Experimental Validation of Real Gas CO_2 Model near Critical Conditions

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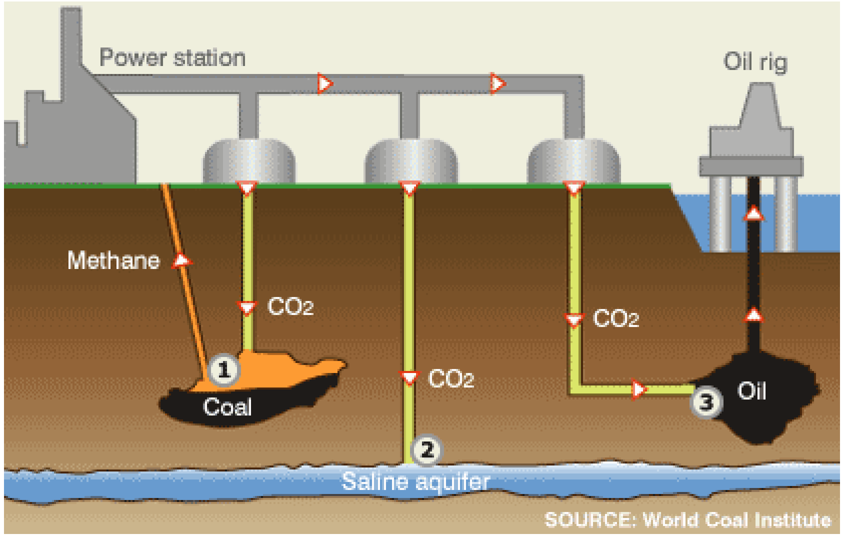
Key Takeaways

- First experimental characterization of metastable CO_2
- Preliminary CO_2 measurements demonstrate applicability of RefProp implementation of Span and Wagner equation of state in metastable region

CO_2 Compression for Carbon Capture and Sequestration

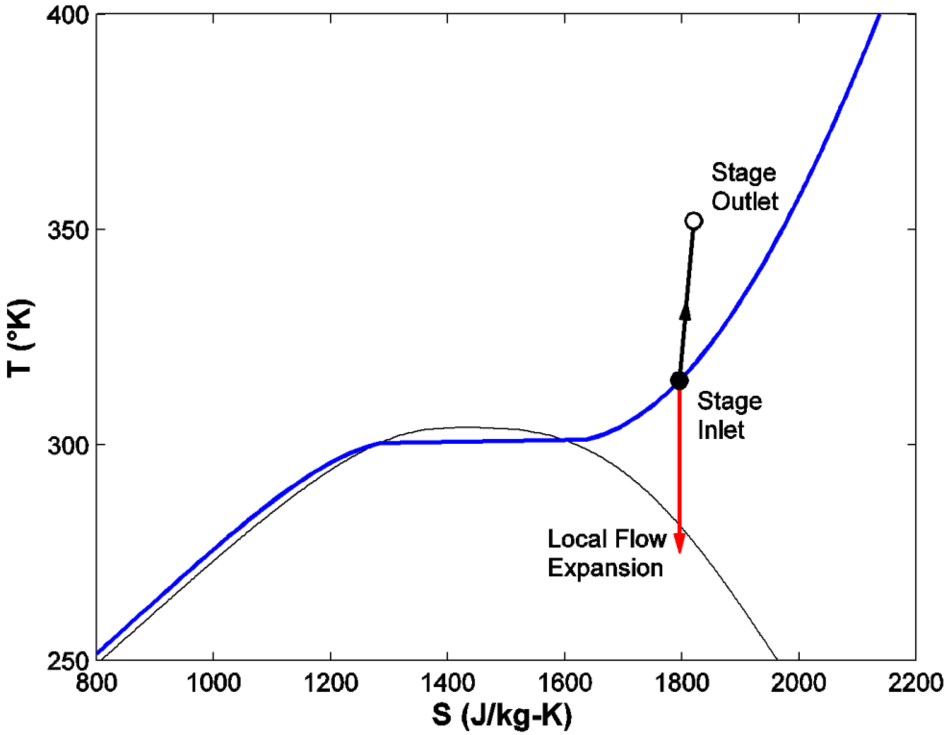


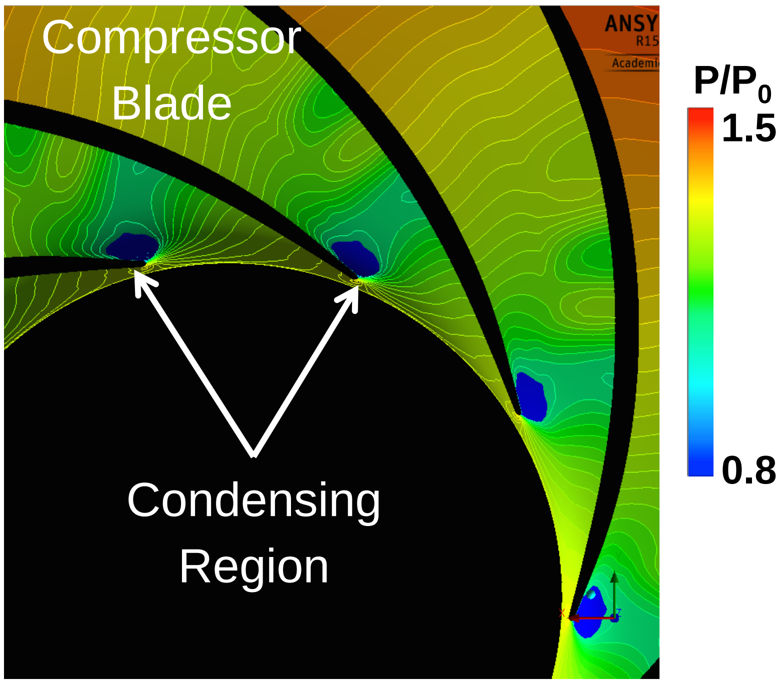
Imaged Credit: Cal CCS

Image Credit Mitsubishi Heavy Industries

- Mitigation of CO_2 emissions require compression to high pressure
- Compressor power requirements limits large-scale CCS viability

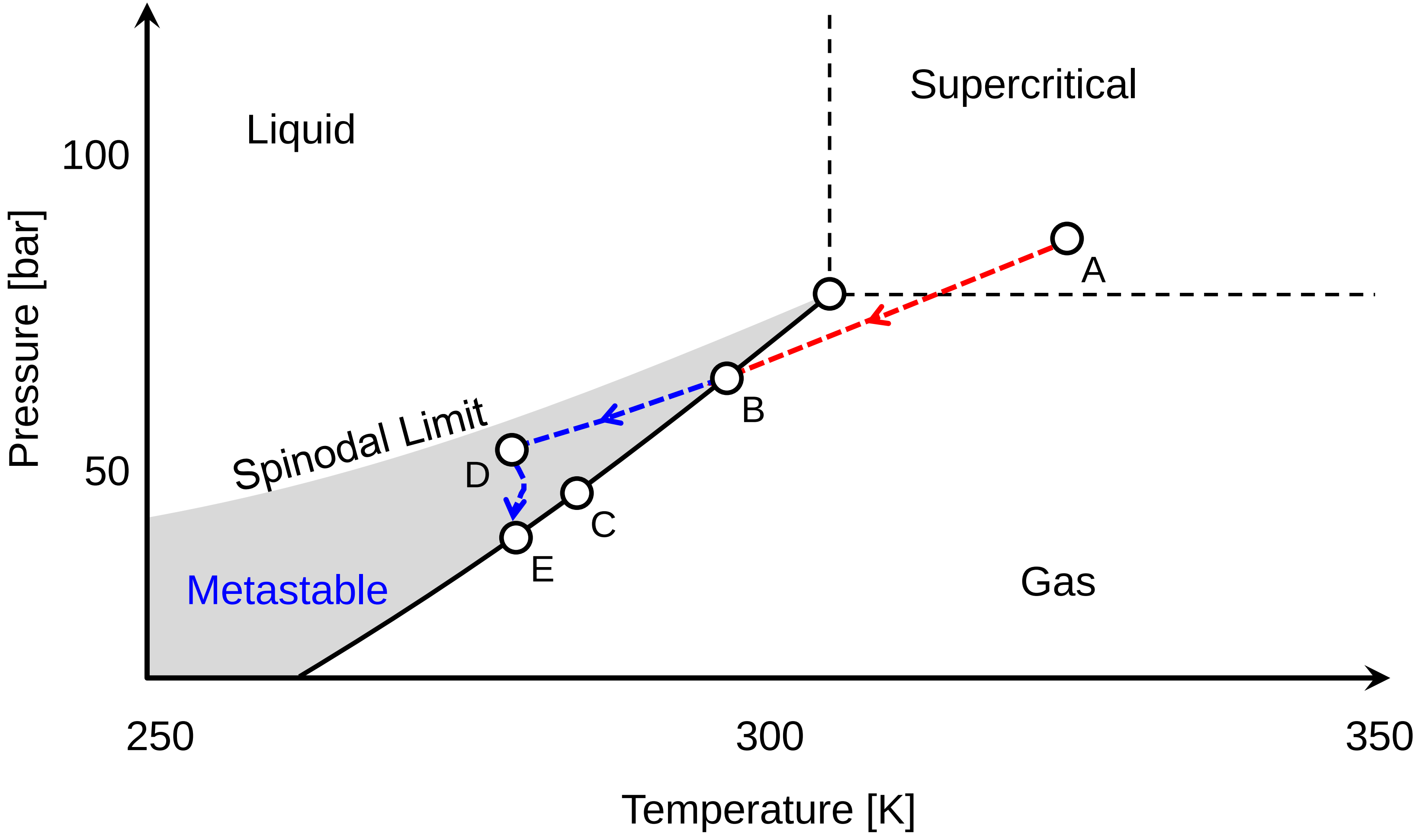
Two-Phase Flow Near Impeller Leading Edge





- Acceleration over leading edge leads to localized cooling and possible condensation[1,2]
- Rapid rate of cooling causes non-equilibrium phase-change

Non-Equilibrium Condensation



Calculating Metastable State Properties

Ideal Gas Approximation

- Used for low density condensing gases[1,2] and gas mixtures[2]

Equation of State (EOS) Extrapolation[3]

- Current state of the art for metastable steam vapor
- Span and Wagner is state-of-the-art EOS for CO_2
- Implemented through Refprop
- Limited to values below EOS spinodal limit

Direct Tabular Extrapolation[4]

- Simpler than EOS extrapolation
- Invalid for large excursions into two-phase dome

