A New Tunnel for Ignition Research

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IC engine	~ 1-10 m/s
Gas turbine combustor	~ 10 m/s
Scramjet cavity	~ 10-100 m/s

Ignition problems! (gas turbine combustor, scramjet cavity)

Two cases:

- High-altitude relight of gas turbines [1]
- Ignition of high-speed engines [2]


U.S. Air Force photo/Chad Bellay

[1] J. G. O'Connor, Starting system for gas turbine engines, *U.S. Patent No. 3,426,527* (1969).
[2] L. S. Jacobsen et al., Plasma-assisted ignition in scramjets, *Journal of Propulsion and Power* 24 (2008) 4, 641-654.

Flow features in high-speed combustors:

- Short flow **residence times:** ~ms
- Highly **turbulent flow** fields in the flame-holder: Re ~ 10^5

Challenges for ignition:

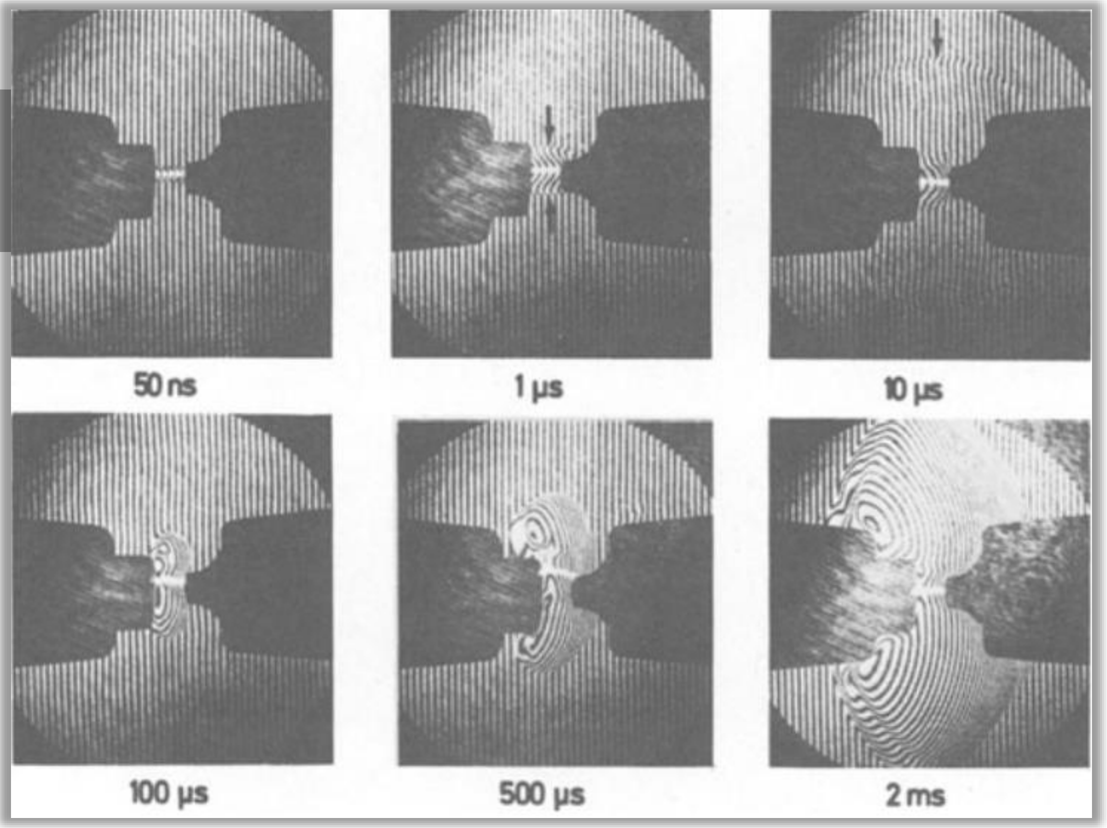
- Establishment in the order of **milliseconds**
- Avoiding **quenching of the kernel** in the turbulent environment

1. Overview of ignition methods:

1984

Optimal method for **quiescent** mixtures:

Single "breakdown" DC discharge: ~10 ns [3]



[3] R. Maly, Spark ignition: its physics and effect on the internal combustion engine, *Fuel economy*, Springer, Boston, MA (1984) 91-148.

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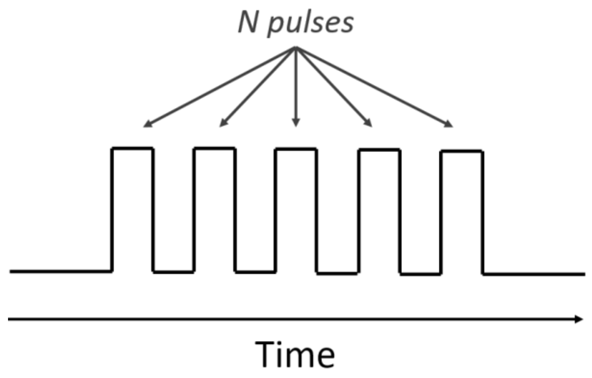
Even better for **quiescent** mixtures:
Repetitive “breakdown” discharges: ~10 ns, ~30 kHz [4]



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[4] S. V. Pancheschnyi et al., Ignition of propane-air mixtures by a repetitively pulsed nanosecond discharge, *IEEE Transactions on Plasma Science* 34 (2006) 6, 2478-2487.

1. Overview of ignition methods:

NANOSECOND
PULSED
HIGH
FREQUENCY
DISCHARGE

- High voltage: 10 – 100 kV
- Short periods of time: 1 – 100 ns
- High PRF: up to 1 MHz

ADVANTAGES:

- Much lower (2 orders of magnitude) power deposition than a DC discharge for the same average electron number density [5]
- Can be applied for a long duration, increasing the volume of gas exposed to the discharge.
- No downstream transportation and breaking of the arc in flowing mixtures.

[5] M. Nagulapally et al., Experiments and simulations of dc and pulsed discharges in air plasmas, *31st Plasmadynamics and Lasers Conference* (2000), 2417.

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Single "breakdown" DC discharge: ~10 ns [3]

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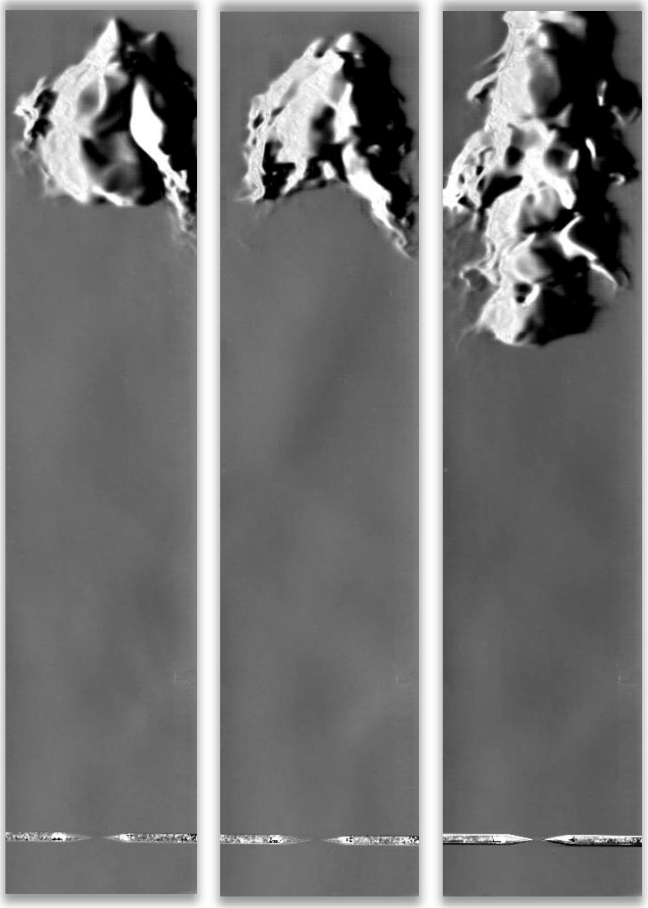
2017 — Probable optimal method for **flowing** mixtures:
NPHFD plasmas: ~10 ns, up to 300 kHz [6]



