SFB TRR40 C3/C7

Experimental and Numerical Study of High-Frequency Combustion Instabilities

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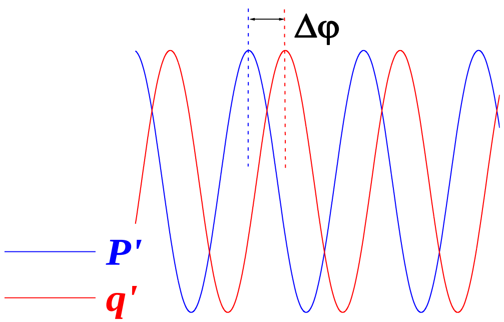
C3: Alexander Chemnitz, Prof. Sattelmayer

Lehrstuhl für THERMODYNAMIK

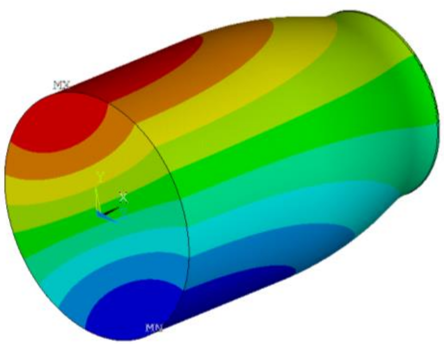
Deutsches Zentrum für Luft- und Raumfahrt

Introduction
HF Combustion Instability

Energy addition to acoustic field



Acoustics

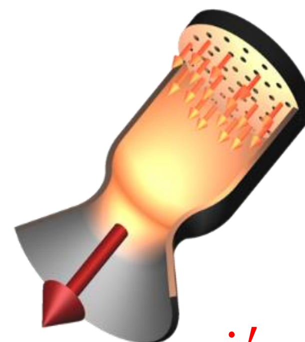


p'

$$\int_V \int_t p'\dot{q}'\,dt\,dV > 0$$

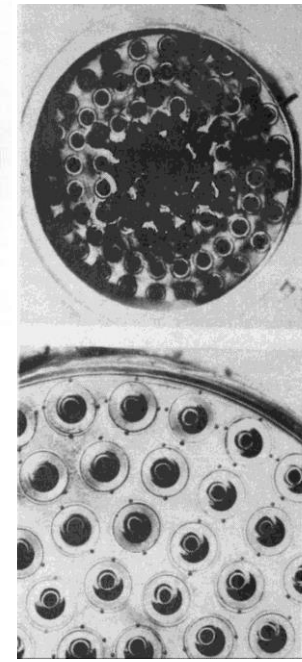
Condition for growth

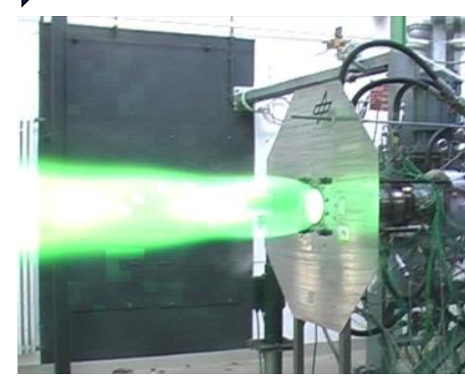
Combustion



$\dot{q}'$

Acoustic perturbation to combustion





Outline

Introduction

Experiment

Numerics

Goals

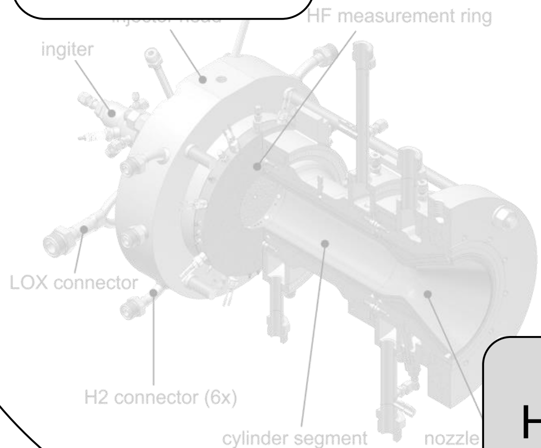
Methodology

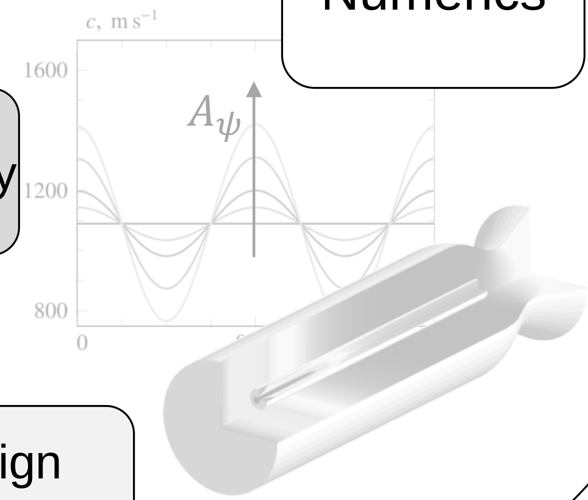
Hardware

Design Adaptions

Results

Mechanisms





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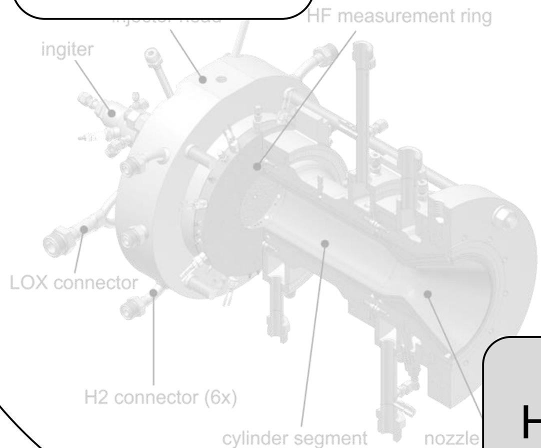

Numerics

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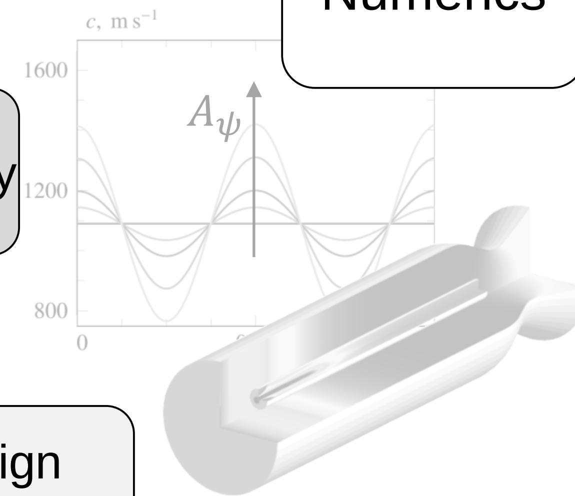
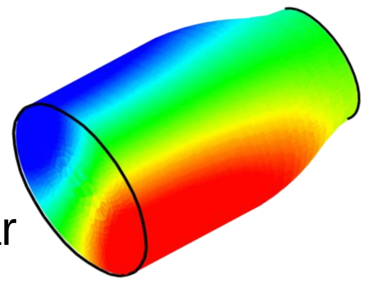
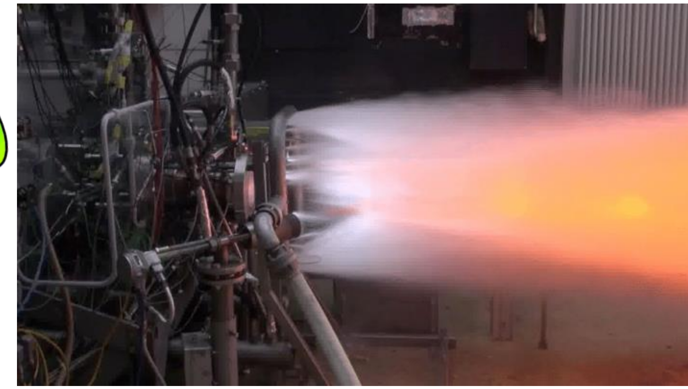
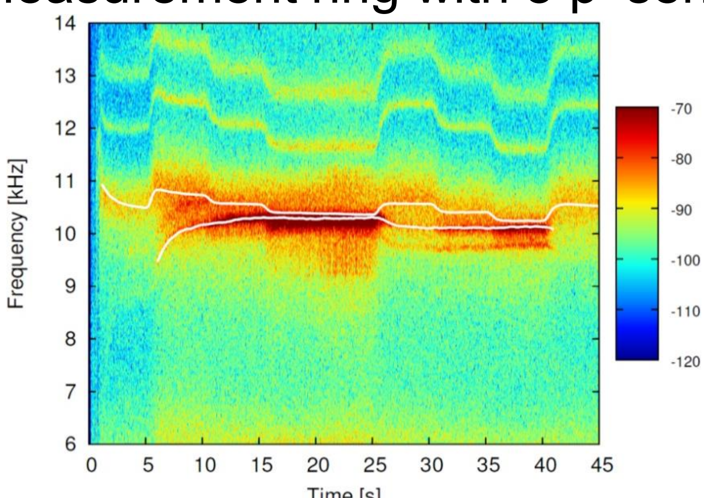


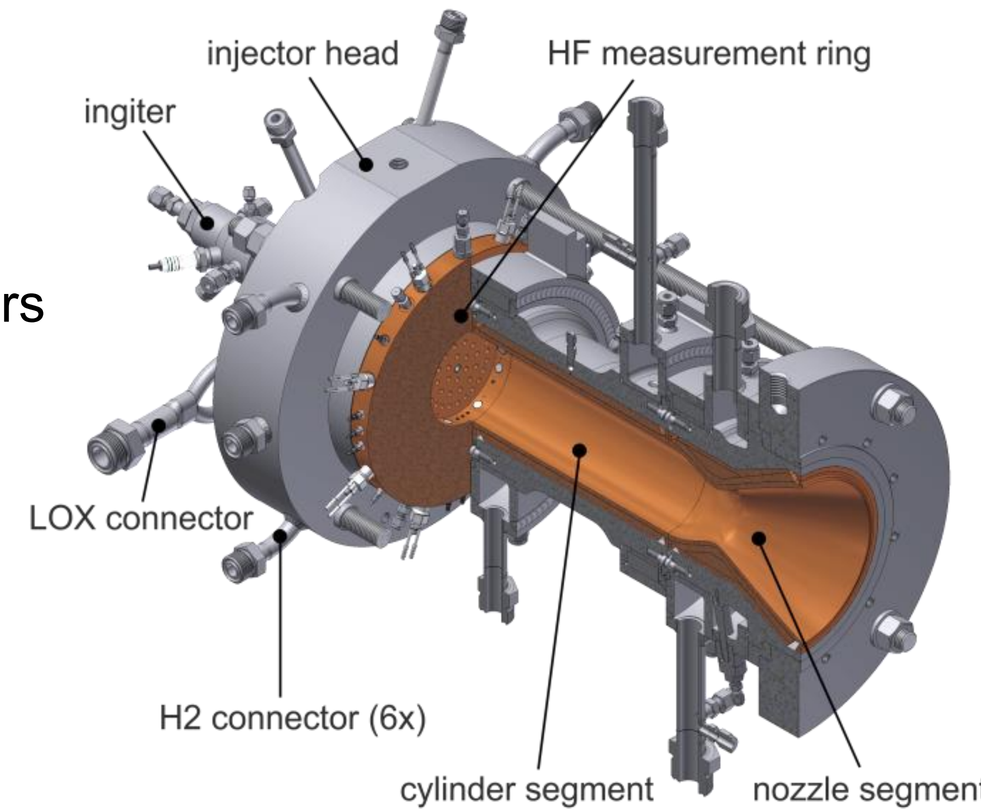
Combustor Model „D“ (BKD)

