Plasma assisted combustor dynamics control

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FY12 LEARN Phase I Technical Seminar

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Outline

- ***The innovation***
- ***Technical approach***
- ***Impact of the innovation if it is eventually implemented***
- ***Results of the LEARN Phase I effort to date***
- ***Distribution/Dissemination—getting the word out***
- ***Next steps***

The Innovation

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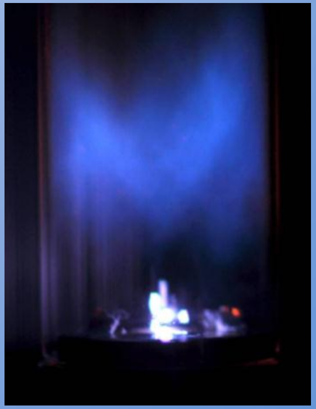
- Dramatically improve dynamic/static flame stability by implementing nanosecond pulsed low temperature plasma discharges (**NSPD**) with a minimal penalty of NO_X production

  - Combustor dynamics is a major challenge of advanced combustor technologies
  - Current research is one of the very first efforts *(Moeck et al. 2013)* to apply plasma on combustion dynamics control
  - Potentially enabling ***ultra-compact***, ***low emission*** combustion ***without damaging pressure oscillations***

Plasma-Assisted Flame



Technical Approach

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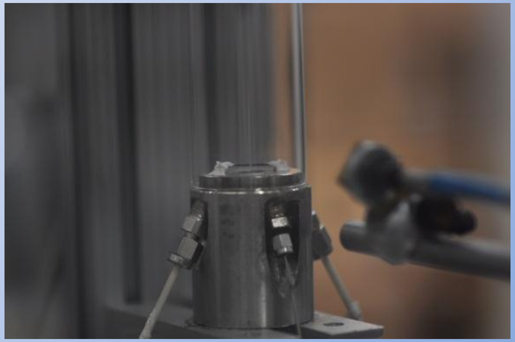
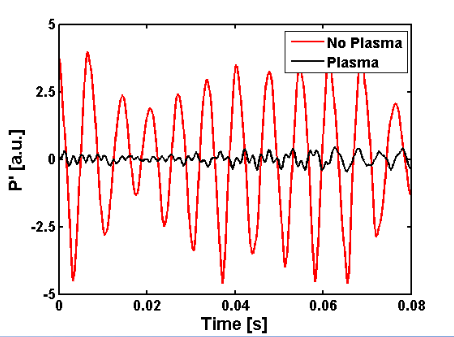
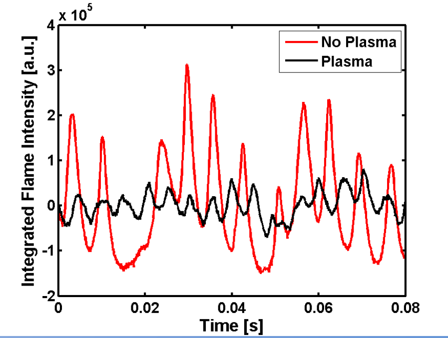
- Task 1: Design/fabrication of a laboratory scale (~ 10 kW) premixed swirl combustor that produces realistic combustor dynamics (~$O(10^4)$ Pa at O(100 Hz))

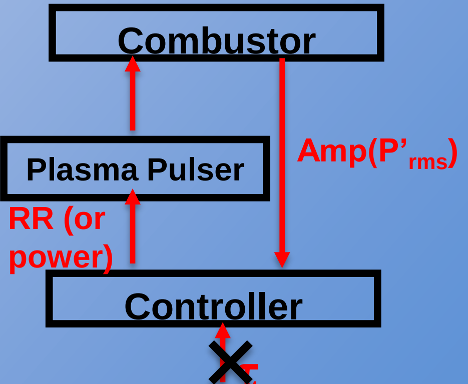


- Task 2: Measurements of pressure and heat release fluctuations, and emission in the absence/presence of NSPD





- Task 3: Development of first generation feedback control scheme



Potential Impact of Innovation

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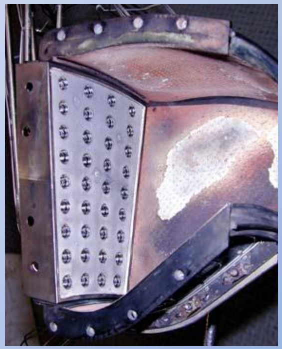
"Potentially enabling ultra-compact, low emission combustion without damaging pressure oscillations"

- 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

Summary of Phase I Effort to Date

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- ✓ R1: A dump combustor which generates self-excited dynamics of ~ O (10^4) Pa pressure fluctuation at ~150-200 Hz was successfully developed
- ✓ R2: More than 10X reduction of sound pressure level (>20 dB) was observed when using NSPD
- ✓ R3: A flame stabilized in the center zone (vortex-shedding-free zone) appears to minimize combustor pressure oscillations
- ✓ R4: It was shown that incremental emission in the presence of NSPD is very small (typically < $0.5EINO_X$)
- ✓ R5: Control algorithm that senses pressure oscillation amplitude, and sets plasma power offers a control actuation that does not require knowledge/measurement of pressure oscillation phase, as in traditional feedback control
- ✓ R6: The effectiveness of plasma is highly dependent on flame shape, decreasing with increasing swirl

Result 1: Dump Combustor

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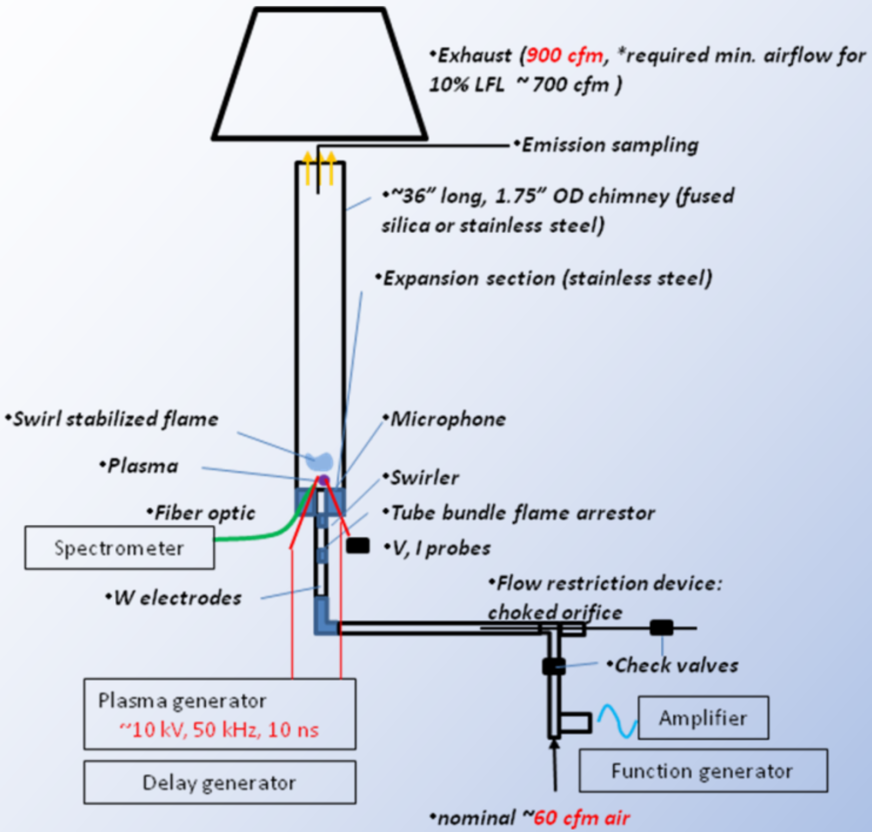

