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Hydrogen Fuel Effects on Stability and Operation of Lean-Premixed and Staged Gas Turbine Combustors

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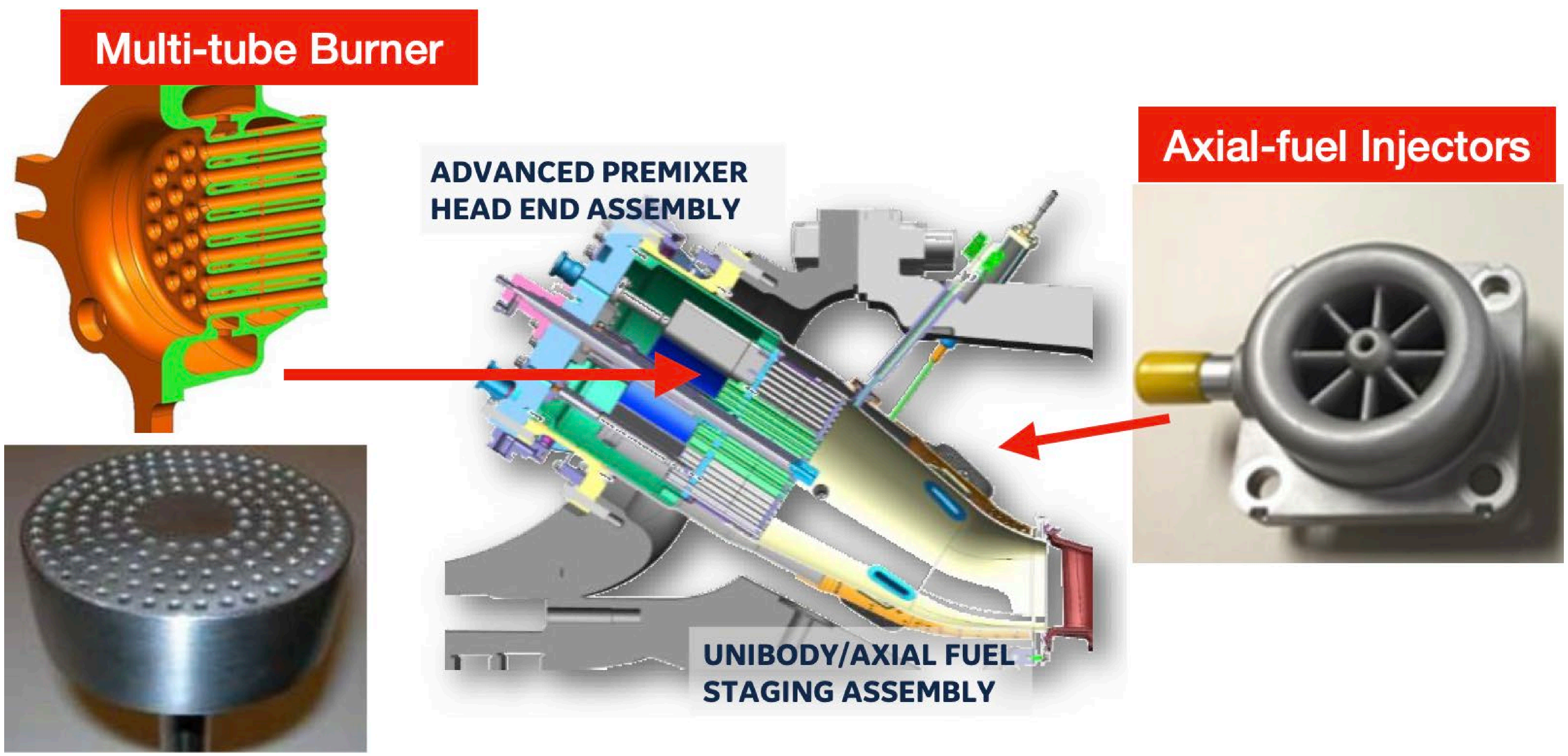
Presentation Outline

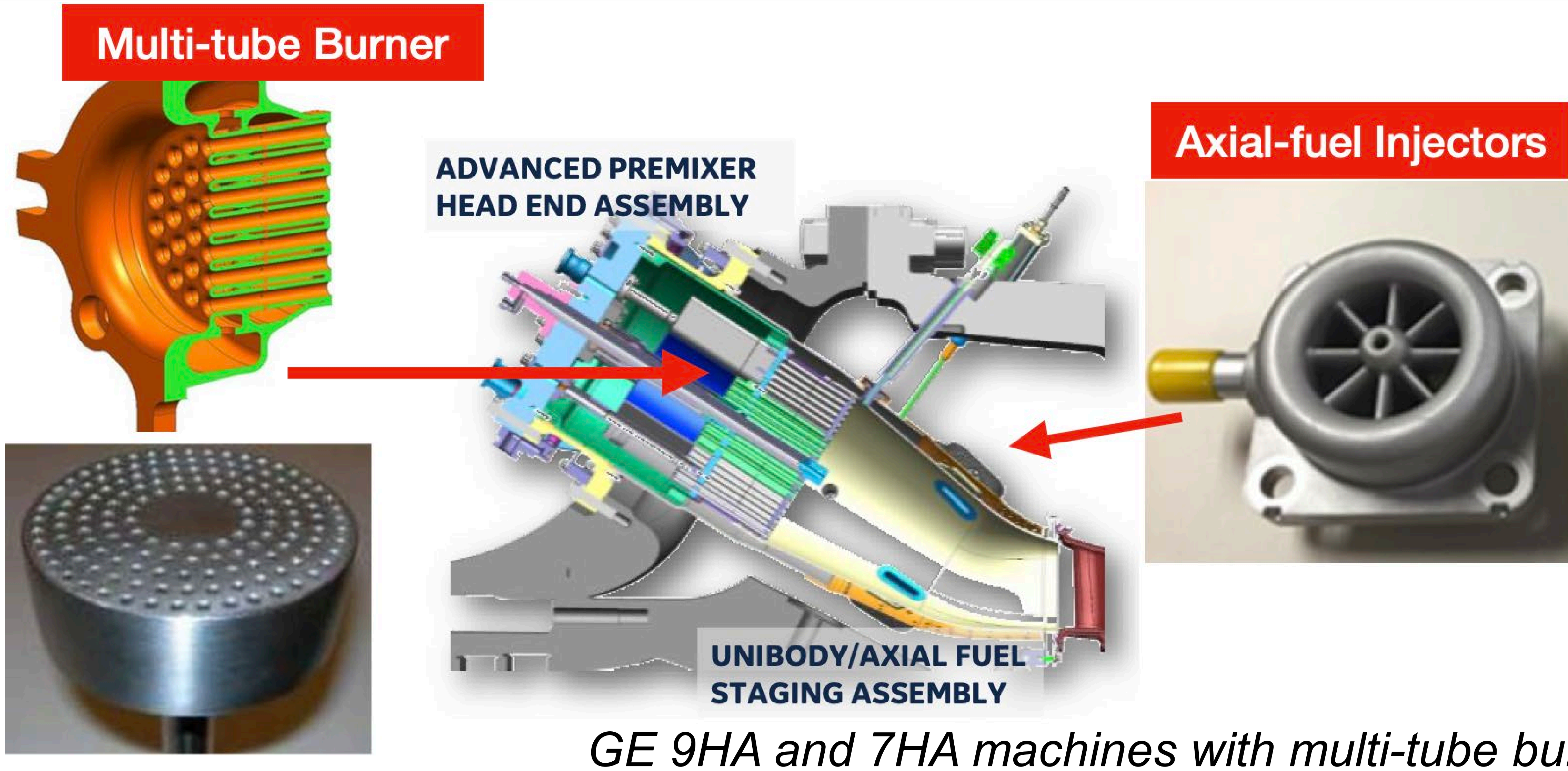
- Background
- Project Objectives
- Technical Approach
- Year 1 Goals and Summary

The focus of this work is on core flow physics and flame processes that control combustor operation using hydrogen and hydrogen-containing (HC) fuels



