Combustion Dynamics in Sequential combustors

Near-Limit Flames Workshop – Beijing 2019

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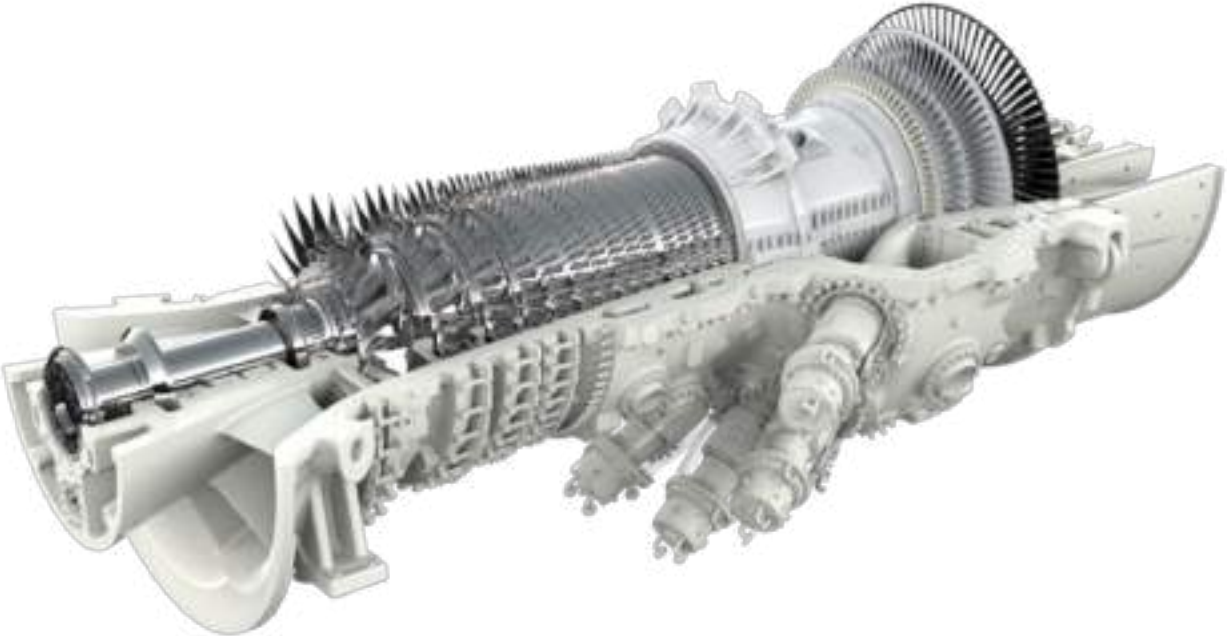
PSI: Dominik Ebi, Ulrich Doll

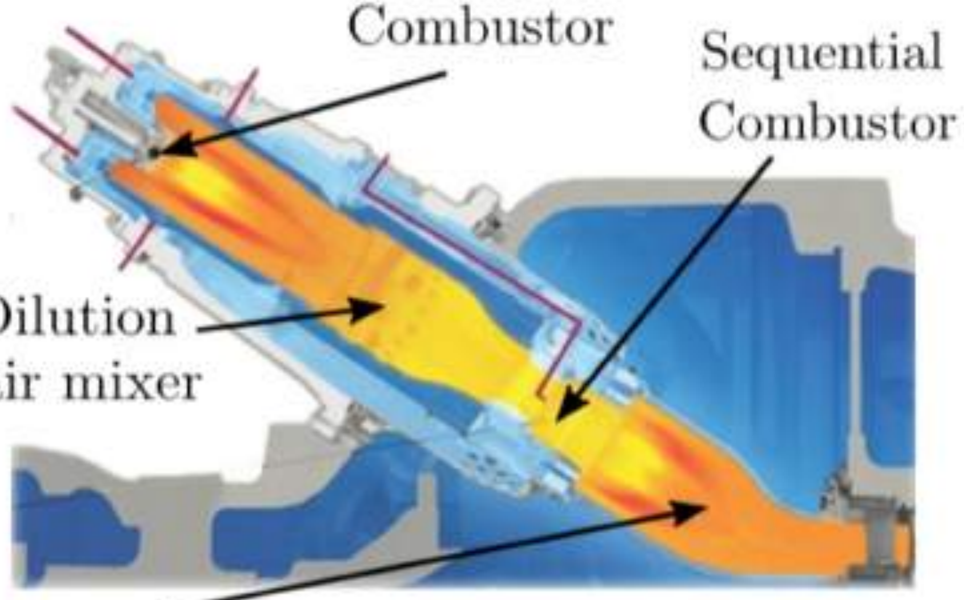
Sequential Combustion for operational and fuel flexibility

Operational flexibility with ultra-low NOx for compensating renewables intermittency and ensuring grid stability



Ansaldo GT36 gas turbine
Single cycle: 538 MW – 42.8% eff.

GT36 sequential combustor



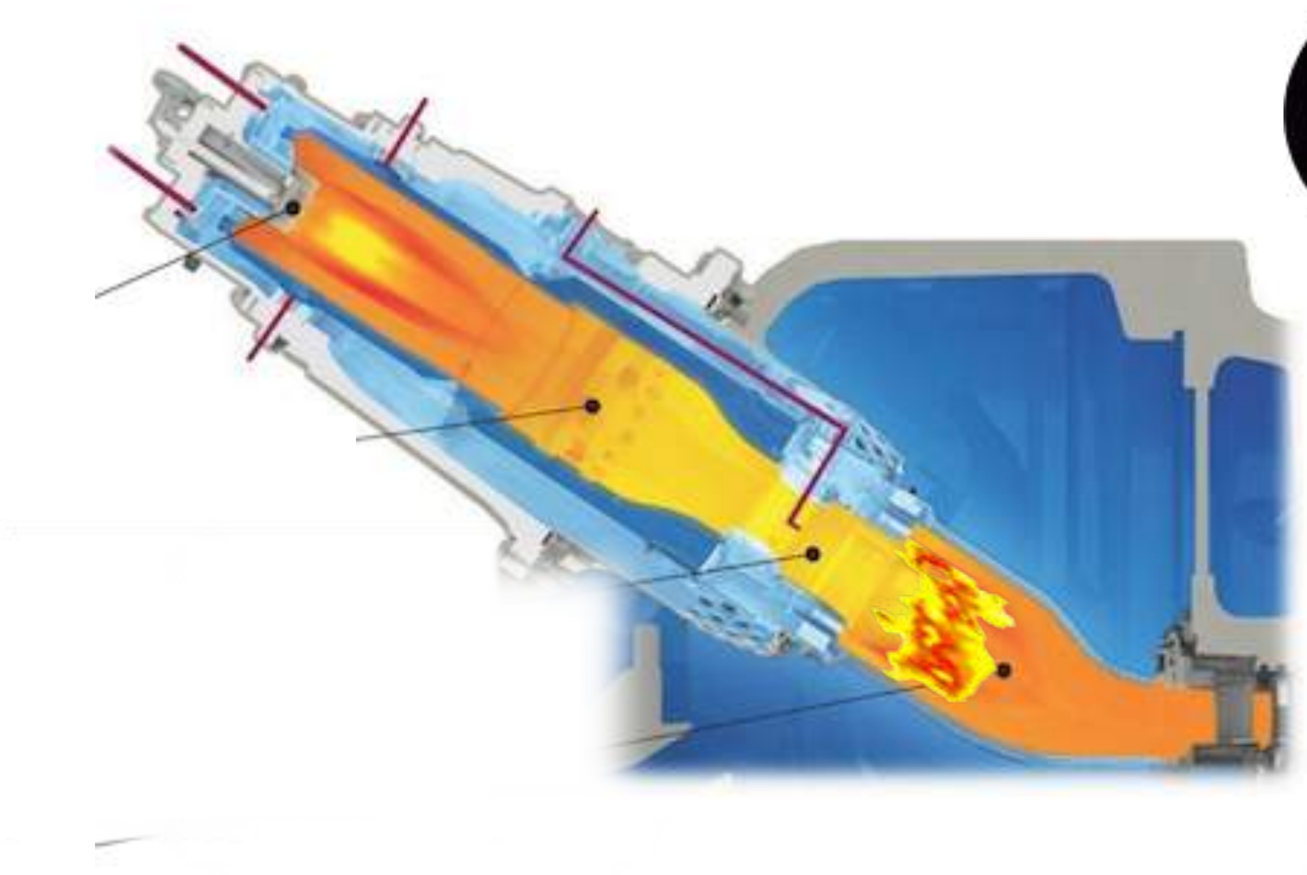
Pennell et al. „An introduction to the Ansaldo GT36 constant pressure sequential combustor.“, ASME Turbo Expo (2017)

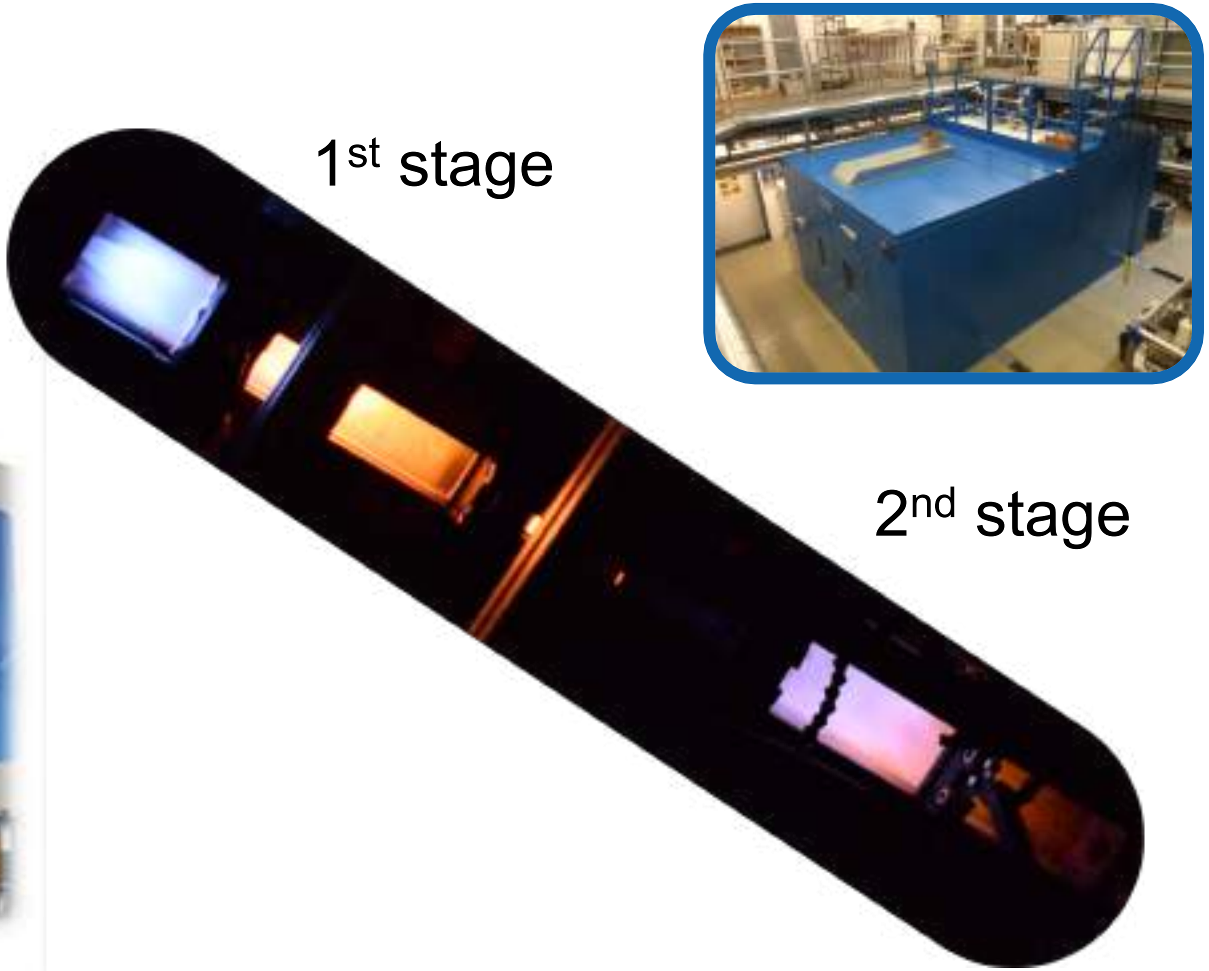
Combustion tomorrow: Burn Hydrogen in large gas turbines → storage, no more CO_2

Bothien et al, GT2019-90798

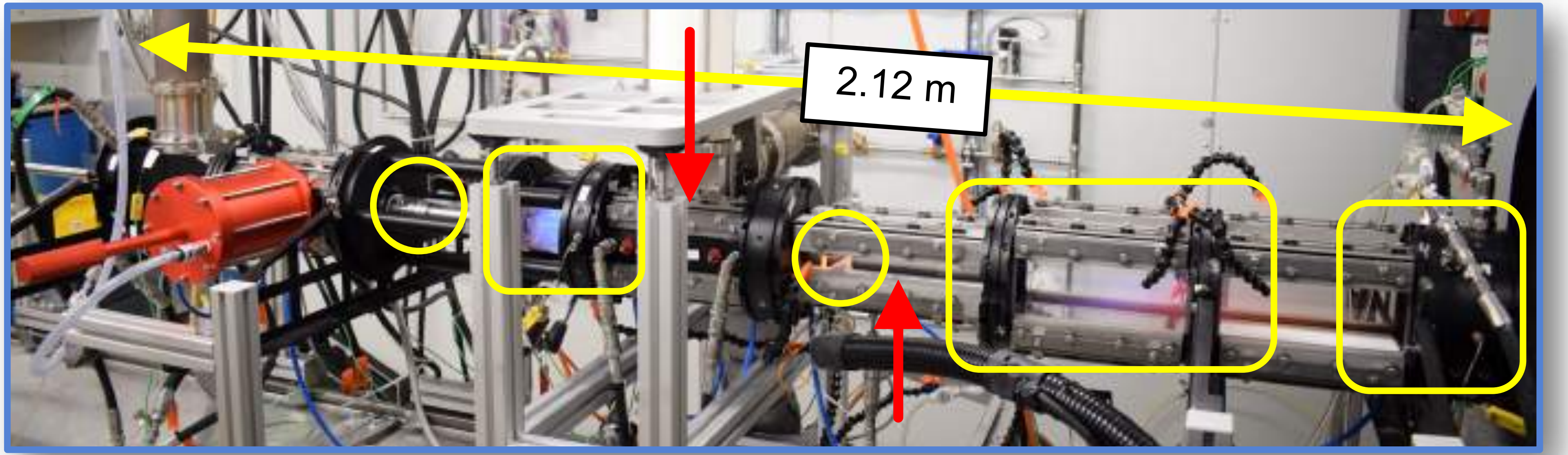
Demonstration of transition from 100% NG to 100% H2 at engine condition with standard GT36 hardware