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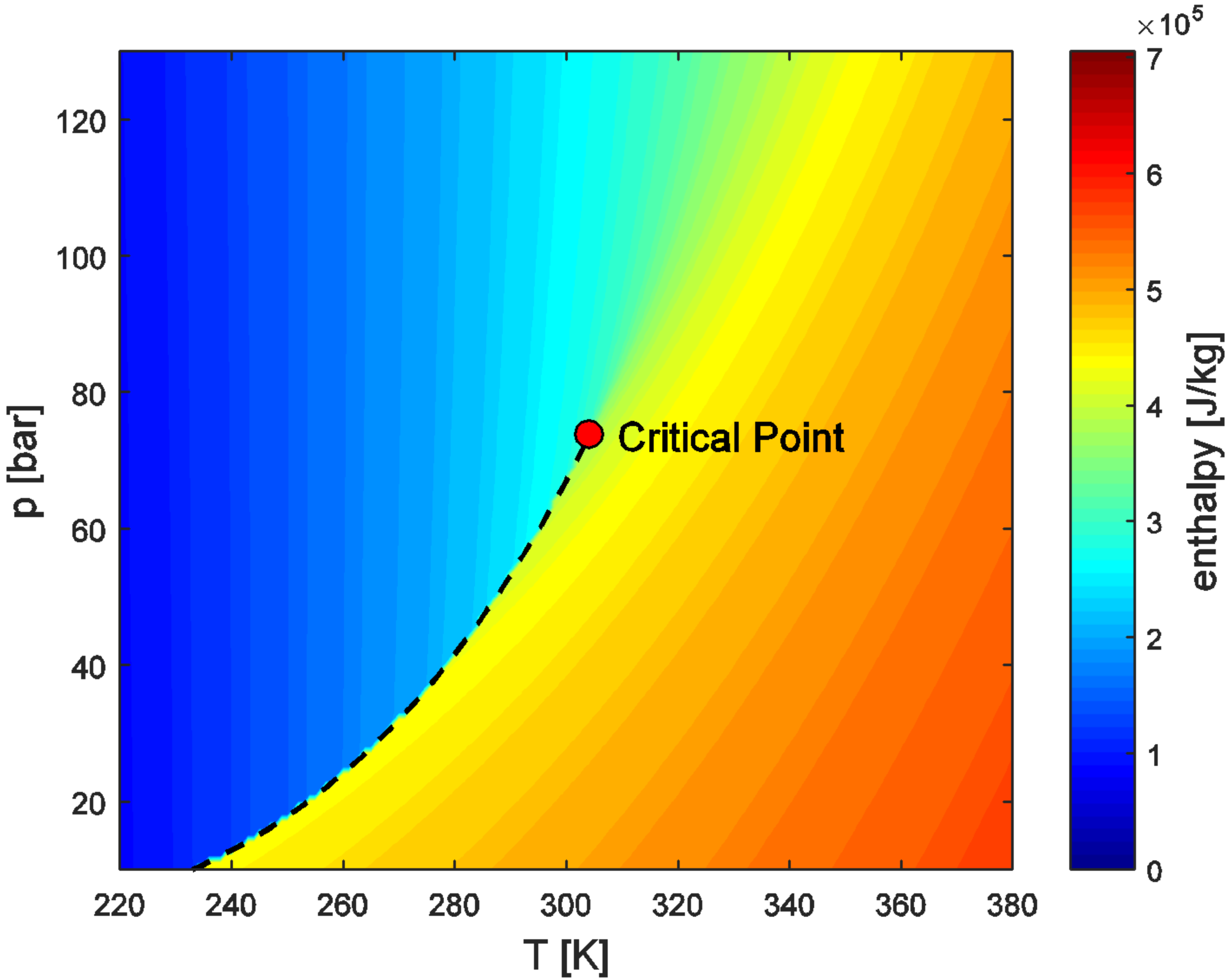
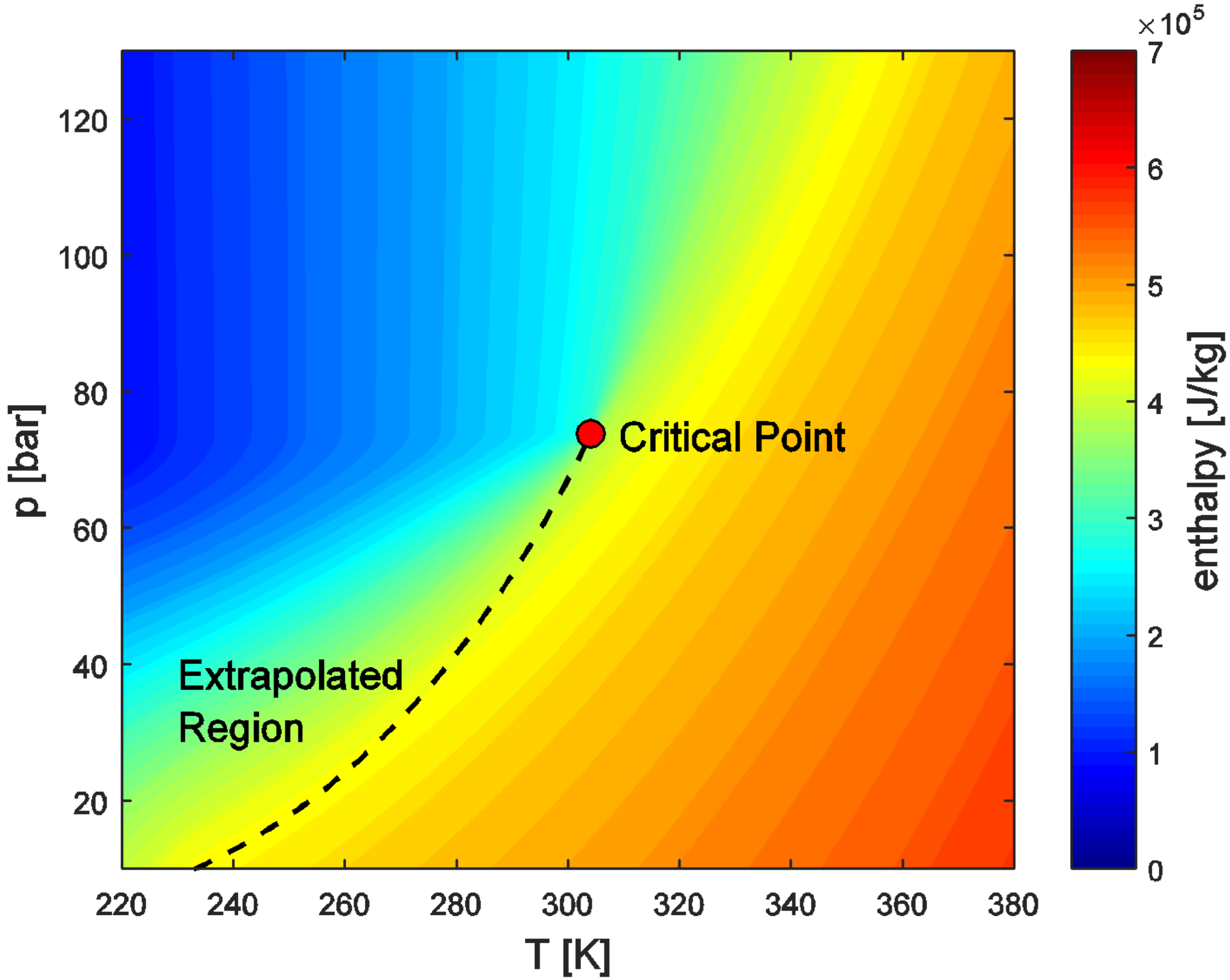
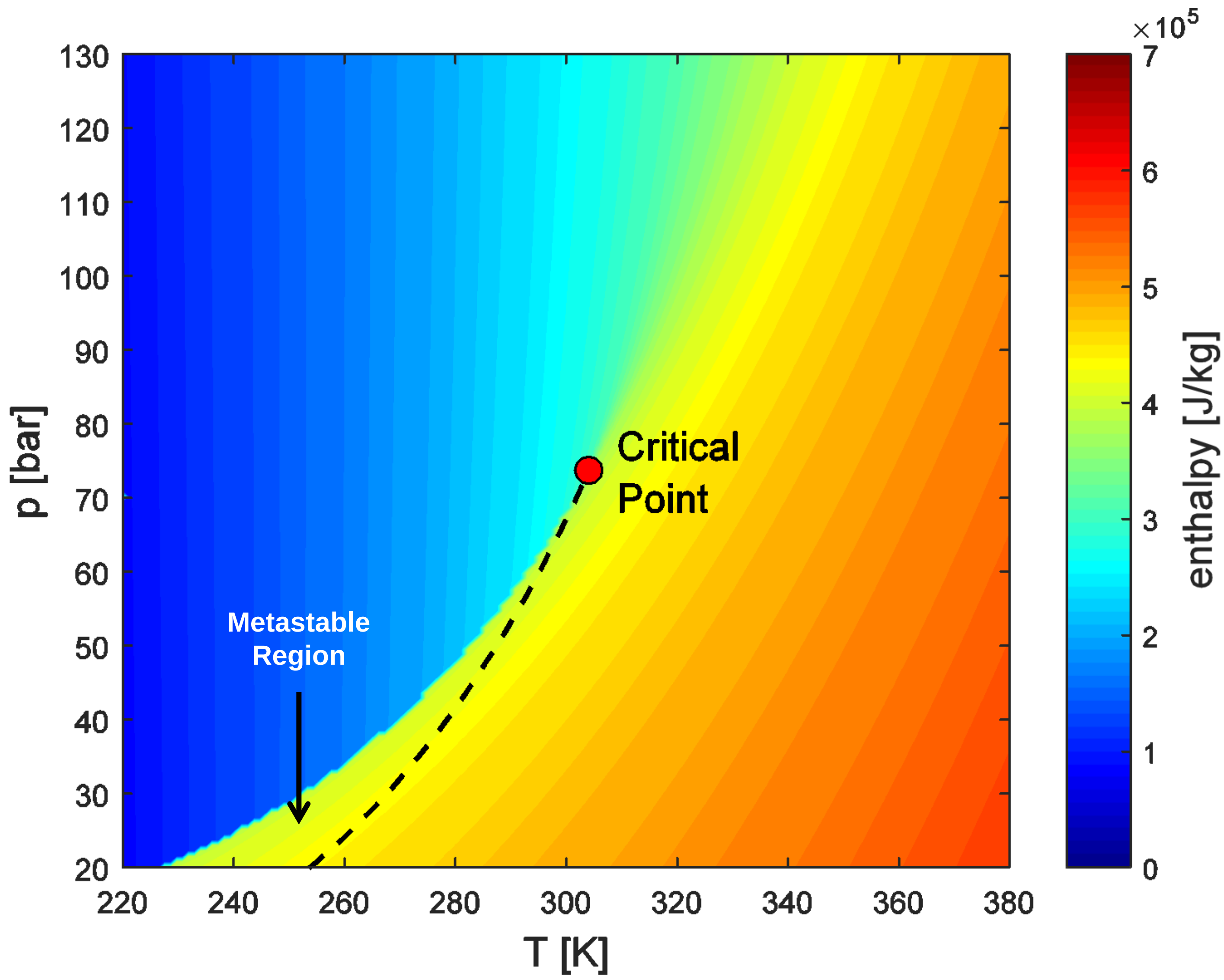
Equilibrium Pressure-Temperature Diagram



Direct Extrapolation of Metastable Properties [7]



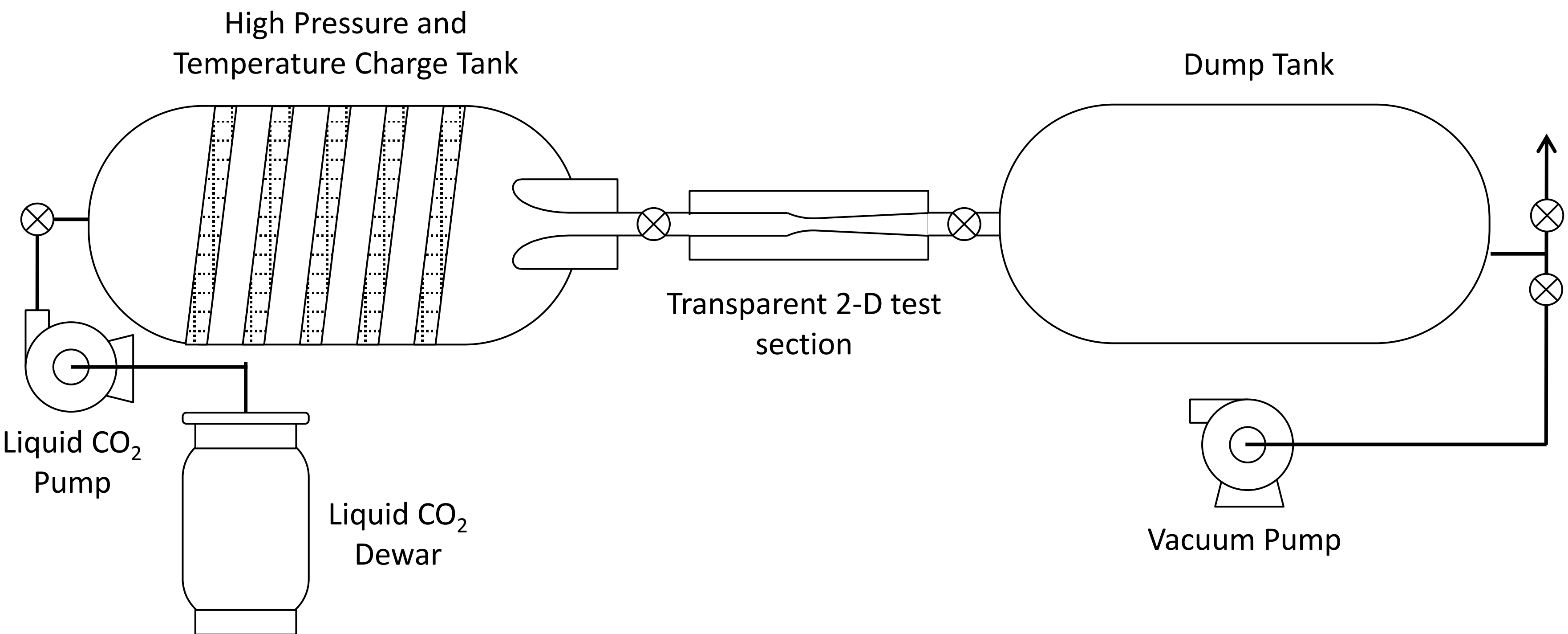
Built-in EOS Extrapolation Capability with RefProp



