# At the tip of an intense laser beam: operando monitoring of laser processing in manufacturing

Troy R Allen, Tristan G Fleming , and James M Fraser
Department of Physics, Engineering Physics & Astronomy
Queen's University
Kingston ON Canada

NSERC CREATE
MATERIALS FOR ADVANCED PHOTONICS AND SENSING

# Acknowledgements




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MATERIALS FOR ADVANCED PHOTONICS AND SENSING

# Grounded in a problem

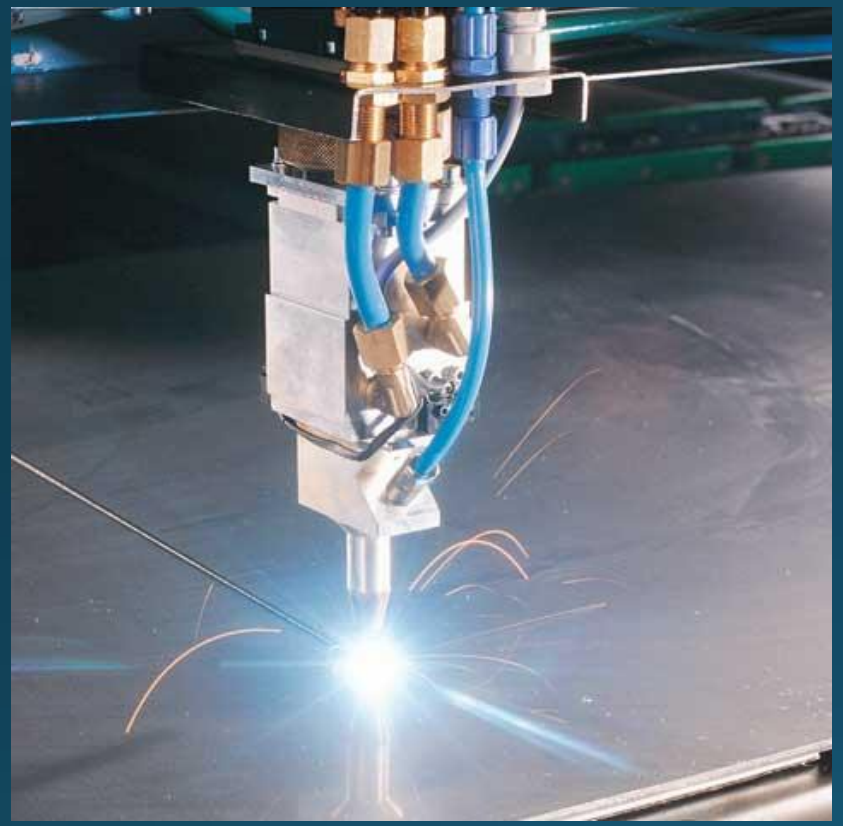


Image: www.wausaubusinessdirectory.com

## How deep is the laser weld?

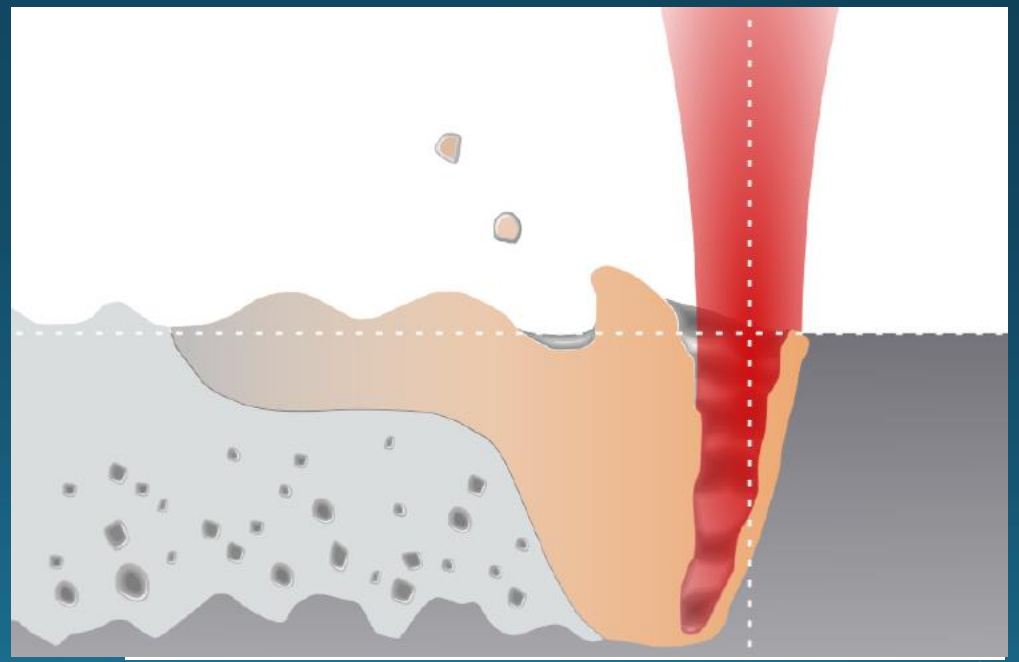
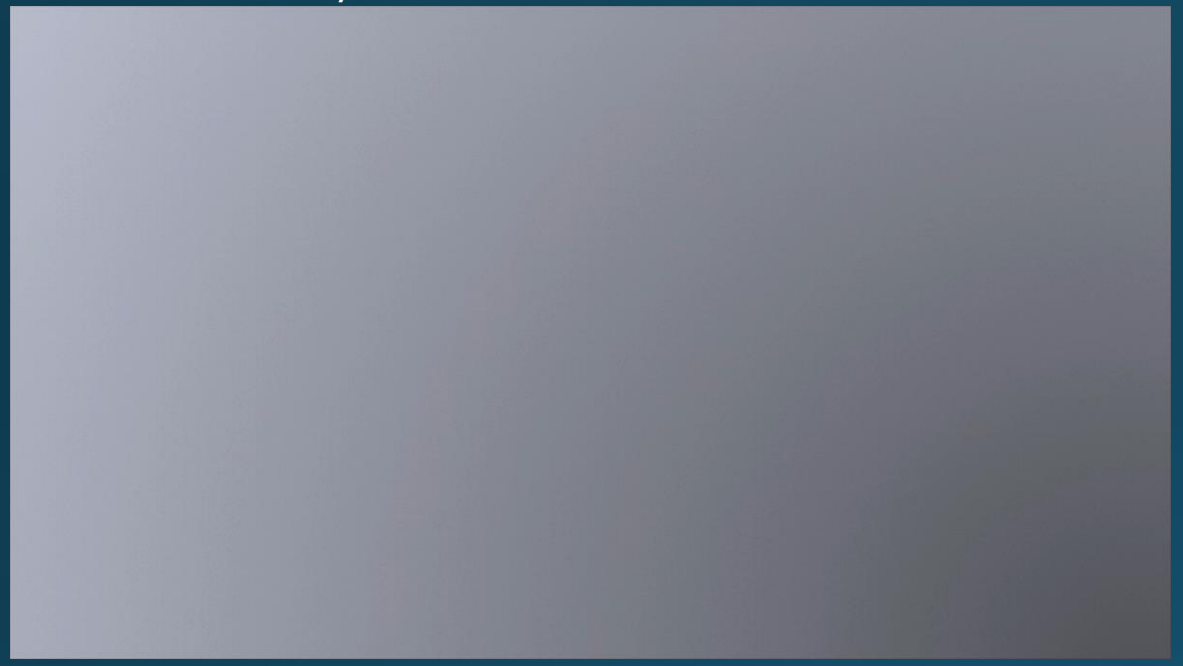


Image: Galbraith, Queen's

# Grounded in a problem

A lot of welds in your electric car…



IPG Photonics Inc.

How deep is the laser weld?
Need a measuring stick!

