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Group Meeting, 12th Nov 2024

Dynamic Stability and Emissions in Premixed CH_4/NH_3 Swirling Flames with Nanosecond Pulsed Discharges

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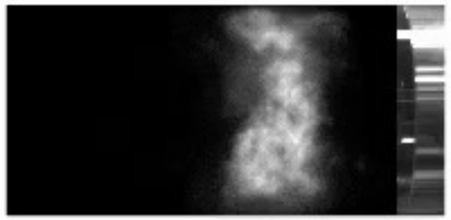
Background - I

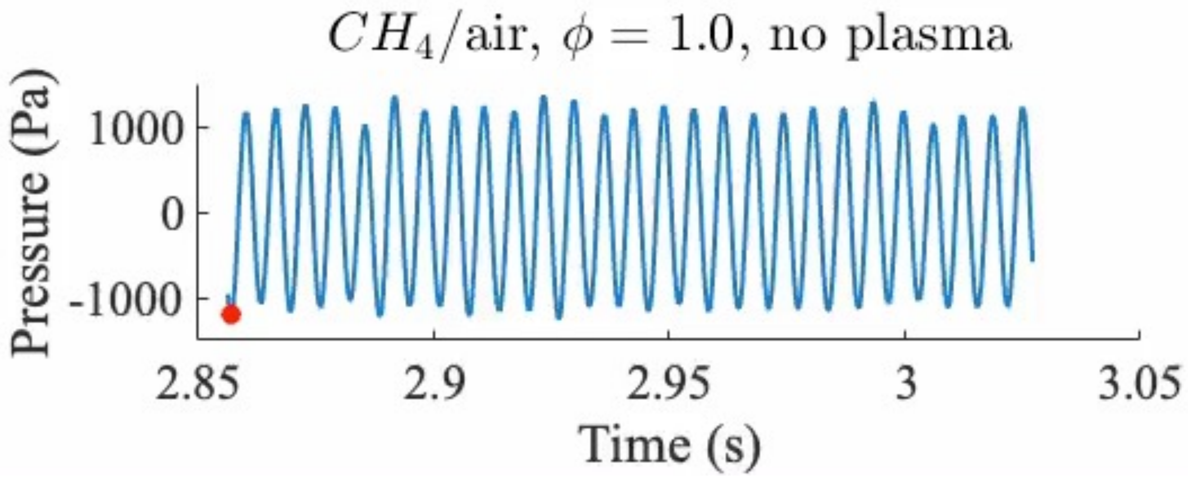
Dynamic Stability of NH_3/air flames : Definitions

- Dynamic Stability:
    - Occurrence of large pressure pulsations in the combustion chamber
    - Most dangerous of these is when the peak amplitude is a few percent of the chamber pressure

- All things being equal, how does substituting C_xH_y with NH_3 change characteristics of these oscillations
    - Can we link these to some flamelet characteristic or fuel chemistry/transport?

- How do we reduce/eliminate these oscillations?
    - (preferably in a way that affects the fuel chemistry/transport?)





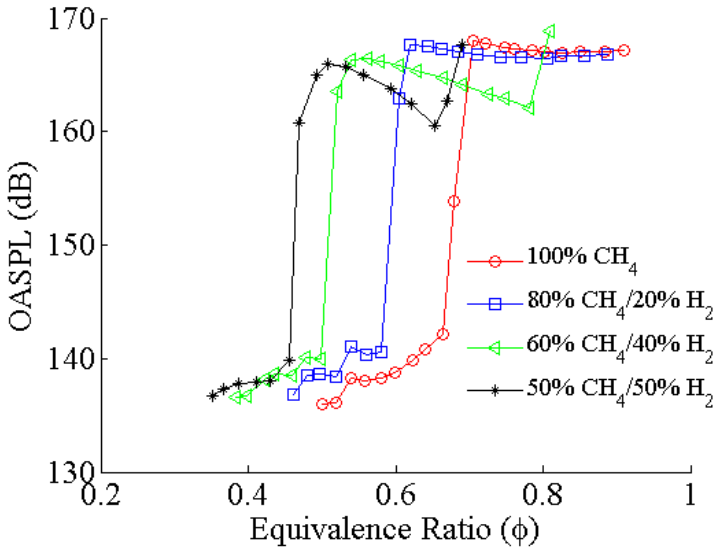
1000 Pa ≡ 154 dB

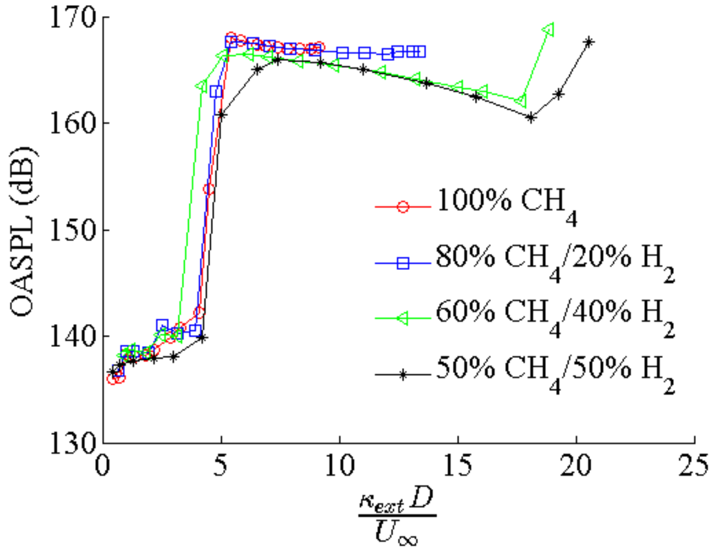
Background - I

Related: Dynamic Stability due to H_2 addition

- Related question, that we have addressed before:
    - How does switching from C_xH_y to H_2 change the dynamic stability of the combustor
- What changes:
    - Frequency, amplitude
    - Point of onset

At stoichiometric conditions	NH_3	CH_4	H_2
$T_{equil.}$ (K)	2075	2225	2400
S_u^o ($^{cm}/_{s}$)	7	35	175
$K_{ext}(s^{-1})$	~ 100	> 2200	> 30,000





Ref: Shanbhogue,..,Ghoniem, 2015 Comb. & Flame

Background – II

The effects of NRPD on Flame Stability and Emissions

- Prior work by us and others have shown that NRPDs can improve flame stability, but only for CH_4/air or other hydrocarbon flames

- Studies have shown that NRPDs can reduce NO_x in NH_3/air flames

- Can all the benefits of NRPDs be exploited for CH_4/NH_3/air flames? Improve stability and reduce NO_x?
    - This is a key motivation for the present work

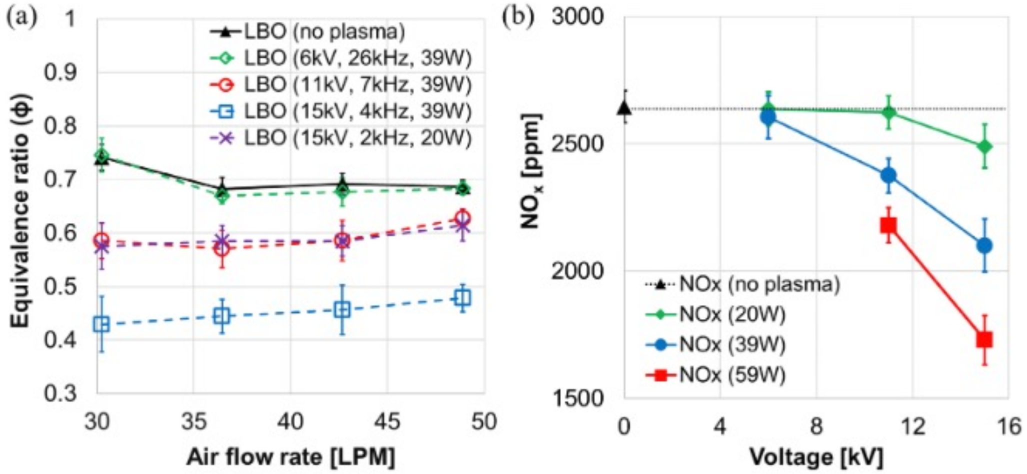
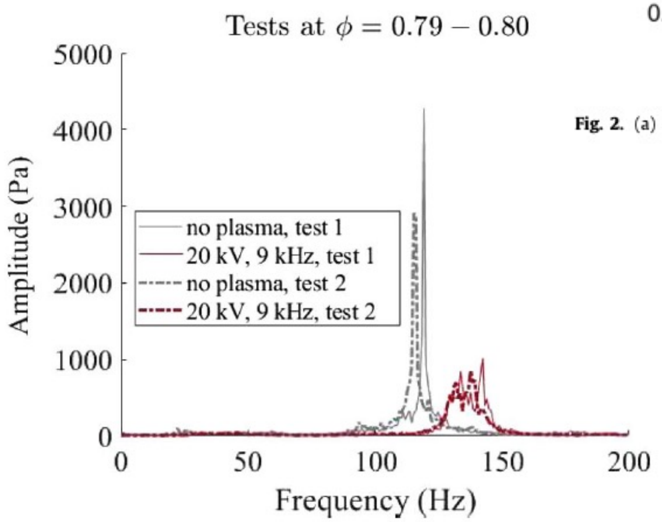


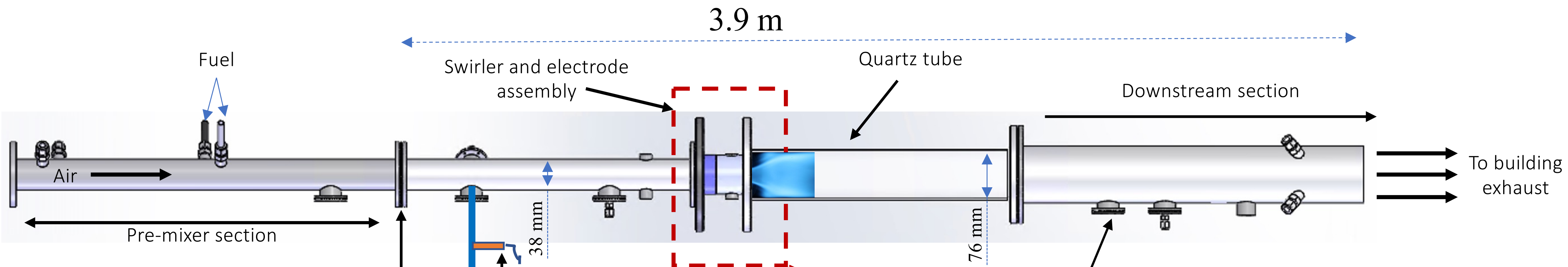
Fig. 2. (a) lean blowoff limits of ammonia/air flames with and without plasma, (b) NO_x emissions without and with plasma ($\phi = 0.94$).

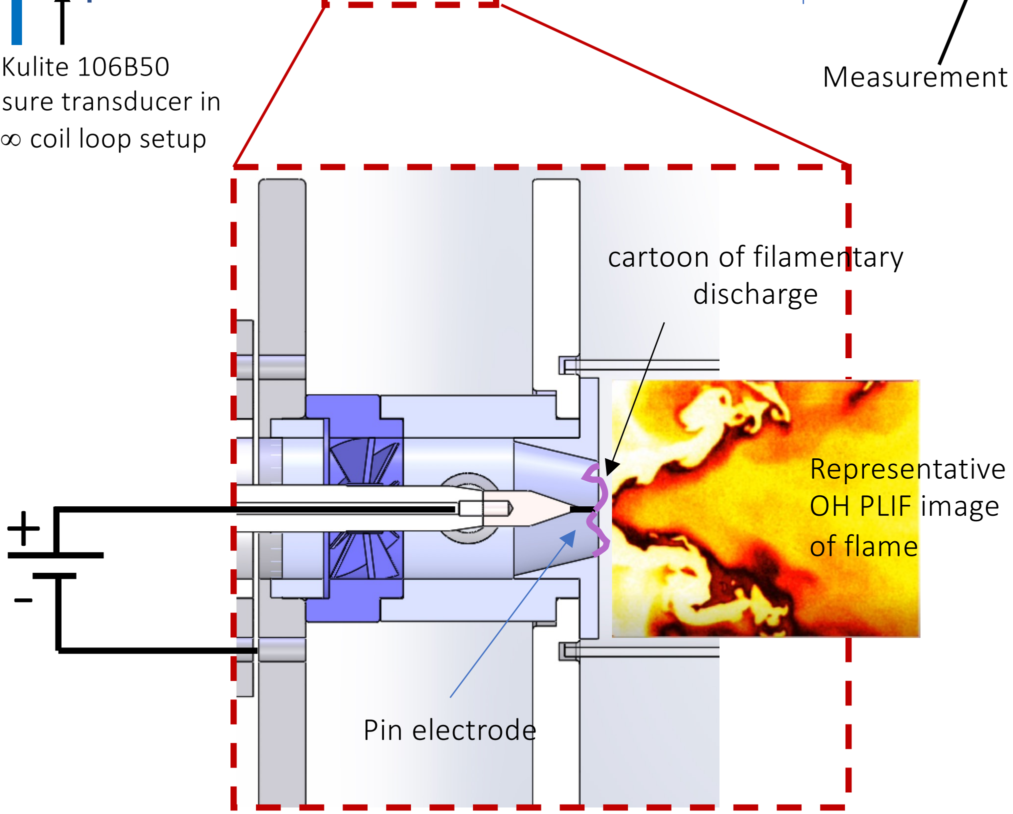
Effect of NRPDs NOx reduction. Reproduced form Choon,…,Sun, Comb. Flame, 2021

