Combustion Instability in the Project Morpheus Liquid Oxygen/Liquid Methane Main Engine

PROPULSION SYSTEMS

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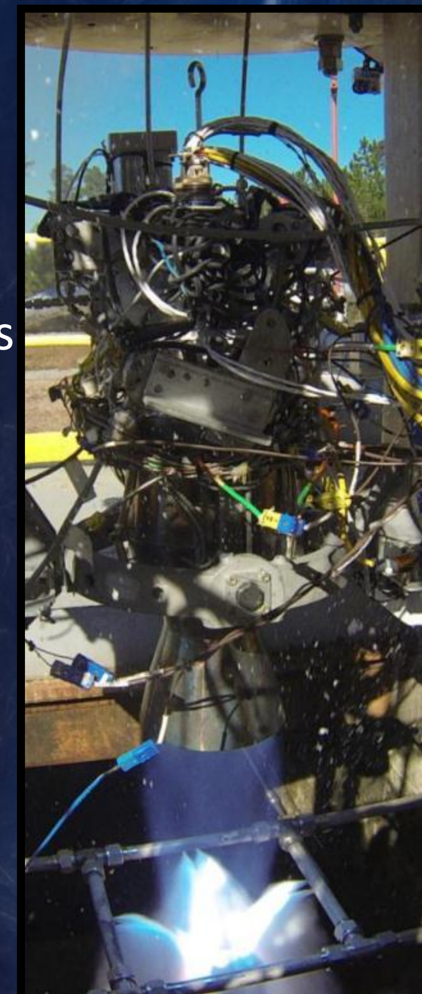
Agenda

- Executive summary
- Project Morpheus Propulsion Overview
- Morpheus Main Engine Overview
- Combustion Instability background
- Overview of Instability signatures and spectral analysis
- Overview of Instability Working Theory
- Discussion on vehicle applicability, redline



HD4-LT in test at SSC
Stennis Stand E-3

Executive Summary

- The Project Morpheus Liquid Oxygen (LOX)/Liquid Methane HD4-LT and HD5 demonstrated acoustic-coupled combustion instabilities during testing at Stennis Space Center (SSC).
- The instabilities have two causes and signatures
  - Overchilled CH4 with high CH4 injection velocity causes a high-amplitude, 1T, 1R, 1T1R (and higher order R harmonics). This instability usually manifests during low-throttle startup conditions and can propagate through mainstage throttle-up. It has never been shown to start after mainstage throtte-up.
  - Warm LOX causes transient, self-limiting instabilities that appear as 1T-1L or 1R (with harmonics). These instabilities typically happen at ignition (or shortly thereafter) and dampen out once the LOX injector chills in.
- Vehicle-HD4 tests at JSC typically only demonstrate low-amplitude transient tones near ignition, which are probably due to “warm” LOX type instabilities which always dampen
- The explanation for the lack of vehicle-test instabilities are theories in work:
  - The vehicle tests demonstrate a faster fuel injector pressurization fill compared to SSC, and the vehicle tests also have a higher frequency, more quickly dampened start water hammer.
- To protect for the possibility of instability occurrence on the Morpheus vehicle, a new high-speed redline cutoff system has been designed, tested, and installed.

Project Morpheus Overview

- Morpheus is an autonomous, reusable rocket powered terrestrial Vertical Take-off /Vertical Landing (VTVL) vehicle for testing integrated spacecraft and planetary lander technologies
- Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project has advanced the technologies for autonomous precision landing and hazard avoidance.
- In FY13, the Morpheus vehicle will provide a flying platform to test the ALHAT system for the first time

Morpheus Vehicle – Tether Test TT19, July 17, 2012

Project Morpheus Main Engine Overview

- Morpheus Propulsion uses integrated Main Engine / Reaction Control System (RCS) with LOX/methane propellants
  - Historical First: demonstrated integrated LOX/Methane propulsion, 5/1/2013
- The JSC Propulsion & Power Division developed 3 inexpensive development prototype LOX/Methane engines for Project Morpheus from 2010-2012
  - HD3,4,5: 3800, 4200, 5200 lbf max thrust; all designed and built at JSC

HD3: Yr2011, 27 tests (incl. 8 vehicle tests), 363 sec total run time, burnthrough-damaged

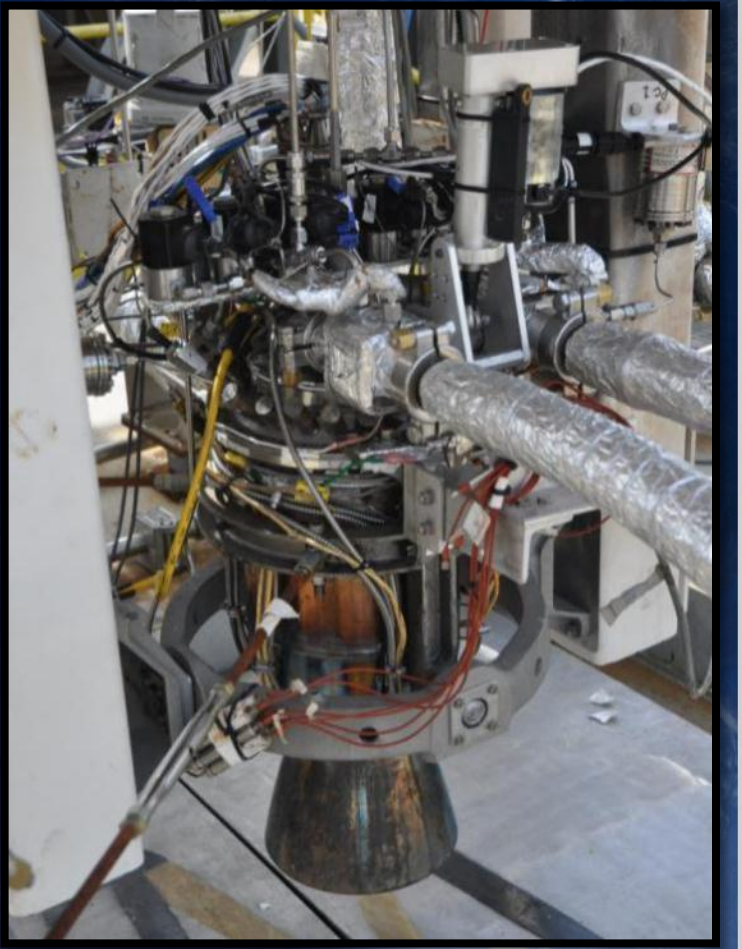
HD4: Yr2011-2012, 20 vehicle tests, 923 sec total run time, damaged in Morpheus crash at KSC

Yr2012-2013, rebuilt as HD4-LT (large throat), 36 starts (incl. 12 vehicle tests), 285 sec total run time, current Morpheus engine

HD5: Yr2012-2013 , 67 tests at SSC, >160 sec total run time. Instability, thermal issues.

Morpheus HD4 Main Engine Design

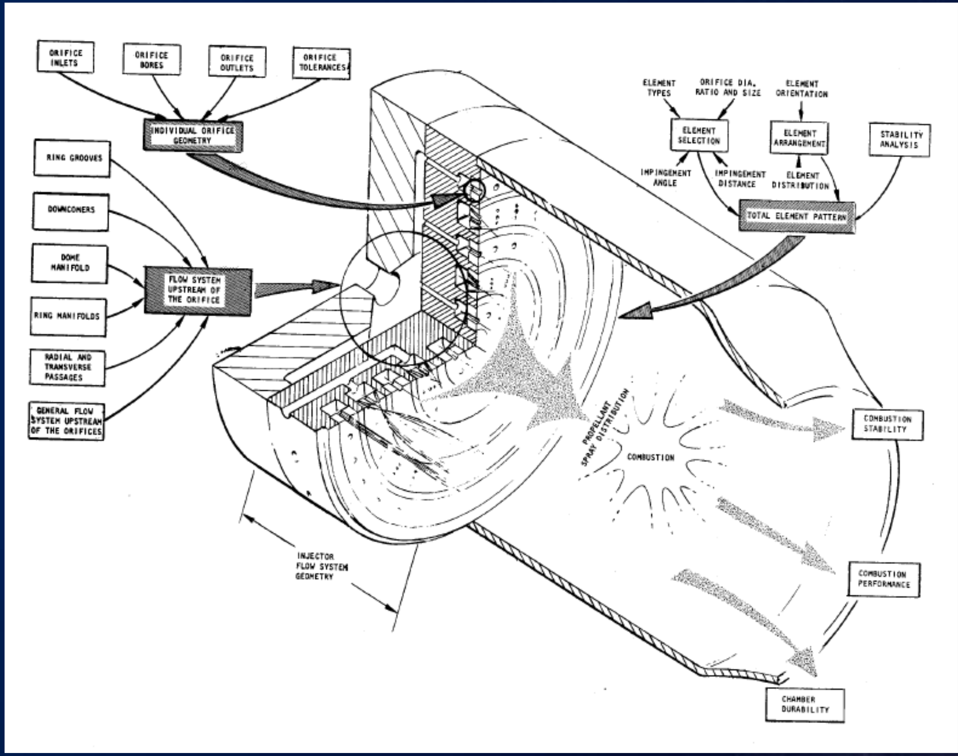
- Requirements: (Demonstrated on Morpheus)
  - 4,200 lbf thrust max (4,350 lbf)
  - 4:1 throttle range (5:1 w/minimal chug on vehicle)
  - 215 sec ISP avg (sea-level) (221 sec max, 204 sec mid thrust flight avg)
  - 210+ sec duration per flight (126 sec, steady state thermal)
- Impinging element injector
  - Like doublets, arranged in pairs and triplets
- Methane film cooling
- Adjustable acoustic cavities allow engine to be tuned between firings

