National Aeronautics and Space Administration

Overview of CCE-LIMX Testing

Hypersonics Project

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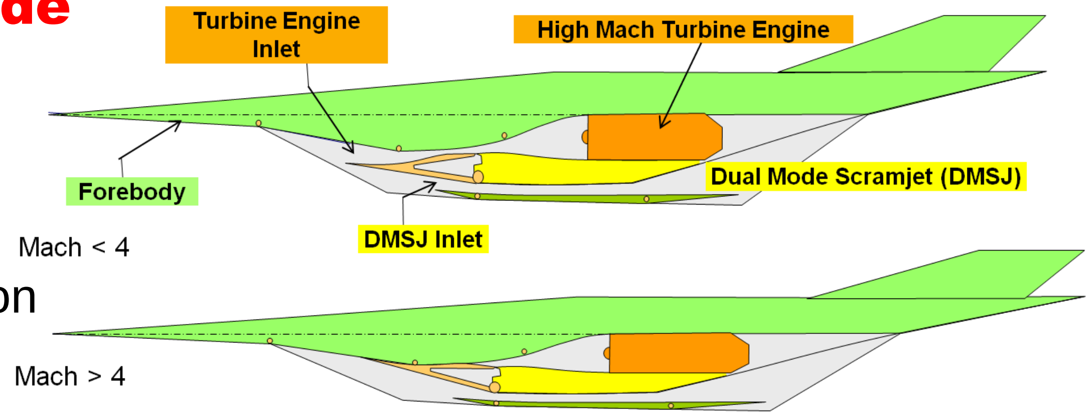
Cleveland, OH

Combined Cycle Engine

Overview of CCE-LIMX Testing

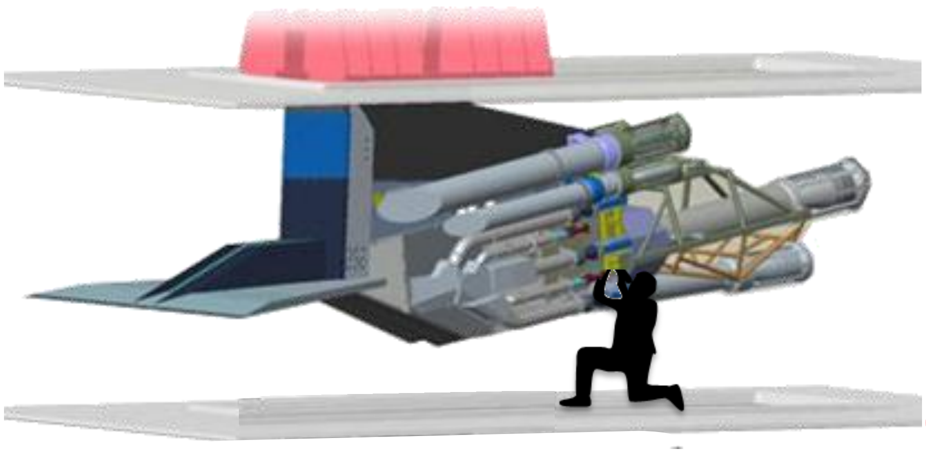
Large-Scale Inlet for Mode Transition Experiments

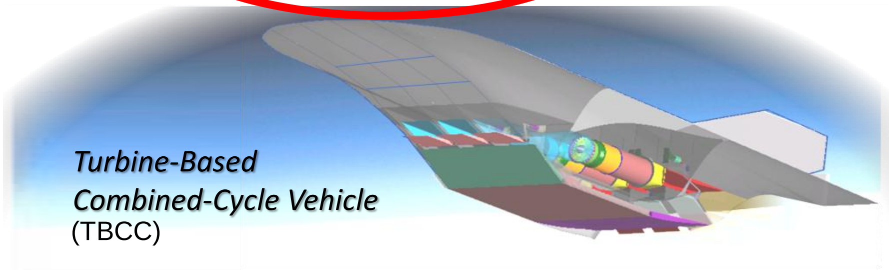
- Test Plan
- Inlet System
- Phase 1 –Inlet Characterization
  - Objectives
  - Inlet testing progress
    - Data restrictions
    - Planned configurations
    - CFD collaborations
  - Testing Procedures
  - Accomplishments
- Phase 2 –System Identification and Dynamics
  - Objectives
  - Testing Procedures
  - Accomplishments
- Future Plans
- Summary



10- x 10-foot Supersonic Wind Tunnel

CCE-LIMX in the GRC 10x10 SWT.





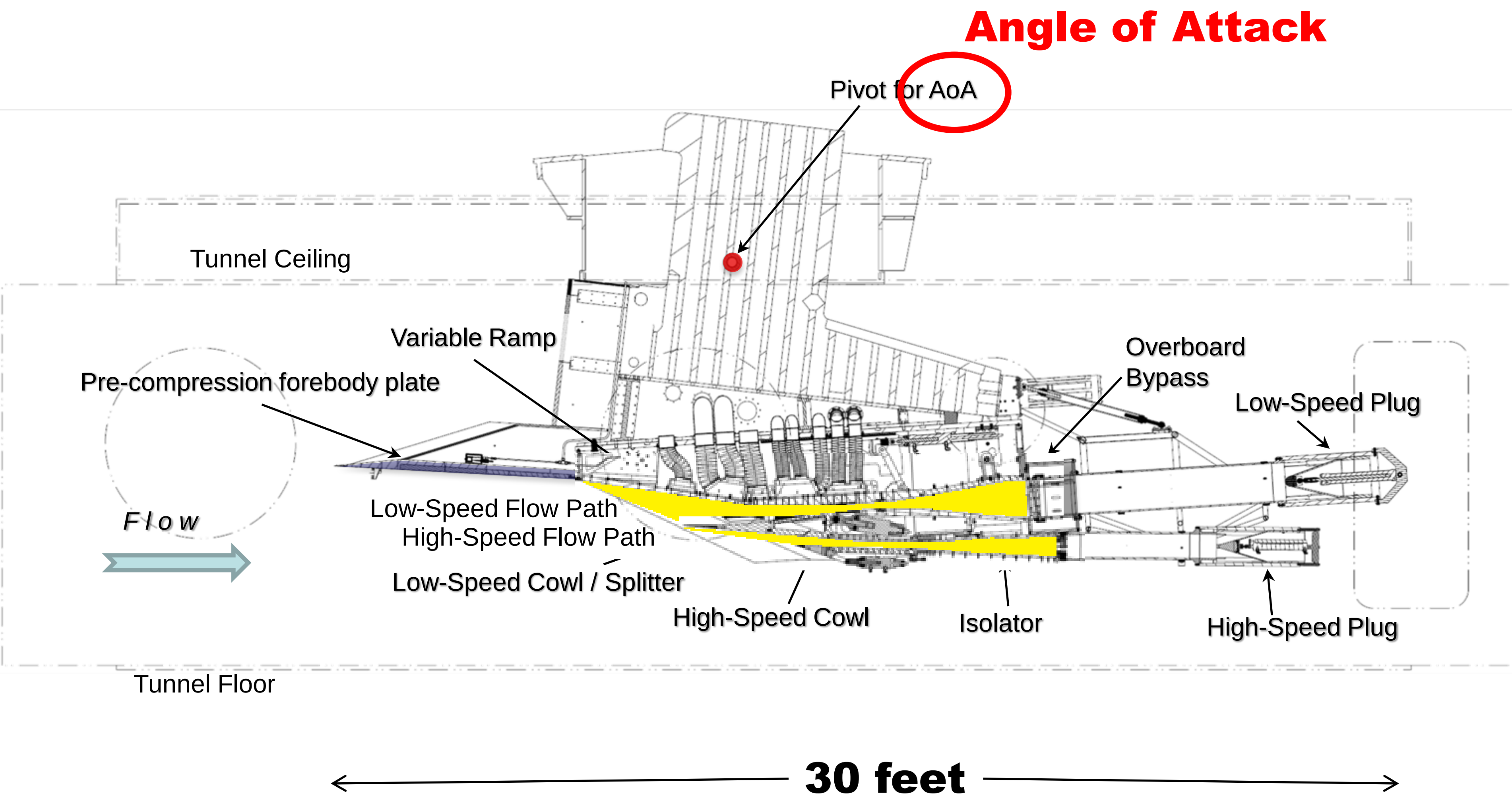
Test Approach - 4 Phases

1. Inlet performance and operability characterization, open-loop mode transition sequencing
2. System identification of inlet dynamics for controls
3. Demonstrate control strategies for smooth & stable closed-loop mode transition (not funded)
4. Add turbine engine and nozzle for integrated system test with simulated scramjet (not funded)

Testbed Features

- Variable Low Speed Cowl
- Variable High Speed cowl
- Variable Ramp
- Variable Compartmented Bleed (13)
- Low Speed Mass flow / Backpressure Device
- High Speed Mass flow / Backpressure Device
- Inlet Performance Instrumentation (~800)
- Engine Face: Flow Characteristics (AIP)