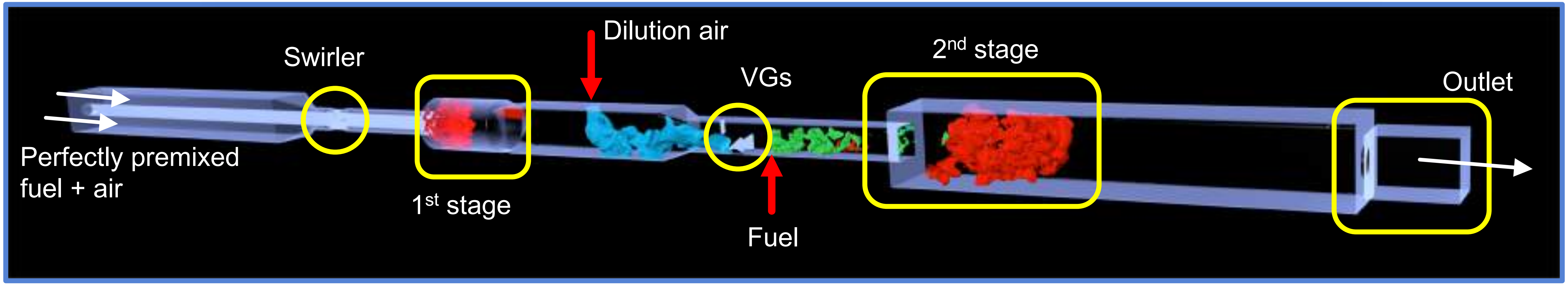
Sequential combustion research at ETH





The experiment and the computational domain





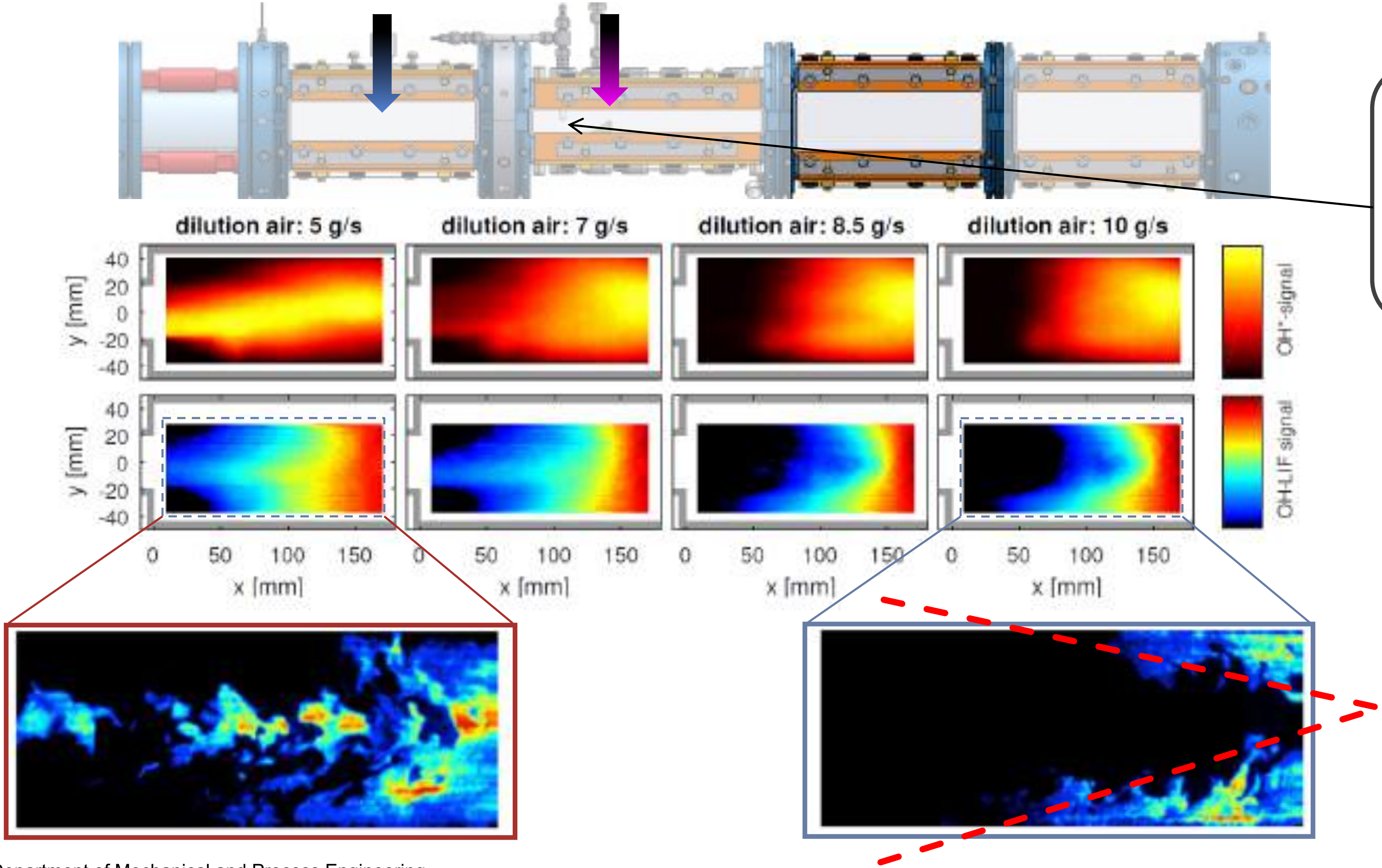
Combustion Dynamics in Sequential Combustor

1. From spontaneous ignition to deflagration

2. Thermoacoustic instabilities in sequential combustors

3. Sequential flame stabilization using NRP discharges

The combustion process in the sequential stage is complex

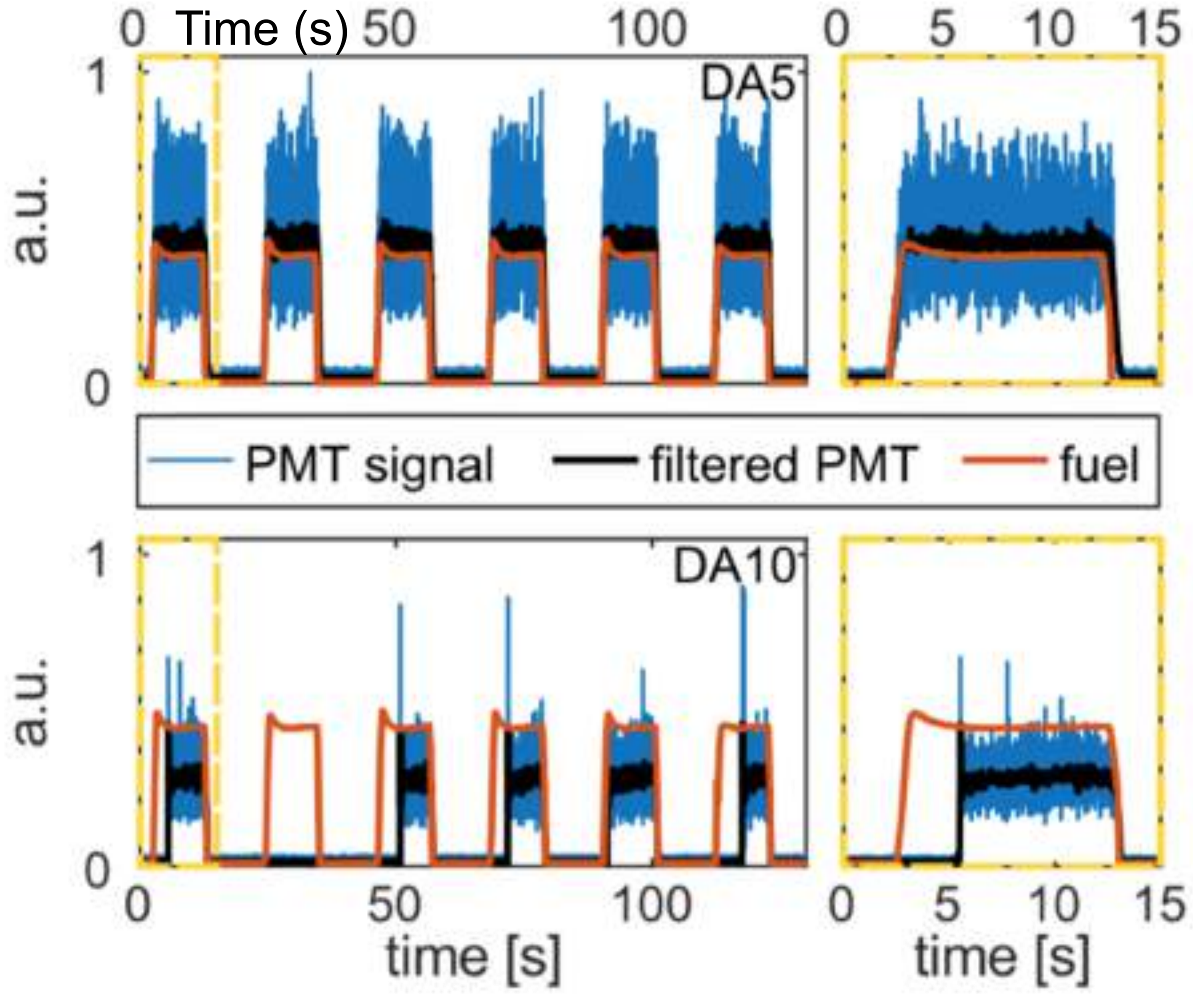


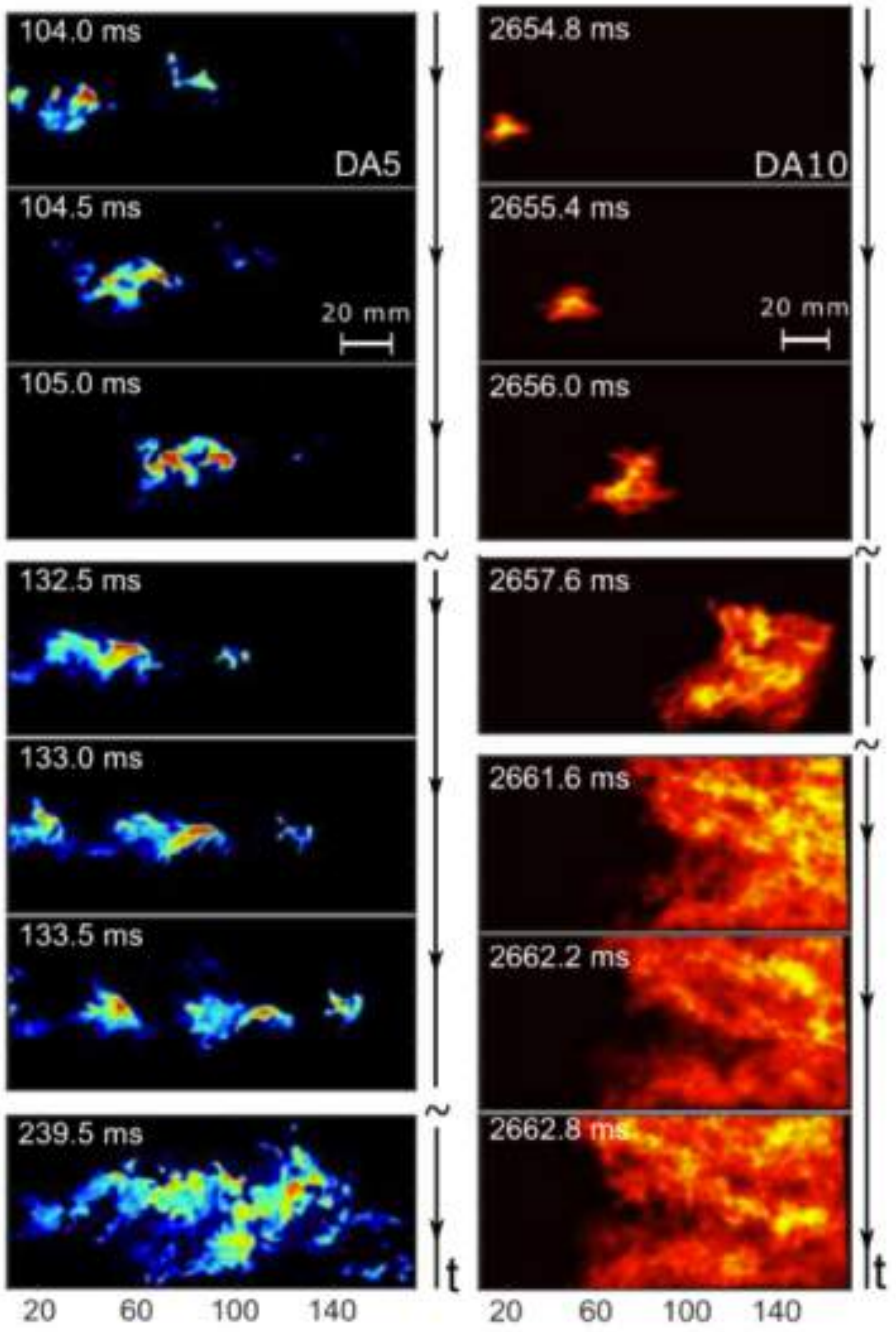
Temperature at the inlet of the sequential burner decrease with increasing dilution air.

8% decrease from 1278K to 1129K

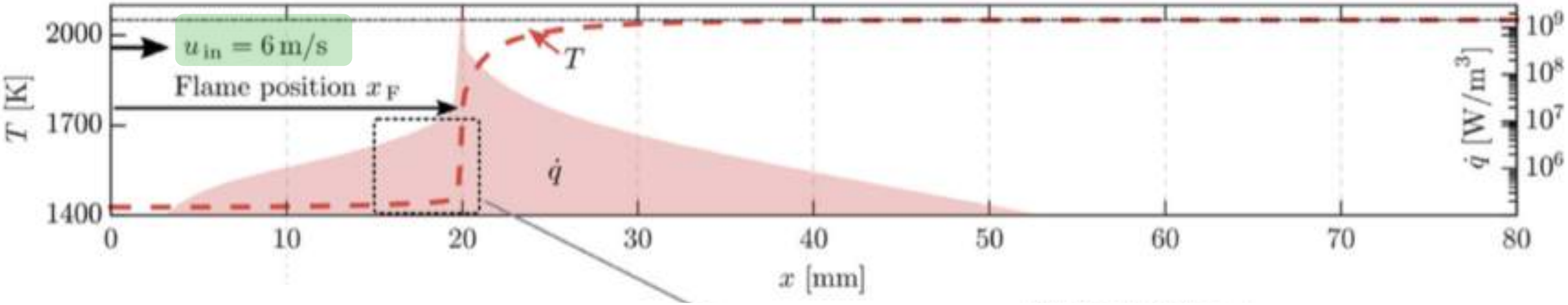
Ebi et al.
Proc. Comb. Inst. 2019

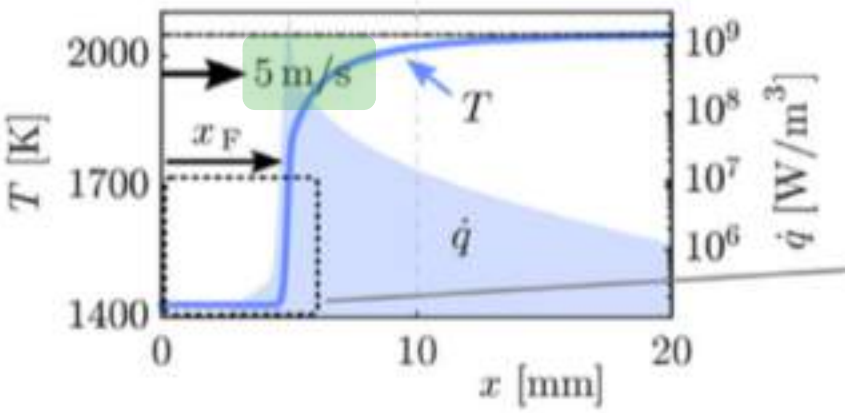
Sequential stage ignition at low and high dilution air mass flow