- Representative conditions:
  - Cryogenic propellants LOX/H2
  - 42 shear coaxial elements
  - Chamber pressure up to 80 bar
  - Thrust: up to ~ 24 kN
  - Power up to 90 MW
- Self-excited instabilities
  - 1T mode at 10 kHz
  - Driven by LOX injection-coupling
- Measurement ring with 8 p’ sensors

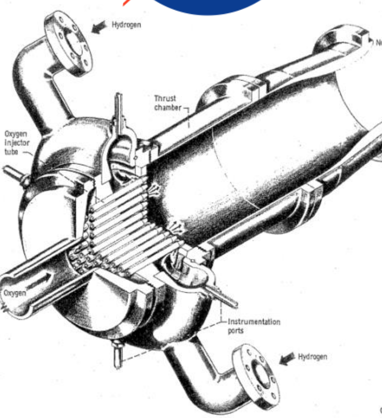








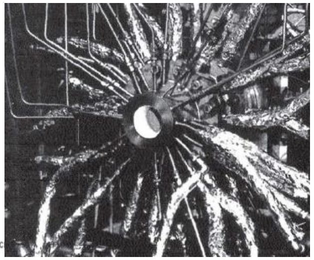
Motivation: Injection-coupling



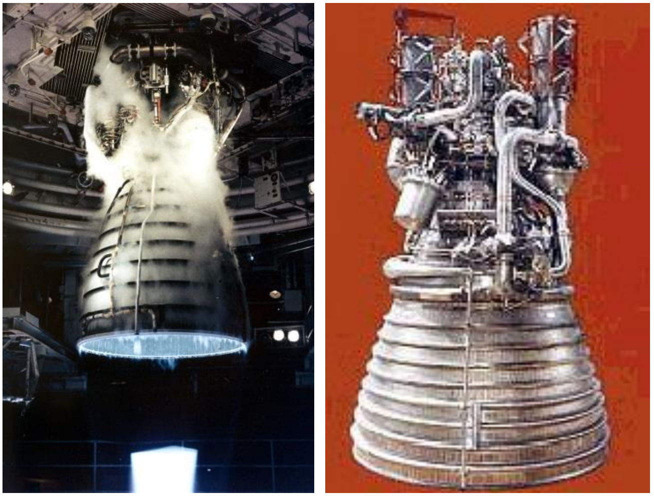
Wanhainen et. al. (1966)

Rockwell International

Rocketdyne

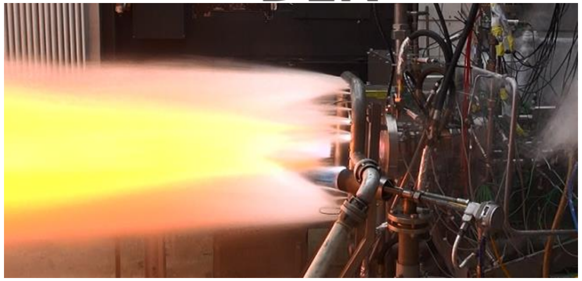


Jensen et. al. (1989)

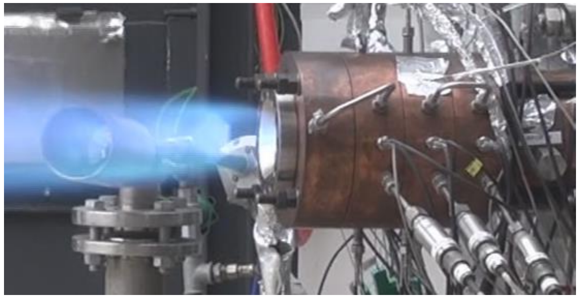


Hulka and Hutt (1995)

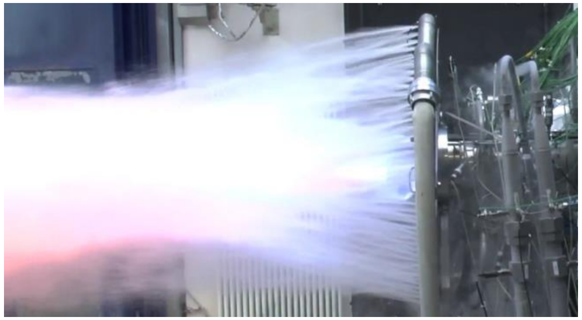
DLR



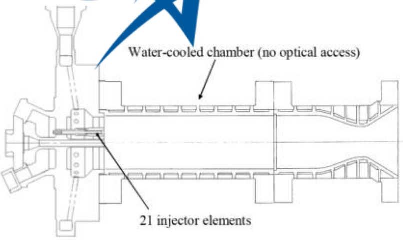
Gröning et. al. (2016)



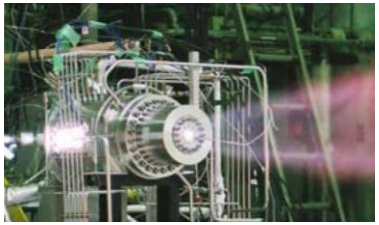
Klein et. al. (2019)



Martin et. al. (2020)



Kawashima et. al. (2010)



Nunome et. al. (2011)

Watanabe et. al. (2016)

Experimental Goals for FP3

- In general:
  - Gain a better understanding of injection-coupling
  - Prevent injection-coupling for future rocket engines
- Detailed objectives:
  - Identify excitation source for LOX post acoustics
  - Investigate energy transfer from oscillating flame into acoustic field
  - Understand 2D flame response to LOX post eigenmodes

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- In general
  - Gain a better understanding of injection-coupling
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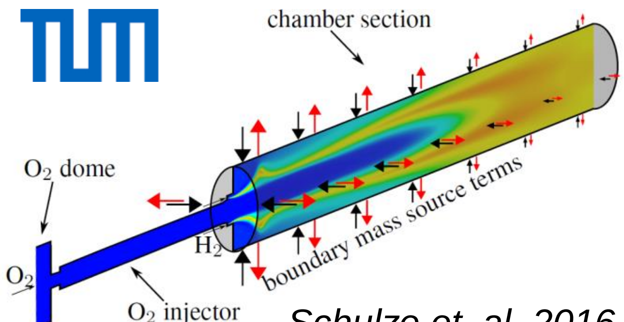
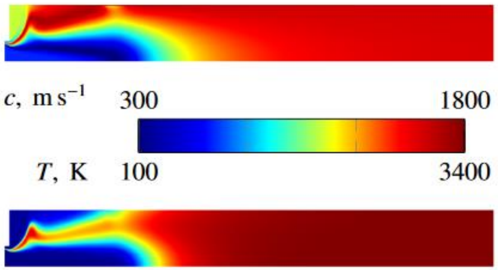
- Detailed objectives
  - Identify excitation source for LOX post acoustics
  - Investigate energy transfer from oscillating flame into acoustic field
  - Understand flame response to LOX post eigenmodes
    - → 2D flame visualization needs to be realized

Also valuable validation data for numerical partners (C3)



