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# Evaluating Keyhole Mode Laser Welds via High Speed Imaging

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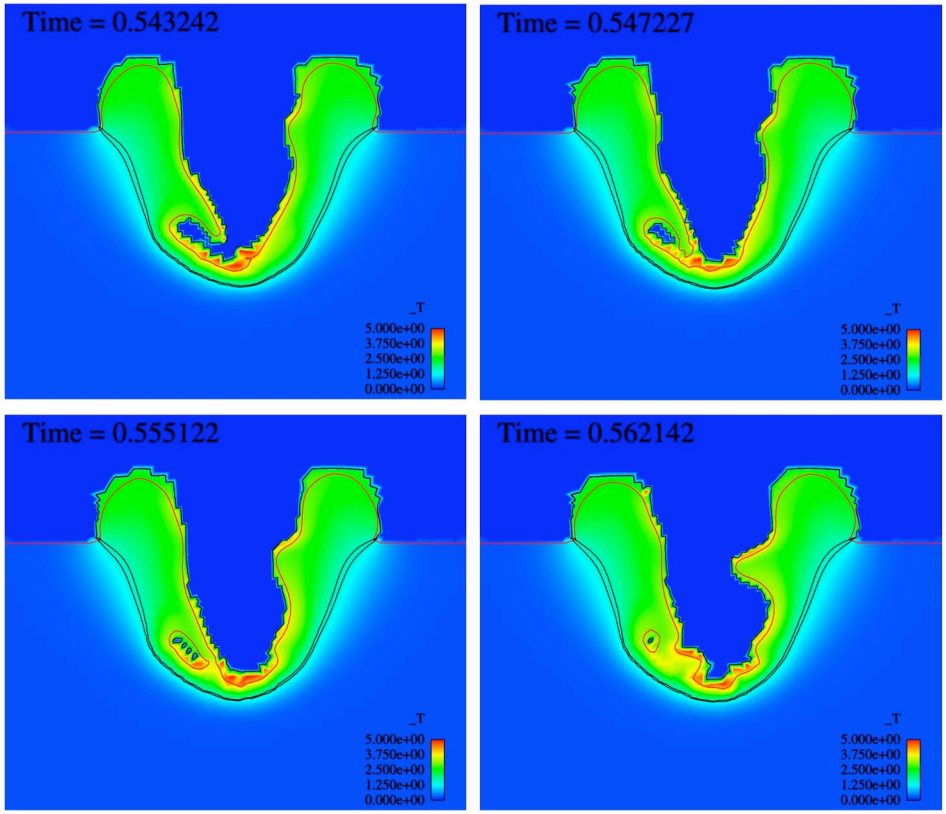
# Current Approaches to Laser Weld Characterization




## Basic Methods Under Development

- Modeling
- Generate experimental data for 2D rendering of a 3D process
- High speed imaging to view weld pool dynamics and keyhole characteristics
- Provide temporal energy absorption measurements to verify energy absorption subroutine

## Challenges

- Highly dynamic environment
- High laser brightness environment
- Weld size and feature definition
- Quantitative measurements

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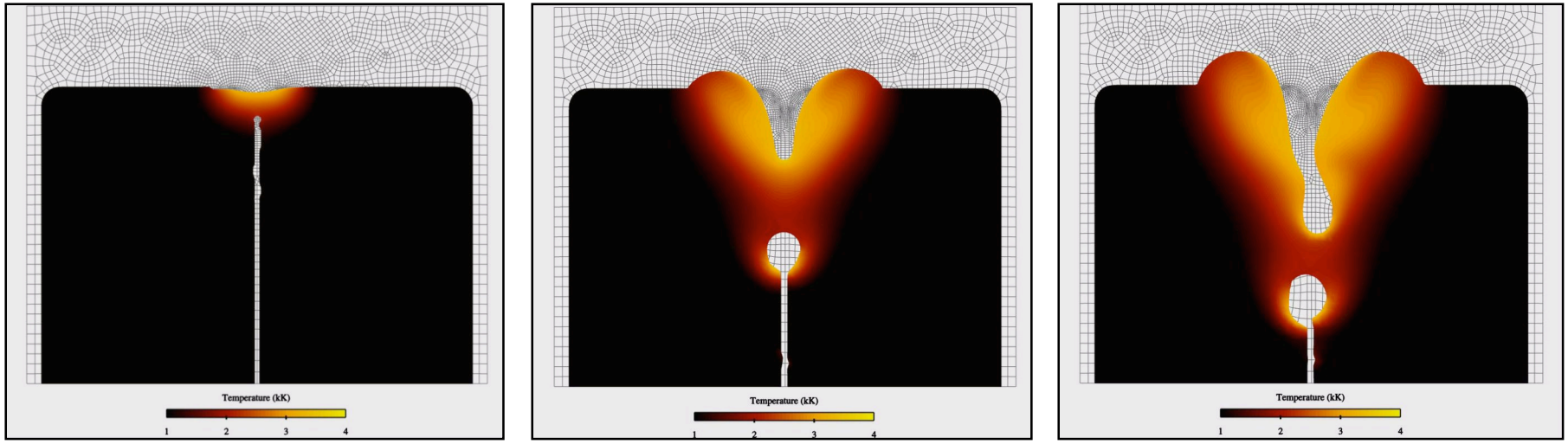
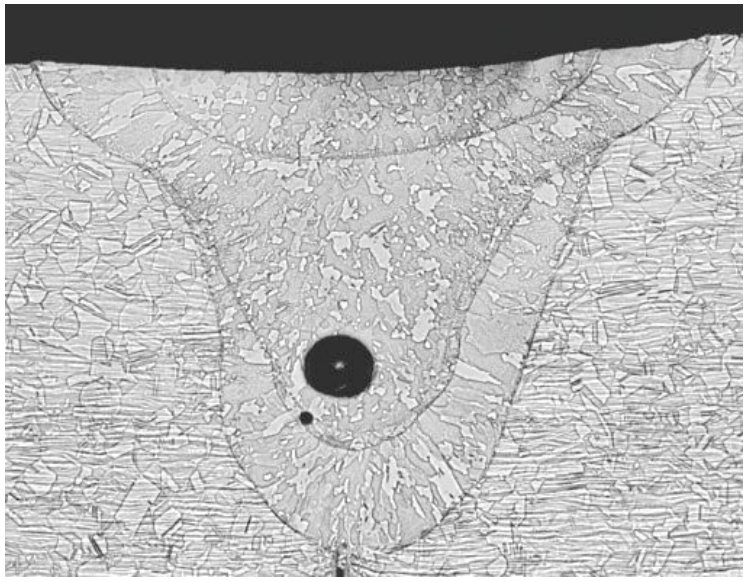
# Motivation for Weld Imaging



- **Model physics and validation**
- **Process optimization**
- **Process monitors and controls**

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# High Speed Imaging to Capture Fluid Dynamics