1D solutions, detailed chemistry (GRI 3.0) for 2 domain lengths



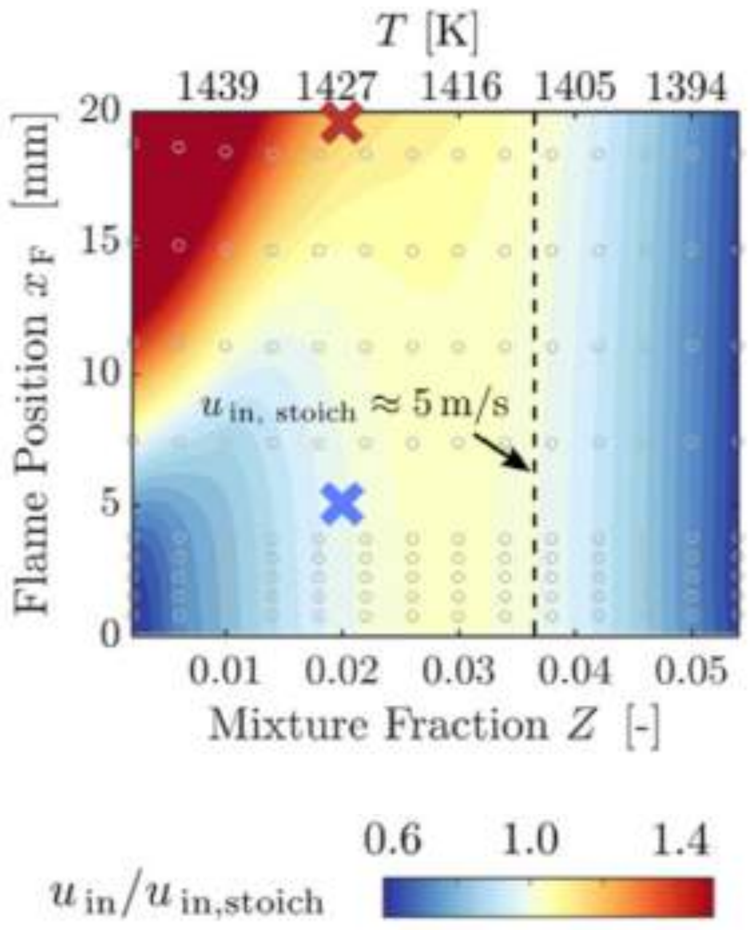


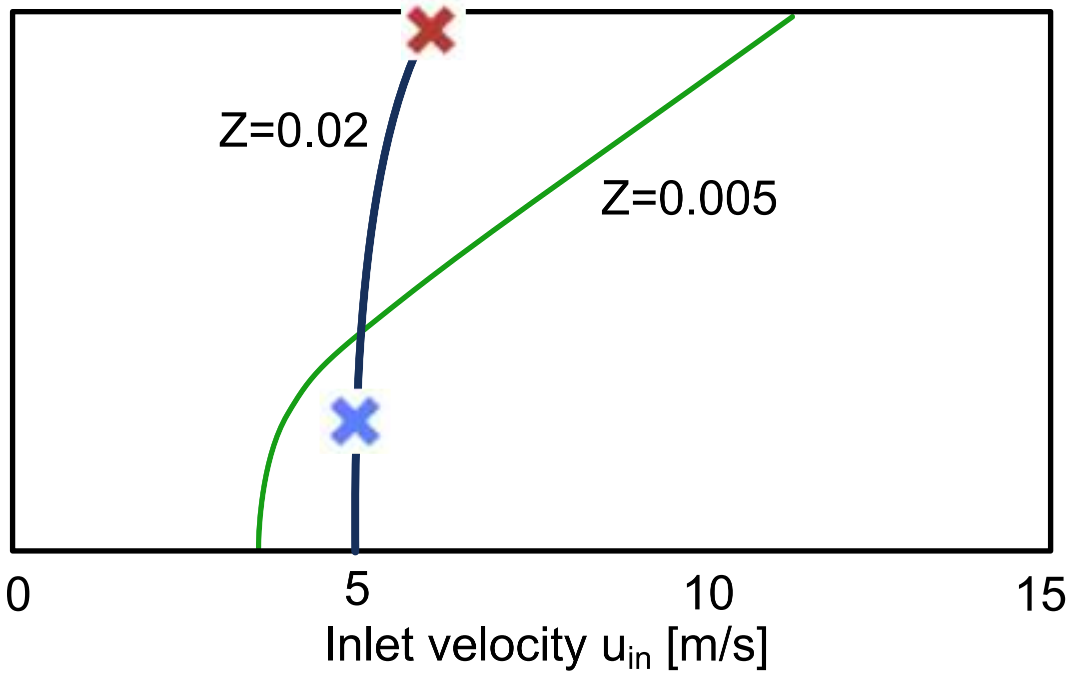
Mixing between CH_4 and air-diluted vitiated flow (N_2,CO_2,H_2O,O_2)

Mixture fraction $Z = 0.02\ (\phi = 0.54)$

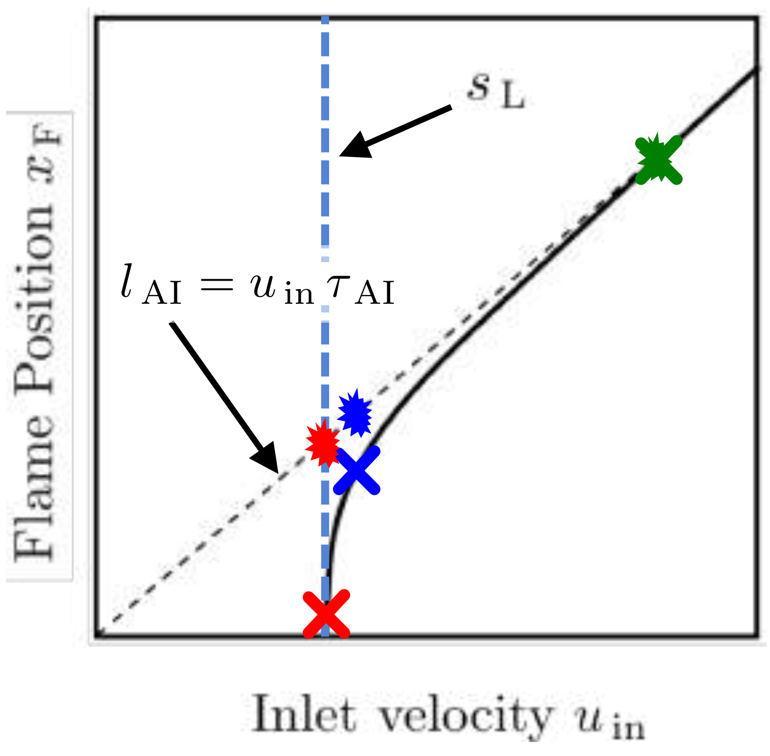
Mixture Temperature 1450 K (atm. pressure)

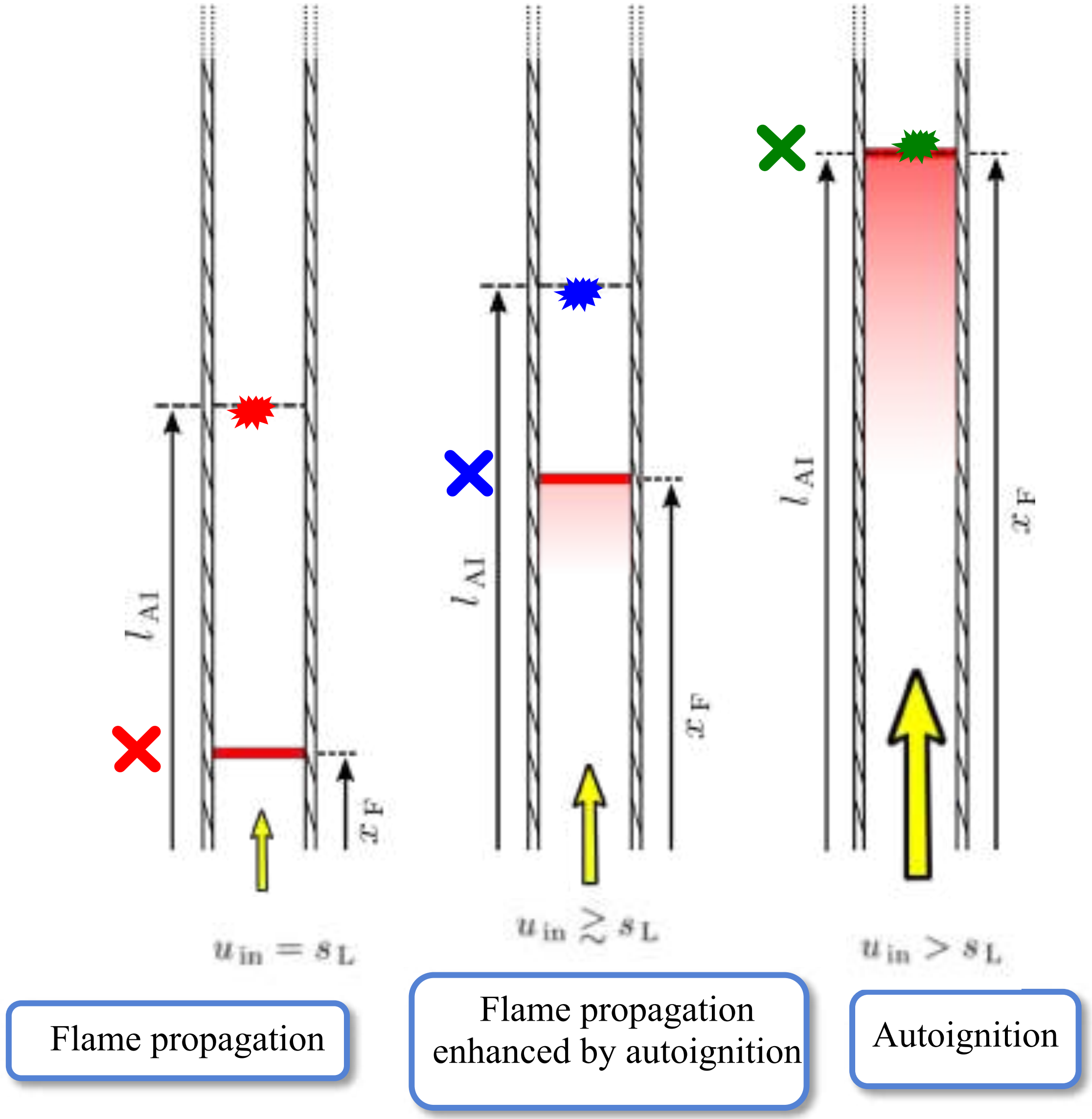
1D solutions, detailed chemistry (GRI 3.0) for 2 domain lengths





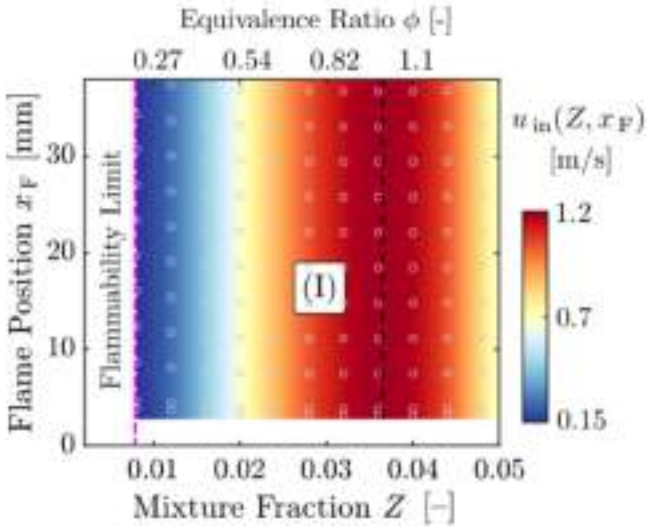
Transient combustion regimes (1-D flames) at elevated temperatures

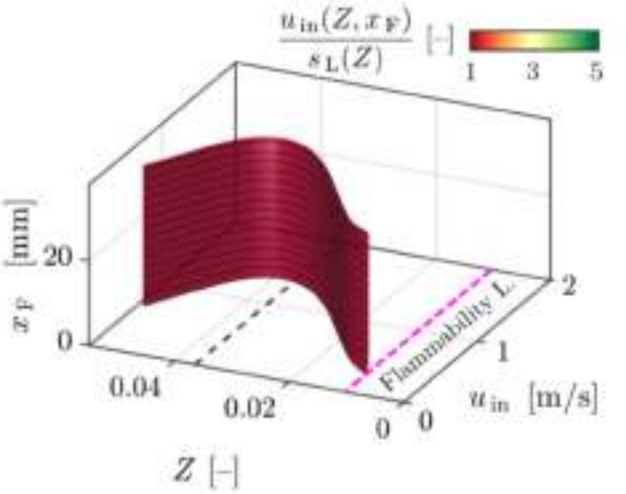




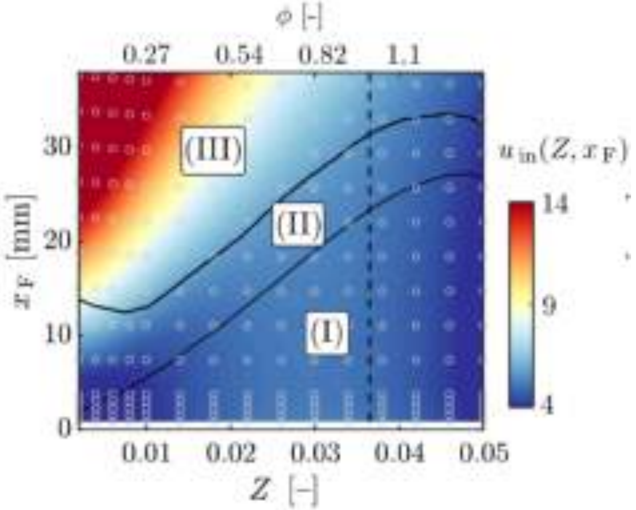
Combustion regimes (1-D flames) at elevated temperatures

