CHALLENGES OF DETONATION ENGINES FOR FUTURE JET PROPULSION

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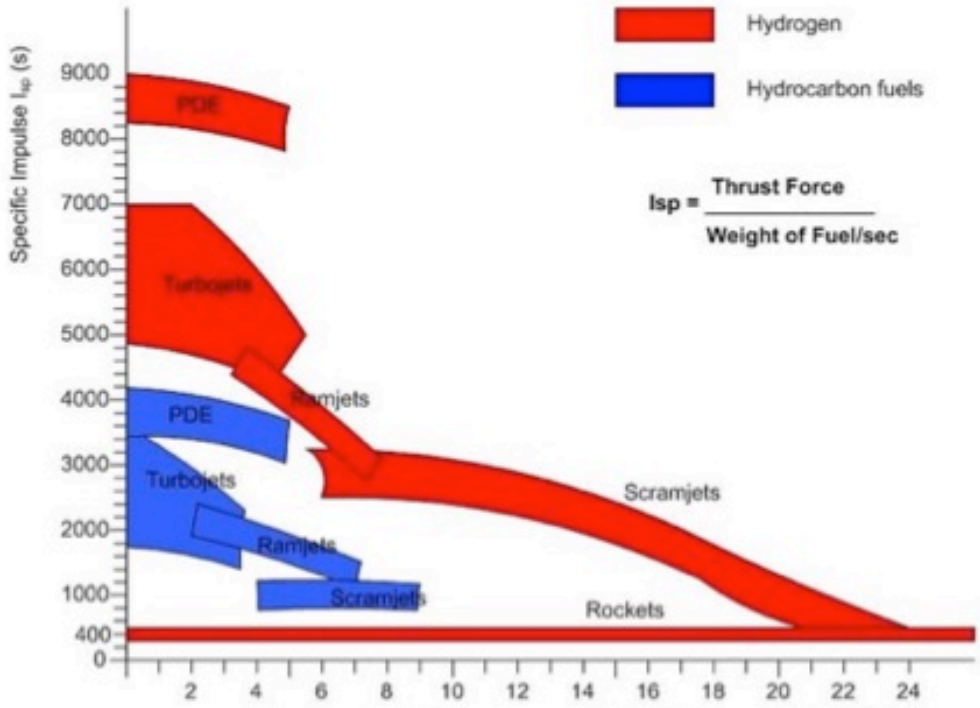
November 17th, 2016

Need for a new architecture

- Realization of efficient high speed flight demanding efficient propulsion systems
- State-of-the-art propulsion reaching its limits through incremental improvements
- A radical change in architecture required to achieve a step-up in paradigm
- Detonation engines promising higher ISPs
- Better performance foreseen upon other propulsion systems under R&D for supersonic flight



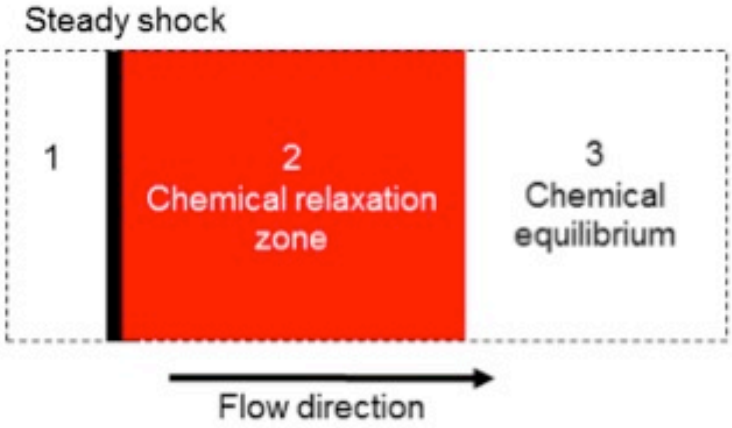
Texas A&M University (2014)

What is detonation?

Pressure gain combustion:

"an unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure"

AIAA - Pressure Gain Combustion Program Committee



(1) Initial condition

↓ P & T increase through shock

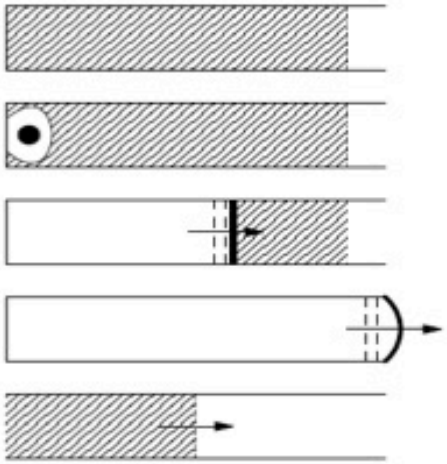
(2) Chemical reaction

↓ Heat release

(3) Chemical equilibrium of products

Ways to achieve detonation

- Pulsed detonation Wave combustors (PDE)
  - Periodical detonation at low frequencies
    - Ignition system
    - Purge and refill

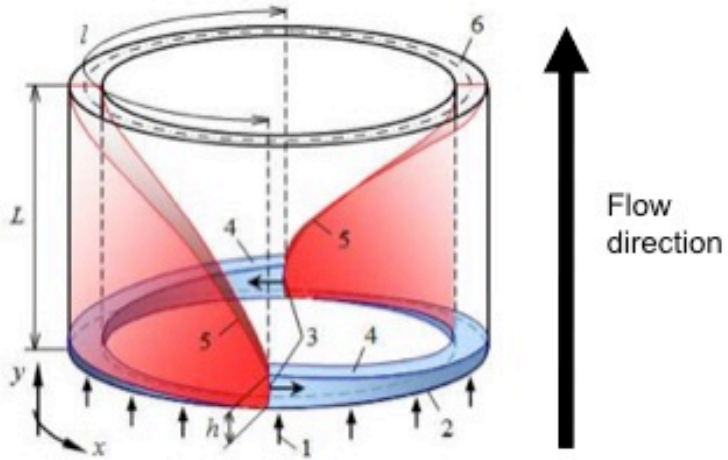


C. Schmitt, 2013

- Resonator detonation combustors
  - Autoperiodic supply and detonation of fresh mixture
  - Resonator design: difficult

G. D. Roy et al., 2004

- Rotating Detonation Combustors (RDE)
  - Continuous detonation
  - High operating frequency (order of kHz)
  - Simultaneous expulsion of exhaust gases and continuous refill of fresh mixture
  - Complex 3D flow field
  - Compact



Y. Eude, 2011

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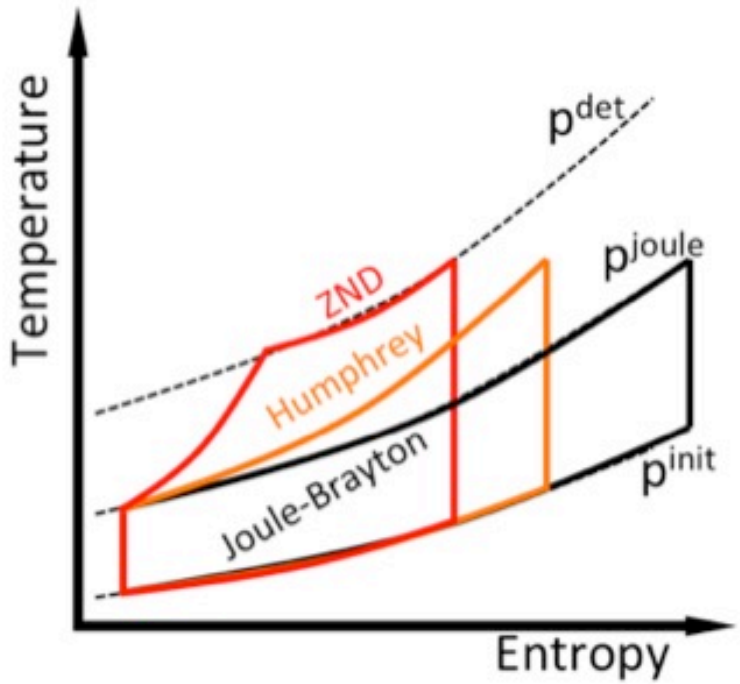
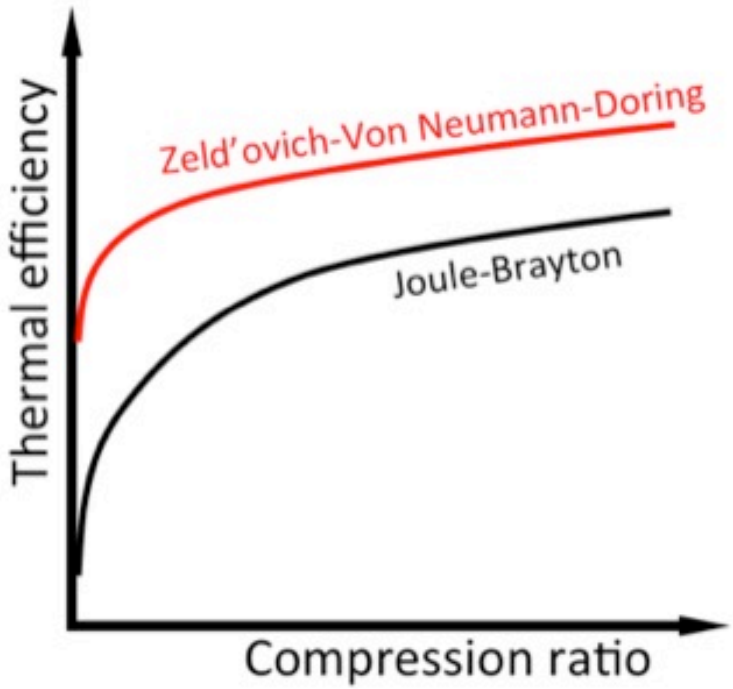
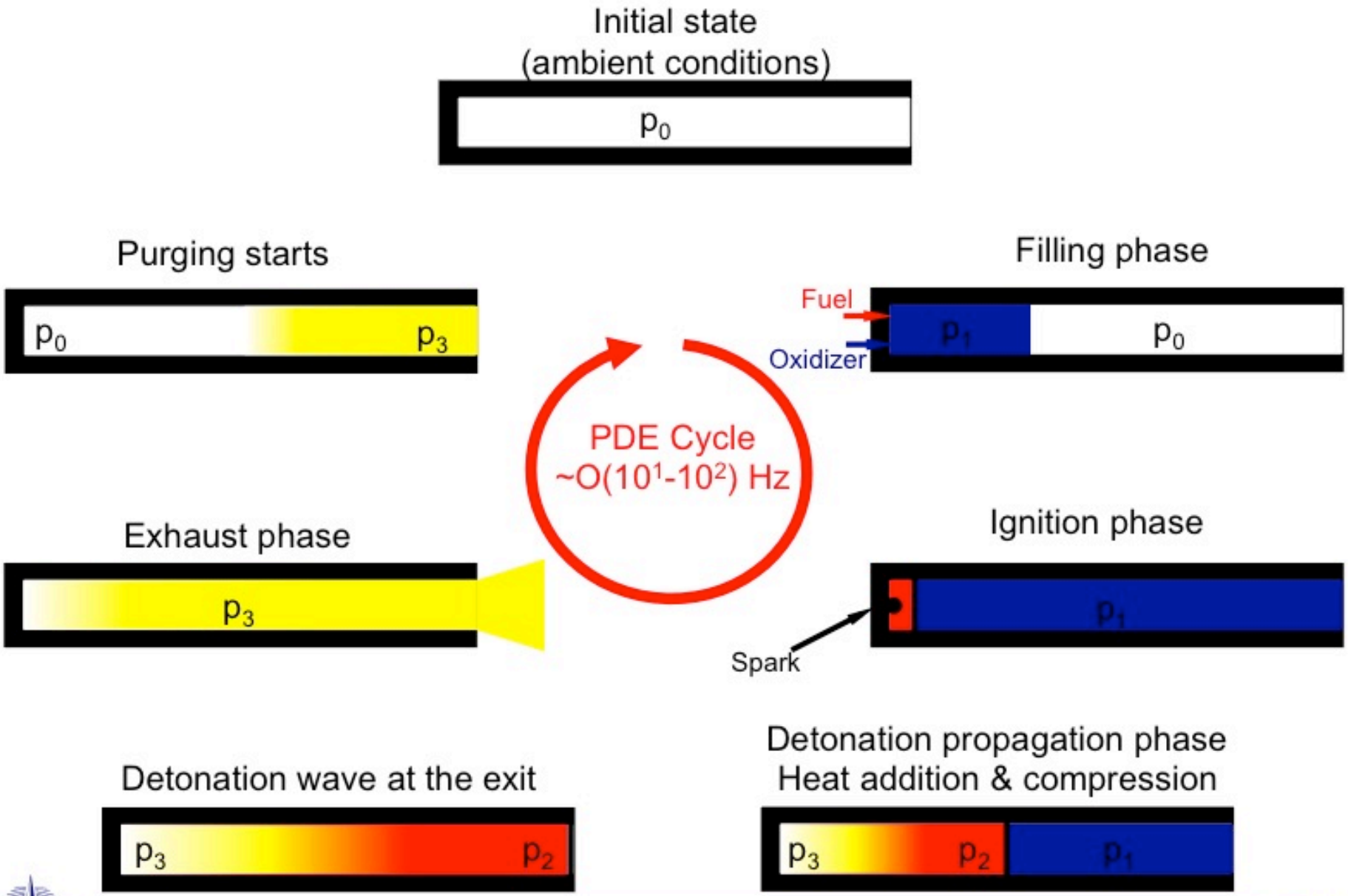
Thermodynamics of theoretical detonation cycle