## Illumination

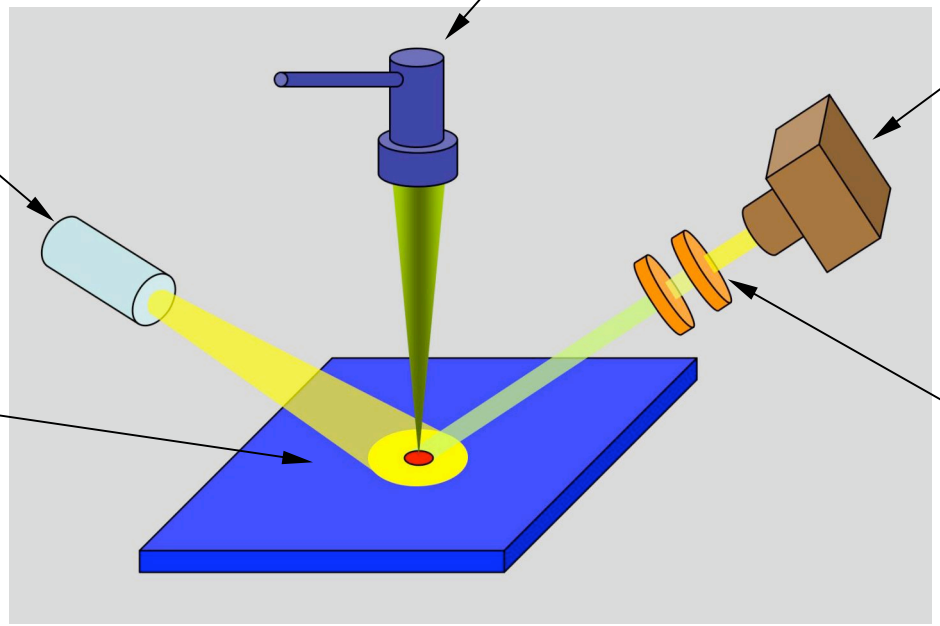
- Pool incandescence
- 150 W Tungsten Halogen lamp delivered with 8mm fiber bundle
- Cu Vapor Laser – 20 W, 514 nm λ
- 750 mW ion laser (511 nm)

## Welding Lasers

- Lasag SLS 200 C16 Nd-YAG pulsed laser – 40 W output, 100 & 150 mm focusing lens
- Rofin Sinar 1440W CW Nd-YAG laser – 120 mm lens

## Camera

- Photron APX RS high speed imager
- 125,000 fps capable
- Up to 1/125,000 sec exposure time



## Joint Configurations

- Spot-on-Plate – 304L
- Butt Joint – 304L
- Standing Edge Joint – 304L
- Gapped Lap Joint - Kovar
- Shielding Gases

## Filtering

- *Spectral* – Nd-YAG reflecting mirror, Neutral density #03
- *Spectral* – filter, 540 nm notch filter
- *Temporal* - Synced with Cu Vapor Laser

- A wide range of welding conditions and imaging parameters have been evaluated

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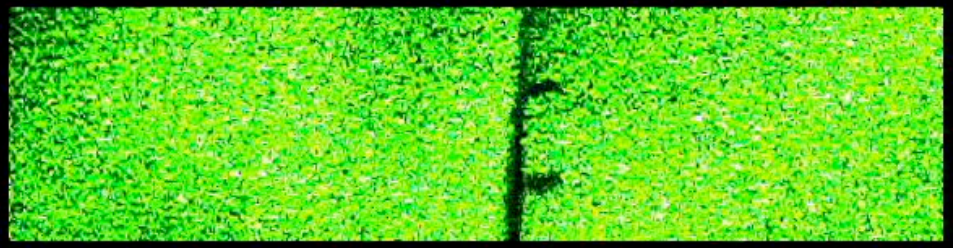
# Early Imaging Capability

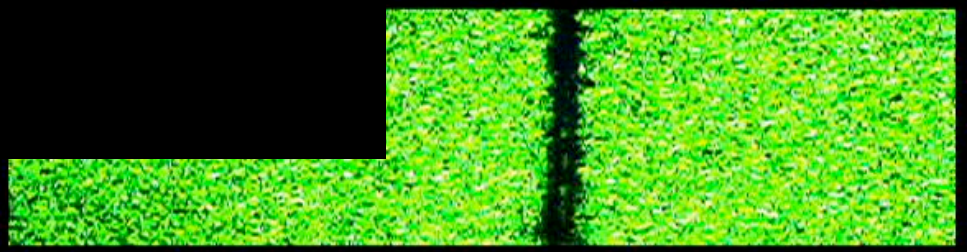
*Gapped Lap-Joint Spot Weld*



Ion laser illumination:

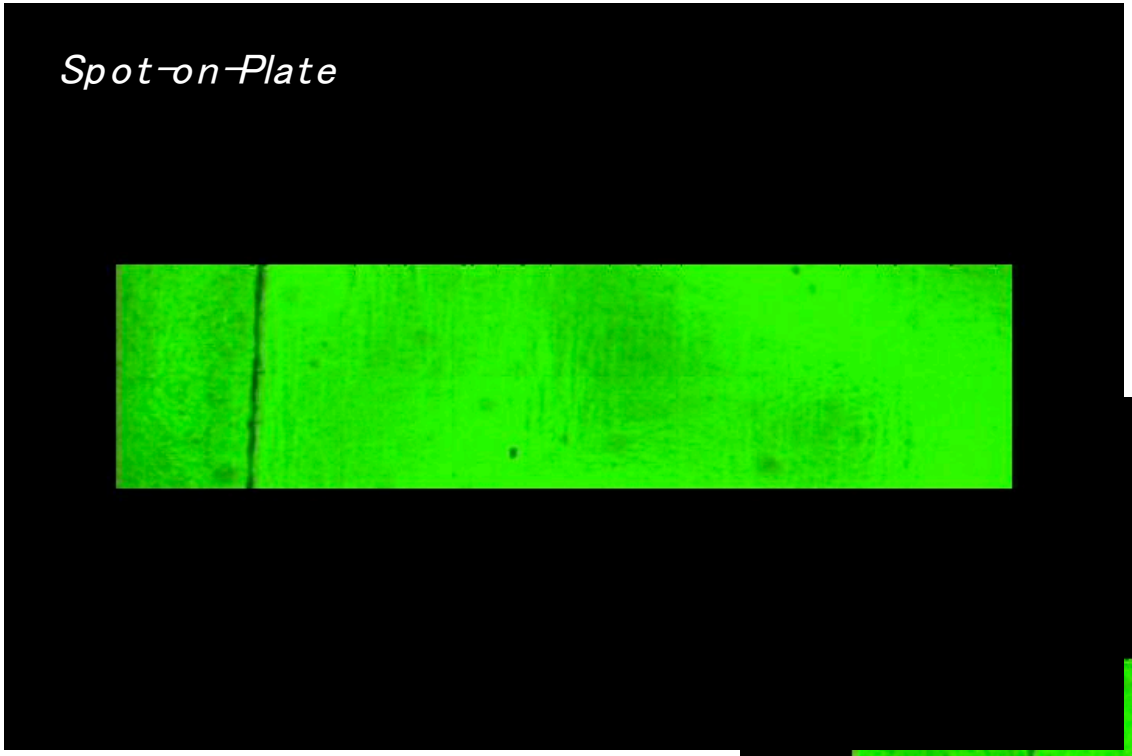
- Power limited (750 mW max)
- Heavily speckled images
- 1 – 2k fps