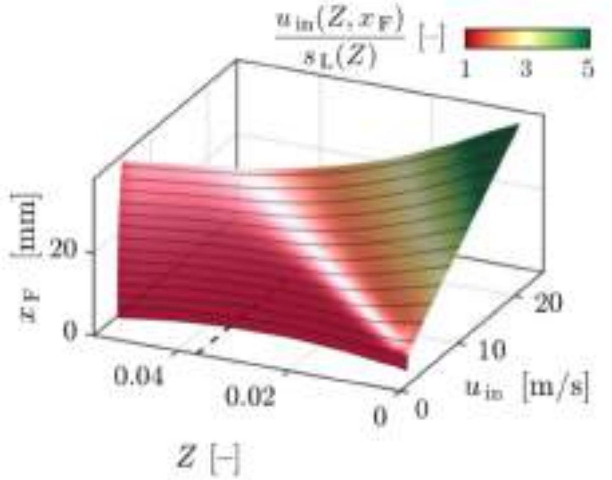
1000 K



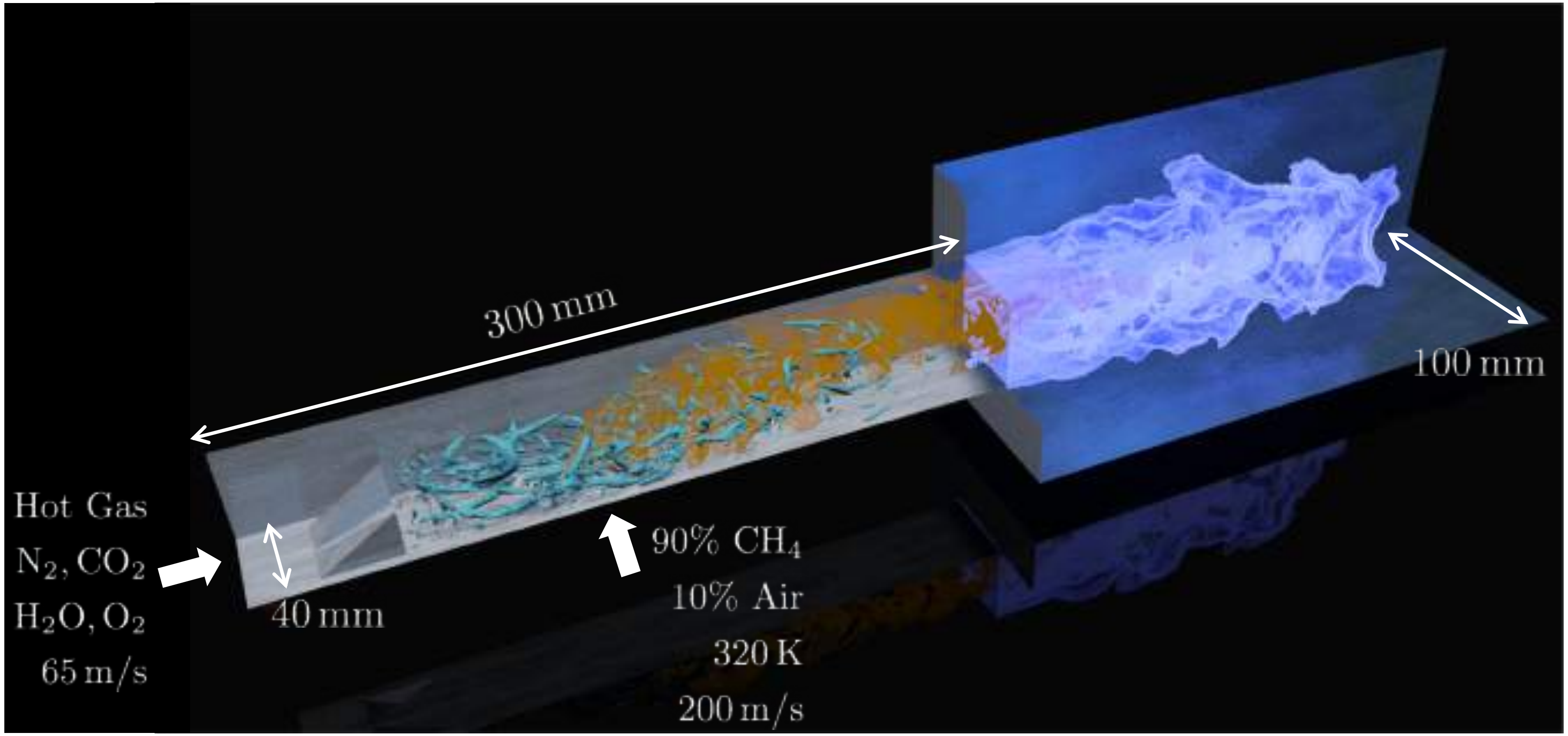


1450 K





Application to a laboratory sequential combustor



Numerical methods

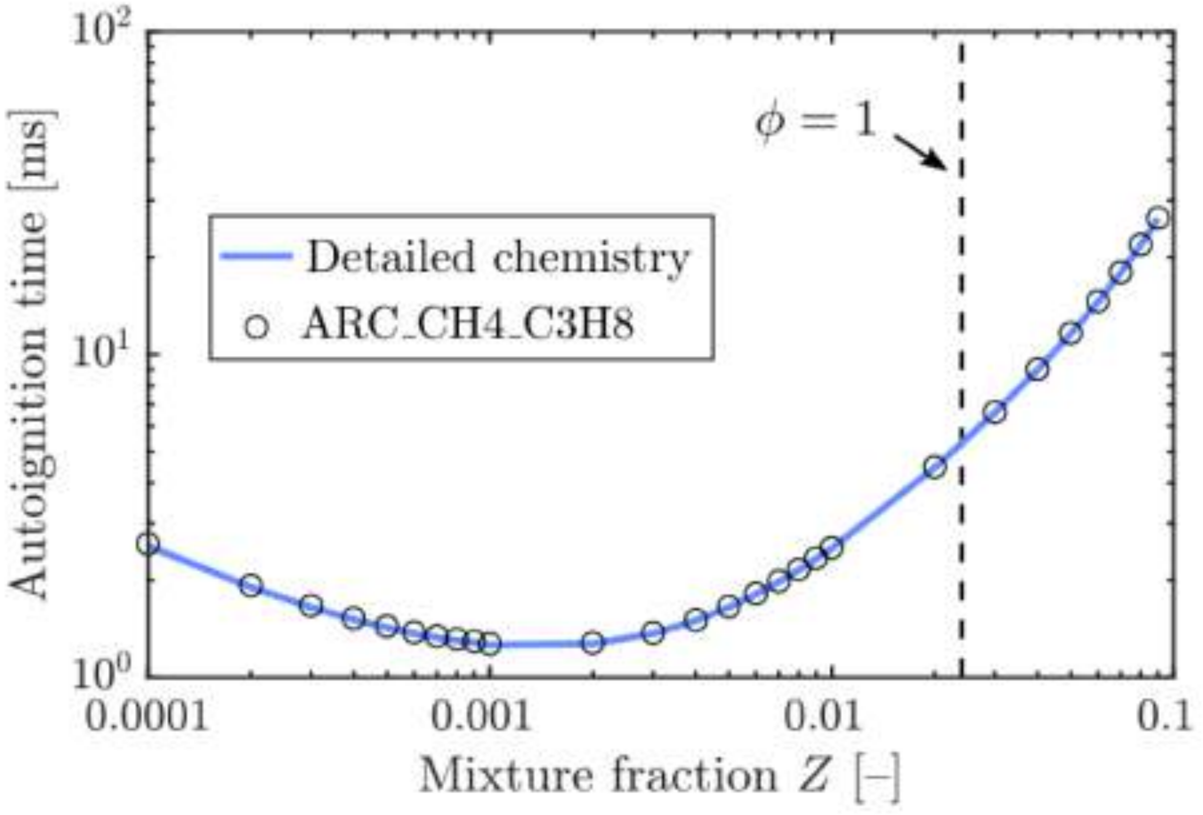
- 16 and 65 millions mesh cells at 1 bar and 10 bar

- LES with AVBP
  (Gicquel et al. Comptes Rendus – Mec., 2011)

- Dynamic Thickened Flame (DTF) model
  (Colin et al. Phys. Fluids 12, 2000)

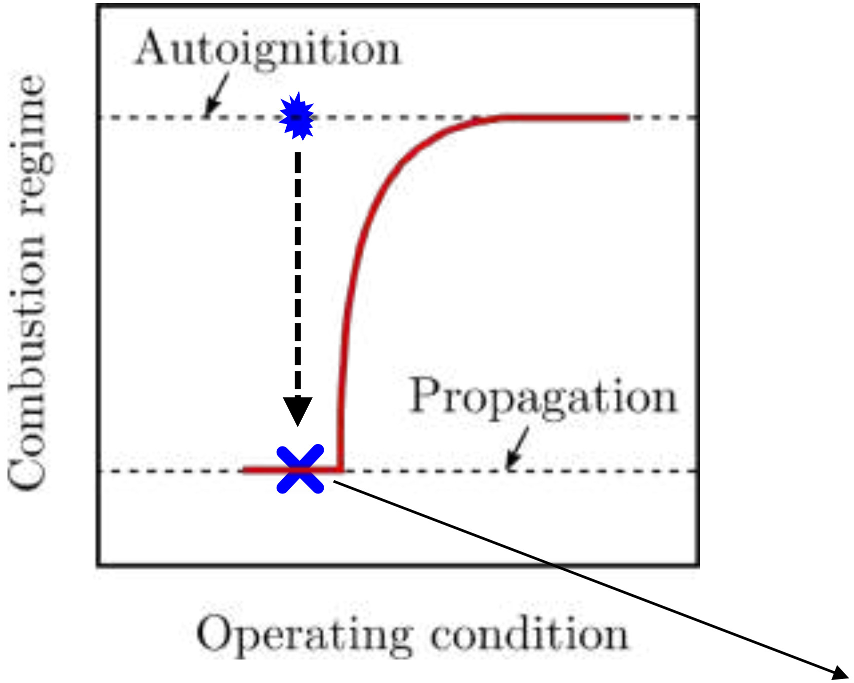
- Wall heat losses

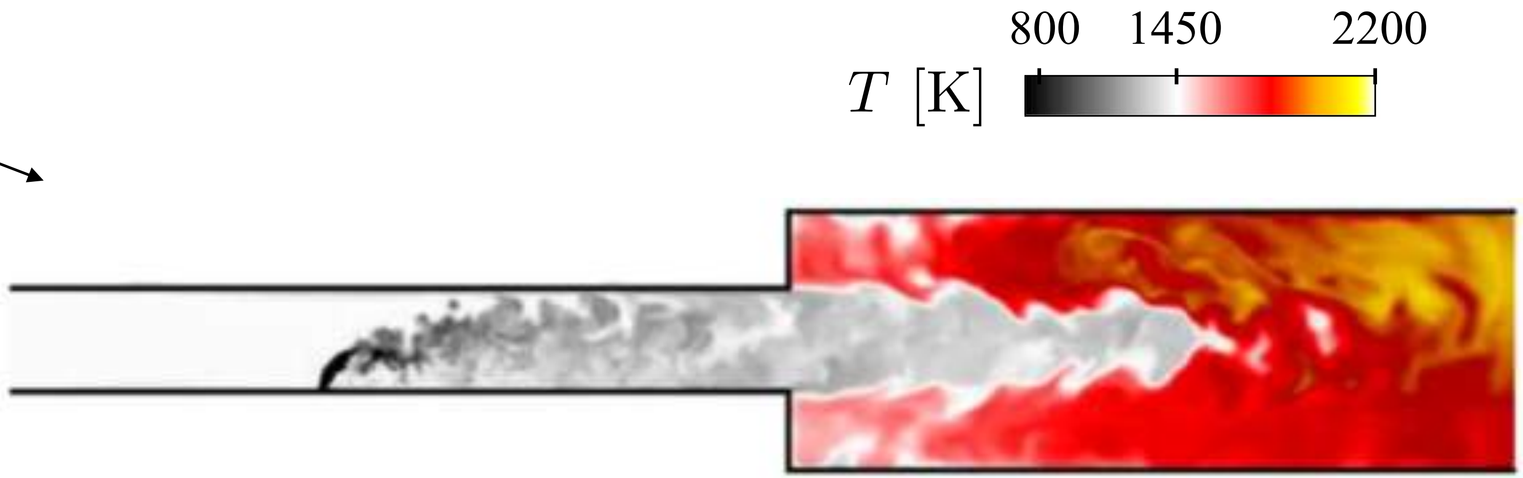
- Analytically Reduced Chemistry (ARC) mechanism for CH_4 combustion



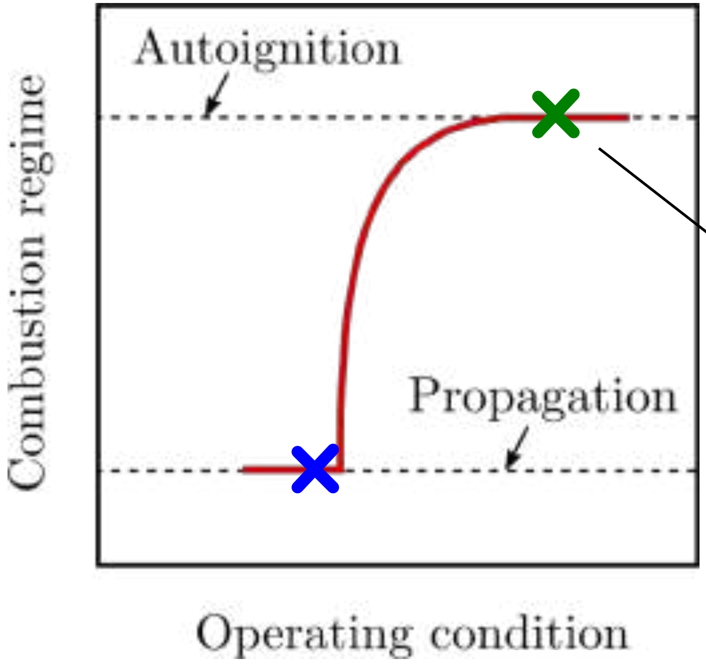
Ignition of the sequential combustor (1 bar)

Pressure 1 bar
Inlet Temperature 1450 K

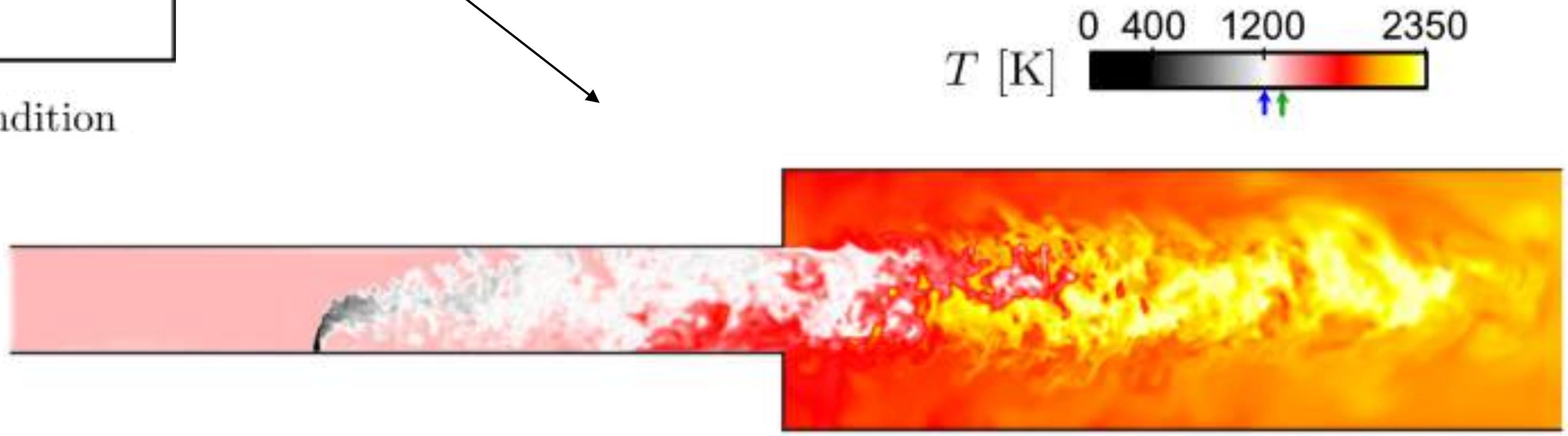




Transient change of operating conditions



- Inlet velocity = 60 m/s
- Simulated physical time = 60 ms
- Pressure 10 bar
- Inlet Temperature changed **from1350 K to 1200 K**



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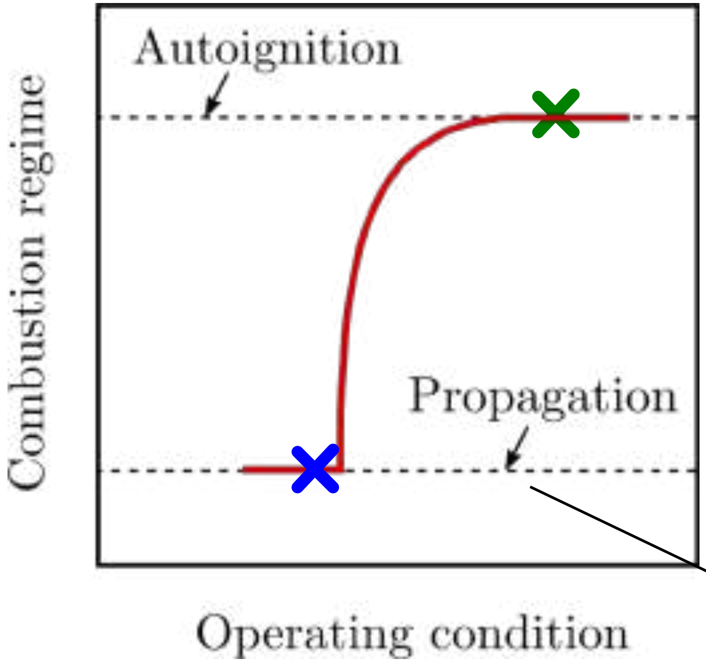

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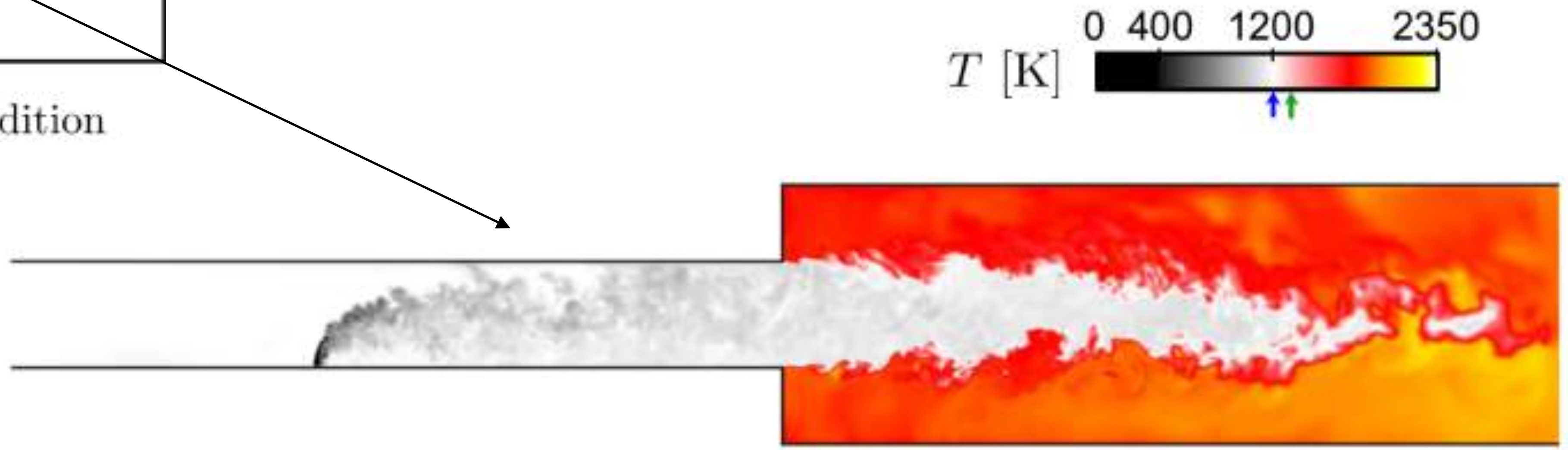