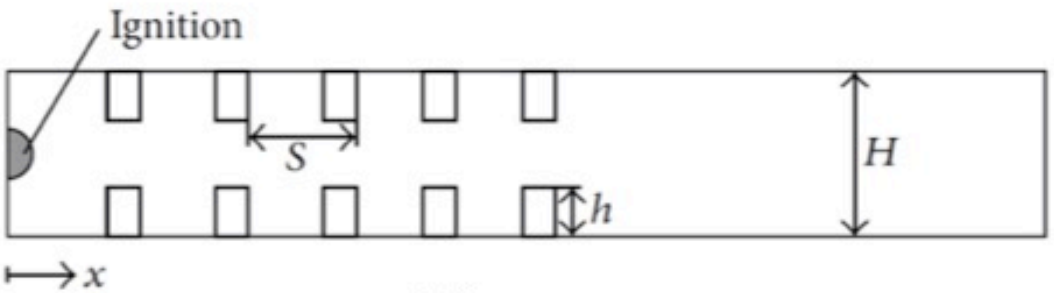


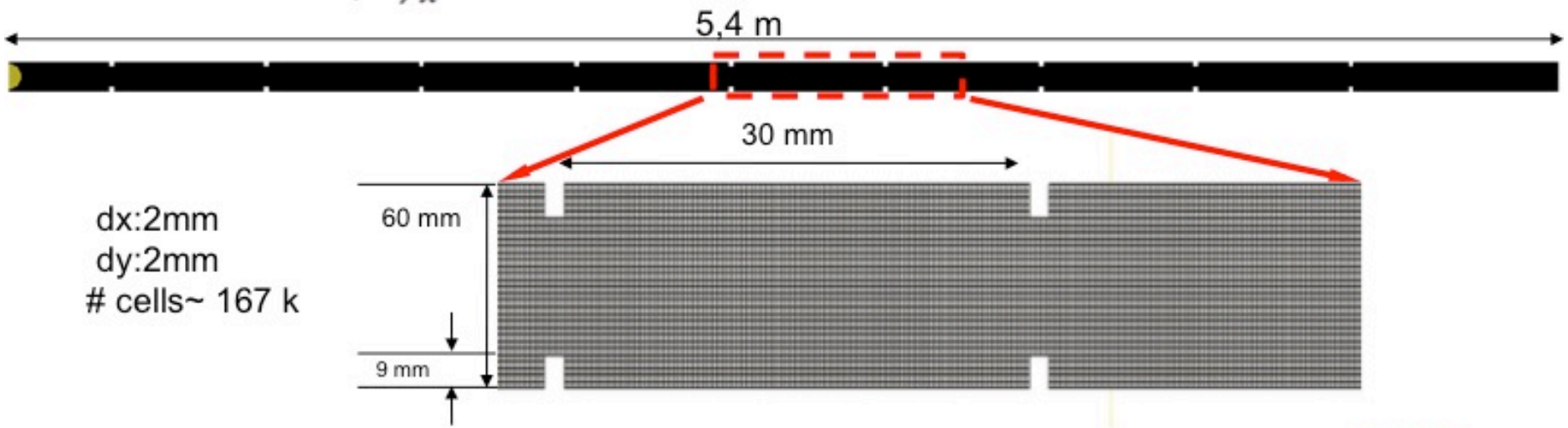
- Detonation based cycles attaining higher pressure for the same temperature
- High pressure rise during the combustion process
- Less entropy generation to reach the same expander inlet temperatures
- Significant thermal efficiency augmentation as compared to Brayton Cycle

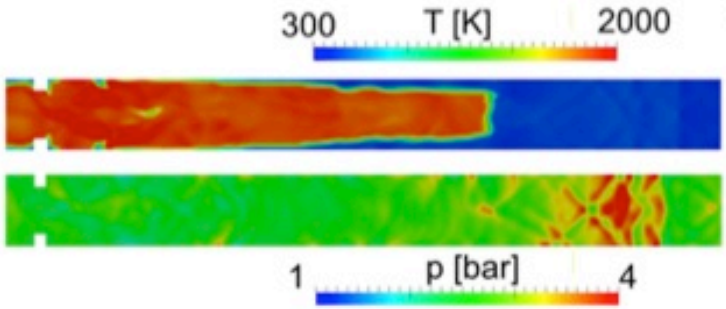
Pulse detonation engine (PDE)

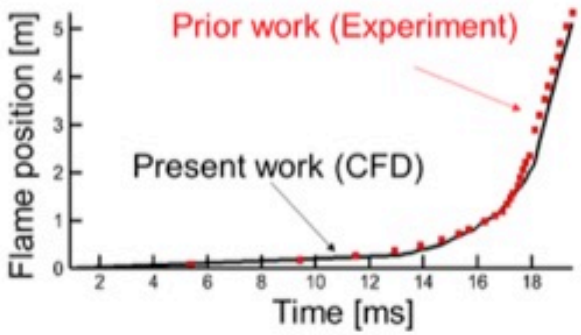


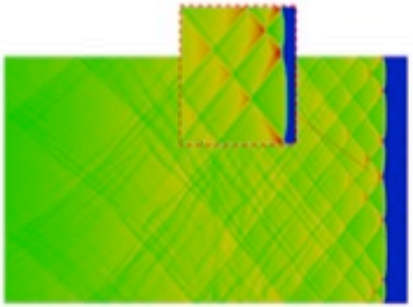
Pulse detonation engine (PDE)





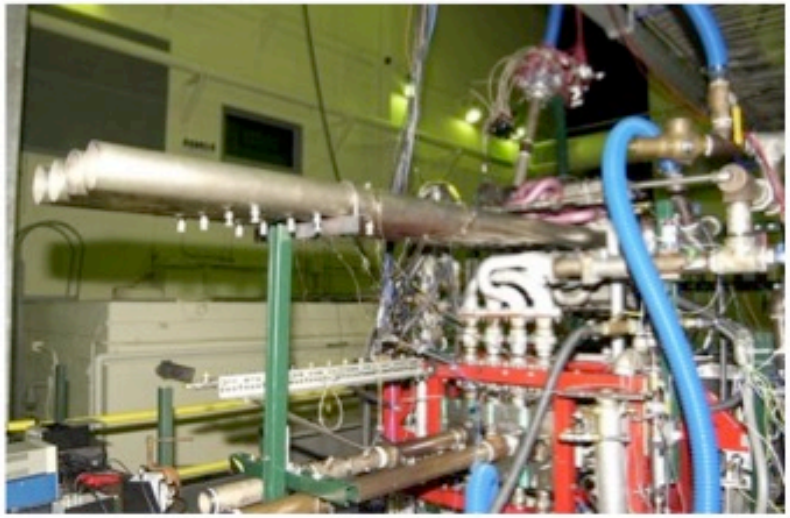






Pulse detonation engine (PDE) – Jet propulsion

- Detonation pulses utilized to augment thrust
- Direct implementation of multiple PDE tubes to propel Borealis aircraft
- Is there any room for improvement?