CCE-LIMX Model Features



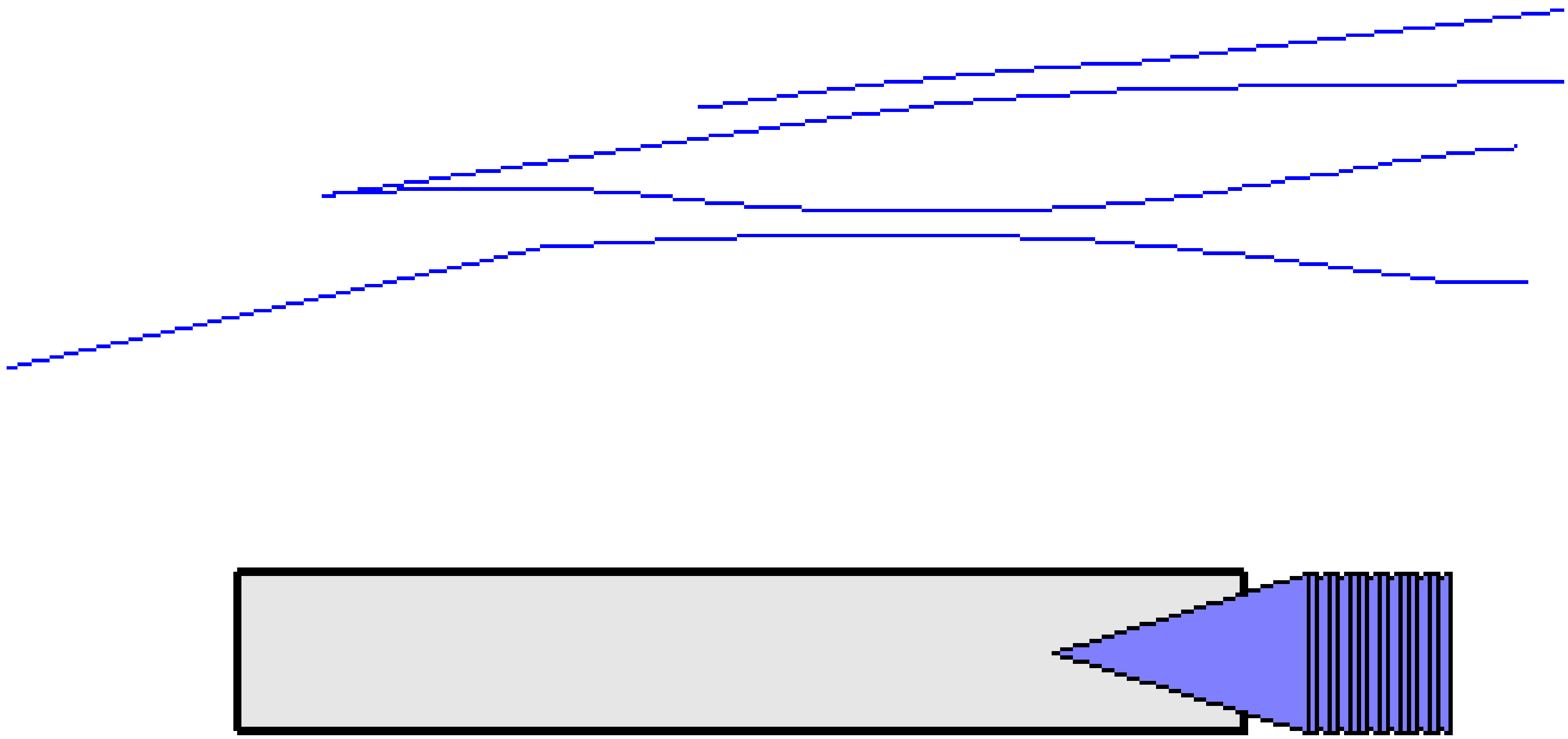
Phase 1 –Objectives for Inlet Characterization

- Investigate inlet mode transition from turbine to dual-mode ramjet (DMRJ)
  - Provide relevant inlet design information about the mode transition Mach number
    - Use a turbine inlet design that is capable of high performance.
    - Airflow amounts relevant to both turbine and DMRJ.
  - Document performance and operability (or stability).

- Generate a validation database
  - Provides key information for CFD tool development.
  - Information to guide future TBCC mission analysis.

- Prepare control information for latter test phases
  - System identification schedules.
  - Coherent, straight-forward control strategy.
  - Prepare for turbine engine integration which could occur in phase 4.

Phase 1: Inlet Characterization and Performance Testing



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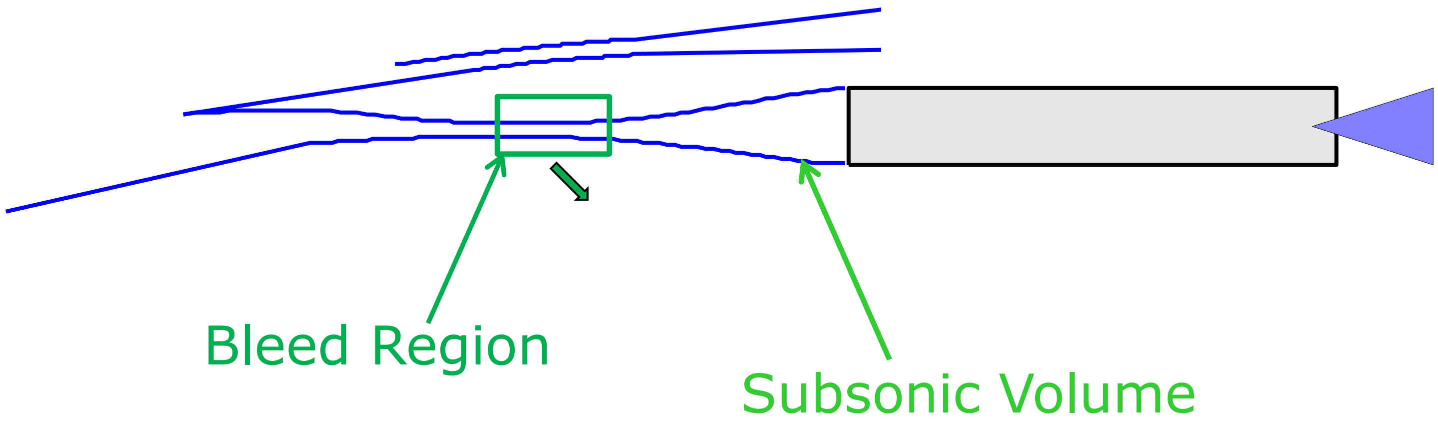

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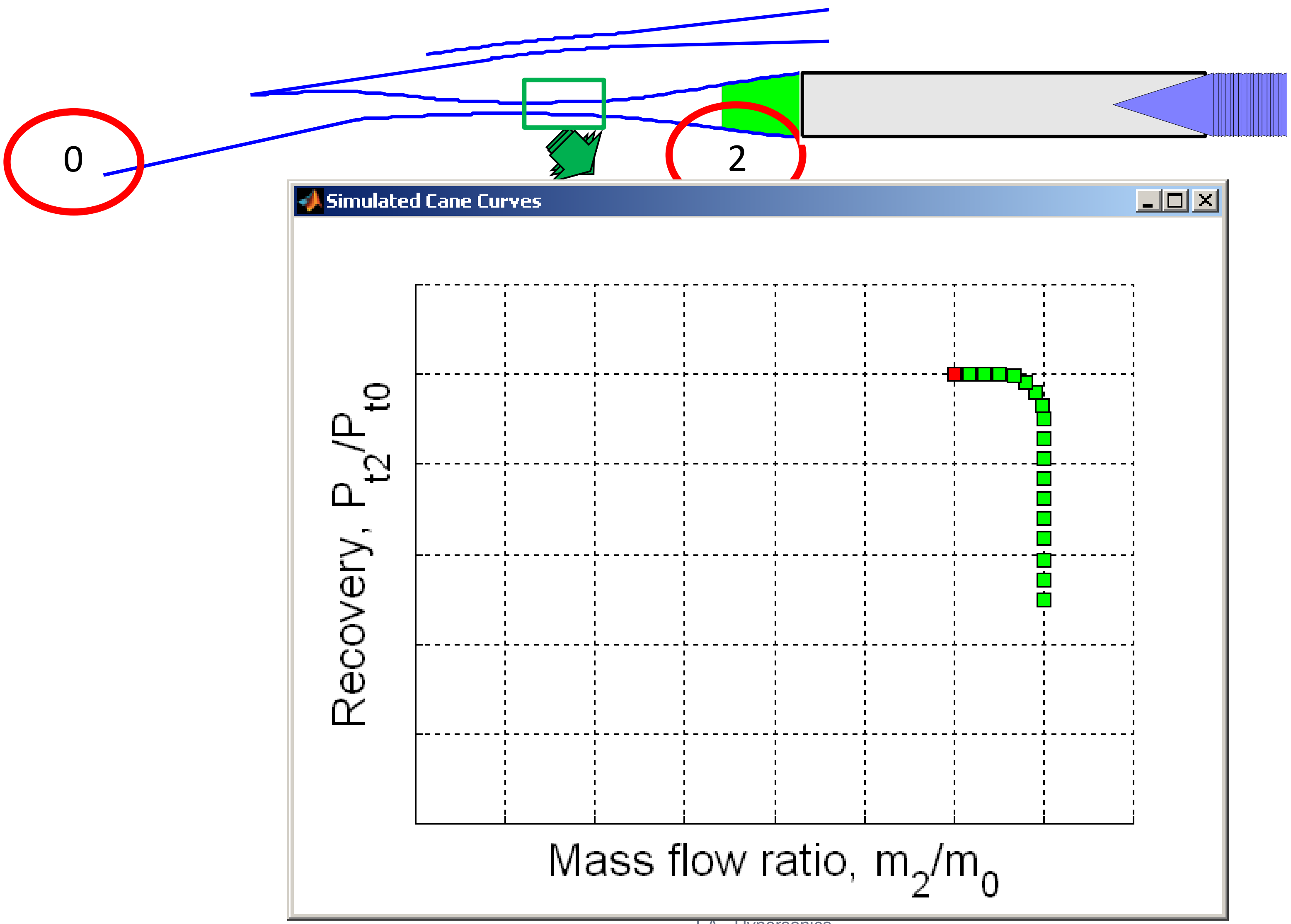