*Butt-Joint Spot Weld*



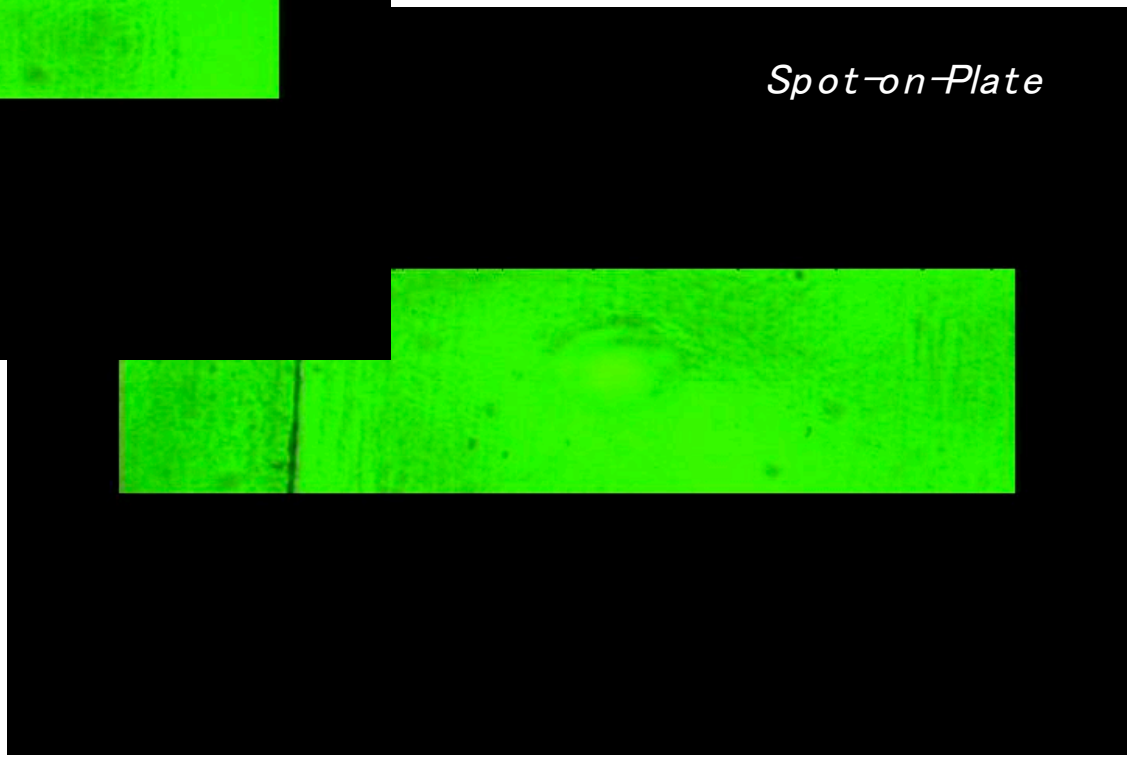
– **Considerable effect of gas shielding observed for spot-on-plate welds**

# Early Imaging Capability




White light illumination:

- 150W Halogen lamp fiber bundle delivered
- Improved image quality
- 2k fps




– **Considerable effect of gas shielding observed for spot-on-plate welds**

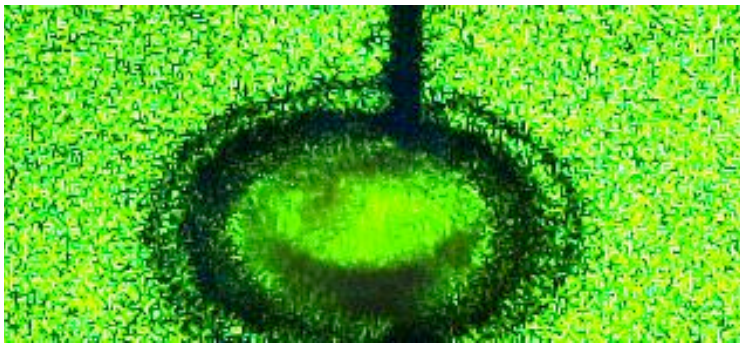
# Early Imaging Capability

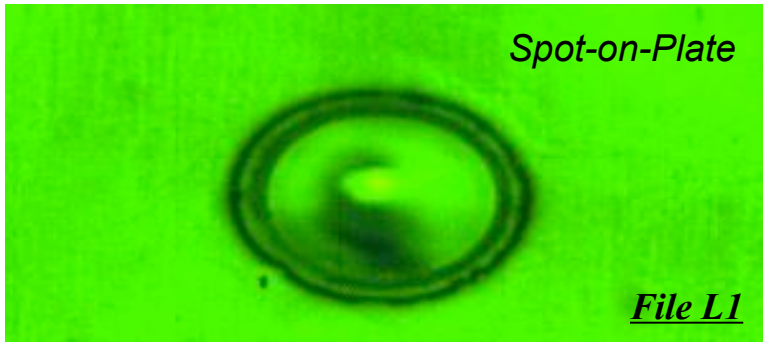
**Ion laser illumination:**

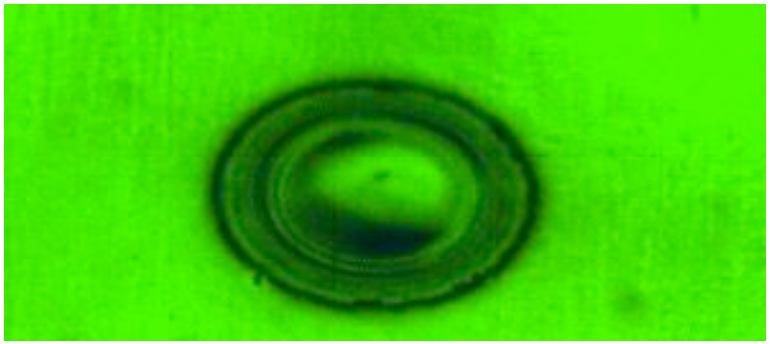
- Power limited (750 mW max)
- Heavily speckled images
- 2000 frames/sec

**White light illumination:**

- 150W Halogen lamp fiber delivered
- Improved image quality
  2000 frames/sec



- **Suitable for lower power, non-keyhole welds**
- **Considerable effect of gas shielding observed for spot-on-plate welds**
- **Images too blurred or frame rate too slow for dynamic observations other than pool solidification**
- **Keyhole too bright to observe details**

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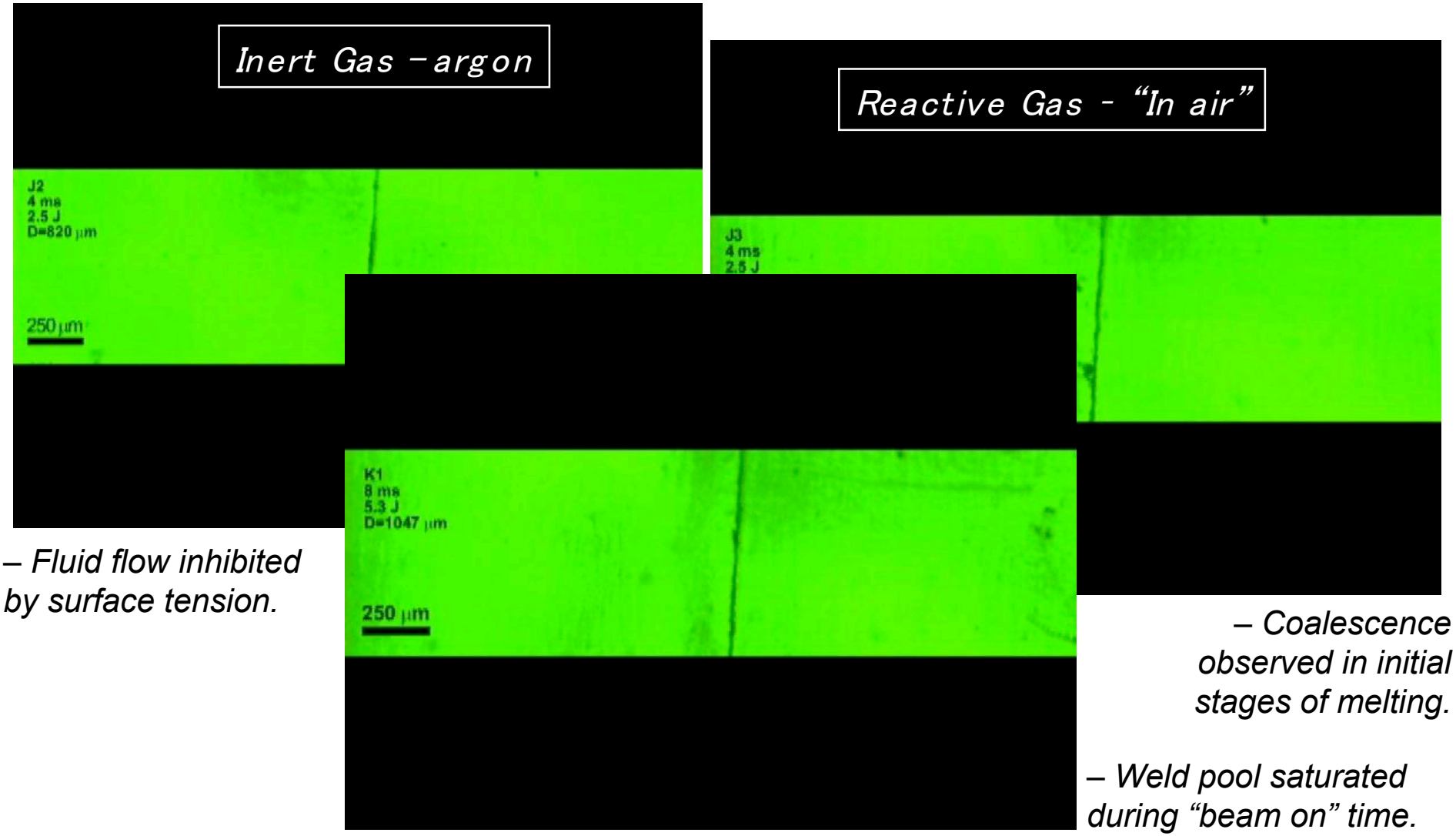
# Imaging with White Light Illumination




