Stable & Unstable combustion in propulsion systems

- Systems considered – Gas turbine engines, Rocket engines - Main and after burner combustion systems, Solid propellant rockets, Hypergolic liquid rockets, Full-cryo rockets
- Why does unstable combustion creep in?
- How to understand and avoid unstable combustion - Example from our recent studies on tactical rocket instability study.

H S Mukunda, IISc & CDM, JU, 21 January 2016

Drawn from sources: Joint work with Dr. Varun Shivakumar (IITM)

and briefly the work of Late Prof. P. J. Paul’s students, Biju kumar (LPSC), and Ashirvadam (GTRE)

My encounter with instability

1. 1976-77 With ISRO – High Altitude Test facility instability problem at SHAR range on Diesel-turpentine + RFNA based rocket system for generating hot gases

2. 1976 – 1978 VIKING liquid engine instability related issues with LPSC, VSSC, ISRO

3. 1978 – 1985 Valient engine instability issues – DRDL, Hyderabad

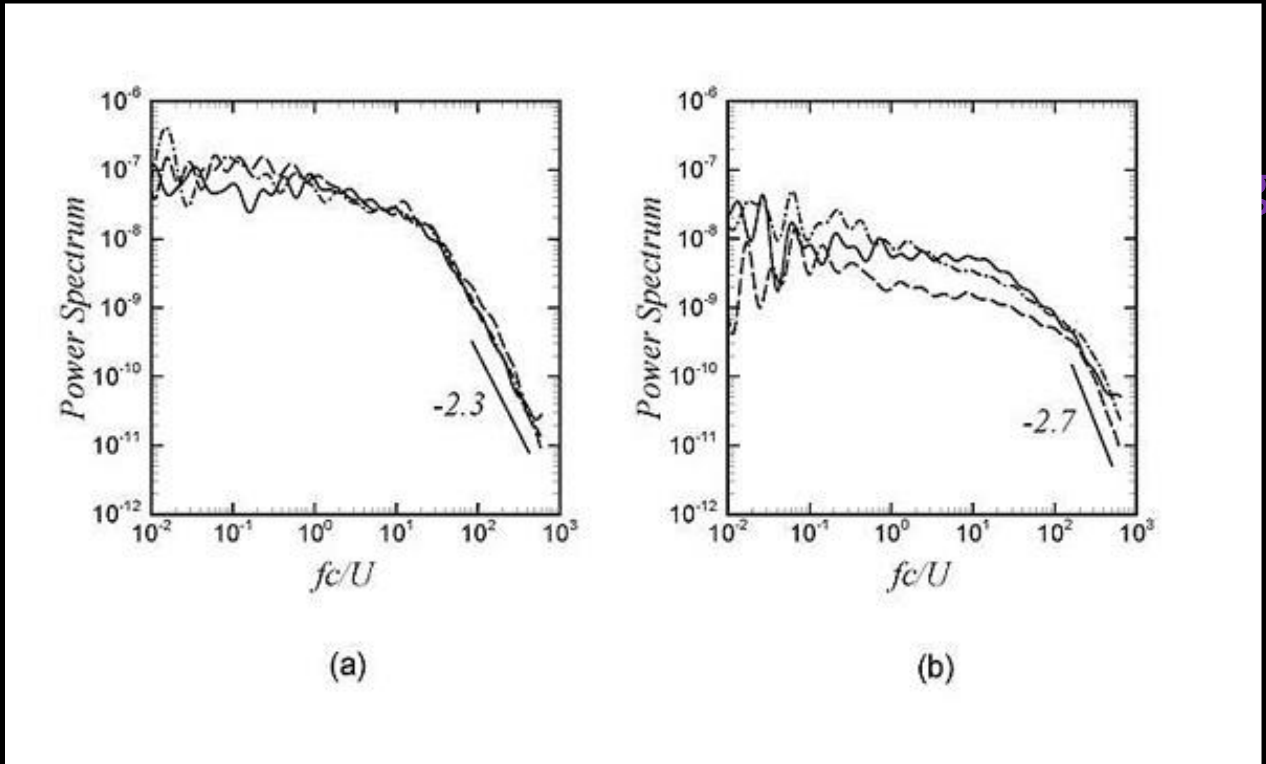
4. 1978 – 1982 Instability in hybrid rockets (P. J. Paul's Ph. D thesis of included this aspect)

5. 2011+ Instability problems in solid rockets – DRDL – started initially as a review committee chairman and became obsessed a student of the problem.

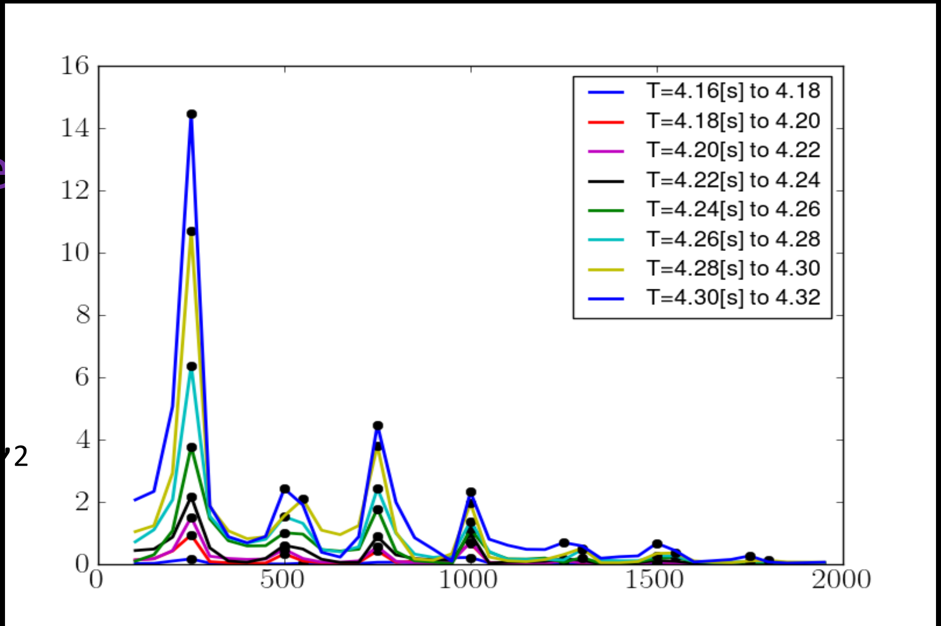
Link between stable and unstable combustion

- Even by definition, instability beginning in a linear regime arises out of a disturbance to the steady state or equilibrium state
- In rigorous studies, you can discuss stability only after steady state is understood.
- In complex systems, sometimes, this step is replaced by intuitive semi-empirical approaches to jump-start overcoming instability.
- It was faced in early fifties in the USA in liquid rocket engines - catastrophic instability problem on the launch pad caused change of ideas.
- The idea of "statistically stable" was replaced by needing to prove that the system is stable on causing a strong disturbance – like a small bomb being fired inside the steadily operating rocket engine and expecting the system to get back to steady state.
- This led a serious effort to understand the mechanisms of instability through experiments and analysis
- Many other fields have not been so blessed.

What of rough combustion?



Normal and acceptable

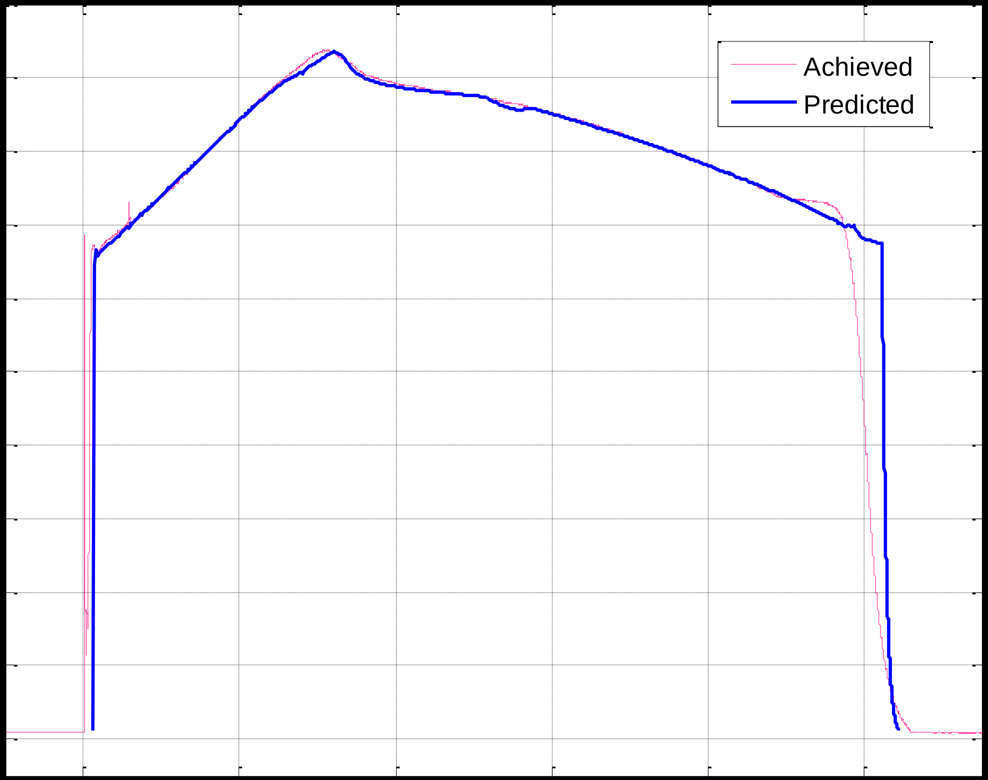


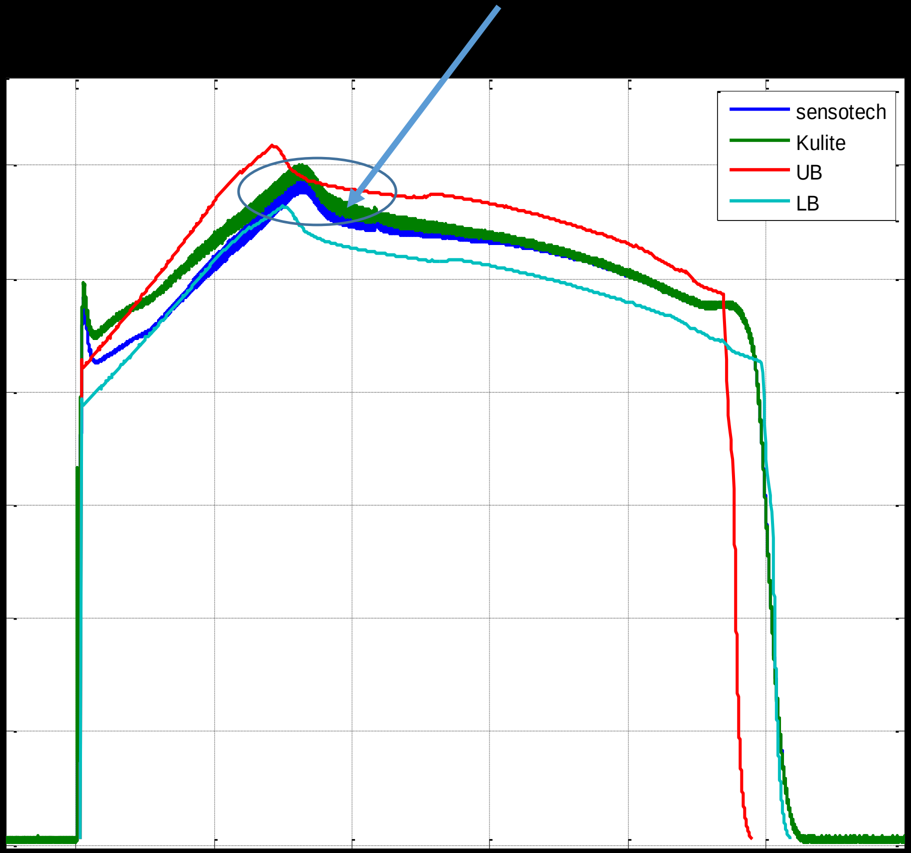
Disastrous and unacceptable

Steady combustion vs. Unsteady combustion

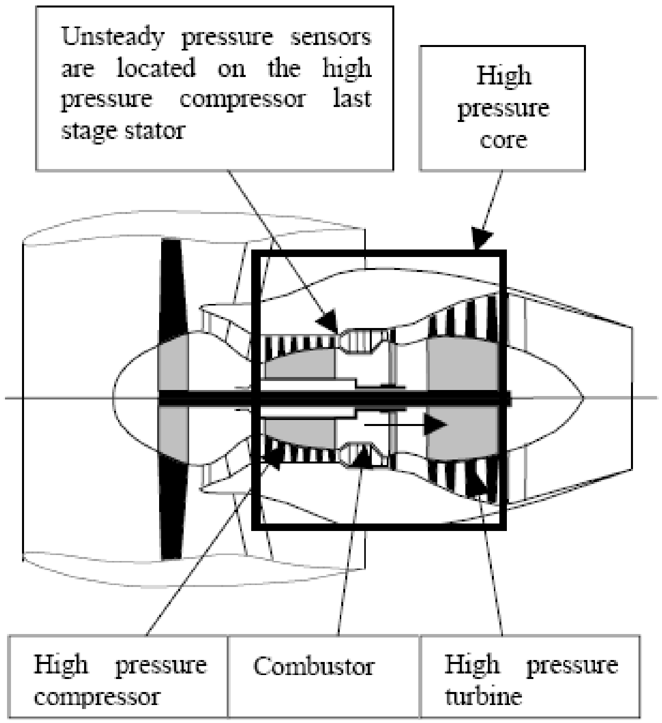
Smooth p_c-time profile
Fluctuations < 0.5 %

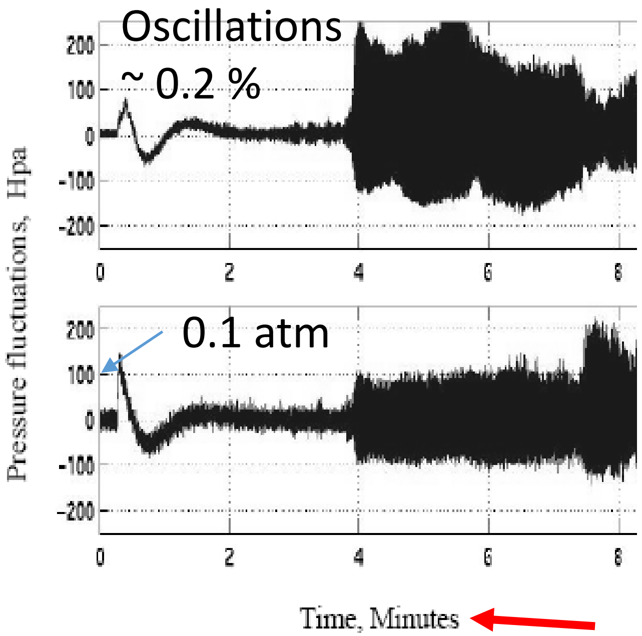
p_c vs. time with undesirable irregular fluctuations (> 2 %)

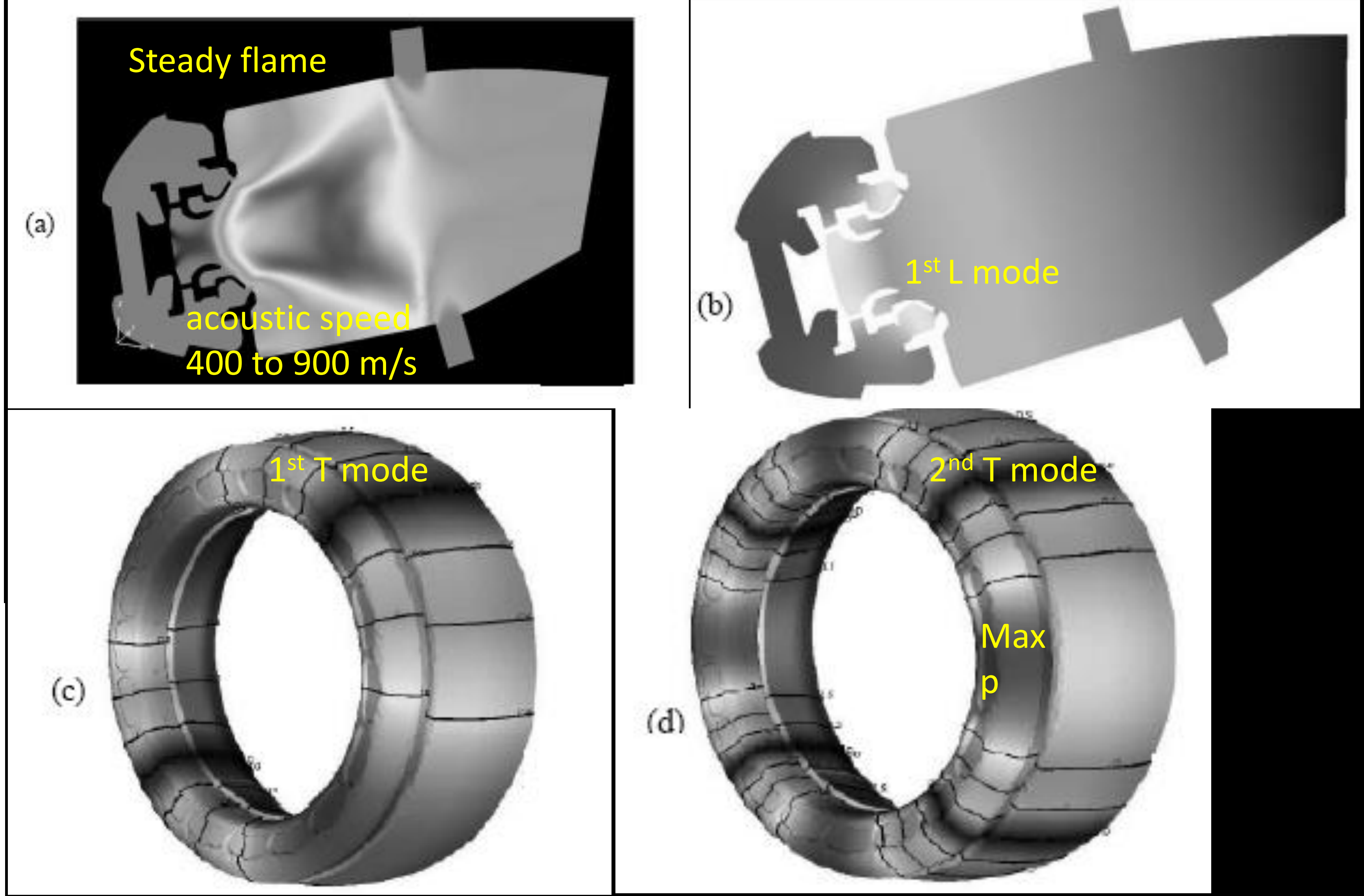




Example here is of solid rockets. But the features are true for all systems – After burners, main combustor as well







A gas turbine and many features of steady and unsteady combustion – acoustic speeds and modes of fluctuation. Up to 3 % fluctuations allowed in practical GT combustors; damping from injection holes and other forms of damping make main combustor less unstable

$$\boxed{\iiint \omega' p' dV > 0}$$

Heat release Pressure

« If heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged.
On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged »

Lord Rayleigh
Nature, 1878, July 18
(Phenomenon of singing flames already identified before 1800 but Rayleigh was the first to formulate a stability criterion)

See youtube video on "Understanding combustion – part III" on solid fuels (last part) – Rijke tube and Ruben's tube of IISc produced educational film on combustion science

From: Active control for military gas turbines

by Marcus and Michael Richman, ADP011147

…Increasing thrust-to-weight ratio calls for all components being light and lean. **This makes the operation unstable as well**. As a result the engine must be smarter. The major components must be actively controlled avoiding stall, surge and vibration along with closed loop combustion…

….Passive control techniques include changing the fueling scheme in areas of the envelope prone to instability, hardware changes to screech control section of the augmentor liner or combustion liner.