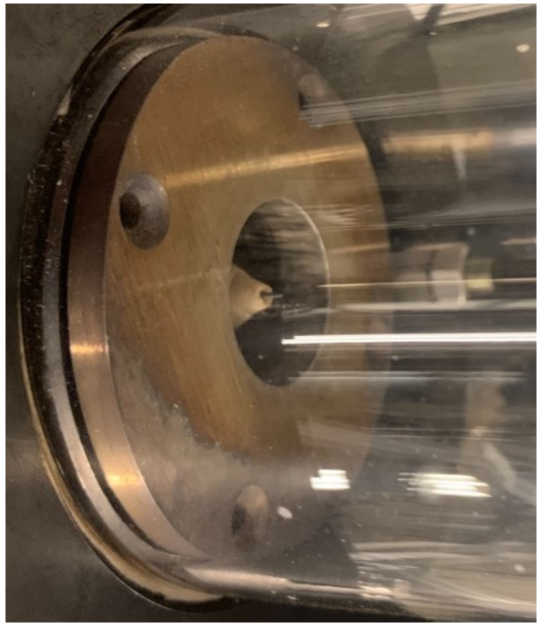


Effect of NRPDs on instability amplitude reduction. Reproduced form Shanbhogue,…,Ghoniem, 2023, J. Prop. Power

Experimental Setup I – RGD Combustor





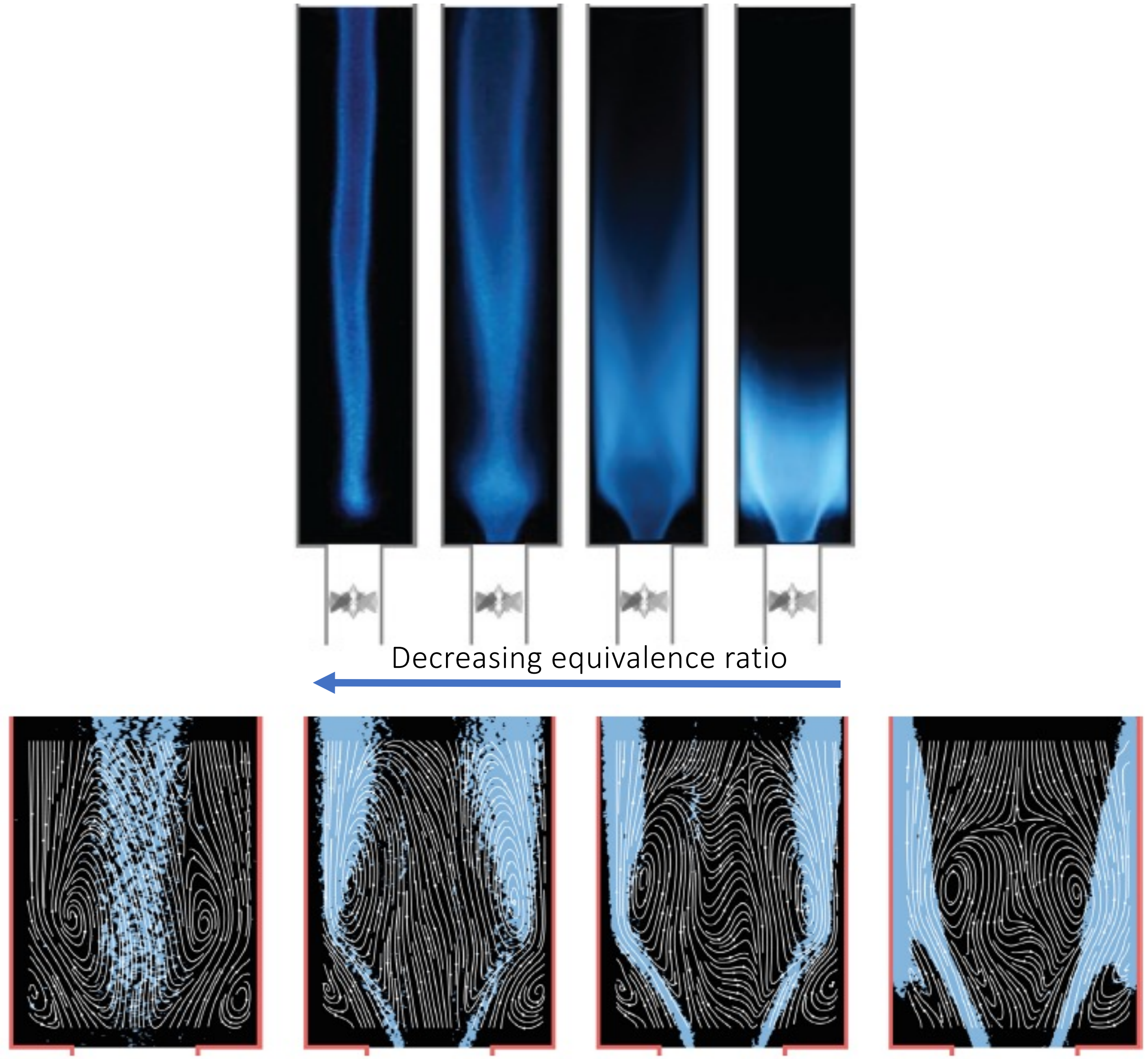


Photograph of the pin-to-ring electrode installed in the combustor

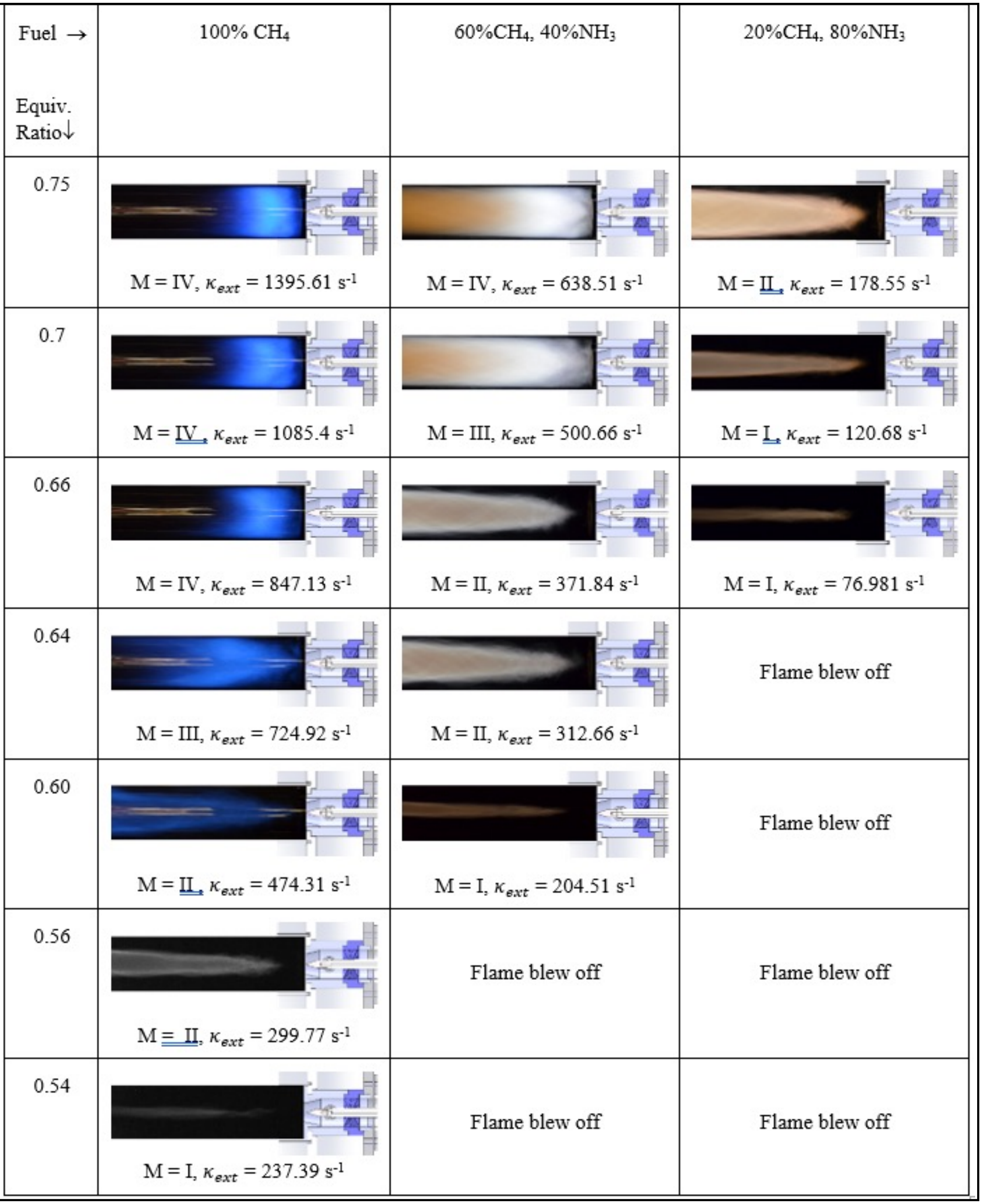
- 14 kW premixed combustor, CH_4/air, $S_\# \approx 0.7$; $U_{bulk} \approx 10$ m/s; $Re \approx 15{,}000$
- NRPs generated using a TPS SSPG-20X-HP1 transient pulse generator
  - $0 < V_{pp} \leq 20$ kV
  - $1 < f_{pulse} \leq 9$ kHz
  - 25 ns pulse, 10-30 mJ/pulse
  - About 270 W of power
  - Discharge gap = 12.7 mm