First flight of pulse detonation engine, Mojave (2008)

Pulse detonation engine (PDE)

Use of optimized nozzles to increase the force at the outlet

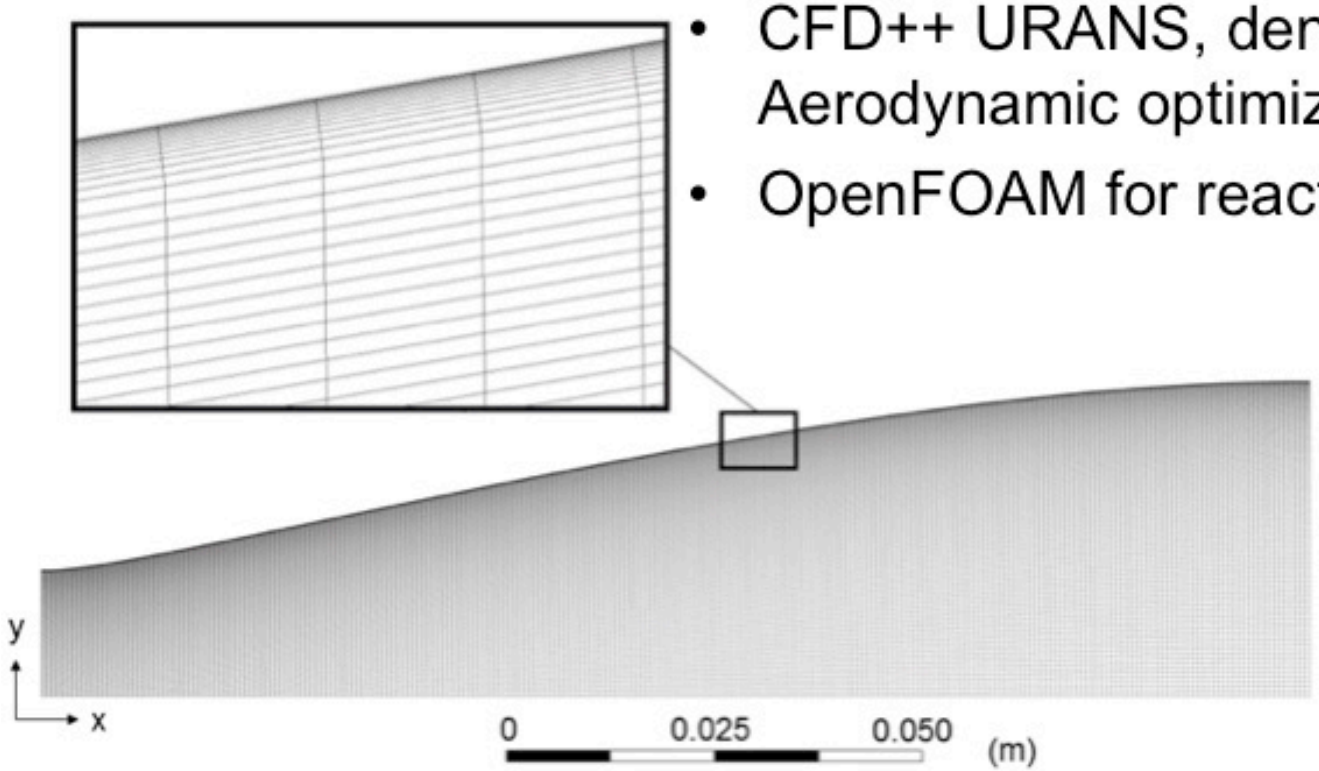
Method:

- Starting from a diverging nozzle geometry
- Parameterization of the nozzle with a Bezier curve
- Letting the optimizer vary the geometry until the optimized objective function obtained

- Nozzle shape:
  - Third order curve
  - Design variables: x_1, x_2, y_2
  - Fixed length and area ratio

Pulse detonation engine (PDE) – CFD evaluation

- Gambit used for mesh generation
- CFD++ URANS, density based solver: Aerodynamic optimization of nozzle
- OpenFOAM for reacting flow evaluation



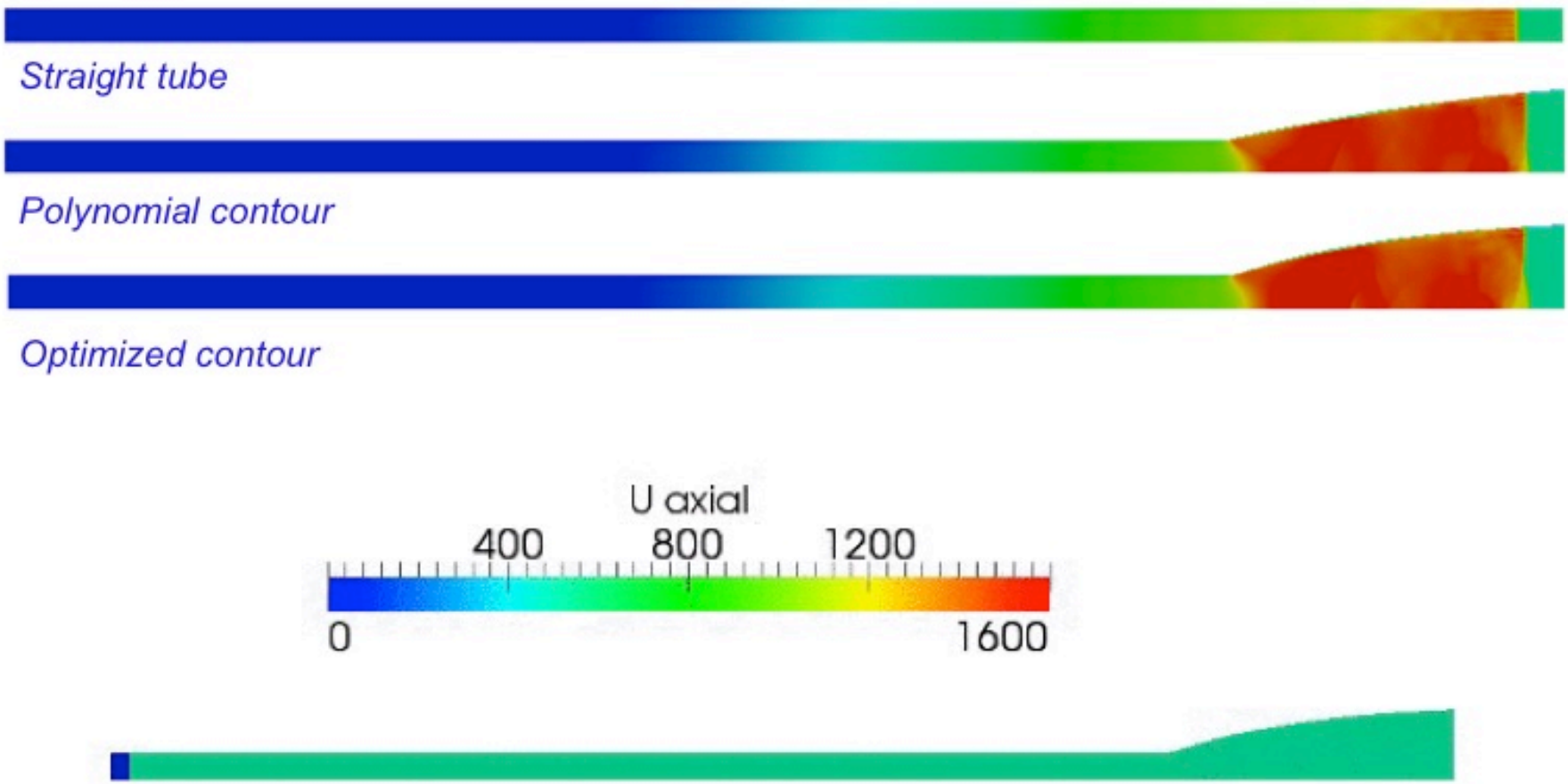
Objective function:

$$F = \dot{m}_e u_e + p_e A_e$$

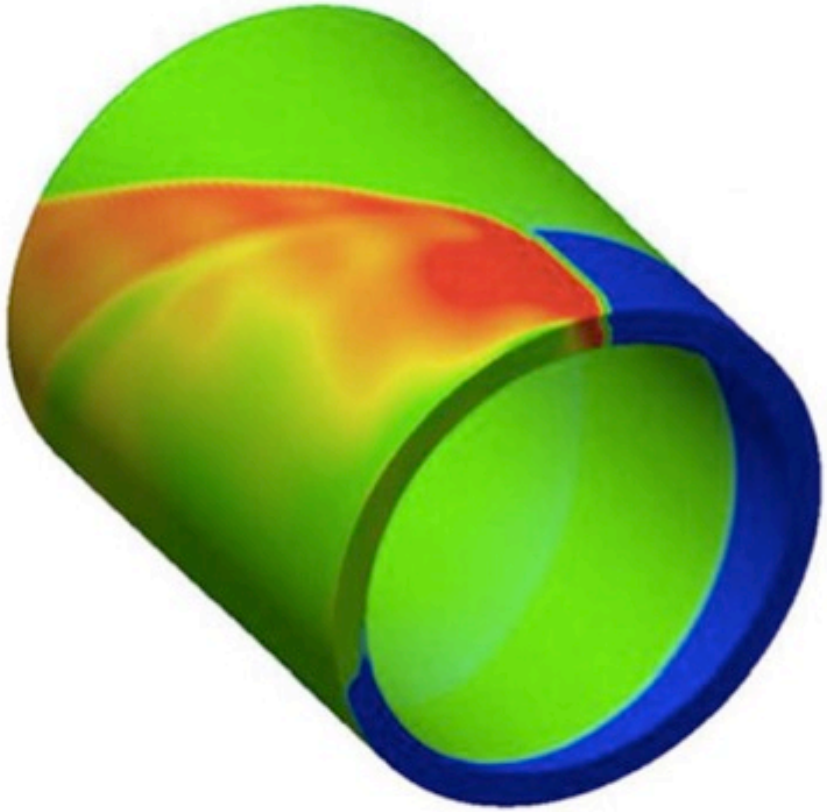
$$\bar{F} = \frac{1}{T_2 - T_1} \int_{T1}^{T2} F(t)dt,$$

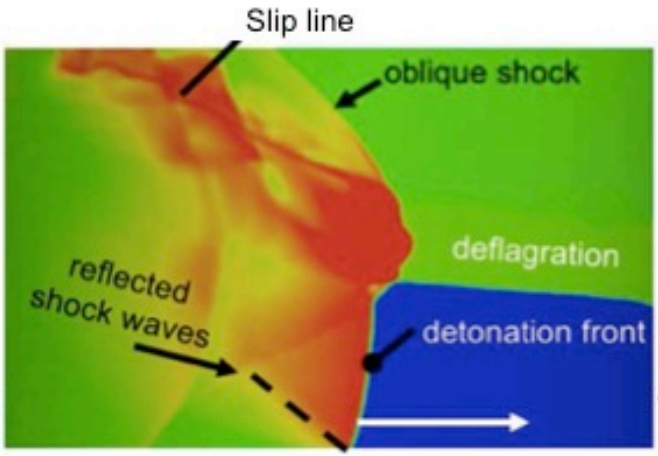
Time averaged force acting on the exit nozzle surface