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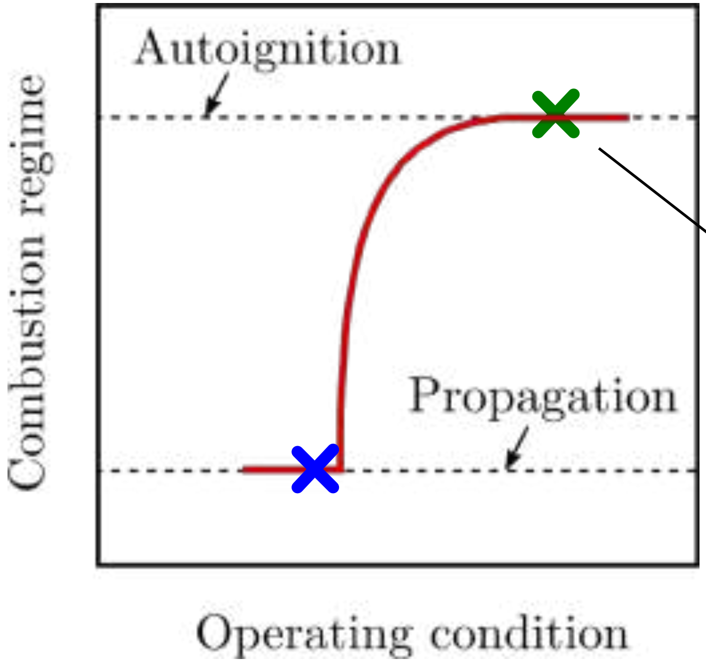

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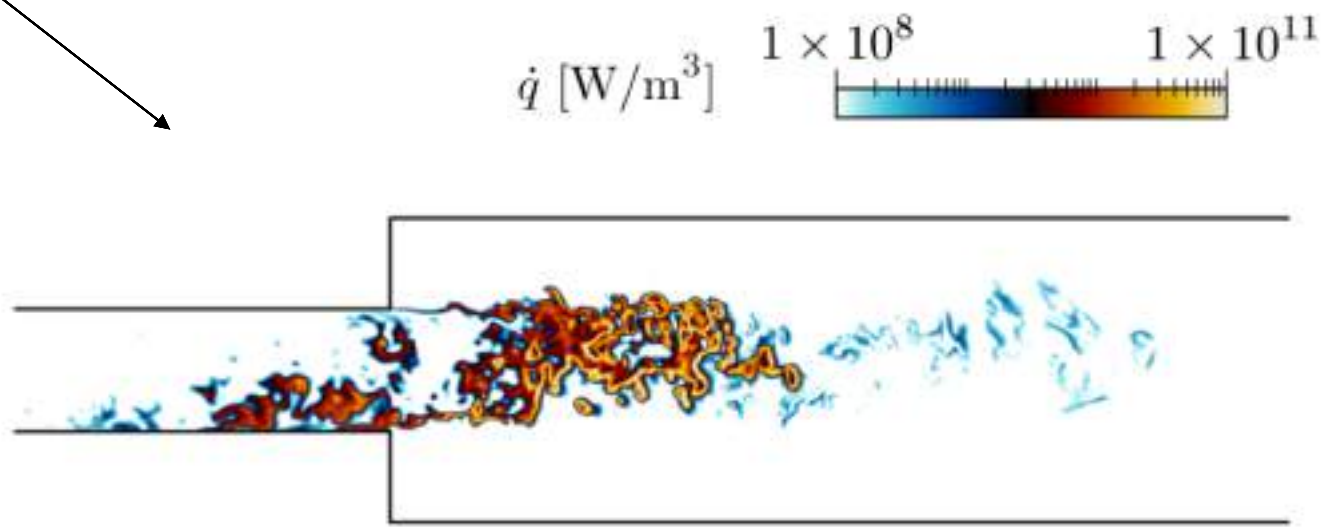

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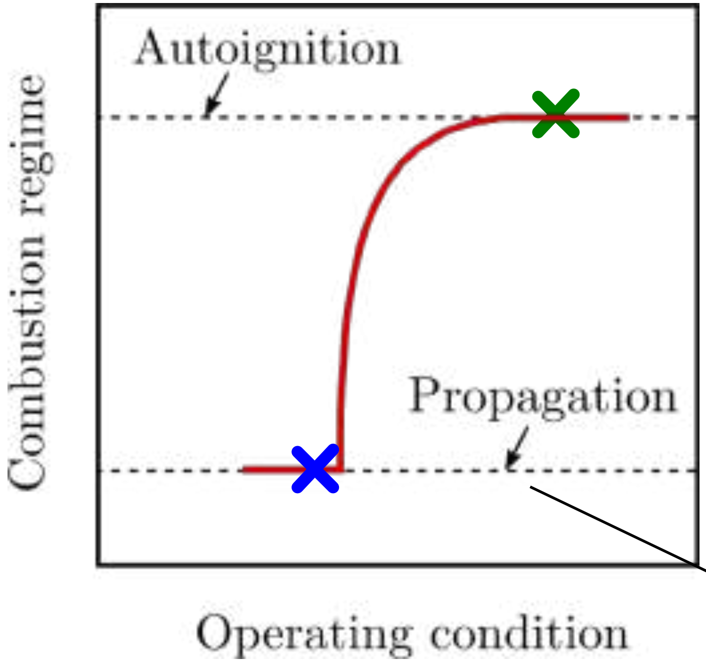

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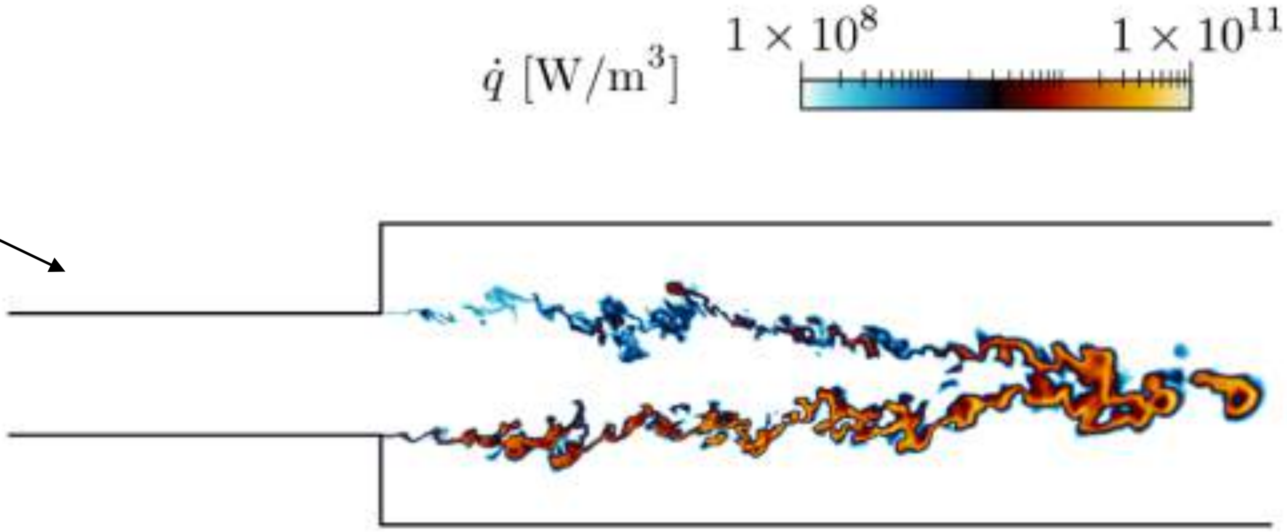


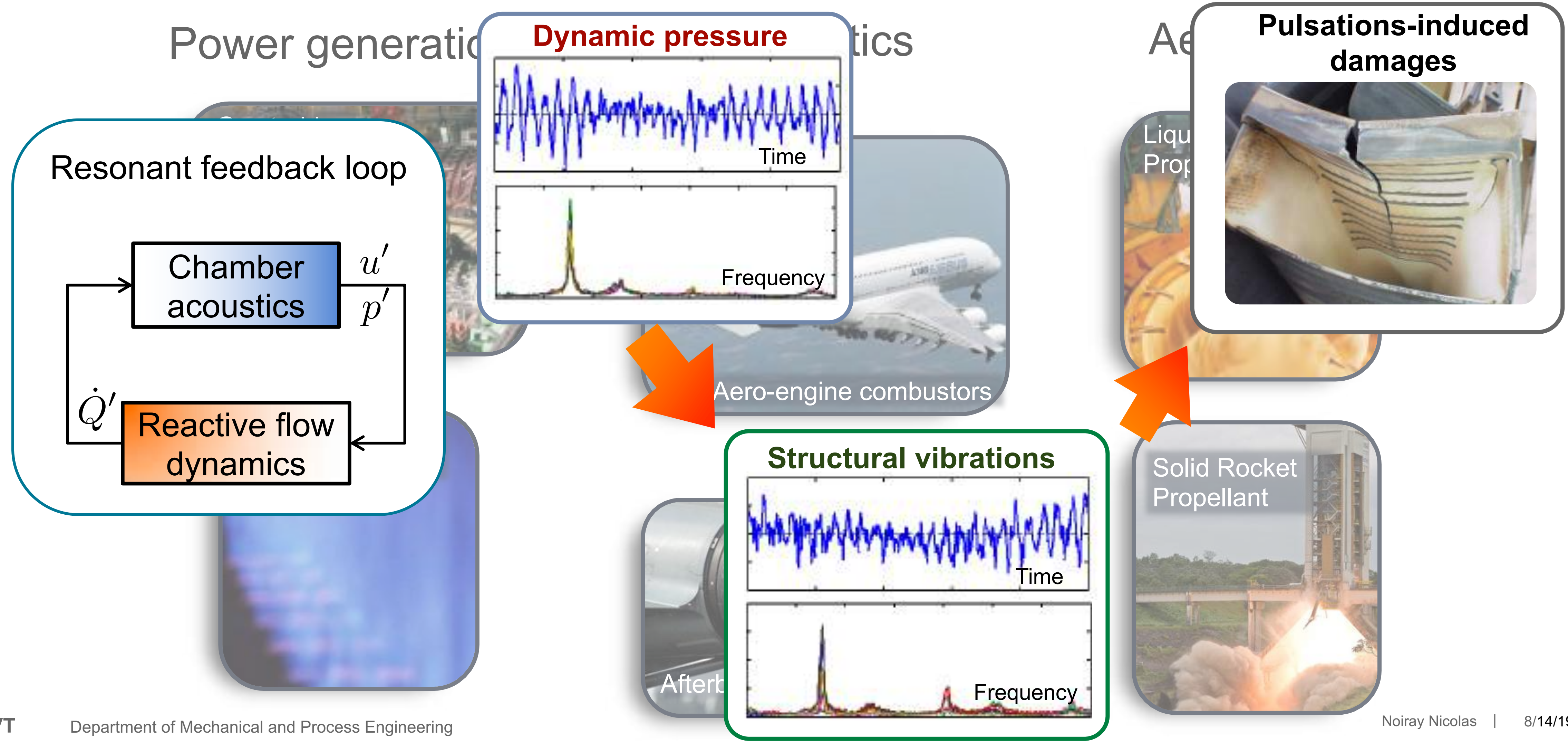
Combustion Dynamics in Sequential Combustor

1. From spontaneous ignition to deflagration

2. **Thermoacoustic instabilities in sequential combustors**

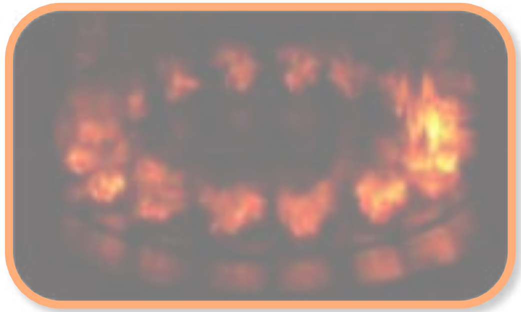
3. Sequential flame stabilization using NRP discharges

Thermoacoustic instabilities are a major obstacle to cleaner combustion



Thermoacoustic Instabilities

Bonciolini et al., Royal Soc. Open Sci., 2018



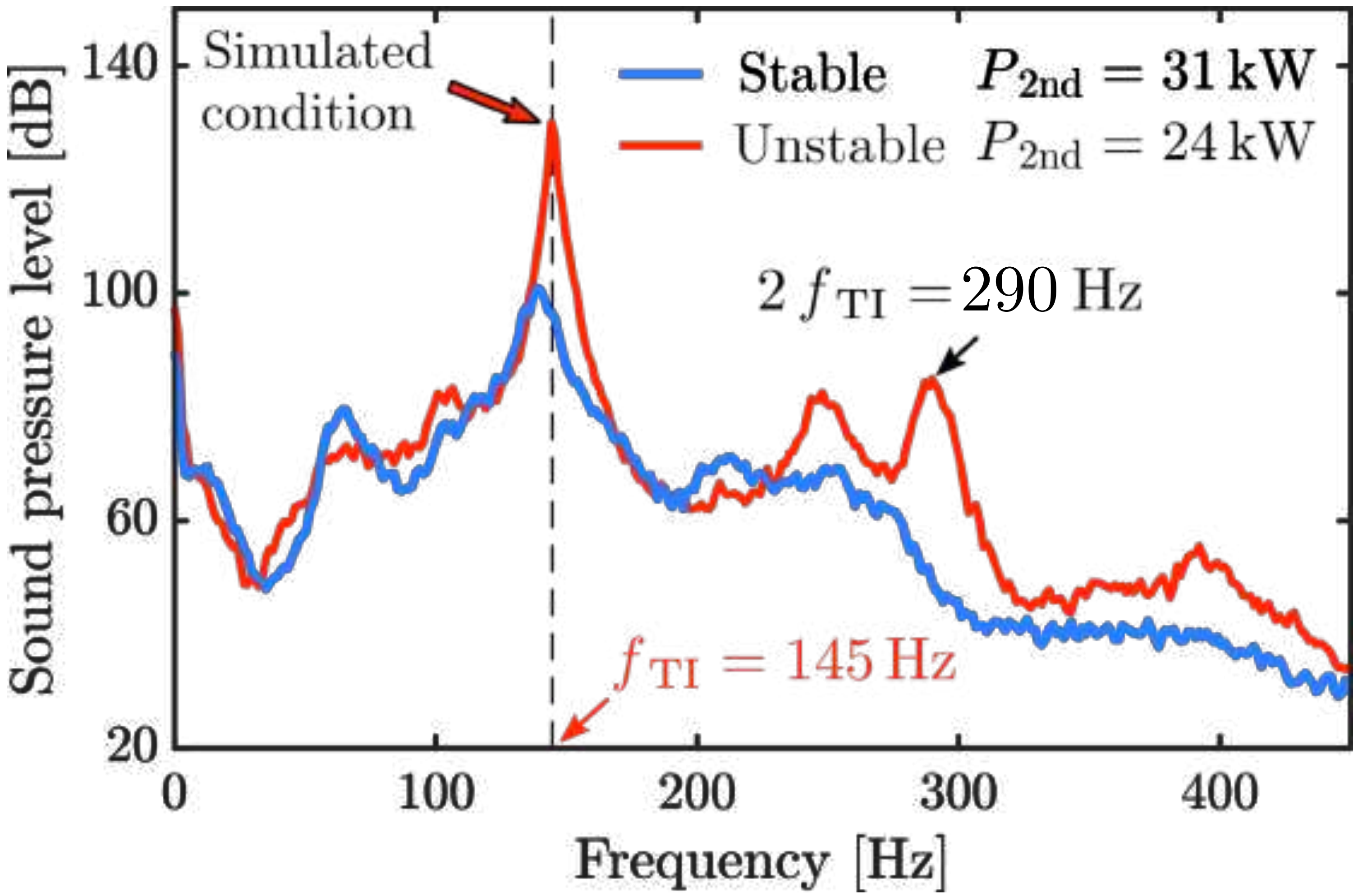
Prieur et al. (EM2C laboratory), J. Eng. Gas Turbines Power 140, 2018