GE 9HA and 7HA machines with premixer/primary combustor and axial fuel staging

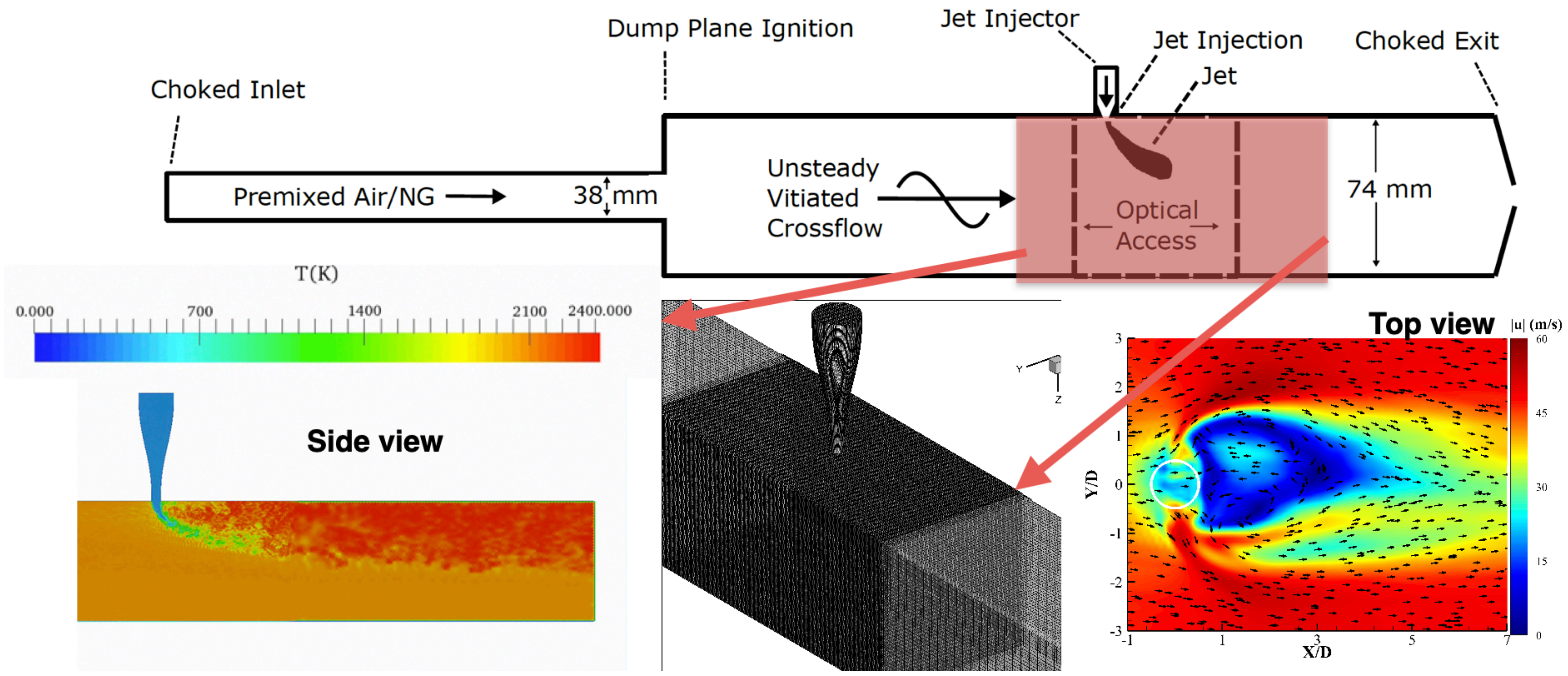
Background



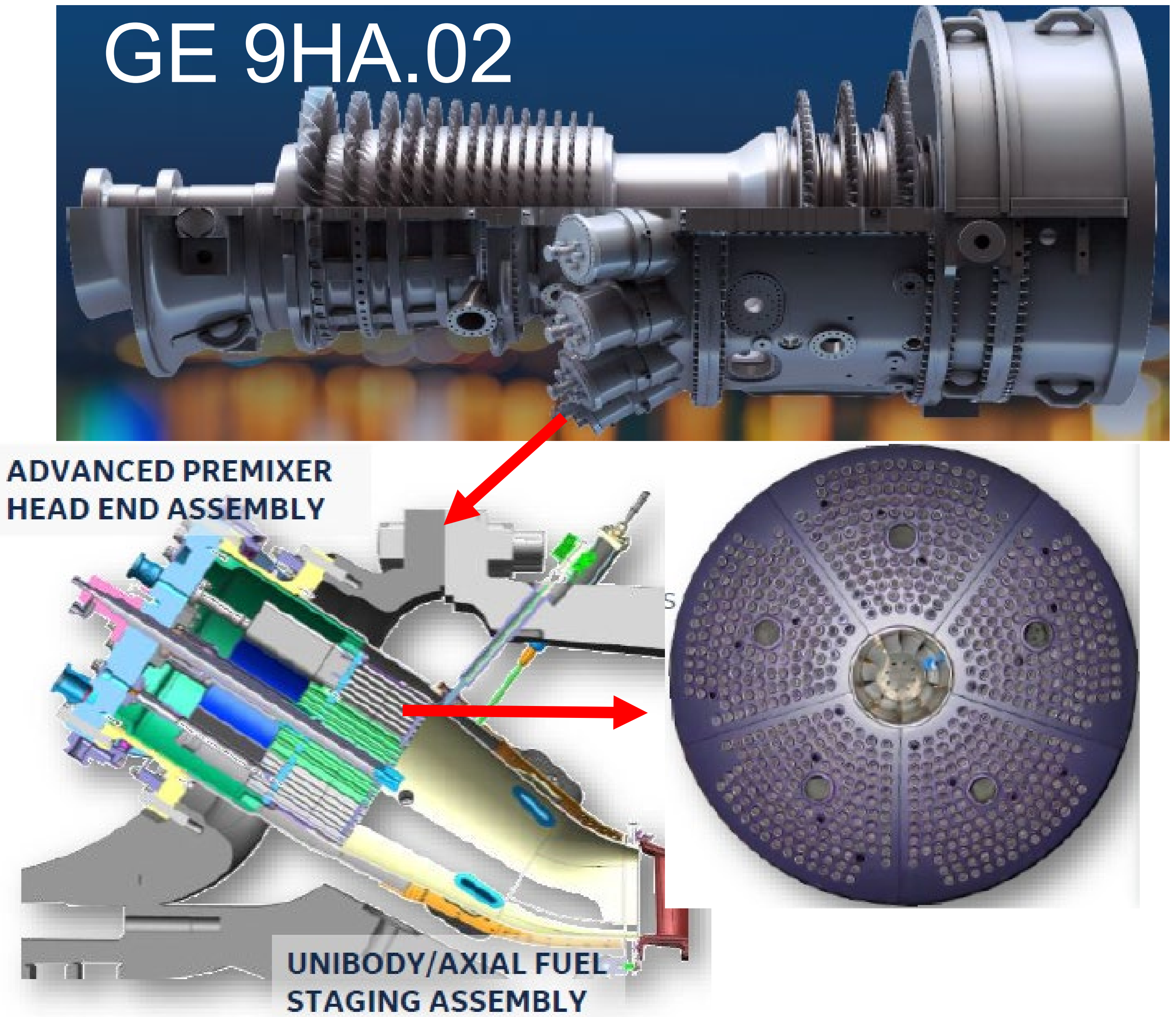
GE 9HA and 7HA machines with multi-tube burner and axial fuel staging

- Many modern designs use both a lean, premixed primary burner and an axially staged secondary burner
- Many core physics governing flameholding, flashback (primary burner) and axial fuel staging are similar
- We contend a controlling factor is the interaction of stratified fuel-air mixtures with a propagating turbulent flame (stratified combustion in highly turbulent crossflow!)

Background
(Key Physics – flame stabilization)



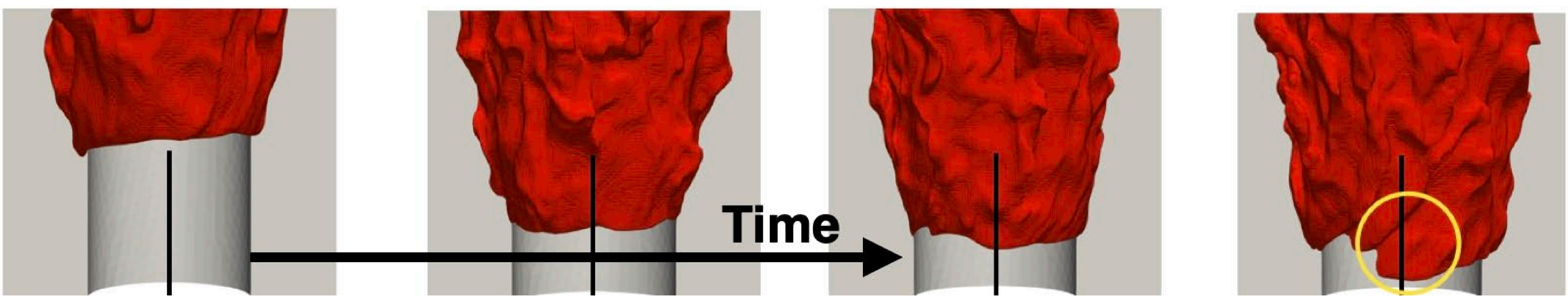
Experiment (Lucht, Purdue) and LES (co-I Raman, UM) of AFS



- Example AFS shows JICF (fuel/air into combustion products)
- Structure/stabilization location depends on jet-to-crossflow momentum ratio and thermo-chemical states
- Primary burner (i.e., premixer) flameholding physics can be cast similarly– fuel jets into high-pressure air from compressor – **JICF**
- *Flame stabilization*, including unwanted flameholding in premixing section, is likely the limiting design constraint for low-to-medium hydrogen operation

Background (Key Physics - flashback)

- For higher hydrogen content *flashback* (through boundary layer) becomes very important and limiting design constraint
- Flashback is heavily influenced by flow at exit of premixer
- Near-wall flow and heat transfer adds challenges



Simulation of flashback along a centerbody in swirling flow using LES (co-I Raman and co-workers)

Technical Objectives: (1) investigate physics governing flame stabilization and flashback (2) develop predictive computational tools for simulating gas turbine combustion ***when burning hydrogen-containing (HC) fuels***

Project Objectives:

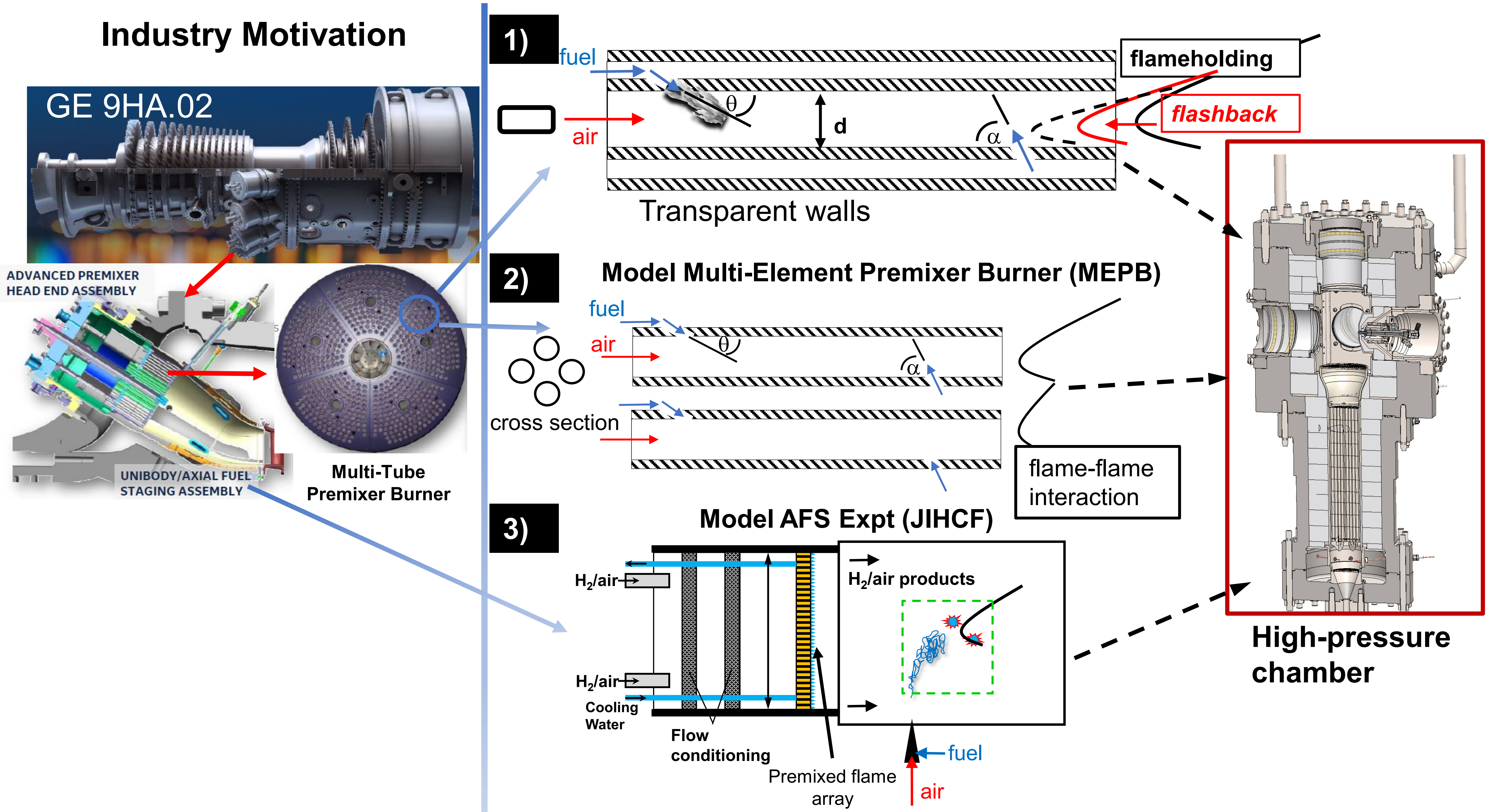
- Objective 1 – use hierarchy of experiments/laser diagnostics to quantify rate-limiting physics; what physics need to be captured in models?
- Objective 2 – develop suite of validated, multi-regime computational models
- Objective 3 – characterize operability and operational limits (exploration of parameter space) for burner and AFS systems through coupled expt-CFD discovery/design approach

Project Structure

Hydrogen Fuel Effects on Stability and Operation of Lean-Premixed and Staged Gas Turbine Combustors

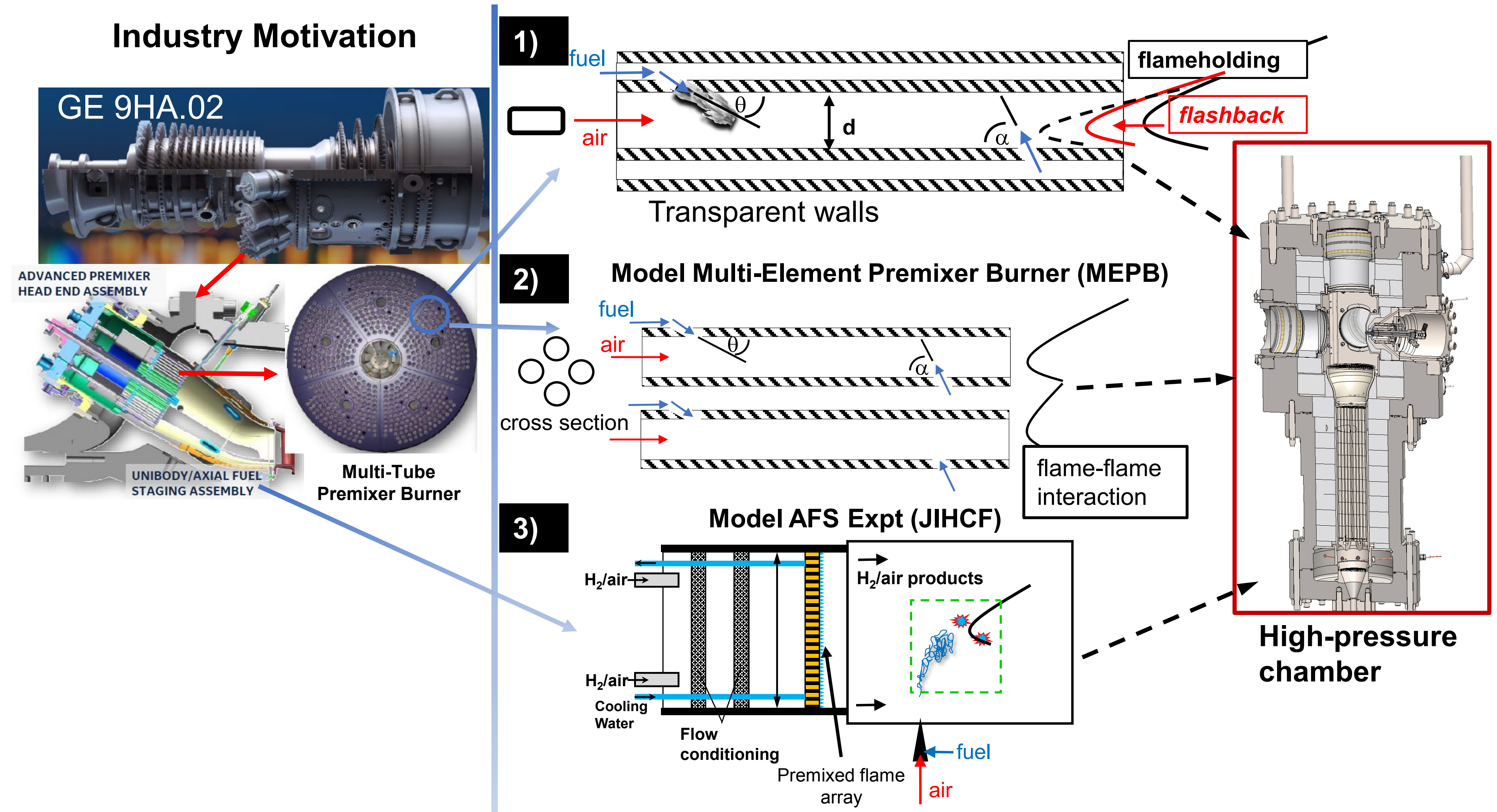
- **Objective 1**
  Experimental study of flameholding, flashback and axial fuel staging for high hydrogen-content operation
  - **Task 2.1**
    Development of hierarchical set of test configurations
  - **Task 2.2**
    Flame stabilization mechanisms from spatially and temporally resolved measurements
  - **Task 2.3**
    Mixing and flow dynamics during flashback
- **Objective 2**
  Computational modeling of flashback, flameholding and axial fuel staging
  - **Task 3.1**
    Flame-generated manifolds for multi-regime combustion
  - **Task 3.2**
    Turbulence modification due to flame propagation
  - **Task 3.3**
    DNS-based model discovery
- **Objective 3**
  Validation and exploration of parameter space for burner and AFS design
  - **Task 4.1**
    Validation of LES models using hierarchical experiments
  - **Task 4.2**
    Exploration of parameter space for flameholding and AFS systems
  - **Task 4.3**
    Exploration of parameter space for flashback

Technical Approach (Experimental)



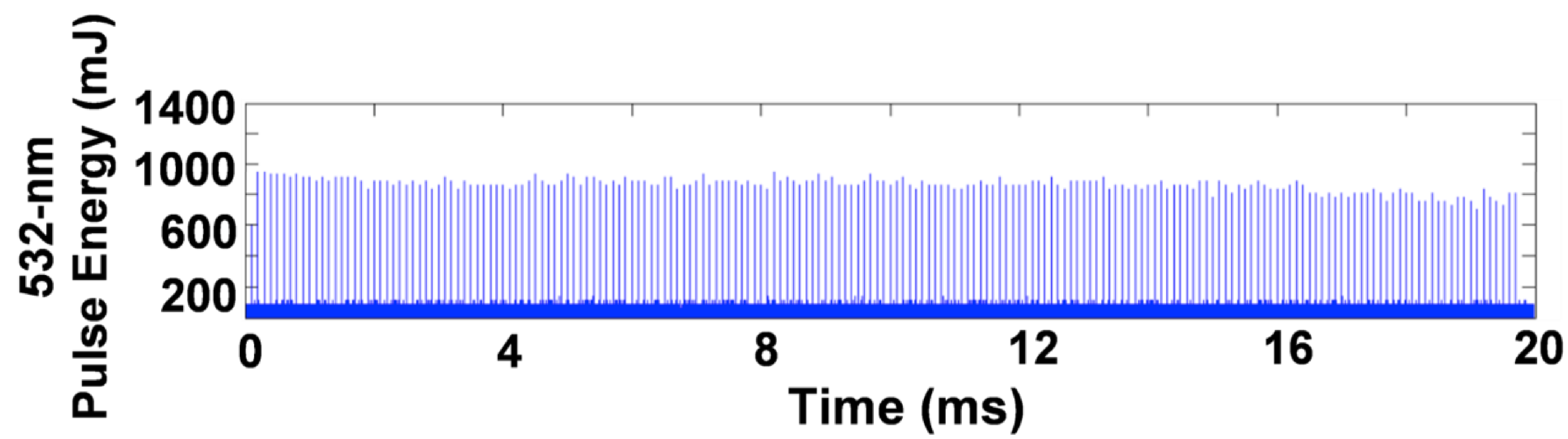
- Configurations model important flow and geometric features of multi-tube premixer burner and AFS systems under engine-relevant conditions
- NOT a duplication – captures key features that influence flameholding and flashback and should be modeled

