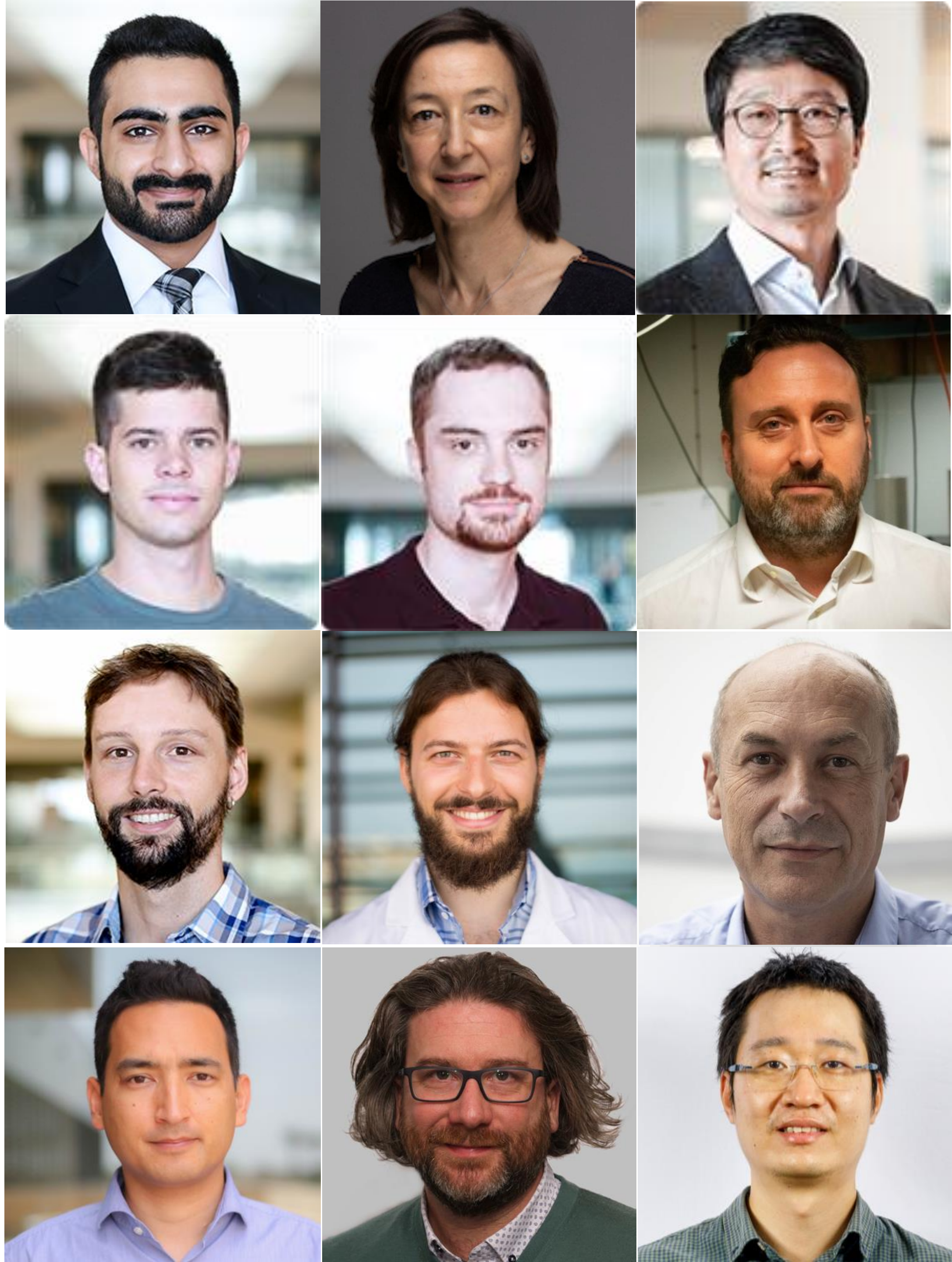
Non-equilibrium Plasmas for Climate Change Mitigation

Deanna A. Lacoste

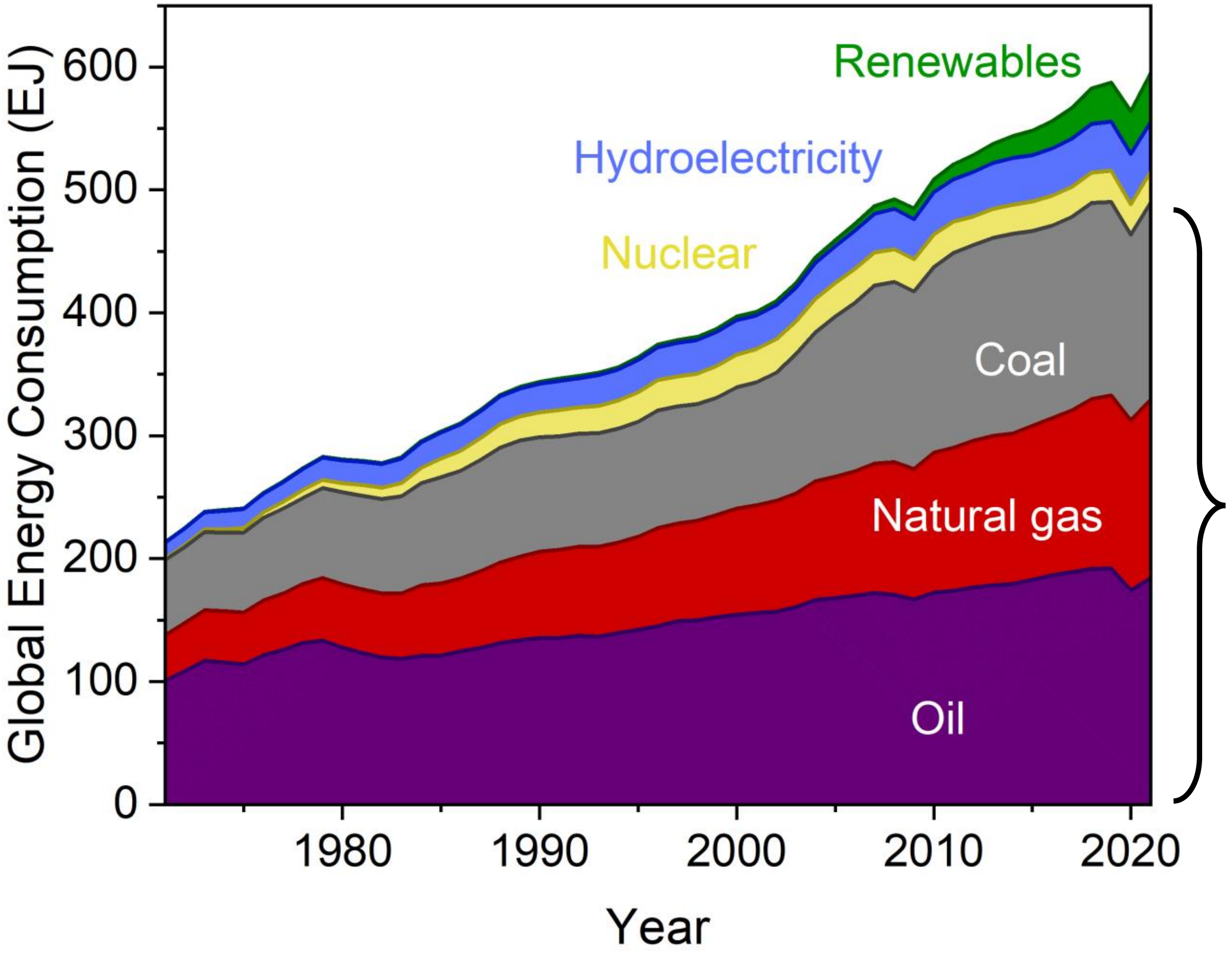
جامعة الملك عبدالله للعلوم والتقنية
King Abdullah University of Science and Technology
Clean Combustion Research Center

Main Collaborators

Ammar Alkhalifa, Anne Bourdon
Min Suk Cha, Davide Del Cont-Bernard
Francesco Di Sabatino, Andreas Ehn
Thibault Guiberti, Sylvain Heitz
Christophe Laux, Jonas Moeck
Guillaume Pilla, Da Xu



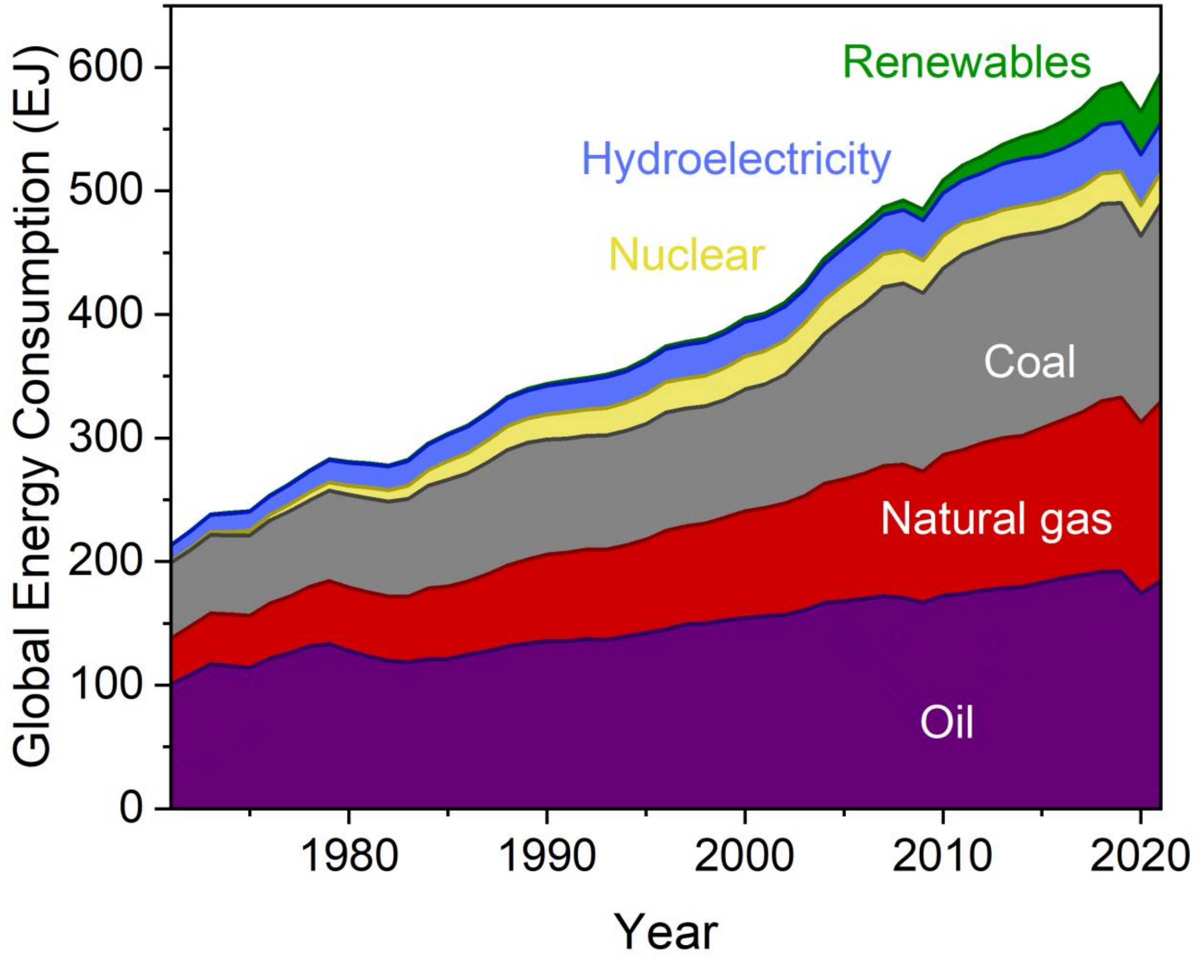
Climate change

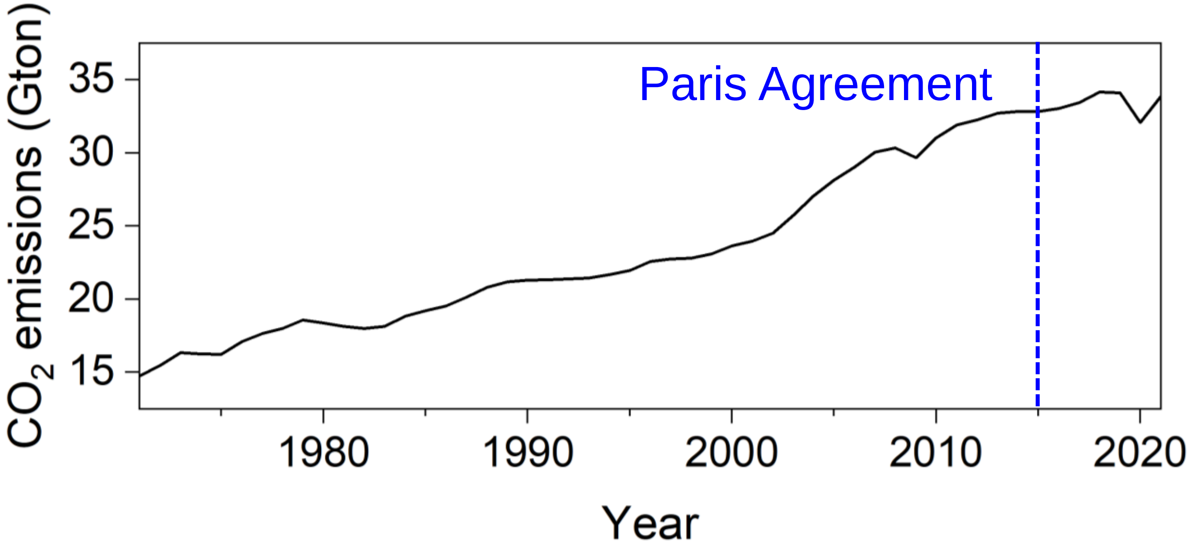


80% Combustion of fossil fuels

Data from BP Statistical Review of World Energy, 2022

Climate change





Data from BP Statistical Review of World Energy, 2022

Most common combustion systems

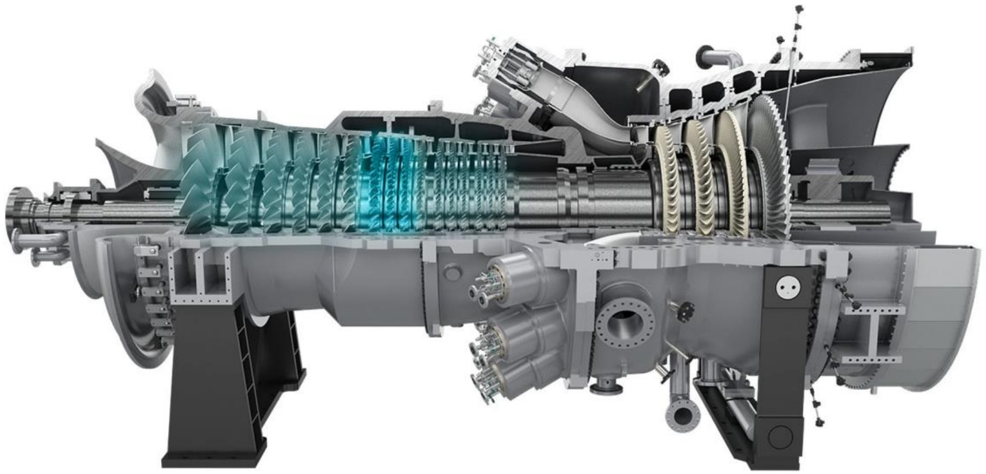
Boilers / Furnaces			
Gas turbines			
Piston engines			
	Transportation	Buildings	Industry

