Experiments and Numerical Simulation of Deflagration-to-Detonation Transition and Detonations in Gaseous and Two-Phase Systems

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Outline

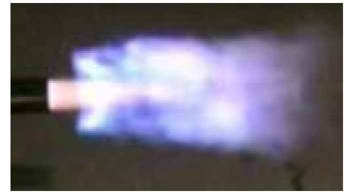
- **Motivation**
- **Fast DDT concept**
- **Pulsed detonations**
  - natural-gas pulsed detonation burner
  - PDE for orbit correction
  - estimation of PDE ramjet flight performances
- **Continuous detonations**
  - hydrogen-fueled continuous detonation chamber with nonpremixed fuel and air
- **Conclusions**

Motivation

Deflagration vs. Detonation (I)

Flame

$U \sim 0.5 - 10$ m/s



Detonation

$U \sim 1500 - 2500$ m/s

Reaction mode

Frontal, transport controlled at $p \sim p_0$

Volumetric, shock-induced at $p \sim 30\text{-}50 p_0$

Reaction time

$\sim (1 - 0.1)$ ms

$\sim (0.1 - 0.01)$ ms

Mass flow rate

$\sim (0.5 - 10)$ kg/(m^{2}s)

$\sim (1.5 - 2.5) 10^3$ kg/(m^{2}s)

Combustion power

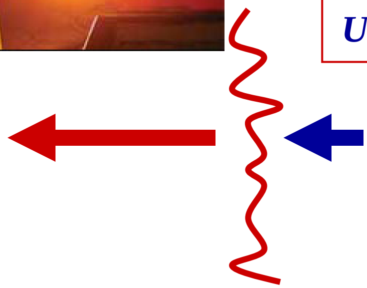
~ 1.0 MW/m^2

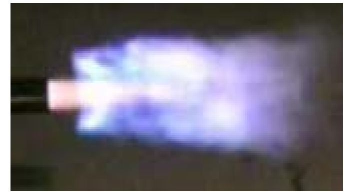
$\sim (3 - 10) 10^3$ MW/m^2

Deflagration vs. Detonation (II)

Flame

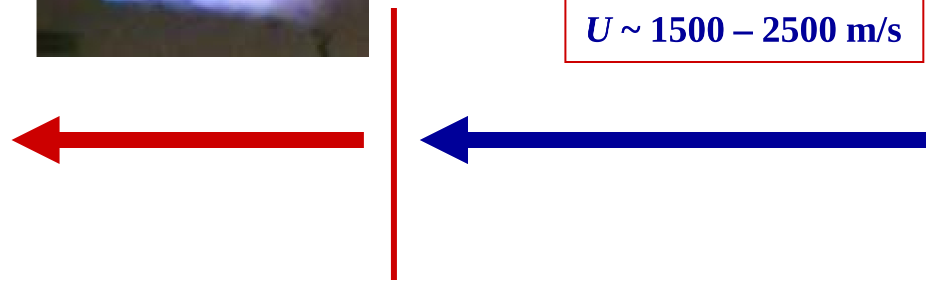
U ~ 0.5 – 10 m/s





Detonation

U ~ 1500 – 2500 m/s



Maximum pressure of reaction products

$p \sim p_0$ $\qquad$ $p \sim (17\text{–}20)p_0$

Maximum temperature of reaction products

~ 2200 – 3000 K $\qquad$ ~ 2800 – 4000 K

Density of reaction products

$\sim (0.1 - 0.15)\ \rho_0$ $\qquad$ $\sim (1.7 - 2.0)\ \rho_0$

Convective velocity of reaction products

~ (4 – 9)U $\qquad$ ~ (0.4 – 0.5)U

1455

1940 г. ЖУРНАЛ ТЕХНИЧЕСКОЙ ФИЗИКИ Том X, вып. 17

1940 JOURNAL OF TECHNICAL PHYSICS Vol. X, No 17

К ВОПРОСУ ОБ ЭНЕРГЕТИЧЕСКОМ ИСПОЛЬЗОВАНИИ ДЕТОНАЦИОННОГО ГОРЕНИЯ

Я. Б. Зельдович

При детонационном горении[1] взрывчатых газовых смесей в момент, непосредственно следующий за прохождением детонационной волны (протеканием химической реакции), продукты горения оказываются в состоянии (назовем его „состояние D“), весьма богатом энергией тепловой и кинетической (поступательного движения).

Классическая термодинамическая теория Жуге позволяет вычислить, в предположении отсутствия потерь, „состояние D“ продуктов горения. Получаемое одновременно в таком расчете значение скорости распространения детонации находится в хорошем согласии с опытом, подтверждая правильность термодинамической теории как предельного случая в отсутствии потерь.

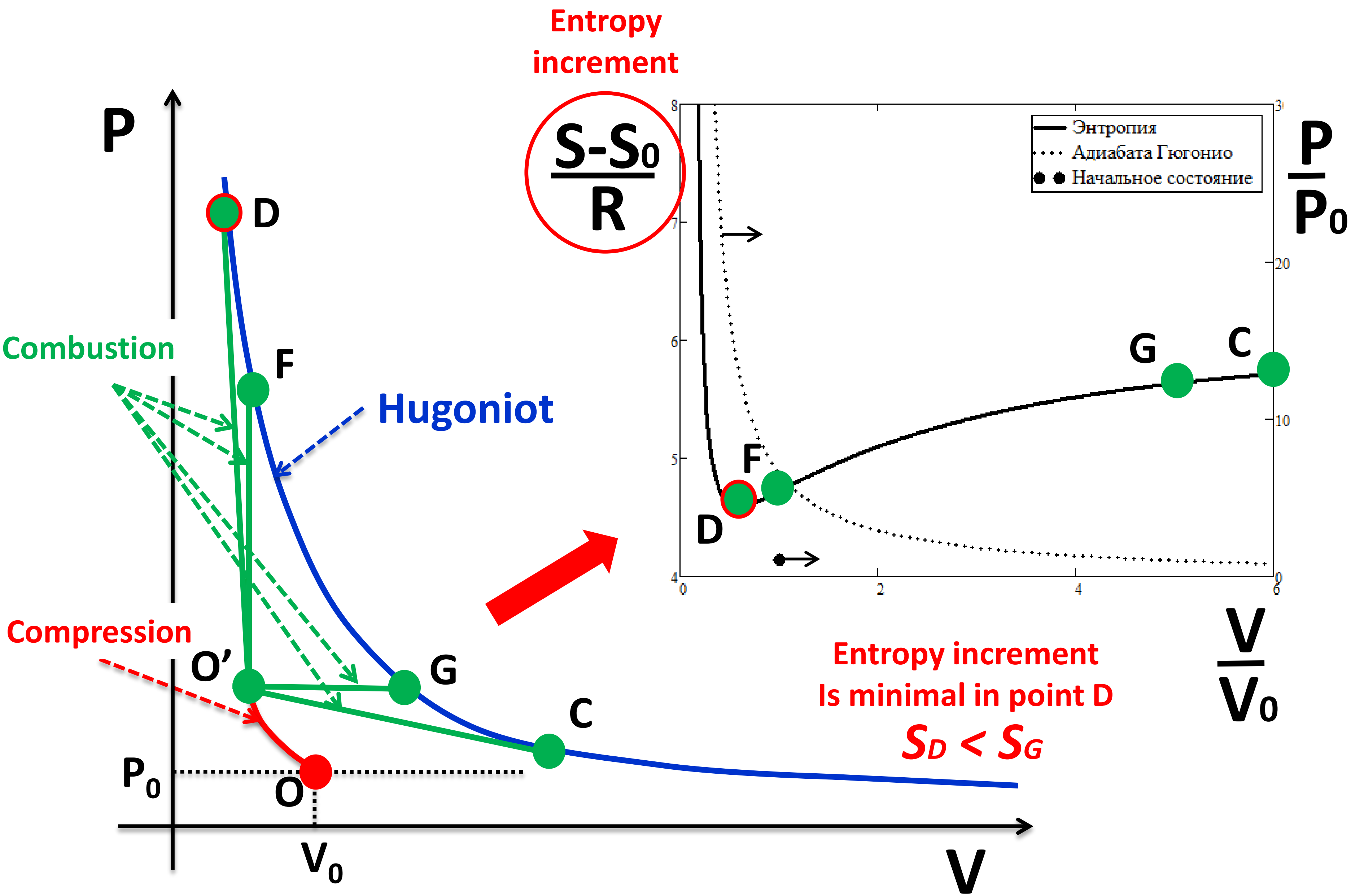
Расчет дает для продуктов горения в детонационной волне:

плотность — в $2 \div 1.7$ раза больше плотности начальной смеси (приблизительно в $k+1/k$ раза, где k показатель адиабаты $pv^k = \text{const}$ для продуктов горения);

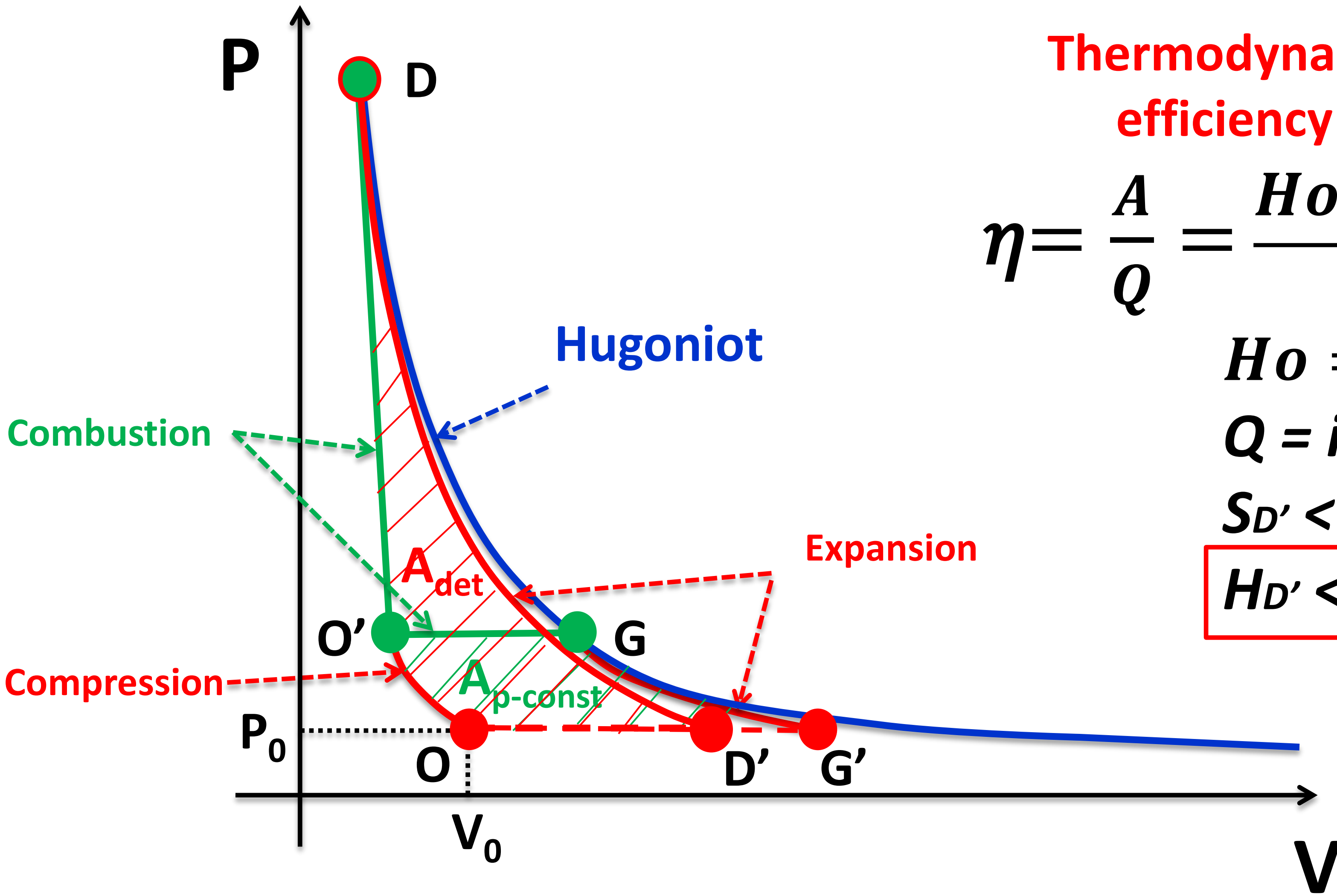
Ya. B. Zel’dovich

$$\eta_{Detonation} > \eta_{V=const} > \eta_{P=const}$$

Steady-State Combustion Modes



Zel'dovich and Brayton cycles



Thermodynamic efficiency:

$$\eta = \frac{A}{Q} = \frac{Ho - H}{Q}$$

$$Ho = idem$$

$$Q = idem$$

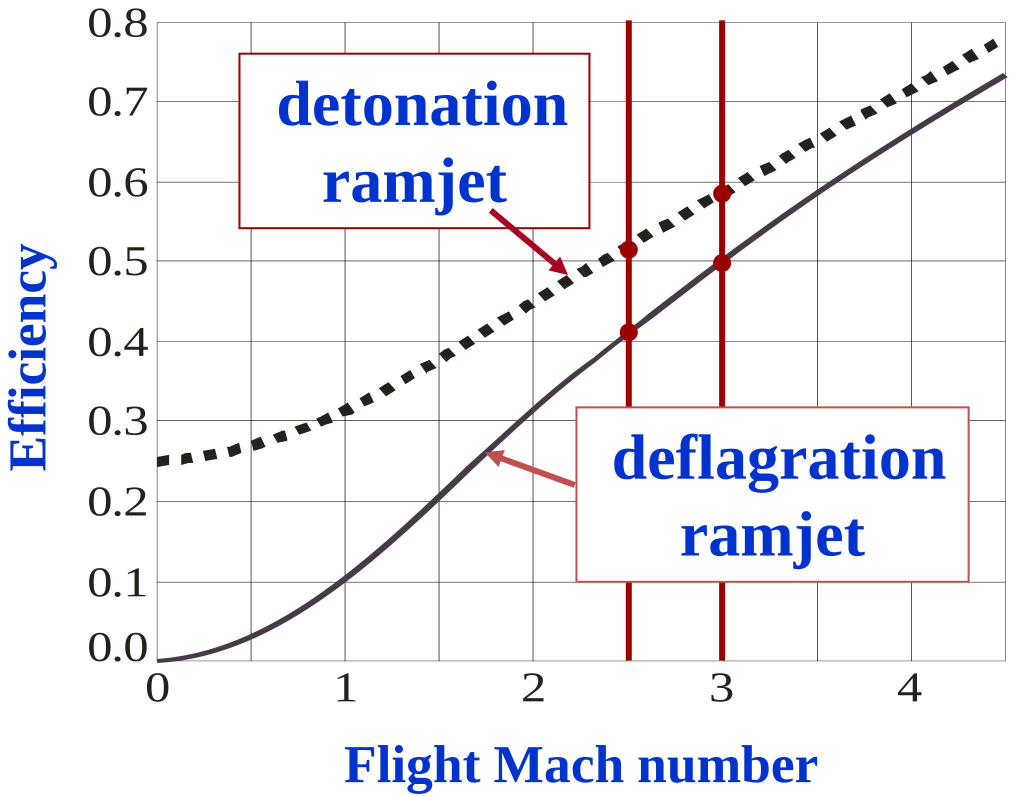
$$S_{D'} < S_{G'}$$

$$\boxed{H_{D'} < H_{G'}}$$

$A_{det} > A_{p\text{-const}} \rightarrow$ **Considerable gain in efficiency**

$\eta \sim 50\%\text{-}55\%$

<u>Example:</u> Thermodynamic efficiency of ramjets



• Theoretical gain in efficiency – up to 30% at M = 2.5
– up to 20% at M = 3.0

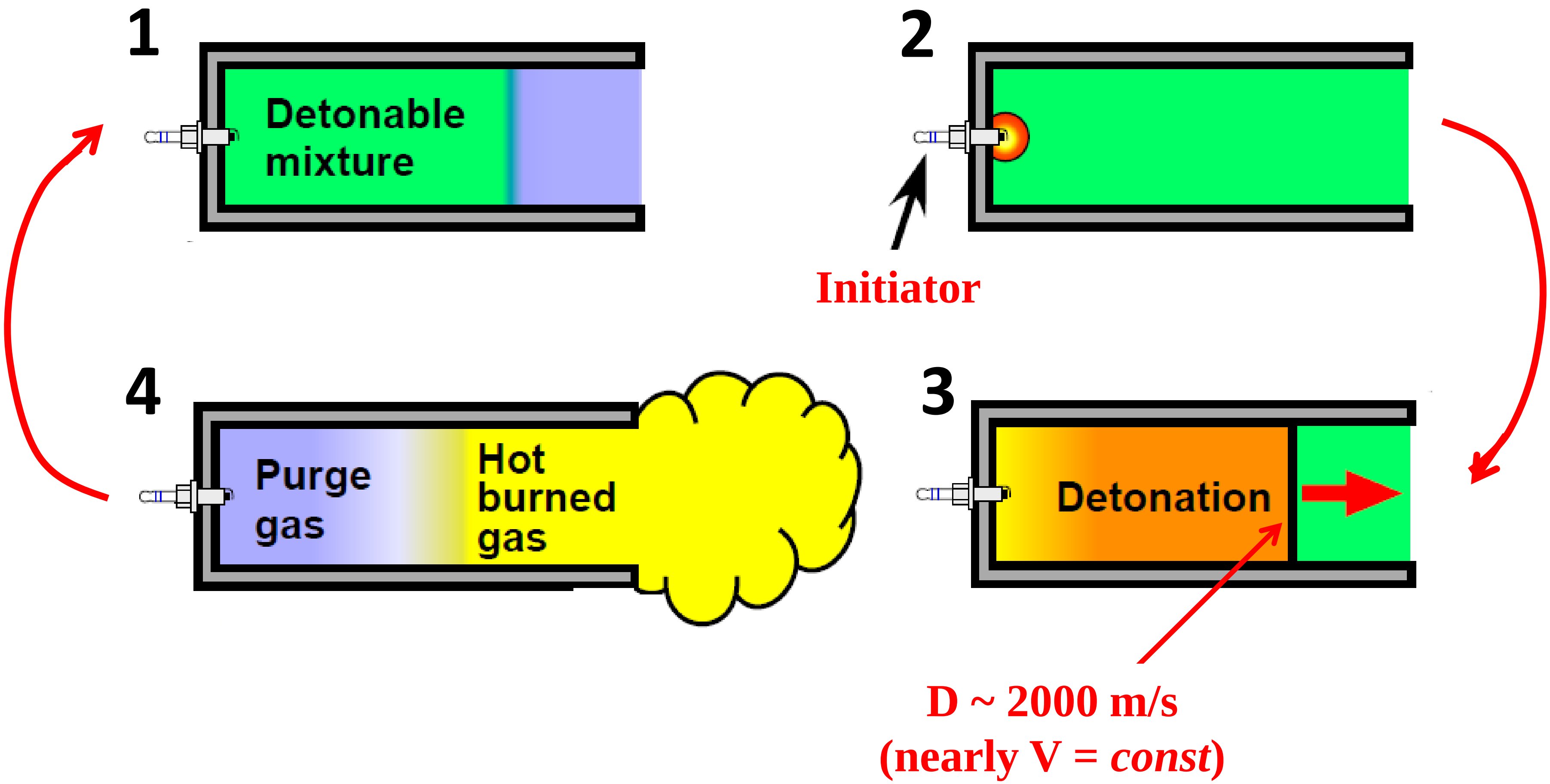
Is it feasible to realize efficient detonation (Zel'dovich) cycle?

Two variants of operation process:

- Intermittent (pulsed) detonation mode
- Continuous (rotating) detonation mode

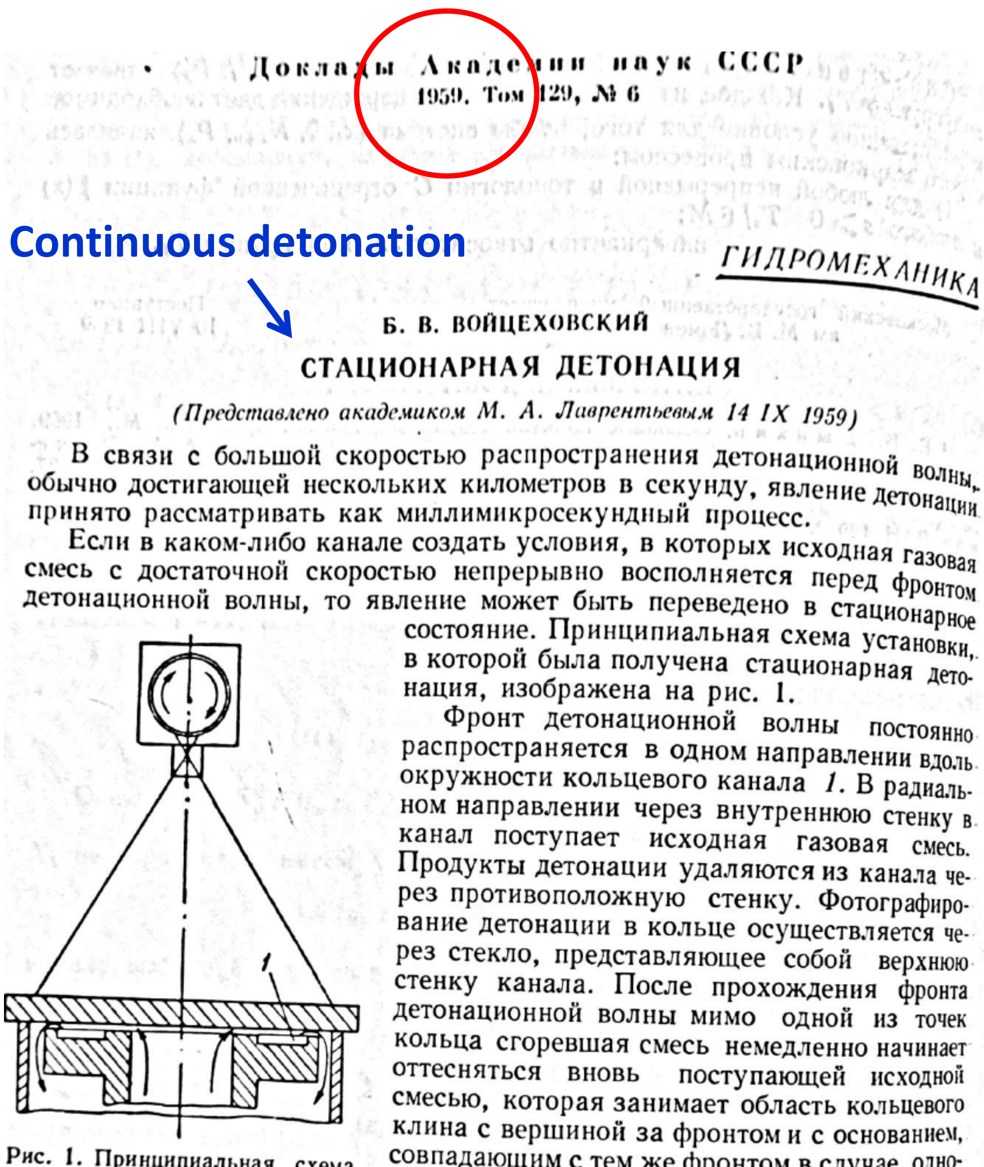
Intermittent (pulsed) detonations:
Physical principles

Operation cycle



Bussing (~1991)

Continuous (rotating) detonations:
Physical principles



Доклады Академии наук СССР
1959. Том 129, № 6

ГИДРОМЕХАНИКА

Б. В. ВОЙЦЕХОВСКИЙ

СТАЦИОНАРНАЯ ДЕТОНАЦИЯ

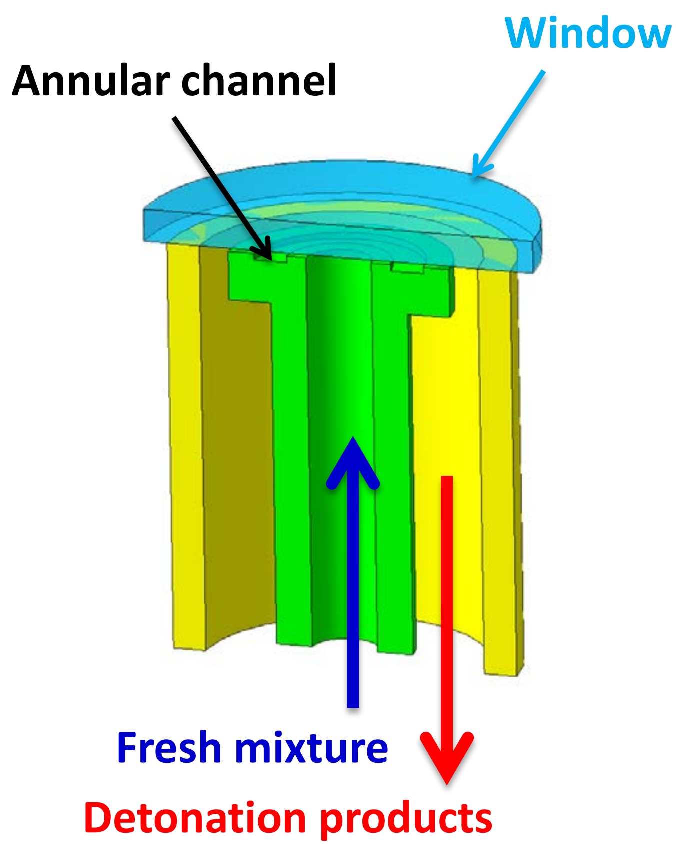
(Представлено академиком М. А. Лаврентьевым 14 IX 1959)

В связи с большой скоростью распространения детонационной волны, обычно достигающей нескольких километров в секунду, явление детонации принято рассматривать как миллимикросекундный процесс.

Если в каком-либо канале создать условия, в которых исходная газовая смесь с достаточной скоростью непрерывно восполняется перед фронтом детонационной волны, то явление может быть переведено в стационарное состояние. Принципиальная схема установки, в которой была получена стационарная детонация, изображена на рис. 1.

Фронт детонационной волны постоянно распространяется в одном направлении вдоль окружности кольцевого канала *1*. В радиальном направлении через внутреннюю стенку в канал поступает исходная газовая смесь. Продукты детонации удаляются из канала через противоположную стенку. Фотографирование детонации в кольце осуществляется через стекло, представляющее собой верхнюю стенку канала. После прохождения фронта детонационной волны мимо одной из точек кольца сгоревшая смесь немедленно начинает оттесняться вновь поступающей исходной смесью, которая занимает область кольцевого клина с вершиной за фронтом и с основанием, совпадающим с тем же фронтом в случае одно-

Рис. 1. Принципиальная схема



Center for Pulsed Detonation Combustion at Semenov Institute of Chemical Physics

General objective

Development of scientific grounds for the design of advanced pulse and continuous detonation combustors for power engineering and propulsion applications

Standard DDT scenario

Accelerating flame

↓

Shock wave formation

↓

Collisions of flame-generated compression waves

↓

“Explosion in the explosion”

↓

Overdriven detonation

↓

Self-sustained detonation

Fast (controlled) DDT scenario

Idea

No matter how energy is deposited in the shock induced flow:

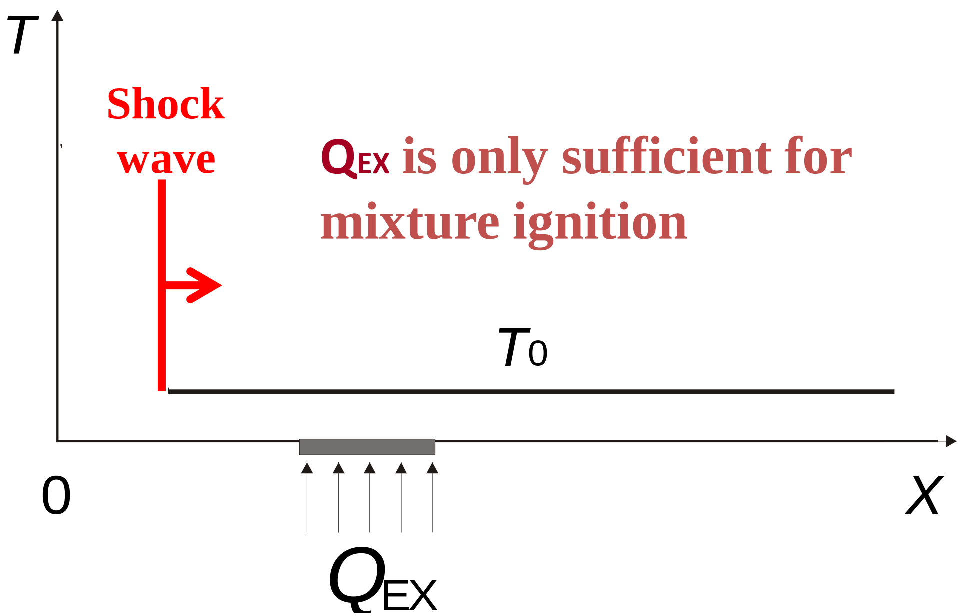
- spontaneously due to shock induced chemical reactions (strong shocks)

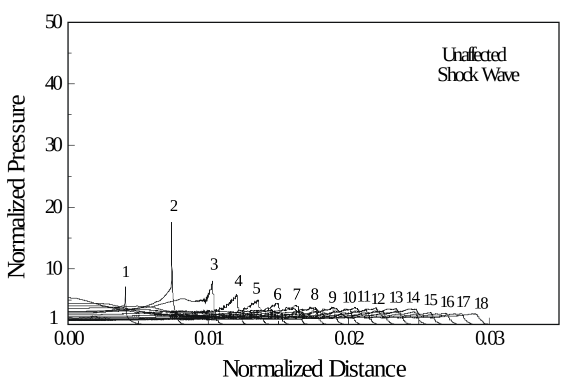
or

- by external stimulation of chemical activity (continuous or pulsed flow activation)

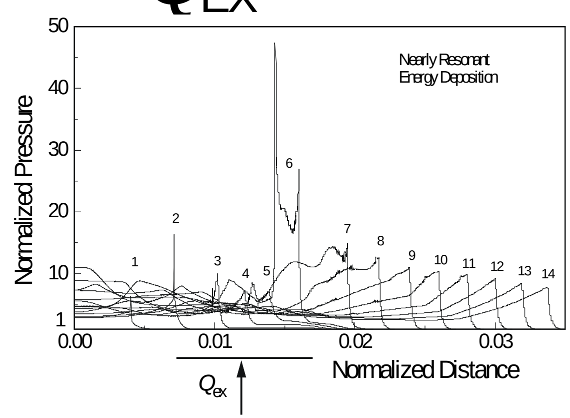
Initiation of gas detonation
by traveling (coherent) ignition pulse

1D simulation

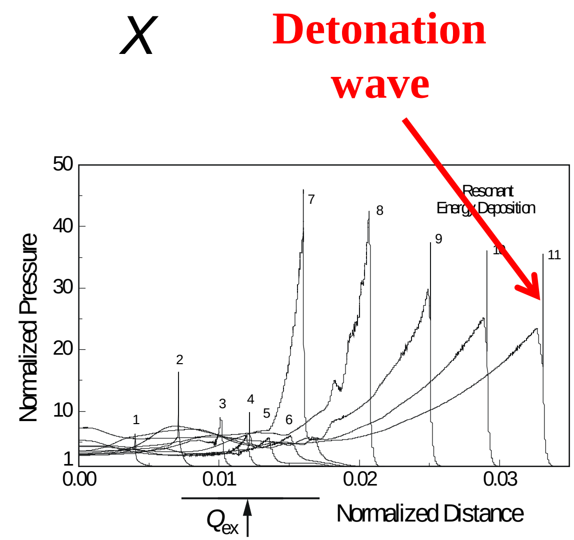




Primary shock



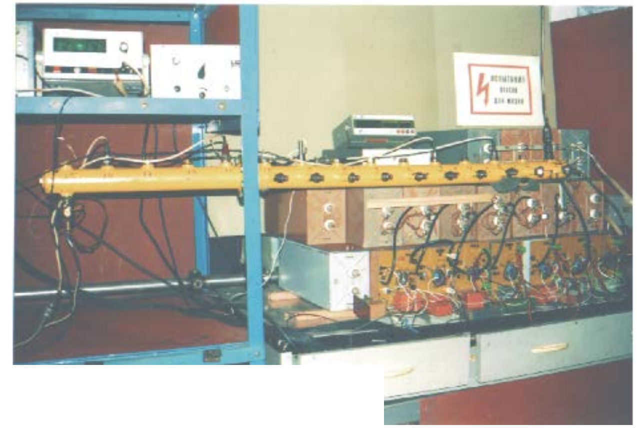
Nearly coherent energy deposition

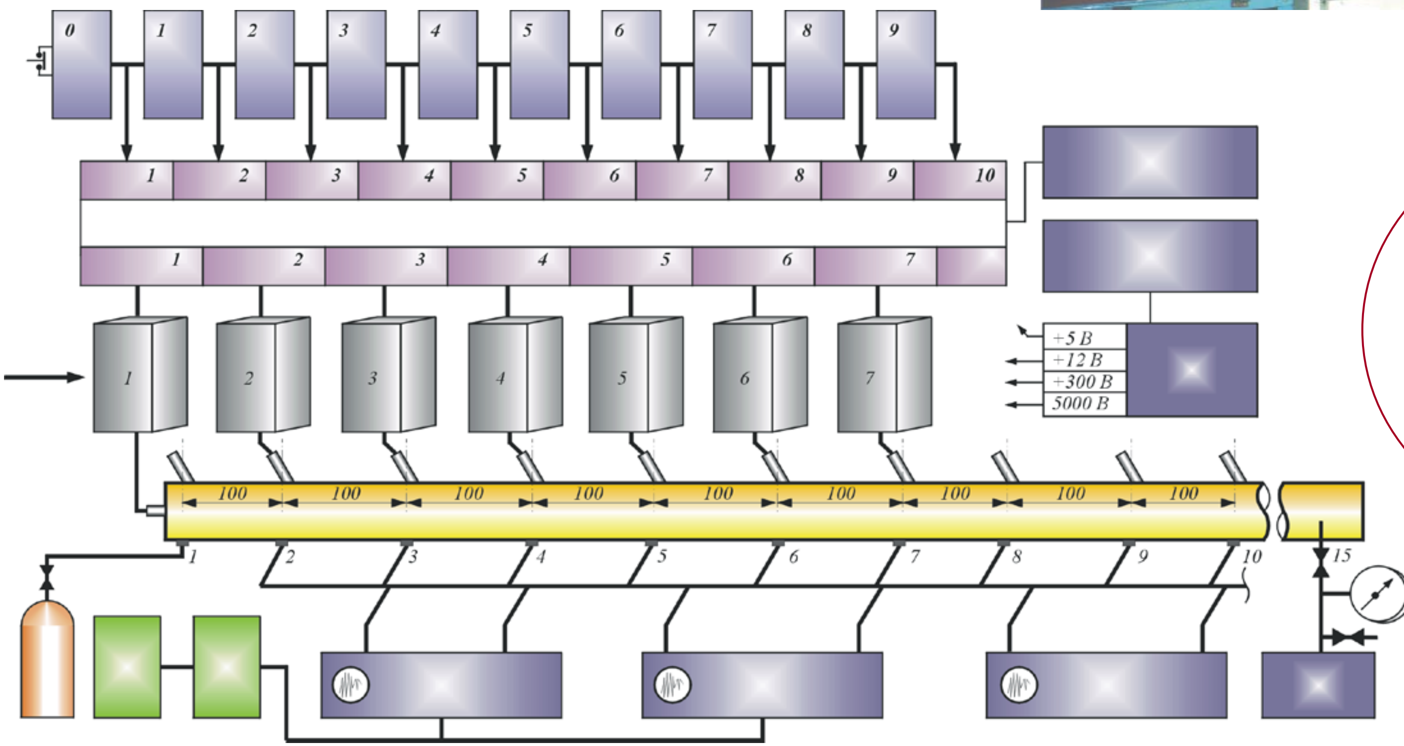


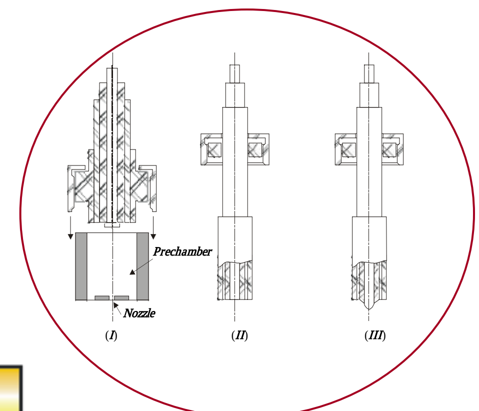
Coherent energy deposition

Experiment: propane–air (st.)