Technical Approach (Operating Conditions)

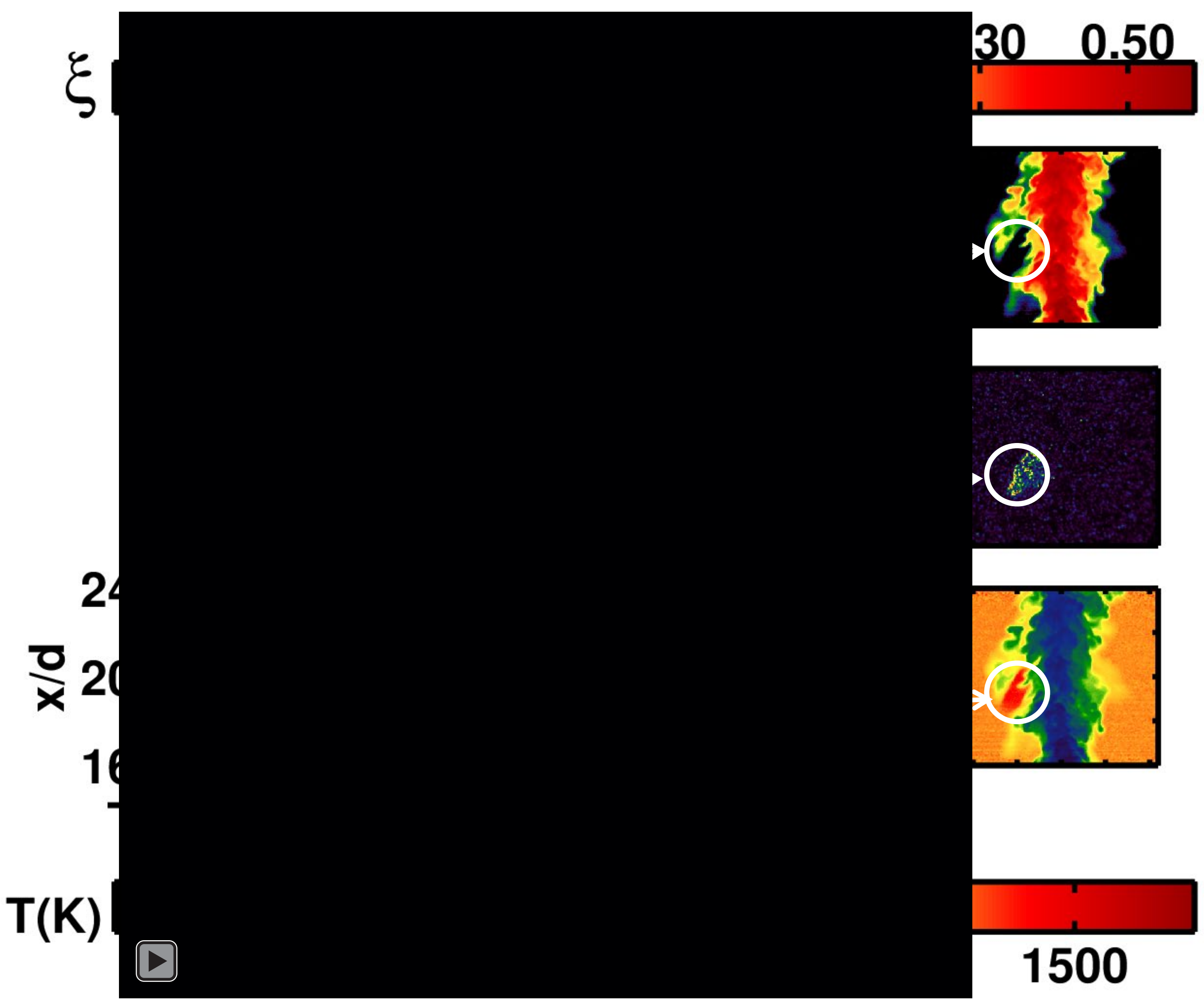


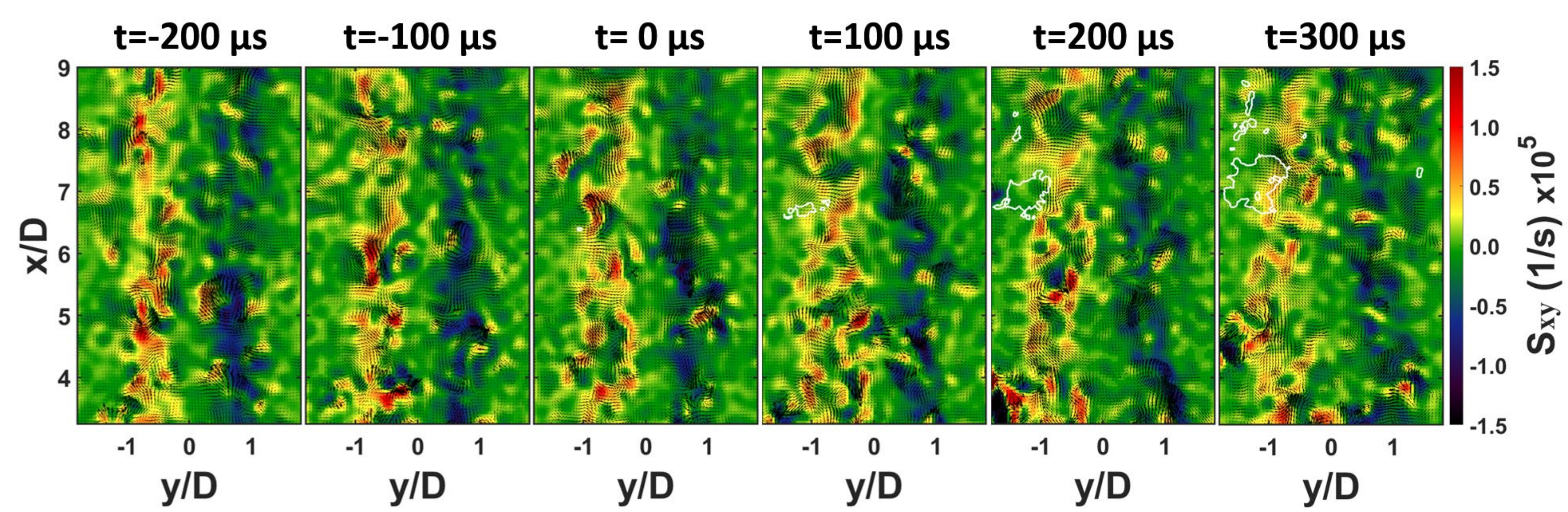
- Partially premixed injection into thermally/compositionally stratified streams
- Significant confinement effects – can affect jet trajectories when jet-to-crossflow momentum is low
- High pressure (up to 30 bar); air temperature up to 700K ; fuel mixtures of 50% to 100% H_2 (balance CH_4); NH_3 considered
- Variations in injection angle, # of injection sites, and inflow conditions

- The controlling processes are transient – time-resolved measurements are critical to describe interactions



OSU High-Energy Pulse Burst Laser System (HEPBLS)

