Digital Twin for Phase Transition Prediction in Laser-Based Additive Manufacturing
A Phase-Field and U-Net Model Framework

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Introduction

Objective

1. To study phase transitions and LIQUID phase behavior under different laser beam profiles.
2. To analyze the effects of Free Energy expressions on phase evolution.
3. To train a U-Net *[1]* ML model using data generated from FEM simulations.
4. To construct a *Digital-Twin* framework capable of predicting phase transitions.

Approach

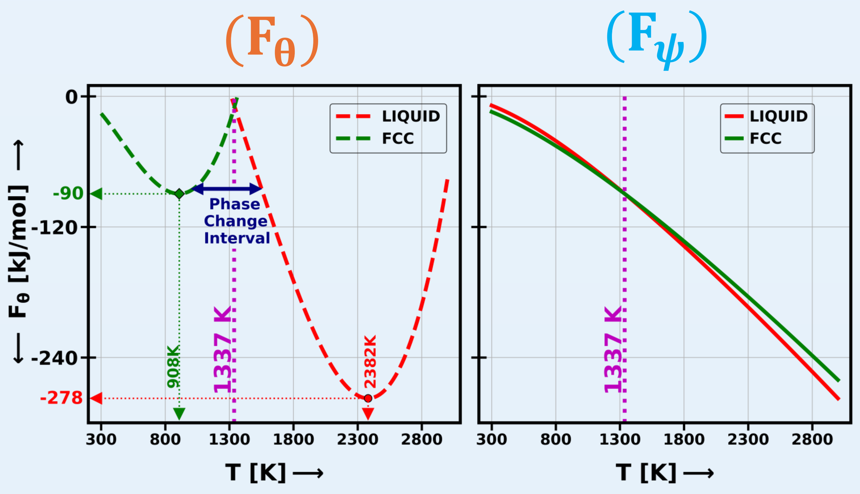
Raspberry-Pi based *Digital-Twin Framework* using a trained ML model to predict real-time phase transition from T-data captured by an *IR Camera*.

Methodology

Thermodynamics

.TDB

- Thermodynamic Database *[2]*
- Free Energies
  - Polynomial Fitting (F_θ)
  - Expression Extraction (F_ψ)