Technical challenges of the gas turbine industry

New fuels

Efficiency

Fuel versatility



CO_2 emissions

Siemens-energy.com

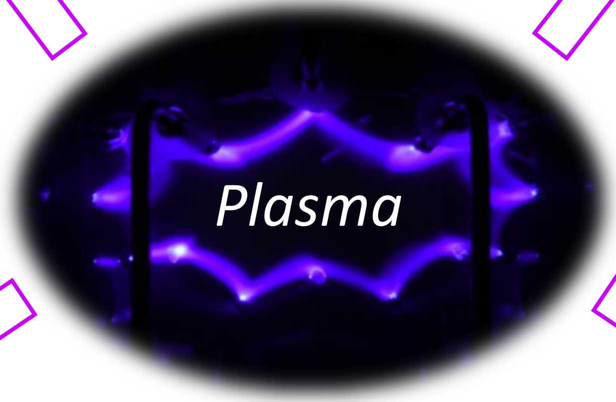
Combustion stability

Pollutant emissions

Where non-equilibrium plasmas could contribute

New combustions
Mild combustion
Detonation
Highly-diluted flame

New engine technologies
Two-stage Combustors
PDE
RDE



Fuel reforming
Ammonia
Methanol
HFO

Pollutant emission
NOx, VOCs, soot

Combustion stability
Lean-flammability limit
Thermoacoustic instabilities

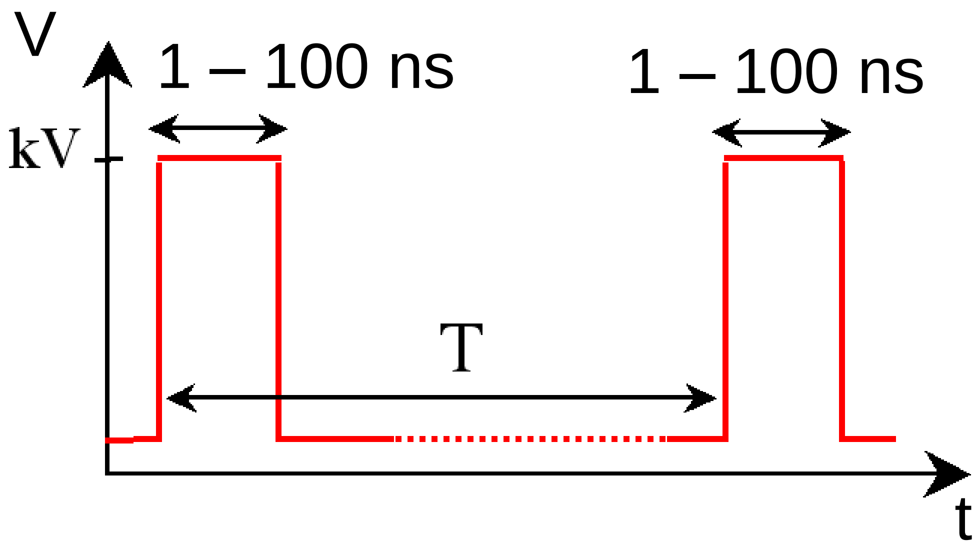
Content

Nanosecond repetitively pulsed (NRP) discharges

Enhancement of the lean stability limit

Control of thermoacoustic instabilities

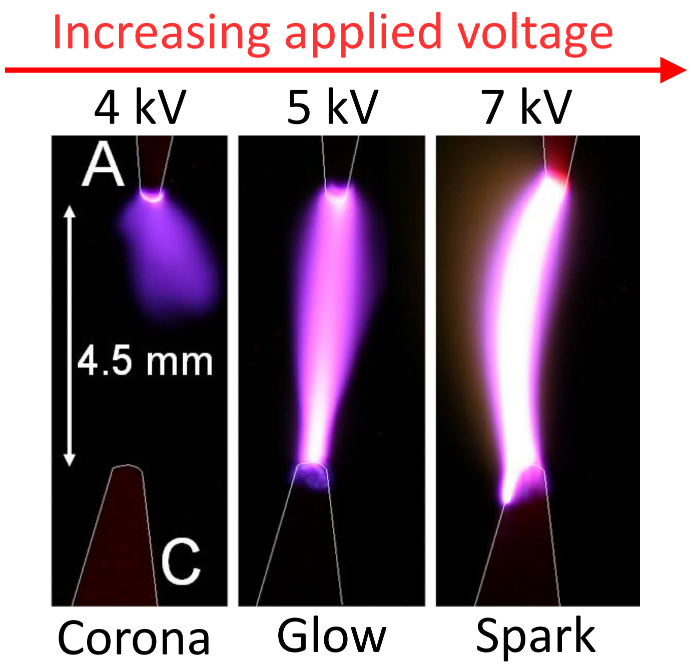
NRP discharges



V = 5 – 100 kV
PRF = 10 – 100 kHz

NRP discharges

In ambient air



Pai et al., Plasma Sources Sci. Technol., 2010

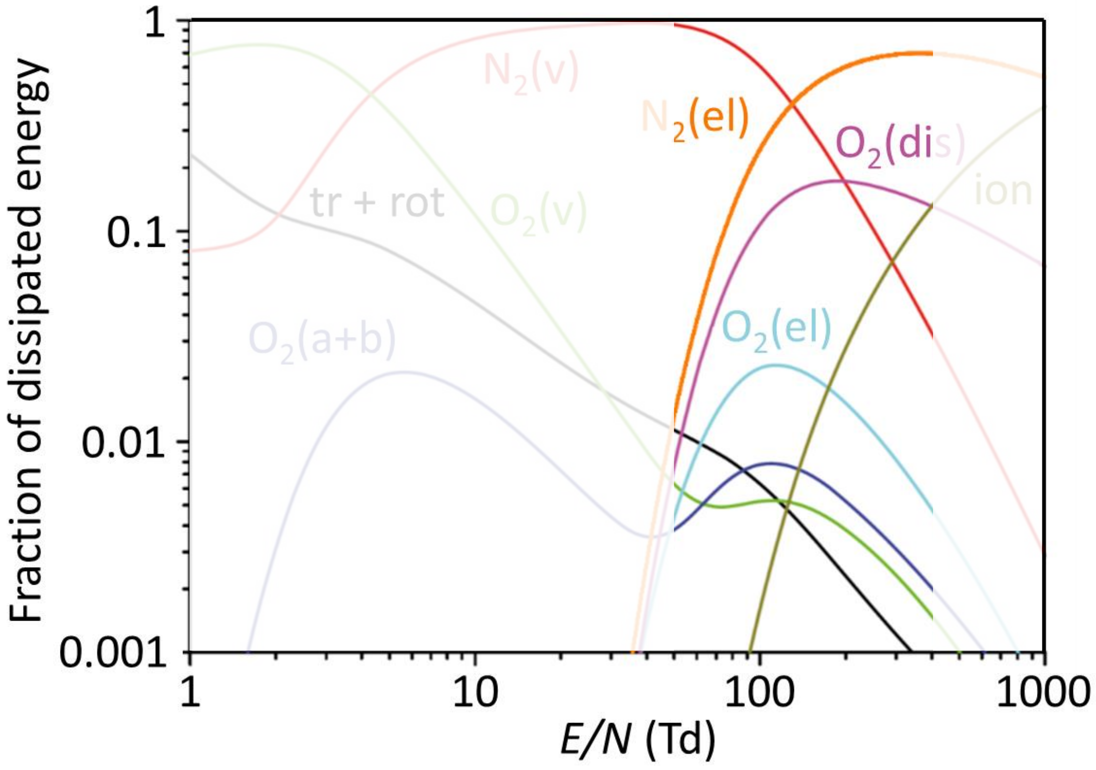
Regime	Glow	Spark
Conduction current	negligible	10’s of amperes
Energy per pulse	< 200 µJ	0,2 - 20 mJ
Dynamics	Streamer and return wave	Uniform discharge across the gap
Gas heating	negligible	2000 – 4000 K
O_2 dissociation	up to 5%	50%

Pai et al., Plasma Sources Sci. Technol., 2009

Stancu et al., J. Phys. D: Applied Physics, 2010

NRP discharges

In ambient air



Data from Starikovskiy et al., Phil. Trans. R. Soc. A, 2012

During a ns-pulse (~ 10 ns):

$N_2 + e^- \rightarrow N_2(v) + e^-$

$N_2 + e^- \rightarrow N_2(A, B, C, a' \ldots) + e^-$

$O_2 + e^- \rightarrow O + O + e^-$

Just after a pulse (~ 20 ns):

$N_2(A, B, C, a' \ldots) + O_2 \rightarrow N_2(X) + 2O + heat$

In between pulses (~ 10 μs):

$N_2(v) + M \rightarrow N_2 + heat$

NRP discharges

In ambient air

Two-step mechanism of fast gas heating and atomic oxygen production

Popov, Plasma Phys. Rep., 2001

During a ns-pulse (~ 10 ns):

$N_2 + e^- \rightarrow N_2(v) + e^-$

$\mathbf{N_2 + e^- \rightarrow N_2(A, B, C, a'\ldots) + e^-}$

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In ambient air

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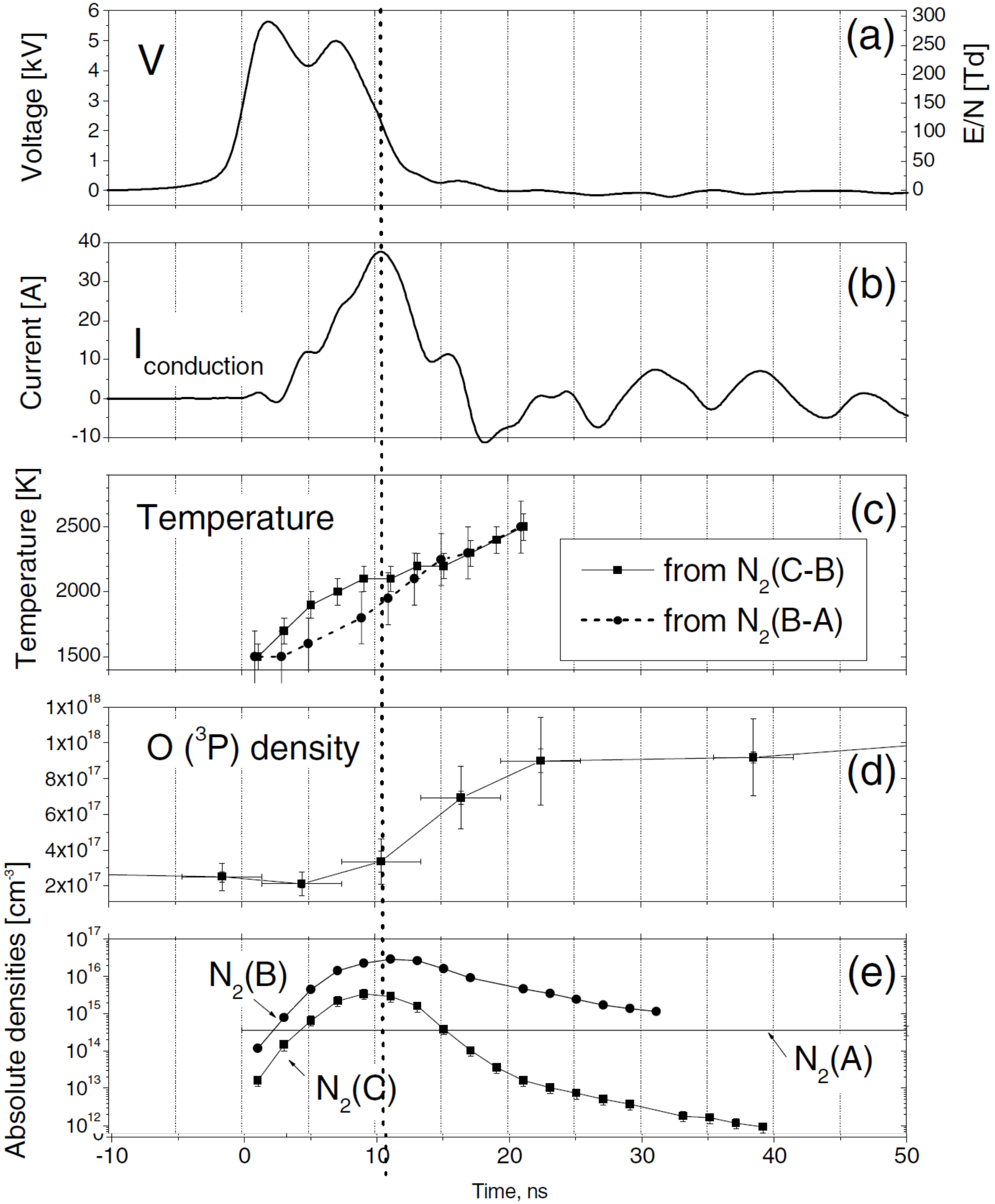
Popov, Plasma Phys. Rep., 2001