Detailed in 2023, Shanbhogue,…,Guerra-Garcia, Ghoniem, JPP

Results: Flame Macrostructure Transitions

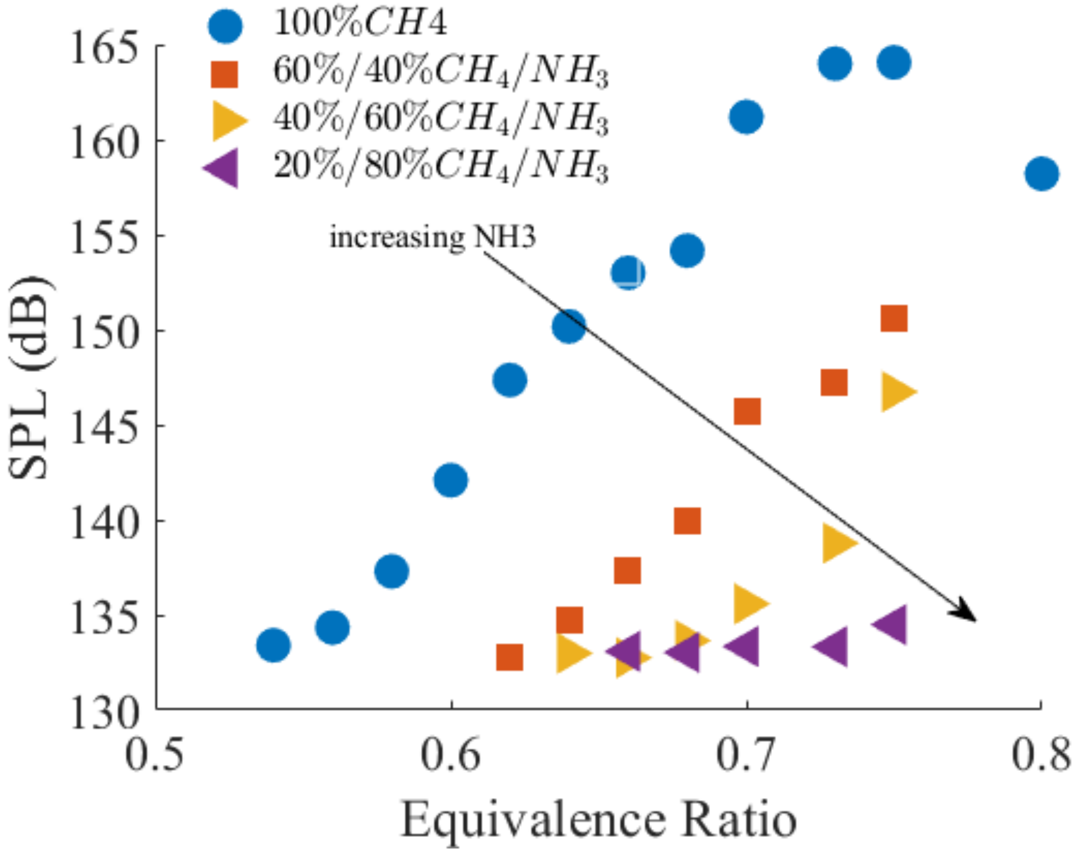


Ref: Taamallah, Shanbhogue & Ghoniem, 2016, Comb. & Flame



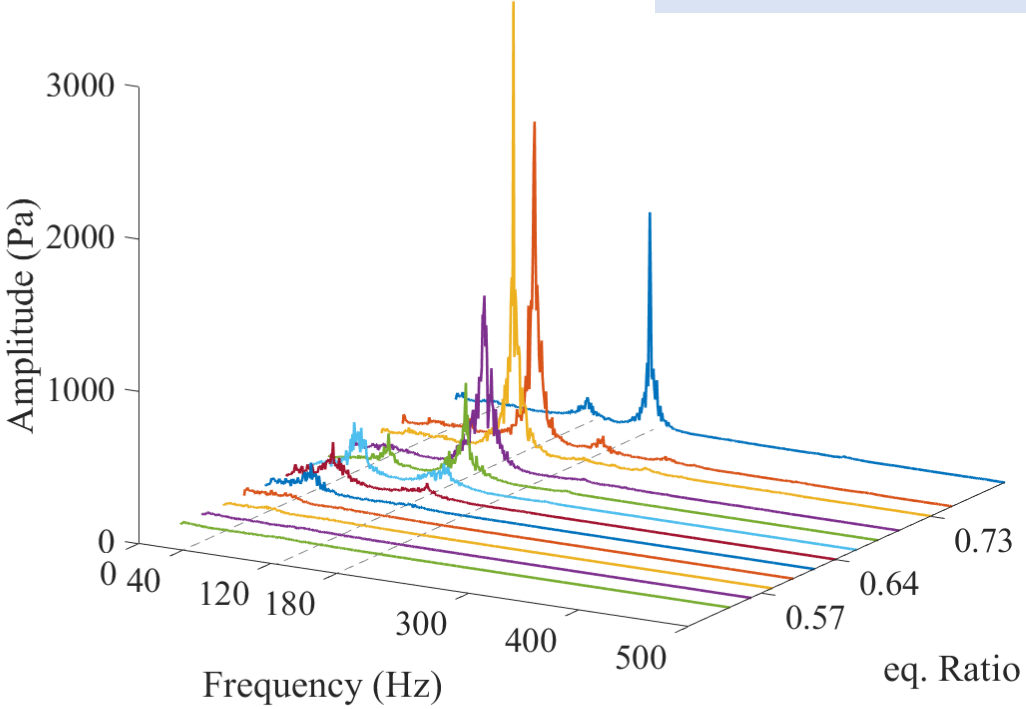
Fuel → Equiv. Ratio↓	100% CH_4	60%CH_4, 40%NH_3	20%CH_4, 80%NH_3
0.75	M = IV, κ_{ext} = 1395.61 s^{-1}	M = IV, κ_{ext} = 638.51 s^{-1}	M = II, κ_{ext} = 178.55 s^{-1}
0.7	M = IV, κ_{ext} = 1085.4 s^{-1}	M = III, κ_{ext} = 500.66 s^{-1}	M = I, κ_{ext} = 120.68 s^{-1}
0.66	M = IV, κ_{ext} = 847.13 s^{-1}	M = II, κ_{ext} = 371.84 s^{-1}	M = I, κ_{ext} = 76.981 s^{-1}
0.64	M = III, κ_{ext} = 724.92 s^{-1}	M = II, κ_{ext} = 312.66 s^{-1}	Flame blew off
0.60	M = II, κ_{ext} = 474.31 s^{-1}	M = I, κ_{ext} = 204.51 s^{-1}	Flame blew off
0.56	M = II, κ_{ext} = 299.77 s^{-1}	Flame blew off	Flame blew off
0.54	M = I, κ_{ext} = 237.39 s^{-1}	Flame blew off	Flame blew off

Results: Combustion Instabilities for different CH_4/NH_3 blends

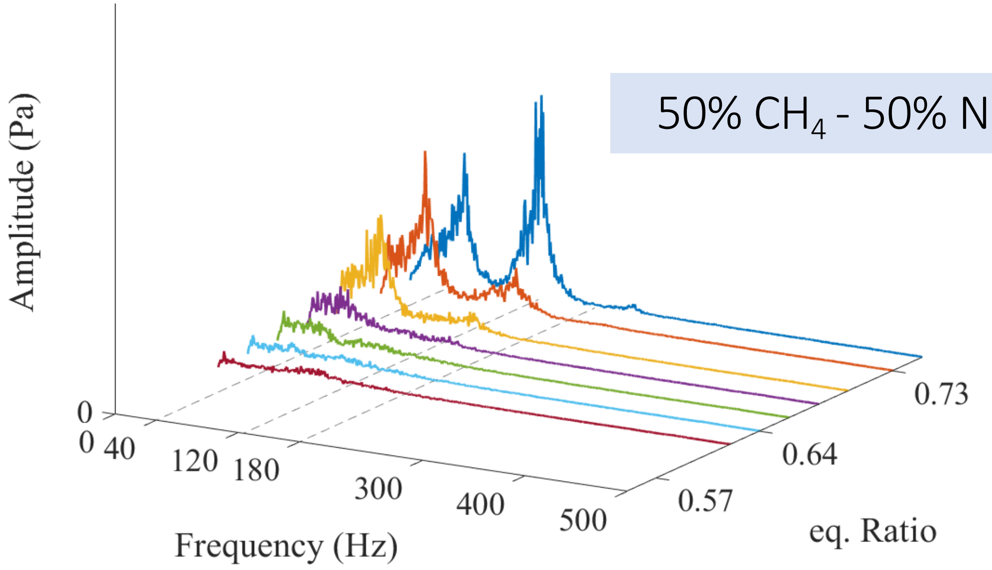


As the percentage of NH_3 in increased, the oscillations are suppressed, and transitions delayed or gone

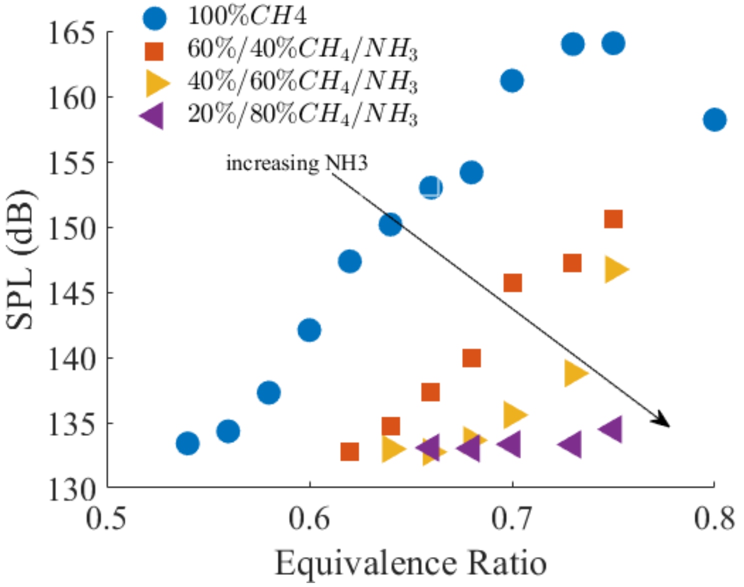
100% CH_4



50% CH_4 - 50% NH_3



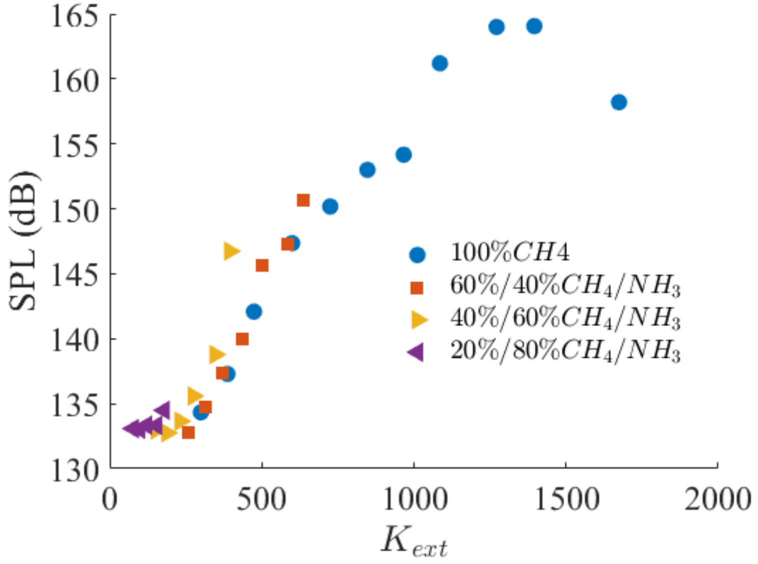
Scaling with flame time scale

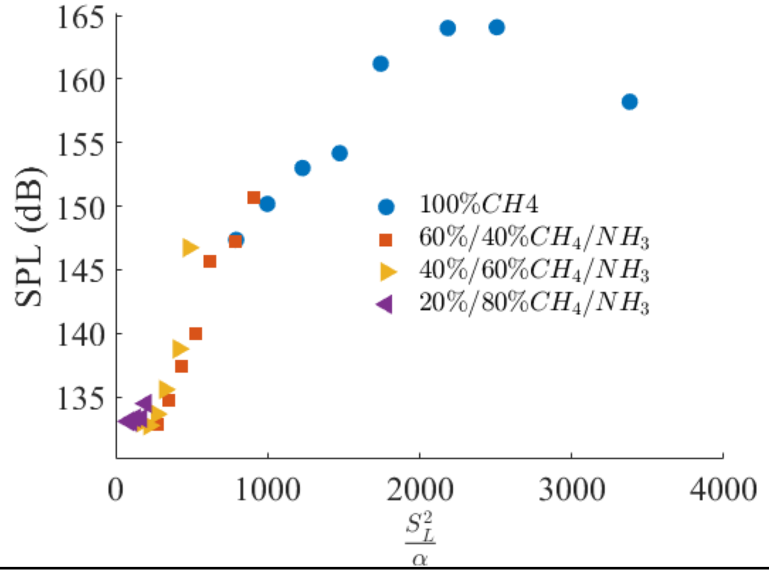


Damköhler number: $Da = \frac{\tau_{flow}}{\tau_{flame}}$

$$\tau_{flame} = \frac{1}{K_{ext}}, \frac{\alpha}{S_L^2}$$

$Da = \tau_{flow} K_{ext}$ or $\tau_{flow} \frac{S_L^2}{\alpha}$

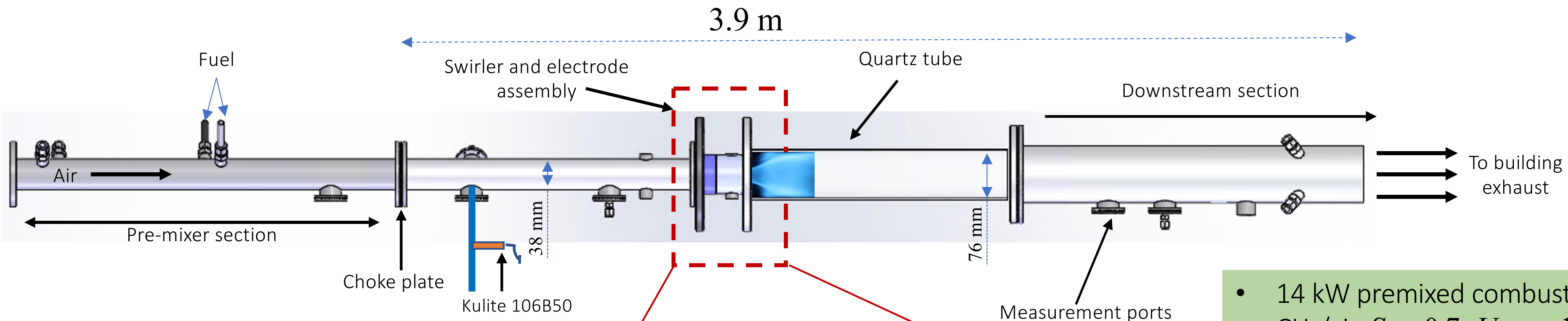


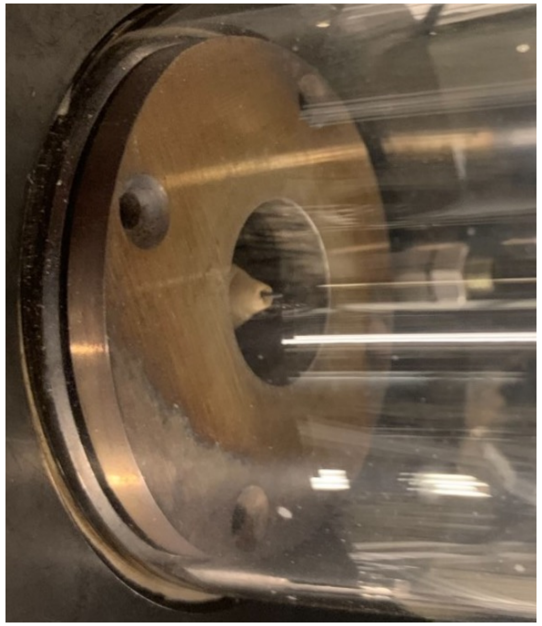


- If the transitions and amplitudes as measured by SPL are a function of the Damköhler number
- Then should be scale as $(\frac{1}{\tau_{flame}})$
- K_{ext}: Extinction Strain Rate
  - Computed using CHEMKIN
- $\frac{\alpha}{S_L^2}$: Based on thermal diffusivity and burning velocity
  - Computed using Cantera