300 kHz 3.3 µs | 100 kHz 10 µs | 10 kHz 100 µs

[3] R. Maly, Spark ignition: its physics and effect on the internal combustion engine, *Fuel economy*, Springer, Boston, MA (1984) 91-148.
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[6] J. K. Lefkowitz, T. Ombrello, An exploration of inter-pulse coupling in nanosecond pulsed high frequency discharge ignition, *Combustion and Flame* 180 (2017) 136-147.

1. Overview of ignition methods:

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Parameters that determine a successful and optimal ignition:

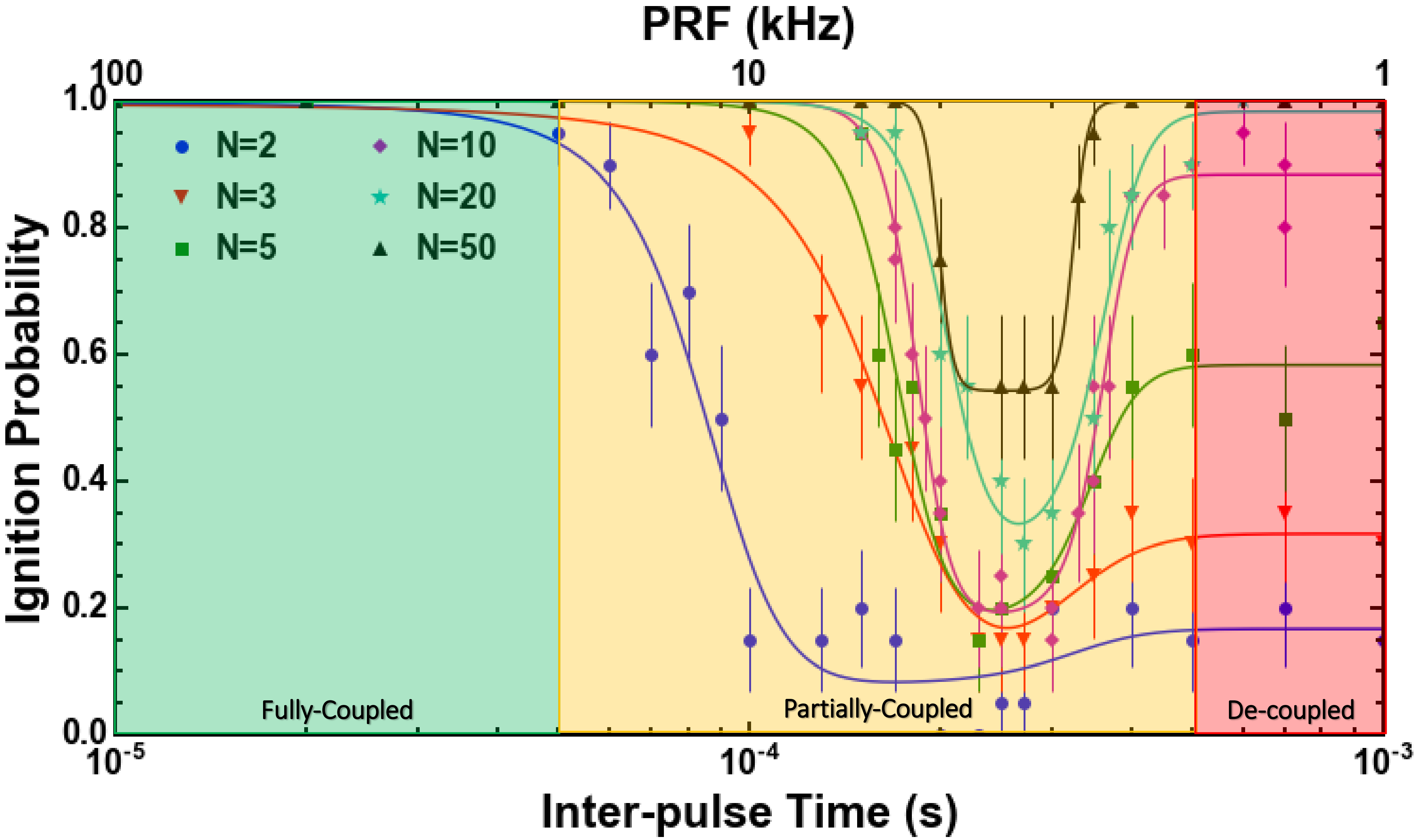
NPHFD

- Total deposited energy (E)
- Pulse repetition frequency (PRF) / Inter-pulse time (τ)
- Number of pulses (N)
- Gap distance (D)

Upstream in the flow

- Equivalence ratio (Φ)
- Flow velocity (U)
- Initial temperature (T_0)
- Initial pressure (P_0)
- Turbulence regime
- Fuel