Objectives and Goals

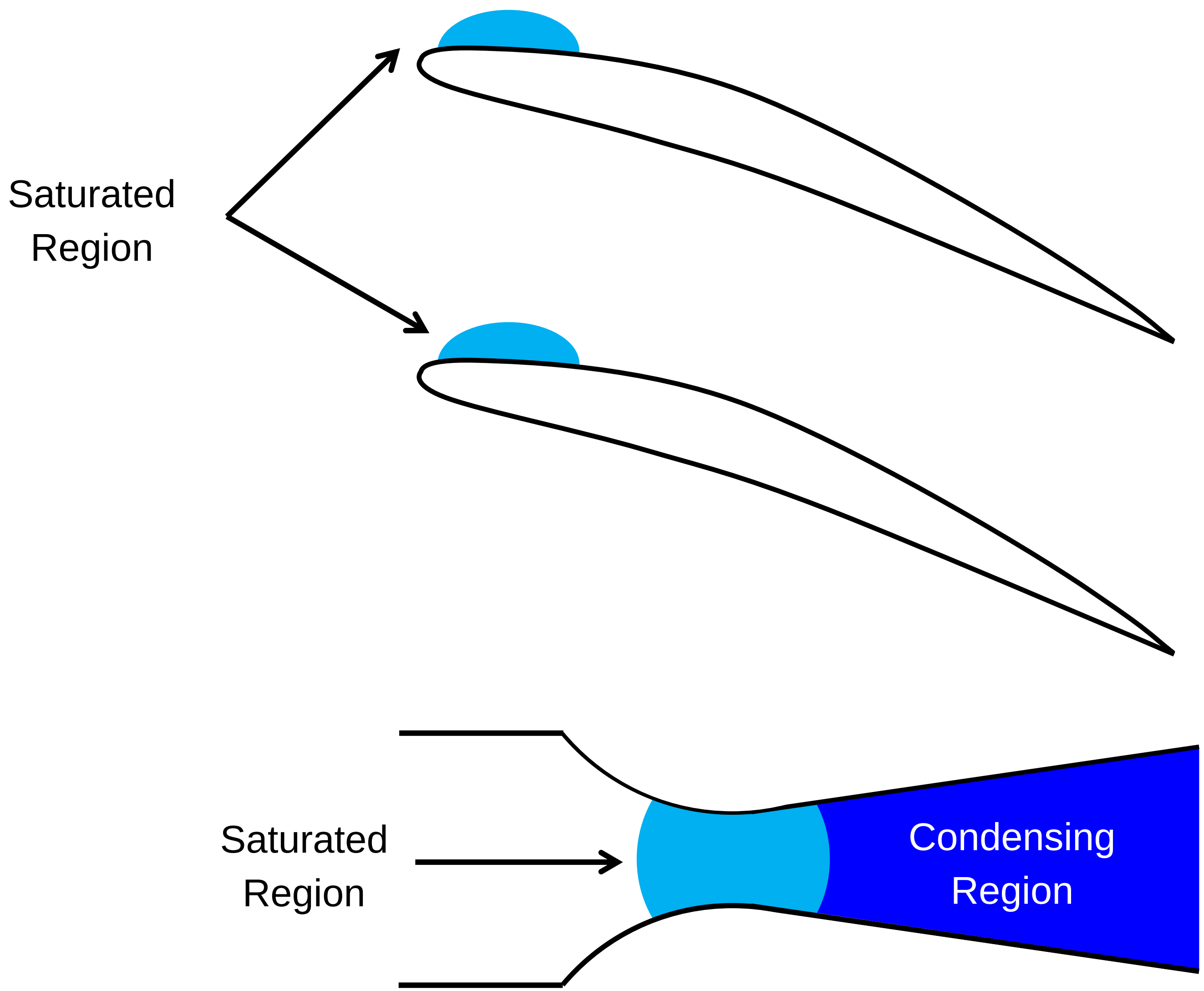
- Demonstrate the use of interferometery for density measurement in a metastable vapor
- Fully characterize the thermodynamic state of metastable CO_2
- Determine the ranges of applicability for EOS and direct extrapolation methods

Experimental Blowdown Rig

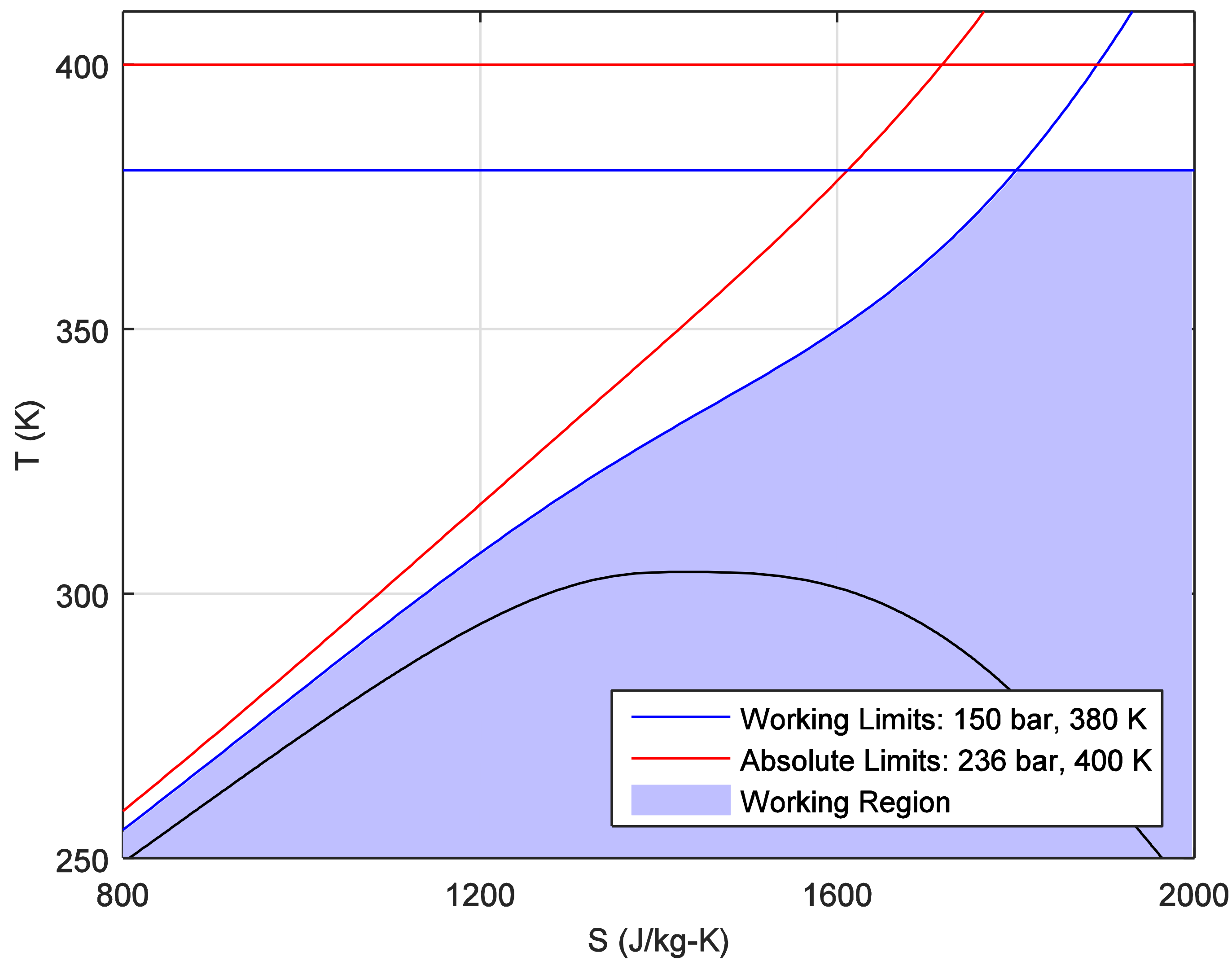


Typical Rig Parameters	
Parameter	Typical Value
Throat Area [mm^2]	50
Tank CO_2 Mass [kg]	50-500
Blowdown Time [s]	0.5-2

Con-Di Nozzle as Surrogate for Impeller Leading Edge



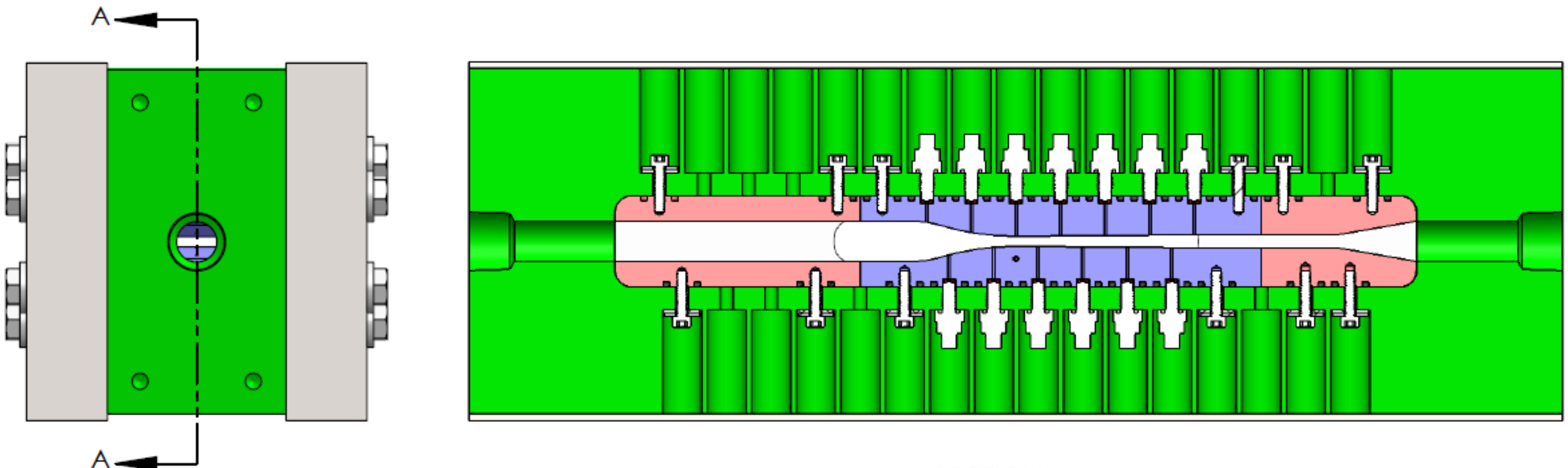
Absolute Limits on Test-Rig Operating Conditions



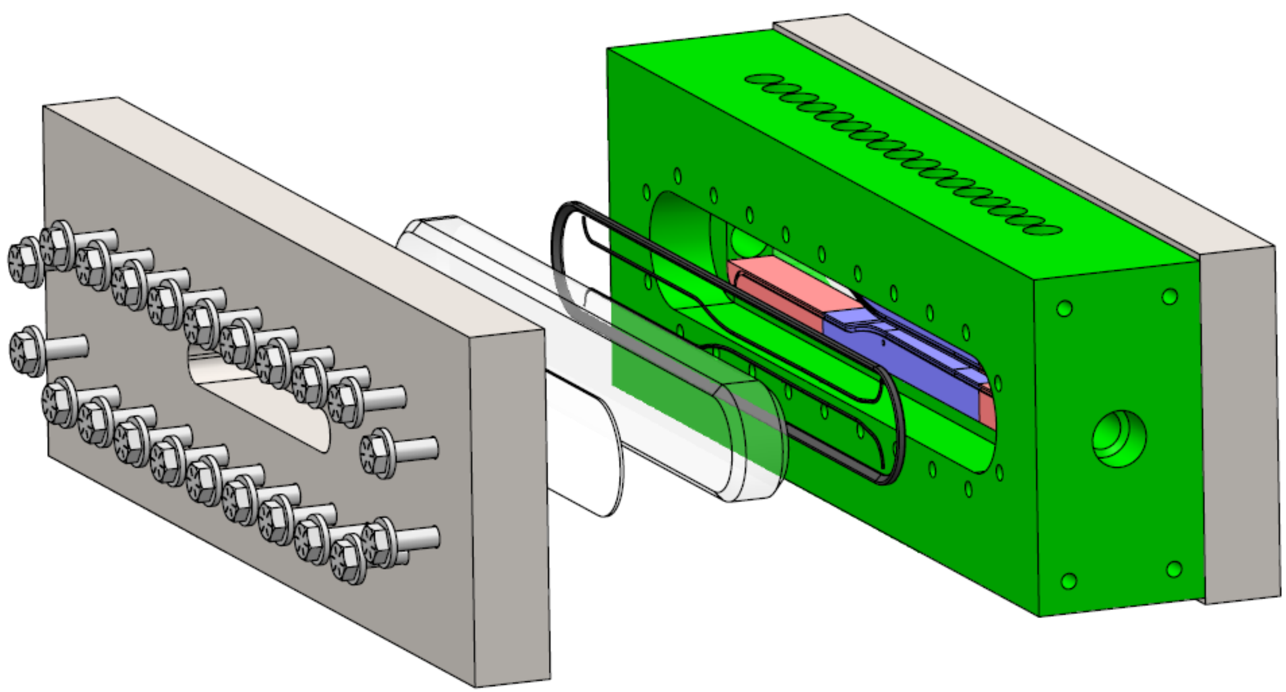
Test-Section Requirements

- Optical access
- High pressure measurement resolution
- Ability to easily modify nozzle geometry
- Short testing turn-around time

Test-Section Design



SECTION A-A



Interferometry for Nozzle Density Measurement

Lamanna et. al.[5]

- Measured density distribution across condensation shocks in low pressure nitrogen
- Densities on the order of **$1 kg/m^3$**