Pulse detonation engine (PDE) – Reactive flow analysis



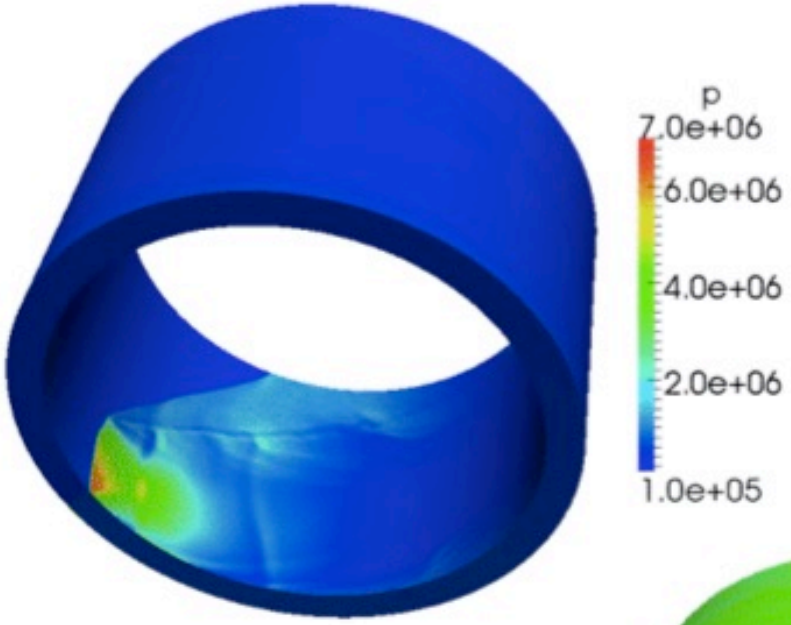
Rotating detonation engines (RDE)

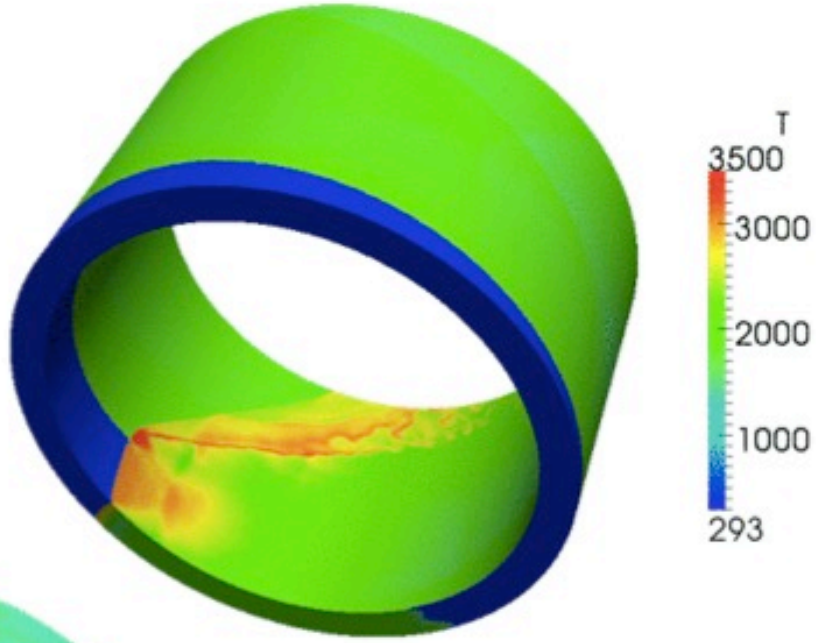


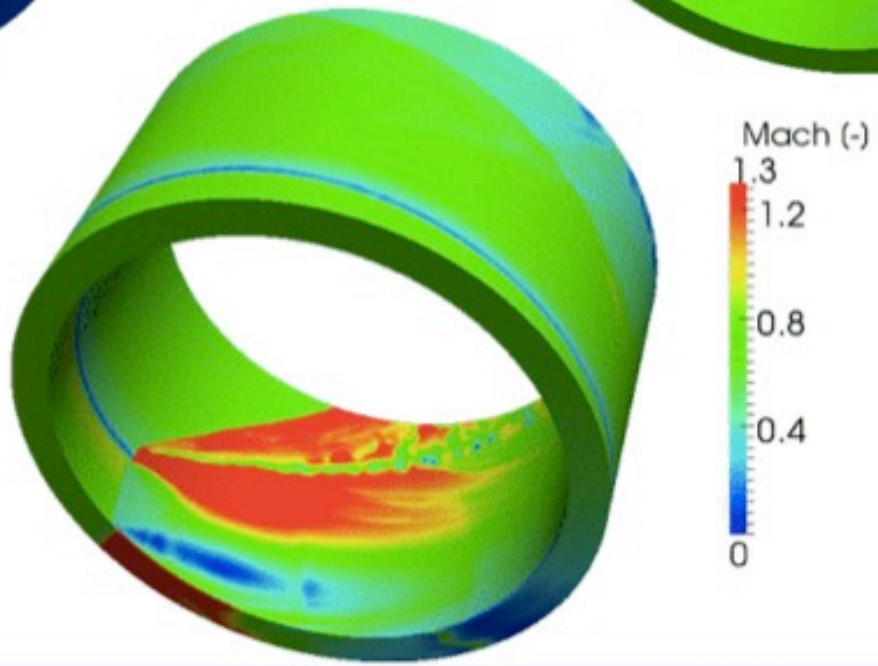


- Periodic ignition not required
- Continuous combustion of the reactants
- Much higher frequencies attained – order of kHz
- Integration to the radial machinery
- Jet propulsion applications

Rotating detonation engine – General flow field

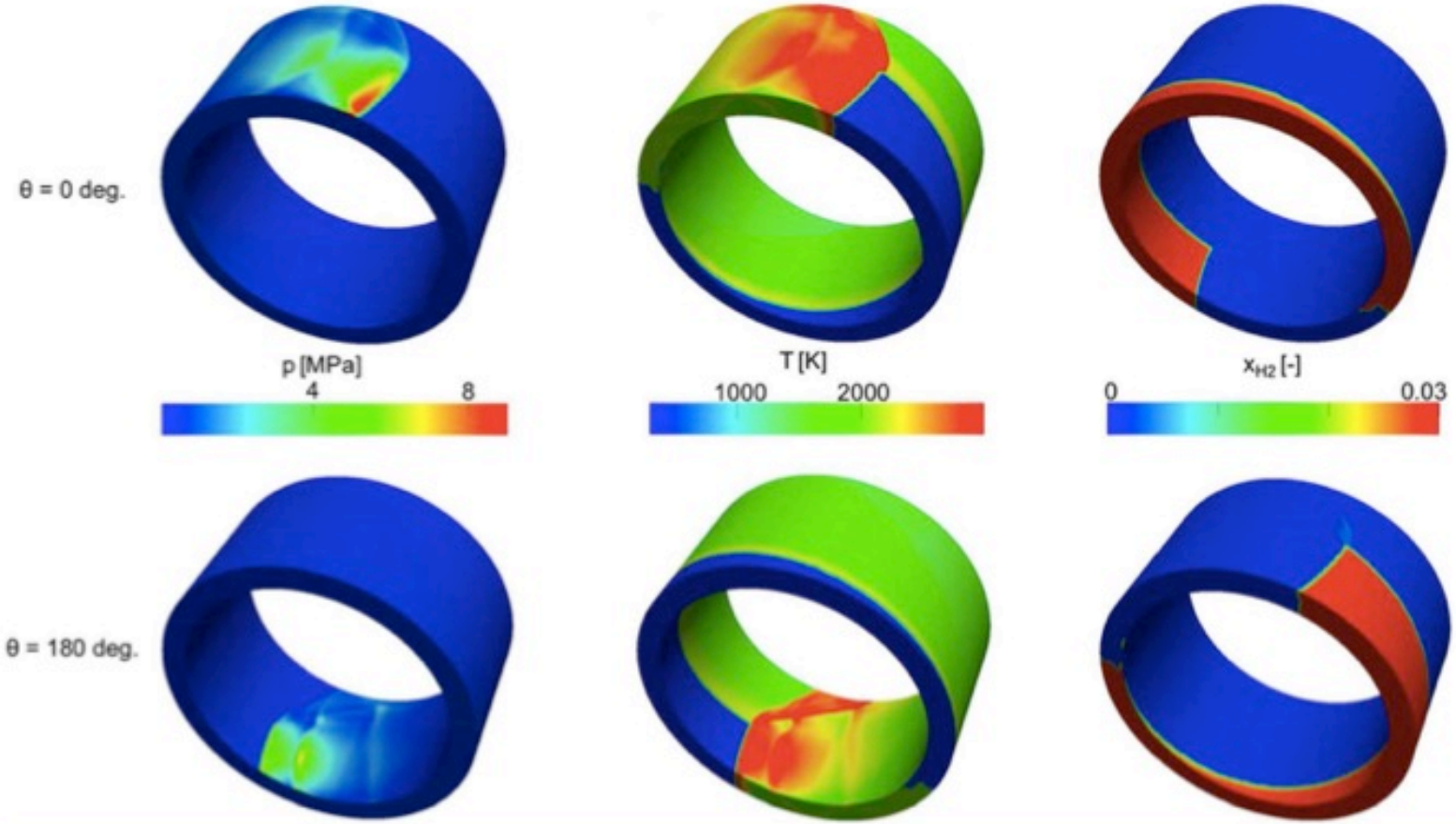




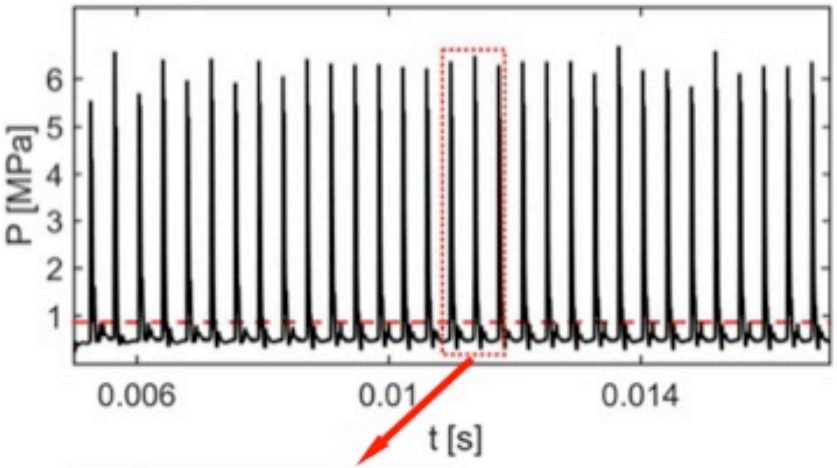


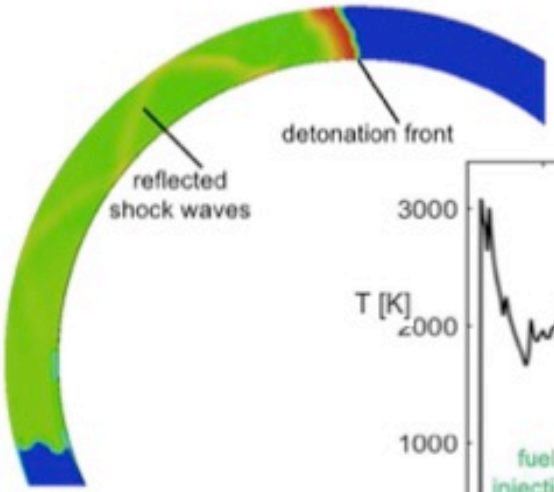
Rotating detonation engine – General flow field