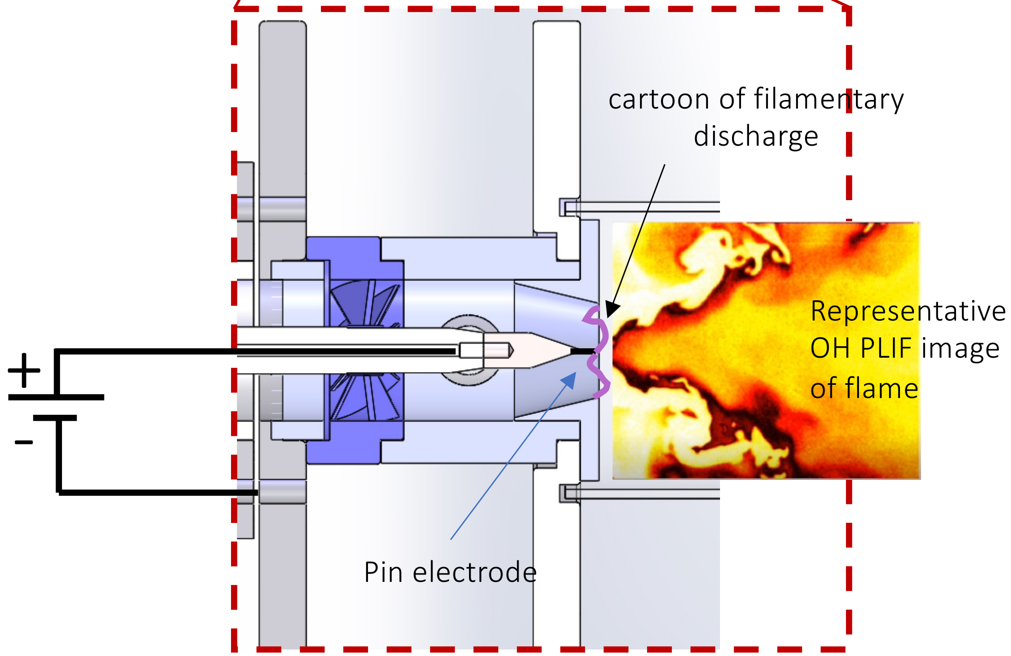
- For appropriate flow time scales, see Taamallah, Shanbhogue & Ghoniem, 2016, Comb. & Flame
  - $\tau_{flow} = {}^{1}/_{2\pi f_{ORZ}}$

Experimental Setup I – RGD Combustor





Photograph of the pin-to-ring electrode installed in the combustor



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- NRPs generated using a TPS SSPG-20X-HP1 transient pulse generator
  - $0 < V_{pp} \leq 20$ kV
  - $1 < f_{pulse} \leq 9$ kHz
  - 25 ns pulse, 10-30 mJ/pulse
  - About 270 W of power
  - Discharge gap = 12.7 mm

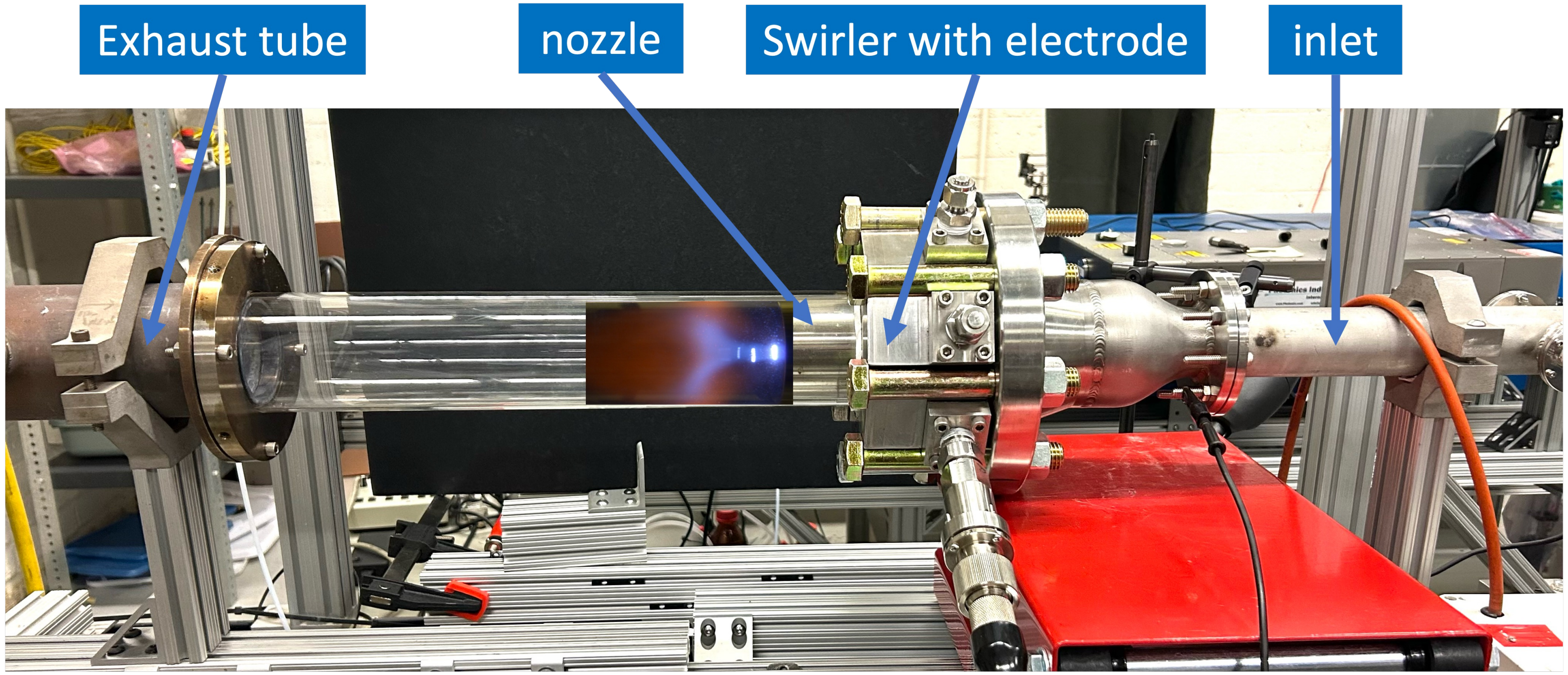
Detailed in 2023, Shanbhogue,…,Guerra-Garcia, Ghoniem, JPP

Experimental Setup II – Specter injector

- 6 kW, premixed, non-preheated combustor at atmospheric pressure
  - Re ≈ 20,000
  - $U_\infty \approx 30$ m/s
  - CH_4 & NH_3 mixed well upstream of swirler
  - Entire setup ≈ 4 m long
  - Emissions tap at 2.66 downstream of dump plane

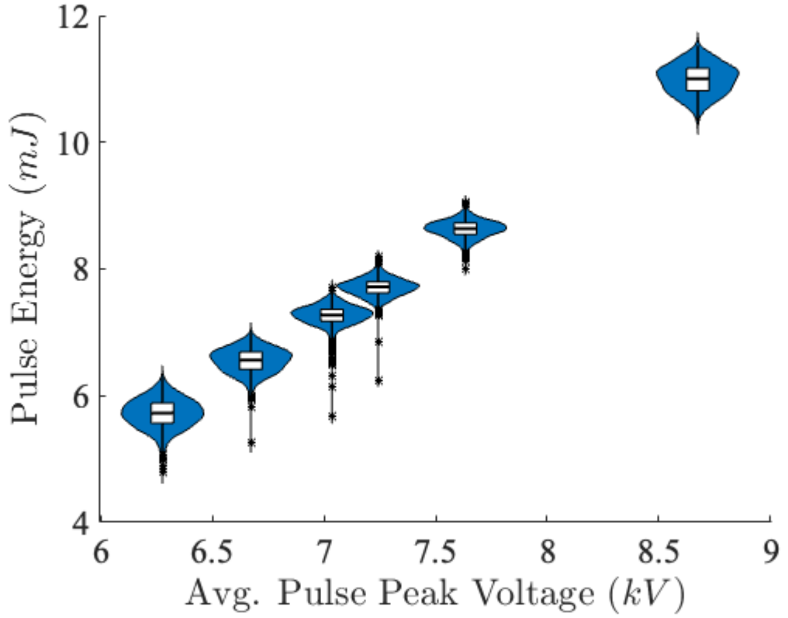
- The quartz tube in the picture is about 75 mm in diameter

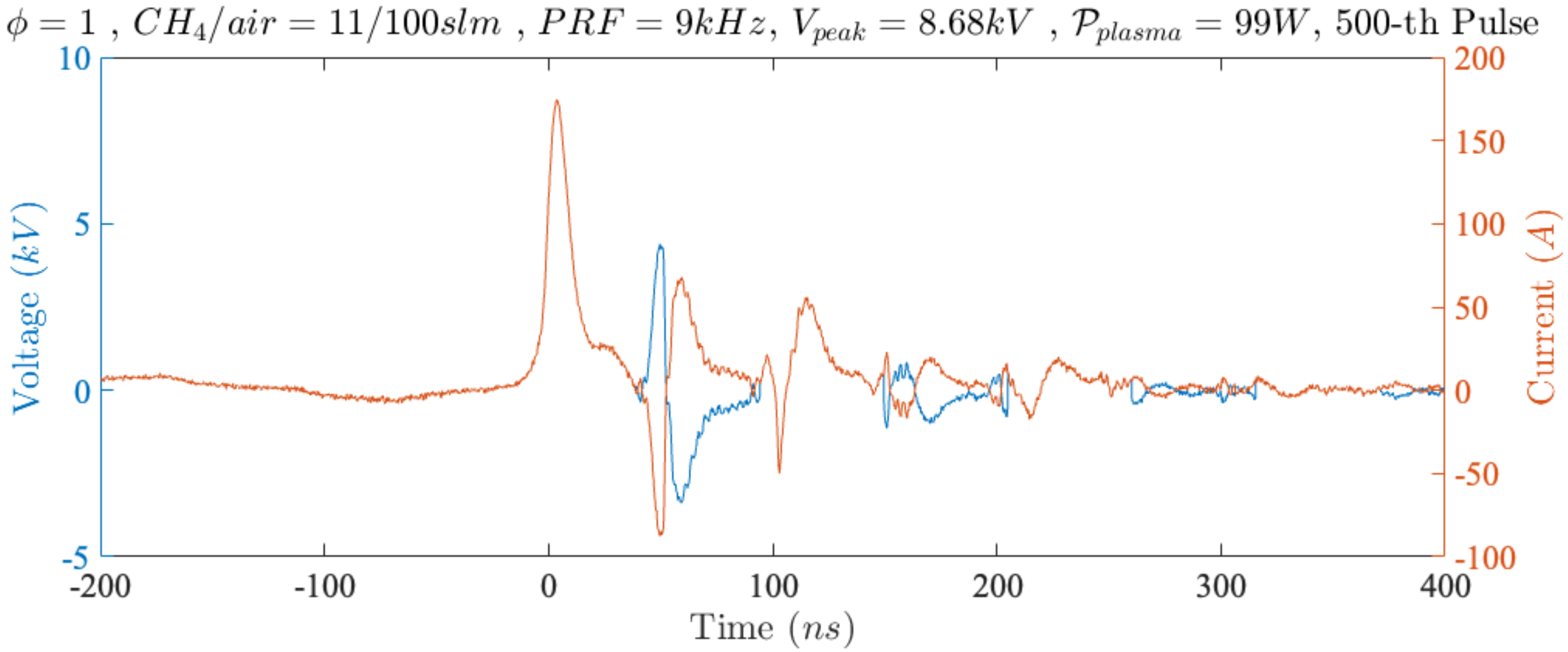
- The flow flows into the quartz tube via a 9.1 mm nozzle
  - Center body with sharp tip functions as the anode
  - Discharge gap is thus 4.55 mm



- Key difference between this combustor and the RGD combustor
  - Discharge gap is 4.55 mm vs. 12.7 mm
  - Pulse energy for actuation is < 10 mJ/pulse vs.