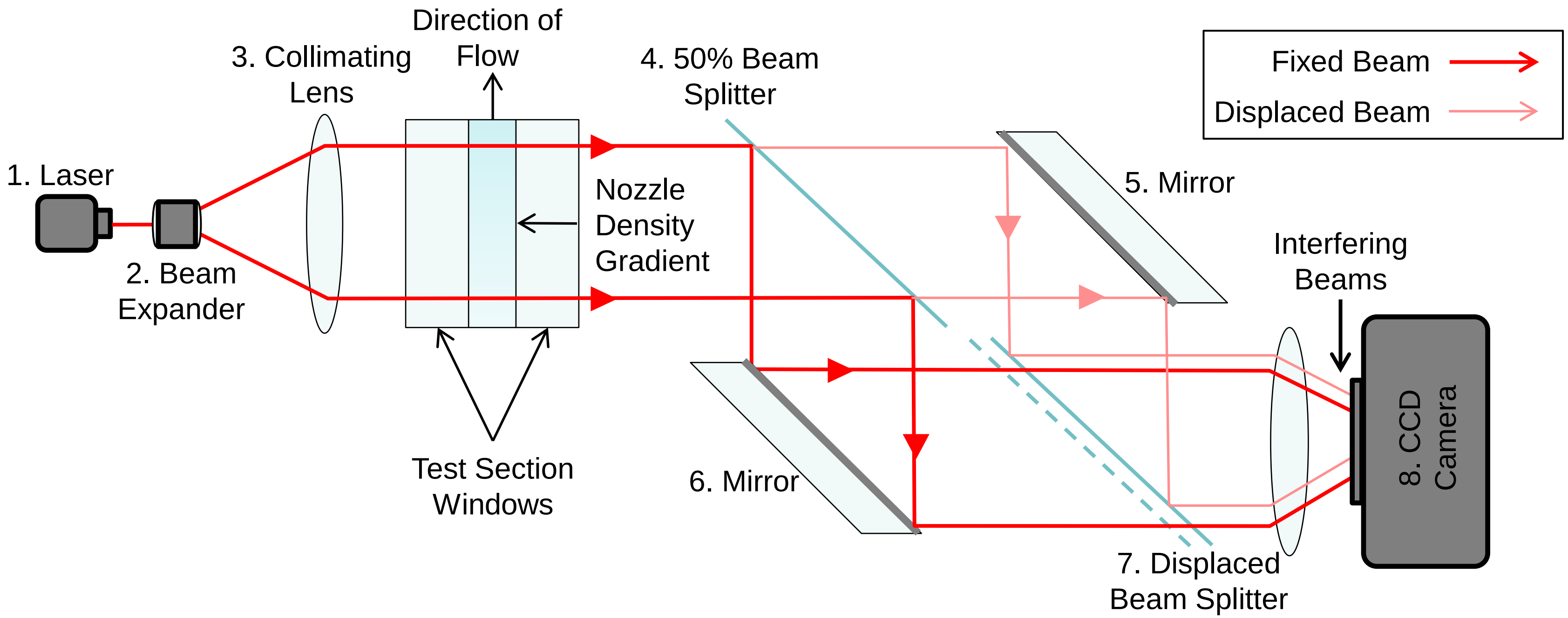
Duff[4]

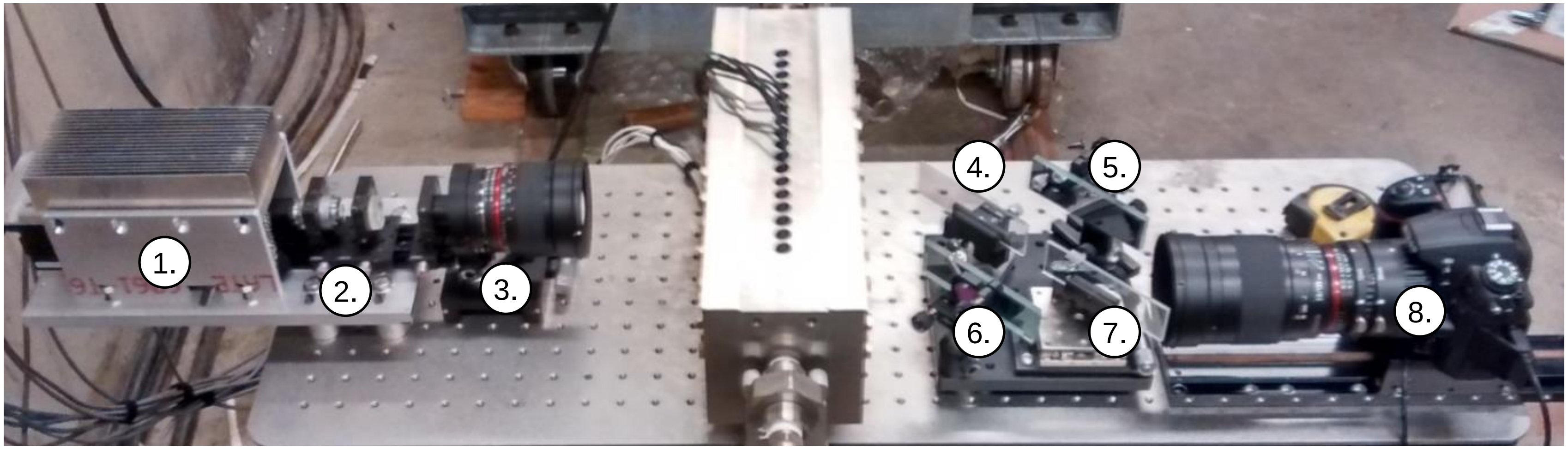
- Measured densities in condensing CO_2 away from the critical point
- Densities on the order of **$10 kg/m^3$**

Current Research

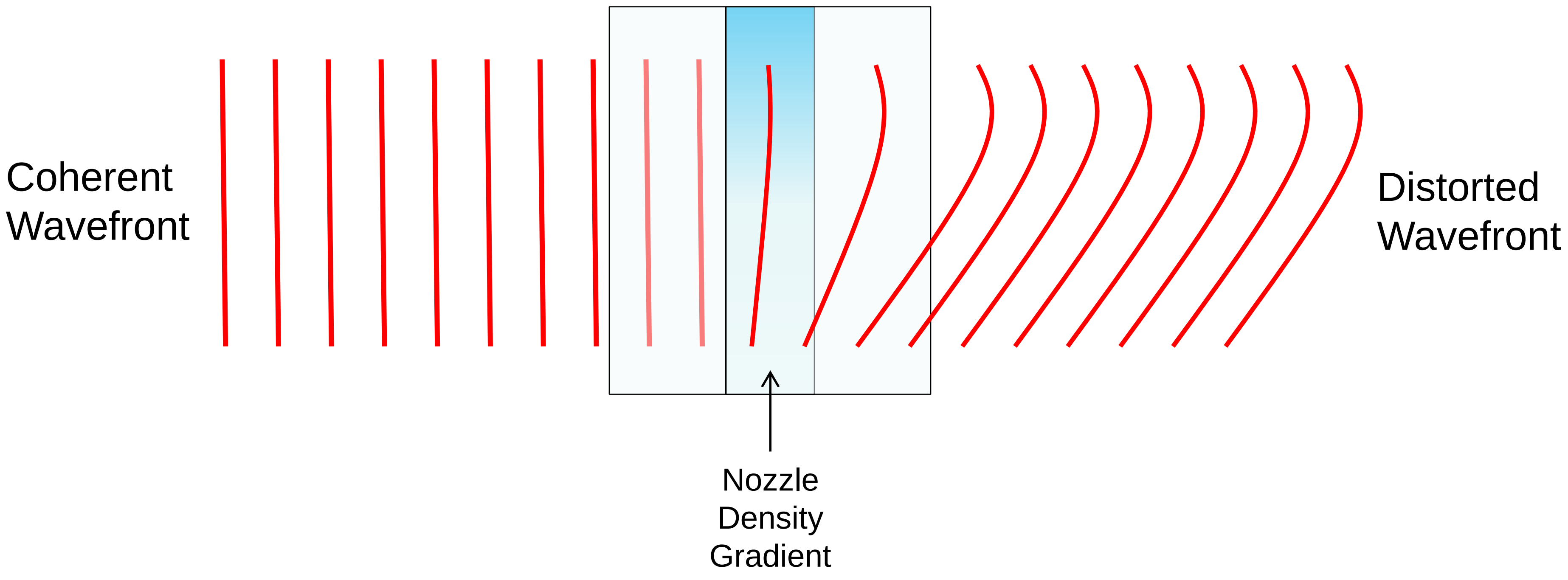
- Measured densities in condensing CO_2 near the critical point
- Densities on the order of **$100\text{-}1000 kg/m^3$**

Shearing Interferometer



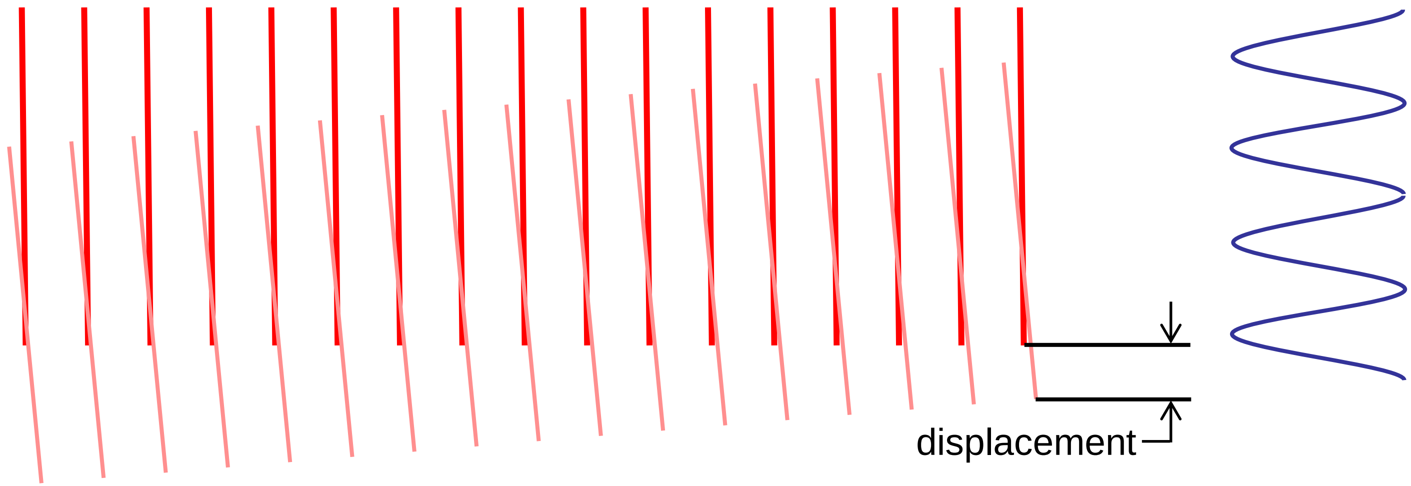


Wavefront Distortion through Nozzle Density Gradient



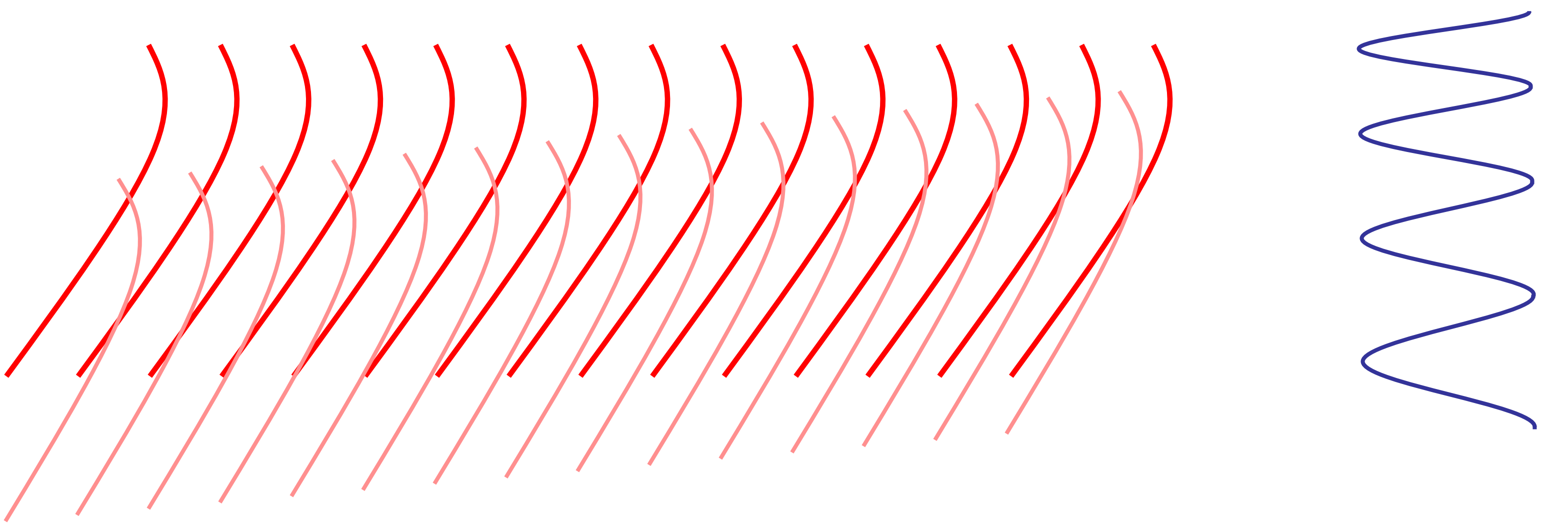
Fringe Pattern in Shearing Interferometer