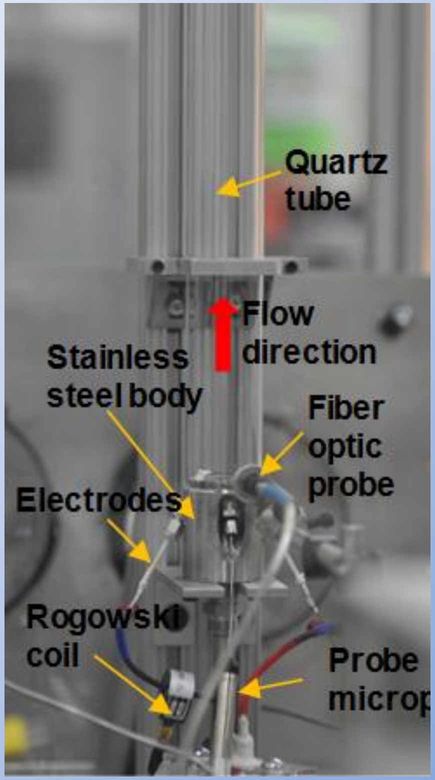

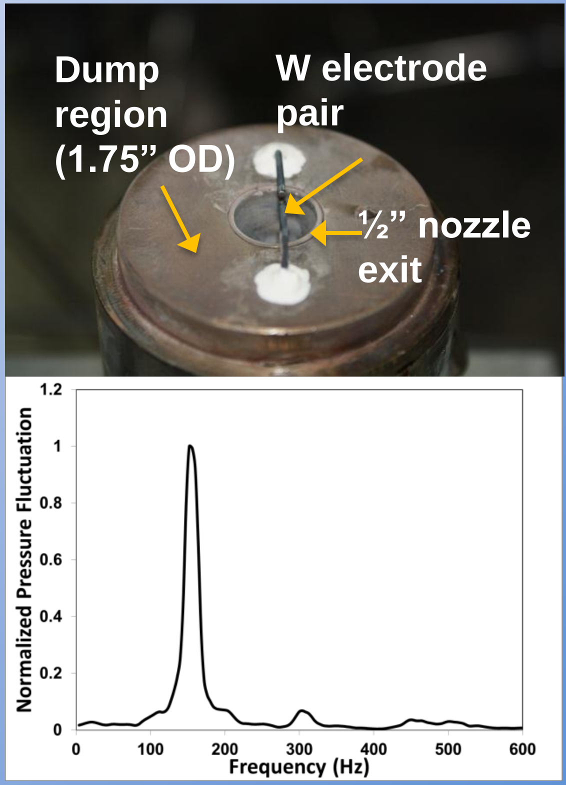

Representative condition: 6 kW combustion power, ~10 W plasma power, 25 m/s nozzle exit bulk velocity

A dump combustor that produces ~15000 Pa pressure oscillation was successfully developed

Result 2: Noise Reduction with NSPD

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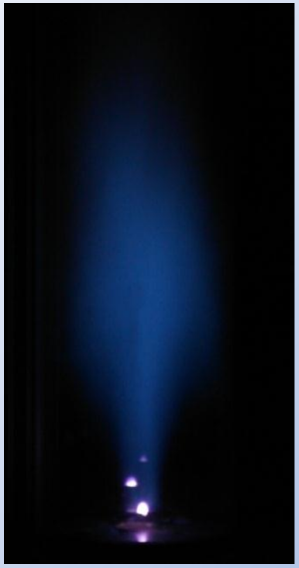
No NSPD