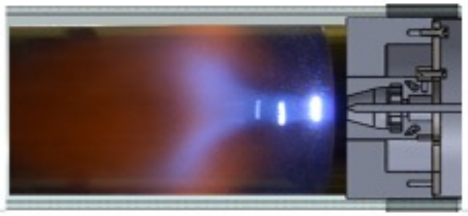
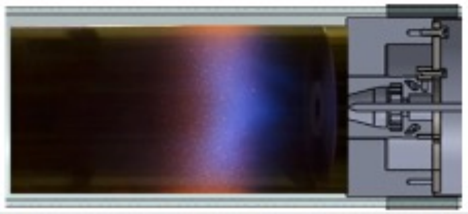
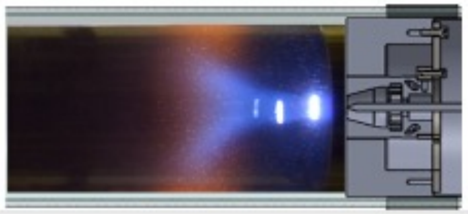
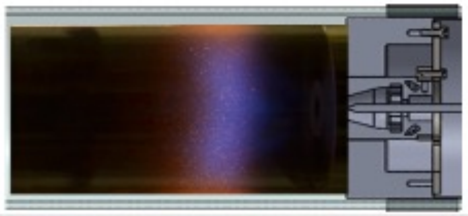
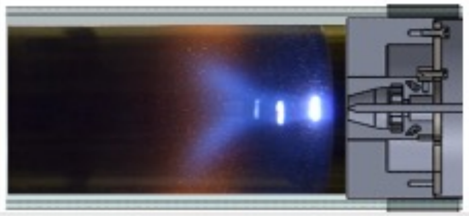
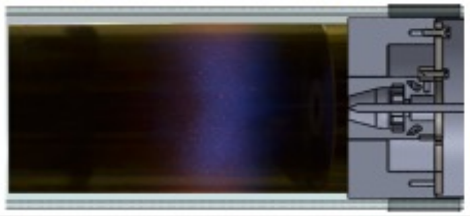
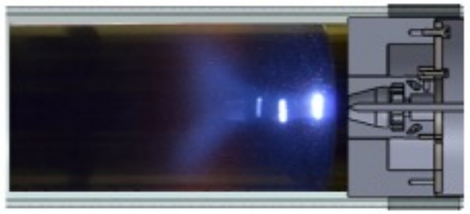
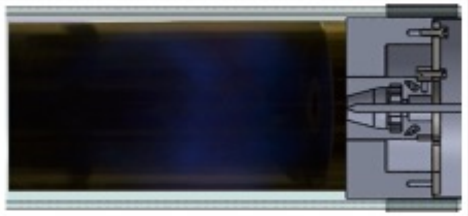
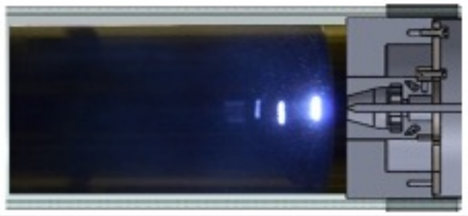
Discharge Generation & Quantification (Specter Injector)

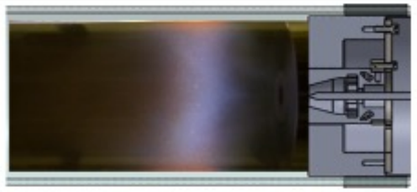




- NRP discharges generated using a TPS transient pulse generator (SSPG-20X-HP1)
- Typical FWHM pulse widths are about 12 ns in duration with a frequency of 9 kHz. Peak voltage, at the measurement location, is 6-9 kV
- Energy deposited in the discharge per pulse is 5-12 mJ
- Electrical waveforms measured using a single current shunt in the middle of a 10m coaxial cable
- Ref: C. Pavan, S. Rao, and C. Guerra-Garcia, “Tutorial: Electrical Measurements in Nanosecond Pulsed Plasma Reactors”, J Phys D: Appl. Phys 2024 (https://doi.org/10.1088/1361-6463/ad73e5)

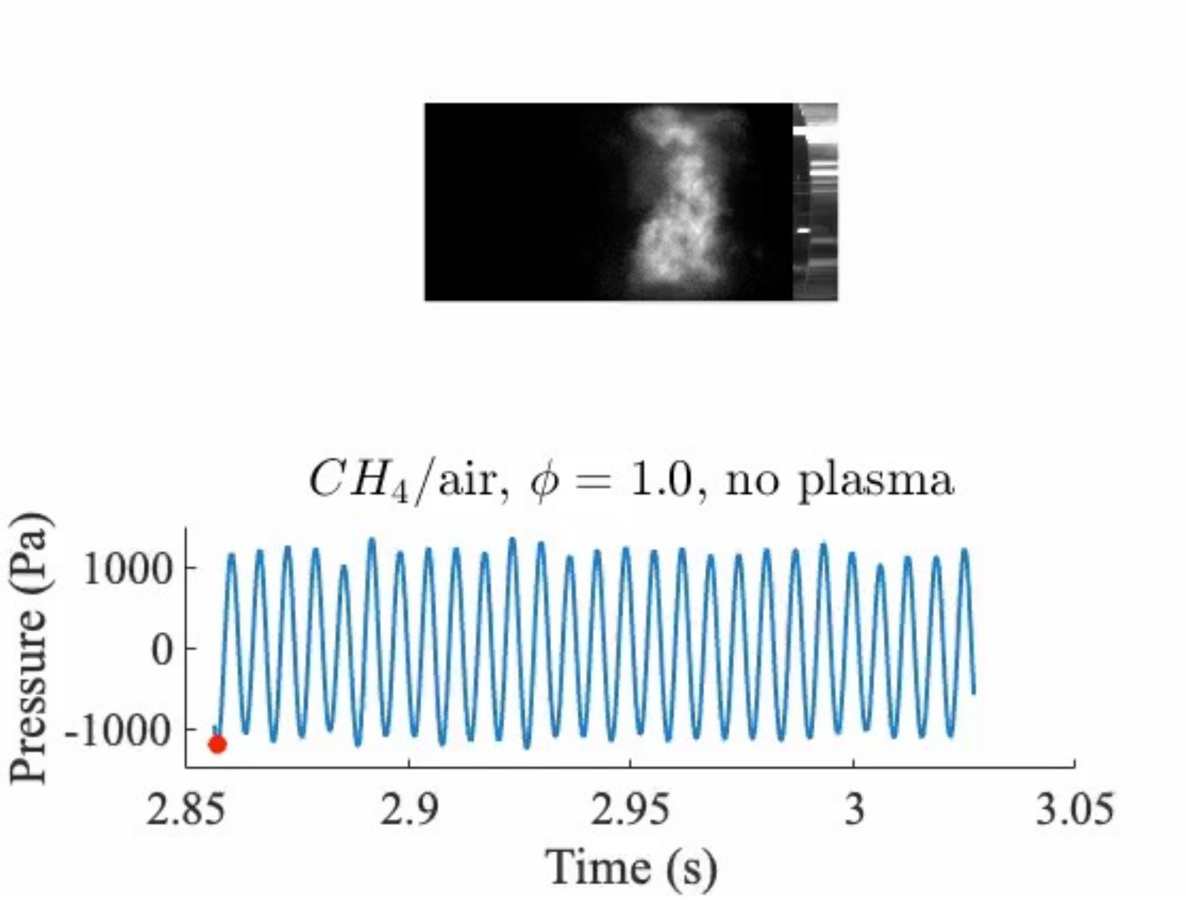
Flame Macrostructures

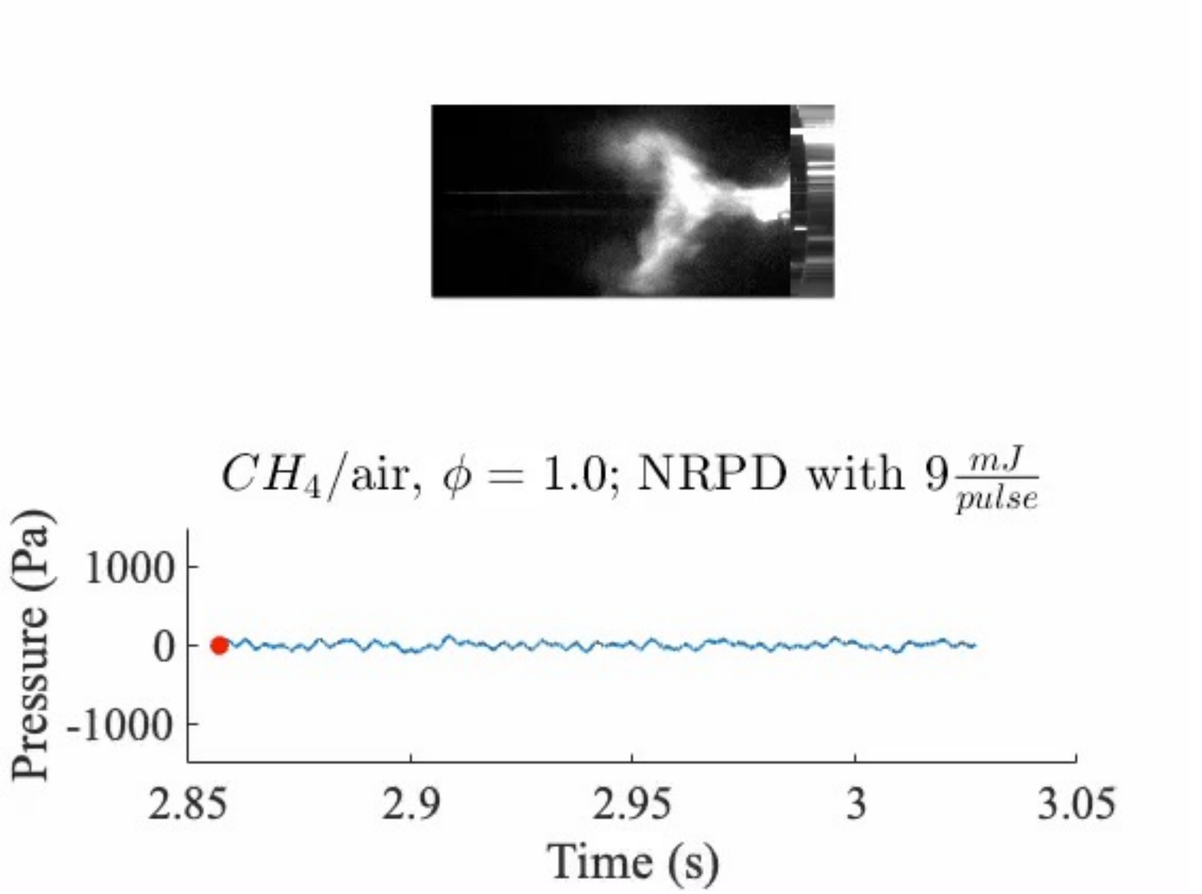
Equivalence Ratio	Flame Without Plasma	Flame With Plasma
1.0		
0.9		
0.8		
0.7		
0.6		

Equivalence Ratio	90% CH_4/10% NH_3	20% CH_4/80% NH_3
1.0		
0.9		

- Without plasma: Identical compact flames at a very broad range of equivalence ratios
  - Unlike many other studies no macrostructure transitions or very long flames
- With plasma: Clear anchored flame resembling the letter Y
  - For large amounts of NH_3, the flame is more distributed downstream, but still relatively compact (no tubular flames observed)