Free Energy Curves

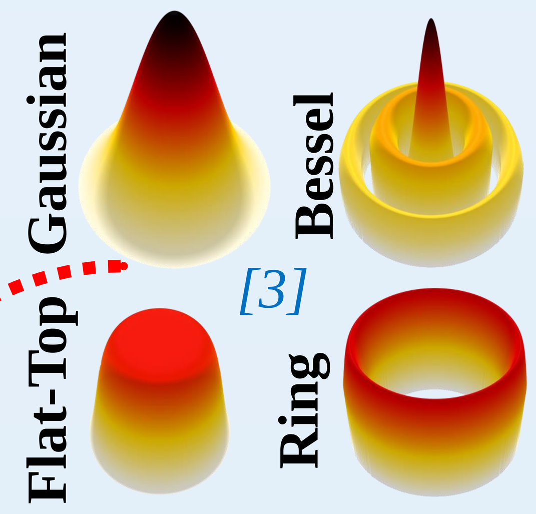
Multi-Physics Modeling

- **Heat Transfer**

i → i^th Phase

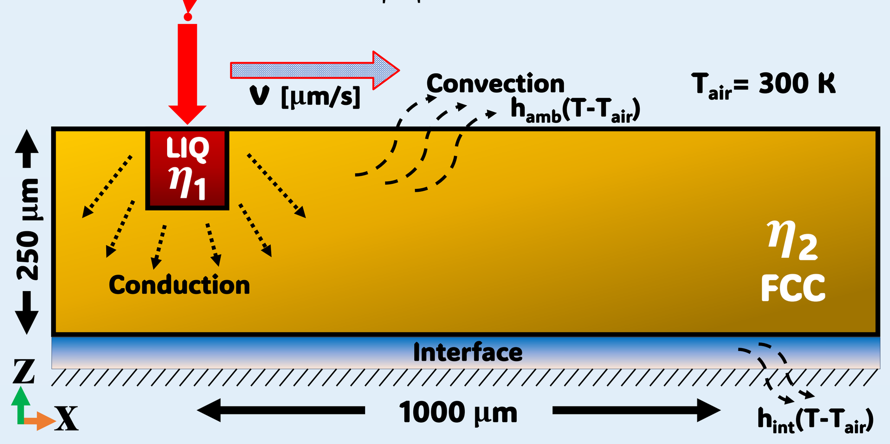
⟨T⟩ → Temperature Dependent

$$\rho^i \langle T\rangle\, C_p^i \langle T\rangle \left(\frac{\partial \boldsymbol{T}}{\partial t} + \vec{u}\,.\nabla T\right) = k_{th}^i \langle T\rangle \nabla^2 \boldsymbol{T} + \boldsymbol{Q}$$



- **Phase-Field**

$$\frac{\partial \eta_i}{\partial t} = -L_i \left(\frac{\partial f_{bulk}\langle T\rangle}{\partial \eta_i} - \nabla.\frac{\partial f_{int}}{\partial \nabla \eta_i}\right)$$