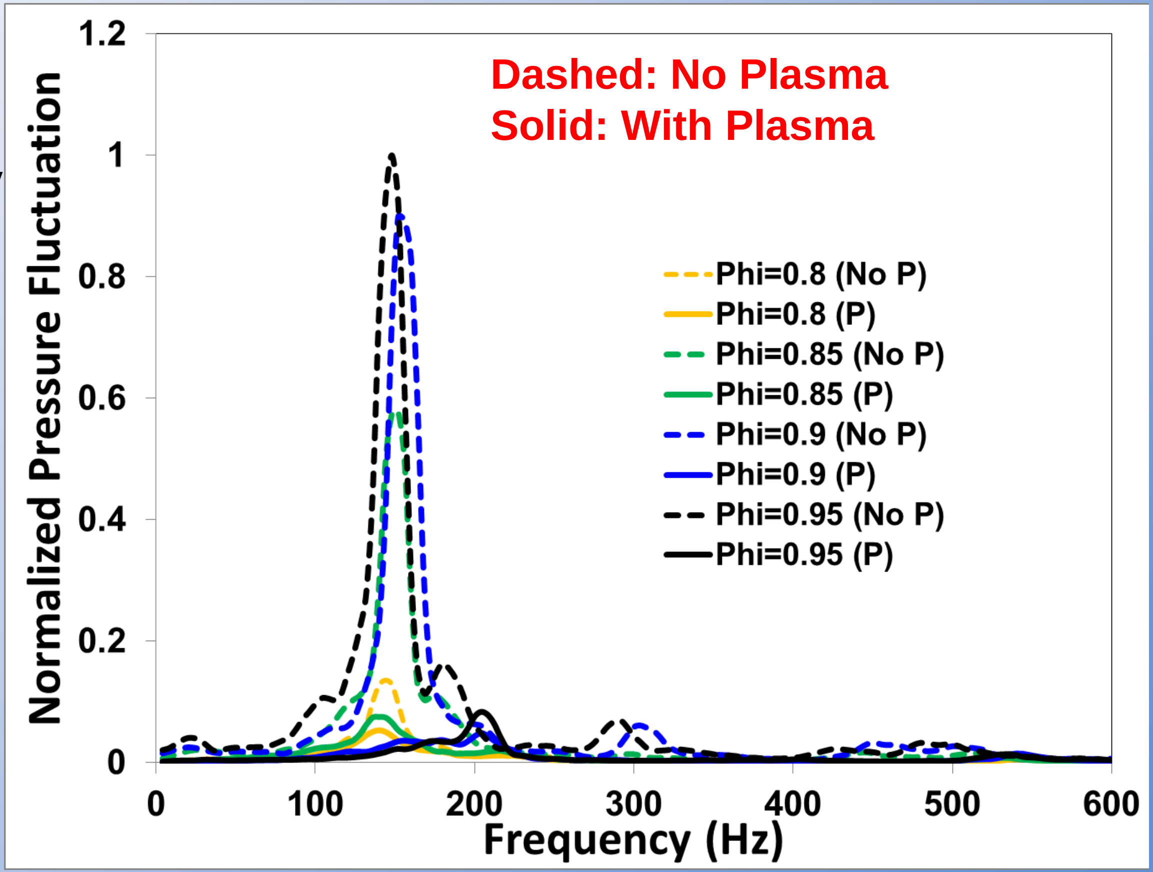
ϕ=0.9, u~25 m/s
Exp.: 1/6 sec

With NSPD

ϕ=0.9, u~25 m/s
RR=25 kHz, V_{peak}=7.8 kV
Exp.: 1/25 sec



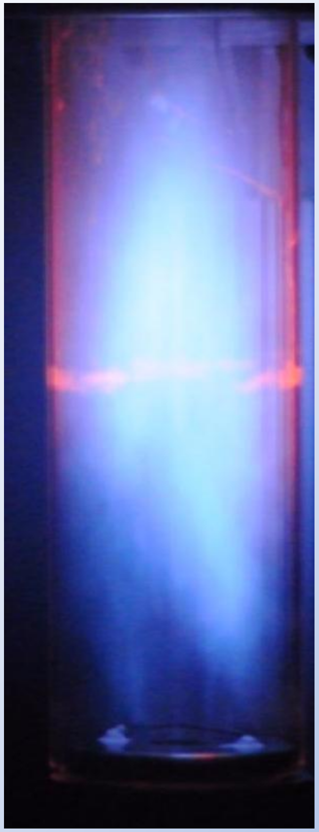
<FFT(P’) with varying equivalence ratio>



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

Result 3: How Does the NSPD Reduce the Noise? (Qualitative Observation)

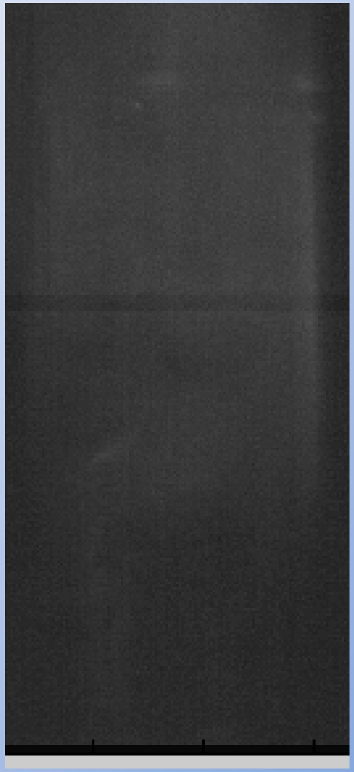
24Hz video



ϕ=0.9, u~25 m/s
RR=25 kHz, V_{peak}=7.8 kV

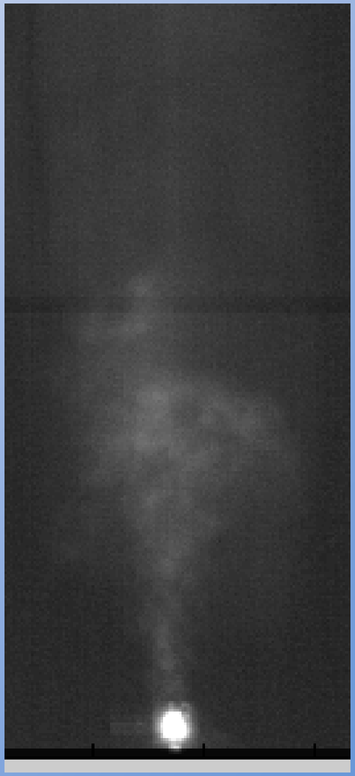
10 kHz video

No NSPD



ϕ=0.9, u~25 m/s

With NSPD



ϕ=0.9, u~25 m/s
RR=25 kHz, V_{peak}=7.8 kV

The NSPD relocates and fixes the flame stabilization point, decoupling the process from disruptive unsteady fluid mechanics and increasing the robustness of the process.

Result 3: More Details from the High Speed Video

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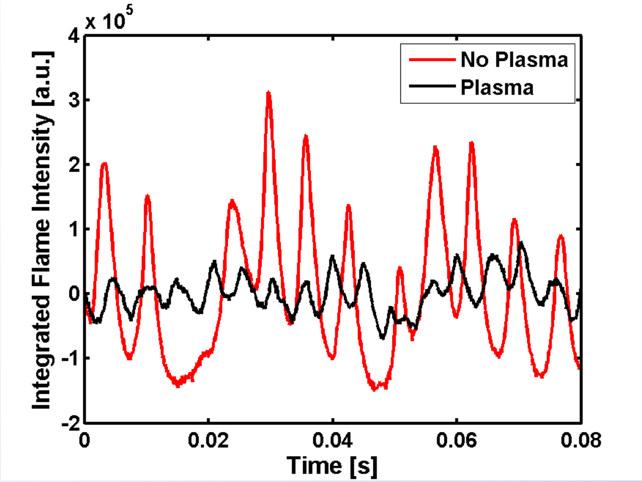
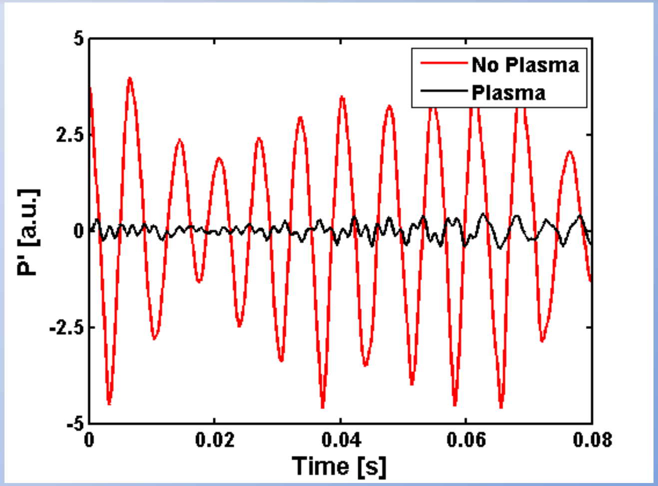
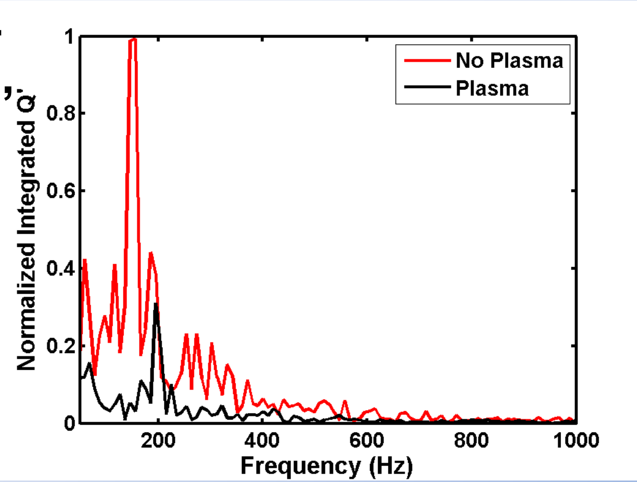
q’



