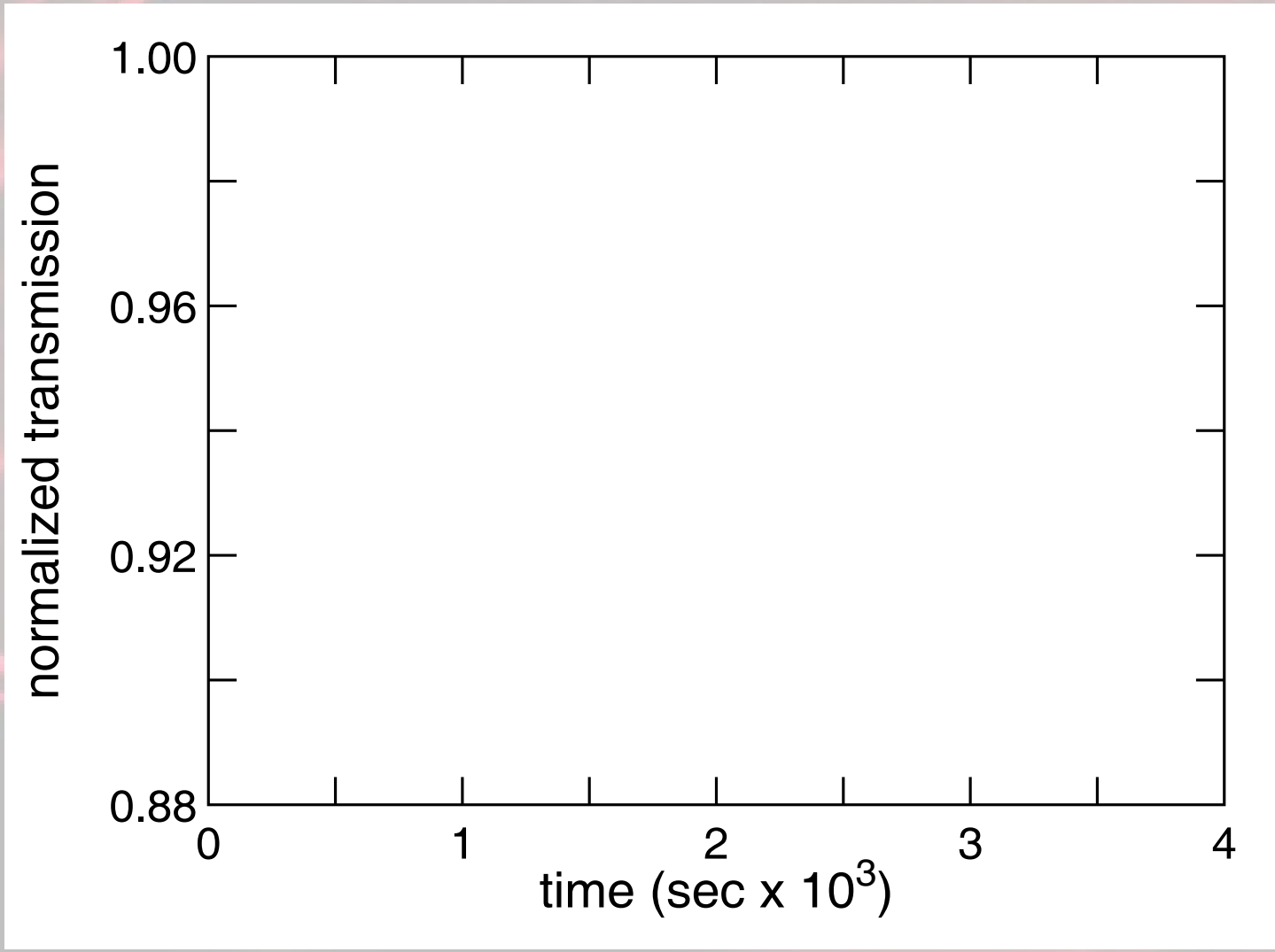


Standard z-scan

What is the time scale of the darkening?

Standard z-scan

Timed Exposure (Open Aperture)



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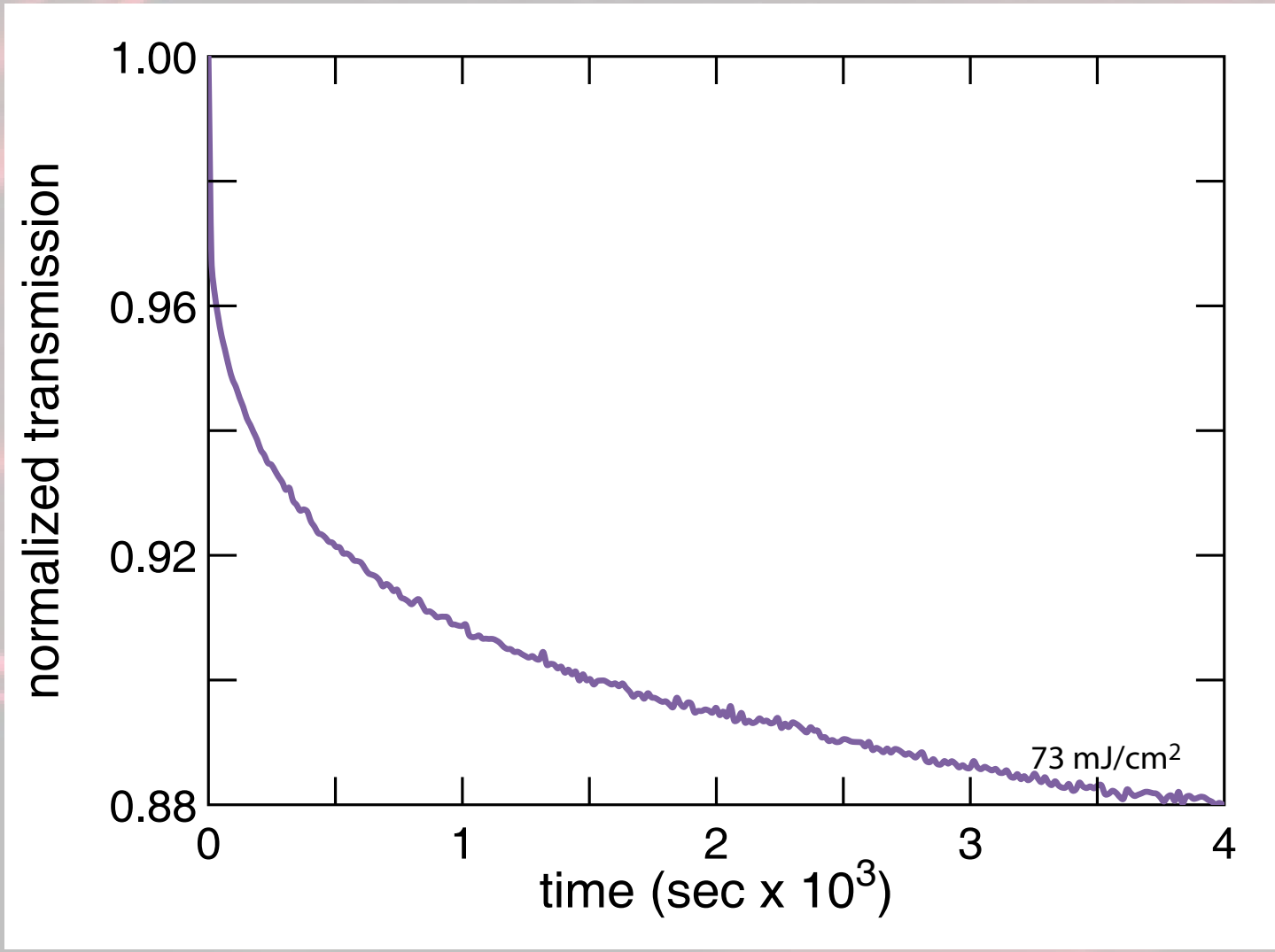
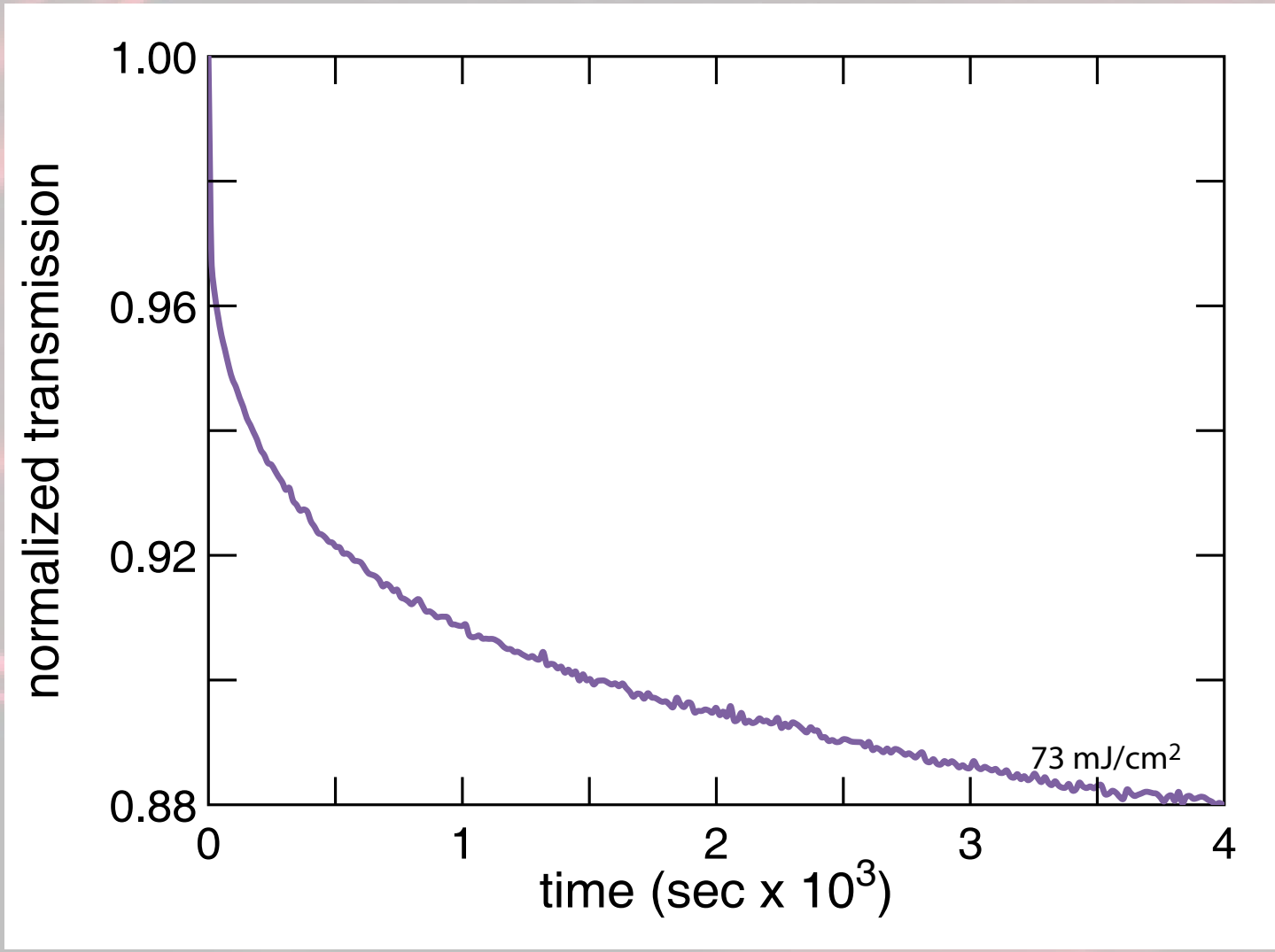