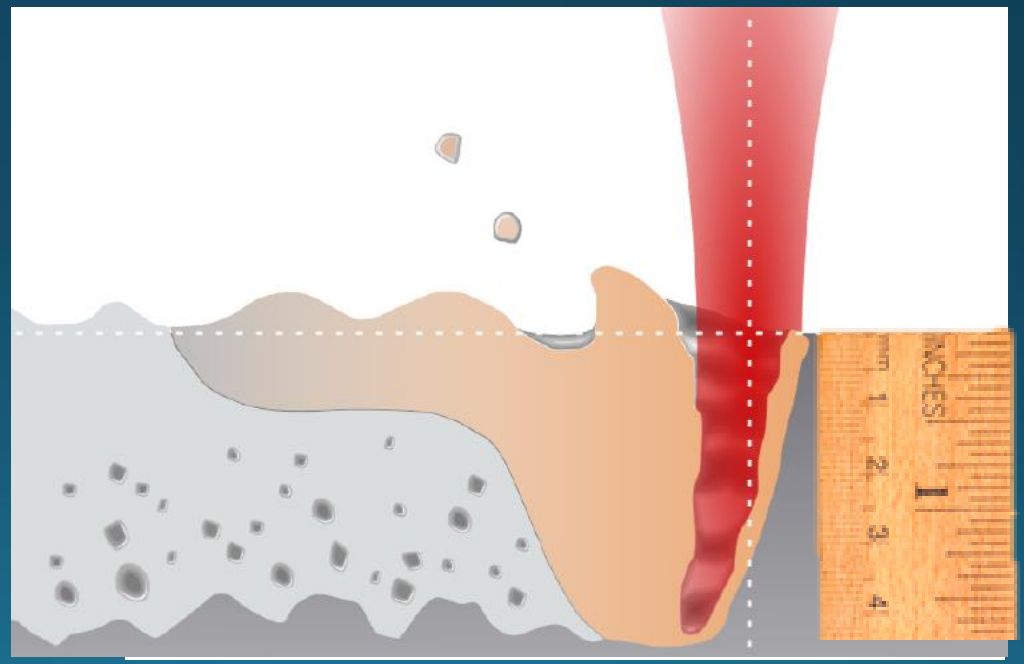


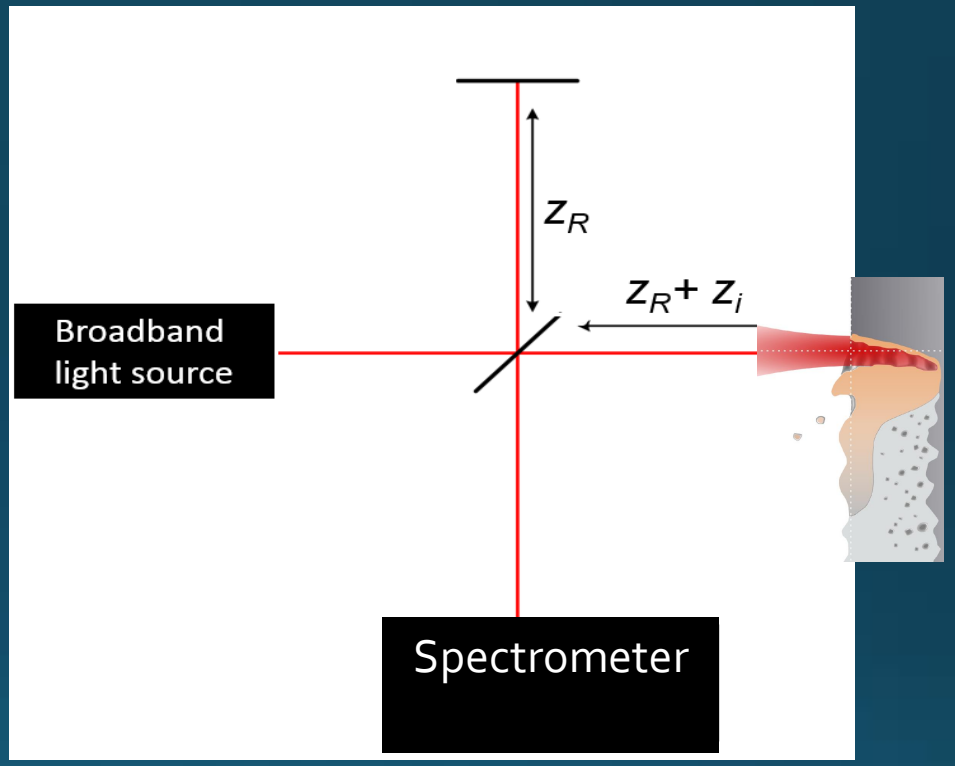

Image: Galbraith, Queen's

# Our approach: optical measuring stick

## Inline coherent imaging (ICI)

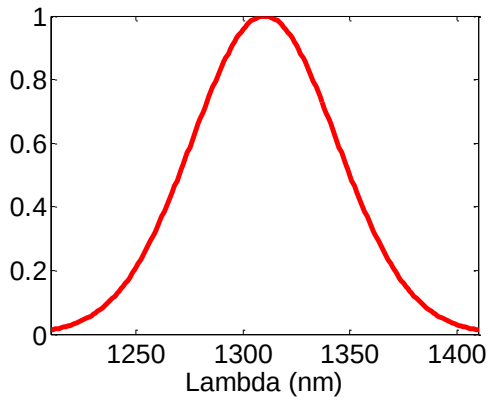
Fourier-domain broadband interferometry.

Similar to optical coherence tomography




$$I(k) = A(k)\left(\frac{I_{ref}}{2} + \frac{I_i}{2} + \sqrt{I_{ref} I_i}\cos(n z_i k)\right)$$

# Tutorial: OCT

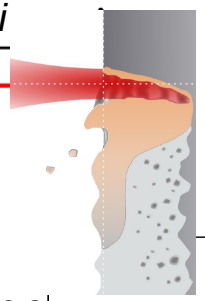



$$I_{spec}(k) = A(k)\left(\frac{I_{ref}}{2} + \frac{I_i}{2} + \sqrt{I_{ref} I_i}\cos(nz_i k)\right)$$

Broadband light source

$z_R$

$z_R + z_i$



Spectrometer / detector

Fringe separation: $\Delta k = \frac{2\pi}{nz_i}$

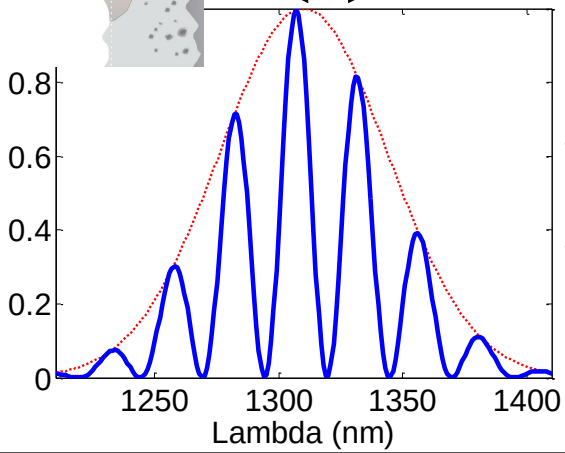
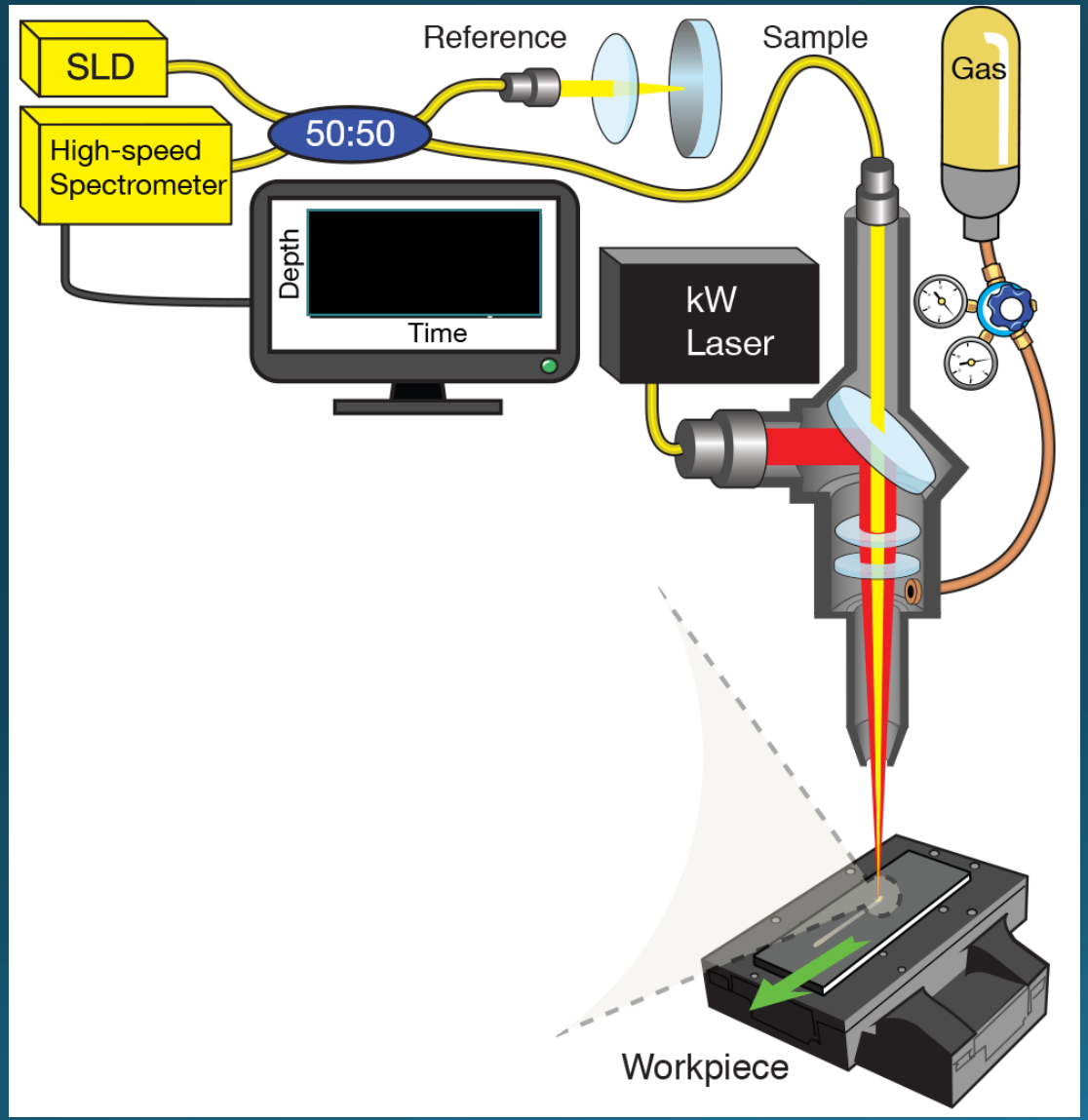


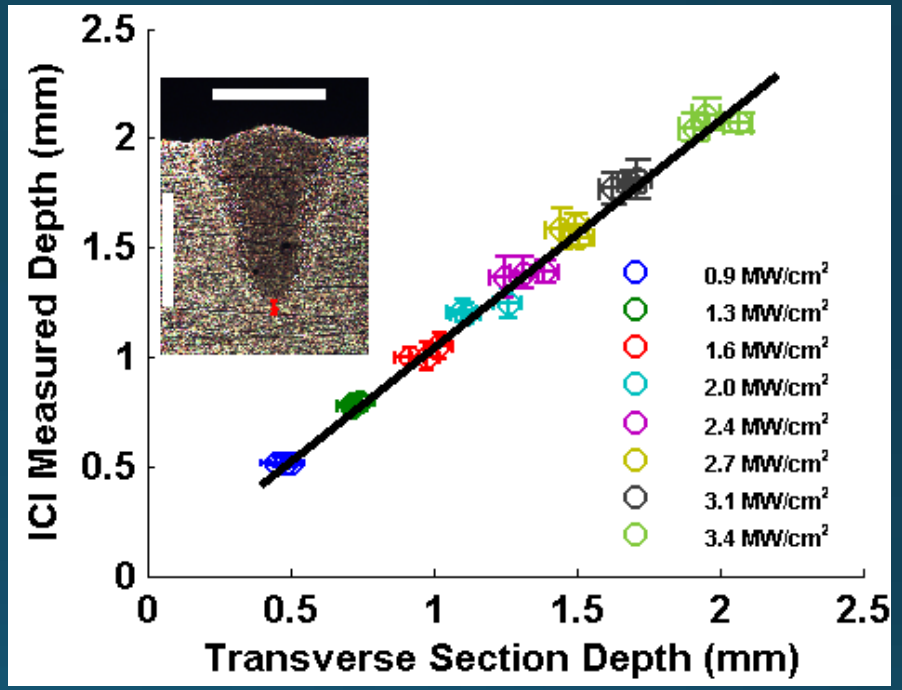

Image as fast as your *Spectro:* .. array camera can go!
*Swept-source:* .. light source can scan!

See also: A. F. Fercher *et al., Rep. Prog. Phys.* 66: 239-303 (2003).