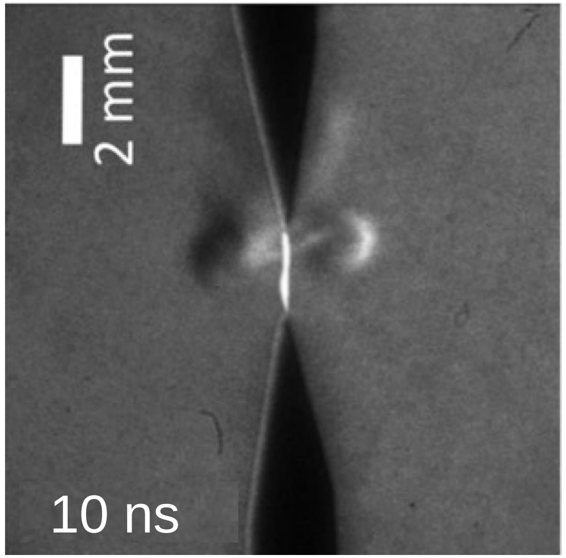
Rusterholtz et al., J. Phys. D: Appl. Phys., 2013



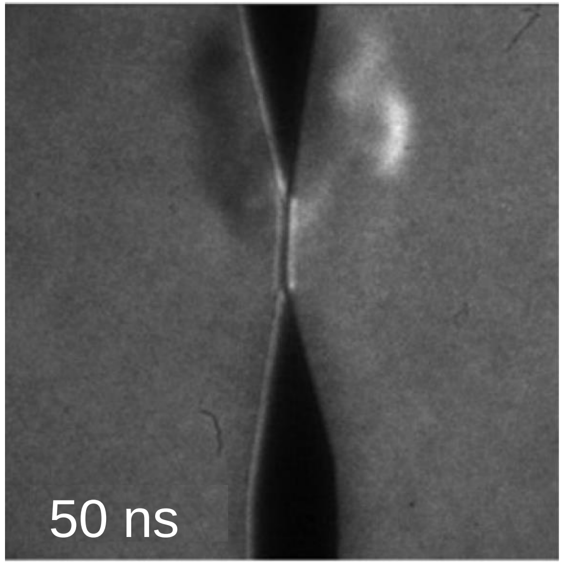
NRP discharges

In ambient air

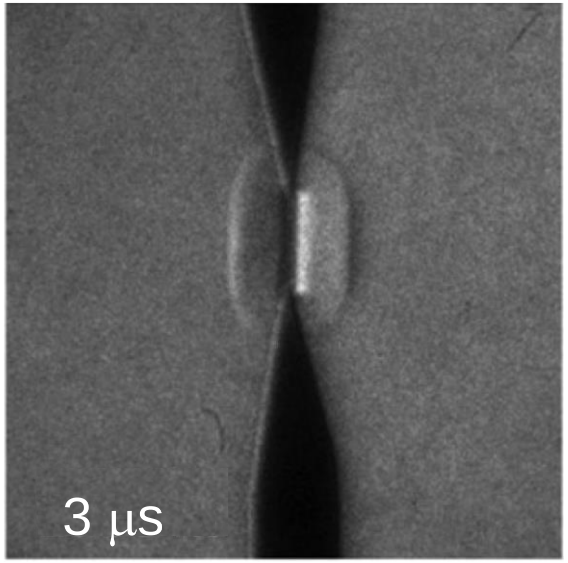
NRP spark discharges at 1 kHz



Light emission



Heated channel

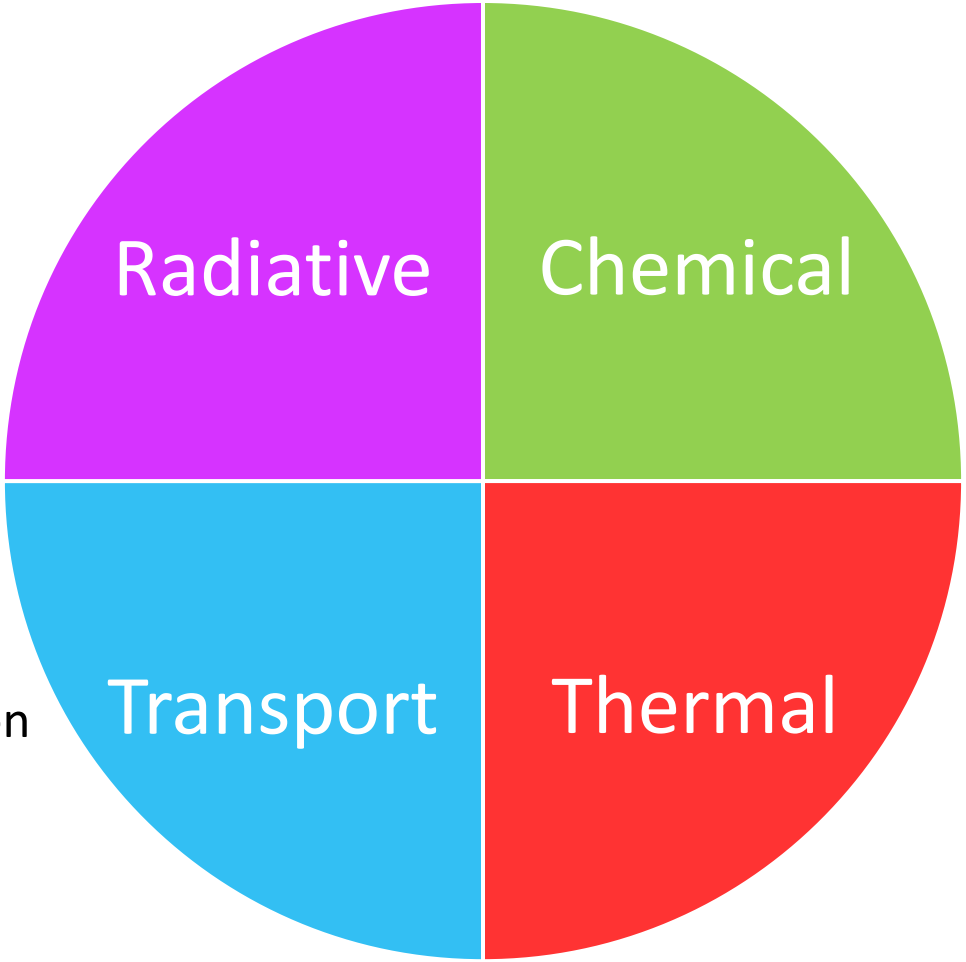


Shock wave

Xu et al., Appl. Phys. Lett., 2011

NRP discharges

- UV light
- Visible light



- Atoms: O, H, N…
- Excited species: N_2 (A, B, C…)
- Molecules: NO, CH_3, O_3…

- Shock waves
- Gas expansion
- Diffusion

- Fast gas heating
- Slow gas heating

Content

Nanosecond repetitively pulsed (NRP) discharges

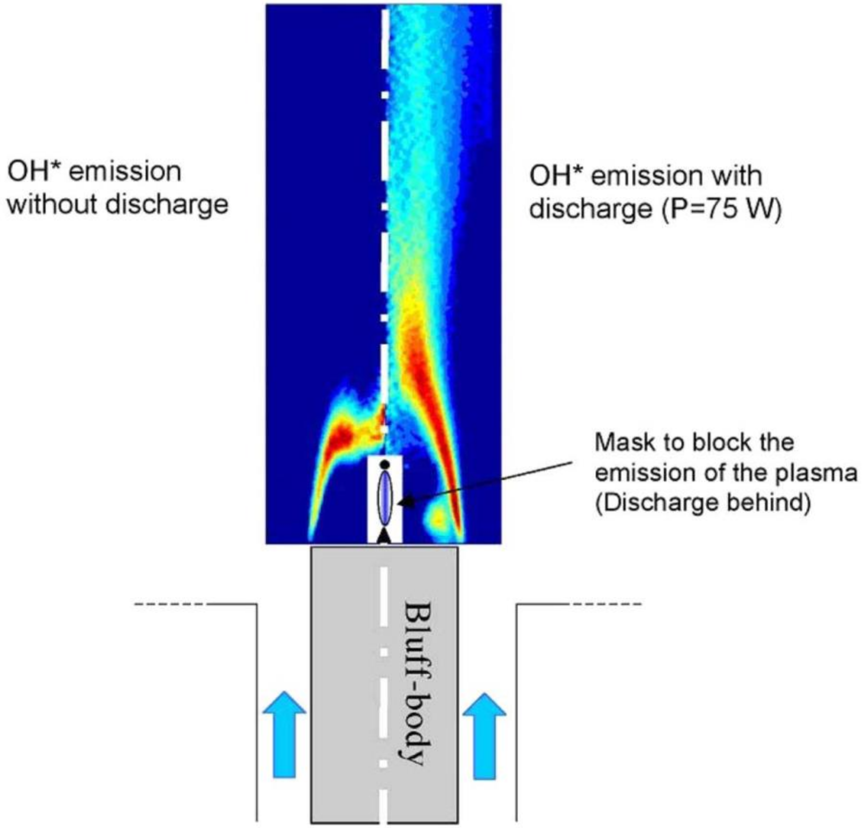
Enhancement of the lean stability limit

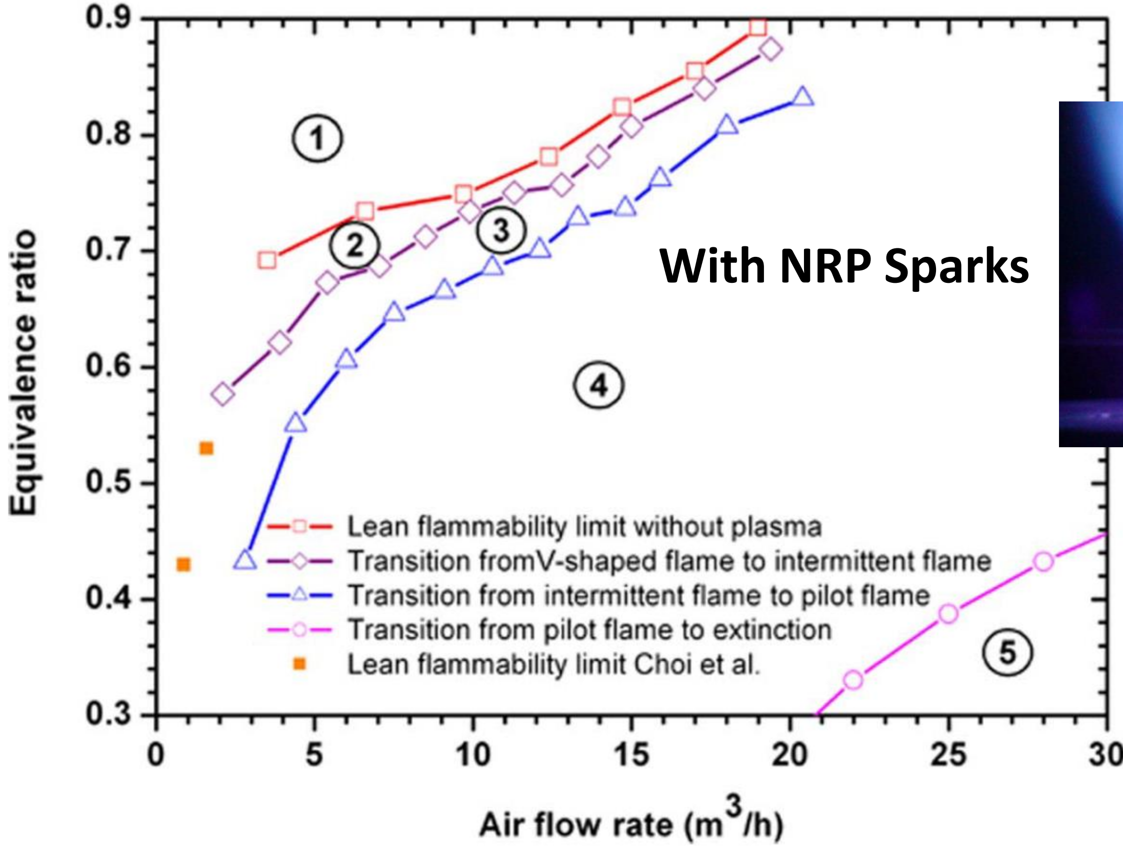
Control of thermoacoustic instabilities

Enhancement of the lean stability limit

At atmospheric pressure: by thermal and chemical effect

C_3H_8-air jet flame - NRP spark discharges at 30 kHz





With NRP Sparks

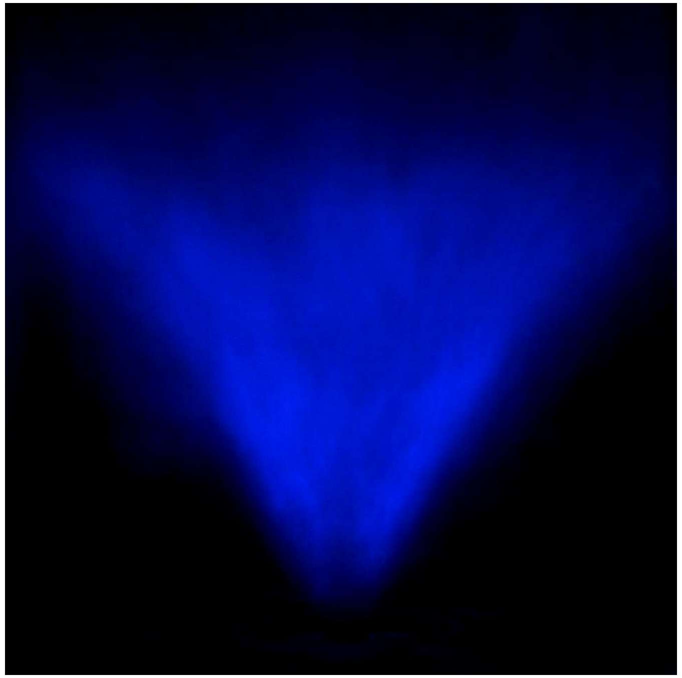
Pilla et al., IEEE Trans. Plasma Sci., 2006