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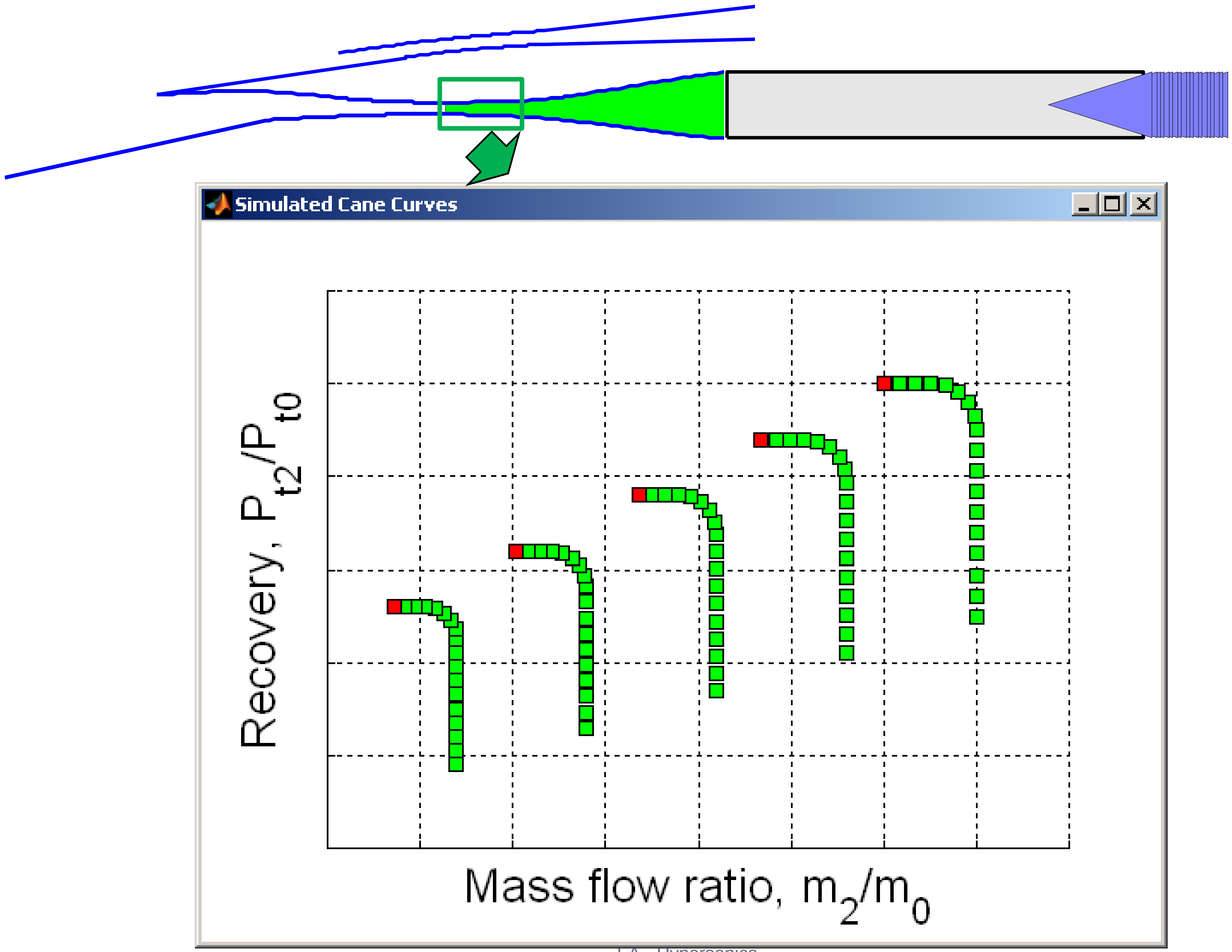
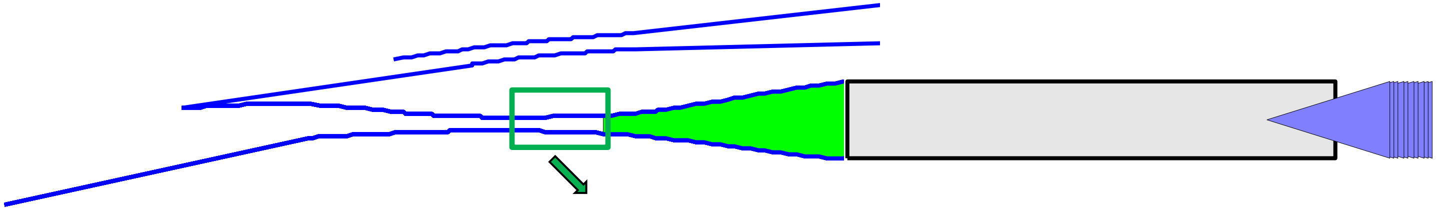
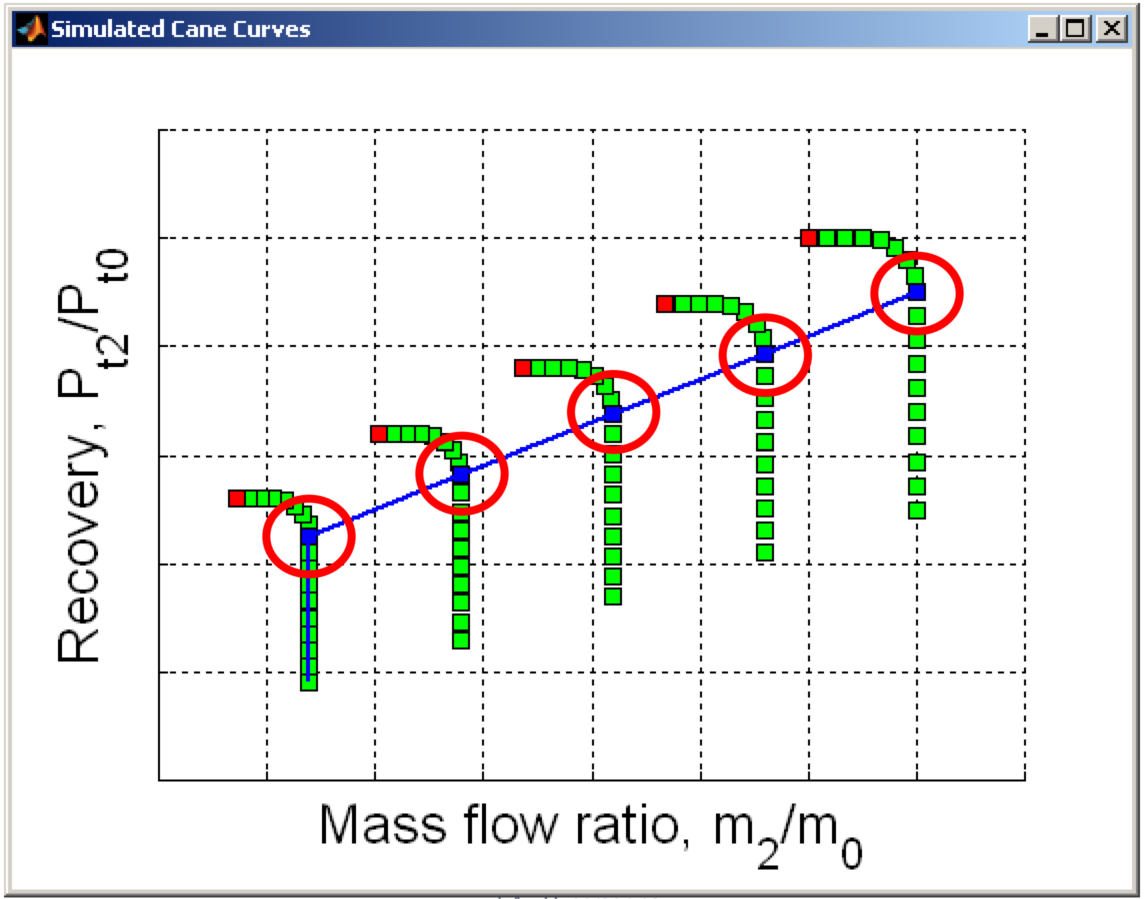


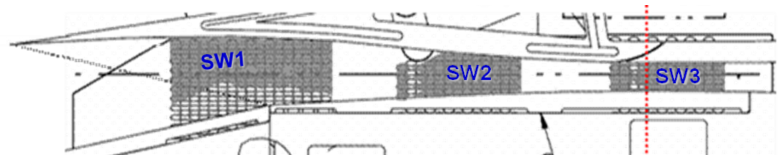
Phase 1: Inlet Characterization and Performance Testing

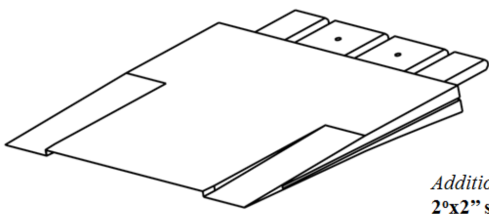




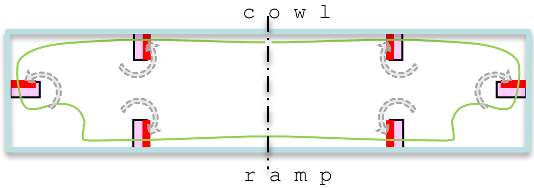
Phase I –Inlet Testing Progress

- Data restrictions
  - 10x10 SWT test data is ITAR.
  - Pre-test planning, 1x1 test data, and CFD predictions (non-validated) are open.
- Planned configurations
  - bleed patterns
  - vortex generators
  - low-speed cowl
- CFD collaboration
  - GRC in-house
  - Boeing
  - NCHCCP—Boeing and NC State predictions typified by:
    - TM-2012-217219, 58th JANNAF, “Computational Analyses of the LIMX TBCC Inlet High-speed Flowpath,” (Dippold), April 2011
    - TM-2010-216362, “Computational Fluid Dynamics (CFD) Simulation of Hypersonic Turbine-Based Combined-Cycle (TBCC) Inlet Mode Transition,” (Slater et al.)
    - 2011, 2010 AFOSR/NASA Hypersonics Fundamental Review, “TBCC Dual-Inlet Mode Transition: TBCC Inlet Analysis & Modeling,” (Sexton, et. al).



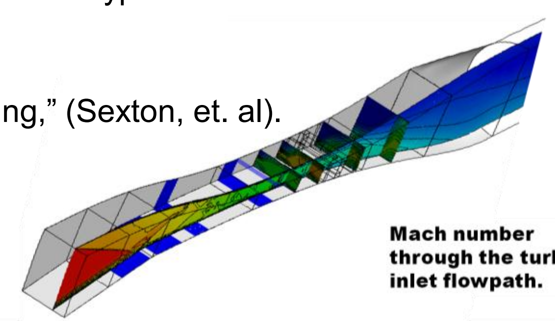


Additional ~0.8% spillage
2"x2" scoop each side(S2D)



AIP flow field for Basic VG Configuration

Shock structure within scramjet isolator.



Mach number through the turbine inlet flowpath.

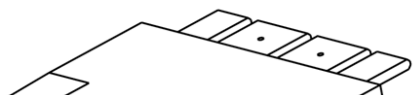
Phase I –Inlet Testing Progress

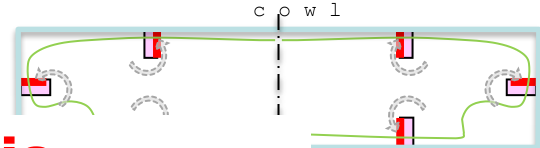
- Data restrictions
  - 10x10 SWT test data is ITAR.
  - Pre-test planning, 1x1 test data

International Traffic in Arms Regulation

- Planned configurations
  - bleed patterns
  - vortex generators
  - low-speed cowl lips

NASA GRC 1- x 1-foot Supersonic Wind Tunnel





- CFD collaborations
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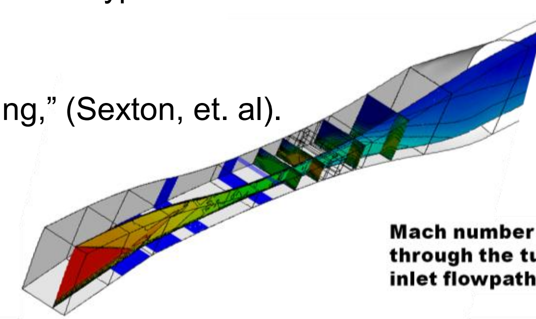
National Center for Hypersonic Combined Cycle Propulsion

North Carolina State University

Shock structure within scramjet isolator.