– *Fluid flow inhibited by surface tension.*

– *Coalescence observed in initial stages of melting.*

– *Weld pool saturated during "beam on" time.*

- ***Higher frame rate necessary to better capture weld pool dynamics.***

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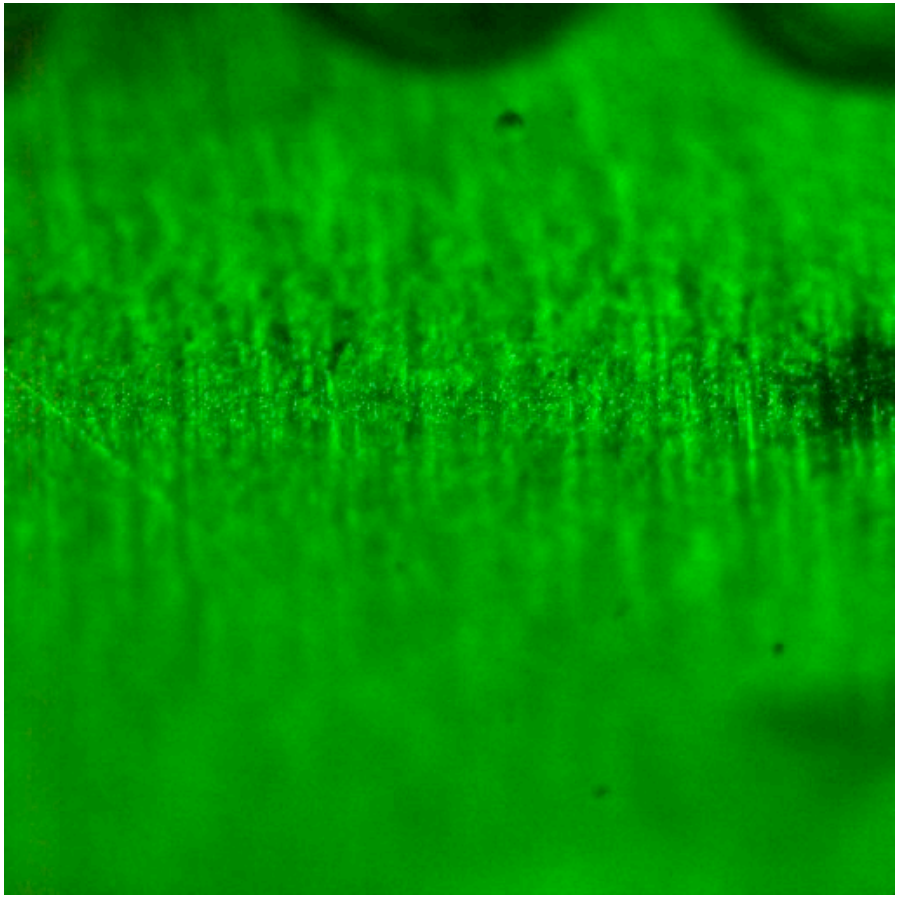
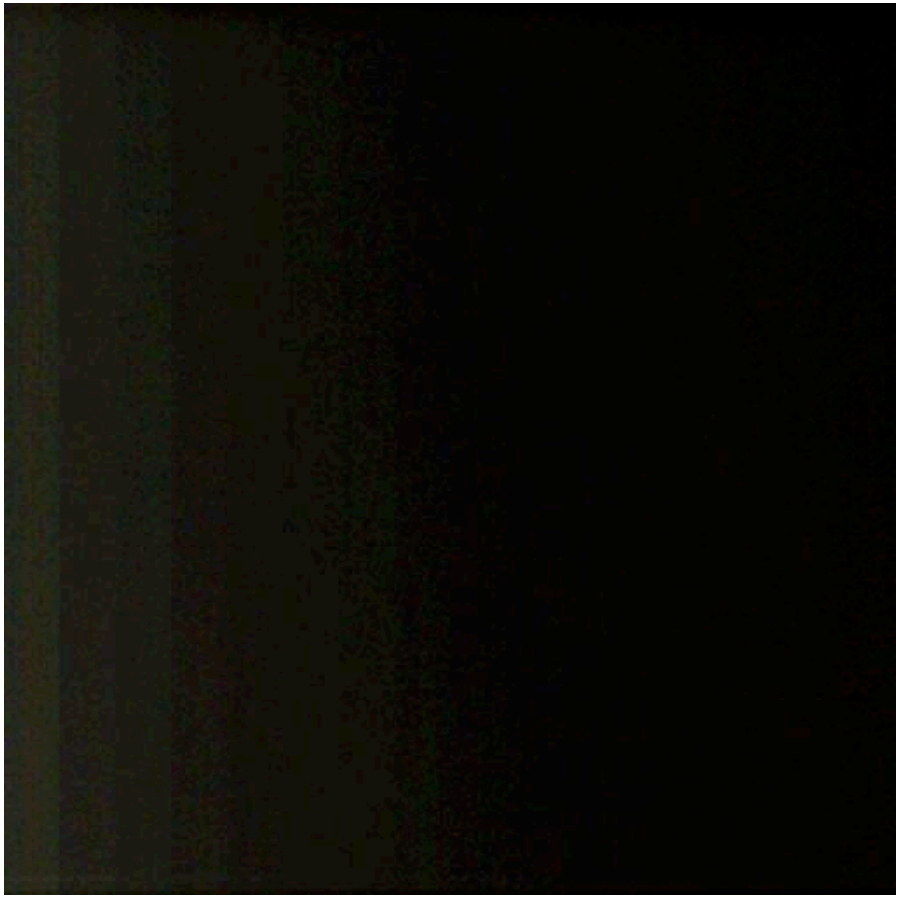
# Imaging Inside the Keyhole

- 10k fps, 100 µs exposure time
- Diffuser needed to remove speckling
- 20 ND and 99% Nd:YAG reflective filter



- 10k fps, 4 µs exposure time
- No external illumination
- 10 ND and 99% Nd:YAG reflective filter