Enhancement of the lean stability limit

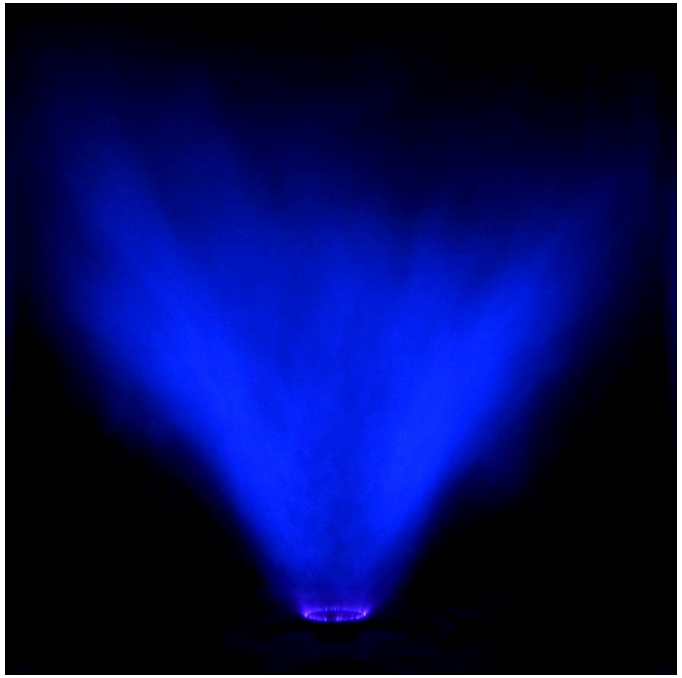
At pressures up to 5 bar: by promotting the chemical effect

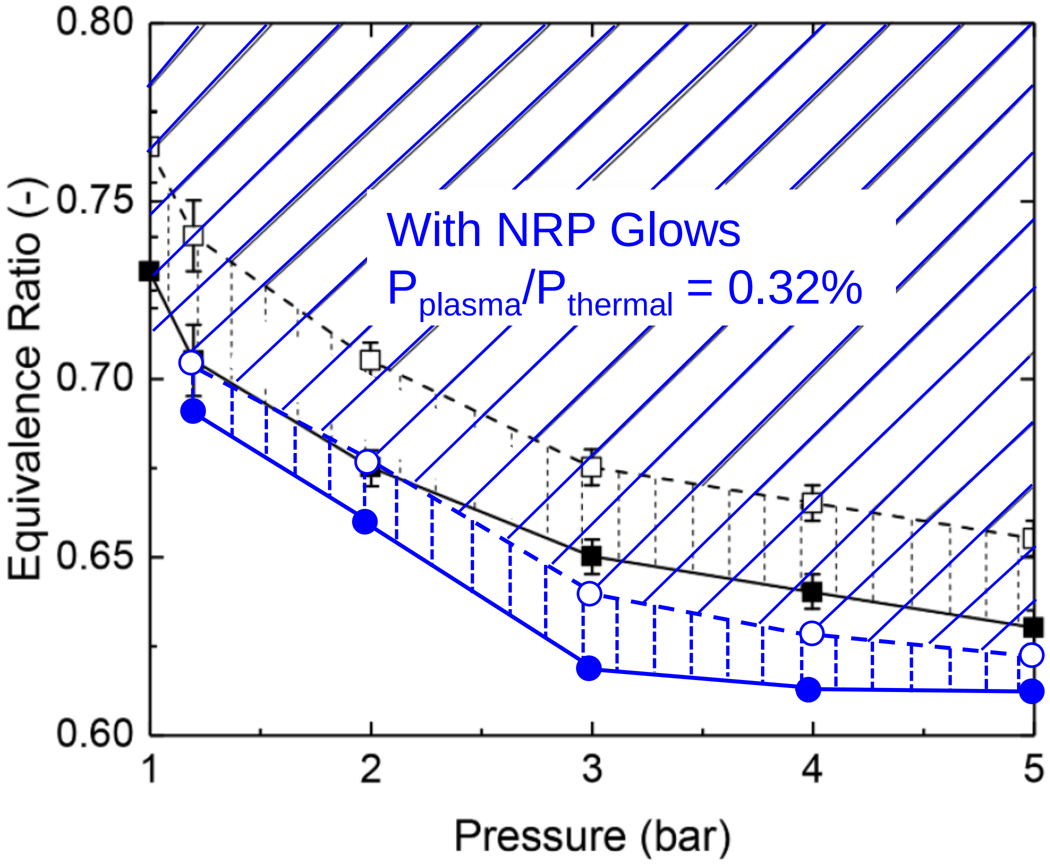
CH_4-air swirl flame - NRP glow discharges at 30 kHz

Flame at 3 bar, Φ = 0.67



With NRP Glows

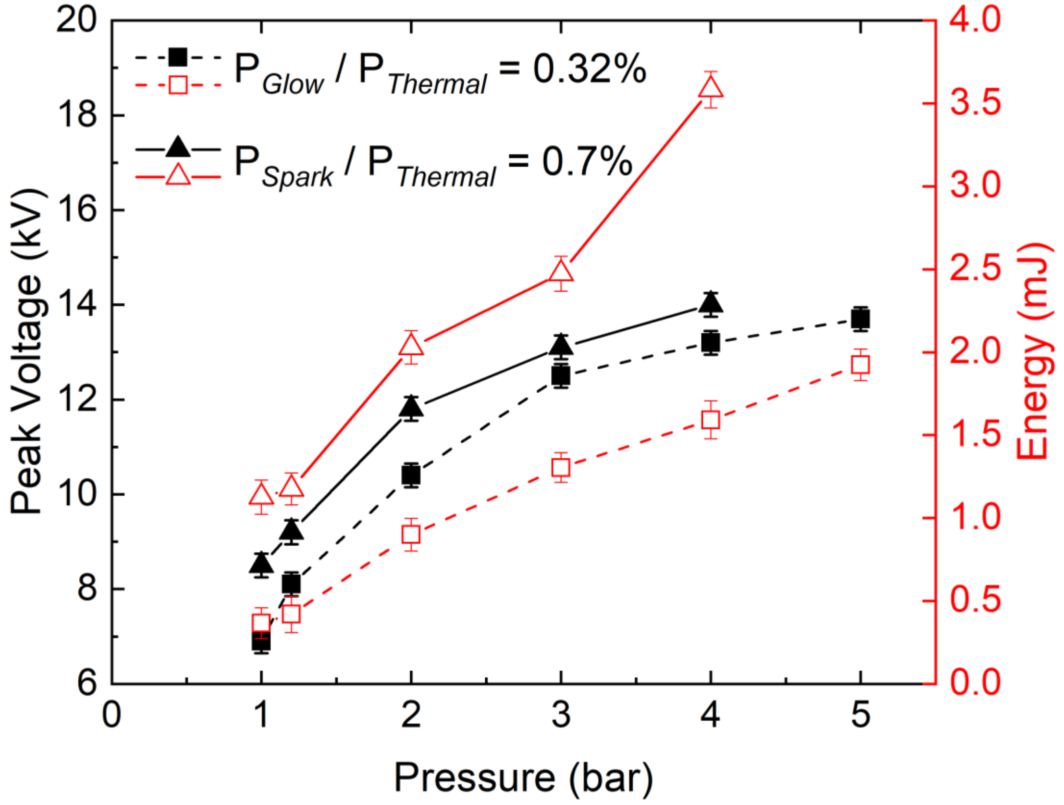


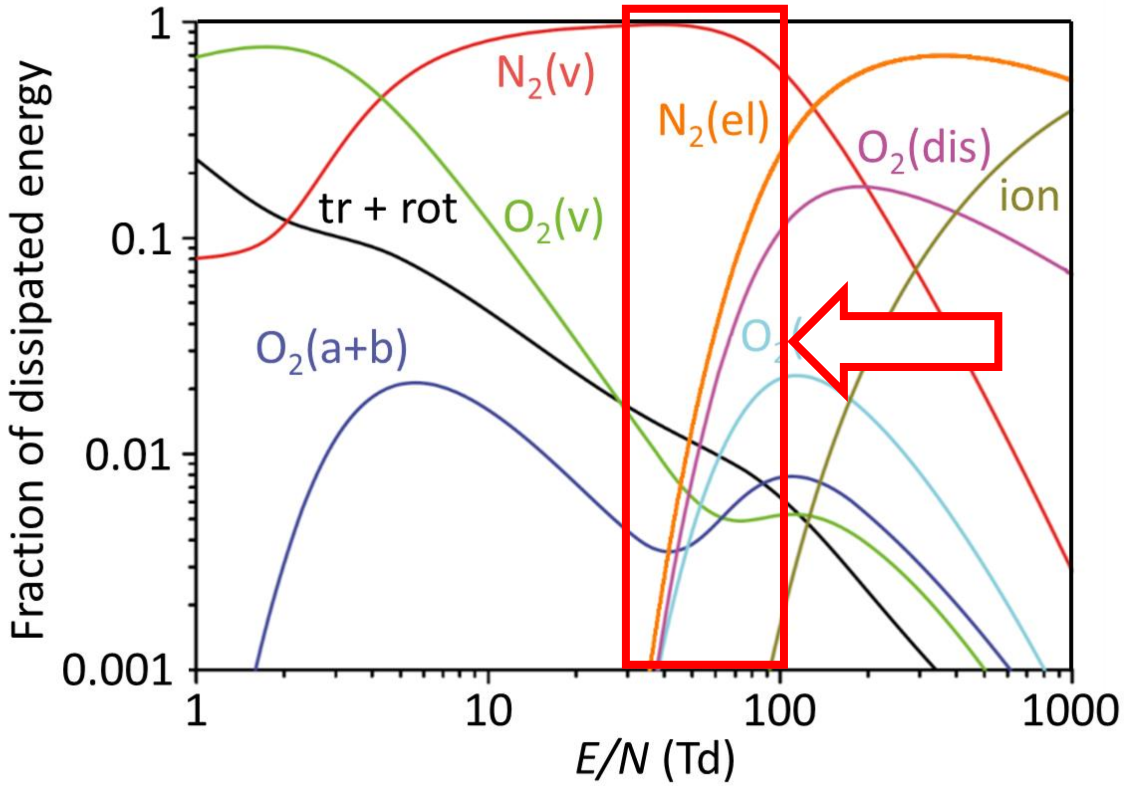


Di Sabatino and Lacoste, J. Phys. D: Appl. Phys., 2020

Enhancement of the lean stability limit

At pressures up to 5 bar:



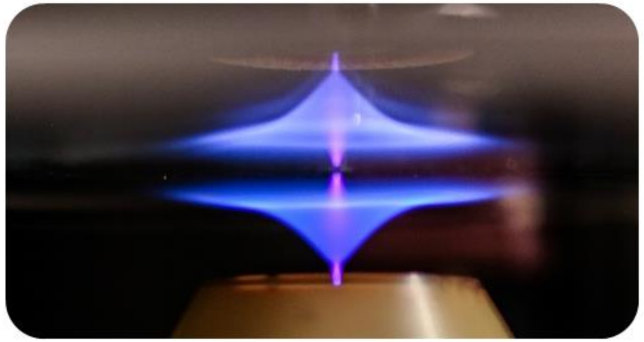


NRP glow discharges at high pressure: **Chemical effect** + **Slow gas heating**

Content

Nanosecond repetitively pulsed (NRP) discharges

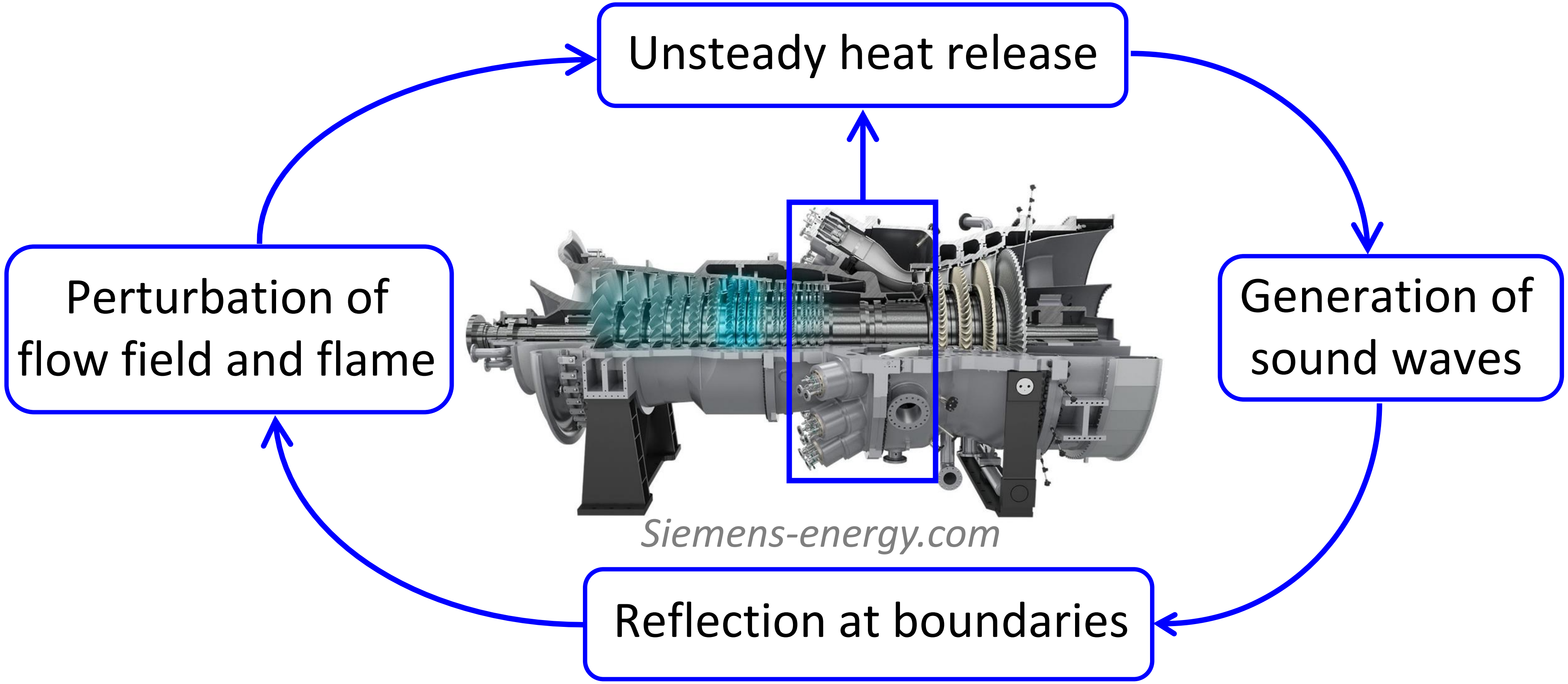
Enhancement of the lean stability limit



Control of thermoacoustic instabilities

Thermoacoustic instabilities

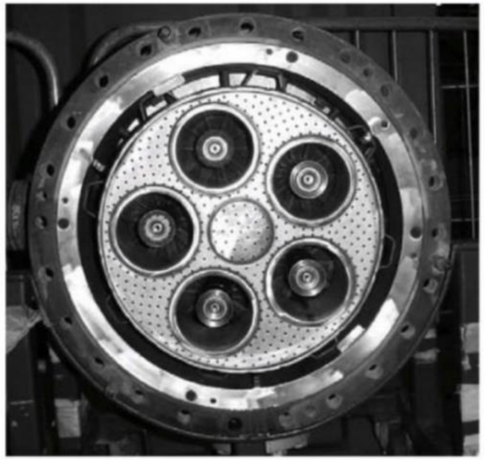
Coupling between unsteady heat release rate and acoustic modes of an engine