Mach number through the turbine inlet flowpath.

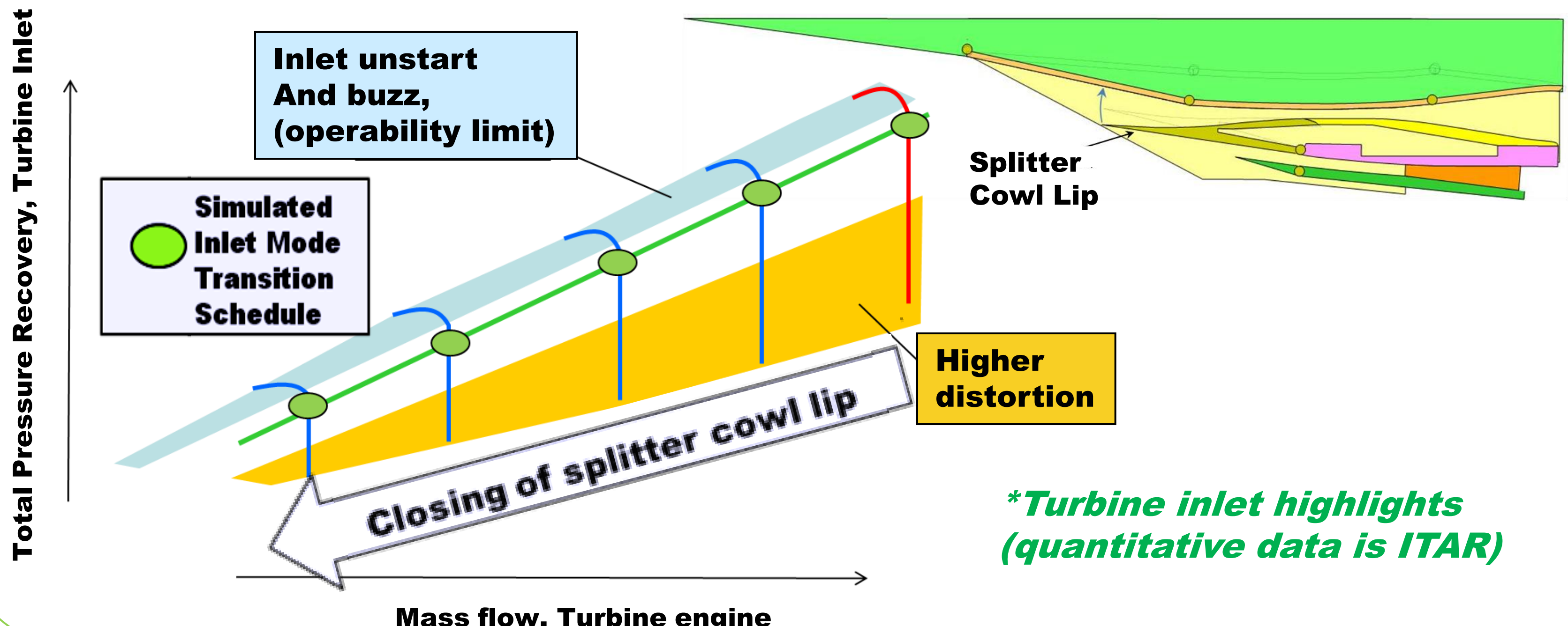
Phase 1 –Accomplishments

- Test matrix status Phase 1a
  - Mach 4, ~90%, Mach 3, >5%, + off-design
  - 1,942 steady-state and 670 dynamic data points (or readings)
  - Test sequences:
    - Cane curves, to document: recovery, distortion, flow, and unstart limits.
    - Mode transition, to hold a constant corrected flow or schedule flow operating line
      to document operation while low speed cowl is closing
      - Steady state points
      - 5-10 second sequences using facility control
      - Snap sequence using research control
    - Operability due to ΔMach or Δangle perturbations at Mach 4
- Test window: 3/7/2011 – 6/17/2011, 23 run nights (data collection)
  - ~80 hrs at high Mach numbers (> M3).
  - 14.9 Gwatt-hours of energy (power is ~200MWatts with tunnel Mach at 3.5).

- Smooth open-loop mode transition was successfully demonstrated with a high performance inlet suitable for a turbine operating at Mach 4.

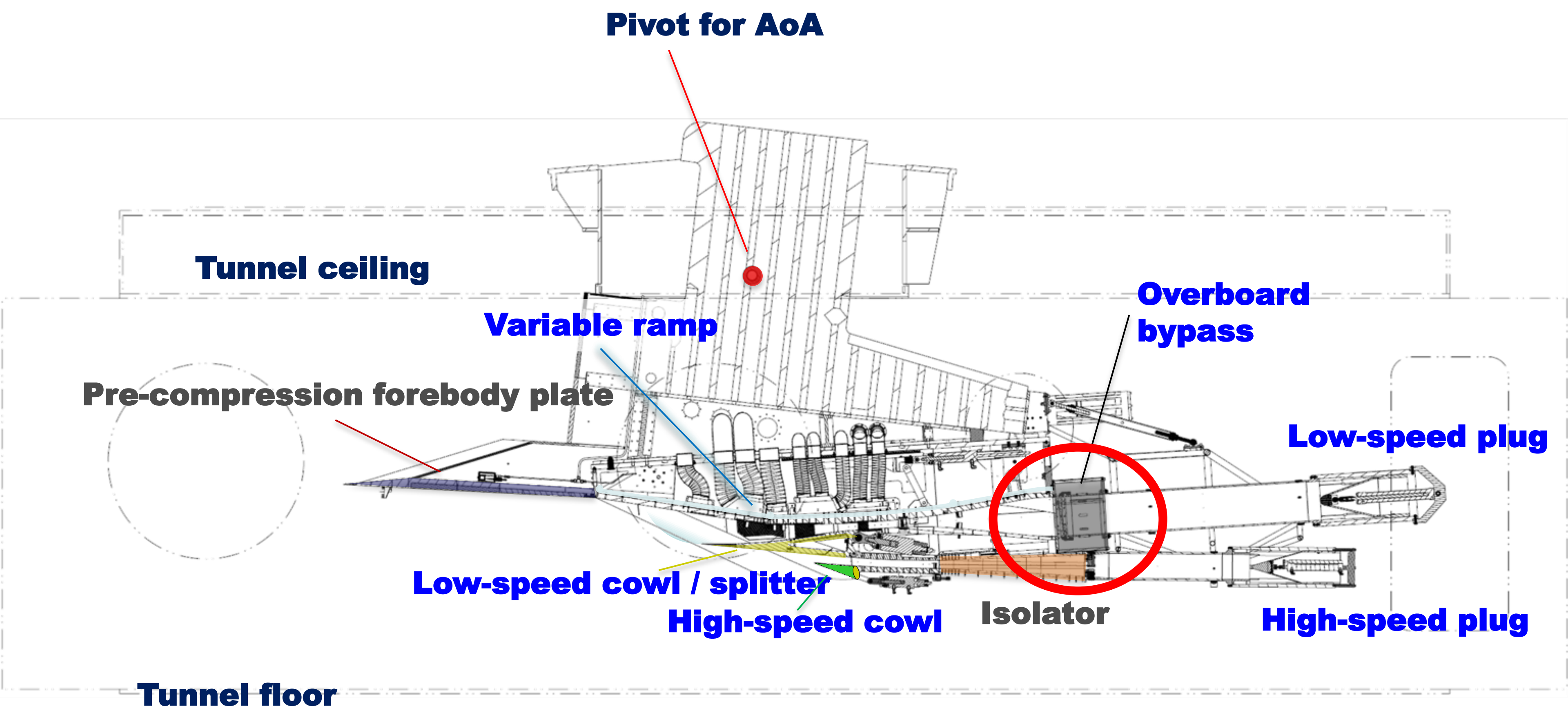
Phase 1 –Accomplishments

- Test sequences:
  - Cane curves, to document: recovery, distortion, flow, and unstart limits.
  - Mode transition, to hold a constant corrected flow or schedule flow operating line to document operation while low speed cowl is closing
  - Both turbine engine* and DMRJ inlet databases developed.

