ALE3D Simulations of Laser Heating Steel

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ALE3D Default Units

- Length: 1 cm = 0.01 m
- Volume: 1 cc = 1 cm^3 = 10^{-6} m^3
- Mass: 1 g = 10^{-3} kg
- Time: 1 μs = 10^{-6} s
- Pressure: 1 Mbar = 10^{11} Pa
- Energy: 1 Mbar·cc = 10^5 J
- Power: 1 Mbar·cc/μs = 10^{11} W
- Temperature: 1 K

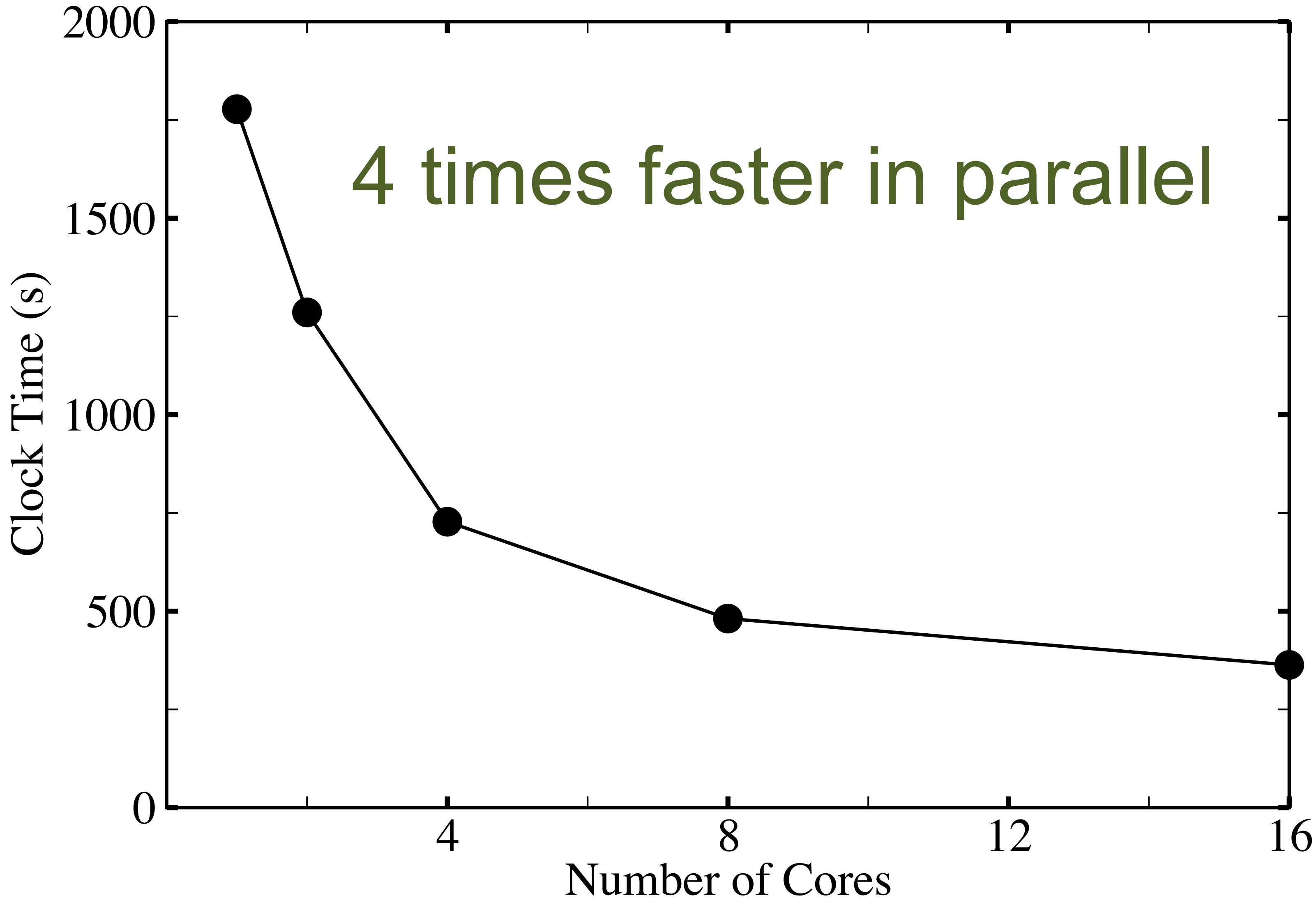
https://wci.llnl.gov/simulation/computer-codes/ale3d

Notes

- Turning on axis-symmetry leads to failure—fixed by changing the integrator.
- All the 2D simulations were redone with axis-symmetry (x-axis).
- Technical points in ALE3D simulations:
  - The x-axis is always the rotation axis in 2D calculation when the axis-symmetry is turned on.
  - In present calculations because the energy density is very high near the axis, a mode is erroneously excited using the default integrator.
  - No physics of laser-plasma interaction is implemented in ALE3D, so the absorption table is constructed using a simple linear rule: extinction parameter is proportional to density. Using available experimental data, or set the parameter based on zone size; e.g., for millimeter zoning, set absorb = 10 cm^{-1}.

ALE3D Parallel Calculation

- Partition: multiple of # of cores
- Decomp block
- -p in command line



Cross-Section of Laser Heating Steel Substrate (Bulk)

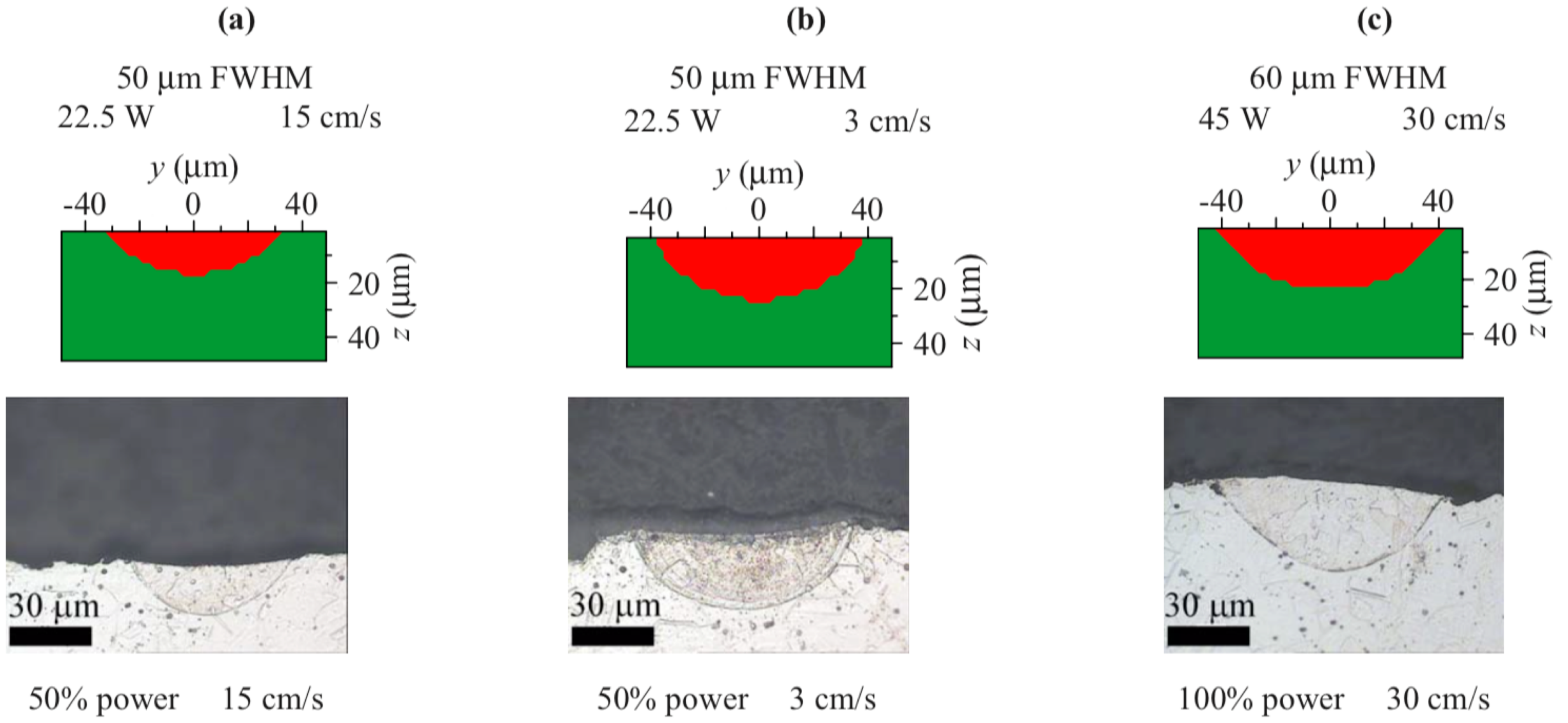


Fig. 6 Cross-sections of laser tracks on the stainless steel substrate without powder: calculated phase diagrams (upper row) and experimental micrographs (lower row)

J. Heat Transfer **131**, 072101 (2009)

Previous ALE3D Simulations

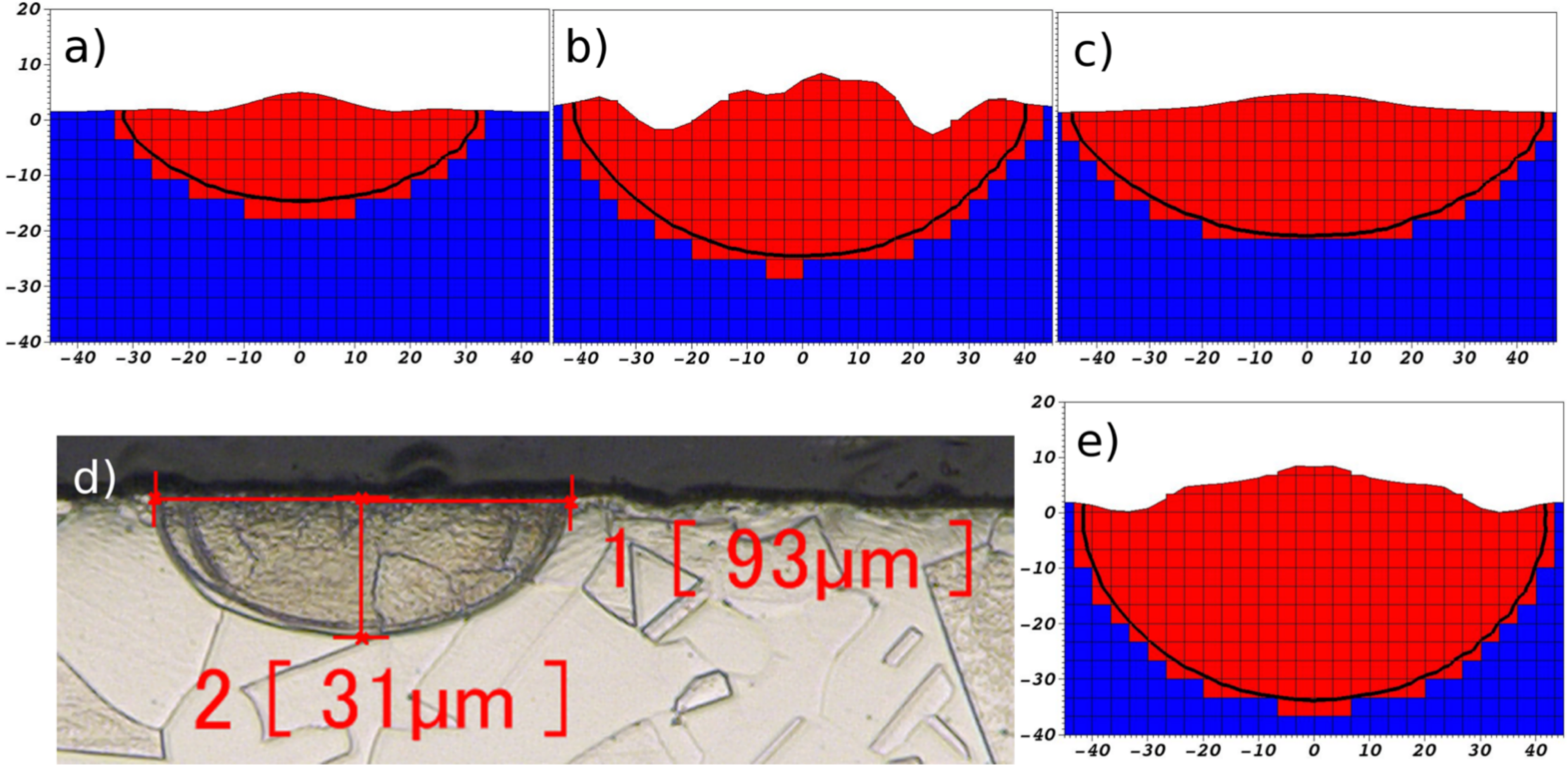
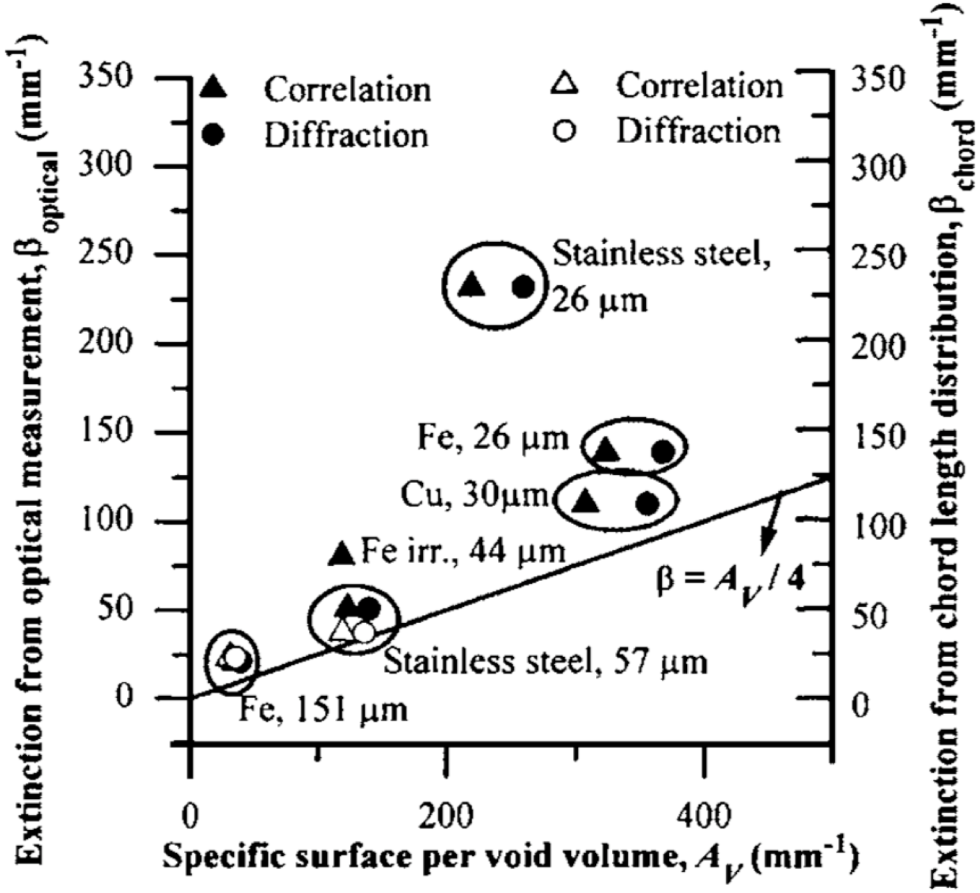