Inter-pulse coupling phenomena



CH_4 + air
$\Phi = 0.6$
U = 10 m/s
D = 2 mm
N = 20
T_0 = 300 K
P_0 = 100 kPa

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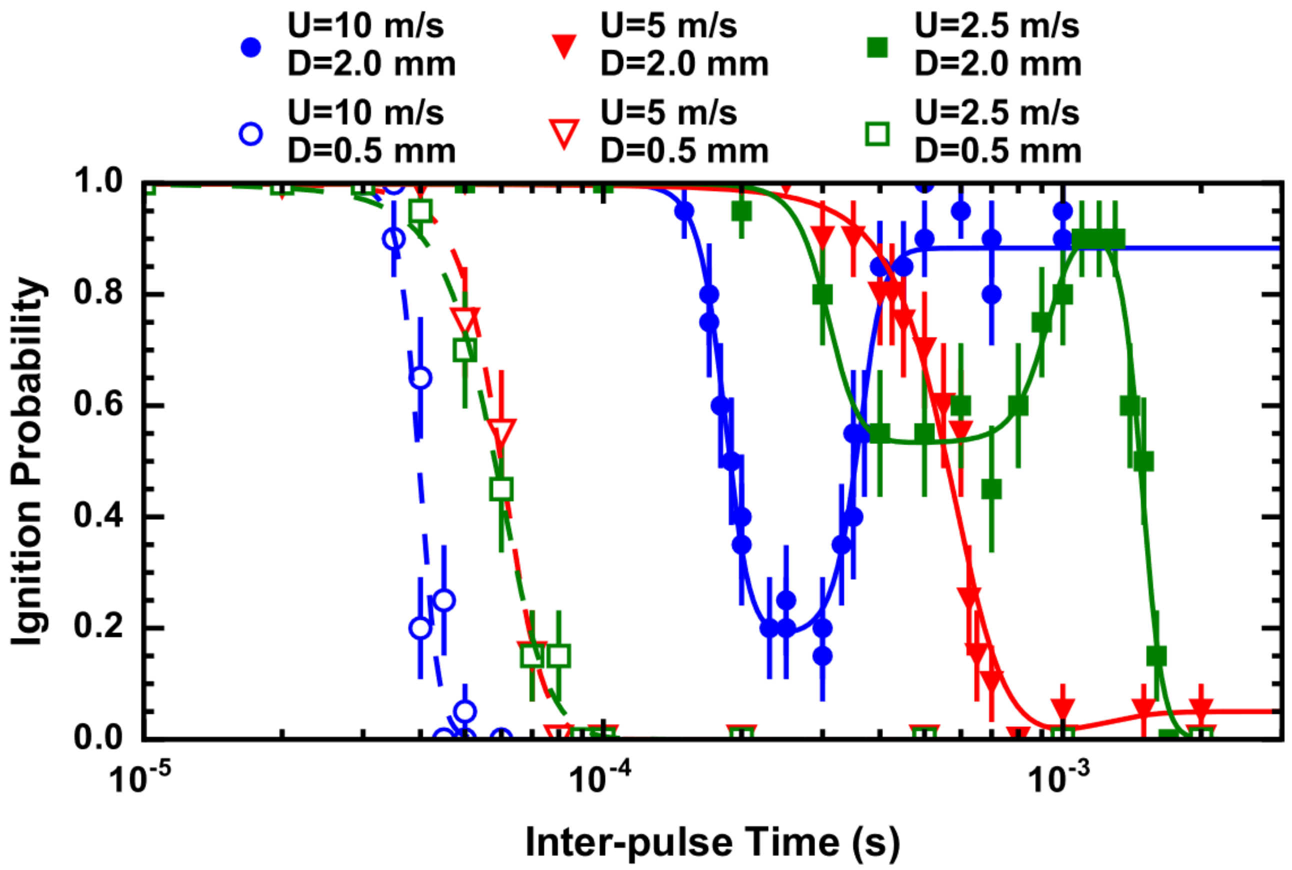
Flow velocity (U), Initial temperature (T_0), Turbulence regime, Fuel → **Ignition phenomena and kernel growth rate**

2. Flow parameters: Velocity (U)



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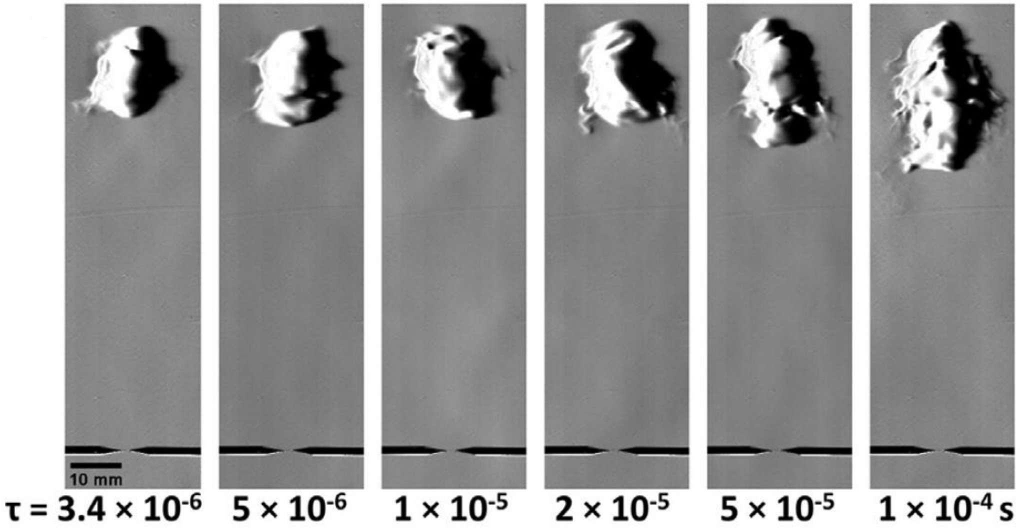
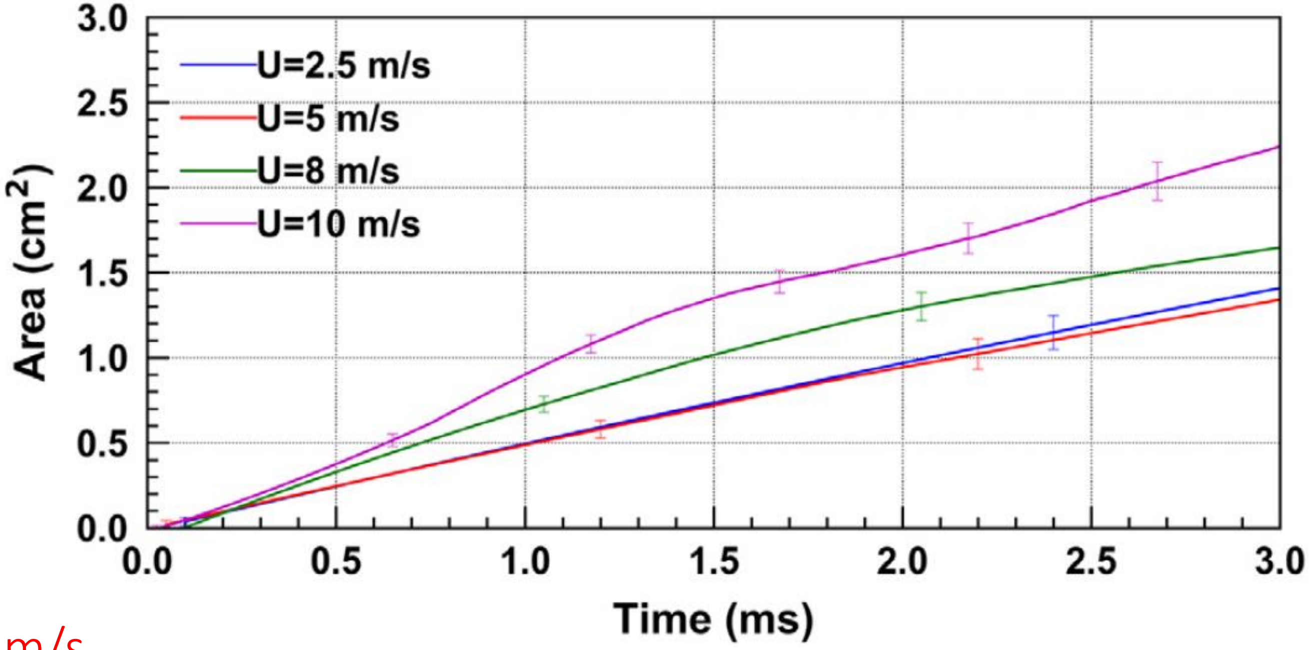


CH_4 + air   N = 10
Φ = 0.6 T_0 = 300 K
D = 2 mm P_0 = 100 kPa



Three timescales:

- Flow residence timescale
- Plasma timescale
- ~~Timescale of the flame front~~ ← U > 10 m/s

[7] J. K. Lefkowitz, T. Ombrello, Reduction of flame development time in nanosecond pulsed high frequency discharge ignition of flowing mixtures, *Combustion and Flame* 193 (2018) 471-480.

