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Plasma-assisted combustor dynamics control at realistic gas turbine conditions

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Summary

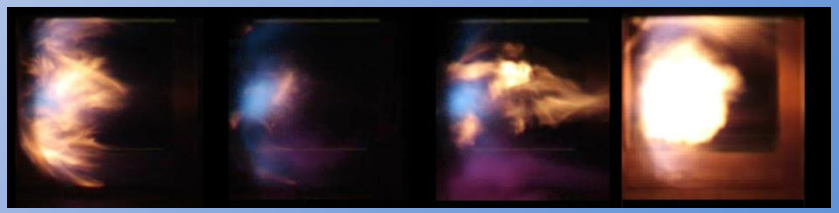
- ✓ R1: A dump combustor which generates self-excited dynamics of ~ O (10^3) Pa pressure fluctuation at ~ 200 Hz at realistic gas turbine conditions was developed
- ✓ R2: Significant reduction of combustor dynamics (~6 – 12 dB) was observed over a wide range of velocity (70 to 110 m/s) when using NSPD (NanoSecond Pulsed Discharge)
- ✓ R3: The power required for the reduction increased with increasing velocity. The behavior of noise reduction were different depending on pressure and type of fuel
- ✓ R4: The lean blowout (LBO) limit was significantly extended with the NSPD, however, substantial incomplete combustion occurred in the extended regime
- ✓ R5: Incremental NO_X production in the presence of NSPD is low (~< 1EINOX), but it is a strong function of velocity/pressure/temperature

Potential Impacts

*"Potentially enabling **ultra-wide operability**, low emission combustor in a compact profile without damaging pressure oscillations"*

- Reduction of staging requirements which leads to **a less complex, less costly and lighter weight combustor**
- **Improved efficiency** over a larger turndown ratio
- Transition from current Rich-Quench-Lean (RQL) to **Lean Direct Injection (LDI) combustors** with minimal combustor dynamics and minimal NO_X

Concept of NASA radially staged LDI combustor



Kilinc et al. (U. of Cambridge)

- Possibly **transferrable to other aero-engine combustor problems**, such as lean-limit stability enhancement and augmentor applications

Overview of Phase I Results -Noise Reduction

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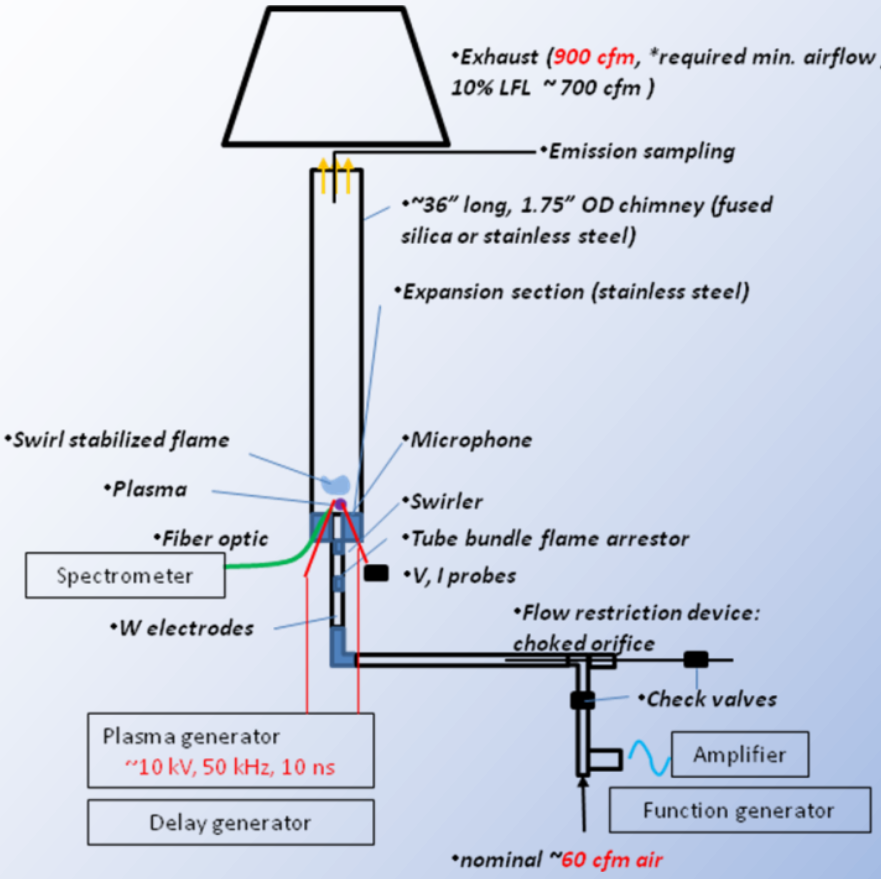
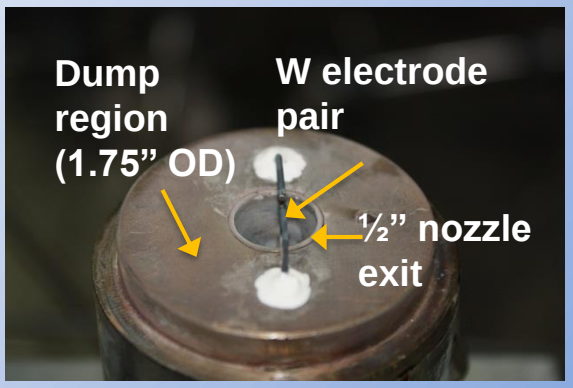
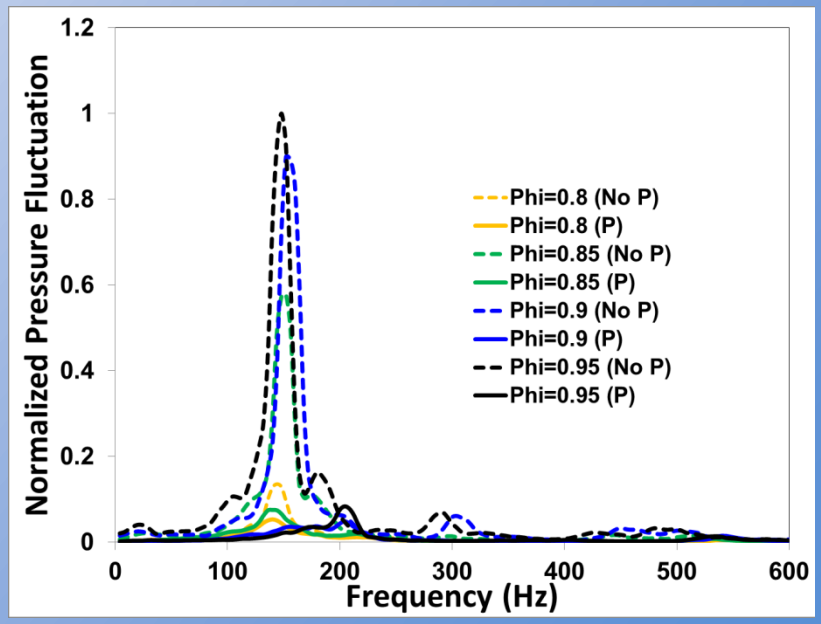
- More than 10X noise reduction (>20 dB) is observed







Representative condition: 6 kW combustion power, ~10-30 W plasma power, 25 m/s nozzle exit bulk velocity, ambient P/T

Overview of Phase I Results -Noise Reduction Mechanism

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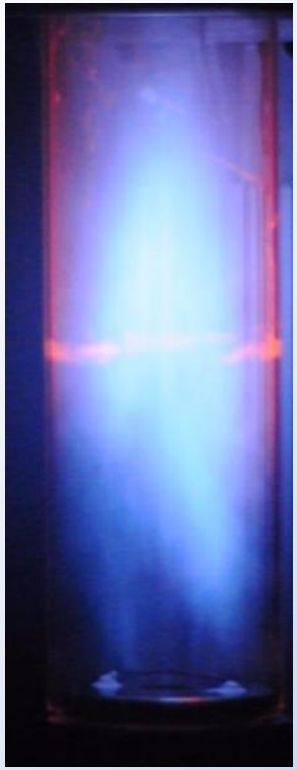
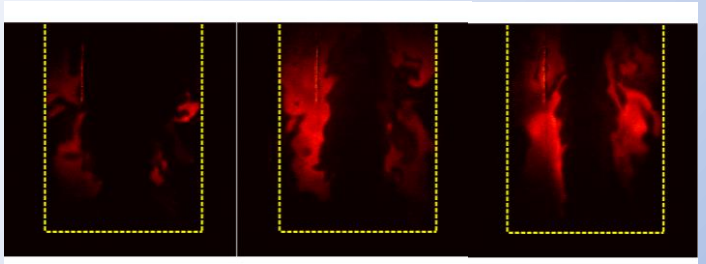
<Spatial investigation>

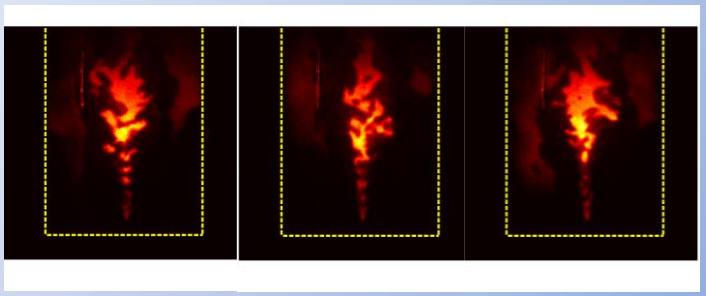
24Hz video



With no plasma



With plasma



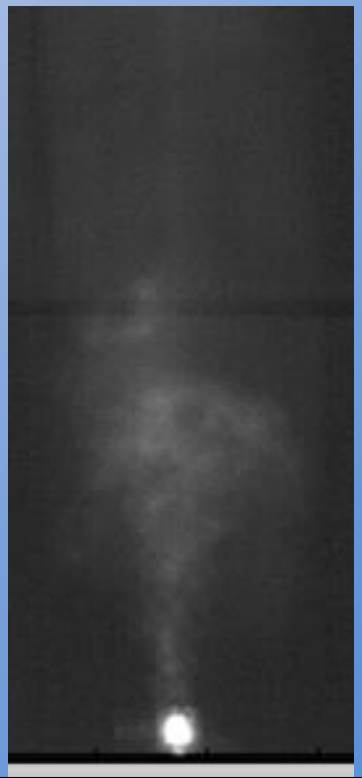
- **The NSPD relocates and fixes the flame stabilization point, decoupling the process from disruptive unsteady fluid mechanics**