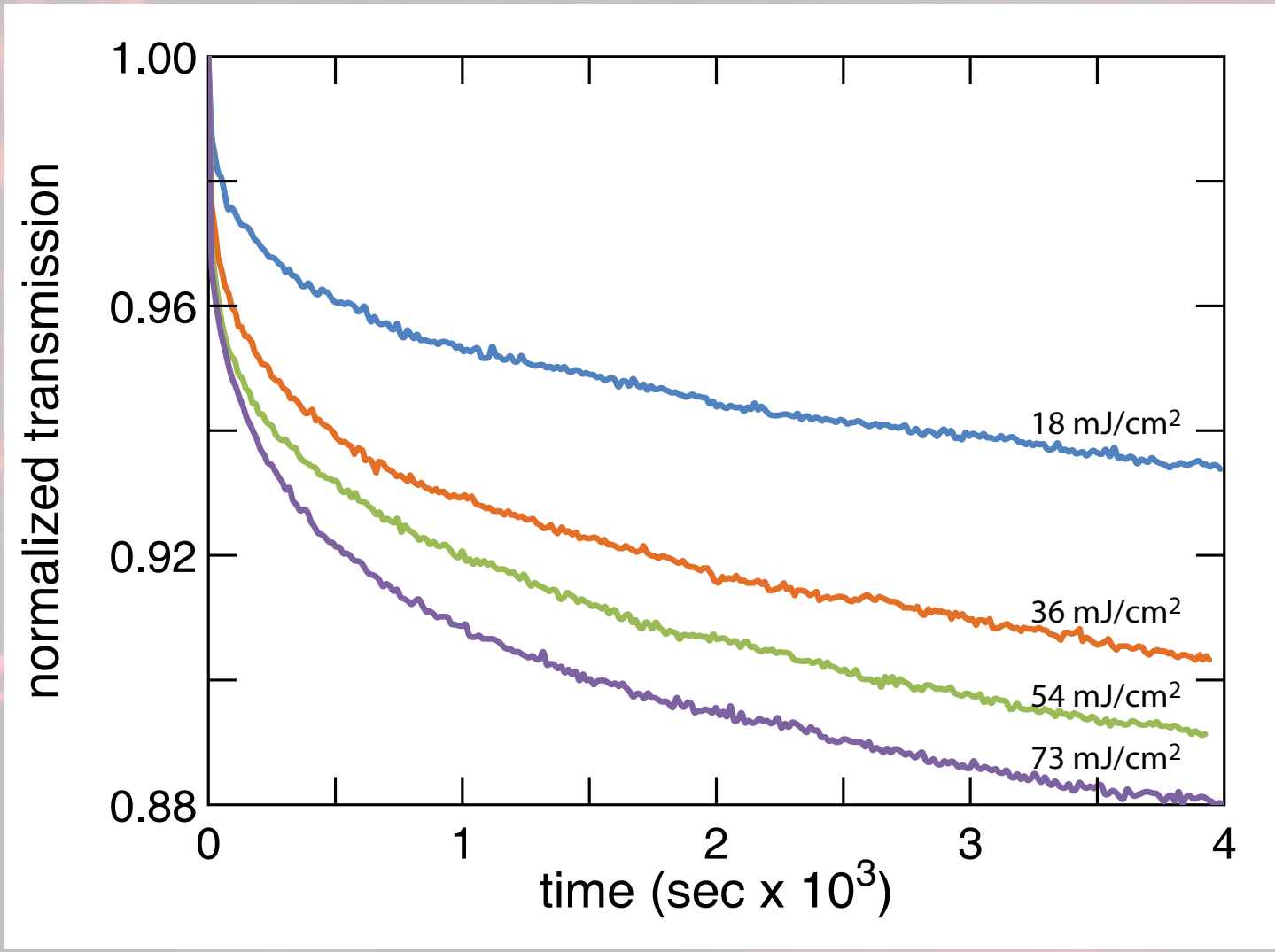
Standard z-scan

Not stabilized over > 1 hour



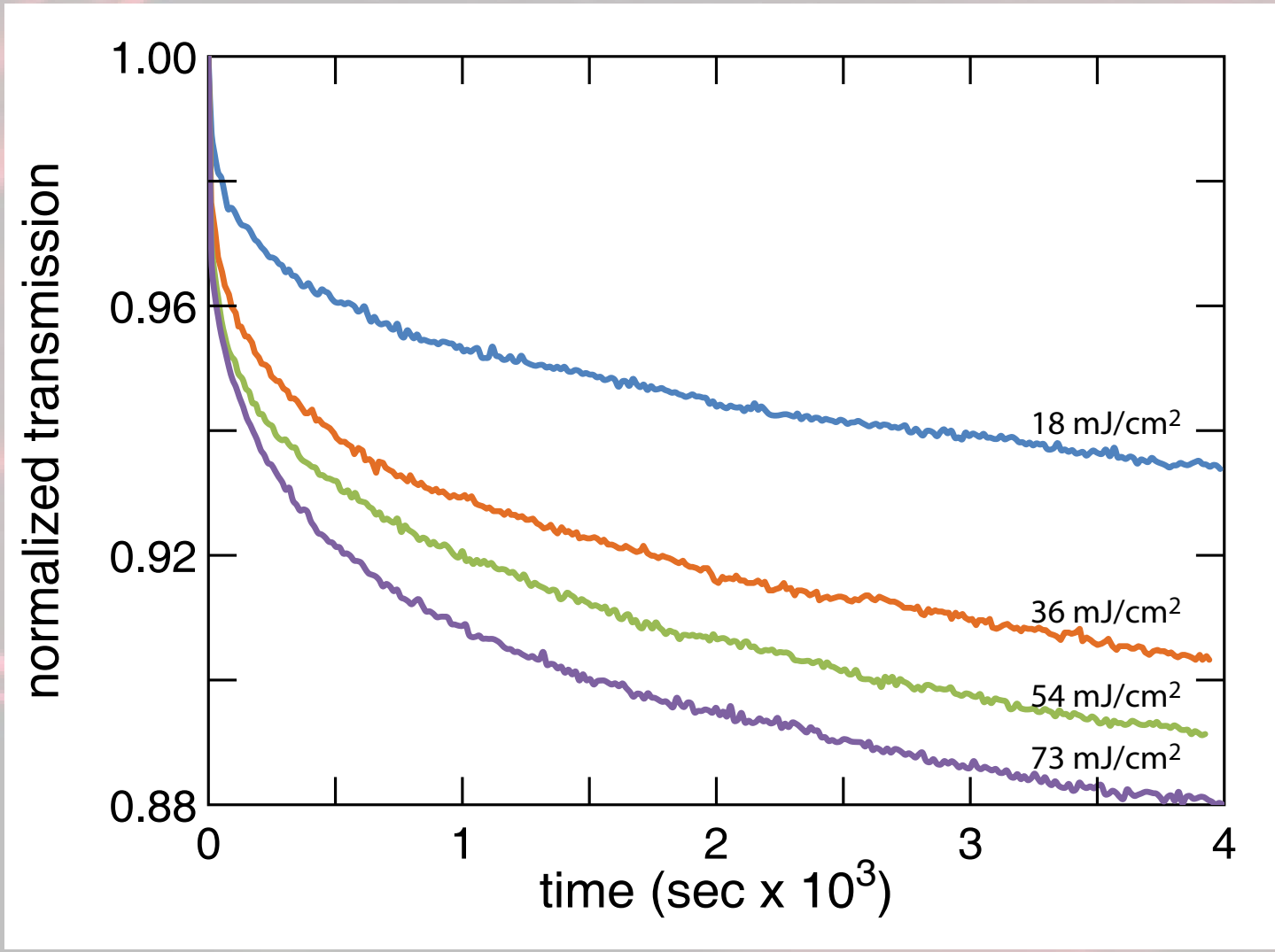
Standard z-scan

Even Low Power Decreases



Standard z-scan

Empirical Fit: $A_1(P)\exp(-t/\tau_1) + A_2(P)\exp(-t/\tau_2)$



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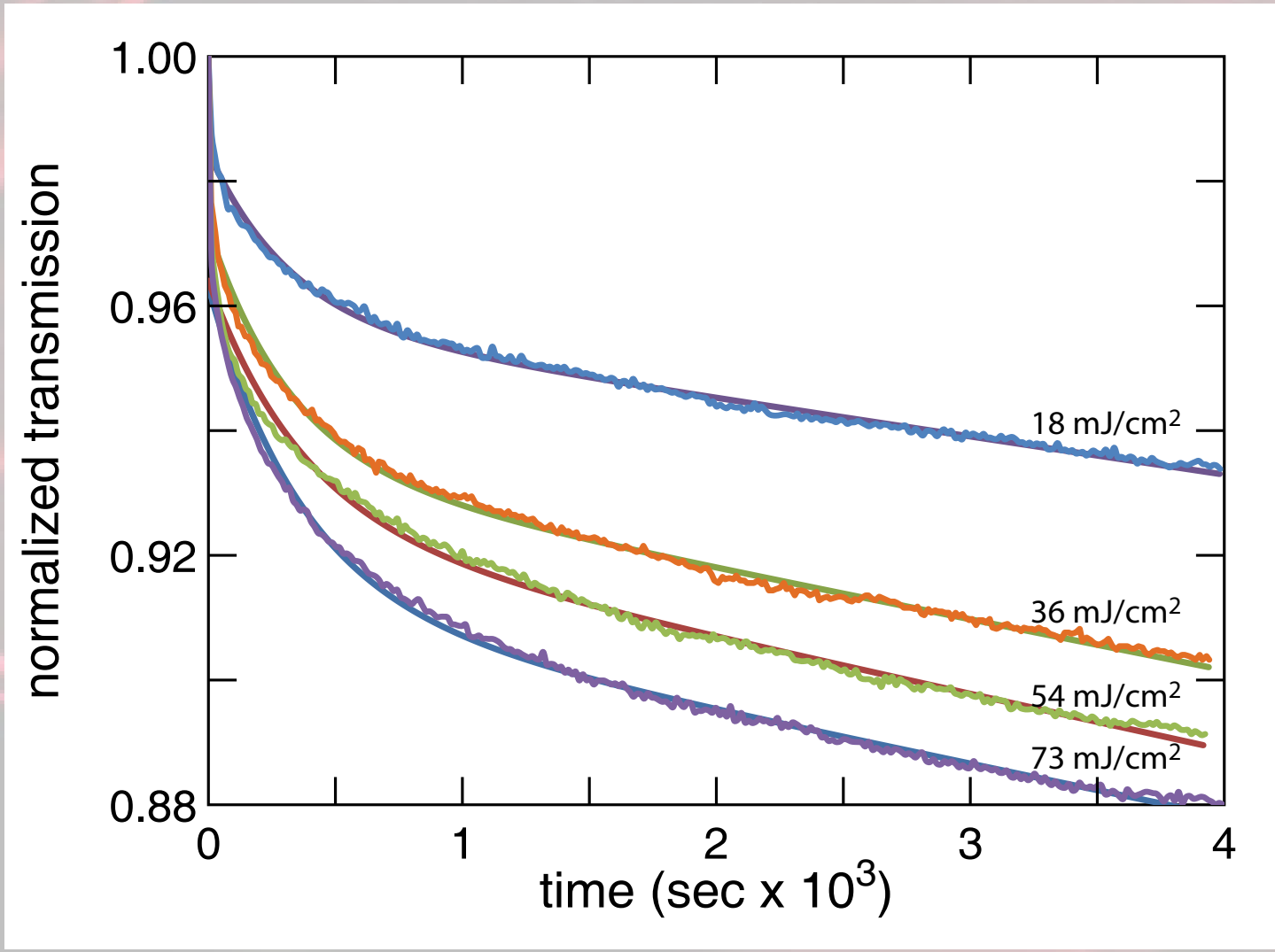

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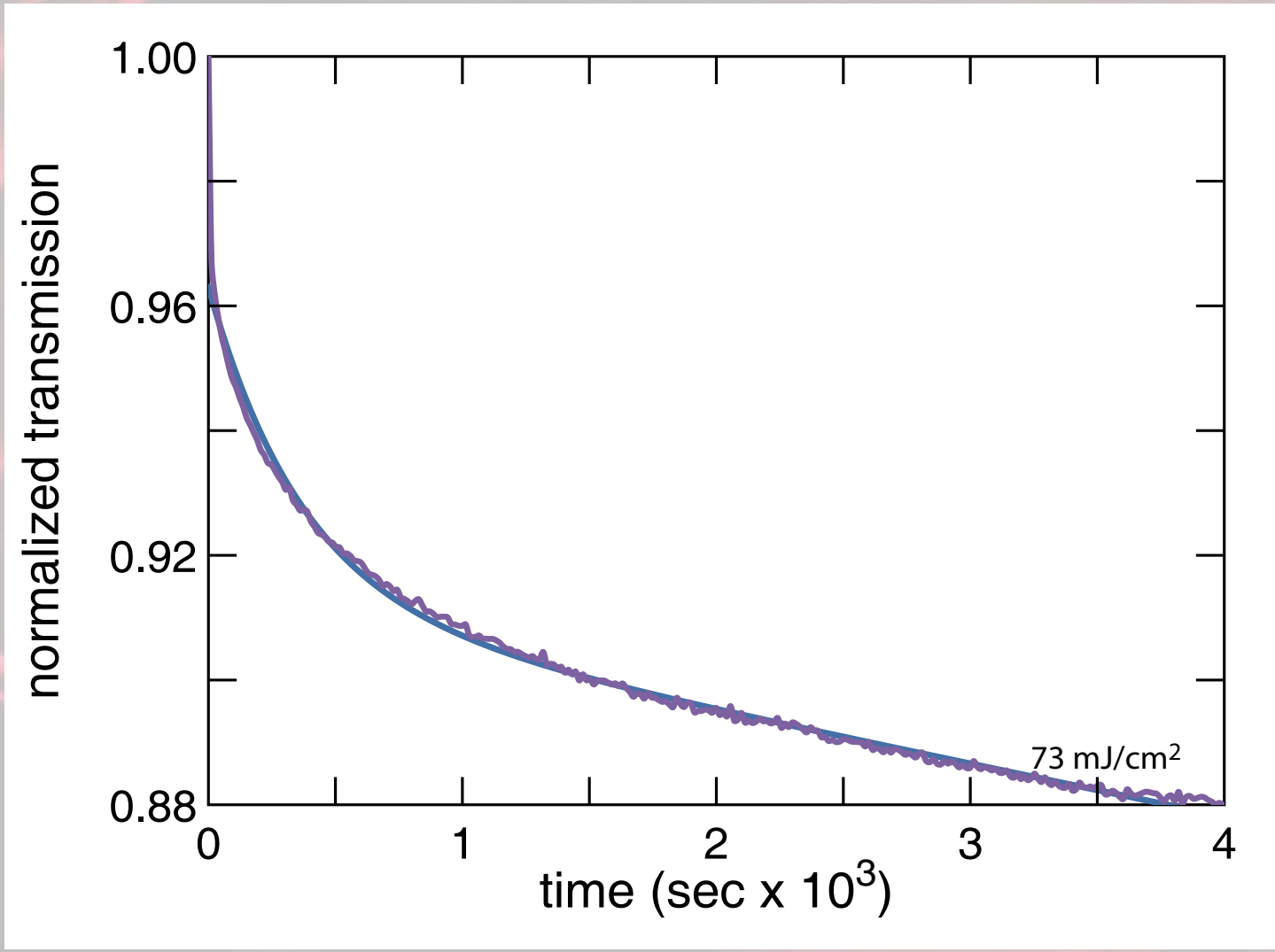

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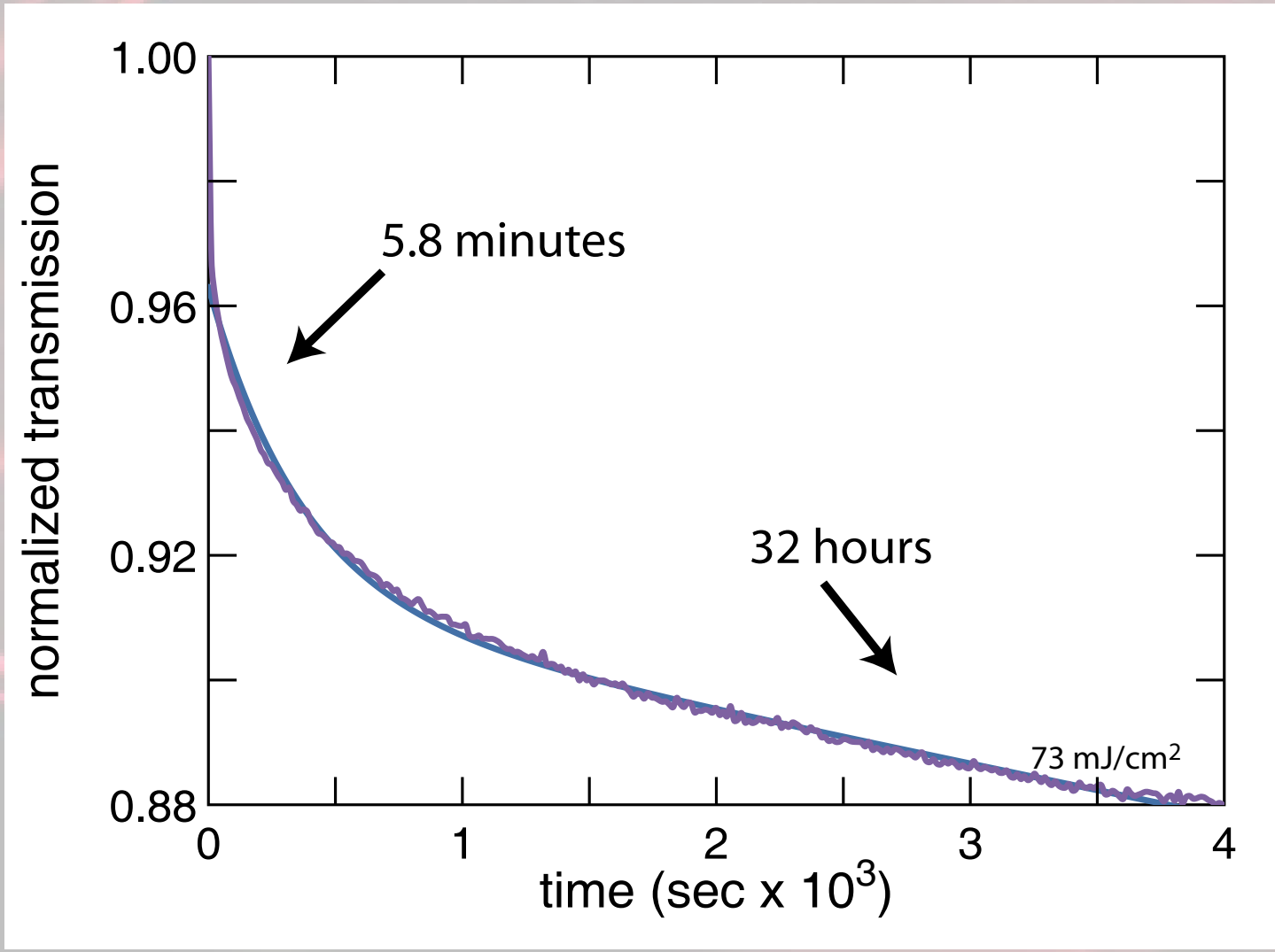
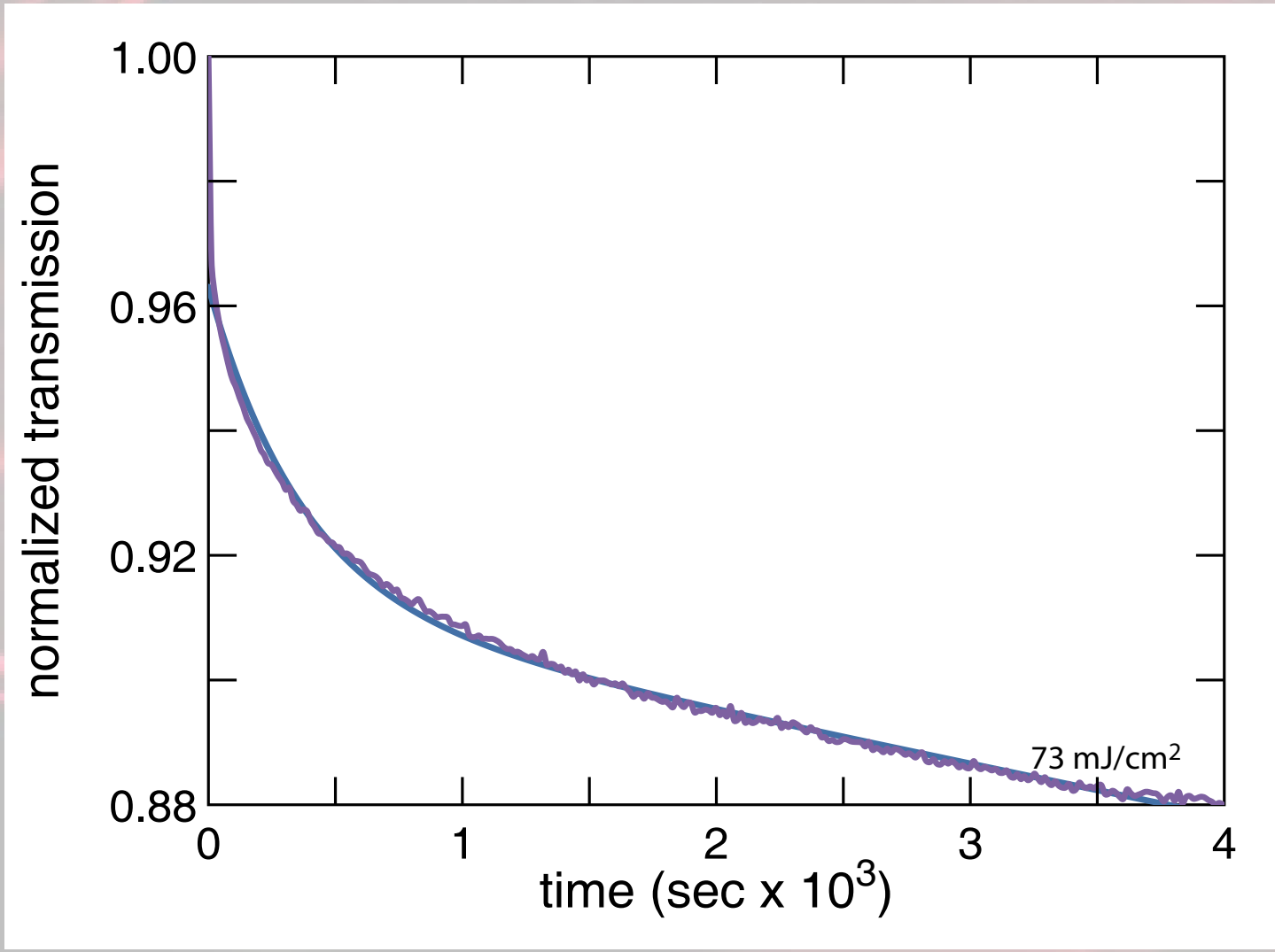


Standard z-scan

Can we still measure the film?