Without Flow in Nozzle



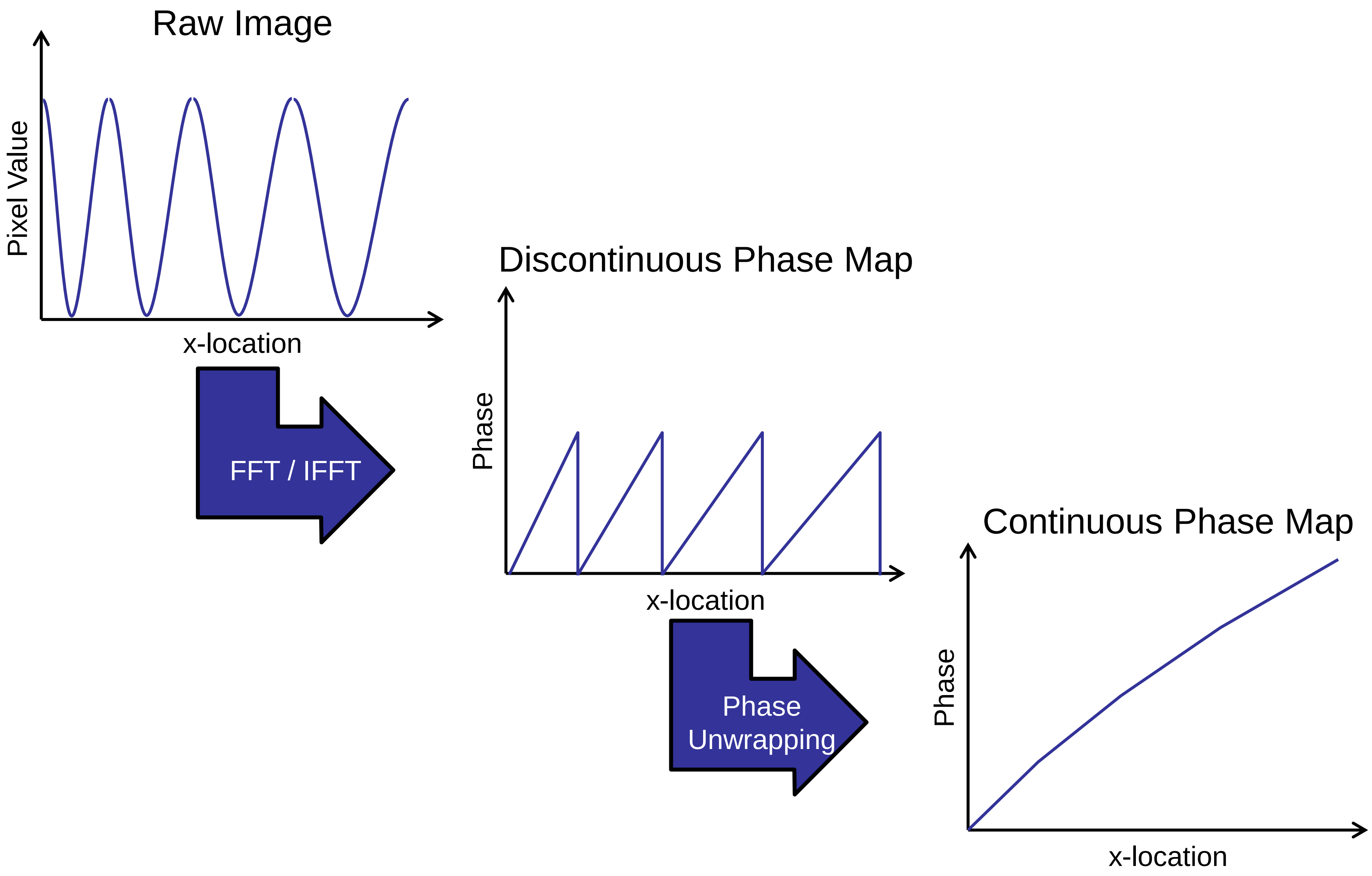
Carrier Fringe Pattern

With Flow in Nozzle



Phase Stretched Fringe Pattern

1-D Phase Unwrapping Method



Post-Processing Procedure

Derivative of Fringe Phase Lag

↓ Integration

Phase Lag

↓ x λ/2π

Optical Path Length Difference

↓ /T-S Width

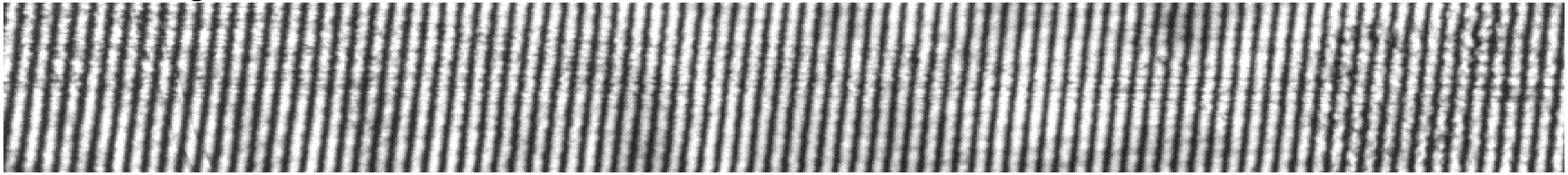
Index of Refraction

↓ Lorentz-Lorenz

Density

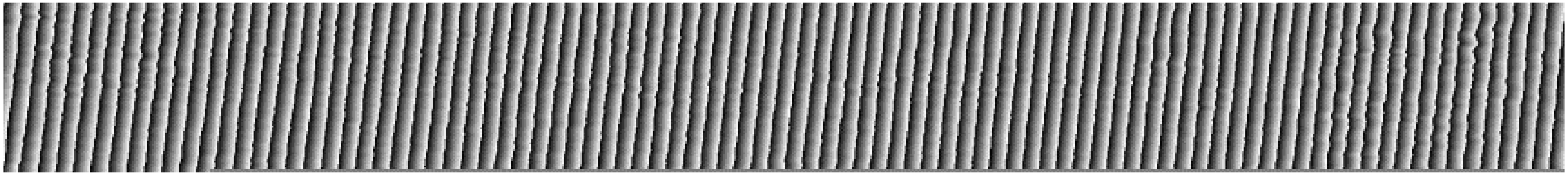
2-D Phase Unwrapping Method[8]

Raw Image



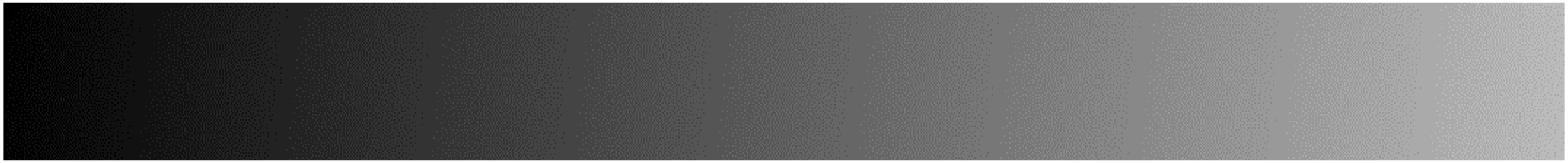
FFT

Discontinuous Phase Map

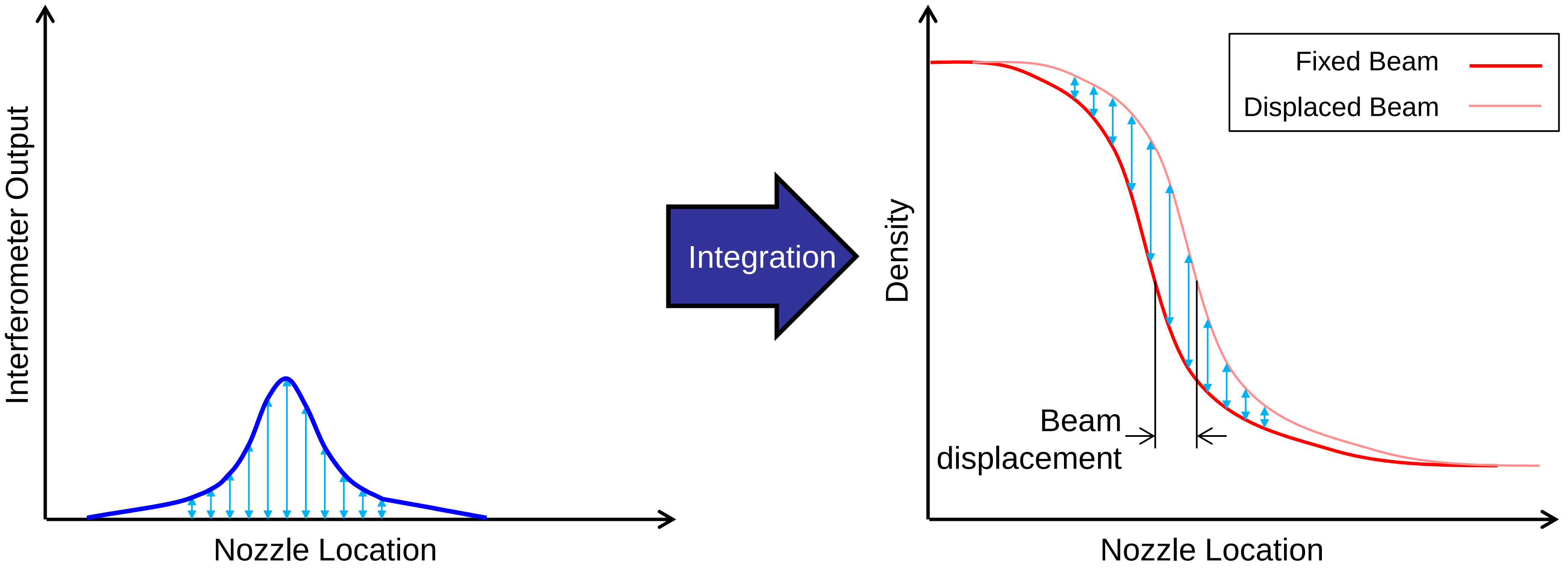


Phase Unwrapping

Continuous Phase Map

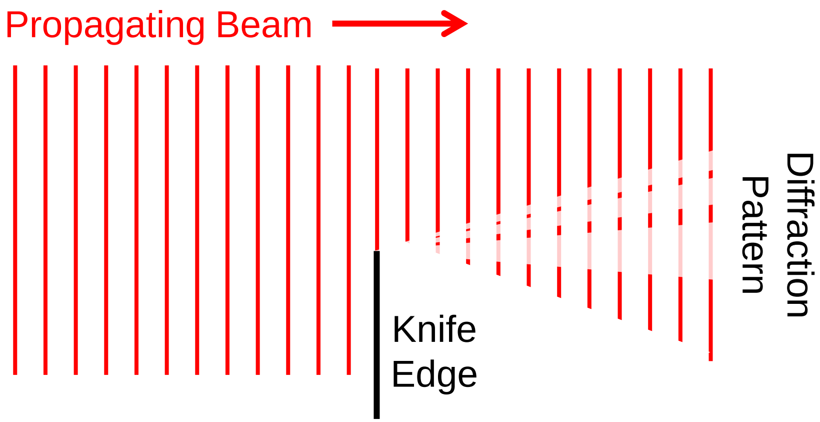


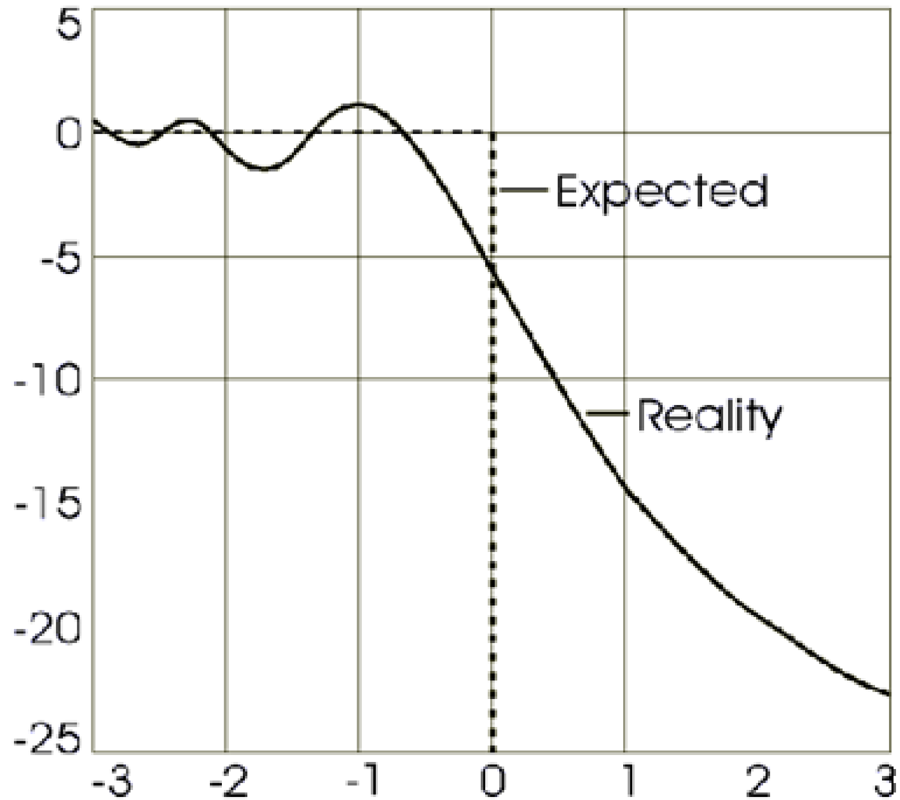
Shearing Interferometer Measures Density Gradient