Effect of NRPD on Instabilities





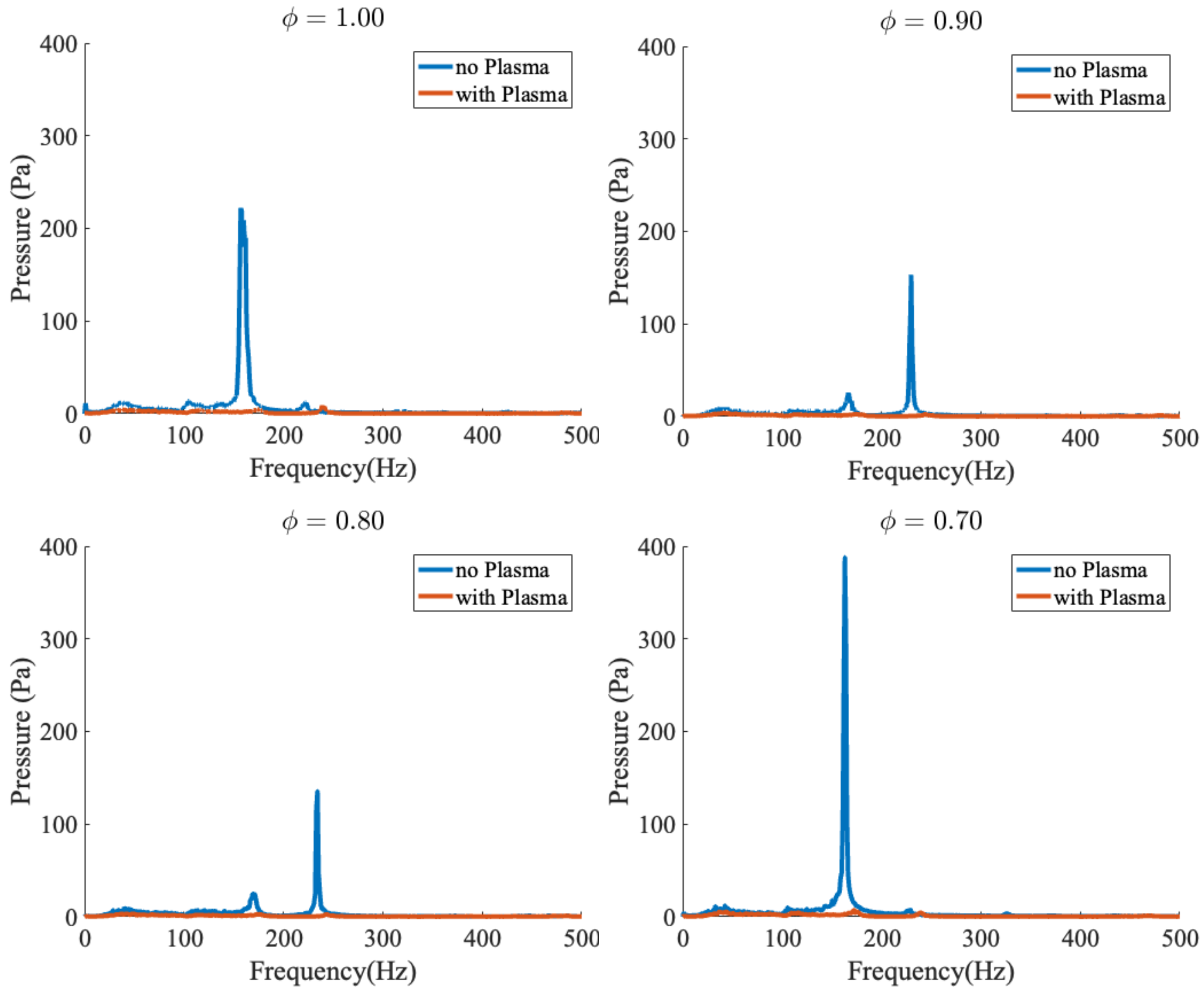
	Without plasma	With Plasma
Amplitude	≈ 1000 Pa, 154 dB	< 50 Pa, 133 dB
Flame Shape	Lifted, compact	Anchored, compact

Effect of NRPD on Instability Suppression

Spectra for various conditions

- We measured instability amplitudes and frequencies at various equivalence ratios
  - The instability frequency depends on equivalence ratio
  - Why the combustor chooses one mode over other discussed in Hong, Shanbhogue, Speth & Ghoniem, 2013, Comb. & Flame

- For **all cases**, with plasma, the instability vanishes with at sufficiently high pulse energies
  - By this we mean the spectra reverts to broadband flow noise
  - Peak noise reduction ≈ 25 dB
  - This is a significant improvement compared to our previous work (J. Prop. Power, 2023) where we saw only 3 dB or so reduction (amplitude is halved due to NRPD's)



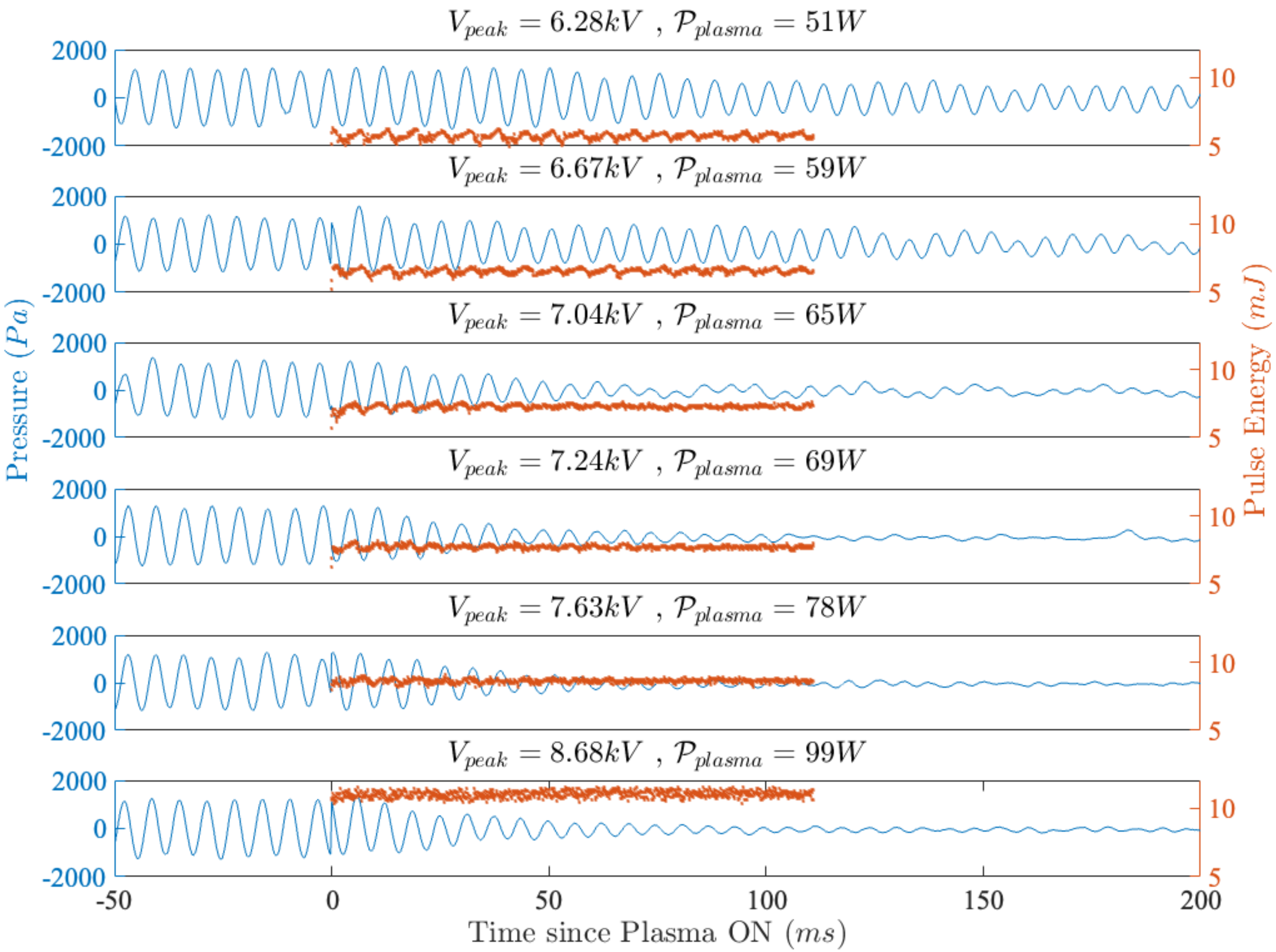
NRPD Characteristics During Instability Suppression

- A question of great interest is how much plasma power is required to suppress the instability
  - This is measured in the figure
  - For all conditions in the figure, the flame was that of a stoichiometric CH_4/air mixture

- The plasma is turned on at t = 0 and stays on
  - Power measurements done only till 110 ms
  - Note that the instability dies out in a few milliseconds
  - At 69 W & above, the instability dies
  - The flame power is nearly 6 kW

- The required plasma power is 1-2% of the flame power

- The energy deposited doesn't remain constant but fluctuates due to the periodic motion of the flame, the "backward problem". See Pavan,…,Guerra-Garcia, Plas. Sour. Sci. & Tech. 2024.



Background - IV

NO_x emissions from NH_3/air flames

- For conventional hydrocarbon fuels in gas-turbines, NO_x is in single digits, even without post-combustion emissions controls
    - This is even when there is substantial N_2 in the gas-mixture (e.g. process gas)
- For NH_3, NO_x can easily reach 1000 ppm (in laboratory flames) without any post-combustion emissions controls

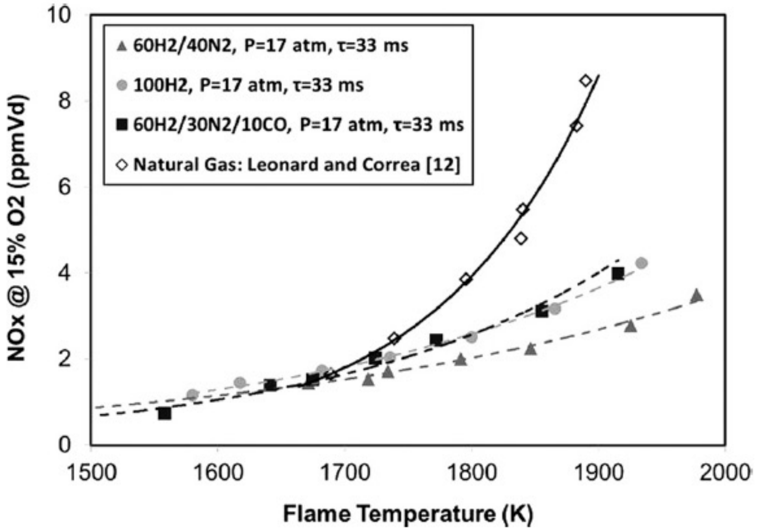


Fig. 7 Perfectly premixed NO_x measurements for high hydrogen fuels taken at $P = 17$ atm and $\tau = 33$ ms

Baseline: NOx emissions from hydrocarbon flames. Reproduced from York,..,Yilmaz, 2013, ASME TurboExpo

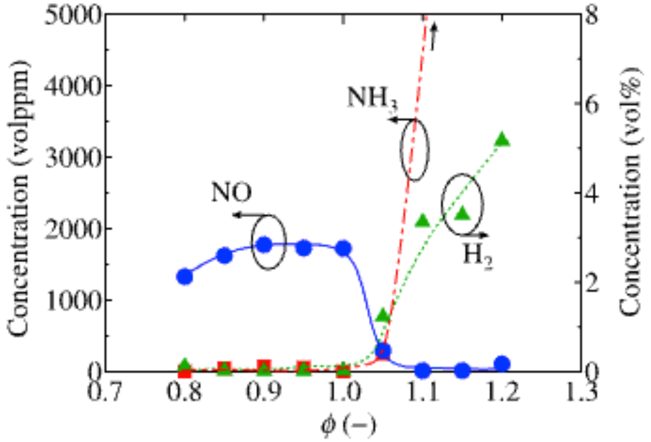


Fig. 7 – Concentrations of NO, NH_3 and H_2 for cylindrical liner with 200 mm liner length in the case of the swirl number of S = 0.736.

NOx emissions from laboratory scale NH_3/air flames. Reproduced from Hayakawa,..,Kobayashi 2017. Int J. H2 energy

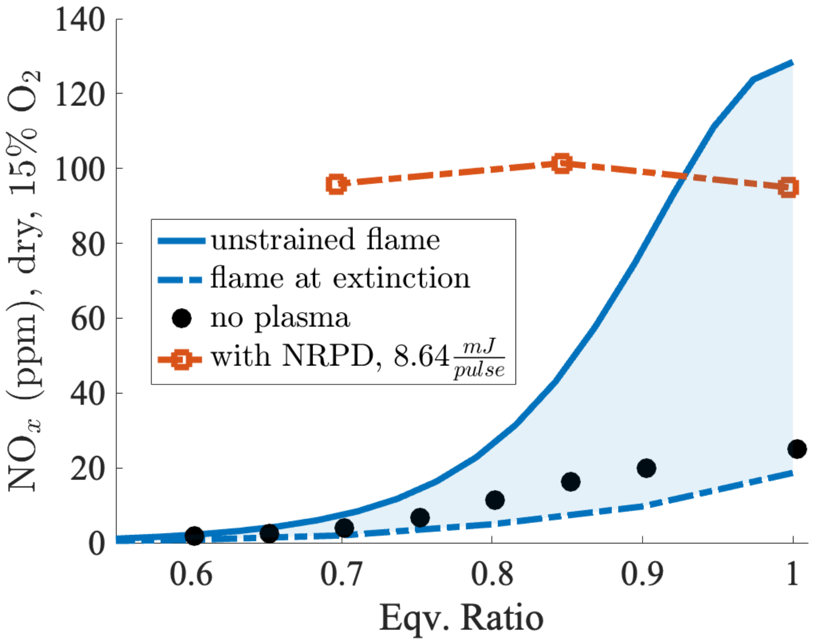
Another key question is what kind of kinetic models and flamelet models can model NO_x from these combustors. Kinetic models that reproduce ignition delays and burning velocities are available in literature, but struggle with NO_x prediction.