Standard z-scan

Minimize Darkening



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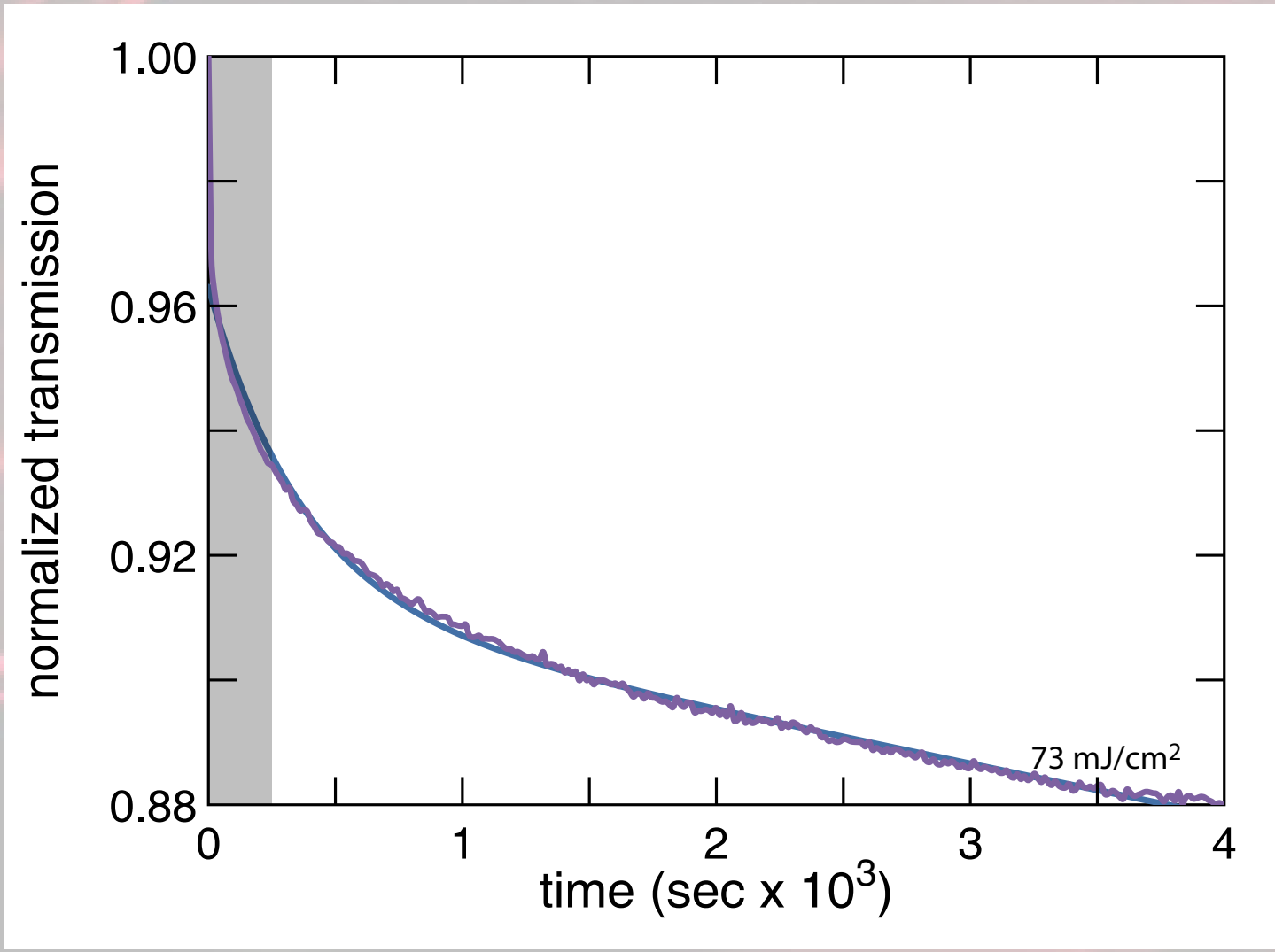
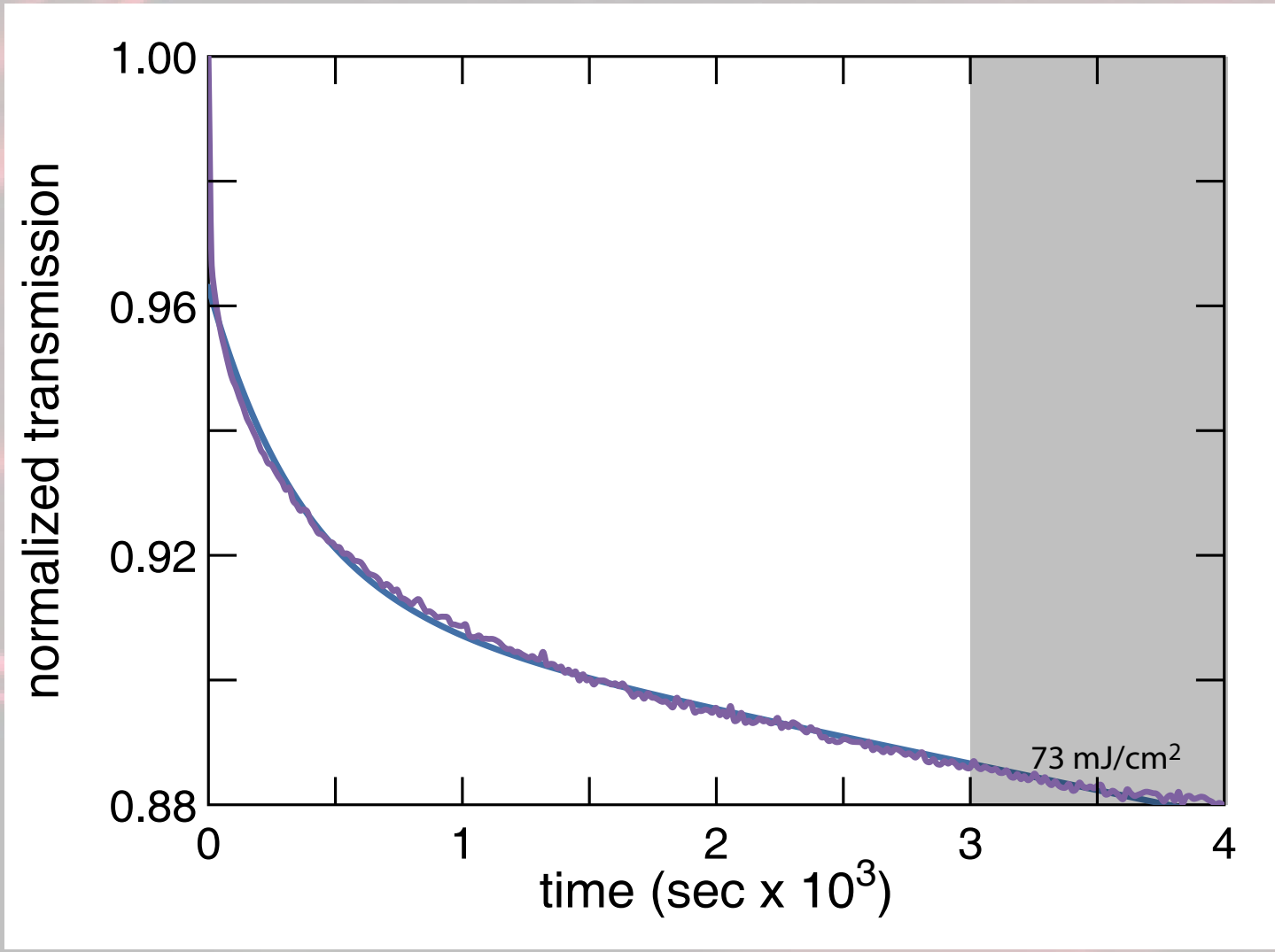


Standard z-scan

Allow for darkening



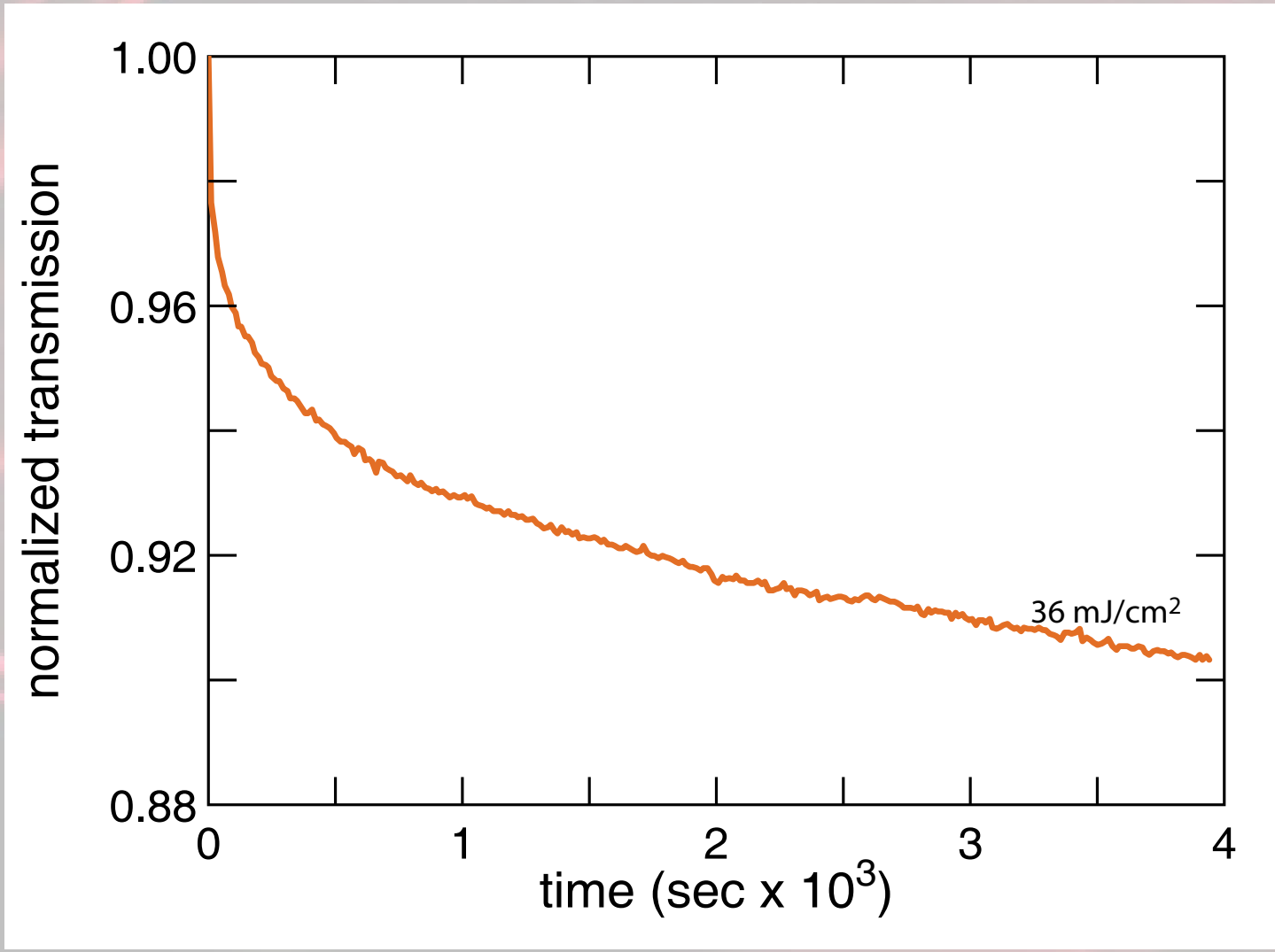
Standard z-scan

Comparison:

With TiO_2 Film <u>versus</u> Without TiO_2 Film

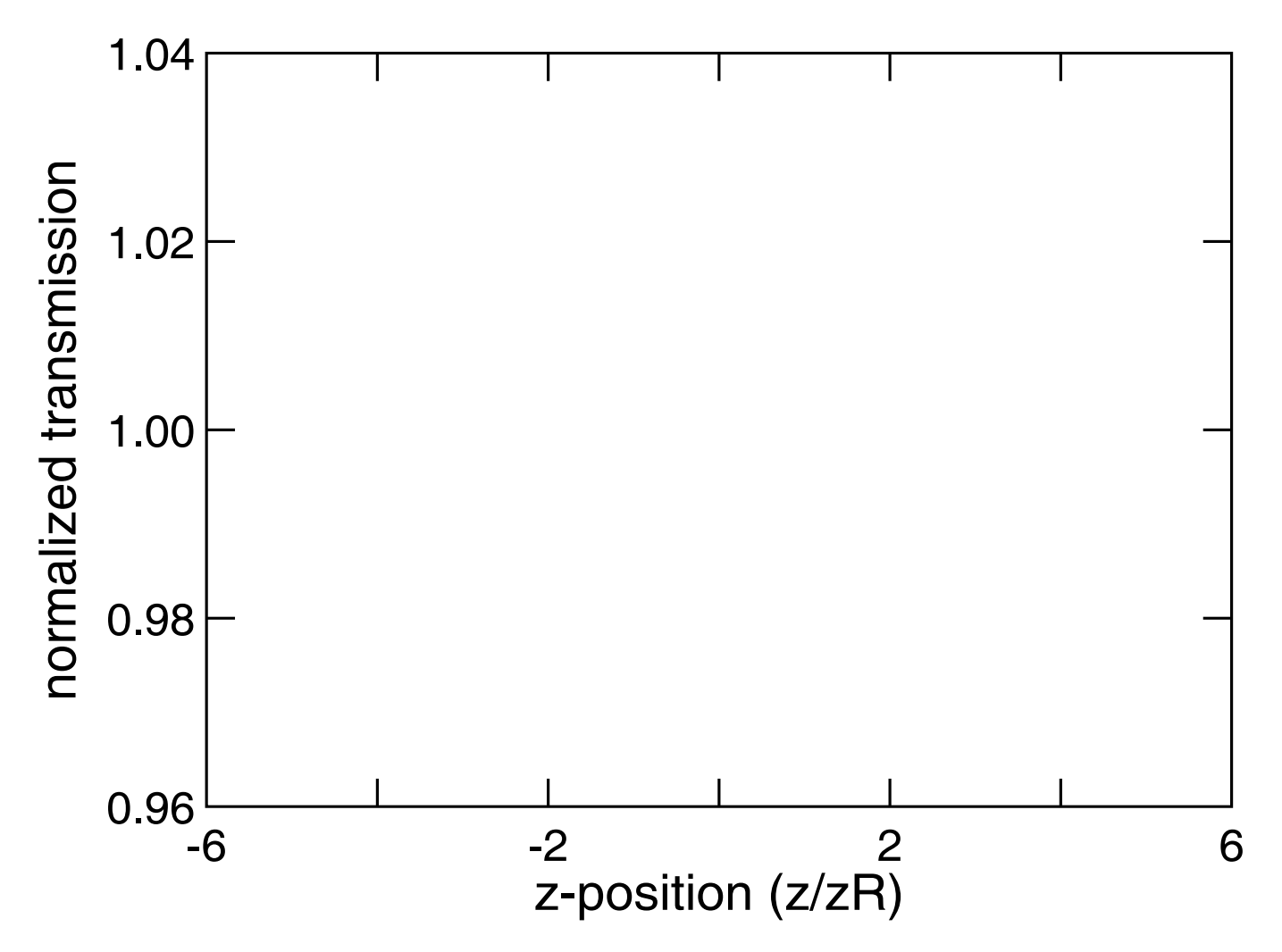
Standard z-scan

Fluence used (TiO_2): 36 mJ/cm^2



Standard z-scan

Comparison with and without film



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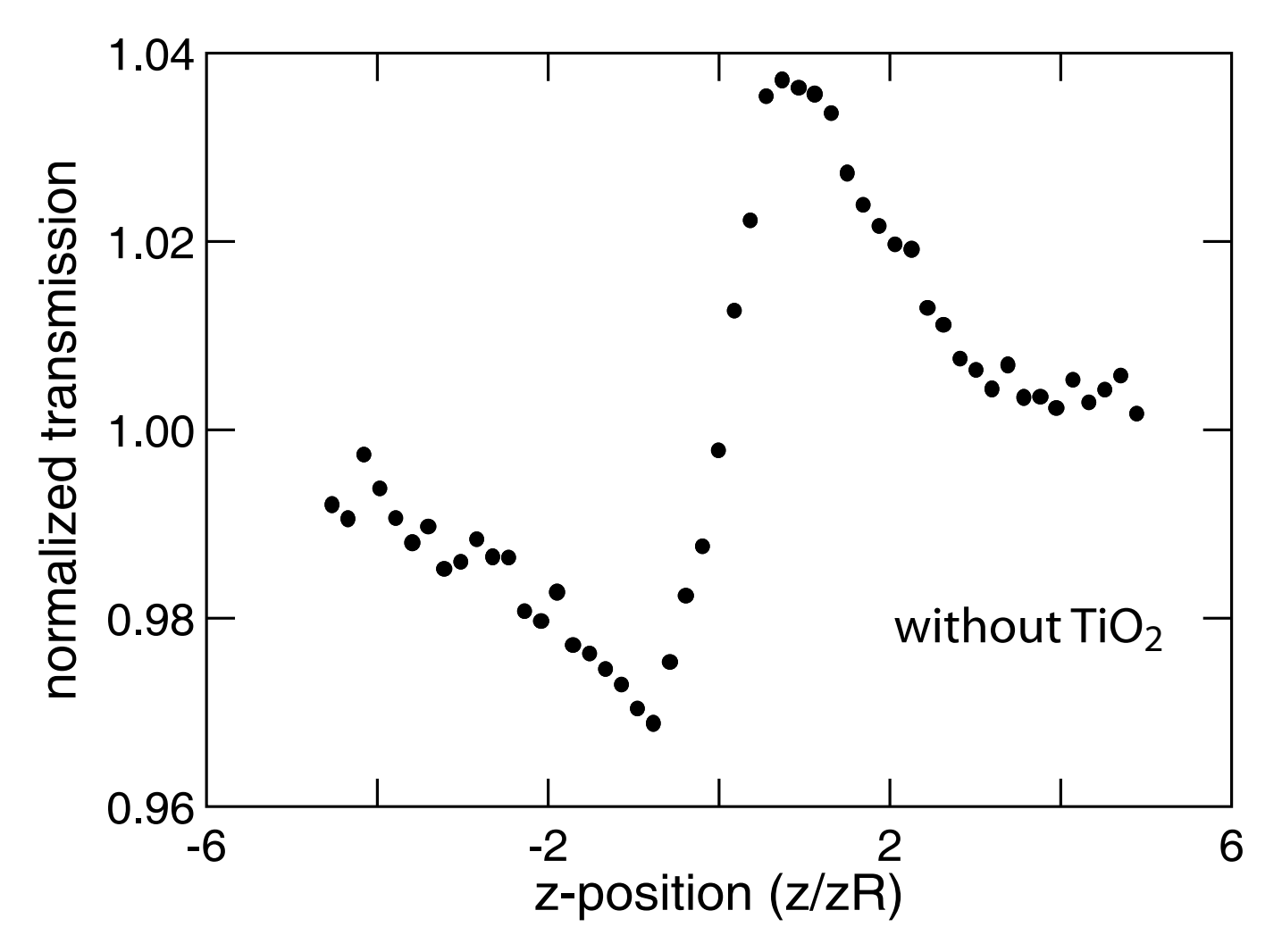

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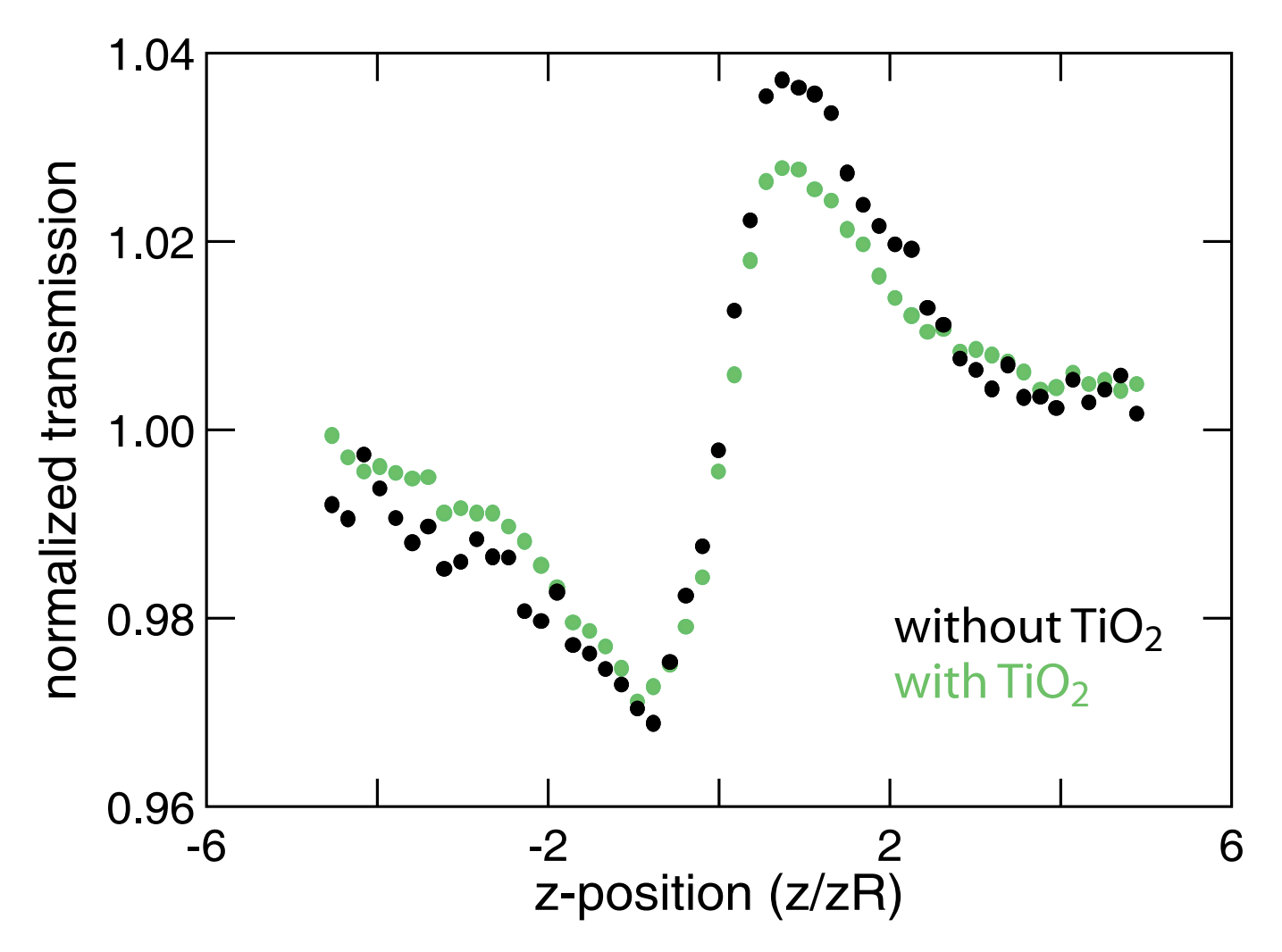
Comparison with and without film



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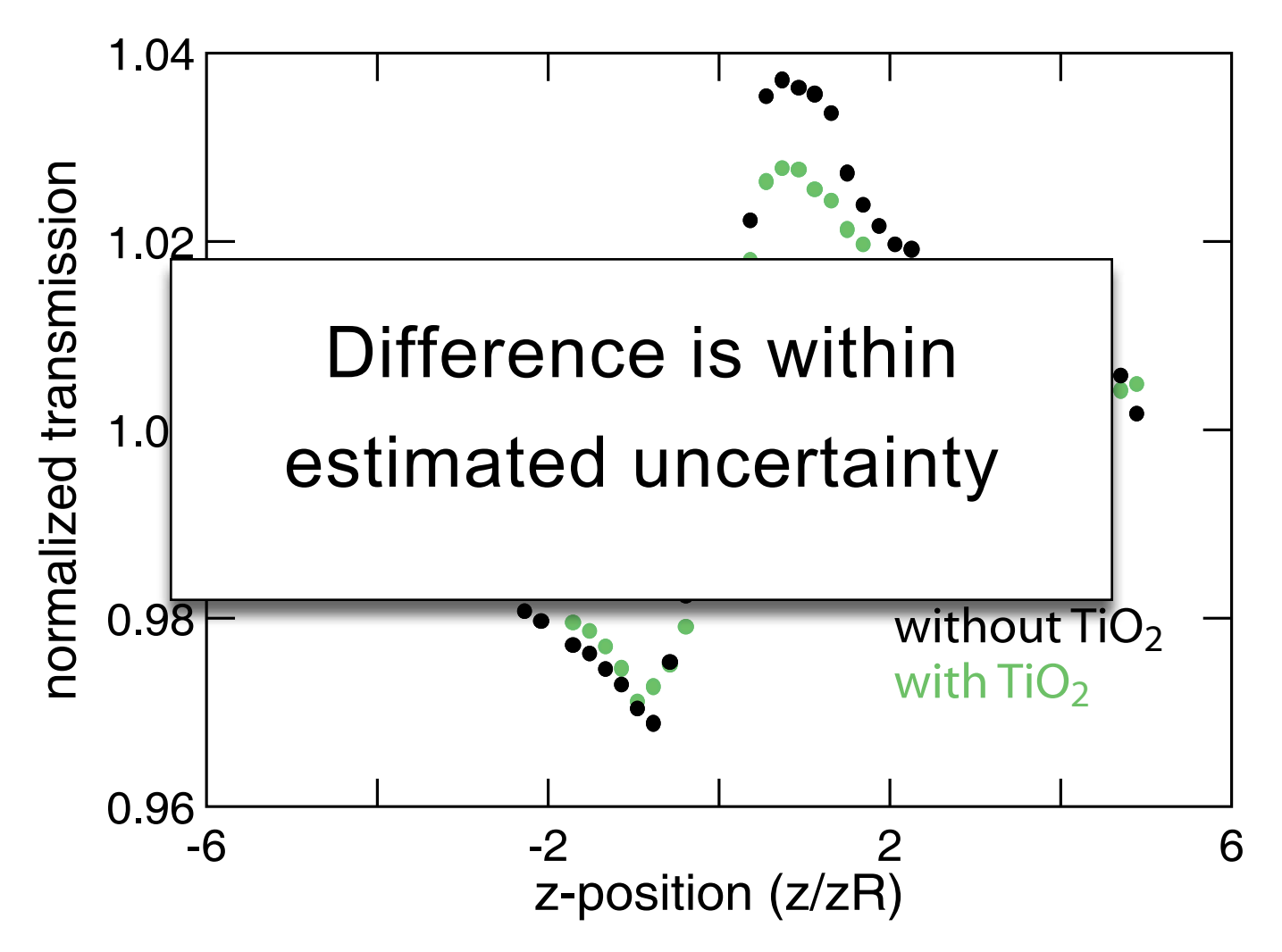

Difference is within estimated uncertainty

Do the darkened samples show thermal nonlinearities and how can we measure it?

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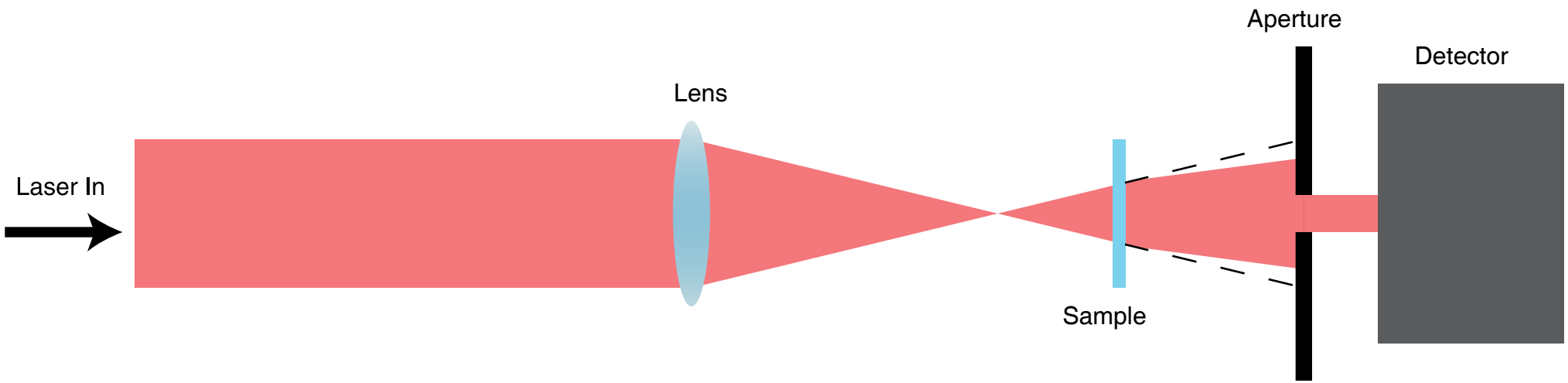
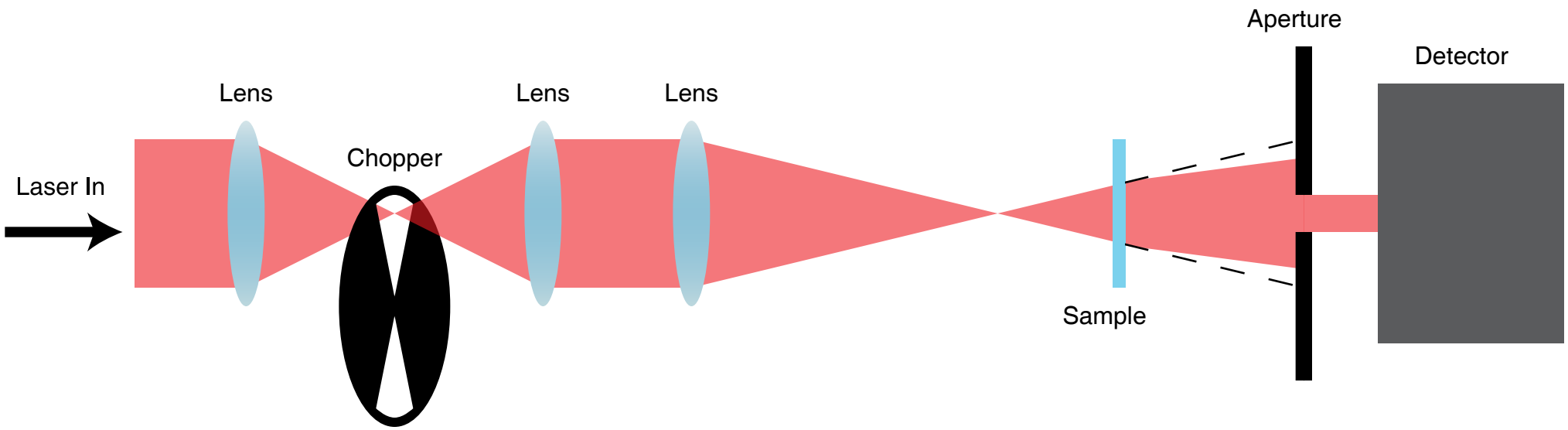


Falconieri & Salvetti App. Phys. B, 69, 133-136 (1999).

Thermally Managed Z-Scan



Falconieri & Salvetti App. Phys. B, 69, 133-136 (1999).