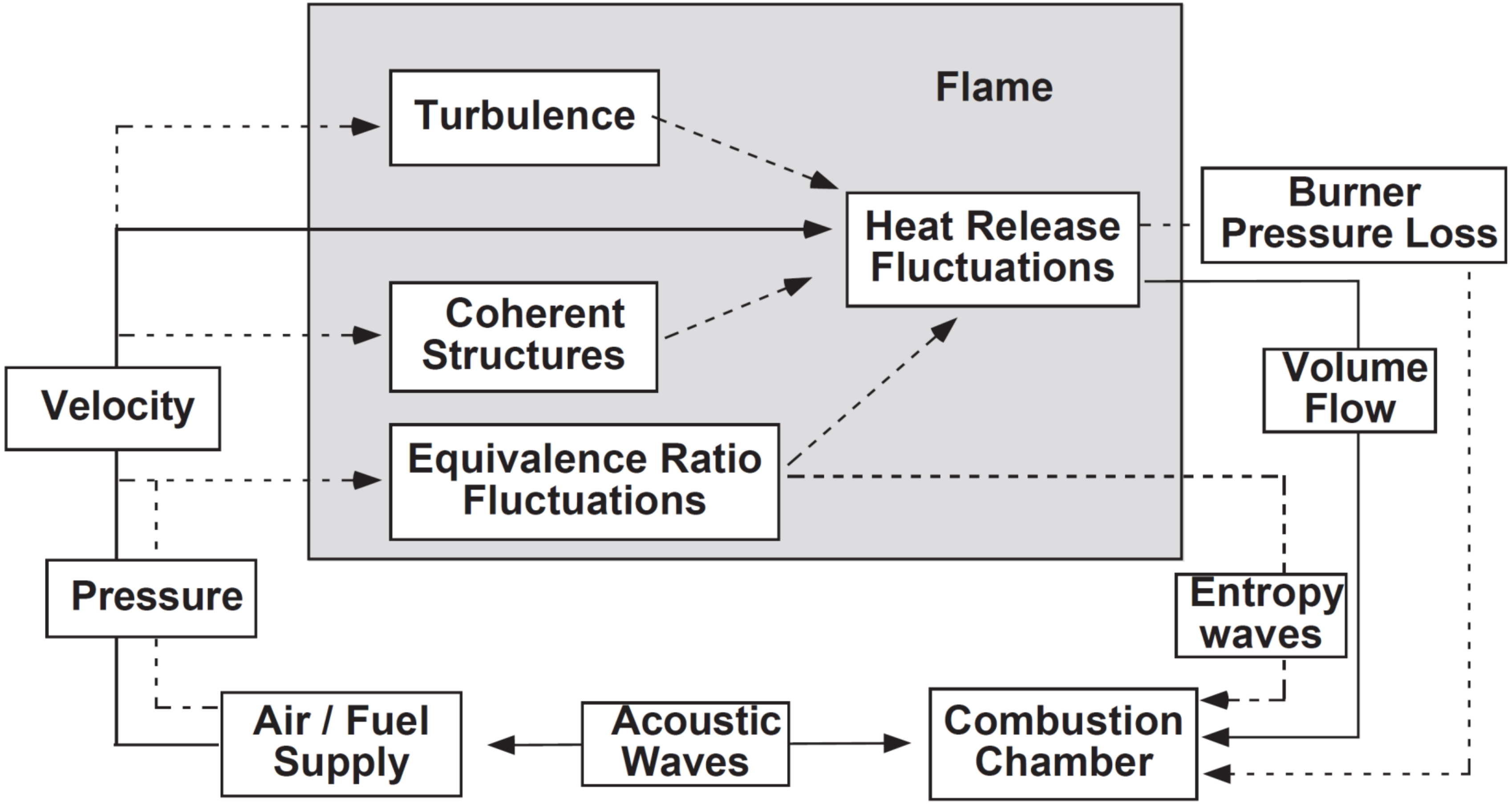
Thermoacoustic instabilities

Coupling between unsteady heat release rate and acoustic modes of an engine



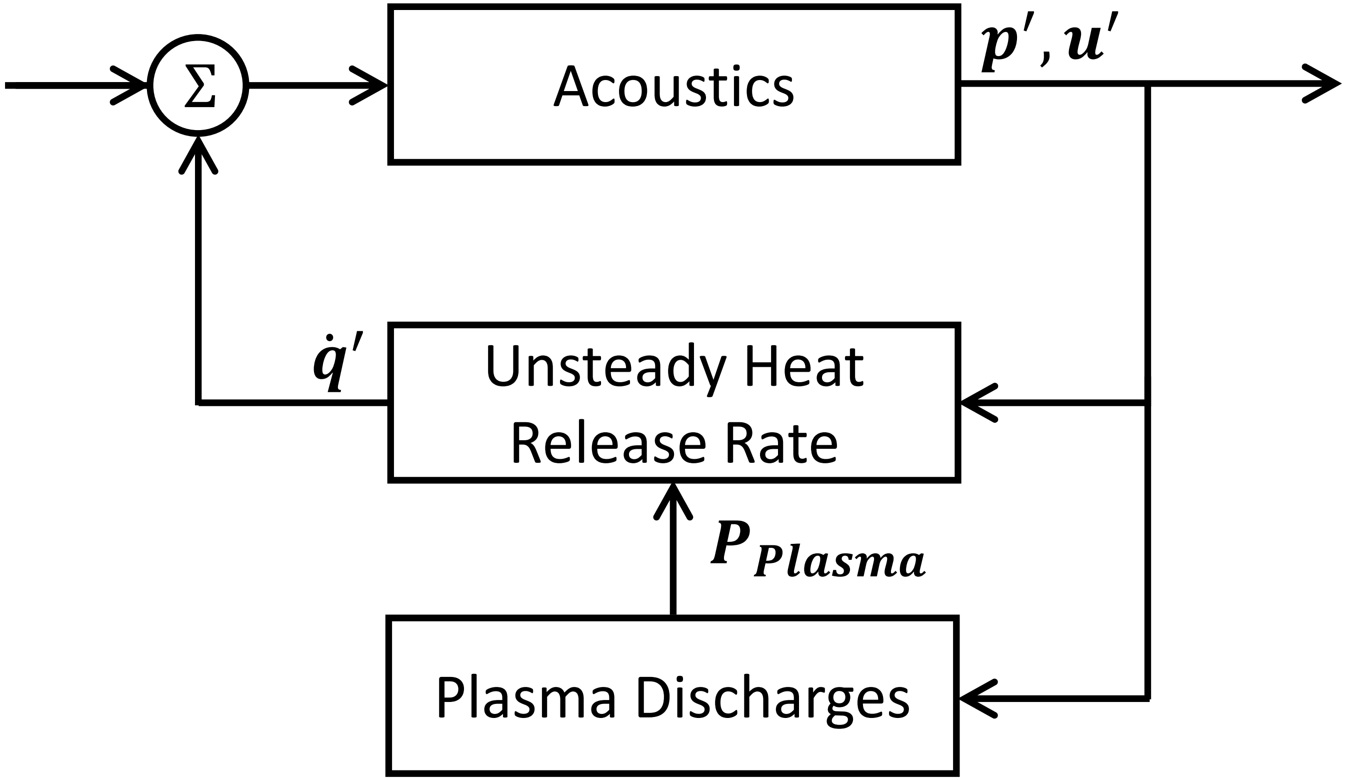



Thermoacoustic instabilities



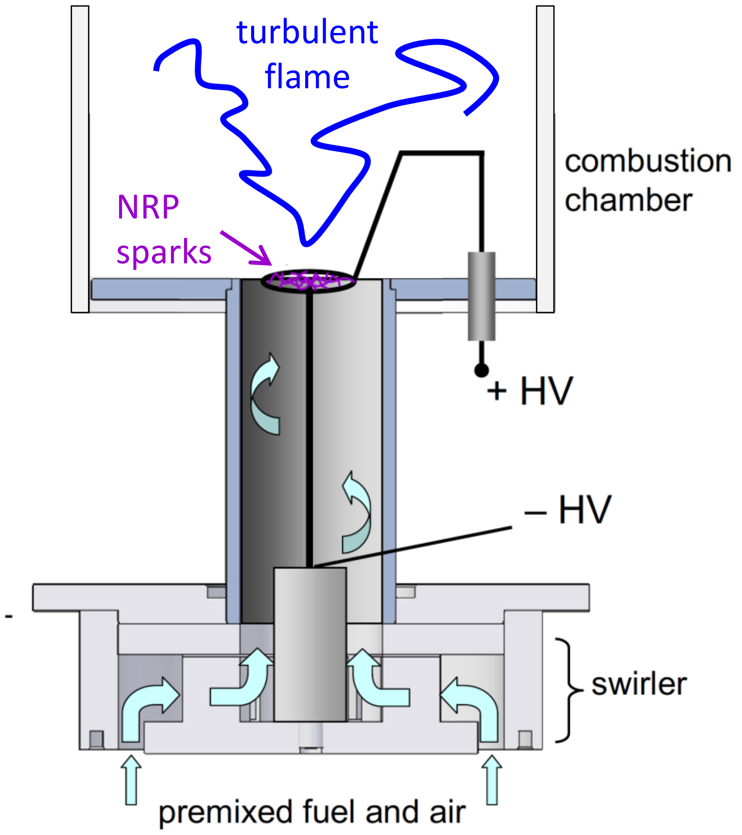
Polifke, Combustion Instabilities, 2004

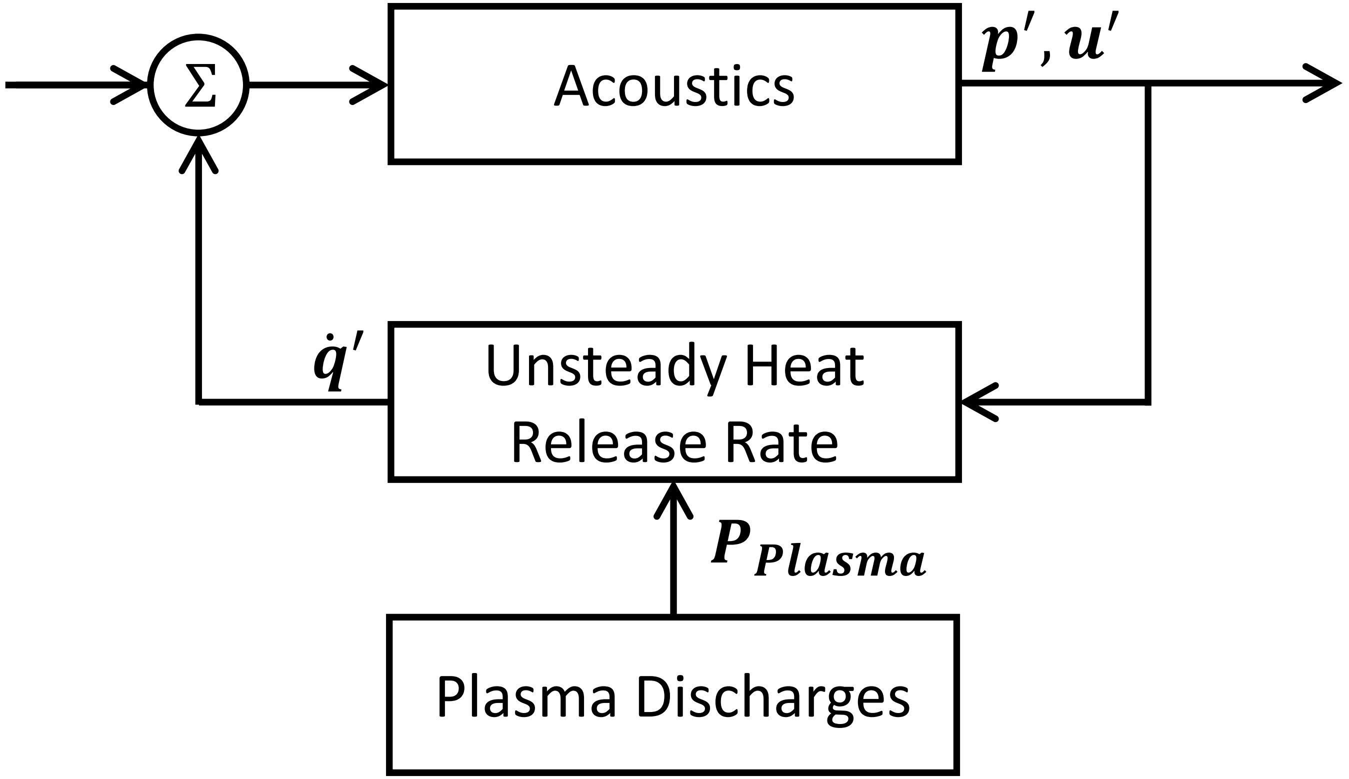
Thermoacoustic instabilities



With NRP sparks