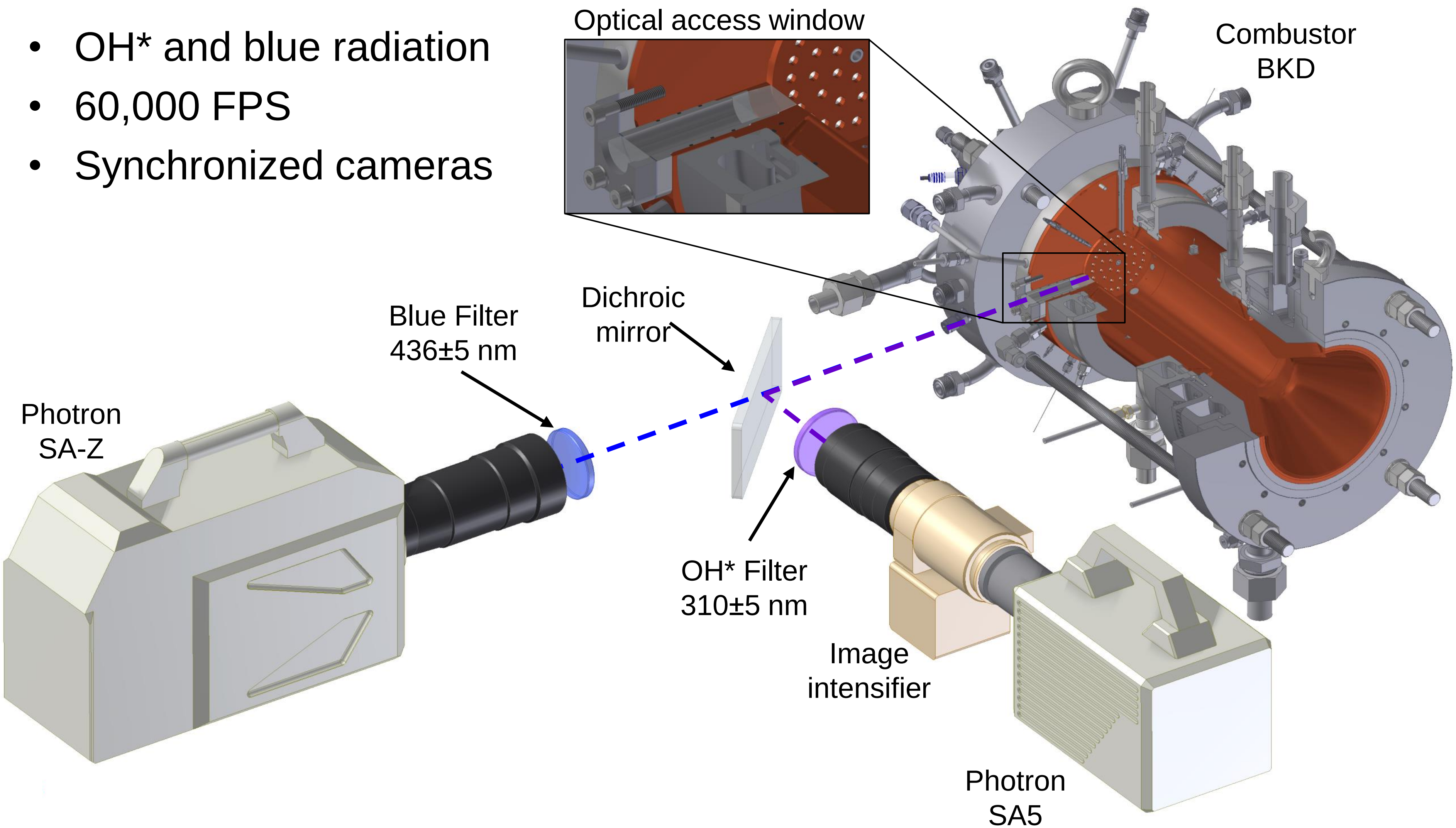
Schulze et. al. 2016

Chemnitz et al. 2019



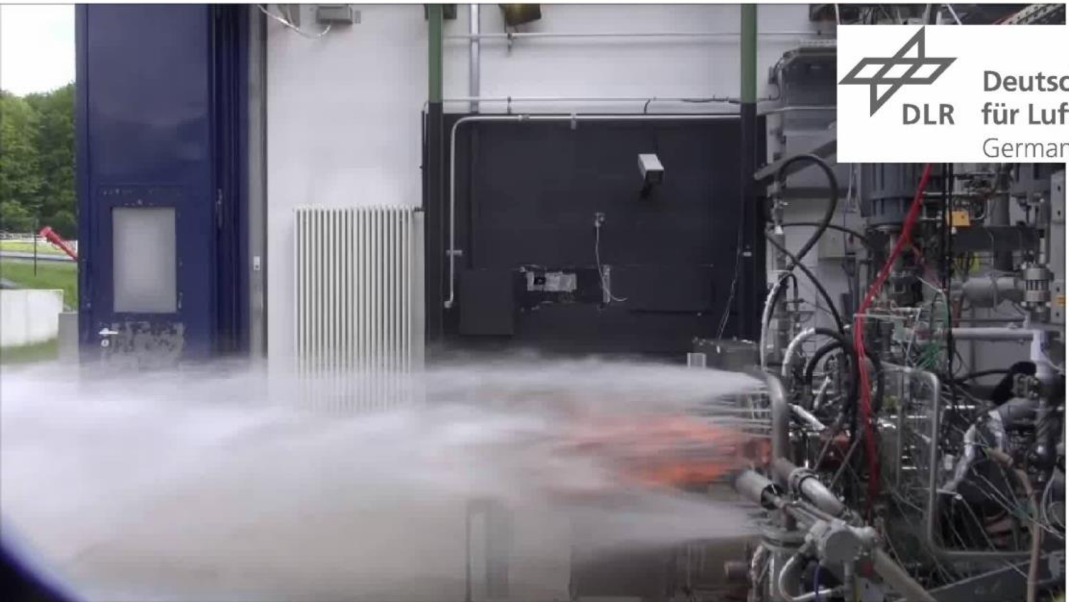
Optical Diagnostics Setup

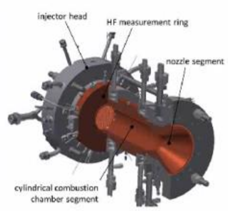
- OH* and blue radiation
- 60,000 FPS
- Synchronized cameras

