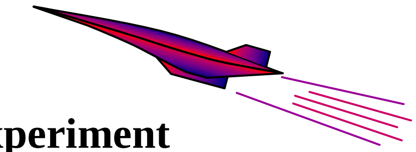
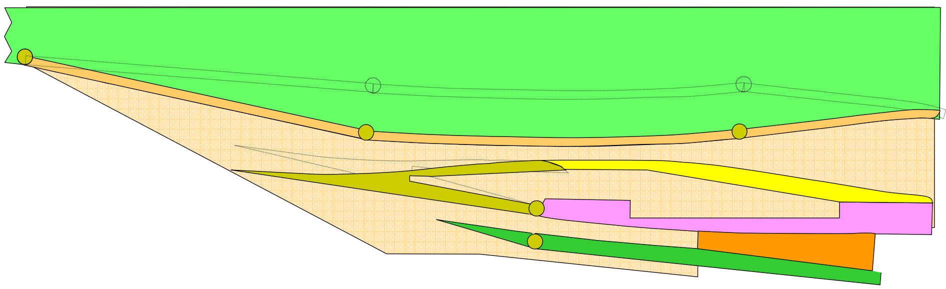
TBCC Inlet Experiments and Analysis

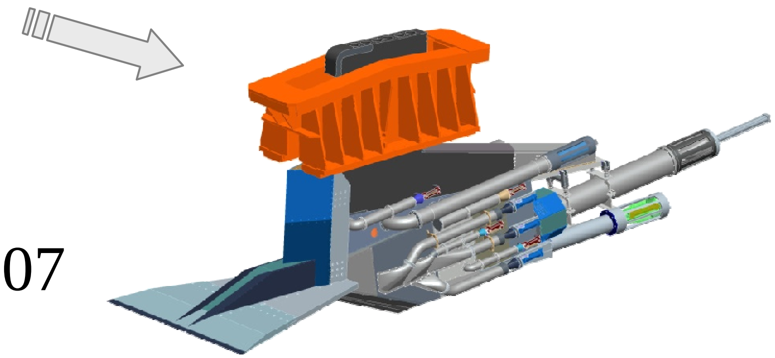
A research plan is being implemented at NASA to investigate inlet mode transition for turbine-based combined-cycle (TBCC) propulsion for the hypersonic community. Unresolved issues have remained on how to design an inlet system to supply both a turbine engine and a ram/scramjet flowpath that operate with both high performance and stability. The current plan is aimed at characterizing the design, performance and operability of TBCC inlets through a series of experiments and analyses. A TBCC inlet has been designed that is capable of high performance (near MIL-E-5008B recovery) with smooth transitioning characteristics. Traditional design techniques were used in an innovative approach to balance the aerodynamic and mechanical constraints to create a new TBCC inlet concept. The inlet was designed for top-end Mach 7 scramjet speeds with an over/under turbine that becomes cocooned beyond its Mach 4 peak design point. Conceptually, this propulsion system was picked to meet the needs of the first stage of a two-stage to orbit vehicle. A series of increasing fidelity CFD-based tools are being used throughout this effort. A small-scale inlet experiment is on-going in the GRC 1’x1’ Supersonic Wind Tunnel (SWT). Initial results from both the CFD analyses and test are discussed showing that high performance and smooth mode transitions are possible. The effort validates the design and is contributing to a large-scale inlet/propulsion test being planned for the GRC 10’x10’ SWT. This large-scale effort provide the basis for a Combined Cycle Engine Testbed, (CCET), that will be able to address integrated propulsion system and controls objectives.

TBCC Inlet Experiments and Analysis



(Initial Screening Results of a Small-Scale Inlet Mode Transition Experiment and progress toward a Large-scale IMX testbed)





October 31st 2007

Dave Saunders, John Slater, Vance Dippold & Jinho Lee
NASA Glenn Research Center
Cleveland, Ohio

Bobby Sanders & Lois Weir
TechLand Research, Inc.
North Olmsted, Ohio

TBCC Inlet Experiments and Analysis

Overview

Background, (definition, history & objectives)

TBCC Inlet Design, (dual flow path, constraints & CFD)

CFD Results, (validation, performance & test guidance)