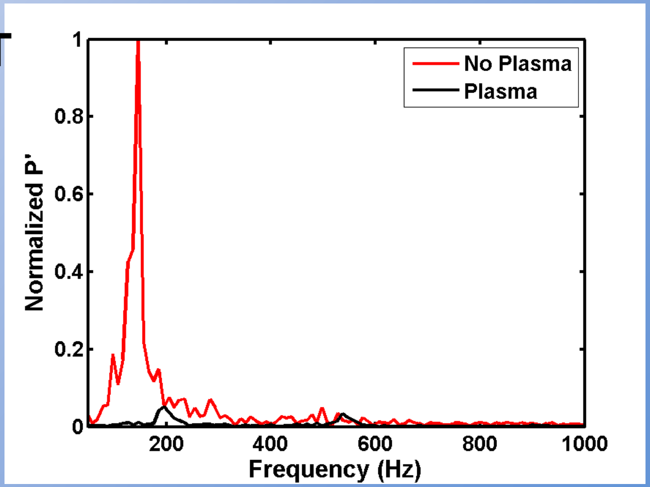
P’



FFT of q’

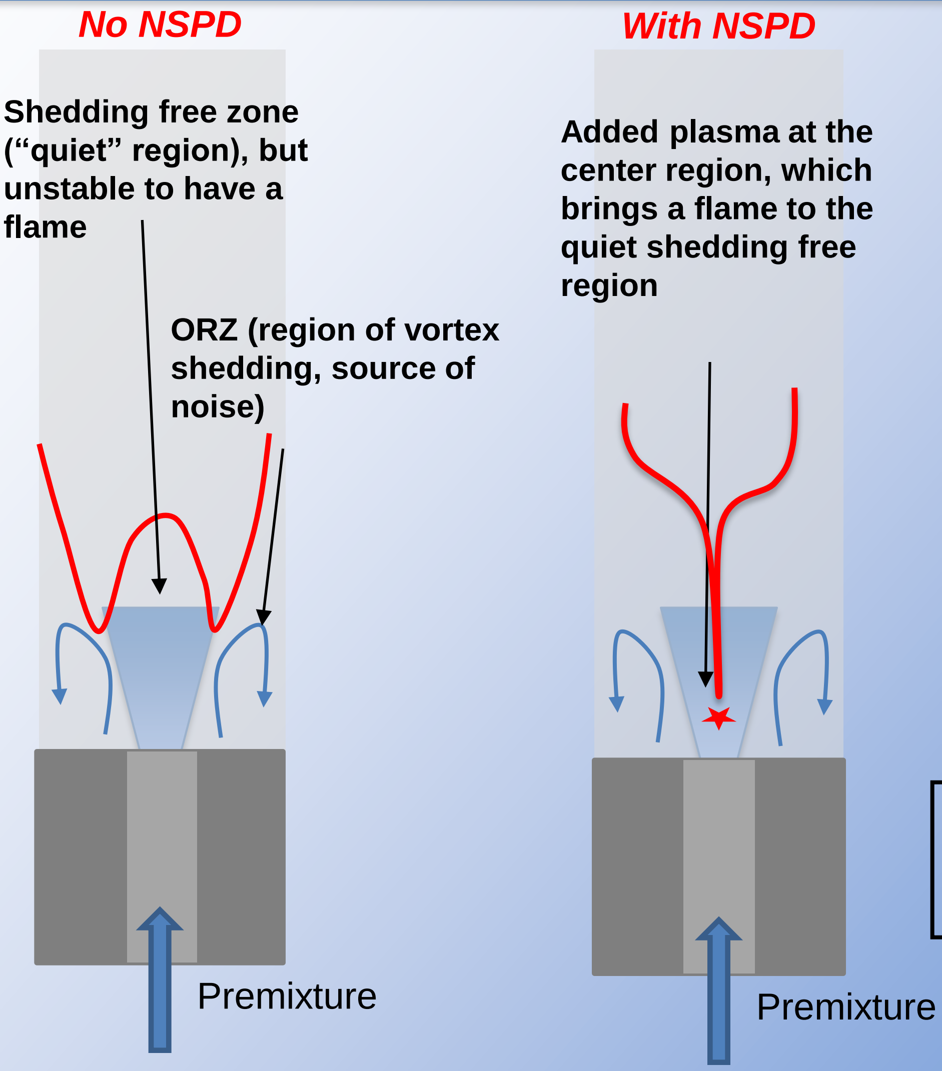


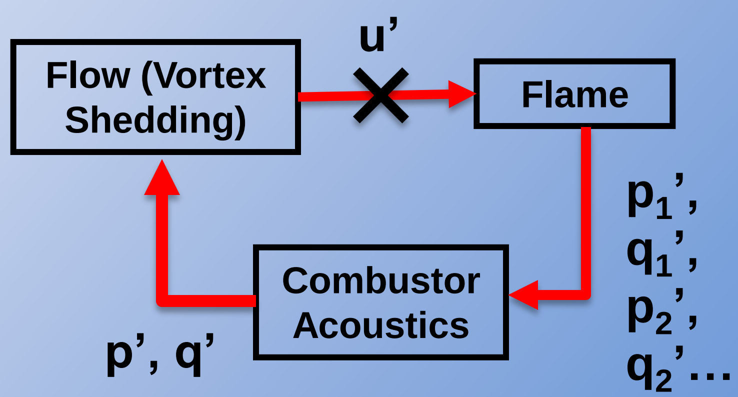
FFT of P’



Application of NSPD breaks the coupling between velocity oscillations and combustion heat release by fixing and holding the flame stabilization location at the center

Result 3: How Does the NSPD Reduce the Noise?





Locating flame base in the vortex shedding free zone (Center Zone) is a key to increasing its robustness