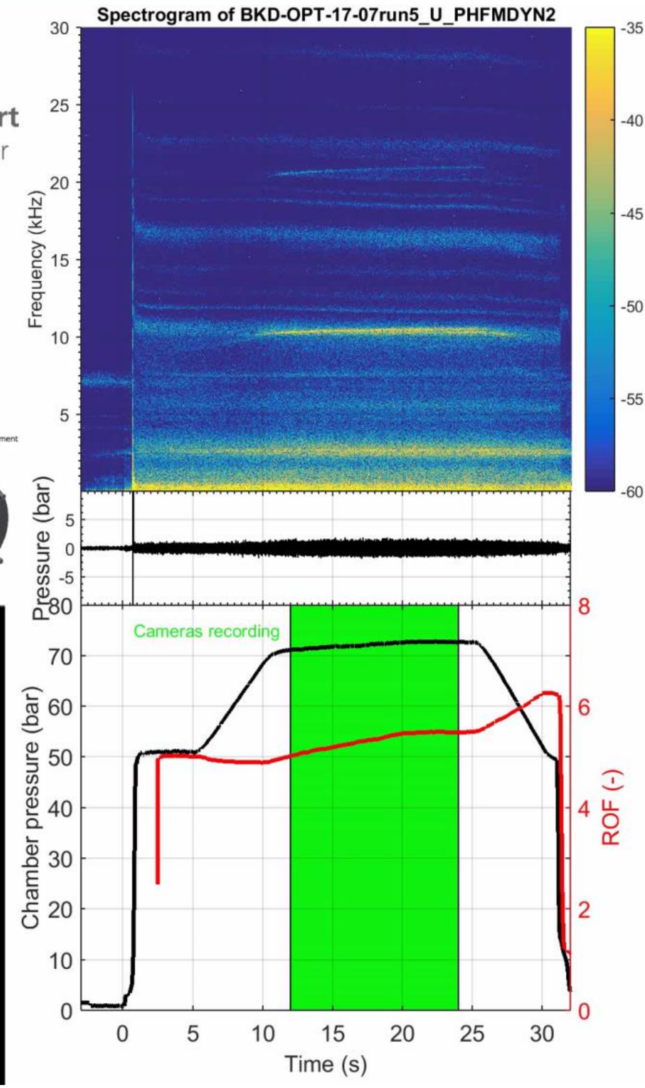


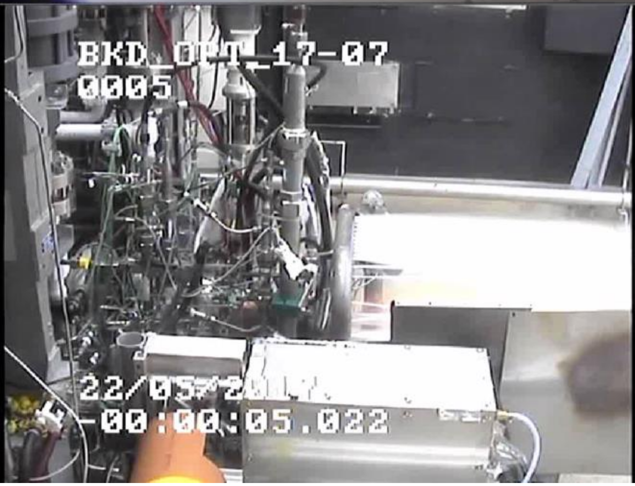
BKD Test with Optical Access

DFG SFB TRR 40







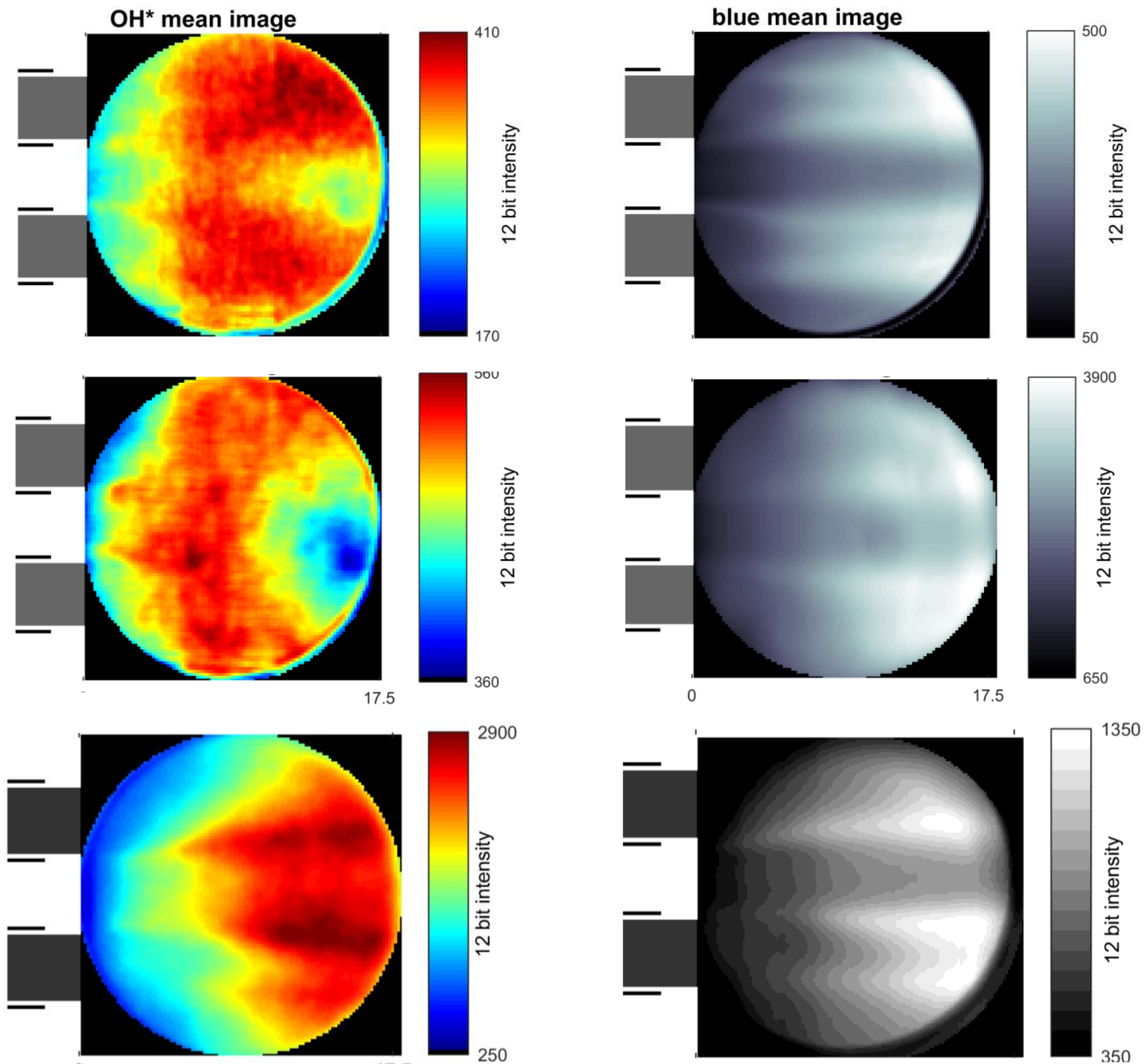


Mean Flame Images

LP1
- 50 bar
- ROF 5

LP2
- 80 bar
- ROF 4.7

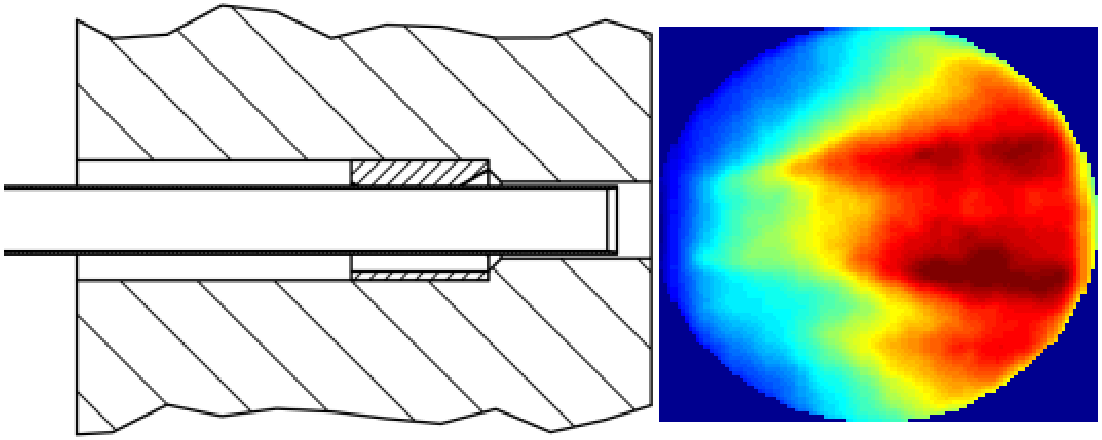
LP3
- 80 bar
- ROF 5.2



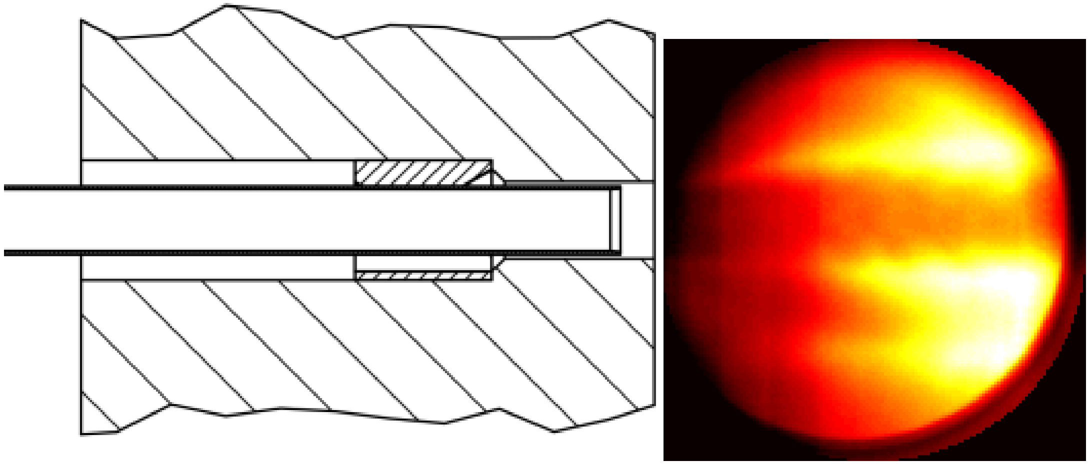
Flame Dynamics at 1T Mode

- 1T response

- OH*



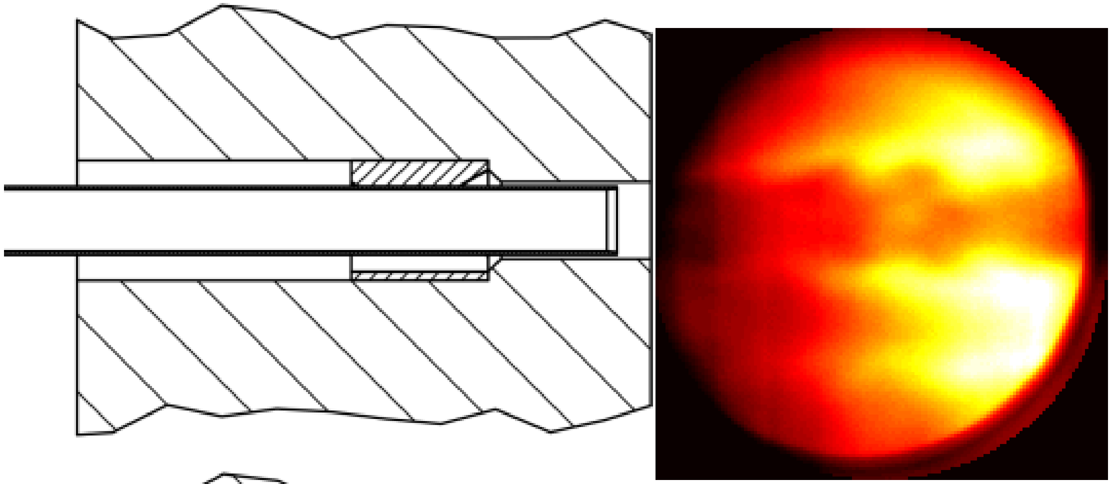
- Blue Rad.



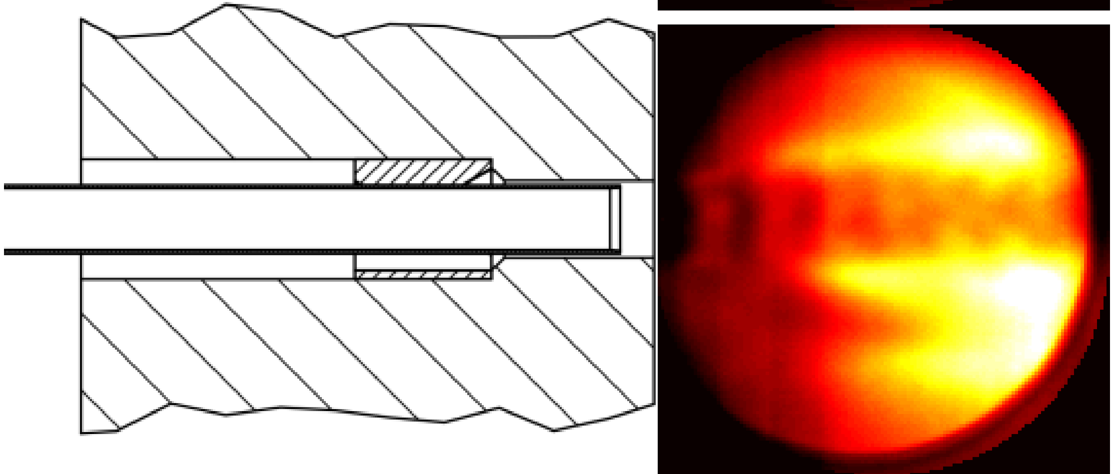
Flame Dynamics for LOX Modes

- Flame and LOX core response to excited LOX post eigenmodes in Blue radiation:

- LOX Post 1L

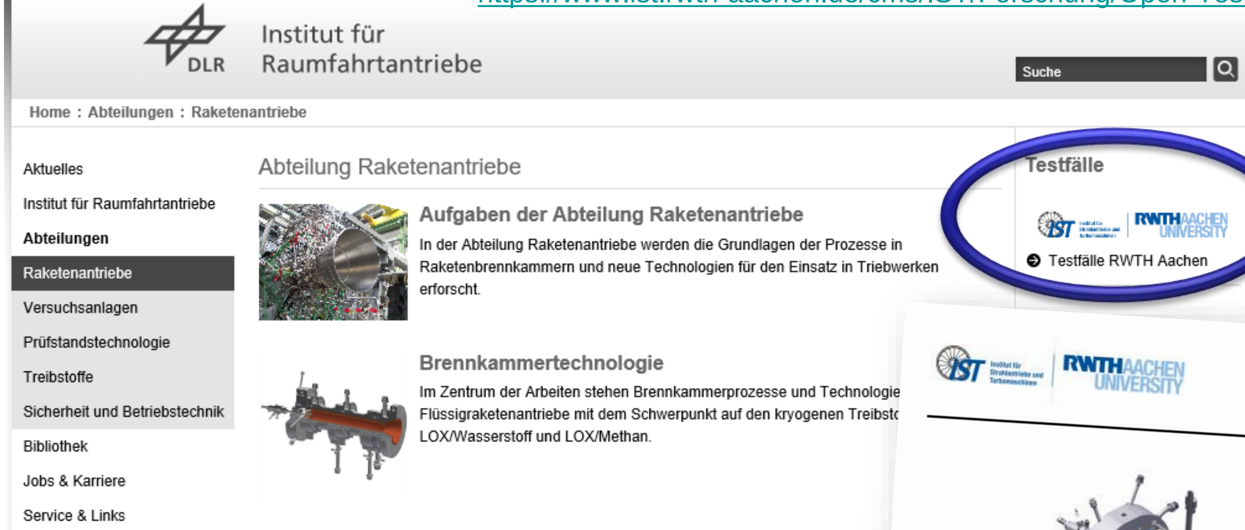


- LOX Post 2L



Published DLR Test Cases

https://www.ist.rwth-aachen.de/cms/IST/Forschung/Open-TestCases/~bvvsb/DLR-Open-Testcases/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Abteilung Raketenantriebe