<Temporal investigation>

10 kHz video

No NSPD

With NSPD



- **The NSPD facilitates continuous burning without severe global extinction**

Overview of Phase I Results -Noise Reduction Mechanism

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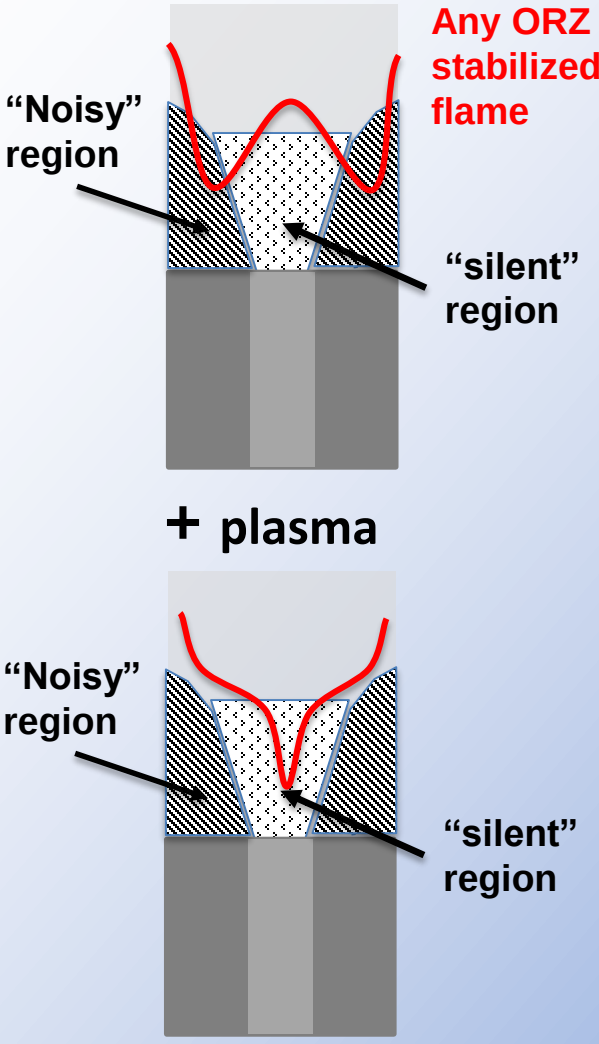
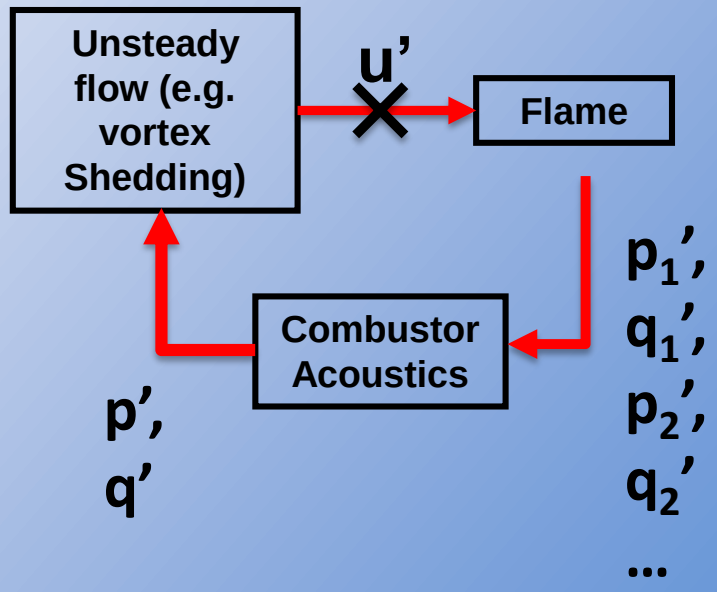
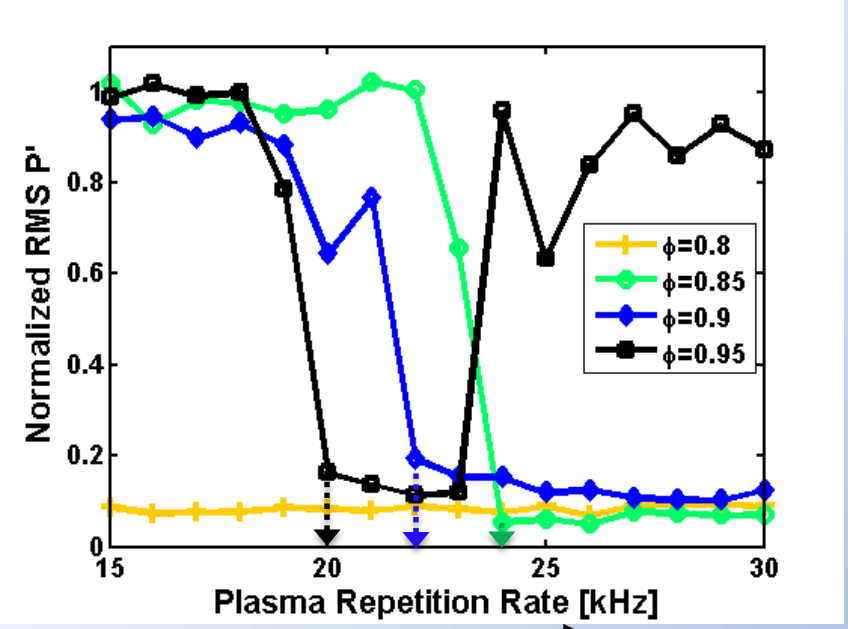


Any ORZ stabilized flame

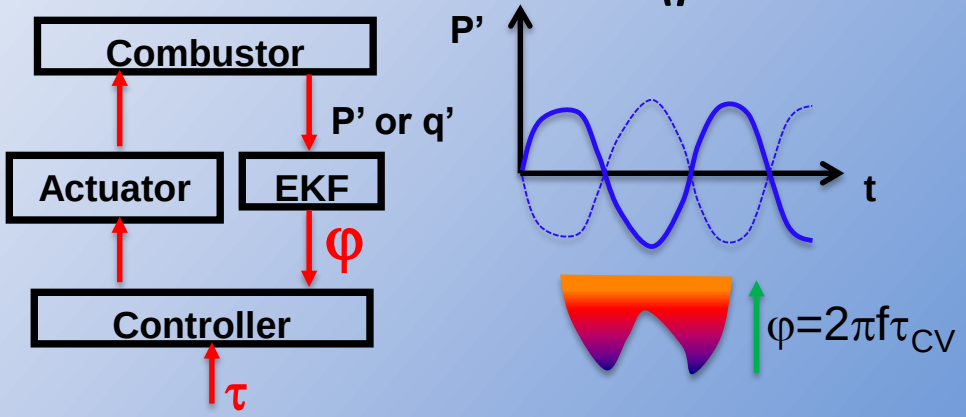
Locating flame base in steady aero zone (Center Zone) is a key to increasing its robustness



Overview of Phase I Results -Control

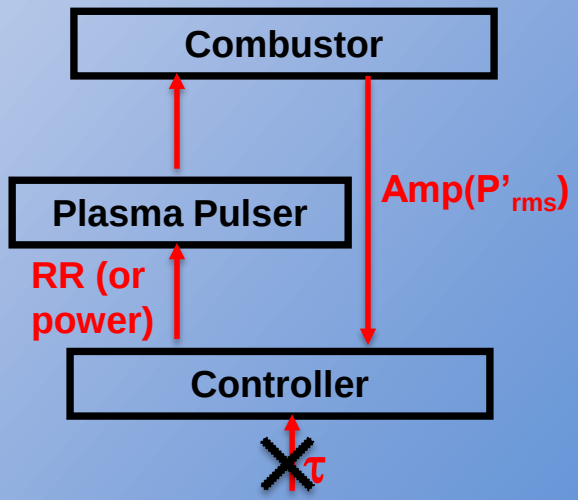


Conventional control scheme (phase control)



Limitations: Actuator and convective delays and flame incoherence

Proposed control scheme (power control)



Control objective: Maintaining centrally stabilized flame with minimal power input

Overview of Phase I Results -Emission and Swirl

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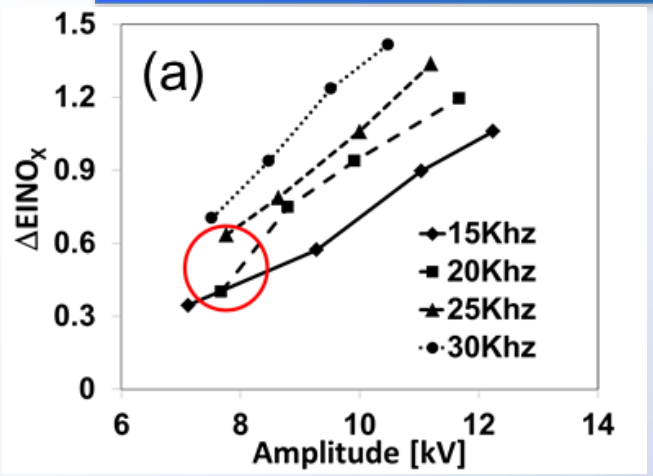
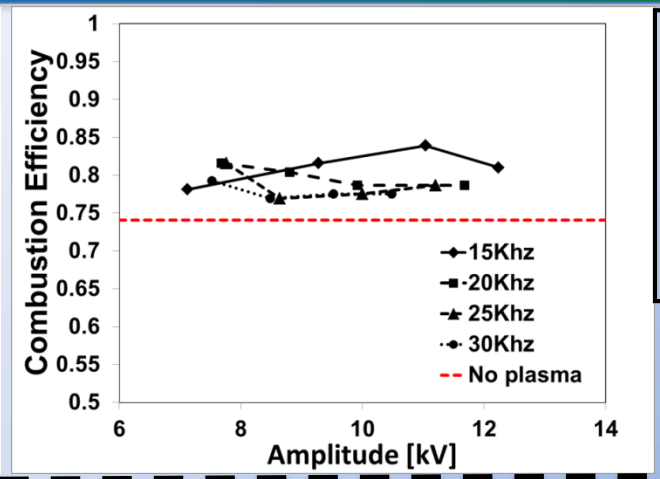
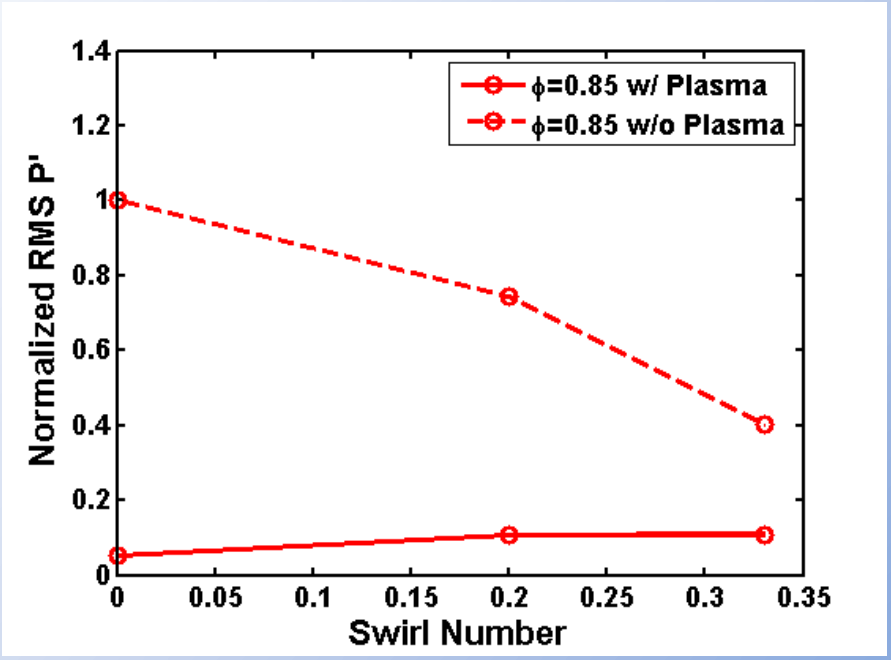