$d = 51$ mm



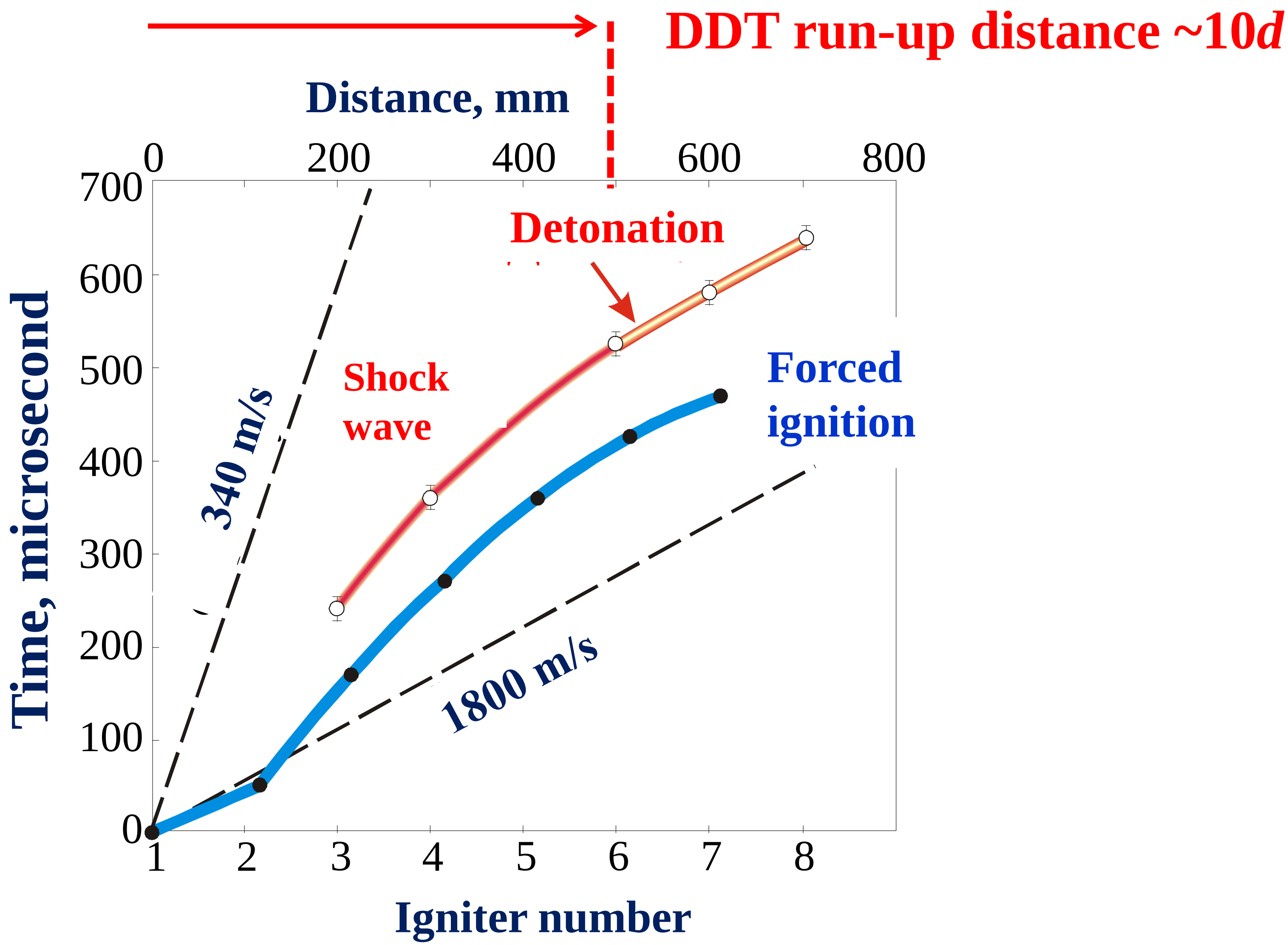




Igniters

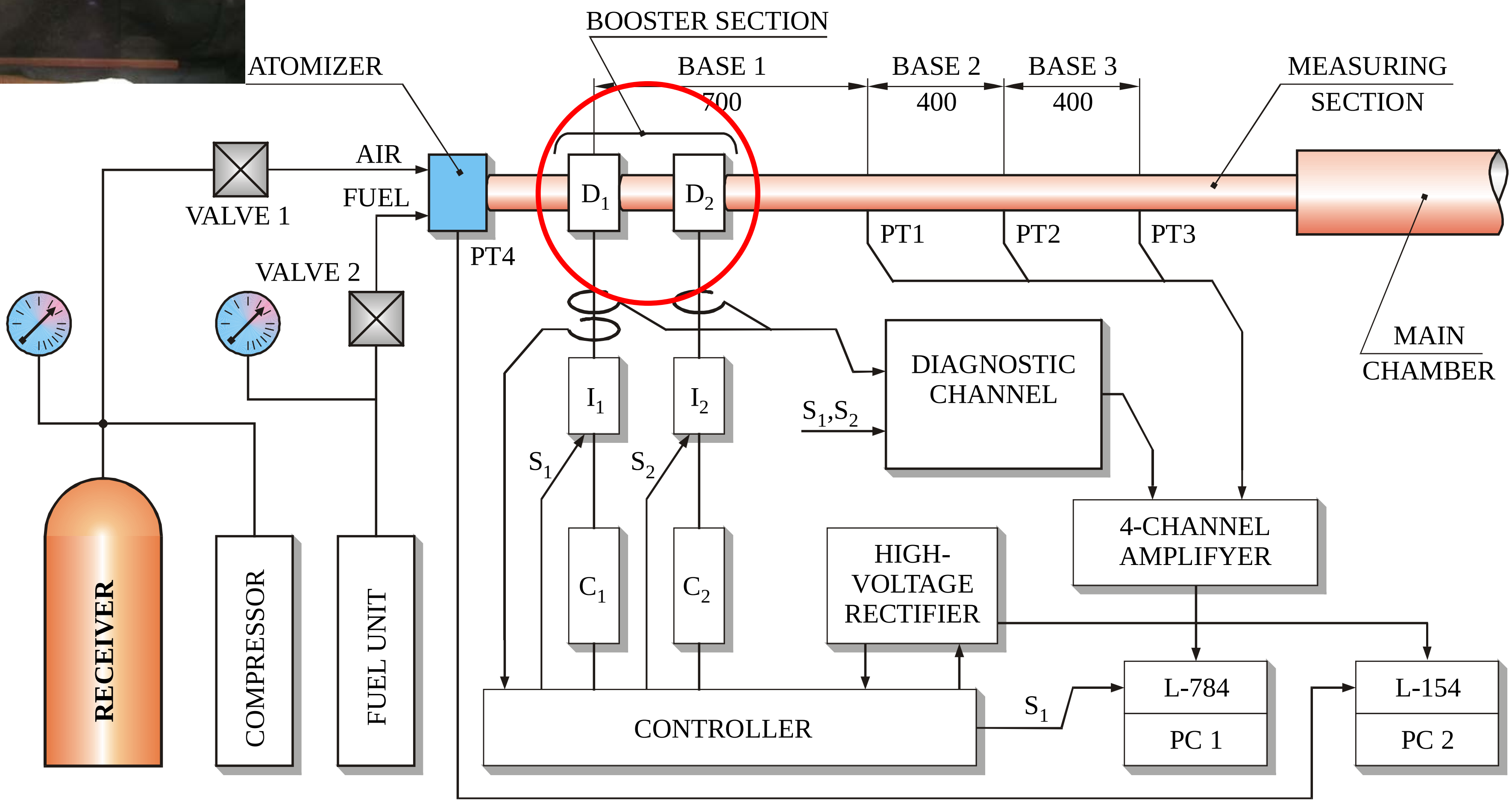
Frolov et al (2001)

Time – Distance Diagram



Experiment: *n*-heptane–air

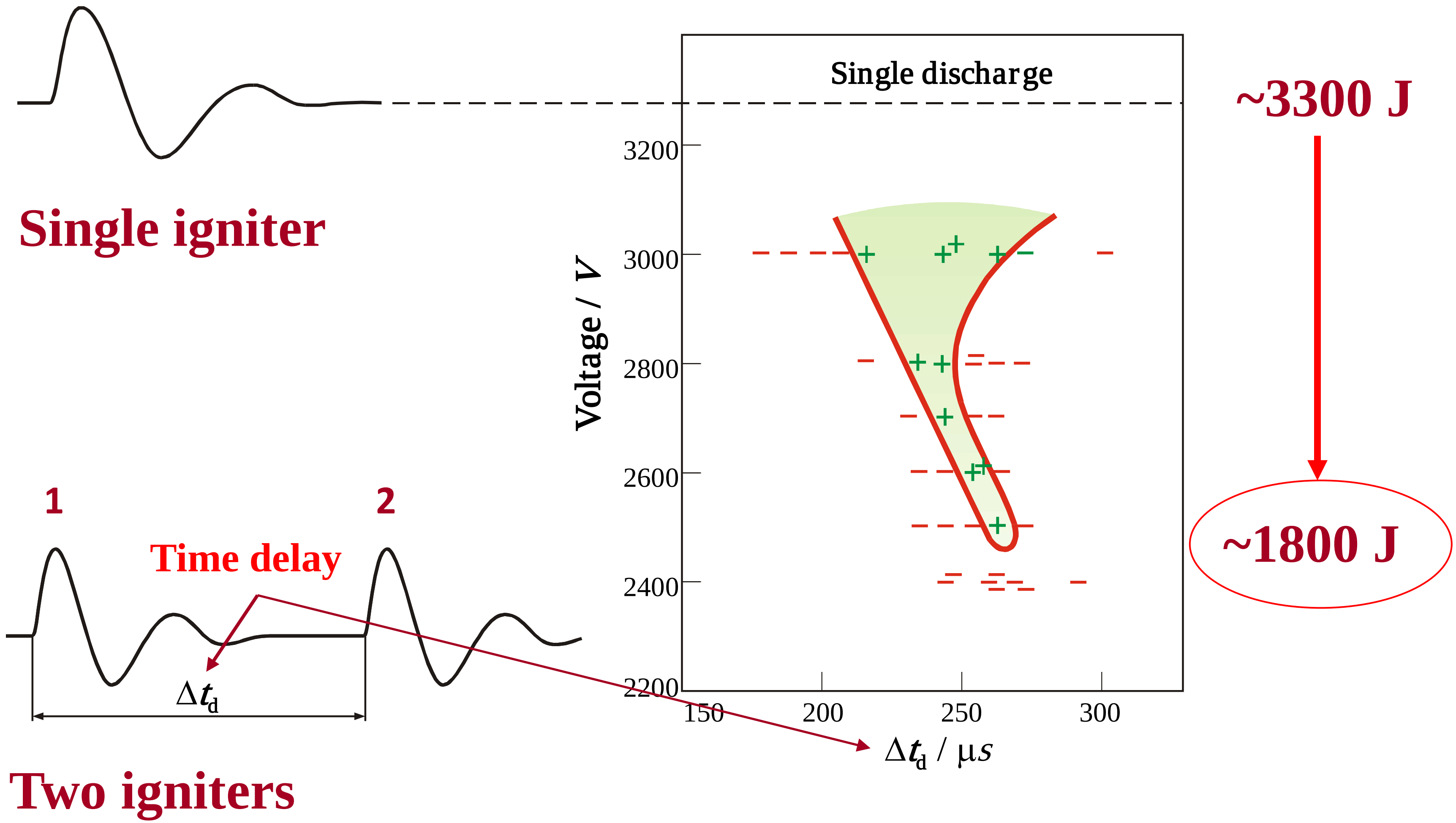
***d* = 51 mm**



Frolov et al (2002)

Detonation peninsula

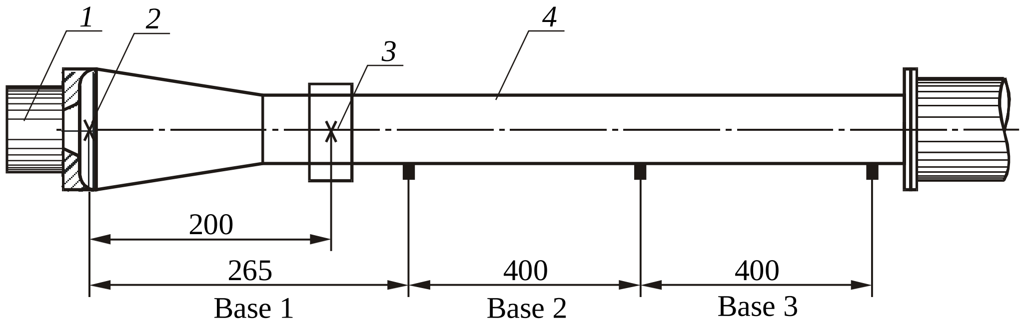
d = 51 mm



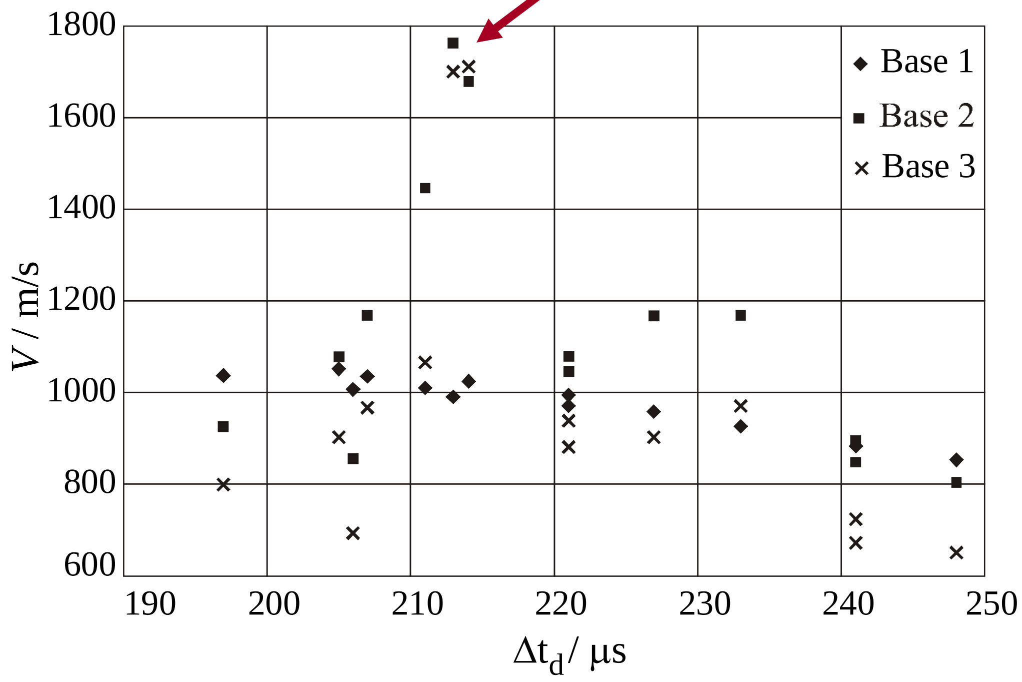
Detonation peninsula

d = 28 mm

~3300 J



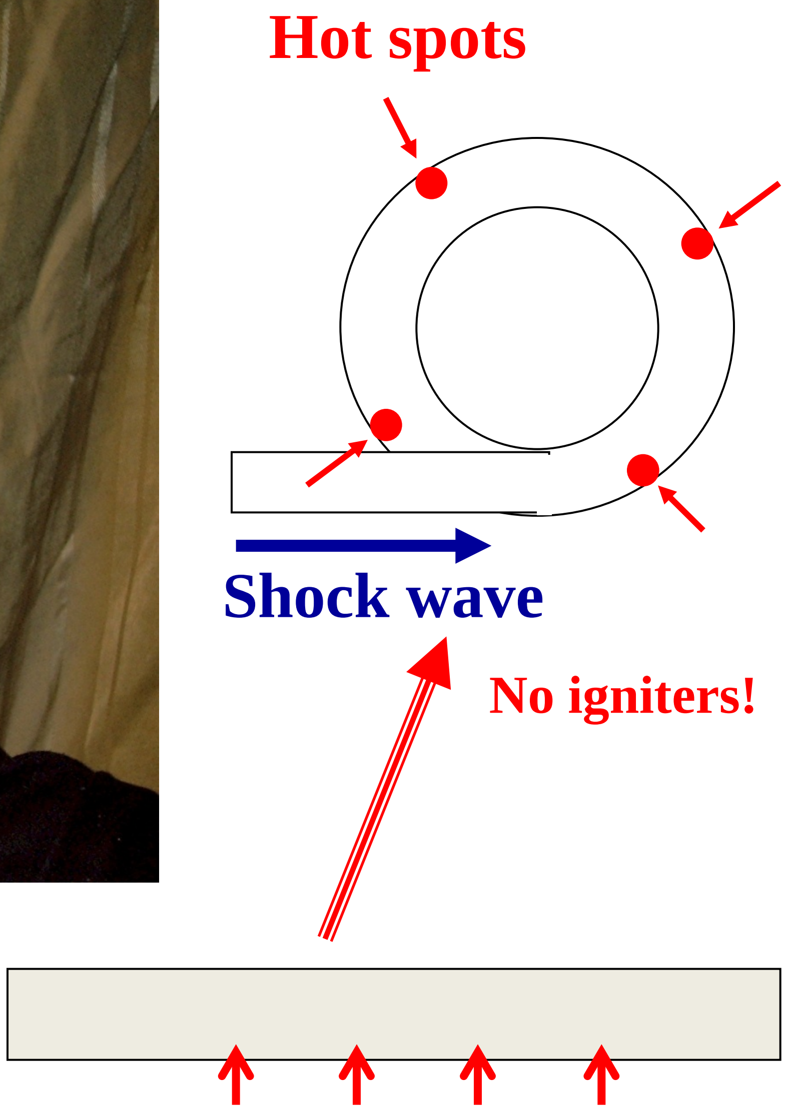
~900 J



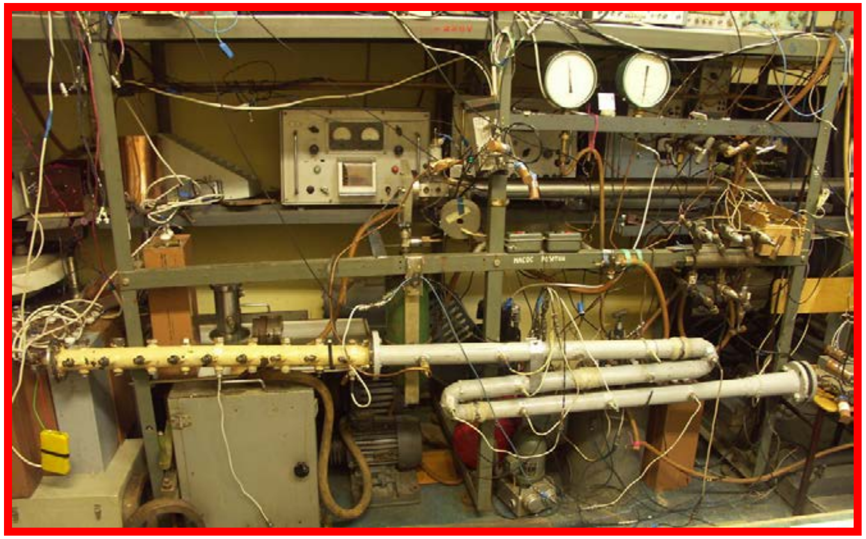
From traveling ignition pulse to curved tubes

Tube loop

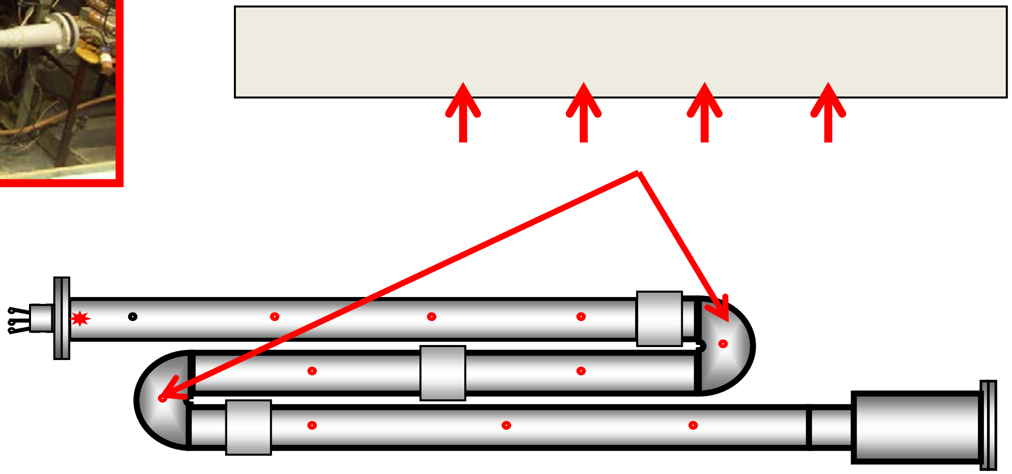
Frolov et al (2005)



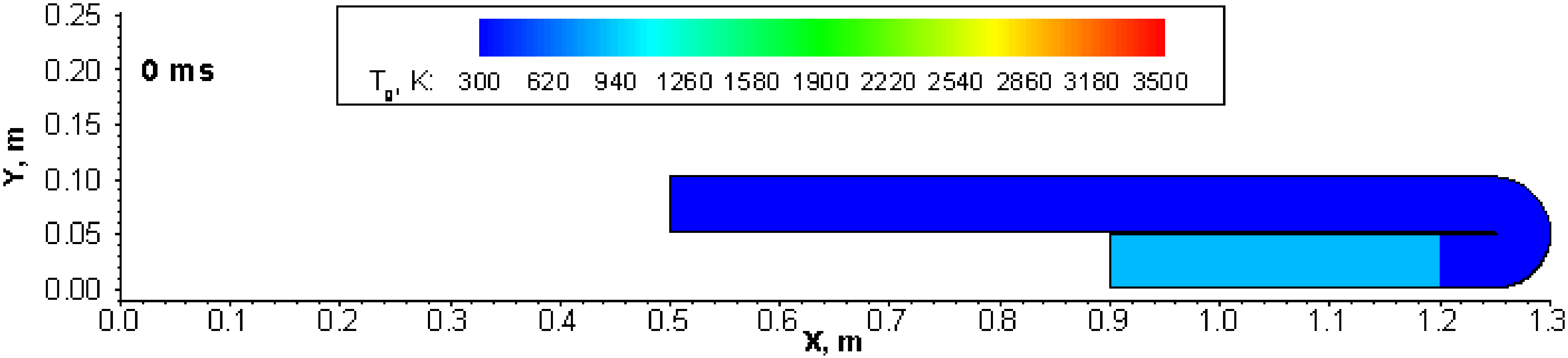
Tube U-bends



Frolov et al (2006)



2D simulation

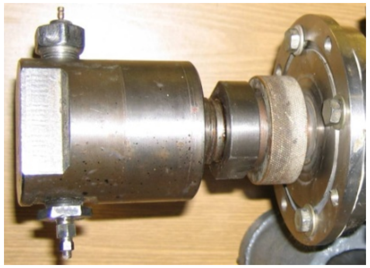


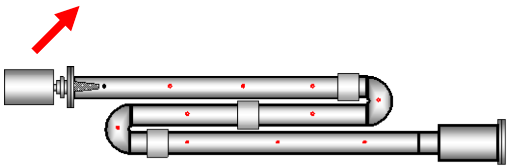
Propane – air (st.)

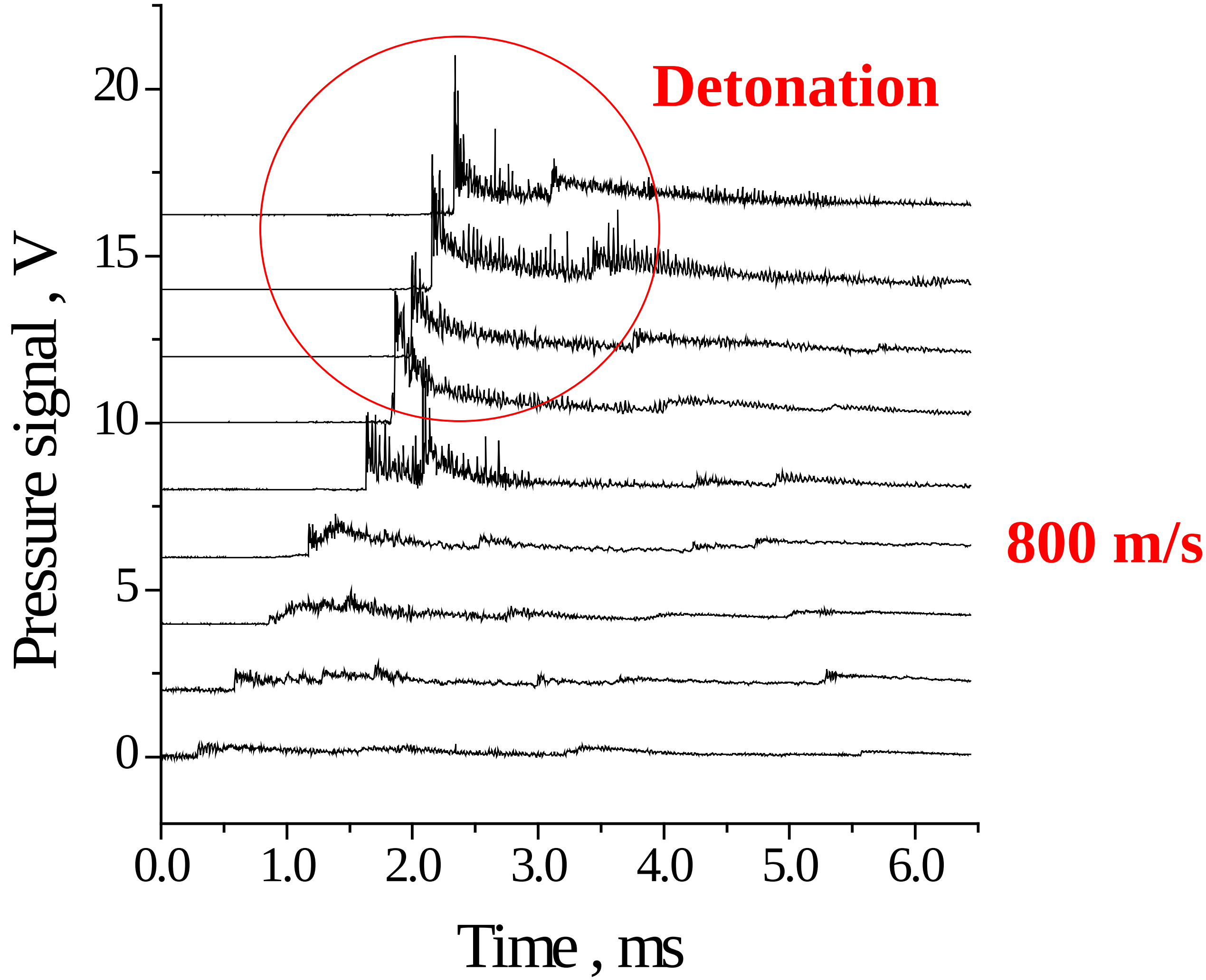
Movie skipped because of large size

Experiment: propane–air (st.)

Gas generator

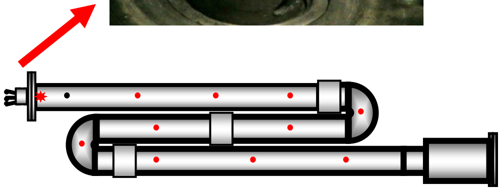


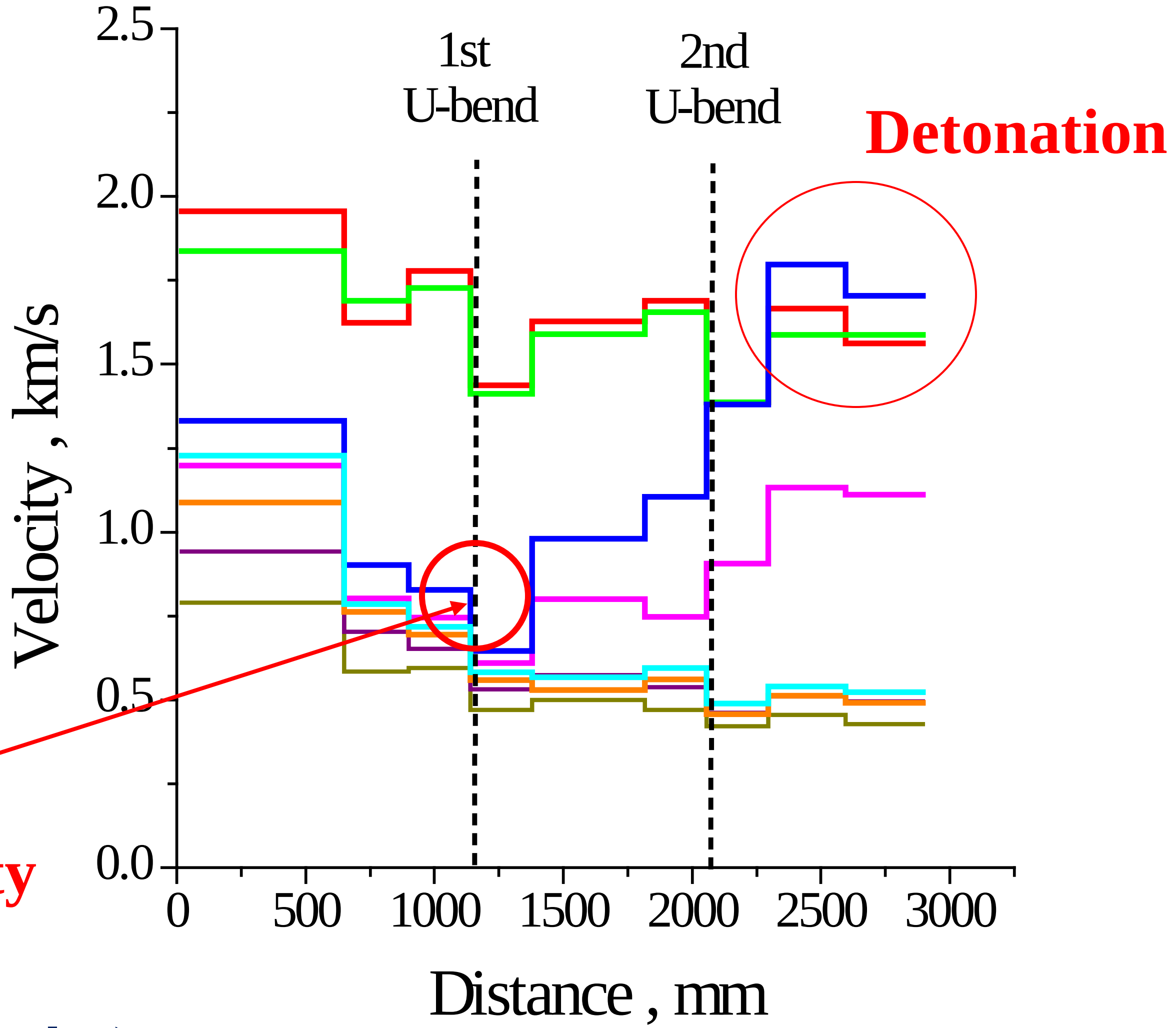




Experiment: propane–air (st.)