Figure 2. Cross-section micrographs of laser tracks on stainless steel bare plate. All length units are in micrometer. The laser absorptivity is taken to be *0.44* for (a, b, c) and *0.33* in (e). The zones in red indicate a liquid melt. The black contour line is the melting temperature line, T = *1700*K. The melt depth and width in (a, b, c, e) agree respectively with the experimental results (a, b, c) in Fig. 6 of (A.V. Gusarov I. Y., 2009) and our experiment (d) where the laser power is *92*W and scan speed *380*m/s.

J. Mater. Proc. Tech. **214**, 2627 (2014)

Property Parameters For Steel (Stainless, 316L)

- Melting point: 1700 K
- Thermal conductivity:
  - 20 W/m·K = 20×10^{-13} Mbar·cc/cm·μs·K
- Thermal capacity:
  - 0.5 J/g·K = 0.5×10^{-5} Mbar·cc/g·K
- Optical properties:
  – Absorptivity: 44% (reflectivity: 56%)
  – Extinction coefficient (bulk): 7.53×10^{5} cm^{-1}
  – Extinction coefficient (d = 57 μm, powder): 500 cm^{-1}

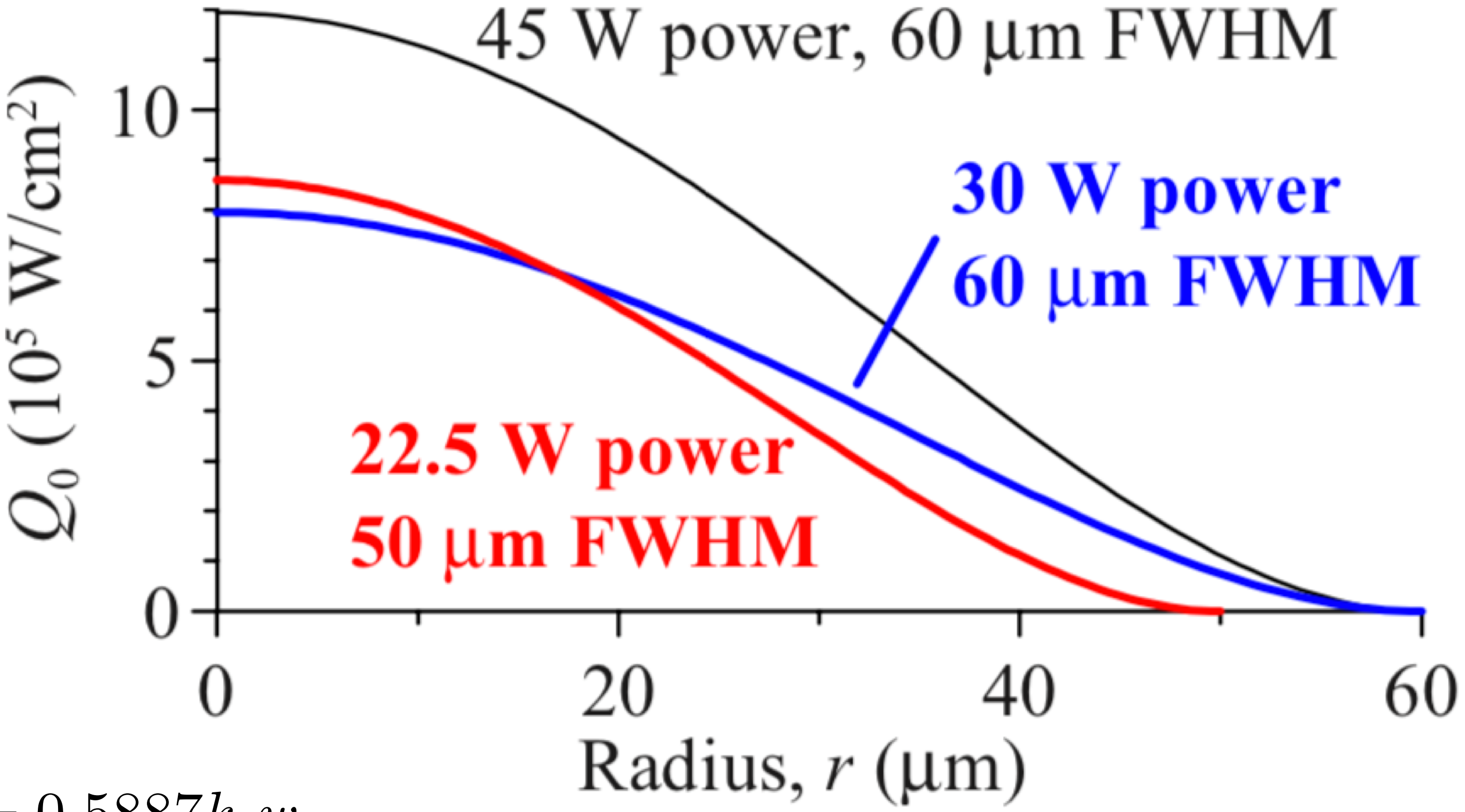


J. Appl. Phys. **98**, 013533 (2005)

Parameters For Laser

- Shape and Size
  - Circular
  - Gaussian

$$p(r) = p_0 \exp\left[-2\left(\frac{r}{k_G w / 2}\right)^2\right]$$



k_G: Gaussian parameter

$$FWHM = k_G \sqrt{\ln(2)/2} \cdot \text{width} = 0.5887 k_G w$$

$k_G = 0.6$ (default), $FWHM = 0.353w$ (w: width)
at the edge ($r = w/2$), $p = 0.004\, p_0$

Parameters For Laser

- Shape and Size
  - Circular
  - Gaussian
  - *FWHM*: 50 μm
    w: 141.6 μm
  - *FWHM*: 60 μm
    w: 169.9 μm
  - Power (P):
    22.5 W & 45 W

$$p(r) = p_0 \exp\left(-r^2 / 2\sigma^2\right)$$

$$\sigma = \frac{k_G w}{4} = \frac{FWHM}{\sqrt{8\ln(2)}} = FWHM/2.355$$

$$p_0 = \frac{P}{2\pi\sigma^2} = \frac{4\ln(2)}{\pi}\frac{P}{FWHM^2}$$

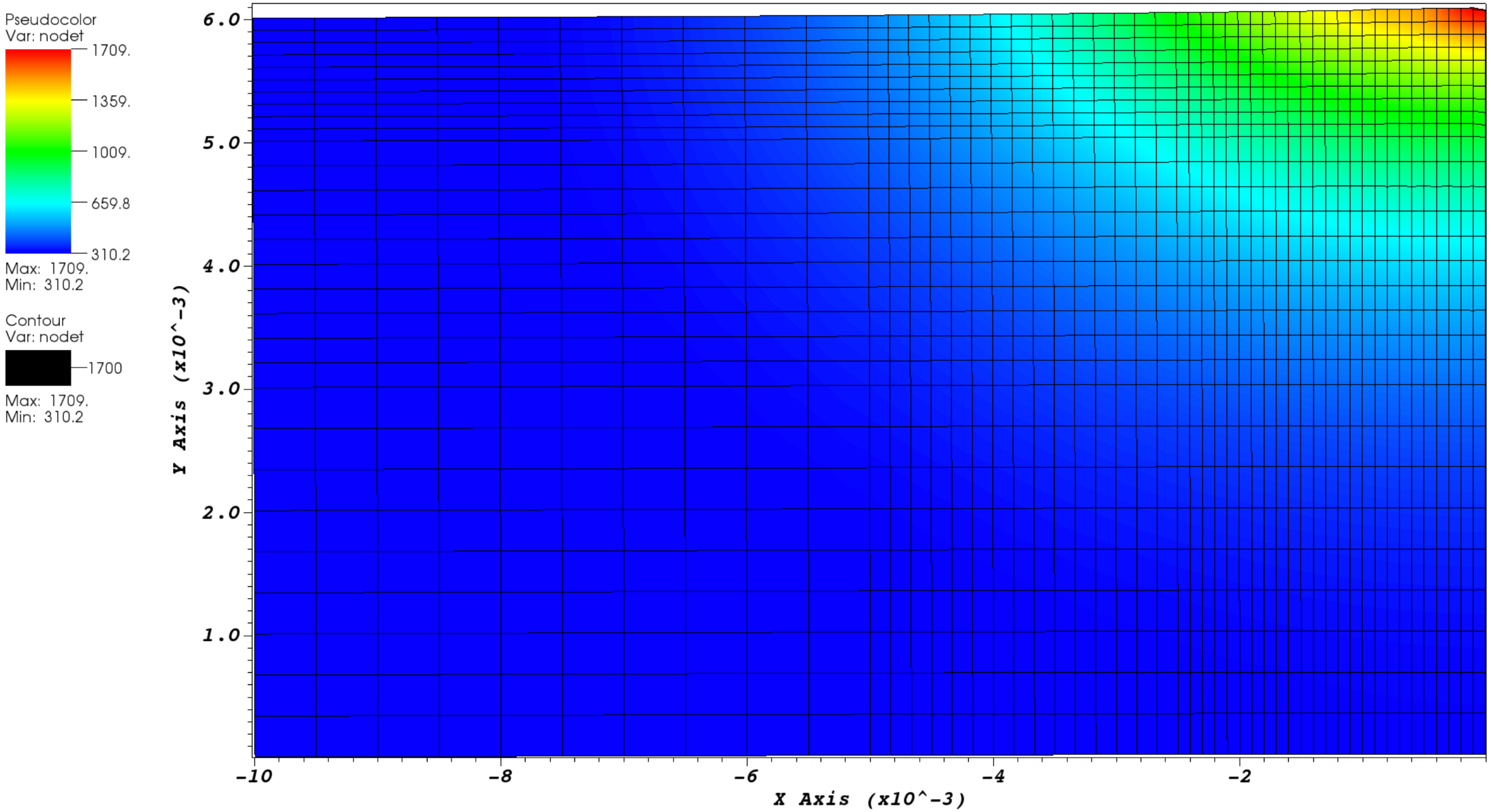
$$= 0.88254\frac{P}{FWHM^2}$$

$P = 22.5$ W, $FWHM = 50$ μm, $p_0 = 7.94\times10^5$ W/cm^2

$P = 45.0$ W, $FWHM = 60$ μm, $p_0 = 1.10\times10^6$ W/cm^2

Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; scanning speed $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 7.53×10^5 cm^{-1} (bulk)