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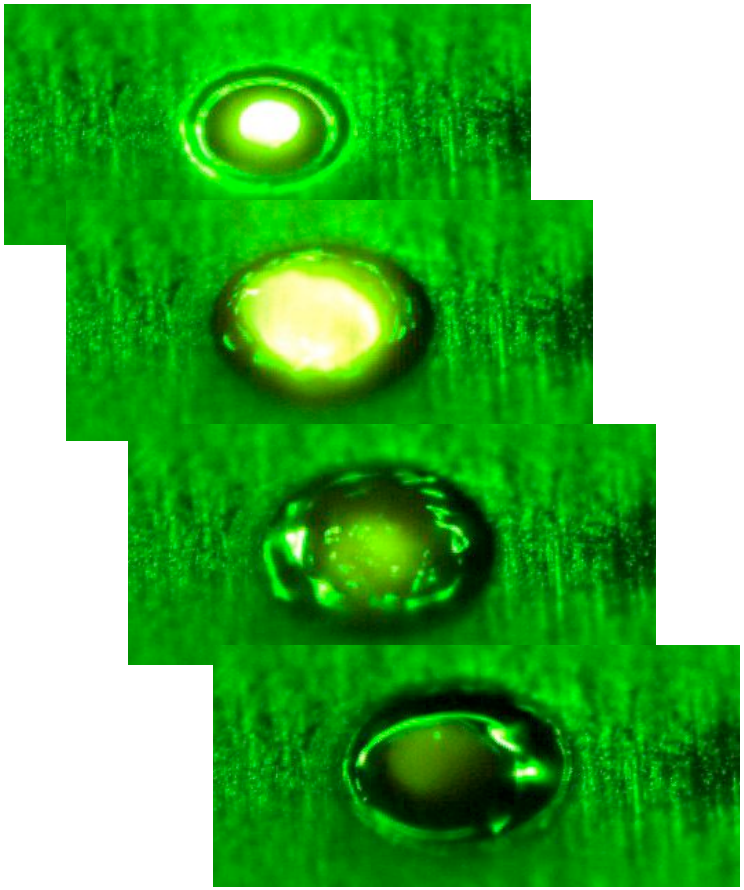

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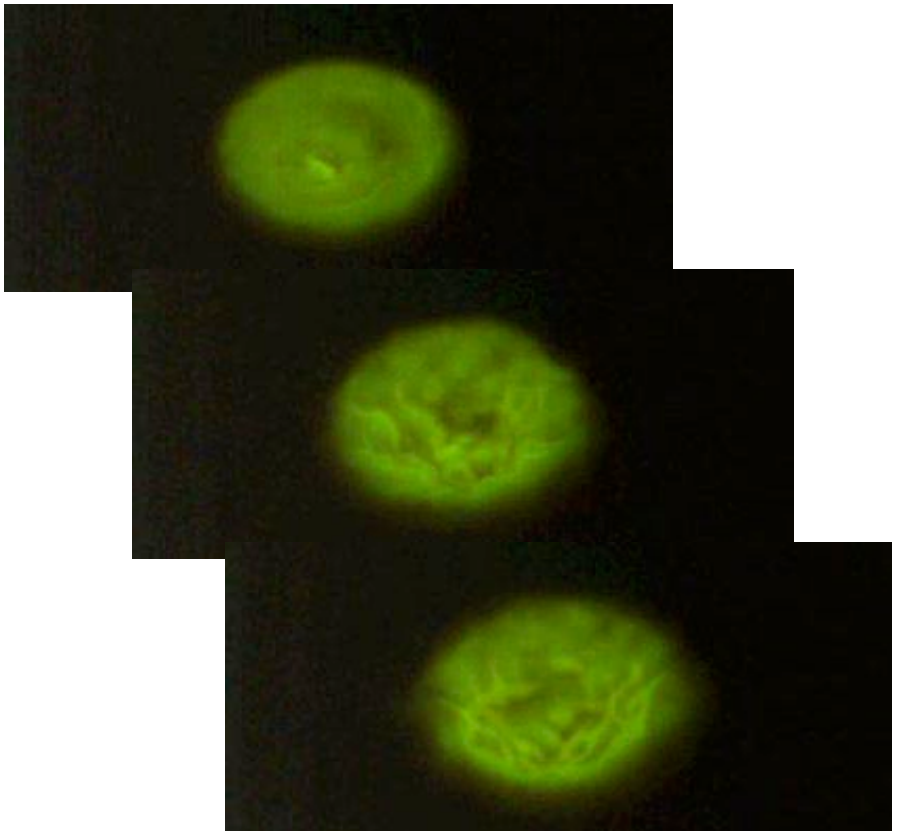

- First images of keyhole interior
- Keyhole interior extremely rough

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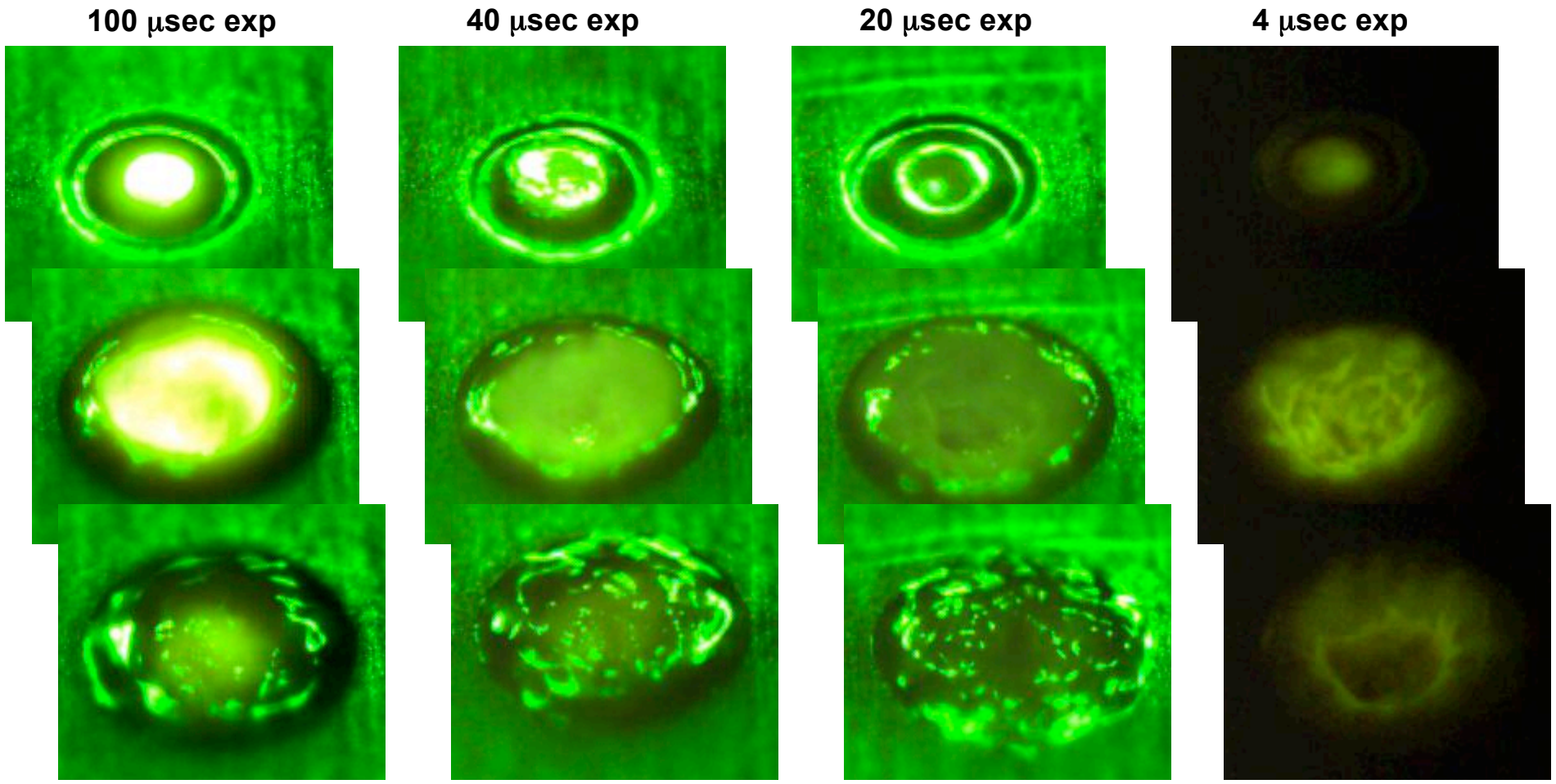
# Cu Vapor Laser Illumination