43-kW CH_4-air flame at P = 1 bar – 350-W NRP spark discharges at 50 kHz





Moeck et al., AIAA 2013-0565, 2013

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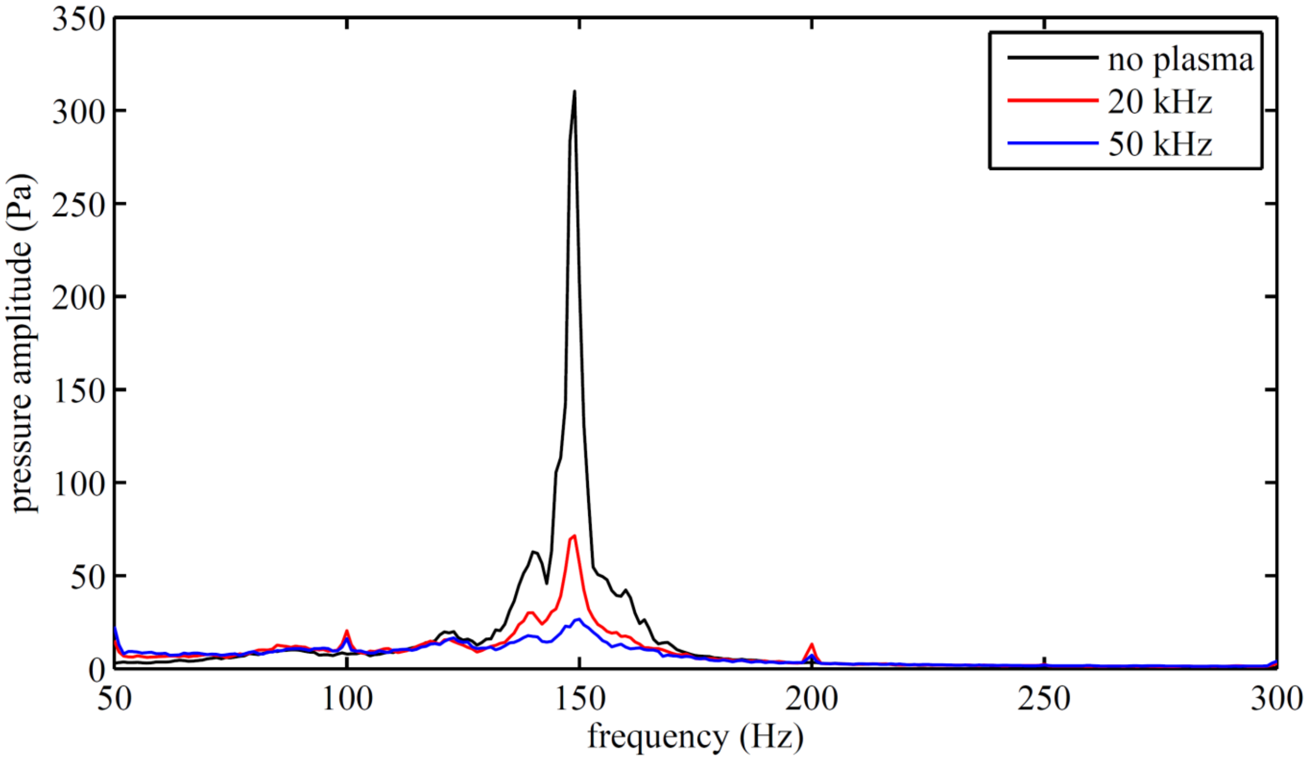

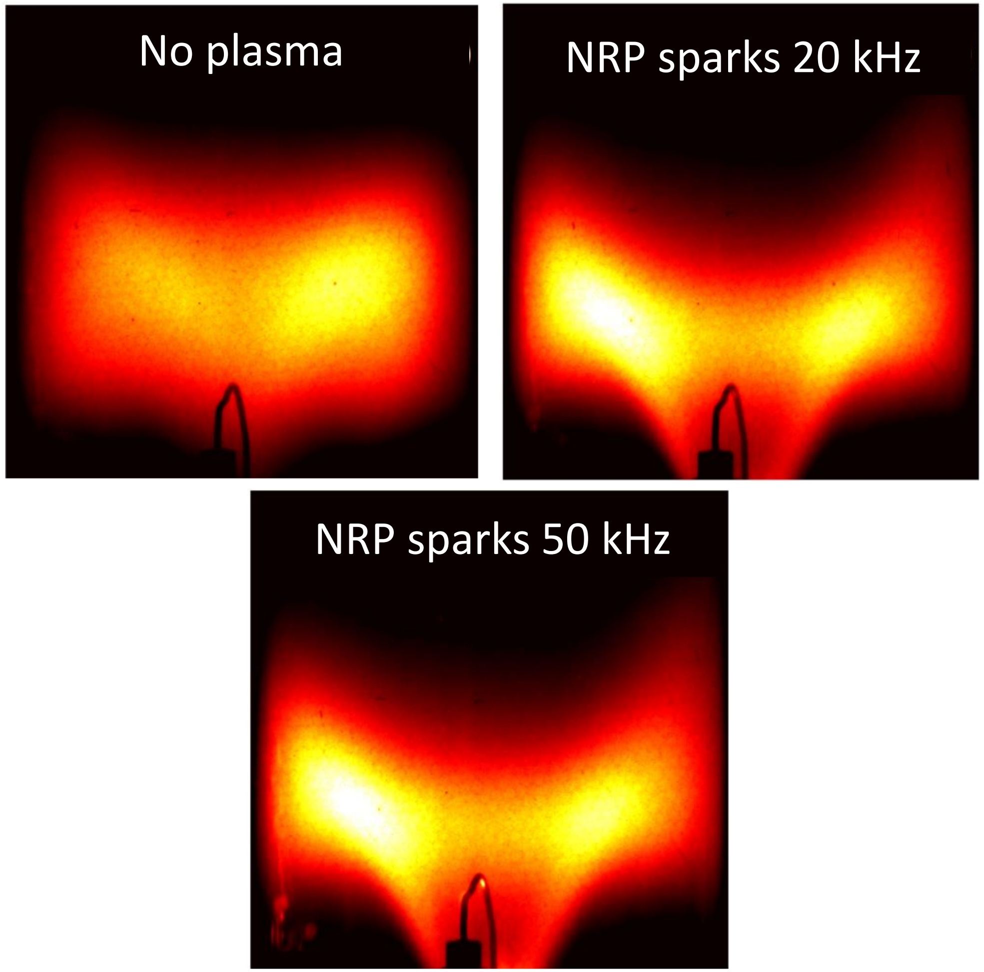

Moeck et al., AIAA 2013-0565, 2013

With NRP sparks

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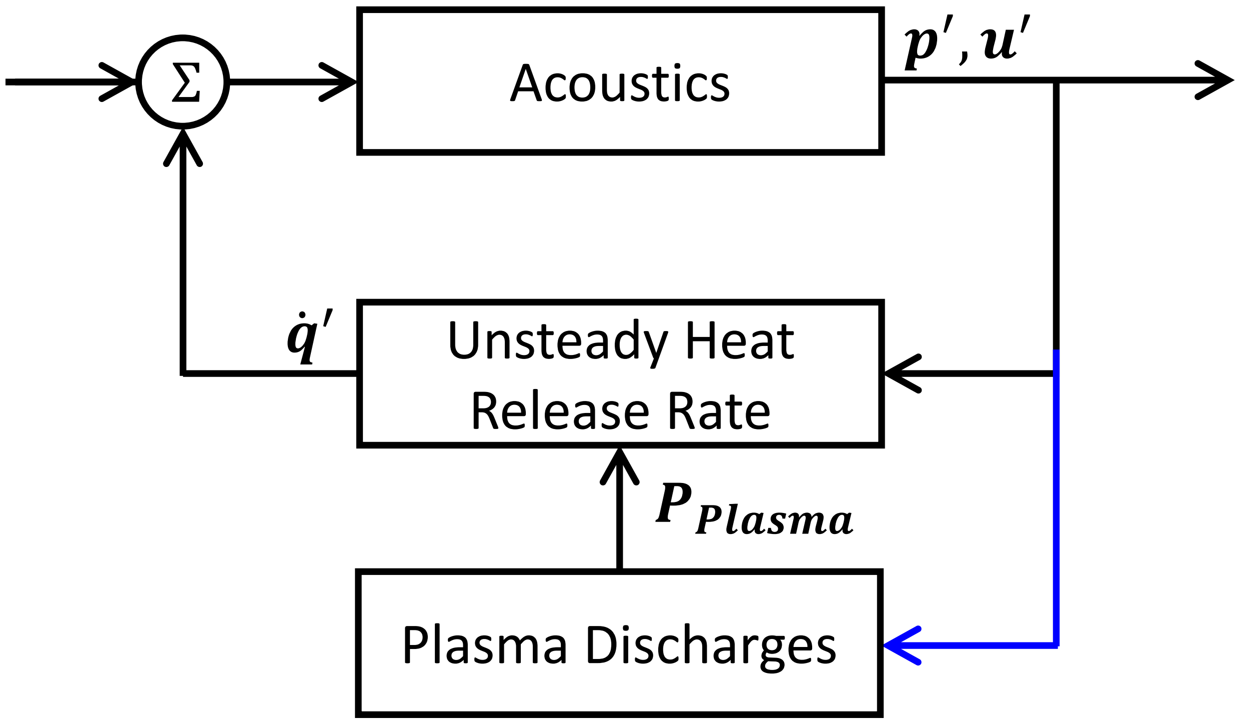
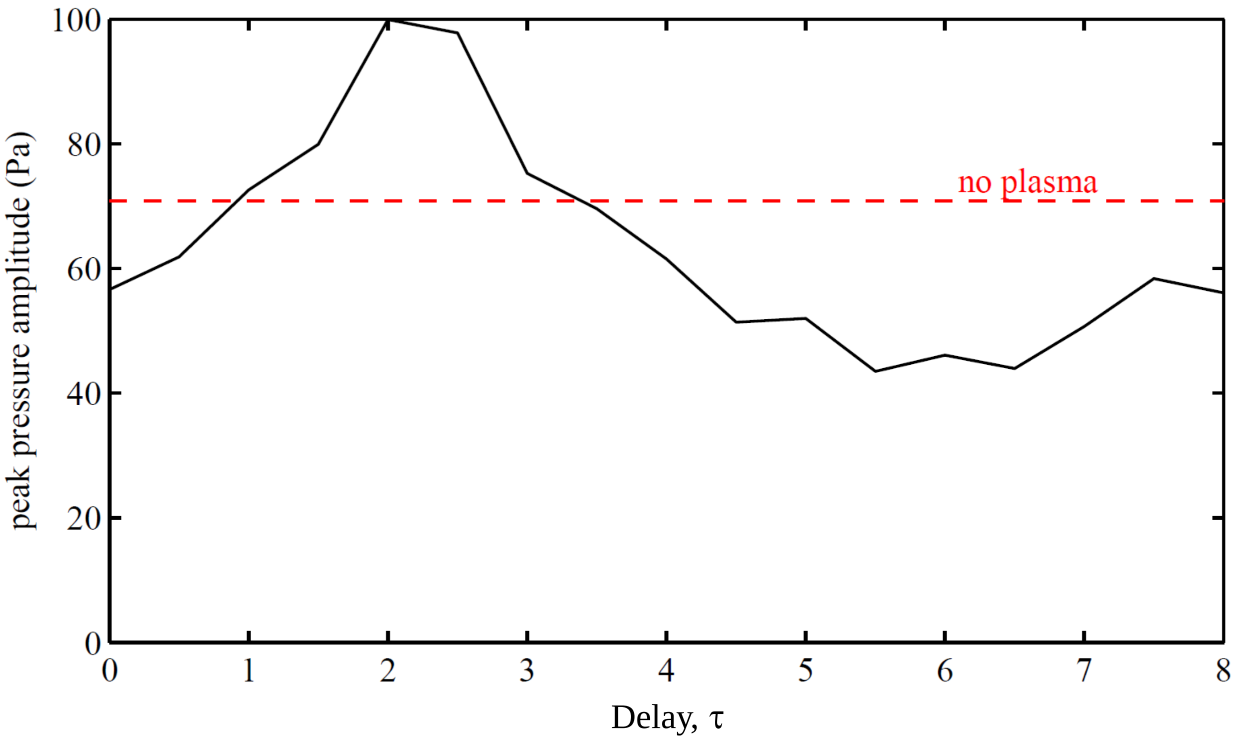
Close-loop control scheme