- The added $EINO_X$ in the presence of the NSPD is very low (typically ~ 0.5EI)
- In general, combustion efficiency is improved with the NSPD



- The incremental benefit of NSPD decreases with increasing swirl, because uncontrolled flame becomes quieter

Overview of Phase I Results -Operability Expansion

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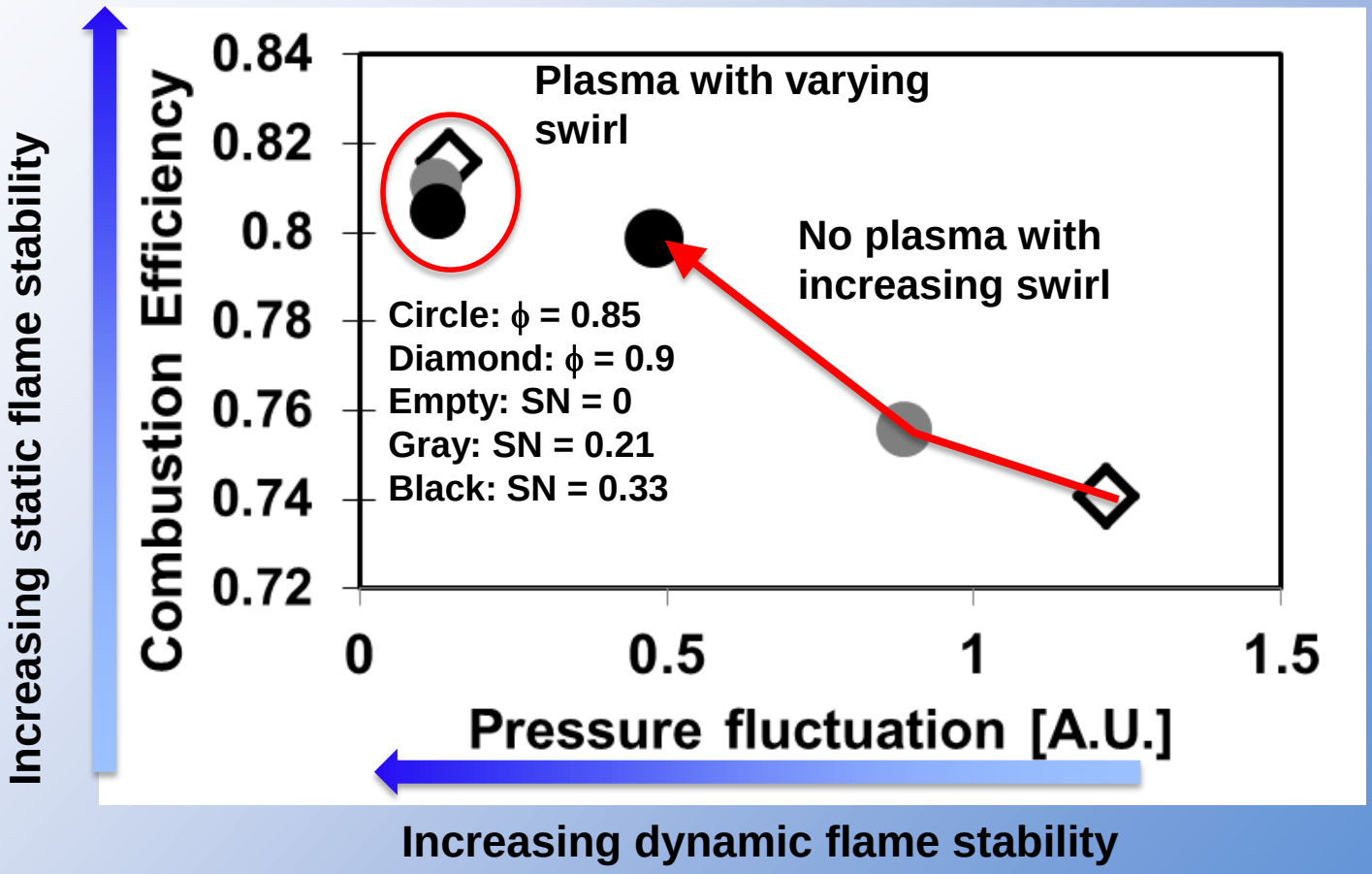
- **The NSPD significantly improve the operability limit**



Transition to Phase II

- Major limitation of Phase I

  Low velocity (~25 m/s)/pressure (1 atm)/temperature (300K)

Can one get similar level of improvements at realistic gas turbine conditions?

Result 1: Dump Combustor at high V/P/T

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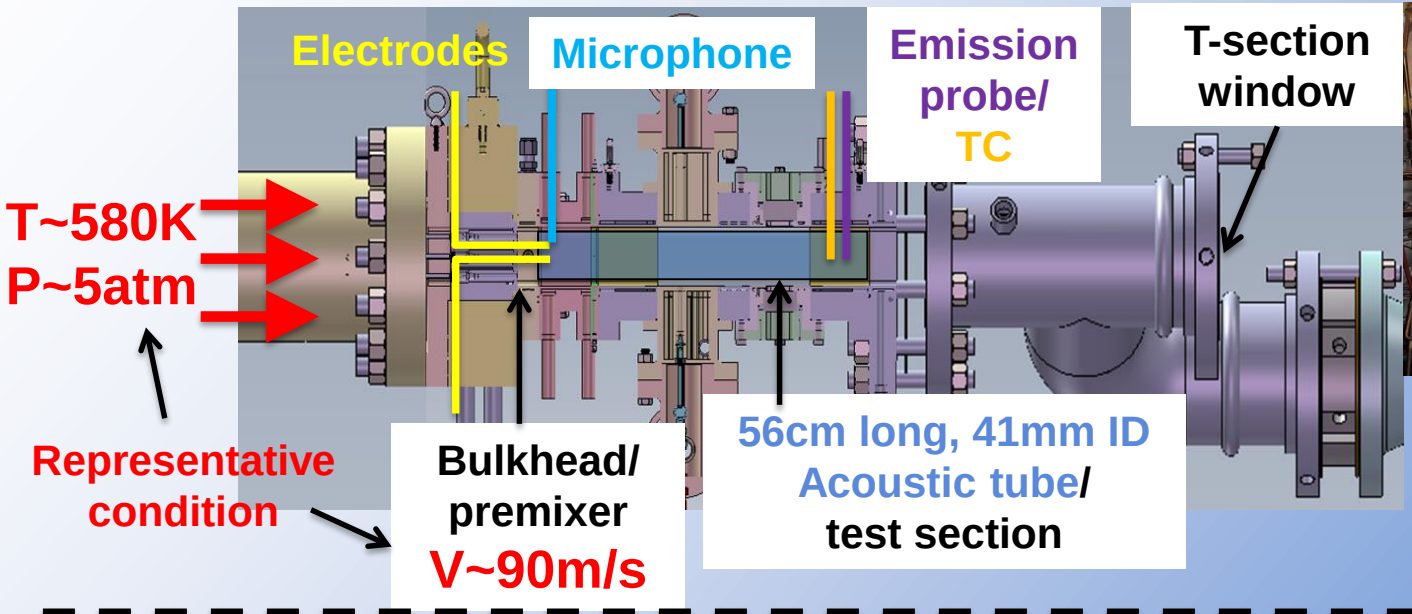
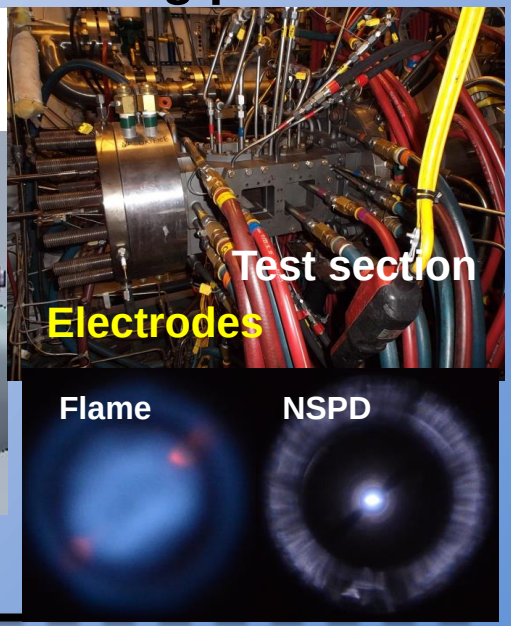
<Rig schematic>