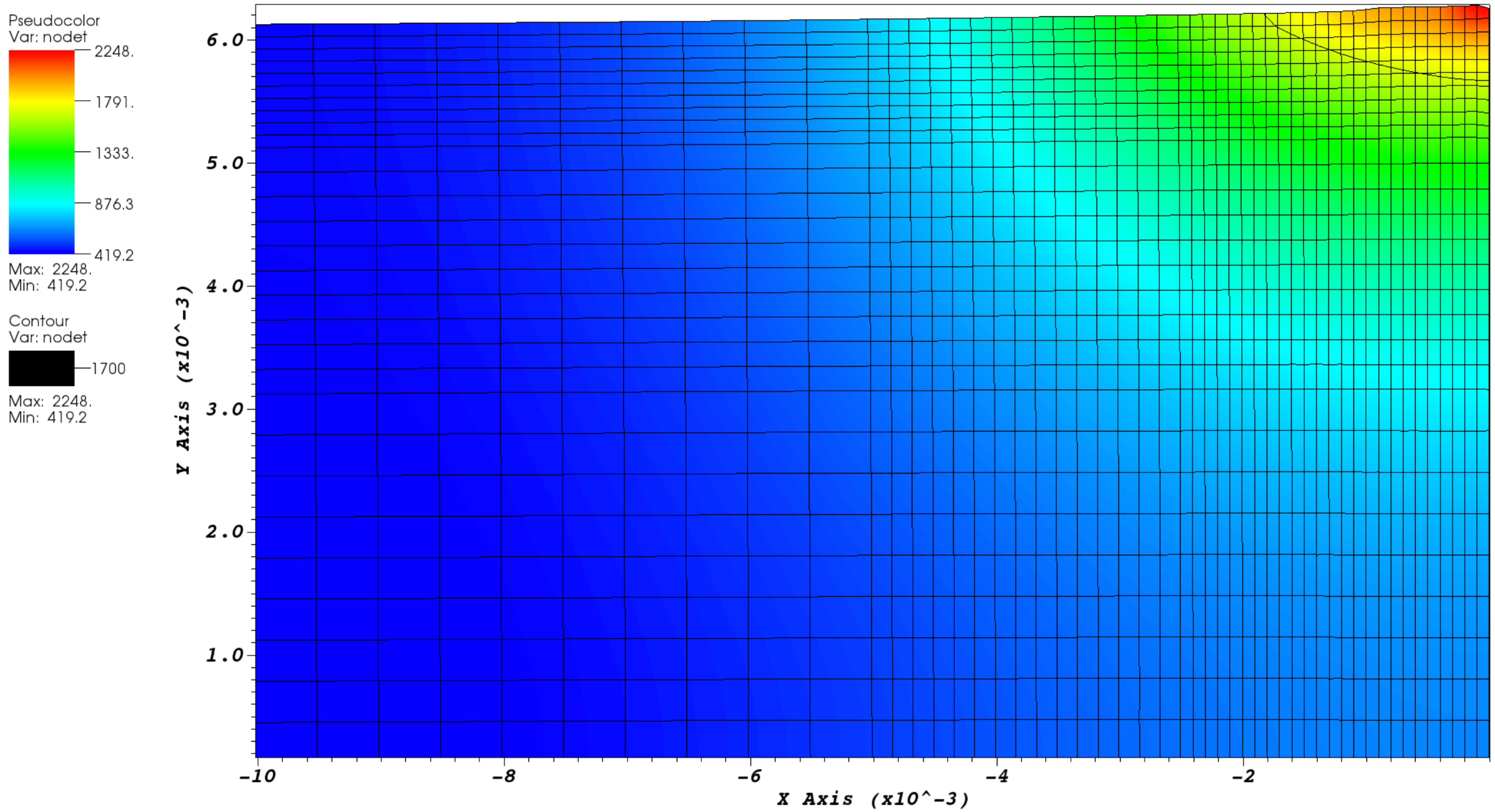
$t = 30\ \mu s$

Start to melt:
Reaching 1700 K

10^{-3} cm = 10 μm

Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; scanning speed $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 7.53×10^5 cm^{-1} (bulk)



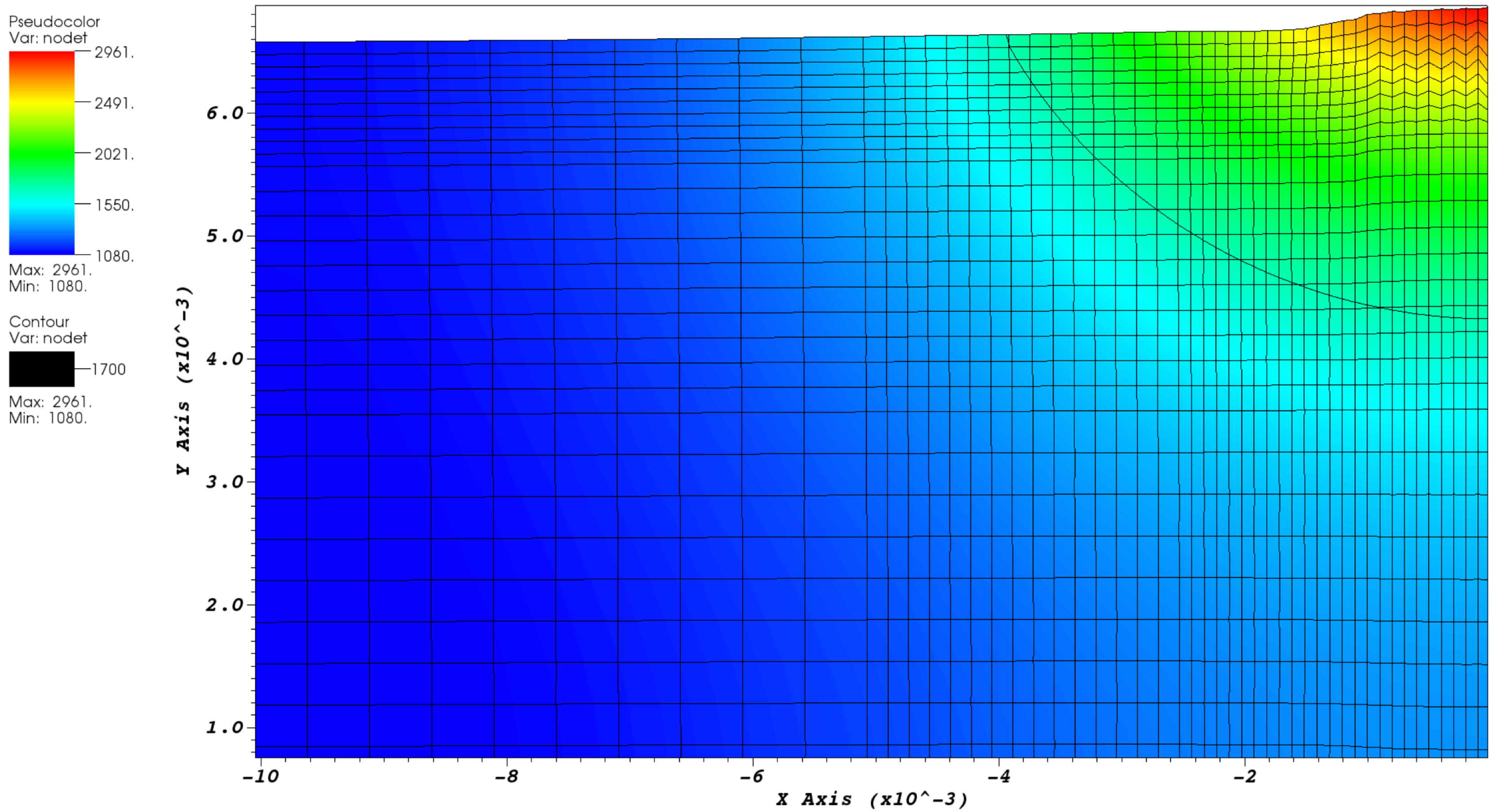
$t = 170\ \mu s$

melt width: 36 μm
melt depth: 4.5 μm

width:depth = 8:1

Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; scanning speed $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 7.53×10^5 cm^{-1} (bulk)