Electrical discharge



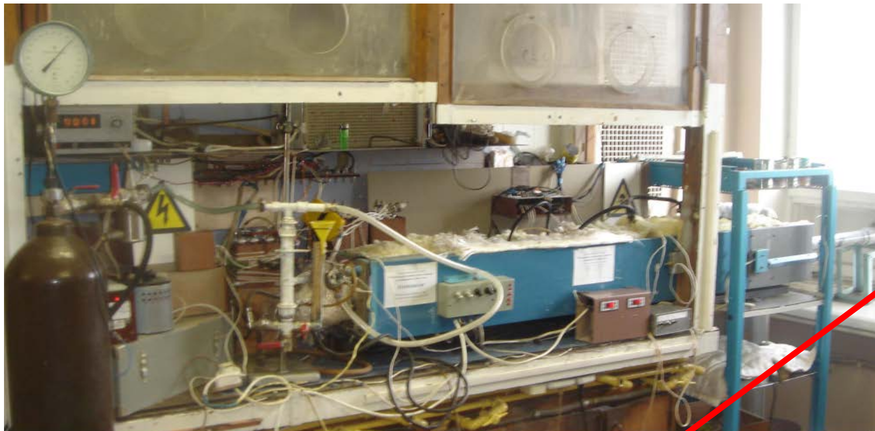


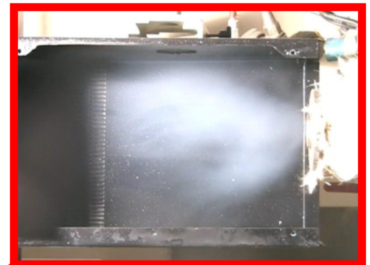
Critical shock velocity 800 m/s

(readily obtained in obstructed tubes)

Detonation of aviation kerosene in air

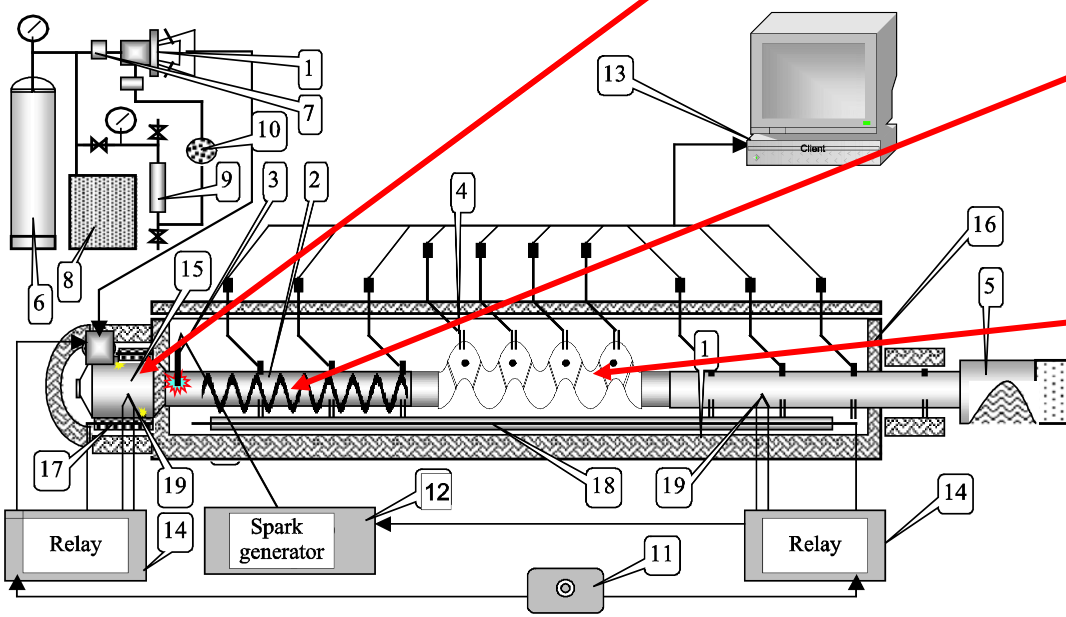
Experimental setup





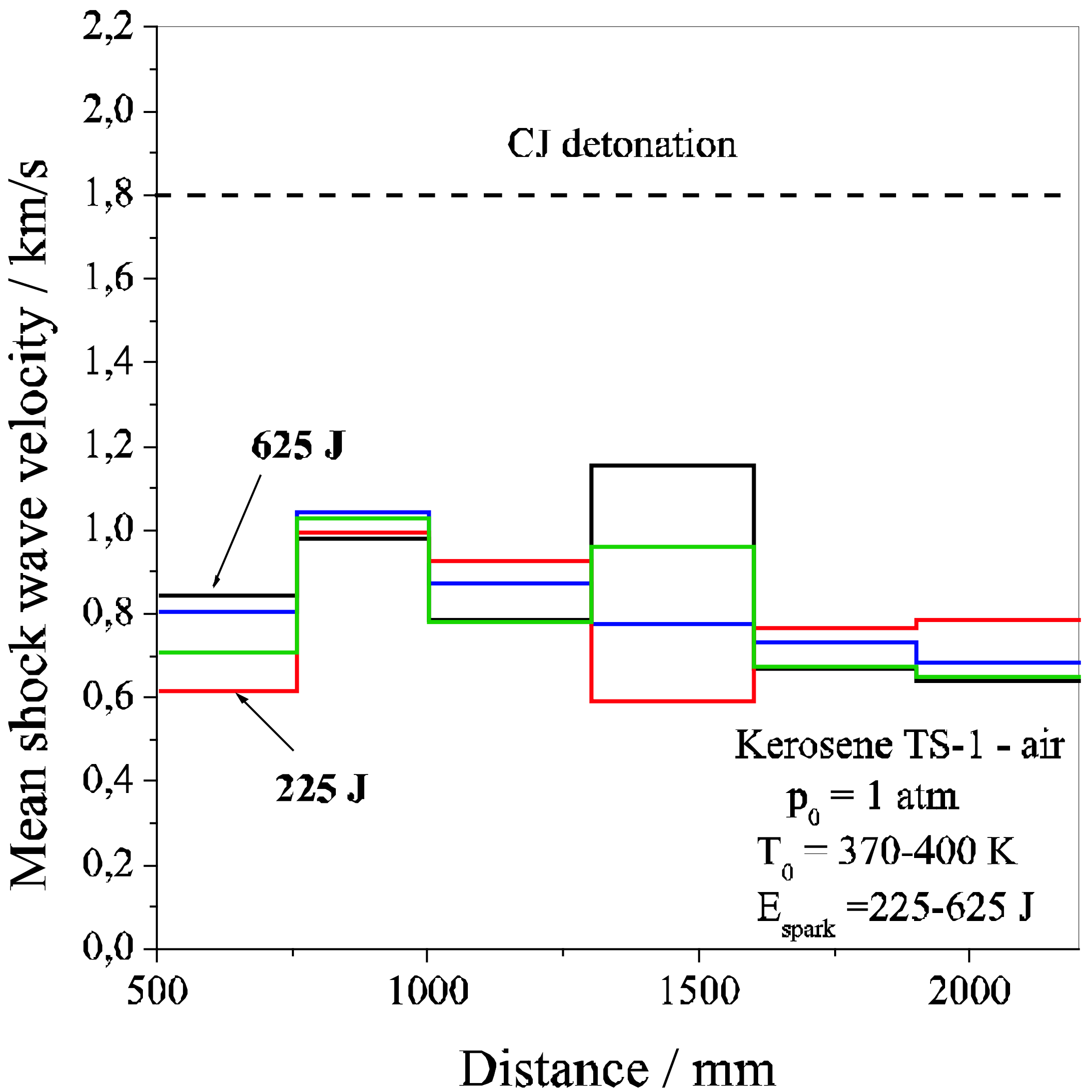
Partial prevaporization

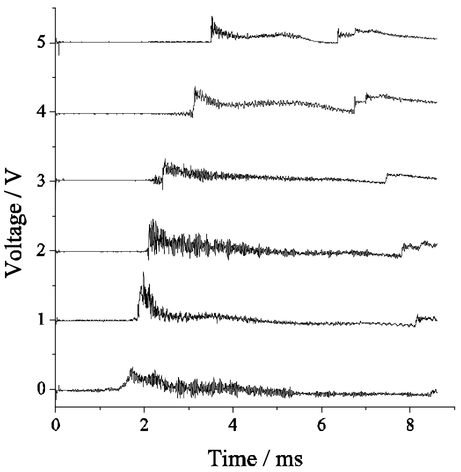
Shchelkin spiral

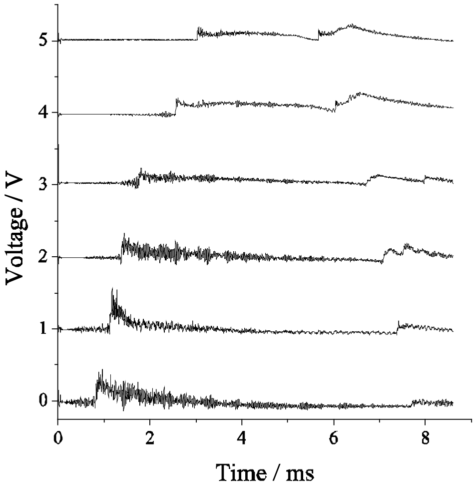


Curved tube section

Shchelkin spiral + straight tube

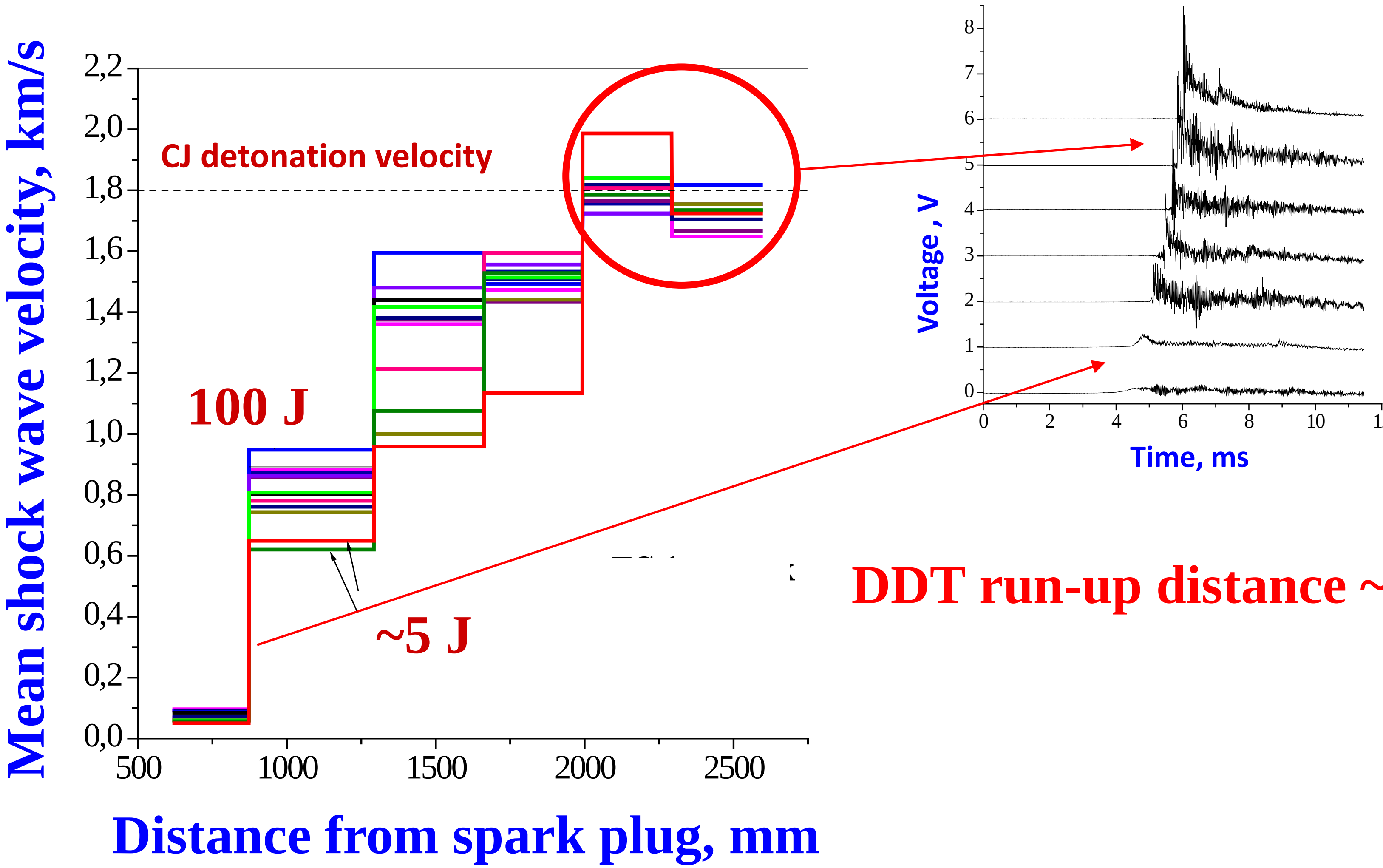






Provided solely by Shchelkin spiral

Shchelkin spiral + curved tube

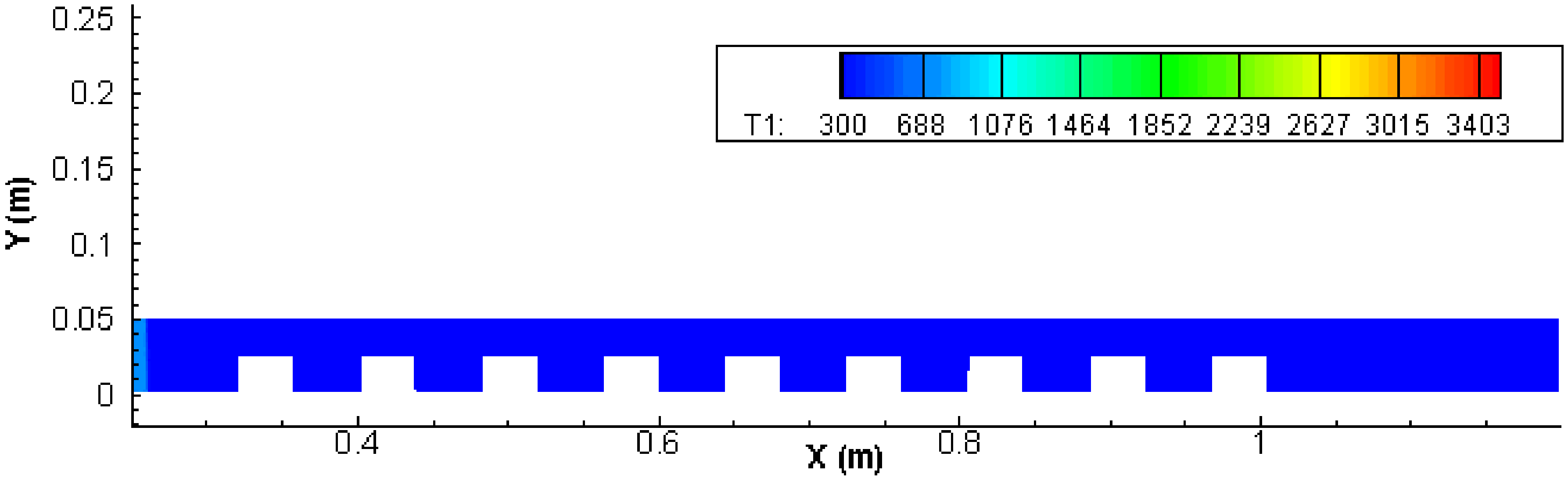


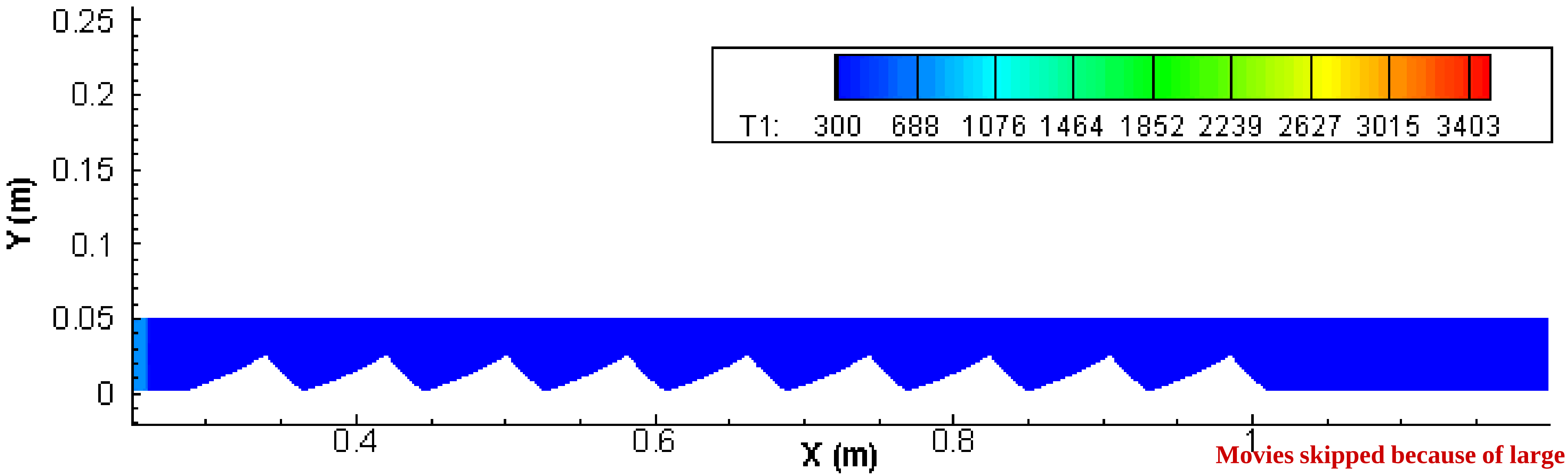
DDT run-up distance ~2 m

Frolov et al (2006)

From curved tubes
to shaped obstacle(s)

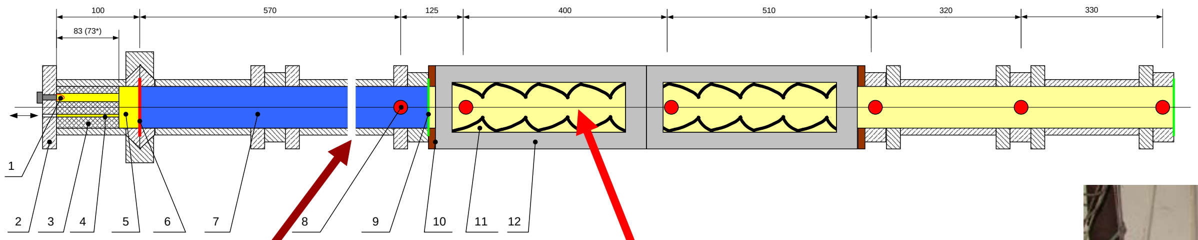
2D simulation





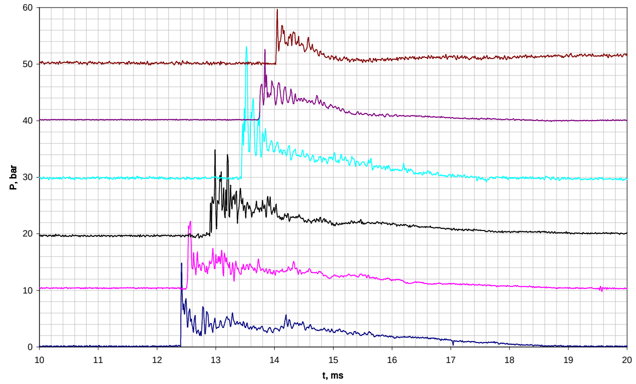
Movies skipped because of large size

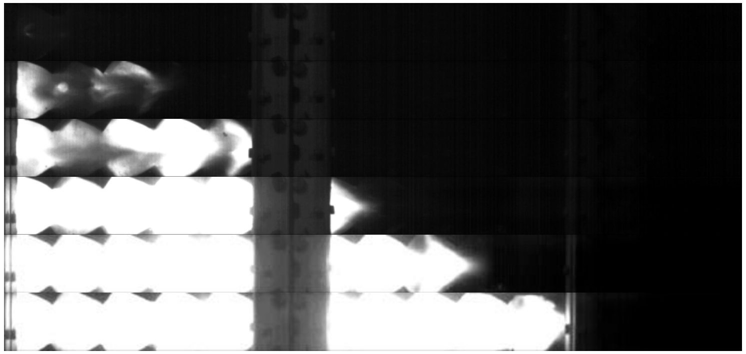
Experiment: propelene-air (st.)



Shock wave **Shaped obstacles**

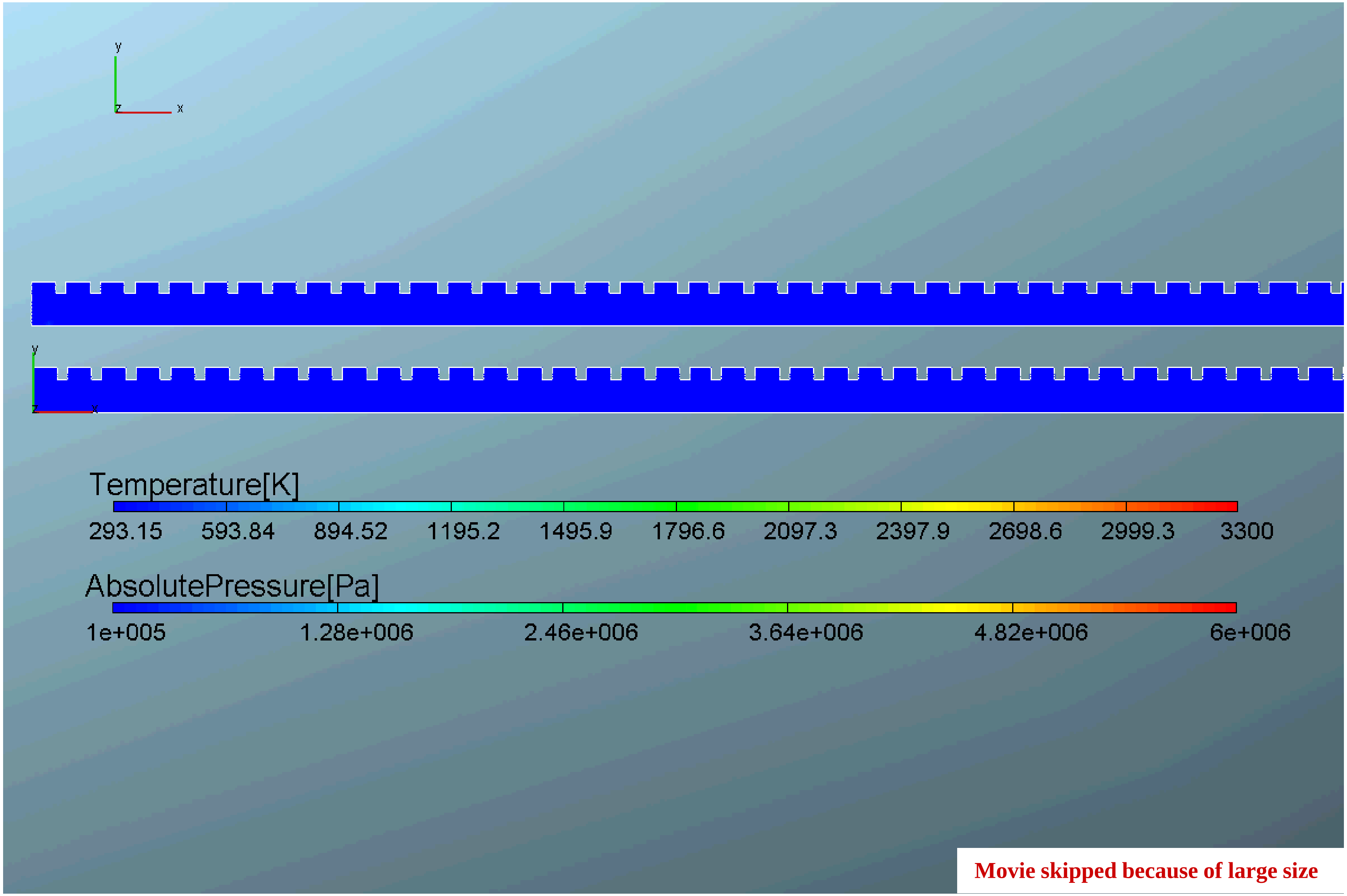
Shock-to-Detonation transition at M = 3





Frolov et al (2007)

2D simulation
(propane – air)



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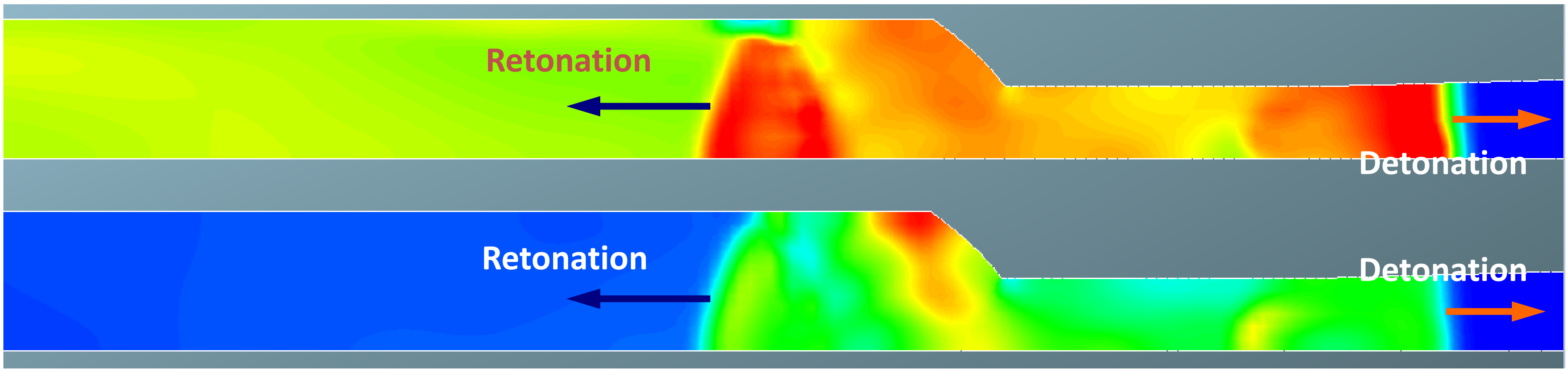
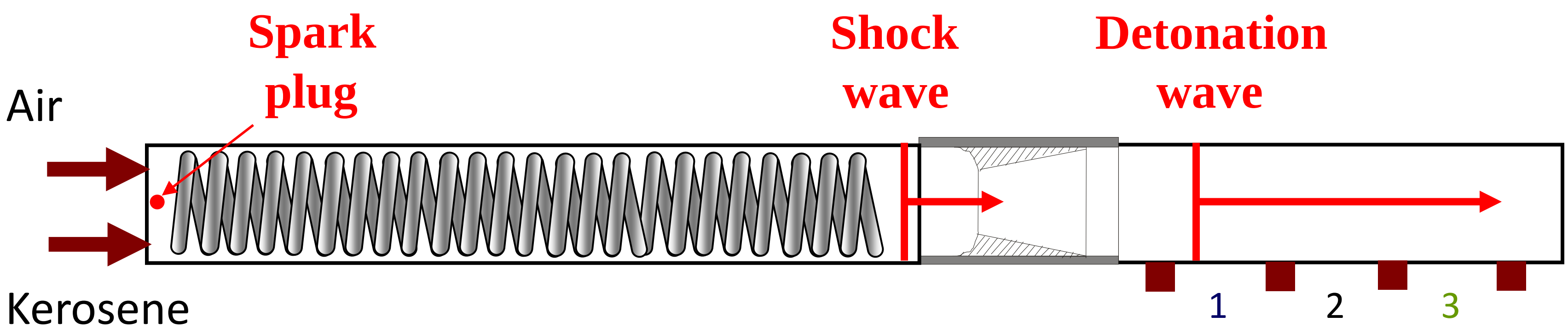
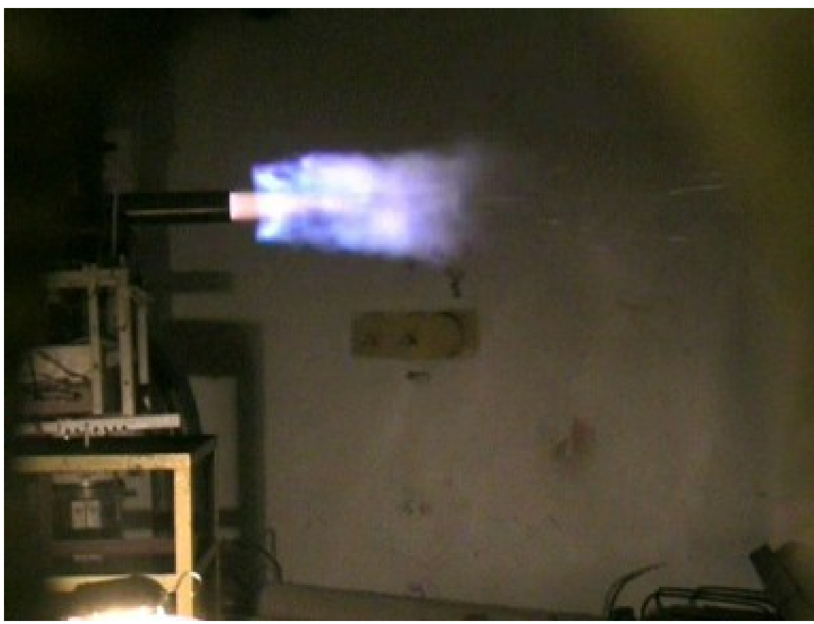
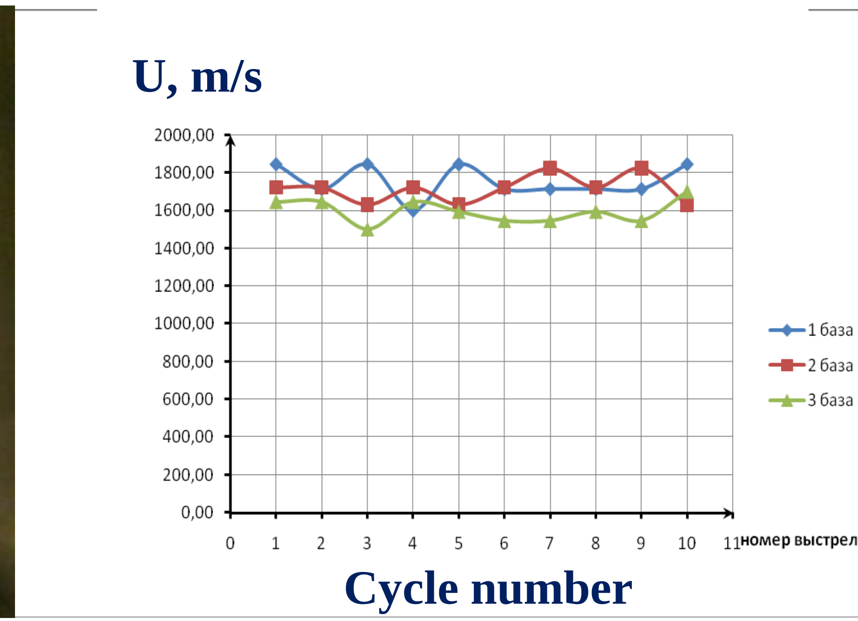
Detonation onset
due to shock focusing



Experiment: aviation kerosene – air







Frolov et al (2008)

Fast DDT:

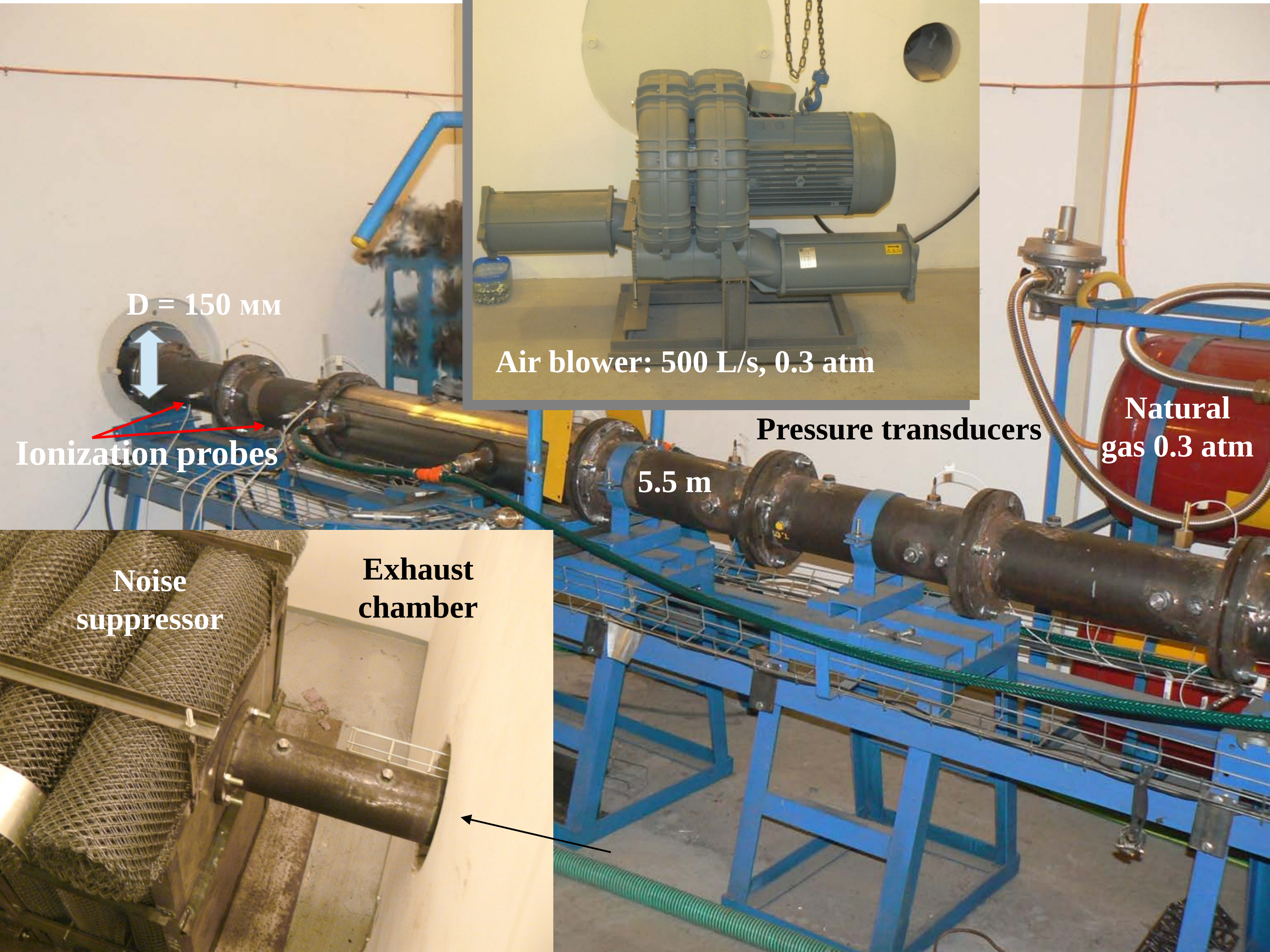
Natural-gas fueled pulse detonation burner for power engineering