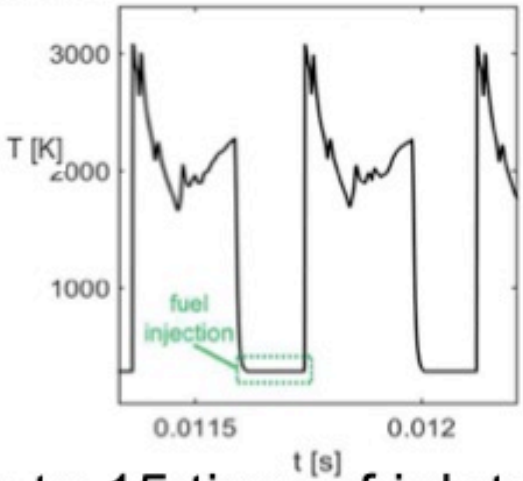
- Continuous consumption of the incoming fuel
- Significant pressure gain attained through the detonation wave
- High temperature field (mainly above 2000K) dominating the outlet of the combustor

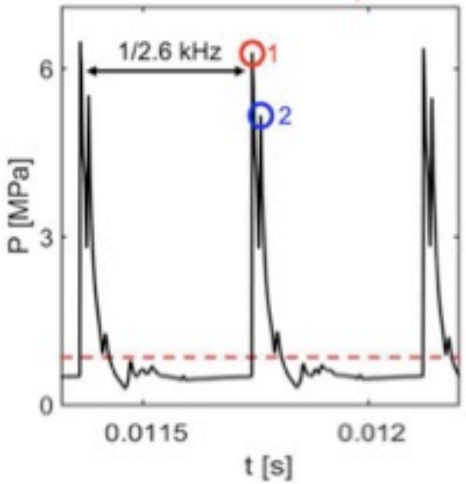


Rotating detonation engine – Detailed flow field (inlet)





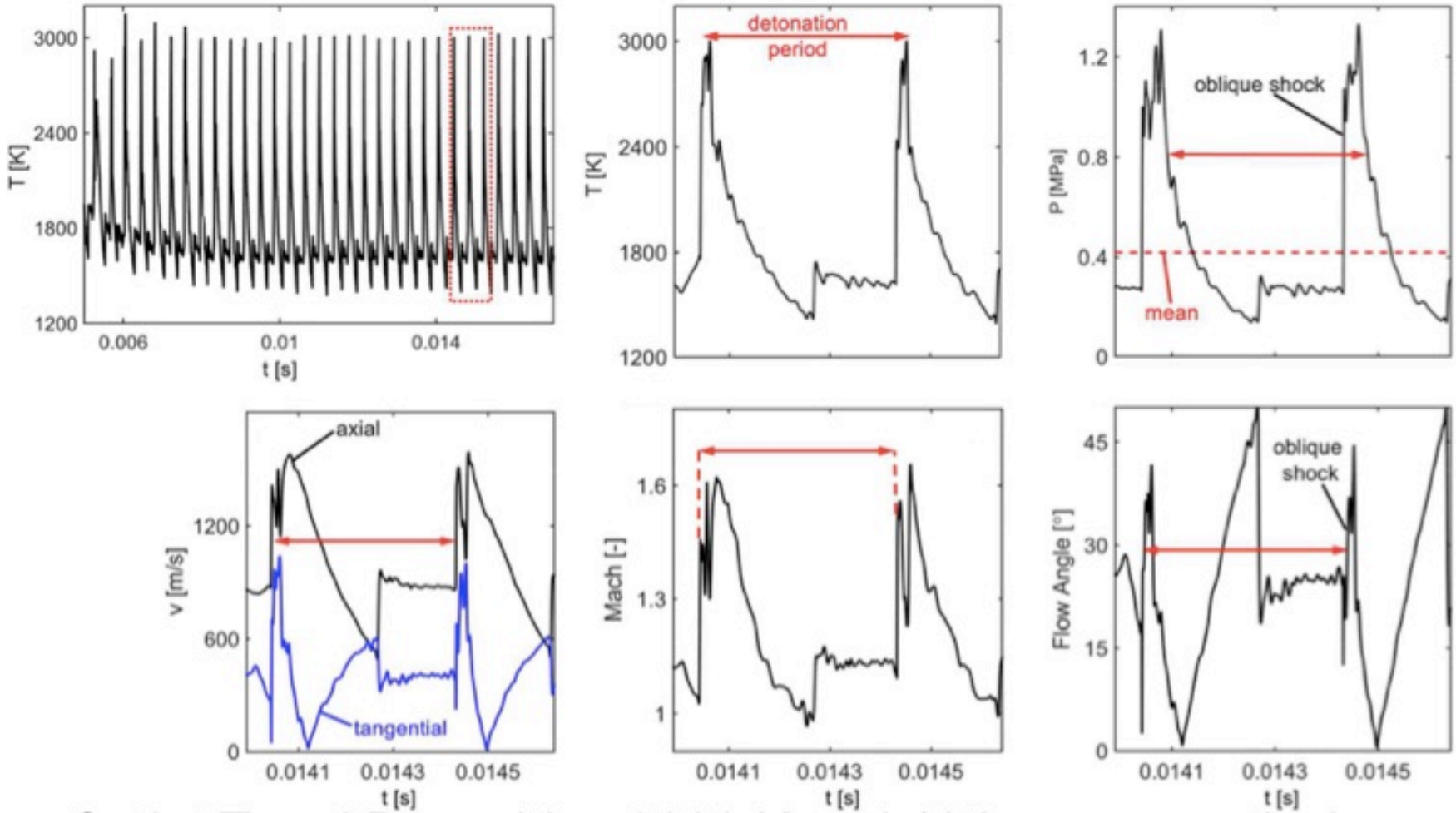




- Periodic pressure rise up to 15 time of inlet P
- The temperature increase up to 3000 K
- Inlet Mach number reaching 0.8

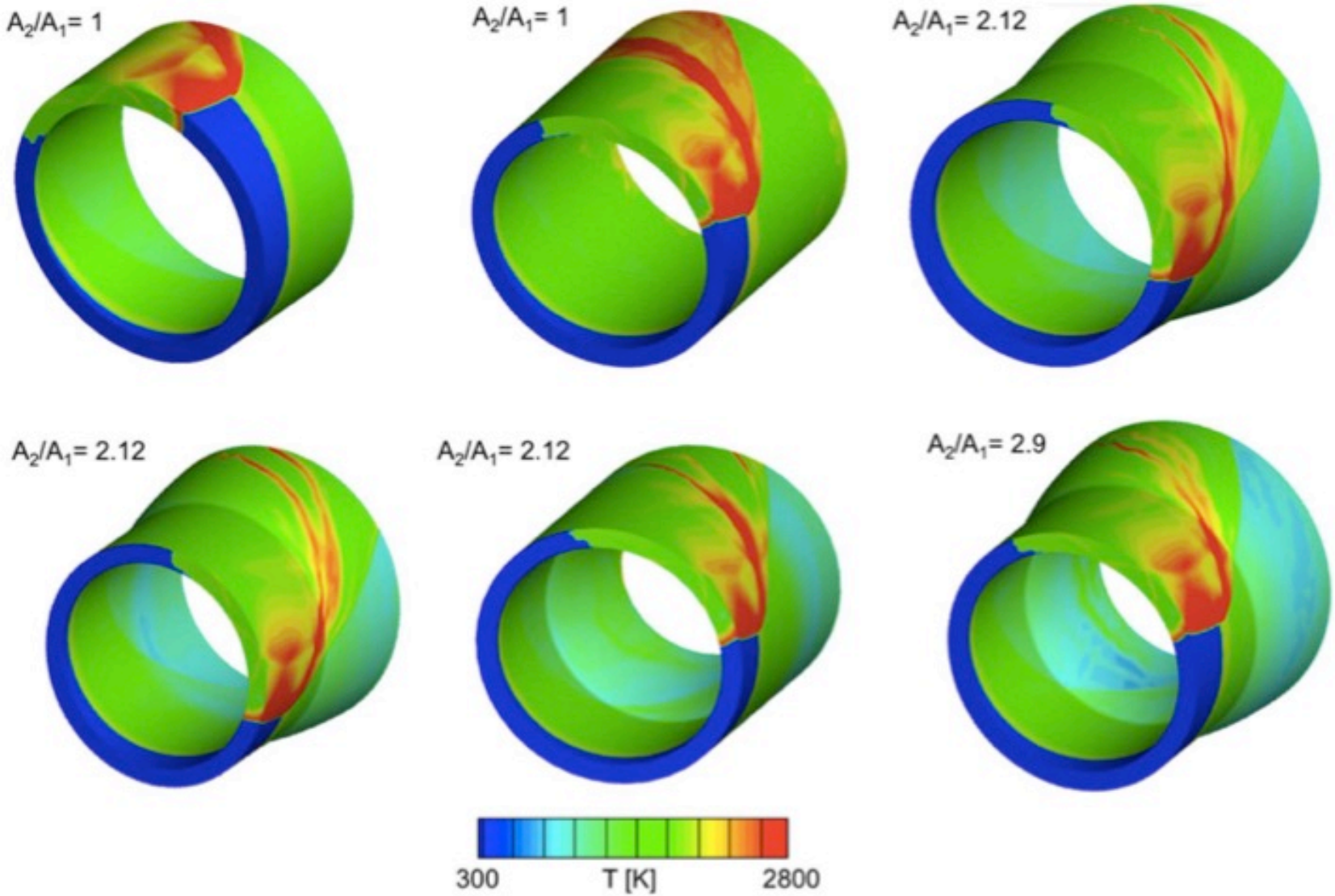
- Circumferential pressure reflection behind the detonation wave

Rotating detonation engines – Detailed flow field (outlet)