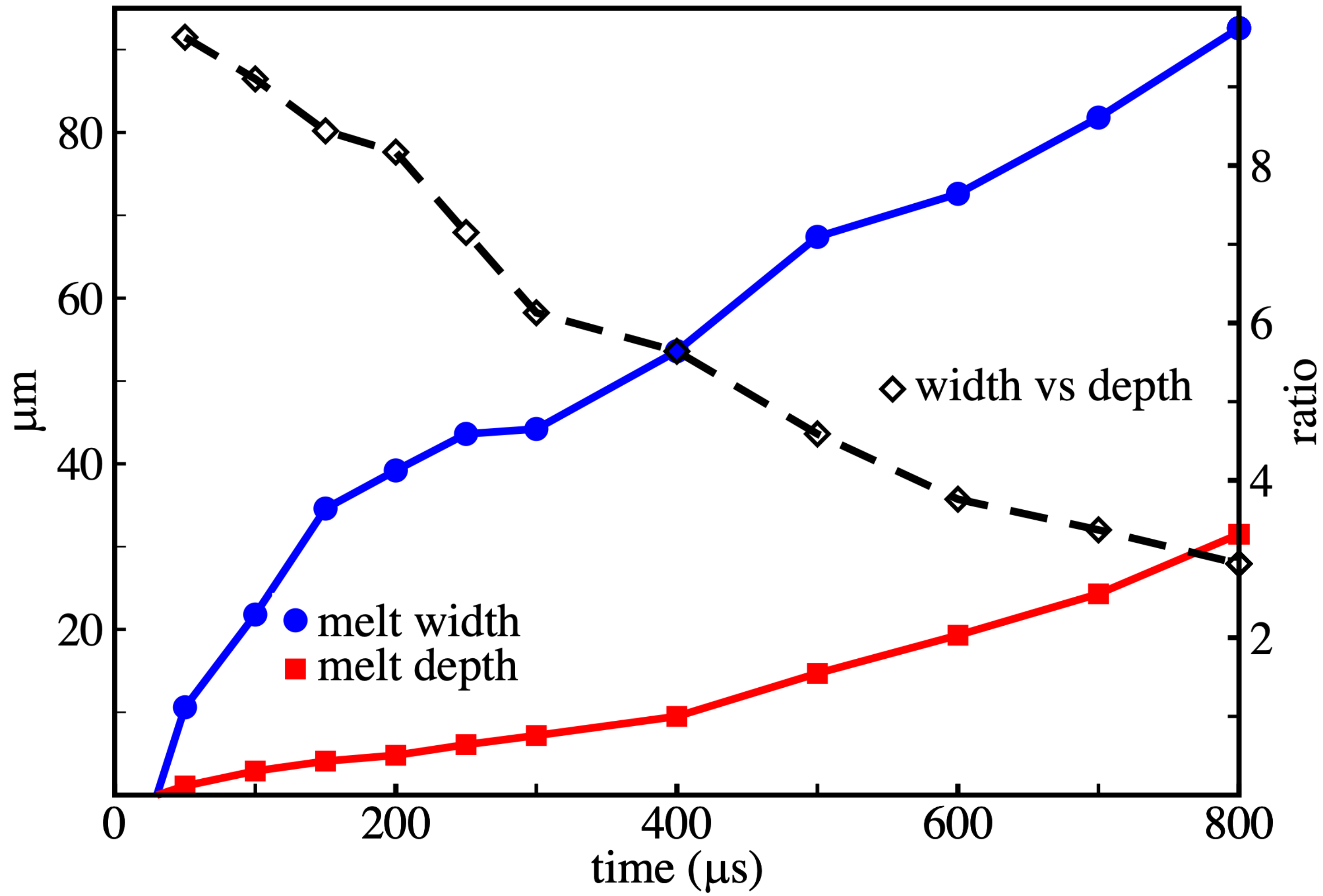
$t = 670$ μs

melt width: 79 μm
melt depth: 23 μm

width:depth = 3.4:1

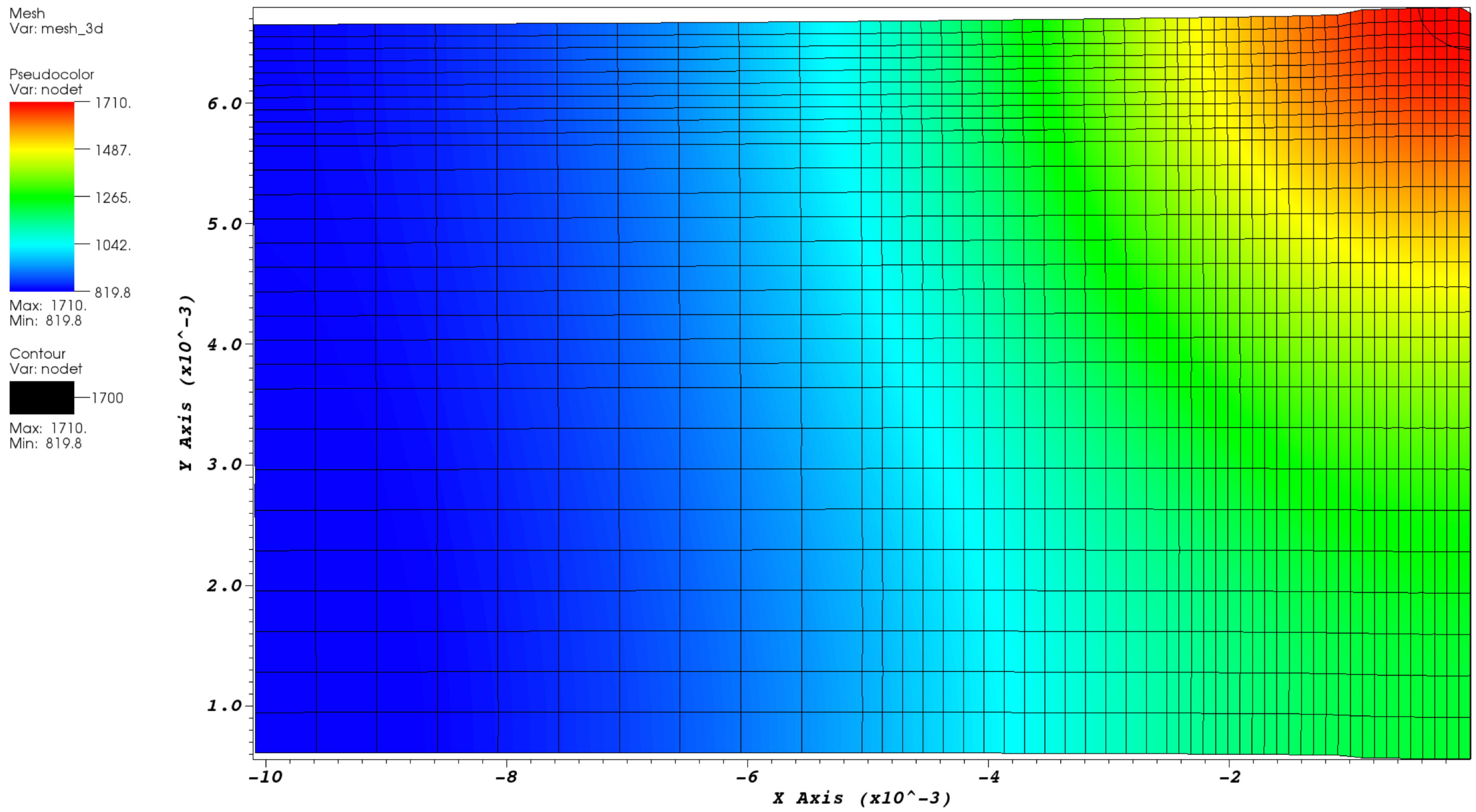
Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; scanning speed $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 7.53×10^5 cm^{-1} (bulk)



Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 500 cm^{-1} (powder, $d = 57$ μm)



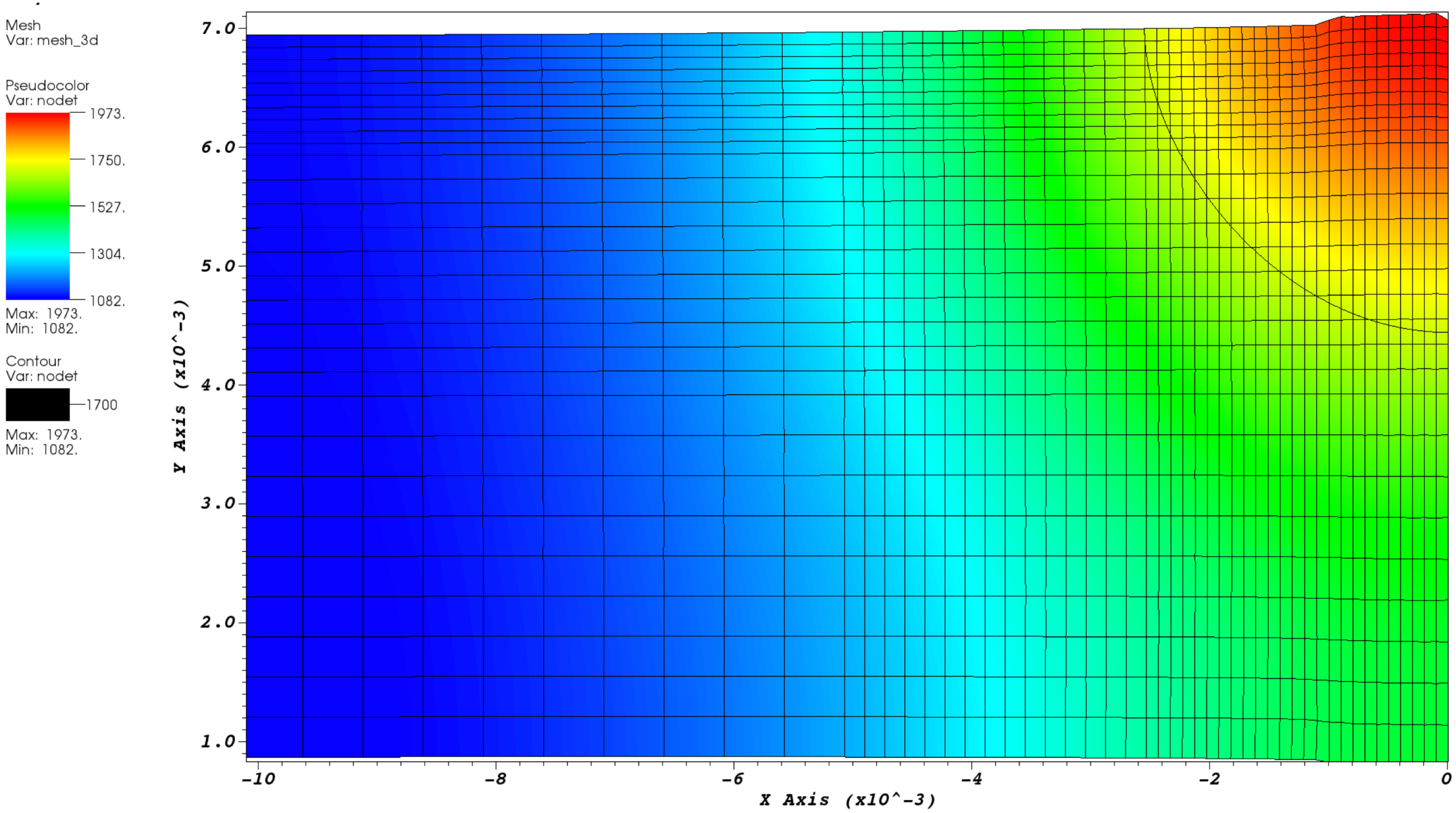
$t = 470$ μs

Start to melt

10^{-3} cm = 10 μm

Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 500 cm^{-1} (powder, $d = 57$ μm)



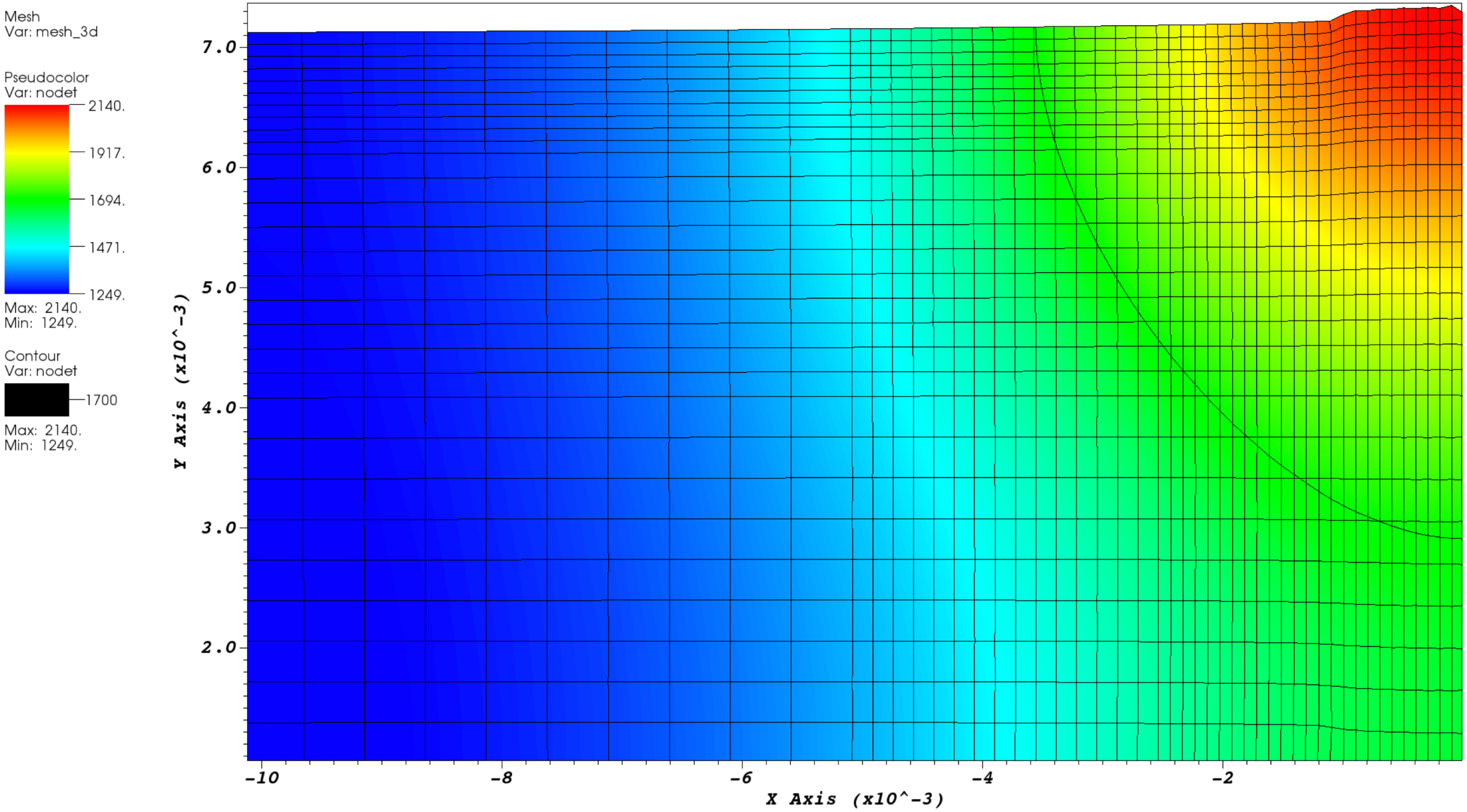
$t = 670$ μs

melt width: 50 μm
melt depth: 25 μm

width:depth = 2:1

Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94 \times 10^5$ W/cm^2; $v = 0$
- Absorptivity: 0.44; Extinction coefficient β: 500 cm^{-1} (powder, $d = 57$ μm)