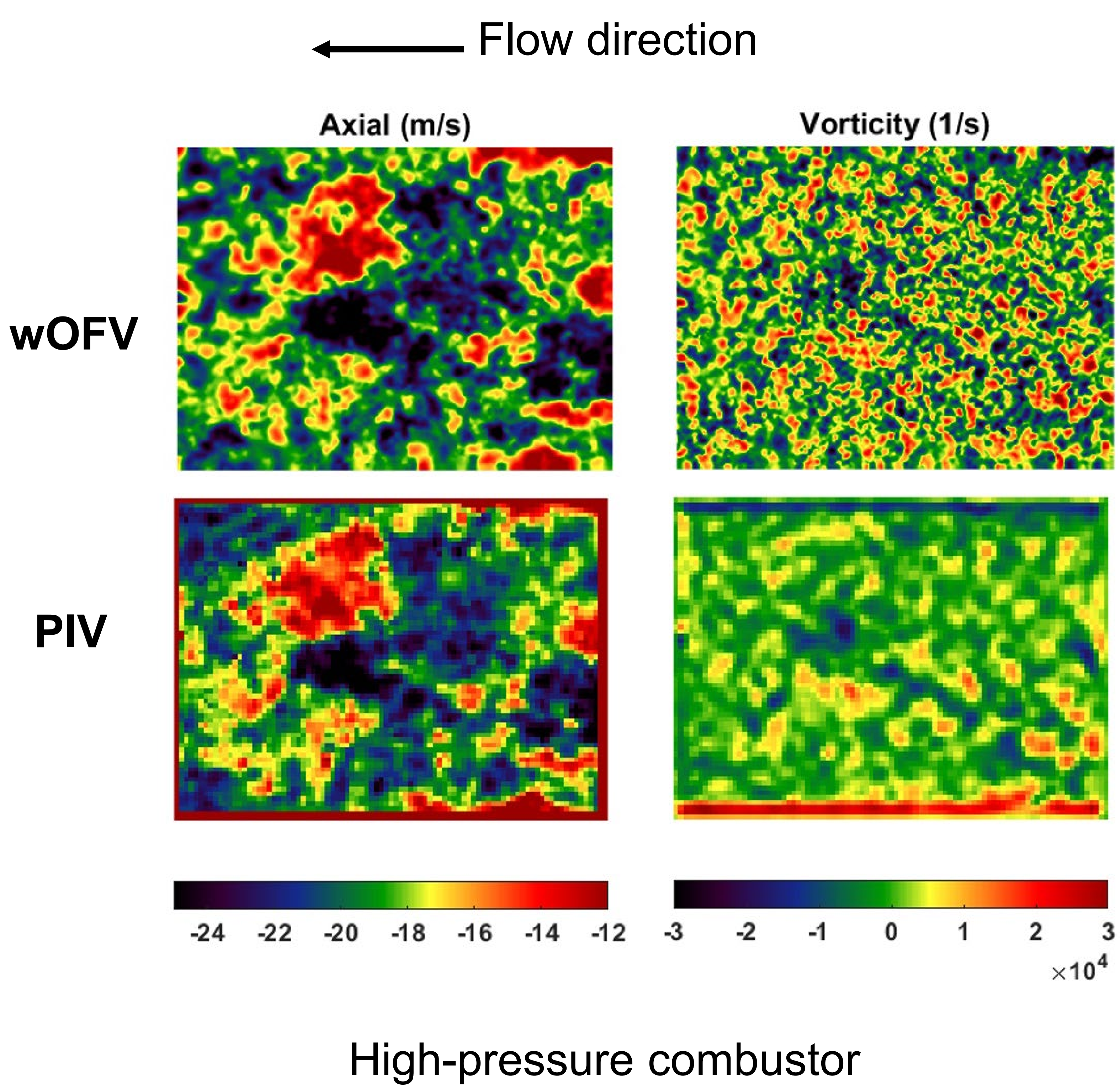


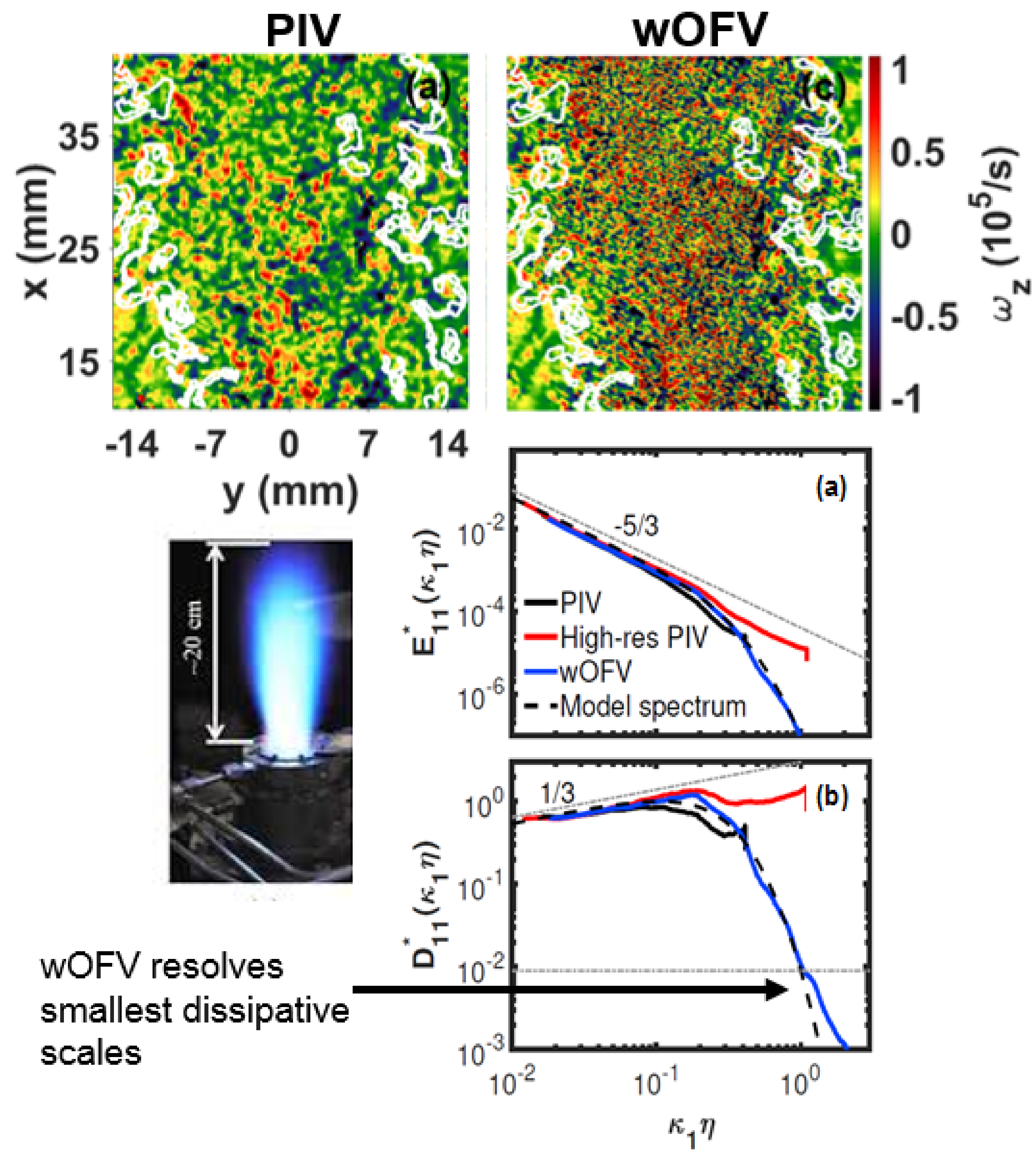


(Left) Time-resolved image sequence of mixture fraction and scalar dissipation rate during ignition of a co-axial configuration. (Right) Time-resolved image sequence of flow field during same type of ignition sequence

Technical Approach (Laser Diagnostics)

- New velocimetry approach offers ultra-high spatial resolution



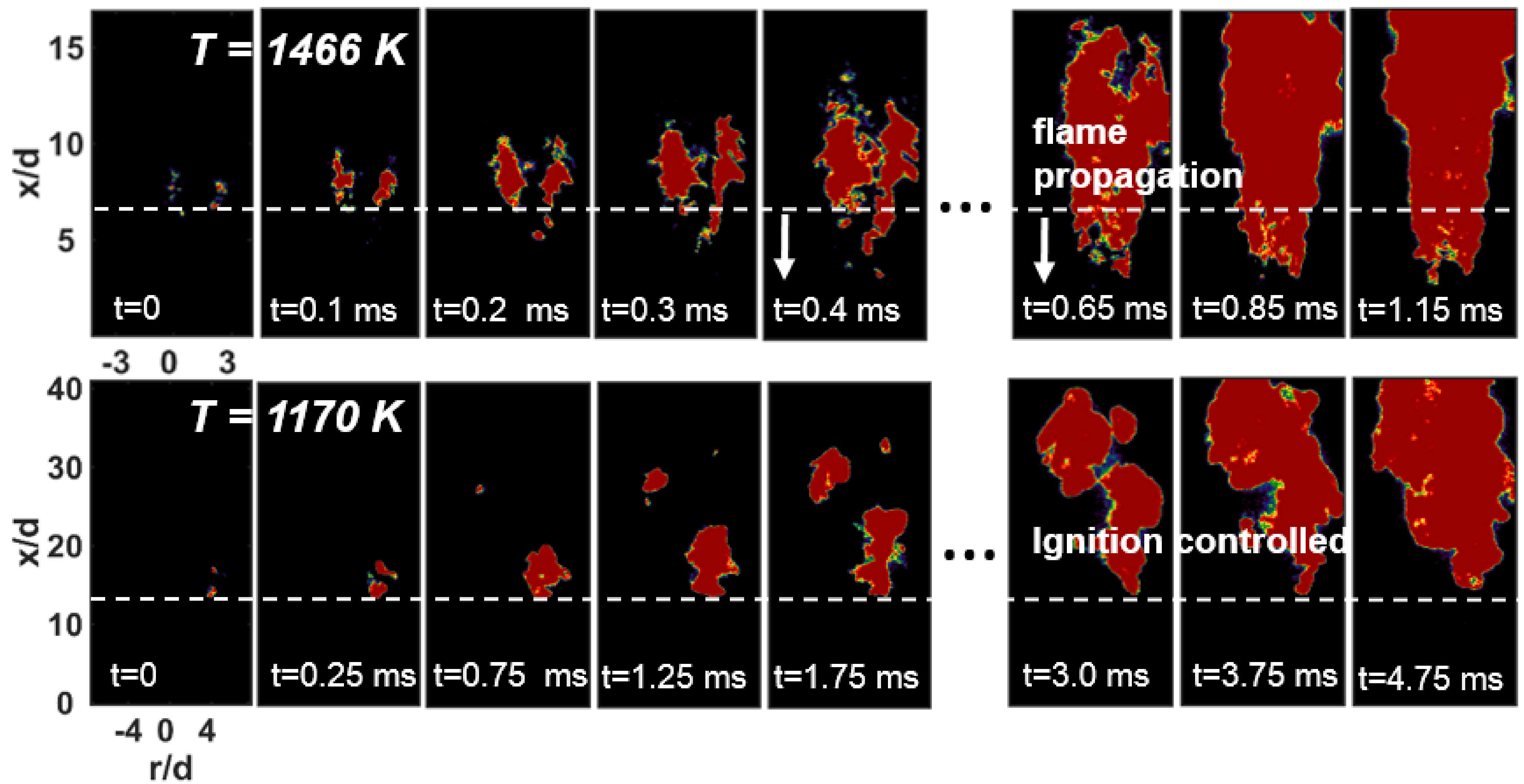


Comparison between wOFV (OSU developed) and PIV in (Left) 5-atm, swirl-stabilized combustor (at DLR Germany) and (Right) 1-atm turbulent premixed flame. ***wOFV allows resolution of smallest flow scales!***

Simultaneous time-resolved measurements of mixing, velocity, and flame front

- Flame stabilization (primary premixer and AFS):
  - Mixing measurements used to understand the degree of partial premixing (unmixedness) at stabilization point (re-circulation of products or through the shear layer)
  - Mixing sensitivity – what unmixedness leads to detachment or blowout? Effect of multiple injection points?
  - Fluid velocity ahead of the flame front and at the stabilization point is critical. Used to infer characteristic residence times and size of re-circulation zone (affects partial premixing)
  - What is the role of flame-induced turbulence suppression?