My comments: Methods must be found to battle these problems through analysis and limited experimentation

Specifications:

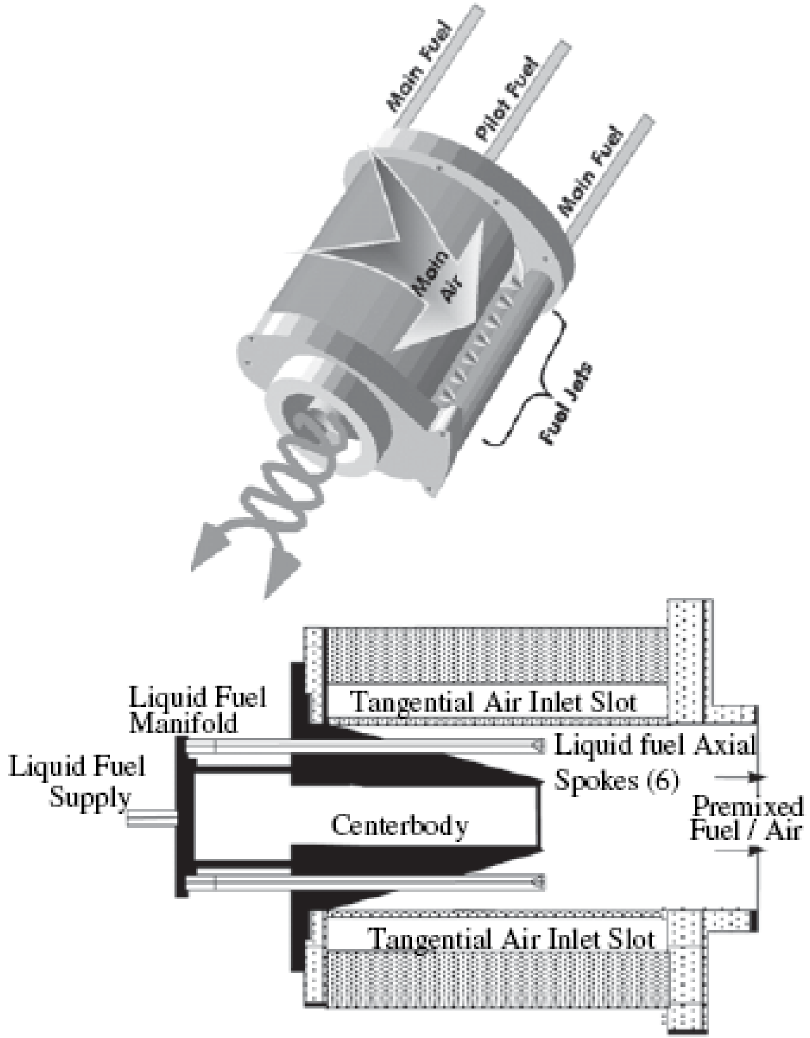
- NO_x < 23.5 ppm and CO < 16 ppm for gaseous fuel
- Annular combustion chamber
- Tangential entry fuel nozzle
- Thermal barrier coating, and film cooling

Instability control strategies:

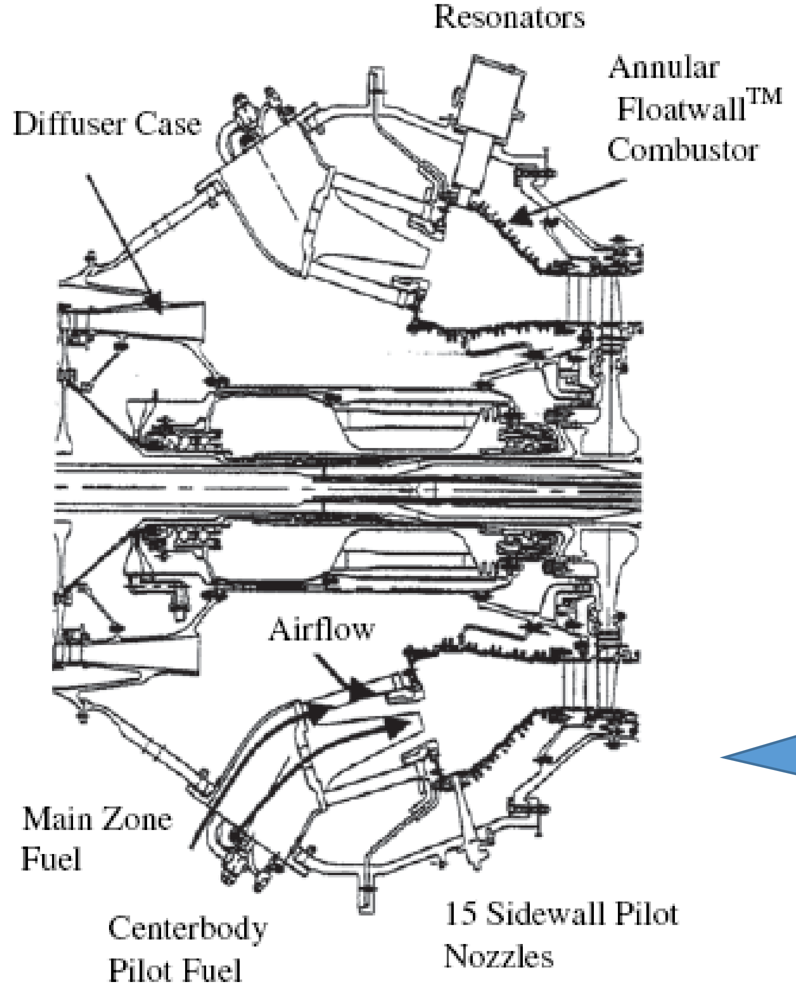
- Helmoltz resonators
- Re-schedules pilot fuel flow or reduces output power
- Active control through modulation of fuel flow rate based on phase-shift or adaptive control algorithm

P & W FT8 engine

Note the several devices ased here. active control requires analysis and design



(a) Fuel nozzle with tangential entry

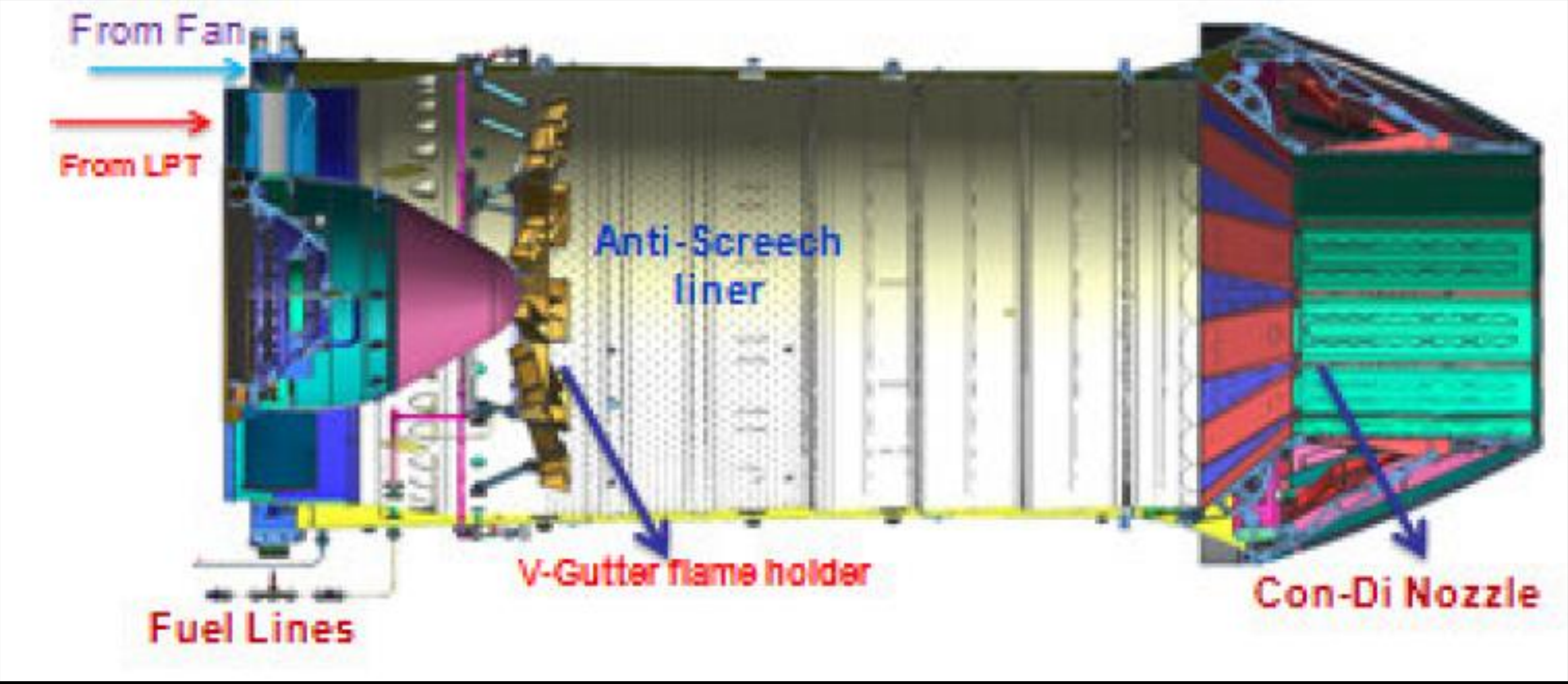


(b) Annular combustor

Huang and Vigor Yang

Amplifying and damping mechanisms

- Even if the heat release fluctuations occur in phase with acoustics leading to amplification as per Rayleigh's criterion, there could be other damping mechanisms.
- In a GT after-burner, the use of a perforated inner sheet through which air flows in causes damping due to exchange of acoustical energy. This depends on the frequency and the modes involved.



Reduced-order oscillator models

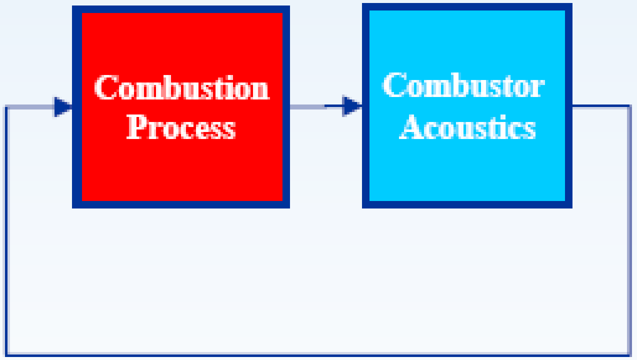
Run fast to allow parametric studies in support of control system development

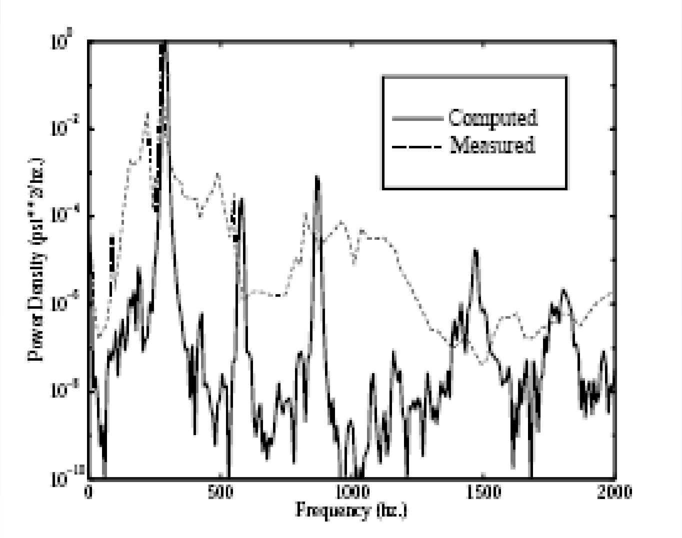
Simplified Quasi-1D dynamic models

Allow physics-based control method validation

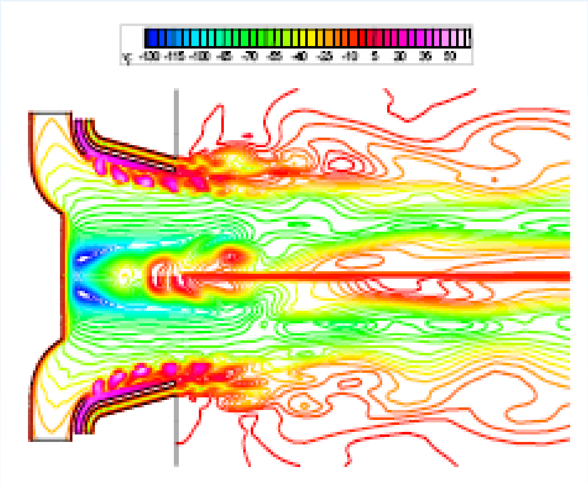
Detailed, physics-based dynamic models

Fundamental understanding of combustor dynamics to aid passive, active instability suppression





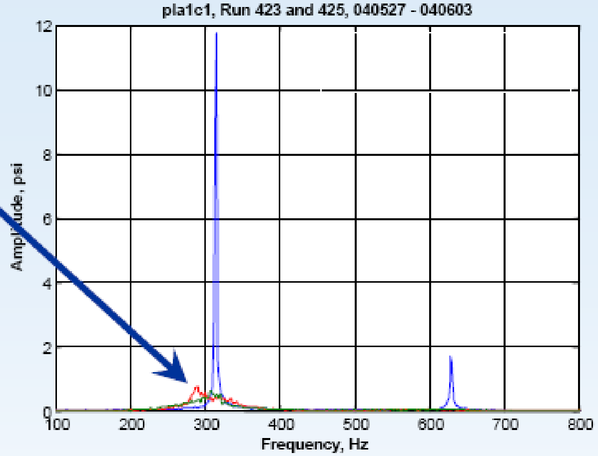
Results from NASA Sectored-1D Model of LPP Combustor Rig – D. Paxson

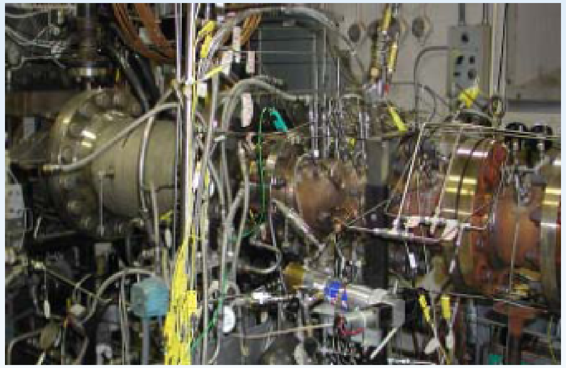


Penn State Injector Response Model Plot

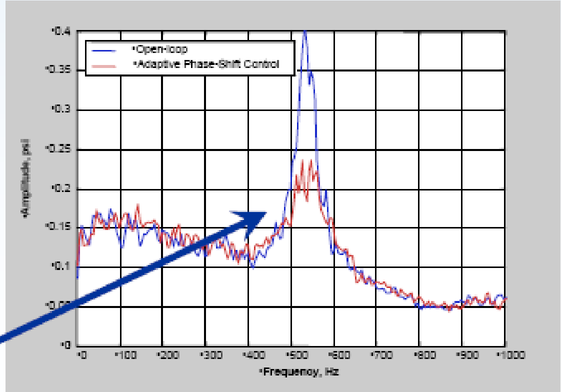
Active Combustion Instability Control Demonstrated Experimentally

Large amplitude, low-frequency instability suppressed by 90%





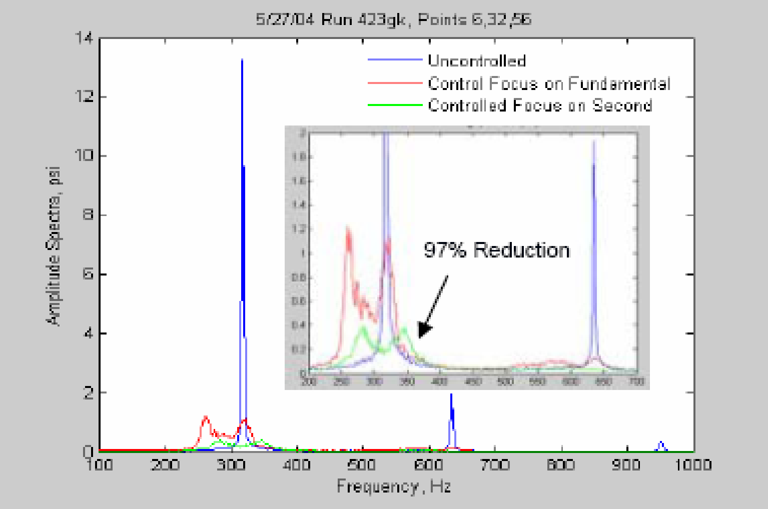
Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows



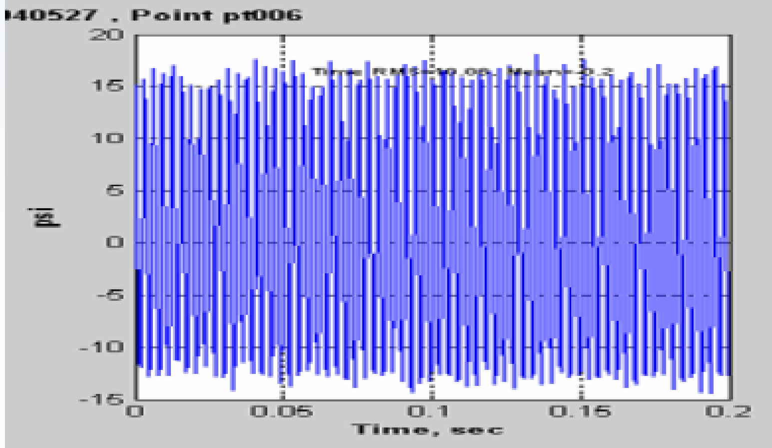
High-frequency, low-amplitude instability is identified, <u>while still small</u>, and suppressed almost to the noise floor.