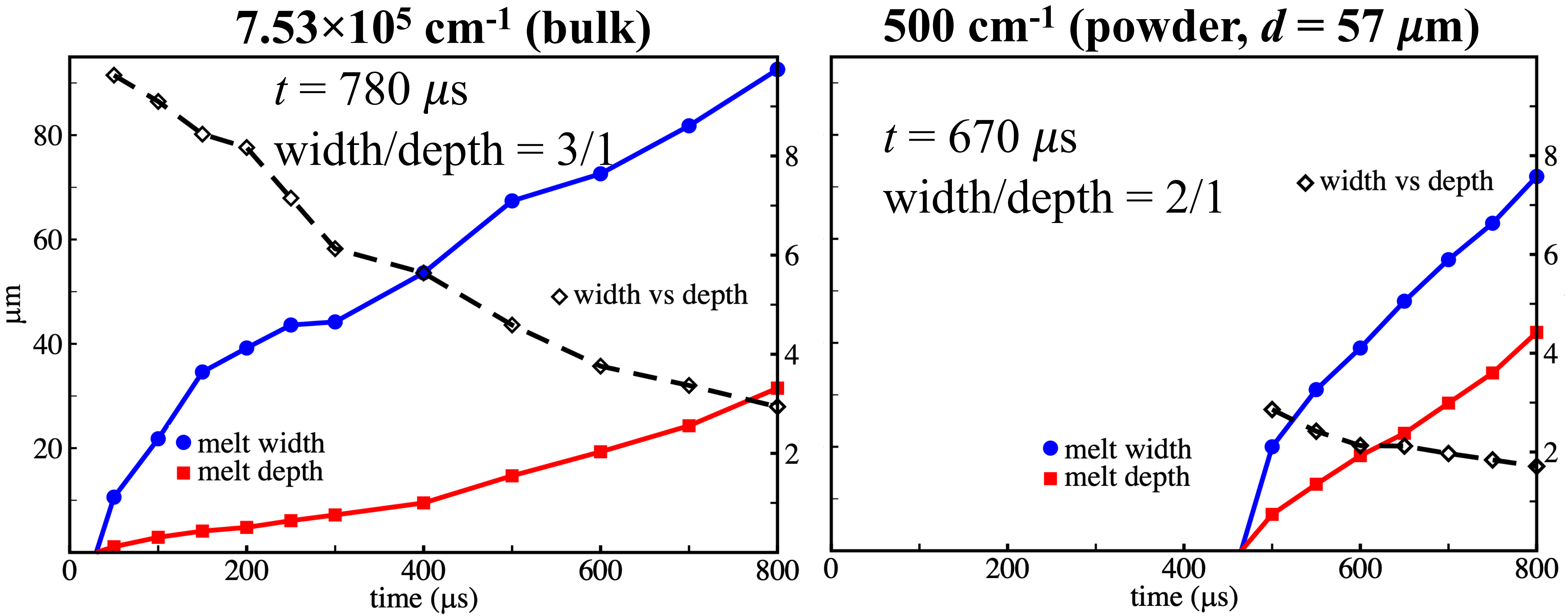
$t = 800$ μs

melt width: 72 μm
melt depth: 42 μm

width:depth = 1.7:1

Present ALE3D Simulations

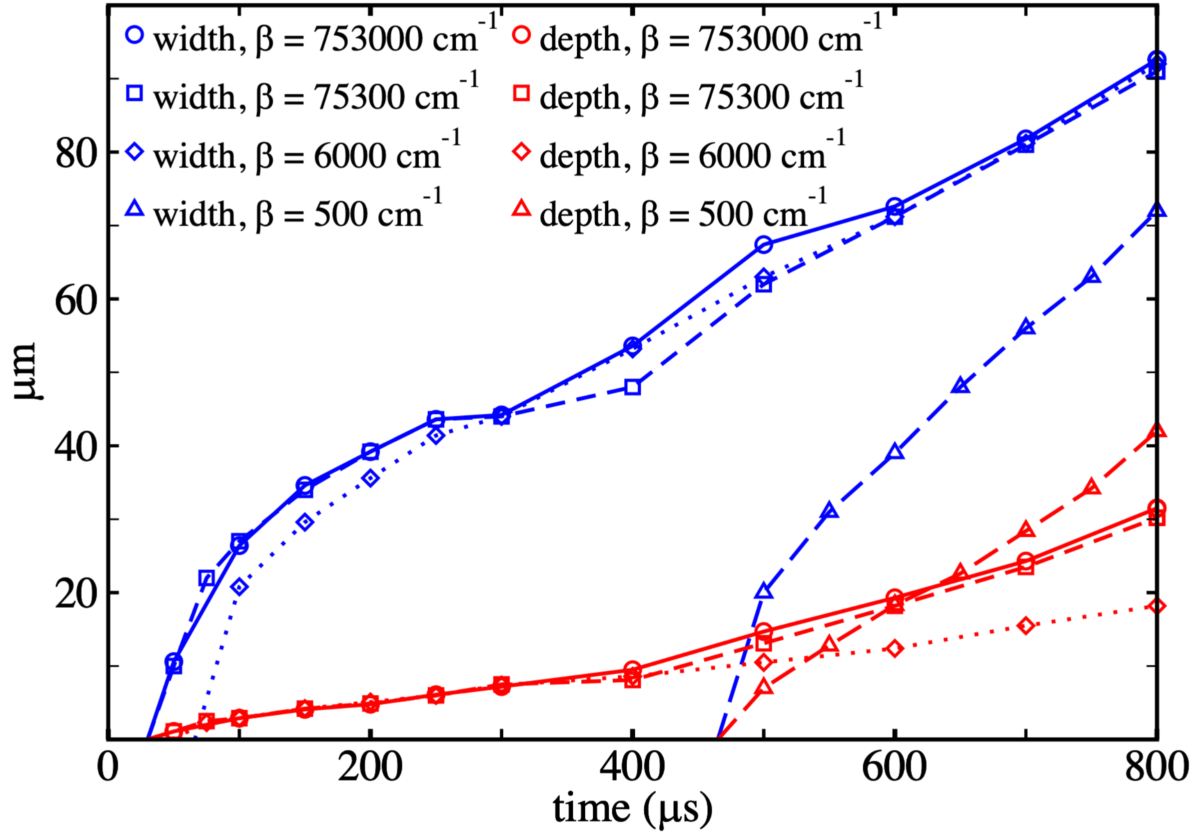
- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; $v = 0$
- Absorptivity: 0.44; Extinction coefficient β are different



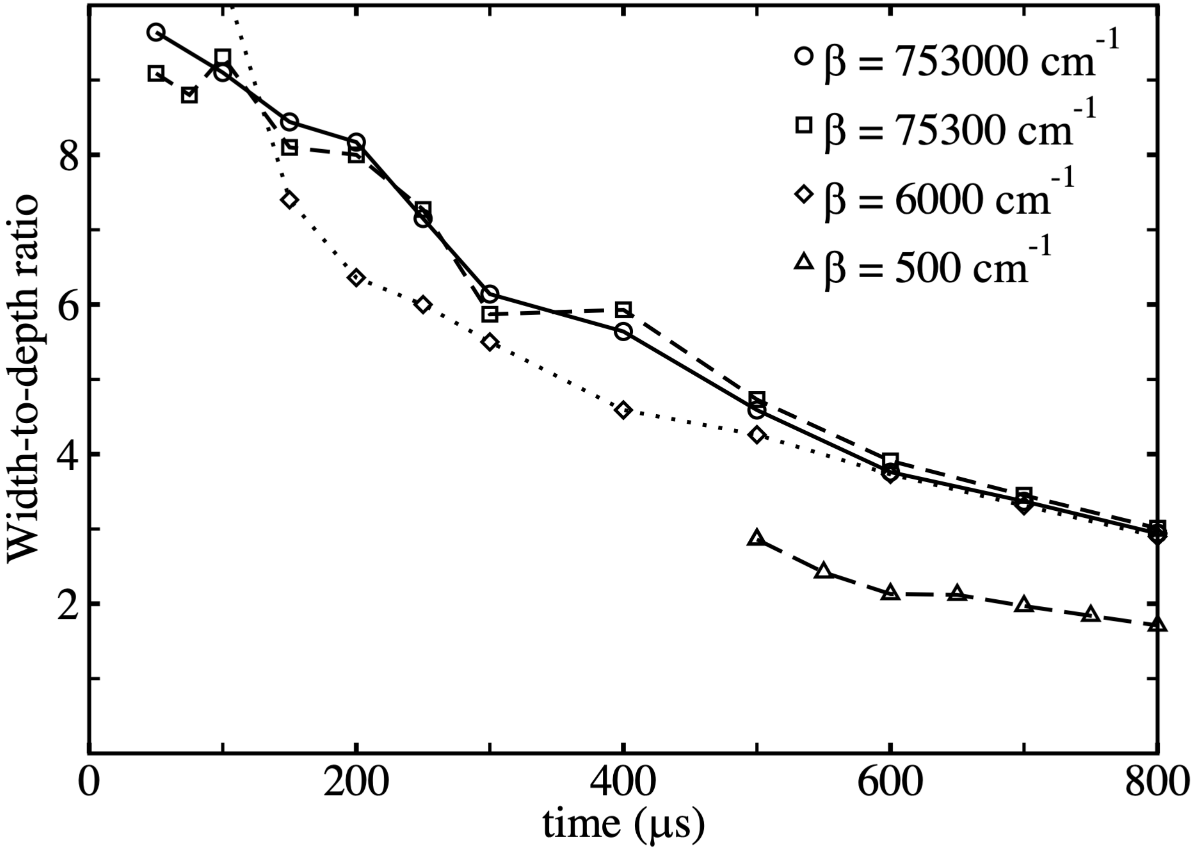
Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; $v = 0$
- Absorptivity: 0.44; Extinction coefficient β are different