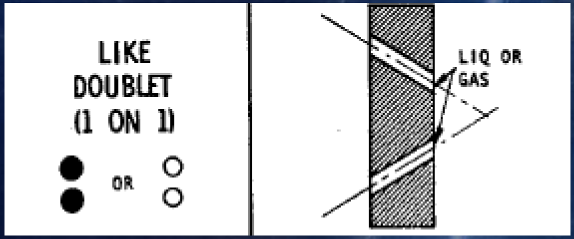


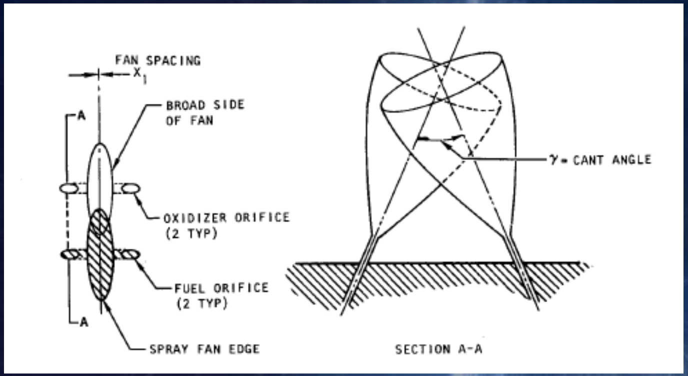
HD4-LT installed in SSC stand E-3

Like Doublet Injector Element Design

- Like-on-Like (LOL) double design chosen for improved mixing and stability compared to unlike doublet design (e.g., RS-18 3500 lbf Apollo lunar module ascent engine)





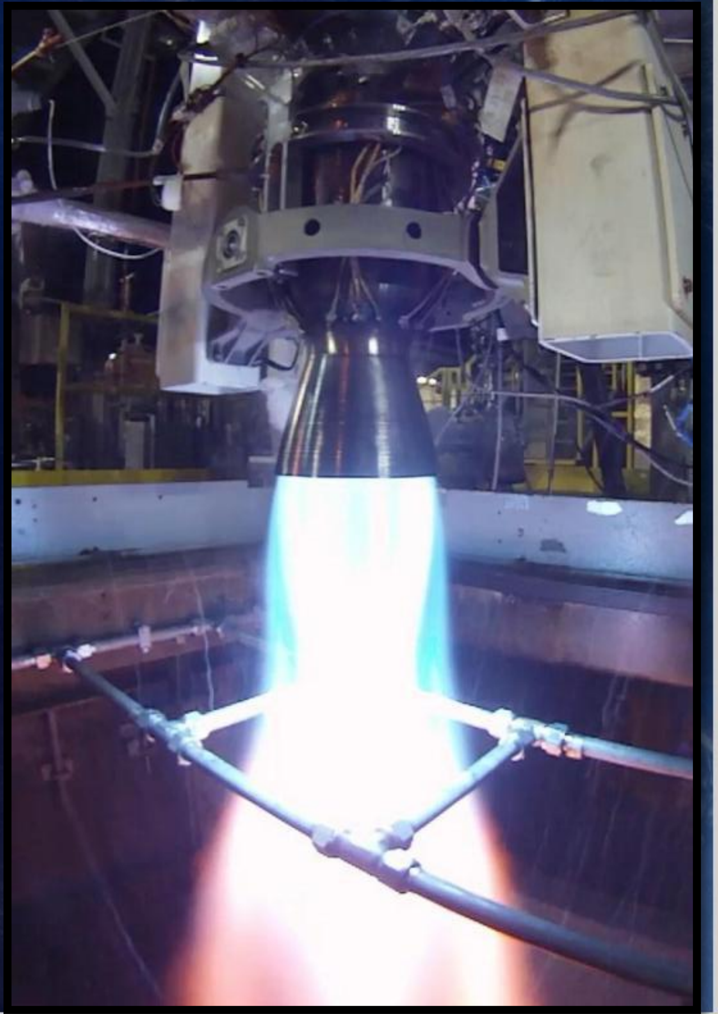


NASA-SP-8089 (1976)

HD4-LT SSC Test #19

HD4/HD5 Combustion Instability Problems at SSC

- HD3 showed no instability problems, until a 1T-related burn-through during a vehicle test (triggered at ignition)
  - Suspect cold-CH4 issue
- HD4 was tested 20 times on Morpheus vehicle with no detected instability problems in 2012
  - Any acoustic tones were low-amplitude and auto-damped after ignition
- HD5 testing at SSC in 2012-2013 revealed significant combustion instability issues (1T, 1R, 1T1R, etc.)
- HD4-LT rebuilt following KSC crash, and SSC revealed significant combustion instability problems in 2012-2013



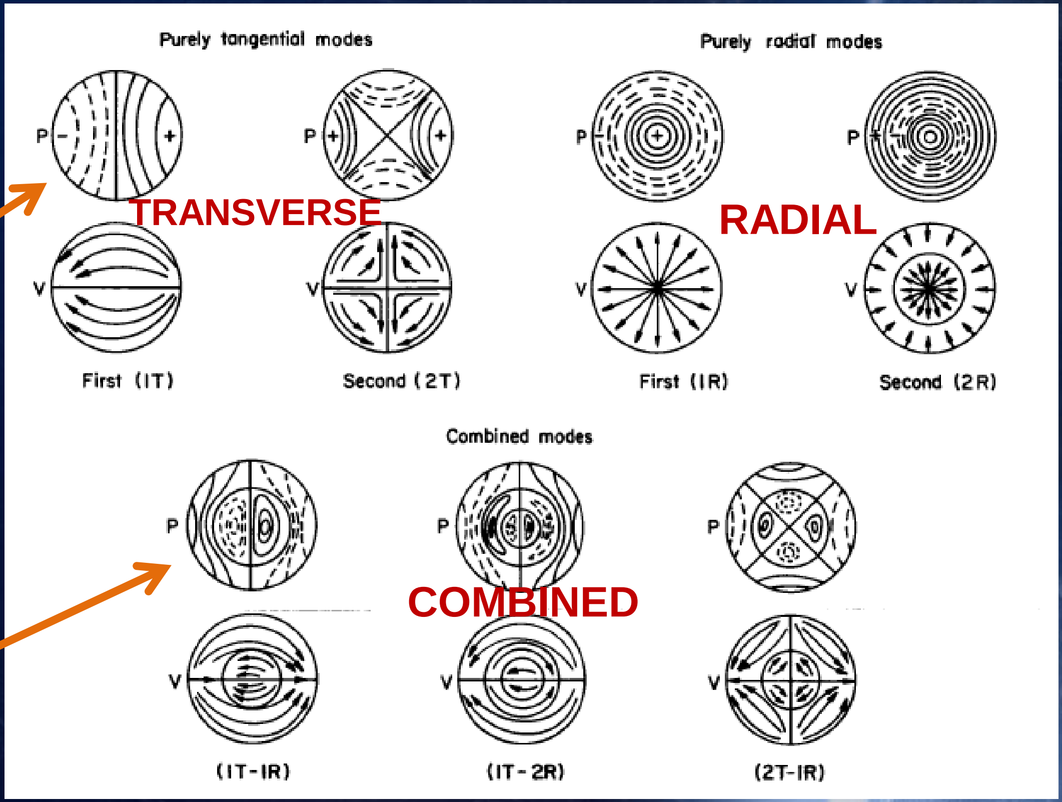
HD5 installed in
SSC stand E-3

Predicted Combustion Chamber Acoustic Modes

- Chamber L-modes behave similar to organ-pipe (coke-bottle) tone
- Chamber T, R modes act on the chamber diameter
- Predictions for HD4:
  - 1L ~ 1,600 Hz
  - 2L ~ 3,200 Hz
  - 1T ~ 3,150 Hz
  - 2T ~ 5,200 Hz
  - 1R ~ 6,550 Hz
  - 2R ~ 12,000 Hz
  - 1T1R ~ 9,100 Hz
  - 1T2R ~ 15,000 Hz