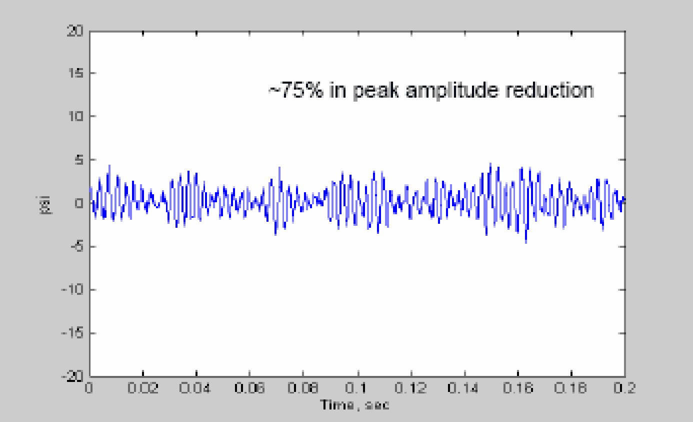
Additional Test Results:

Harmonic-focused control provides over 90% reduction in pressure spectral peak for large, low-frequency instability



Uncontrolled –vs- Controlled Instability Pressure





Why of rough combustion in rockets?

- Combustion instability has specific sources – feed system coupling or acoustics.
- Feed system coupling occurs mostly in liquid rockets with a low frequency fluctuation (< 100 Hz).
- Acoustic coupling occurs in after burners, liquid rockets – UDMH-N_2O_4 (PSLV 2nd Stage), Kerosene-oxygen (Apollo mission, Russian Boosters, GSLV related ISRO development), LOX-Hydrogen (GSLV fourth stage), Tactical solid rockets (LRSAM, MRSAM, ASTRA, PJ10..)
- Acoustic coupled problem (100 to 3000 Hz) is very serious
- $f_{acoustics} = a/md$, a/mL, $m = 1.5$ to 4, d = diameter, L = Length – characteristic size
- $a \sim 1000$ m/s, for $m \sim 1$, $d = 0.5$ m, $f_{acoustics} = 2$ kHz; for $m = 2$, $L = 2$ m, $f_{acoustics} = 250$ Hz
- *Tangential mode in VIKING Liq engine (High freq. instab) and longitudinal in LRSAM (solid)*
- The acoustically coupled problems are specific frequency sensitized and are due to undesirable favorable phase dominated coupling between acoustic energy and heat release due to combustion.

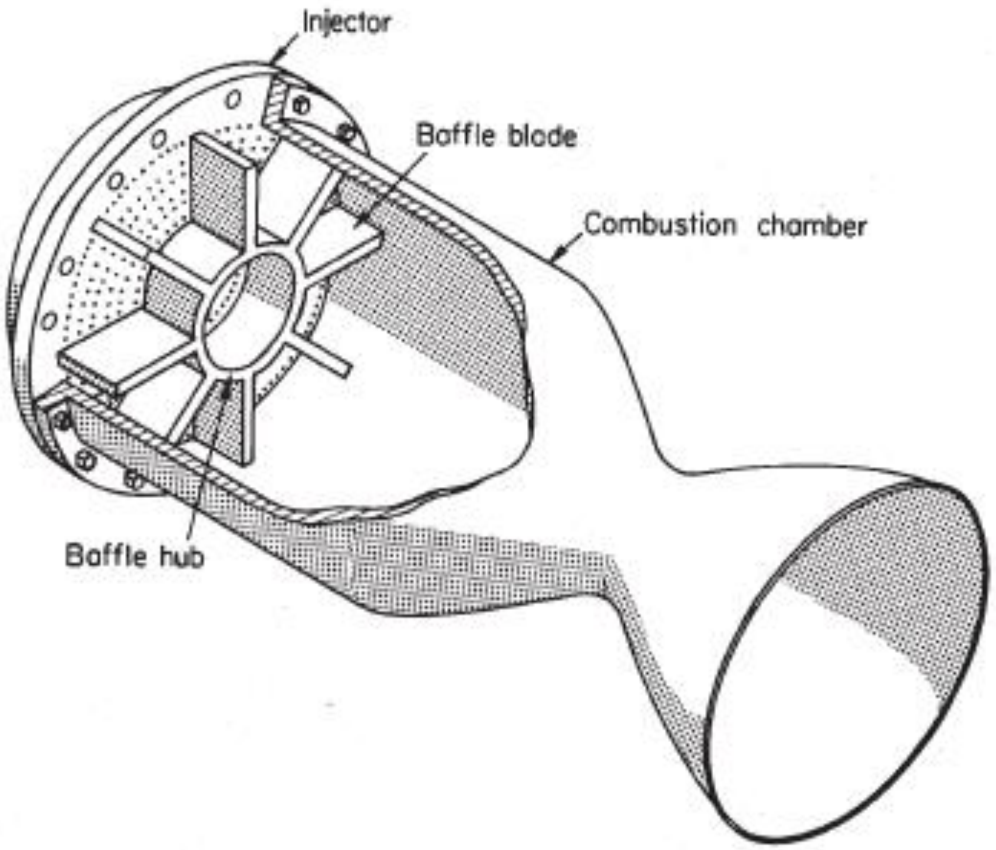


FIGURE 8.7. Perspective view of a rocket combustion chamber with longitudinal baffles installed on the injector face (Harrje and Reardon 1972).

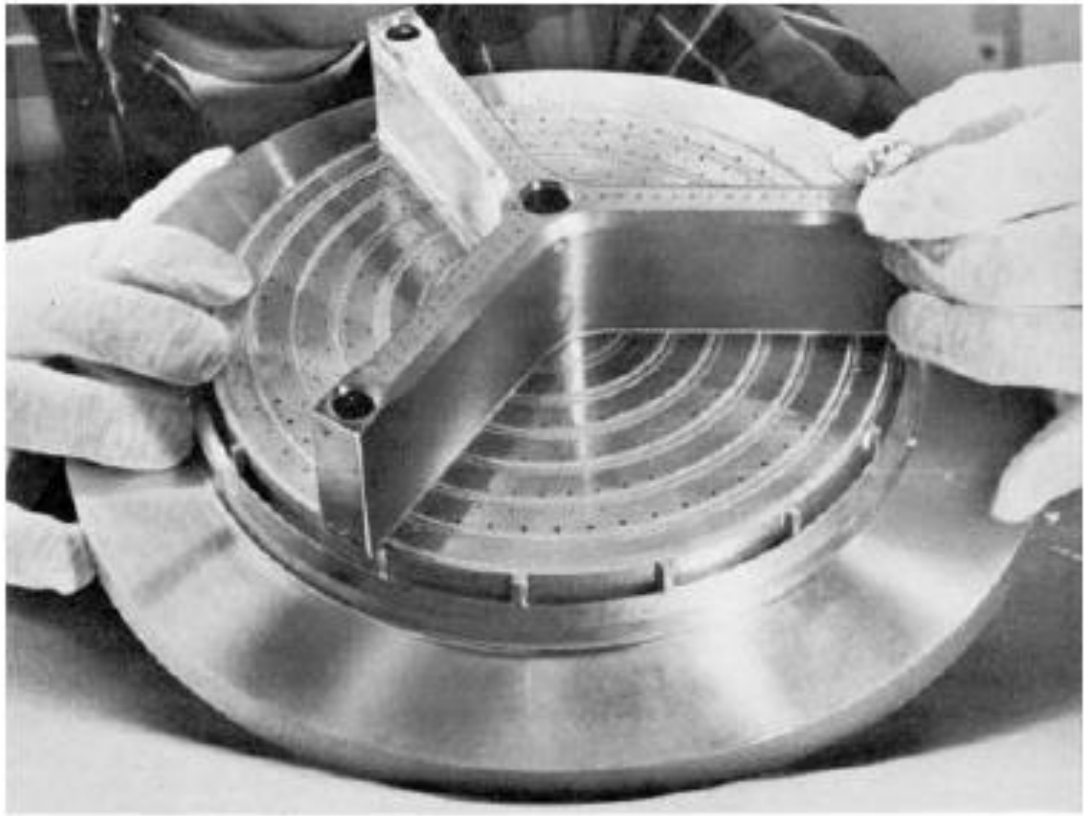


FIGURE 8.8. An injector with baffles and azimuthal slots (Harrje and Reardon 1972).

Liquid rocket engine using baffles whose height is more than the heat release zone and also acoustic dampers. The nozzle also provides damping. The net unsteady energy balance causes damping or enhancement of pressure oscillations.

Broad comparison between different classes of engines

- Afterburners (GT engines) have low p (2 to 5 atms), and Rocket engines have high p ~ 70 to 200 atm.
- Heat release rates ~ p^2 and so the intensity of heat release in rocket engines is much more than in afterburner combustion process.
- Both afterburners and liquid rocket engines have liquid drop vaporization process as the rate determining step in combustion.
- Short combustion chambers experience tangential and radial modes more than longitudinal modes [freq ~ Const x acoustic speed/characteristic size, Const = f(mode)]
- Very long combustion systems as it is with tactical solid rockets and some cases of afterburners experience longitudinal instabilities.
- Screech in afterburners is not disastrous even if it is considered very undesirable.
- HFI in liquids is simply disastrous and is to be eliminated. Longitudinal instabilities (~HFI class) in solid rockets are mostly unacceptable.
- In each of these cases, it is programmatically *demanded that the systems be proved stable*.

Viking
N_2O_4 / UH25
786 kN
295 s

Storable Liquid engine instabilities

The technology of Viking engine of France was acquired for PSLV II stage. The engine is called VIKAS.

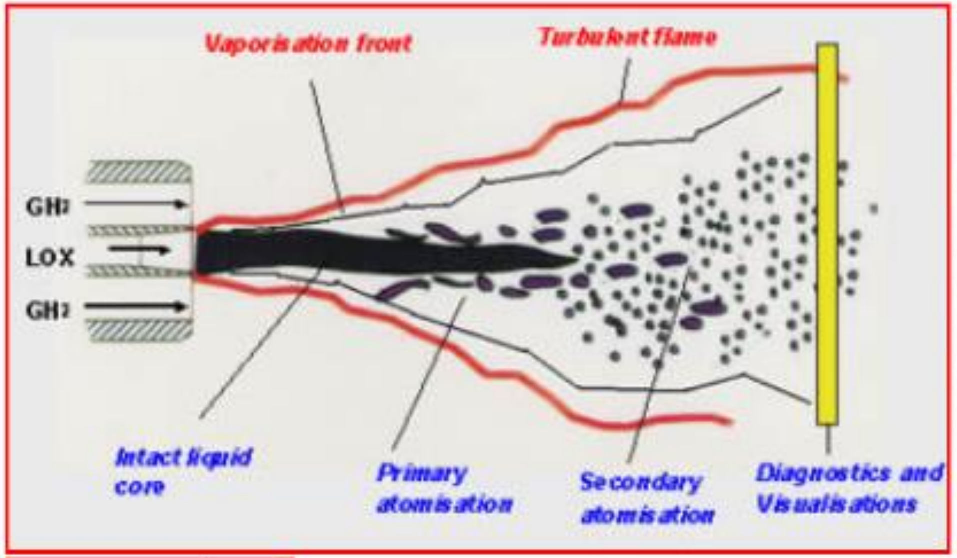
The Viking engine went through severe combustion instability problem – **high frequency 1st and 2nd tangential mode** – about 140 sets of hardware were tested over a six month period in France

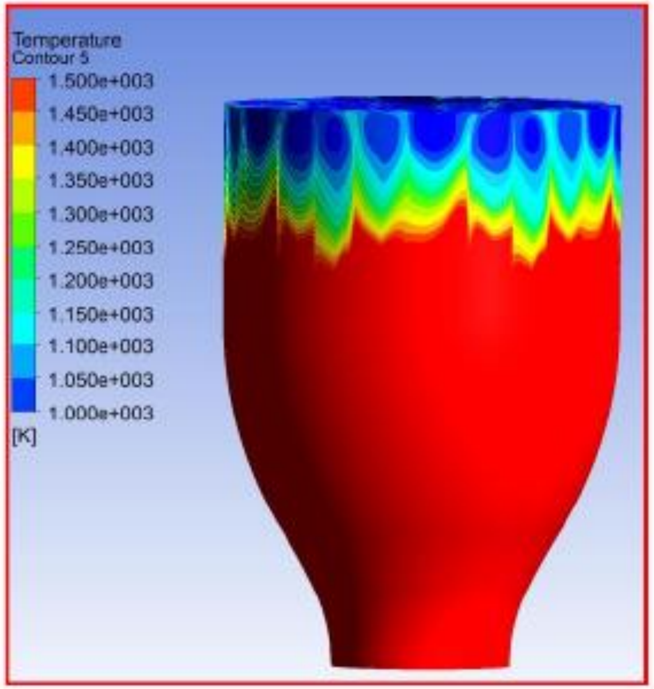
In terms of combustion intensity, storable hypergolic propellants (UDMH-N_2O_4) are more intense than Kerosene-LOX system which is more intense than LOX-Liq H_2 system

How is instability overcome in LPR

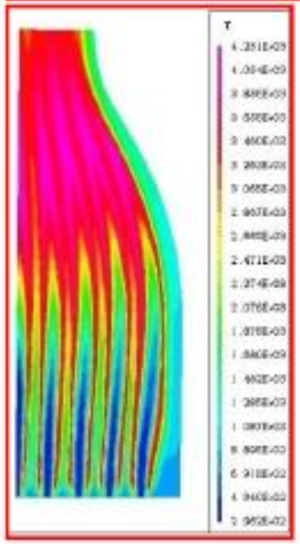
- In the case of LPR, acoustic damping, avoidance of standing modes and coarsening of combustion to make it more distributed are done appropriately.
- The most widely used technique in LPR is the use of baffles to cover the peak heat release zone to break the possible standing waves – most used in American engines.
- In Viking engine, there is a radial injector.
- The oxidizer and fuel jet diameters were increased to make the drop sizes more and henceTmake combustion zone less intense.
- For LOX-LH_2 engines, the use of reactive flow CFD and approach to understand instability was made by Biju kumar (LPPSC) as a part of his Ph. D thesis.

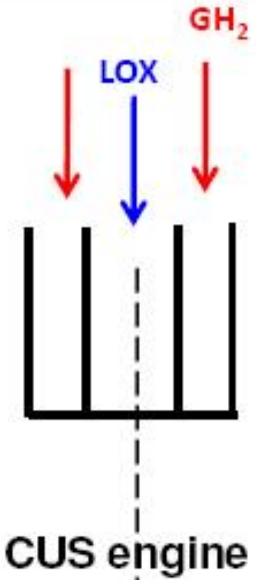
From Bijukumar's presentation at 2nd P J Paul memorial workshop held at JU in 2014





Saw tooth pattern observed in the wall after hot test



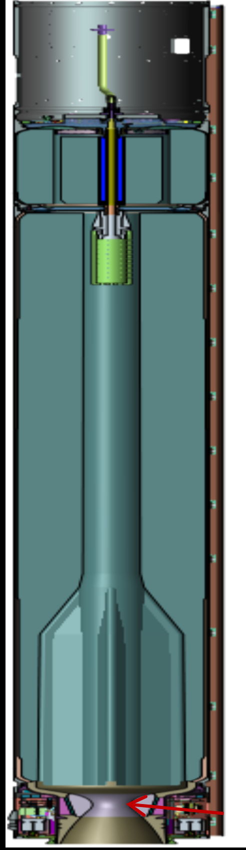


Temp. distribution in CUS engine

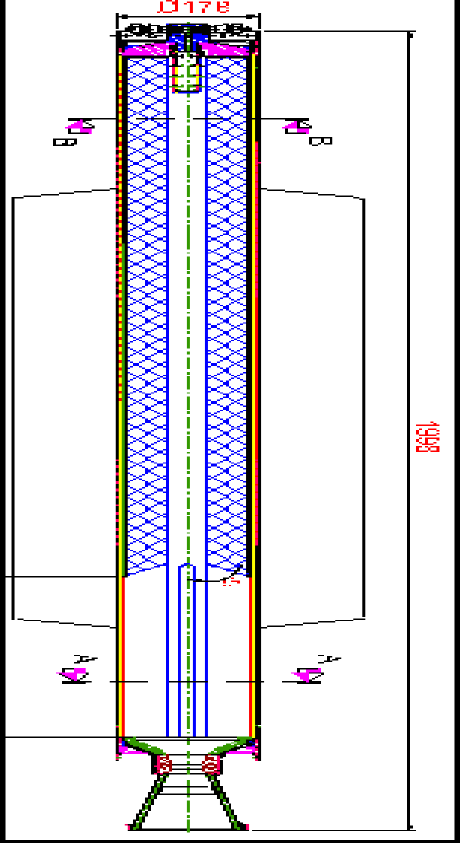
More studies are required for understanding the saw tooth pattern in the combustion chamber.