Susceptibility to thermoacoustic instabilities

Complexity of pathways of thermoacoustic instabilities

Complexity of numerical modeling

The experiment and the computational domain



P_{1st} = 40 kW

Φ_{1st} = 0.8

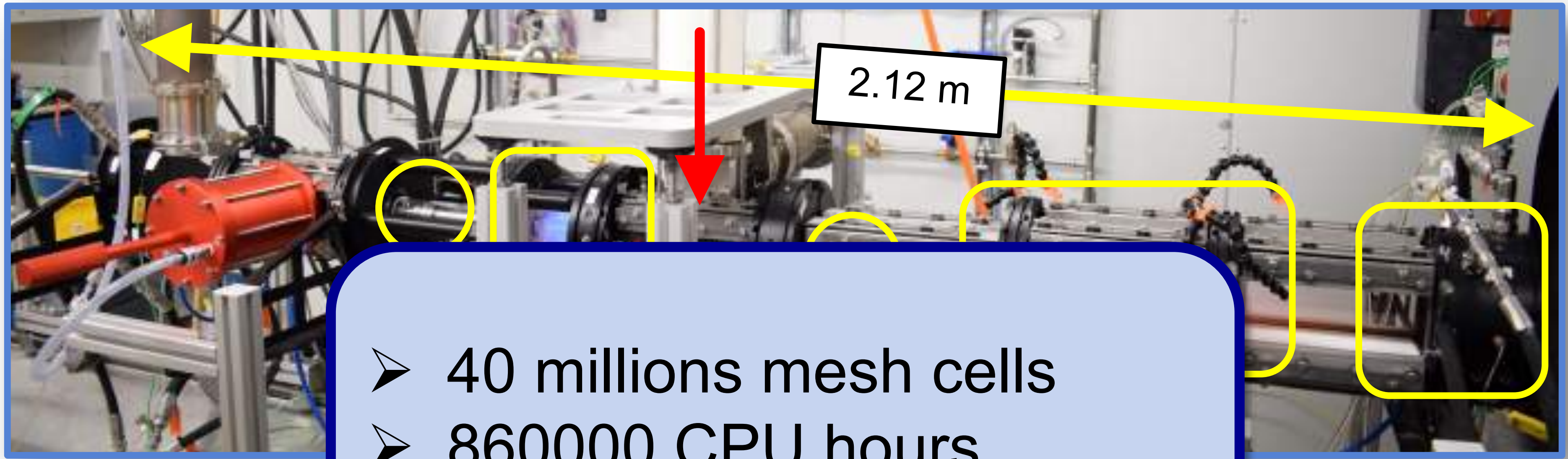
Fuel $_{1st}$: CH_4

P_{2nd} = 24 kW

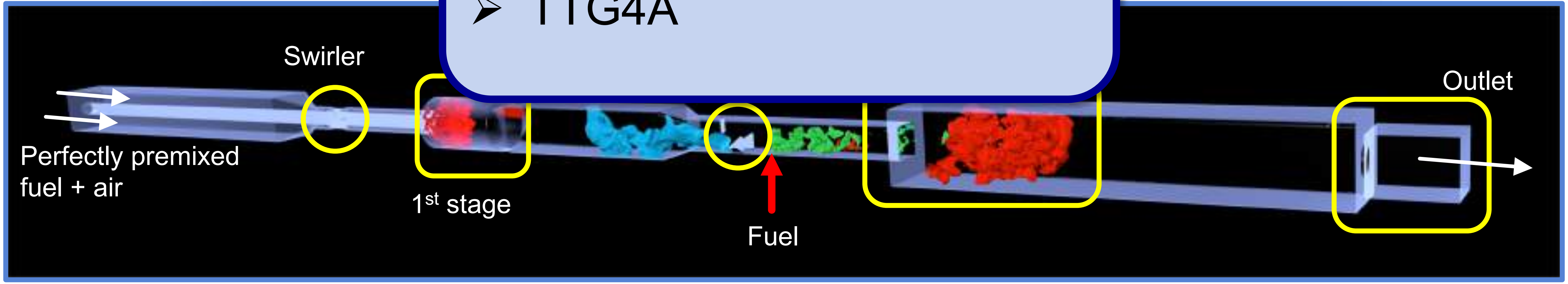
Φ_{2nd} = 0.77

Fuel $_{2nd}$: $CH_4 + C_3H_8$

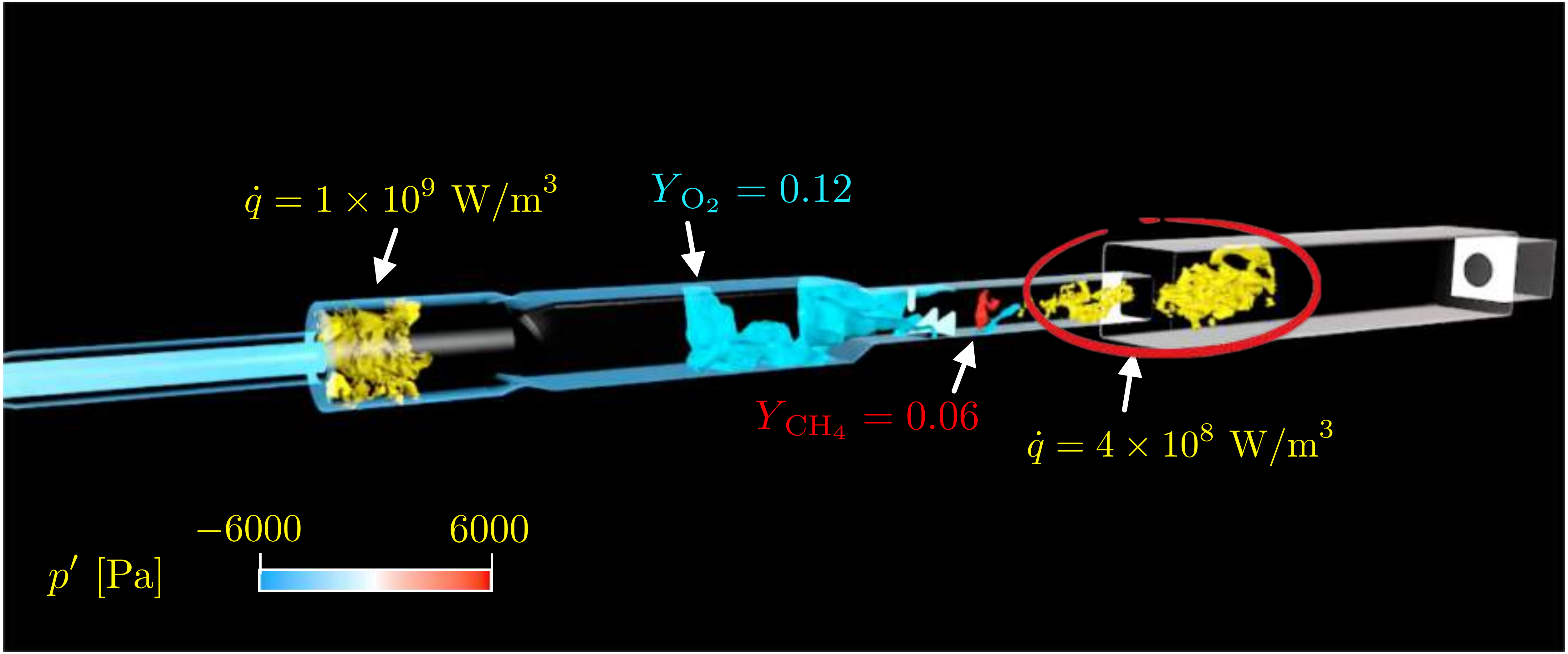
The experiment and the computational domain



- 40 millions mesh cells
- 860000 CPU hours
- TTG4A

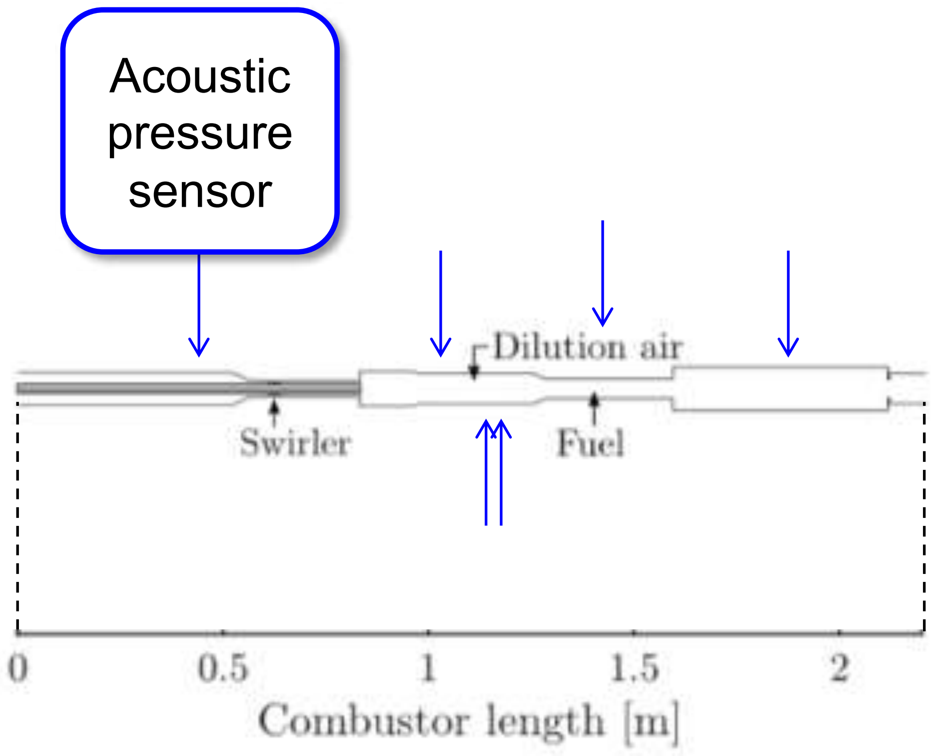


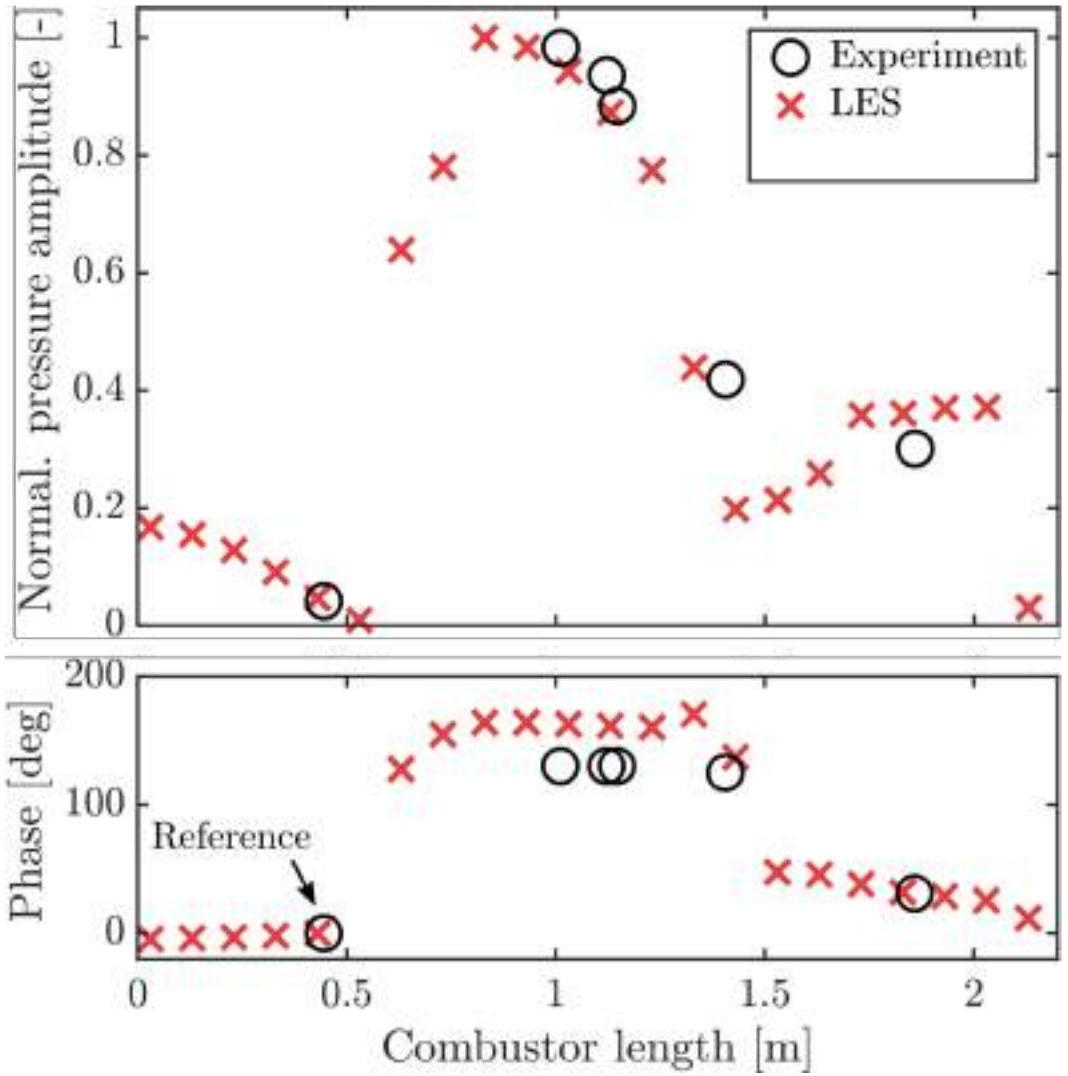
3-D LES



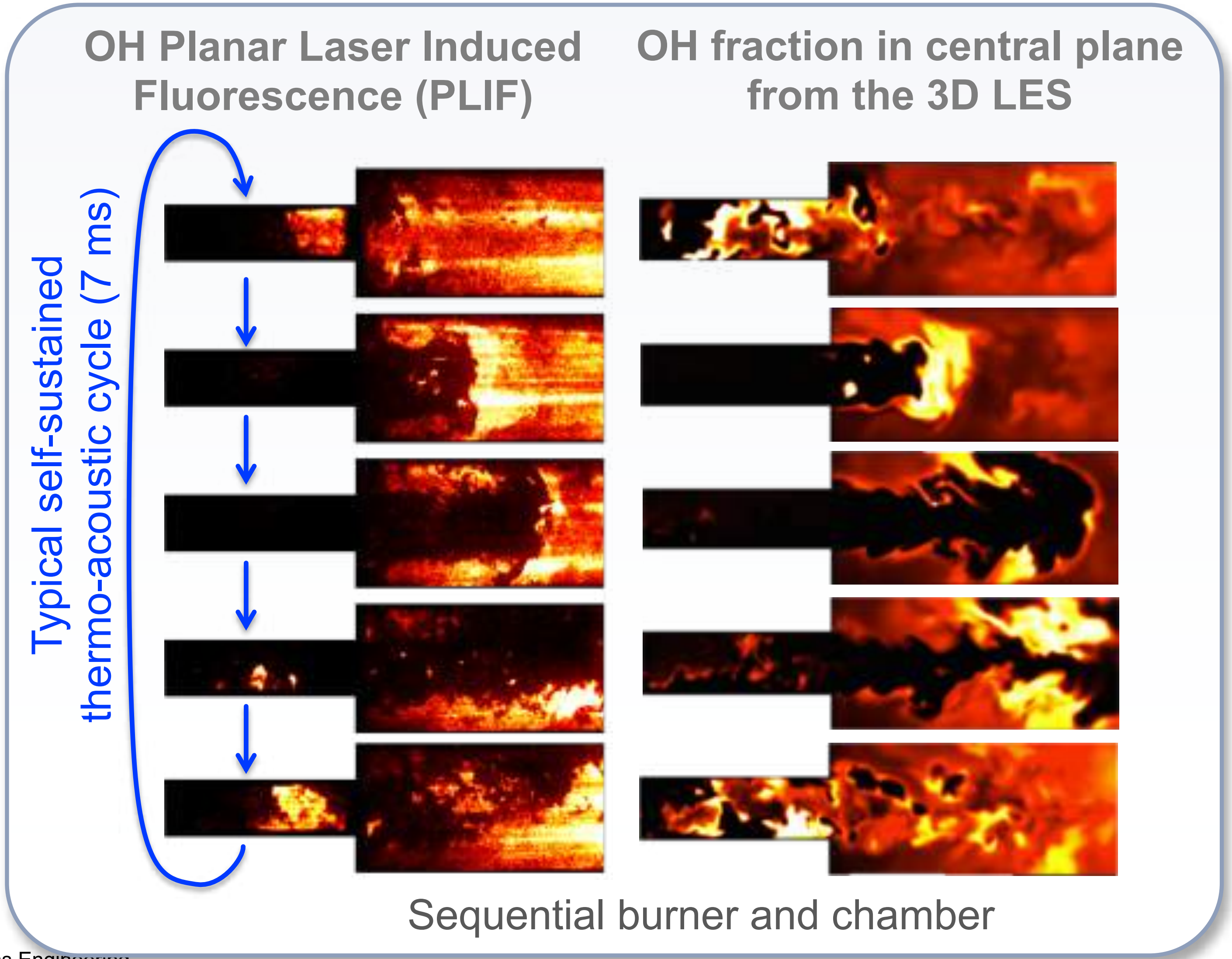
$\dot{q} = 1 \times 10^9\ \mathrm{W/m^3}$
$Y_{O_2} = 0.12$
$Y_{CH_4} = 0.06$
$\dot{q} = 4 \times 10^8\ \mathrm{W/m^3}$
-6000
6000
p' [Pa]