Result 3: Investigation of Noise Reduction Mechanism

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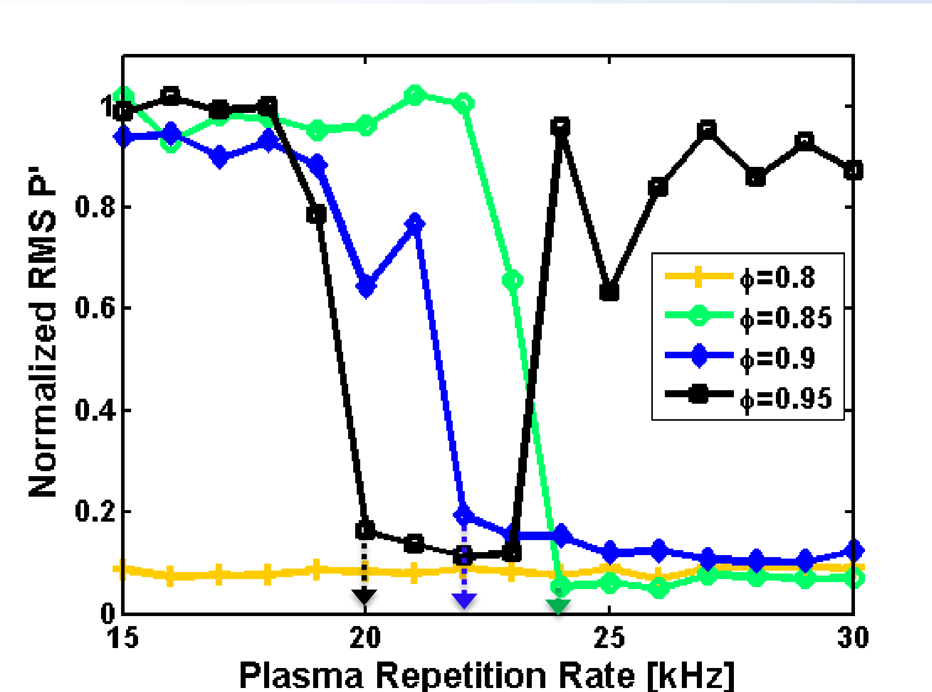
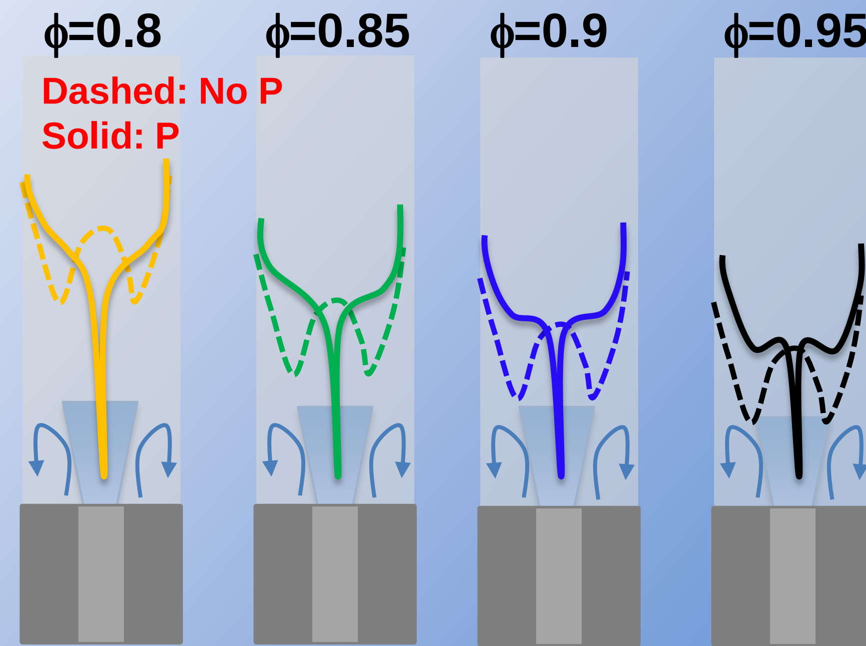


u~25 m/s

Higher plasma power



ϕ=0.8	ϕ=0.85	ϕ=0.9	ϕ=0.95
Too far from the shedding region to have dynamics	Needs relatively higher power to control due to low ϕ	Less power required to move flame to the center	Lesser power required to move flame to the center, but too much power increases noise

- Crossover RR is inversely proportional to ϕ
- Controlled noise level is not a strong function of ϕ

Noise level with no plasma becomes higher

What is impact of plasma on flame emission?

Result 4: Emission and Combustion Efficiency

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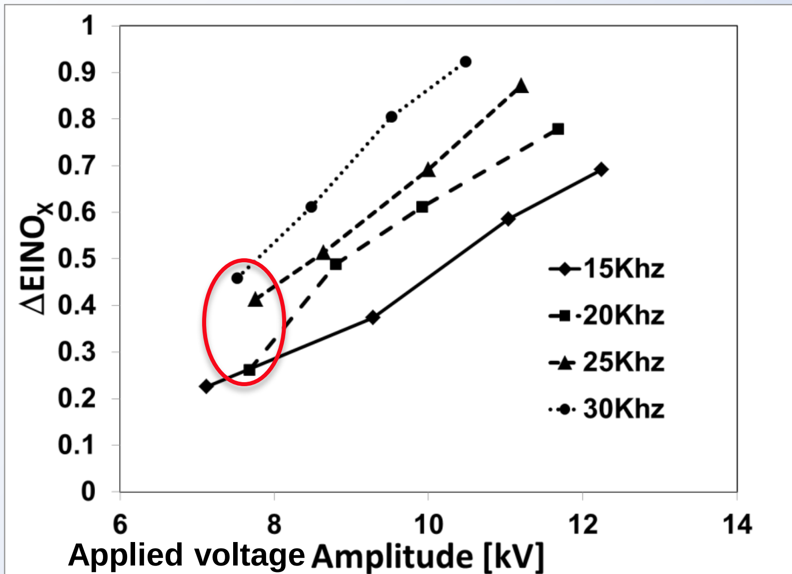
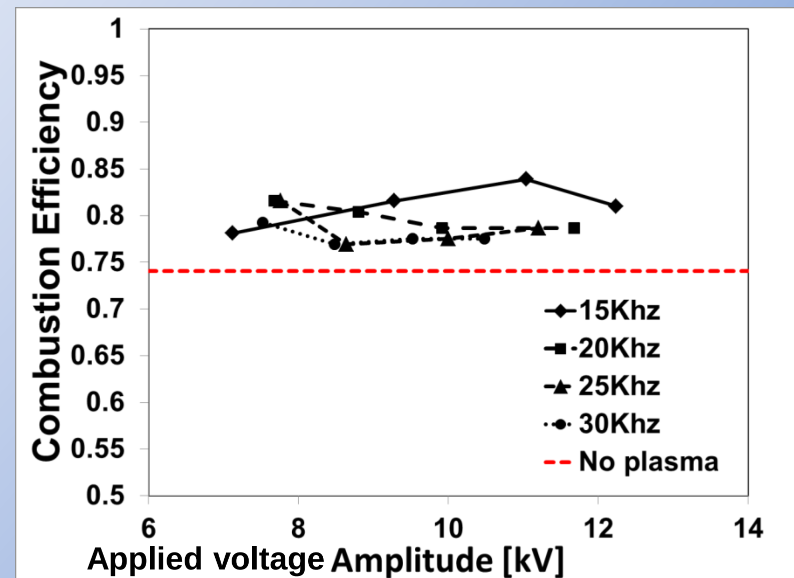
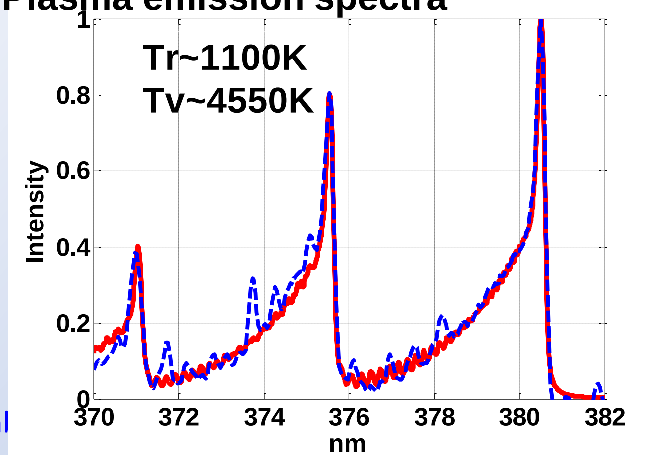
Added EINOX with the NSPD