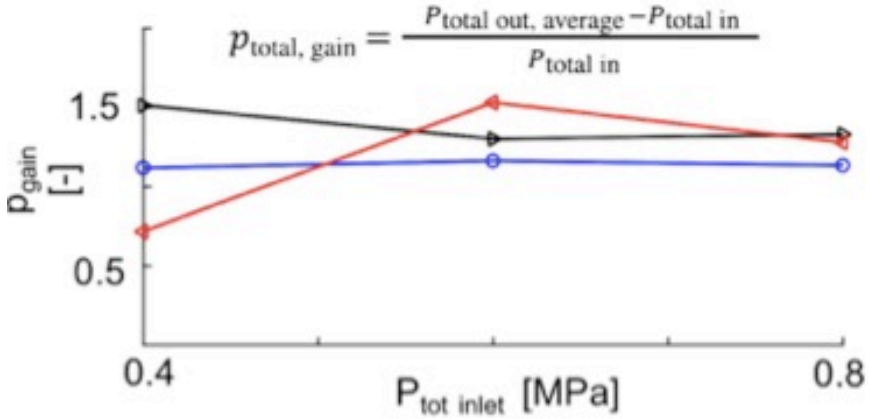


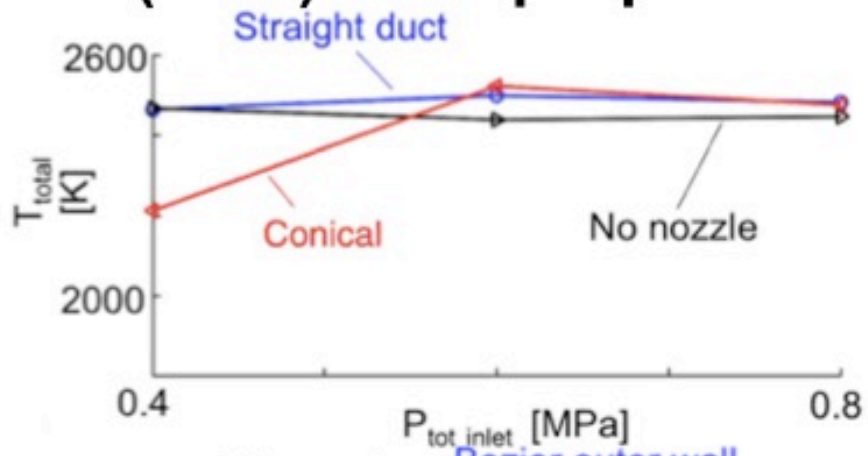
- Outlet T and P reaching 3000 K and 12 bars respectively
- Flow remaining supersonic for almost complete cycle
- Strong flow angle change due high variation on both components

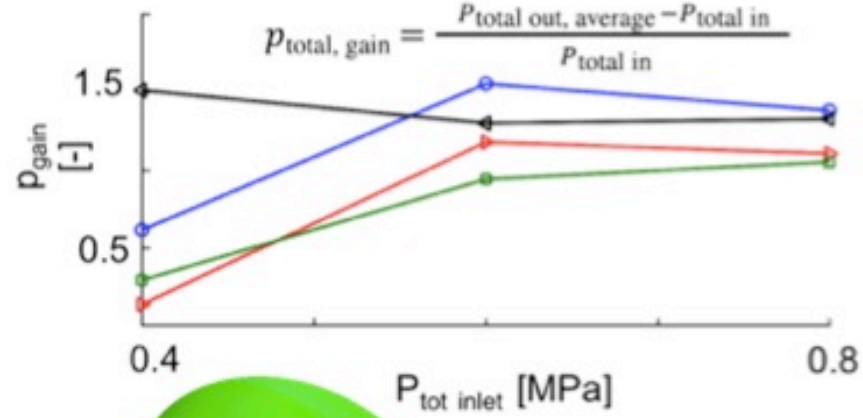
Rotating detonation engines (RDE) – Jet propulsion

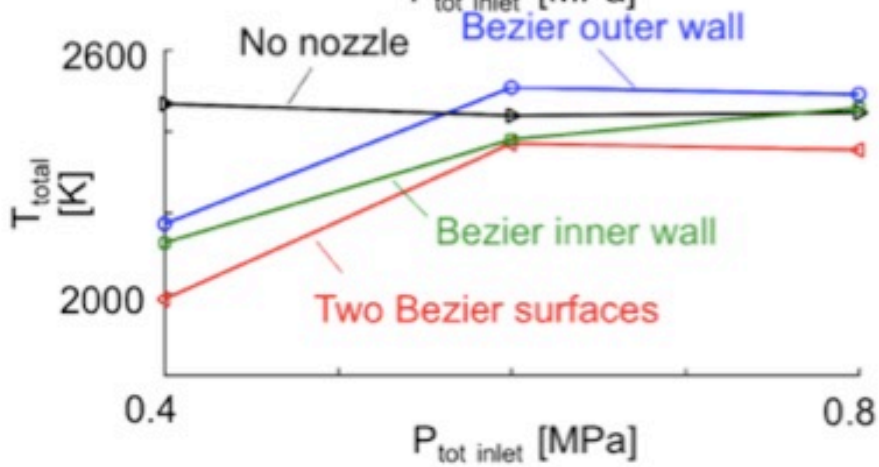


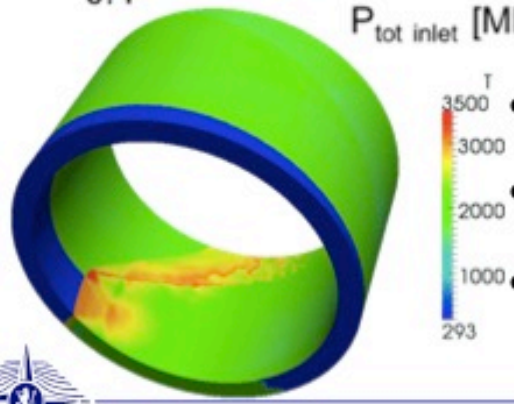
Rotating detonation engines (RDE) – Jet propulsion





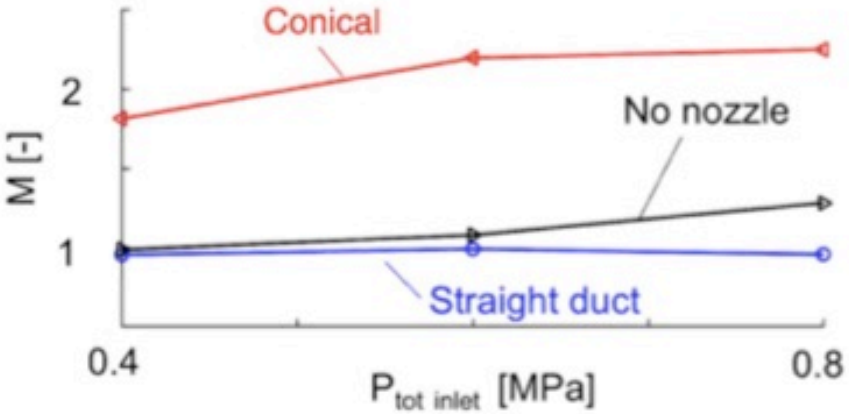


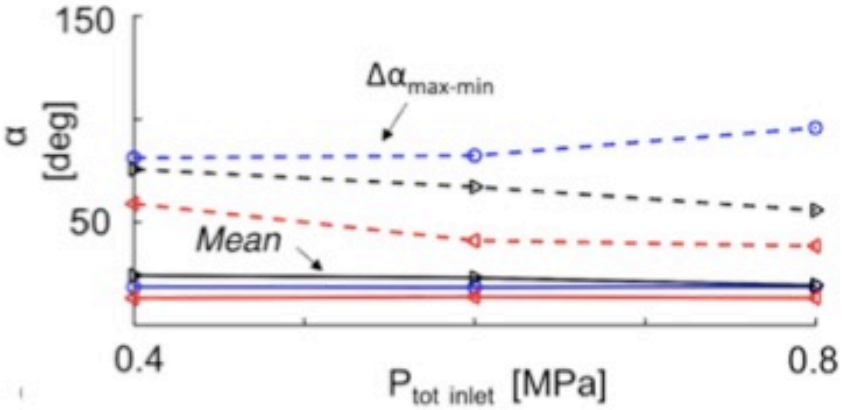


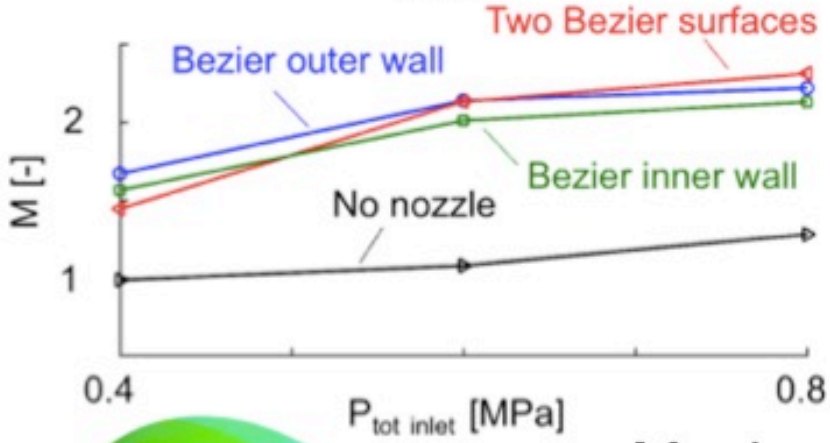


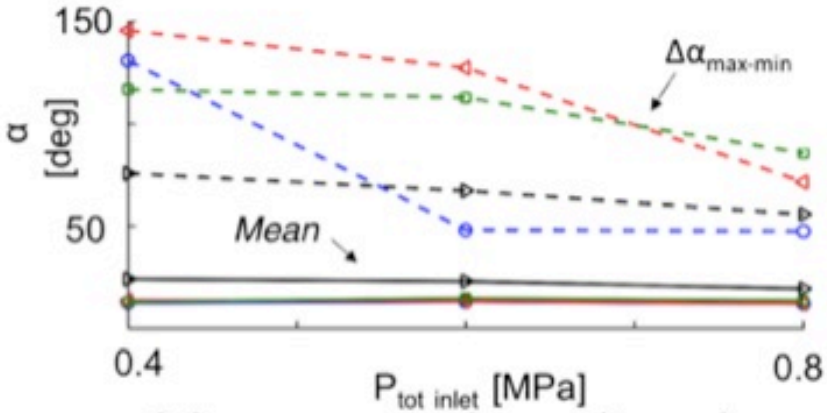
- Nozzle strongly affect the outlet flow field
- Highest pressure gain for outer Bezier nozzle
- Total temperatures raising above 2500 K

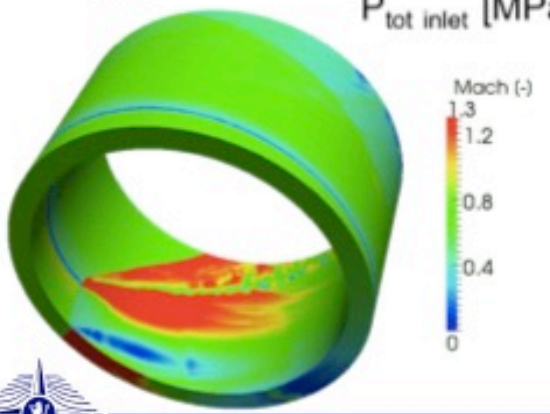
Rotating detonation engines (RDE) – Jet propulsion