Melt width and depth



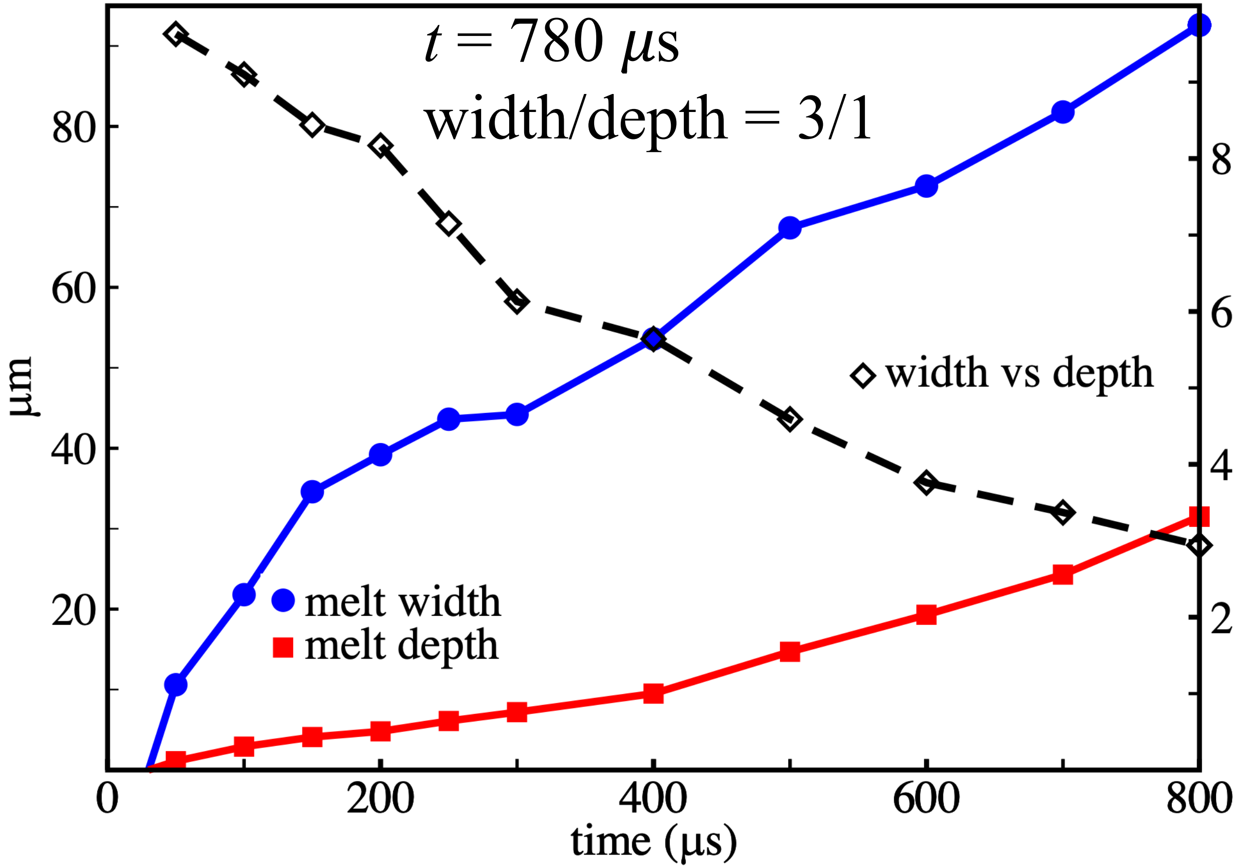
Width-to-depth ratio



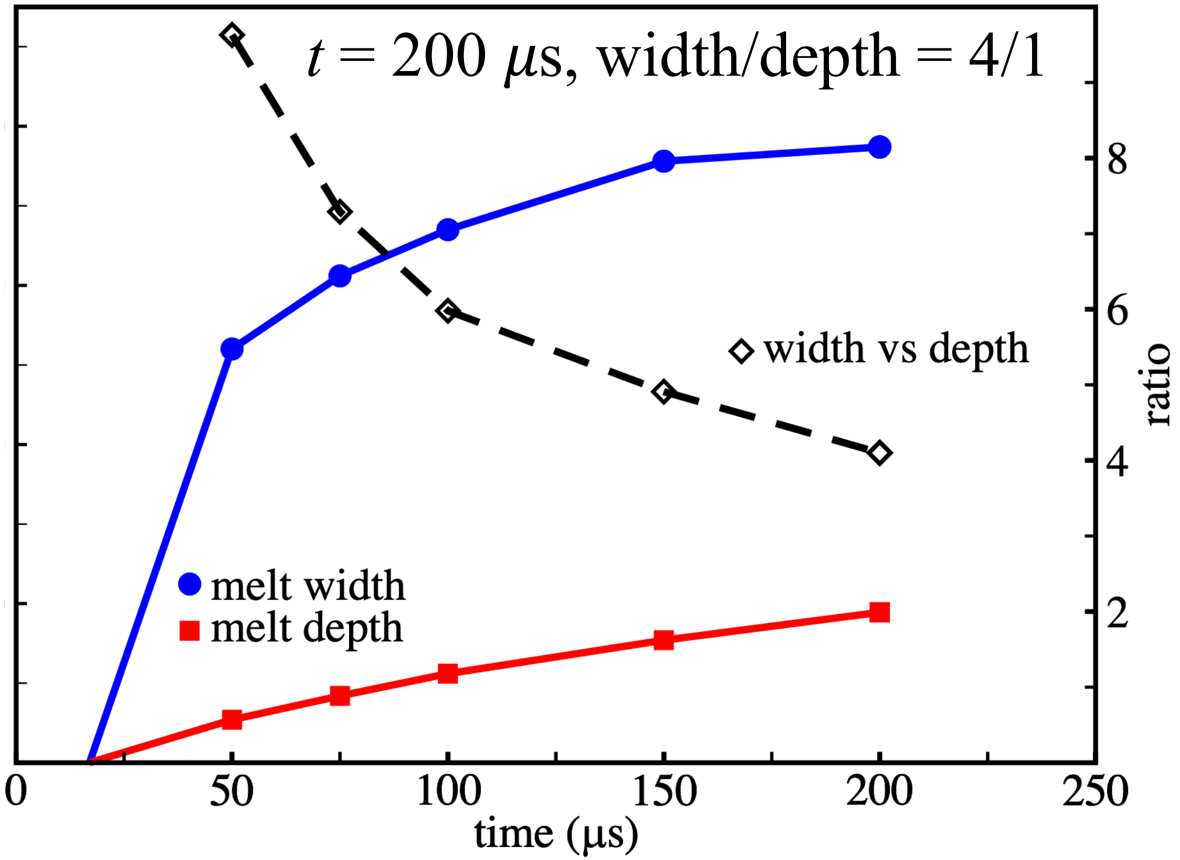
Present ALE3D Simulations

- $v = 0$; absorptivity: 0.44; β: 7.53×10^5 cm^{-1}

P = 22.5 W, FWHM = 50 μm
$p_0 = 7.94\times10^5$ W/cm^2



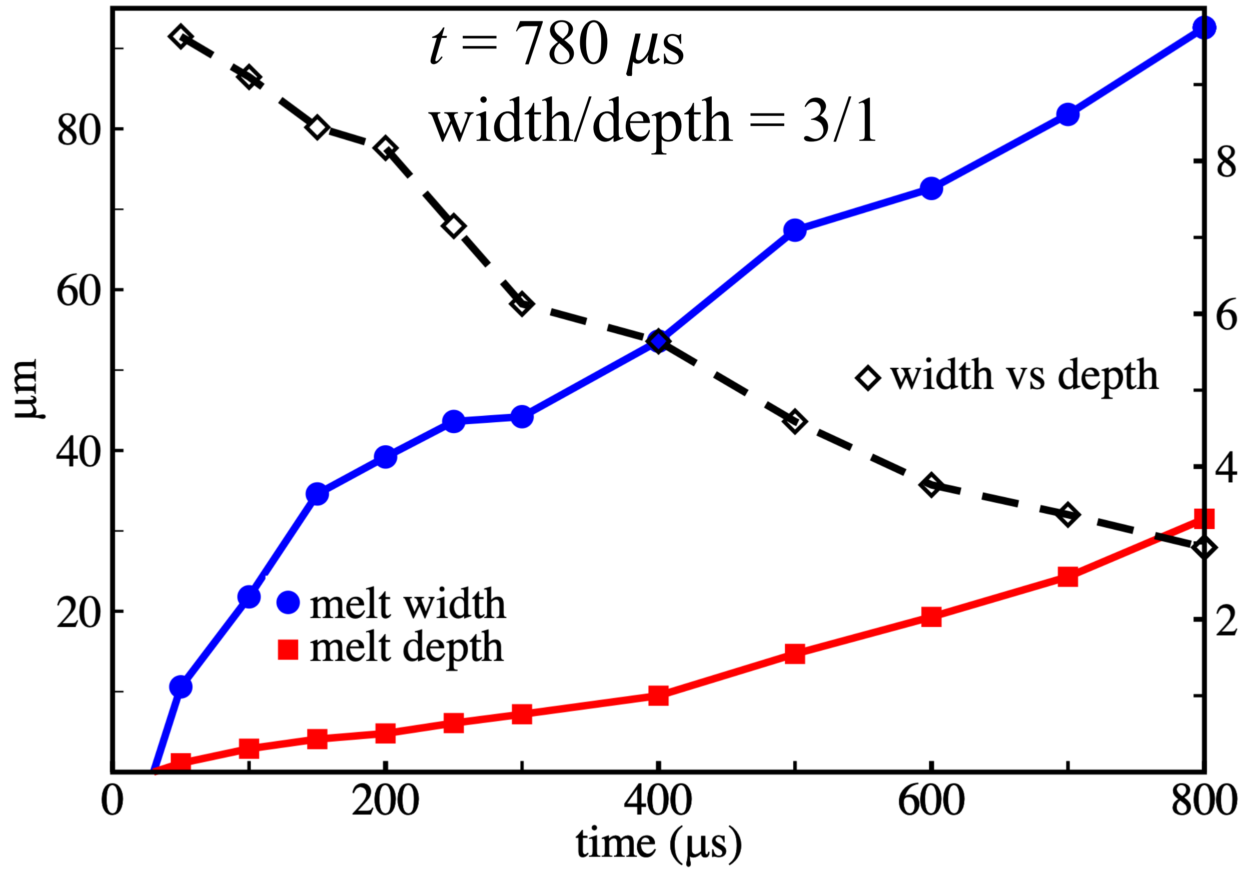
P = 45 W, FWHM = 60 μm
$p_0 = 11.03\times10^5$ W/cm^2



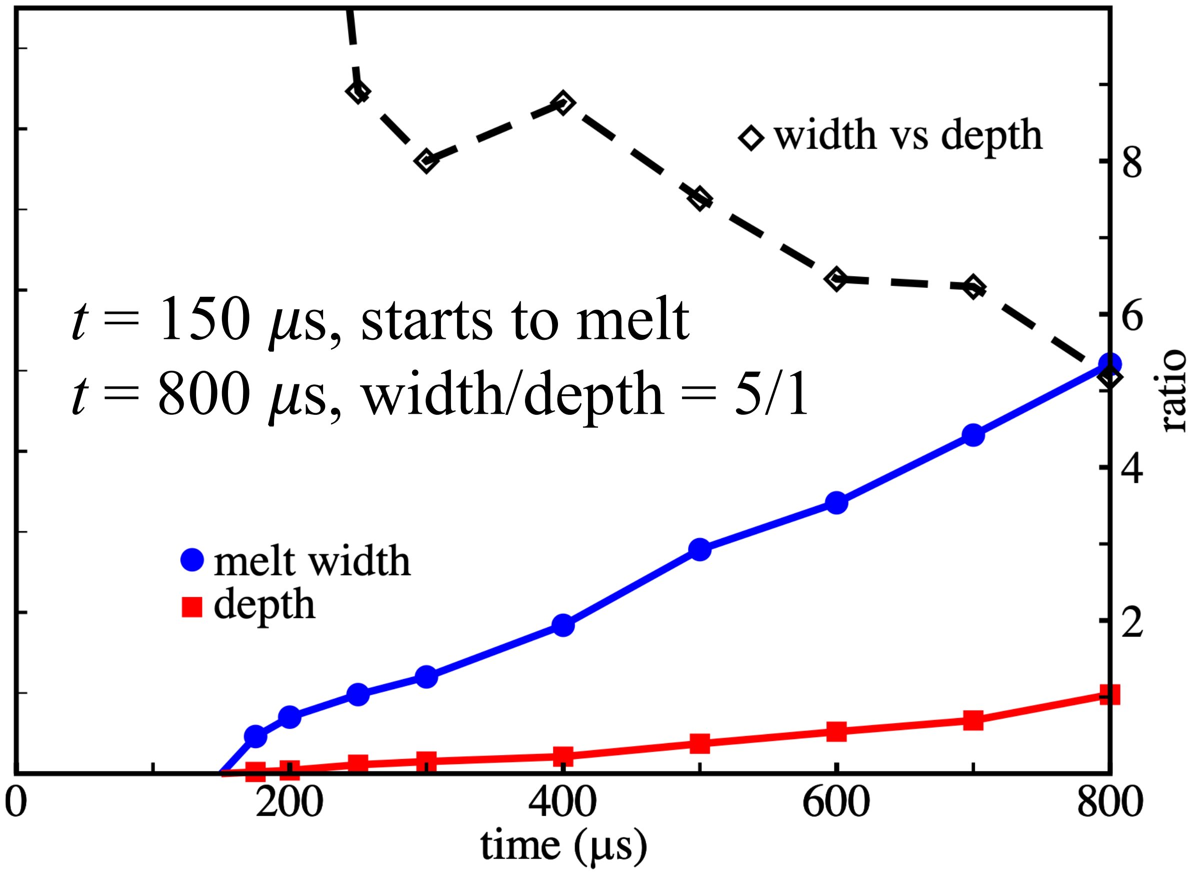
Present ALE3D Simulations

- Power: 22.5 W; FWHM: 50 μm; $p_0 = 7.94\times10^5$ W/cm^2; $v = 0$
- Extinction coefficient β: 7.53×10^5 cm^{-1} (bulk)

Absorptivity: 0.44



Absorptivity: 0.30



Laser Scanning

- q_0 is the maximum incident energy per unit area (J/cm^2)
- For on-spot laser ($v = 0$)

$$q_0(x,z) = q_0 \exp\left(-\frac{x^2}{2\sigma^2} - \frac{z^2}{2\sigma^2}\right)$$

with $q_0 = \tau p_0$

- $P = 22.5$ W, $FWHM = 50$ µm, $v = 15$ cm/s, $q_0 = 282$ J/cm^2
- $P = 45.0$ W, $FWHM = 60$ µm, $v = 30$ cm/s, $q_0 = 235$ J/cm^2

Assuming laser is circular:

$$p(x,z,t) = p_0 \exp\left(-\frac{x^2}{2\sigma^2} - \frac{(z-vt)^2}{2\sigma^2}\right)$$

$$q_0(x) = q_0 \exp\left(-x^2 / 2\sigma^2\right)$$

$$q_0 = \frac{1}{\sqrt{2\pi}} \frac{P}{\sigma v} = 2\sqrt{\frac{\ln(2)}{\pi}} \frac{P}{FWHM \cdot v}$$