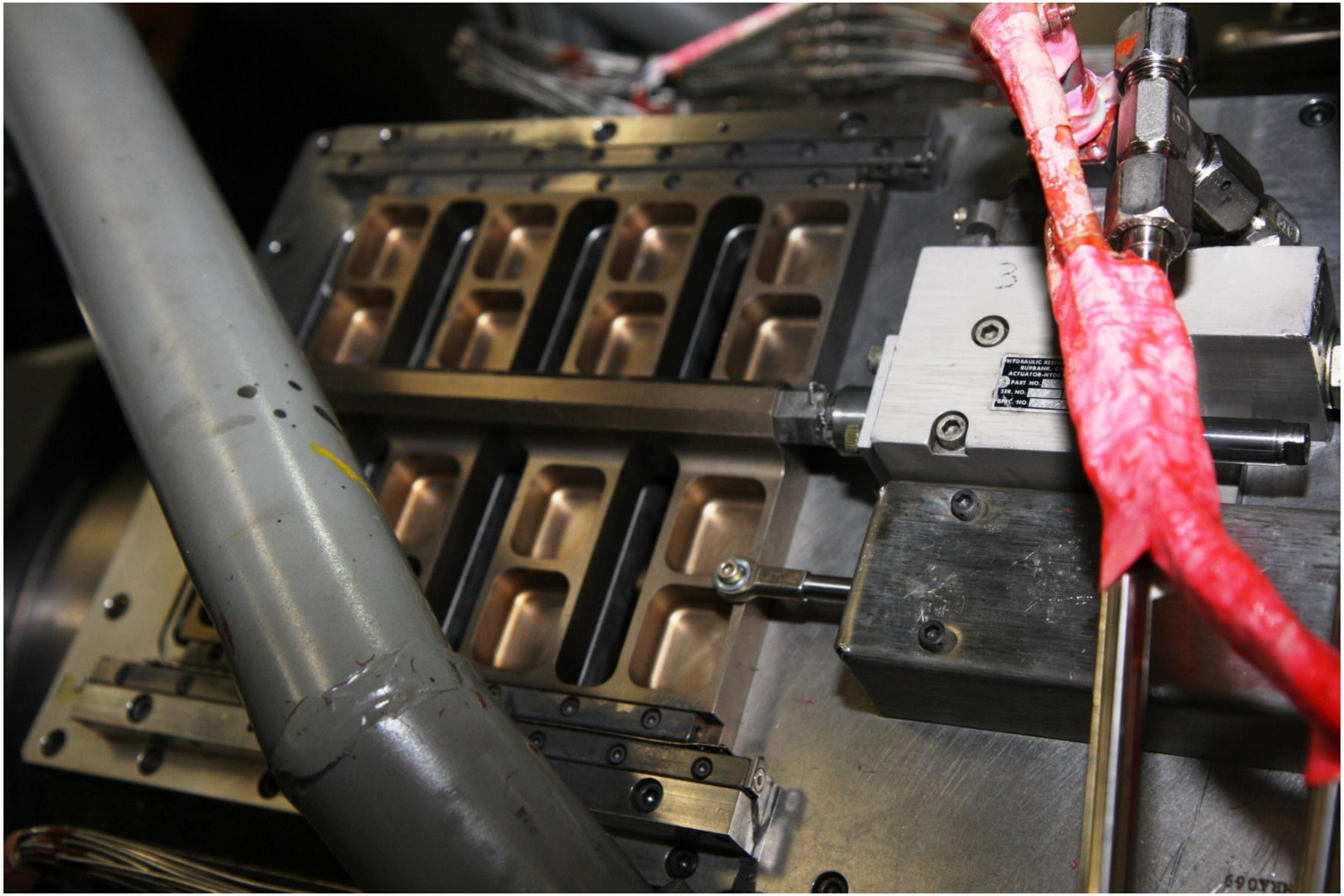


Turbine inlet highlights (quantitative data is ITAR)

Phase 2 Objective: Designing a controller for the CCE-LIMX



#3 of Four Bypass Doors



Controls Team Objectives

Provide a system capable of meeting the following objectives:

- Automate the mode-transition schedule
- Automate system identification process
- Support controls investigations

System Identification Instrument Rack (SysID Rack)

Requirements:

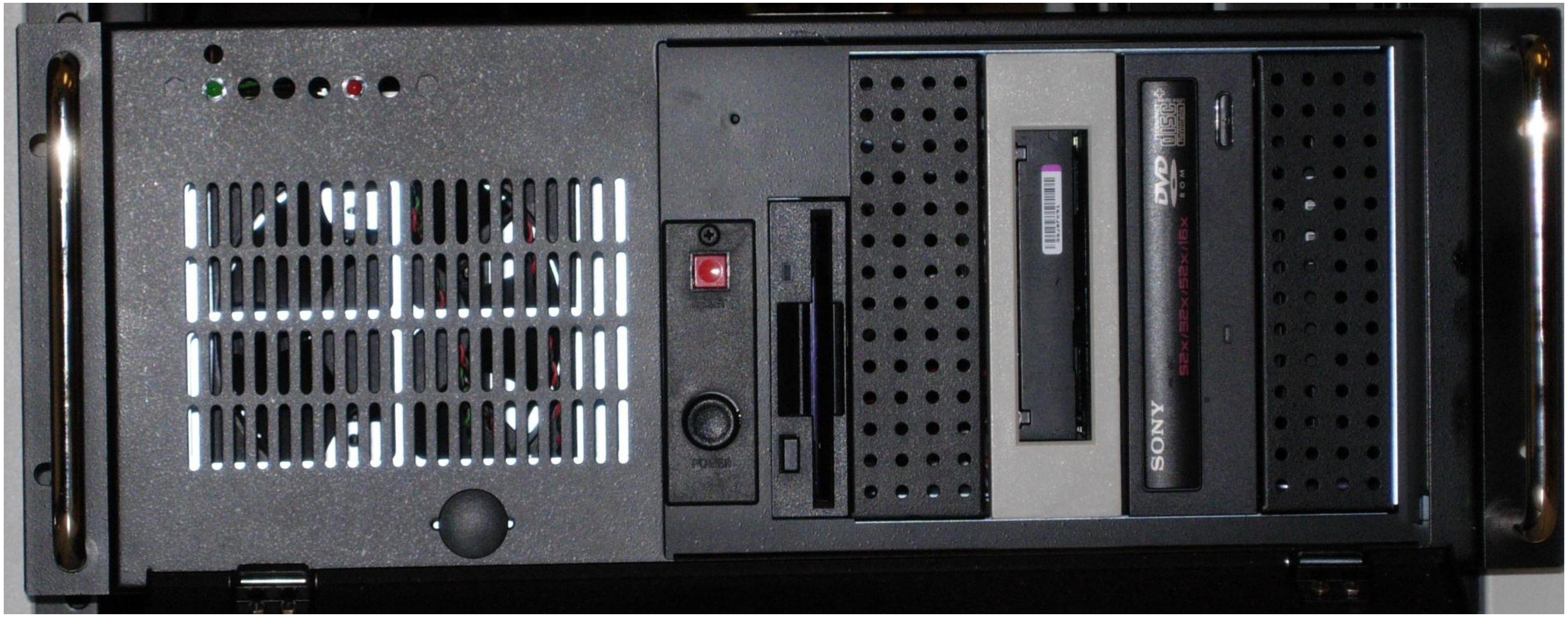
- Move multiple actuators synchronously
- Automate the mode-transition schedule
- Read and save high-speed pressure sensor measurements
- Read and save actuator position feedback signals
- Apply system identification stimulating signals
- Implement closed-loop stability control algorithms.

System Identification Instrument Rack (SysID Rack)