**10k frame/sec, 2.25kW, 1.75 msec, 3.5J, Ar Shielding**




- **Use of various imaging modes and exposure provides tailoring of information**

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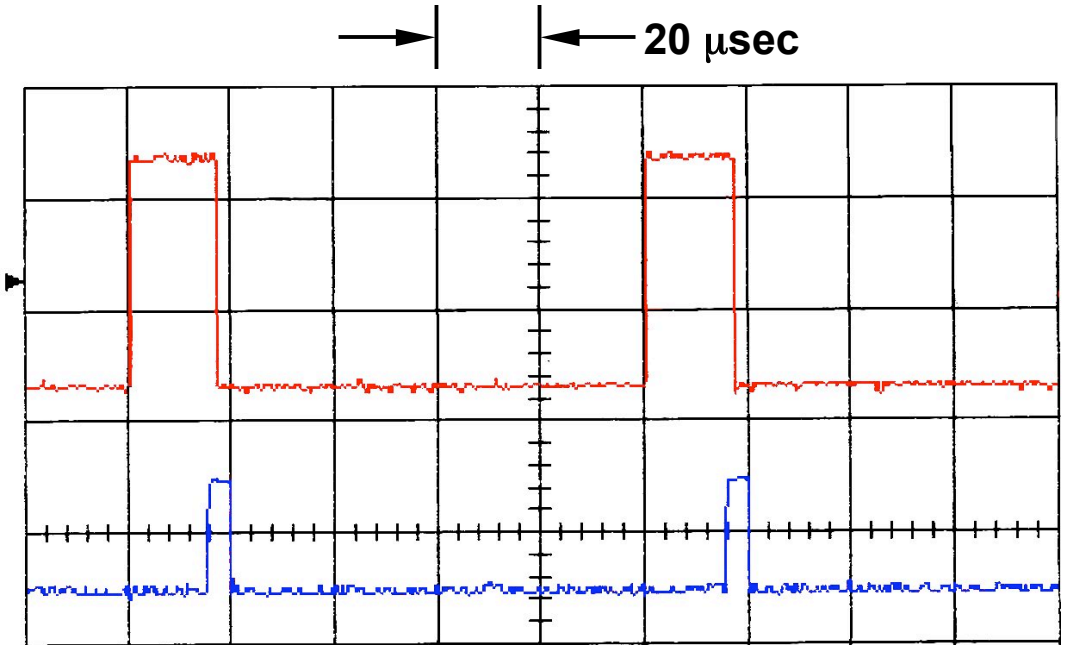
# Exposure Considerations

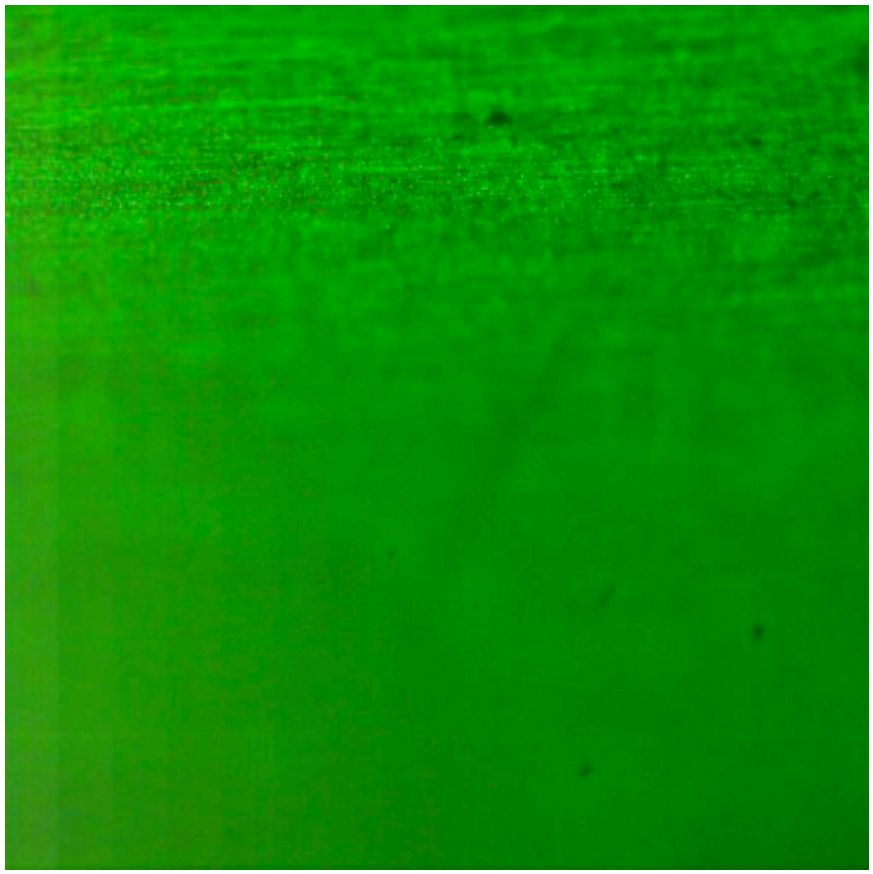



- Some blurring from pool incandescence prior to Cu laser pulse
- With 4 μsec exposures, we can resolve ≈45 μm sidewall features that are difficult to resolve at 20 μsec - this implies that characteristic fluid velocities on the interior of the keyhole are on the order of 10 m/sec
- Higher frame rate experiments underway to track keyhole surface features

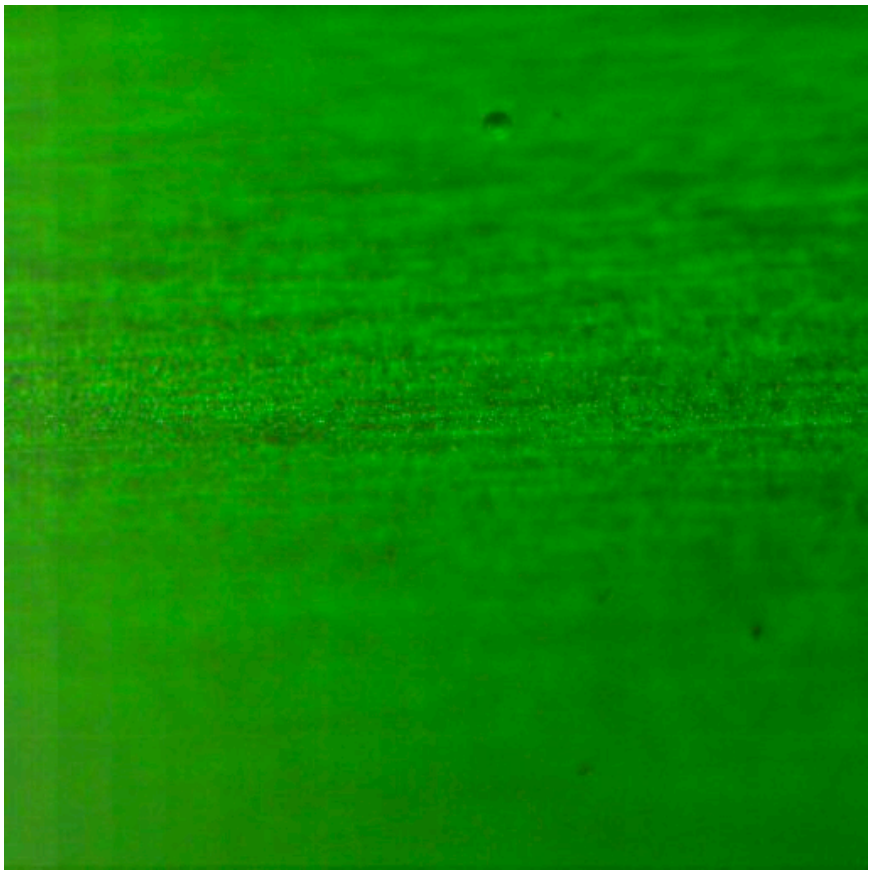
# Effect of Shielding

**10,000 fps, 17 microsec exp, ND Filter, Cu vapor illumination**

Ar 2 EXT 60K_C001S0001.avi



Air 3 EXT 60K_C001S0001 new.avi



- **Shielding gas (Ar vs Air) has a significant effect on surface tension and pool dynamics**
- **Keyhole smaller with air shielding**