Aufgaben der Abteilung Raketenantriebe

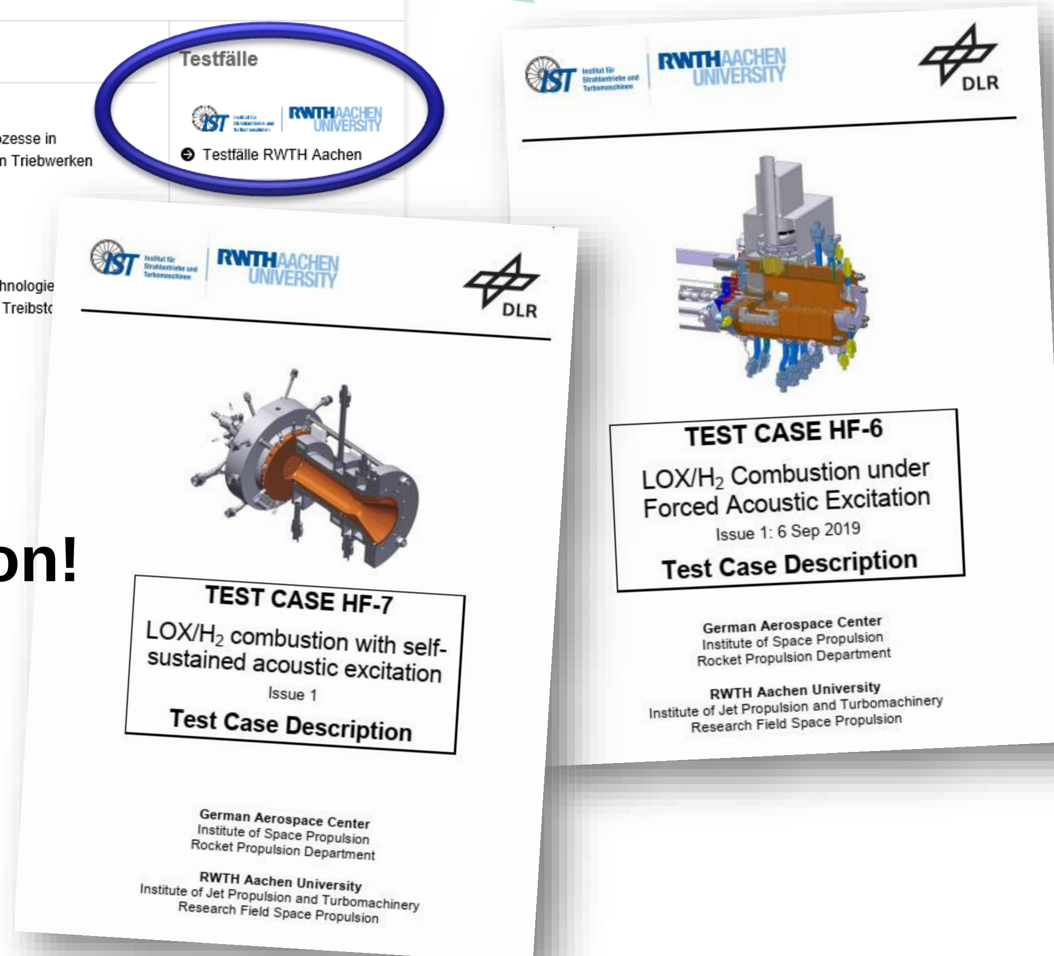
In der Abteilung Raketenantriebe werden die Grundlagen der Prozesse in Raketenbrennkammern und neue Technologien für den Einsatz in Triebwerken erforscht.

Brennkammertechnologie

Im Zentrum der Arbeiten stehen Brennkammerprozesse und Technologie Flüssigraketenantriebe mit dem Schwerpunkt auf den kryogenen Treibstc LOX/Wasserstoff und LOX/Methan.

Testfälle

Testfälle RWTH Aachen


TEST CASE HF-6

LOX/H_2 Combustion under Forced Acoustic Excitation

Issue 1: 6 Sep 2019

Test Case Description

German Aerospace Center
Institute of Space Propulsion
Rocket Propulsion Department

RWTH Aachen University
Institute of Jet Propulsion and Turbomachinery
Research Field Space Propulsion

TEST CASE HF-7

LOX/H_2 combustion with self-sustained acoustic excitation

Issue 1

Test Case Description

German Aerospace Center
Institute of Space Propulsion
Rocket Propulsion Department

RWTH Aachen University
Institute of Jet Propulsion and Turbomachinery
Research Field Space Propulsion

Thank you for your attention!

Outline

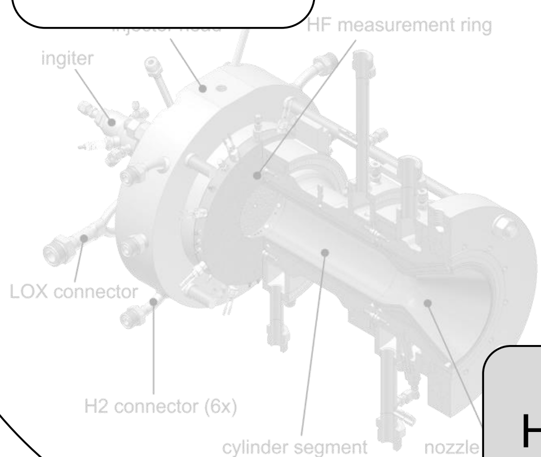
Introduction

Experiment

Goals

Hardware

Results

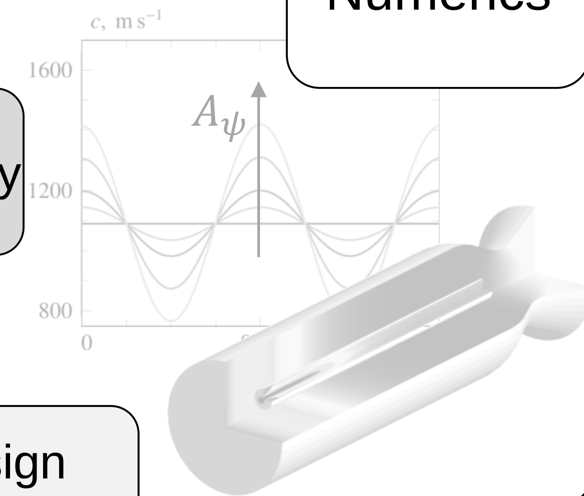


Numerics

Methodology

Design Adaptions

Mechanisms



C3: Stability Assessment

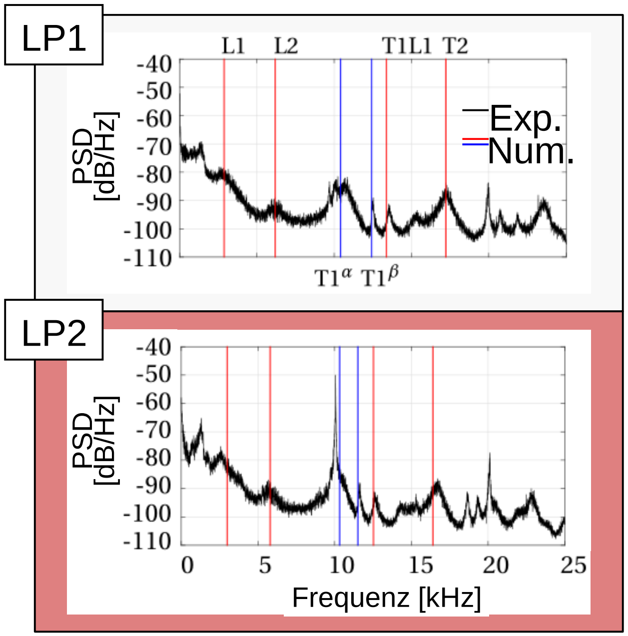
Stability assessment

Mechanisms

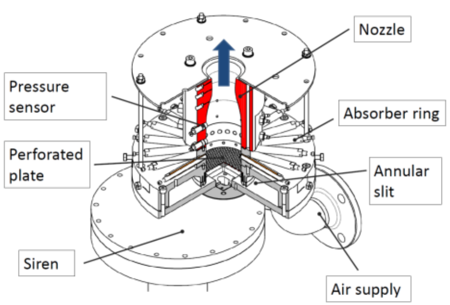
Design adaption

Validation

- Hybrid methodology
  - Integration by end of FP2
  - Continuous development



- Validation
  - C7: BKD
  - Cold-flow test rig



- Absorber characteristic specifications

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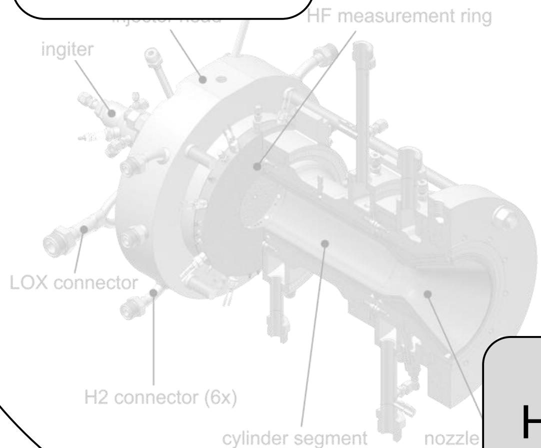

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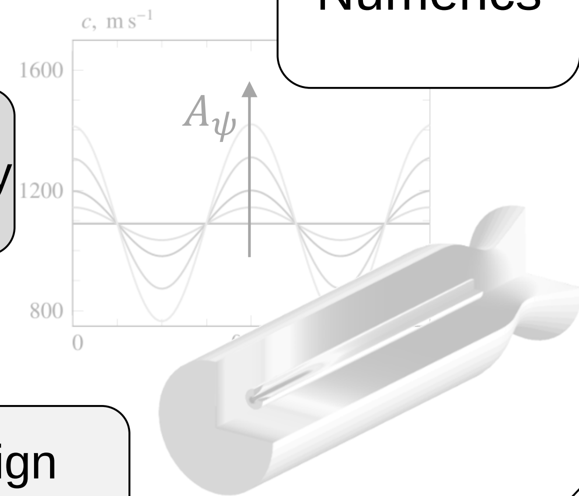
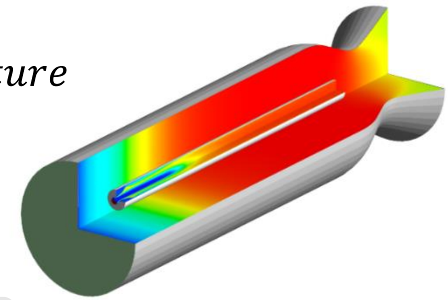


Stability Assessment

Sound Speed

Temperature



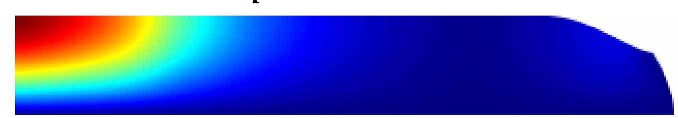
Single Flame Simulation → Mean Flow

Single Flame Simulation → Flame Dynamics

Mean Flow → LEE Eigensolution

Flame Dynamics → LEE Eigensolution

Pressure Amplitude



e.g. $n - \tau$ Modell

$\Omega = \omega + i\alpha$

min *max*

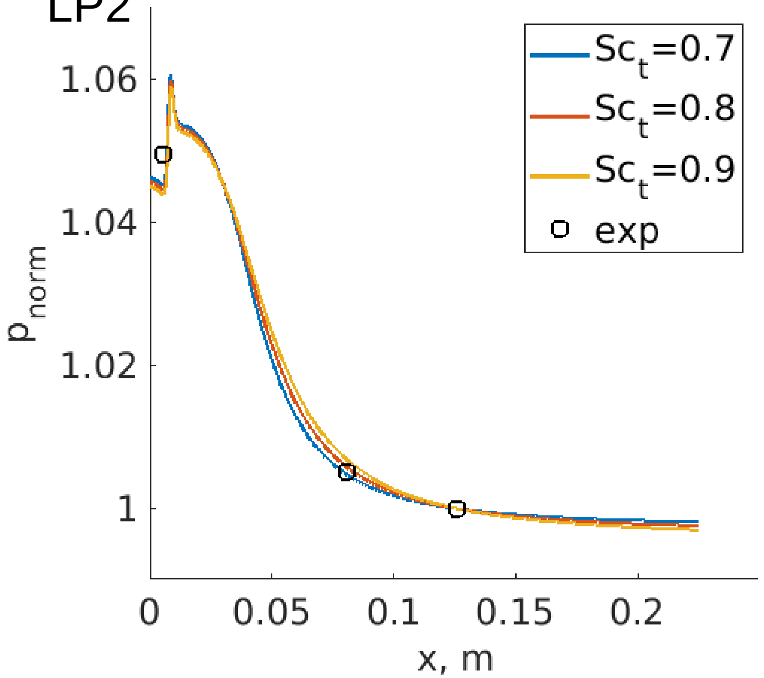
- Hybrid approach
- Eigenvalue characterizes stability