Objectives

- Develop scientific grounds for the design of **industrial high-intensity pulsed-detonation burners** operating on **natural gas**
- **Design, fabricate and test** the natural-gas fueled pulsed detonation burner

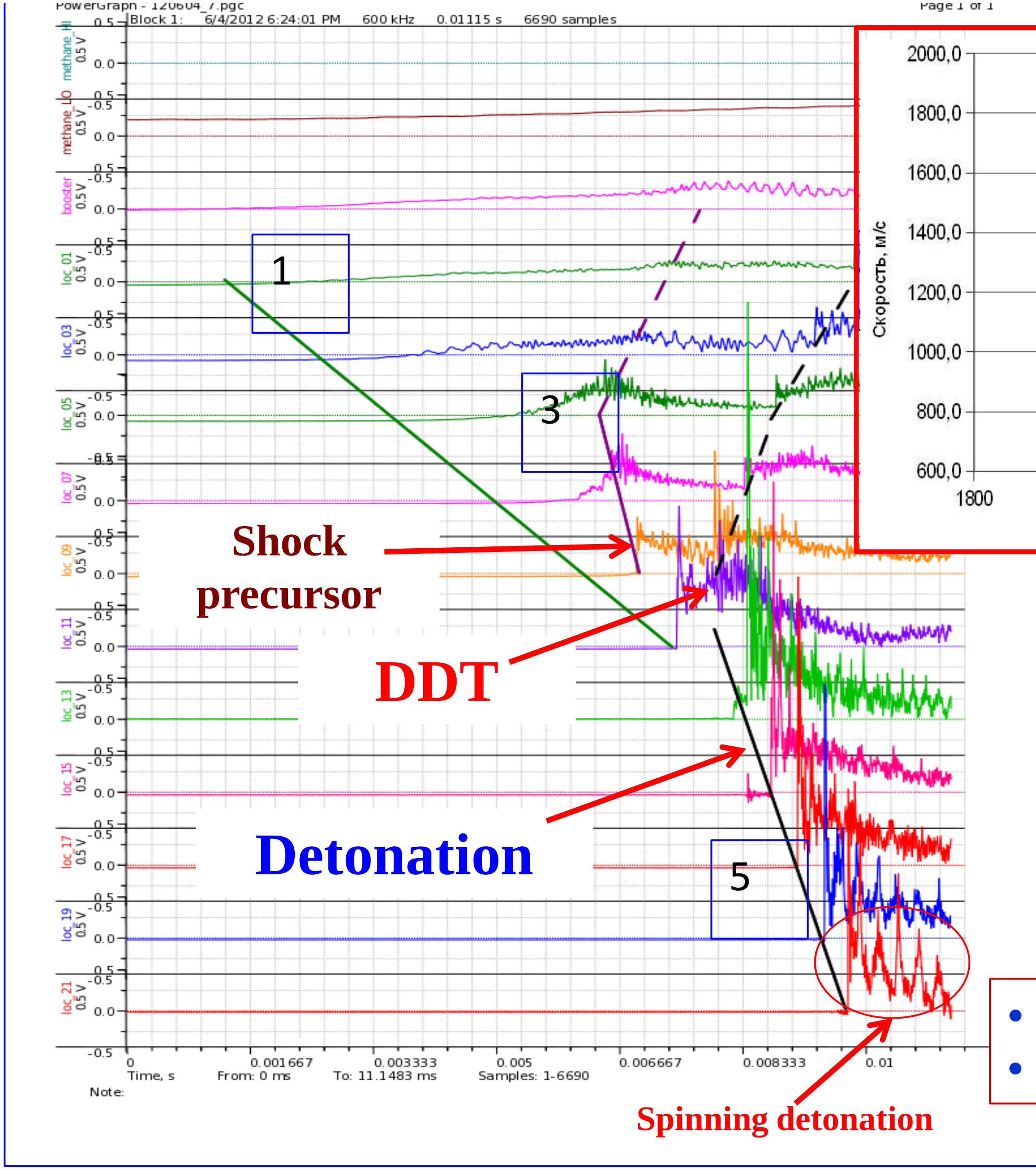
Implications:

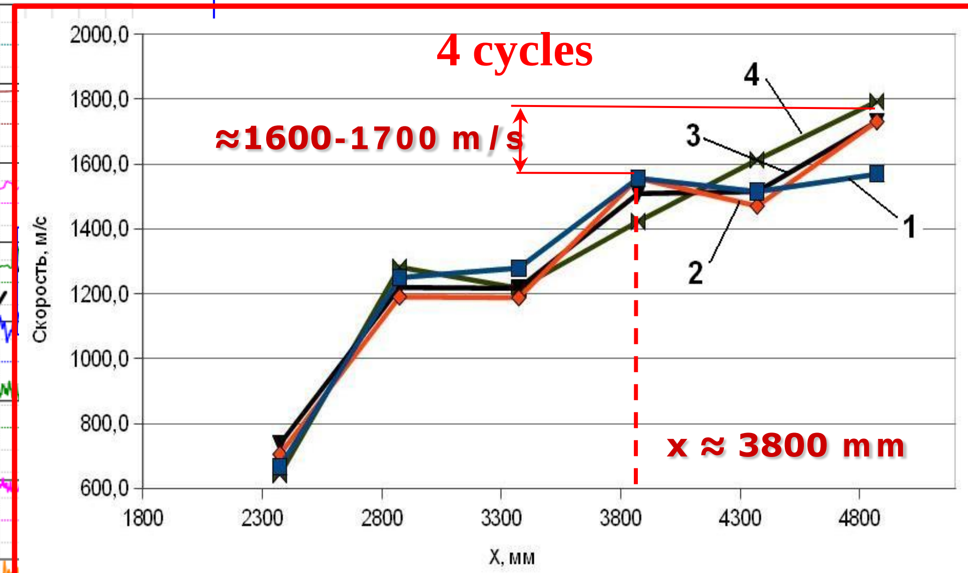
- **Fast DDT concept**: The best obstacle configuration for DDT should provide the fastest growth of flame surface area (flame acceleration) and the lowest momentum loss for the arising shock wave (shock amplification)
- **Optimum obstacles' shaping and positioning**

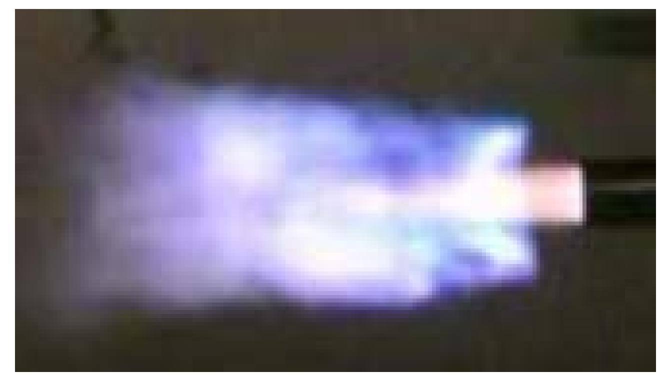


Air blower: 500 L/s, 0.3 atm
D = 150 мм
Ionization probes
Pressure transducers
Natural
gas 0.3 atm
5.5 m
Noise
suppressor
Exhaust
chamber

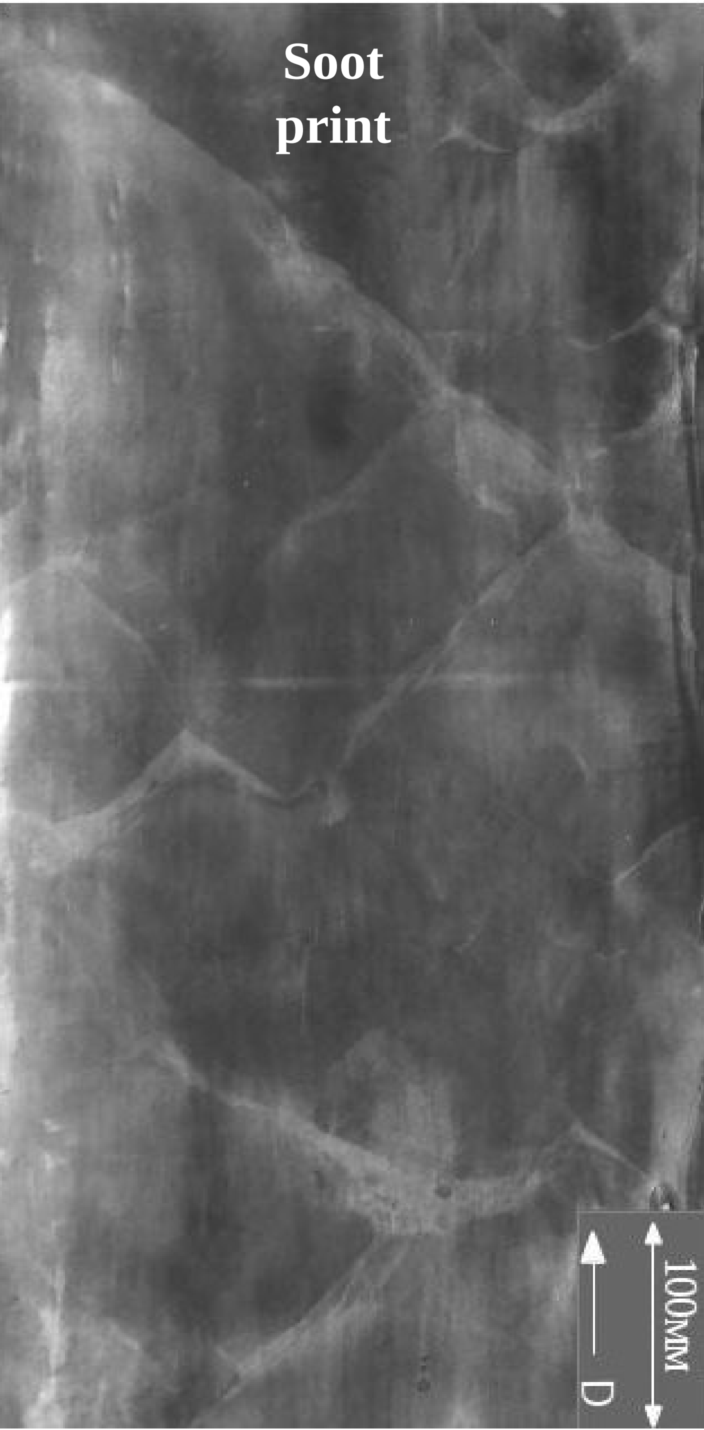
Cyclic DDT





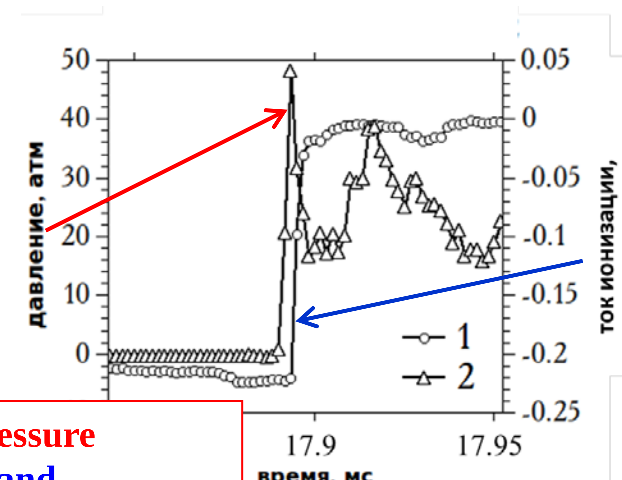


- Spark ignition: ~0.2 J
- DDT run-up: ~3.6–3.8 m



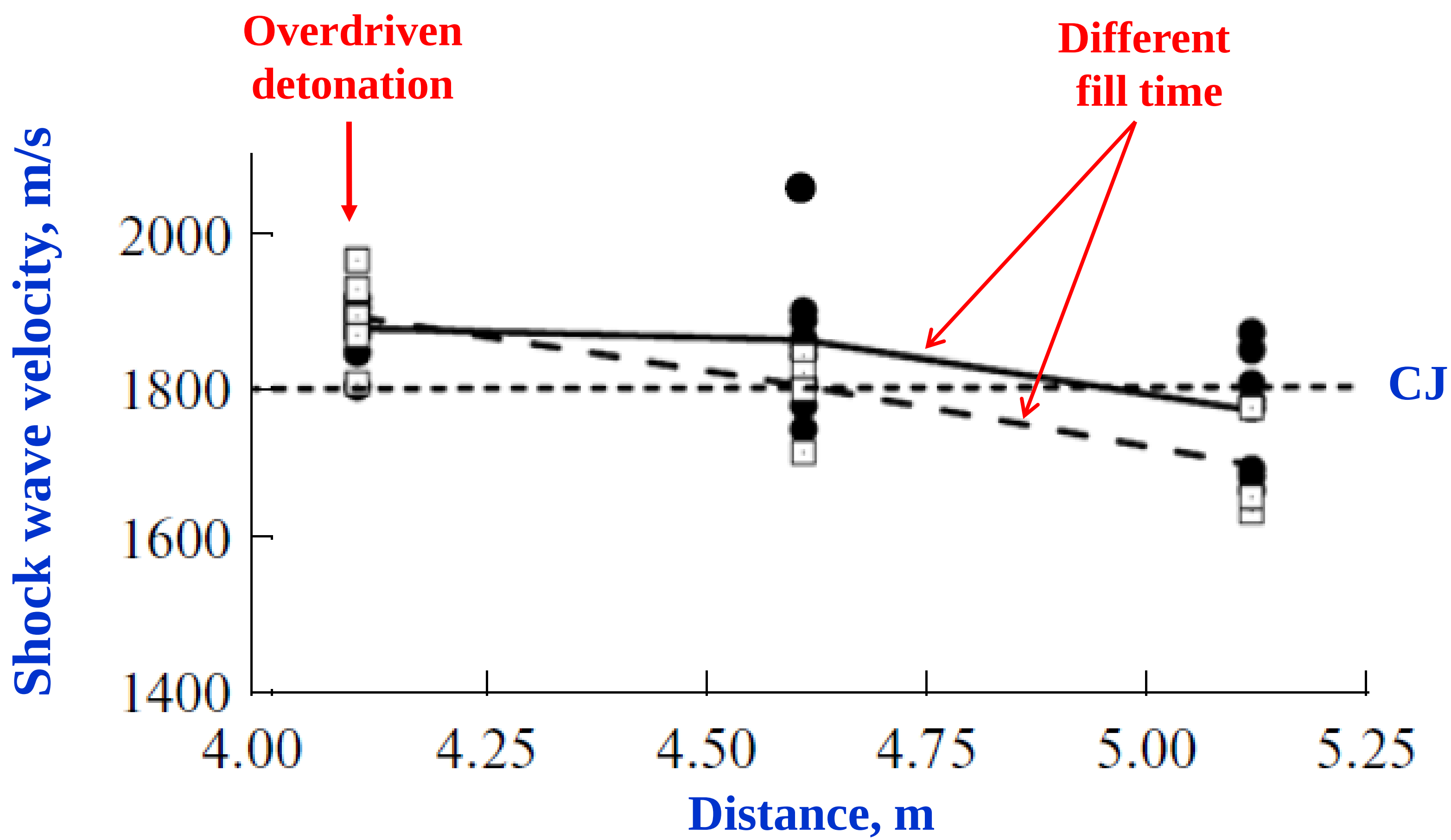
Spinning
detonation

Overdriven
detonation



Pressure
and
ionization current

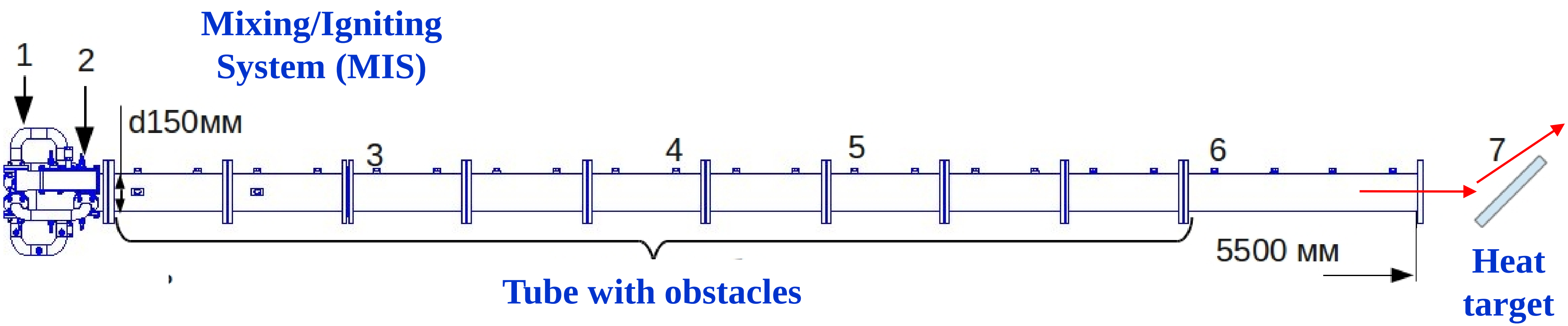
10 successive cycles



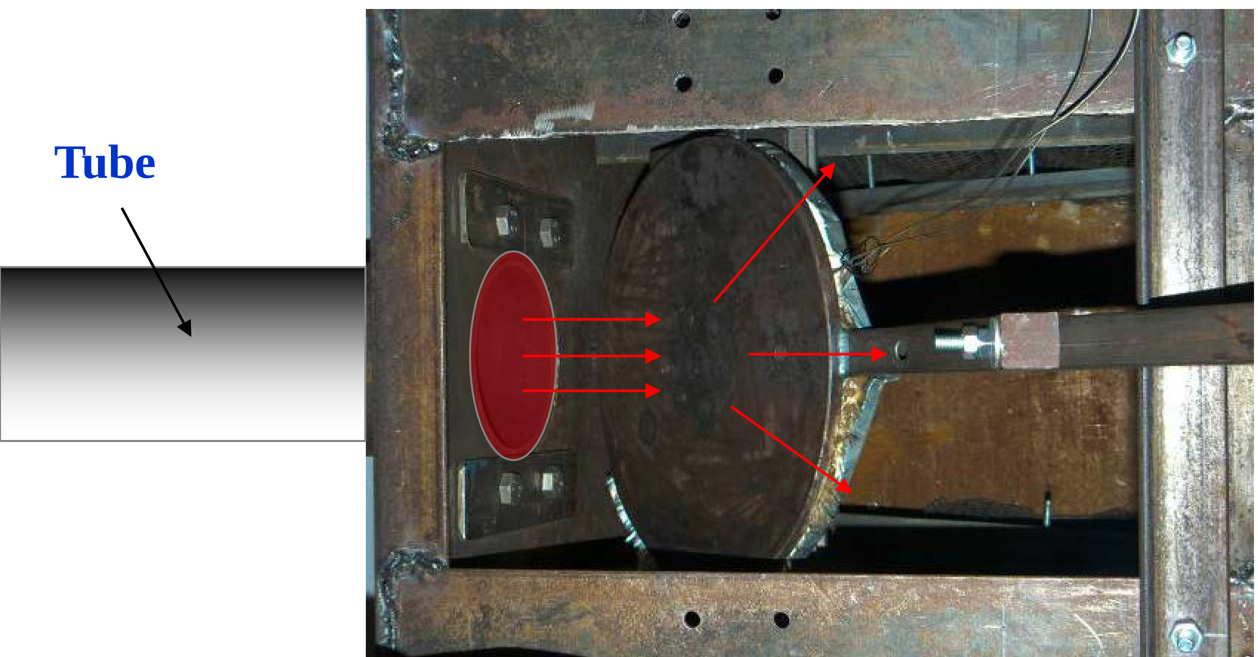
$$\eta = \max_{N} \left.\frac{D - D}{D}\right| \times 100\%$$

Cycle-to-cycle variability < 10%

Thermal mode



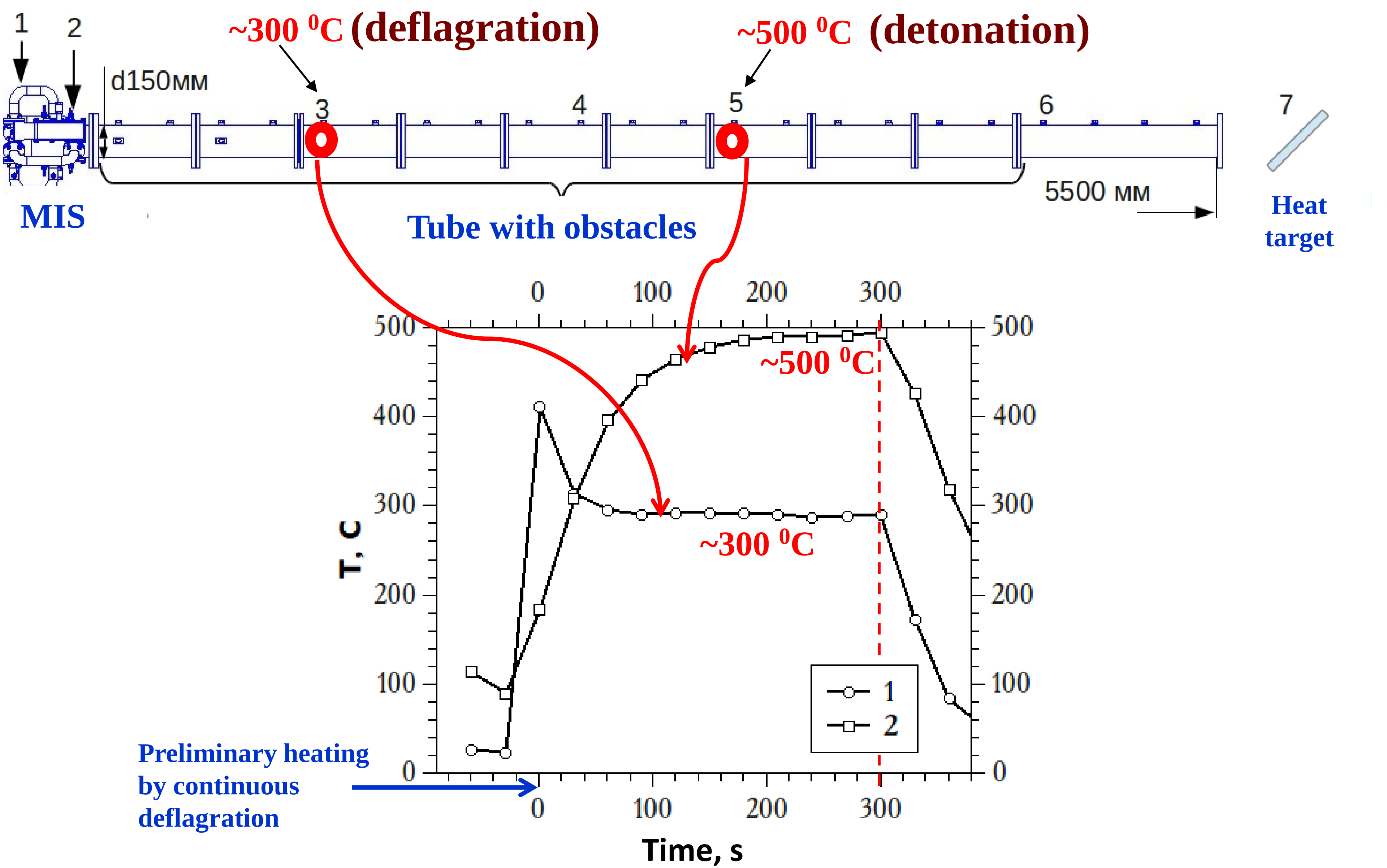
Thermocouples:
1 – prechamber; 2 – MIS; 3, 5 – obstacles; 4, 6 – walls; 7 – heat target



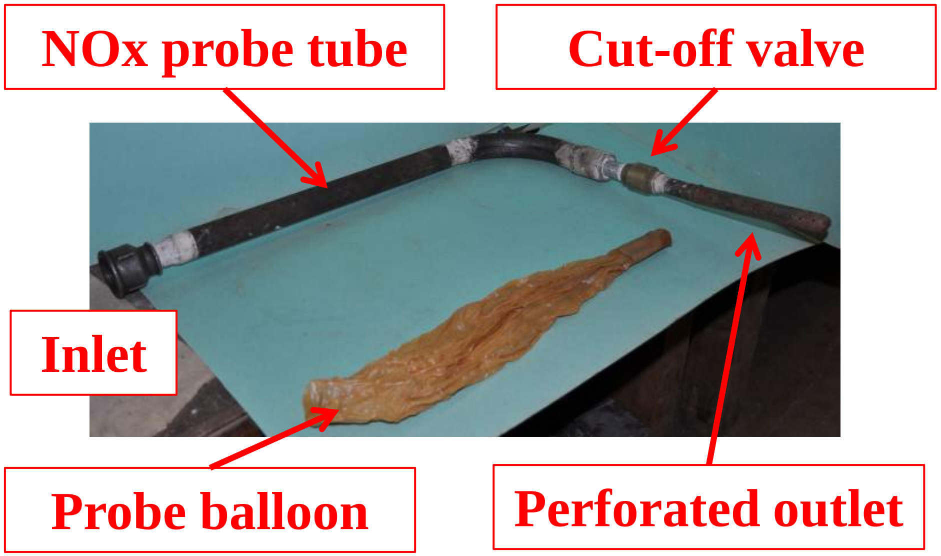
Measuring tools and test duration

- ADC
- Sampling frequency 10 Hz
- Thermocouples K
- Error <3 ^{o}C
- Thermal imager Testo
- Test duration with frequency 1.8 Hz: <u>300 s</u>

Temperature of obstacles



Nitrogen oxides



- Gas Analyzer TESTO-335 (Testo AG, Germany)

RUN	Medium	NO_x, ppm	NO, ppm
1	Detonation products of stoichiometric natural gas – air mixture	214	204
2		193	184
3		221	221
Mean value		~210	

- Available high-intensity burners operating on deflagration: 500-700 ppm

Parameters of issuing jets:

Pulsed detonation burner vs. conventional burner

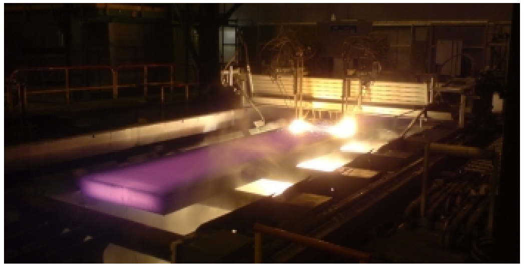
Parameter	Mes. unit	Pulsed Detonation Burner	Conventional burner
Velocity	m/s	~1000	~50–200
Temperature	K	~1600-1800	~1600-1800
Overpressure	bar	~6.0-16.0	~0.05
NOx	ppm	~200	~500-700

- **Applications of PDE burners:**
  Combined mechanical and thermal action of detonation products

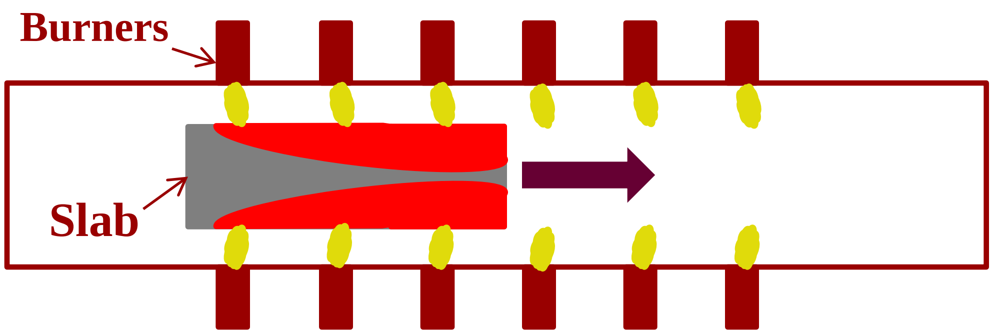
Heating furnaces in metallurgy

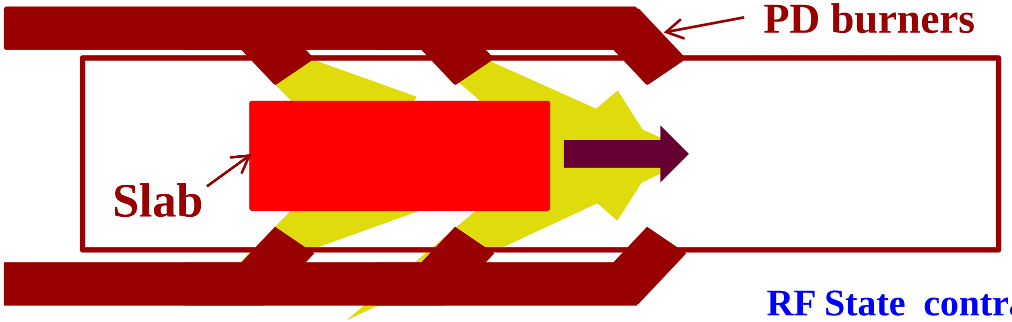
Requirements

- **High productivity;**
- **High quality of heating** in terms of metal structure and mechanical properties, the degree of oxidation and decarbonization;
- **Natural gas as a fuel;**
- **Air as oxidizer;**
- **Fuel efficiency;**
- **Low pollutant emissions;**
- **Automatic control** of operation modes, etc.



Standard flame furnace





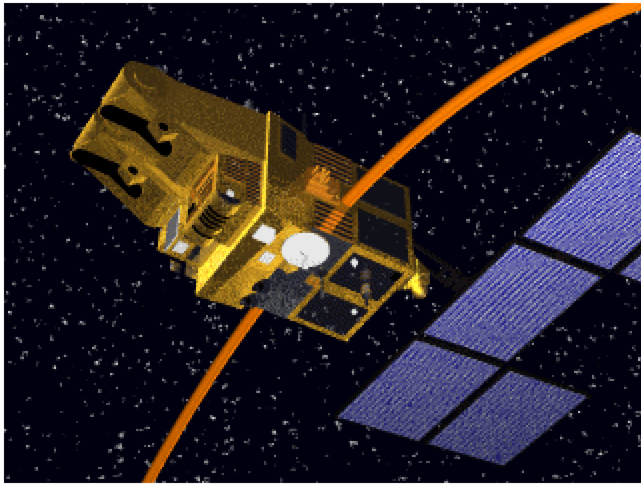
RF State contract

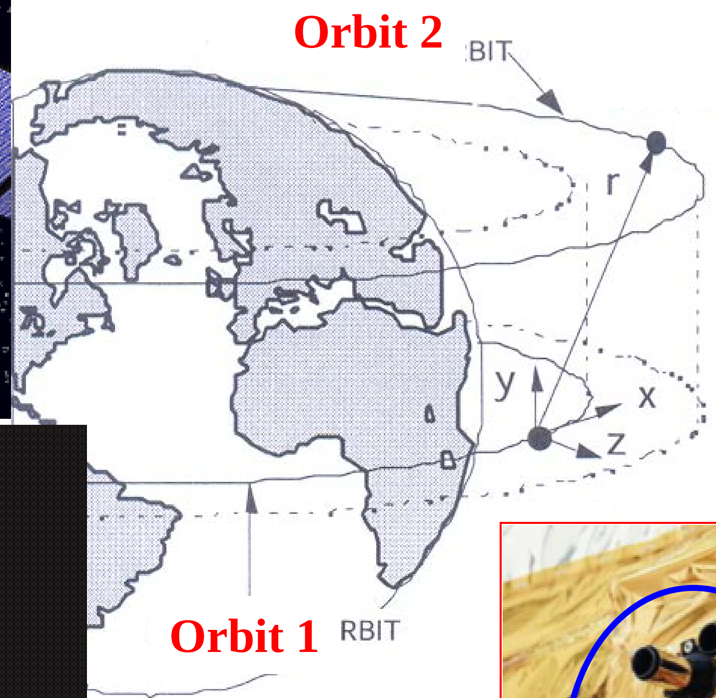
- **High speed of issuing jet**
- **High heating uniformity**
- **Minimum heat loss to furnace walls**
- **Low-oxidation heating**
- **Low NOx**

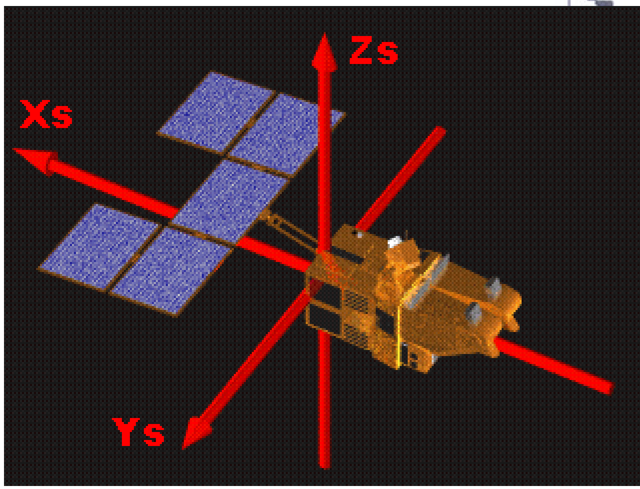
Fast DDT:

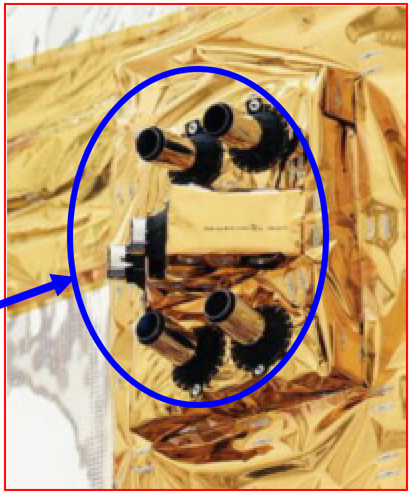
Liquid-propellant pulse detonation rocket engine for orbit correction

Engines for orbit correction









Existing engines for orbit correction

- **monofuel (hydrazine, etc.)**
- **low specific impulse (140-160 s)**
- **pulse mode**

Pulse detonation rocket engine (mini rocket PDE)?