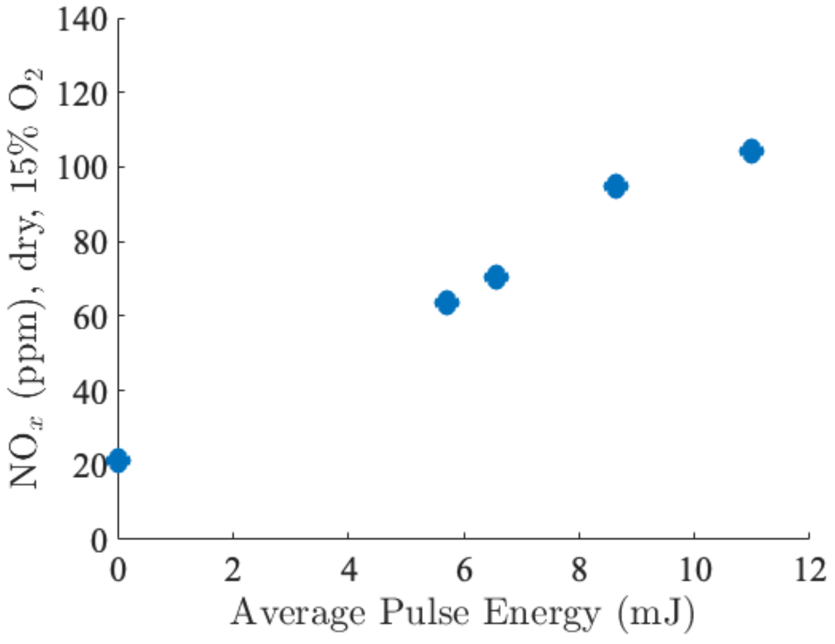
Effect of NRPD on NO_x Emissions

CH_4/air flames

Basic question: What kind of flamelet model is appropriate for NO_x predictions in CH_4/air flames (without NRPD)

- Blue shaded area shows the NO_x emissions for strained flames
    - Lower limit – unstrained flame
    - Upper limit – flame at extinction strain rate
- Calculations done using GRI 3.0
    - There are more comprehensive and validated mechanisms such as NUIGMech1.3, but these are computationally expensive
- Measurements indicate that the emissions in this combustor are consistent with a strained flame





- With NPRD the NO_x emissions jump to a constant value, apparently independent of the equivalence ratio

- The emissions are dependent on the pulse energy deposited in the flow
- The highest pulse energies guarantee complete suppression but produce more NO_x
- Optimal pulse energy a balance between allowable instability amplitude and excess NO_x

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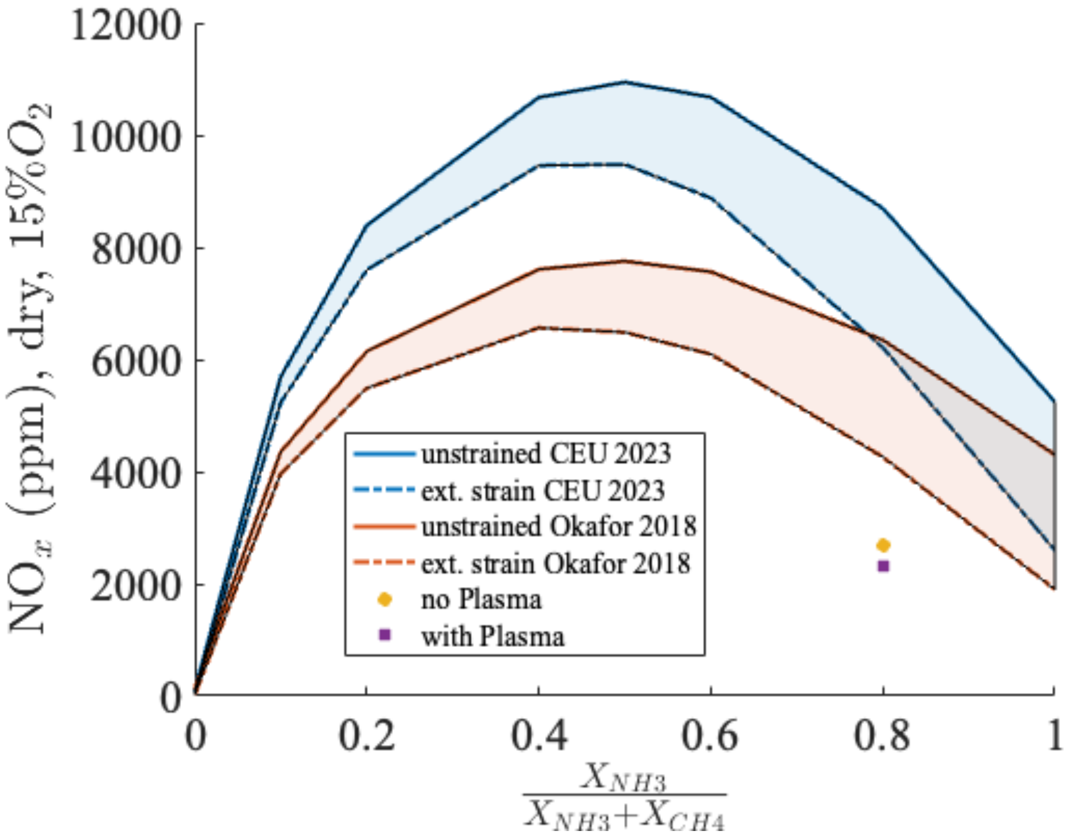
Effect of NRPD on NO_x Emissions

CH_4/NH_3/air flames

- We were able to test the effect of NPRD on NO_x for just one condition – 80% NH_3 and 20% CH_4 + air
  - For higher ammonia fractions, we couldn't stabilize the flame at these velocities
  - For lower ammonia fractions, the NO_x values exceed 5000 ppm, which is the detection limit of of our analyzer.
- But NRPD **reduces NO_x** by nearly 200 ppm at these conditions
- Just like for CH_4/air flames, we attempted to model the emissions using different kinetic model, but none of these match our experimental observations



Conclusions

Dynamic Stability:

- What does ammonia addition do to a combustor nominally fired with hydrocarbons:
    - It makes it more stable, -- narrow window of pulsations
    - This is the opposite of what addition of hydrogen does to the combustor, i.e. makes it more unstable – wider window of conditions where pulsations occur
    - Data scales with $Da = \tau_{flow} K_{ext}$ or $\tau_{flow}\frac{S_L^2}{\alpha}$ suggesting a direct link to chemistry/transport at the flamelet level

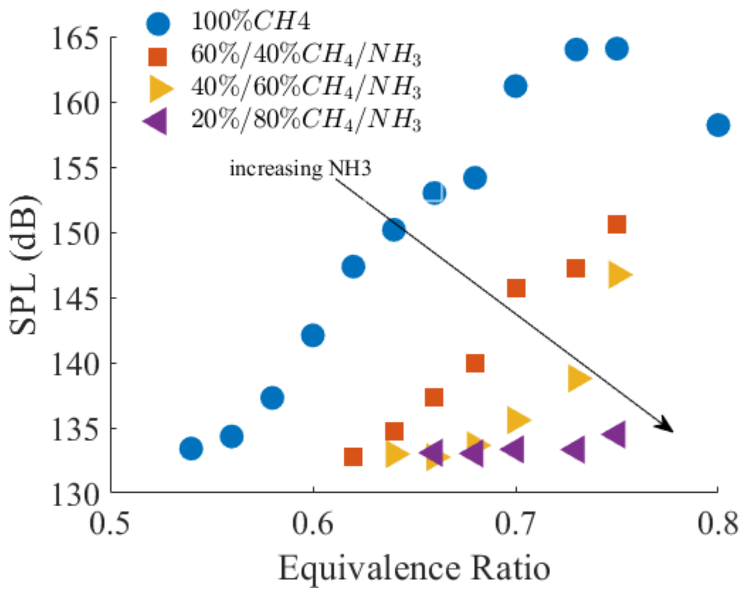
Effect of NRPD (plasmas) on dynamic stability:

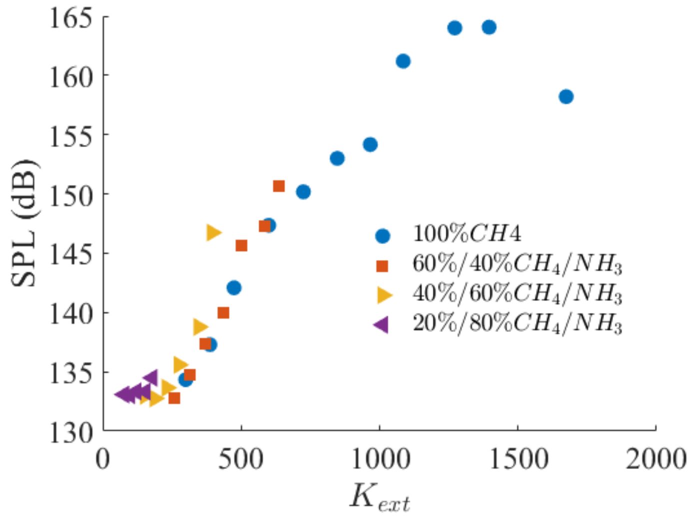
- Plasmas can suppress instabilities by up to 25 dB across a wide range of conditions
- Electrode design/arrangement is important here – we found success with a pin-to-ring discharge

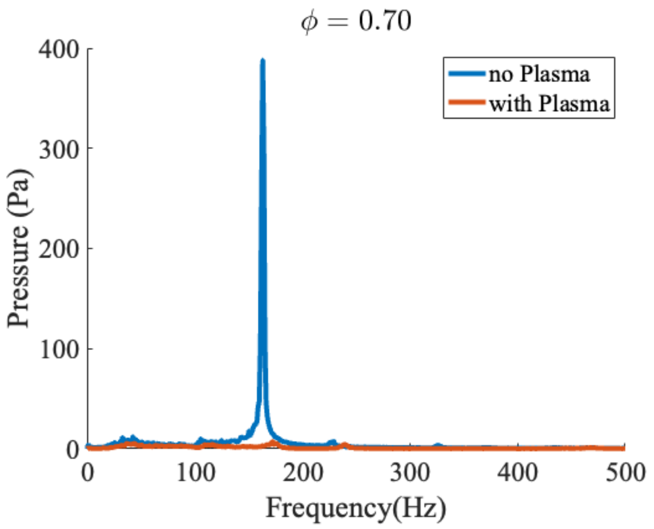
Effect of of NRPD on NO_x

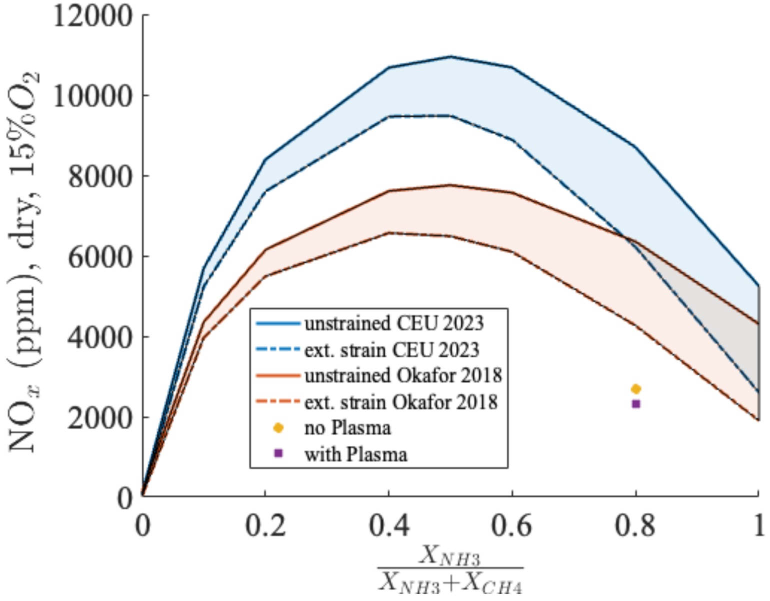
- For CH_4/air flames, plasmas increase NO_x – at least at the levels required to suppress combustion oscillations

- For CH_4/NH_3/air flames, plasmas reduce NO_x









Presentation at NETL Ammonia Combustion Technology
Group Meeting, 12th Nov 2024

Dynamic Stability and Emissions in Premixed CH_4/NH_3 Swirling Flames with Nanosecond Pulsed Discharges

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Questions?