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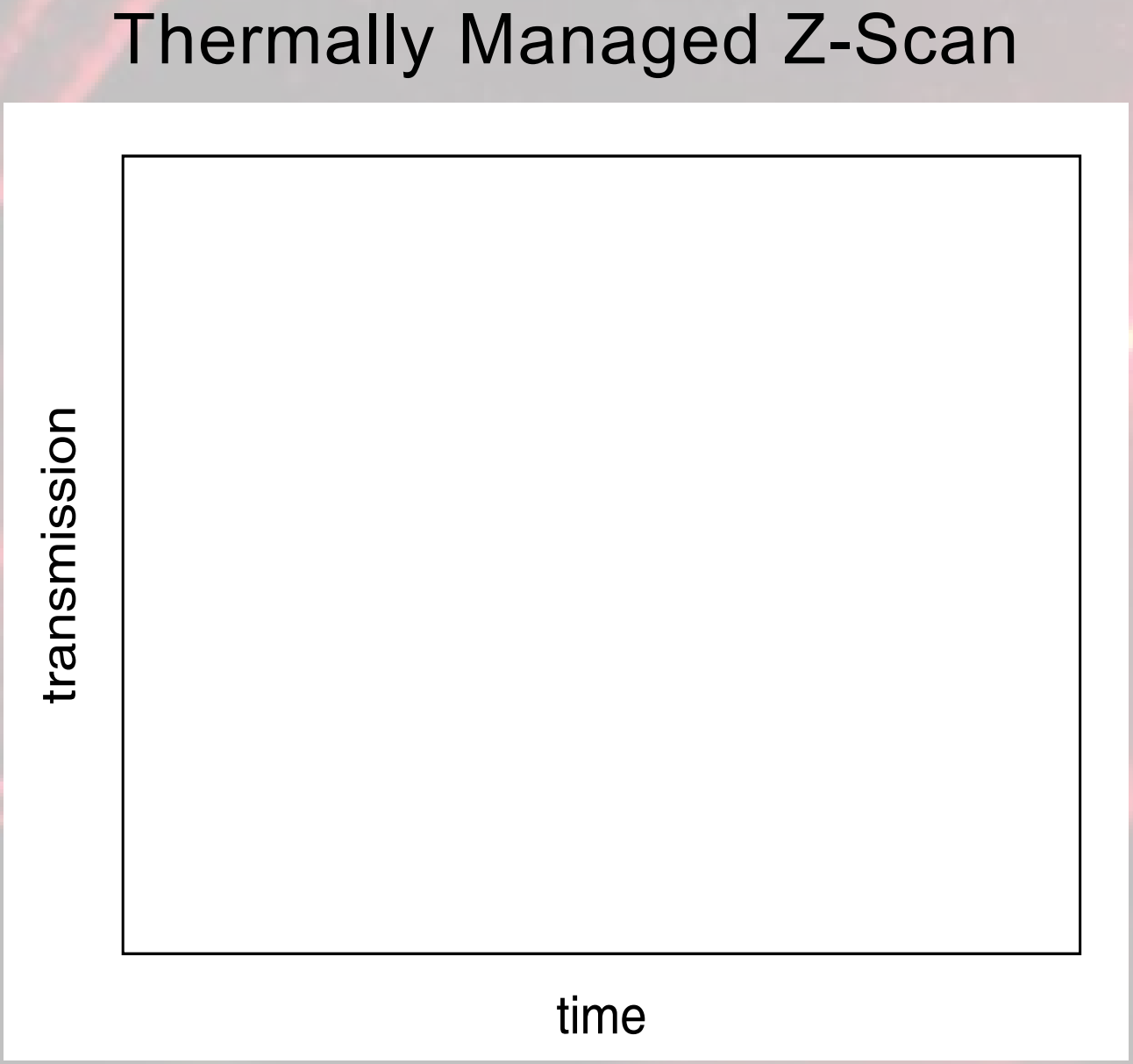

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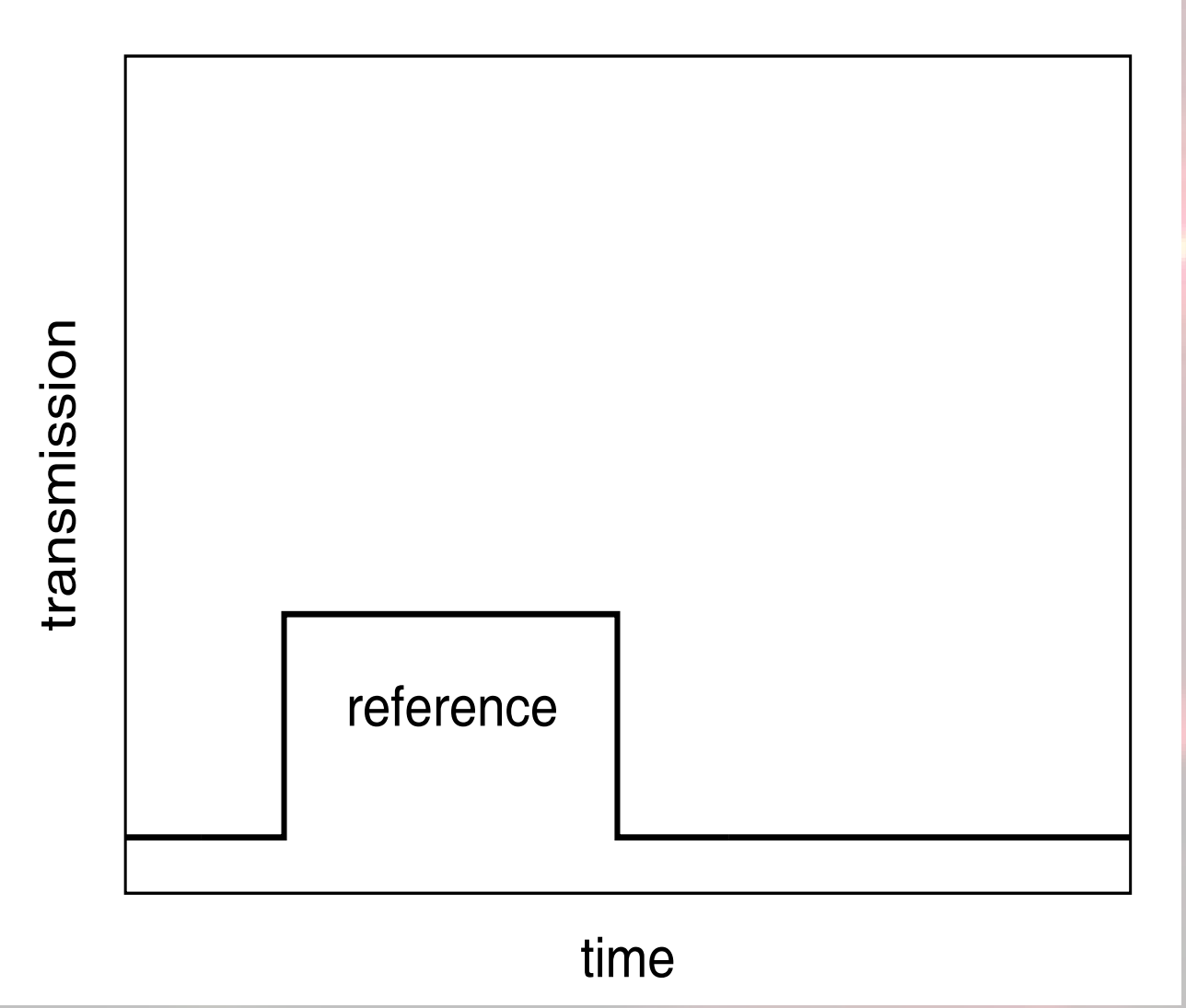

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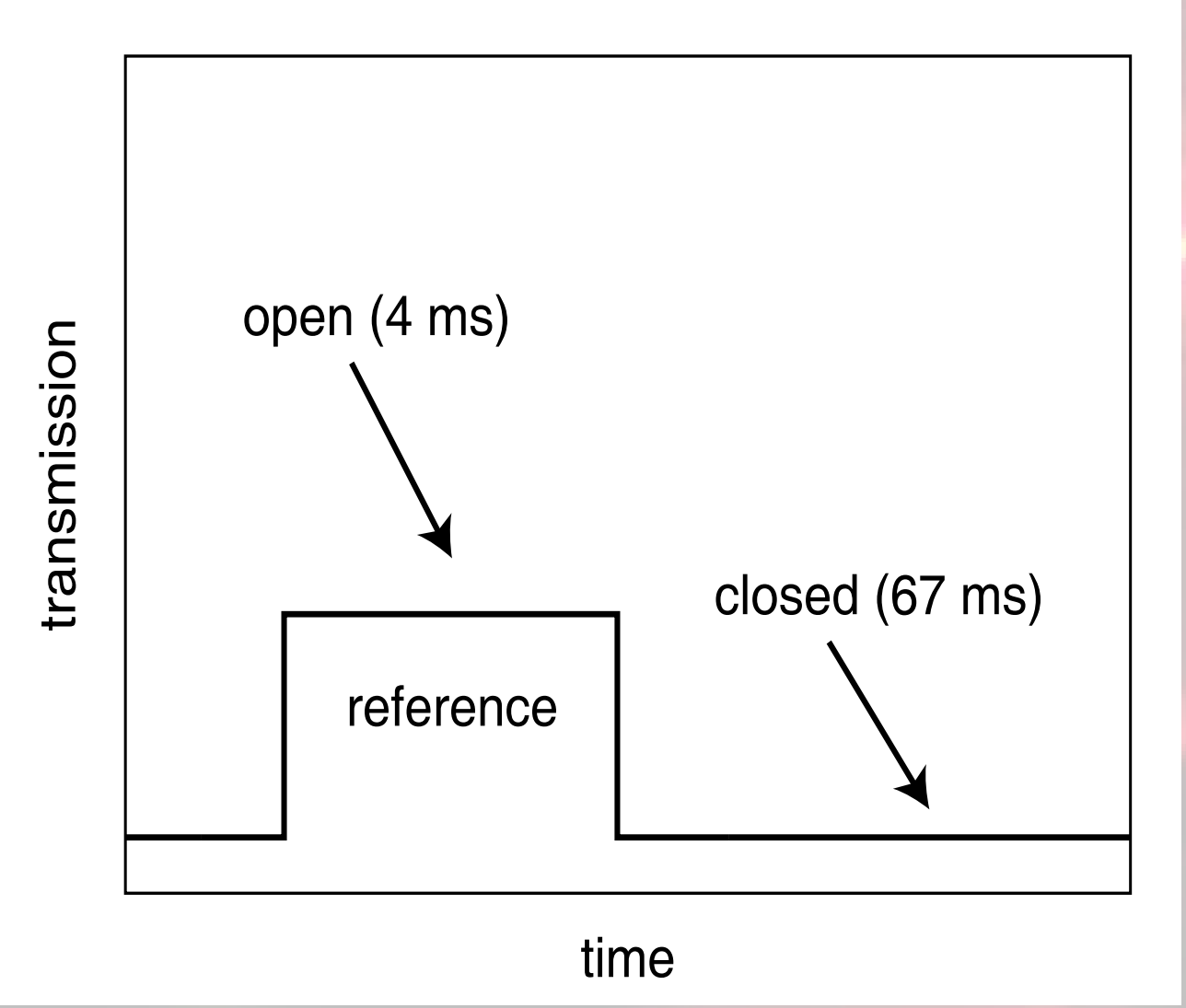

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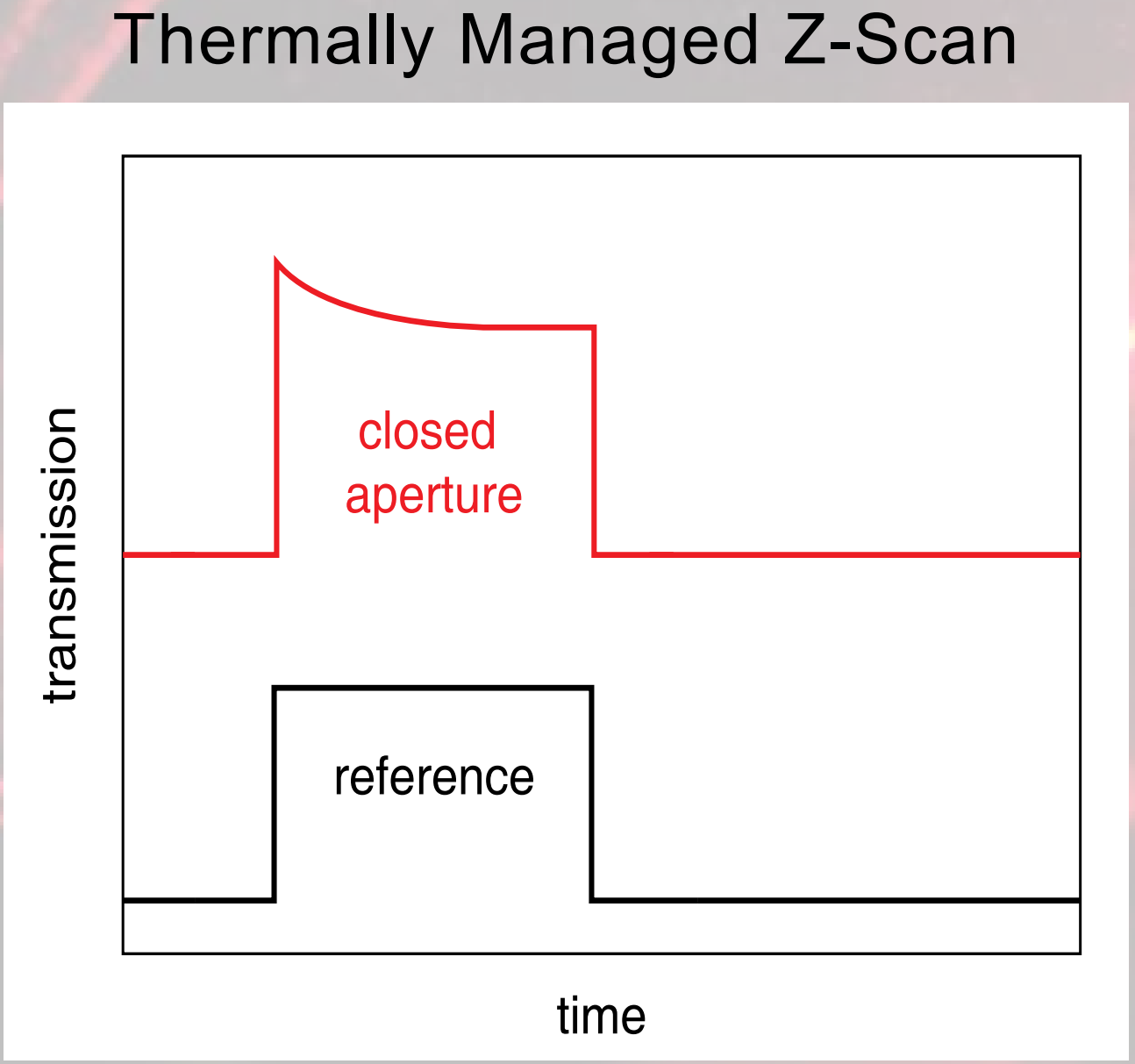

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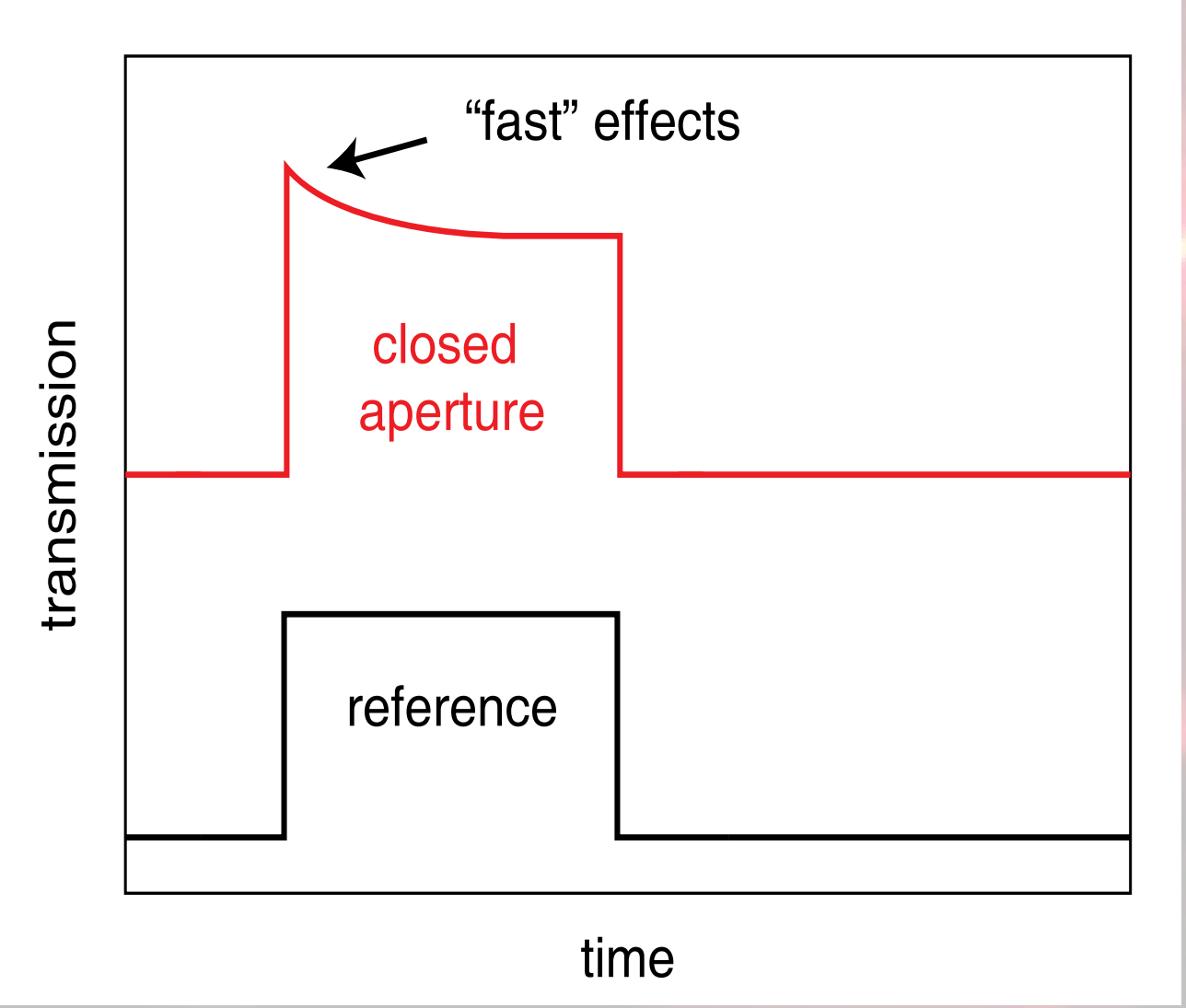