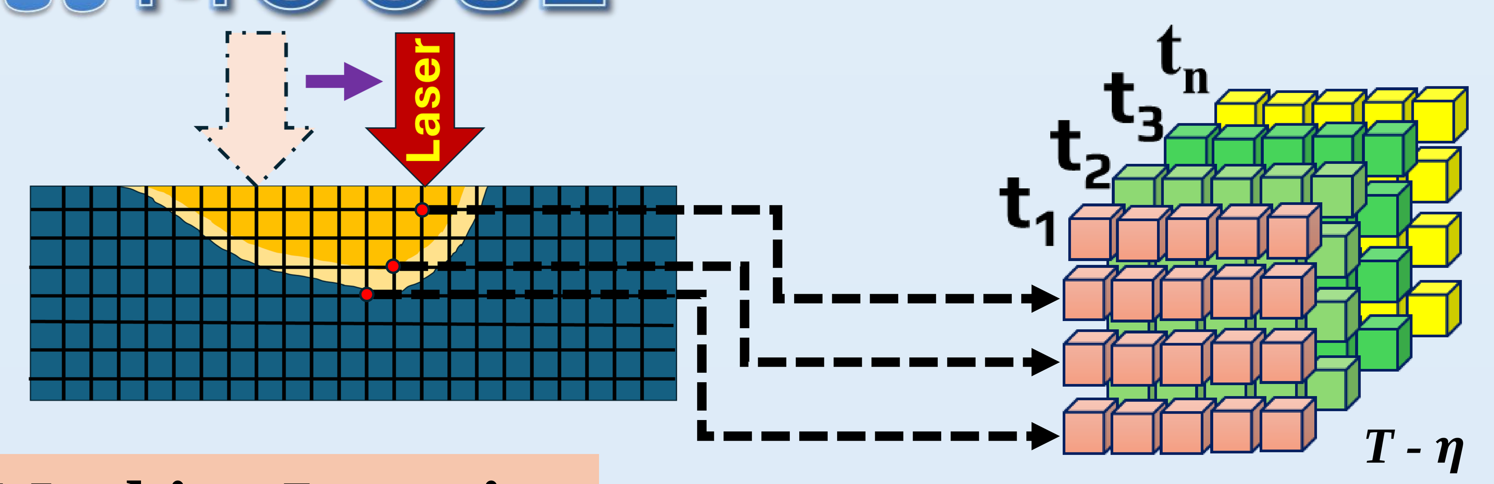


- **Fluid Flow**

$$\nabla.\vec{u} = 0$$

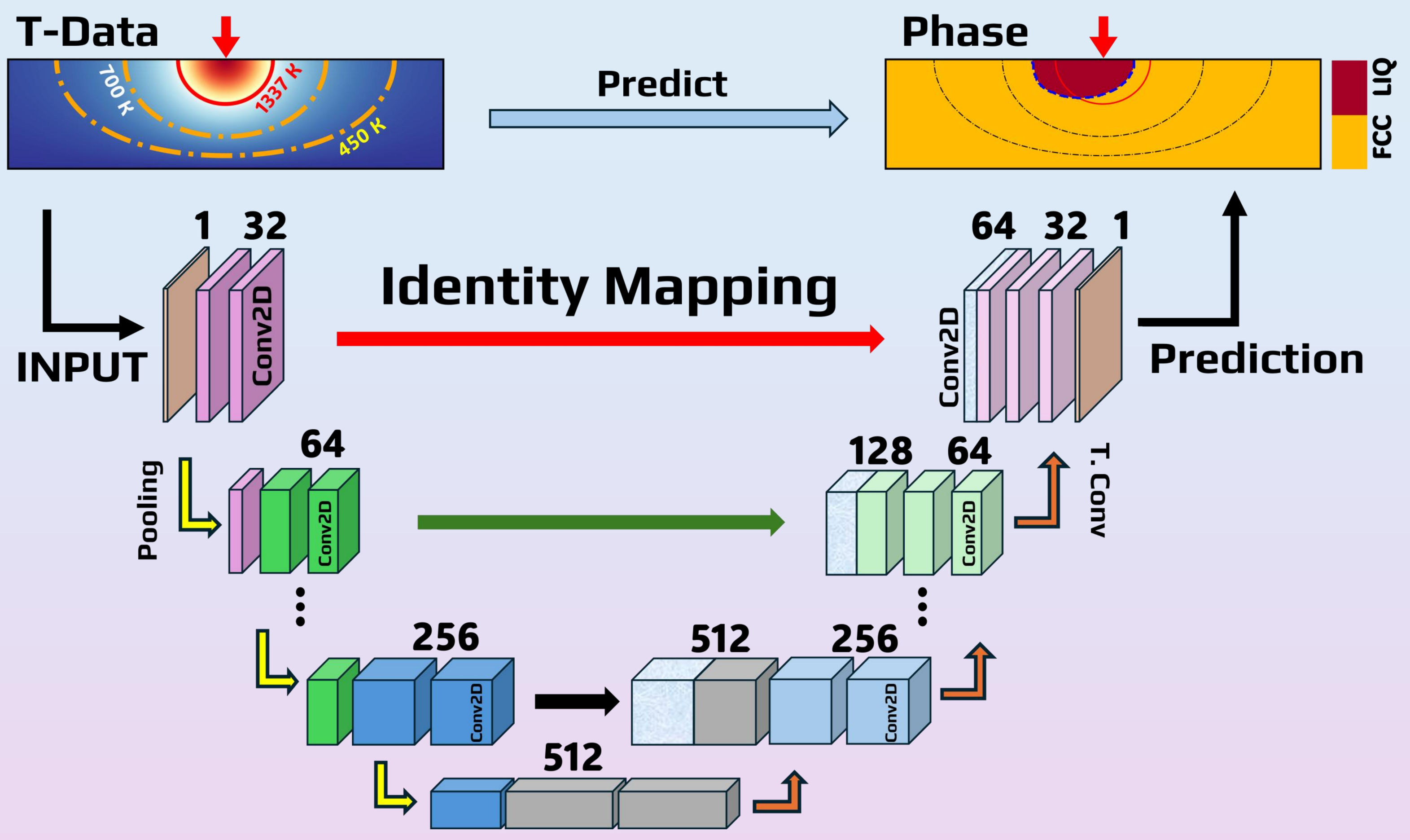
$$\rho^{LIQ}\langle T\rangle \frac{\partial u}{\partial t} + \rho^{LIQ}\langle T\rangle (\vec{u}.\nabla)\vec{u} = -\nabla p \;+\; \mu^{LIQ}\langle T\rangle\, \nabla^2 \vec{u} + F_{bou}$$