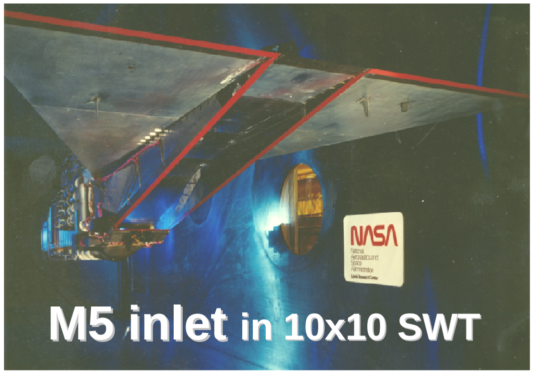
1x1 SWT screening results (configurations, M4, & off-design)

Conclusions and 10x10 Large-scale tests

TBCC Inlet Experiments and Analysis

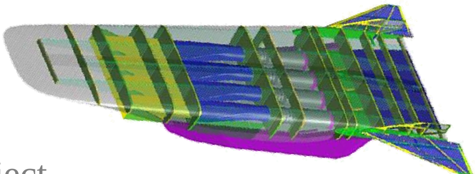
Background: (*TBCC=Turbine Based Combined Cycle*)

- Mode-transition: definitions (***IMX***= ***I***nlet ***M***ode ***X***,transition)
- Previous/related programs:
  - M5, X43b
  - HiSTED, Robust Scramjet, RATTLRS, FALCON



- Over-under concept and TBCC
- Current effort: Two-pronged testing
  - (S) IMX = small-scale
  - (L) Large-scale Combined Cycle Engine (inlet/controls/engines) Collaborative effort with ATK/Boeing/Williams

- TBCC IMX Objectives



TBCC Inlet Experiments and Analysis

TBCC Inlet Research Objectives

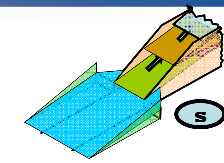
- L/S Research over/under split flow inlet for TBCC.
  - Demonstrate mode transition at S small and L large-scales.
  - Develop a integrated database of performance & operability.
    - S Low-speed inlet (sized for Mach 4 turbine engine).
    - L High-speed inlet (DMRJ for Mach 7 cruise)
- L/S Validate CFD predictions for each inlet's design approach, and performance and operability prediction.

- L Measure distortion characteristics throughout the mode transition Mach number range.
- L Operability database for future mode transition controls research
- L Testbed for integrated inlet/engine propulsion system tests

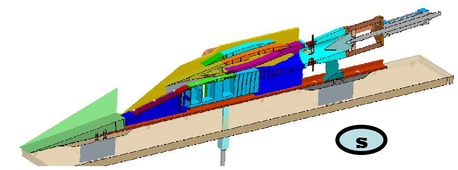
Inlet mode transition addressed by small & large-scale experiments

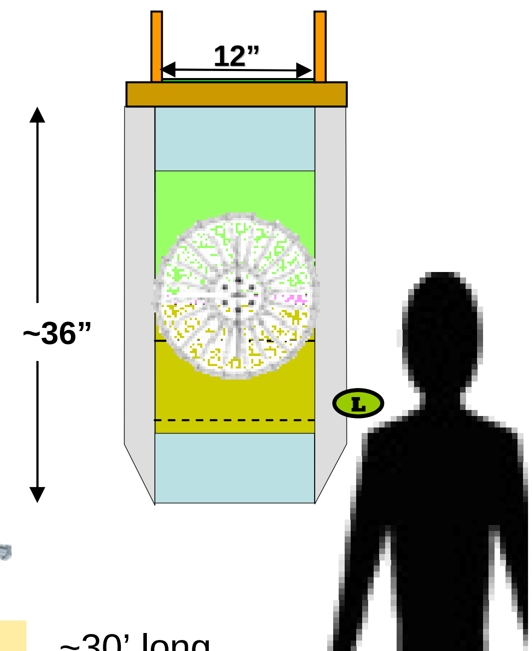
TBCC Inlet Experiments and Analysis

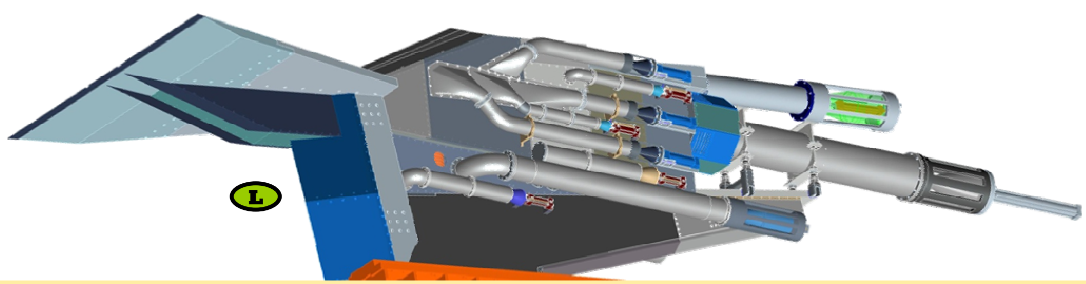
Inlet model requirements for CCET (Combined-Cycle Engine Testbed)