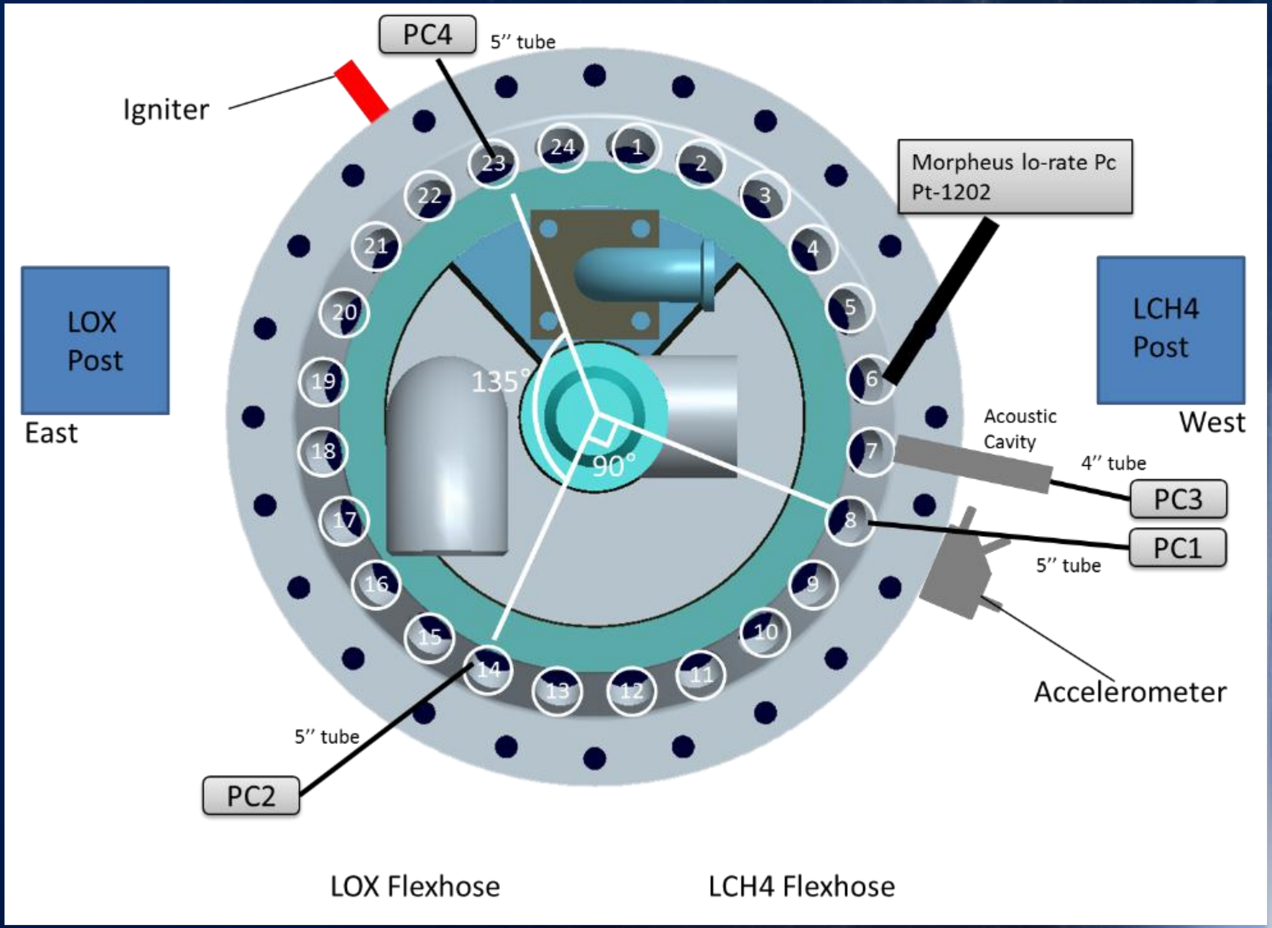
f = C n / 2L

f = C En / D



NASA-SP-194 (1972)

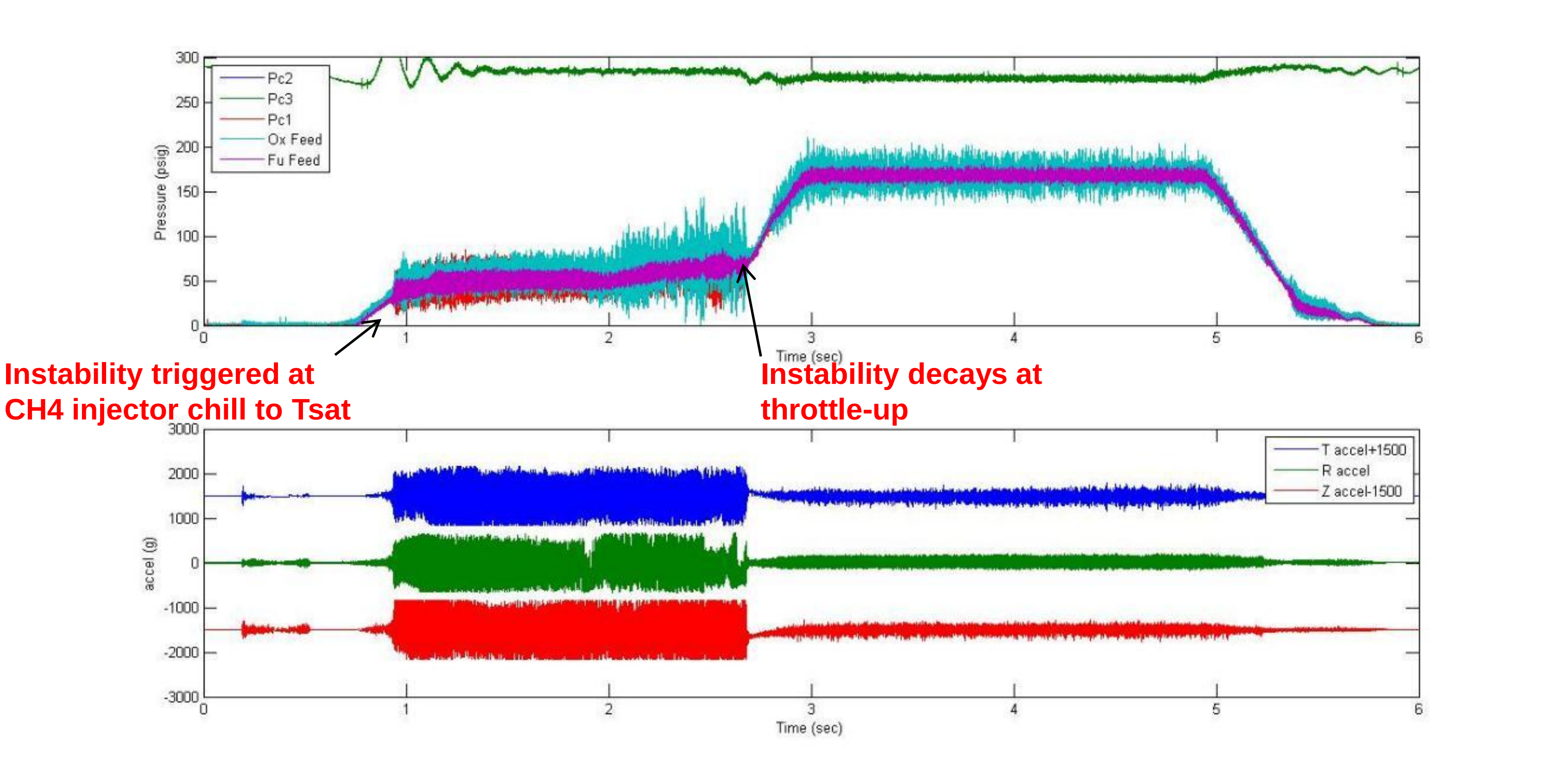
High-Speed Instrumentation Layout



Data rate typically 25 kHz for all high-speed channels, some tests recorded at ~100 kHz

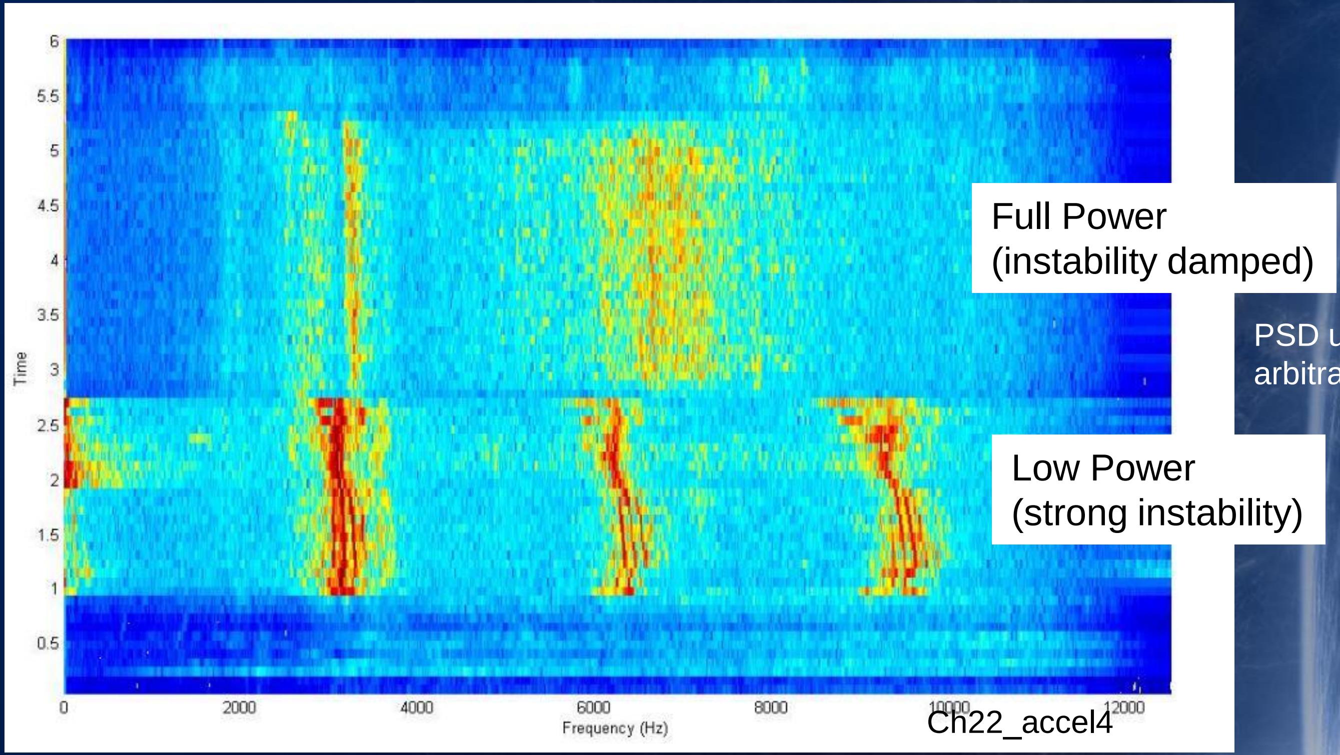
CH4-triggered Instability Example (High-speed Pc and Accel Data)

HD4-LT SSC Test 14 (12/11/2012)



CH4-triggered Instability Example (Accelerometer data)

HD4-LT SSC Test 14 (12/11/2012)