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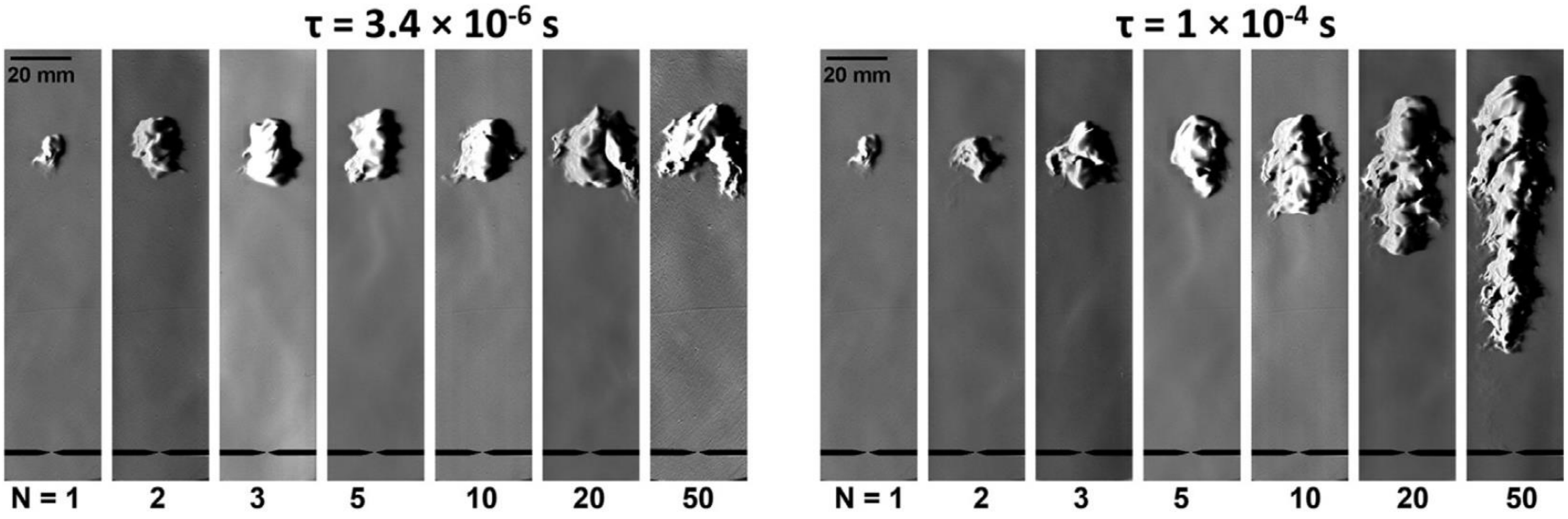
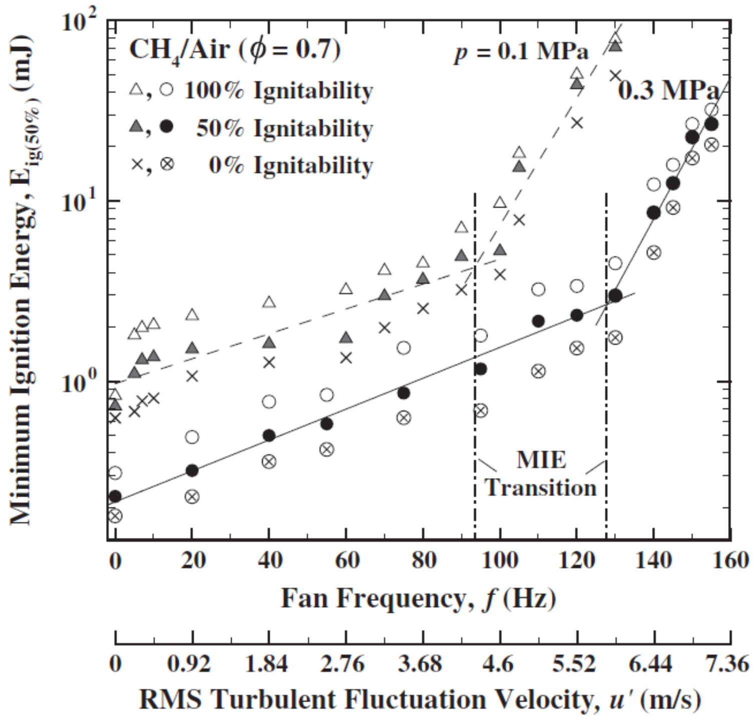
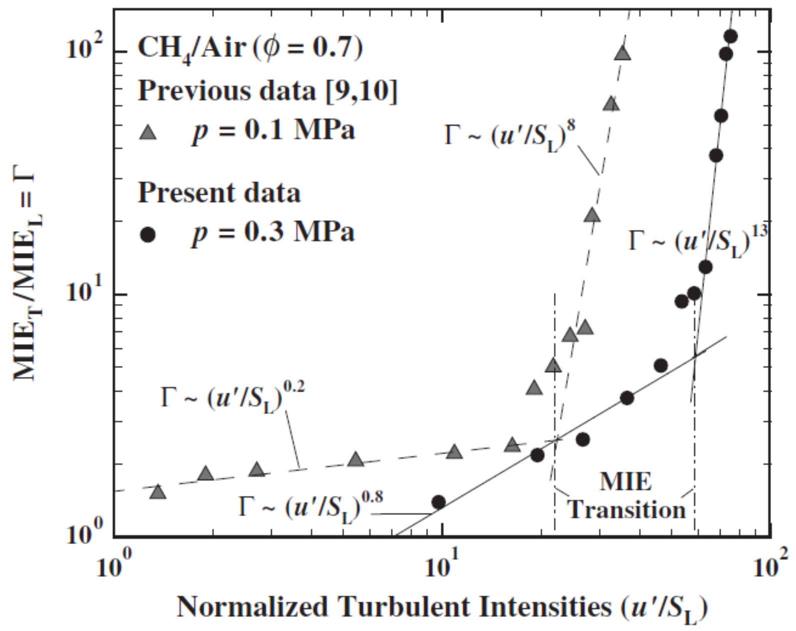


[7] J. K. Lefkowitz, T. Ombrello, Reduction of flame development time in nanosecond pulsed high frequency discharge ignition of flowing mixtures, *Combustion and Flame* 193 (2018) 471-480.

2. Flow parameters: Turbulence regimes





[8] M. W. Peng et al., High pressure ignition kernel development and minimum ignition energy measurements in different regimes of premixed turbulent combustion, *Combustion and Flame* 160 (2013) 9, 1755-1766.