$$= 0.9394 \frac{P}{FWHM \cdot v}$$

Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 15 cm/s**

P = 22.5 W; $FWHM$ = 50 μm

q_0 = 282 J/cm^2

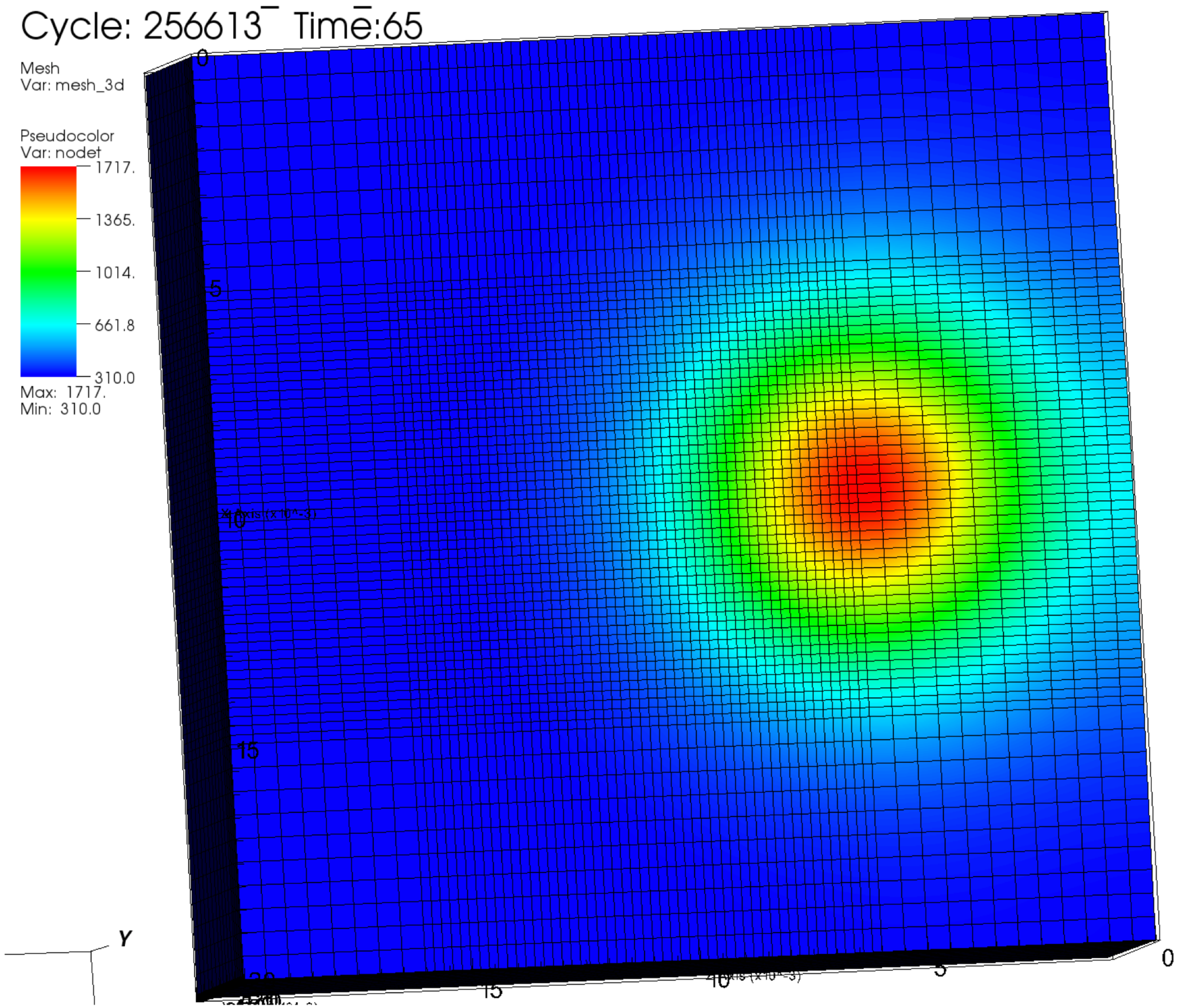
$\tau = FWHM/v$ = 333 μs

Absorptivity: 0.44

$\beta = 7.53\times10^5$ cm^{-1}

t = 65 μs, start to melt v = 15 cm/s

t = 30 μs, start to melt v = 0



Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 15 cm/s**

$P = 22.5$ W; $FWHM = 50\ \mu m$

$q_0 = 282\ \mathrm{J/cm^2}$

$\tau = FWHM/v = 333\ \mu s$

Absorptivity: 0.44

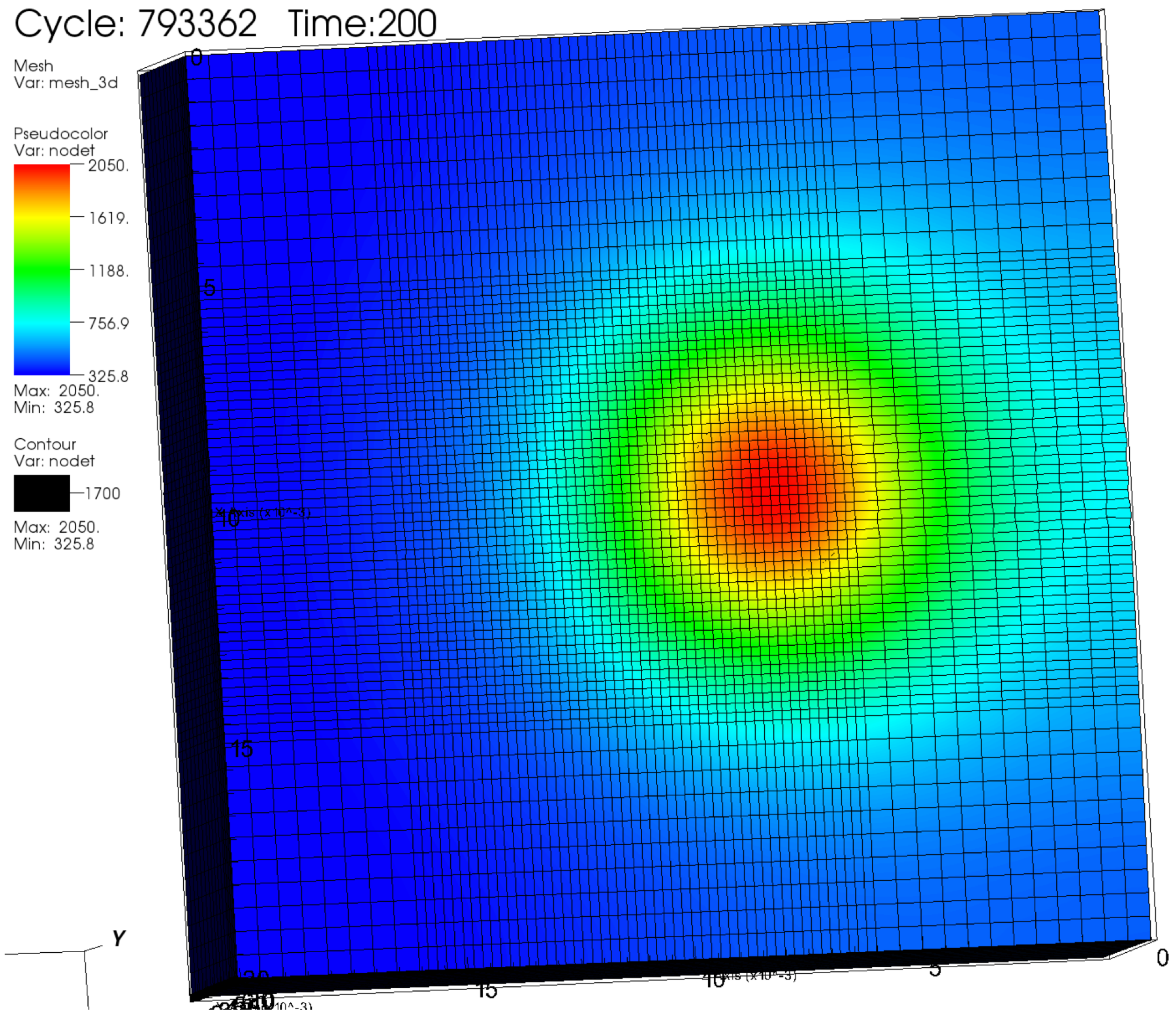
$\beta = 7.53\times10^5\ \mathrm{cm^{-1}}$