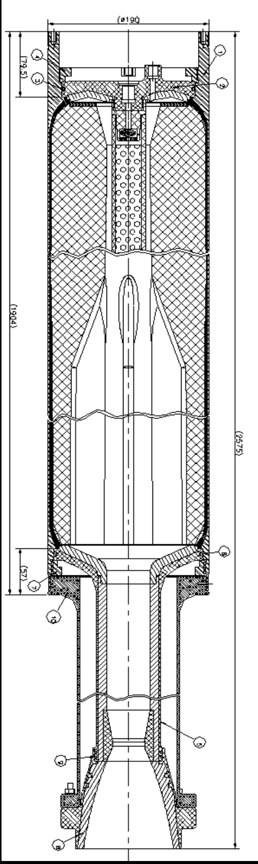
Solid rockets experiencing longitudinal instability

LRSAM uses a non-Al based solid propellant (smoke-less)
It has a 0.06 m ID, 0.2 m OD, 2 m long grain
It experienced instability is about 50 % of development trials that used several propellants chosen to eliminate the instability



Features of Tactical solid rockets



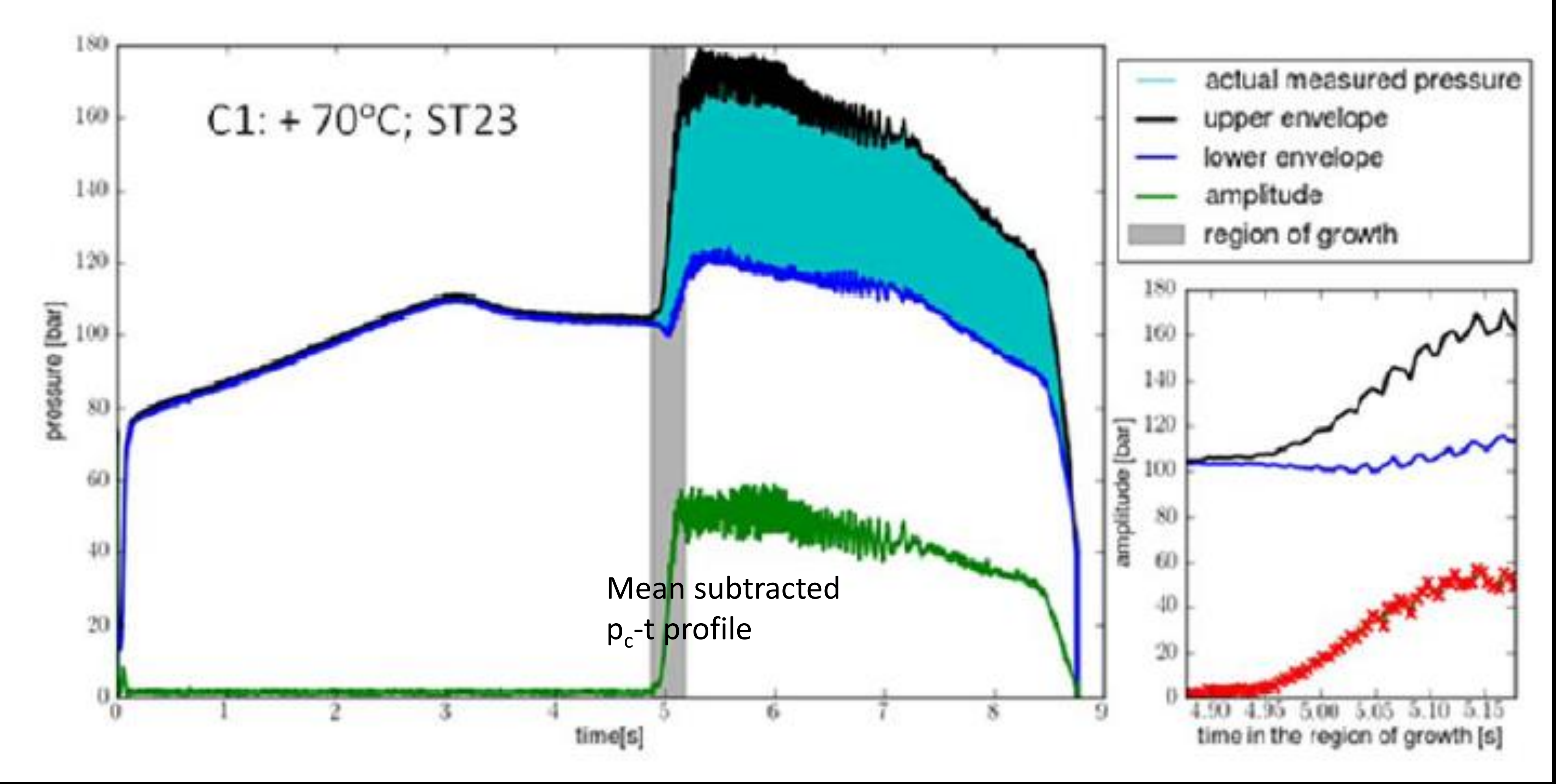


Radial buring grains have Unsteady propellant combustion amplification, damping due to flow turning, and nozzle.

The net change, if negative leads to stability and if positive leads to growth of the oscillations

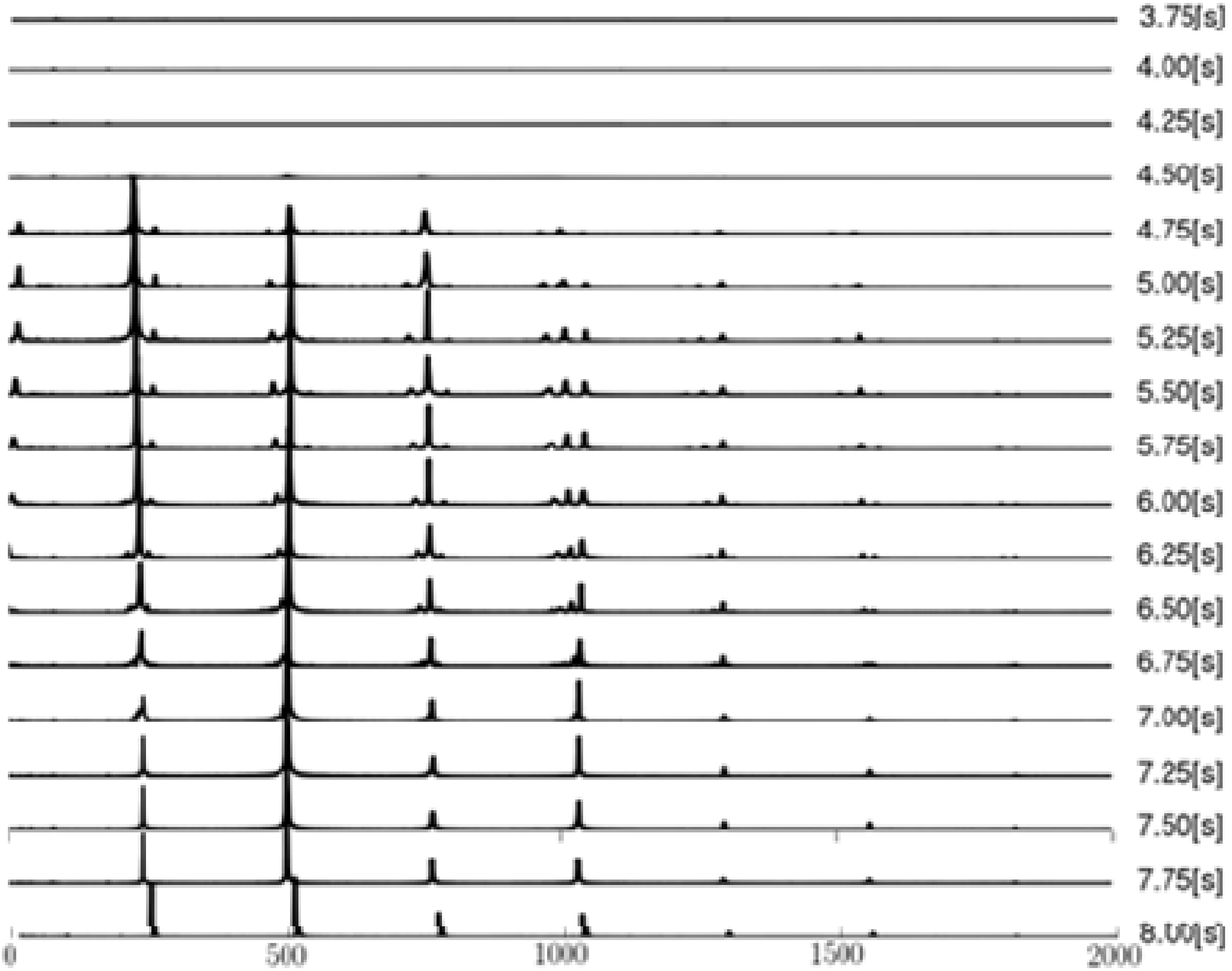
Motor	L, m	Op. Pr. atm	$\dot{r}_{70}$, mm/s	n	Motor ID, mm	Motor OD, mm	f_{acou}, Hz	f_{abs}, Hz	Comments
LRSAM	2.1	90 - 120	7.5	0.3	63	225	250	250	25 +compositions
ASTRA	1.8	80 - 90	8.0	0.3	60	180	300	600	5 + compositions
SRSAM	1.8+	80 - 100	6.2	0.25	50, 100	190	300	300	1 + composition

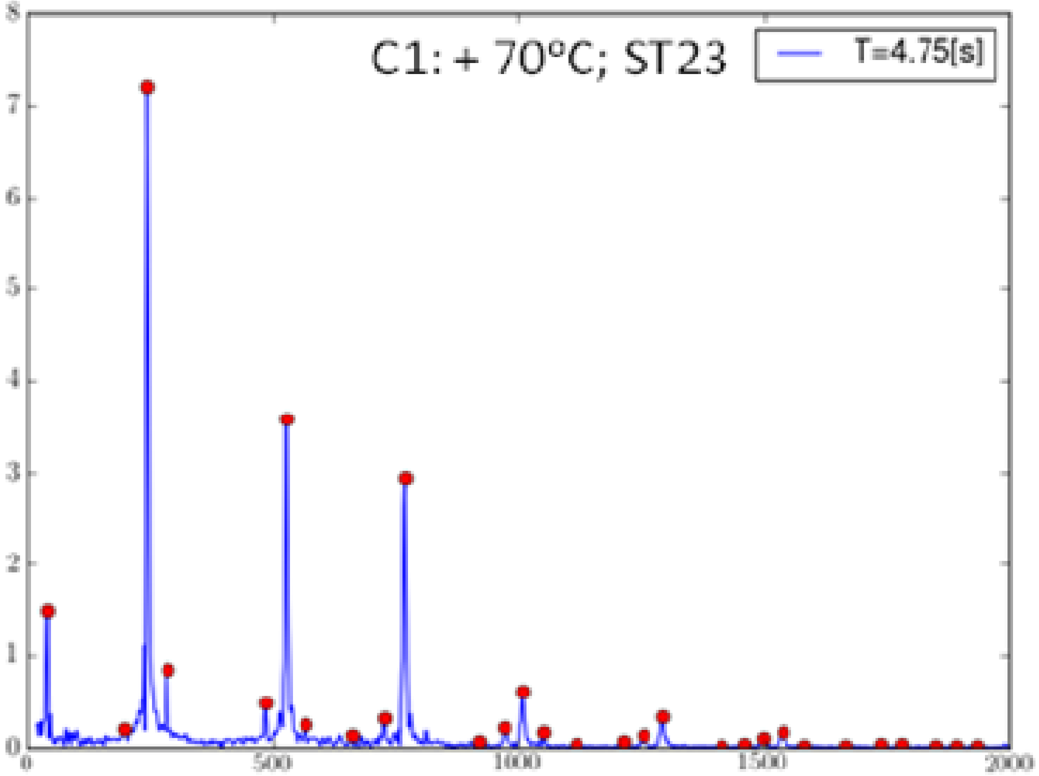
LRSAM: AP 80 % (2.4:1 of 300 µm: 26 µm); RDX up to 9 %; Al 4 %; HTPB 12 %; DOA 3.8 % Sr_2CO_3 2.5 %; $ZrSiO_4$ 0.5 %
ASTRA: AP 82 % (2:1 of 300 µm: 26 µm); HTPB 11.6 %, DOA, 3 %, Sr_2CO_3, 2 %, ACR
SRSAM: AP 79.6 % (Coarse + fine); RDX 2.5 %, HTPB 15.9 %, DOA, 3 %, Al, 1 %, Sb_2O_3, 0.6%, $ZrSiO_4$ 0.5 %



Chamber pressure-time curve of a tactical rocket. Till 4.85 s, the combustion process is smooth. At this time, there are fluctuations that build up in 200 ms with visible oscillation amplitude of 15 bar (atm) and a shift of mean pressure (called DC shift) itself by 50 atm with an expected mean pressure of 120 atm.