# ICI integrates into any laser head




Verification with destructive cross-sectioning

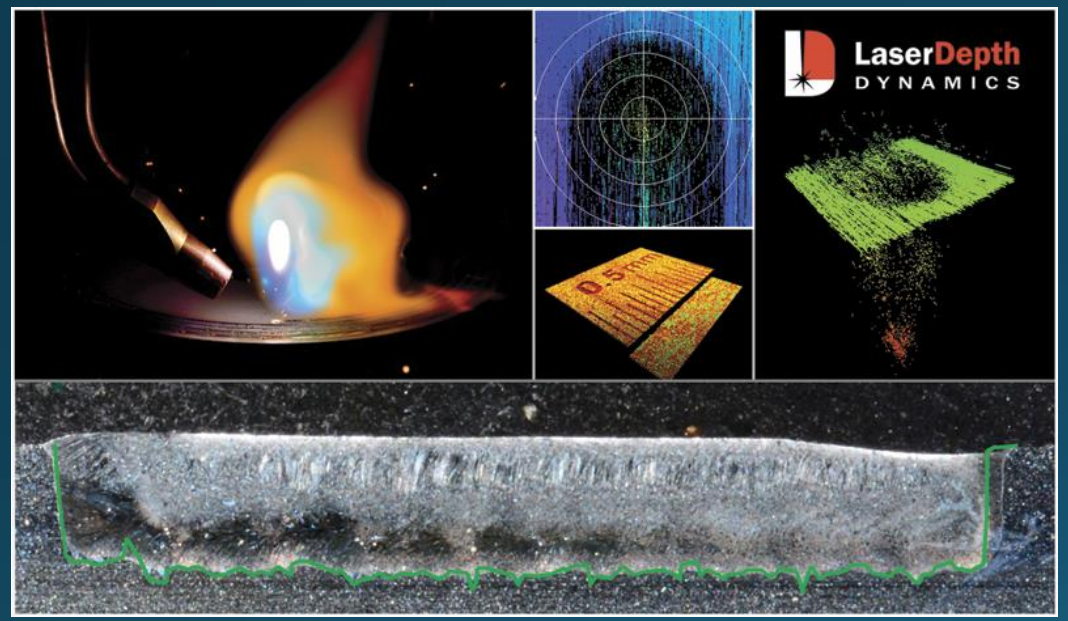


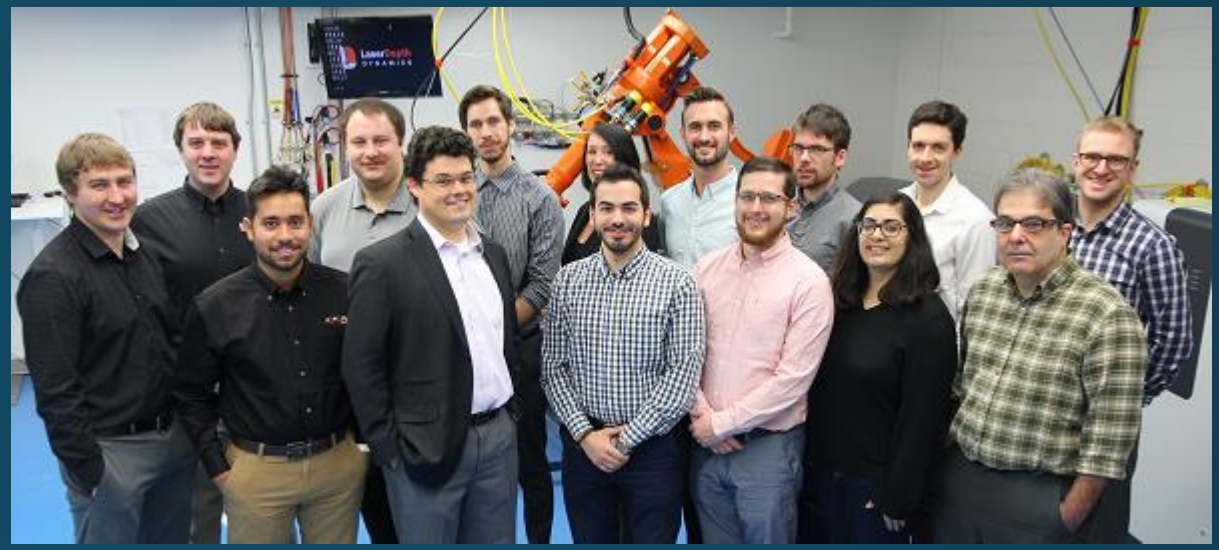

mild steel, 40 mm/s scan speed, argon cover gas

P. Webster *et al.*, *Optics Letters* **39**: 6217-6220 (2014).

# Aiming for impact: spin-off company

LaserDepth DYNAMICS




Dec 4, 2017

Investor Overview
Events and Presentations
Corporate Governance
Press Releases
Annual Reports
Quarterly Results
SEC Filings
Stock Information

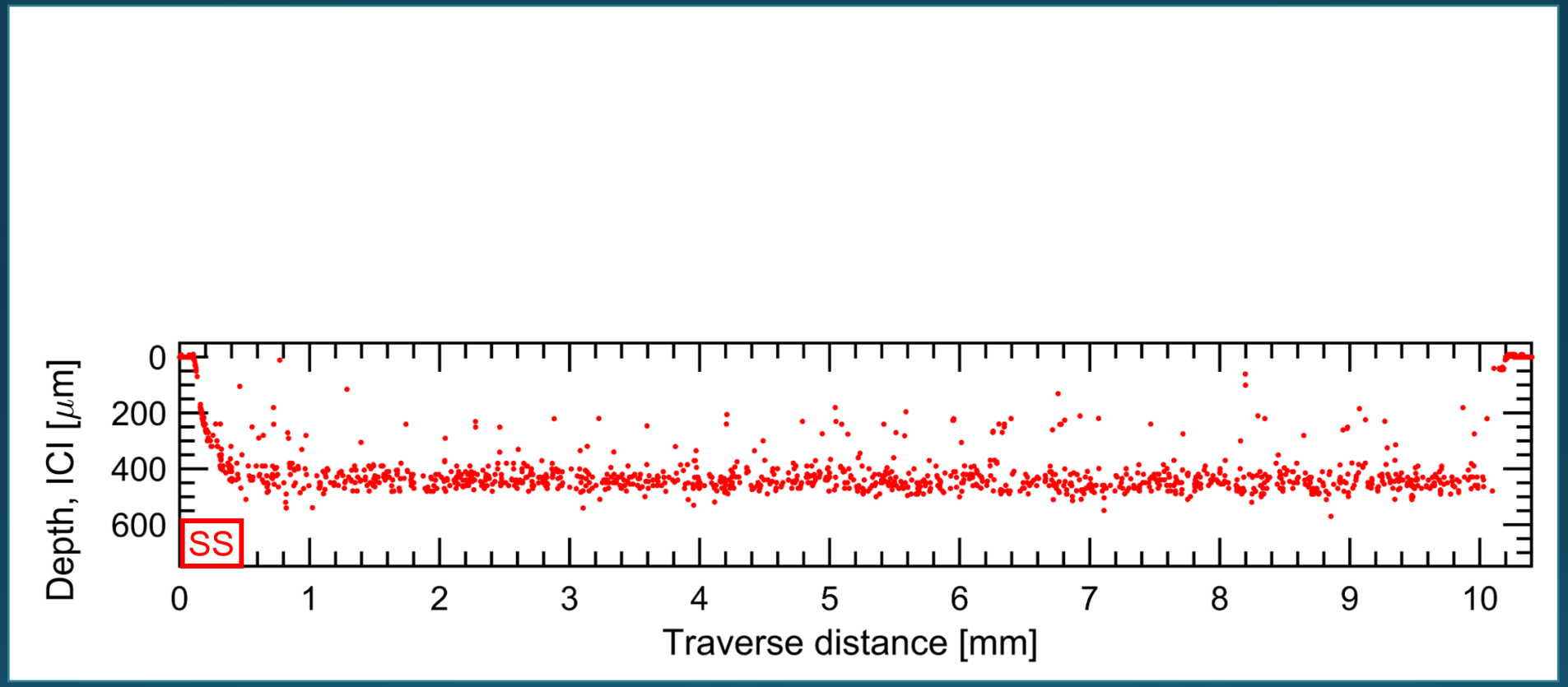
## IPG Photonics Announces Acquisition of Laser Depth Dynamics

LDD produces advanced monitoring and control technology for laser welding applications

OXFORD, Mass., Dec. 04, 2017 (GLOBE NEWSWIRE) -- IPG Photonics Corporation (NASDAQ:IPGP) today announced that it has acquired Laser Depth Dynamics (LDD), an innovative provider of in-process quality monitoring and control solutions for laser-based welding applications.

LDD's proprietary inline coherent imaging (ICI) technology is the first industrial solution to enable direct measurement of weld penetration depth with high precision and in real time by adding a near-infrared