Comparison between experiments and the LES - acoustics

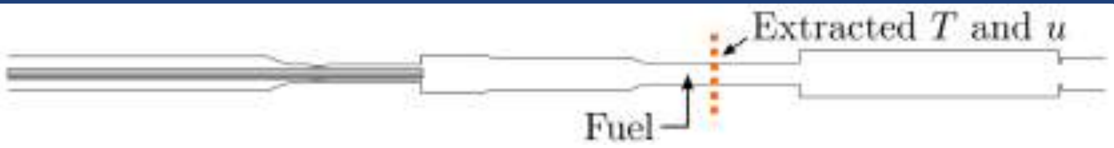


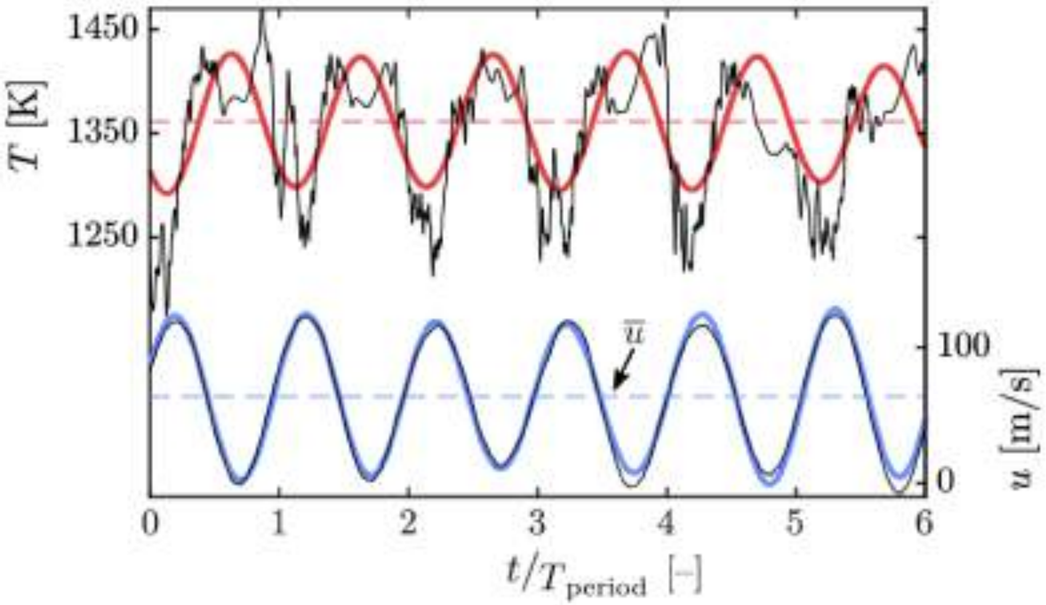


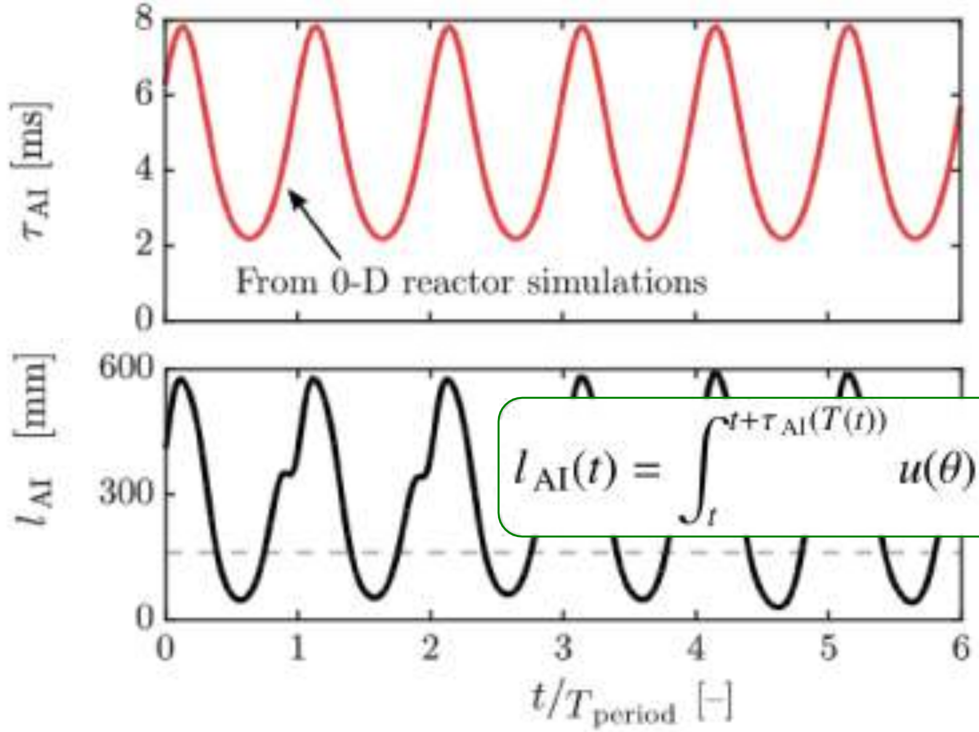
Complex thermoacoustics in sequential combustors



2nd stage autoignition modeling

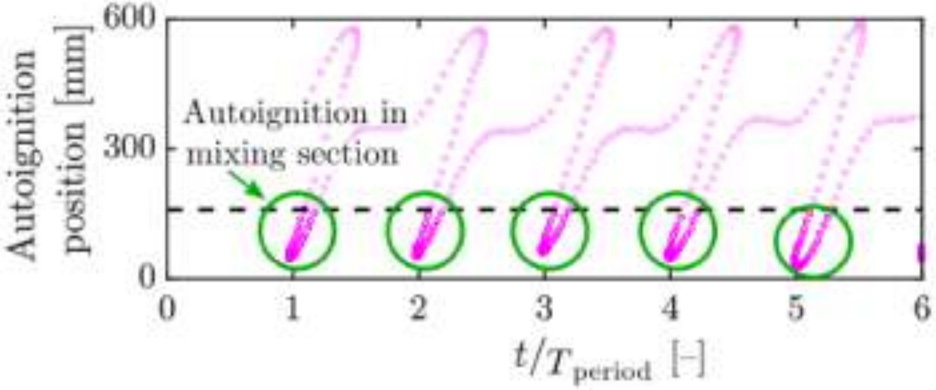




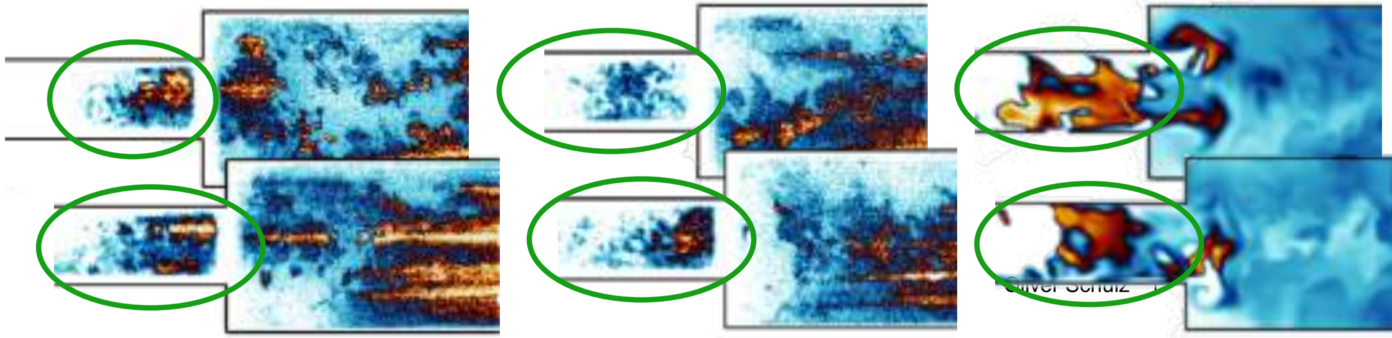


$$l_{\mathrm{AI}}(t) = \int_{t}^{t+\tau_{\mathrm{AI}}(T(t))} u(\theta)\, d\theta$$

$t + \tau_{\mathrm{AI}}(T(t))$



$$t/T_{\mathrm{period}} = 1, 2, 3, \ldots$$



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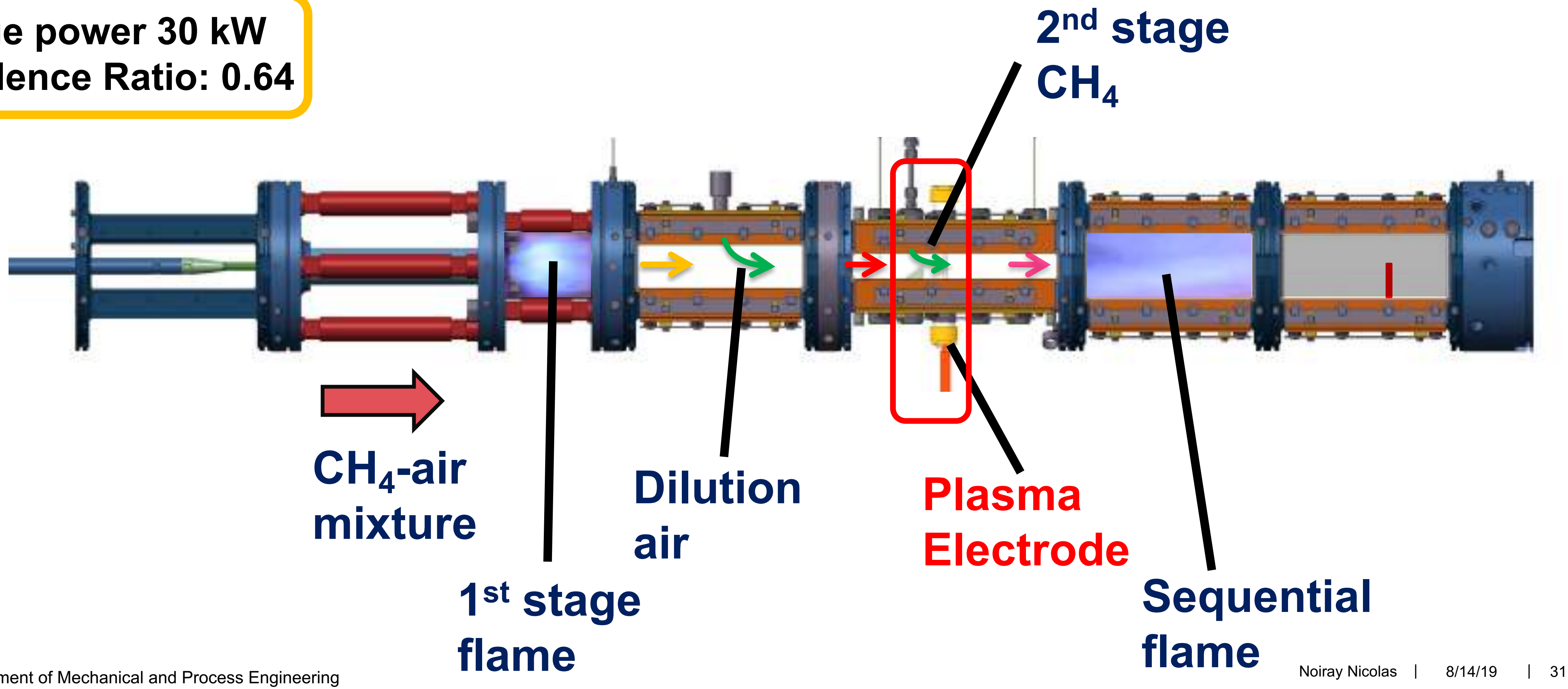
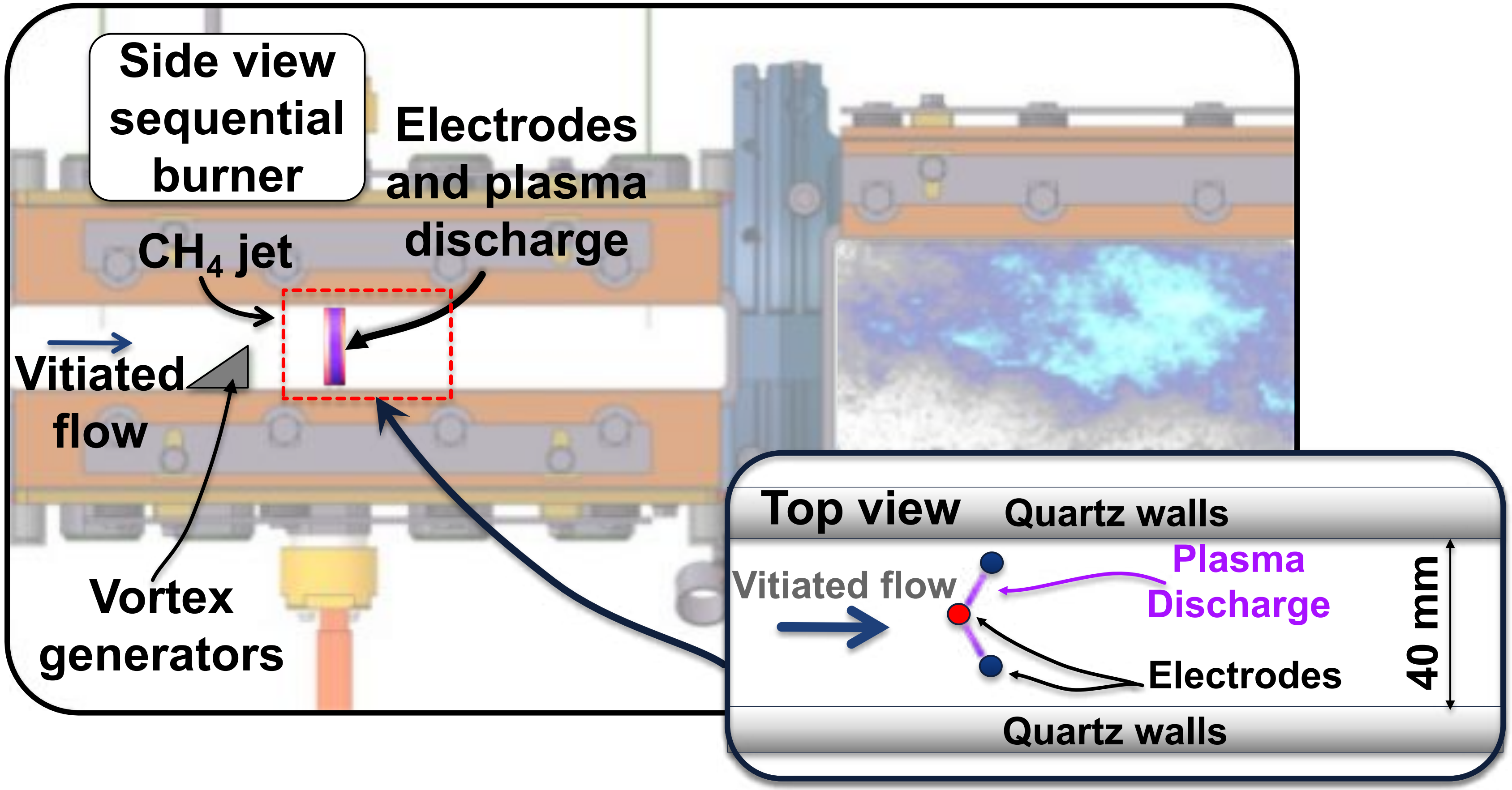
3. **Sequential flame stabilization using NRP discharges**