2. Flow parameters: Initial temperature (T_0)

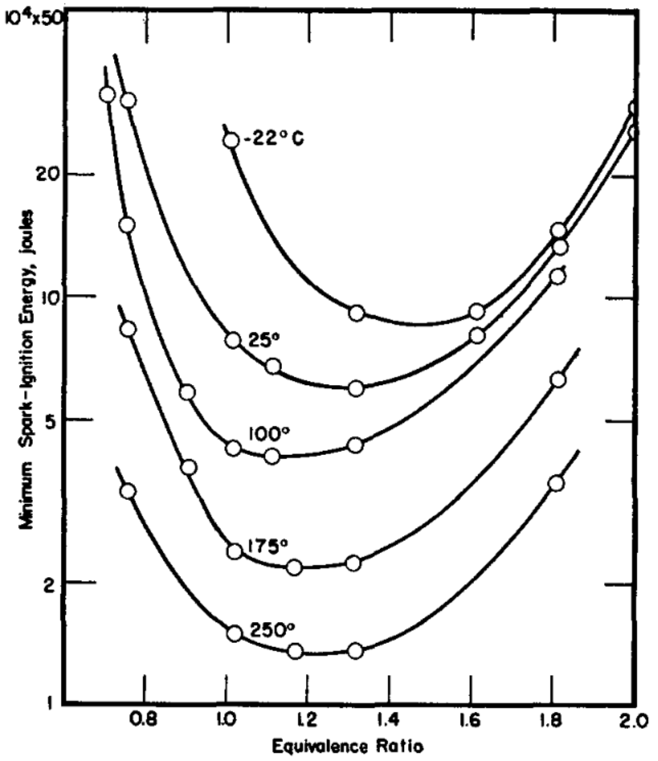
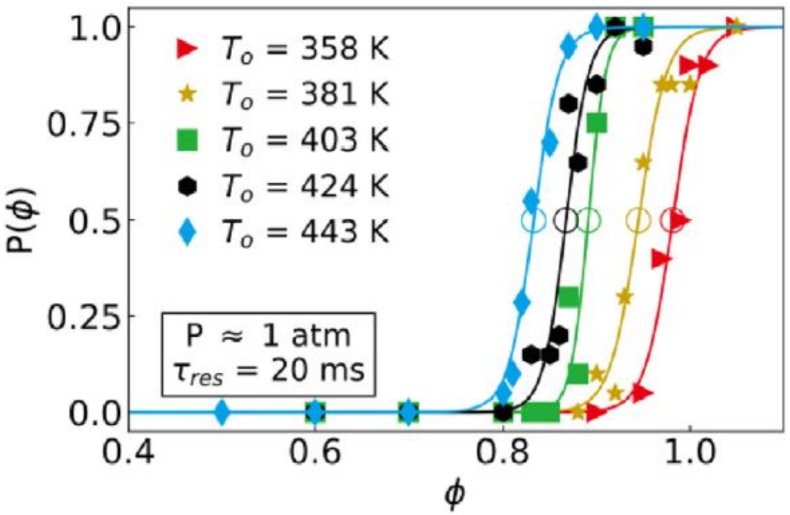
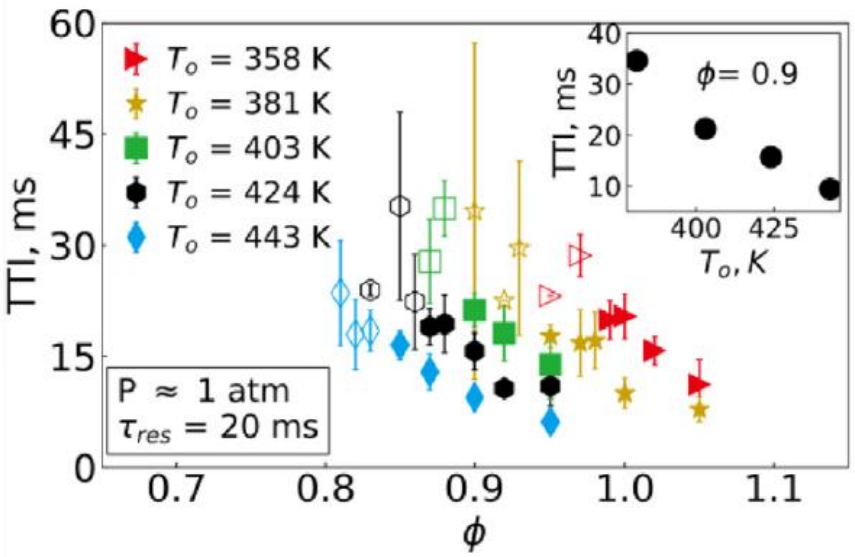


FIG. 1. Effect of initial temperature on minimum spark-ignition energy for *n*-pentane-air mixtures.

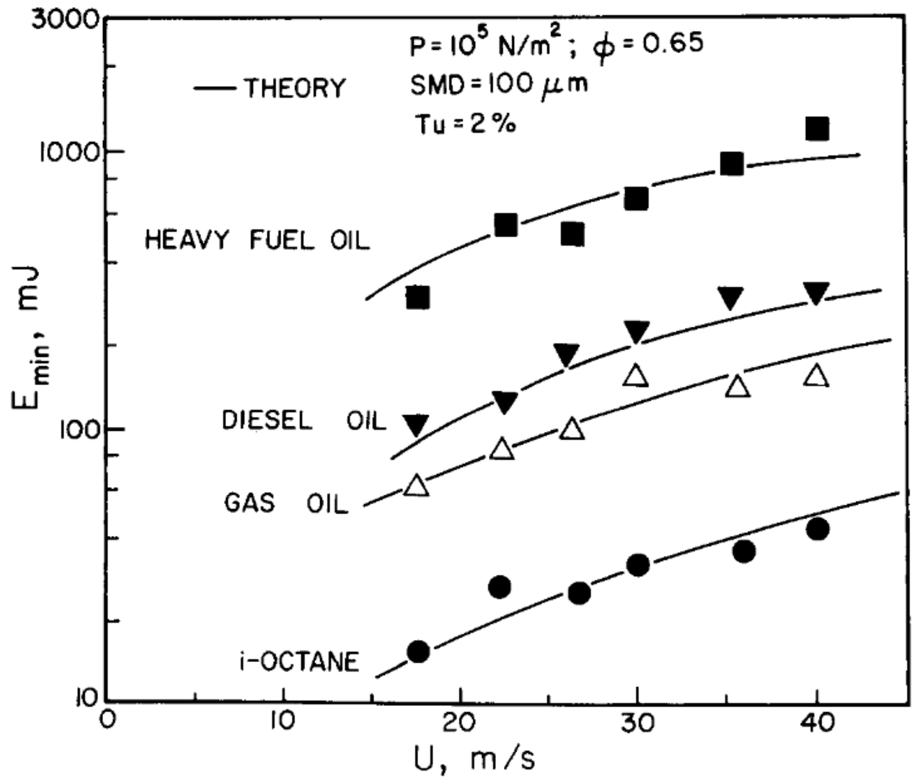




+ Help with the vaporization of liquid fuels

[9] I. R. King, H. F. Calcote, Effect of Initial Temperature on Minimum Spark-Ignition Energy, *The Journal of Chemical Physics* 23 (1955) 12, 2444-2445.
[10] R. D. Stachler et al., The impact of residence time on ignitability and time to ignition in a toroidal jet-stirred reactor, *Proceedings of the Combustion Institute* 37 (2019) 4, 5039-5046.