# But there is more: access to dynamics

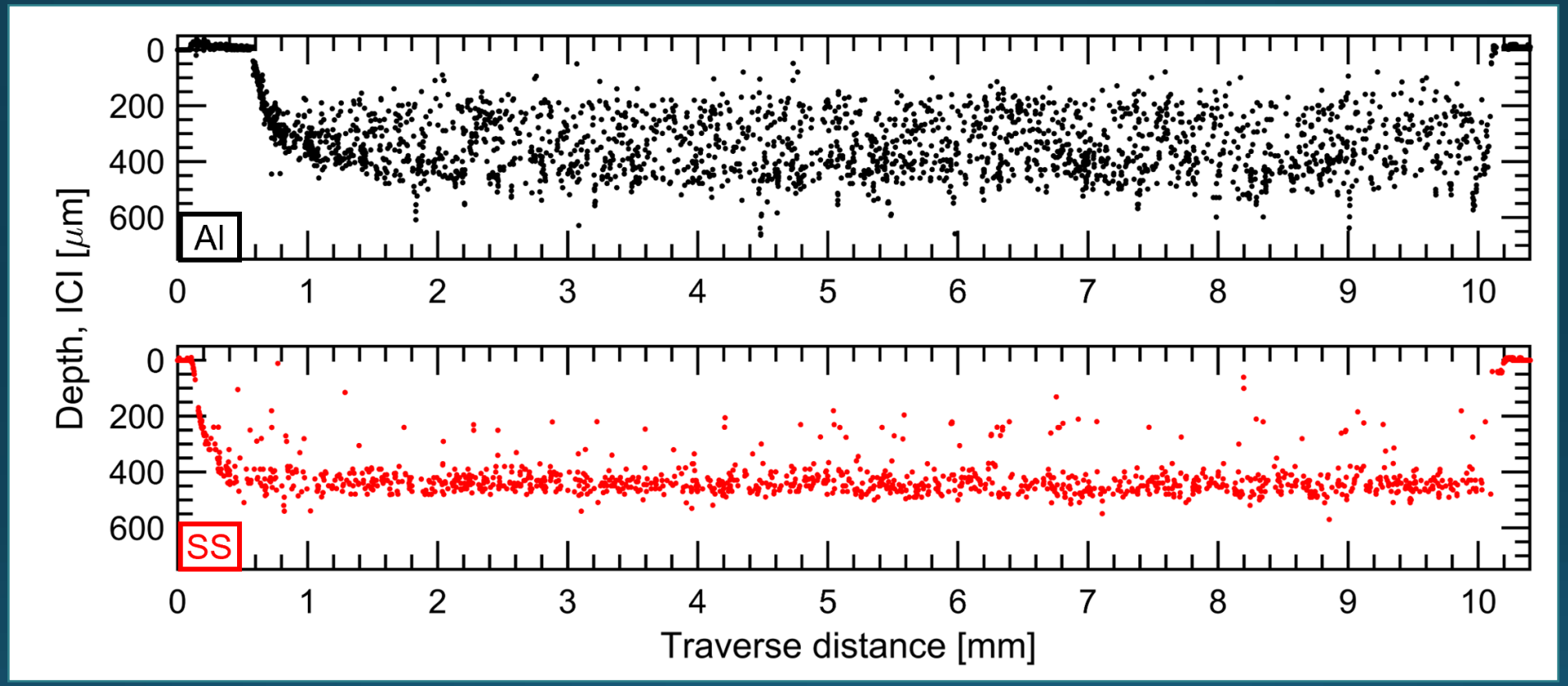
# Access to dynamics

Laser

6061 Al

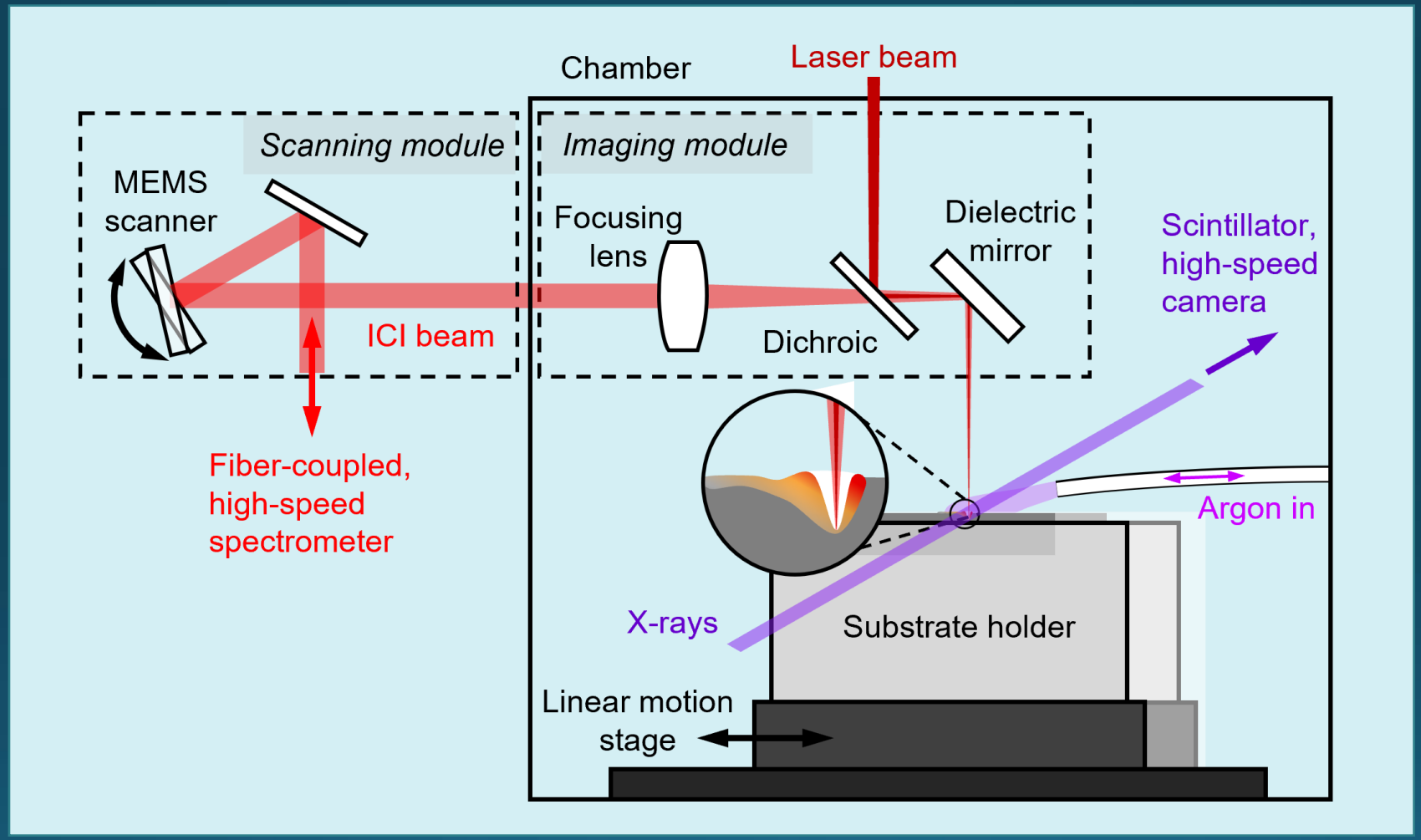
Laser

316L SS



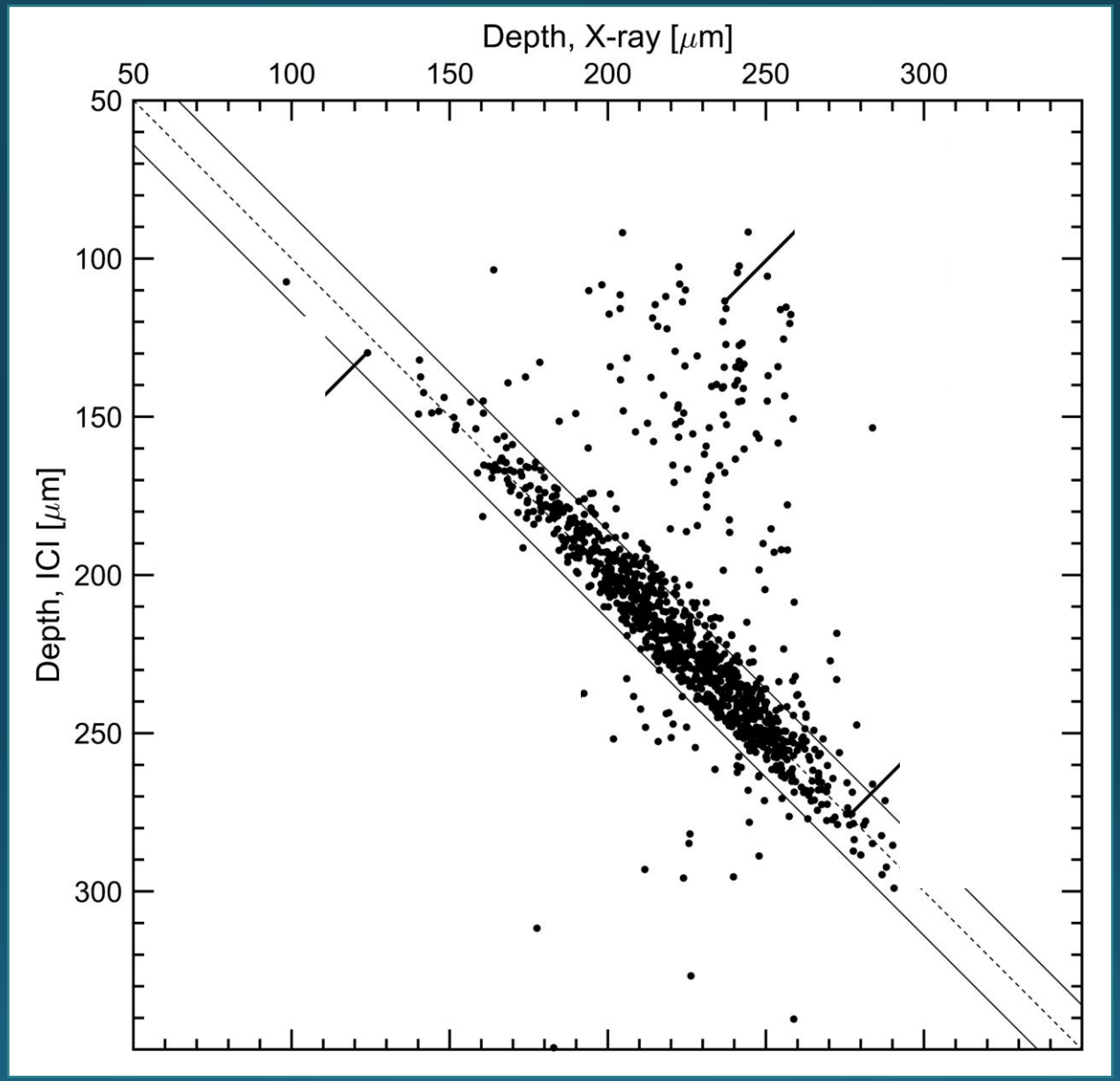

Is it just noise?

# Very recent: compare ICI to gold standard




Lead: Tristan Fleming. In collaboration with Peter Lee, UCL
Synchrotron: Advanced Photon Source, Argonne National Laboratory