Improvement of η with the NSPD



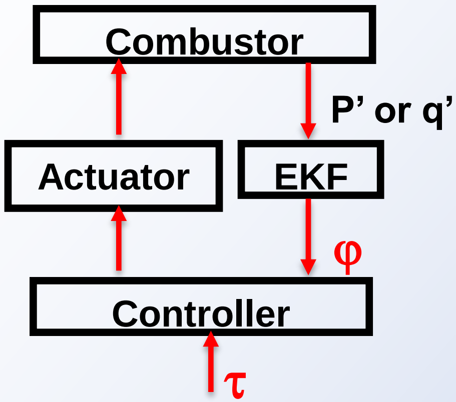
Plasma emission spectra

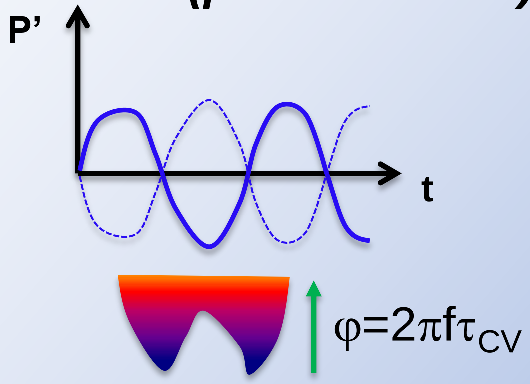


- The added $EINO_X$ in the presence of the NSPD is very low (typically < 0.5EI) due to low temperature characteristic of the NSPD
- The increase of EINOX with the increasing RR and amplitude of plasma shows linear trend
- In general, combustion efficiency is improved with the NSPD, but the case-to-case trends are not well-understood

Result 5: Dynamics Control

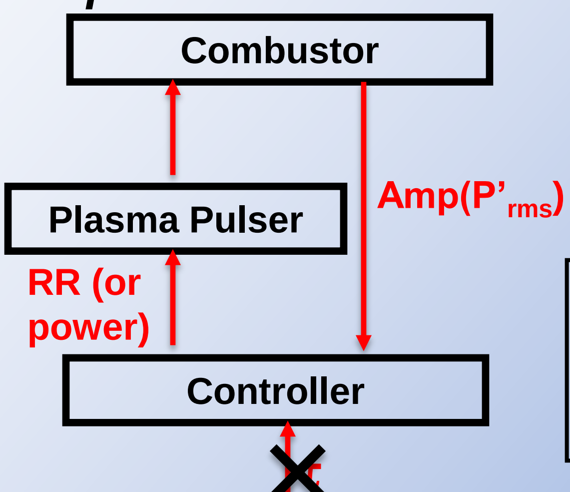
Conventional control scheme (phase control)





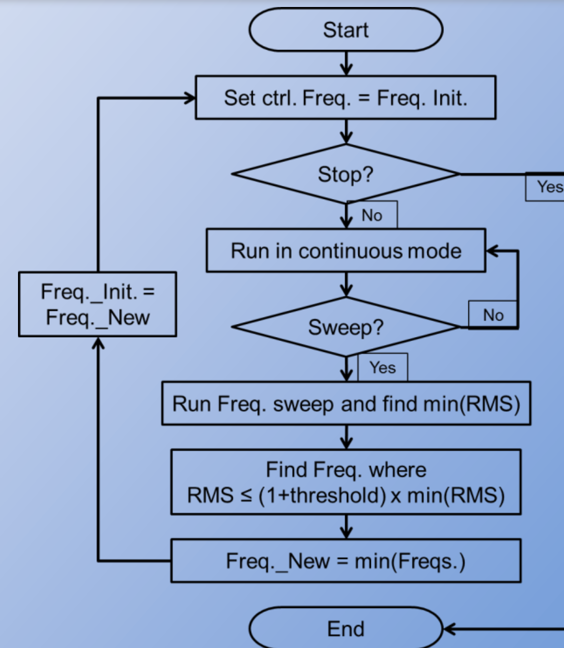
Limitations: Actuator and convective delays and flame incoherence

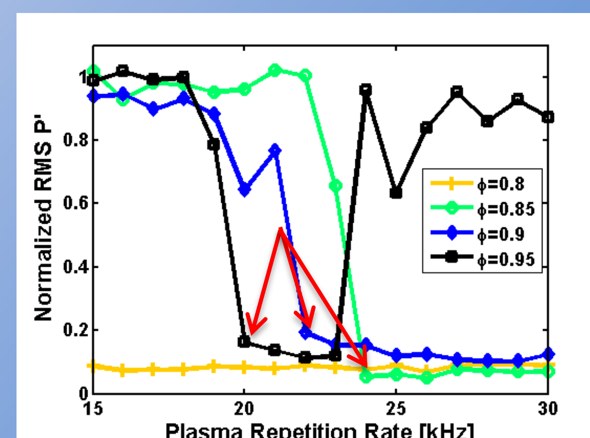
Proposed control scheme (power control)



Control objective: Maintaining centrally stabilized flame with minimal power input

The proposed control scheme can avoid limitations of phase based control





Result 6: Alteration of Swirl

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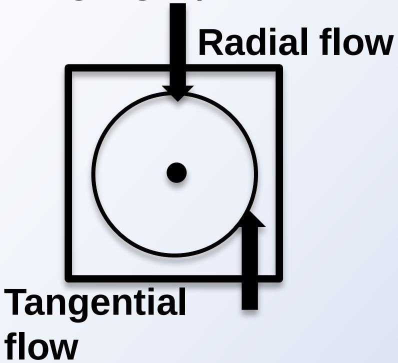
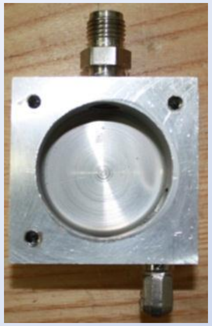
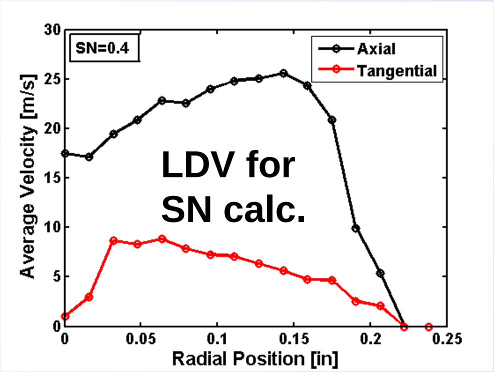
Vortex valve: varying swirler by changing split between RF and TF

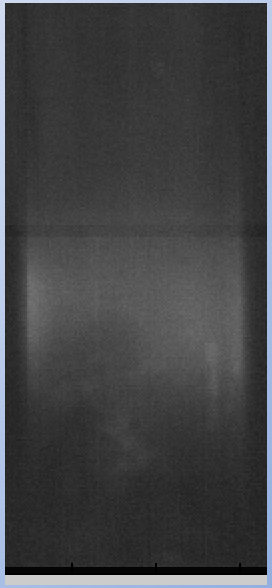






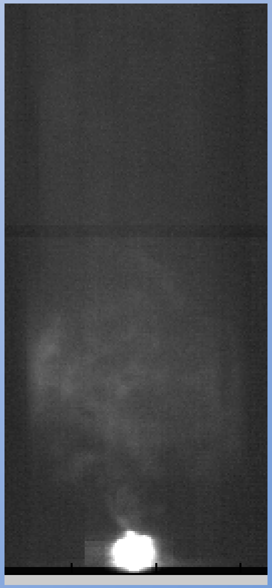
Indication: adding swirl will change the flame location to center and squeeze the ORZ, which leads to a quieter flame