MOOSE *[4]* Finite Element Method



Simulation Data Tensor

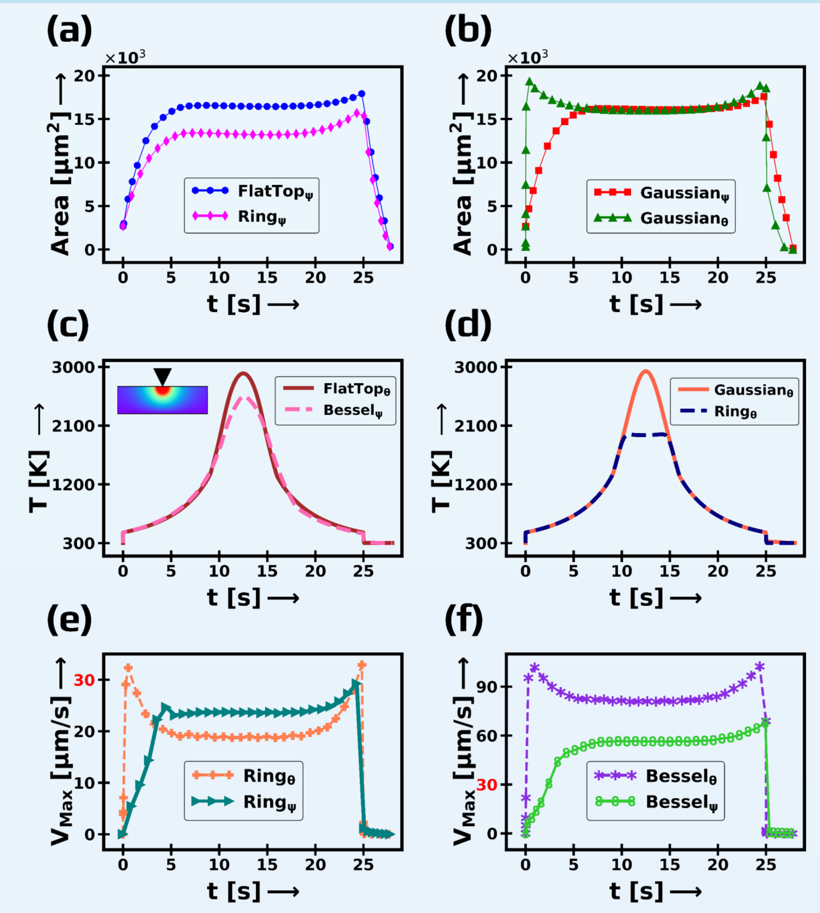
Machine Learning



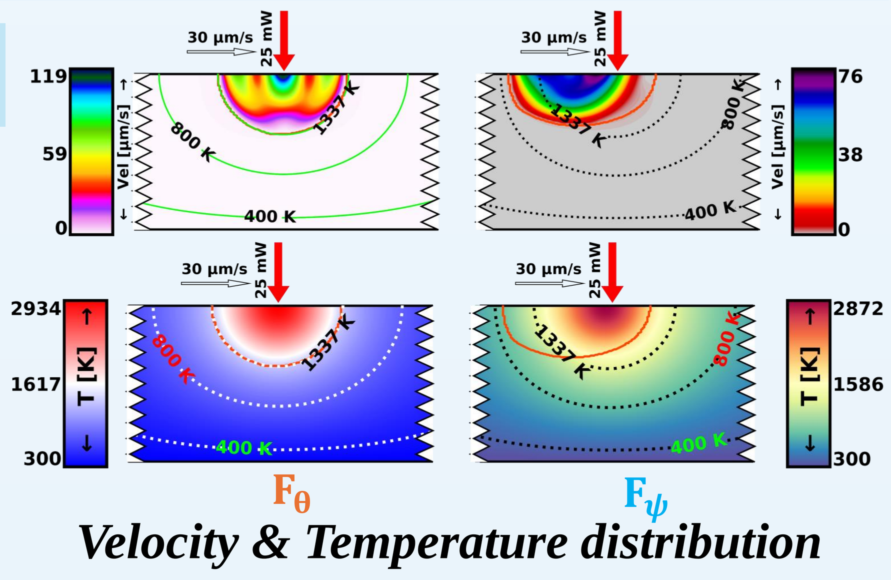
U-Net Model Architecture

Results

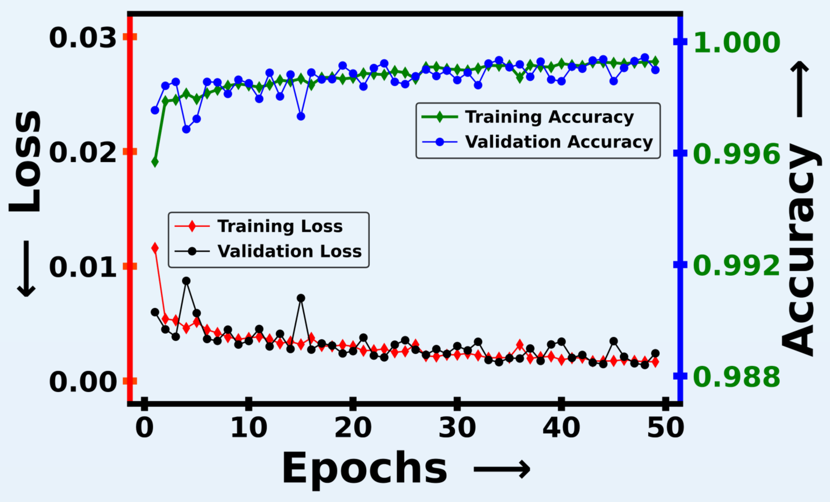
Simulations & Predictions



LIQUID phase area, max Temperature, velocity max (multiple simulation results)