Requirement: Beam displacement measurement accuracy < **5 μm**

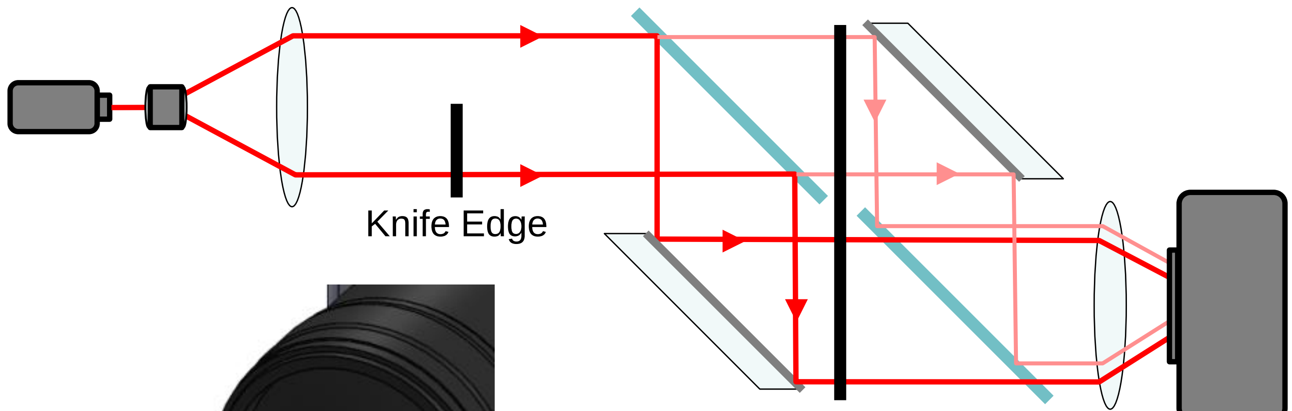
Key Idea: Knife Edge Diffraction Pattern

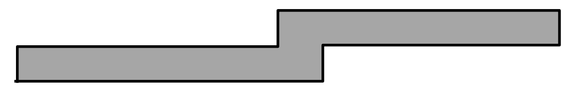




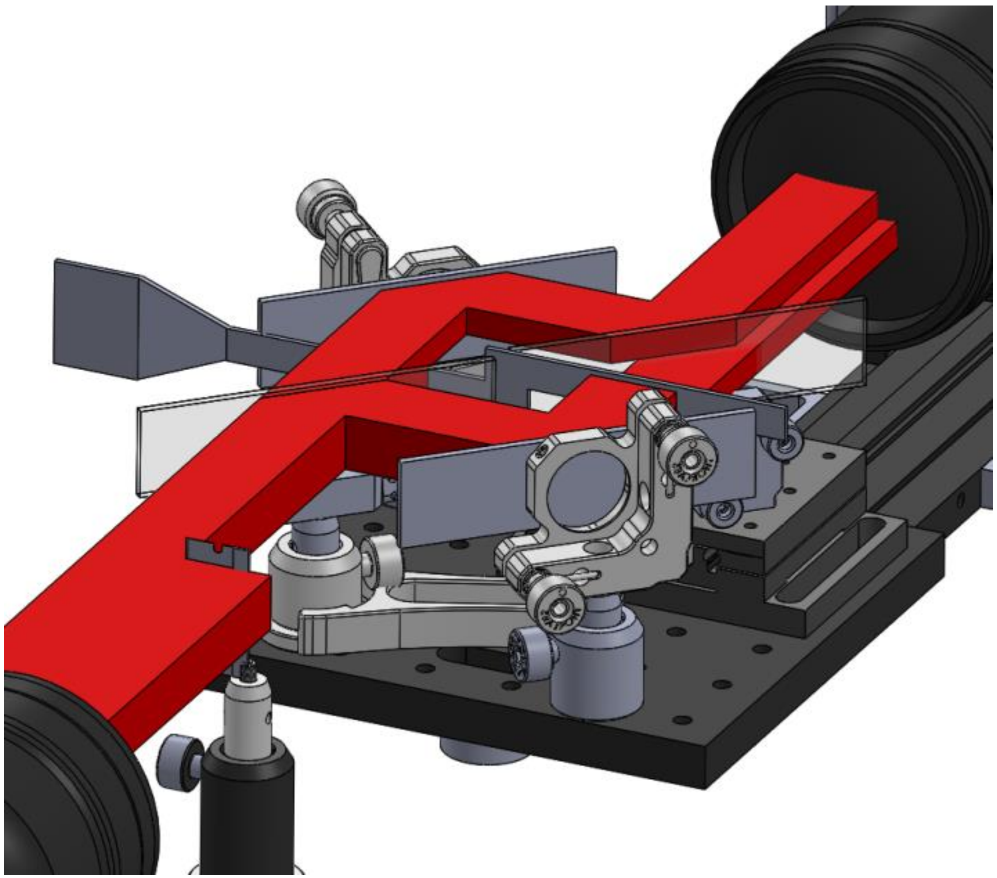
- Perpendicular knife edge produces a repeatable pattern to determine location

Schematic of Displacement Measurement

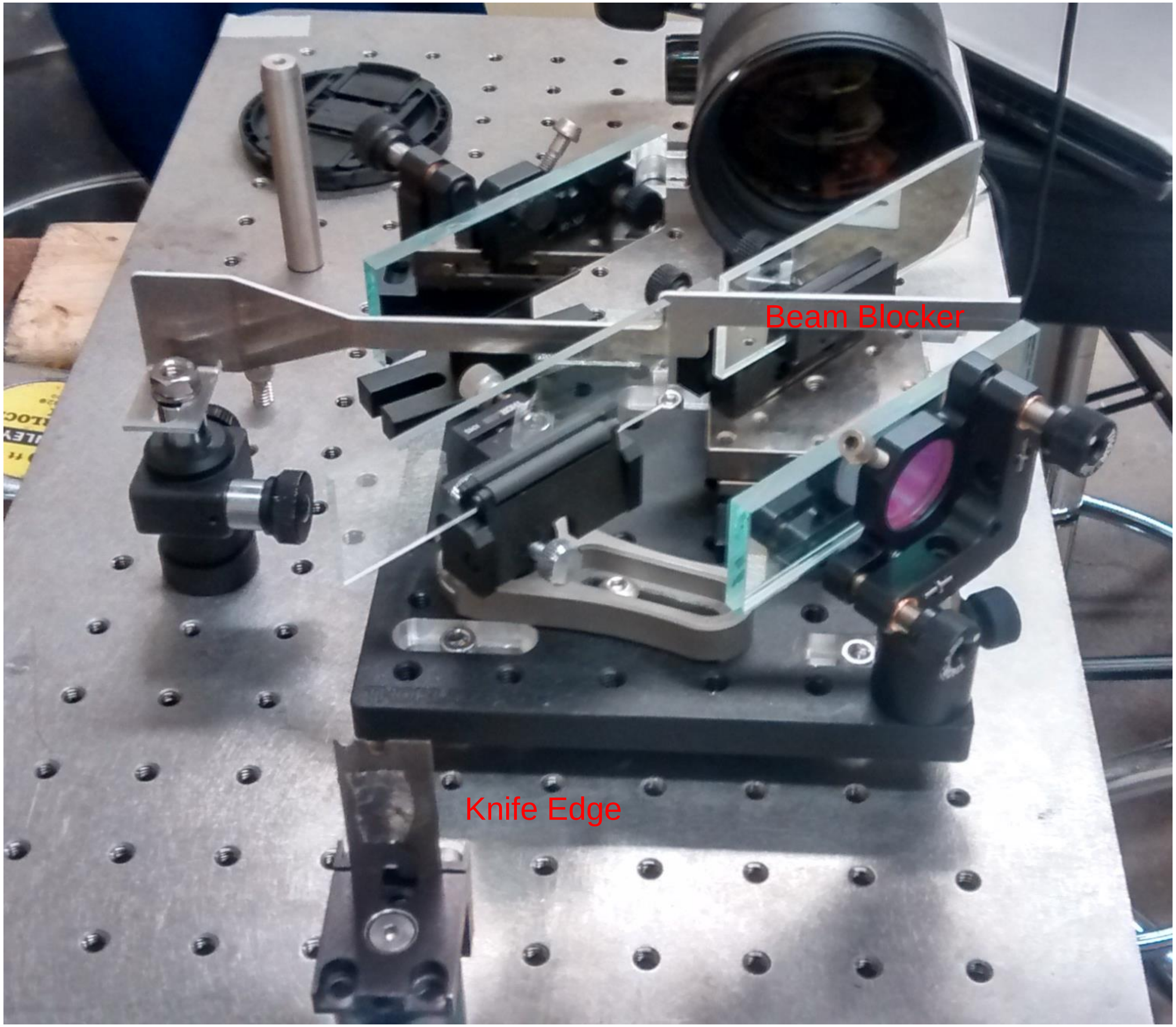




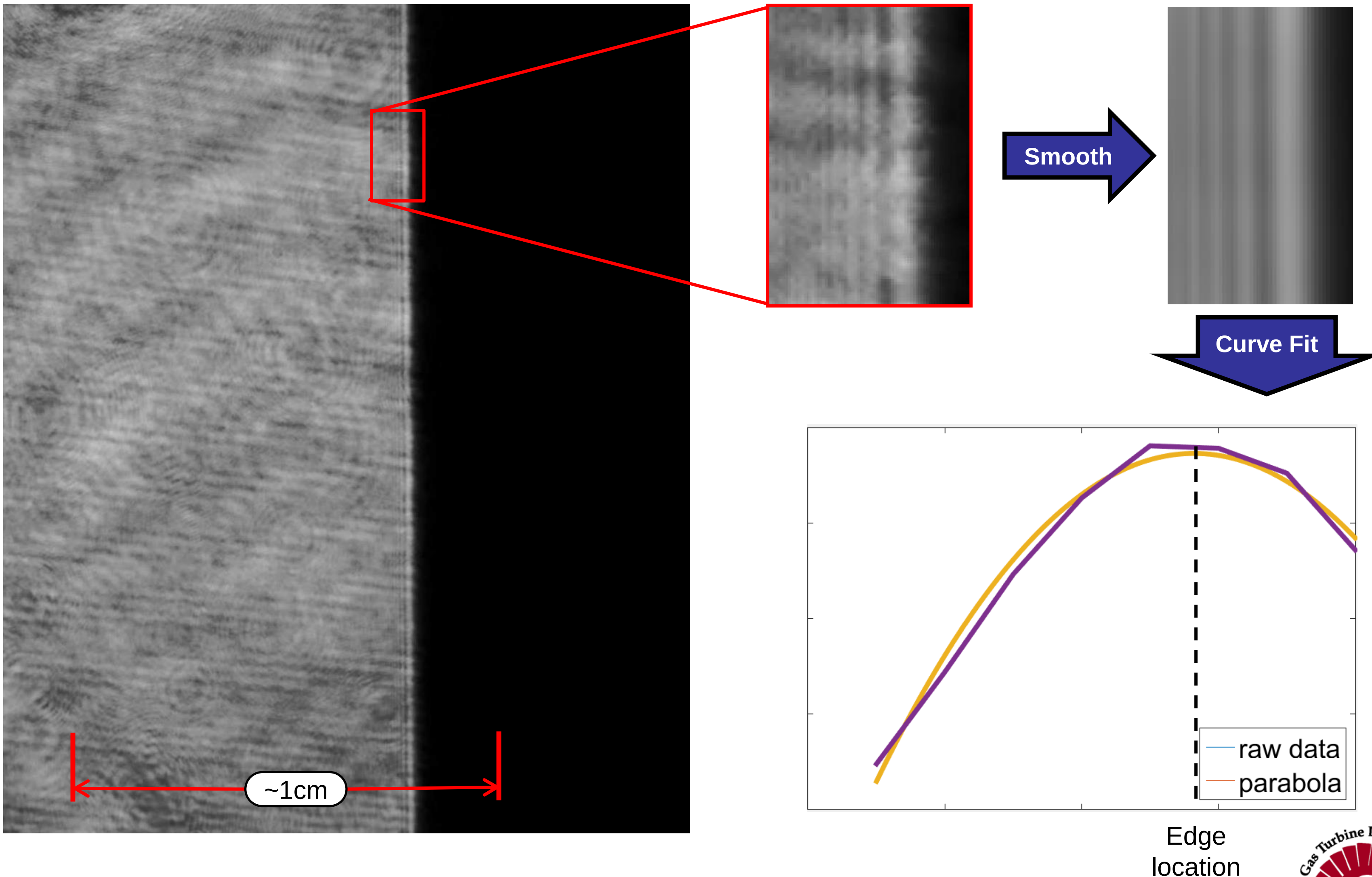
Beam Blocker (Front View)