80% within 14 micron




Aluminum 6061
872 W CW @1070 nm
scan speed 150 mm/s



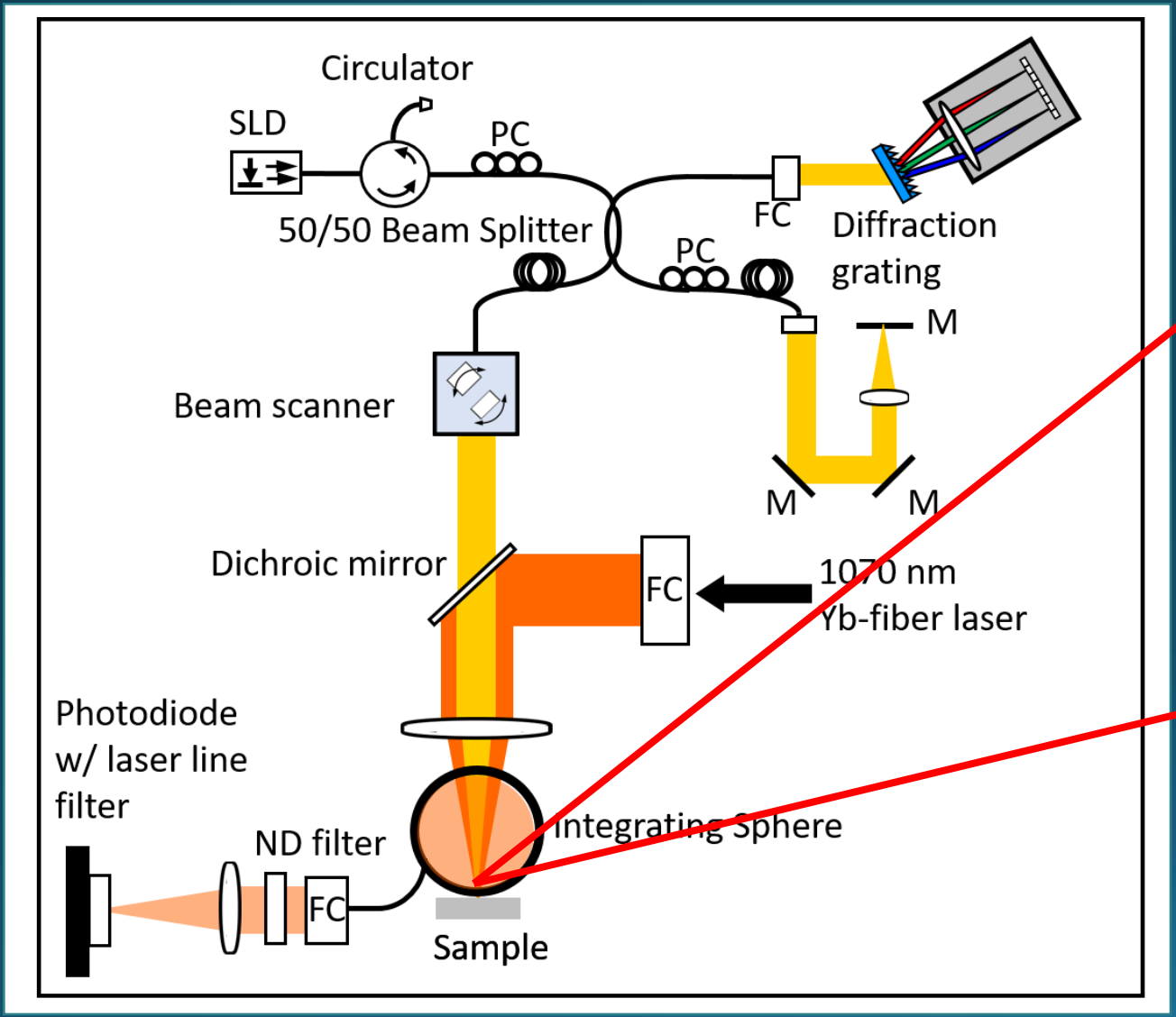
Fleming *et al.*, under review

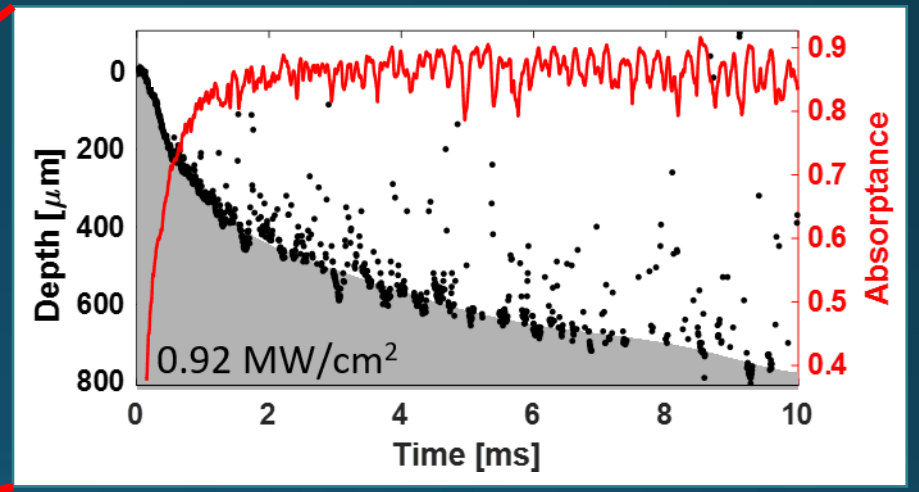
# But why does laser processing work so well?


1070 nm

Reflectance 60-70%

# Measure depth and absorption simultaneously




with Wenkang Huang, Wenda Tan [Utah], Jack Tanner, Brian Simonds [NIST]



Allen *et al*, Physical Review Applied **13**, 064070 (2020)

# New paradigm in manufacturing?

## Additive manufacturing

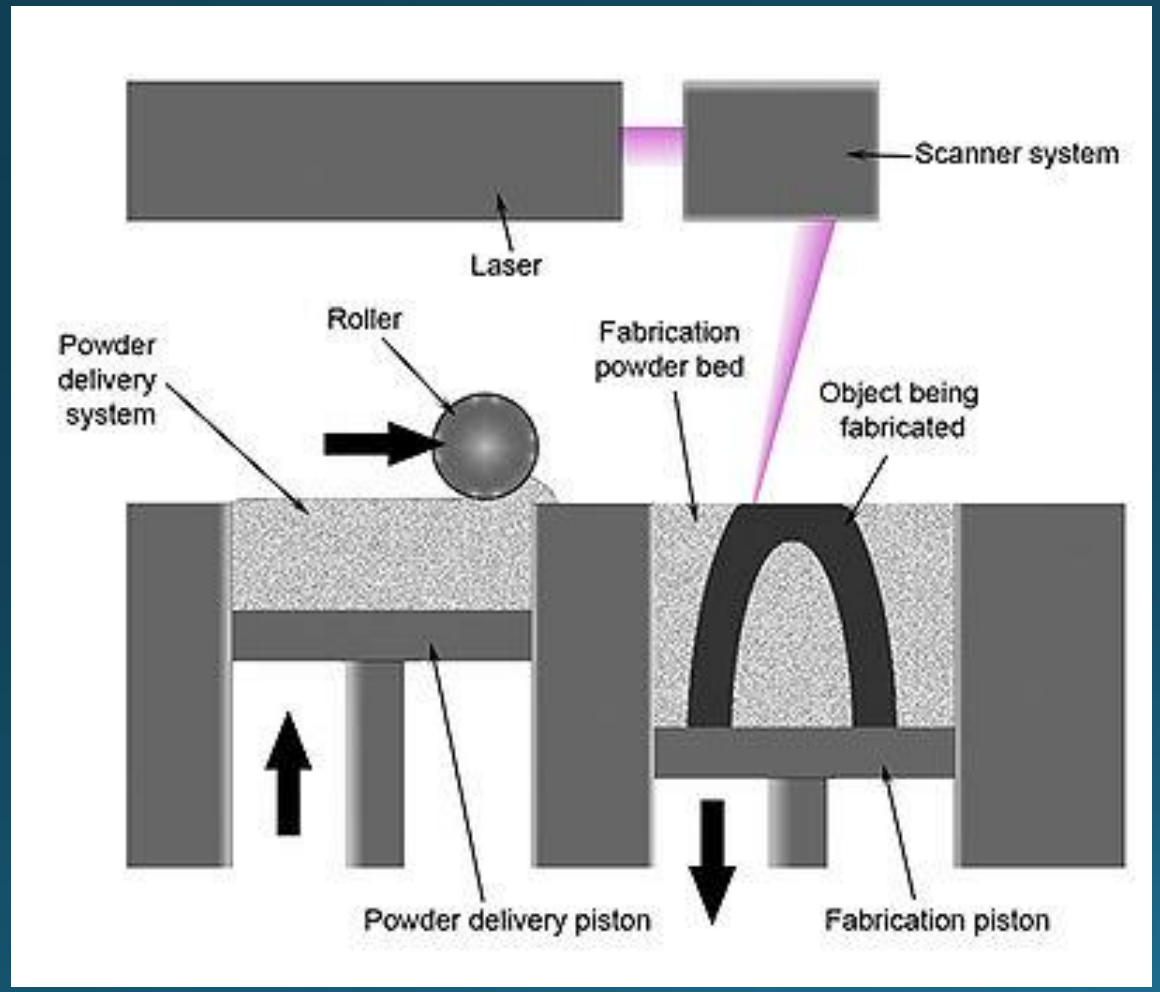



Image: wikipedia

GE fuel nozzle

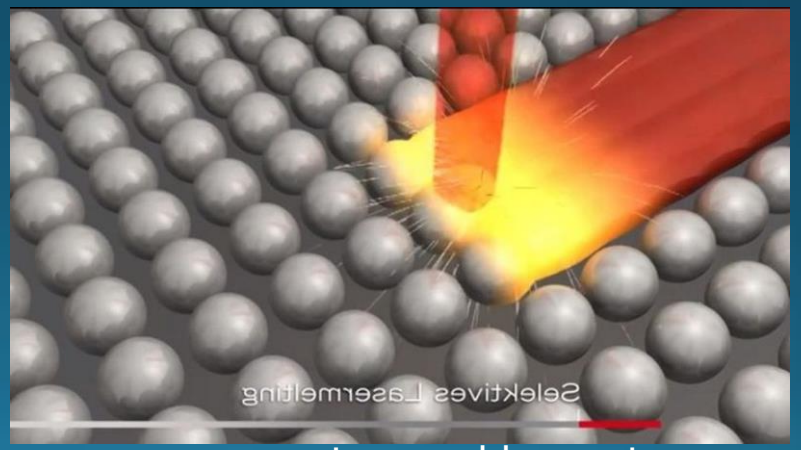
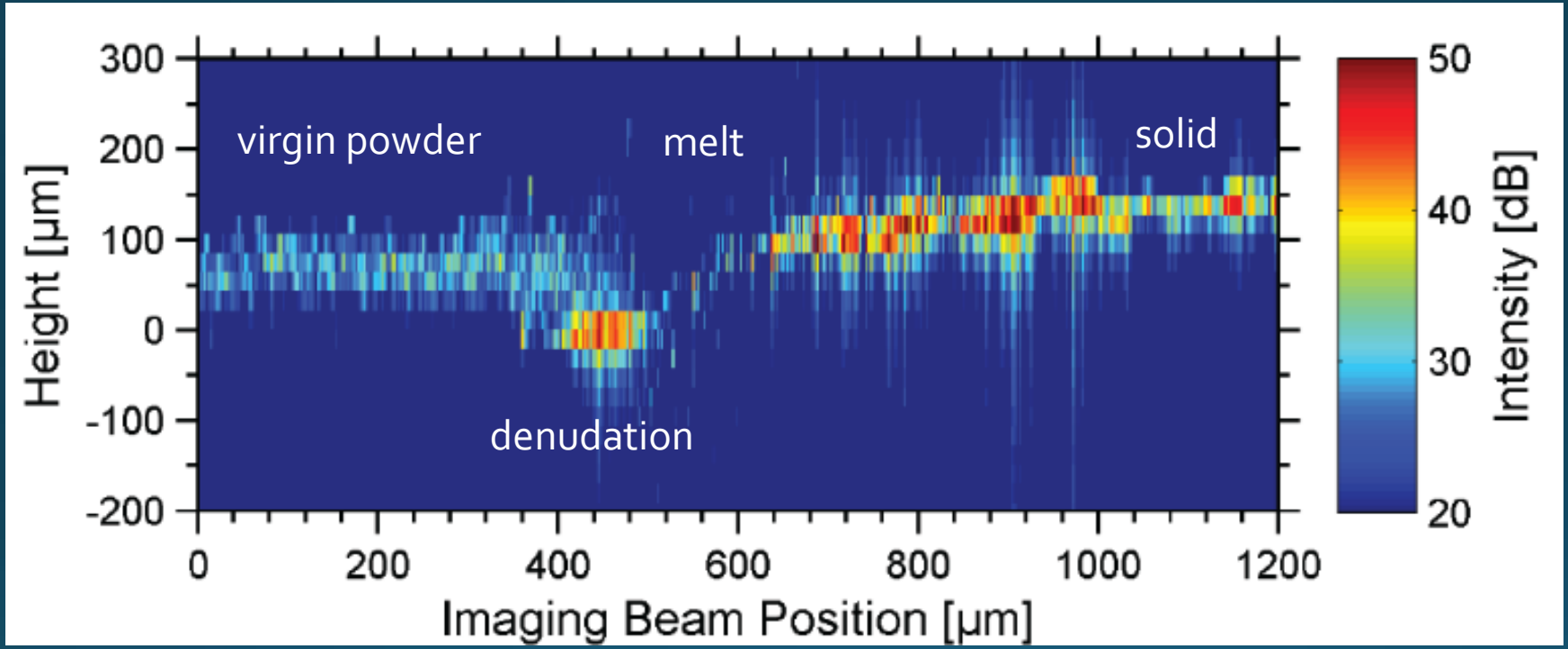