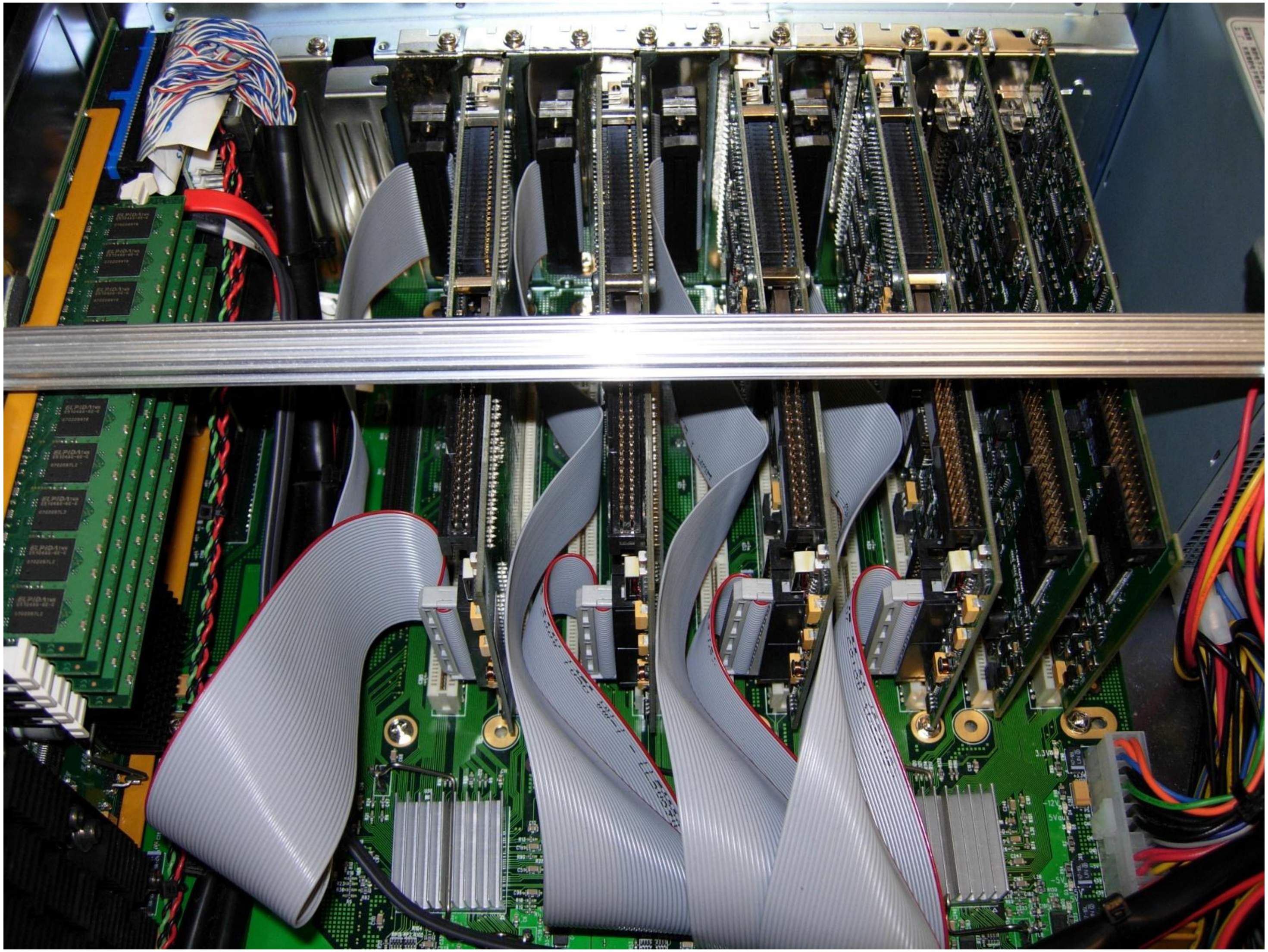
Host Laptop Computer

SysID Rack, Components

Rack-Mount Computer
Real-Time xPC Target™ Operating System



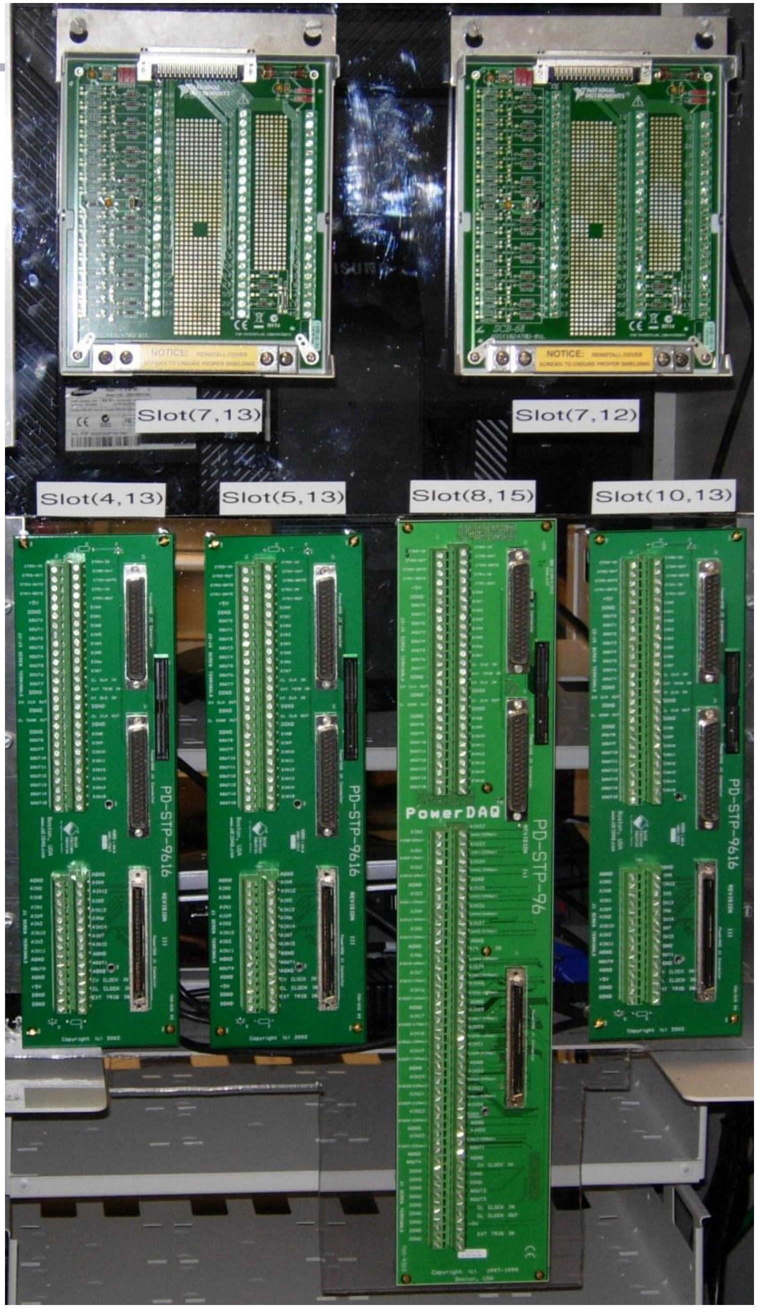
Rack-Mount Computer
Real-Time xPC Target™ Operating System