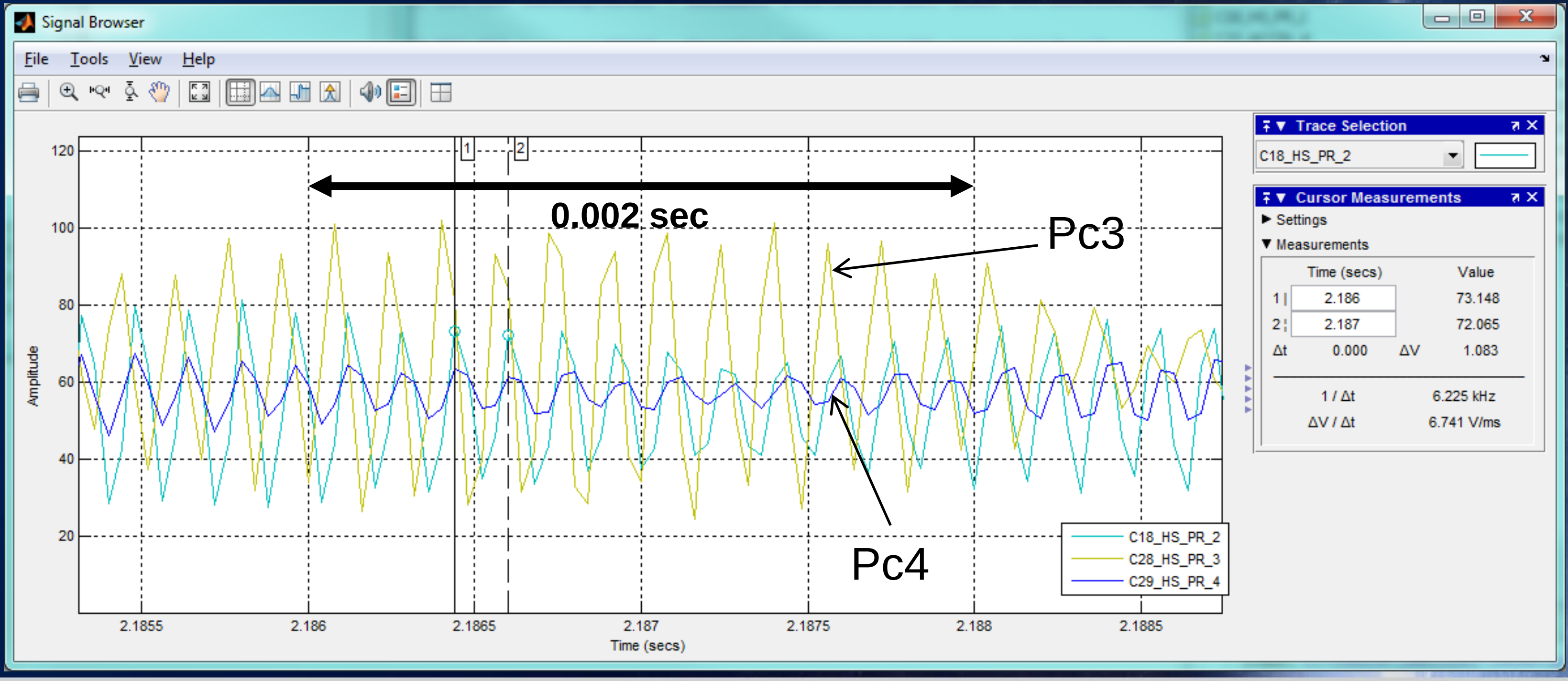


PSD units arbitrary

- Characteristic 3K/6K/9K pattern seen on both HD4-LT and HD5 instabilities: 3125Hz, 6250 Hz, 9400Hz
- Believed to be 1T, 1R, and 1T1R

HD4-LT SSC Test 14 (12/11/2012)

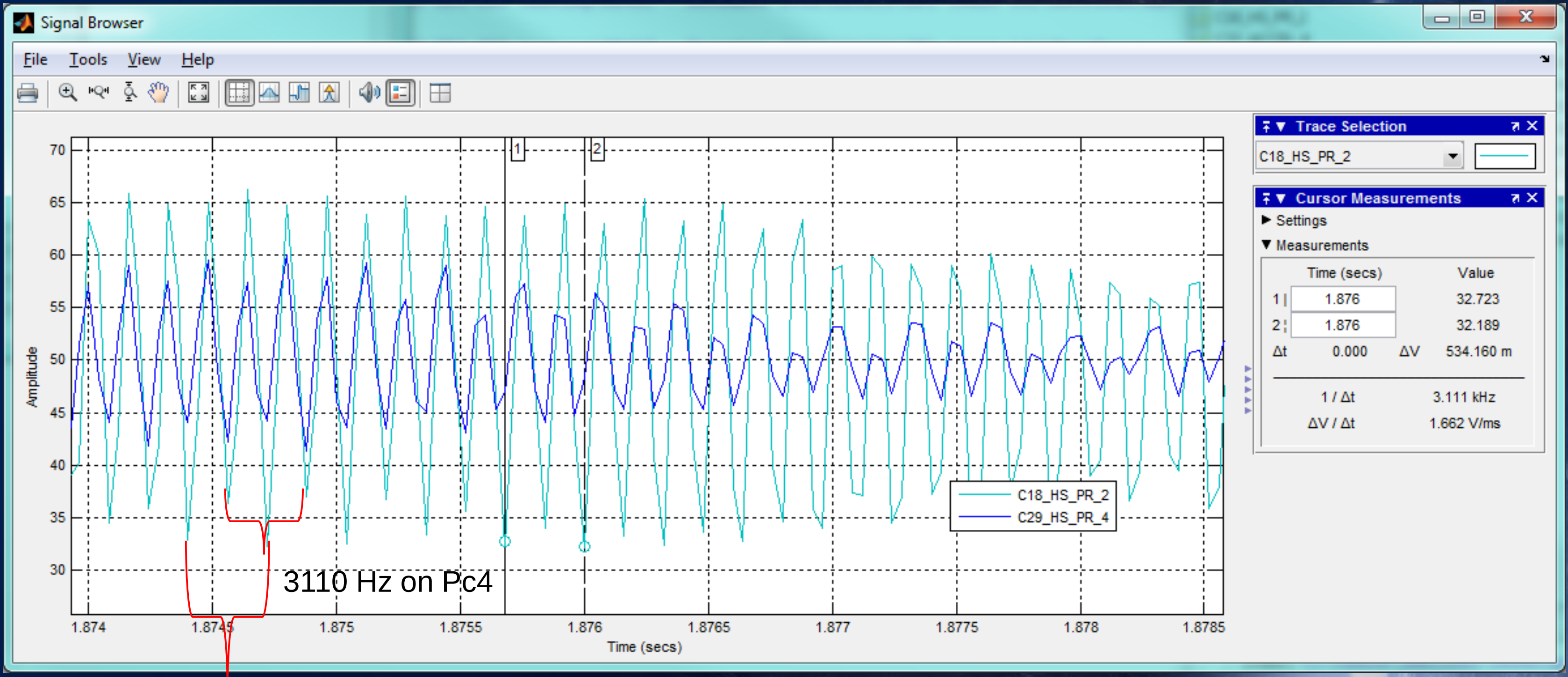
- Pc 2,3,4 at 25 kHz sampling
- Pc2 and Pc4 are mostly in phase at 6225 Hz
  - There is some minor transient variable phasing (possibly due to signal noise interference)
  - Pc3 slightly out of phase, but Pc3 is on the back of a 5-6” long acoustic cavity
  - Pc3 also has a large amplitude noise at ~6000 Hz
- Interpret 6225 Hz as 1R modulated to 2x 1T frequency



HD4LT SSC Test 14 (12/11/2012)

- PC2 and Pc4 are 180 deg out of phase at 3110 Hz
  - Sensors mounted 135 deg apart
- Interpret 3110 Hz as 1T mode

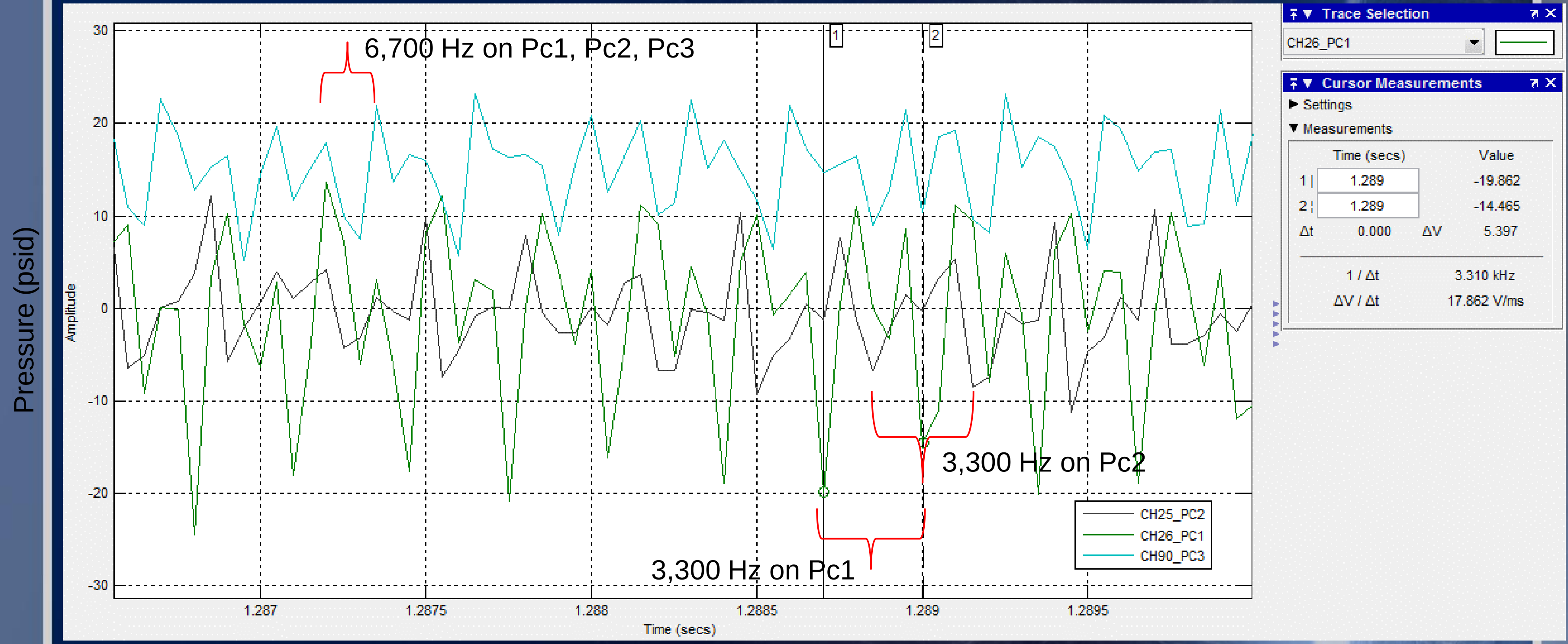
Pressure (psig)