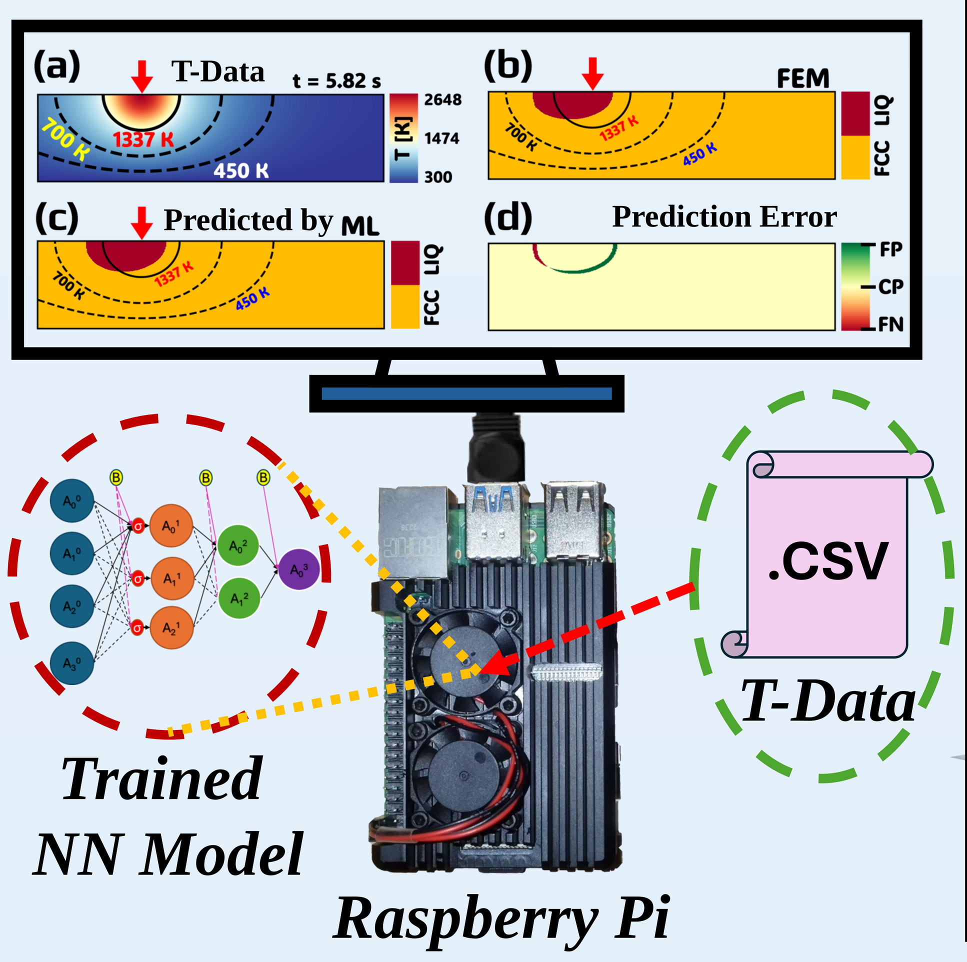


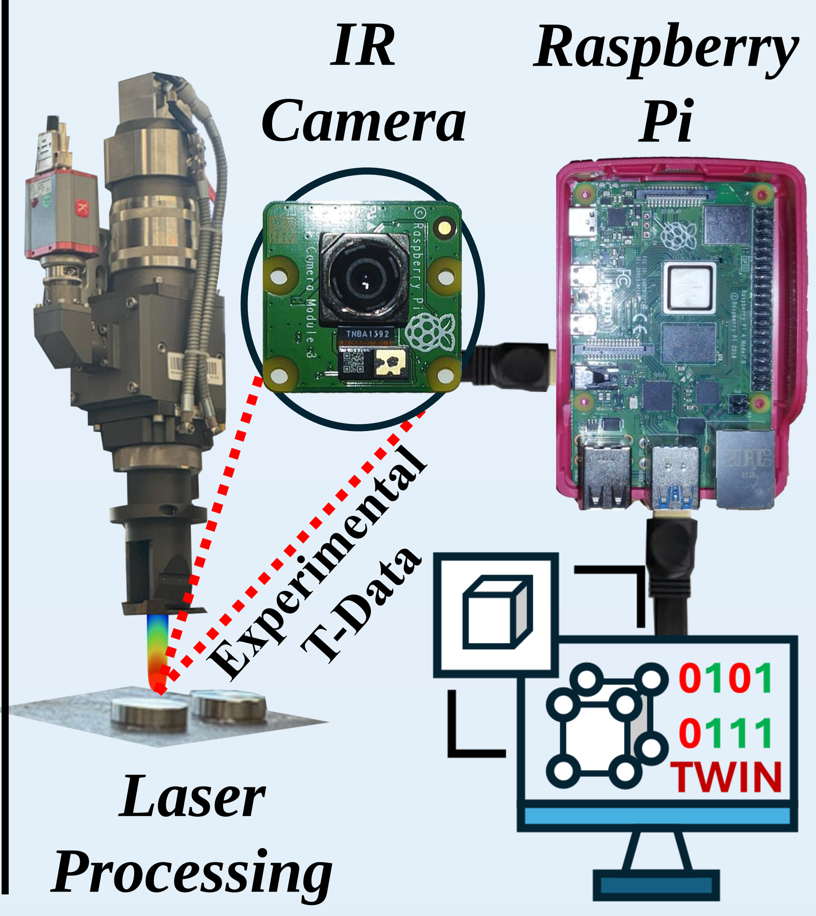
Velocity & Temperature distribution (Gaussian Beam)



ML Train-Valid. Metrics

Digital-Twins





Conclusion

- Performed Multi-Physics FEM laser-processing simulations with varying beam profiles and Free Energy expressions.
- Constructed a U-Net machine learning model trained on data generated from multiple FEM simulations.
- Developed a Raspberry-Pi based *Digital-Twin Framework* utilizing the trained ML model to predict phase transition.

Future Work

- Testing the *Digital-Twin Framework* under laboratory conditions using Temperature data from infrared cameras.

References

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