- Example: for AFS, structure and flame location affect NOx output – determined by mixing composition and method of stabilization
  - does it stabilize in shear layer, core flow, or near the wall?
  - Is it auto-ignition or flame propagation?



Example flame stabilization sequence for different vitiated stream temperatures in co-axial configuration

Simultaneous time-resolved measurements of mixing, velocity, and flame front

- Flashback dynamics:
  - Monitor time history of mixing and velocity upstream of flame and at flame front during flashback
  - Ensemble statistics of mixture fraction, velocity, and turbulence stats along flame front and at leading edge as flame propagates
  - Most probable conditions ahead and at flame promoting flashback
  - Characterization of flame-boundary layer interaction
  - Hydrogen enrichment – role of thermo-diffusive instabilities?

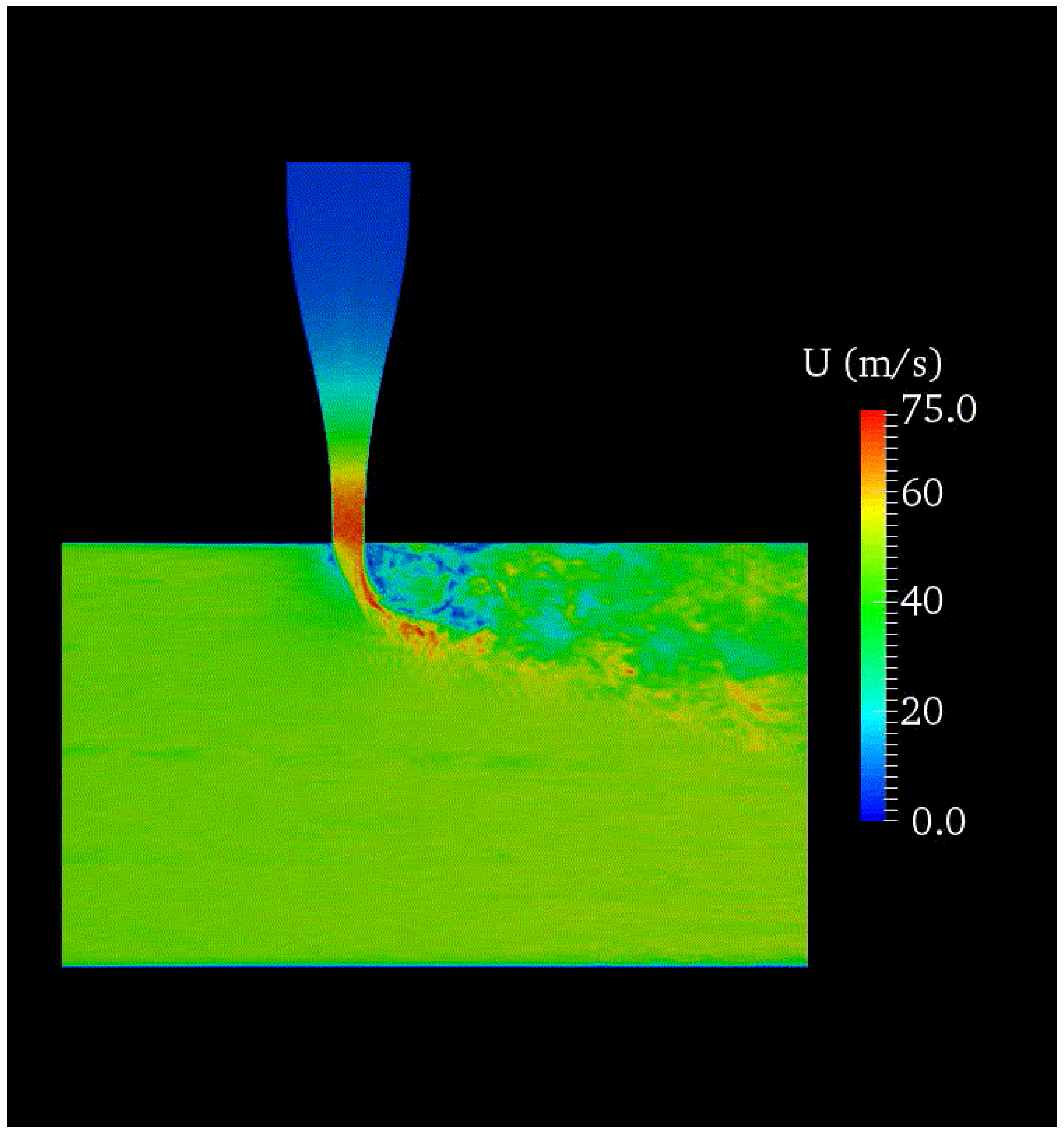
Project Plan for Computations

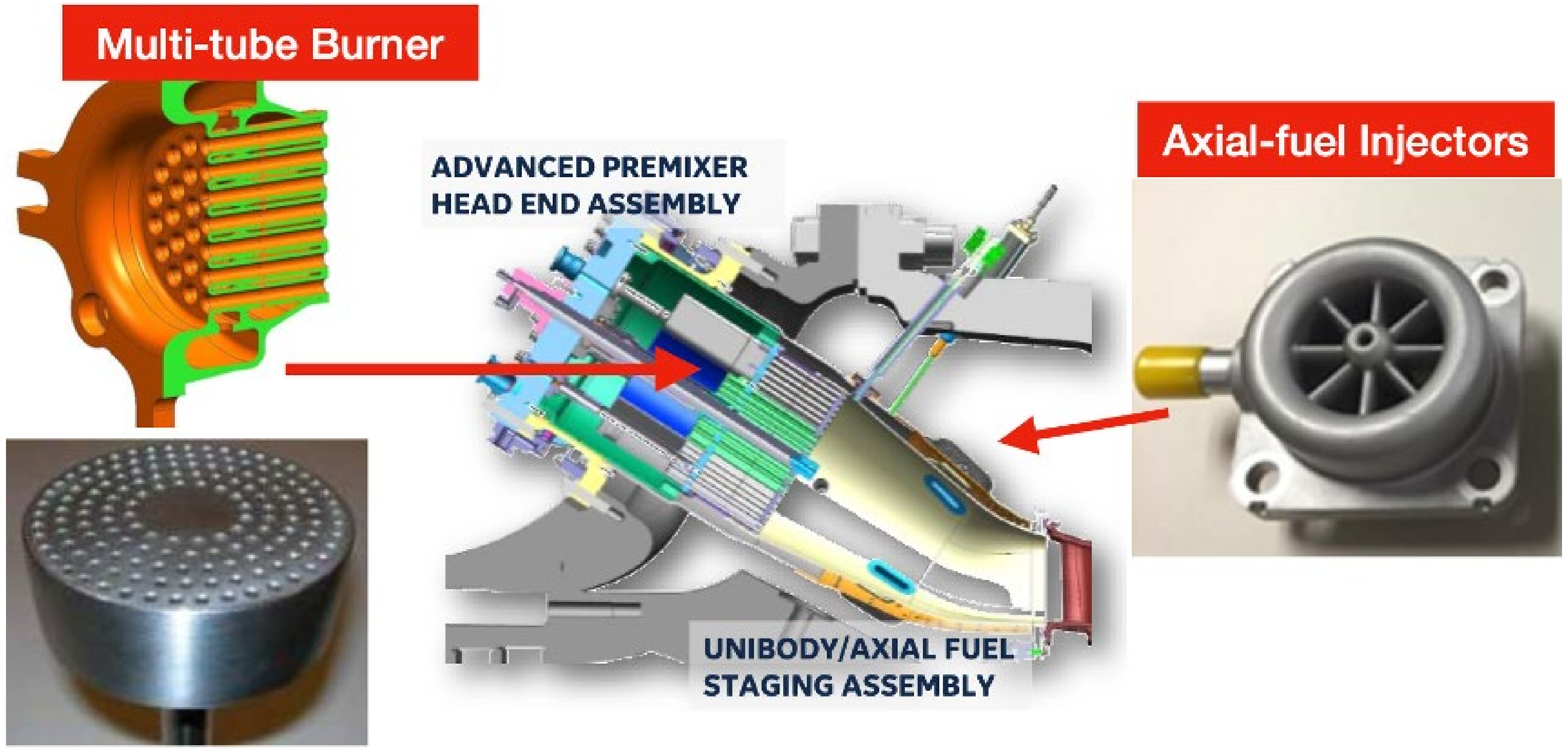
Venkat Raman

University of Michigan, Ann Arbor
Department of Aerospace Engineering

Approach

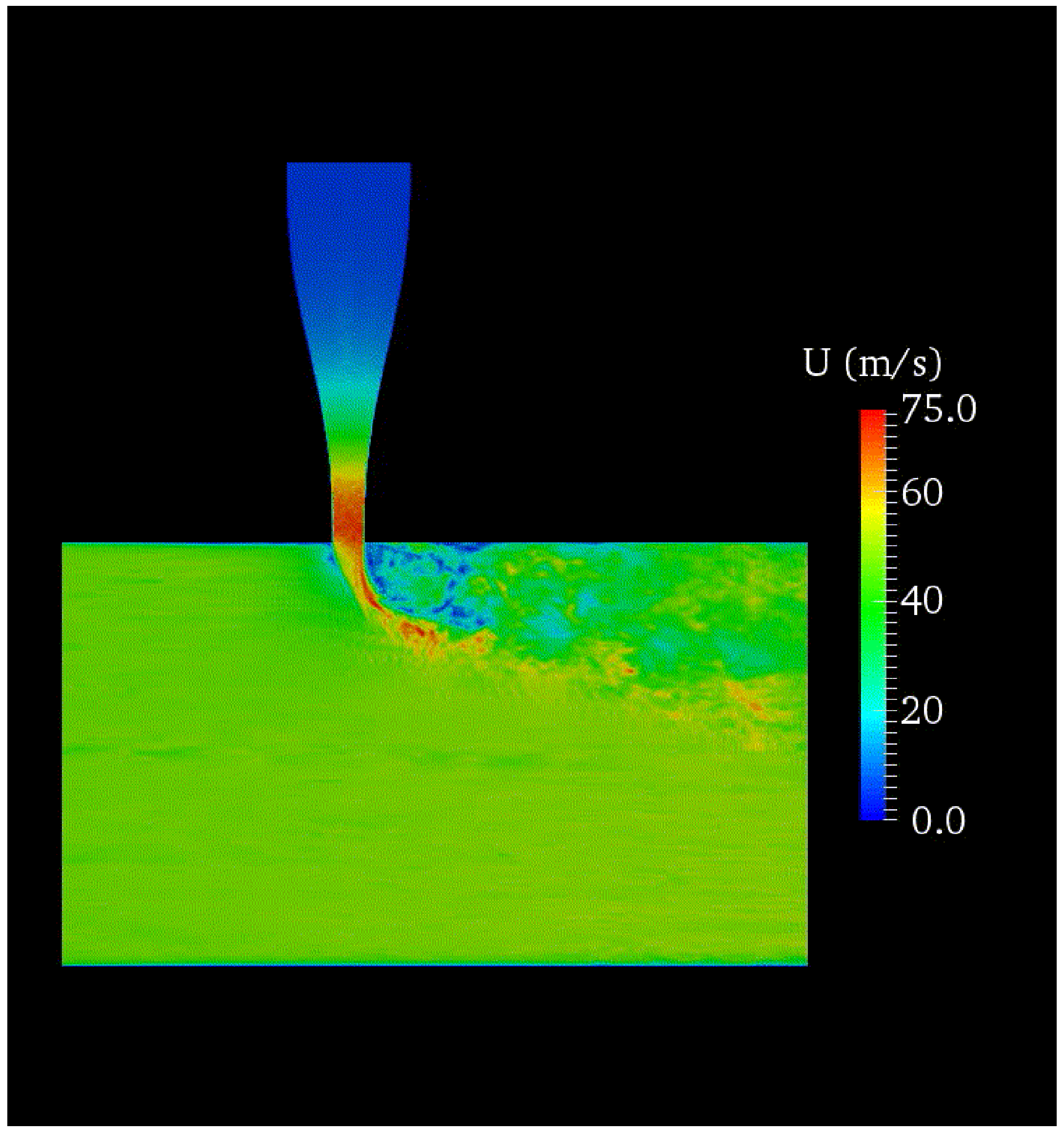
- **Understand limits of stability**
  - Flameholding
    - At low crossflow velocities, recirculation becomes dominant
  - Flashback
    - At high fuel injection velocity, flashback can become important
  - Flame blowout
    - At lean conditions, flame stabilization may be affected