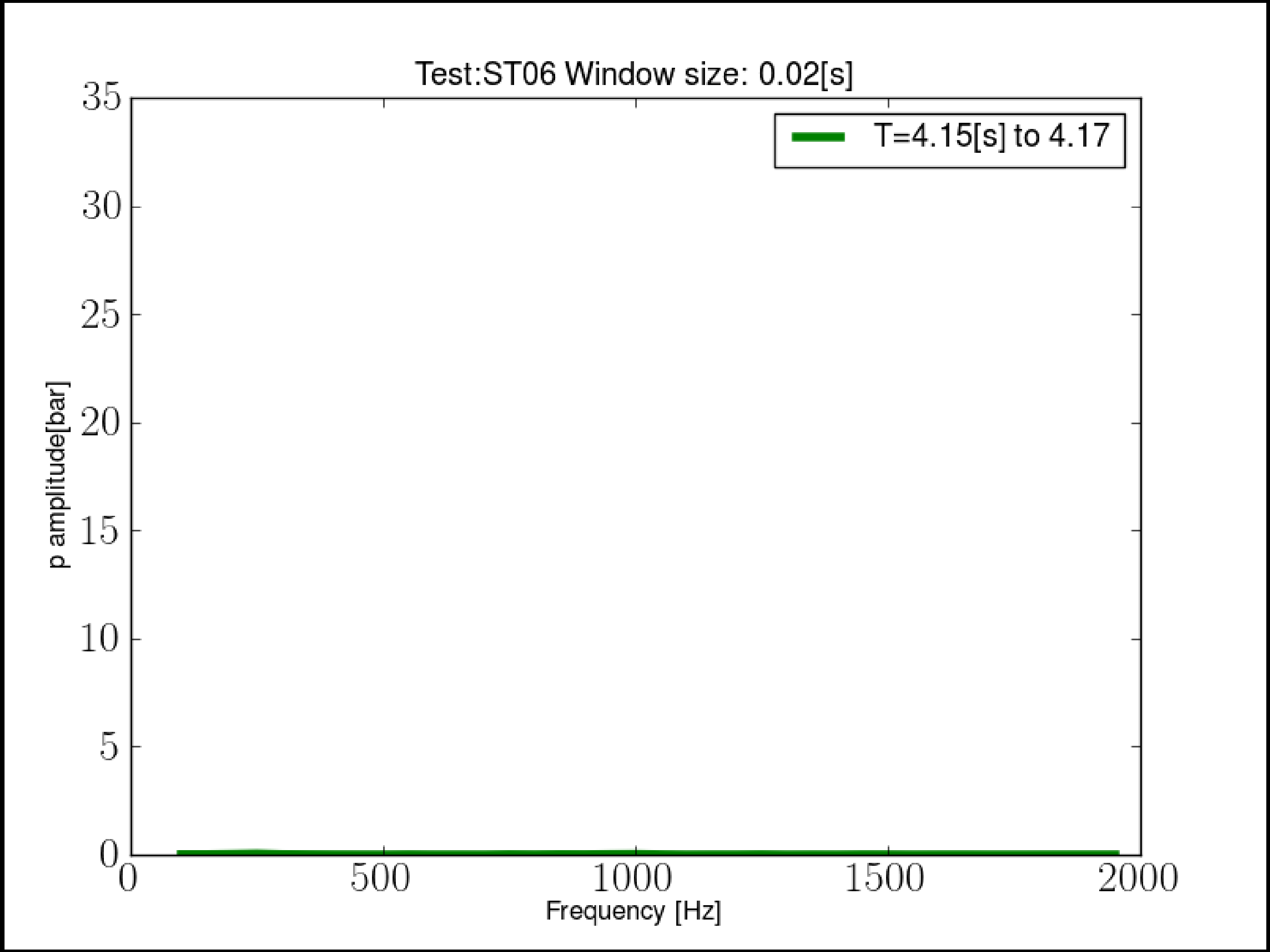
C1: + 70°C; ST23 Water –fall plot

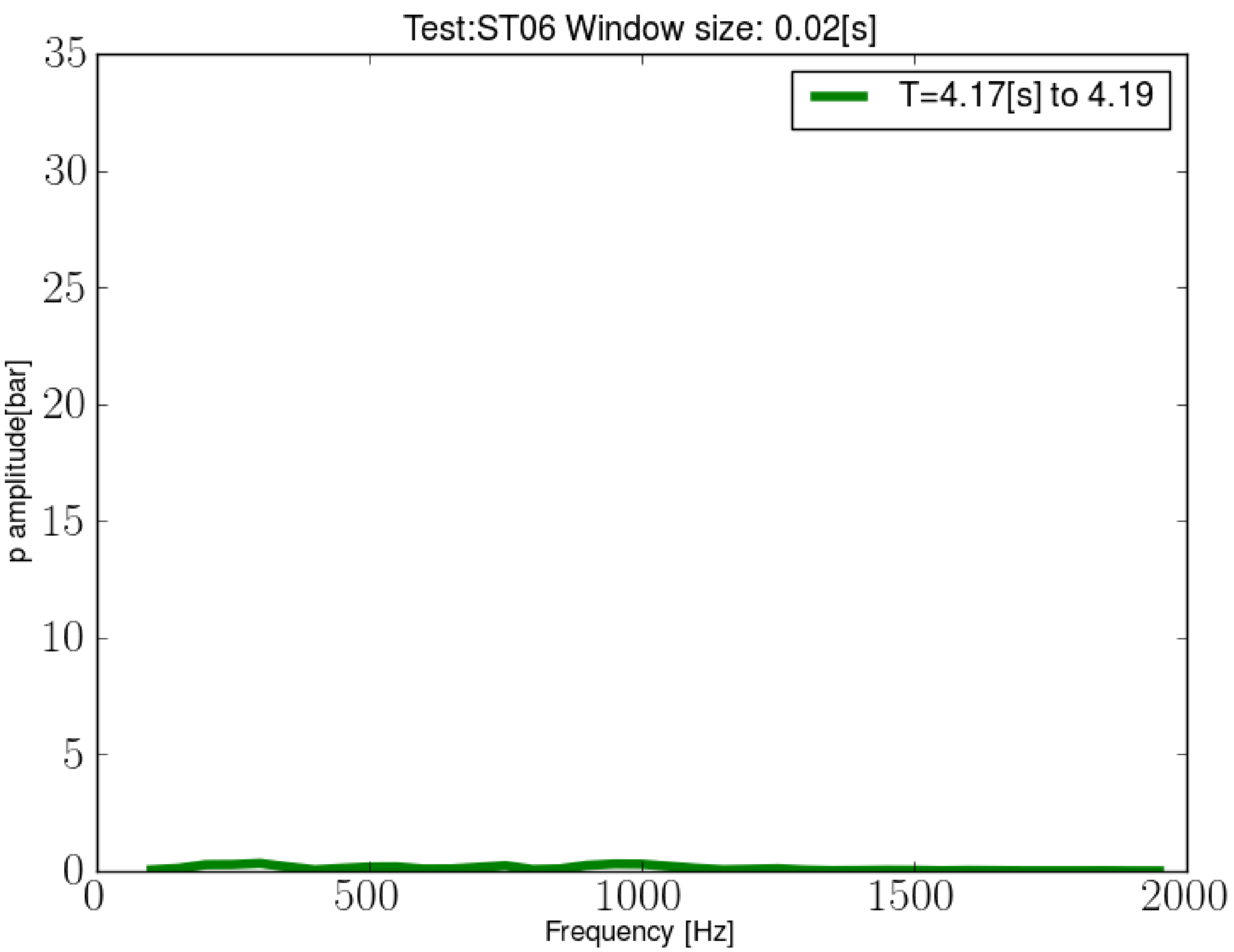


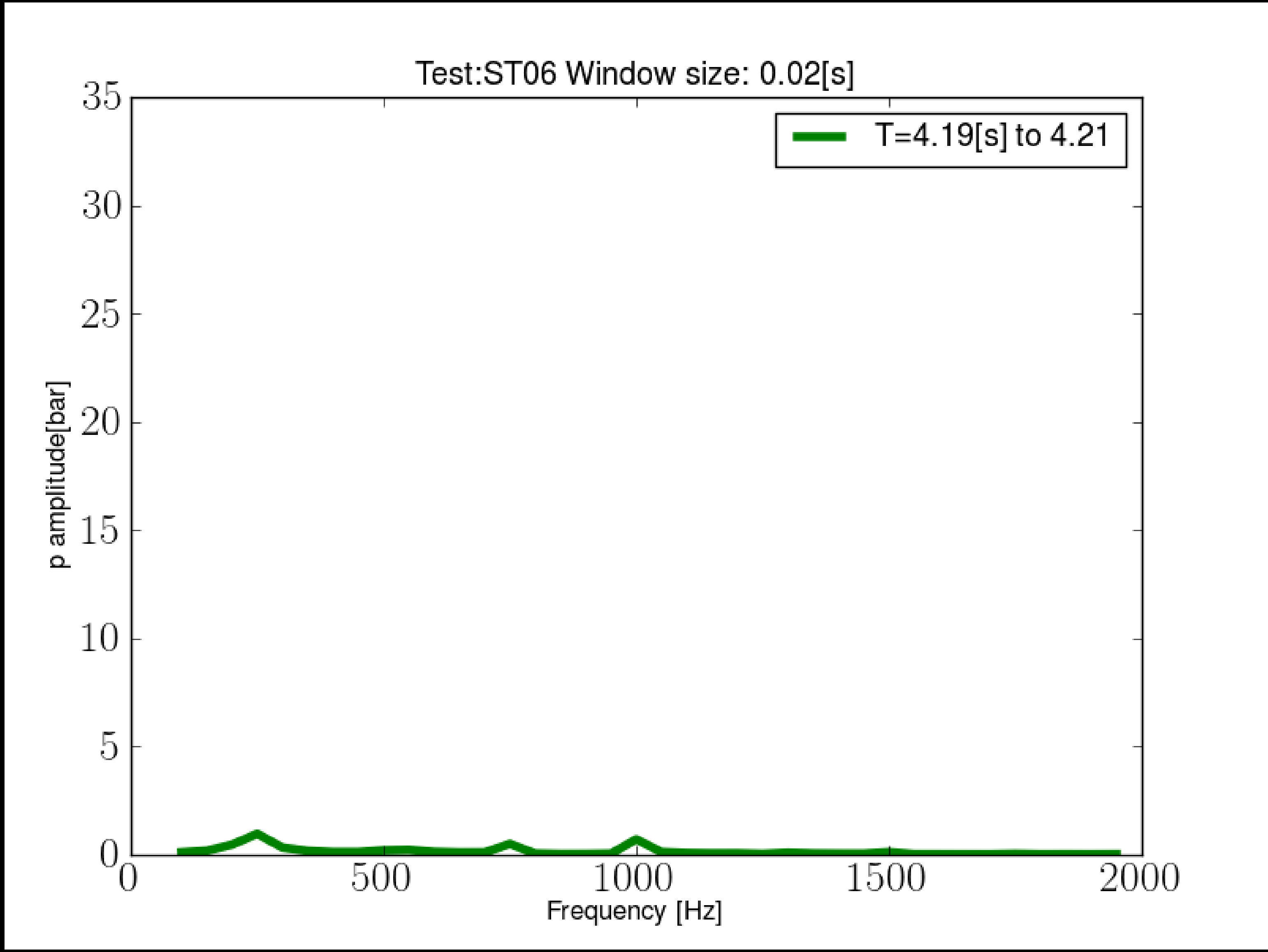


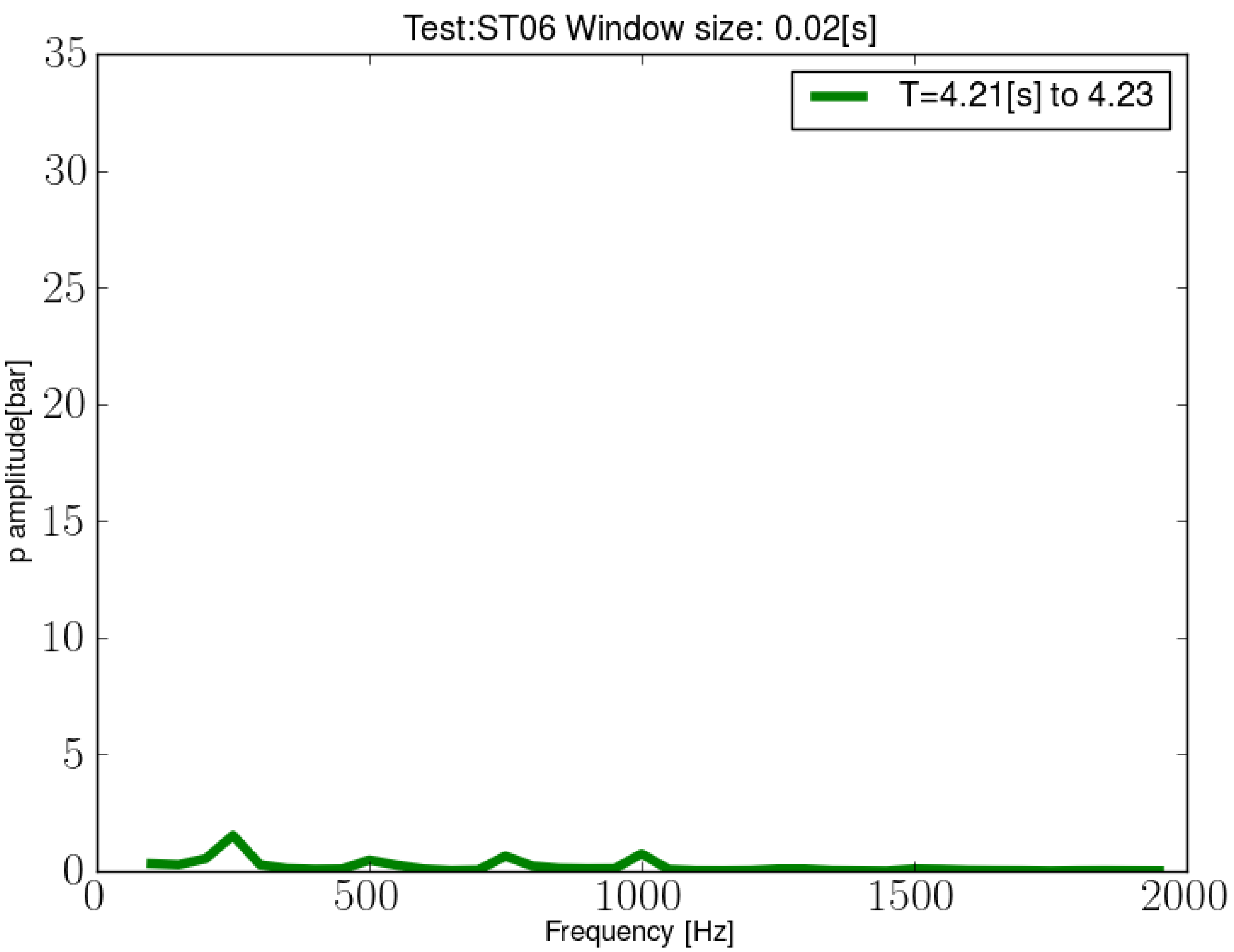
We can do a spectral analysis of the time-sliced pressure time curve and see how the instability is developing. This is set out In the water-fall plot. The specific frequencies – about 250, 500, 750 and 1000 Hz are the ones excited here.

How does the pressure pulse develop at various frequencies

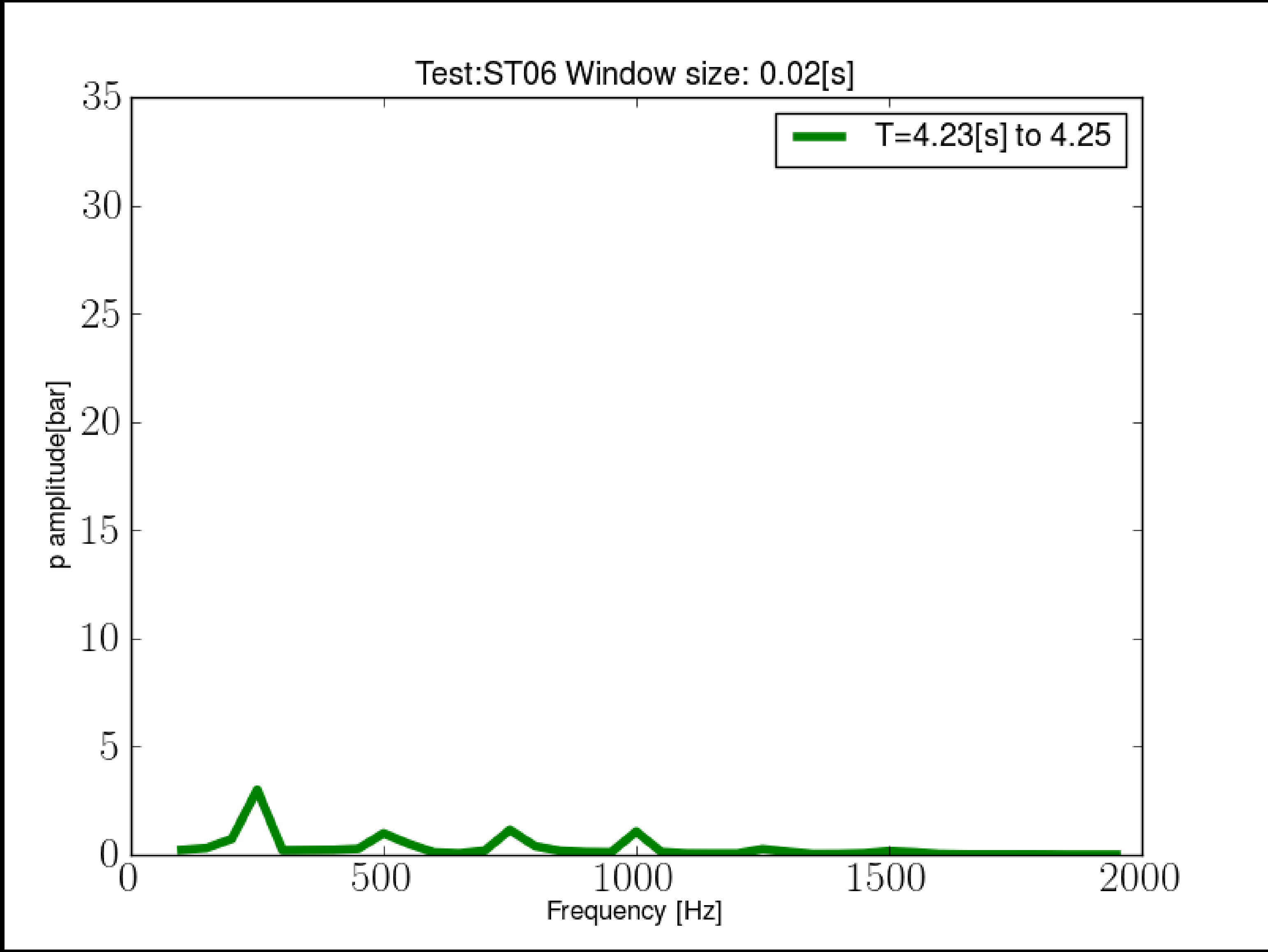


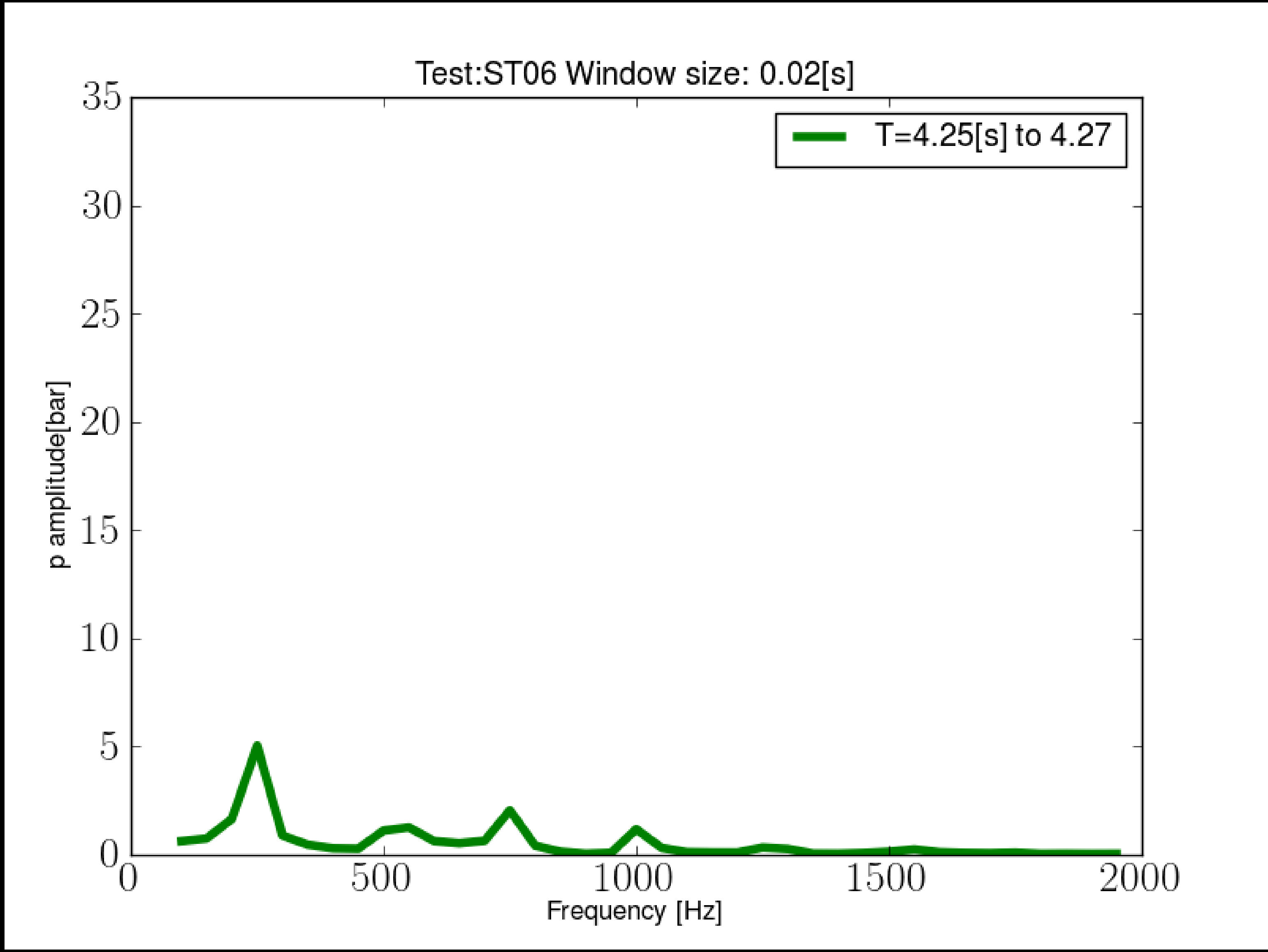

Test:ST06 Window size: 0.02[s]
T=4.17[s] to 4.19
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000


Test:ST06 Window size: 0.02[s]
T=4.19[s] to 4.21
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