Image: klsmartin group

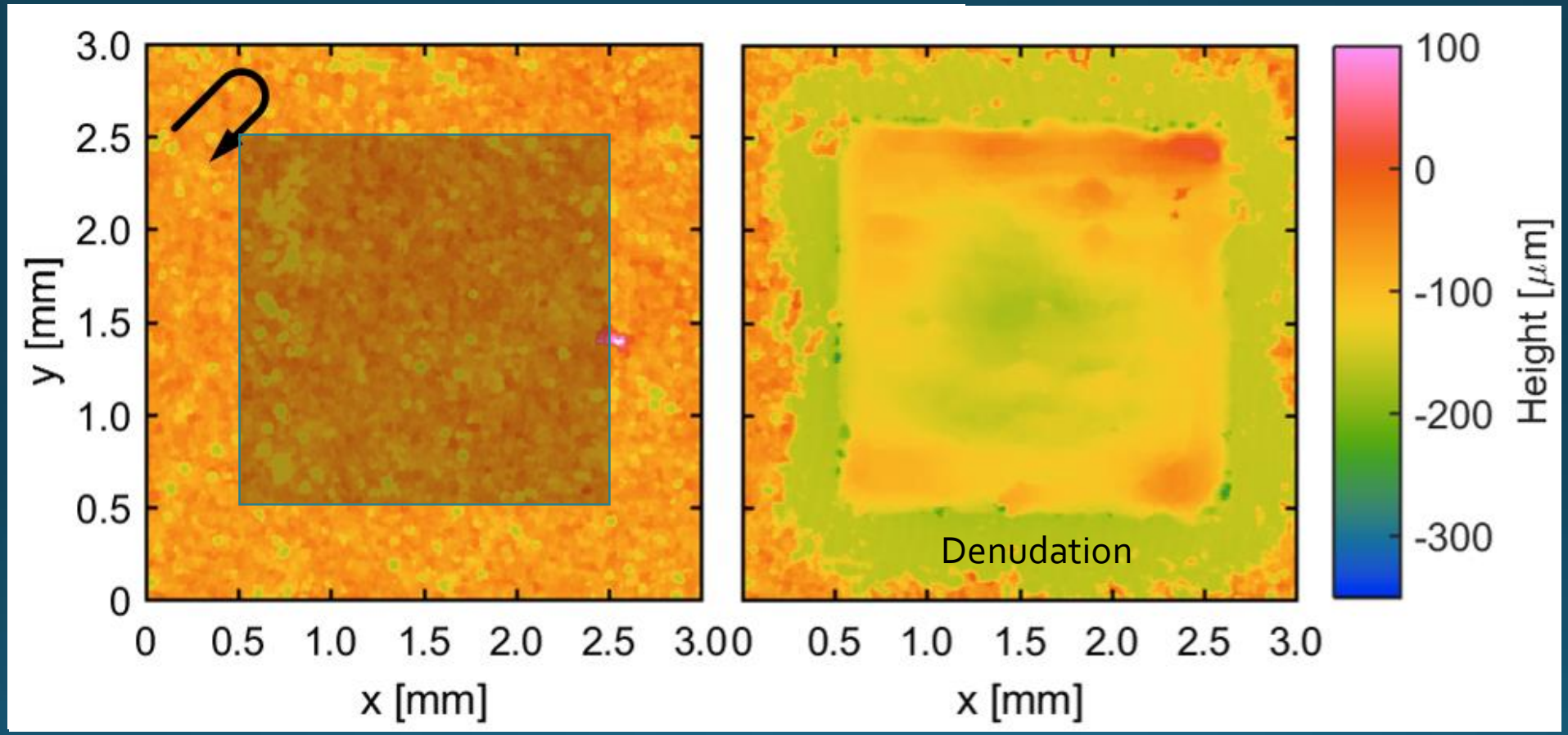
# Image during processing: operando monitoring






Kanko, Sibley, and **Fraser**, J. Mat. Proc. (2016)

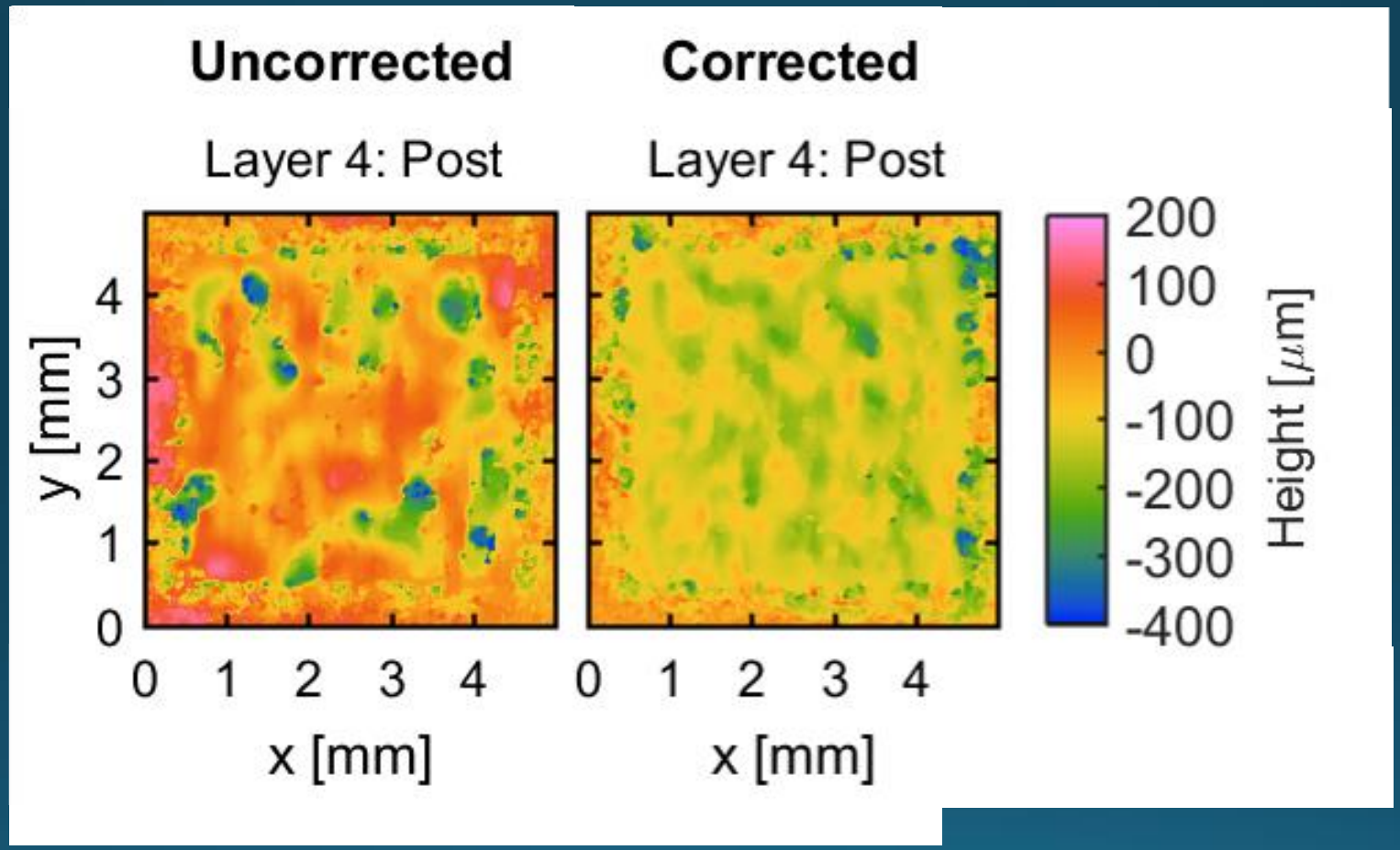
# Capture the full story: pre and post melt






Tristan Fleming *et al.*, Additive Manufacturing **32**, 100978 (2020)