<Rig photo>



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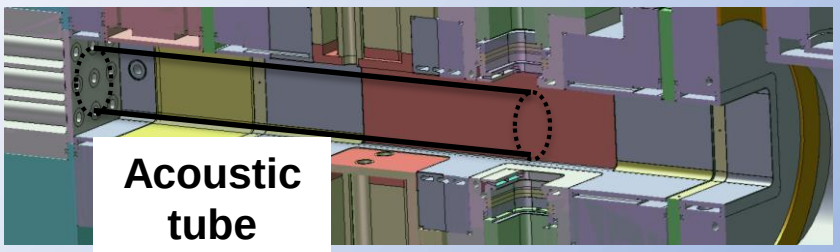
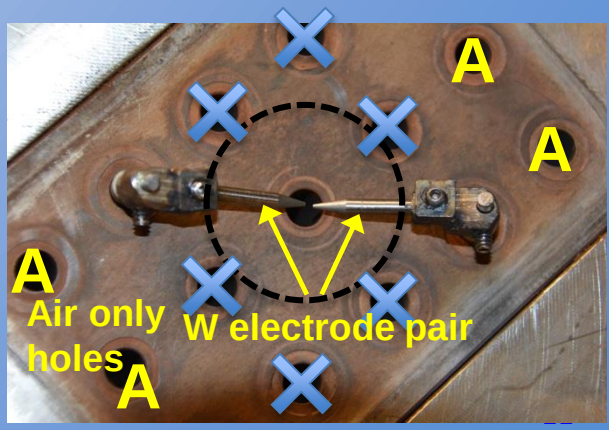


Representative condition: 20 kW combustion power, ~1% plasma power

<Bulkhead aft-looking-foward>



Result 1: Dump Combustor at high V/P/T

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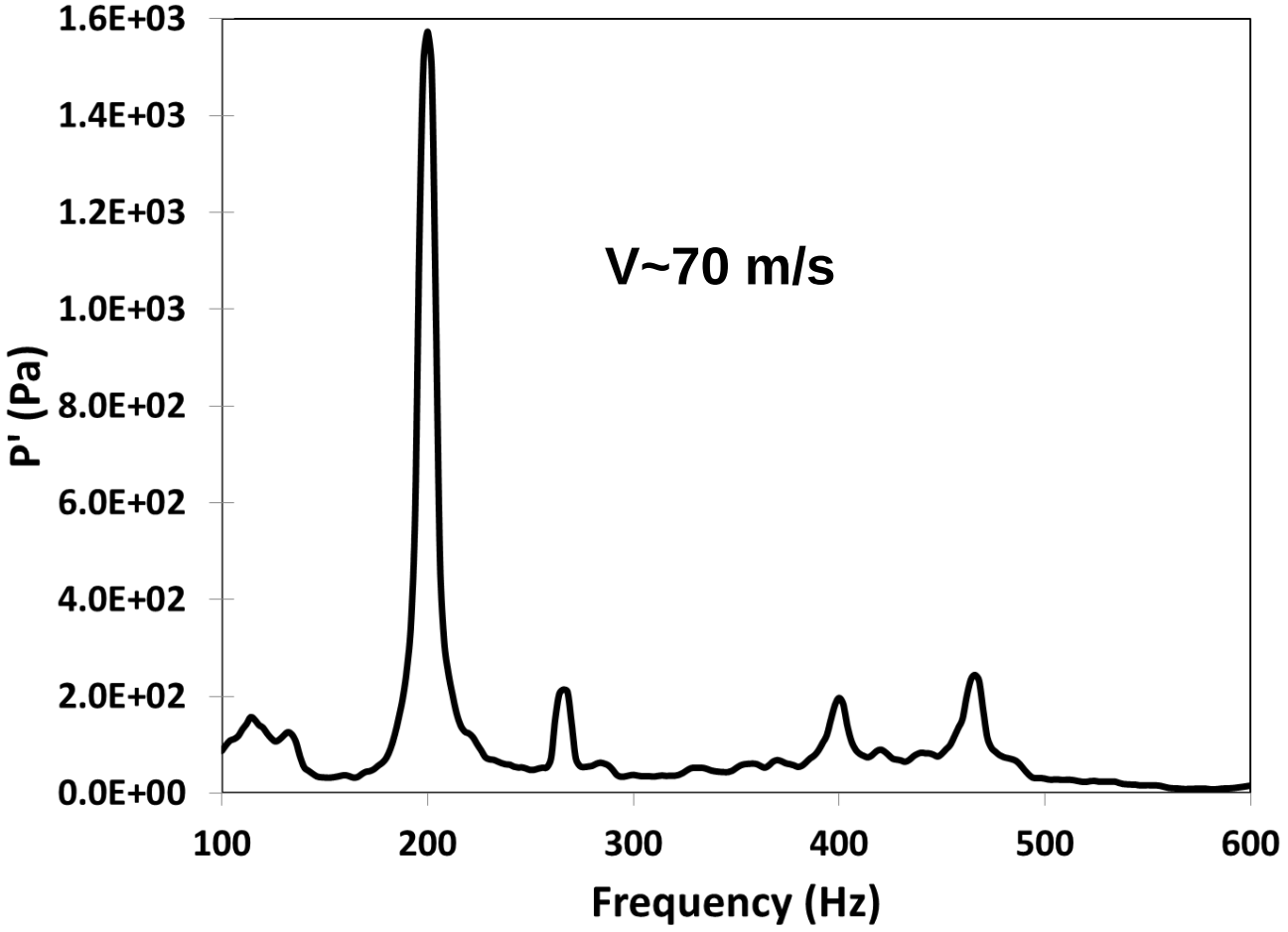
- **A dump combustor that produces ~O(10^3) Pa pressure oscillation at realistic gas turbine conditions was developed**



ϕ = 0.58 (propane)
T~580K
P~5atm

Result 2: Noise Reduction at high V/P/T

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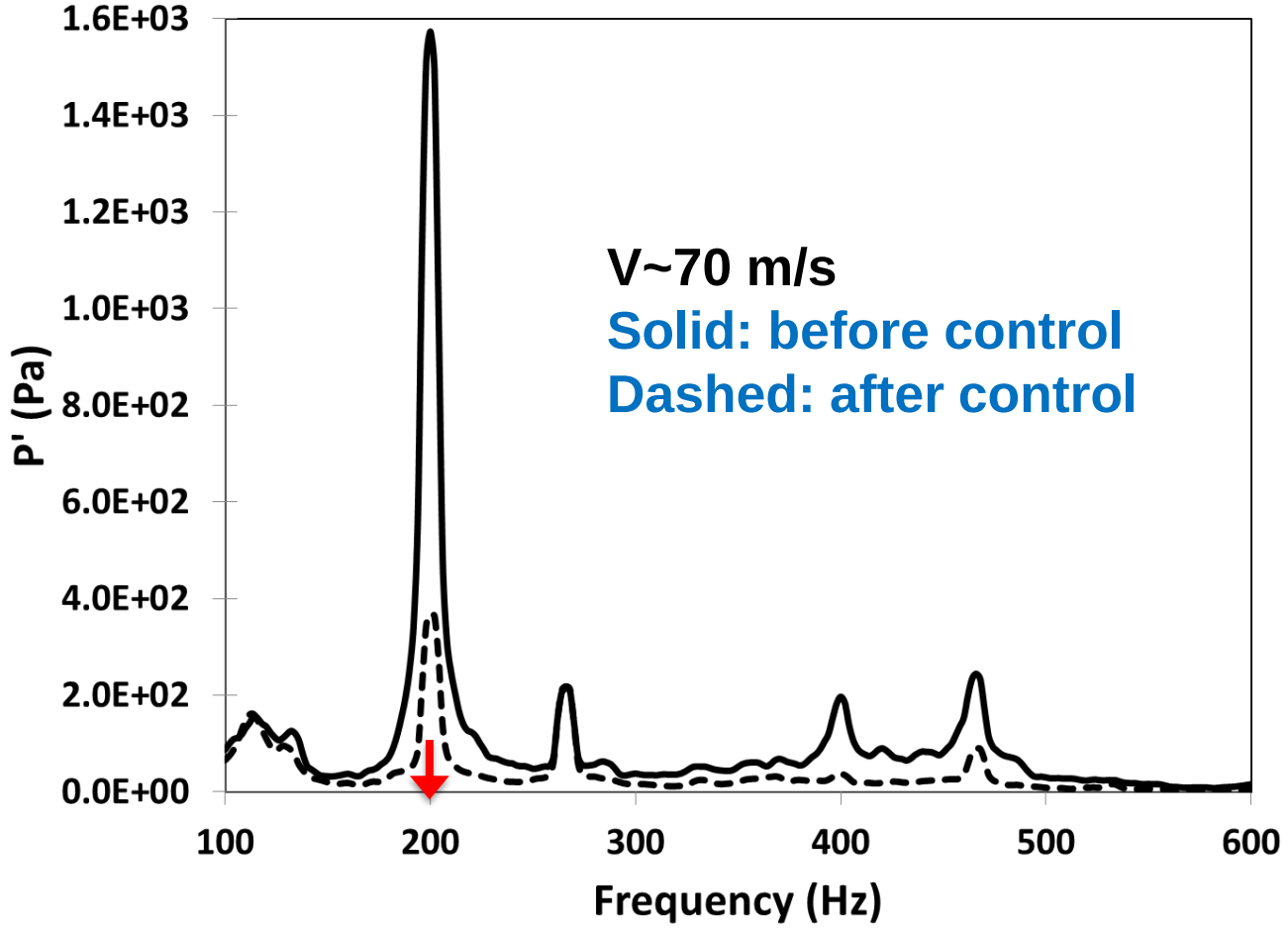
- **Significant reduction of combustor dynamics was observed**