3110 Hz on Pc2

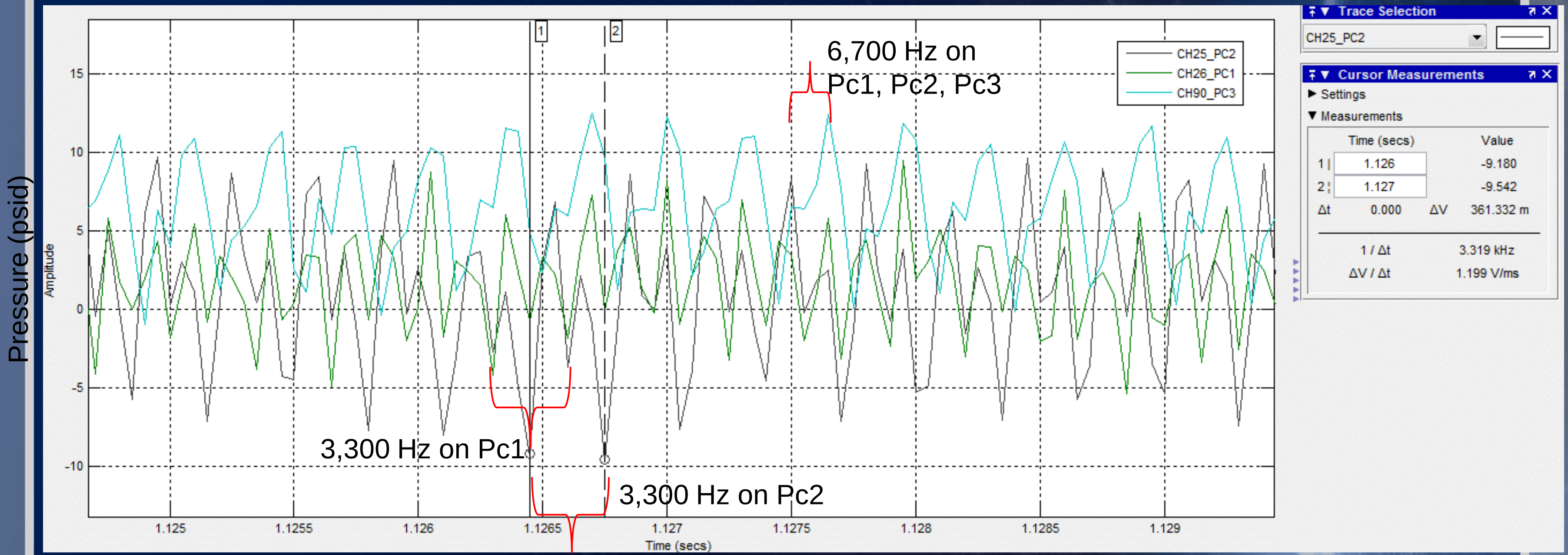
f = C En / D

GTAL2



3110 Hz on Pc2

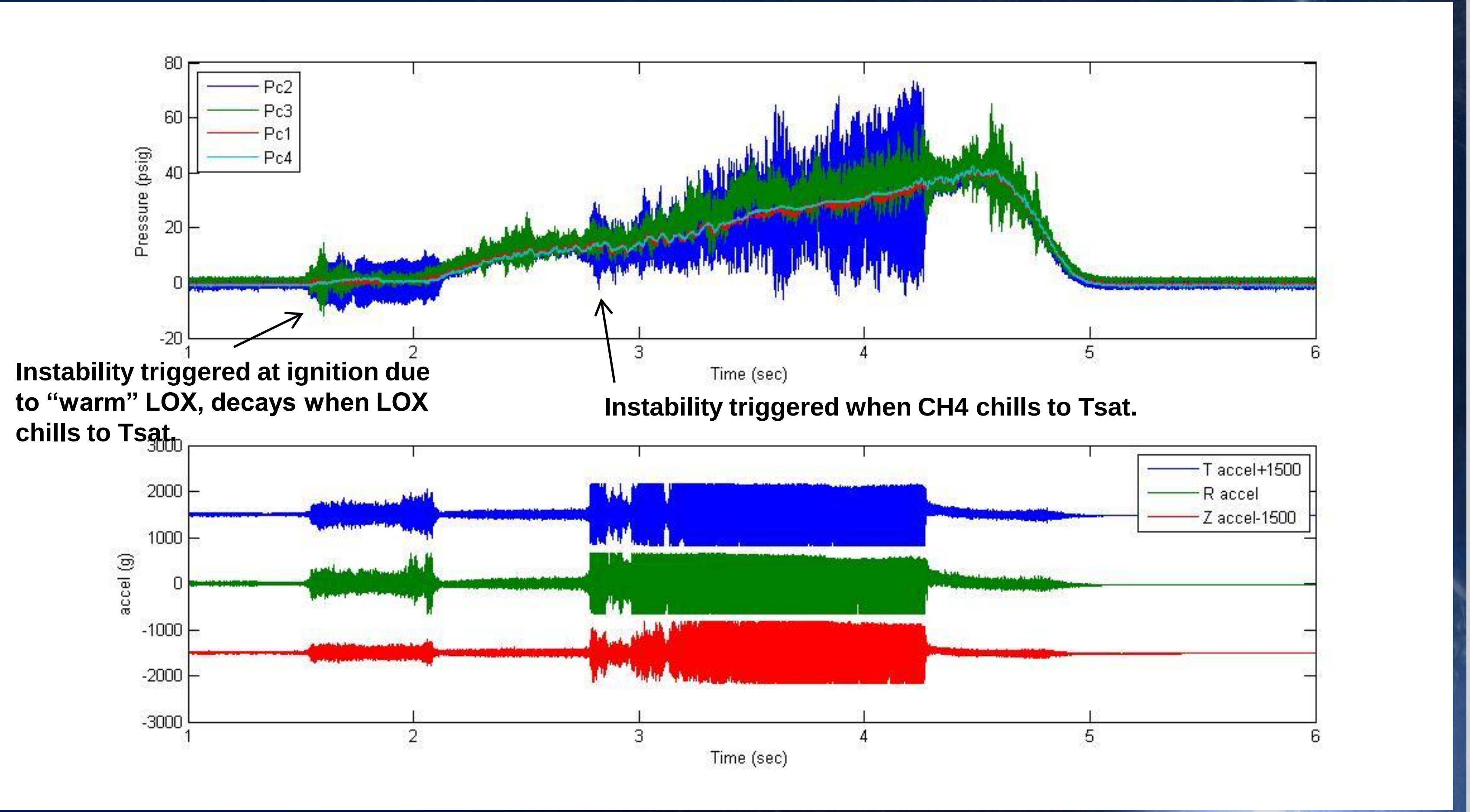
HF9.1



Pressure (psid)
Amplitude
Time (secs)
CH25_PC2
CH26_PC1
CH90_PC3
6,700 Hz on
Pc1, Pc2, Pc3
3,300 Hz on Pc1
3,300 Hz on Pc2
Trace Selection
CH25_PC2
Cursor Measurements
Settings
Measurements
Time (secs)
Value
1.126
-9.180
1.127
-9.542
Δt
0.000
ΔV
361.332 m
1 / Δt
3.319 kHz
ΔV / Δt
1.199 V/ms

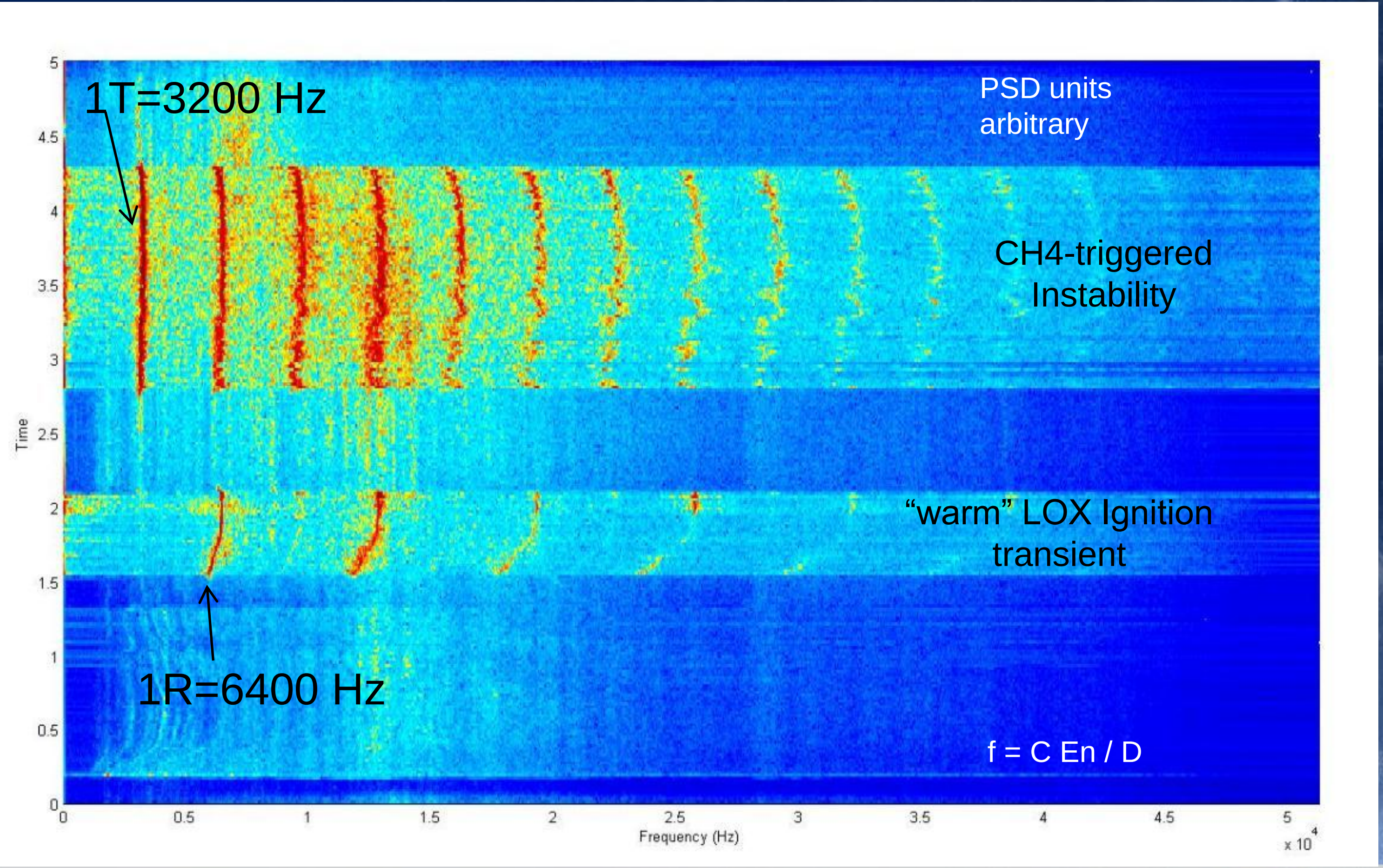
Some HD5 tests show distinct separate causes of Instability