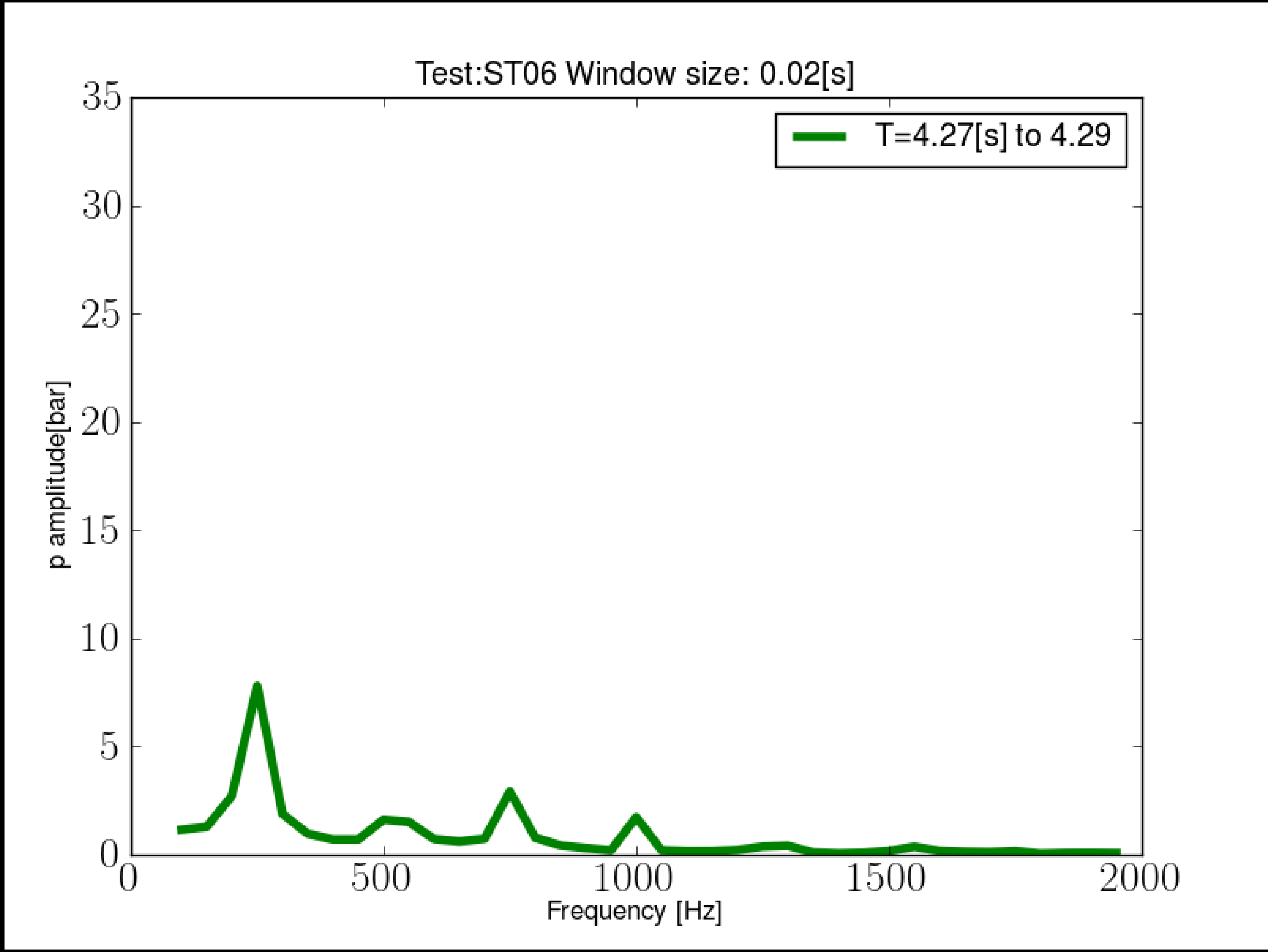


Test:ST06 Window size: 0.02[s]
T=4.21[s] to 4.23
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

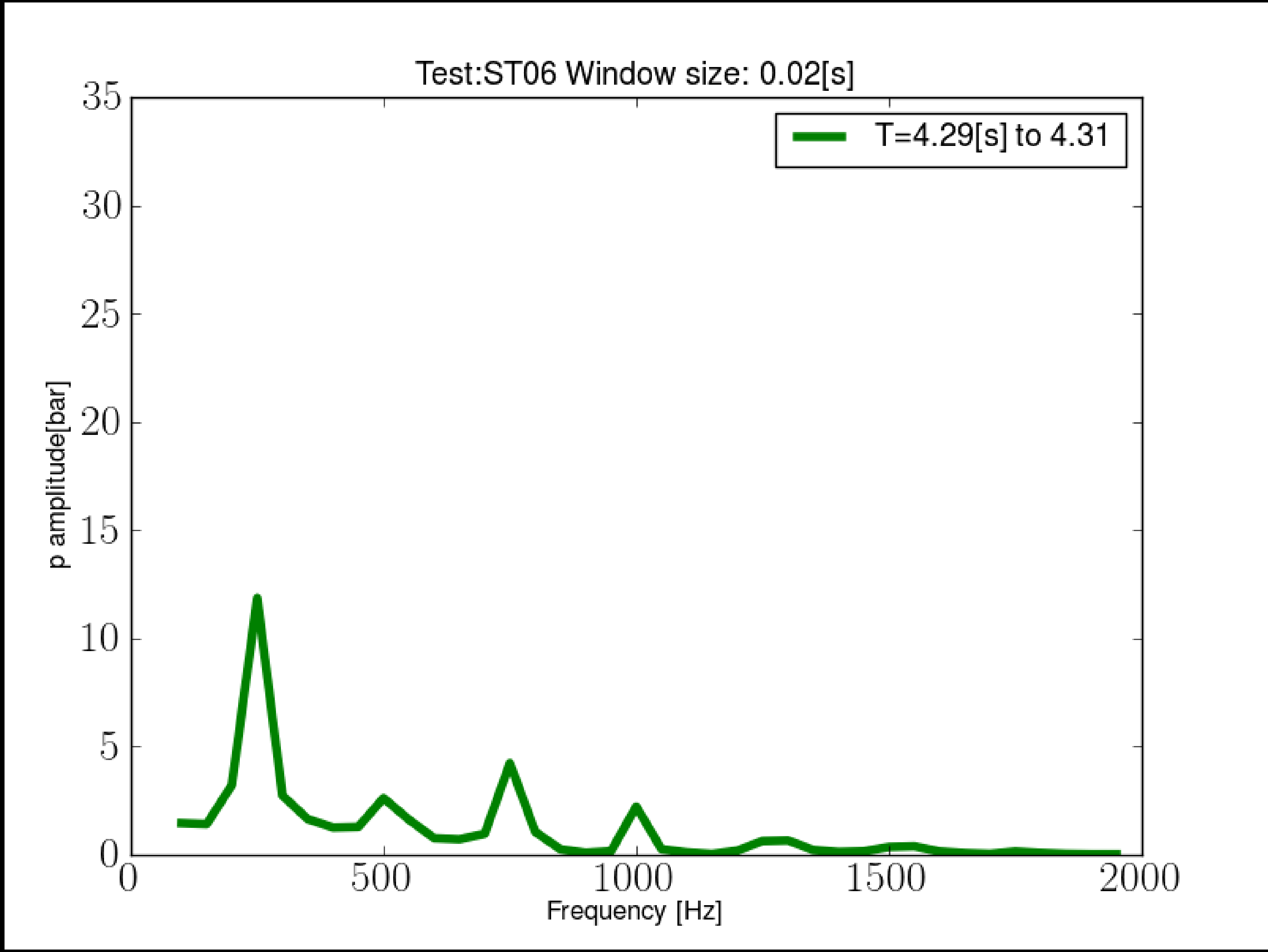

Test:ST06 Window size: 0.02[s]
T=4.23[s] to 4.25
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

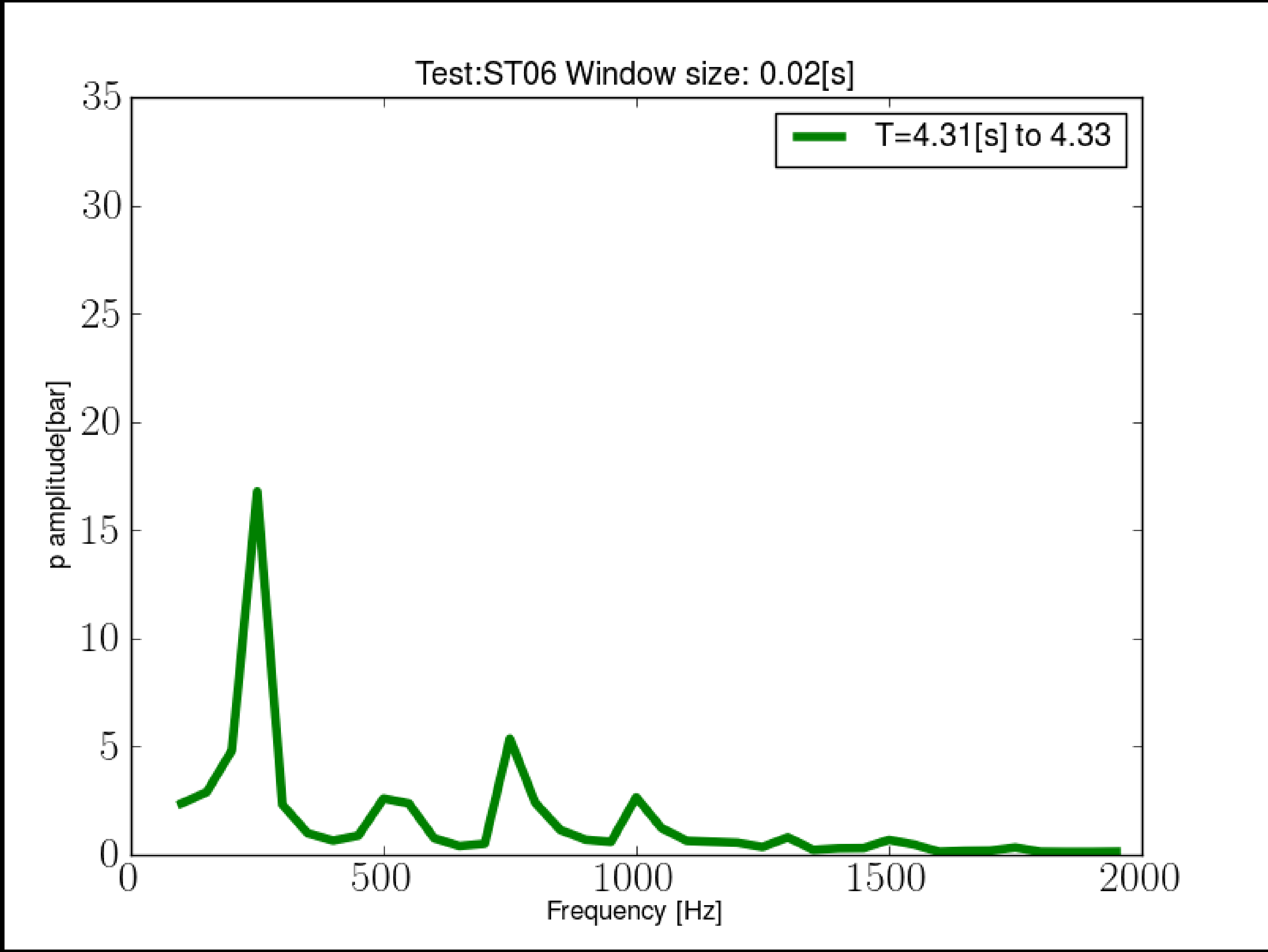


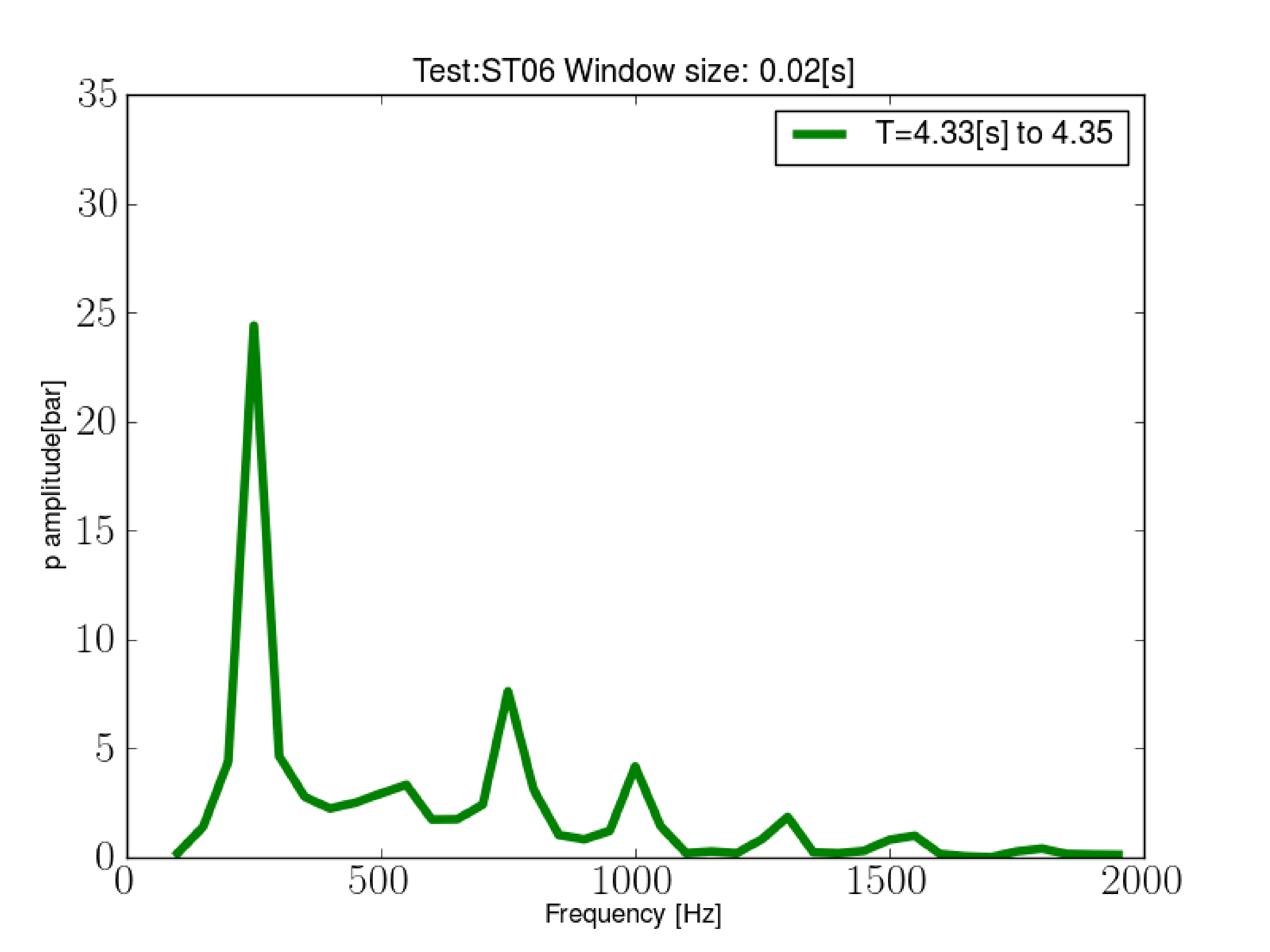
Test:ST06 Window size: 0.02[s]
T=4.25[s] to 4.27
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