Relative Noise: peak P' ratio near 200 Hz in the absence/presence of plasma

ϕ = 0.58 (propane)
T~580K
P~5atm
Plasma Voltage ~15 kV
Plasma RR=80kHz

Result 2: Noise Reduction at high V/P/T

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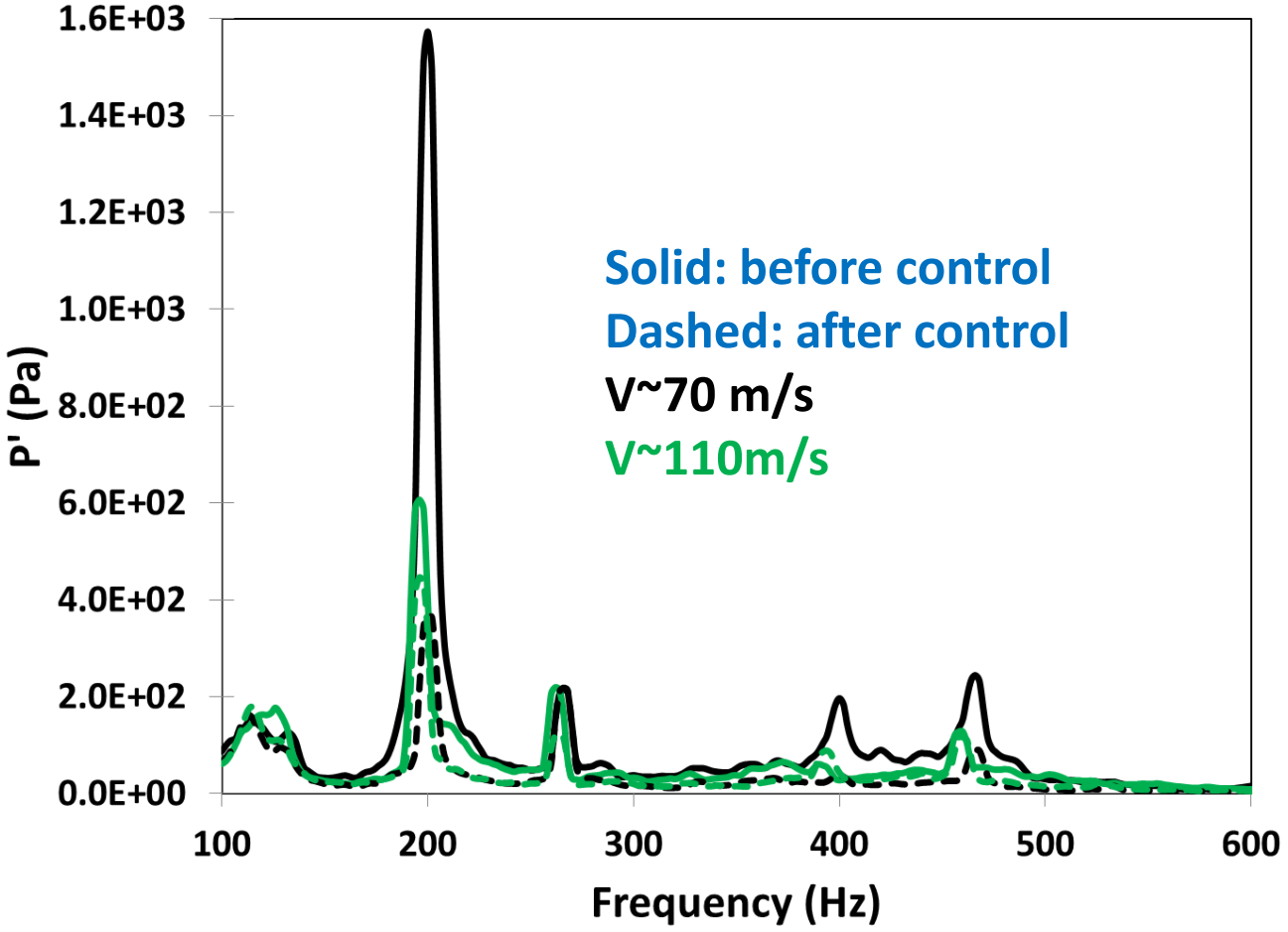
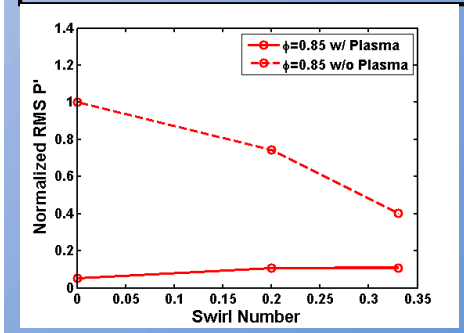
- **Significant reduction of combustor dynamics was observed**



- **The degree of reduction is a function of velocity (and amplitude level before control?)**



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T~580K
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Result 3: Relative Noise vs. Velocity

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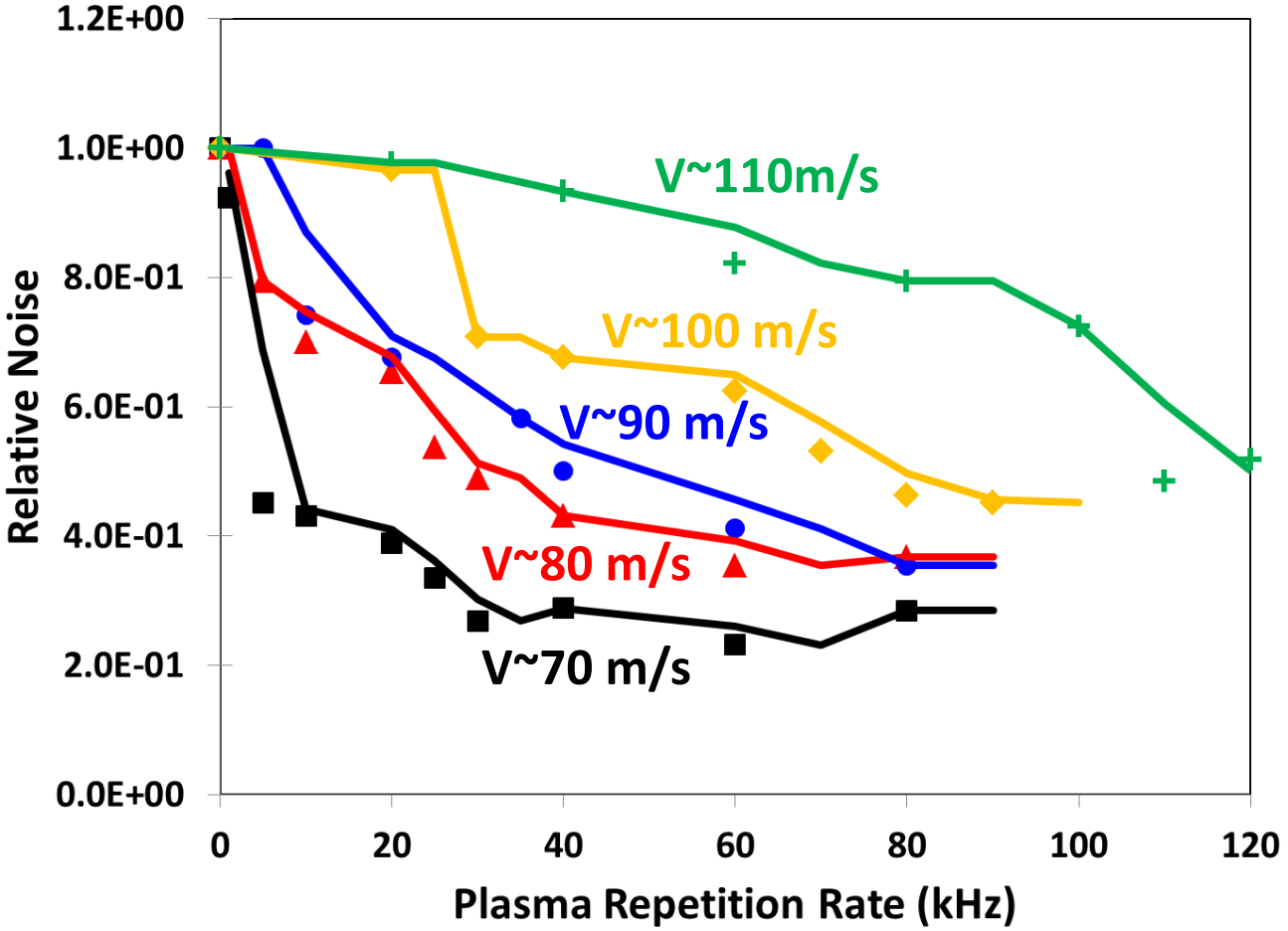
- **The power required for the reduction increased with increasing velocity**