# Beyond QA: feedback control



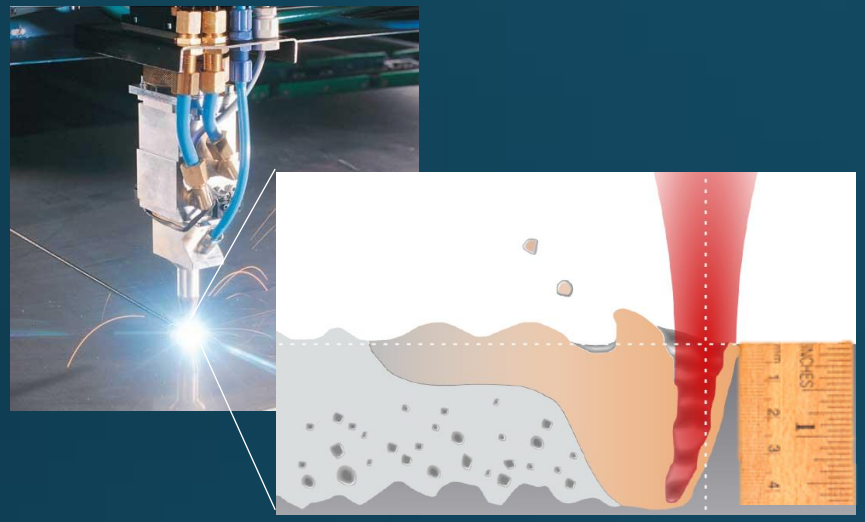

Ablate protrusions and fill in holes



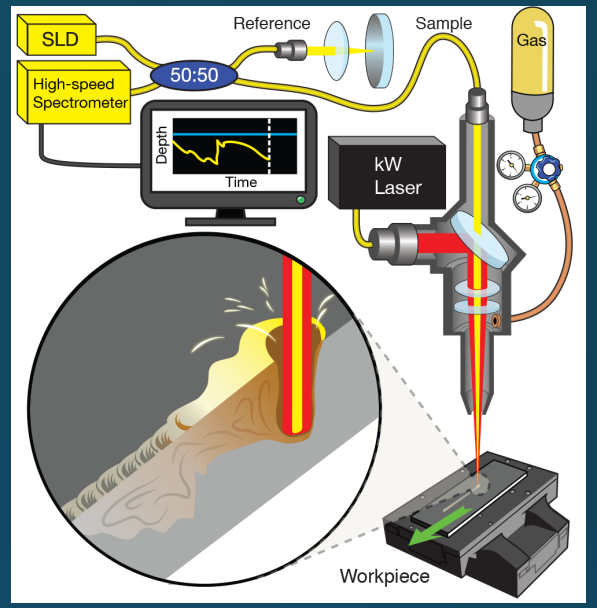
Tristan Fleming *et al.*, Additive Manufacturing **32**, 100978 (2020)

# Summary

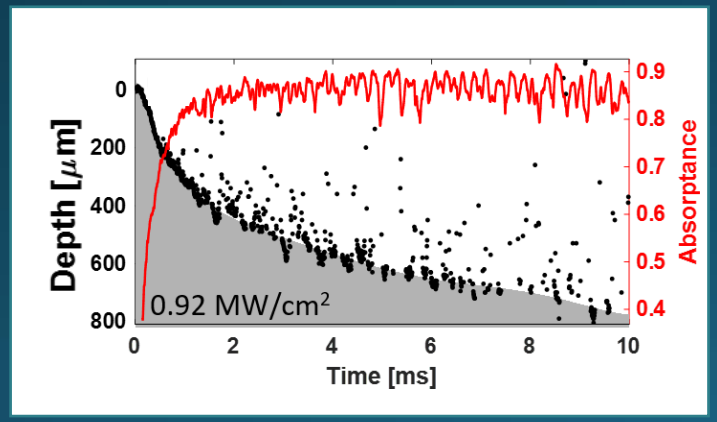
## Starts from a problem



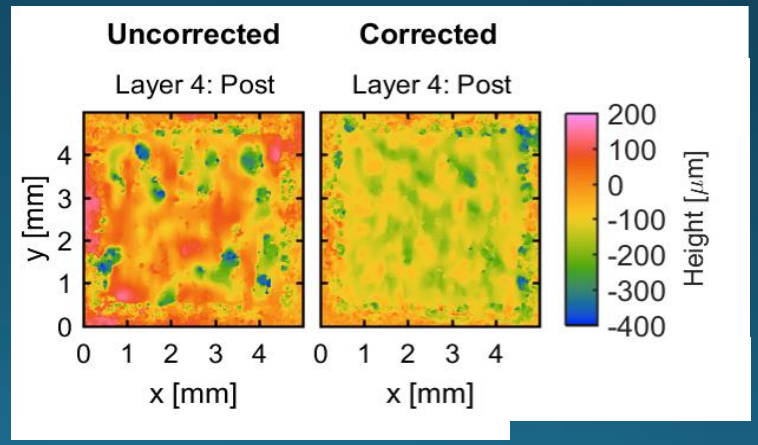
## Optical measuring stick




## Improve our understanding of the process




## Feedback control



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**Troy R. Allen *et al.*** "Simultaneous high-speed keyhole depth and absorptance measurements in laser spot welding of dissimilar metals," *Elsevier Procedia CIRP* **111:** 5-9 (2022).

**TJH Krause *et al.*** "Self-witnessing coherent imaging for artifact removal and noise filtering," *Optics and Lasers in Engineering* **151**: 106936 (2022).

**Troy R. Allen *et al.*** "Simultaneous in operando monitoring of keyhole depth and absorptance in laser processing of AISI 316 stainless steel at 200 kHz," *Elsevier Procedia CIRP* **94:** 419–424 (2020)

**Troy R. Allen *et al.*** "Energy-coupling mechanisms revealed through simultaneous keyhole depth and absorptance measurements during laser-metal processing," *Physical Review Applied* **13**: 064070 (2020).

**Tristan G. Fleming *et al.*** "Tracking and controlling the morphology evolution of 3D powder-bed fusion in situ using inline coherent imaging," *Additive Manufacturing* **32**: 100978 (2020)**.**

**Faleh Altal *et al.*** "Dual-channel inline coherent imaging," *Applied Optics* **58**: 1614-1620 (2019)

**Jordan A. Kanko *et al.*** "In situ morphology-based defect detection of selective laser melting through inline coherent imaging," *Journal of Materials Processing Technology* **231**: 488-500 (2016)

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**Yang Ji *et al.*** "Real-time depth monitoring and control of laser machining through scanning beam delivery system," *Journal of Physics D: Applied Physics* **48**:155301 (2015).

**P.J.L. Webster** *et al.* "Automatic laser welding and milling with in situ inline coherent imaging," *Optics Letters* **39**: 6217-6220 (2014).

Jared Blecher *et al.* "Real-time monitoring of laser beam welding keyhole depth by laser interferometry," *Science and Technology of Welding and Joining* **19**: 560 - 564 (2014).

**Karen X.Z. Yu *et al.*** "Deep nonlinear ablation of silicon with a quasi-continuous wave fiber laser at 1070 nm," *Optics Letters* **38**: 1799-1801 (2013).

**B.Y.C. Leung *et al.*** "Real-time guidance of thermal and ultrashort pulsed laser ablation in hard tissue using inline coherent imaging," *Lasers in Surgery and Medicine* **44**: 249–256 (2012).

**P.J.L. Webster *et al.*** "Automatic real-time guidance of laser machining with inline coherent imaging," *Journal of Laser Applications* **23:** 022001 (2011).

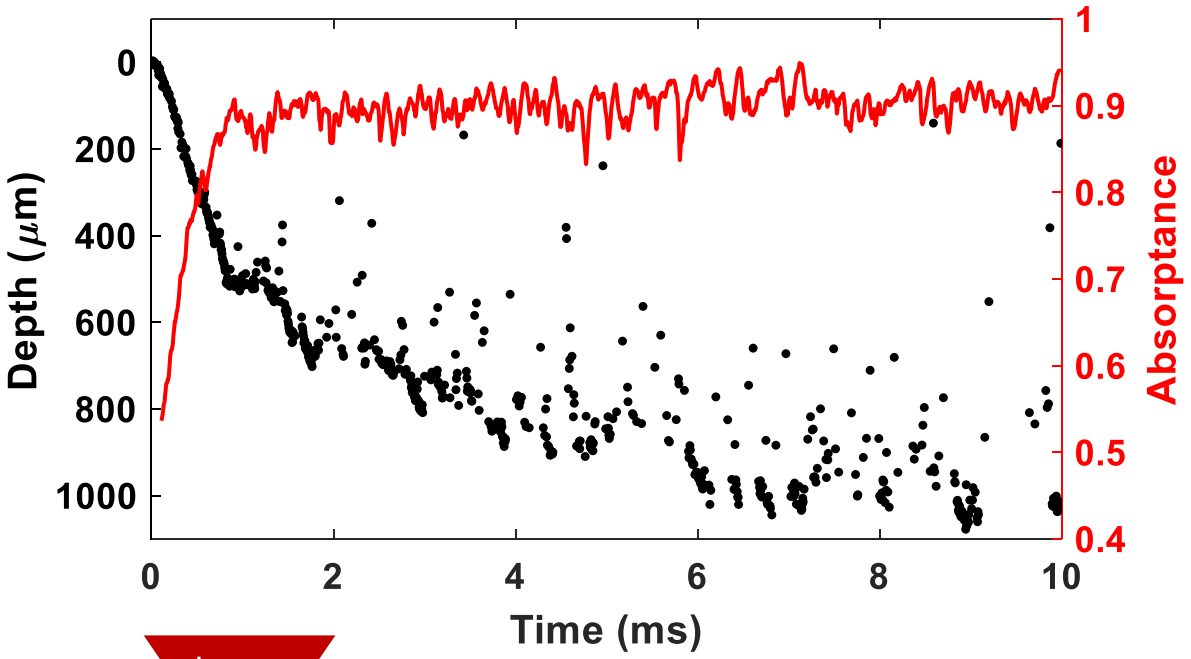
**P.J.L. Webster *et al.*** "In situ high-speed coherent imaging of morphology changes during laser micromachining," *Optics Letters* **35**: 646-648 (2010).

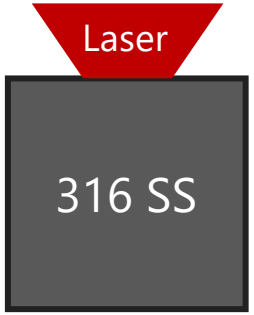
**P.J.L. Webster *et al.*** "High speed in situ depth profiling of ultrafast micromachining," *Optics Express* **15**: 14967-14972 (2007).