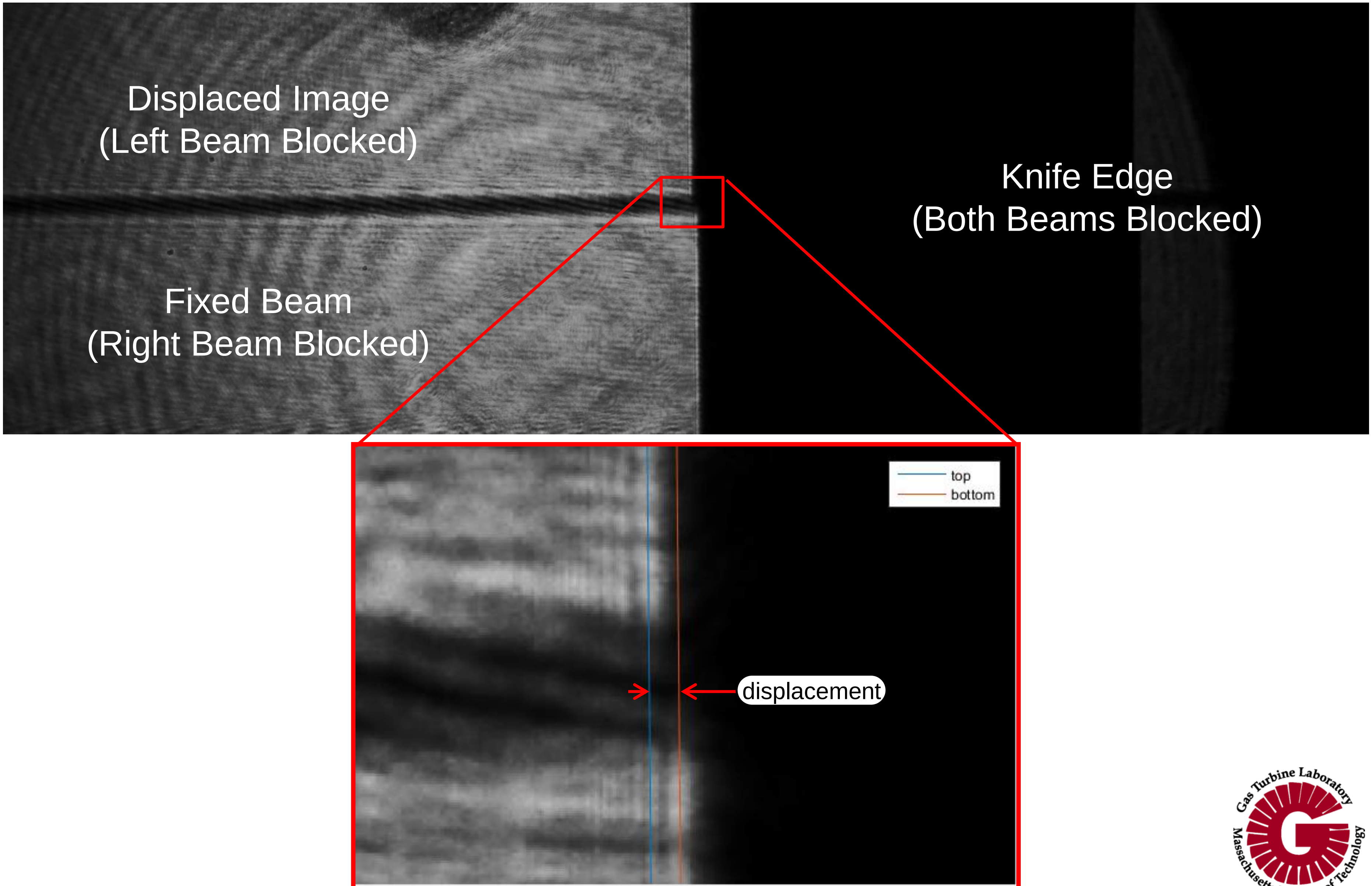
Beam Blocker Setup



Knife Edge Detection



Displaced Knife Edge Image



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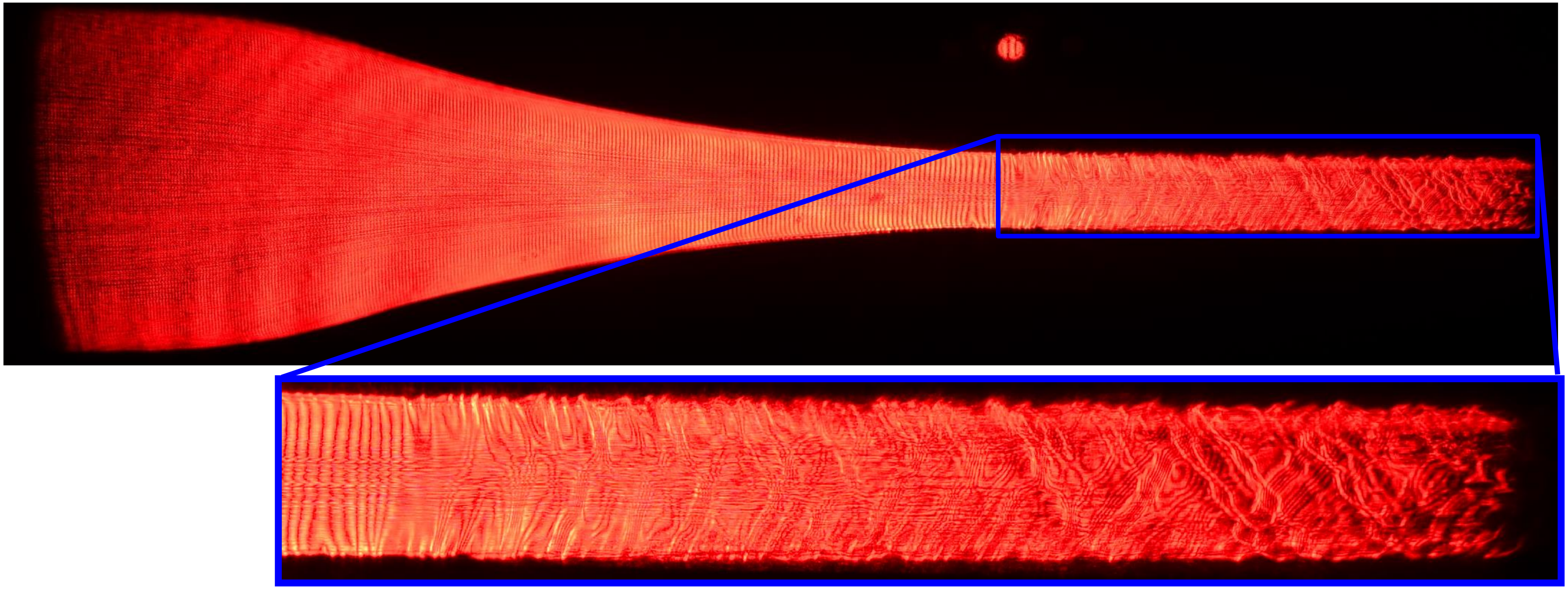
Displacement Measurement Accurate to 5μm (~2%)

Micrometer Setting [μm]	Calculated Displacement [μm]	Error [μm]
0	0	0
50	47.12	2.88
100	103.26	3.26
150	154.36	4.36

- Images taken at 4 micrometer settings to compare multiple points
- Knife edge measurement method yields sub pixel accuracy with error below 5 microns (order of magnitude improvement over traditional method)

Mach Waves Limit Observation to Subsonic Section

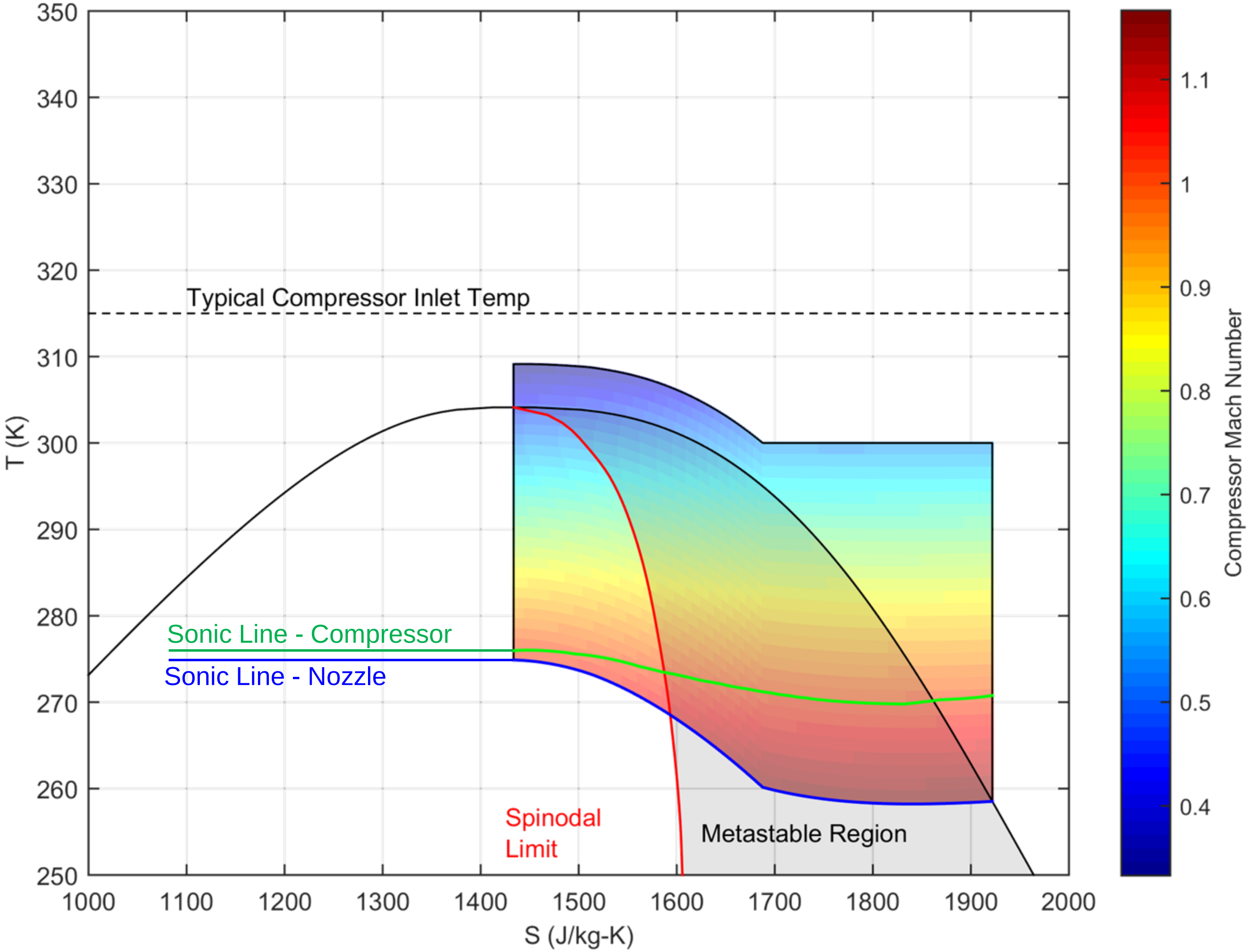


- Density gradients make it difficult to determine fringe pattern and density in downstream section
- Improvements in nozzle surface finish and diverging angle will be investigated to improve performance

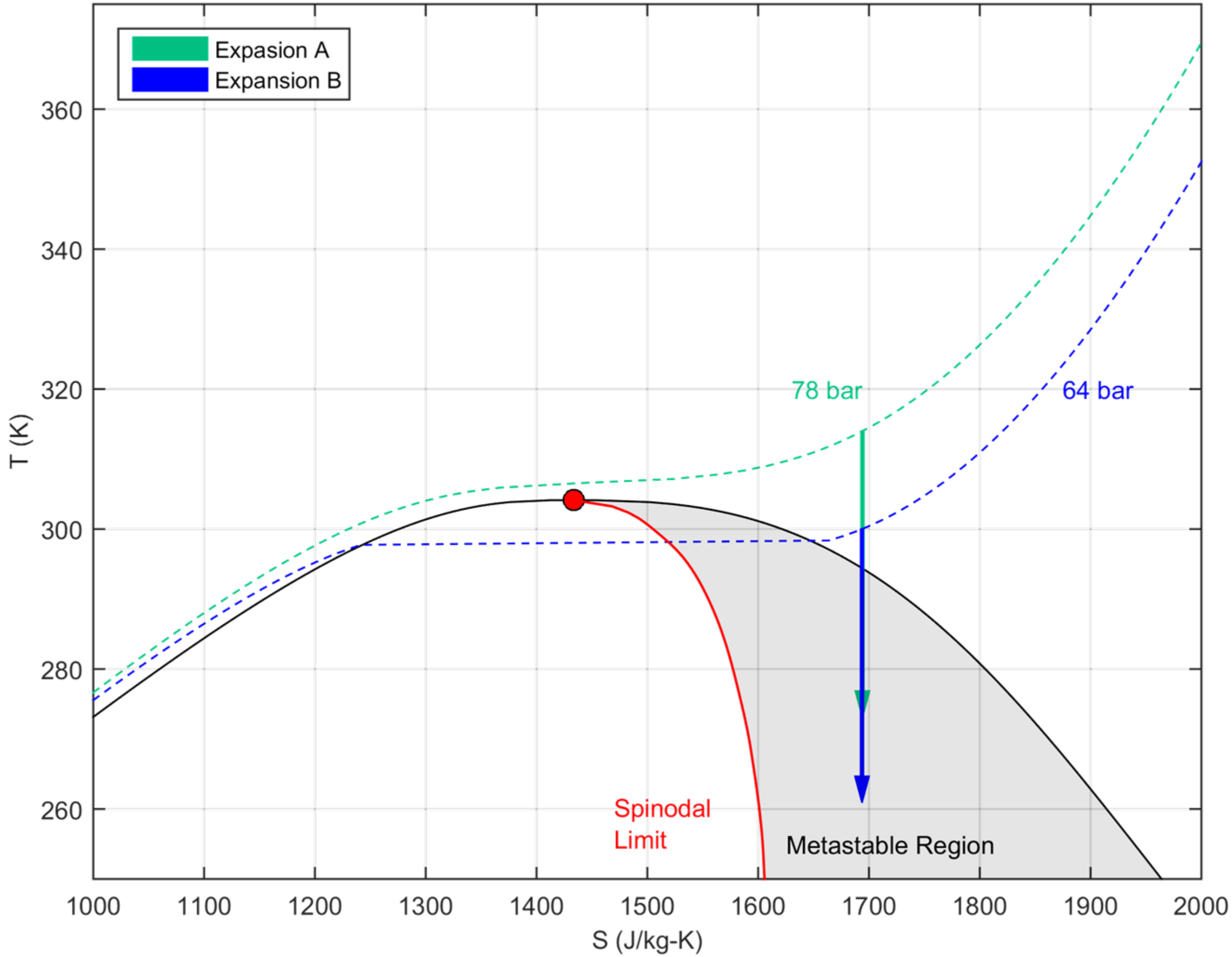
Mapping Compressor Mach Number to Nozzle