- **Relative noise is strong function of Plasma RR (or Power)**

ϕ: "Near LBO" at each velocity

$\phi_{NLBO} \sim \phi_{LBO} + 0.01$

Fuel: methane
T~580K
P~5atm
Plasma Voltage ~15 kV

Result 3: Relative Noise vs. Velocity

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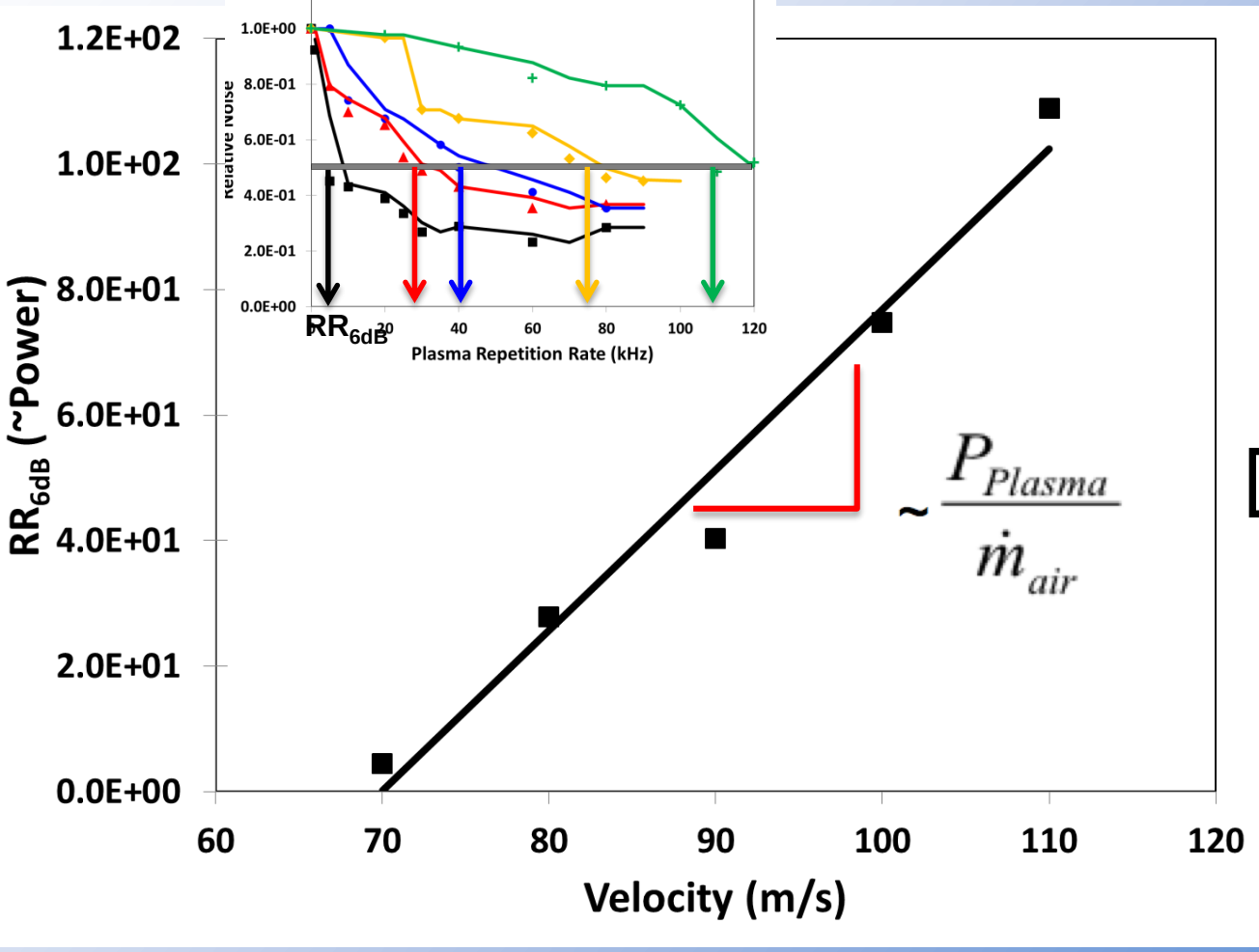
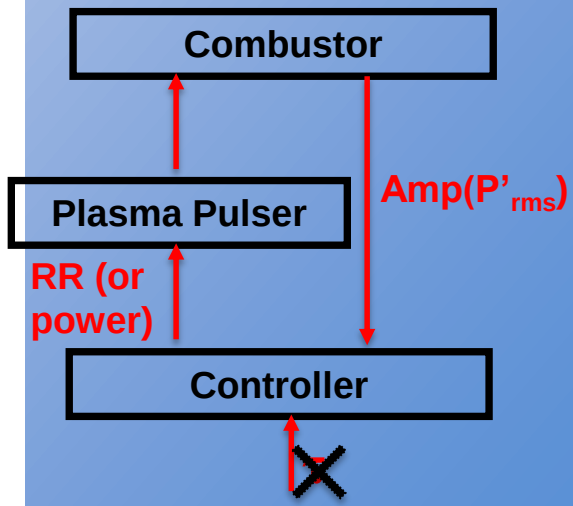
- **The required power for the 6dB reduction is linearly increasing with increasing velocity**



- **Plasma power deposition per unit mass of air can be a key control parameter at a given pressure**



Fuel: methane
T~580K
P~5atm
Plasma Voltage ~15 kV

Result 3: Relative Noise at three different pressures

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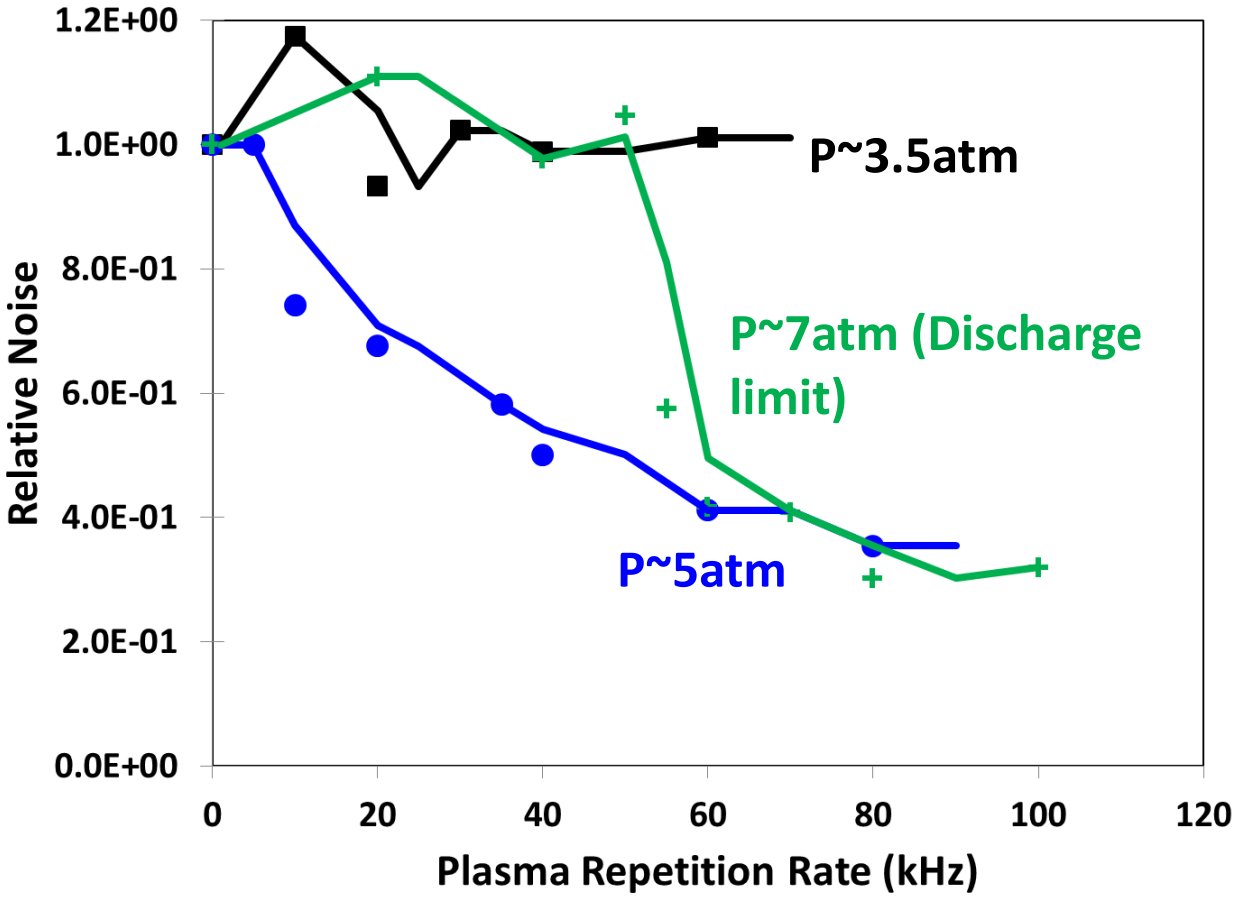
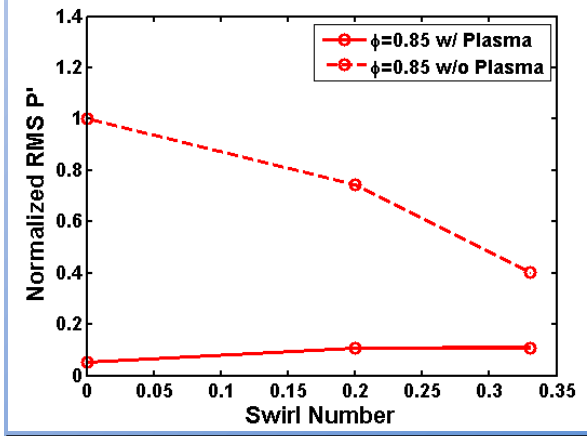
- **The noise reduction could be achieved at different pressures (unless the combustor is already quiet)**



	3.5 atm	5 atm	7 atm
Noise (0kHz, dB)	129.6	139.2	143.4
Noise (80kHz, dB)	129.5	130.2	133



- **NSPD does not make a quiet combustor quieter**

ϕ: "near LBO" at each pressure
$\phi_{NLBO} \sim \phi_{LBO}+0.01$
Fuel: methane
T~580K
V~90m/s
Plasma Voltage ~15 kV

Result 3: Methane vs. Propane

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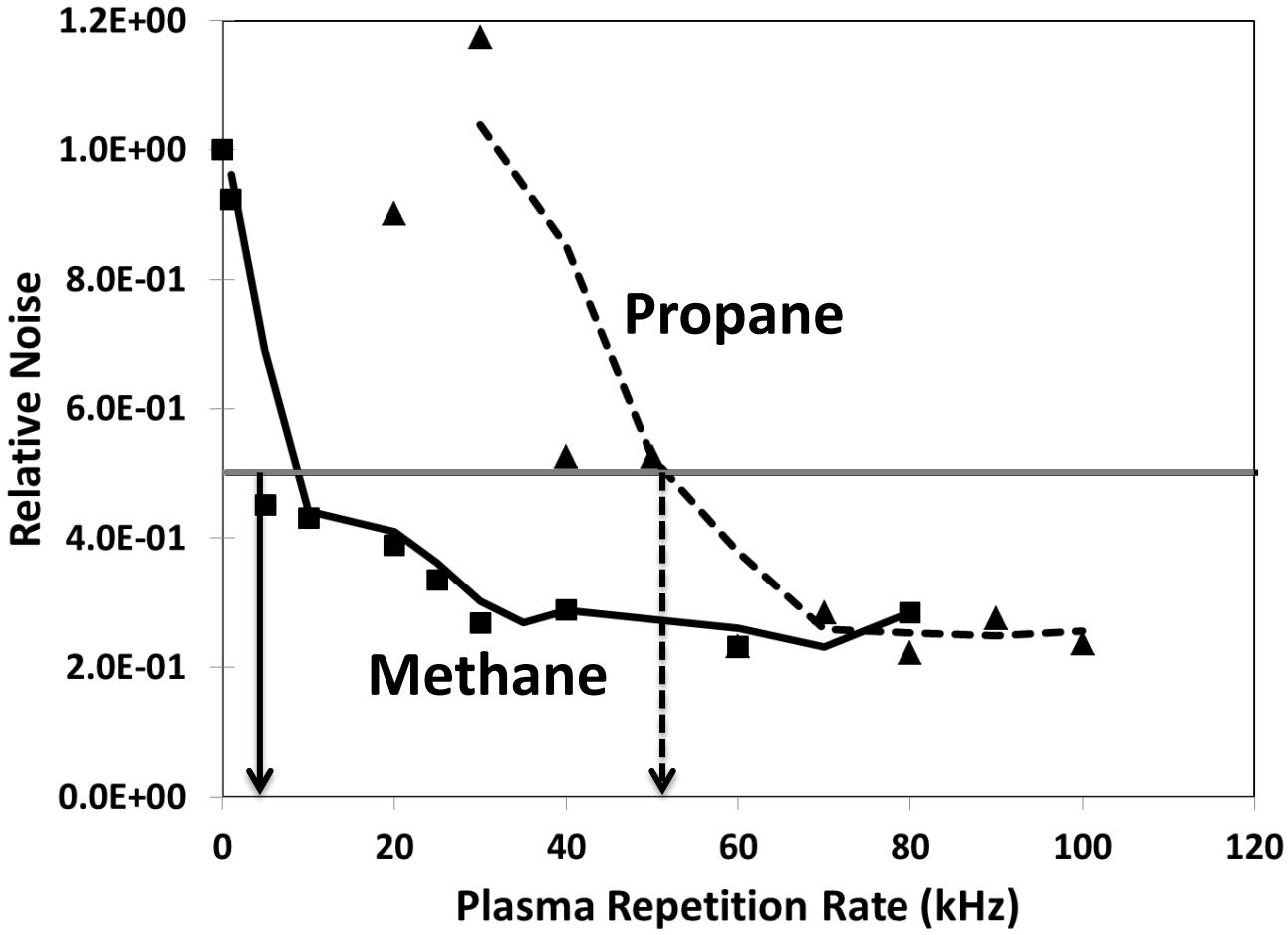
- **At conditions tested, the power required of propane was significantly higher than that of methane**