Objectives

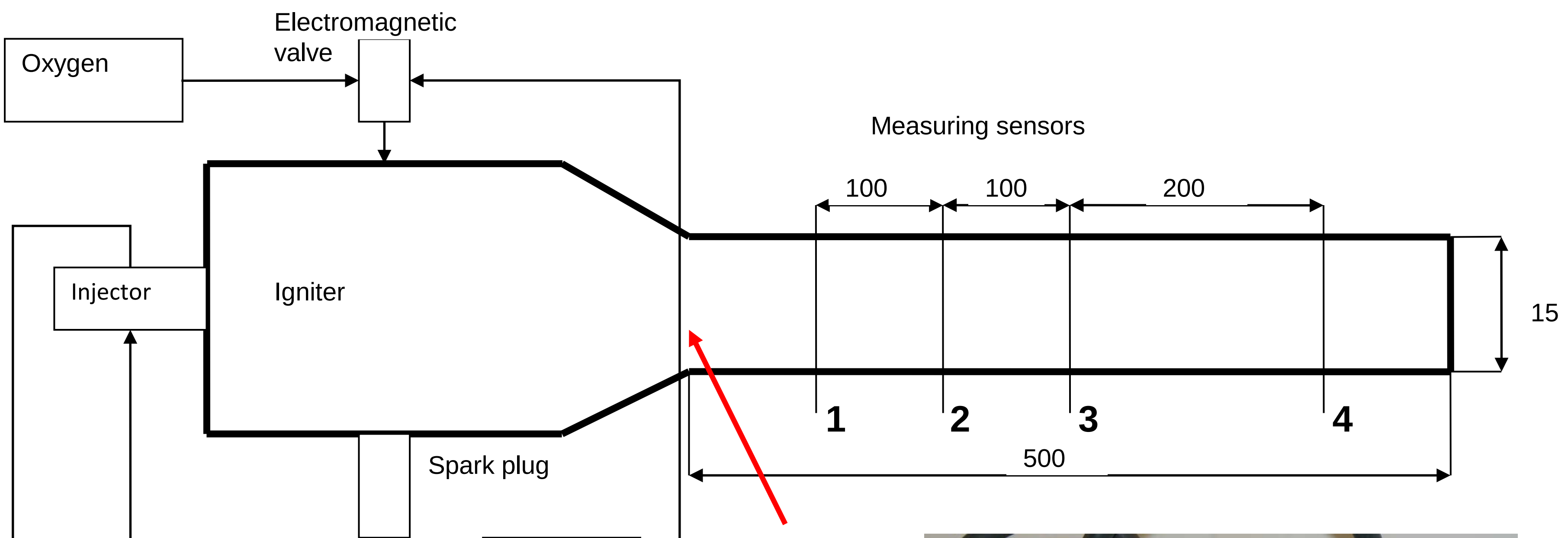
Formulate the **concept of the future micro rocket PDE** for the stabilization system and orbit displacement of the satellites based on the experimental realization of

- **calibrated pulse detonation cycles (thrust bits)** (digitally controlled up to 200 Hz)

- **in drop mixtures** of liquid hydrocarbon fuel with gaseous oxygen

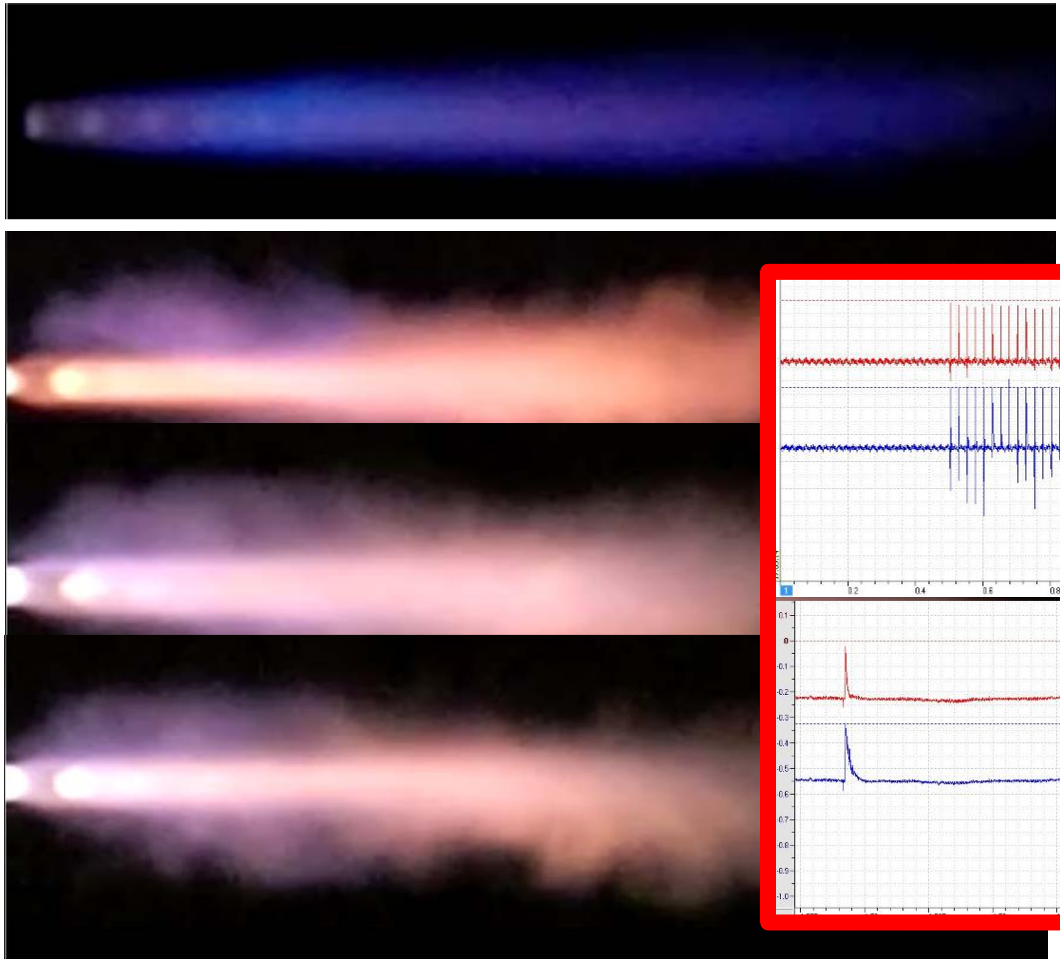
- **in short tubes** of small diameter

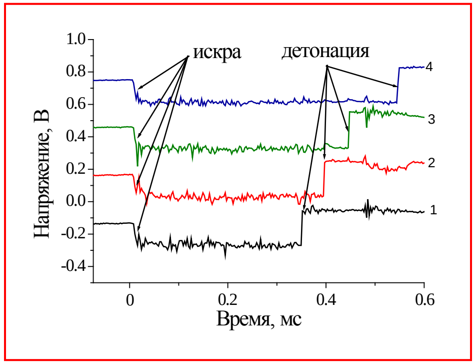
Pulse detonation rocket engine demonstrator

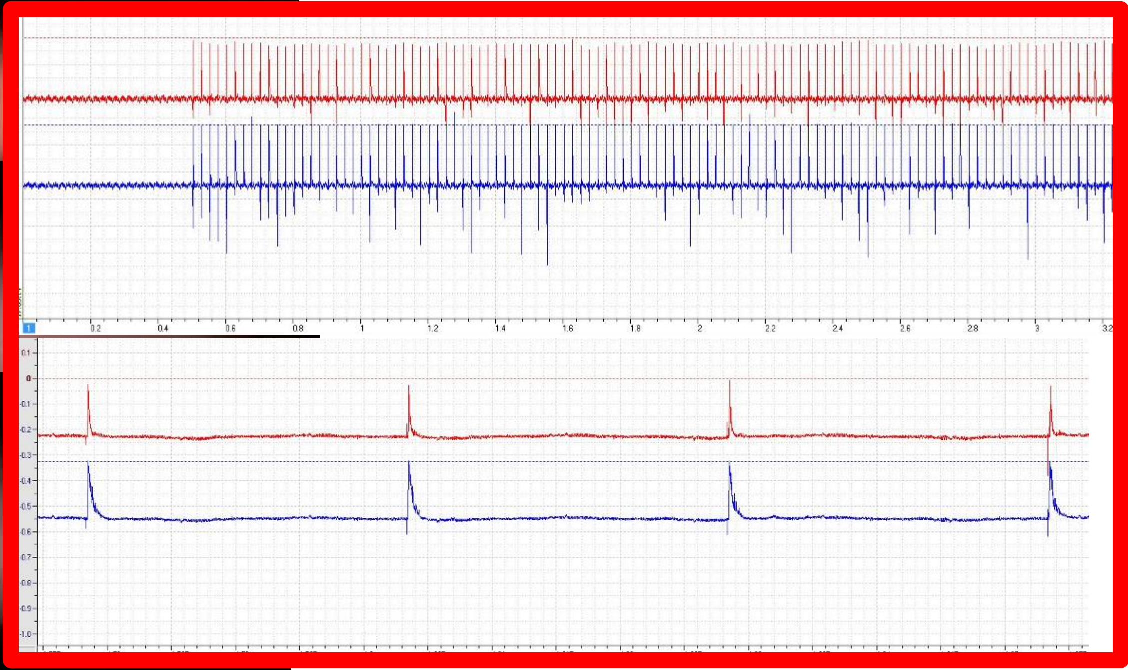


- **Designed, manufactured and tested** demonstrator of the operation process

Pulse operation mode







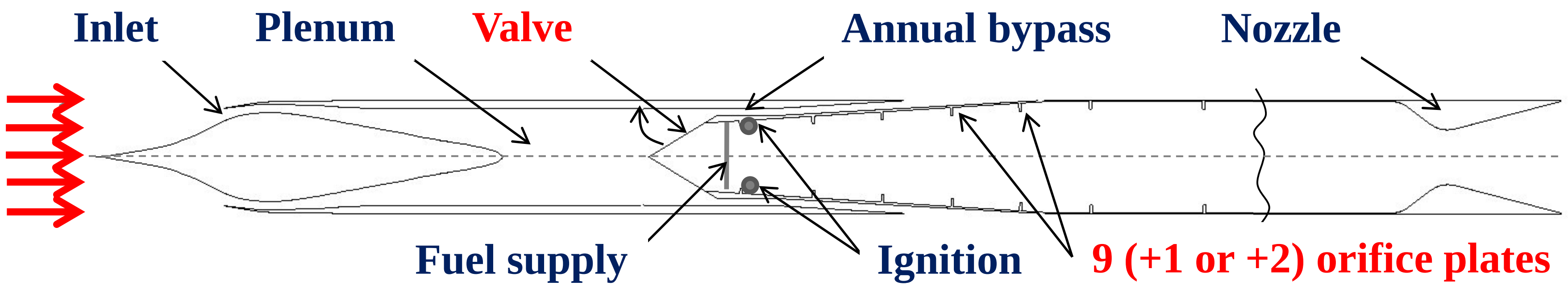
- calibrated thrust bits
- high specific impulse
- no cooling

up to f ~ 200 Hz (in vacuum)
D ~ 2200 m/s

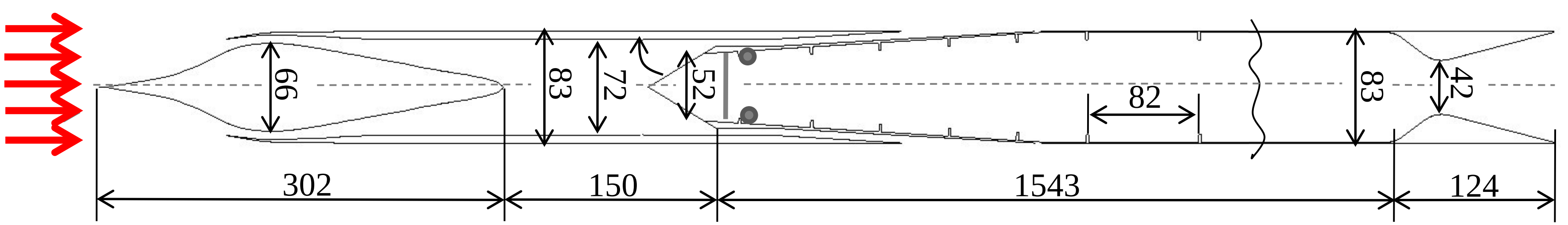
Fast DDT:

Propulsive performance of air-breathing valved pulse detonation engine at Mach 0.8 to 5.0 flight conditions

PDE schematic (Mach 3)



PDE dimensions



Tube diameter **83 mm**

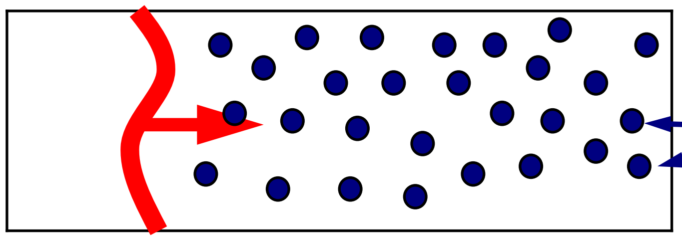
Total length **2120 mm**

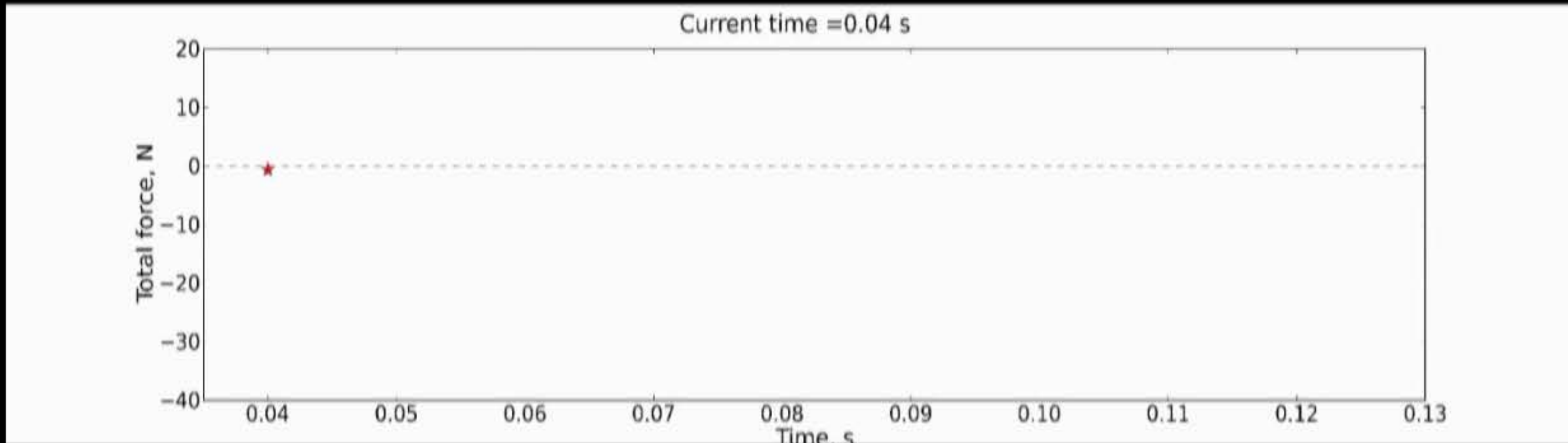
Flight and operation conditions

Flight Mach number	3
Flight altitude	8–28 km
Fuel	propane (Φ = 1.0; 0.7)

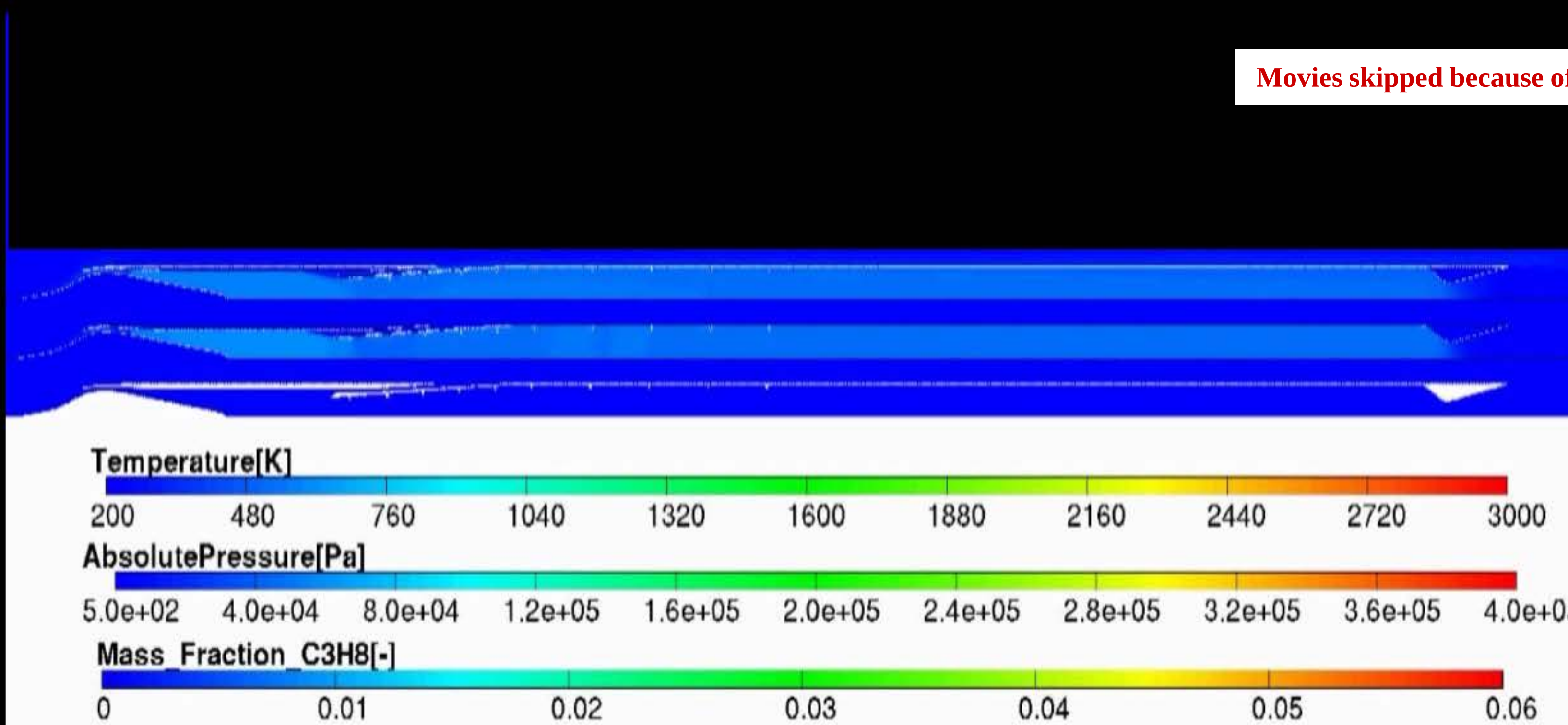
Numerical approach

- 3D URANS equations
- Turbulence model (k-epsilon)
- Multicomponent reactive mixture
- Ideal-gas thermal and calorific equations of state
- Flame Tracking – Particle turbulent combustion model with micromixing

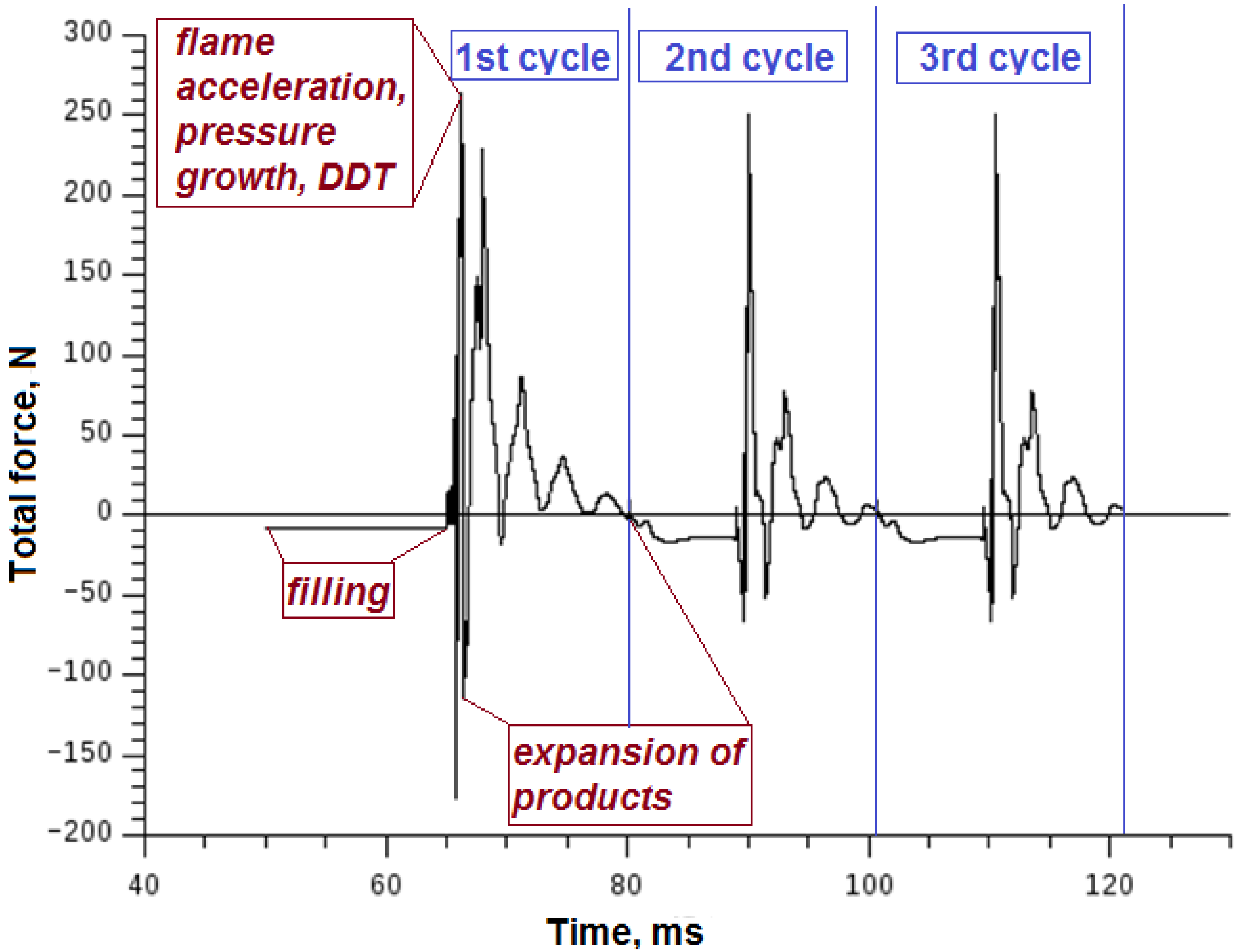




Movies skipped because of large size



PDE cycles (M = 3)



Specific impulse

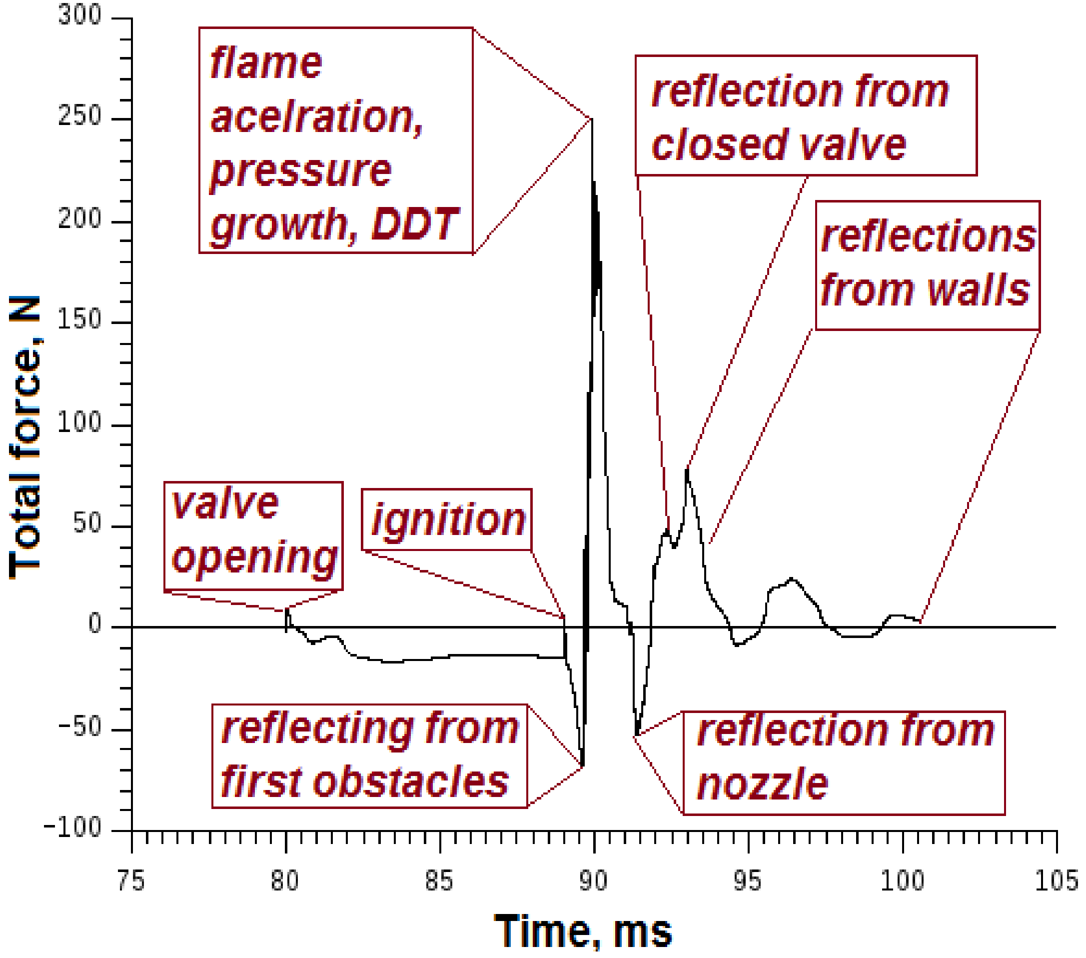
Specific impulse:

$$I = \frac{F}{g * \dot{m}}$$

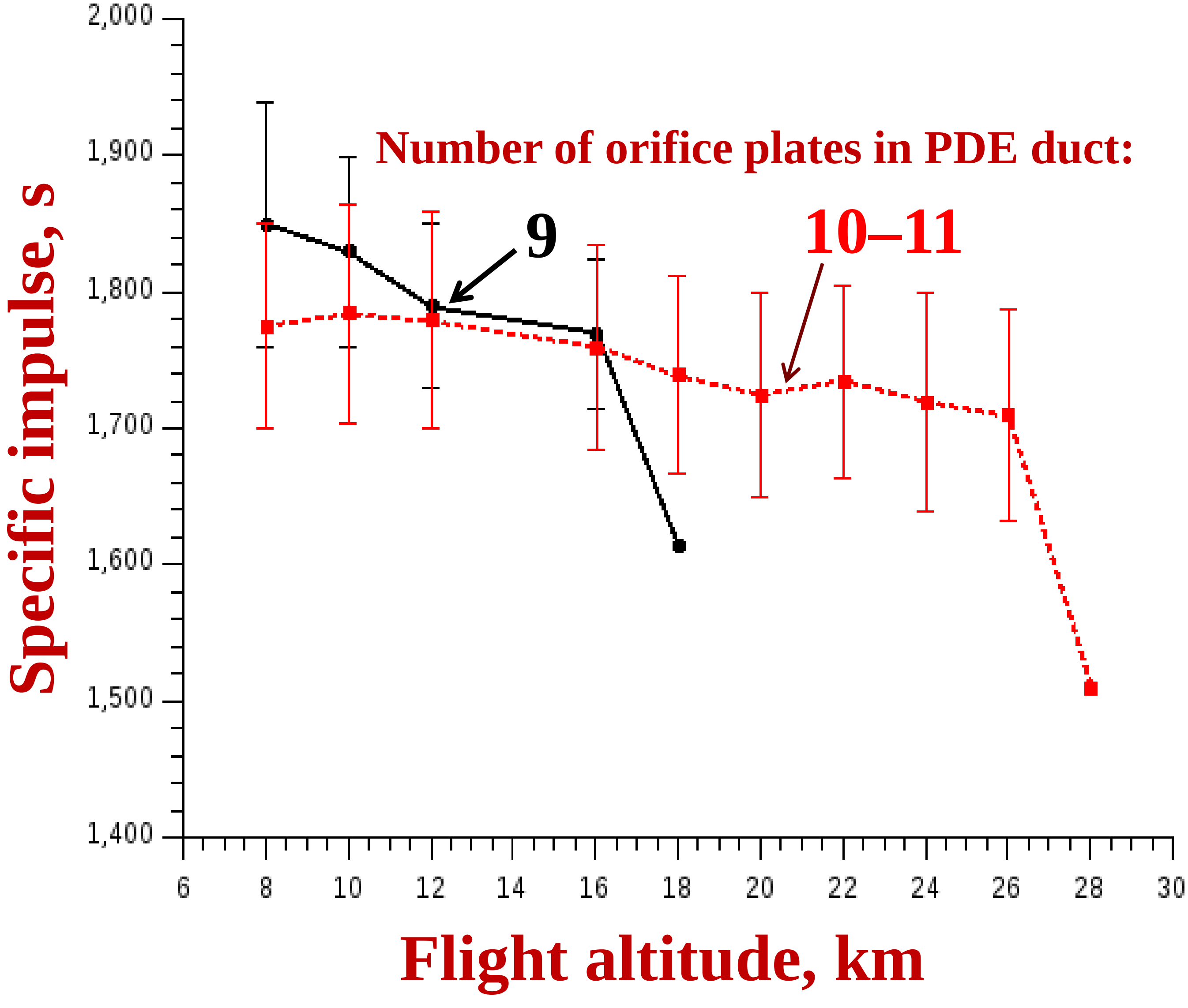
F - thrust (with drag force)

g - acceleration of gravity

$\dot{m}$ - Mass flow rate of fuel



PDE specific impulse (M = 3)



Propulsive performance (M = 3)

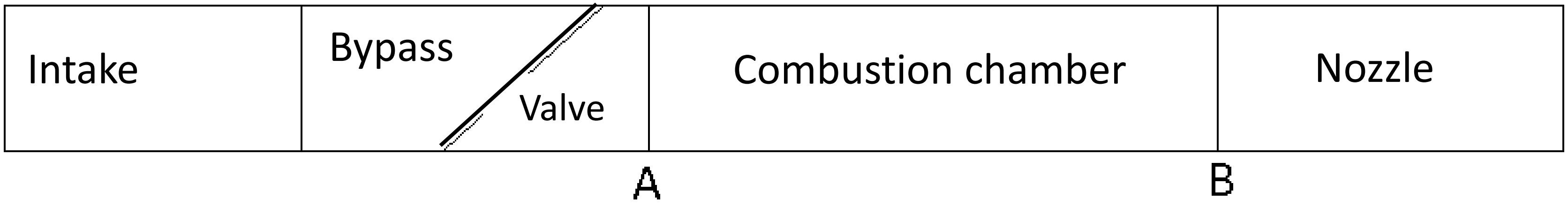
Z, km	f, Hz	I_{sp}, s	R, kN/(kg/s)	SFC, kg/(N-h)
20	50	1655 (1800)	1.05 (1.15)	0.22 (0.20)
26	49	1630 (1790)	1.02 (1.10)	0.22 (0.21)

Similar to ramjet at $\Phi = 0.7$

20%-40% higher then ramjet at $\Phi = 0.7$

Similar to ramjet at $\Phi = 0.7$

PDE schematic (M = 0.8)



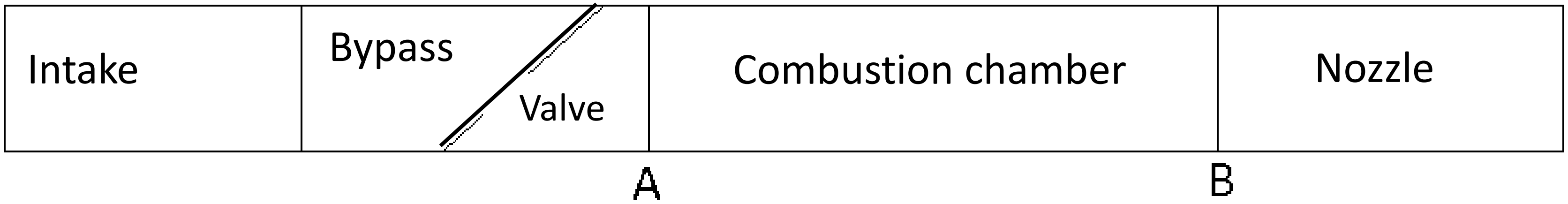
Dimensions and fuel

Tube diameter: 83 mm
Length: 1.3 m
Fuel: propane

Propulsive performance (M = 0.8)

Z, *km*	*P*, *MPa*	T_a, *K*	*f*, Hz	*I*, *s*
0	0.101	288.2	75	1325
0.5	0.095	284.9	70	1340
1	0.090	281.7	70	1330

PDE schematic (M = 5.0)



Dimensions and fuel

Tube diameter: 83 mm
Length: 2.2 m
Fuel: propane

Propulsive performance (M = 5)

Z, *km*	*P*, *MPa*	T_a, *K*	*f*, Hz	I_{sp}, *s*
28	0.0016	224.5	55	1620

Continuous detonations:

CFD of operation process

with narrow gap

and with separate delivery of fuel and air

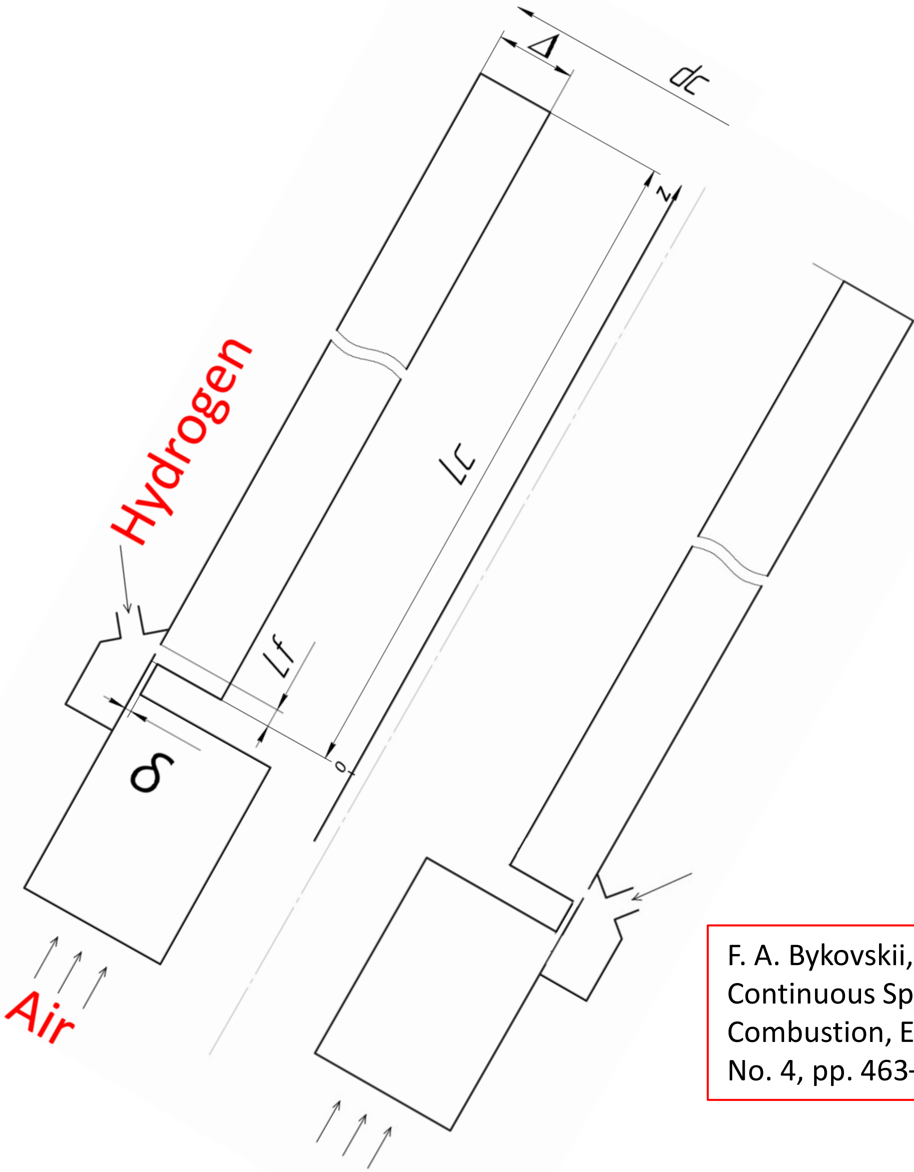
Objectives

- Validate in-house **3D CFD tool for RDE operation on nonpremixed fuel and air;**

- **Design the RDE compatible with the architecture of gas turbine engine**

RDE operating on nonpremixed H_2 – air

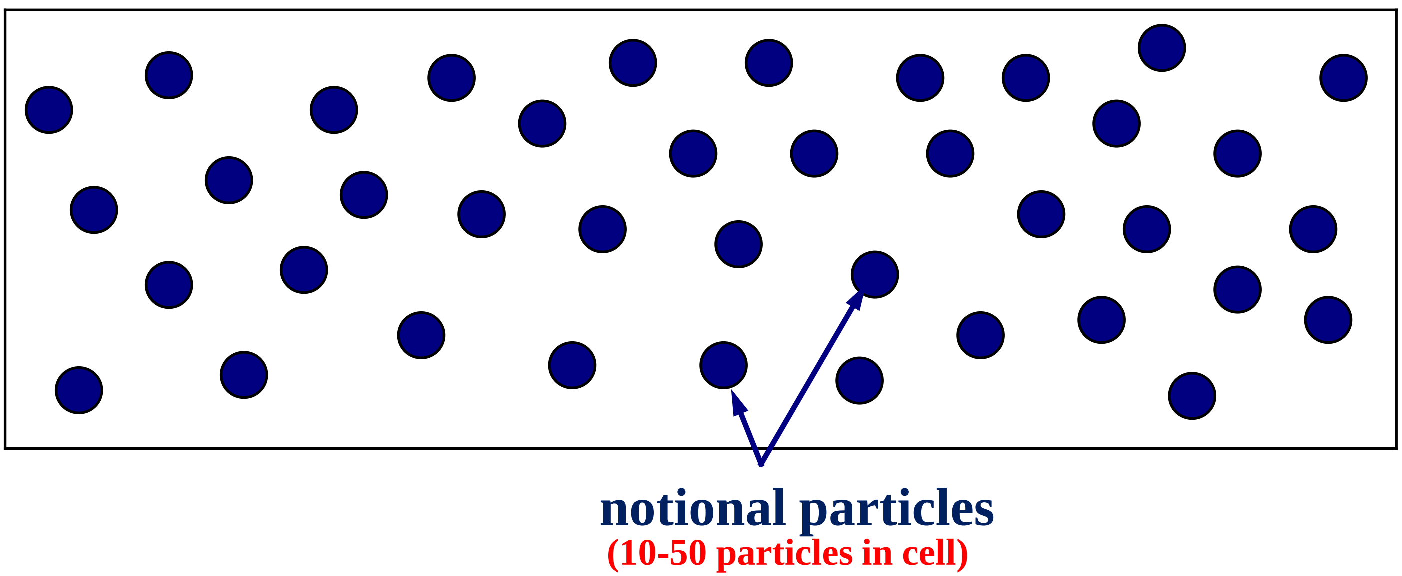
δ = 2 mm
Δ = 23 mm
dc = 306 mm
Lf = 2 mm
Lc =400 mm



F. A. Bykovskii, S. A. Zhdan, and E. F. Vedernikov, Continuous Spin Detonation of Fuel–Air Mixtures, Combustion, Explosion, and Shock Waves, Vol. 42, No. 4, pp. 463–471, 2006

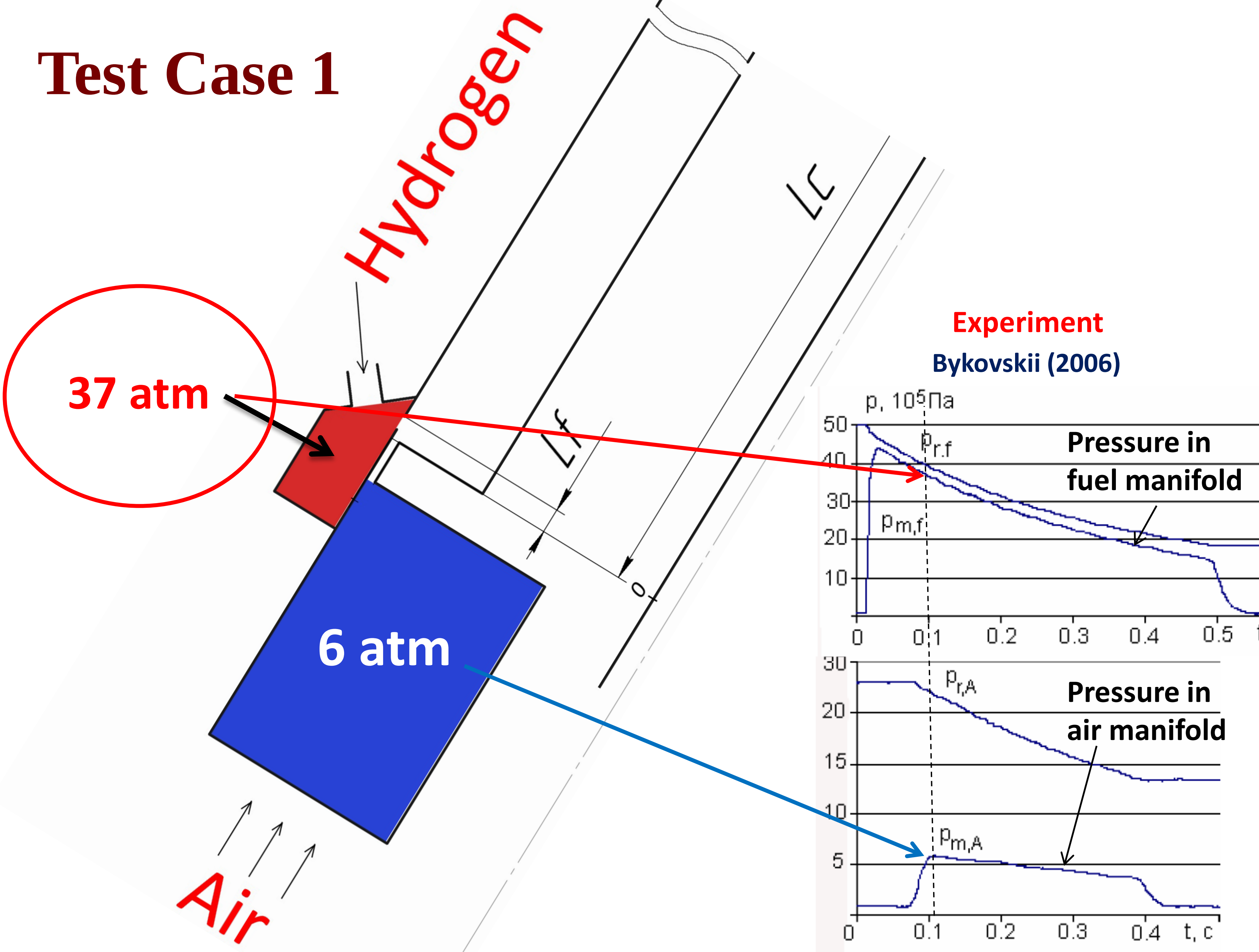
Numerical approach

- 3D URANS equations
- Turbulence model (k-epsilon)
- Multicomponent reactive mixture
- Ideal-gas thermal and calorific equations of state
- Particle method for modeling micromixing and combustion



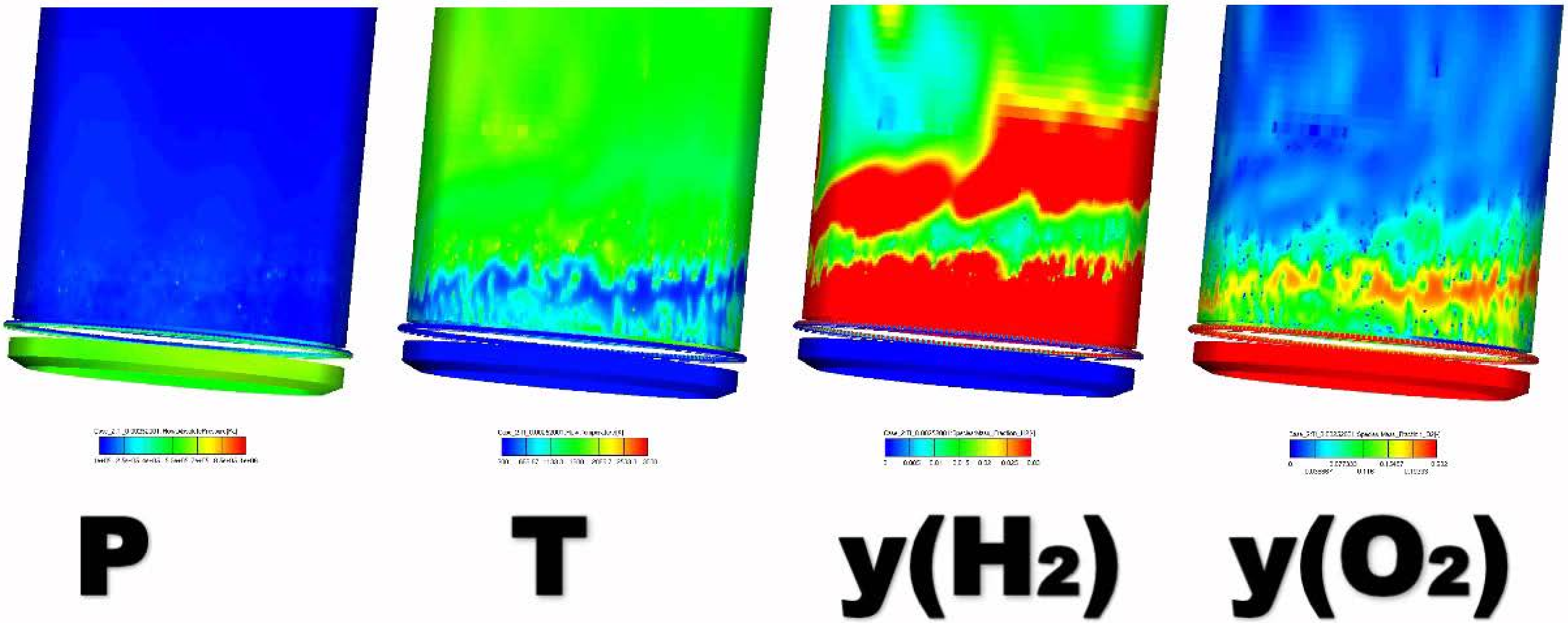
neglect frontal combustion

Test Case 1



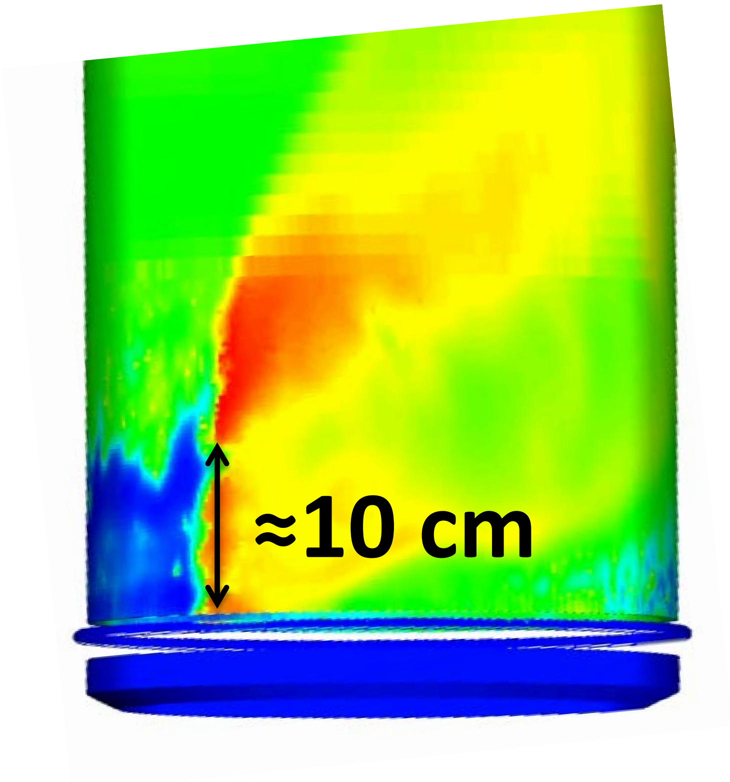
Hydrogen
37 atm
6 atm
Air
Lf
Lc
0
Experiment
Bykovskii (2006)
p, 10⁵Па
Pressure in fuel manifold
Pressure in air manifold
p r,f
p m,f
p r,A
p m,A
t, c

Test case 1:
Detonation propagation in RDE

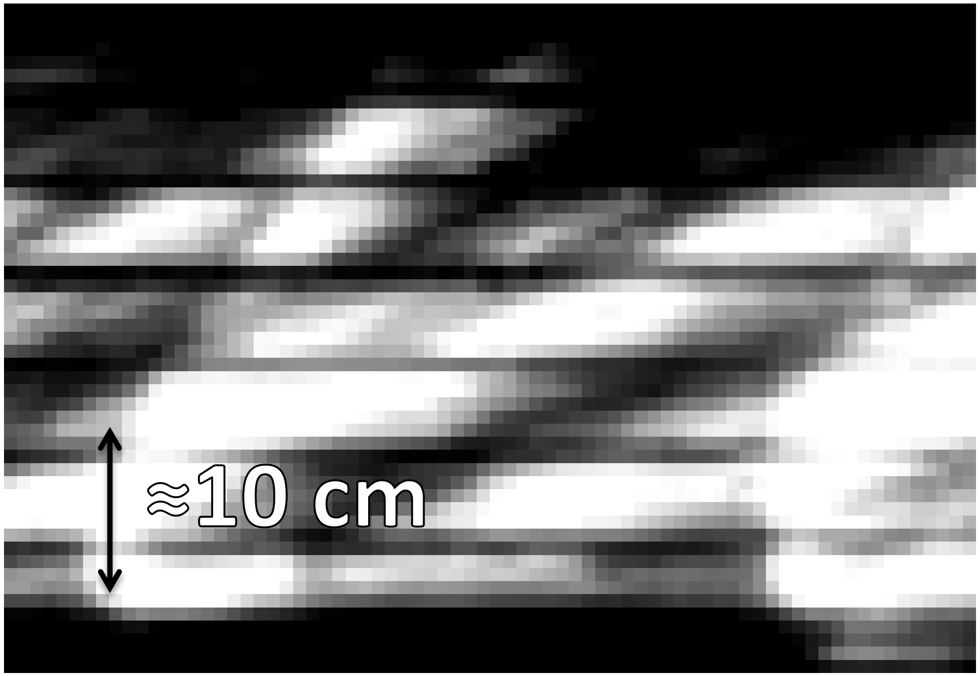


Movies skipped because of large size

Test case 1:
Comparison with experiment

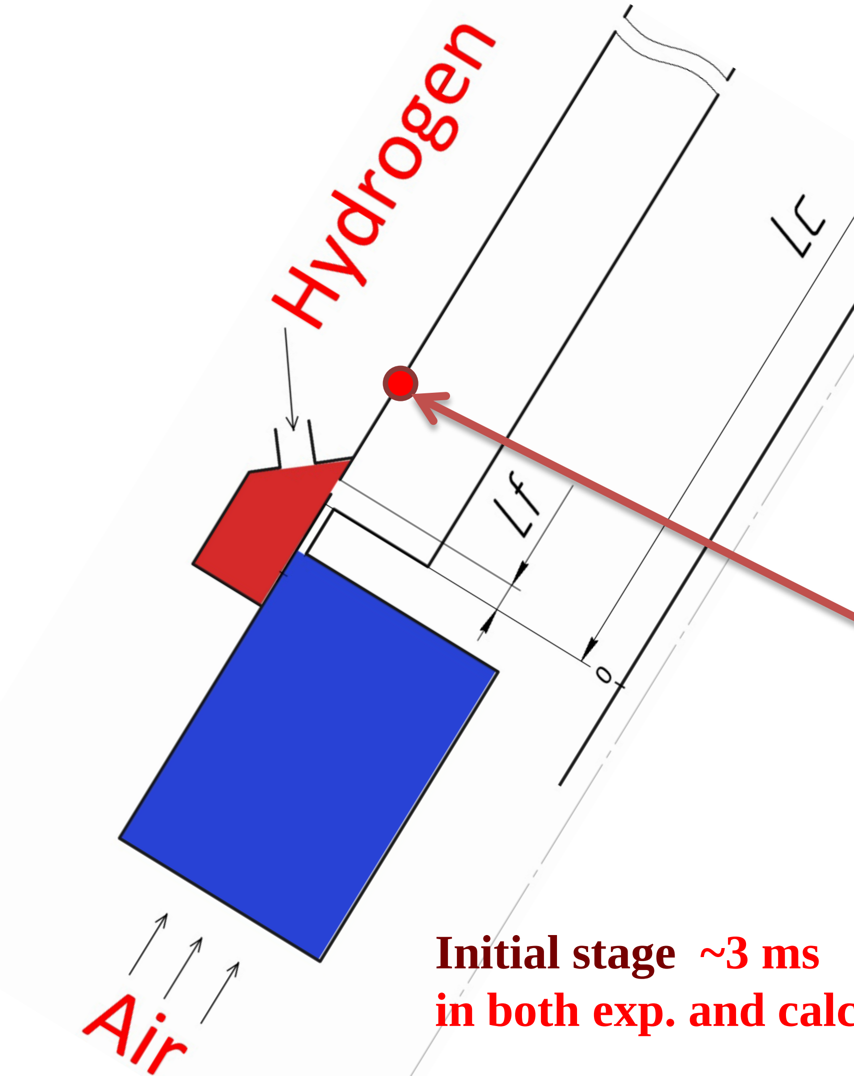


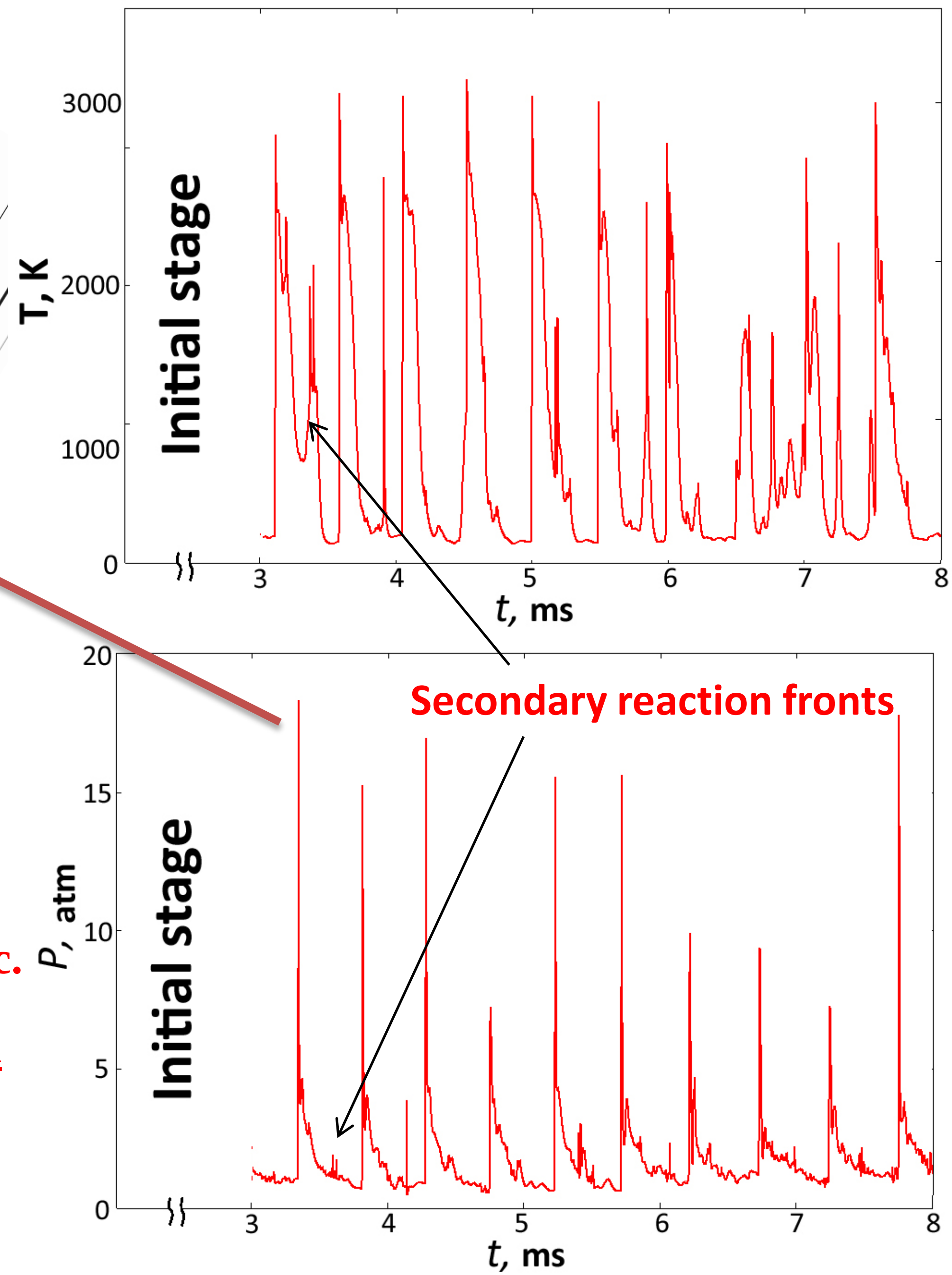
Calculation



Experiment

F. A. Bykovskii, S. A. Zhdan, and E. F. Vedernikov, Continuous Spin Detonation of Fuel–Air Mixtures, Combustion, Explosion, and Shock Waves, Vol. 42, No. 4, pp. 463–471, 2006





Initial stage ~3 ms
in both exp. and calc.

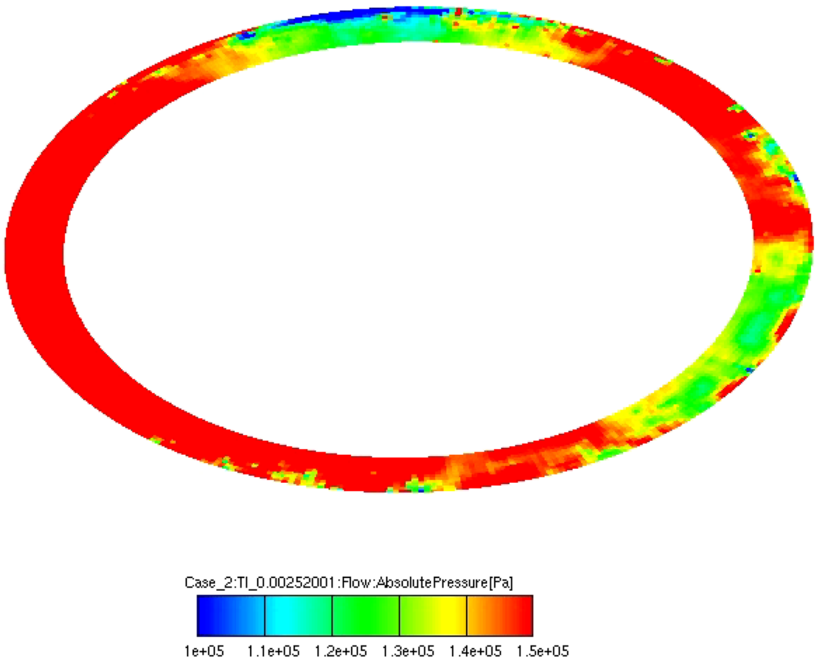
P in chamber (calc.) ≈ <u>1.8 atm</u>

P in chamber (exp.) = <u>1.8 atm</u>

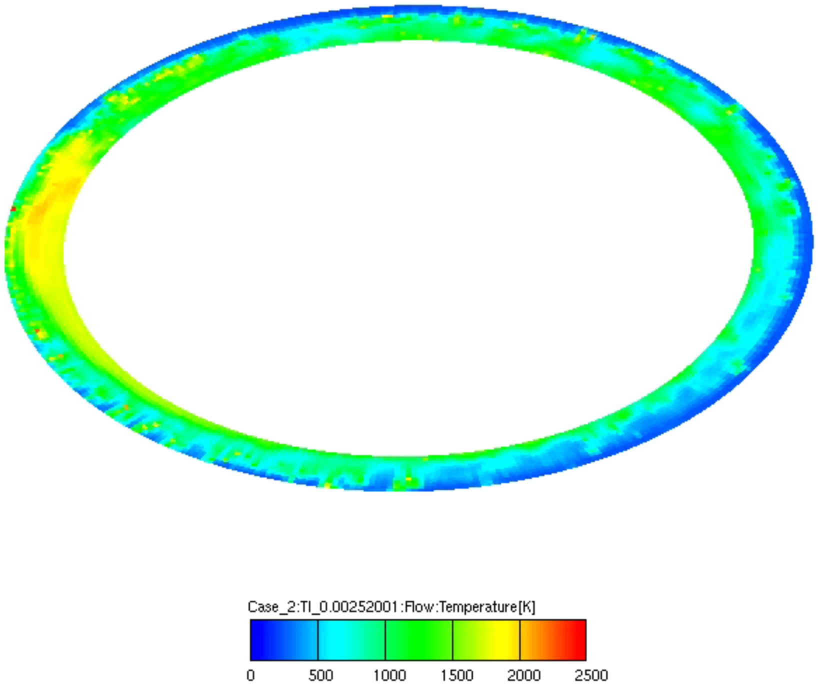
No. of waves (calc.) = 1+
No. of waves (exp.) = 2

Test case 1:

Detonation front propagation: horizontal cut



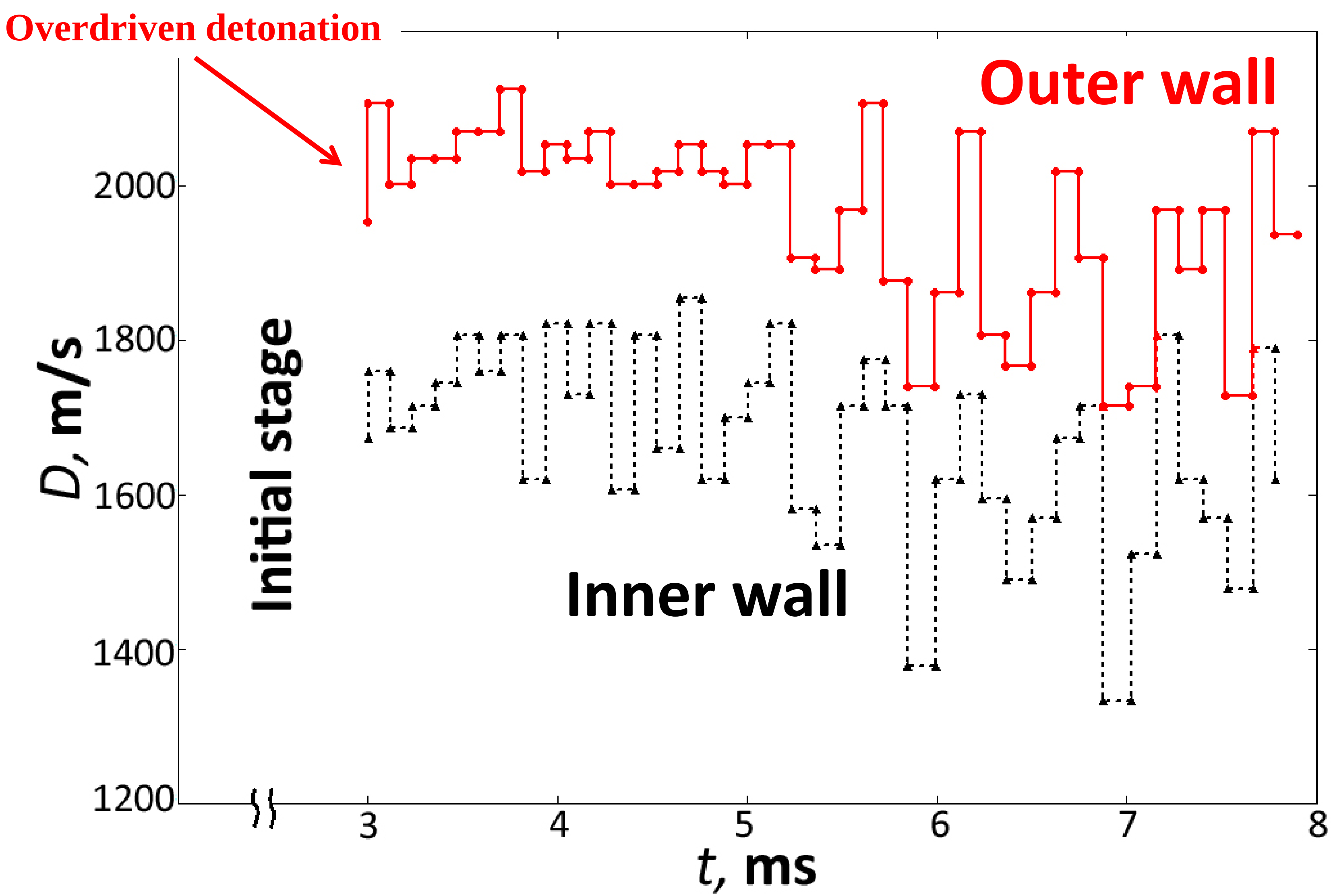
Pressure



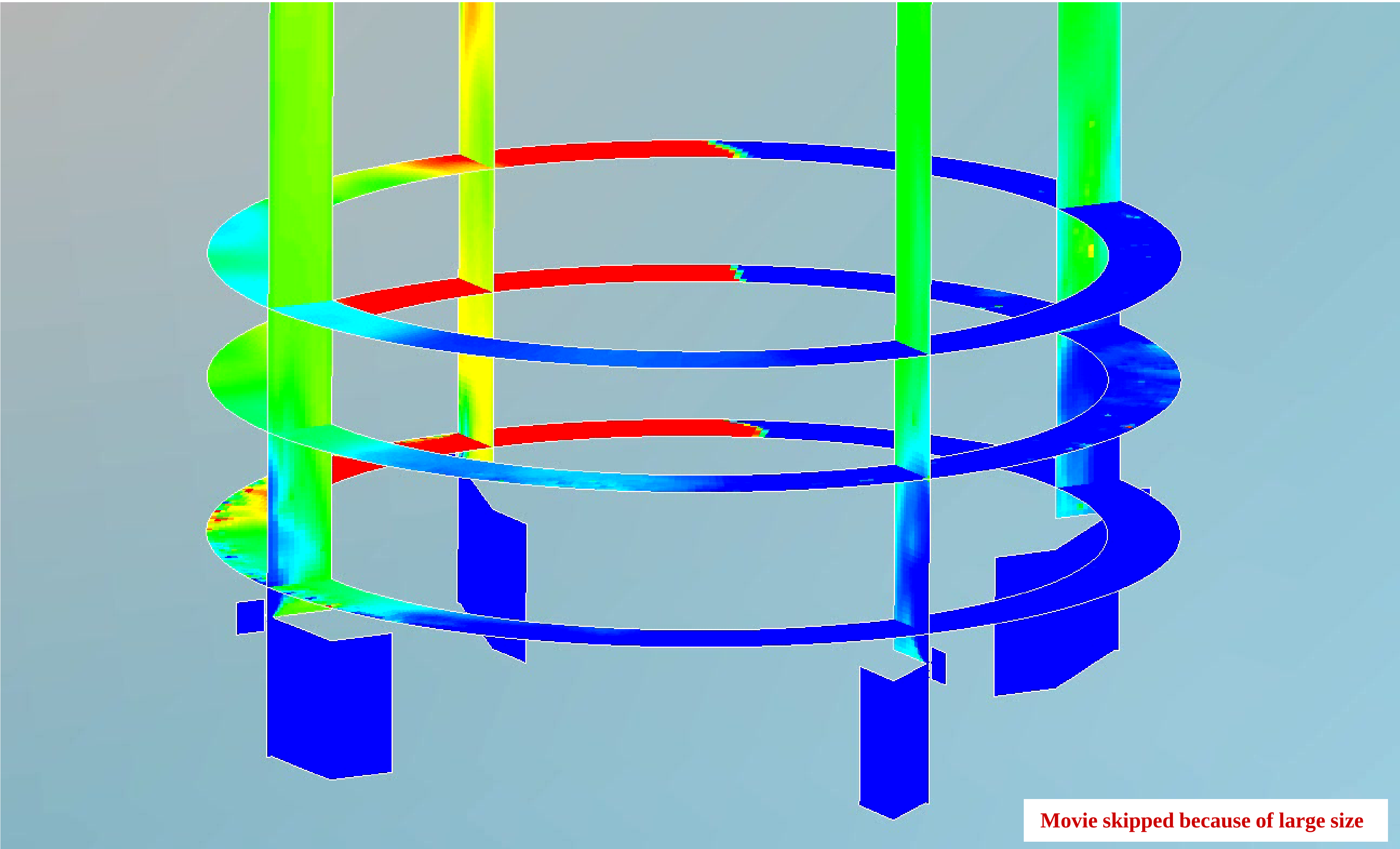
Temperature

Movies skipped because of large size

Test case 1:
Detonation Velocity



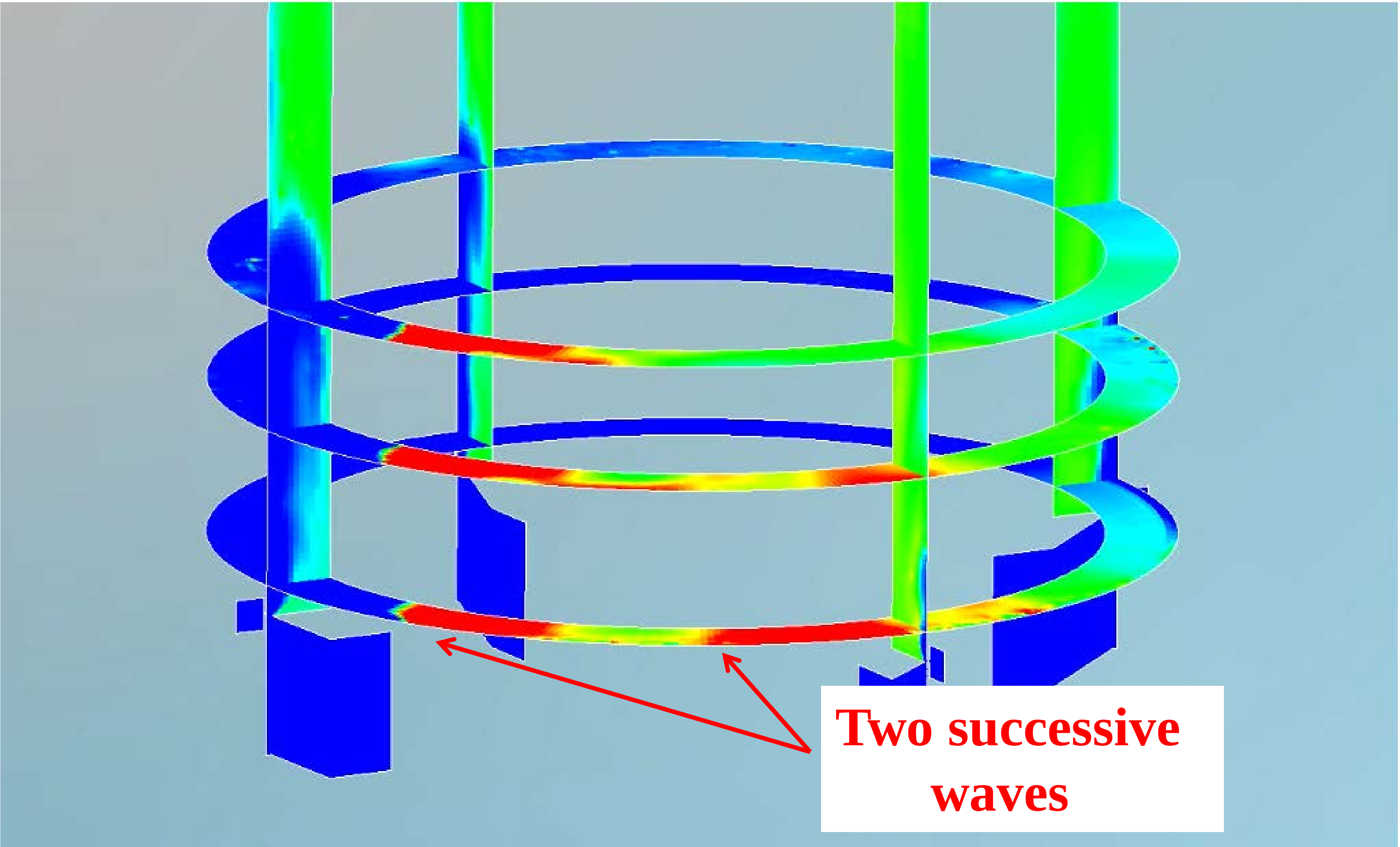
Test case 1:
Transient phenomena: vertical and horizontal cuts