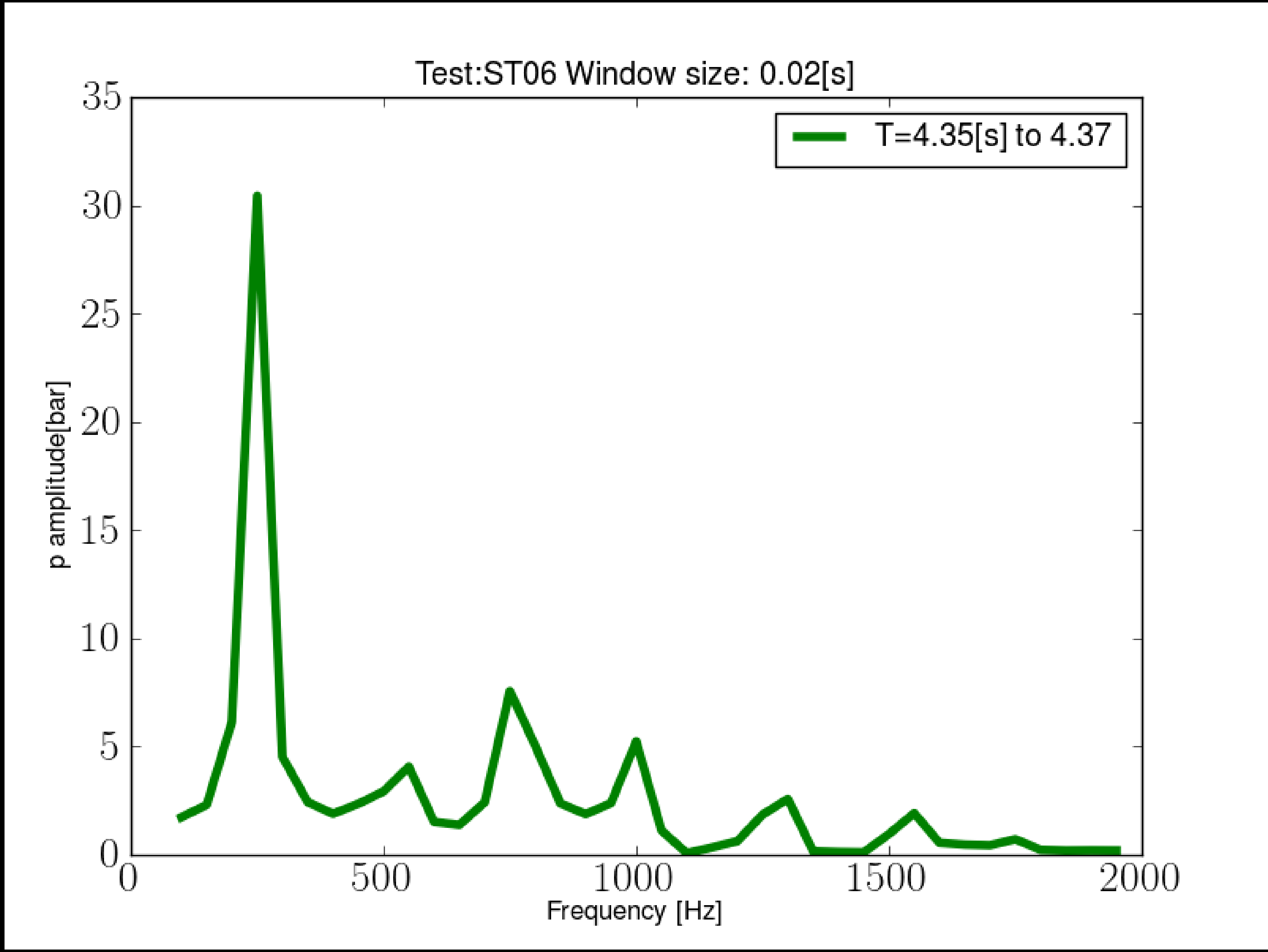


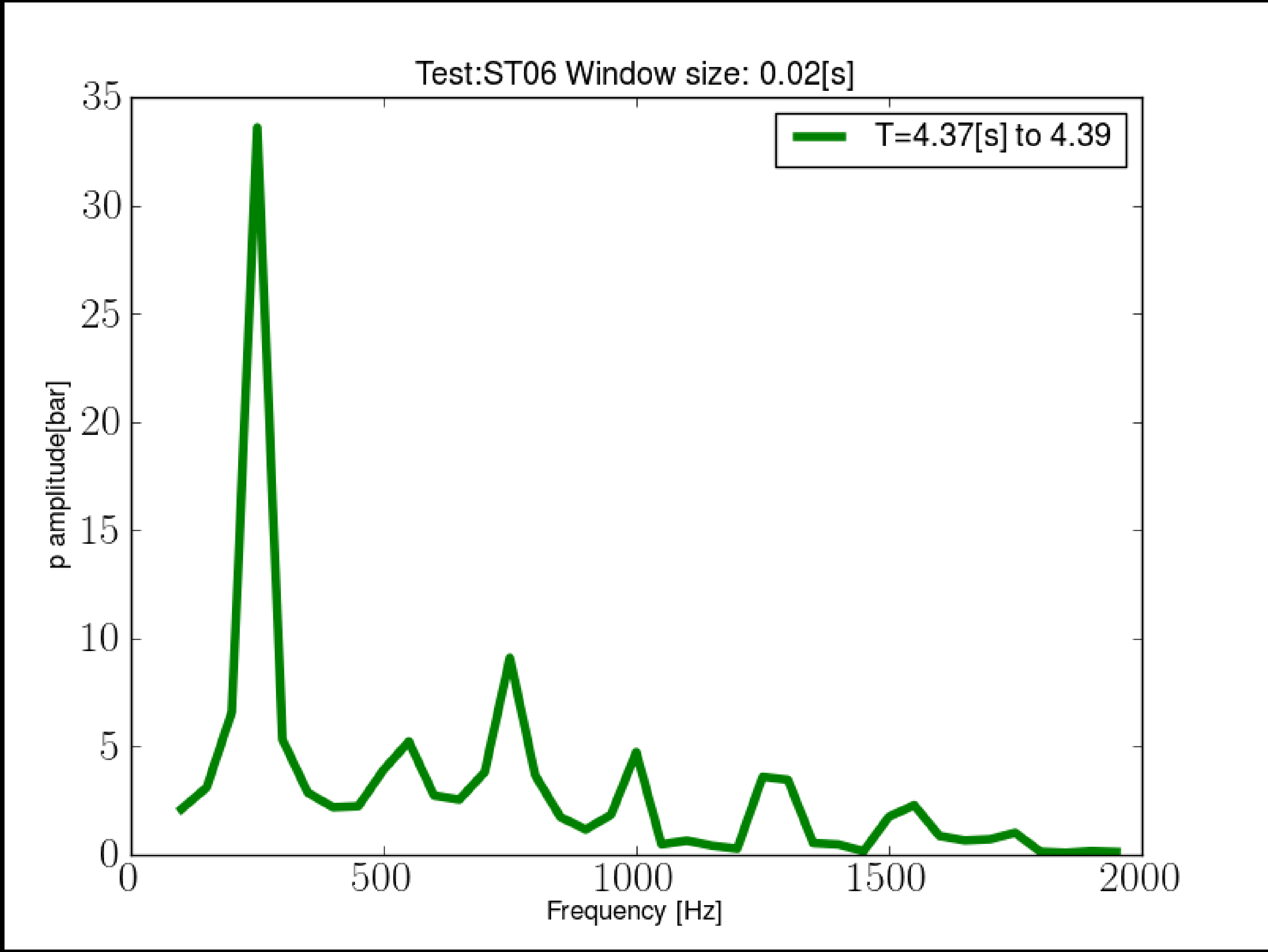
Test:ST06 Window size: 0.02[s]
T=4.27[s] to 4.29
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000


Test:ST06 Window size: 0.02[s]
T=4.29[s] to 4.31
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000


Test:ST06 Window size: 0.02[s]
T=4.31[s] to 4.33
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

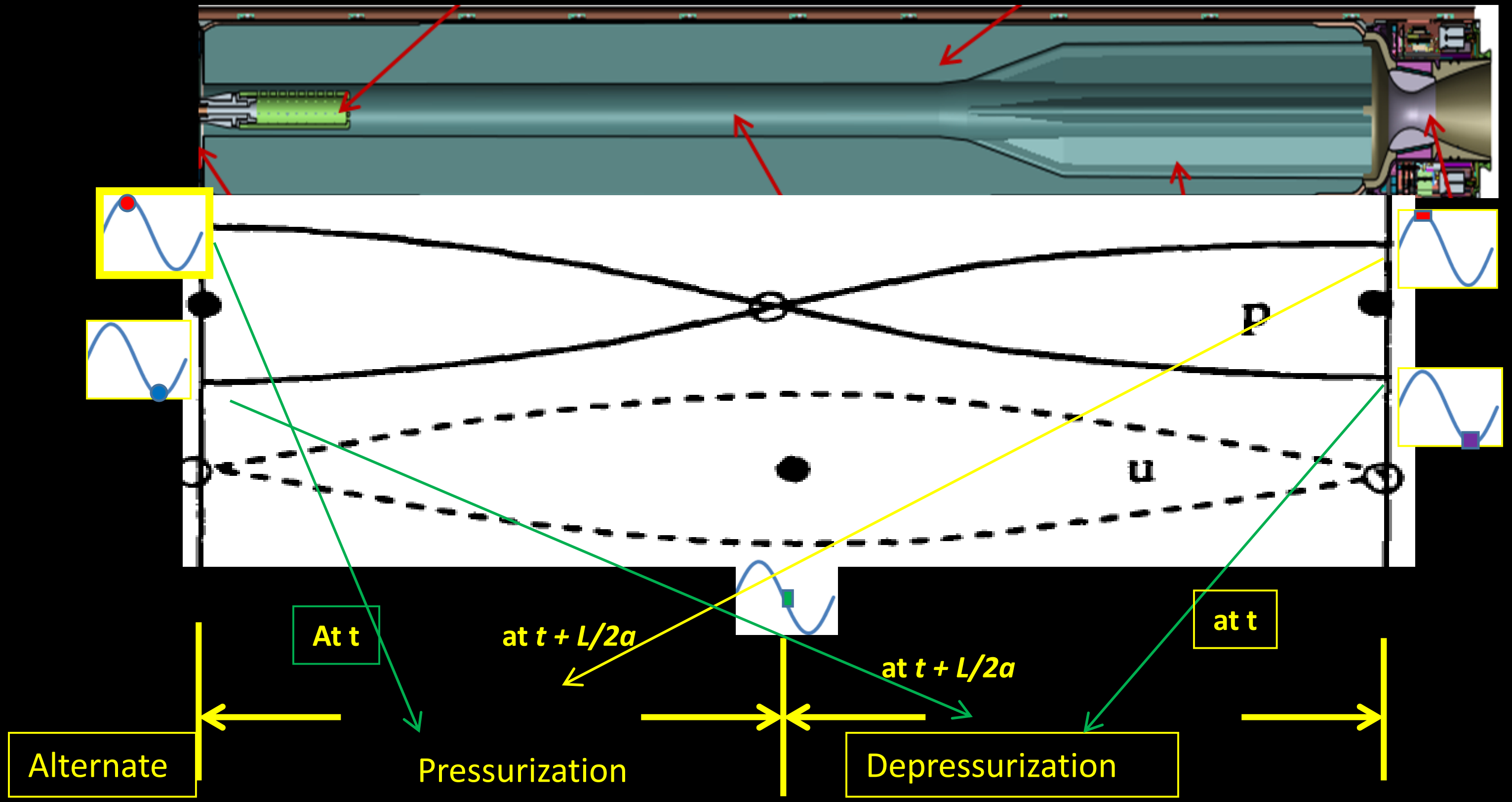

Test:ST06 Window size: 0.02[s]
T=4.33[s] to 4.35
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000


Test:ST06 Window size: 0.02[s]
T=4.35[s] to 4.37
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000



Test:ST06 Window size: 0.02[s]
T=4.37[s] to 4.39
p amplitude[bar]
Frequency [Hz]
0
5
10
15
20
25
30
35
0
500
1000
1500
2000

How does combustion process occur in a radial burning grain during instability?



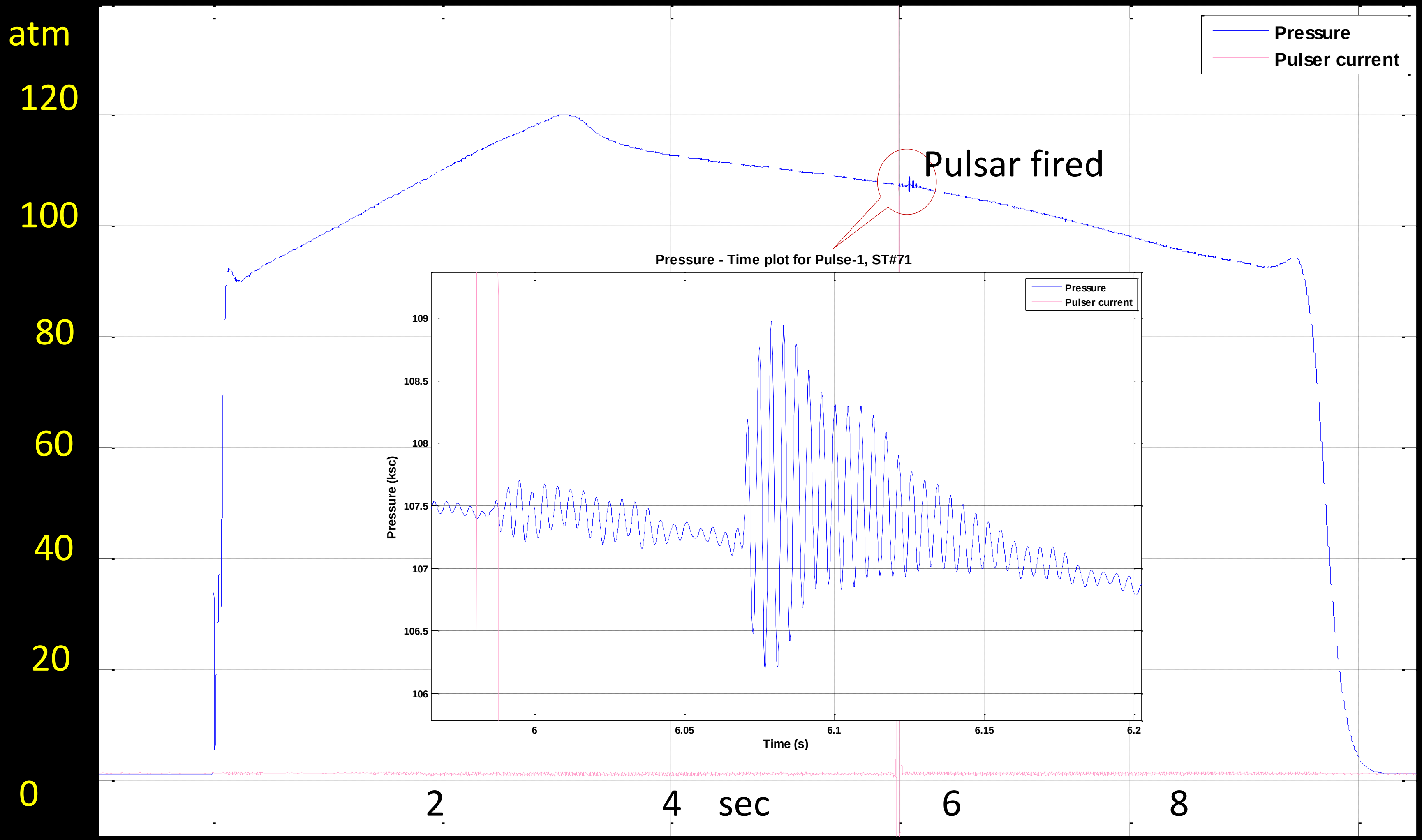
The role of acoustics is essentially limited to set the pressurization and depressurization cycles. The pressure variations affect the gas phase flux and control the burn behavior of the propellant. The sharp pressurization and depressurization aspects cause the high burn rates much beyond steady burn rates.

THIS INSTABILITY IS ONE_DIMENSIONAL

How was the problem solved?

- Based on the data of pc-t and other propellant details provided by DRDL, analysis was performed to determine which one of them were more unstable and which were not.
- Broad inference was obtained on the cause the problem was: the use of exotic compounds with melt temperatures close to the burning surface temperature – some energy absorbing and some energy releasing kind *should be avoided*.
- Meetings were held at DRDL to understand/communicate the analysis on the test results.
- Based on these and energy needs, a propellant composition to meet the project requirements was chosen.
- This propellant was made and tested and found satisfactory under conditions that included the project objectives. *The propulsion system was pulser tested satisfactorily* .
- Even though the understanding was incomplete, the choice was made to accept it.
- Work on creating the right foundations is going on with less interest from DRDL.

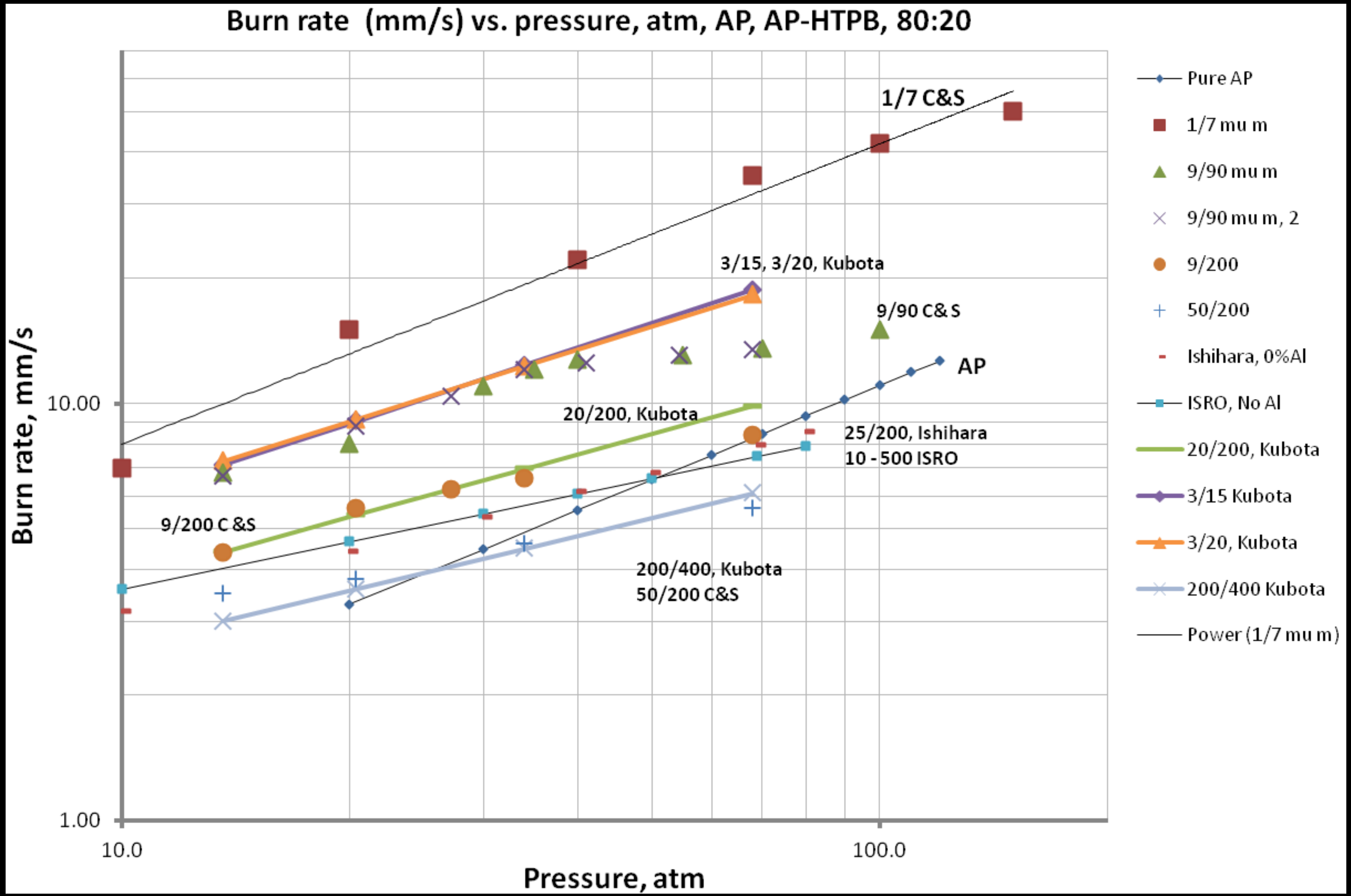
ST #71 **Composition: C9P6,** **d_t=44.5 mm,** **Tested at: -25^{0}C.** **α= -25**



How to resolve this problem more completely?

Identification of the source of the problem – after much study and analysis (Dr. Varun and myself) it was inferred that

- Steady and unstable combustion behavior are deeply interlinked. Unless we this is unraveled at needed detail, it will not be possible to resolve the problem by “cut and try” procedures adopted for over 2 years unsuccessfully.
- The propellant composition must have less complex ingredients and must be characterized for its burn behavior in a mathematical model with minimum “free constants” that must be chosen after due calibration with specifically tailored propellant burn data and then ideas tested for eliminating instabilities.
- Liquid layer over the propellant surface may be the principal cause of the problems. If this is reactive, it is more serious (this is a new surmise not explicit in the literature).
- It is preferable to have as low a melt layer as possible. Burn rate changes to be accomplished by particle size distribution changes.