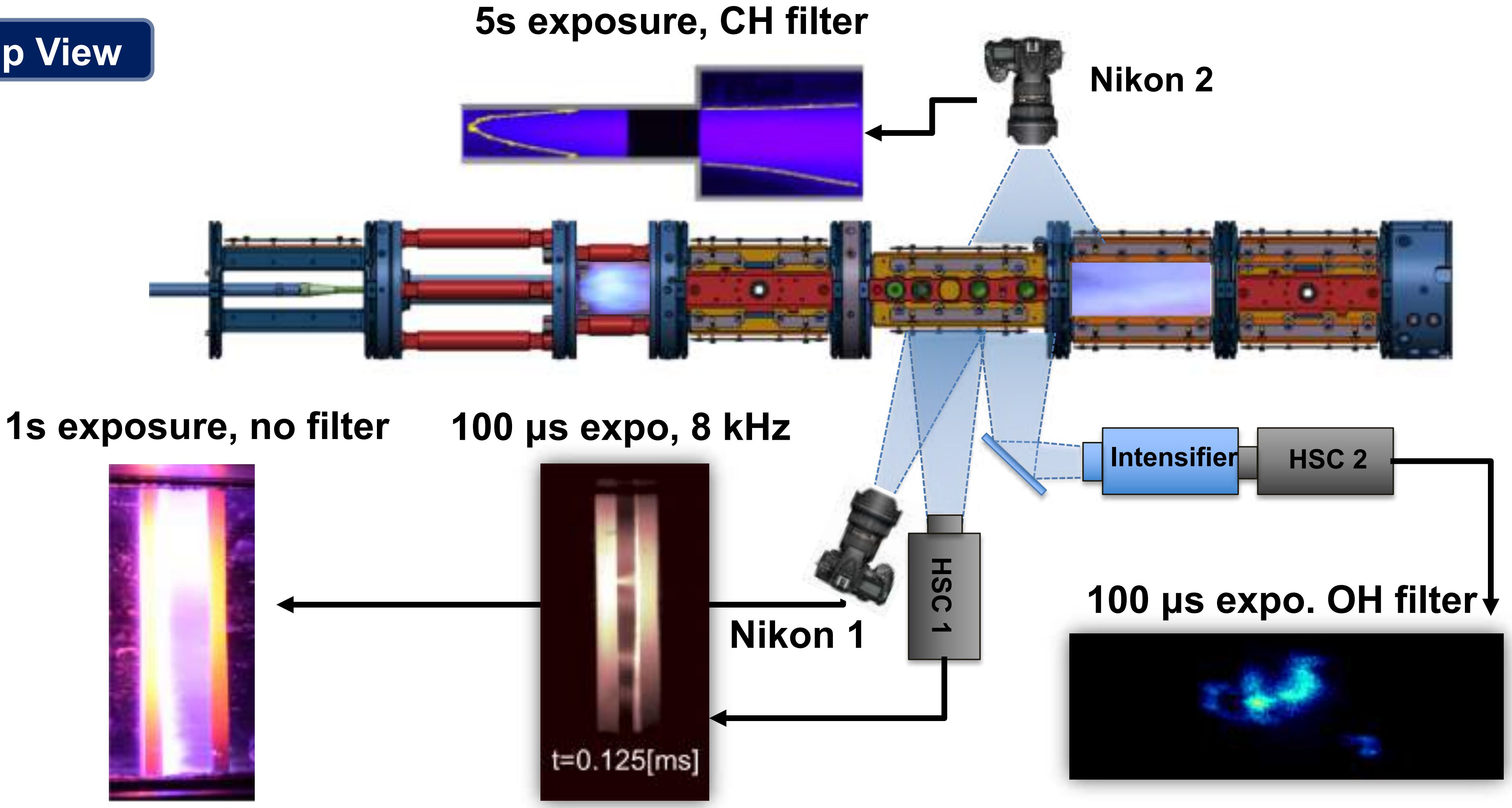
Flame stabilization using nanosecond repetitively pulsed discharges

1st stage power 30 kW
Equivalence Ratio: 0.64



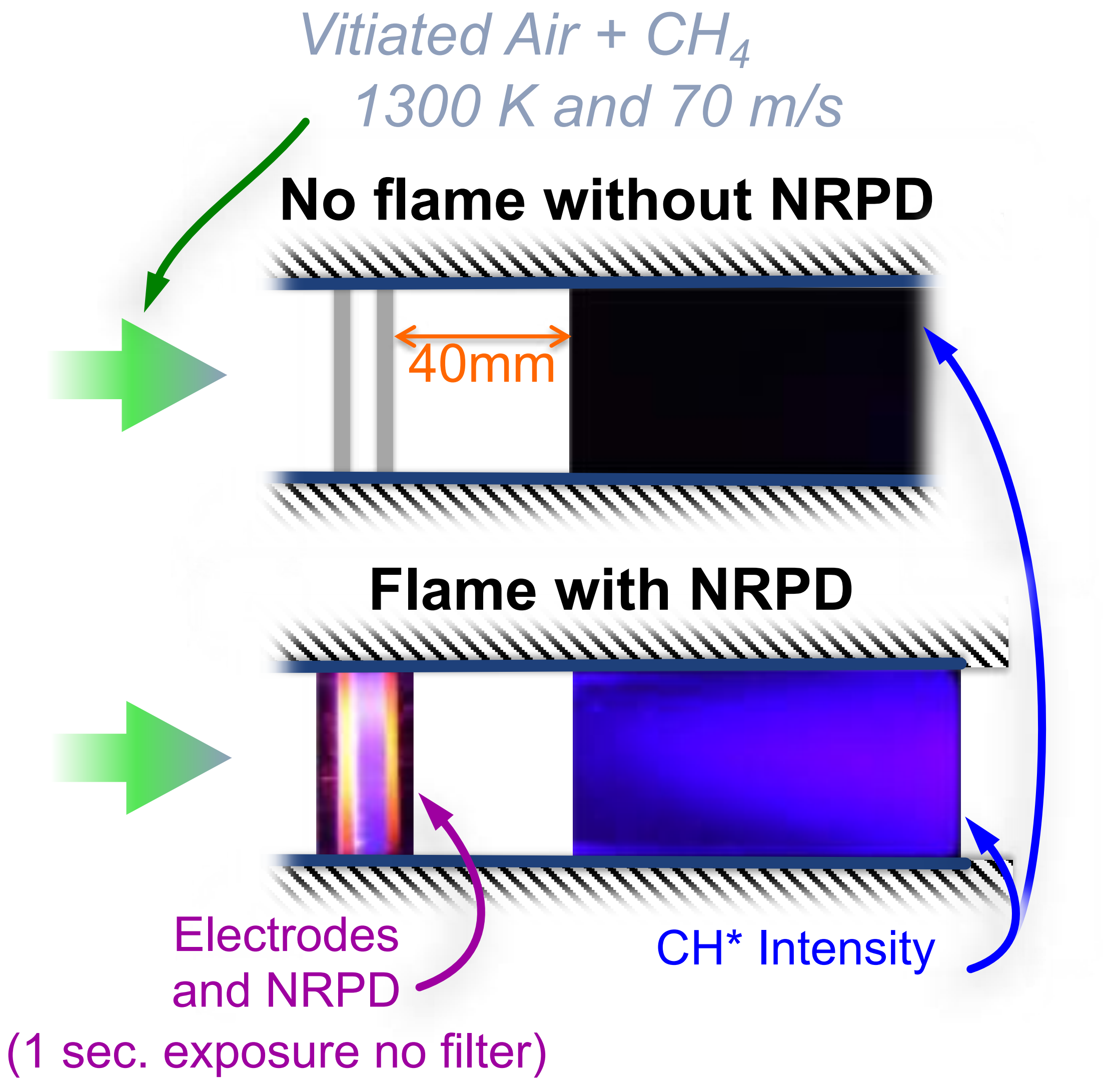

Side view sequential burner
Electrodes and plasma discharge
CH_4 jet
Vitiated flow
Vortex generators
Top view
Quartz walls
Plasma Discharge
Vitiated flow
Electrodes
40 mm
Quartz walls

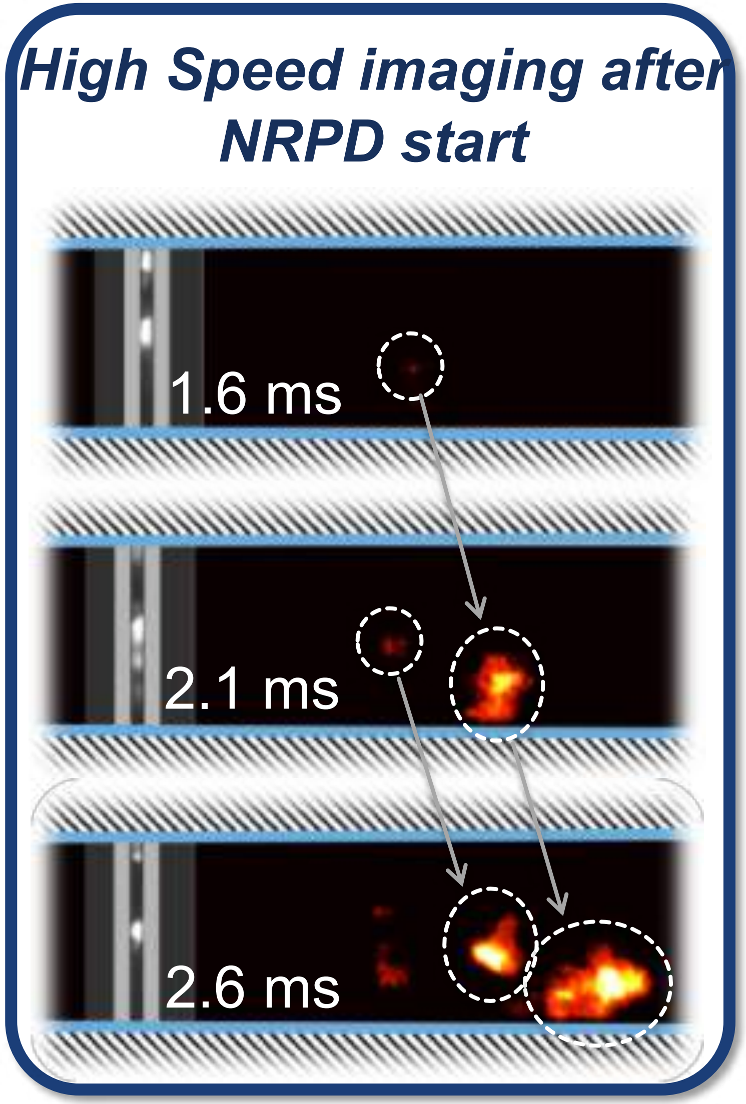
Top View



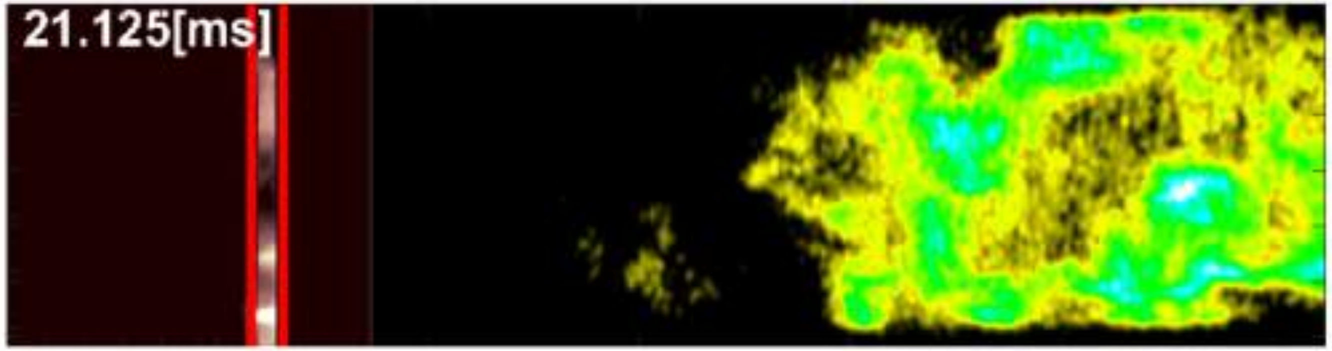
**About 10 ns pulses of 8 kV,
Pulses repetition rate 50 kHz**

Plasma-enhanced autoignition



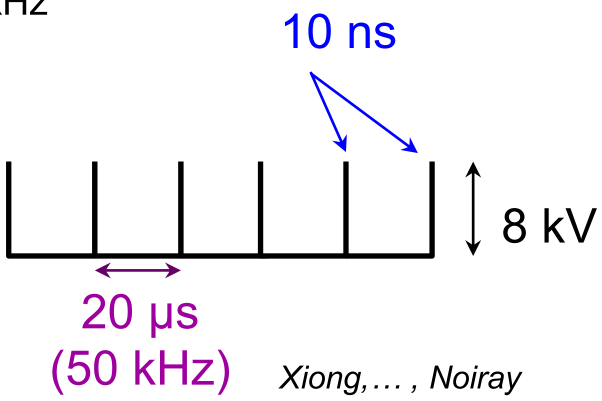


Plasma-enhanced autoignition



Camera settings: 0.1 millisec. exposure 8 kHz

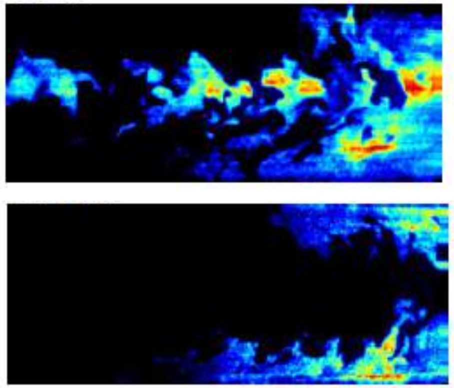
Flame Thermal Power:
45 000 W
Electric Power for Plasma:
115 W (0.25%)



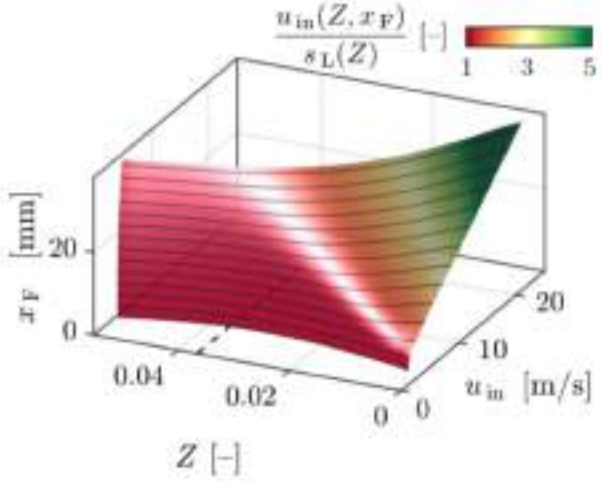
Xiong,… , Noiray
Proc. Comb. Inst. 2019

Summary

- Autoignition and flame propagation can both govern the combustion regime in sequential combustors at relevant conditions
- Understanding, modeling and simulating transitions between these regimes is very challenging but it is key for design of new sequential combustors
- Thermoacoustic instabilities in these combustors involve complex pathways where flames talk to each other via acoustic, but also compositional and entropy waves
- NRP discharges have significant impact on autoignition in sequential combustors, significant research effort is necessary to understand and model it

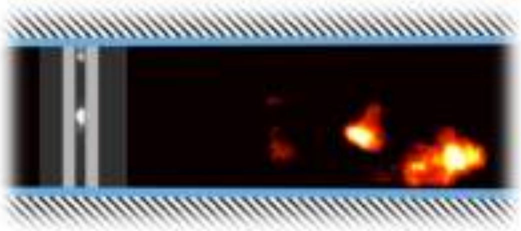


Ebi et al., PROCI 2019



Schulz and Noiray, CNF 2019

Xiong et al., PROCI 2019



Schulz et al., PROCI 2019