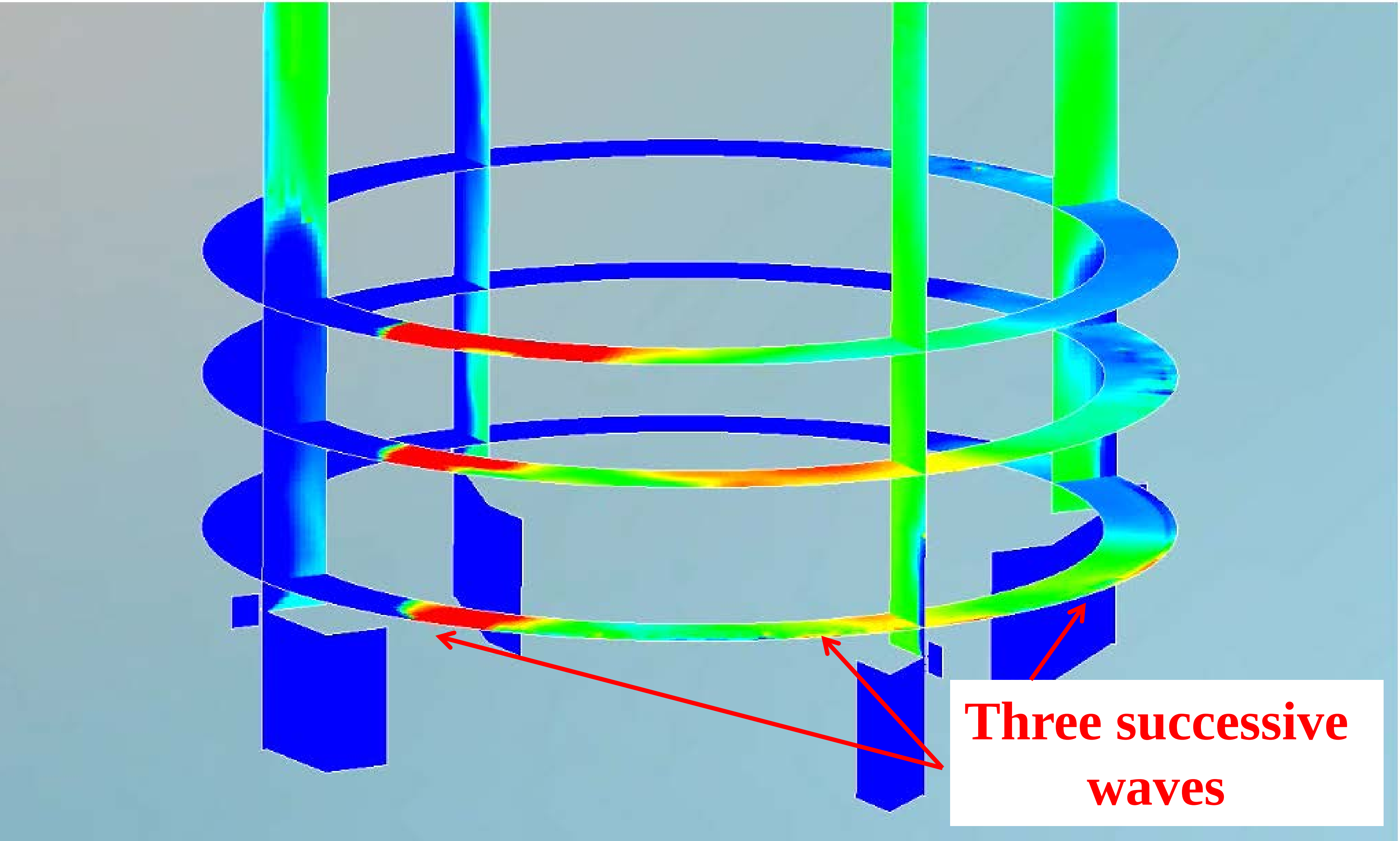
Movie skipped because of large size

Test case 1:

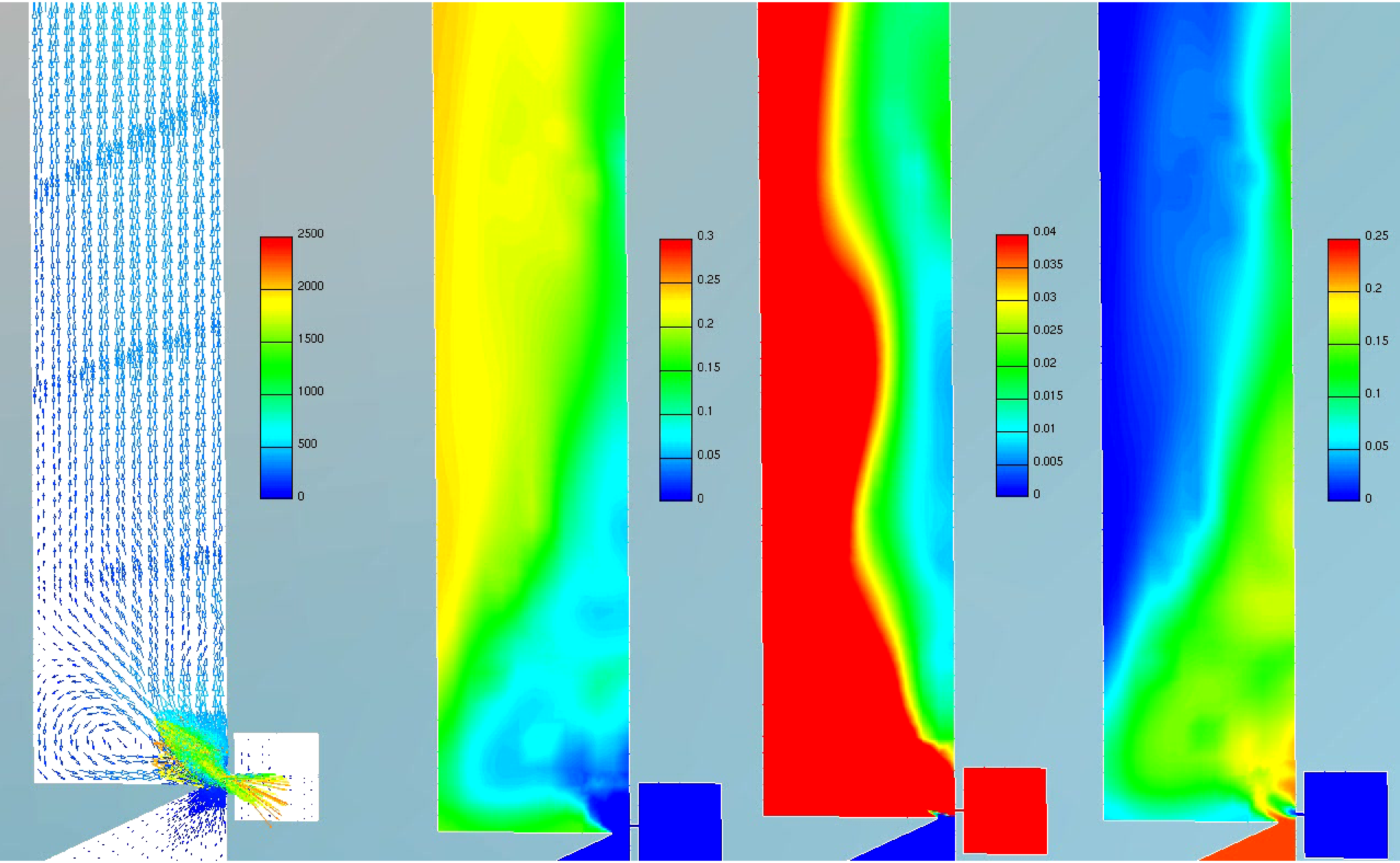
Transient phenomena: vertical and horizontal cuts



Test case 1:
Transient phenomena: vertical and horizontal cuts



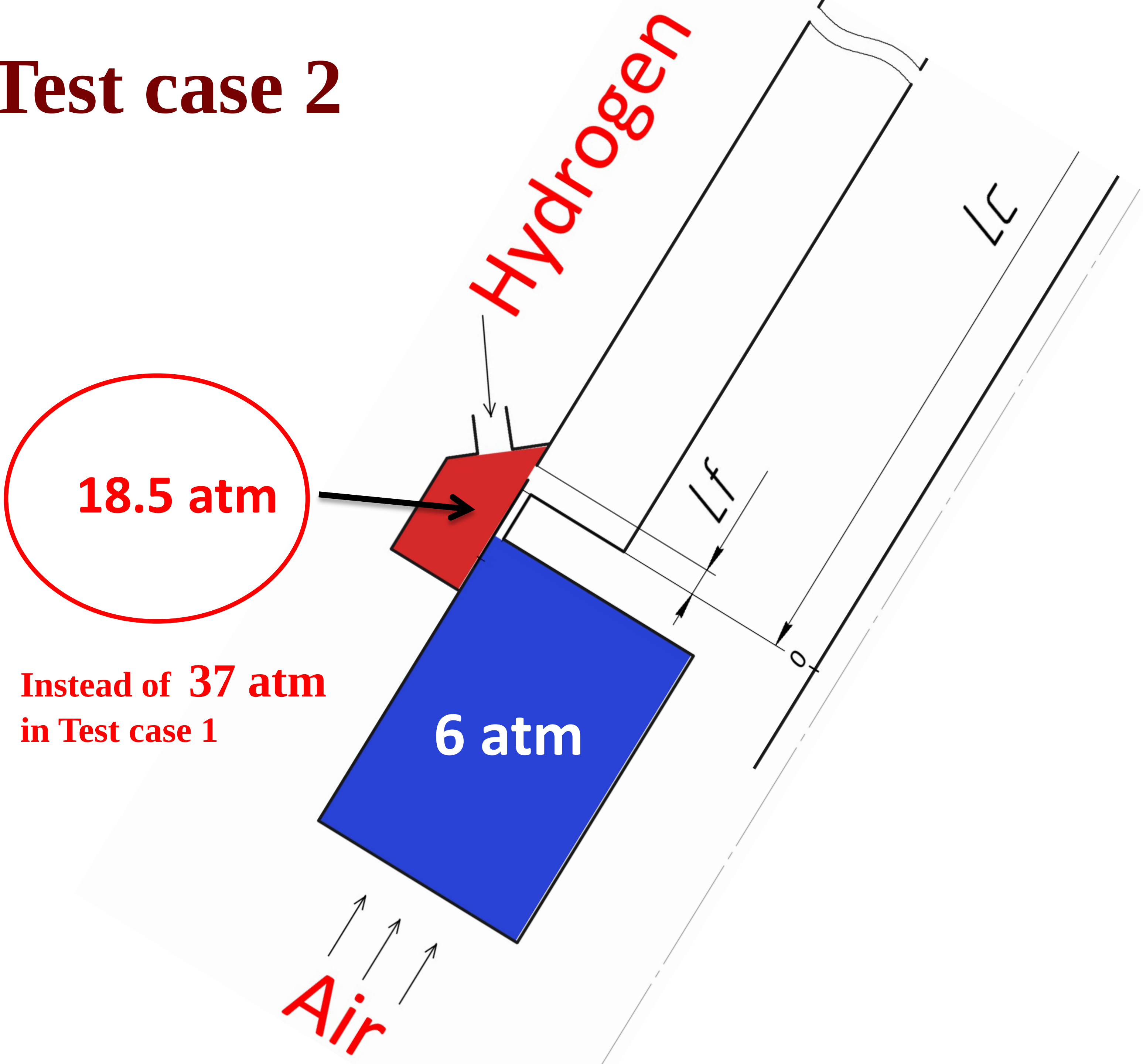
Test case 1: Mixing and burning: vertical cut



Velocity $y(H_2O)$ $y(H_2)$ $y(O_2)$

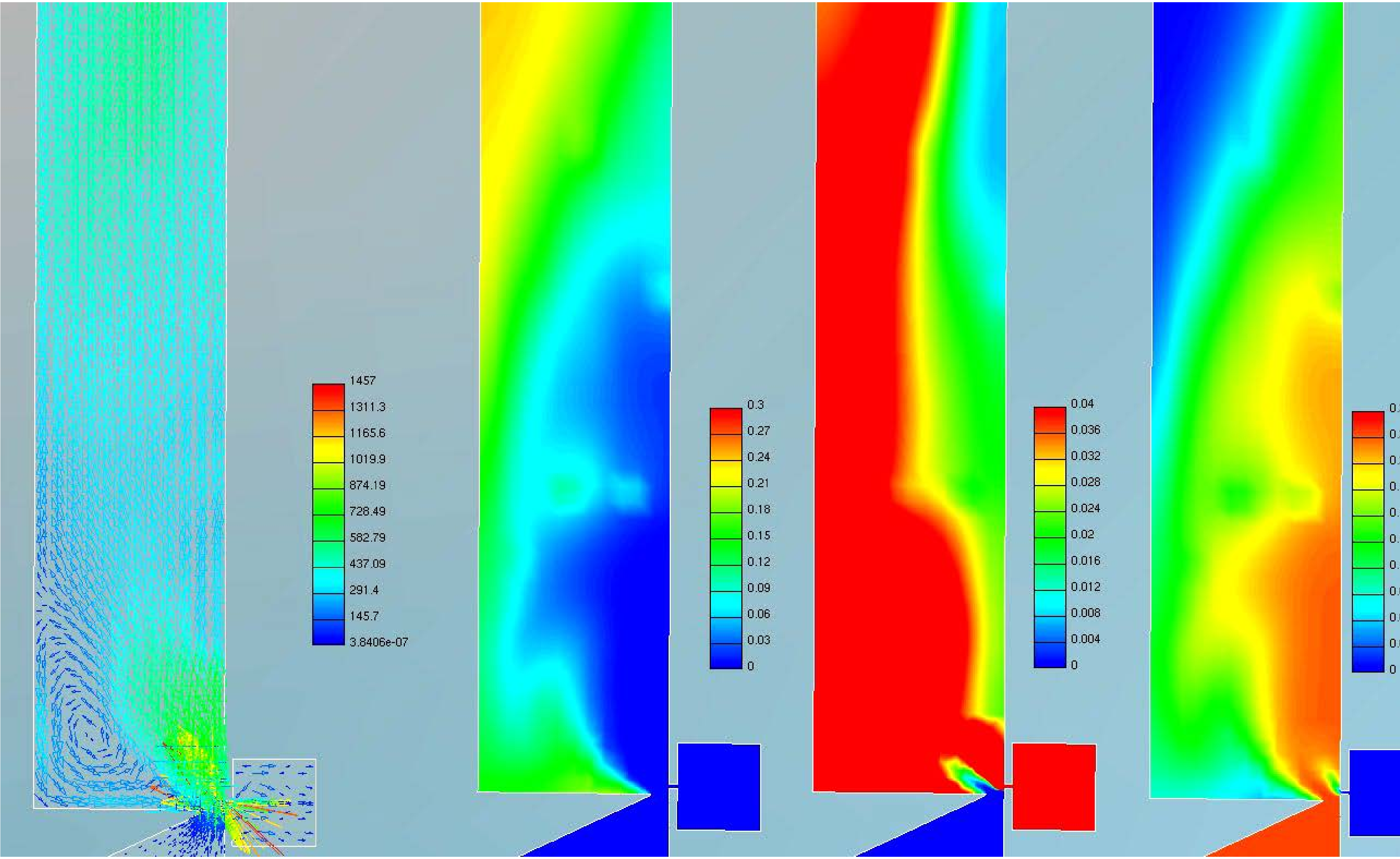
Movies skipped because of large size

Test case 2



Instead of **37 atm**
in Test case 1

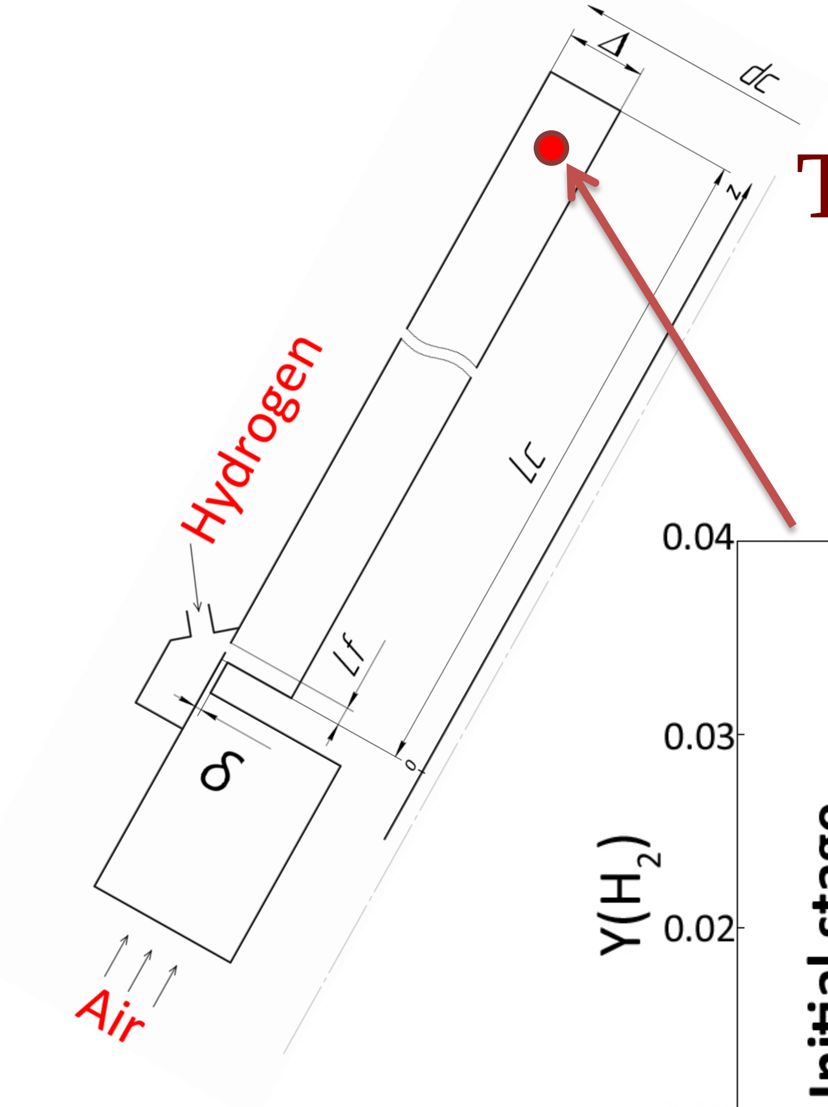
Test case 2: Mixing and burning: vertical cut

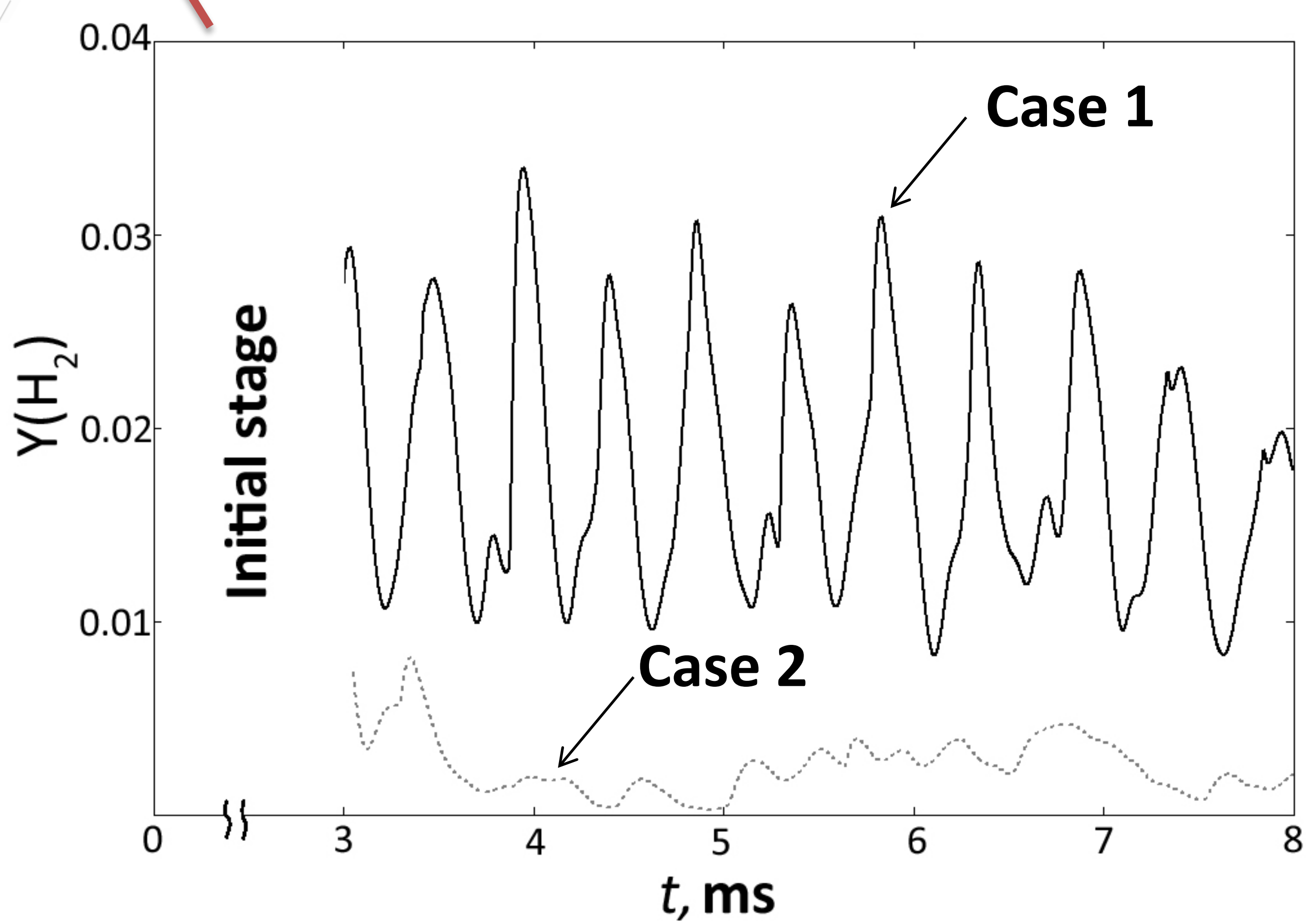


Velocity **$y(H_2O)$** **$y(H_2)$** **$y(O_2)$**

Movies skipped because of large size

Test case 2 vs. Test case 1: unburned fuel





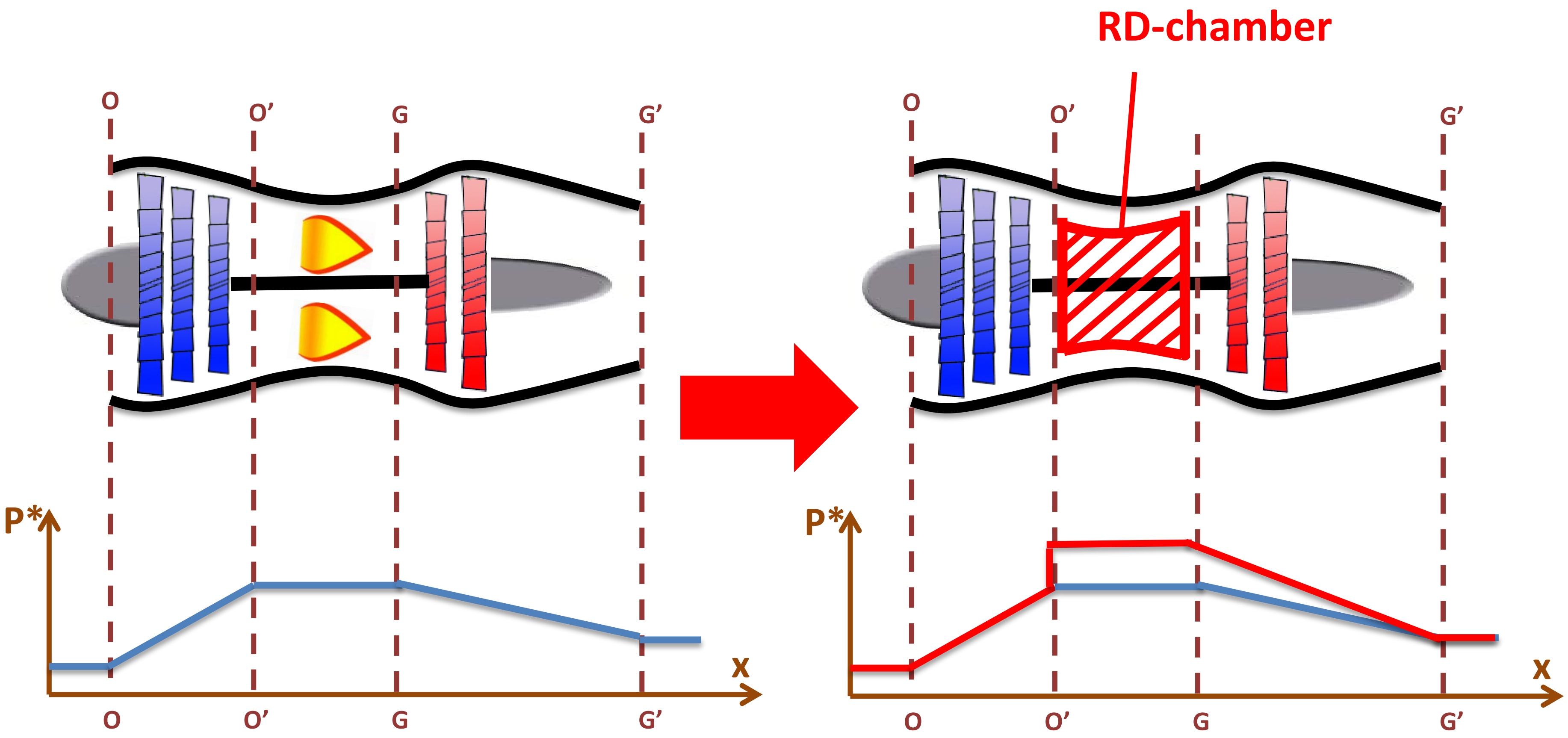
Continuous detonations:

CFD of operation process

with wide gap

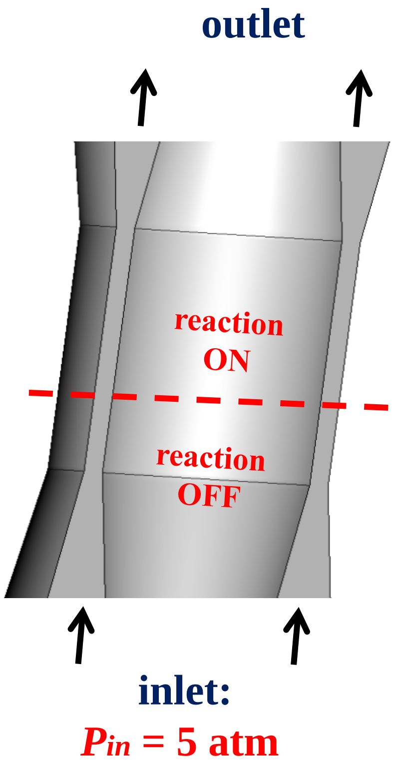
and separate delivery of fuel and air

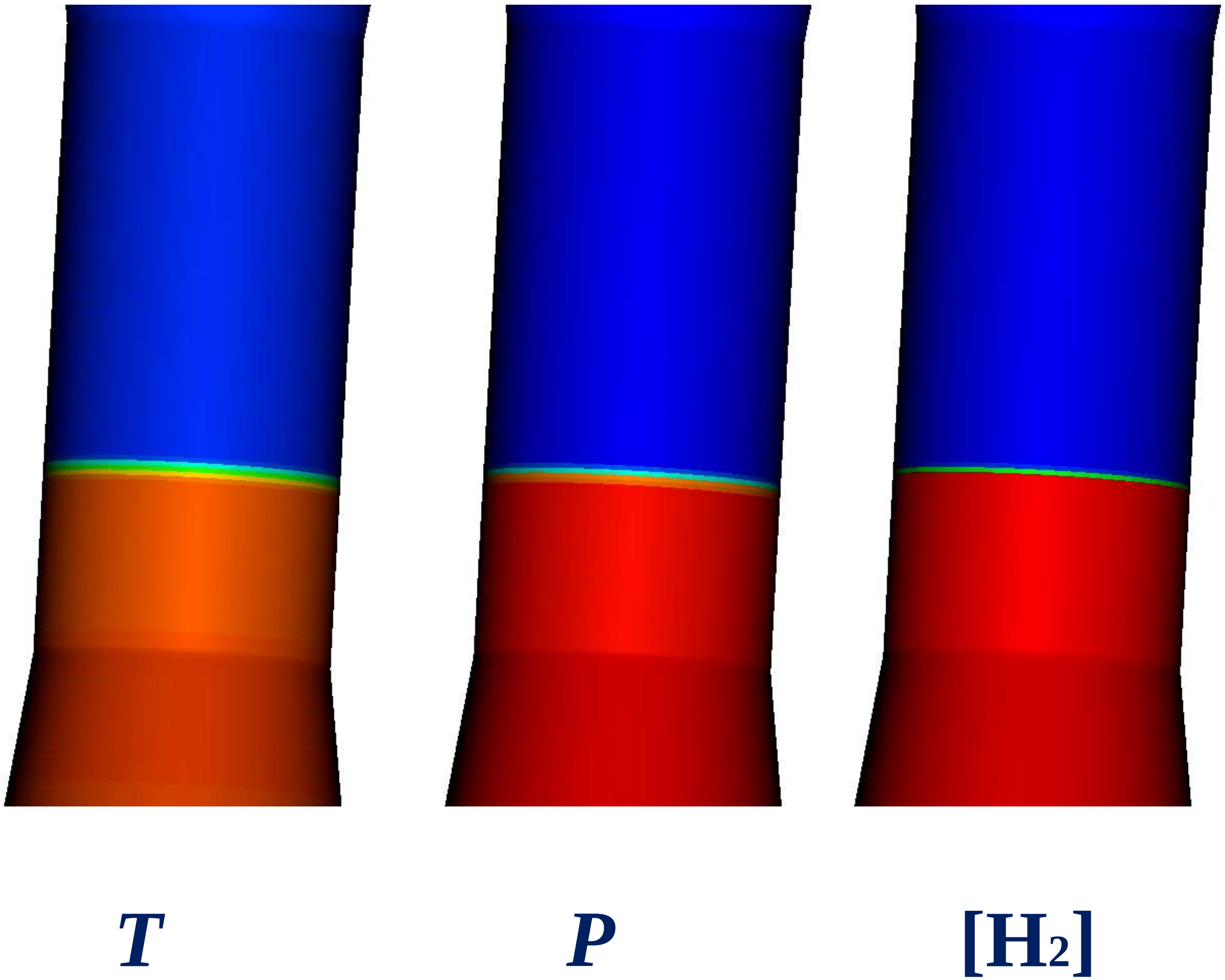
Gas turbine engine



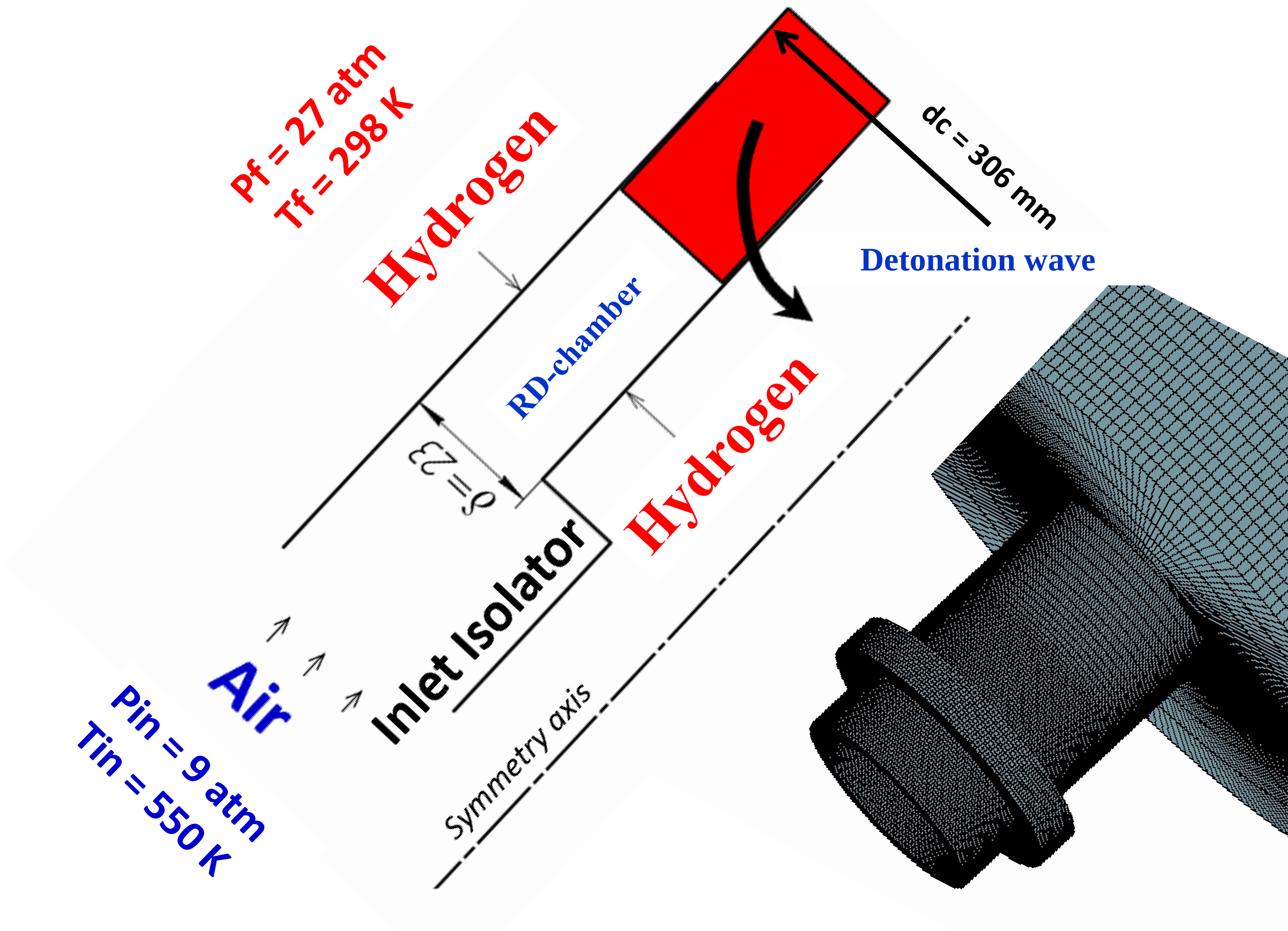
Total pressure gain?