- Measurements in nozzle limited to Mach number of 1
- Typical maximum Mach numbers at impeller leading edge: 1.1-1.2
- Nozzle total conditions reduced to drive throat conditions farther into metastable region.
- Compressor Mach numbers mapped onto experimental capability to characterize metastable behavior in region of interest

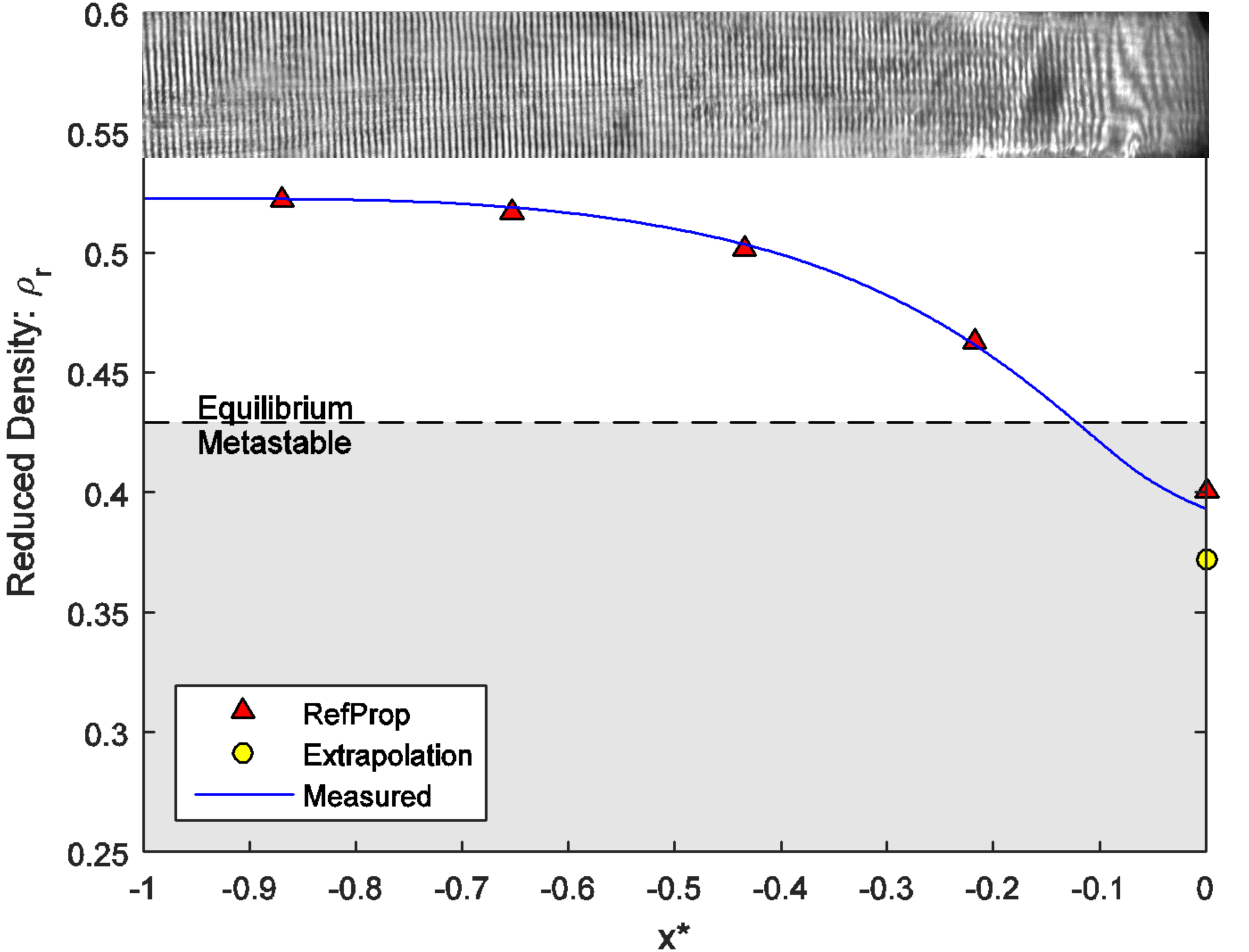
Range of Metastable Region Covered



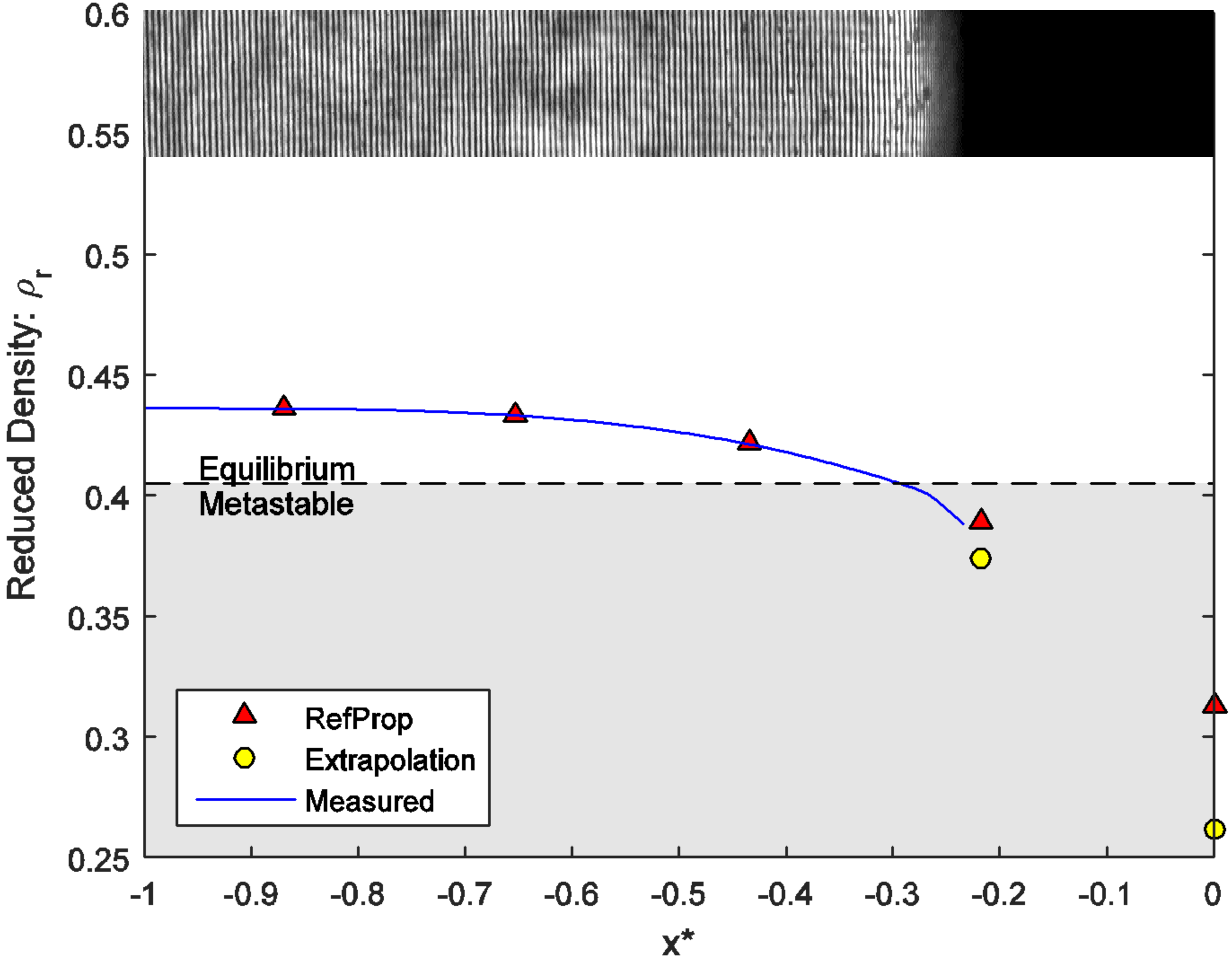
First Experimental Blowdown Runs



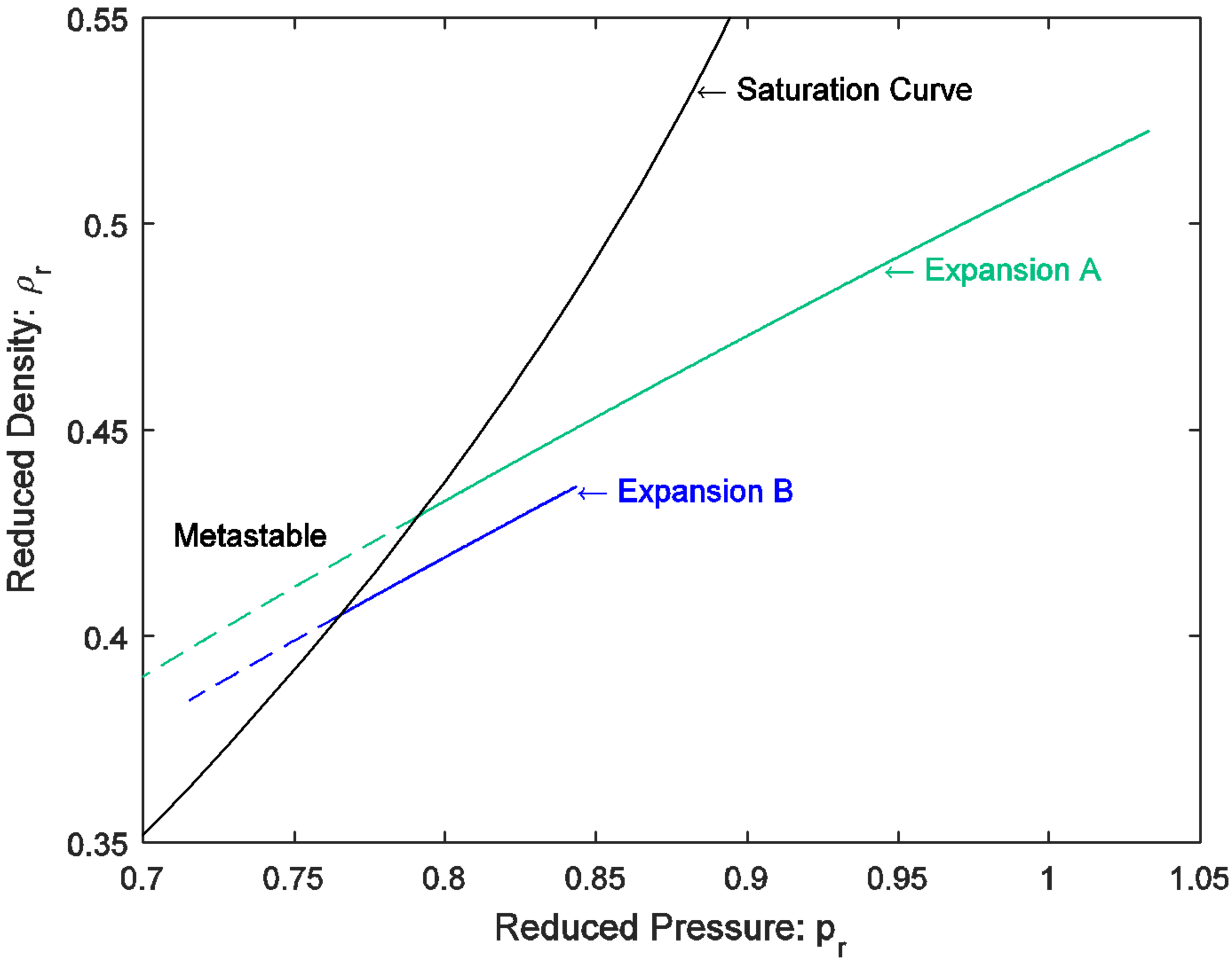
Metastable Density Comparison: Expansion A



Metastable Density Comparison: Expansion B



Blowdown Run Comparison: Reduced Quantities



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Conclusions and Future Work

Conclusions

- First interferometry measurements in S-CO_2 to fully characterize metastable state
- RefProp metastable properties accurate to within 3%
- Direct (tabular) extrapolation of metastable properties accurate to within 7%

Future Work

- Quantify error in density measurement at varying total conditions
- Determine under which conditions direct extrapolation is valid for determination of metastable properties

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