Moeck et al., AIAA 2013-0565, 2013

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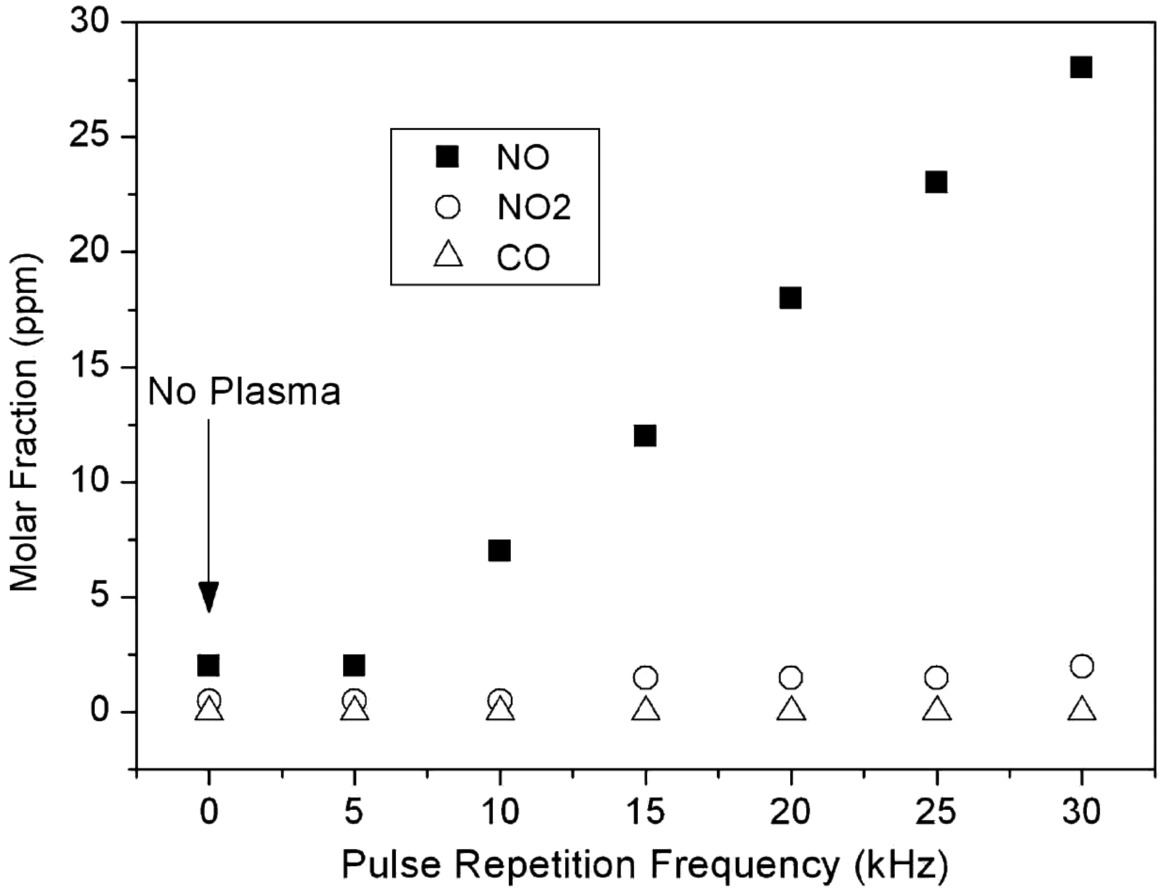
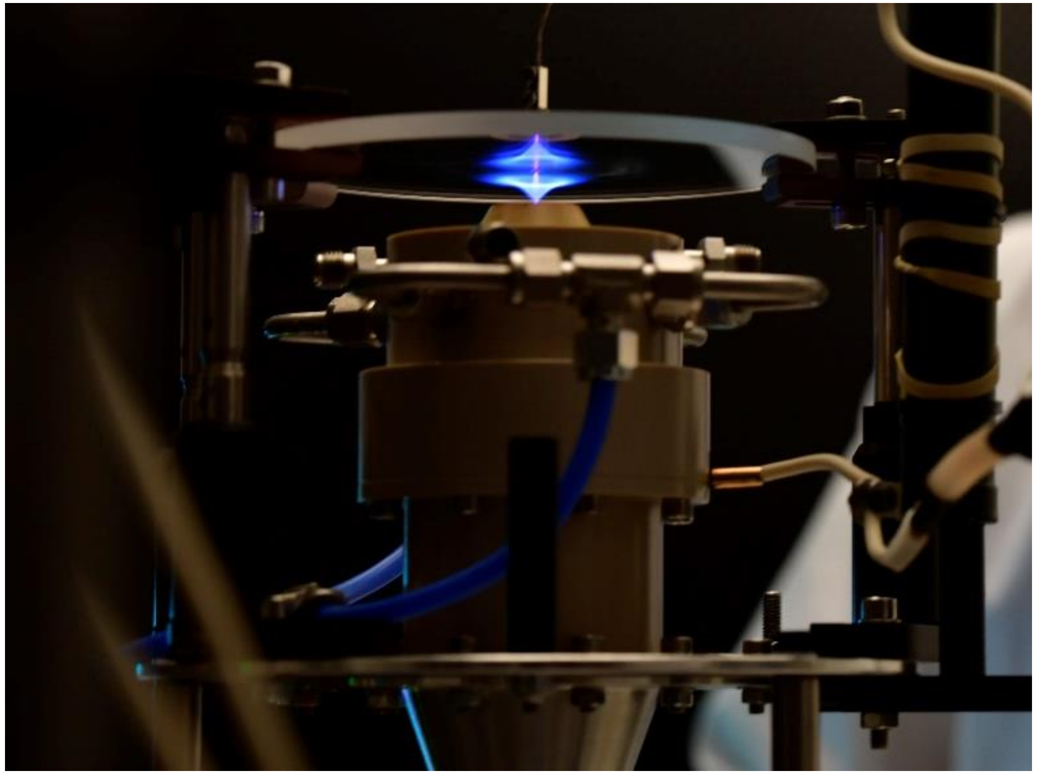
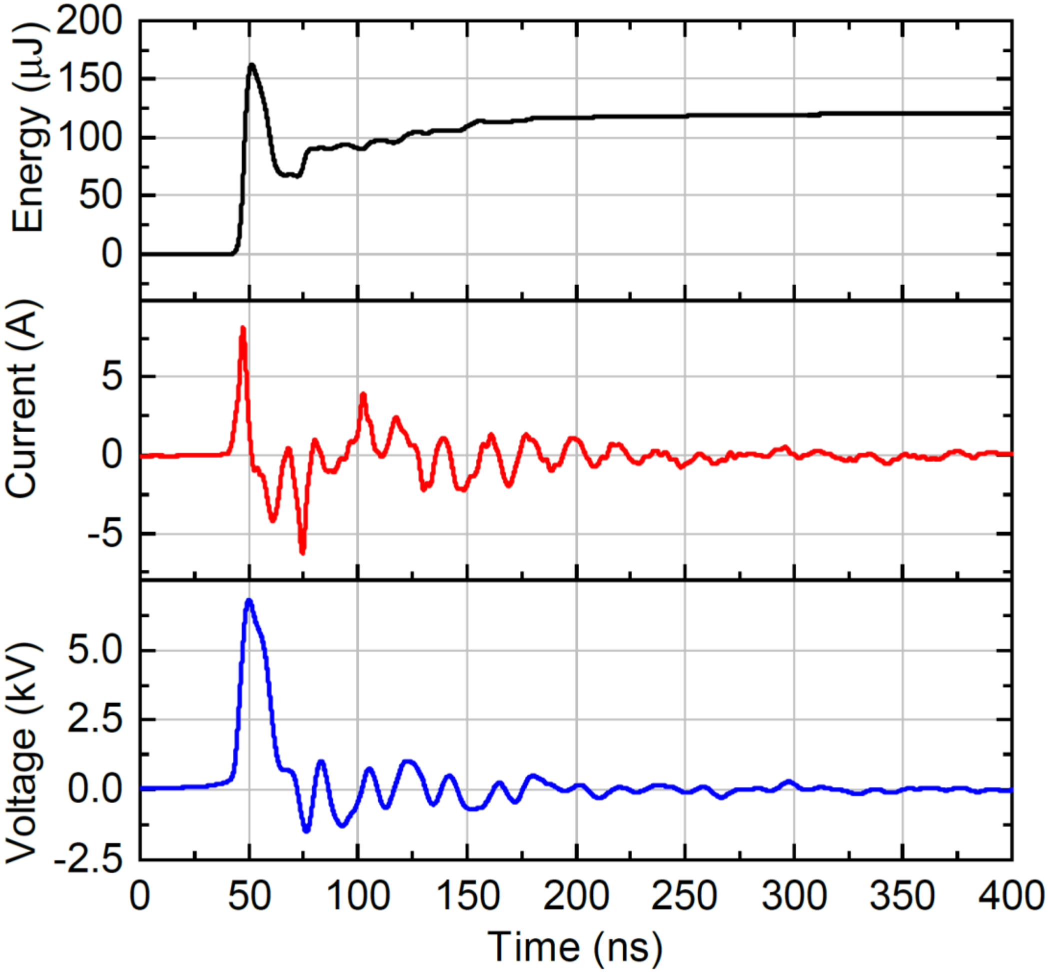


Lacoste et al., J. Propuls. Power, 2013

With NRP glows

200-W CH_4-air flame at P = 1 bar – 2-W NRP glow discharges





Alkhalifa et al., Proc. Combust. Inst., 2023

With NRP glows

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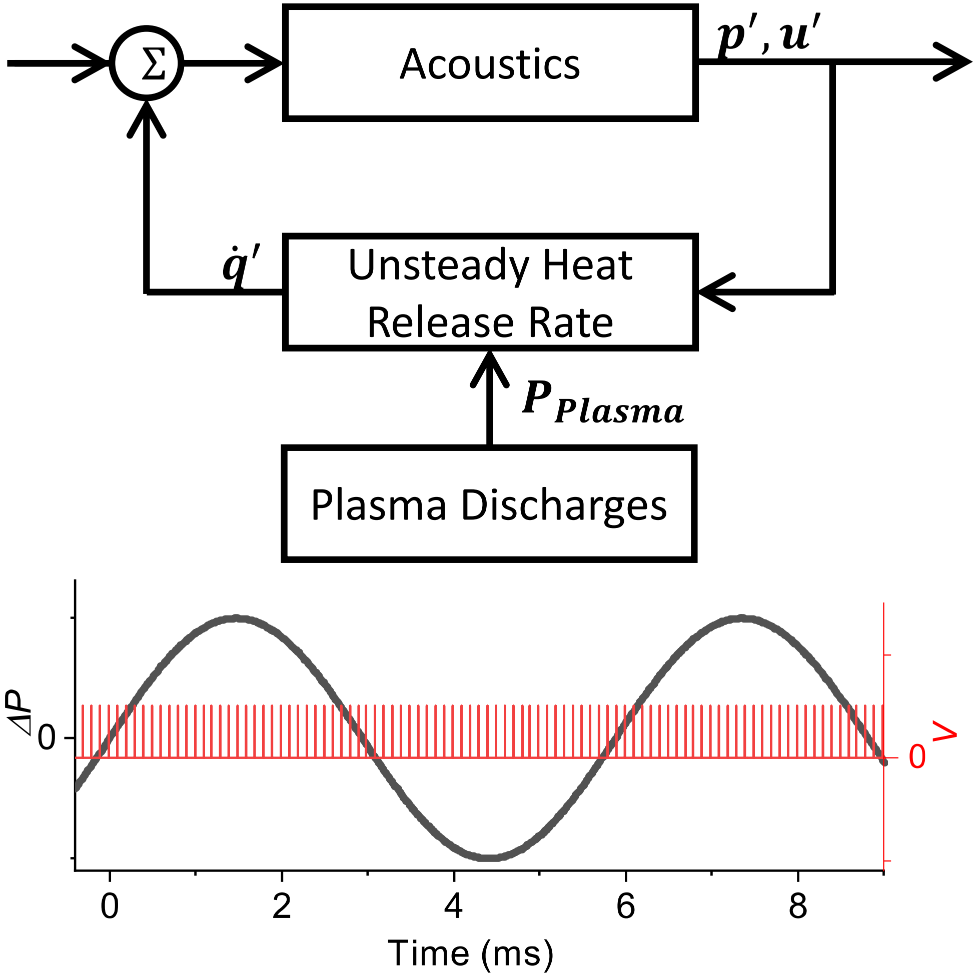
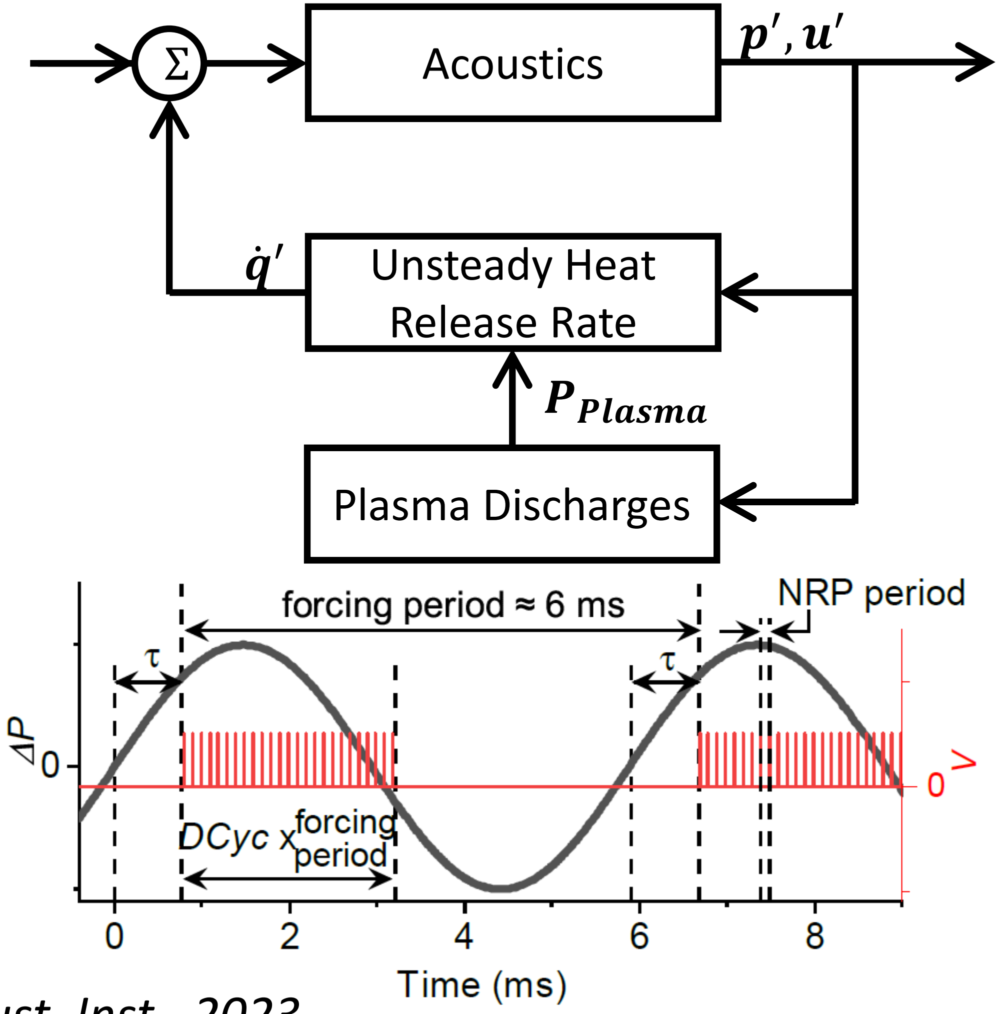
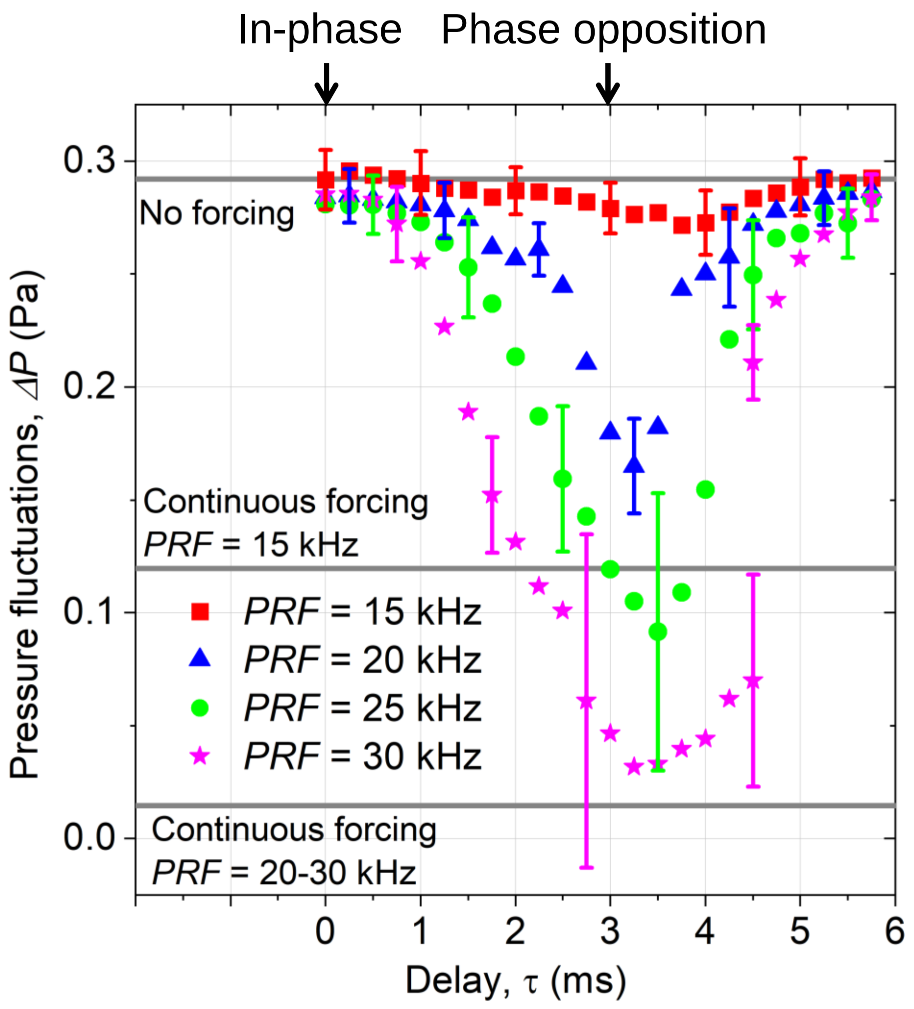