Validation – Single Flame

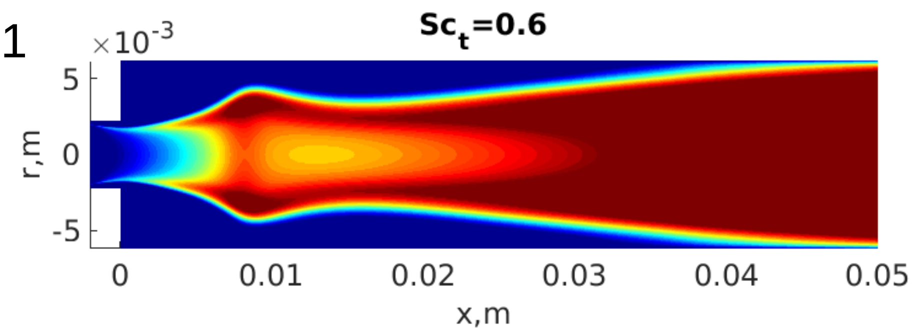
- Static pressure
- Sc_t calibration

- OH* radiation
- Flame structure

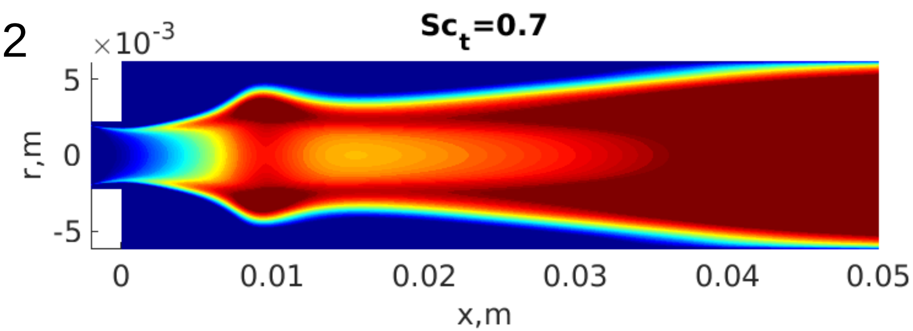
LP2



LP1

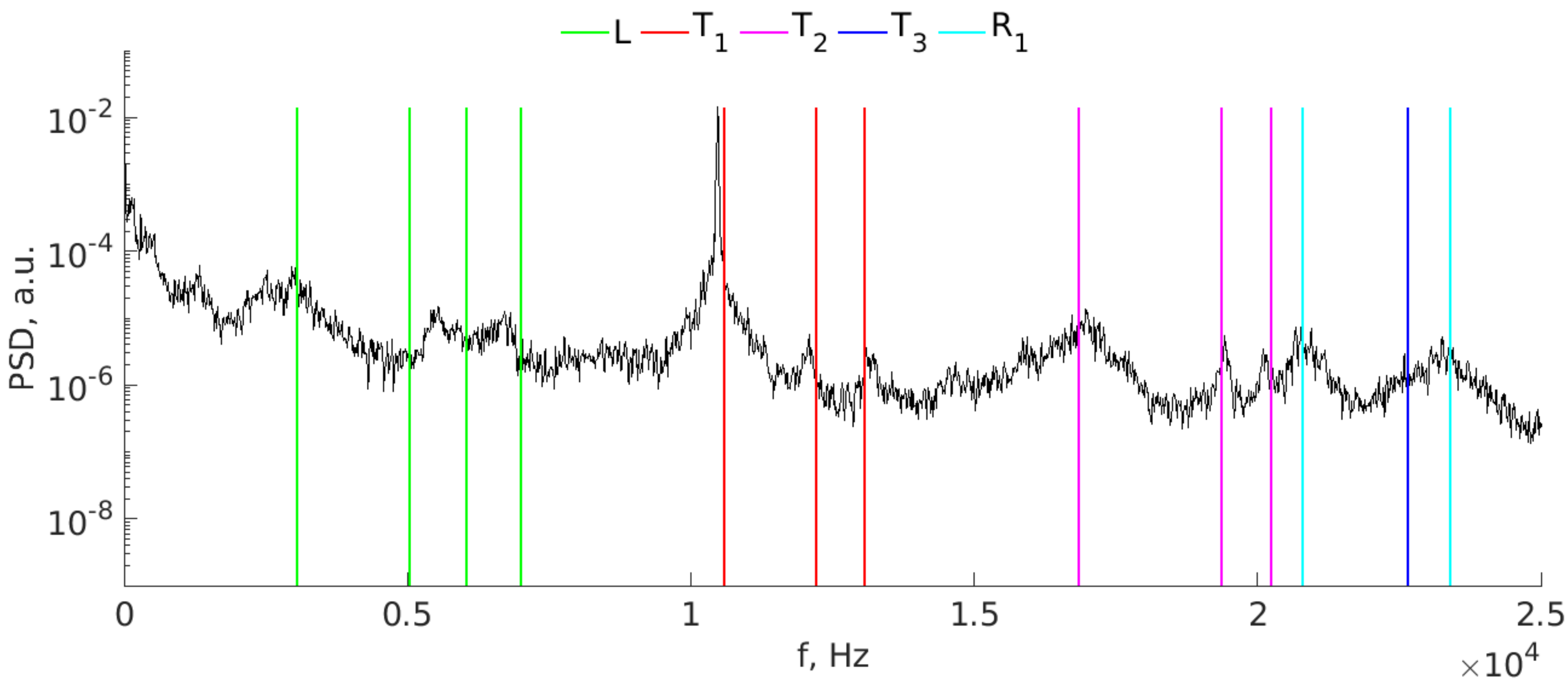


LP2



Acoustics

- BKD OH* load point LP2



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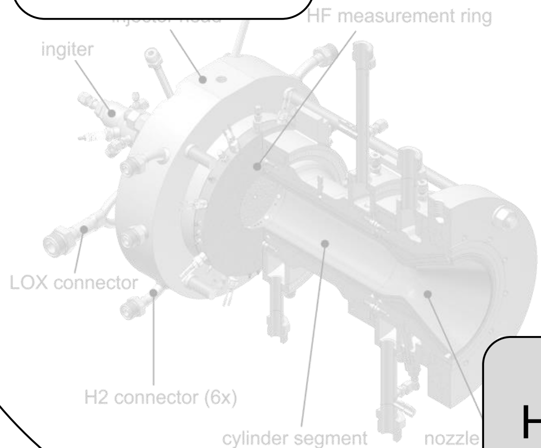

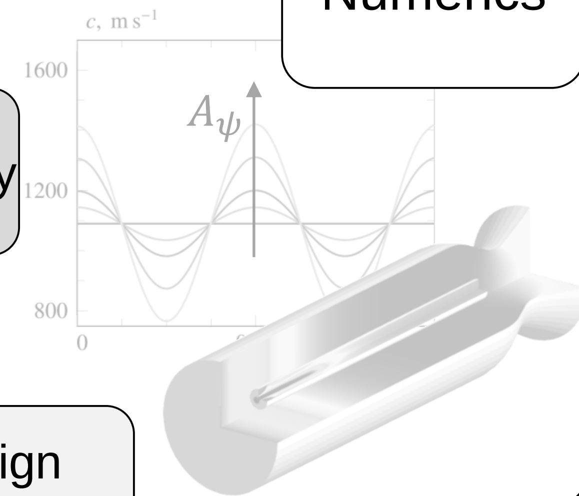

Hardware

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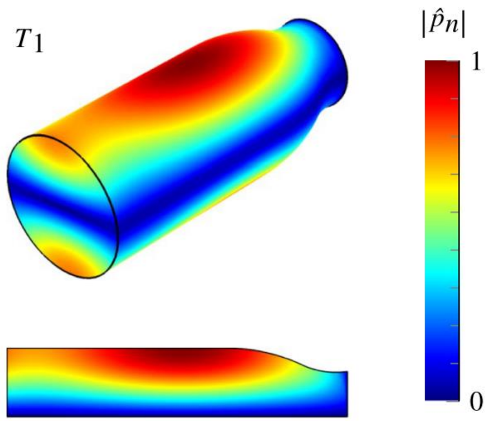
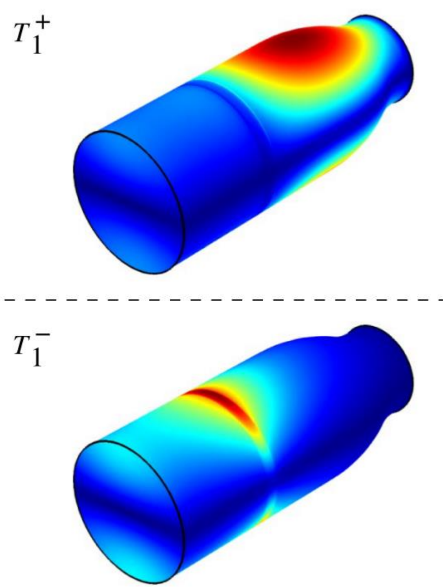
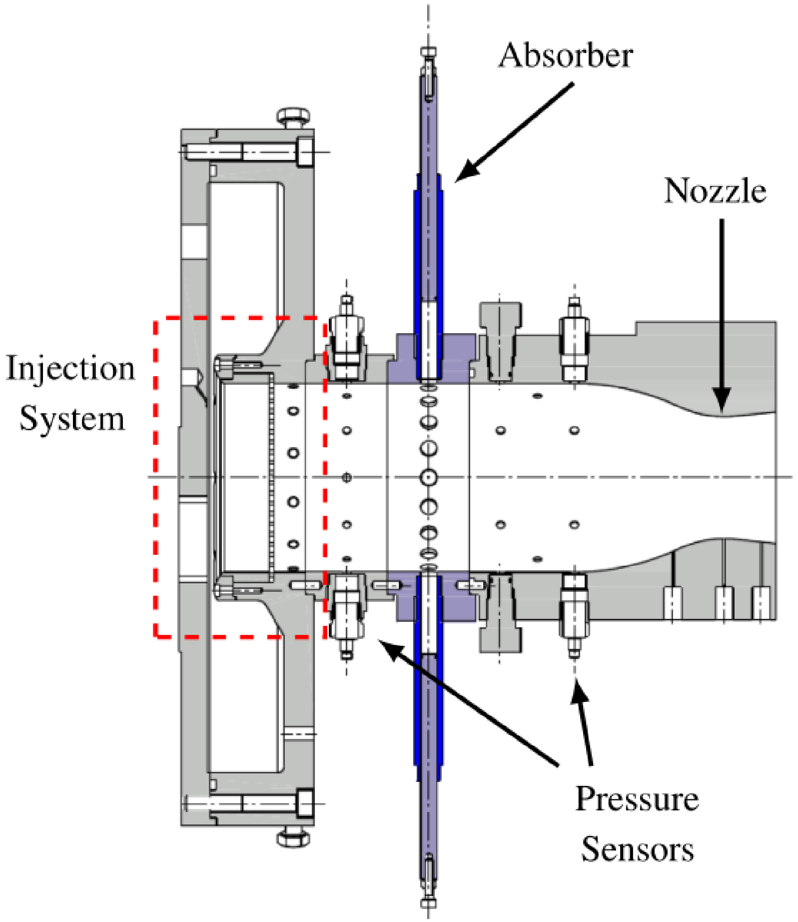
Mechanisms