Wide annual channel (25 mm)





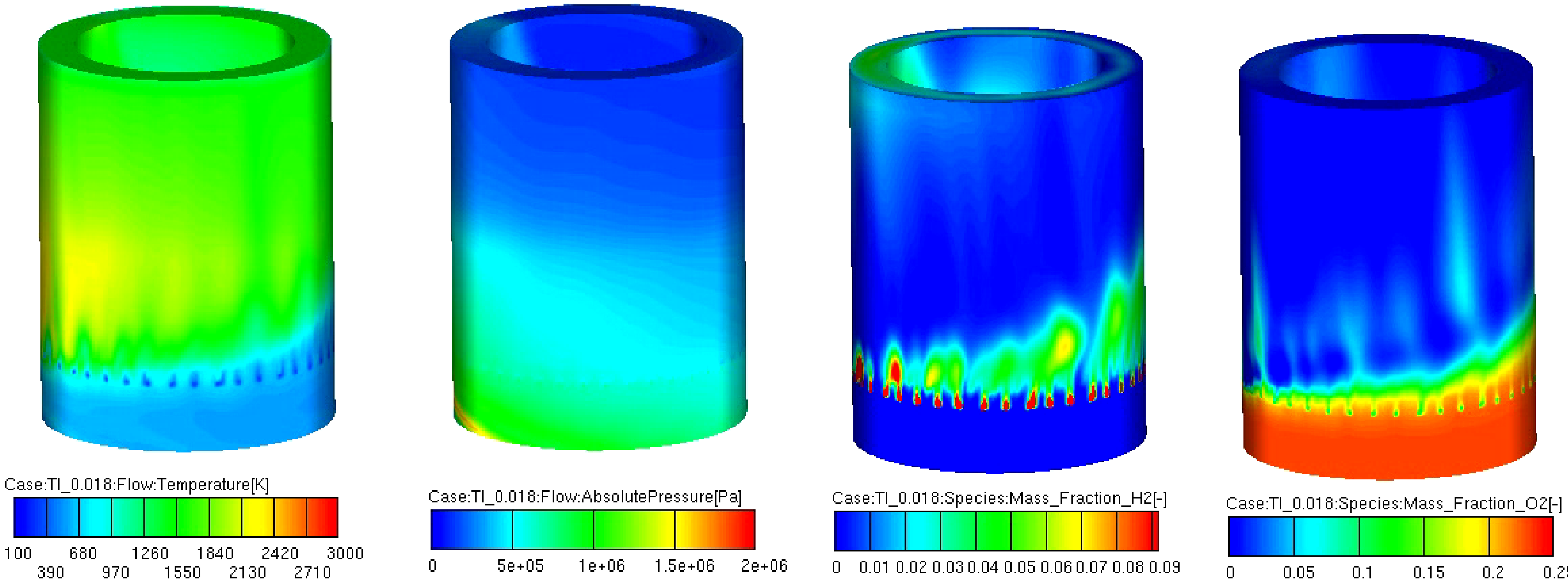
Movies skipped because of large size



Pf = 27 atm
Tf = 298 K
Hydrogen
dc = 306 mm
Detonation wave
RD-chamber
δ=23
Hydrogen
Inlet Isolator
Air
Pin = 9 atm
Tin = 550 K
Symmetry axis

Detonation propagation

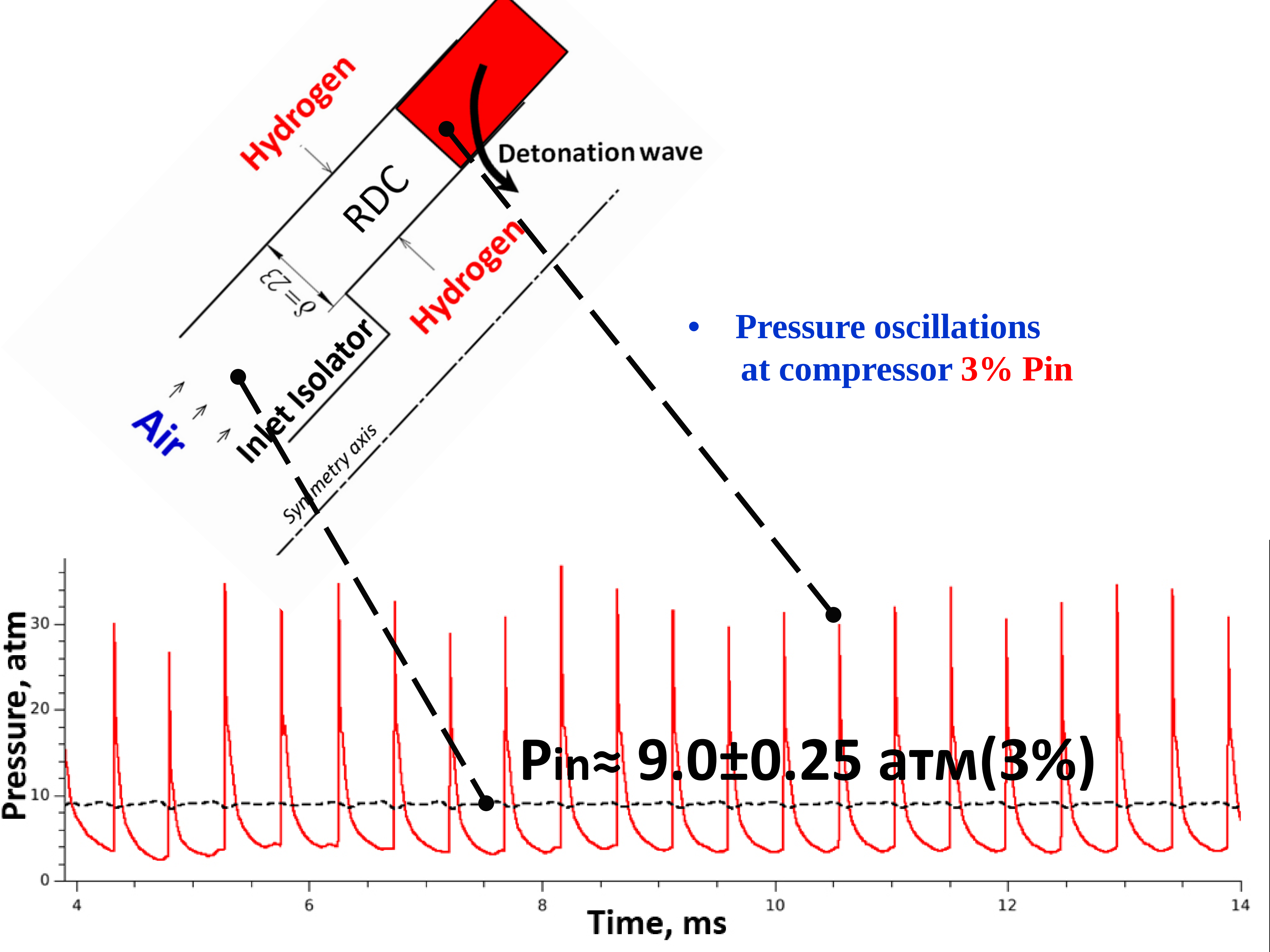
Turbine



Temperature **Pressure** **$y(H_2)$** **$y(O_2)$**

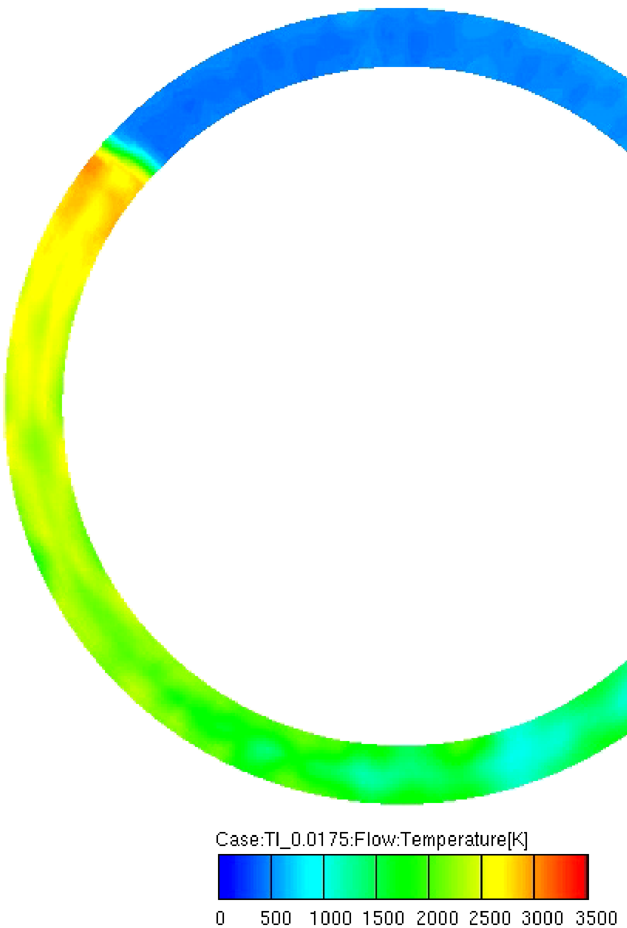
Compressor

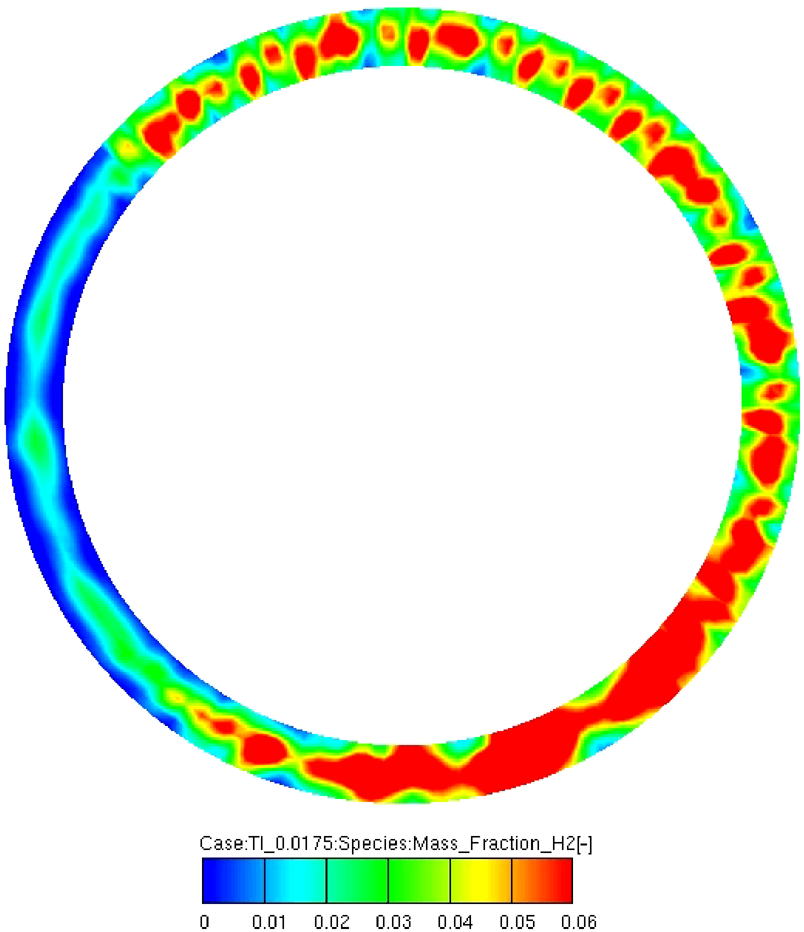
Movies skipped because of large size



- **Pressure oscillations at compressor 3% Pin**

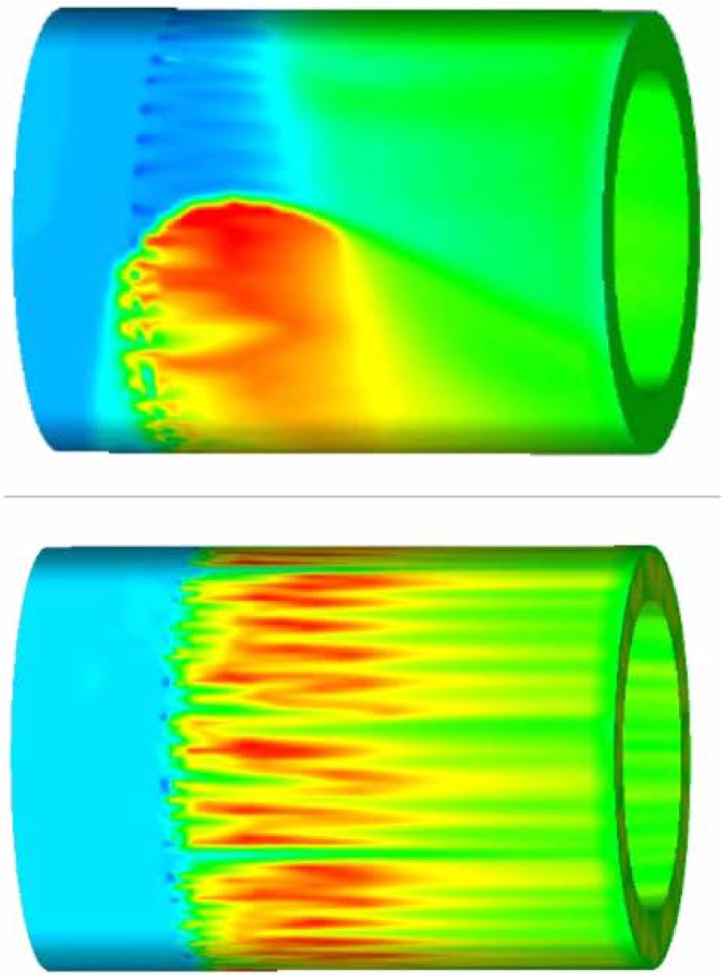
Detonation propagation: horizontal cut





Movies skipped because of large size

Detonation vs. deflagration



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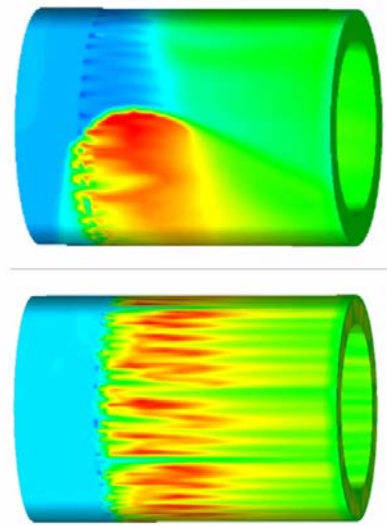
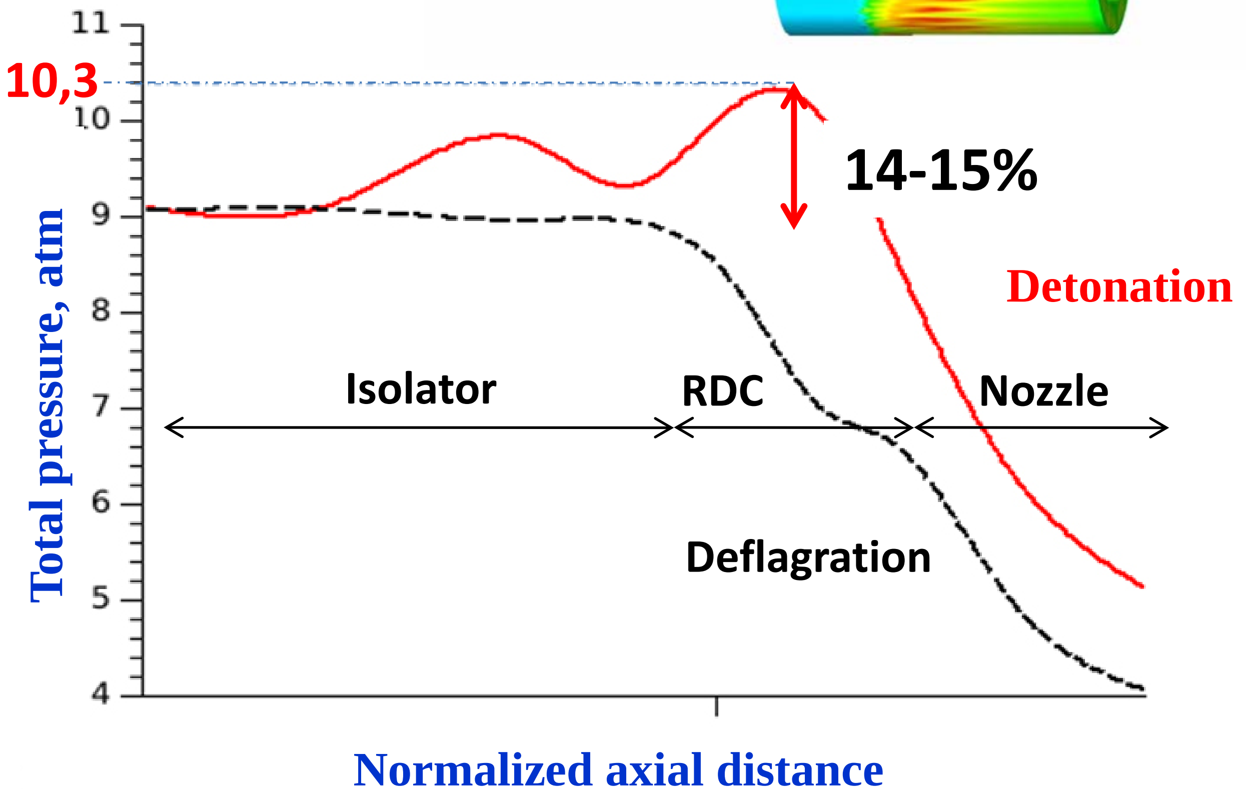
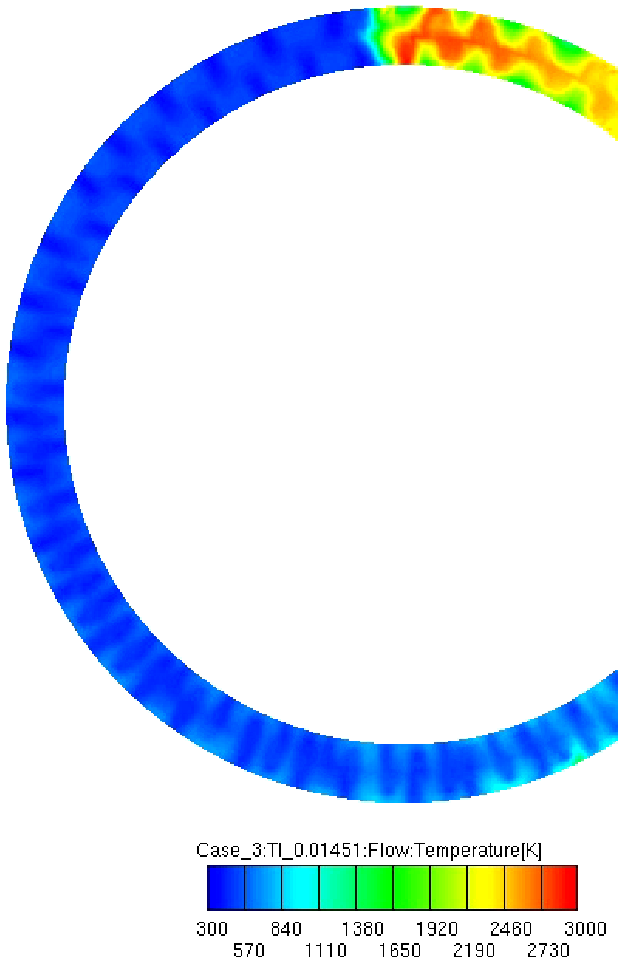
Detonation vs. Deflagration

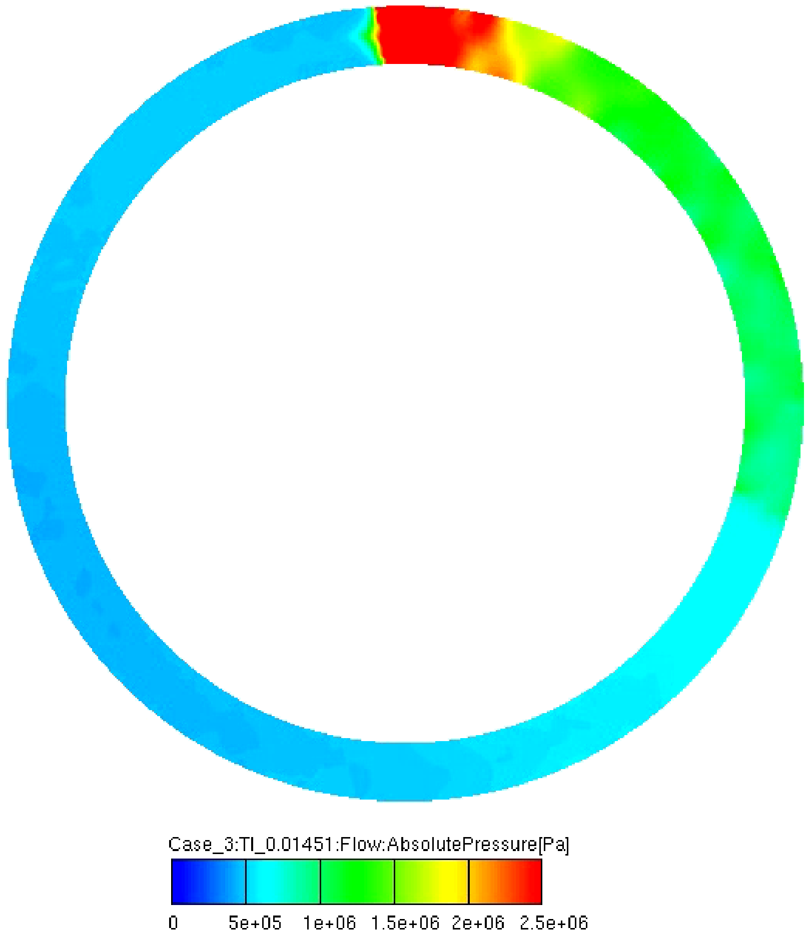




- RDC with total pressure gain!

Several detonation waves





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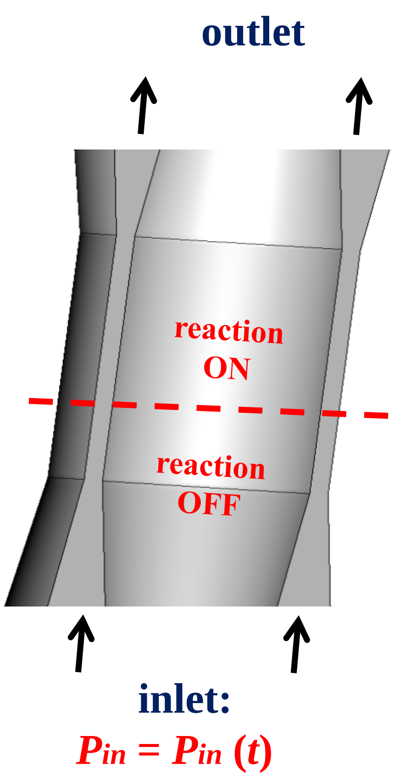
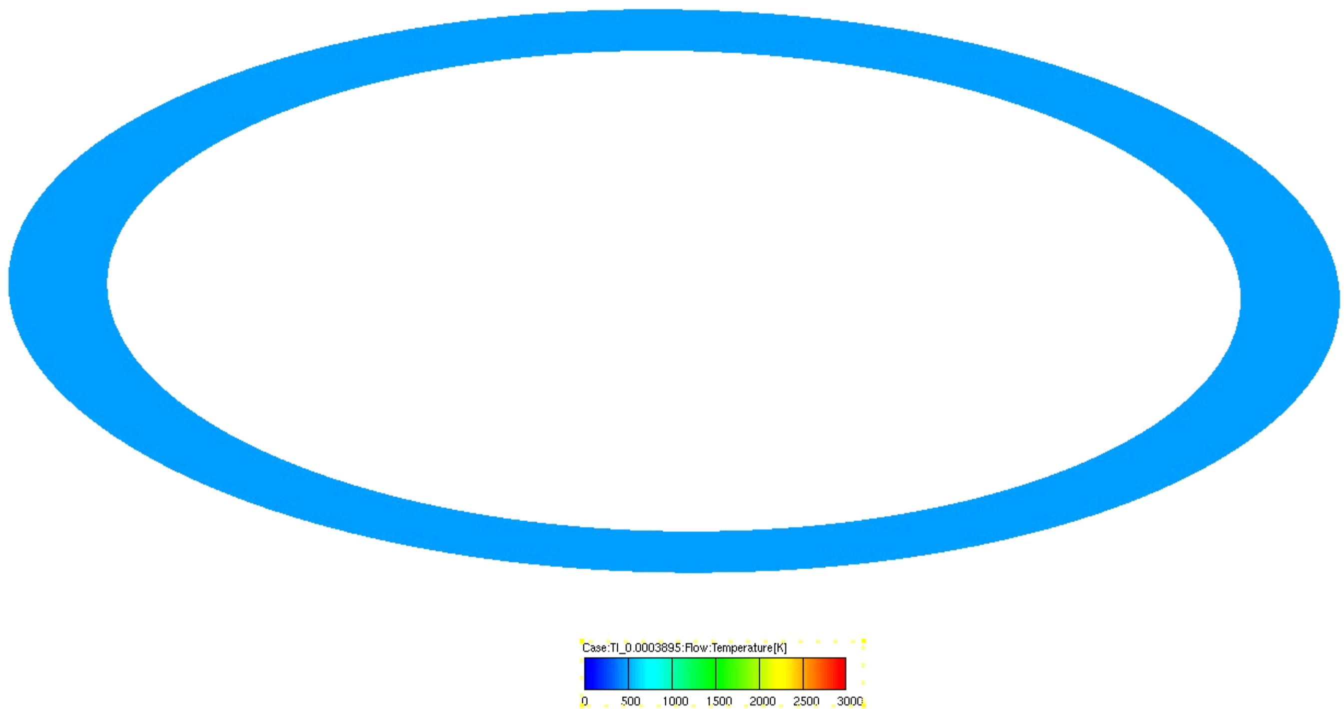
Spontaneous multiplication of waves





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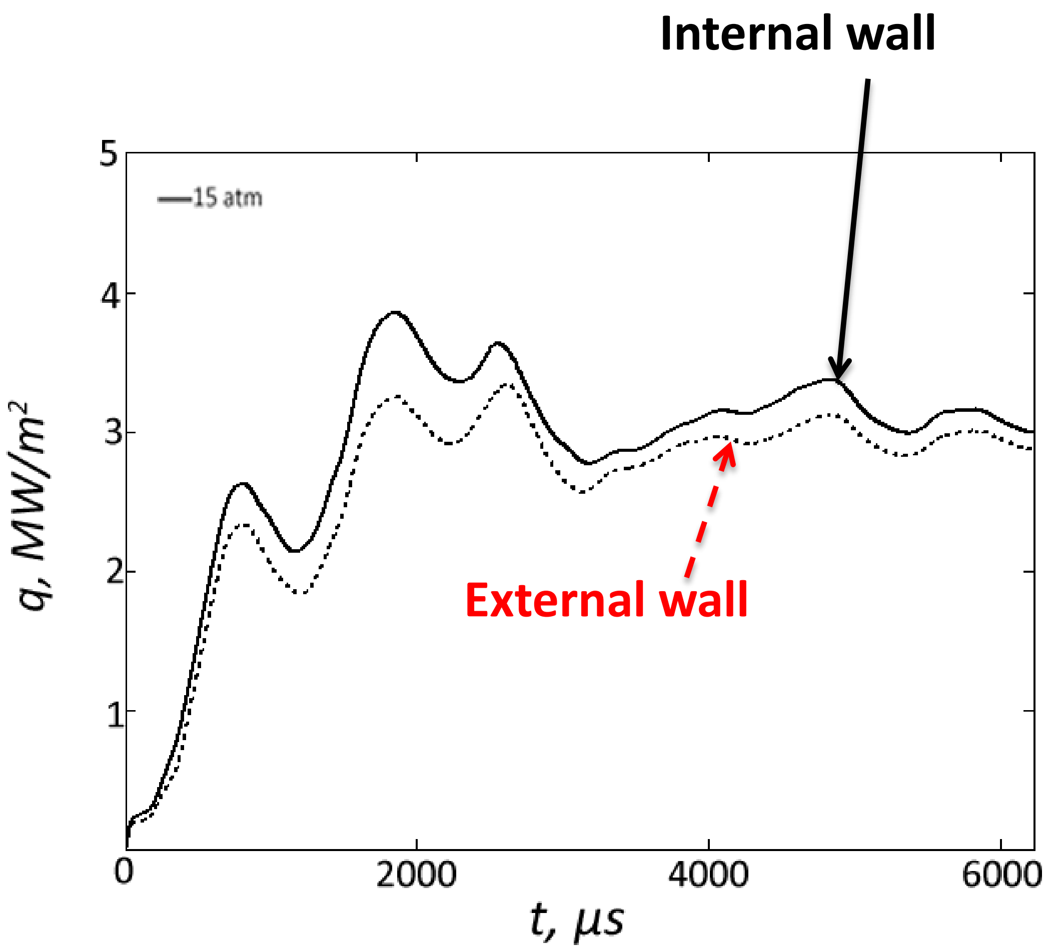
Movie skipped because of large size

Heat fluxes to RDC walls



As in modern Diesel engines !

Conclusions

Based on the Fast DDT concept,

- **Pulse Detonation Burner** has been designed, fabricated and tested (currently it is under preparation for certification and serial production)
- **Micro rocket PDE demonstrator** with the digitally controlled frequency of **calibrated detonation pulses** up to 200 Hz has been produced and tested both in ambient atmosphere and in vacuum
- Feasibility of **high-performance subsonic and supersonic ramjets** operating on pulsed detonations has been proved computationally

- Efficient **computational tool** for transient 3D numerical simulation of the operation process in a Rotating Detonation Engine has been developed and validated for **separate delivery of fuel and air**
- The tool is capable of resolving various specific features of rotating detonations and solving chamber **design, thermal management, and operation control** issues