HD5.a, SSC Test 6, 10/15/2012



HD5.a, SSC Test 6, 10/15/2012

CH22_Accel4 (accelerometer, sampling rate = 102.4 kHz)



HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

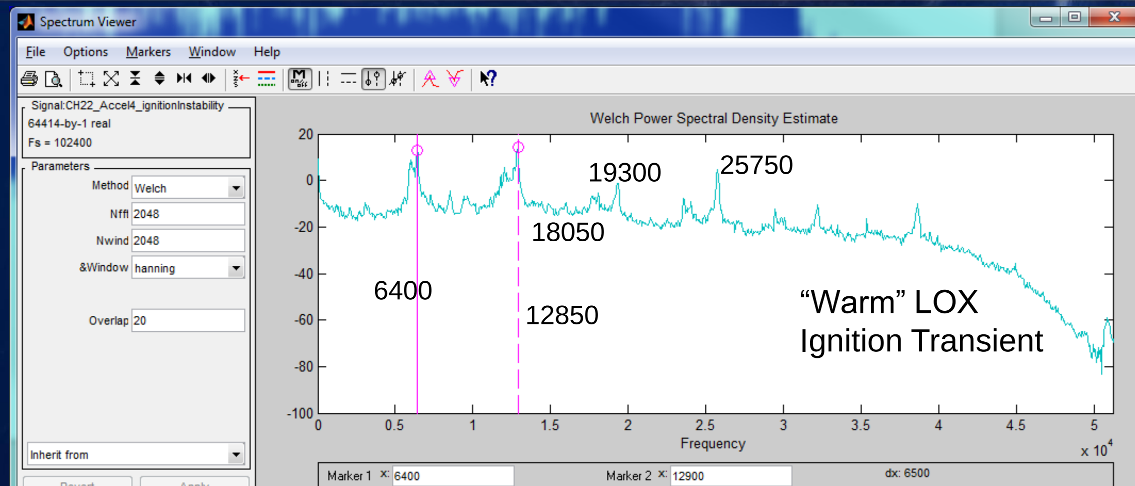
Predictions:

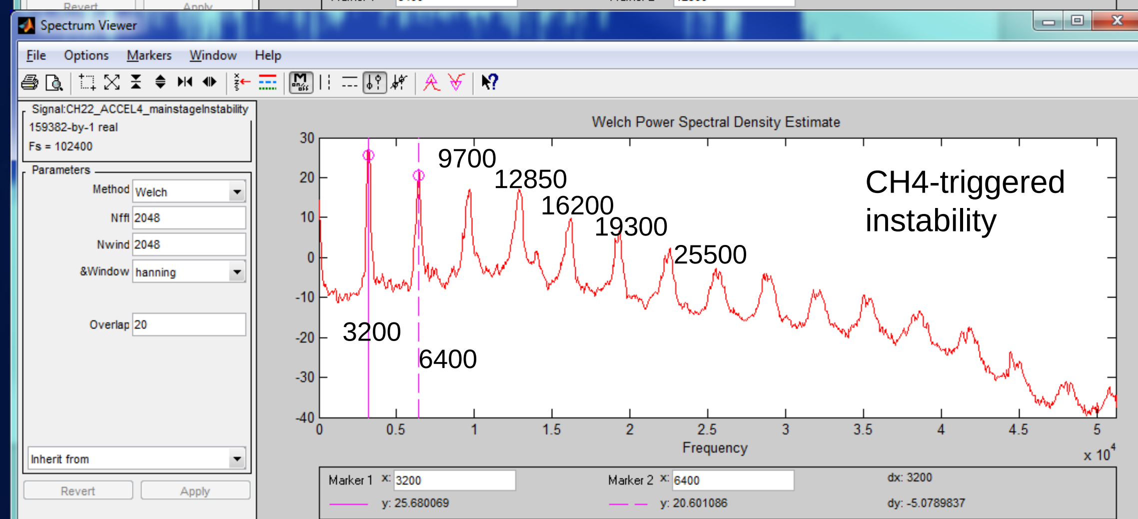
1R = 6,555 Hz
2R = 11,982 Hz
3R = 17,409 Hz

1T = 3,150 Hz
1T1R = 9,134 Hz
1T2R = 14,561 Hz
1T3R = 20,042 Hz

Conclusions:

- Ignition transient tones related to 1R, 2R
- CH4 triggered instability related to 1T, 1R, 1T1R, 2R, 3R, 1T2R