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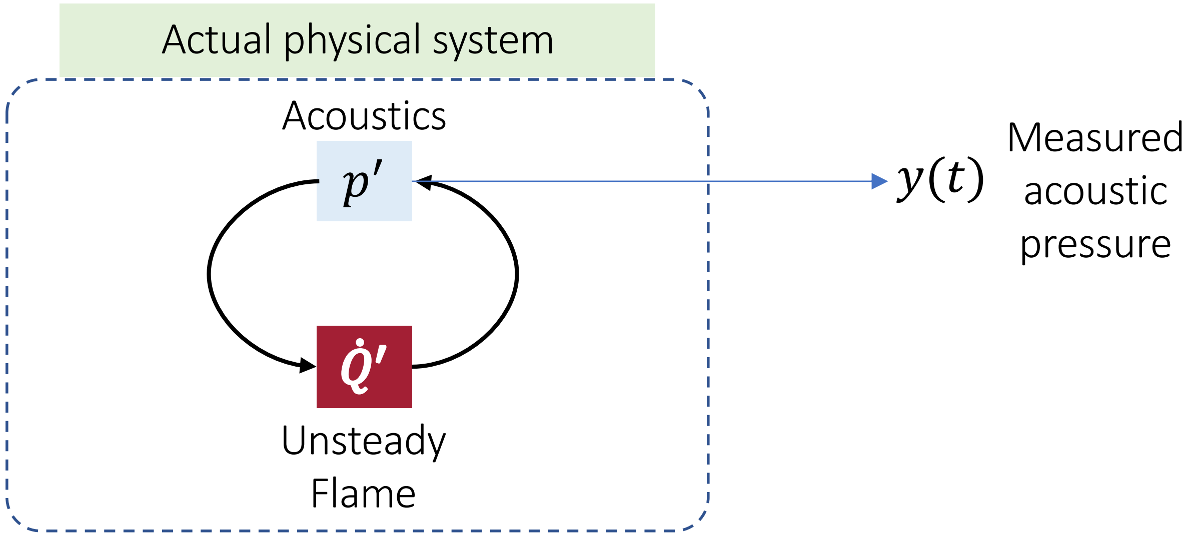
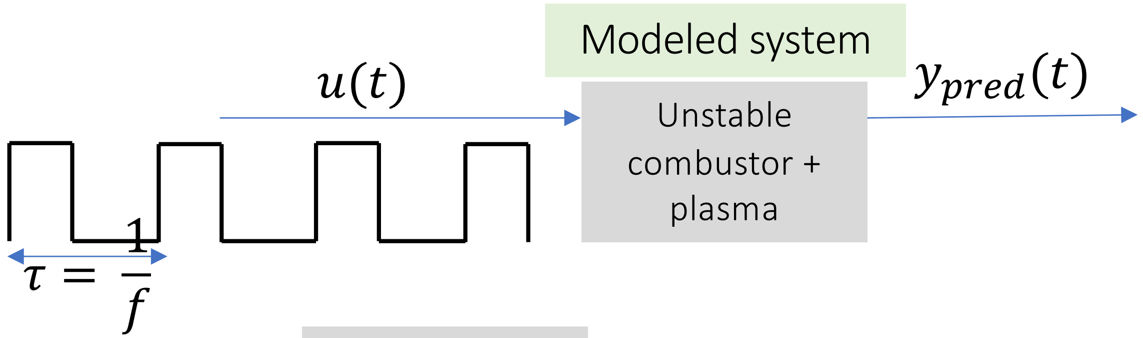
TECHNOLOGY

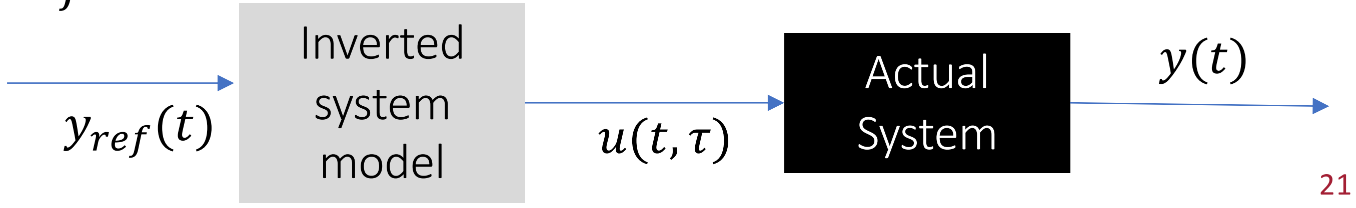
Detailed in 2023, Shanbhogue,…,Guerra-Garcia, Ghoniem, JPP

Modeling for active control

- Feedback models and some feedforward models need a reduced order model of the system for choosing the right controller
    - We've combined the thermoacoustic system into a single model
- The plasma is actually triggered with a frequency ***f*** – this is the input variable
    - 1 < ***f*** (kHz) < 9
    - We set the voltage to the highest value, say 20 kV, which sets the energy per pulse

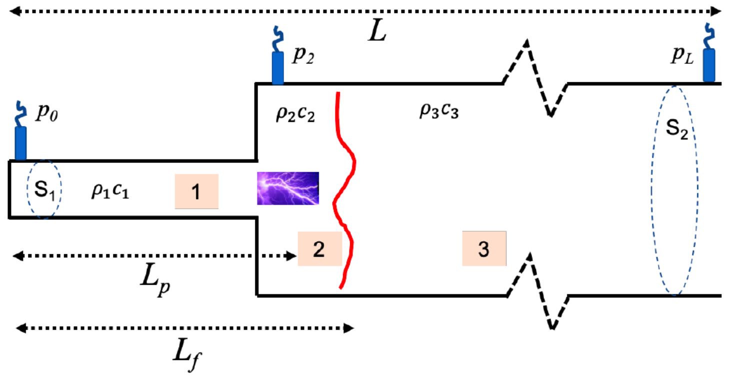






System model
described in detail in the paper

Swirl Combustor Simplifed



Canonical state-space form

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Start with conservation equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0$$
$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial \rho u}{\partial x} = -\frac{\partial p}{\partial x}$$
$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \frac{\partial T}{\partial x} = \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + \dot{E}$$

Split terms into mean + fluctuations

$$p(x,t) = \bar{p} + p'(x,t)$$
$$u(x,t) = \bar{u} + u'(x,t)$$
$$\rho(x,t) = \bar{\rho} + \rho'(x,t)$$
$$\dot{E}(x,t) = \bar{\dot{E}} + \dot{E}'(x,t)$$

Point source assumption

$$\dot{E}'(x,t) = \dot{E}'_{flux}(t)\,\delta(x - x_p)$$

Wave equation

$$\frac{\partial^2 p'}{\partial t^2} - c^2 \frac{\partial^2 p'}{\partial x^2} = (\gamma - 1)\frac{\partial \dot{E}'}{\partial t}$$
$$p'(x,t) = \sum_{j=1}^{N} \psi_j(x)\eta_j(t)$$

Galerkin expansion

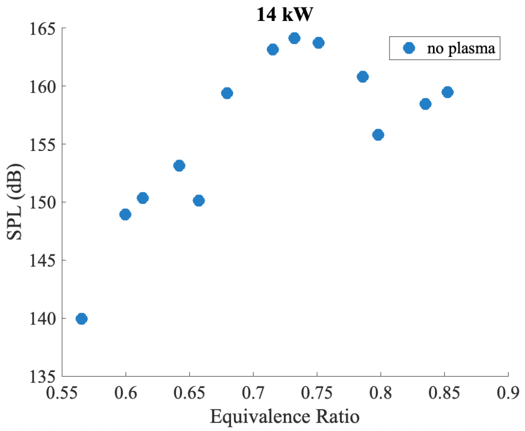
$$\ddot{\eta}_j(t) + \omega_j^2 \eta_j(t) = \frac{(\gamma - 1)}{E} \psi_j^*(x) \frac{\partial \dot{E}'_{flux}}{\partial t}$$
$$\frac{\partial \dot{E}'_{flux}}{\partial t} = K(f_{max} - f)$$

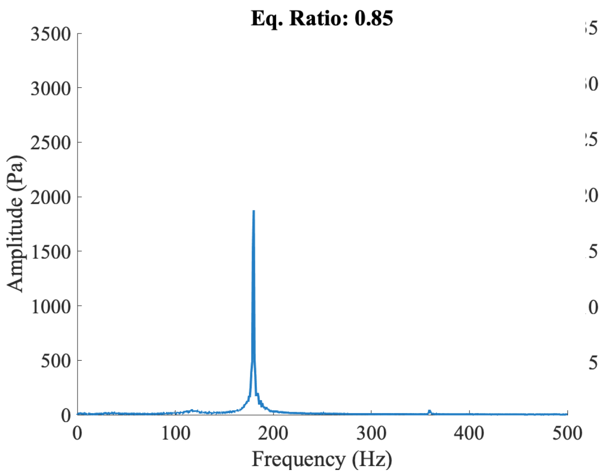
Model: Excitation term linearly decreases with plasma PRF

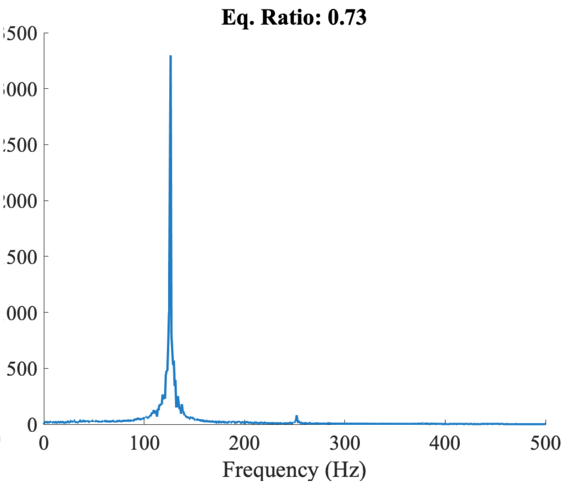
$$\begin{Bmatrix} \dot{\eta}_j \\ \ddot{\eta}_j \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_j & 0 \end{bmatrix} \begin{Bmatrix} \eta_j \\ \dot{\eta}_j \end{Bmatrix} + \begin{bmatrix} 0 \\ K.\frac{(\gamma - 1)}{E} \psi_j^*(x) \end{bmatrix} (f_{max} - f)$$
$$y = \begin{bmatrix} \psi_j(x_{transducer}) & 0 \end{bmatrix} \begin{Bmatrix} \eta_j \\ \dot{\eta}_j \end{Bmatrix}$$

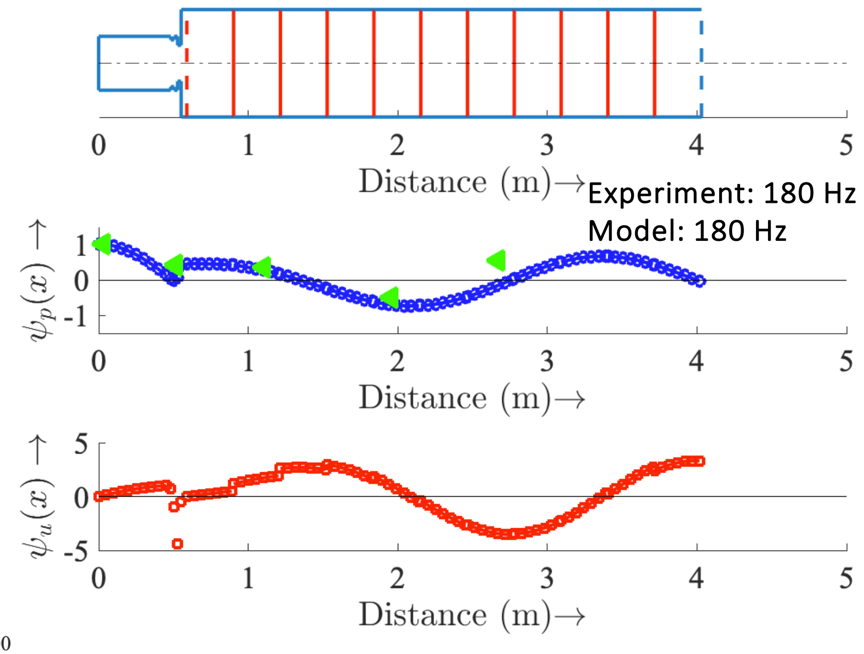
Model Validation

Mode shapes: $\psi_j(x)$ & frequencies: ω_j

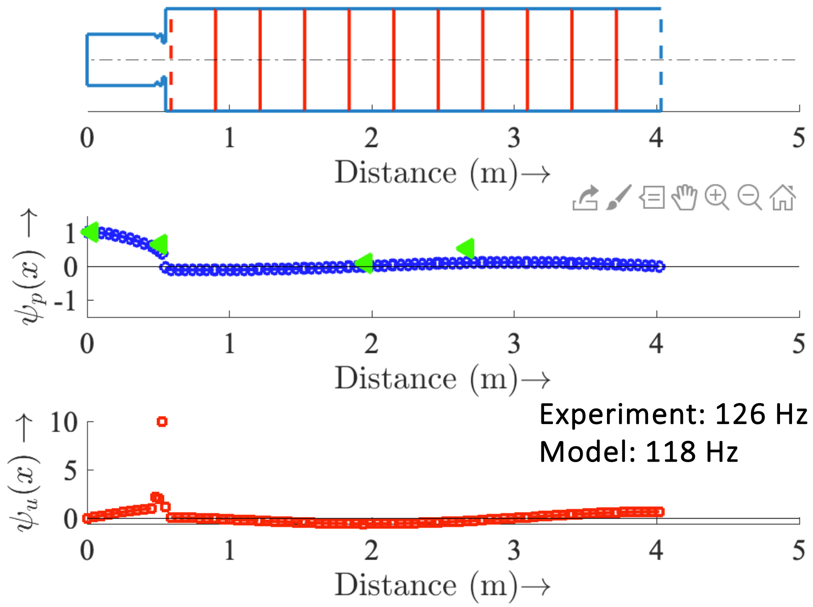








Experiment: 180 Hz
Model: 180 Hz



Experiment: 126 Hz
Model: 118 Hz

- The model requires temperature measurements and pressure measurements at different points in the combustor
- We tested this at two frequencies 130 and 180 Hz and in both cases, the model reasonably matched the data

Open-loop control

- In this experiment, the operator sat down and adjusted the knob between 1000Pa and 3000 Pa

- The model computes the PRF and sends it to the plasma system

- Not a perfect match
  - This will happen only when there is feedback