No NSPD



ϕ=0.85, u~25 m/s
SN=0.33

With NSPD



ϕ=0.85, u~25 m/s
SN=0.33
RR=30 kHz, V_{peak}=7.8 kV

- **NSPD is still effective at stabilizing the flame in a swirling flow**
- **Swirl-stabilized combustion without NSPD is more stable than non-swirling case**

Result 6: Alteration of Swirl

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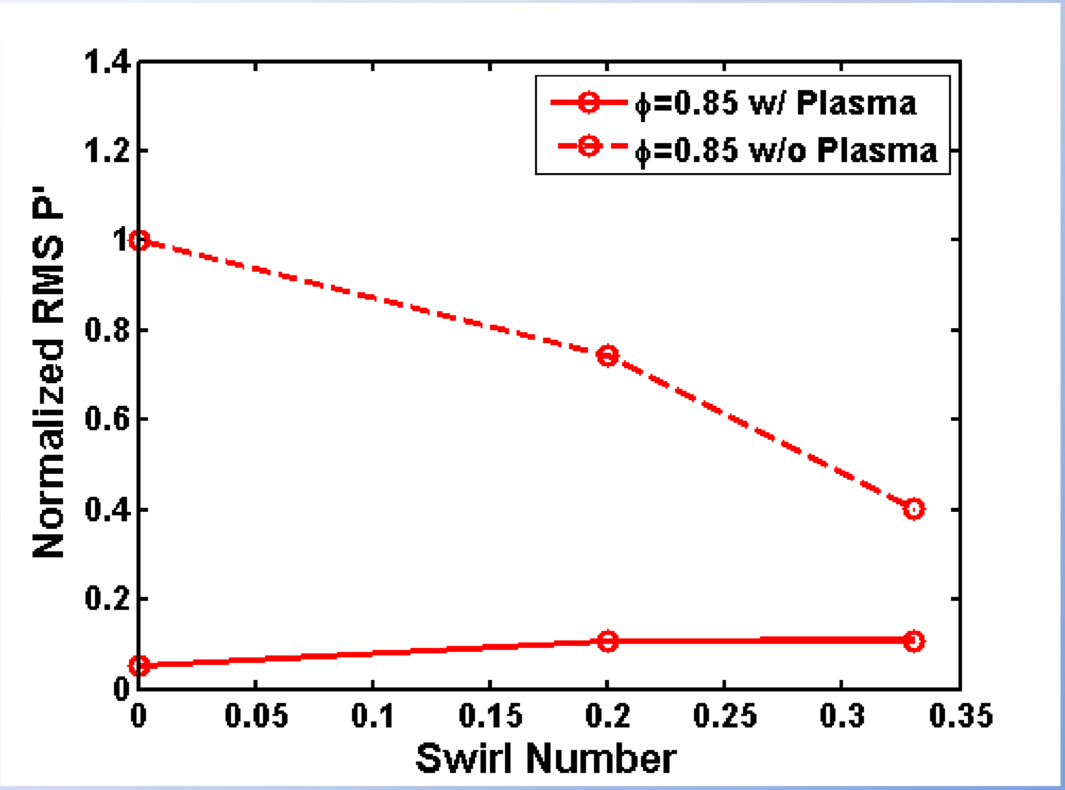
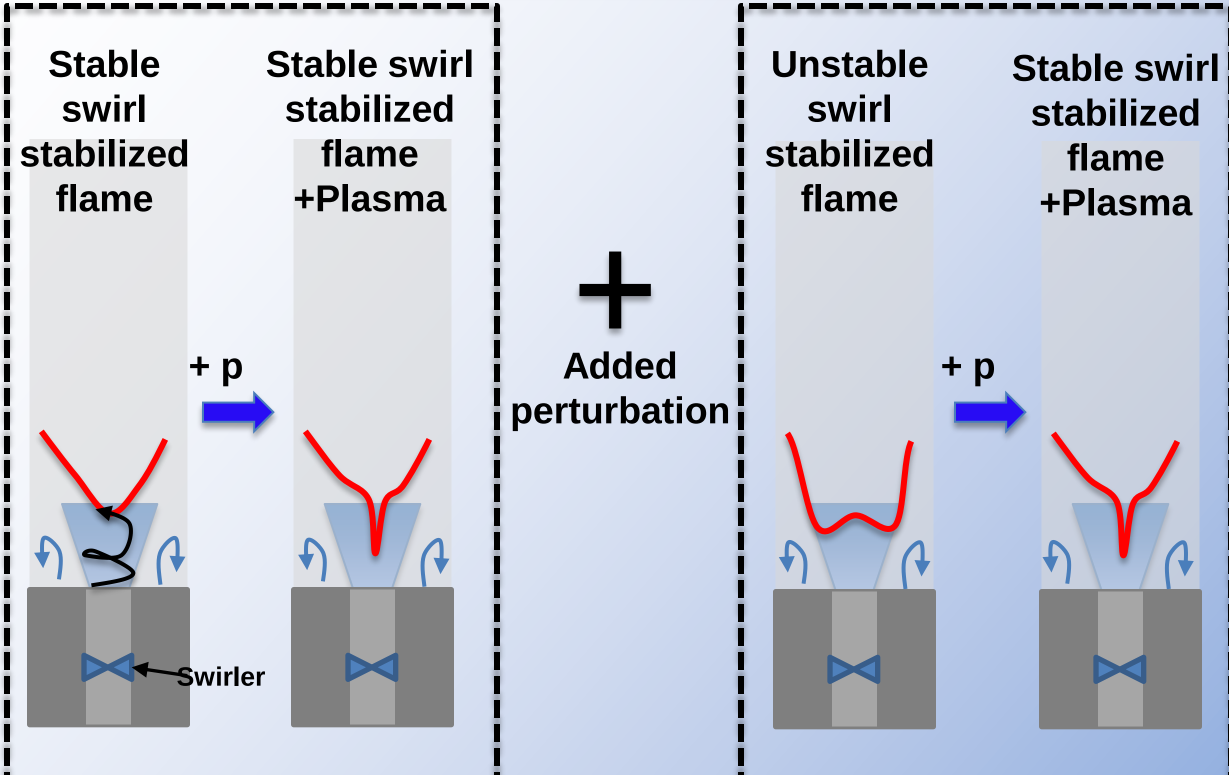