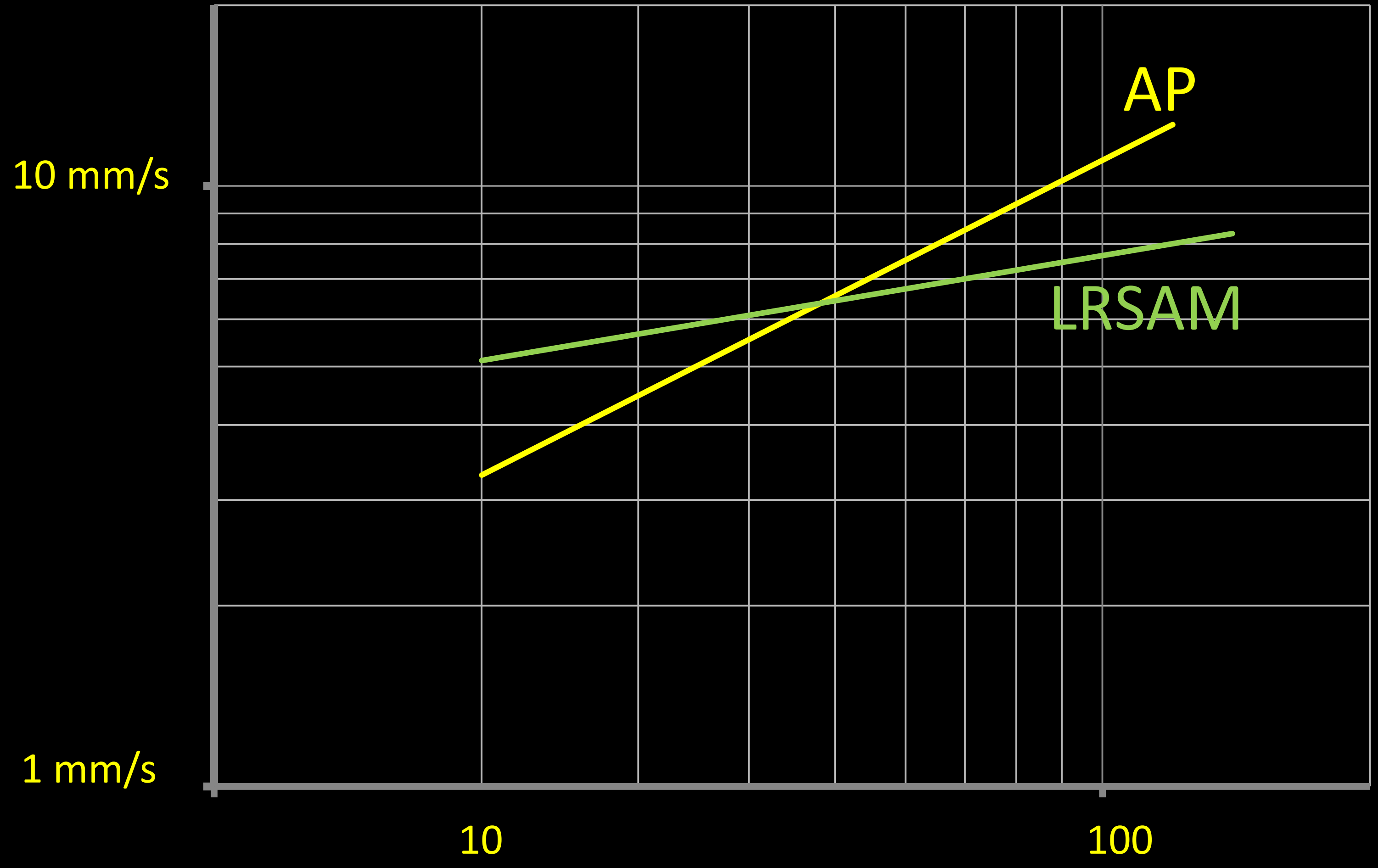


AP burn behavior – premixed flame structure with burn rate r (mm/s) = 8.4 $(p_c/68)^{0.77}$ (for AP, all $p_c > 20$ atm) ; 1 µm/7µm propellant r (mm/s) = 32 $(p_c/68)^{0.75}$

These have similar slopes and can be expected to have premixed flame behavior. Hence small particle size imply about 1 to 7 microns At lower *p*, the energy from the diffusion flame enhances the burn rate significantly. The burn behavior at higher *p* is controlled more by AP and hence, the burn rate approaches the burn rate of AP. In this process, the value of pressure index comes down.

Notice that some burn rate curves intersect that AP curve and the burn rate is below that of AP. This means that energy from the gas flame is being shielded by surface phenomena, presumably melt layers of fuel?

Burn rate behavior with LRSAM vs. AP



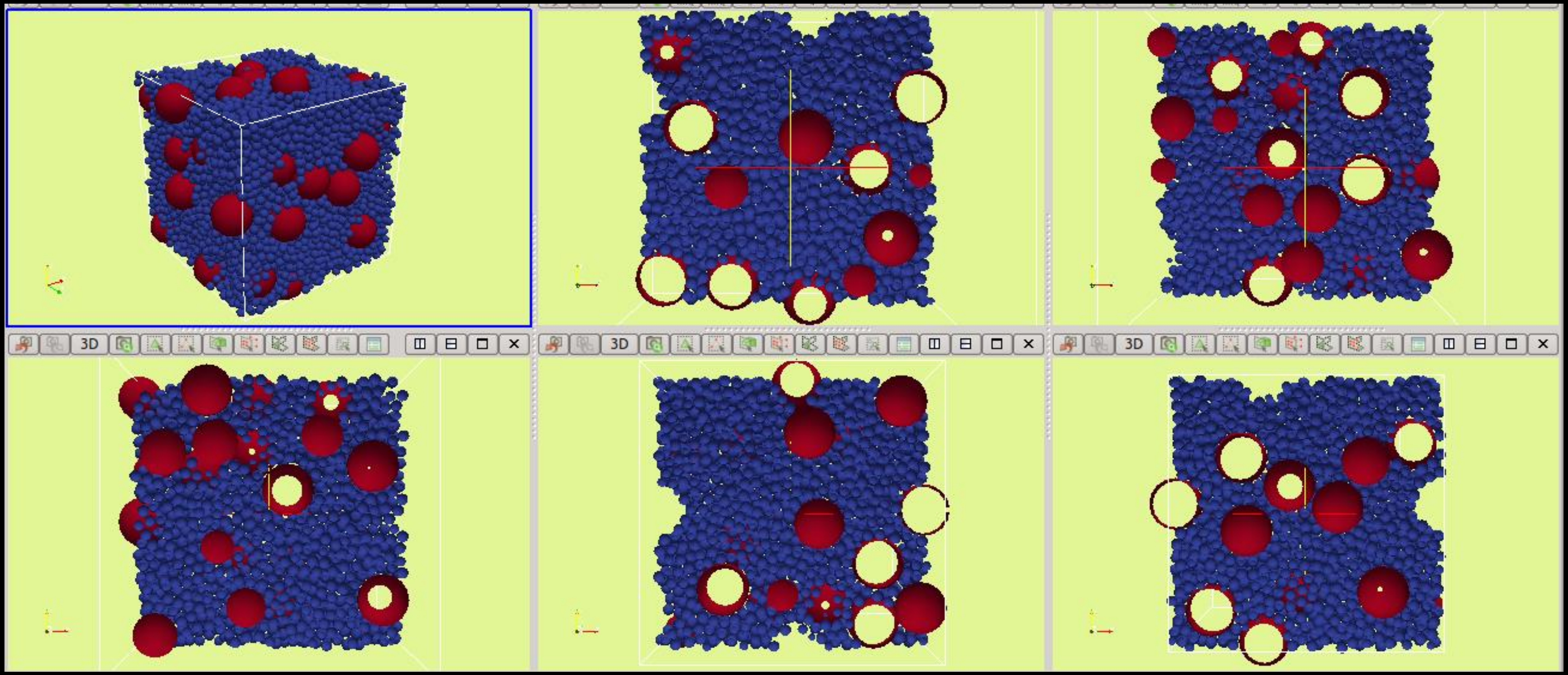
Comment. There is a large region in which the burn rate is below that of AP

Features of Quasi-1D propellant model

- The particle size distribution has a significant effect on the burn rate. Any sacrifice in the quality of input data has deleterious effect on the burn rate vs. p and $T_{initial}$.
- Regressing surface is planar and condensed phase is homogeneous and 1-D as far as conduction in solid is concerned.
- 2-D gas phase heat transfer from the interface diffusion flame to the AP surface is accounted for in a 1-D treatment.
- Pyrolysis kinetic parameters and surface decomposition enthalpy changes are calculated as mass weighted average of that of AP coated with binder and other additives, obtained from geometric packing calculations.

Propellant packing and burn rate model

SD-III-17 – 32% 90 μm/55% 20 μm AP (Miller, 1982)



Results obtained using Dr. Arvind Iyer's packing algorithm code. The weight-averaged particle size is used for each size class (for example 90 and 20 μm here. Packing calculations completed for 6 propellants till now.)

- From the packing a number of horizontal and vertical lines are chosen
- The burn time for each one of these lines is estimated from the fraction of various particle sizes along the line and their corresponding burn rates
- Then the burn rate of each line is the ratio of length to the corresponding burn time
- The propellant burn rate is the average burn rate of all the lines chosen
- The sample size can be changed to get good statistics

$$\dot{r}_i = \frac{L}{t} = \frac{L}{\sum \frac{L_{d,j}}{\dot{r}_j}} = \left[\sum \frac{f_j}{\dot{r}_j}\right]^{-1}$$

$$\dot{r} = \frac{\Sigma r_i}{n}$$

– burn rate of chosen line of length L; t – burn time for that line; $L_{d,j}$ – length of parts of line composed of AP particles of size d_j; f_j – fraction of length composed of AP particles of size d_j; r_j – burn rate of line section composed of AP particle size d_j – only this remains to be calculated and a model for this follows ...

Equation for AP particle burn rate surrounded by binder

$$\rho_p \dot{r} = \sqrt{\frac{k_g}{c_p g} ln(\xi^*) p^{n_r} K_r A_g f_{nll}}$$

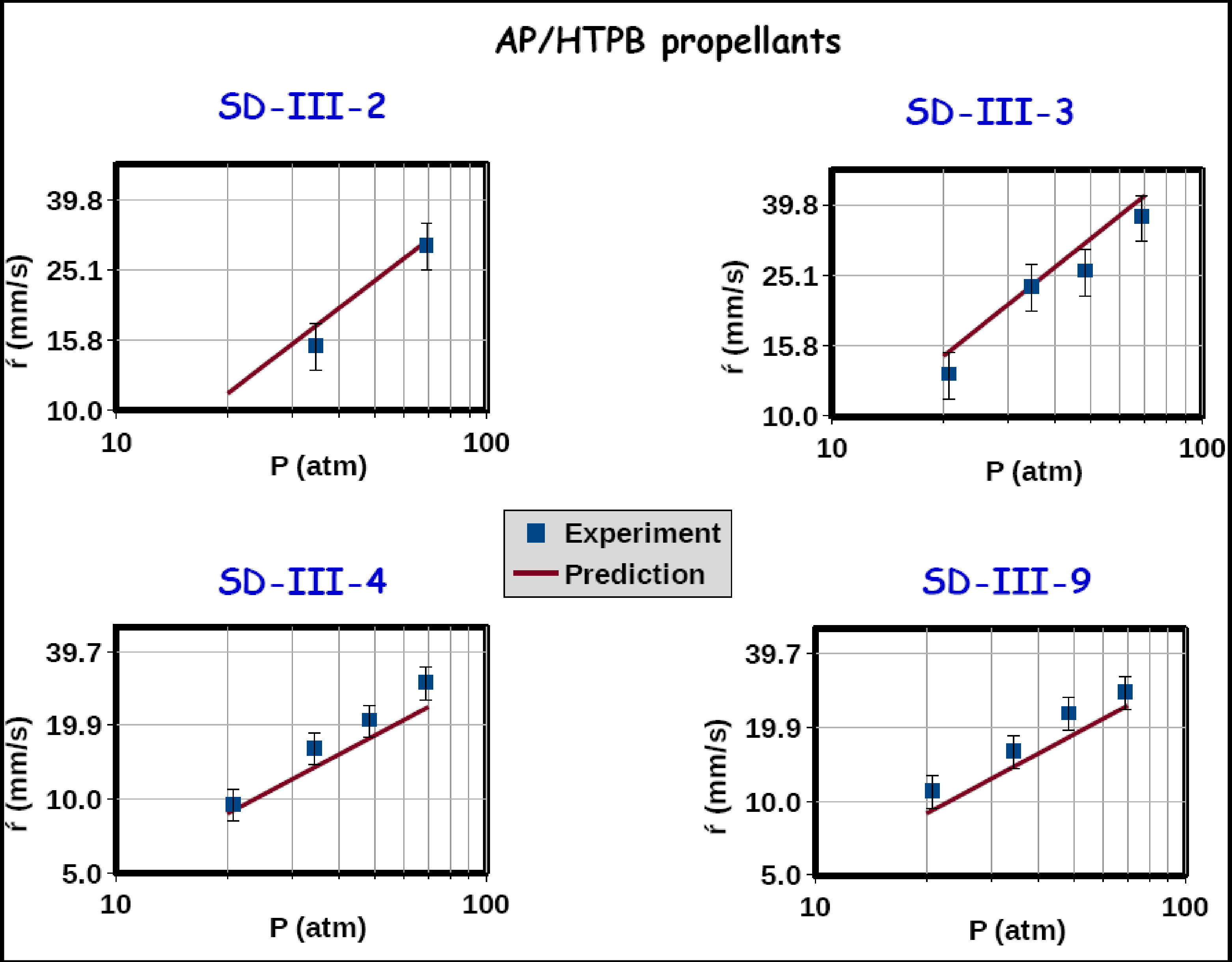
$$\xi^* = 1 + B_{ds} + B_{fd}$$

$$B_{ds} = \frac{T_d - T_s}{(T_s - T_0) - H/c_p}$$

$$B_{fd} = \frac{T_f - T_d}{(T_s - T_0) - (H + H_d/\xi_d)/c_p}$$

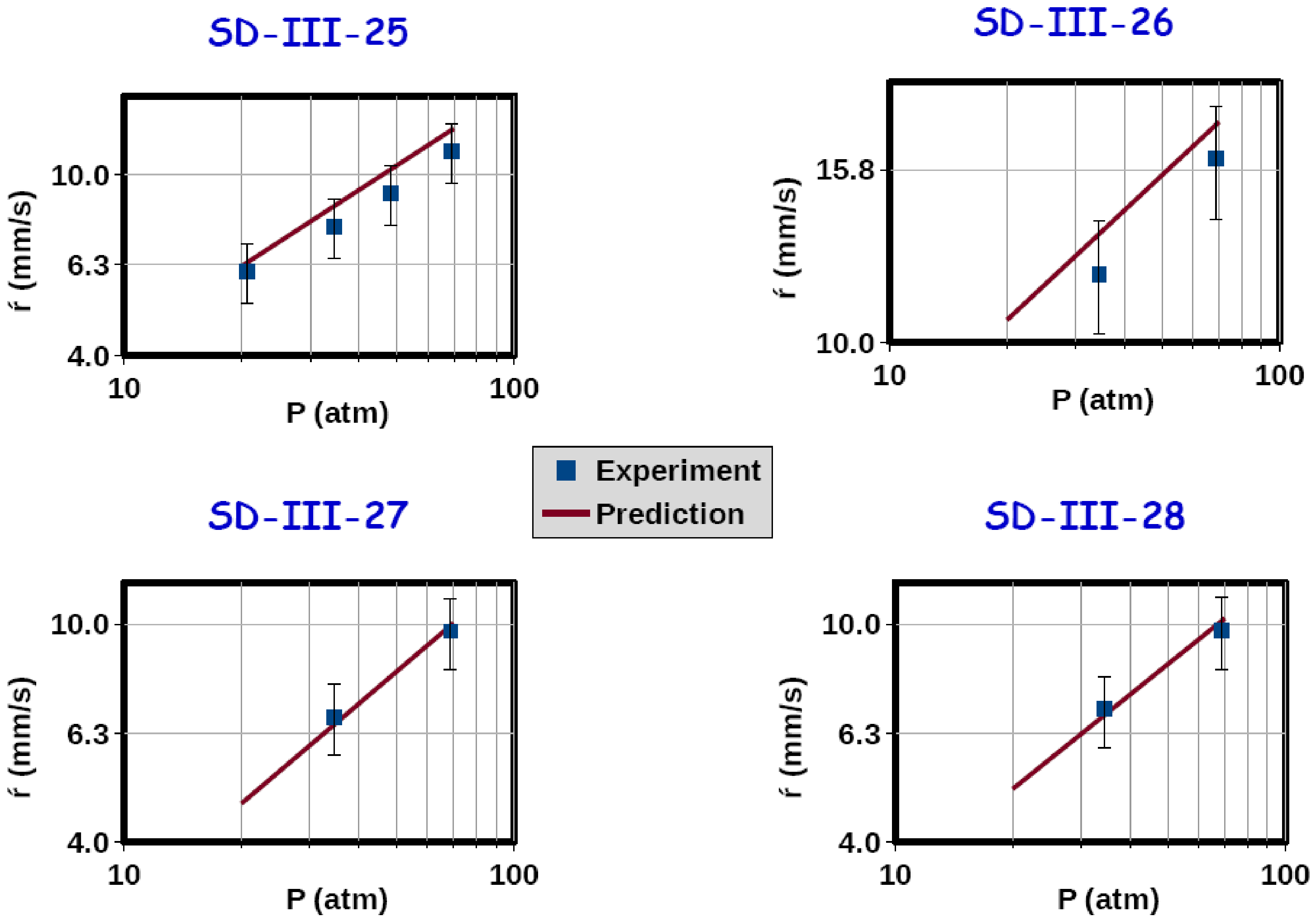
- The burn rate equation for propellants is similar to that of a single exothermic solid (like AP), but,
  - With modified non-dimensional flame stand-off accounting for decomposition
  - Accounting for influence of diffusion flame influence through Ag
  - And for binder melt influence through f_{nll}

Predictions of Miller's propellants – 28 different types.



Contd...

AP/HTPB propellants



What is therefore a scheme to deal with these aspects?

- Steady combustion modeling of composite propellants – calibrated and trustworthy; comparison with experiments – needs some special propellants to be made for calibration.
- About 100 propellant compositions for which data is available are targeted.
- About 70 compositions have given good predictions.
- Work is currently going on to persuade propellant producing people to produce special propellants whose behavior can help calibrate the constants.
- Response function calculation; comparison with experiments
- Full motor calculation to explain linear instability, DC shift and related behavior

Work is currently going on at this time in this area

(IISc + IITM (Dr. Varun) + DRDL)

This is all I need to say. Thanks, indeed