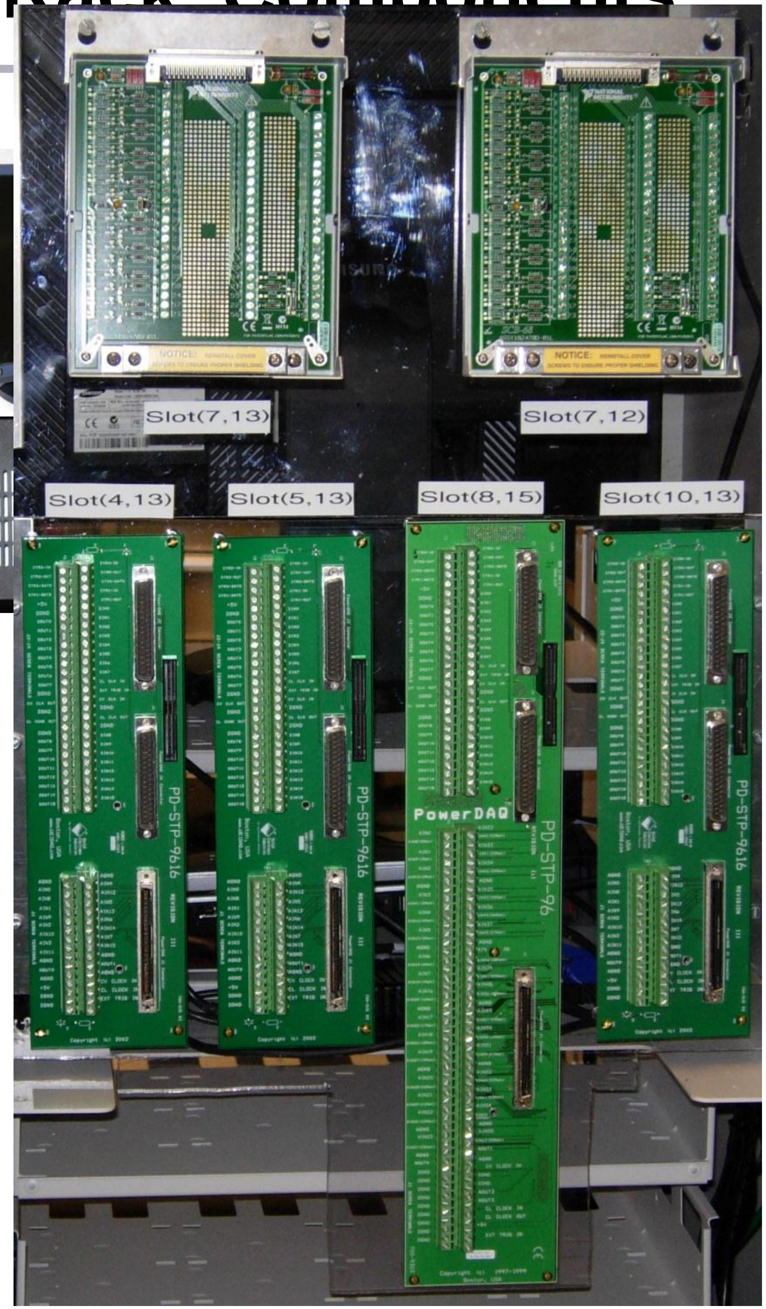
SysID Rack, Components

SysID Rack, Components

Analog-to-Digital and Digital-to-Analog Breakout Panel



SysID Rack Components



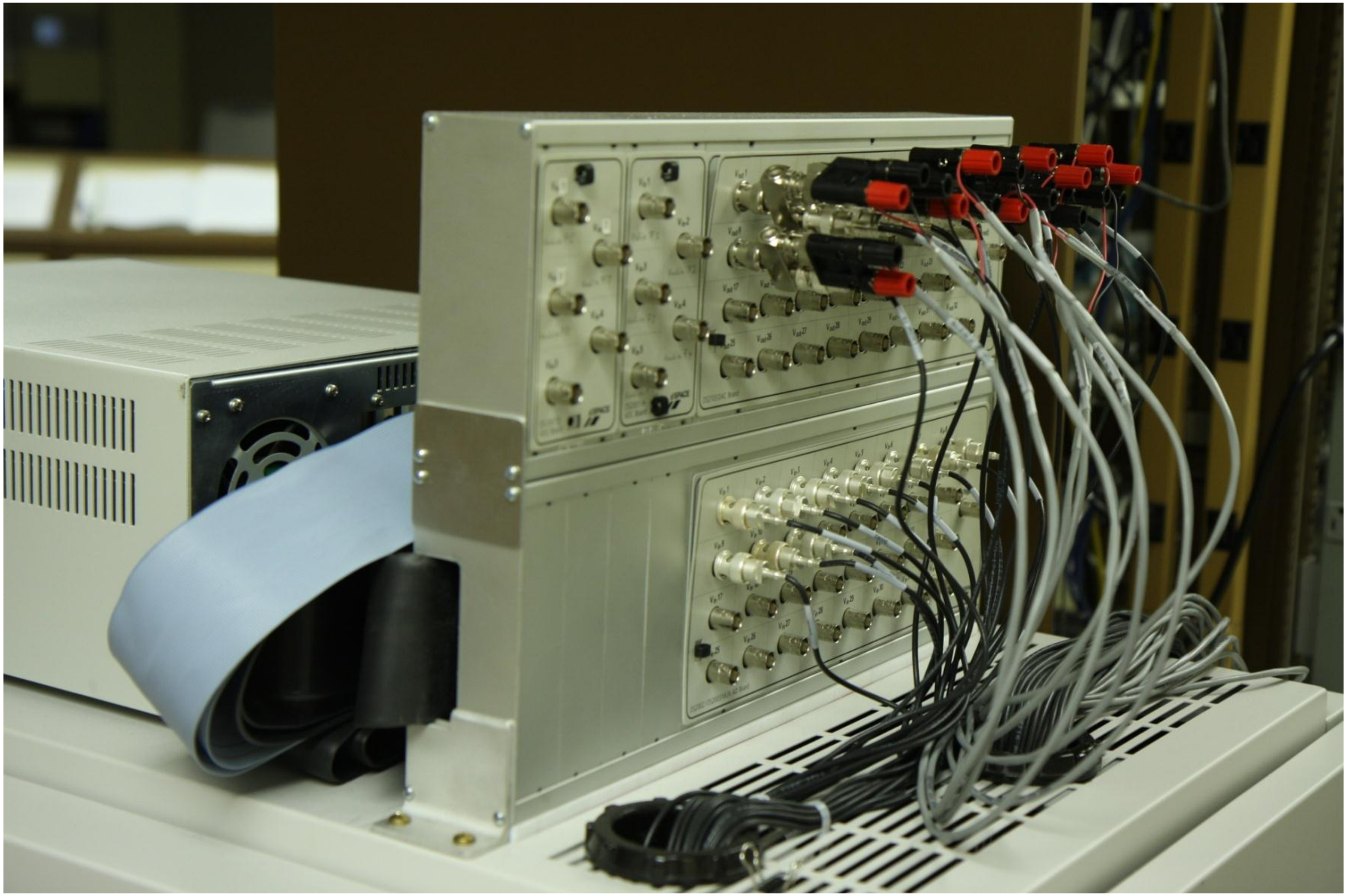
SysID Rack, Components

8th order
Bessel Filters

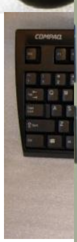
High Frequency
Pressure Sensors

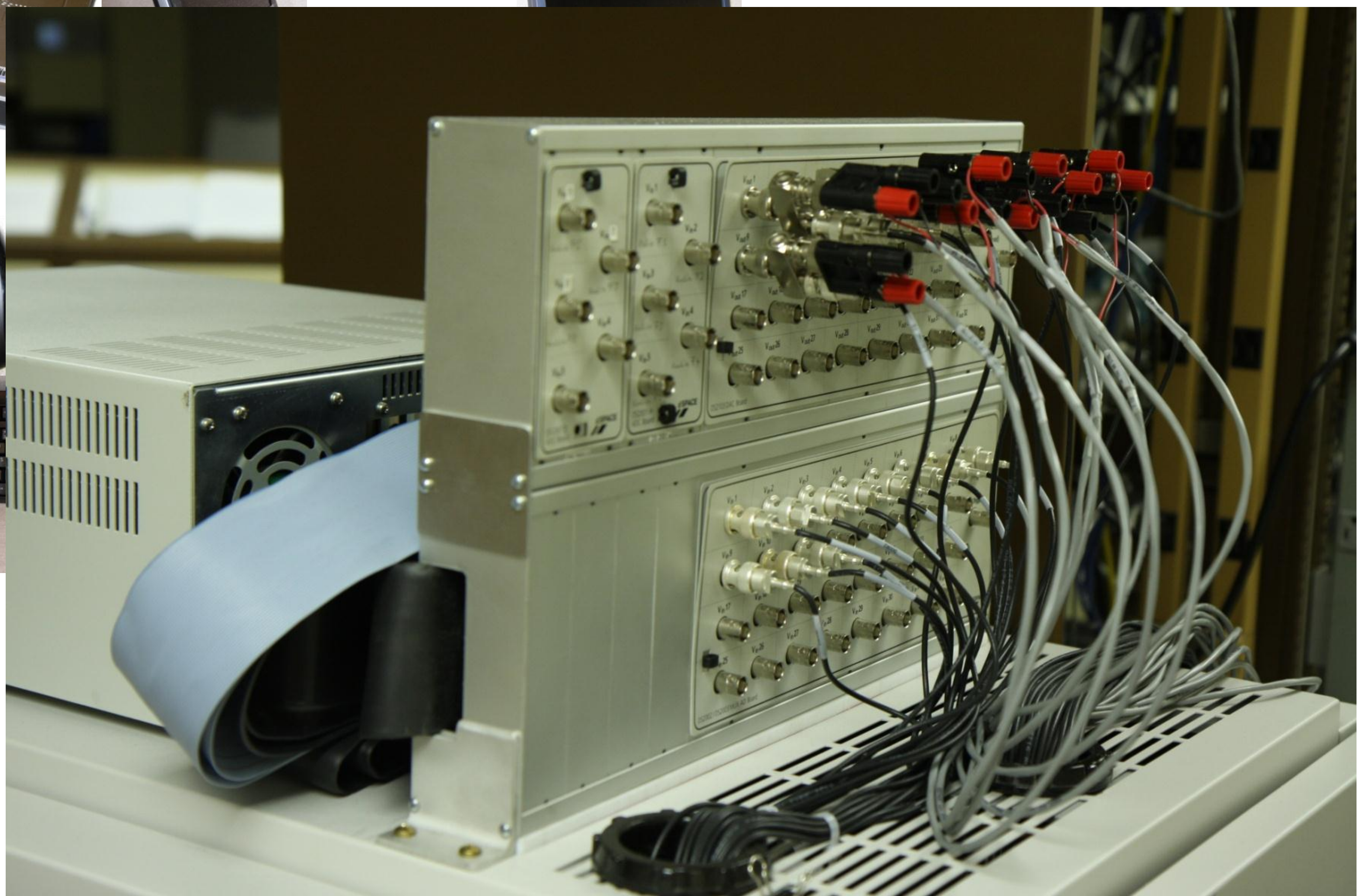
Actuator Feedback
Position Sensors

Dspace® System



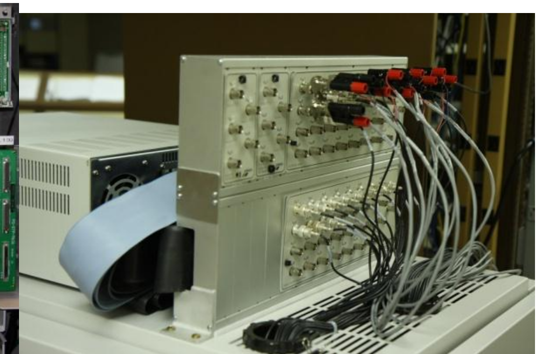
SysID Rack, Components





Position Sensors

SysID Rack, Components



8th order
Bessel Filters

Actuator
Position
Hydraulic
Controllers

High Frequency
Pressure Sensors

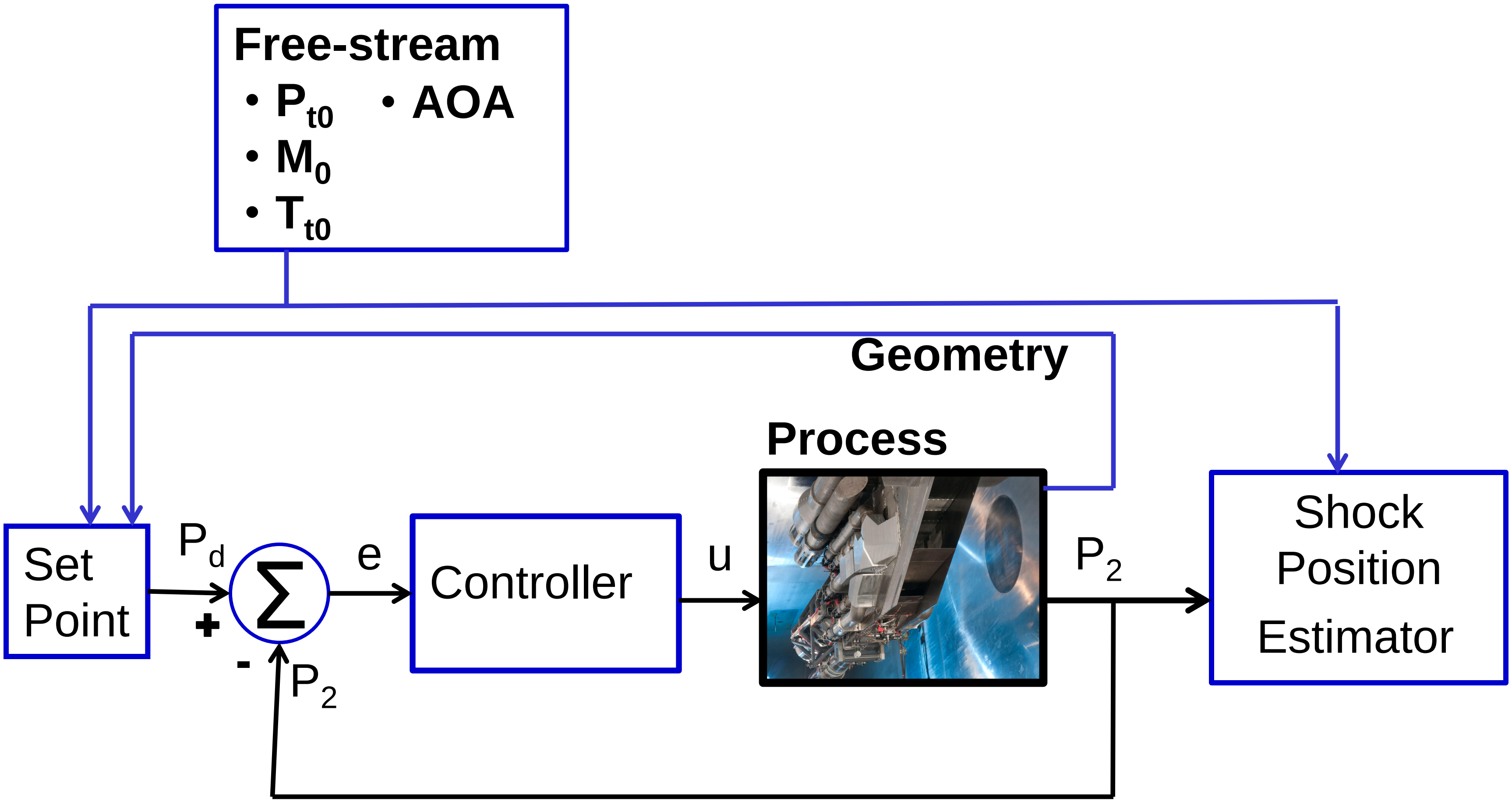
Actuator
Position Sensors

SysID Rack, Software

- Commercial-Off-the-Shelf
  - Mathwork® software
    - Matlab®,
    - Simulink®,
    - xPC Target™,
    - Real-Time Workshop®,
  - Microsoft® Excel®, and
  - a C Compiler.
- Custom Code
  - Target model
  - Host computer interface
  - Host graphical user interfaces (GUIs)

Design a Controller

Design a Controller

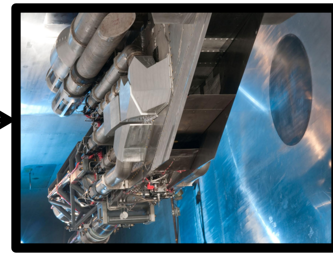


Design a Controller

Bypass Door Moog Control Signal

u(k)

Process



y(k)

P_2

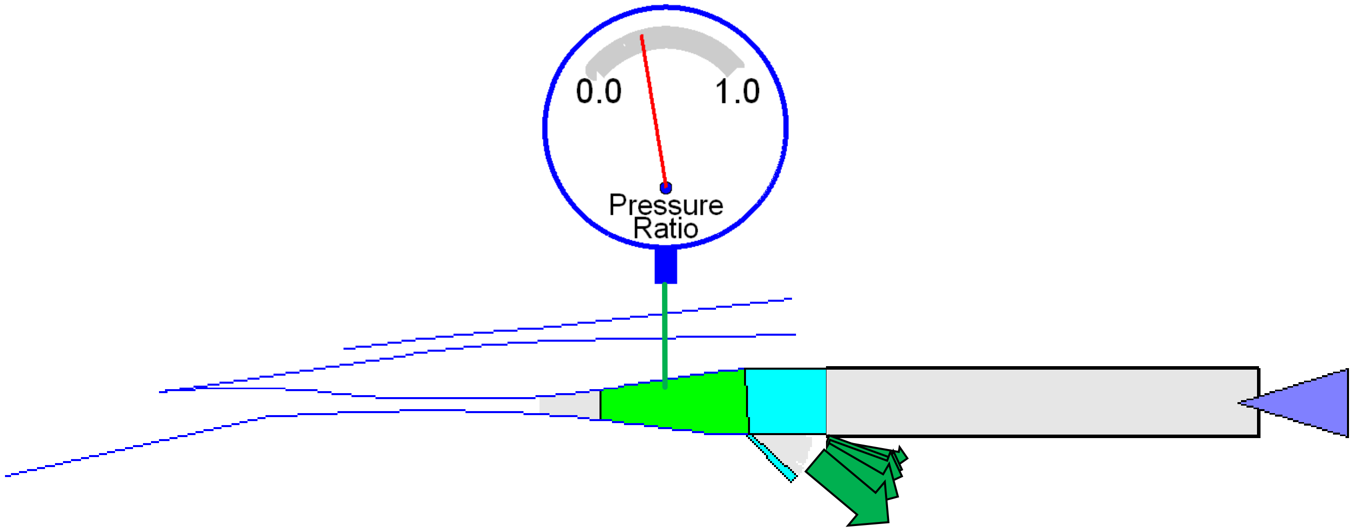
Process Assumptions:

Sufficient control design simulation can be captured in a linear computational autoregressive control model.