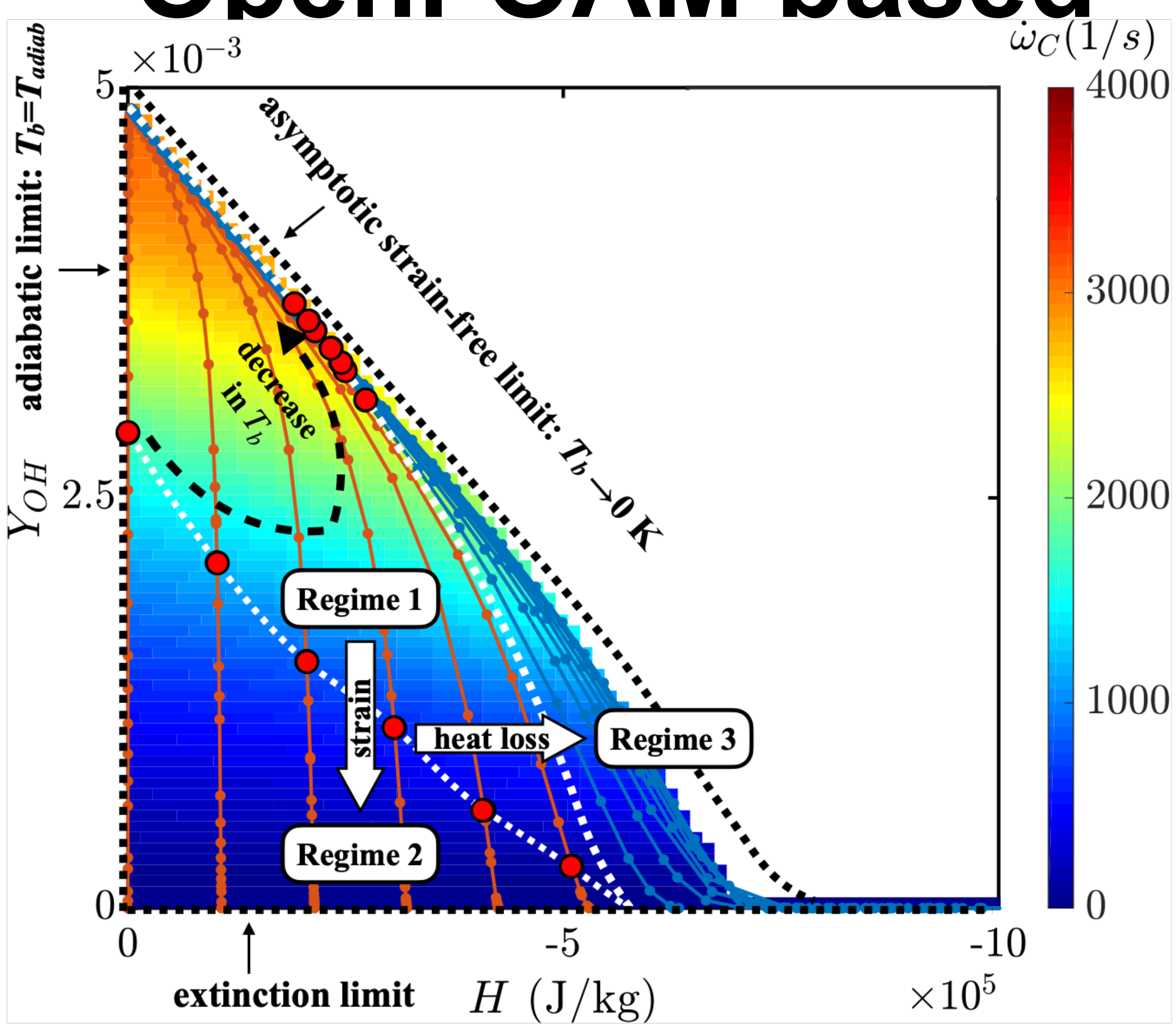
Reacting JICF Structure

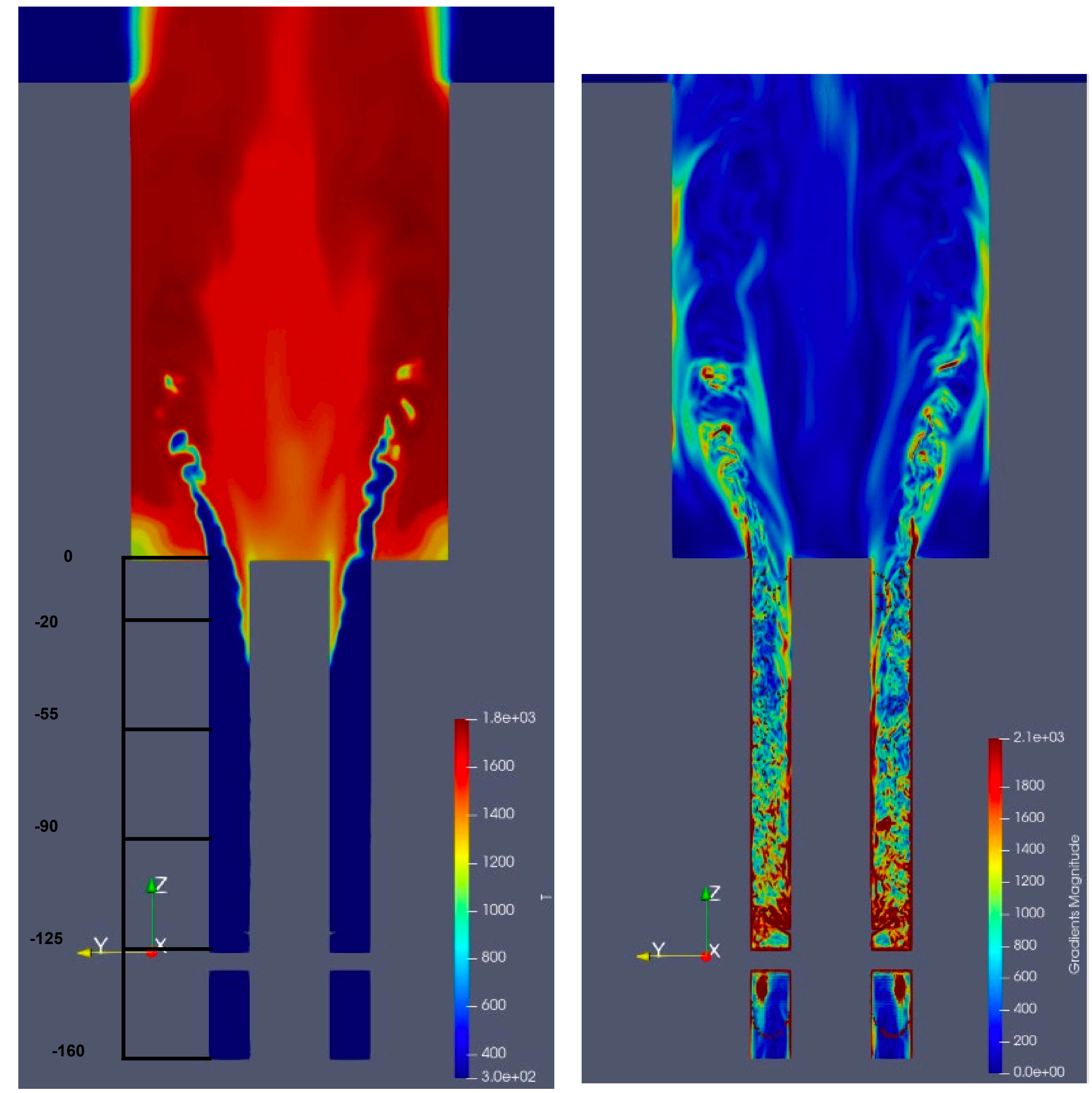
- High momentum ratio to lift jet
- Strong recirculation on left-side stabilizes flame



Flashback and Flame Modeling

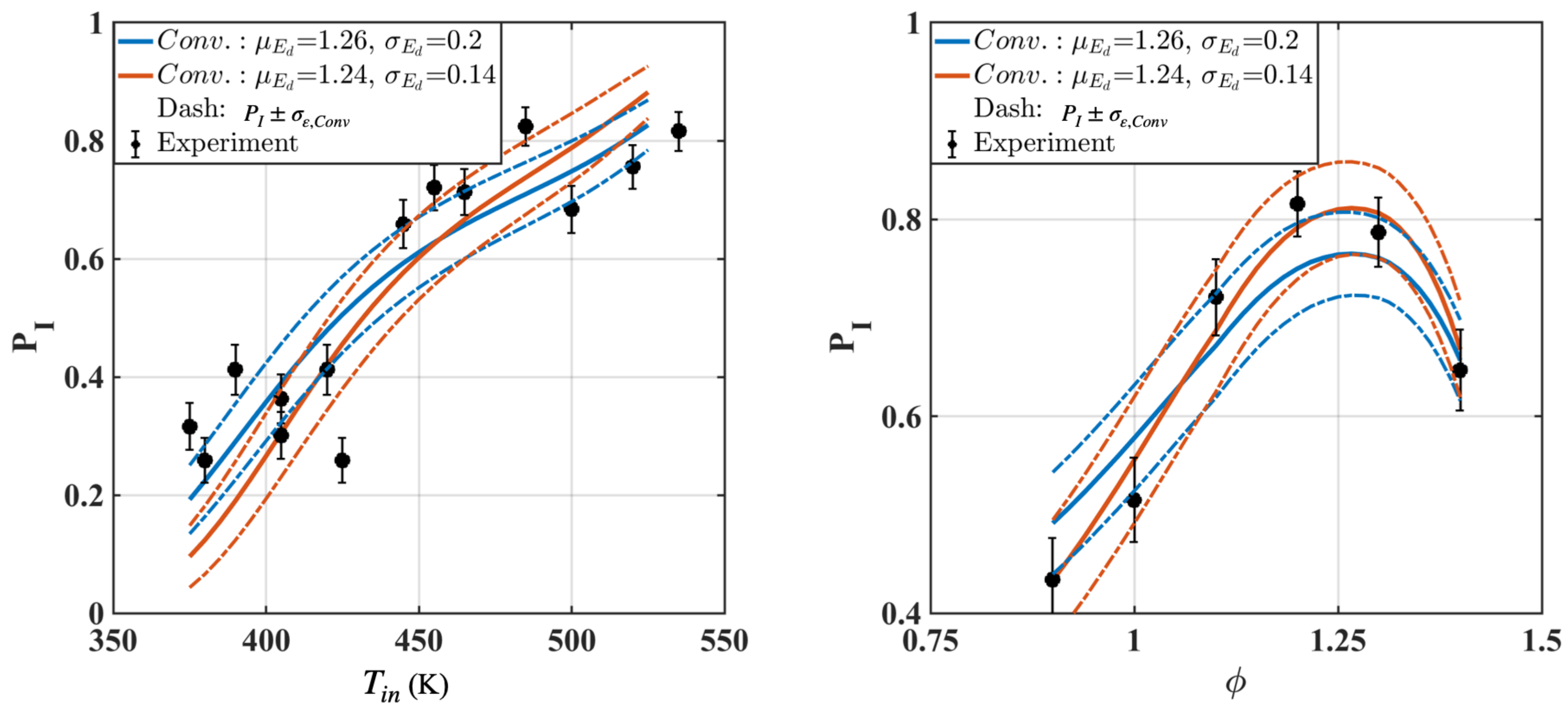
- **Flamelet-based approach**
- **Implemented in OpenFOAM based**

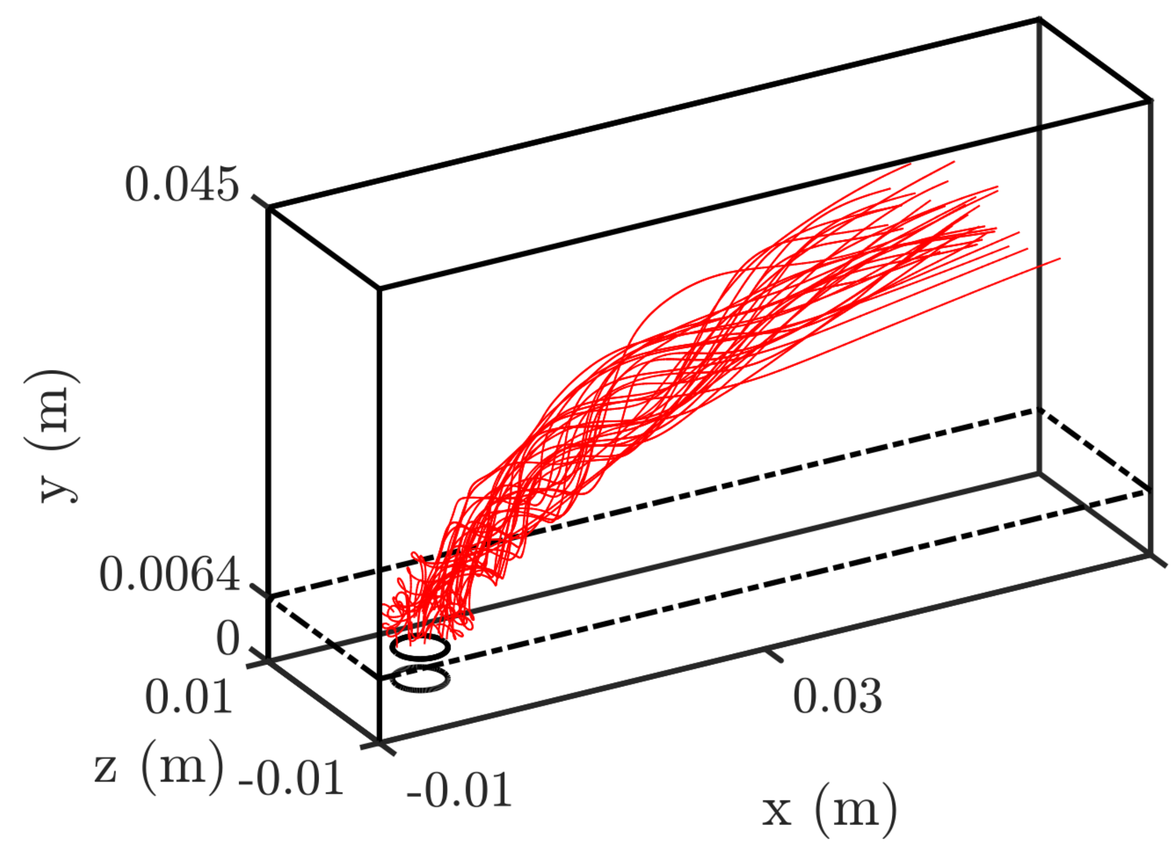




Modeling plan

- **How to describe ignition and flame holding?**
- **How to describe flashback?**
  - → Prior DOE NETL project
  - → Modeling solution available
- **Statistical approach to estimate probability of events**
  - → How to describe probability of ignition/flameholding/flashback?
  - → What are the tools required to do this?





Summary

- We have outlined a joint experimental-CFD program targeting flame stabilization and flashback under hydrogen-enriched fueling conditions
- State-of-the art time-resolved laser diagnostics and multi-regime modeling will be used
- Experiments and CFD are coupled throughout program
- We will use industry collaboration and expertise to guide pathway and decision points
- Design of experimental configurations is in review
- Baseline computations have started