ϕ = 0.8, u = 25 m/s

$SN_{Flashback}$~0.4

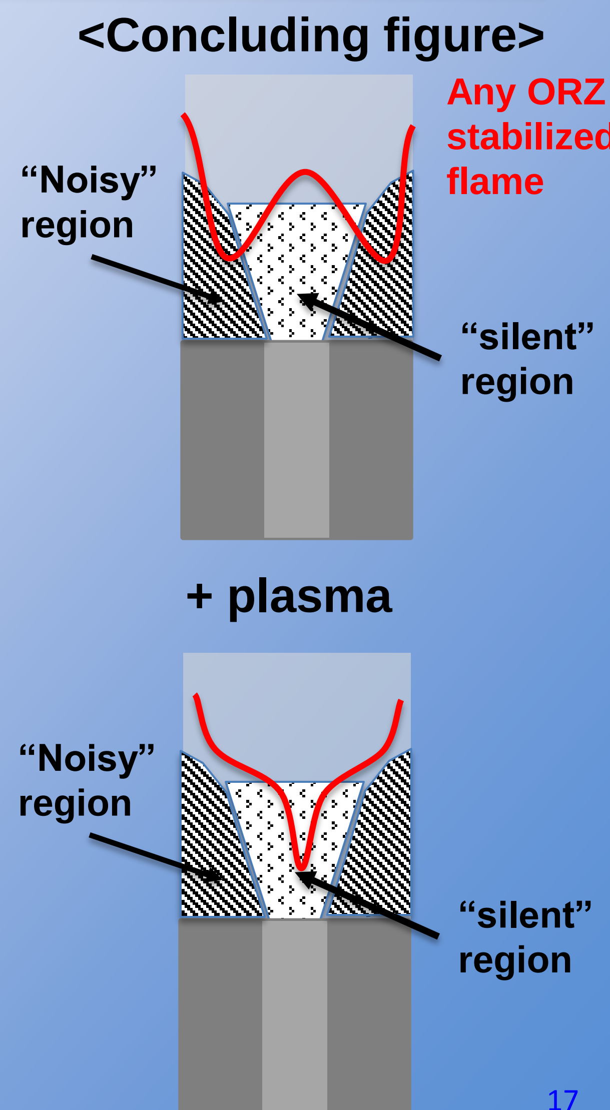
- **Without the NSPD, flame becomes quieter with increasing swirl**
- **The incremental benefit of NSPD decreases with increasing swirl, because uncontrolled flame becomes quieter**

Result 6: Interpretation of SN Effect and Its Generalization



Plasma has less margin to work with increasing swirl because a normal swirl flame is already stabilized in the vicinity of center region

In case the swirled flame is anchored in ORZ, plasma can force the flame back to a centrally-located stabilization



- **Swirl number is only one factor in determining flame shape**
- **We conjecture that the observed plasma stabilization effect will still hold for any ORZ stabilized flame**

Concluding Plot and Vision

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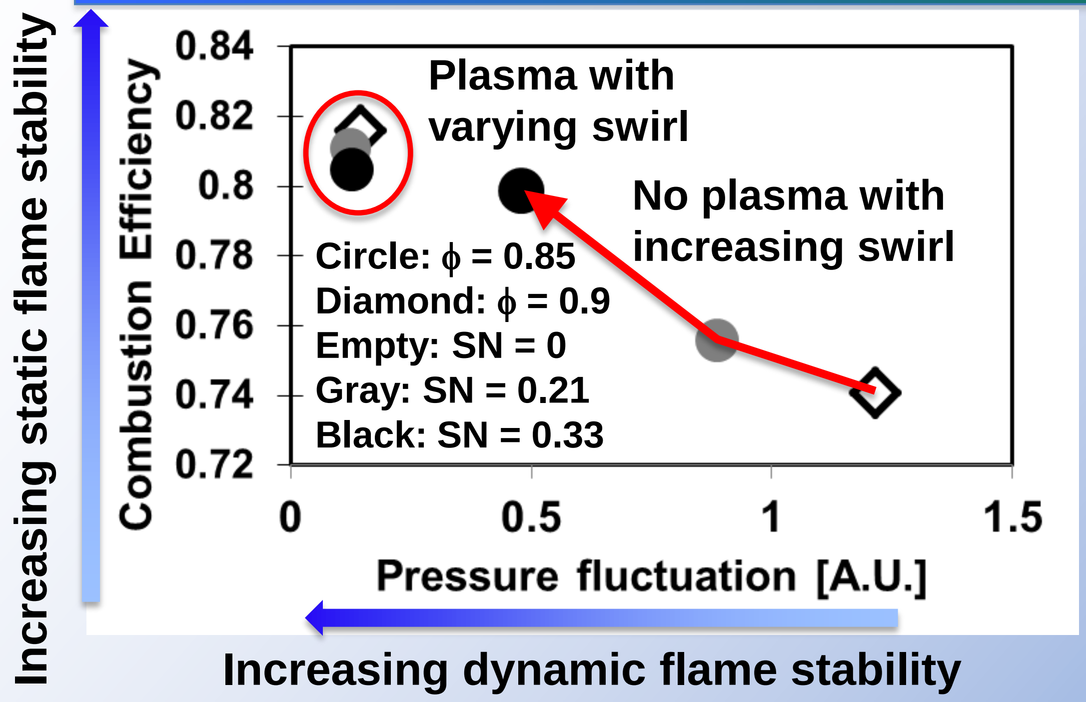


- **Key design constraints (current)**
  - Low power operability
  - Cruise efficiency
  - Ground emission
  - High altitude relight
  - Durability
- **Key design constraints (future)**
  - Overall emission
  - Size/weight/cost
  - Dynamics

- Simpler low-emissions combustor with reduced fuel staging (currently required to meet operability requirements)
- Potential to accelerate burning and increase combustion efficiency, leading to smaller, shorter combustors (weight, shaft dynamics benefits)
- Relieve combustor aerodynamics from responsibility for flame stabilization, enabling potential for new combustor design paradigm
- Total solution package for other flame dynamics problems – lean-limit enhancement, oscillation mitigation, etc.

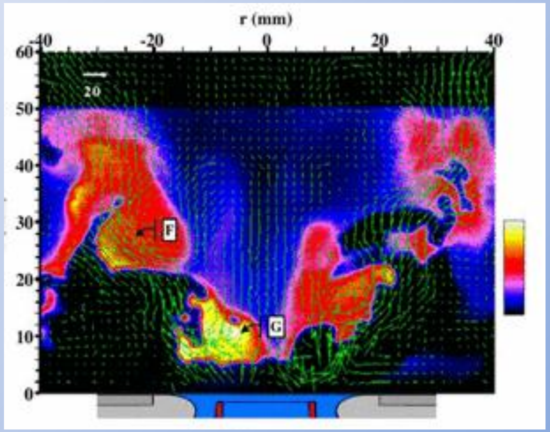
Distribution/Dissemination Plan

- Final report: Before 3 month after the contract end
- Publication (planning) : 35th International Symposium on Combustion (The proceedings of the Combustion Institute) or Combustion and Flame

Next Steps

- Remaining step for phase I (in case no-cost-extension is permitted)
  - ✓ **Simultaneous OH PLIF and PIV** to investigate flame/flow structure interaction

→ a key step to verify the mechanism proposed in this presentation



Sadanandan et al., 2008 (Applied Physic B 90, 609-618)

- Key objective for Phase II:
  - ✓ Demonstrating similar level of plasma effect **at more realistic gas turbine combustor conditions**
- Milestones for Phase II
  - ✓ Intermediate step: **Higher flow** (~ 100 m/s) at ambient T, P with methane fuel
  - ✓ High T test: **T3 up to ~1150 F** at atmospheric P with vaporized Jet A fuel
  - ✓ High T/P test: T3 (up to ~1150F) and **P4 (up to 250 Psia)** with vaporized Jet A fuel
  - ✓ Realistic fuel test: **liquid Jet A**