$t = 200\ \mu s$, $v = 15$ cm/s

width = 31 μm, depth = 4.5 μm

$t = 200\ \mu s$, $v = 0$

width = 39 μm, depth = 5 μm



Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 30 cm/s**

$P = 45$ W; $FWHM = 60\ \mu$m

$q_0 = 235$ J/cm^2

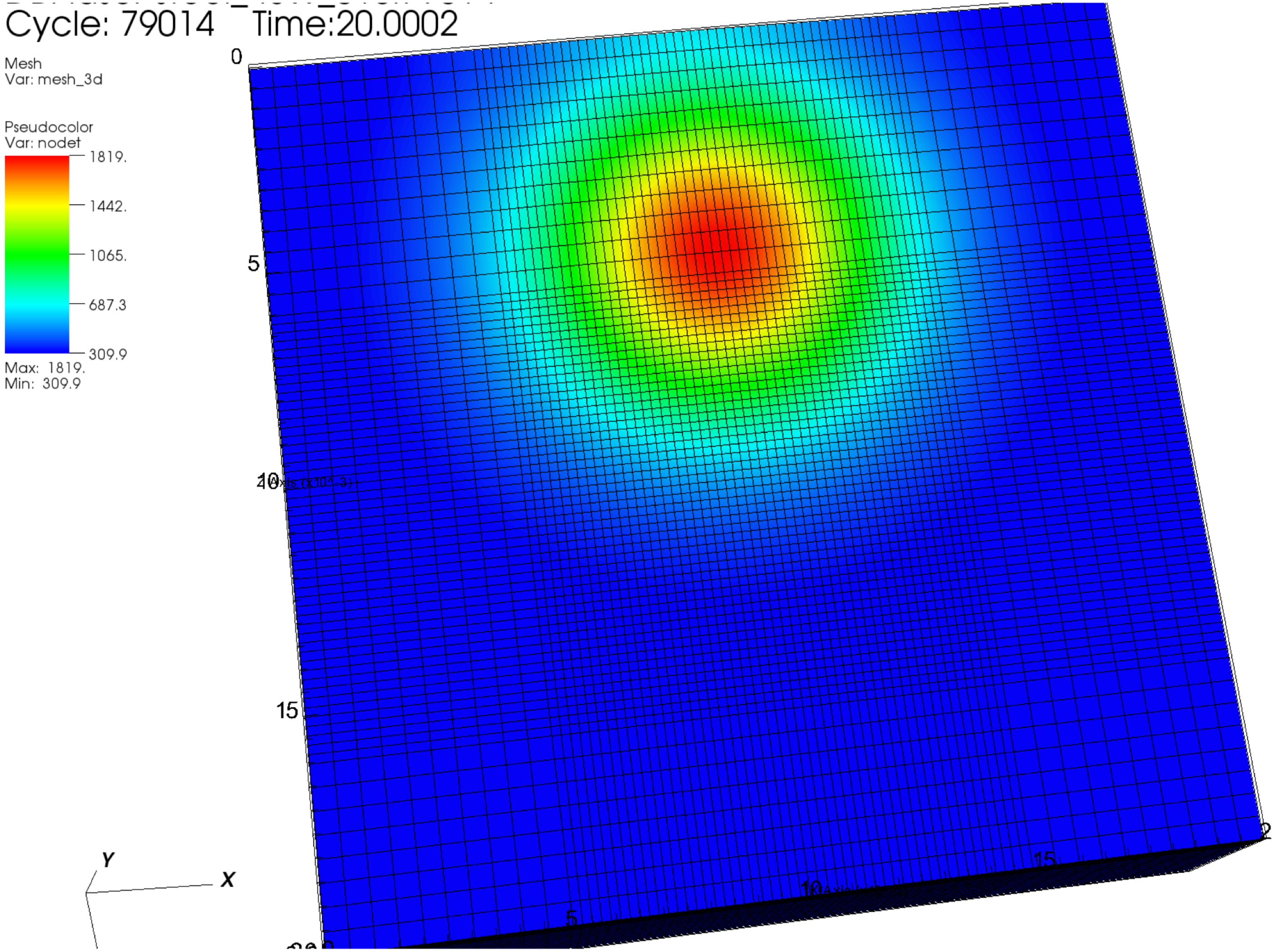
$\tau = FWHM/v = 200\ \mu$s

Absorptivity: 0.44

$\beta = 7.53\times10^5$ cm^{-1}

$t = 18\ \mu$s, start to melt $v = 30$ cm/s

$t = 17\ \mu$s, start to melt $v = 0$



Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 30 cm/s**

$P = 45$ W; $FWHM = 60\ \mu$m

$q_0 = 235$ J/cm^2

$\tau = FWHM/v = 200\ \mu$s

Absorptivity: 0.44

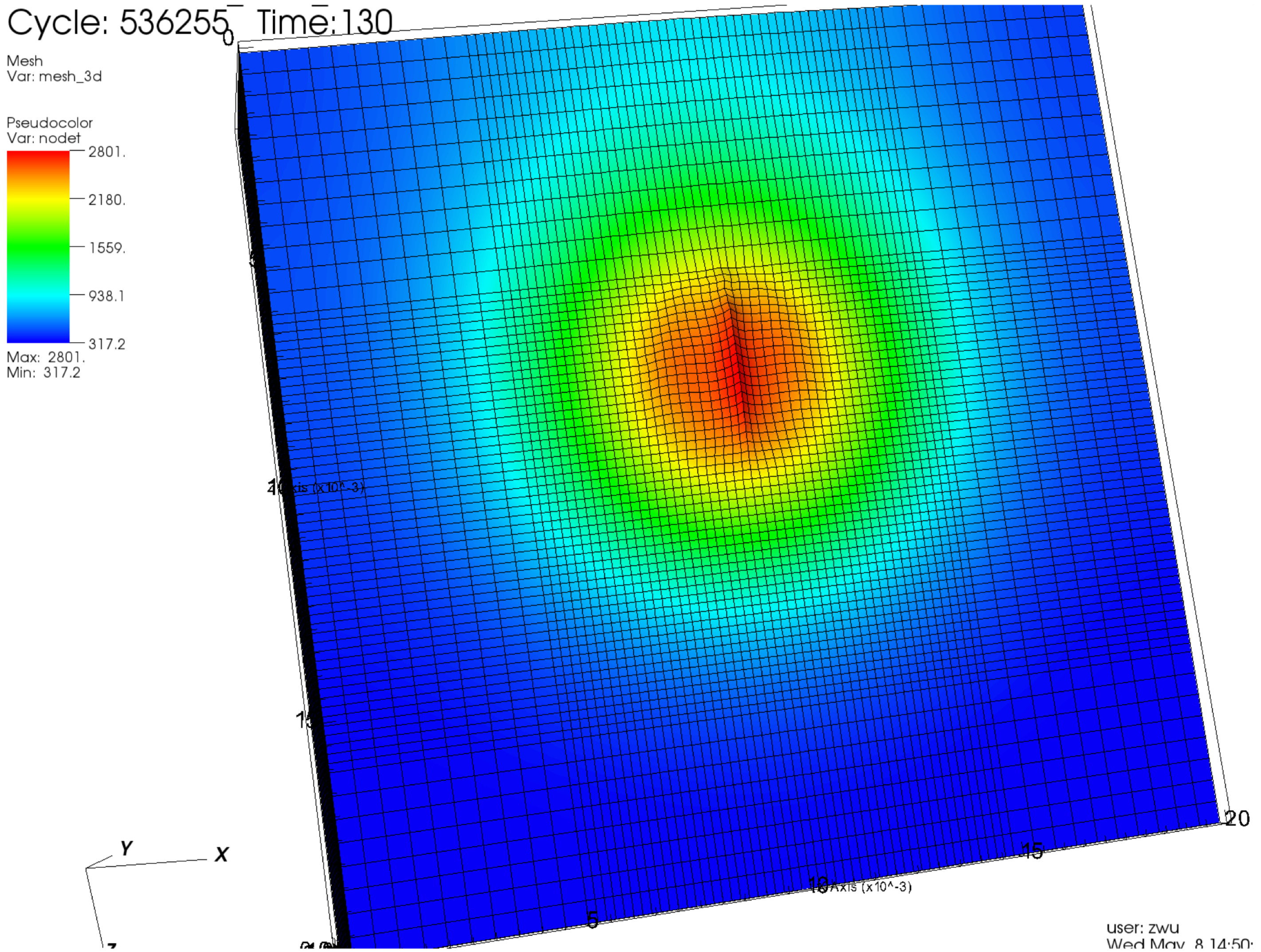
$\beta = 7.53\times10^5$ cm^{-1}

$t = 130\ \mu$s, $v = 30$ cm/s

width = 67 μm, depth = 12 μm

$t = 130\ \mu$s, $v = 0$

width = 72 μm, depth = 13 μm



Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 38 cm/s**

P = 92 W; $FWHM$ = 54 μm

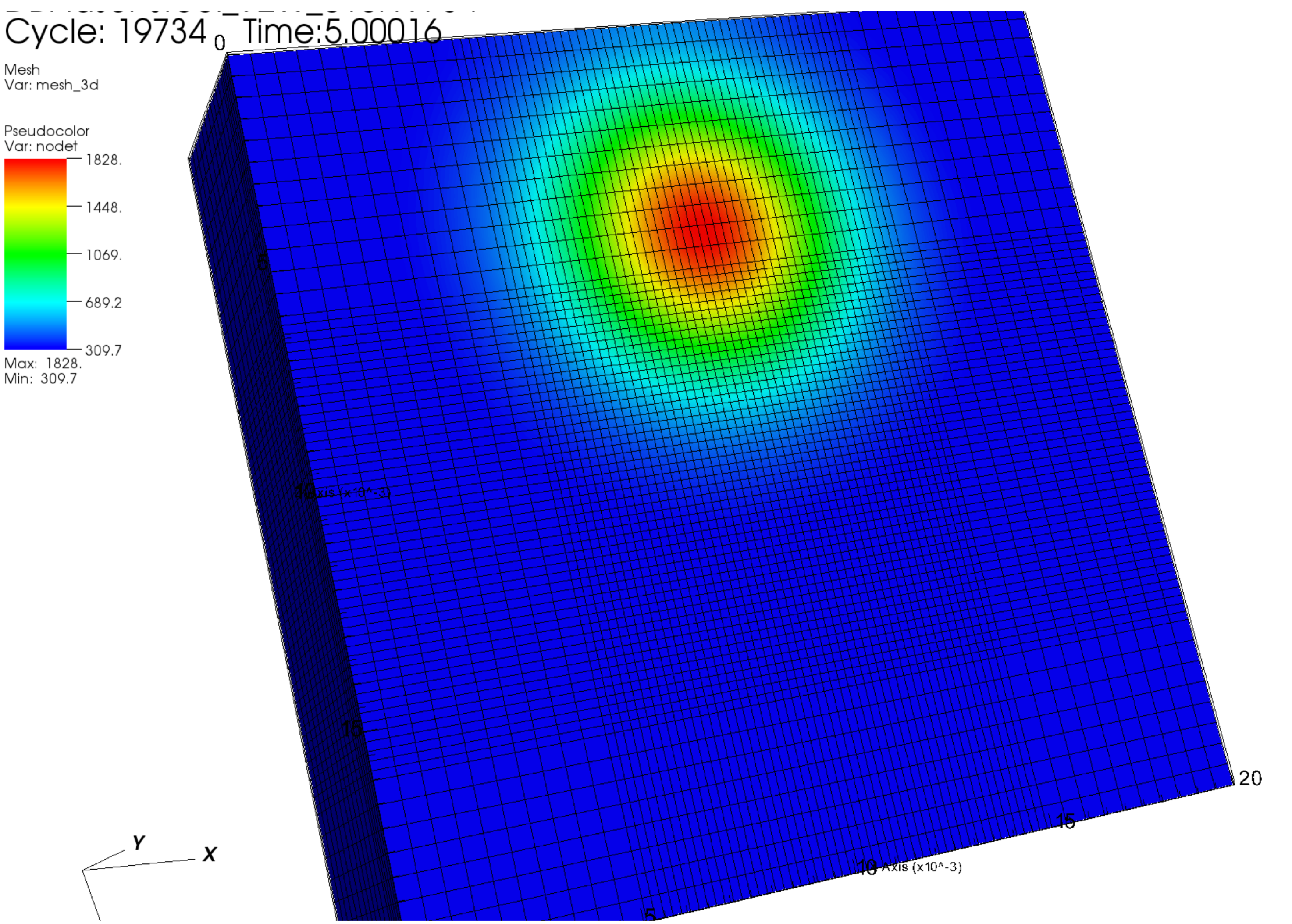
q_0 = 396 J/cm^2

$\tau = FWHM/v$ = 142 μs

Absorptivity: 0.44

$\beta = 7.53 \times 10^5$ cm^{-1}

t = 4 μs, start to melt



Present ALE3D Simulations

- 3D simulations for scanning laser
- **Scanning speed v = 38 cm/s**

$P = 92$ W; $FWHM = 54\ \mu m$

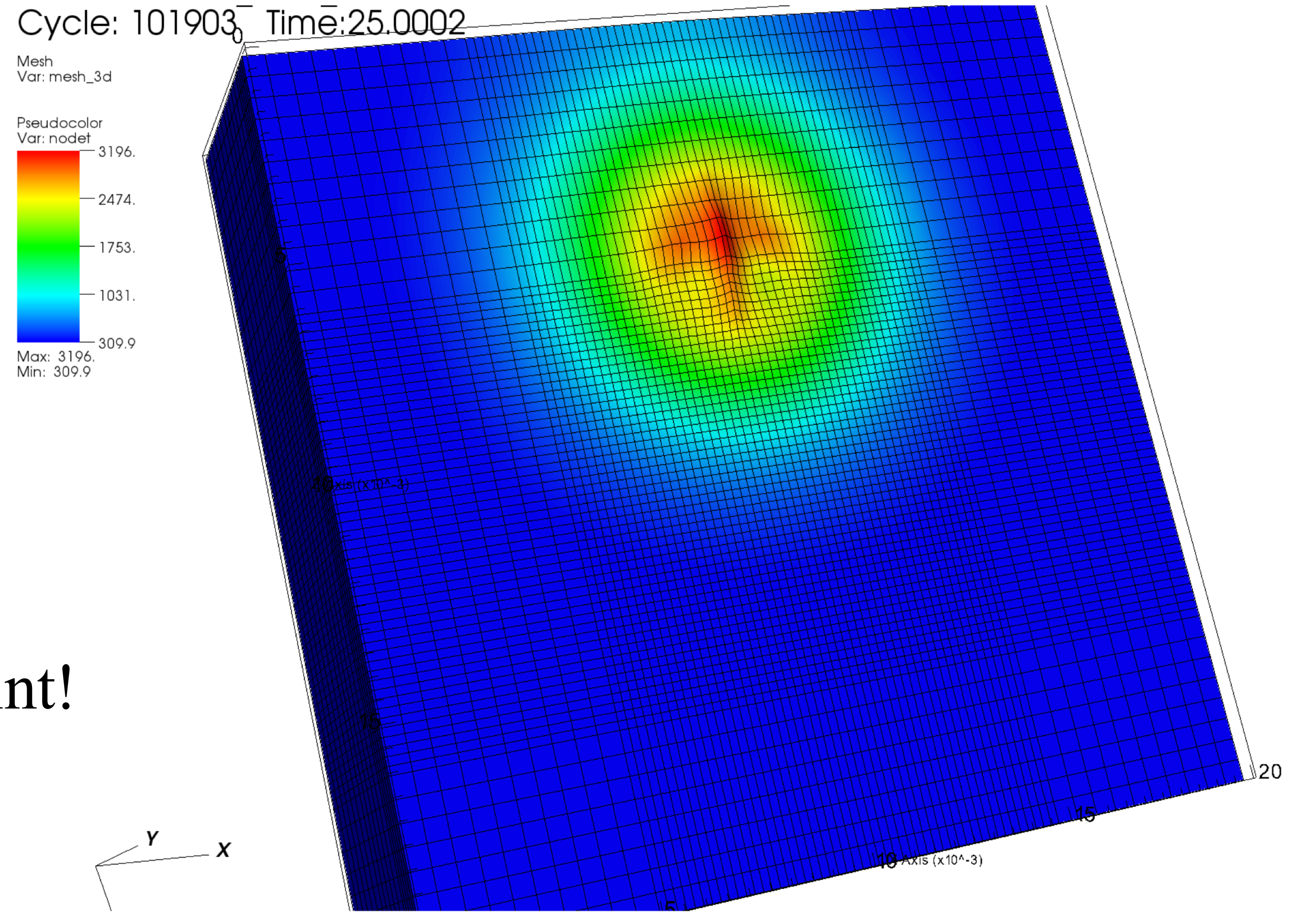
$q_0 = 396$ J/cm^2

$\tau = FWHM/v = 142\ \mu s$

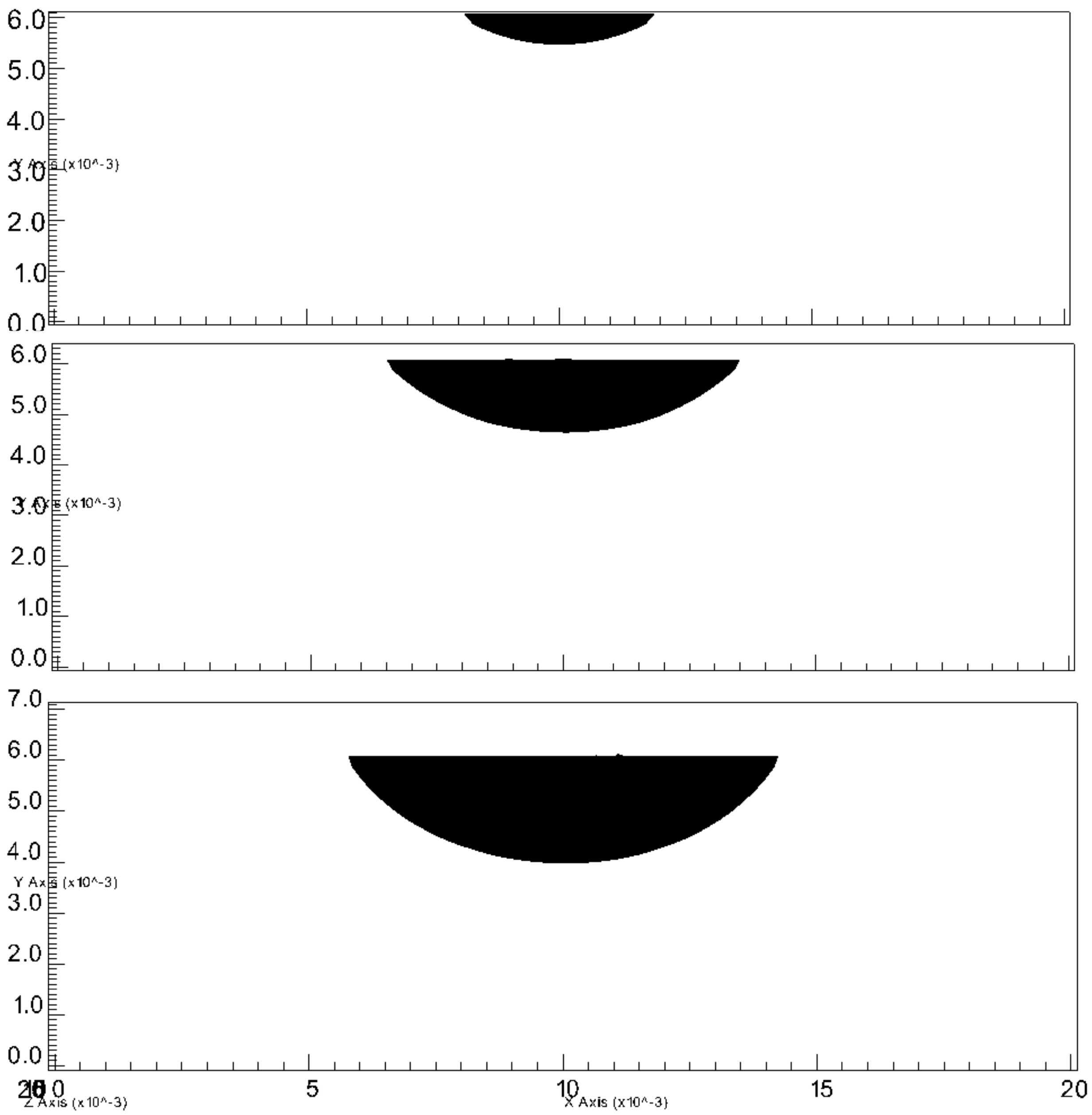
Absorptivity: 0.44

$\beta = 7.53\times10^5$ cm^{-1}

$t = 25\ \mu s$, reaches the boiling point!



Melting of Stainless Steel



- $P = 22.5$ W, $FWHM = 50\ \mu$m
- Absorptivity = 0.44
- $t = 200\ \mu$s

- $P = 45$ W, $FWHM = 60\ \mu$m
- Absorptivity = 0.44
- $t = 130\ \mu$s

- $P = 92$ W, $FWHM = 54\ \mu$m
- Absorptivity = 0.33
- $t = 25\ \mu$s

Conclusions and Future Work

- We have simulated laser heating and melting bulk stainless steel.
- In 2D simulations, we investigated the relations between melt hole size and model parameters, including optical properties of steel and powder distribution of laser, for zero scanning speed.
- In 3D simulations, we studied melting processes using three laser beams with different power, size, and scanning speed.
- In the future we'll study
  - electron beam heating and melting metals
  - electron beam processing metallic powder materials