Cold Flow Test Rig

- Cold flow test rig
- Absorber ring
- Split of T_1 mode

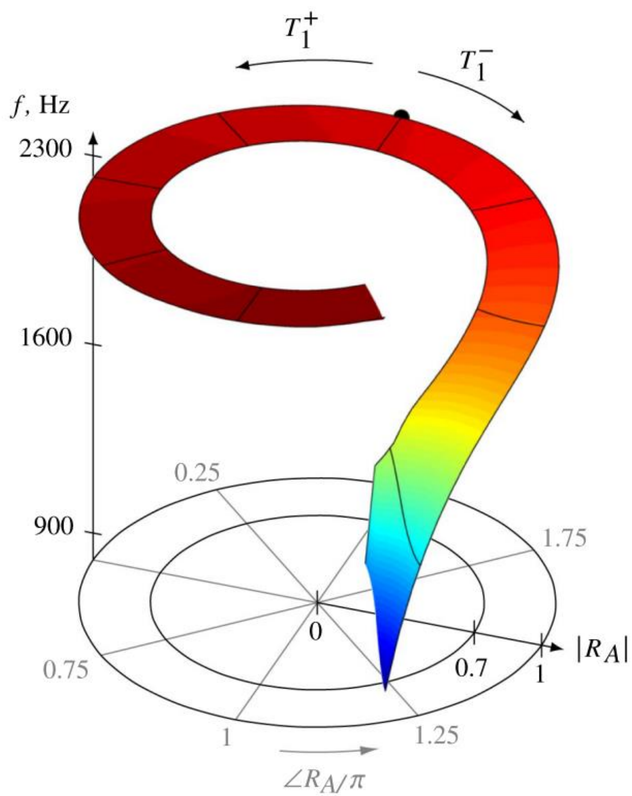




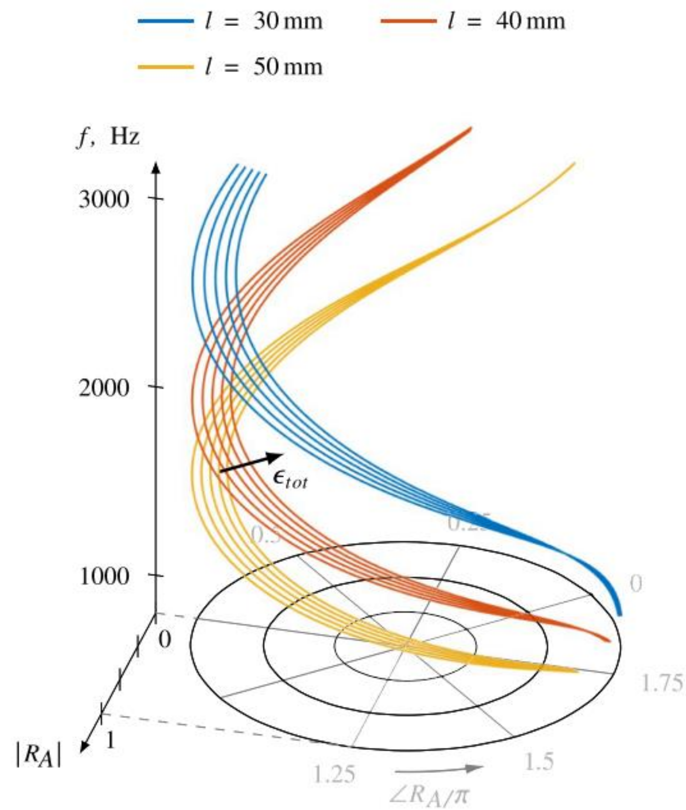


Mode Split Mechanism

Eigenfrequencies

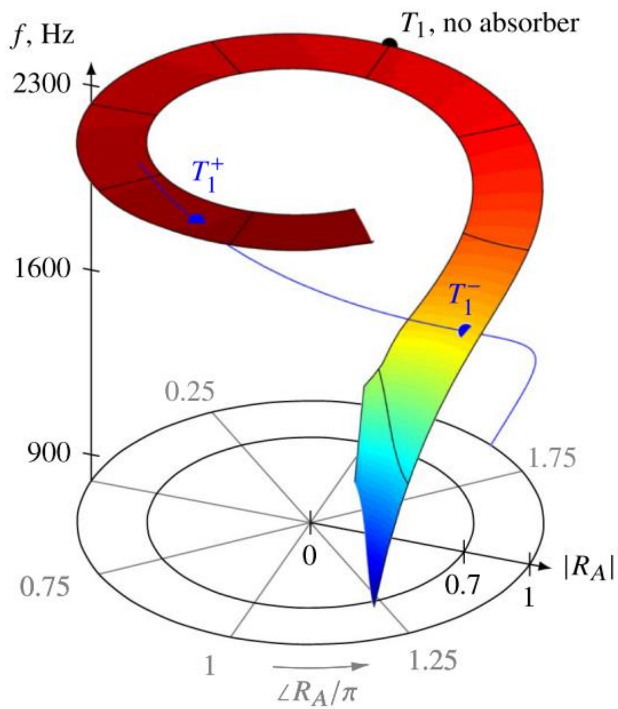


Absorber Characteristic



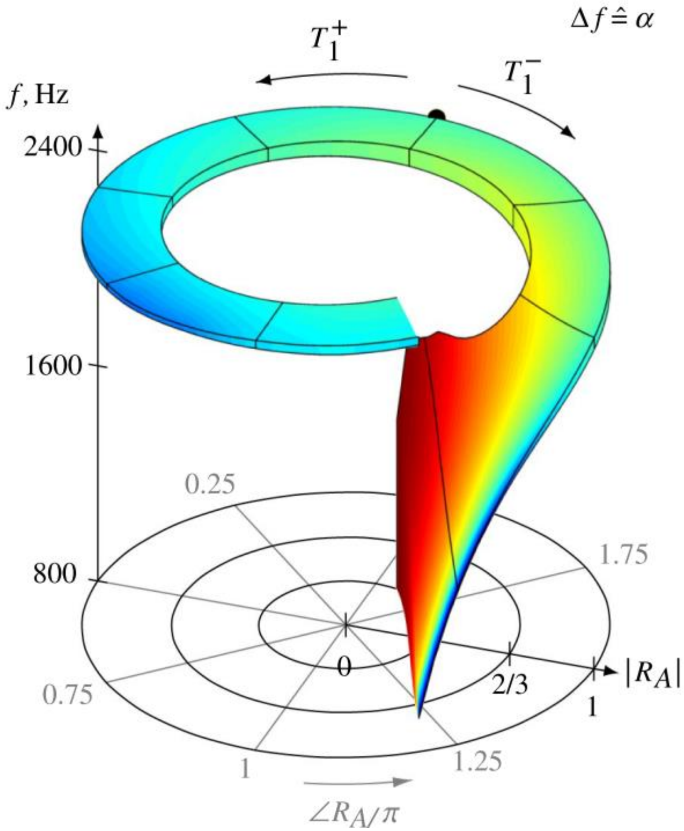
Mode Split Mechanism

- Absorber characteristic induces mode split

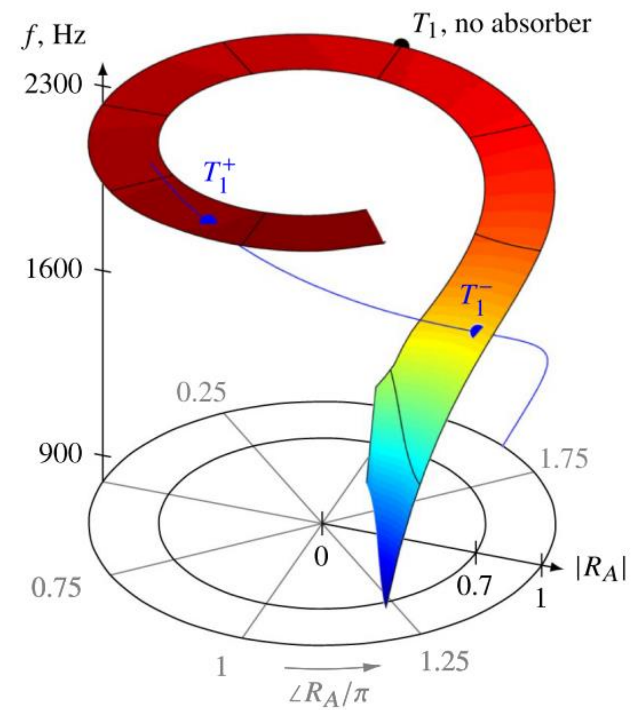


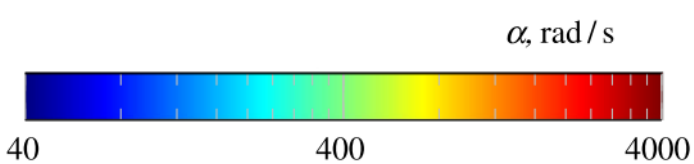
Absorber Constraints

Damping Rate



Operating Point





- Absorber design independent of chamber acoustics

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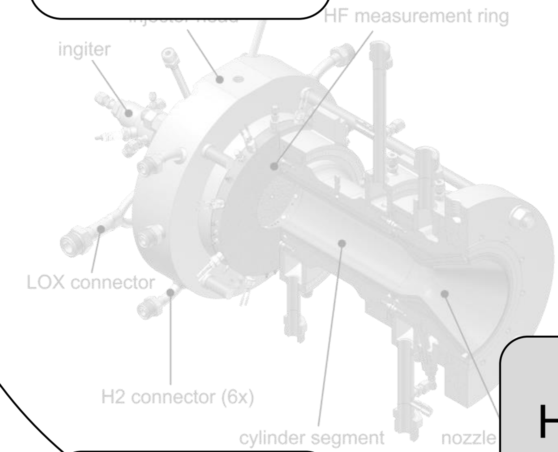
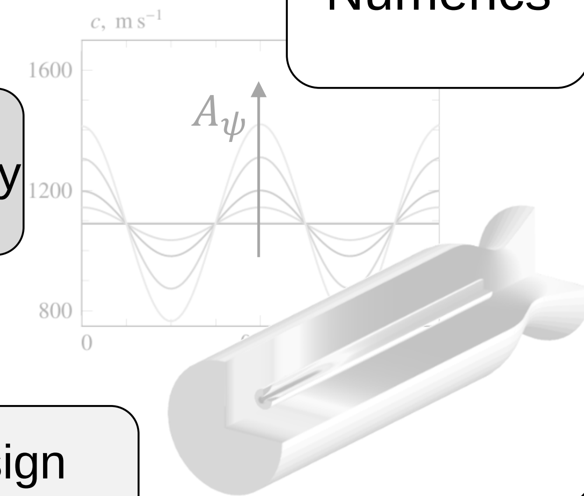
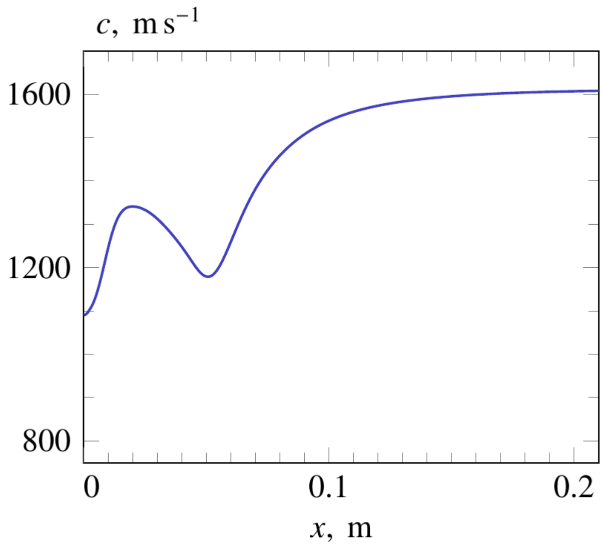
- Mechanisms

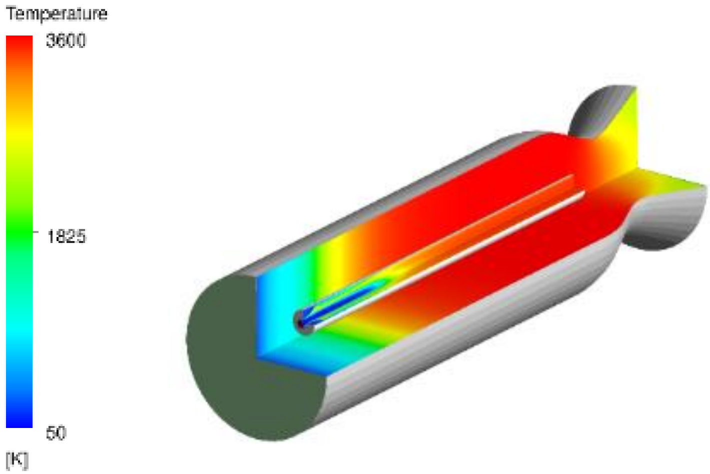




Mean Flow

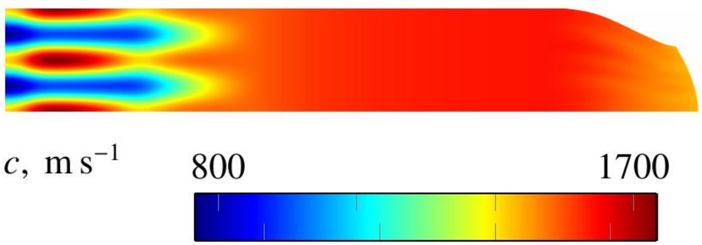
- Quasi one-dimensional
- Reproduces 1D profiles from single flame
  - Sound speed