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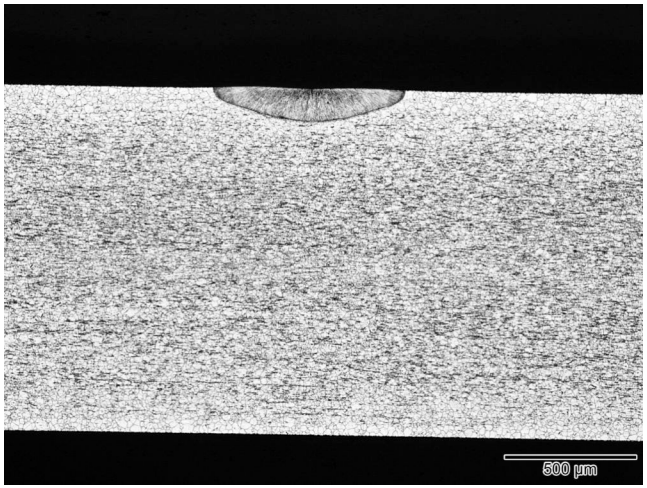
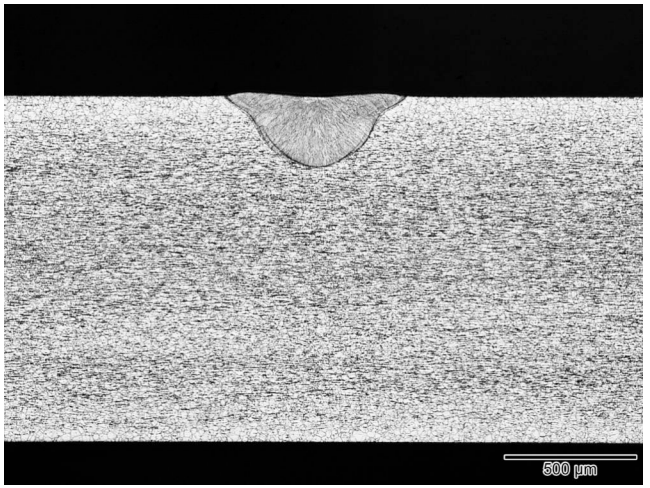
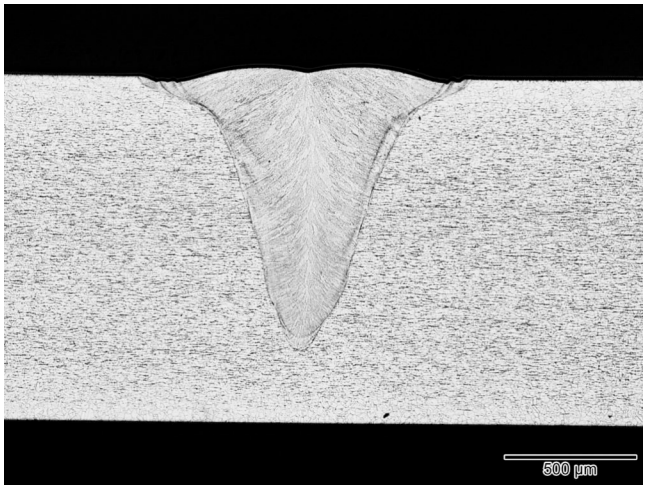
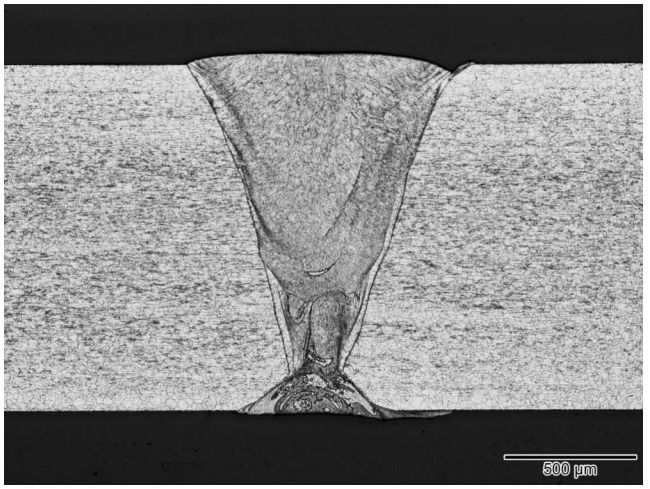
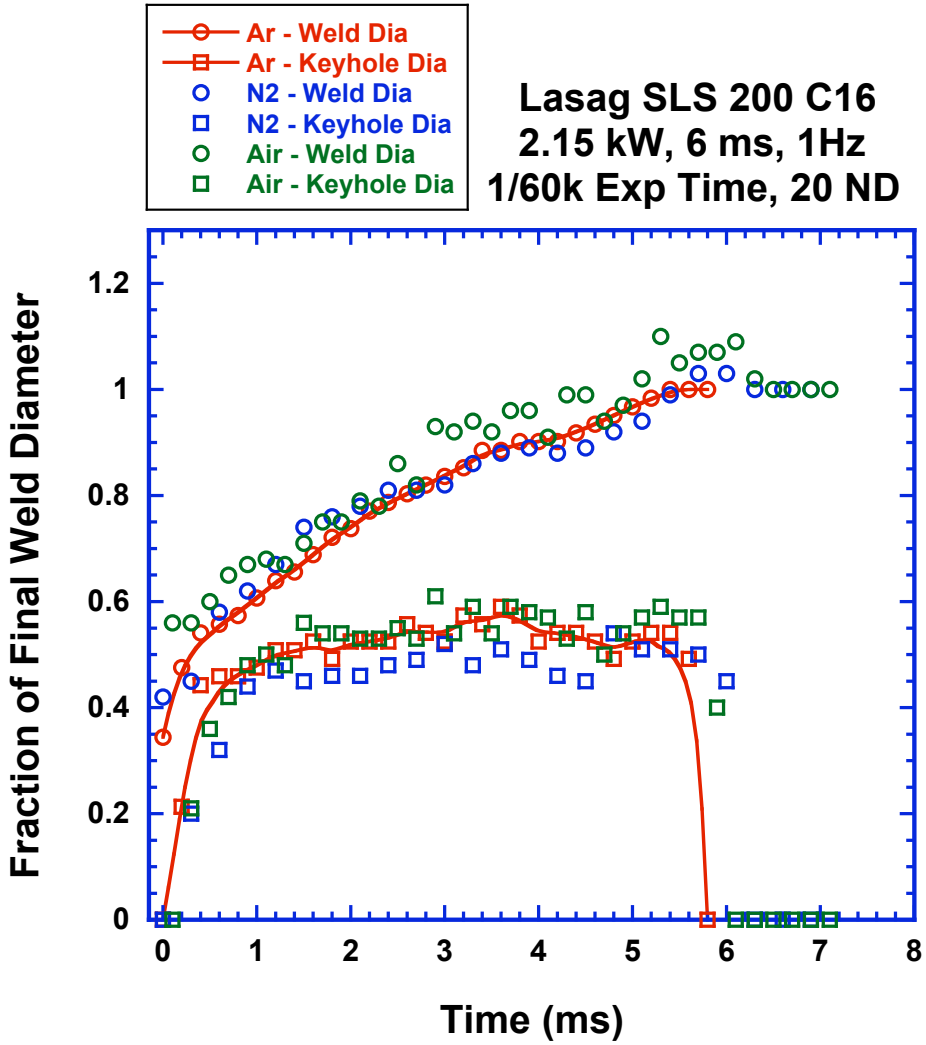
# Effect of Shielding

| Argon | | Air |
|---|---|---|
|   | 550 W<br>6 ms, 3.3 J |   |
|   | 2550 W<br>6 ms,15.3J |   |