- **Noise with no control**
  - **Propane~150 dB**
  - **Methane~140 dB**
- **ϕ at control**
  - **ϕ_{NLBO_C3H8} ~ 0.58**
  - **ϕ_{NLBO_CH4} ~ 0.72**

ϕ: "Near LBO" for each fuel

ϕ_{NLBO} ~ ϕ_{LBO}+0.01

P~5atm
T~580K
V~70m/s
Plasma Voltage ~15 kV

Result 4: Extension of Lean Blowout Limit and incomplete combustion

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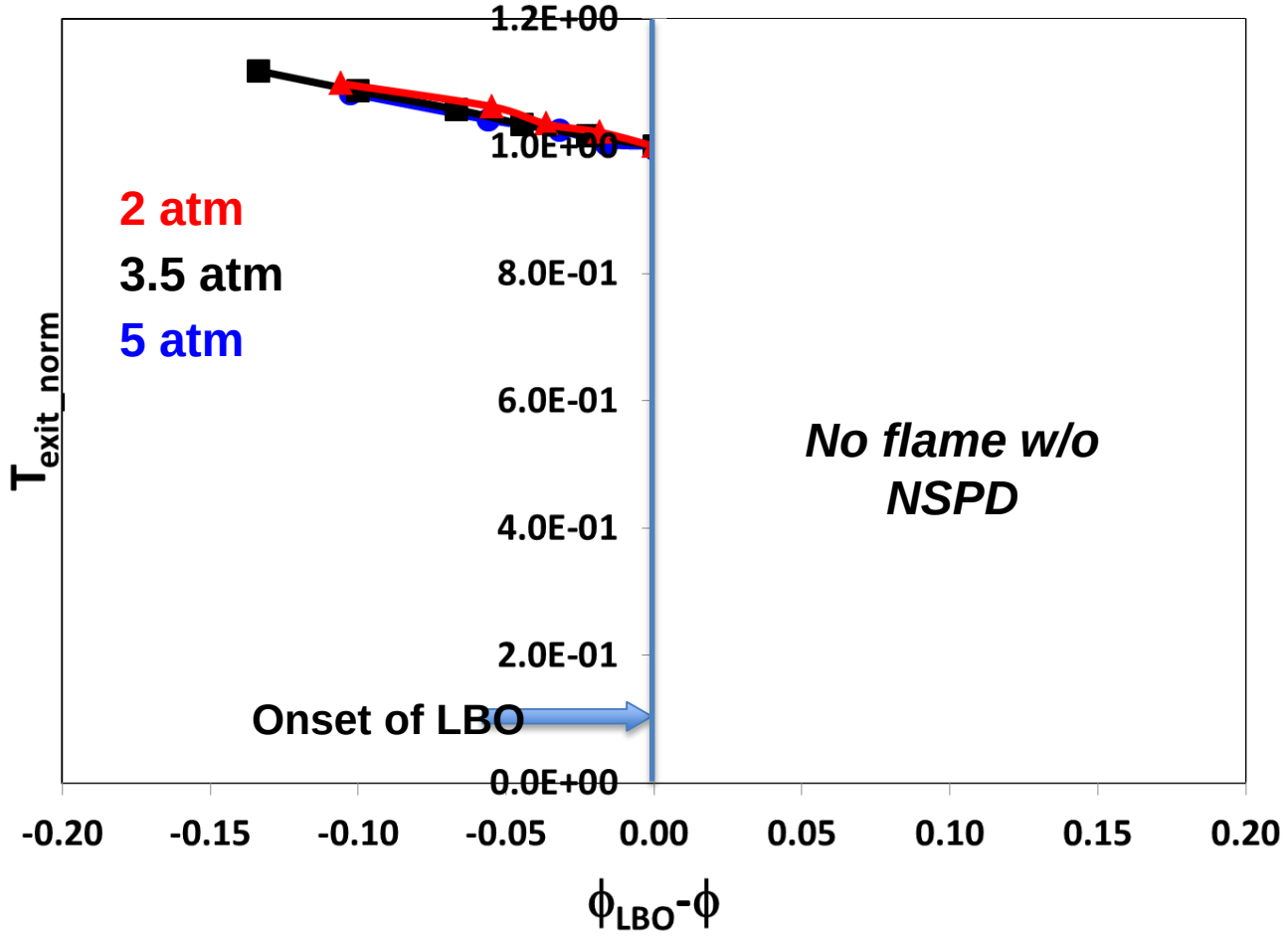
- **LBO is significantly extended (with substantial incomplete combustion)**
- **The extension is harder with increasing pressure and decreasing plasma power**



T_{exit_norm}: Normalized tube exit temperature

$$T_{exit\_norm} = \frac{T - T_{No\_comb}}{T_{LBO} - T_{No\_comb}}$$

Fuel: Methane
P~5atm
T~580K
V~70m/s
Plasma Voltage ~15 kV

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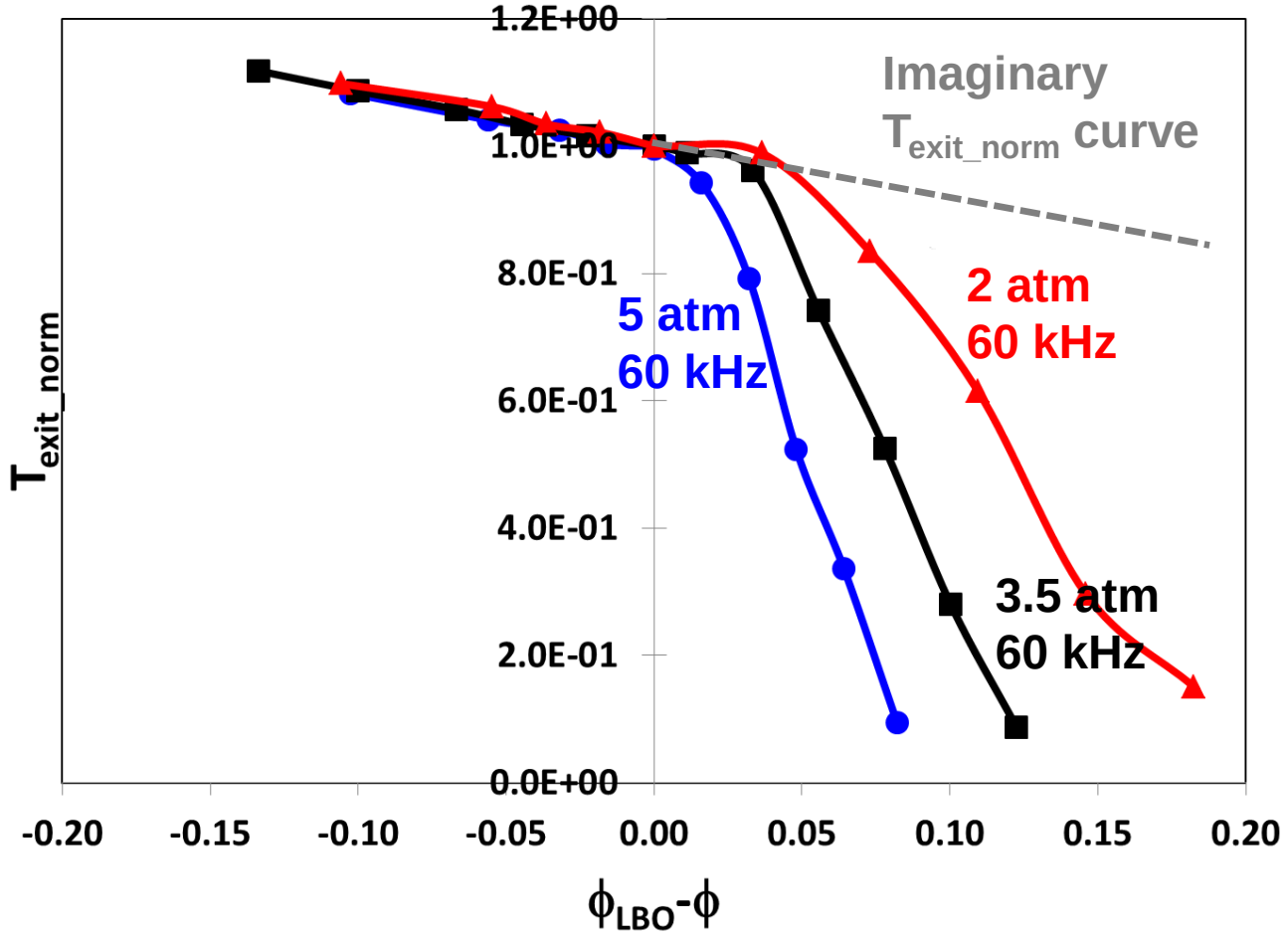