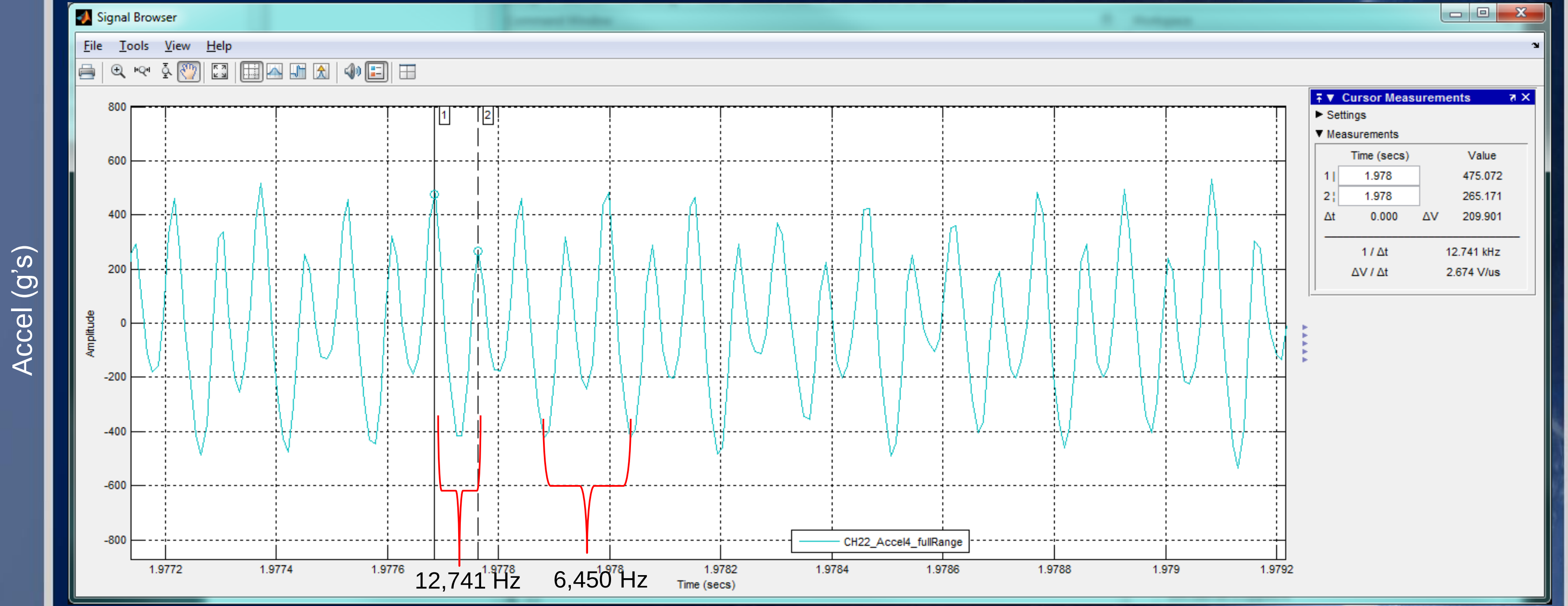




PSD units arbitrary

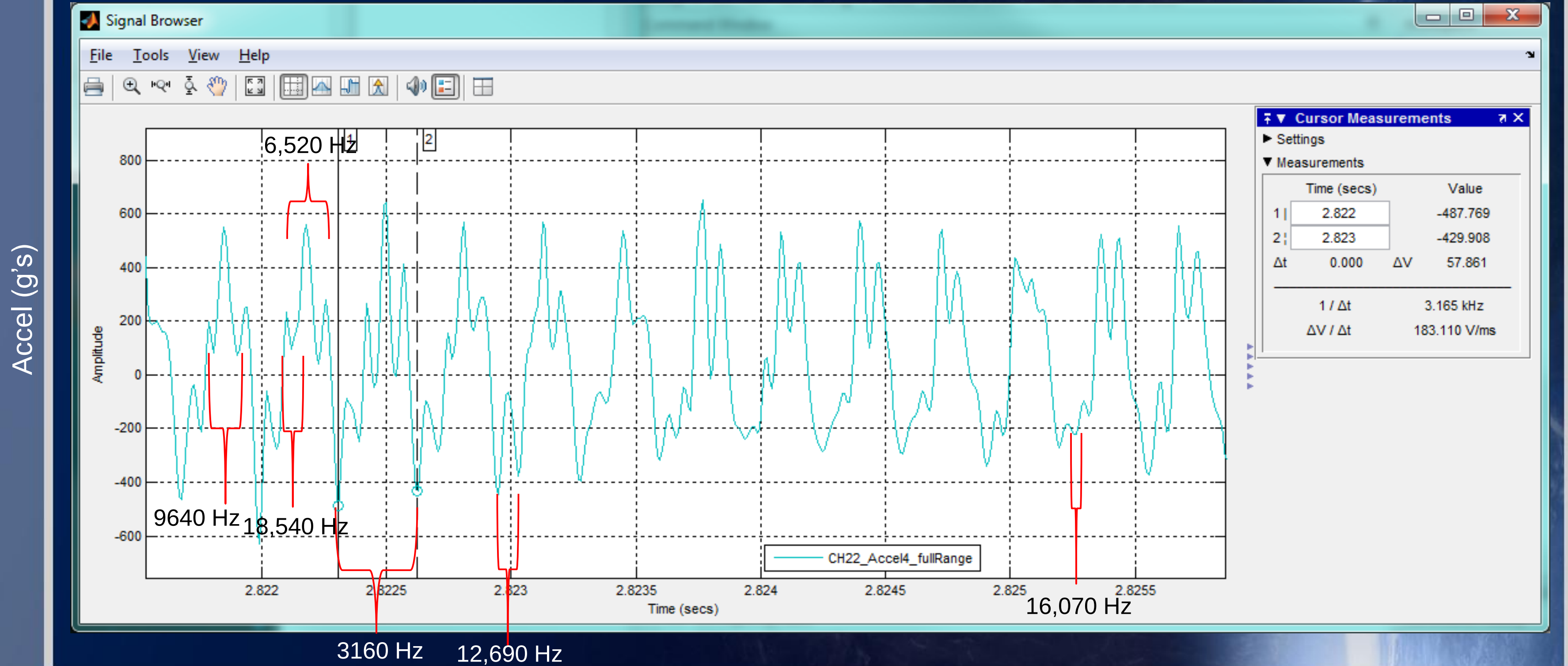
HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

- Accelerometer Data, sampling rate 102.4 kHz data
- During Ignition instability, 1R, 2R signals evident
  - Blips at 3R or above (17 kHz) not easily measured



HD5.a, SSC Test 6, 10/15/2012 (Accelerometer data)

- Accelerometer Data, sampling rate 102.4 kHz data
- During Mainstage instability, 1T, 1R, 1T1R, 2R, 3R, 1T2R signals evident
  - Blips at 1T3R (20 kHz) and higher difficult to distinguish



Is the measured signal 1T, 1R or something else?

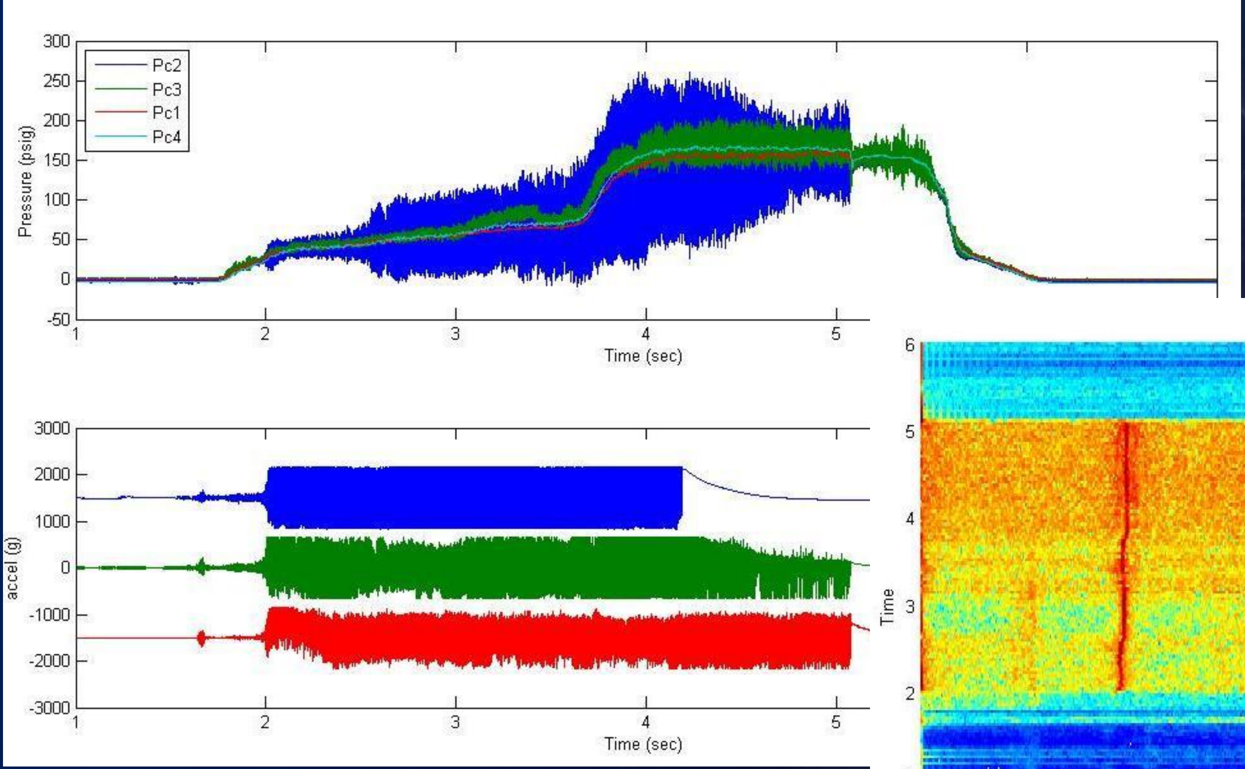
- NASA-internal peer review have raised the possibility that the ~3100-3200 Hz tone is actually a 2L
  - Changes the interpretation of the 6 kHz tones to being 4L instead of 1R
- Evidence against 1R cause:
  - Measured harmonics (3kHz / 6 kHz / 9 kHz pattern) suggests L-modes
  - Variable phasing of the Pc signals at ~6 kHz suggests the tone is not Radial mode
- Evidence for 1R cause:
  - HD4 and HD5 measurements are consistently in the 6200 – 6700 Hz range for this tone, most likely to be 1R based on predictions.
  - Variable phasing between the Pc signals would have to be explained by known sense line interference for the high-speed Pc ducers
  - Published theory shows that non-linear coupling can modulate both 1R and 2T to oscillate at exactly 2x 1T frequency, with 1R higher amplitude (Vigor Yang, AIAA Prog. Vol 169)

Bottom Line:

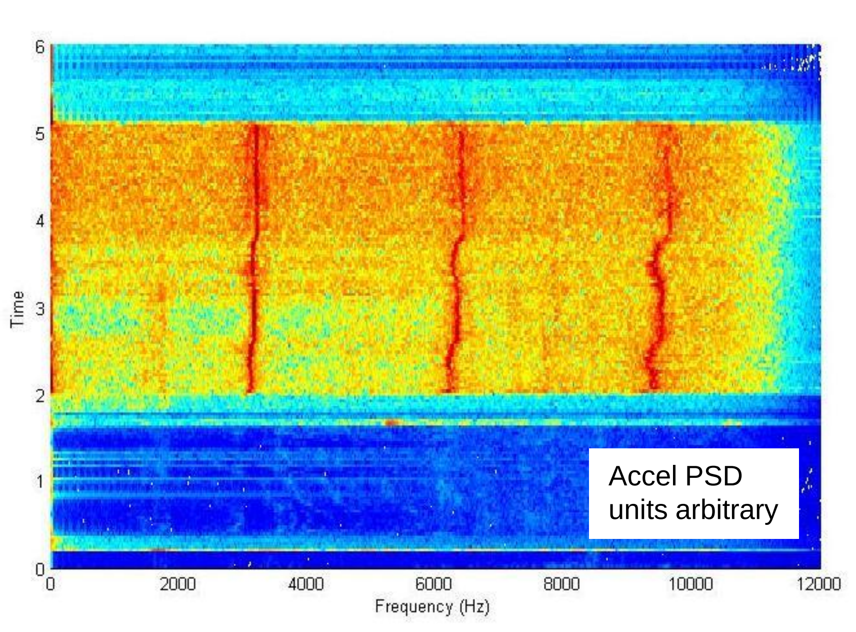
6 kHz Instability may be longitudinal (4L), or radial (1R)

Instability propagation through a throttle transition

- The instability has been shown to propagate through a throttle-transition, but it has never been demonstrated to initiate after main-stage throttle-up



HD5.a,
SSC Test 10
(10/17/2012)



CH4-triggered instabilities: Working Theory

- CH4-triggered Instabilities coupled to high CH4 injection velocity
  - Calculations for injection velocity (not shown here) are higher than originally predicted during startup
  - CH4 injection velocity driven high by orifice flow detachment in CH4 injector during startup high injector pressure drop
  - CH4 orifice flow detachment caused by start surge (Water hammer) combined with or because of “cold” CH4
- Instability appears to “trigger” at moment of injector chill in to CH4 Tsat
  - Unknown: how the CH4-chill-in triggers the instability
- Some tests do show that the instability can dampen out after CH4 flow re-attaches or at throttle-up.
- Issue: Working theory does not explain why Morpheus vehicle engine tests do not demonstrate the undamped instabilities seen in SSC testing