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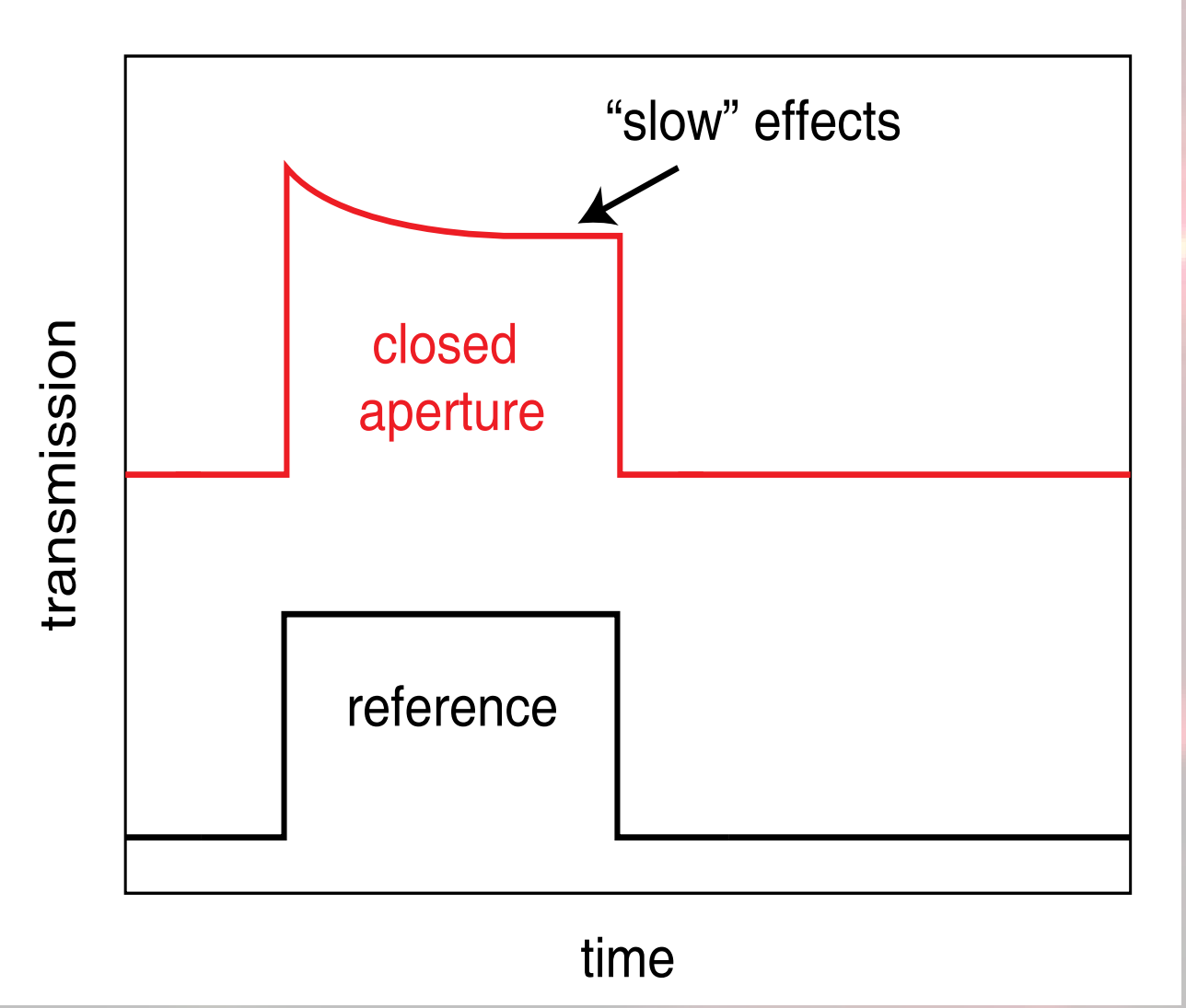


Falconieri & Salvetti App. Phys. B, 69, 133-136 (1999).

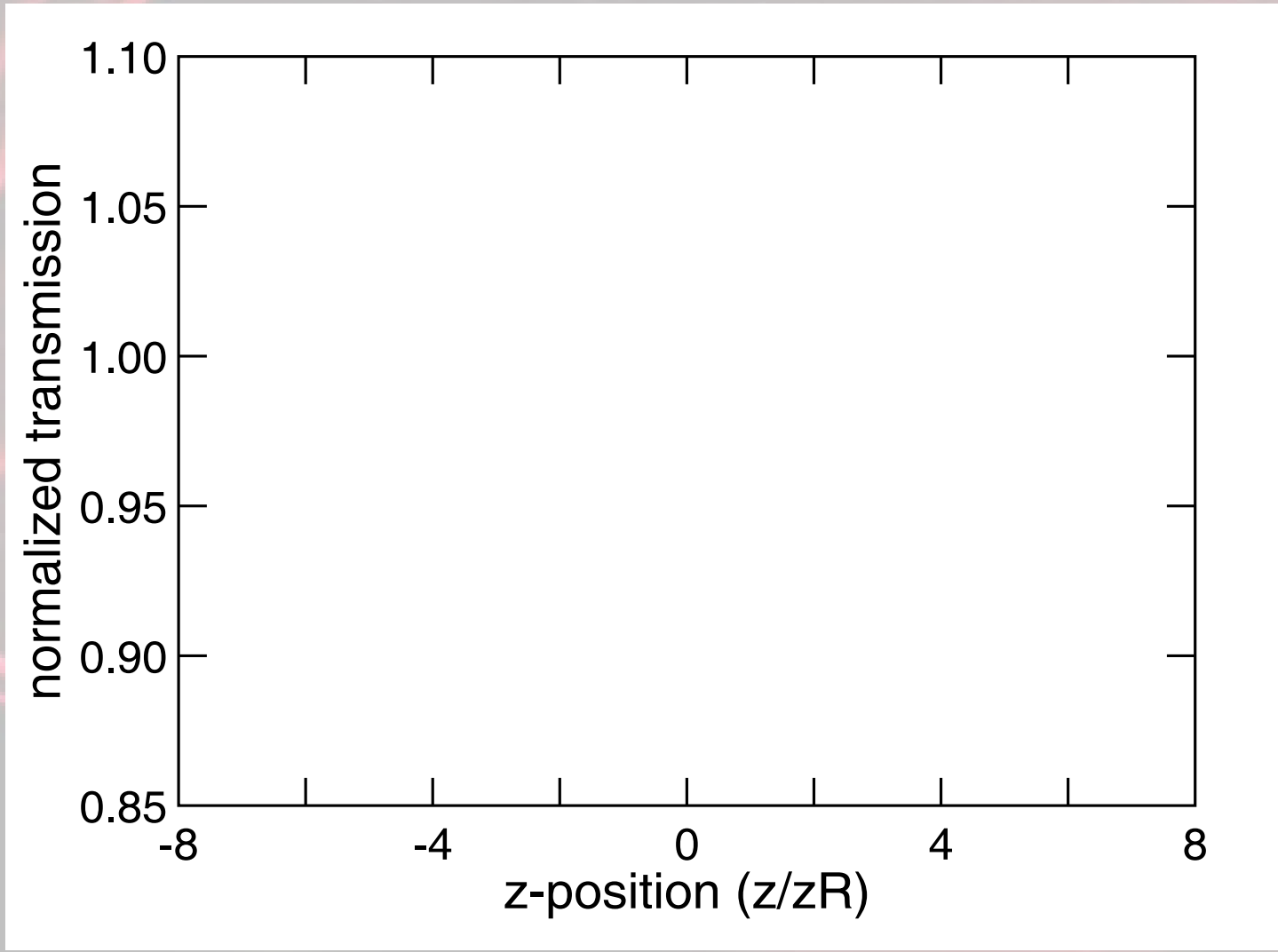
Thermally Managed Z-Scan

Laser Parameters

w0 (measured):	37 micron
zR (from fitting):	2.1 mm
Approximate M^2:	1.8
Repetition Rate:	250 kHz
Pulse Duration:	100 fs
Power Used:	300 mW
Fluence:	0.06 J/cm^2
S parameter:	0.016

Thermally Managed Z-Scan

Amorphous film at start of window



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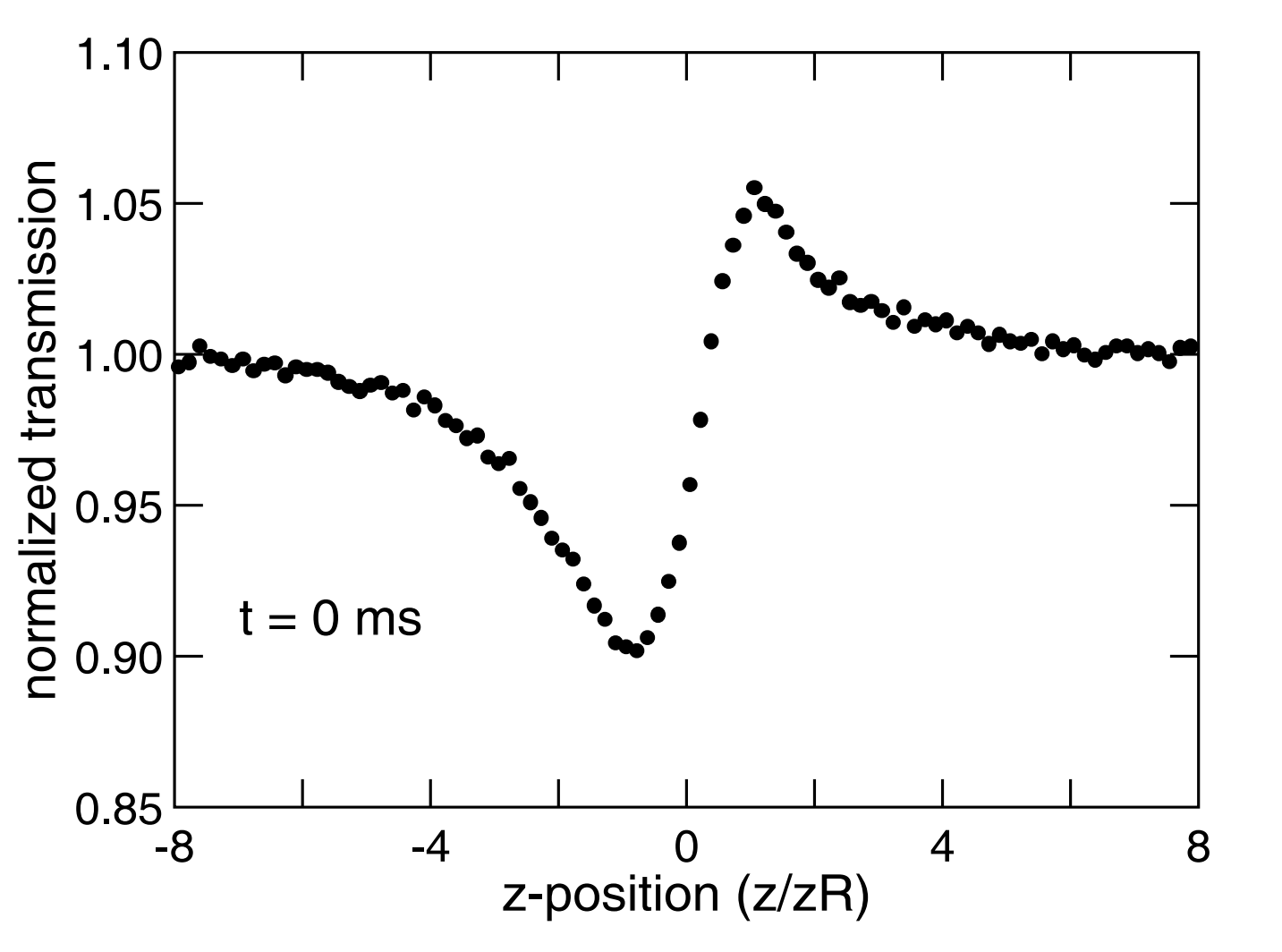

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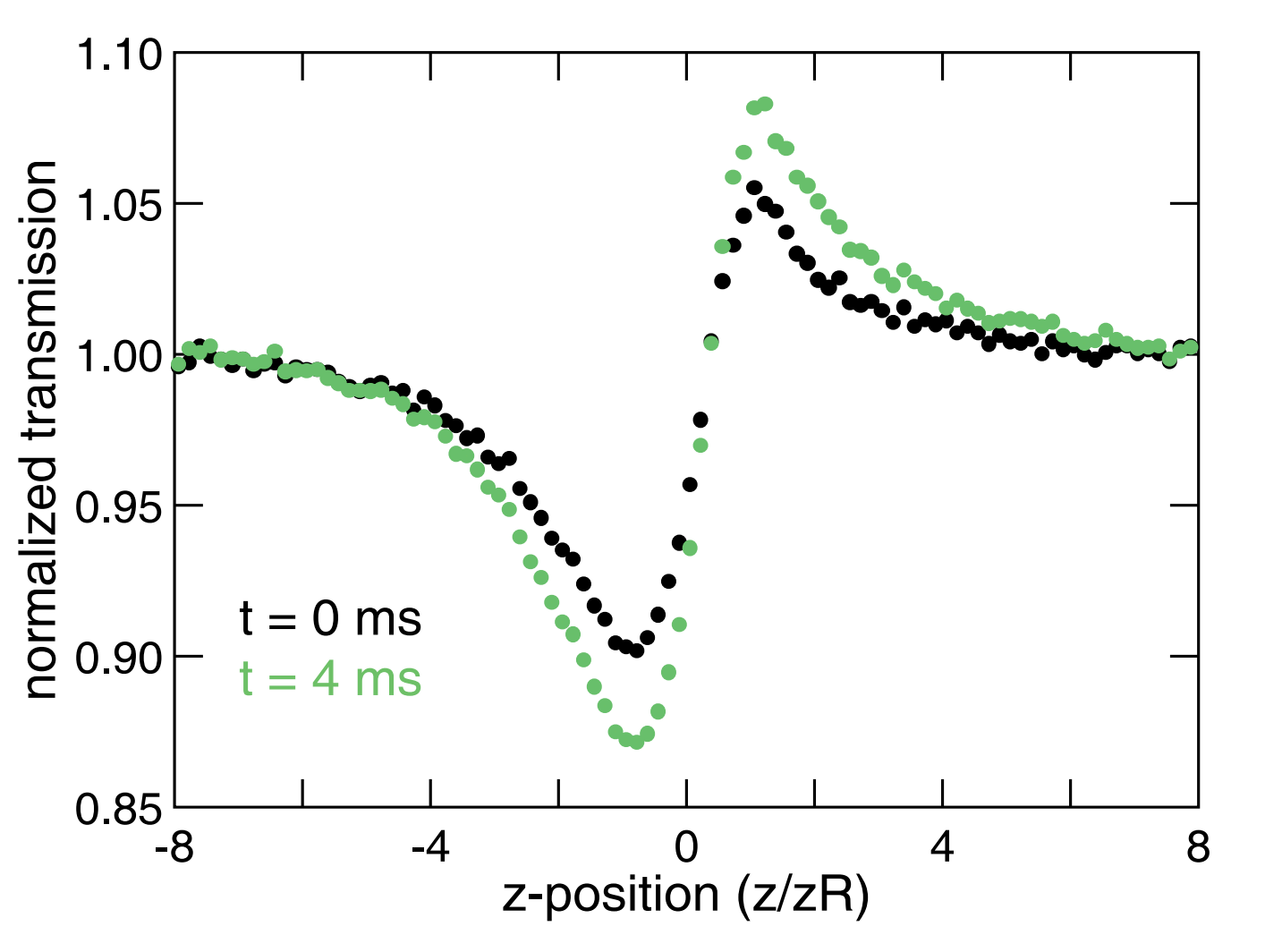
Amorphous film at end of window