- Shielding gas (Ar vs Air) has a significant effect on weld cross sections

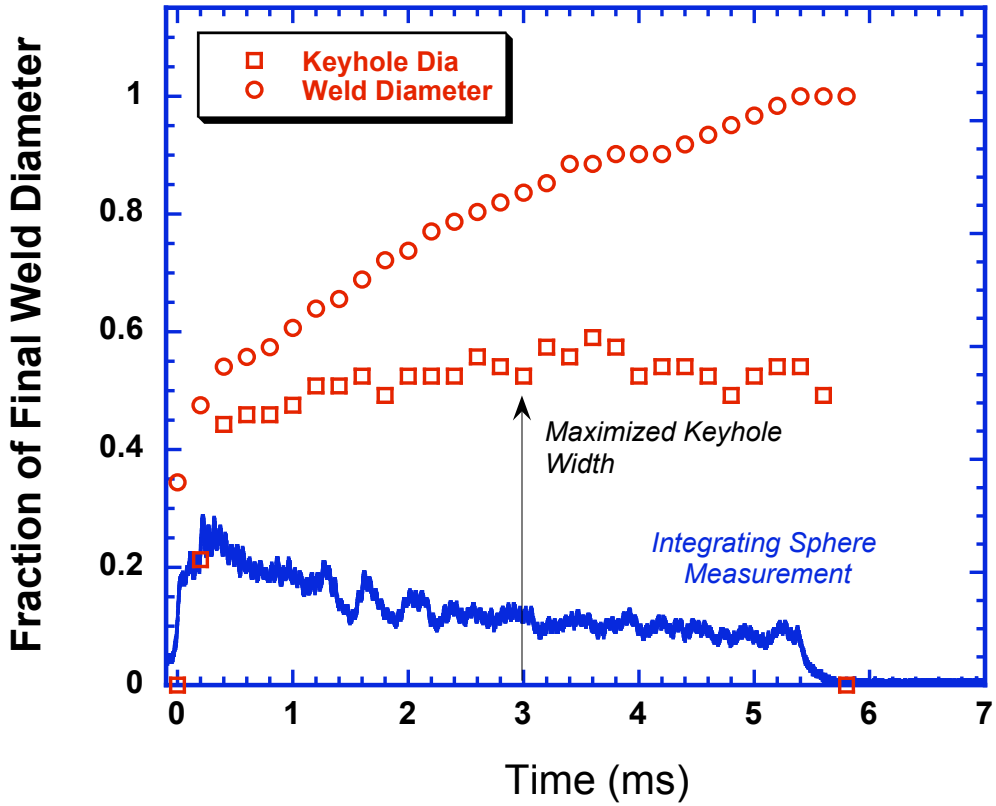
# Additional Observations




- Keyhole diameter saturates relatively quickly during weld pulse
- Subtle differences between air, nitrogen and argon shielded
- Keyhole remains relatively constant as weld grows

# Comparison with Absorption Measurements

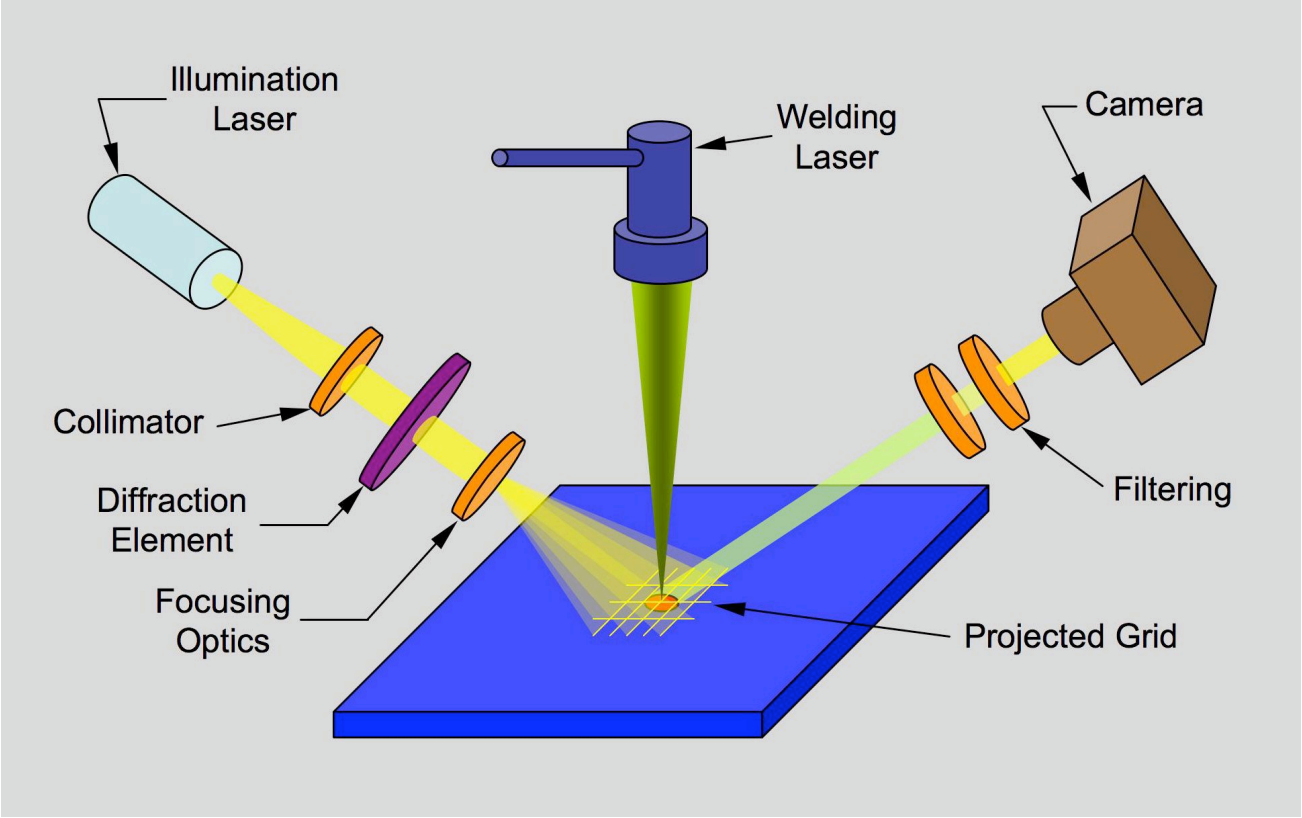
**Lasag Argon Shielded Spot Weld**
**~2 $kW_{set}$, 6 ms, 1Hz**
**1/60k Exp Time, 20 ND**




NOTE: Measurements at similar parameters taken independently.

- **Absorption measurements show that amount of reflected light continues to decrease even after keyhole forms**
- **Implies that keyhole continues to deepen toward a "constant" depth**

# Quantitative Data from High Speed Imaging




- We are preparing to project a visible grid on the surface of the weld
- Requires diffracting element and synchronization of illumination laser and camera shutter

- This approach should allow for at least partial reconstruction of keyhole geometry
- Keyhole geometry provides validation of energy absorption and surface tension descriptions in model

# Summary

**High speed imaging techniques for laser spot welds are being developed**

- **A range of imaging techniques and variables have been examined**
- **Current techniques show keyhole imaging possible and show that the keyhole is very rough and highly dynamic**
- **Shielding gas (surface tension) effects on keyhole size has been documented and shown to be significant**
- **Some quantitative measurements have been extracted**
- **Image analysis methods are being developed to further quantify weld pool geometry and dynamics**