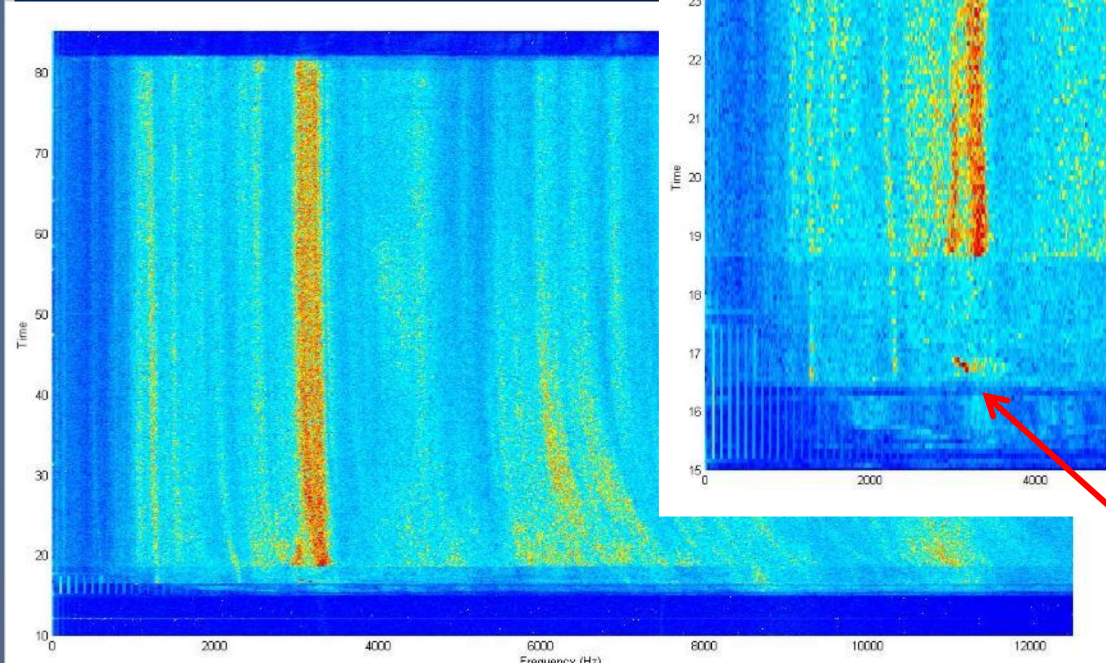
Morpheus Vehicle Tests Observations (31 tests for HD4 and HD4-LT)

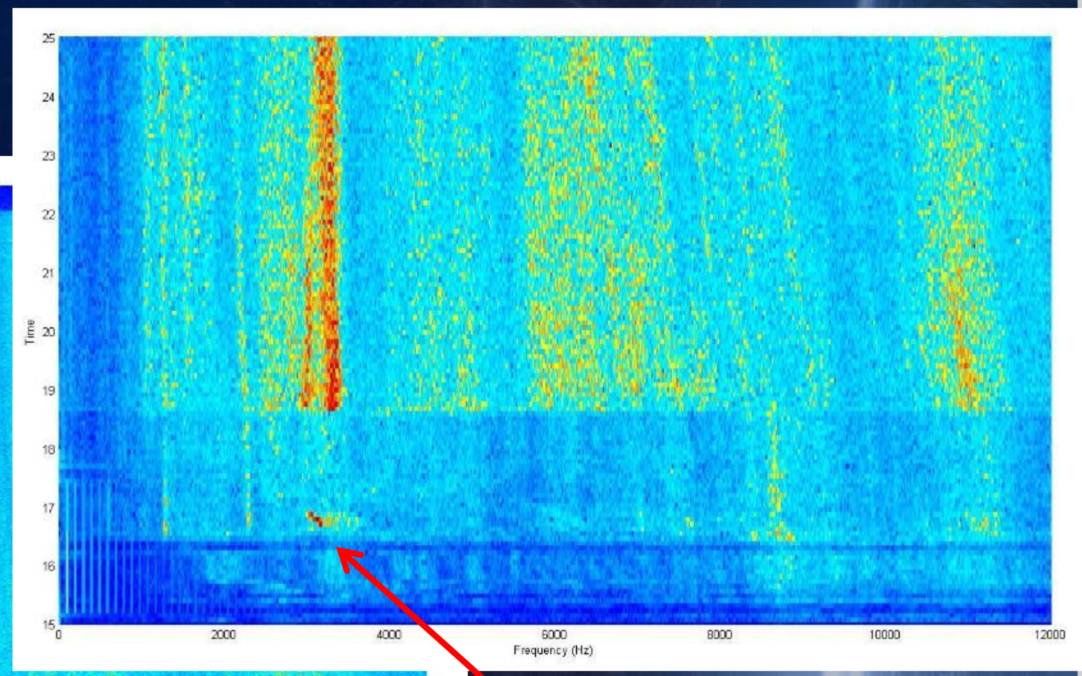
- High-amplitude, undamped instabilities have been recorded on the vehicle using HD4-LT (2013), but not during tests using HD4 (2012)
  - The 3 kHz /6 kHz /9 kHz pattern has been observed, but typically at greatly reduced amplitude, and damped out prior to throttle-up
  - The HD4-LT instability was observed on a test with very cold CH4 chill-in pre-test
- New observations suggest HD4-LT injector pressurization, injection velocity profile is higher than HD4 on the vehicle
  - On the vehicle, the injector operating conditions that appear to cause instabilities at SSC are more severe for HD4-LT than HD4
  - The HD4-LT larger throat affects chamber pressurization and injector pressure drop
- Major differences between SSC and vehicle CH4 flow
  - The CH4 injector pressurizes much more quickly on the vehicle than on the SSC test stand
  - The CH4 start surge has a much shorter wavelength and dampens out quicker than the SSC config (even though magnitudes are in family)
  - These differences due to larger diameter plumbing and 10x longer line lengths

HD4 Vehicle tests are relatively stable

- The HD4 vehicle tests are all relatively stable with minor low-amplitude transients on some tests

Vehicle TT12 Accel

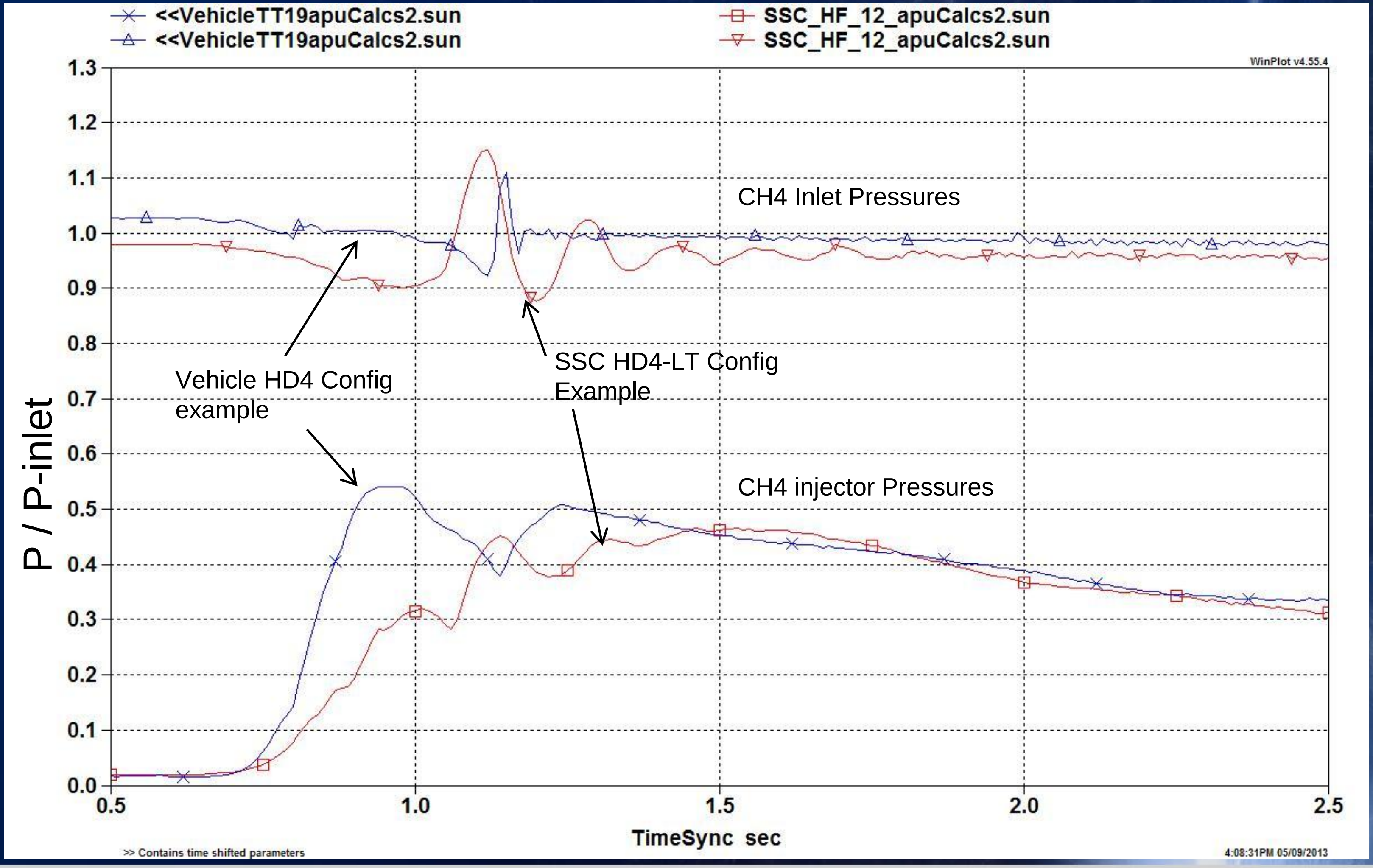




1T transient

Accel PSD units arbitrary

Vehicle vs. SSC Config differences on CH4 flow
(startup transient pressure)



PROPULSION & POWER DIVISION

Instability Detection Redline Implementation

- A new redline system has been designed, tested, and installed on the vehicle
- The system was developed during SSC testing, and demonstrated successful shutdown of the engine during high-amplitude instabilities
  - Vehicle hot-fire test with instability limits has demonstrated cut-off capability
  - SSC recorded instability data played back through vehicle cutoff system to demonstrate cut
- Because the high-amplitude instability recorded at SSC was always observed to initiate prior to throttle-up (and never after), the greatest risk to the vehicle is during engine startup, prior to liftoff.
- Future Vehicle Flight Ops:
  - Detection prior to liftoff results in an engine shutdown
  - Detection after lift-off results in a soft abort and landing followed by engine shutdown

Tether Test

Vertical, Slant Hops, Traverse Hops

Flight Envelope Expansion:

Full Hazard Detection Phase

<u>Autonomous Hazard Avoidance</u>
Identify and land at safe site in landing field with hazards (rocks, craters, slopes)