# Other work slides

# Spot welds: steel vs aluminum

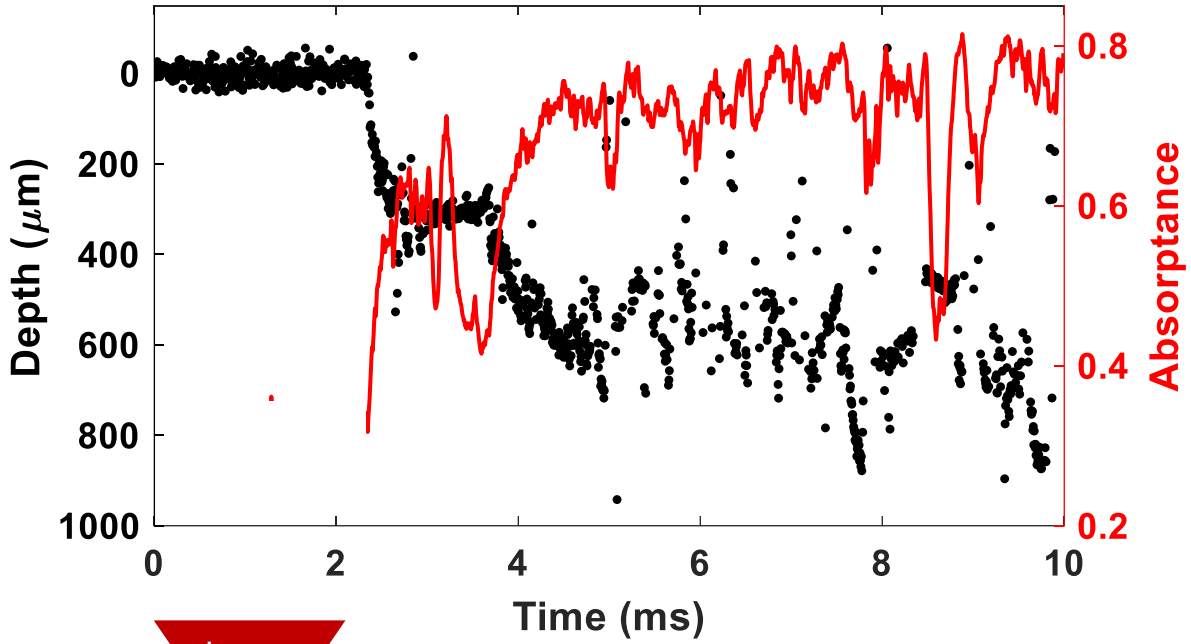
316 Stainless Steel

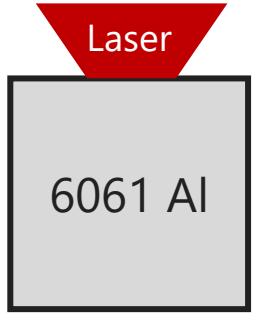



- **Immediate keyhole formation**
- **Rapid initial keyhole growth**
- **Depth appears as diagonal streaks**

6061 Aluminum

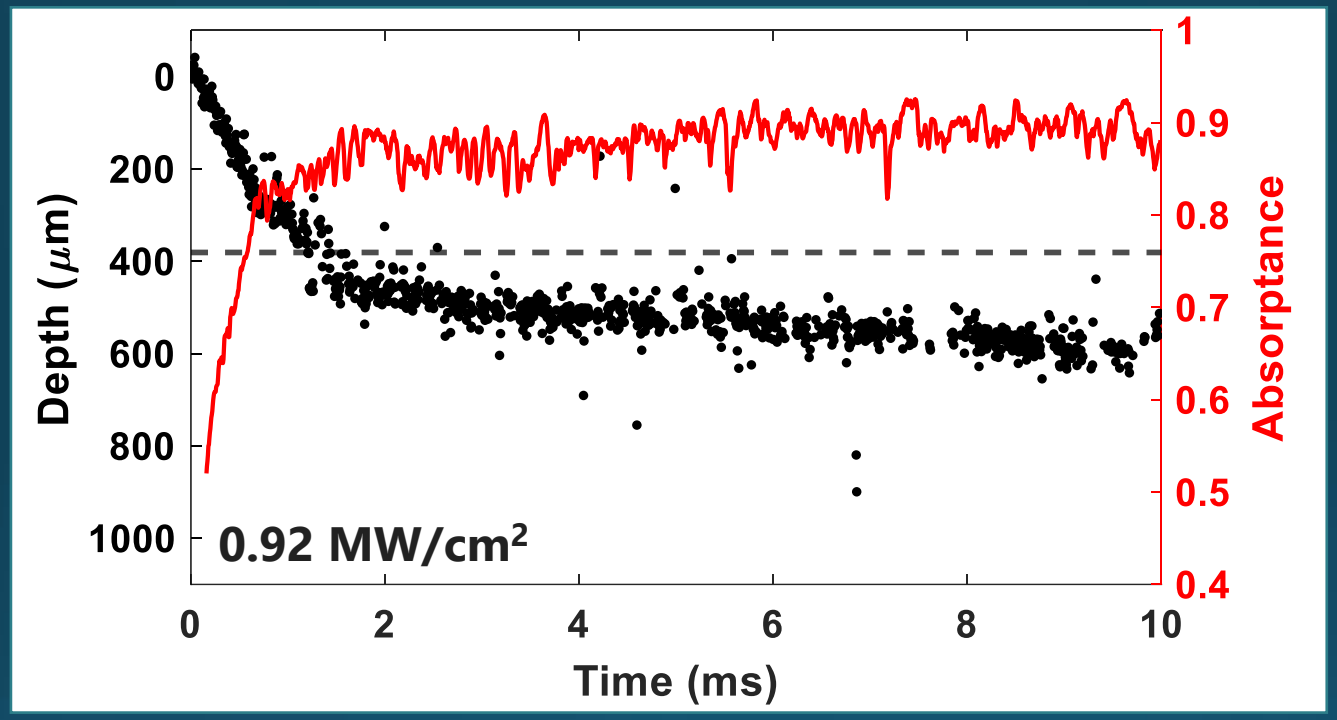


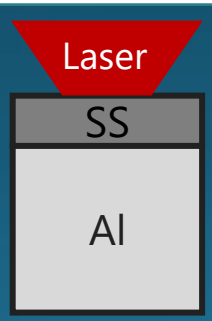




- **Delayed keyhole formation**
- **Sporadic keyhole growth with temporary pauses**

# Steel + Aluminum: completely different

316 Stainless Steel on 6061 Aluminum



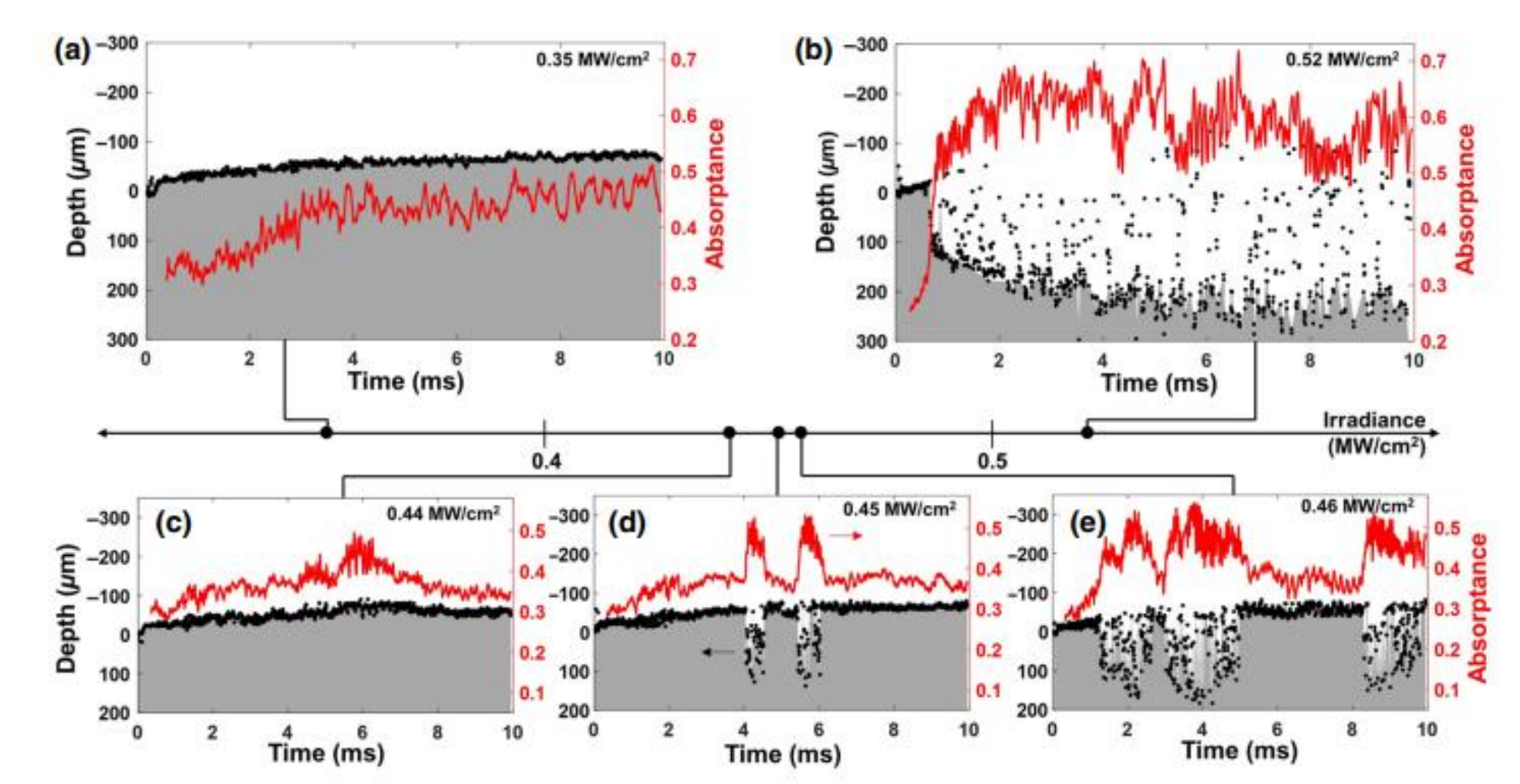

In SS

- **Immediate keyhole formation**
- **Rapid initial keyhole growth**

- **Slow, stable keyhole growth**
- **Completely unlike Al or SS**

In Al

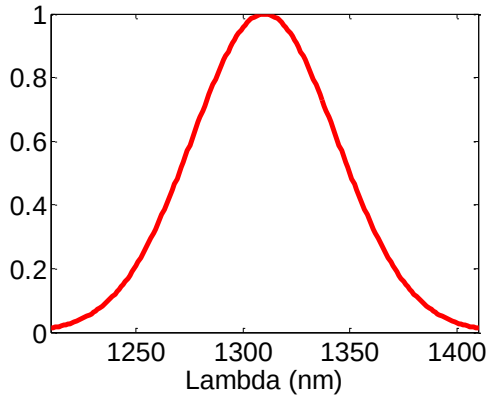
# Zone of particular relevance to additive manufacturing






Allen *et al*, Physical Review Applied **13**, 064070 (2020)

# Other work: increase S:N through balanced detection




$$I_{spec}(k) = A(k)\left(\frac{I_{ref}}{2} + \frac{I_i}{2} + \sqrt{I_{ref} I_i}\cos(nz_i k)\right)$$

$$I_{back}(k) = A(k)\left(\frac{I_{ref}}{2} + \frac{I_i}{2} - \sqrt{I_{ref} I_i}\cos(nz_i k)\right)$$

$z_R$

$z_R + z_i$

Broadband light source

Spectrometer / detector

$$\Delta k = \frac{2\pi}{nz_i}$$

Faleh Altal, Troy R. Allen, Stephen G. L. Nestor, Tristan G. Fleming, and James M. Fraser, *Applied Optics* **58**: 1614-1620 (2019)