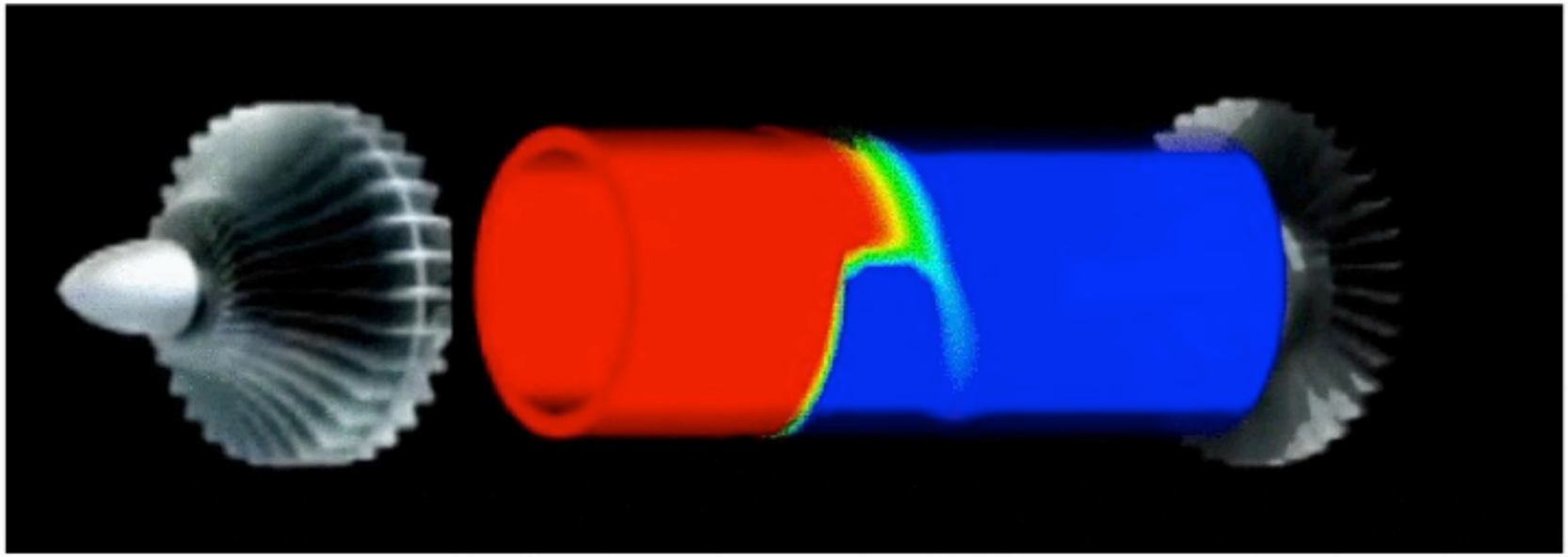




- Mach number reaching more than 2 owing to the nozzle attachment
- Flow angle variation highly affected from nozzle contouring
- Mean flow angle remains unaffected

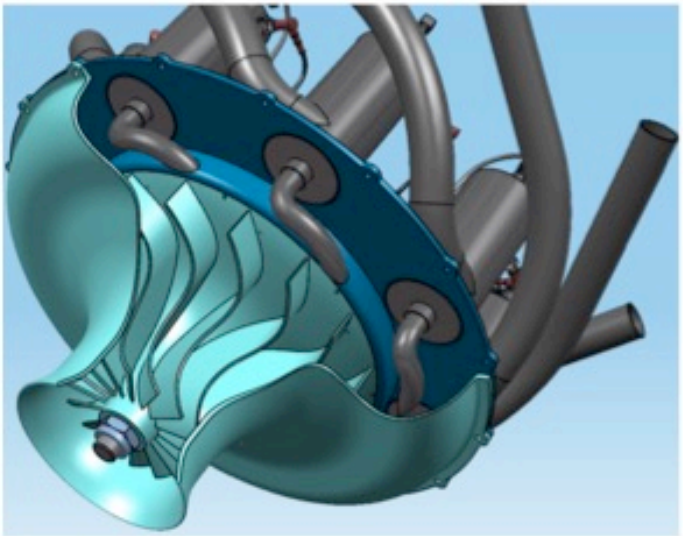
Detonation engines – Turbomachinery integration

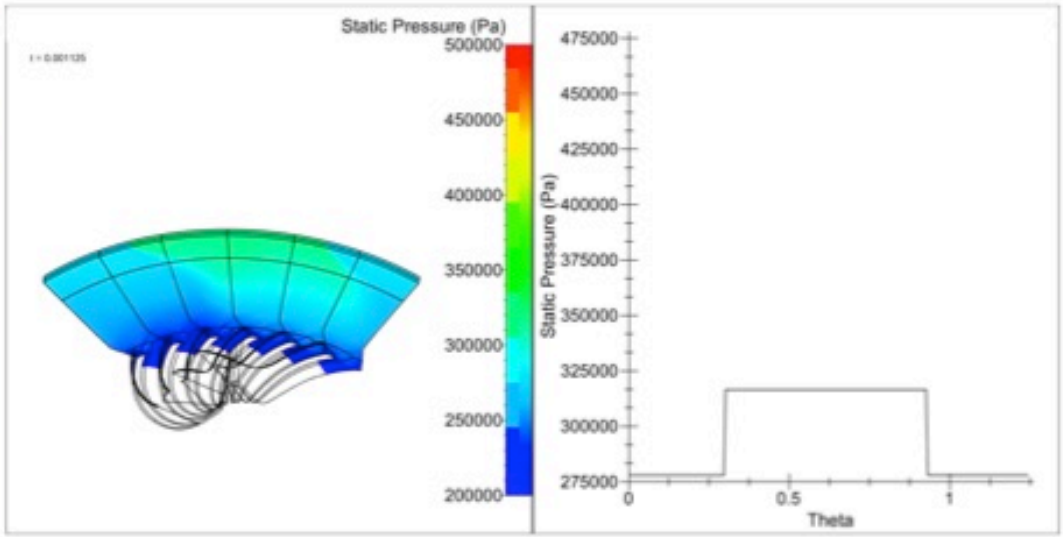
- A challenging task due to:
  - Inherent high amplitude – high frequency unsteadiness
  - Strong blockage at the compressor outlet
  - Possible operational problems due to stall and surge
  - Starting issues of turbine blade passages due to high supersonic flows
  - Unprecedented variation on the incidence angle
  - Strong efficiency abatement due to leading edge shocks on poor designs



Detonation engines – Compressor integration

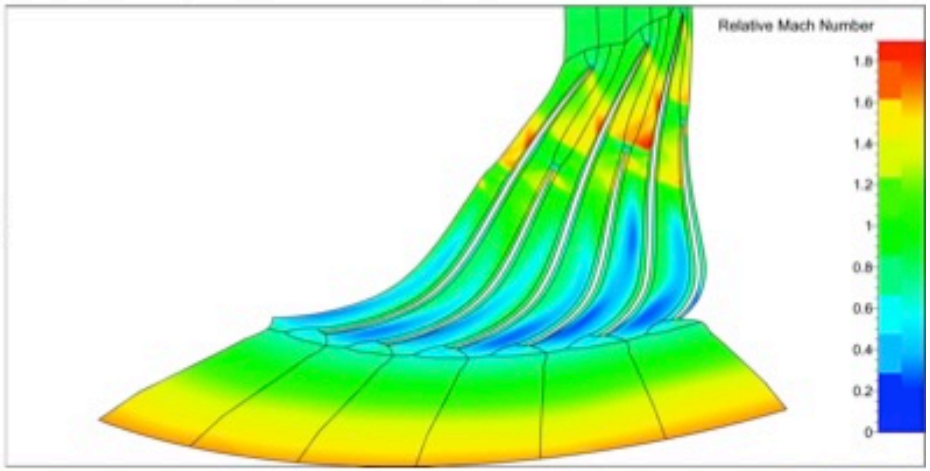
Aerodynamic effect on a radial compressor for EC-Tide Project



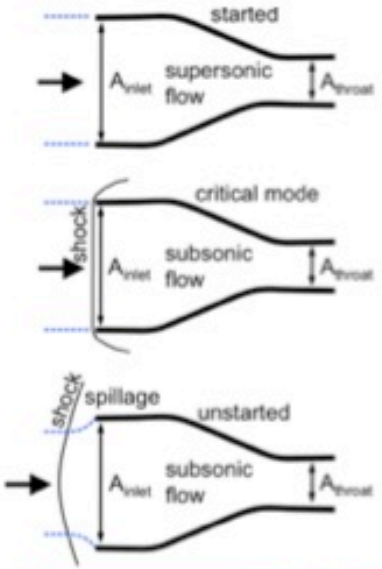


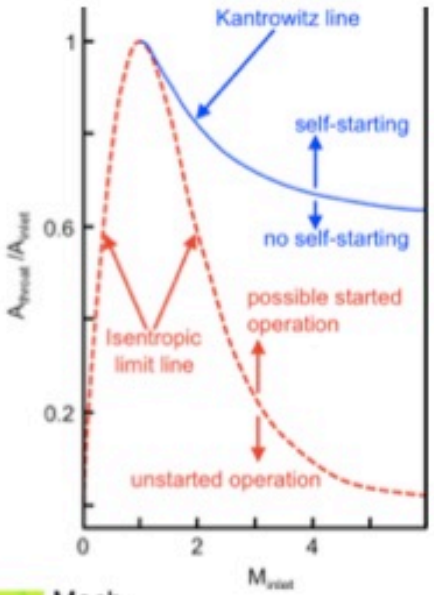
Flow field around the shroud

- Strong deceleration in the flow passages
- Formation of normal shock wave chocking the Main Blade passage
- Migration of a supersonic pocket towards the Suction Side of the Splitter Blades