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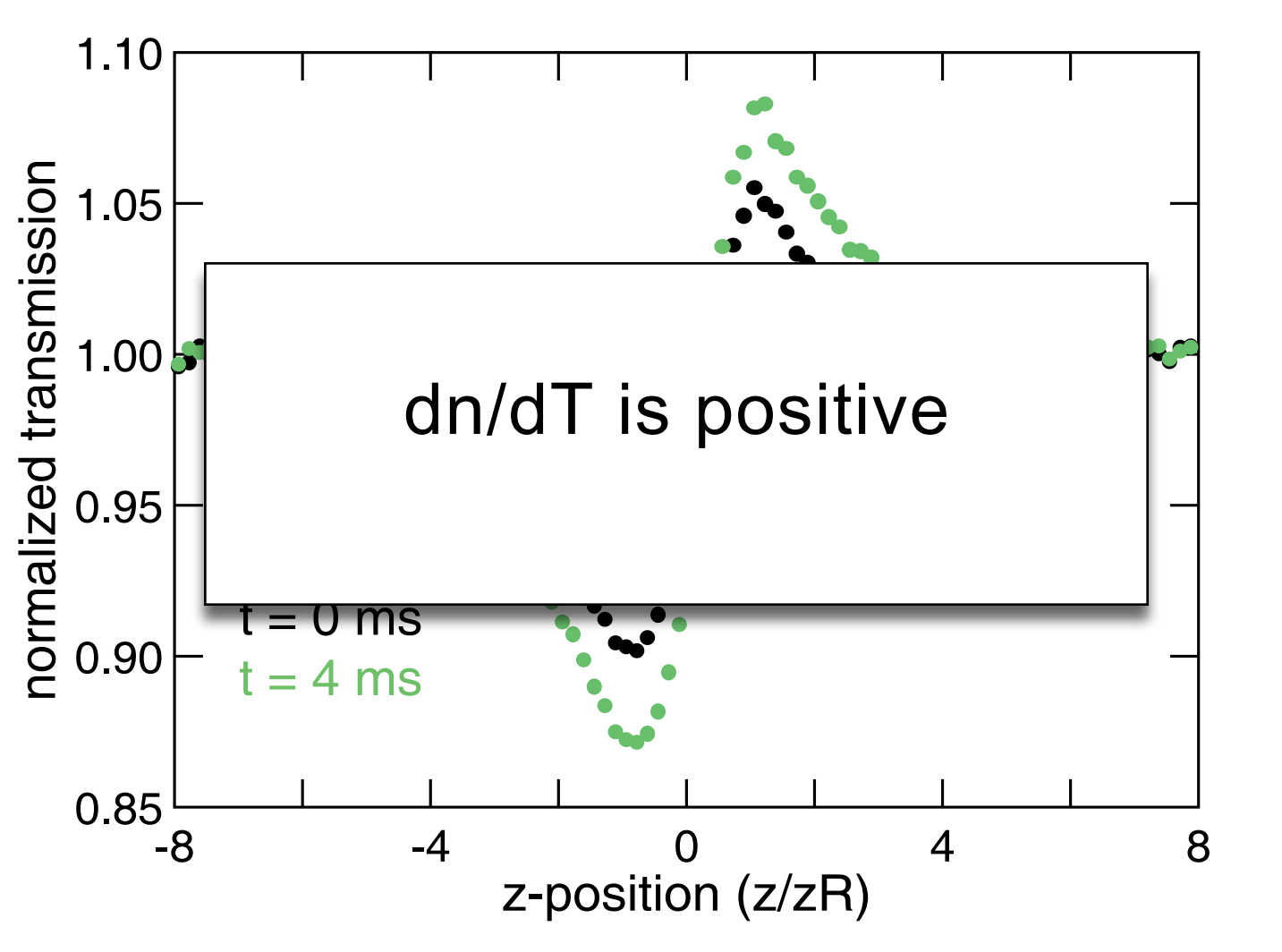
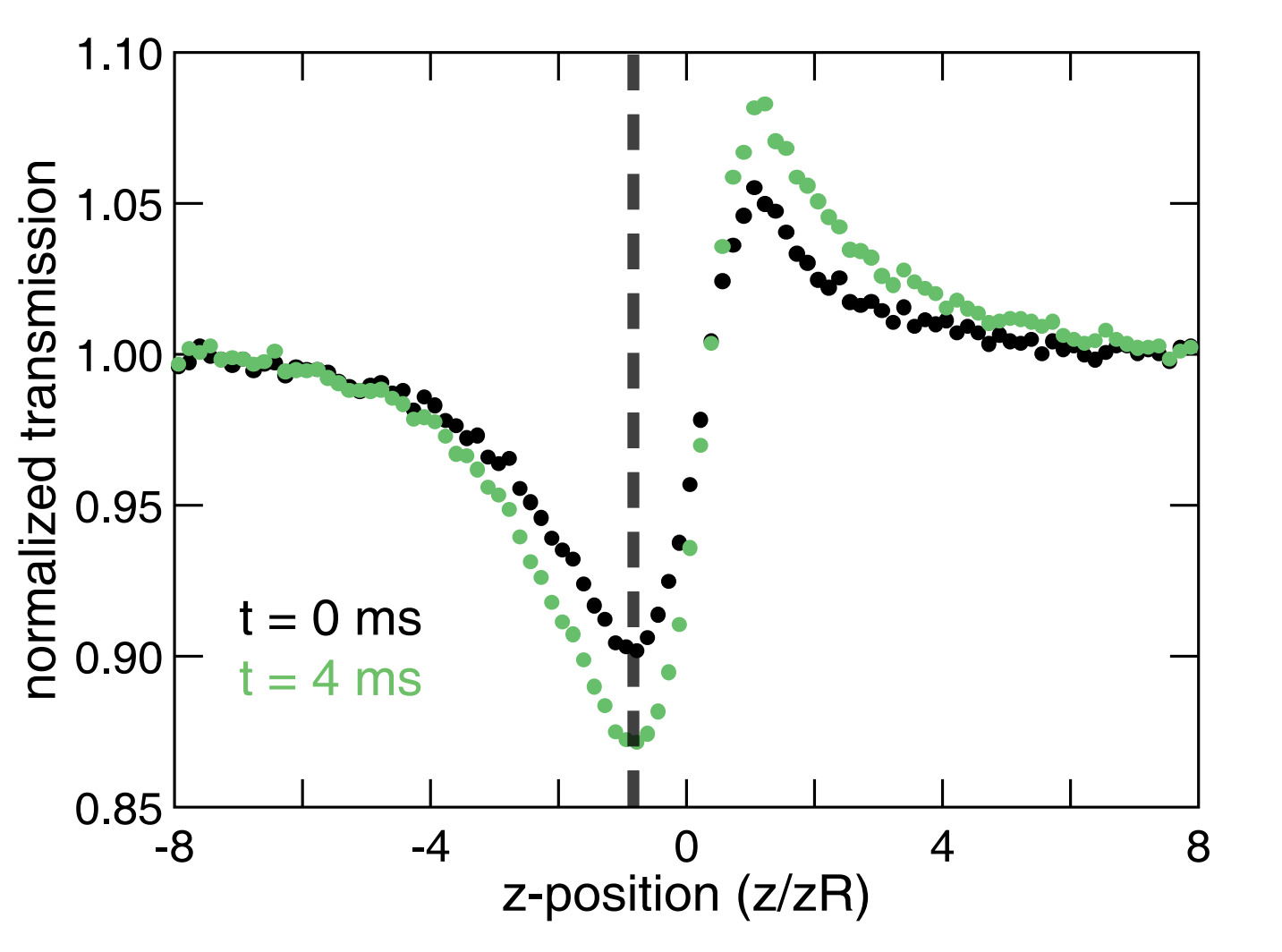
Amorphous film at end of window



Thermally Managed Z-Scan

Prefocal Time Dependence



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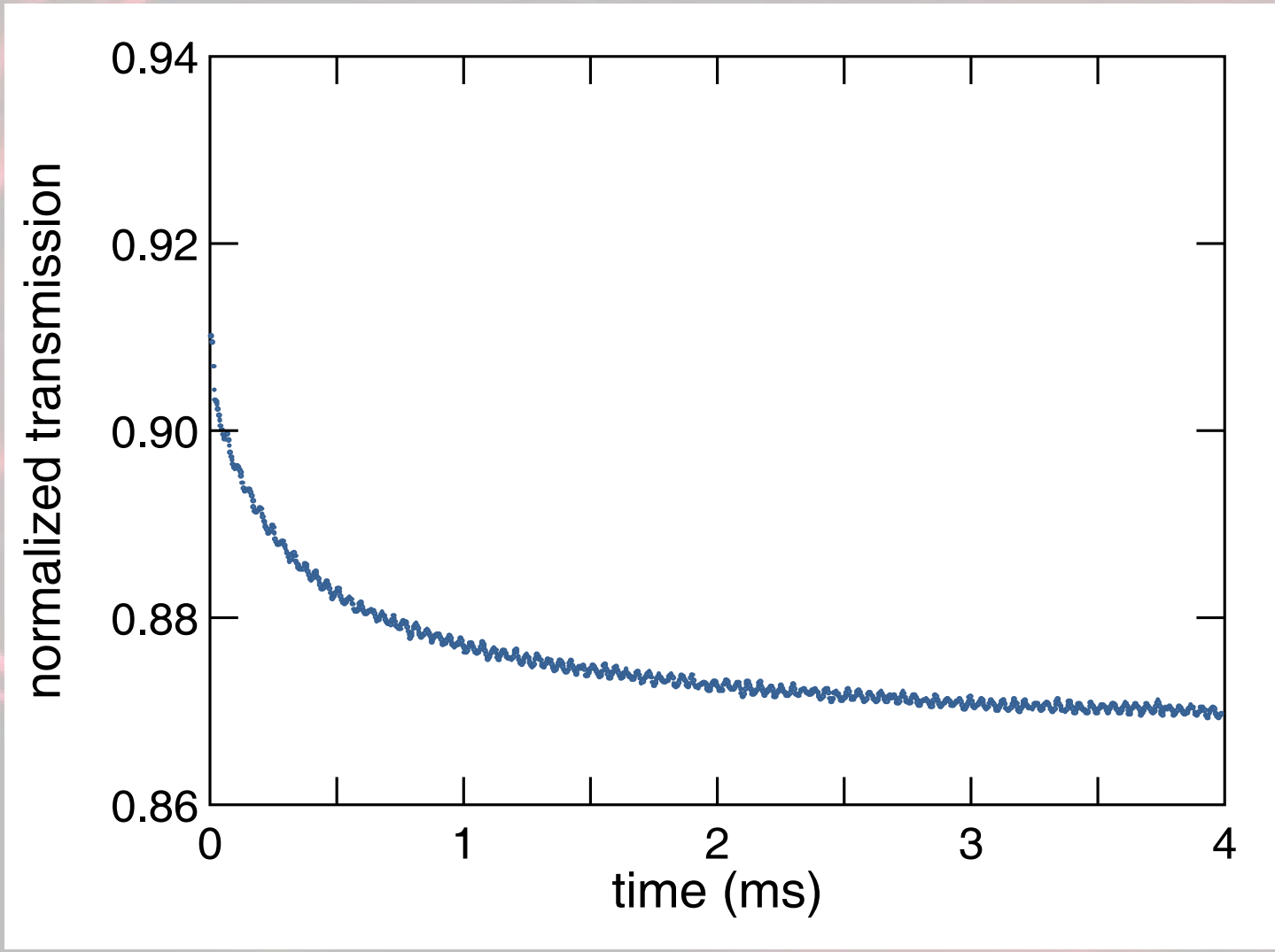

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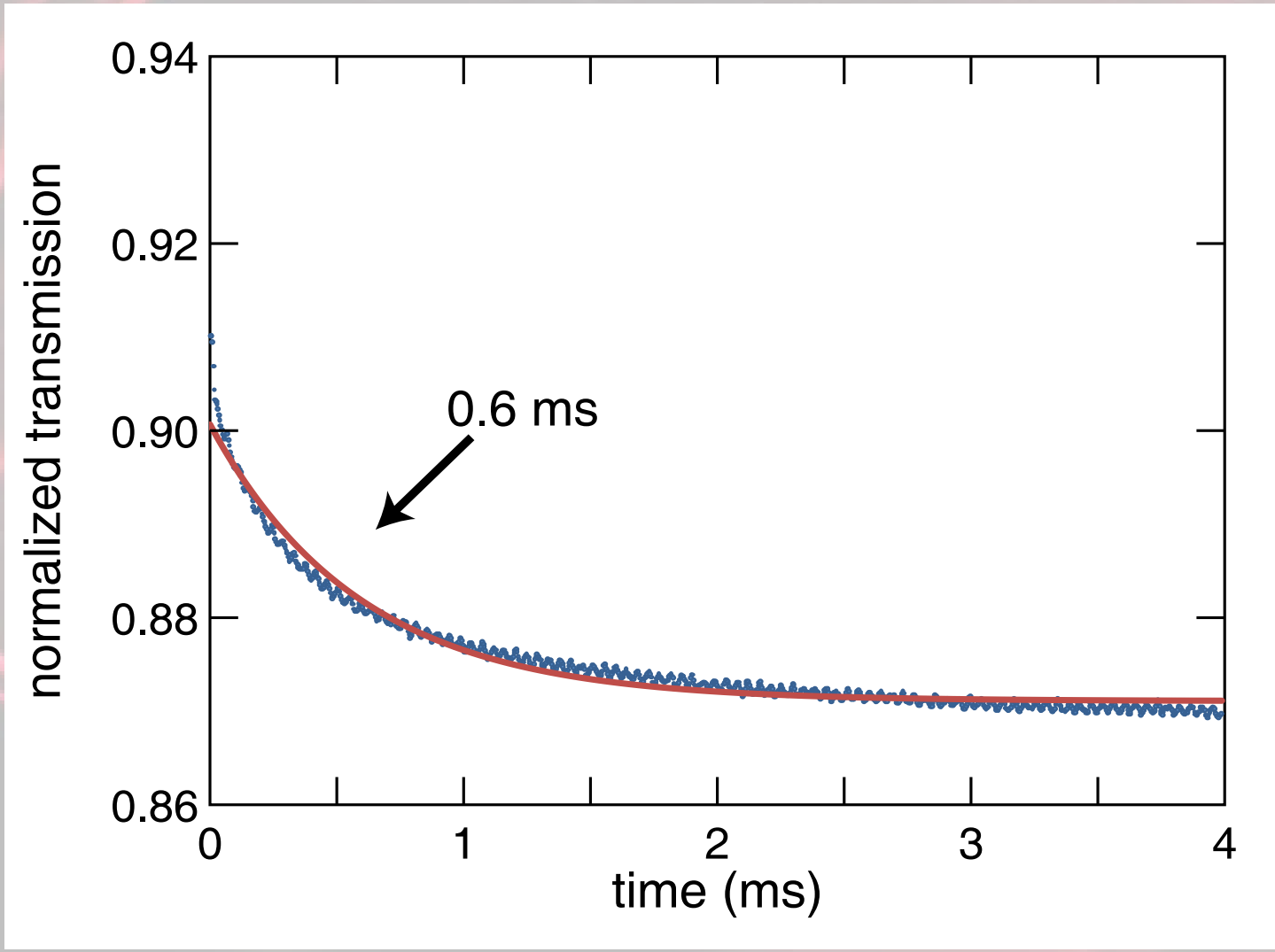
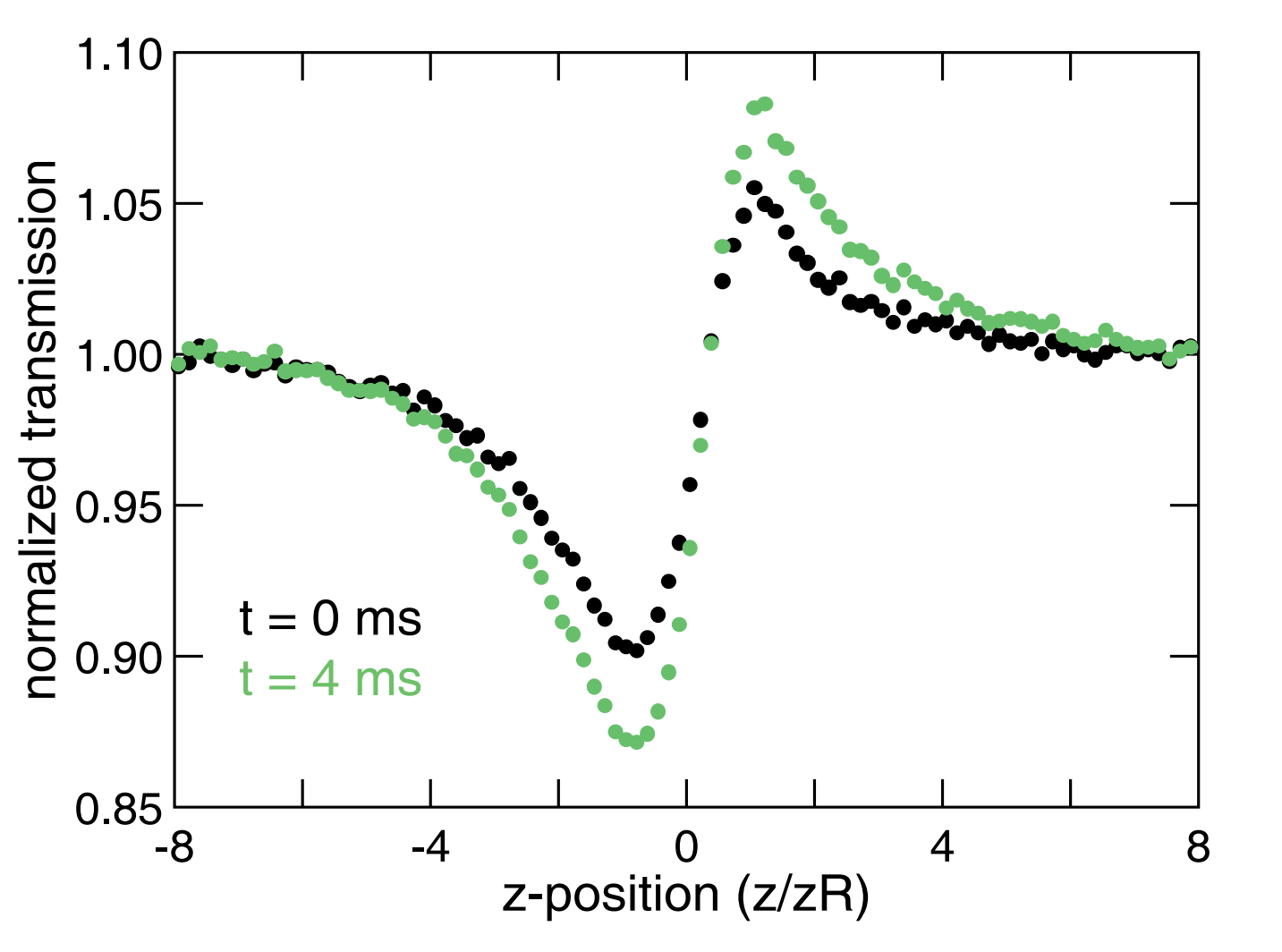