Alkhalifa et al., Proc. Combust. Inst., 2023

With NRP glows: effect of PRF

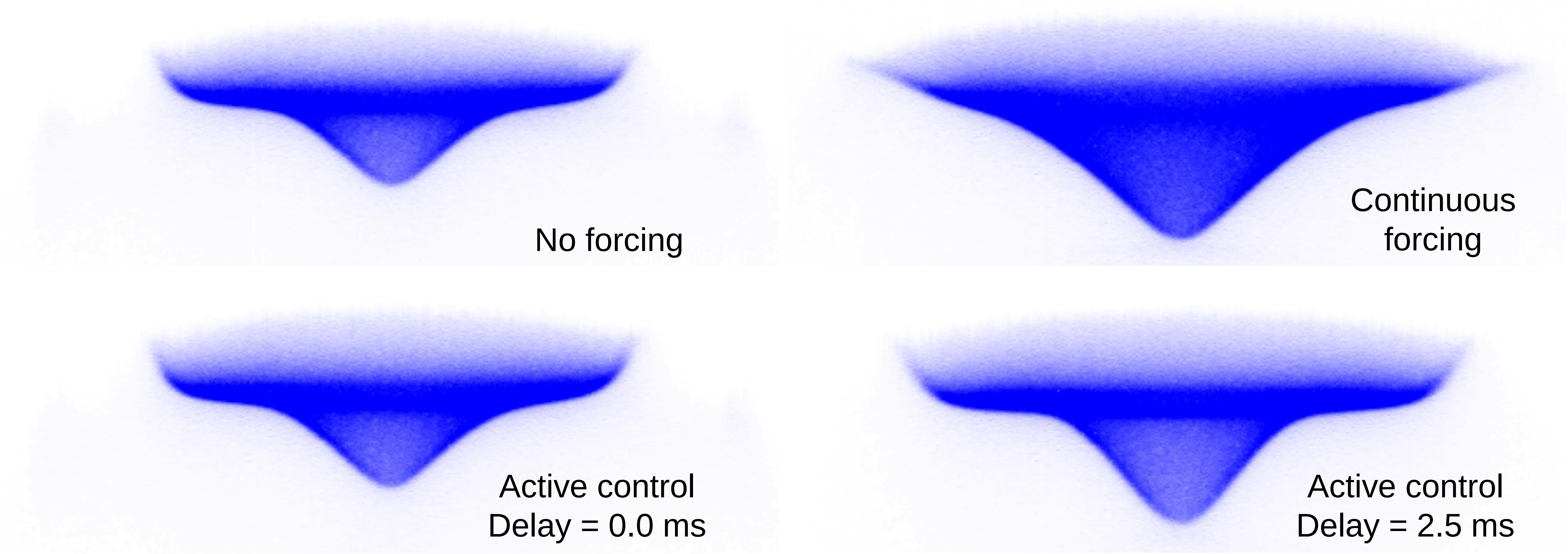


- Best control scheme (0.8% of flame's thermal power) :
  - Forcing frequency = acoustic frequency
  - PRF = 30 kHz
  - Plasma forcing in phase opposition with acoustics

- Active control allows saving 25% of the power required by continuous forcing

Alkhalifa et al., Proc. Combust. Inst., 2023

With NRP glows



Alkhalifa et al., Proc. Combust. Inst., 2023

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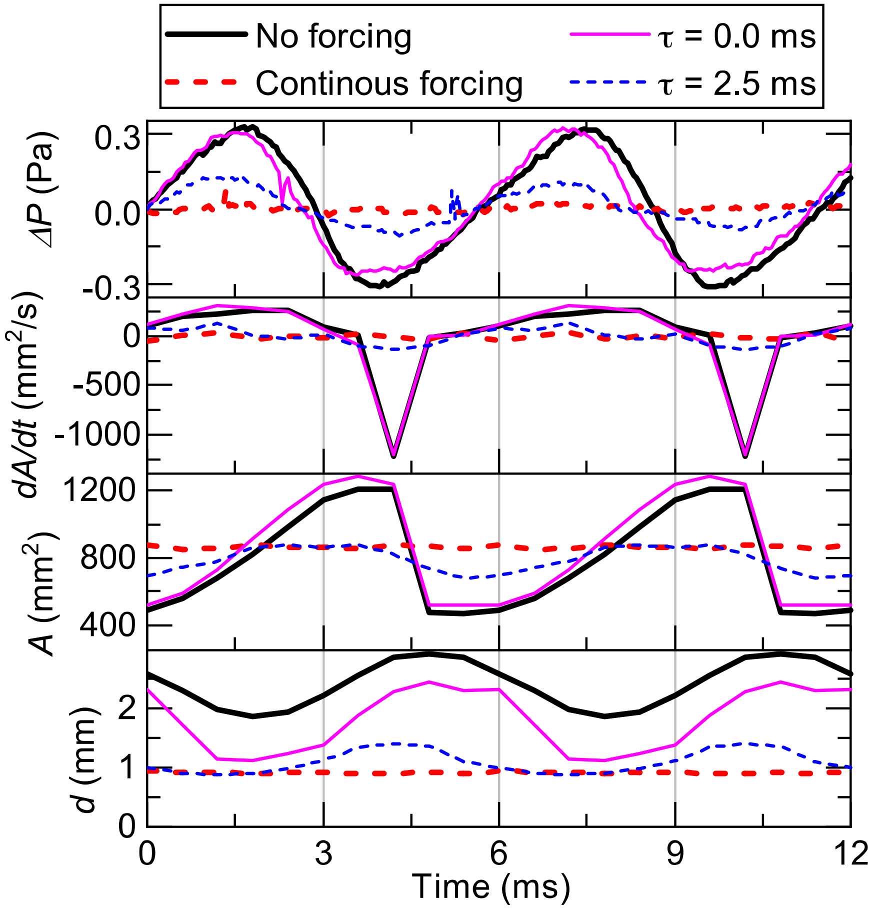


Mechanism of plasma actuation:

- Suppress the fluctuation of flame surface area
- Reduce the response of the flame to acoustic perturbations (anchoring effect)

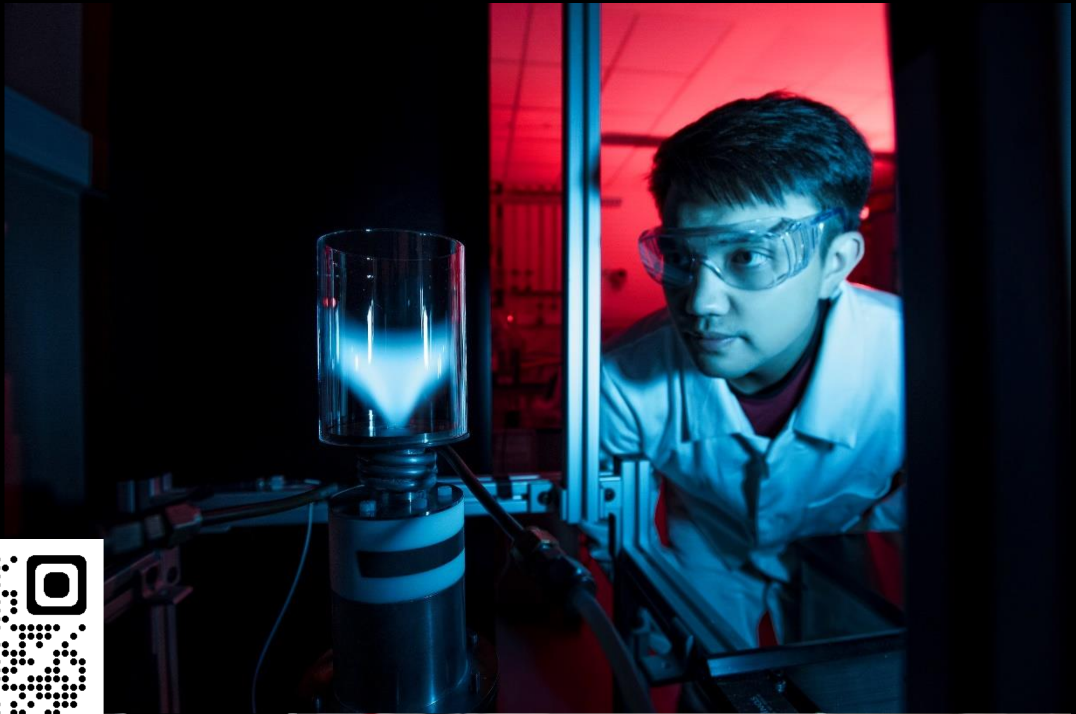
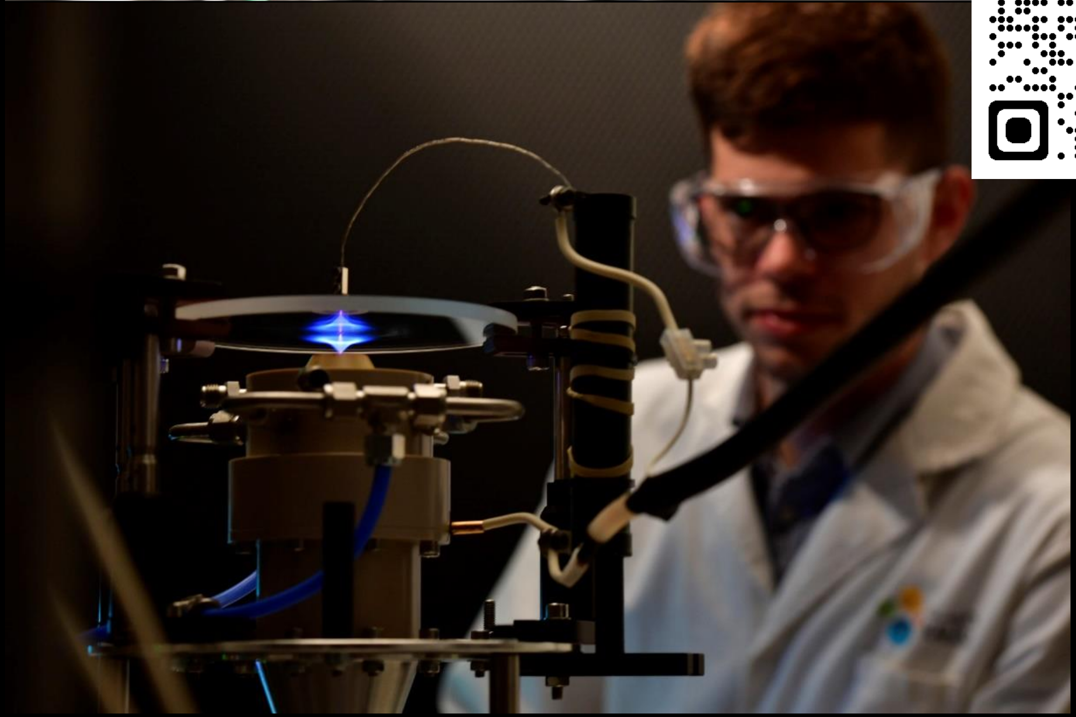
Alkhalifa et al., Proc. Combust. Inst., 2023

Non-equilibrium plasmas for climate change mitigation

It’s working!

Things to do next:

1. Demonstrate plasma actuation on other types of instabilities
2. Demonstrate plasma actuation at higher pressures (10-20 bar)
3. Quantify and control pollutant emissions in PACCI
4. Demonstrate plasma actuation for carbon-free fuels


KAUST



Newport