2. Flow parameters: Fuels



Fuel (Φ=1)	MIE (mJ) [11]
Hydrogen	0.02
Ethylene	0.096
Propane	0.31
Methane	0.49

Properties of liquid fuels that determine the MIE [13]:

- Surface tension
- Droplet size
- Cloud density

[11] J. B. Fenn, Lean Flammability Limit and Minimum Spark Ignition Energy, Commercial Fluids and Pure Hydrocarbons, *Industrial & Engineering Chemistry* 43 (1951) 12, 2865-2869.
[12] D. R. Ballal, A. H. Lefebvre, Ignition and flame quenching of flowing heterogeneous fuel-air mixture, *Combustion and Flame* 35 (1979), 155-168.
[13] P. M. de Oliveira, P. M. Allison, E. Mastorakos, Forced ignition of dispersions of liquid fuel in turbulent air flow, *55th AAIA Aerospace Sciences Meeting* (2017), 829.

Higher U:

- Narrower fully-coupled regime
- Faster kernel growth rate

Let's explore **beyond 10 m/s**!

Different turbulence regimes and intensities:

- For higher turbulence intensities, MIE is higher
- There is a dramatic increase at high altitudes

Effect of **different turbulent intensities** on ignition probability and kernel growth rate?

Higher T:

- Lower MIE and ignition delay times
- Helps with vaporization of liquid fuels

Effect of **high T** on ignition probability and kernel growth rate?

Different fuels:

- Different optimal injection and ignition parameters

Effect of **different fuels** on ignition probability and kernel growth rate?

Challenges for the new design:

- Higher **temperatures**
- Higher **velocities**
- Different **turbulent regimes**
- Different **fuels**:
    - Gaseous fuels (CH_4, H_2, C_2H_4, C_3H_8)
    - Heavy hydrocarbon fuels
    - Liquid fuels
    - Alternative fuels

Maximum flow **properties**:

- Temperature: **1000 K**
- Pressure: **15 bar**
- Air flow rate: **790 m^3/min**
- Flow velocity: **100 m/s**
- Reynolds number: **240,000**

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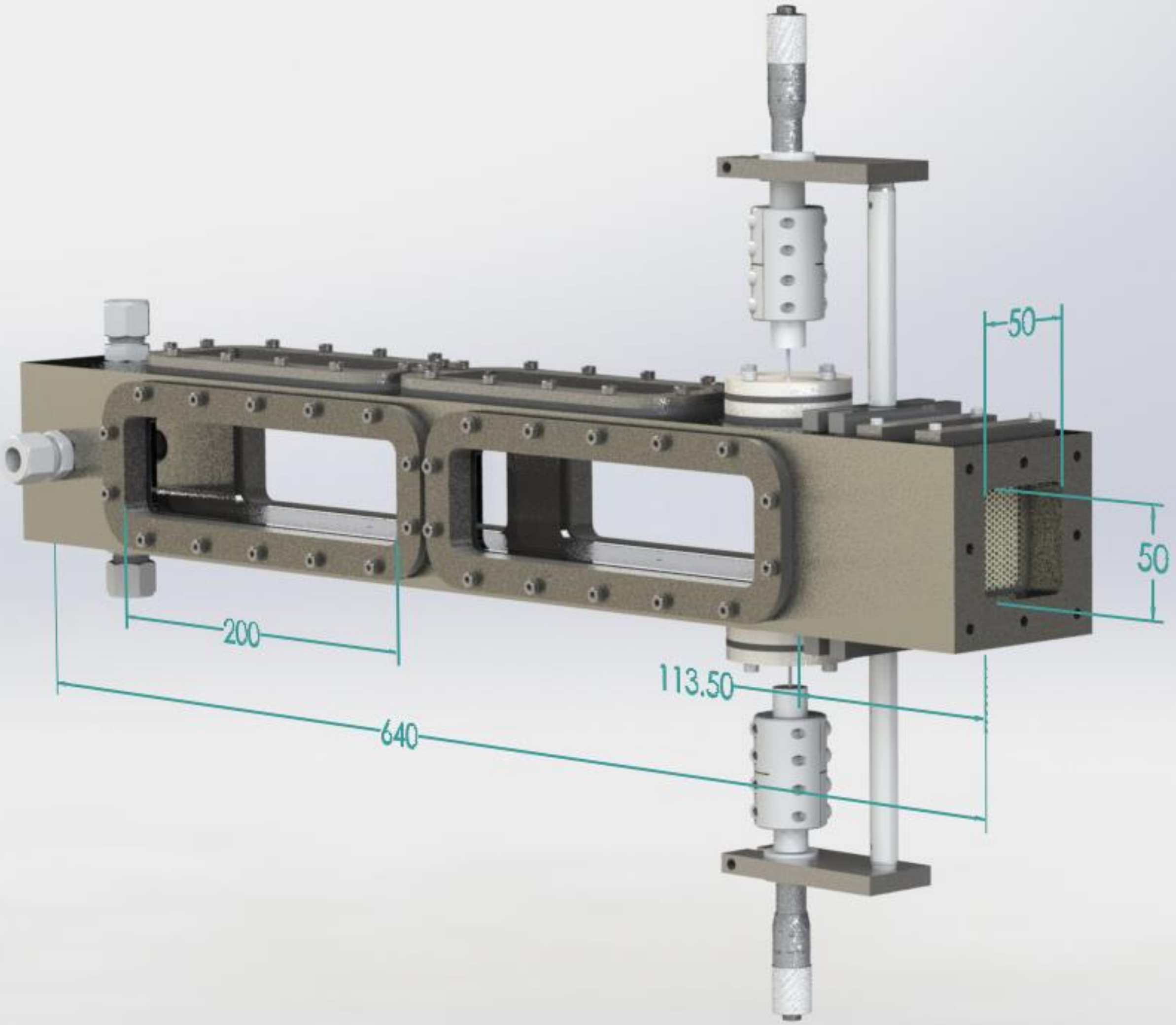
Test section