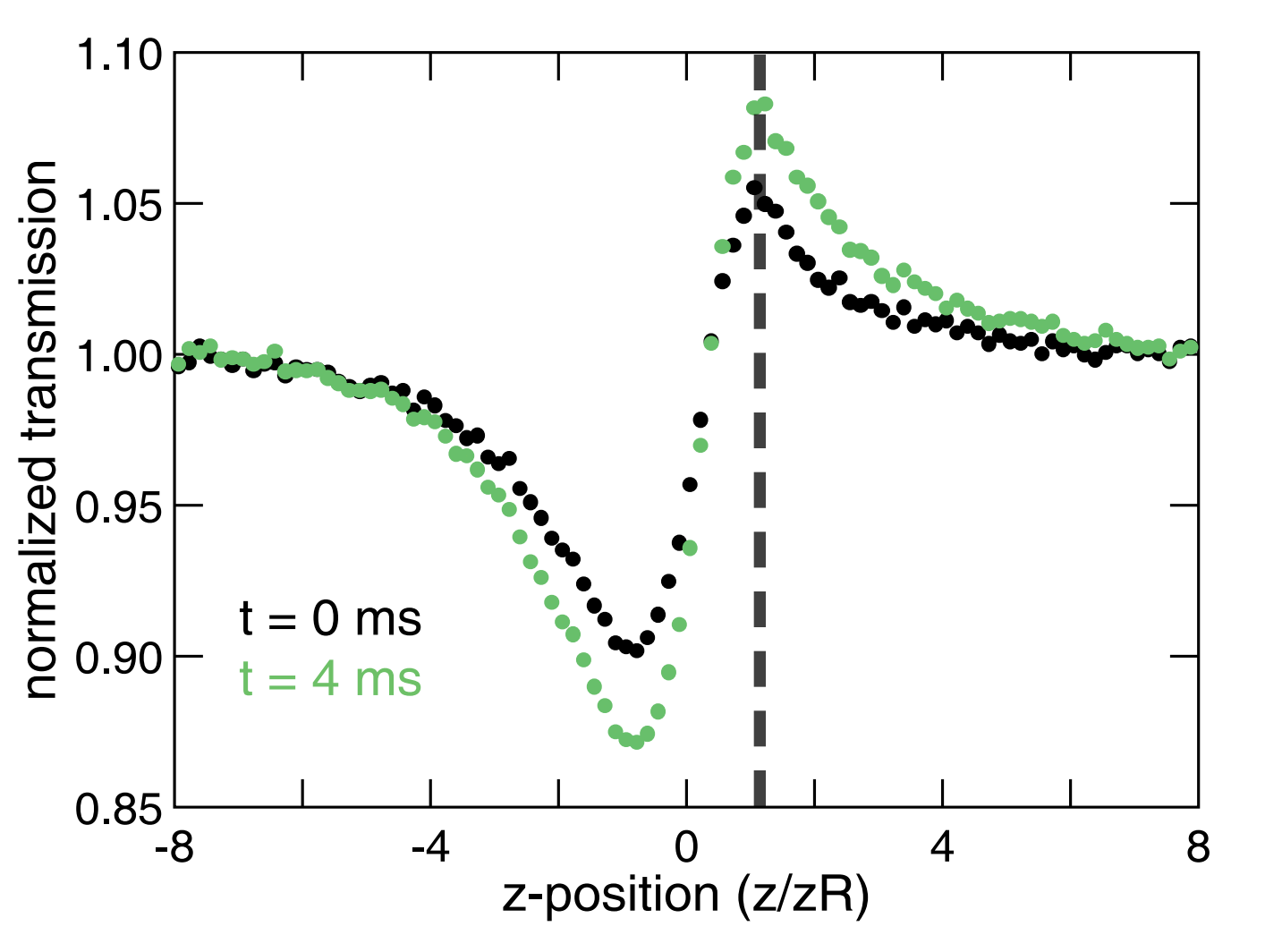
Thermally Managed Z-Scan

Postfocal Time Dependence



Thermally Managed Z-Scan

Postfocal Time Dependence



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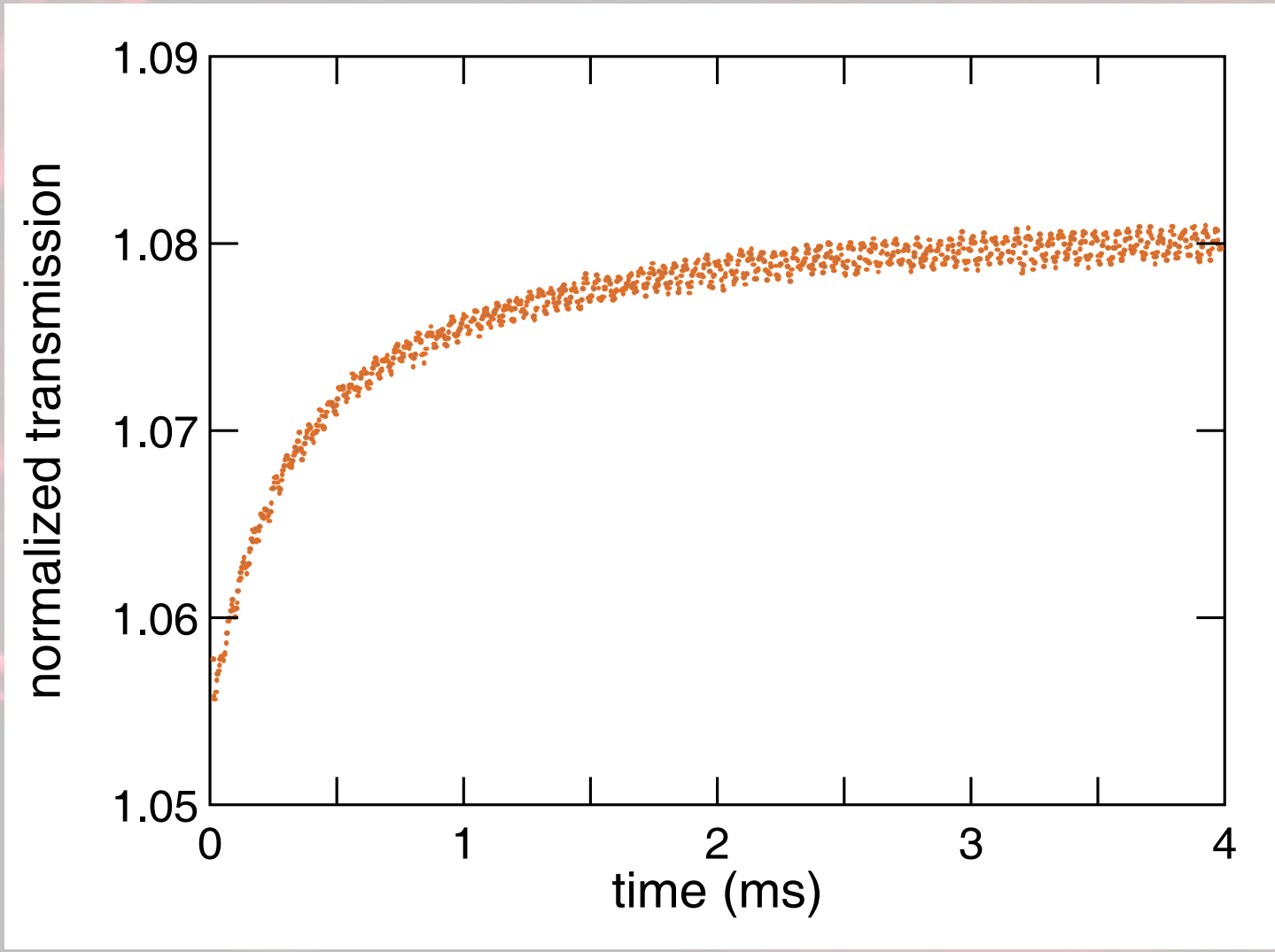
Postfocal Time Dependence



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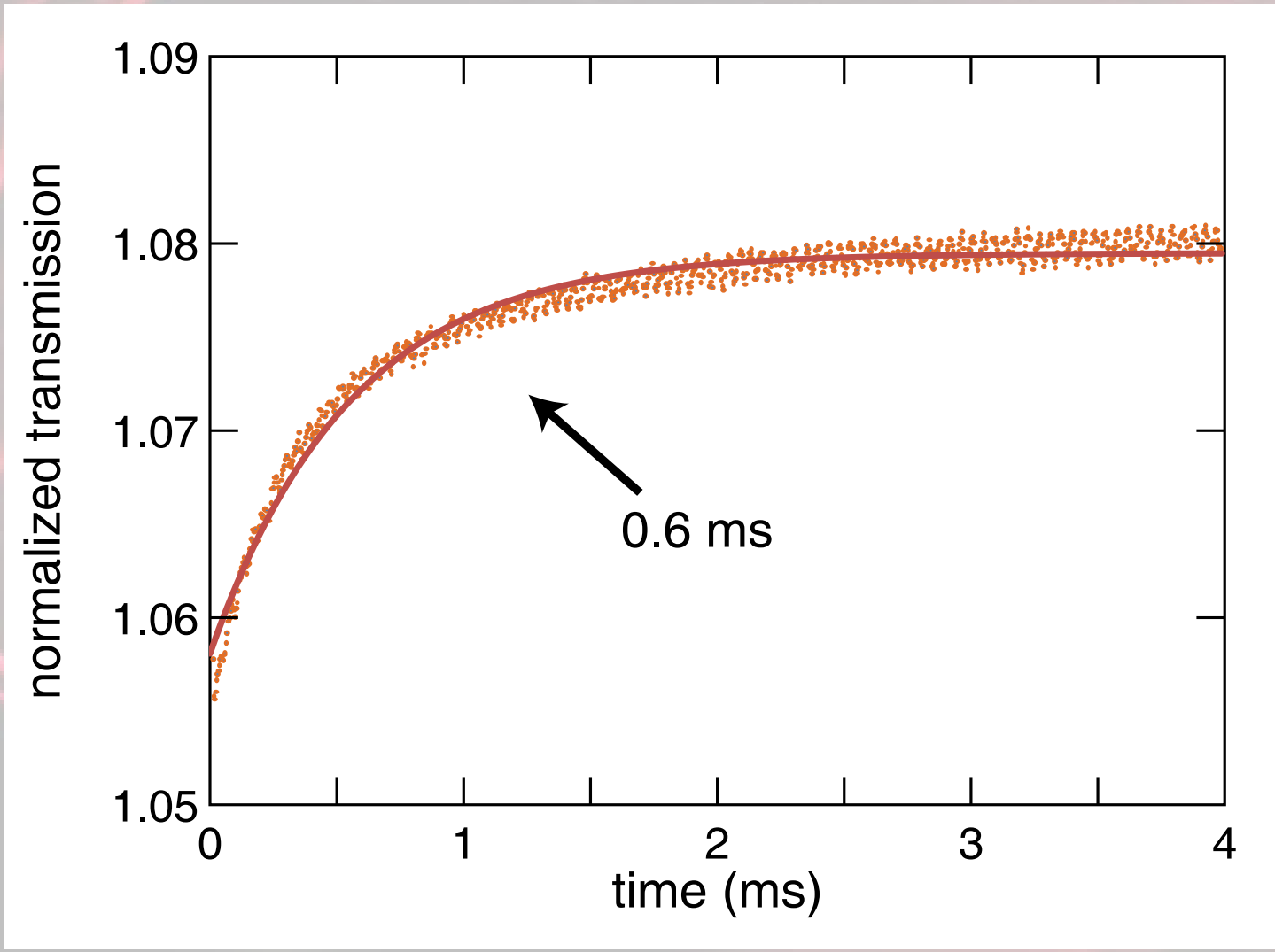
Postfocal Time Dependence



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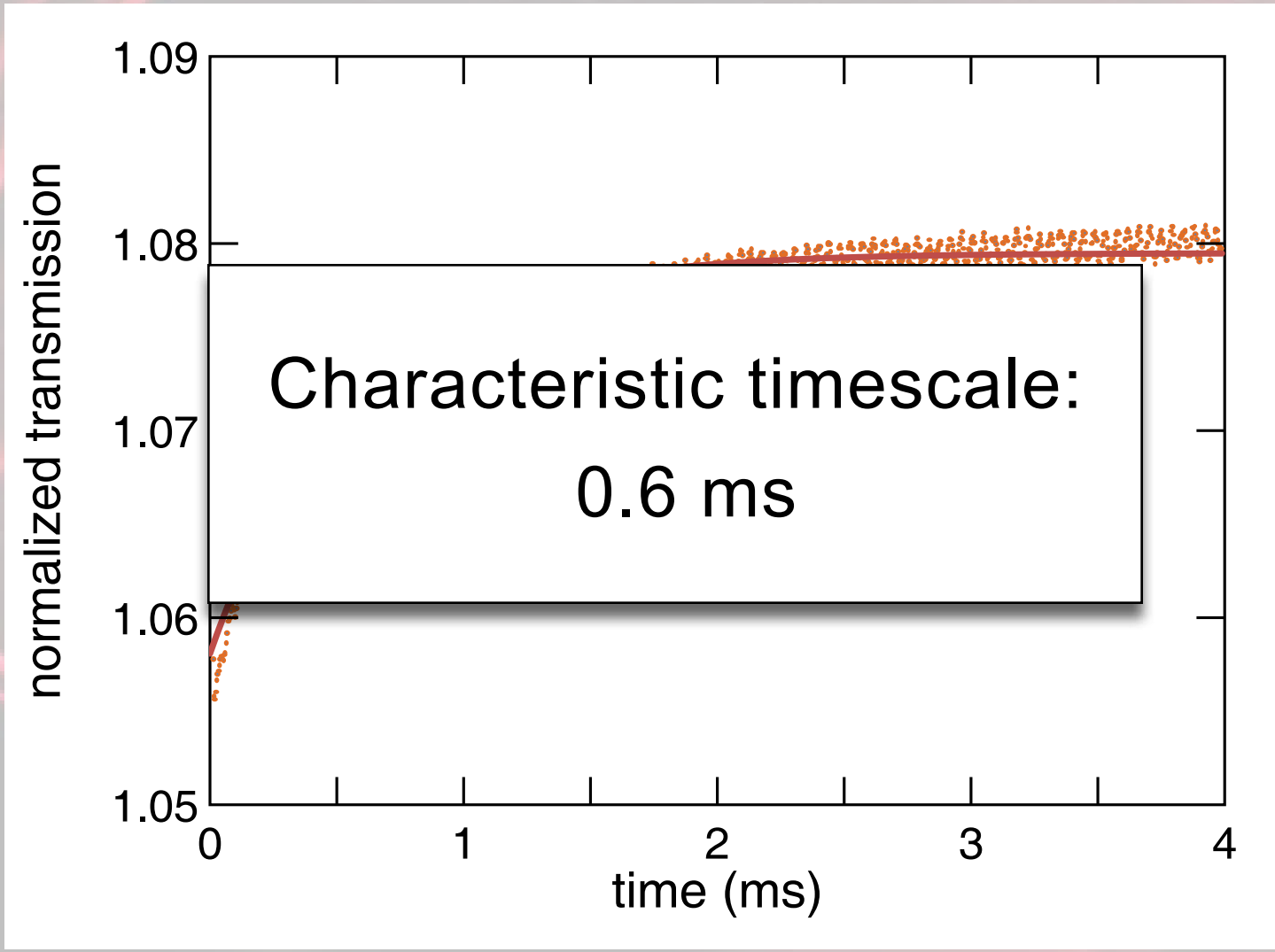

Conclusions

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<u>As-deposited Amorphous Films</u>

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Sensitive to light exposure

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Darkening occurs on two time scale:

Short:	5.8 minutes
Longer:	32 hours

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<u>As-deposited Amorphous Films</u>

Sensitive to light exposure

Darkening occurs on two time scale:

Short: 5.8 minutes

Longer: 32 hours

Does not recover after 12 hours

Conclusions

<u>Darkened Films</u>

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<u>Darkened Films</u>

Nonlinearity is within the uncertainty

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<u>Darkened Films</u>

Nonlinearity is within the uncertainty

Thermal nonlinearity (dn/dT) is positive

Conclusions

Darkened Films

Nonlinearity is within the uncertainty

Thermal nonlinearity (dn/dT) is positive

Thermal response time is 0.6 ms

Discussion

TiO_2 is a promising nonlinear material

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Amorphous films:

- Adapted z-scan to measure n_2
- Processing to enhance/avoid darkening

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- Processing to enhance/avoid darkening

Darkened films require further study to:

- Understand process of darkening
- Explore properties of darkened samples

Acknowledgements

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Nanoscale Science and Engineering Center