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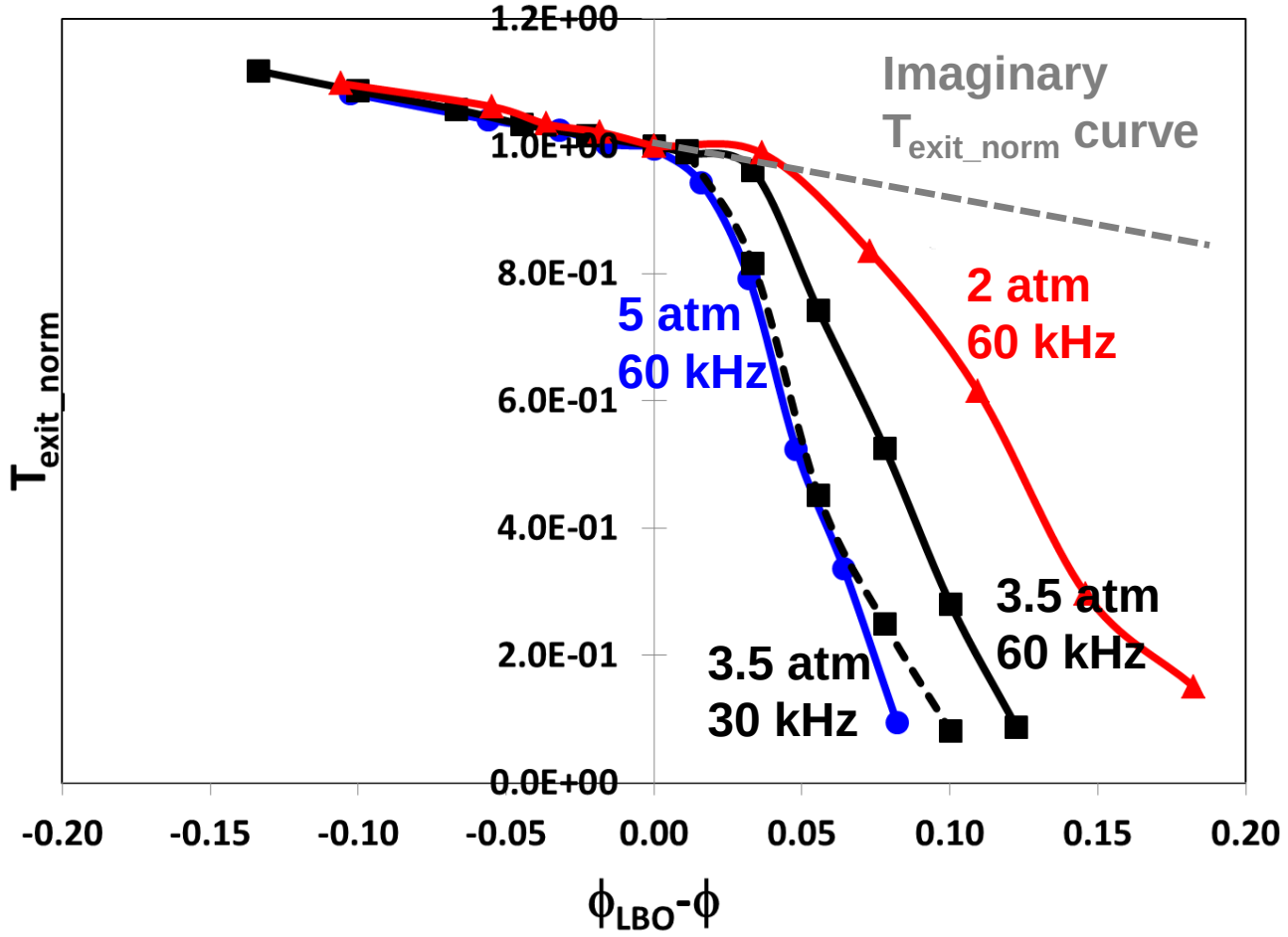

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Fuel: Methane
P~5atm
T~580K
V~70m/s
Plasma Voltage ~15 kV

Result 5: Incremental NO_X Production

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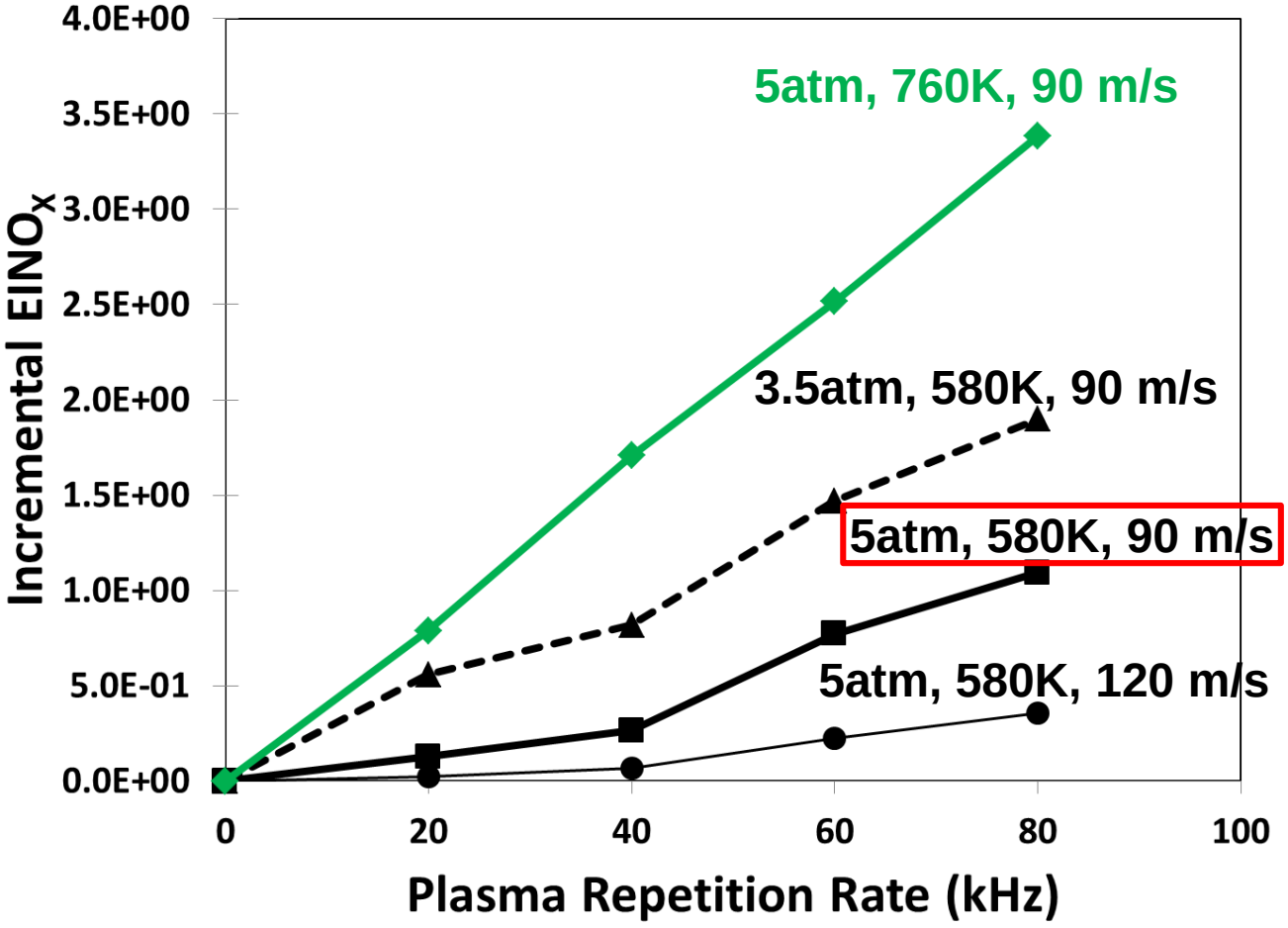
- **Incremental NO_X production in the presence of NSPD is typically low (~< 1EINOX)**
- **It is a strong function of velocity/pressure/temperature**



Plasma Voltage ~15 kV

Concluding Remarks

Can one get similar level of improvements at realistic gas turbine conditions?

- **Realistic V:** required linearly increasing power
- **Realistic P:** required higher voltage (and higher power as well?)
- **Realistic T:** required a caution for potentially high incremental NO_X
- **More realistic fuel (C_3H_8):** may require higher power
- **Static enhancement (LBO/NO_X):** required higher power to eliminate incomplete combustion

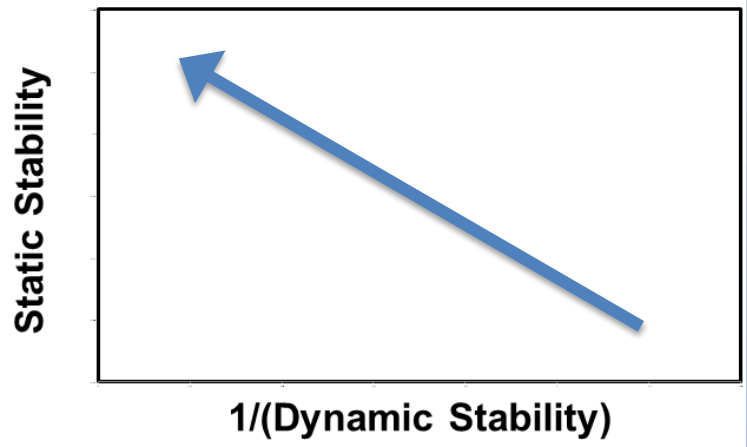
However, yes – they "just" require proportionally increasing, easily achievable power (or voltage) in comparison to ambient condition

Challenges and Long Term Vision

Challenges

- Liquid fuel
- Realistic geometries
- **EMI**
- **Electrode durability**

Long term vision



- Simpler low-emissions combustor with **reduced fuel staging**
- Potential to accelerate burning and increase combustion efficiency, leading to **smaller, shorter combustors**
- Relieve combustor aerodynamics from responsibility for flame stabilization by adding **chemistry-only pathway**
- **Less-geometry dependent solution** package for general flame dynamics problems