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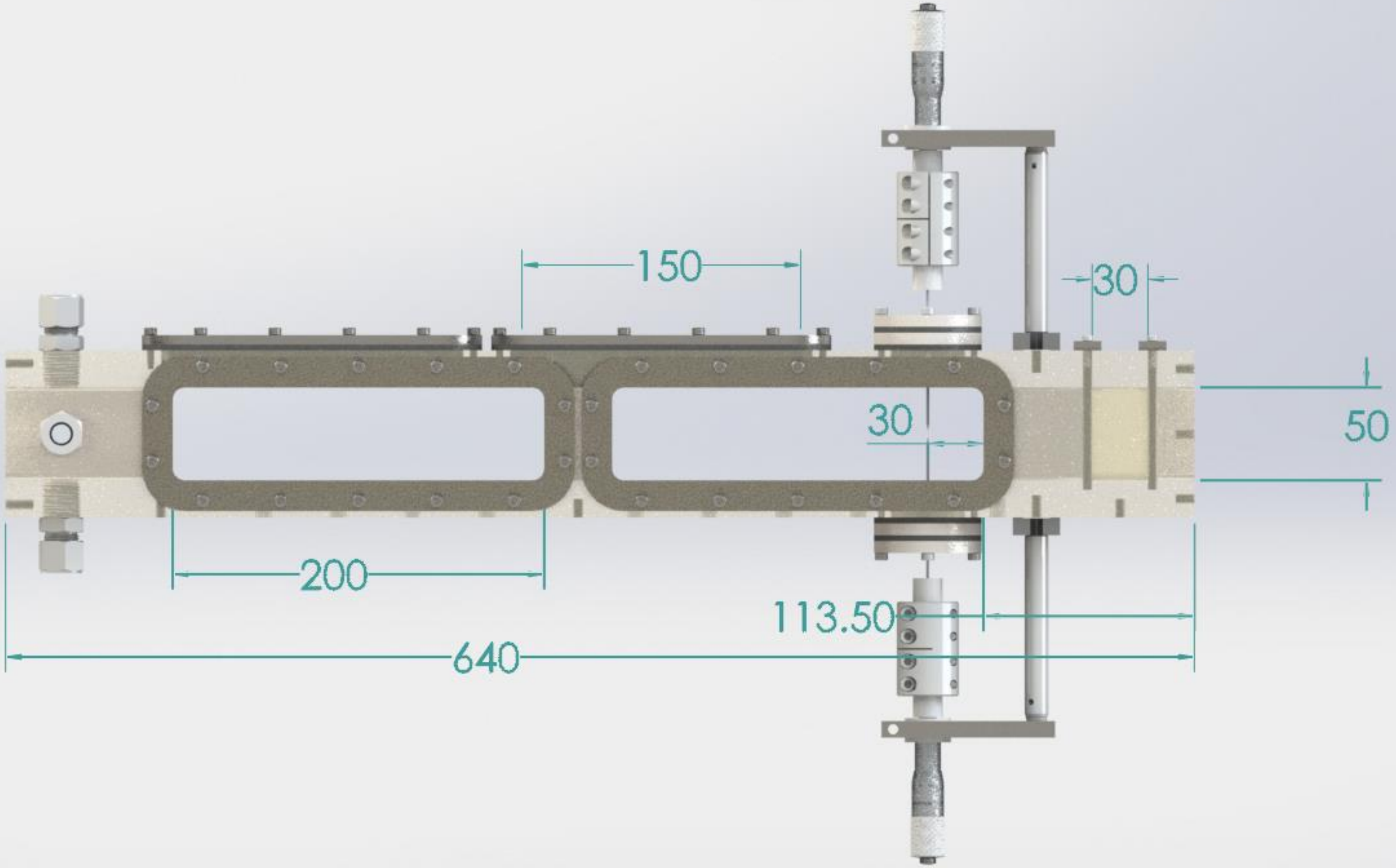
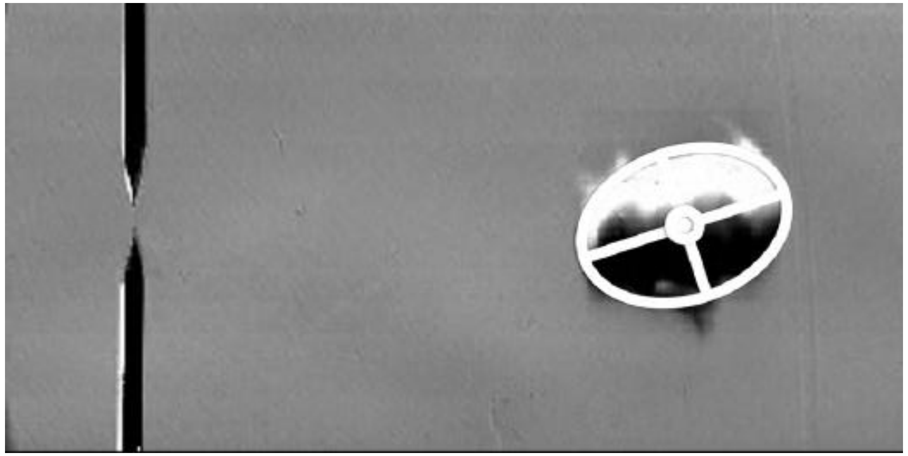
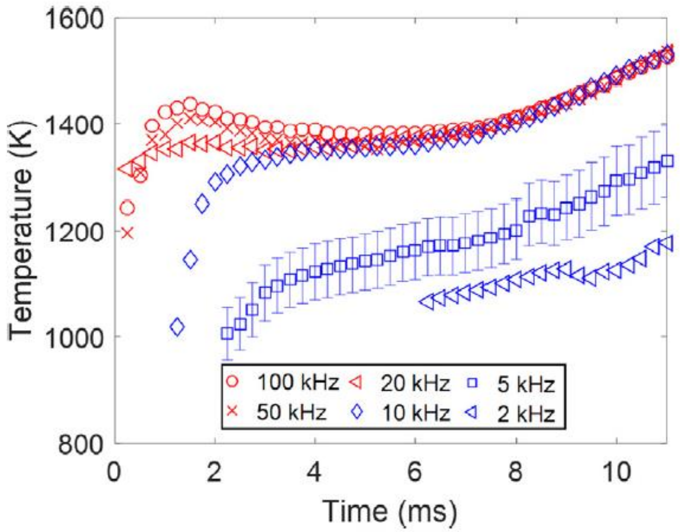


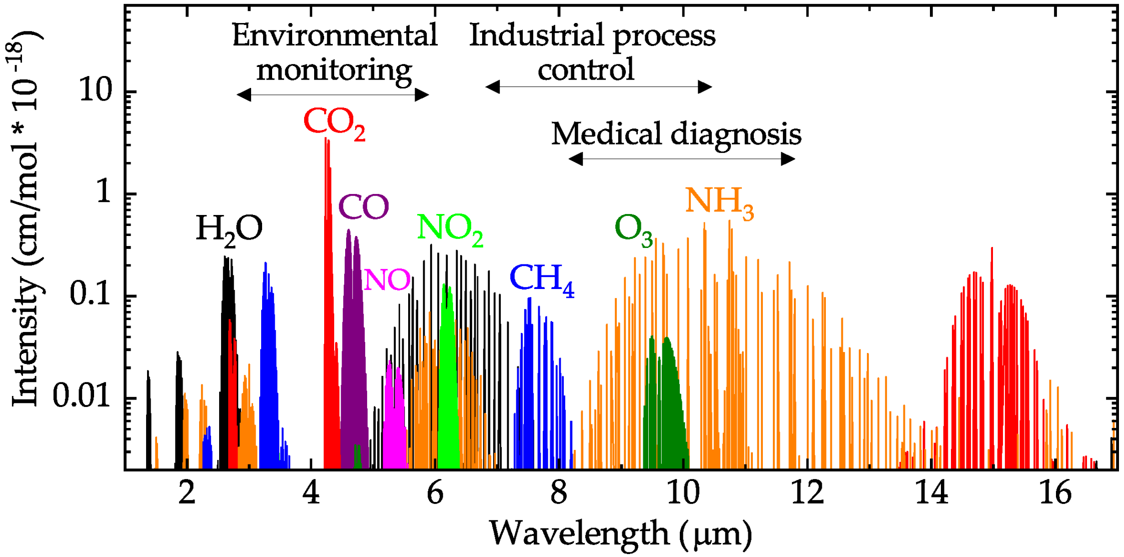
Diagnostics

a) Schlieren imaging:



b) IR imaging:





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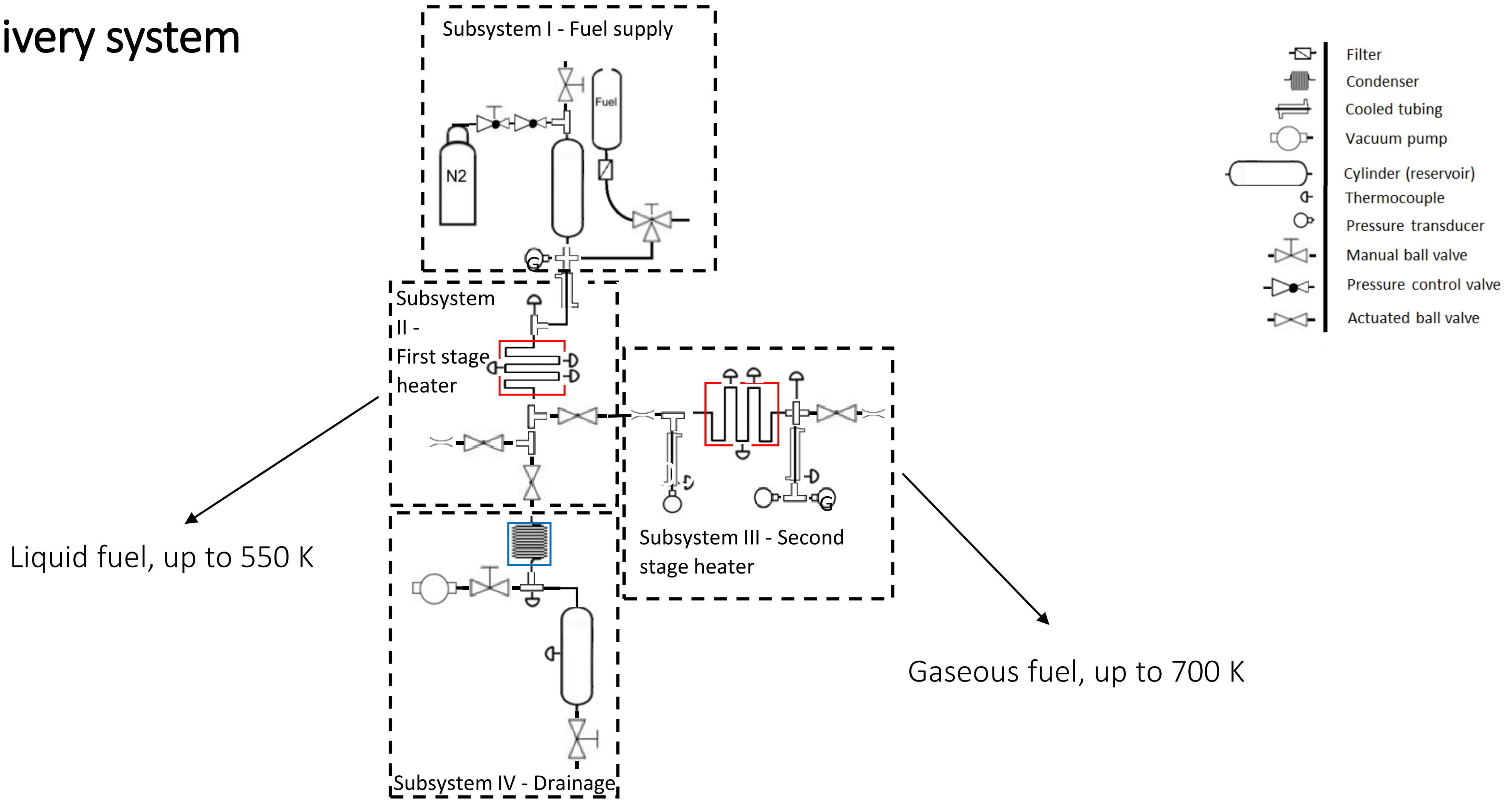
Liquid fuel delivery system



Assembly

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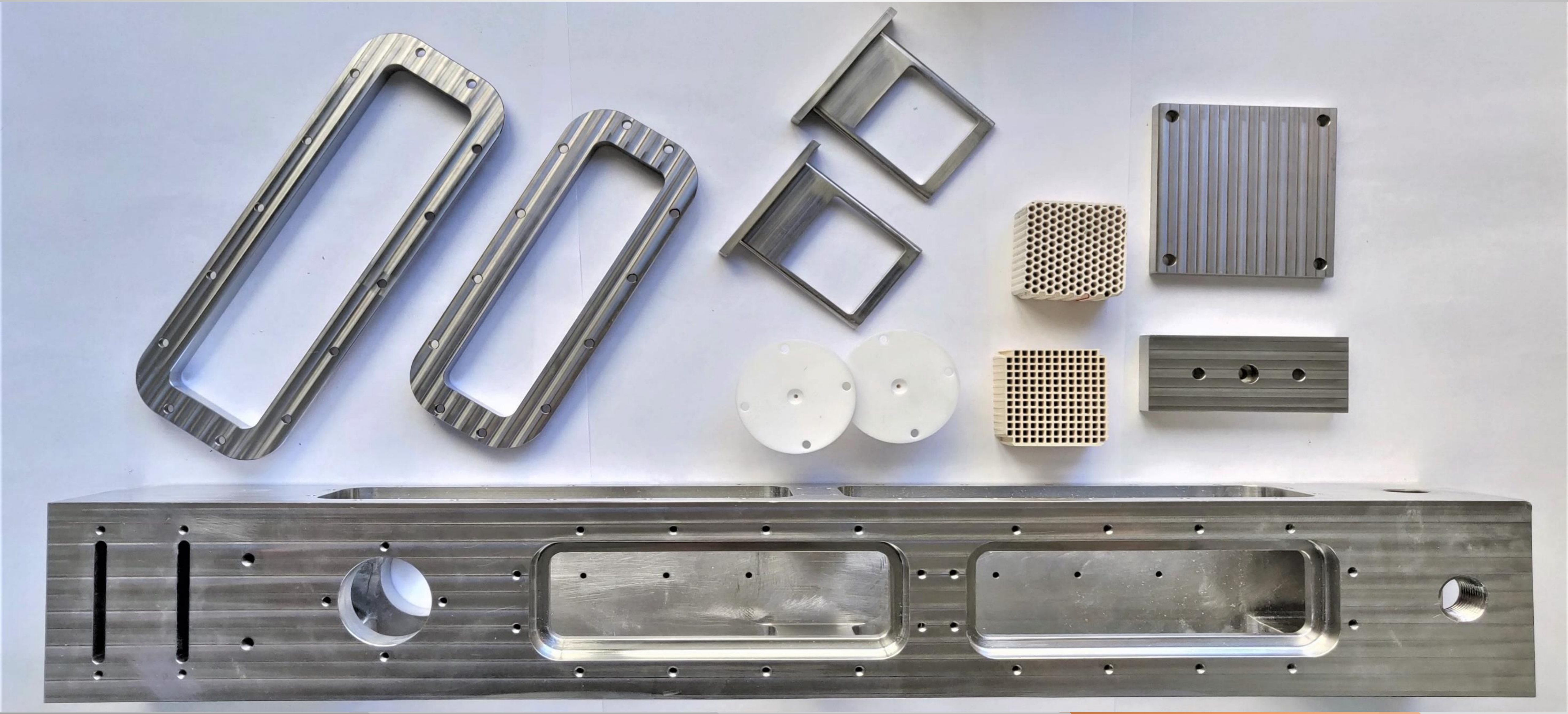

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