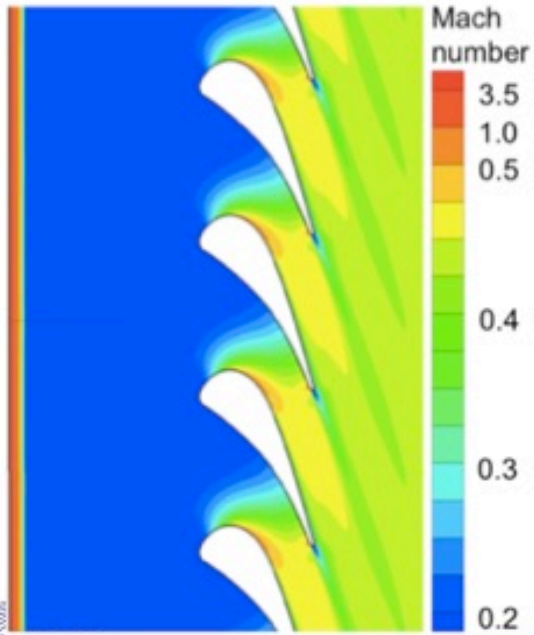


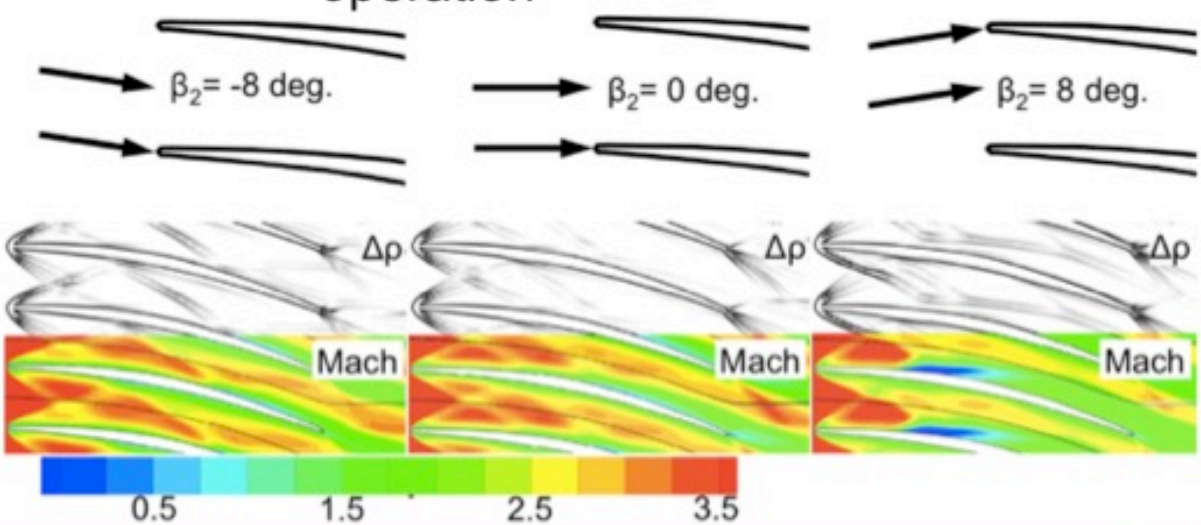
Detonation engines – Integration of turbine





- Starting problem due to periodic change in flow regime
- Turbine blade passage chokes due to high supersonic flows
- Conventional turbine fails to operate
- Strong variation on the incidence angle
- Strong efficiency abatement due to leading edge shocks on poor designs
- Optimization is a must for reliable operation

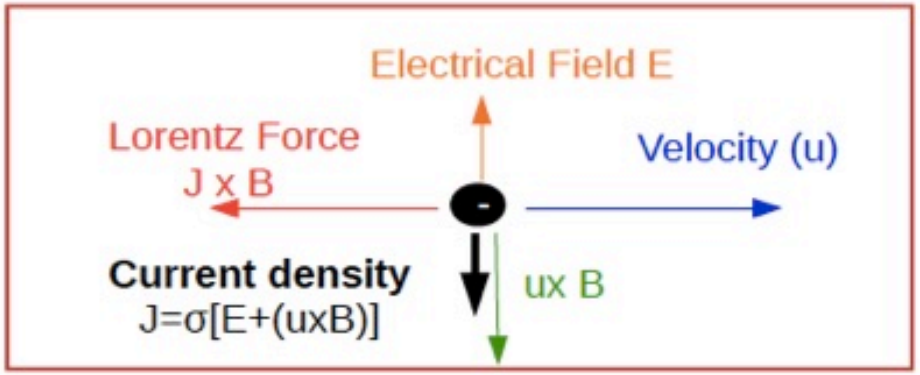




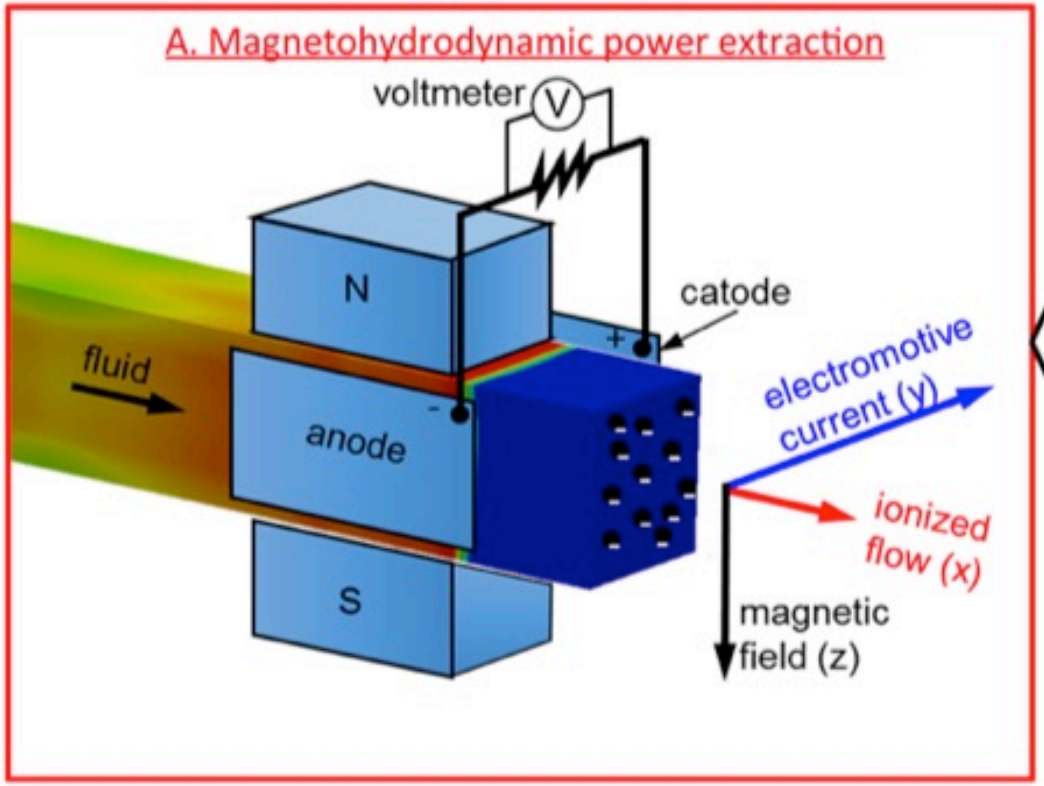
Detonation engines – Direct power extraction

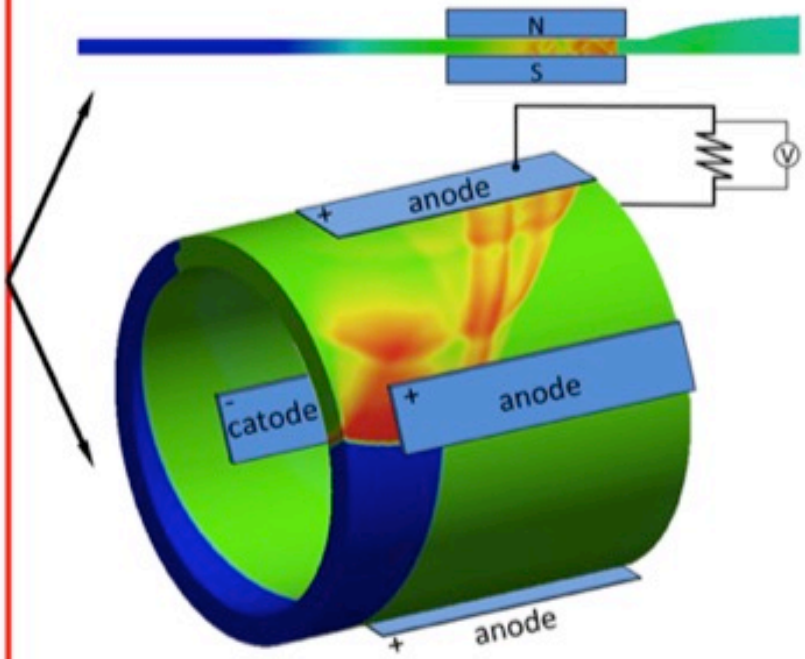
Further exploitation grounds in the fields of energy production

- Magnetohydrodynamic (MHD) effects of fluids at high temperature
- Passage of ionized particles through a magnetic field creating electric field
- Harnessing electrical energy through electrodes
- Ion augmentation with alkali seeding



B. Pulse detonation engine





C. Rotating detonation engine

Closure

- Detonation engine offering great potential for future propulsion
- PDE compromising simpler implementation with low frequency
- PDE already proven potential for jet propulsion
- RDE providing much higher frequencies
- Increasing detonation wave number leading more uniform flow
- Turbomachinery integration stands as a challenging task
- Opening a new venue in direct energy extraction

References

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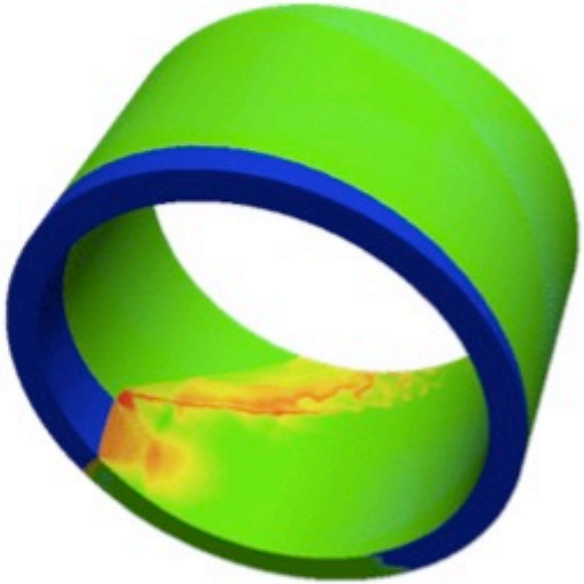
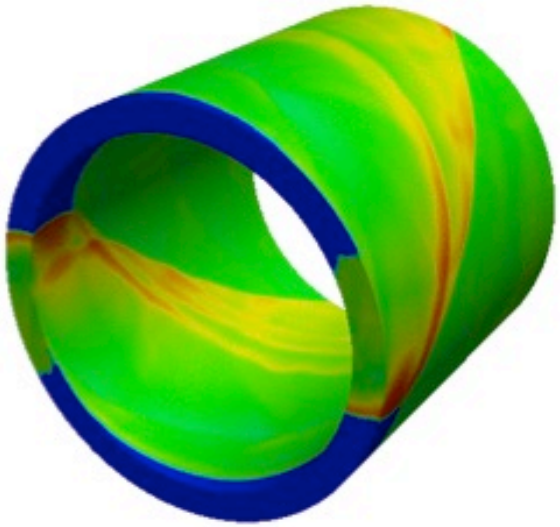
[4] Barun J., Saracoglu B.H., Magin T., Paniagua G., “One-Dimensional Analysis of the Magnetohydrodynamic Effect in Rotating Detonation Combustors” (2016) AIAA Journal





Thank you for your attention