  - Isentropic compressibility
- Fulfills Euler Equations

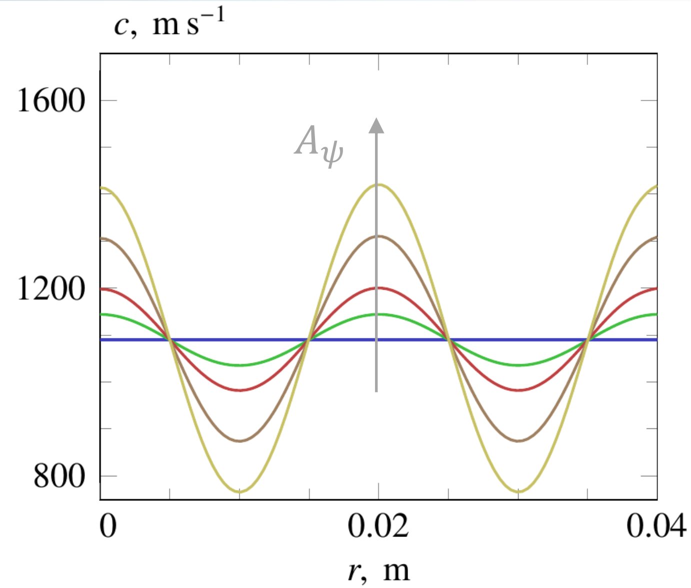




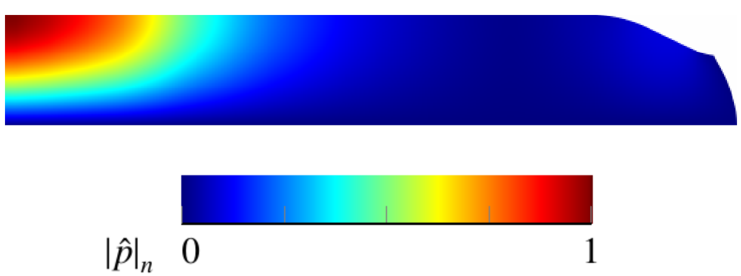
Radial Stratification

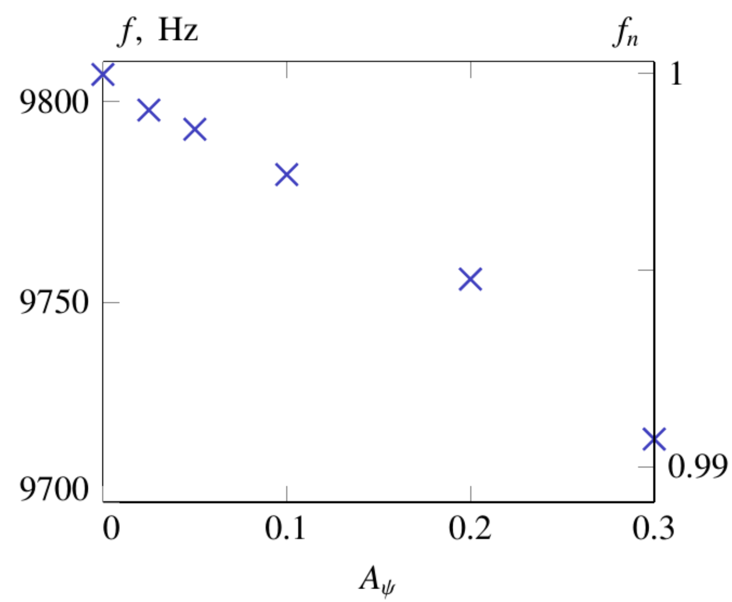
- Artificial flame structures
  - Equivalent 1D mean flows





- Variation of stratification amplitude

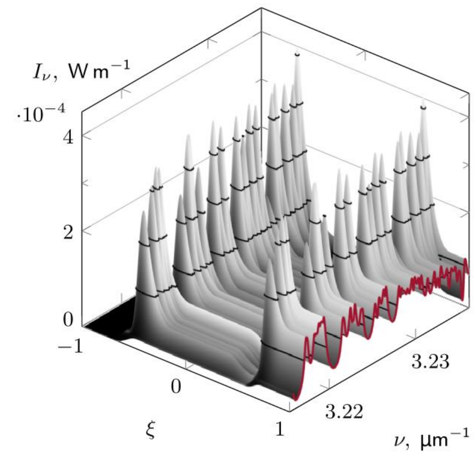




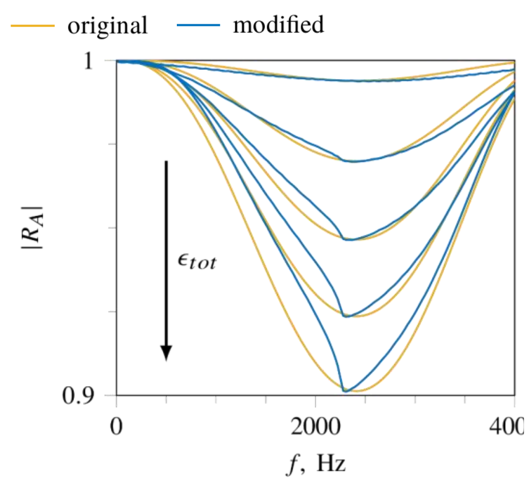
Summary

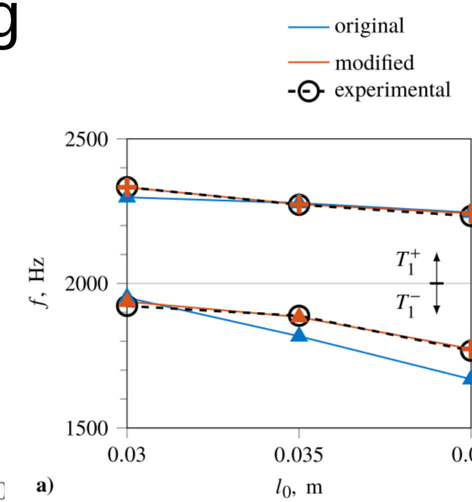
- Hybrid Methodology
  - Validation
  - OH* images
  - Acoustics
- Absorber Design
  - Constraint specification
- Stratification
  - Radial flame structures

Radiation Modeling

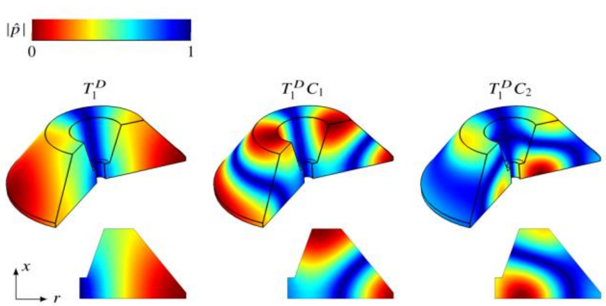


Absorber Modeling





TCDs



SFB TRR40 C3/C7

Experimental and numerical study of high-frequency combustion instabilities

C7: Wolfgang Armbruster, Dr. Justin Hardi, Prof. Dr. rer. nat. Michael Oschwald

C3: Alexander Chemnitz, Prof. Sattelmayer

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