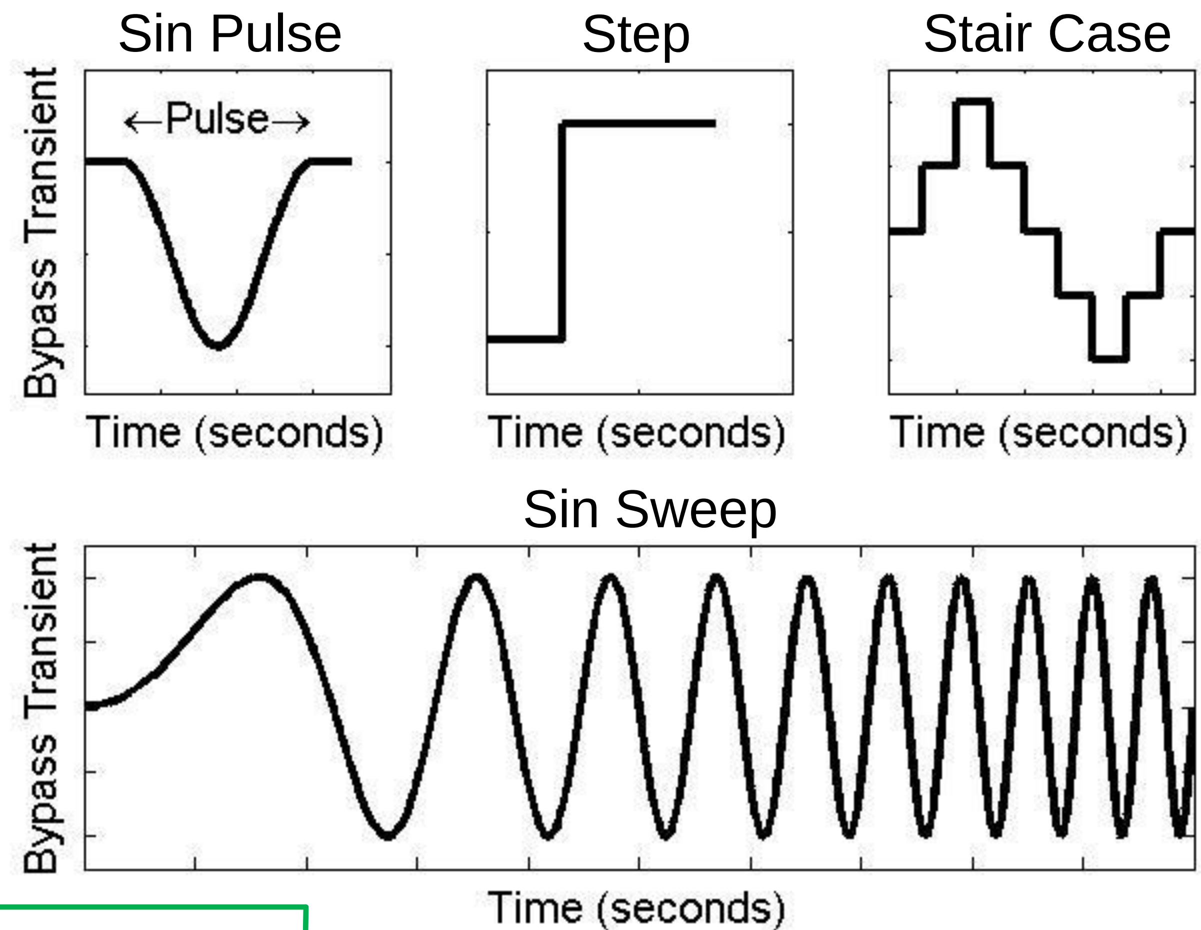
Autoregressive Model:

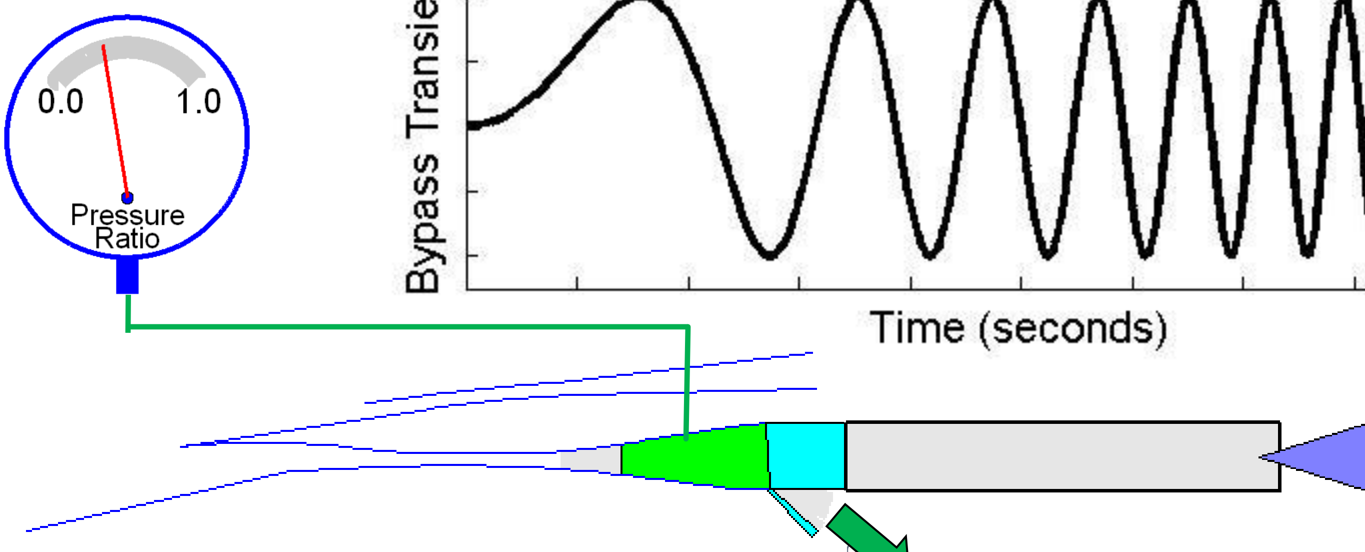
$$y(k+1) = a_0 y(k) + a_1 y(k-1) + \ldots + a_n y(k-n) + b_0 u(k) + b_1 u(k-1) + \ldots + b_n u(k-n)$$

Stimulate the Process



Stimulate the Process





Phase 2 Accomplishments

- Test matrix status Phase 2a Mach 4
  - 642 experiments identified, ~89 hrs
    - Main (LST1 and HST1) schedule—506 experiments, ~49 hrs
    - First alternate (LST1 and HST2) schedule—68 experiments, ~20 hrs
    - Second alternate (LST2 and HST2) schedule—68 experiments, ~20 hrs
  - Reduced matix—393 experiments selected, ~29 hrs
    - Main schedule—378 experiments completed, 38.25 hrs
    - Alternates—0 experiments completed
  - Experiments:
    - Step, Sinusoidal-Sweep, Sustained-Sinusoid
    - Staircase, Transient Stability Index (S_{it}),
    - Unstart, Buzz, Restart
- Test window: 8/29/2011 – 10/19/2011
- 11 run nights (data collection)

Phase 2 Accomplishments

Low-Speed flow path Track-2
High-Speed flow path Track-2

- Test matrix status Phase 2a Mach 4
  - 642 experiments identified, ~89 hrs
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- Test window: 8/29/2011 – 10/19/2011
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SysID Rack Performance

- Calibrations in parallel with 10- x 10-foot facility calibration operations.
- Control transfer from facility to SysID Rack and back
  - Small changes in actuator positions due to discrepancy in interpreted actuator positions—insignificant.
    - We had exposure to feedback signals in engineering units.
    - Better to match voltage signals applied to the controller.
  - Verified SysID rack controllability prior to facility pump down
  - Verified SysID rack data acquisition performance while facility pump down.
- Data acquisition and experiment control performed flawlessly

Future Plans

- Continue to expand Phase 1b database at Mach 4, 3, and off-design
- Prepare for Mach 3 turbine operation (phase 4 with partnerships)
- Continue CCE Phase 2b testing
- Reduce Phase 2 data to Control Design Models (CDMs)
- Compare physics based computational models against CDMs.
- Design control algorithm for maintaining desired pressure recovery
- CCE-LIMX Phase 3 and 4 testing (if funding becomes available)
  - Test controller on physics based computational models
  - Buildup SysID Rack to support Phase 3 experiments
- Investigate control applications for dual-mode scramjet engine flow paths.

Summary

- Well underway to meeting Phase 1 and 2 objectives:
  - Completed:
    - Databases developed for both turbine engine and DMRJ flow paths
    - System identification experiments were designed and conducted to study the dynamic issues associated with inlet mode transition
    - Smooth open-loop mode transition was successfully demonstrated with a high performance inlet suitable for a turbine operating at Mach 4.
      - SysID Rack, hardware and software, was designed:
        - » Demonstrated inlet mode transition.
        - » Automated system identification experiments
        - » Useful for implementing real-time control

Summary

- Well underway to meeting Phase 1 and 2 objectives:
  - Underway
    - Phase 1 databases are being examined:
      - Enhance inlet design capabilities
      - CFD code validation
    - Dynamic analysis of the system identification experiment data
      - frequency spectrum of interest for active control
      - Experiment based Control Design Model (CDM) development
    - Preparing physics based models to simulate dynamics of inlet mode transition (validation)
    - Designing controllers based on:
      - experimental data
      - physics based computational models.
    - Testing controller algorithms on physics based computational models.

NASA