- Used 2D aerodynamic design and mechanical concept from small-scale IMX effort.
  - IMX, ‘Inlet Mode Transition’ is a small screening inlet model to qualitatively understand operability.
  - Key follow-on test is to get large scale data for quantifying performance, operability, controls development
- Forebody required roughly based on Mach 7 X43-b vision vehicles
- Facility selection: Turbine engine siziing requires large facility
  - GRC 10’x10’ propulsion supersonic wind tunnel selected
- Remotely variable ramp and rotating HS&LS inlet cowls
- Over-travel LS cowl to allow M3 to M4 mode transitions
- Variable bleeds, bypasses to allow test flexibility and controls work
- Flow metering on both turbine flowpath **&** DMRSJ flowpaths
- Engines diameter of **~12”** chosen.
  - Mid-sized 12” engine being developed towards M4 in HiSTED, RATTLRS



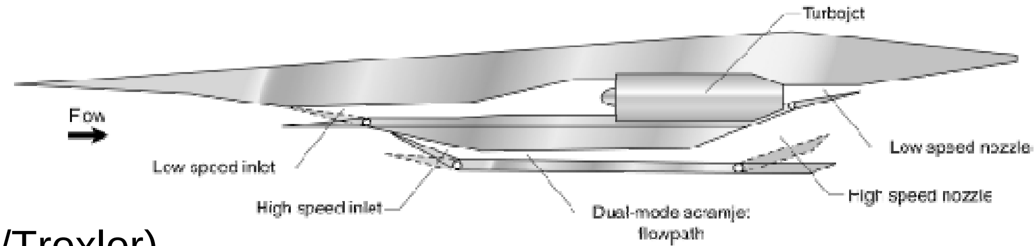




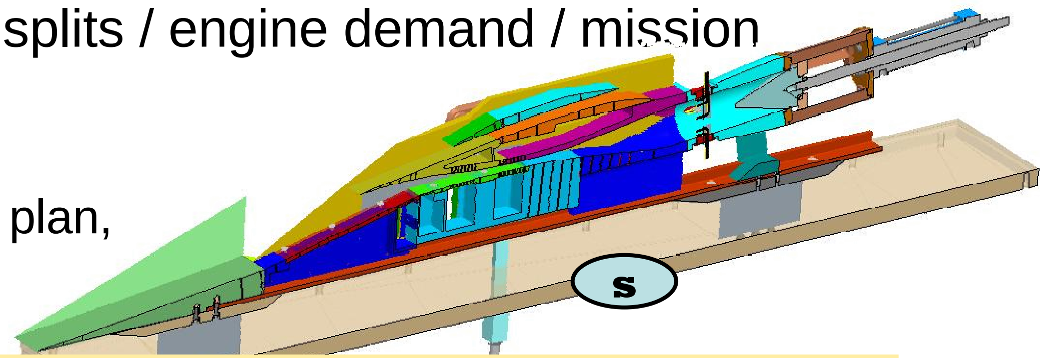
Inlet model provides ‘strongback’ for propulsion integration

~30’ long

TBCC Inlet Design



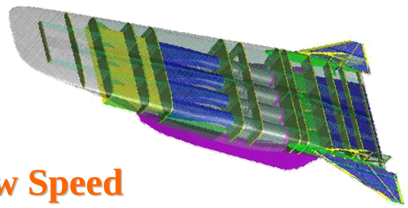
- High-speed: (ref. Albertson/Emami/Trexler)
- Low-speed: supersonics / mixed comp. / bleed / visc.effect / YF-12 / XB-70 / SST>HSCT
- Integration: vehicle, turbofan, high-speed flowpath
- Mach 7 Hydrocarbon fueled Scramjet with Mach 4 transition from Turbine
- Historical recoveries / Flow splits / engine demand / mission
- Impact of CFD:
  - Visualize, Instrument, Test plan,
  - Design, Controls

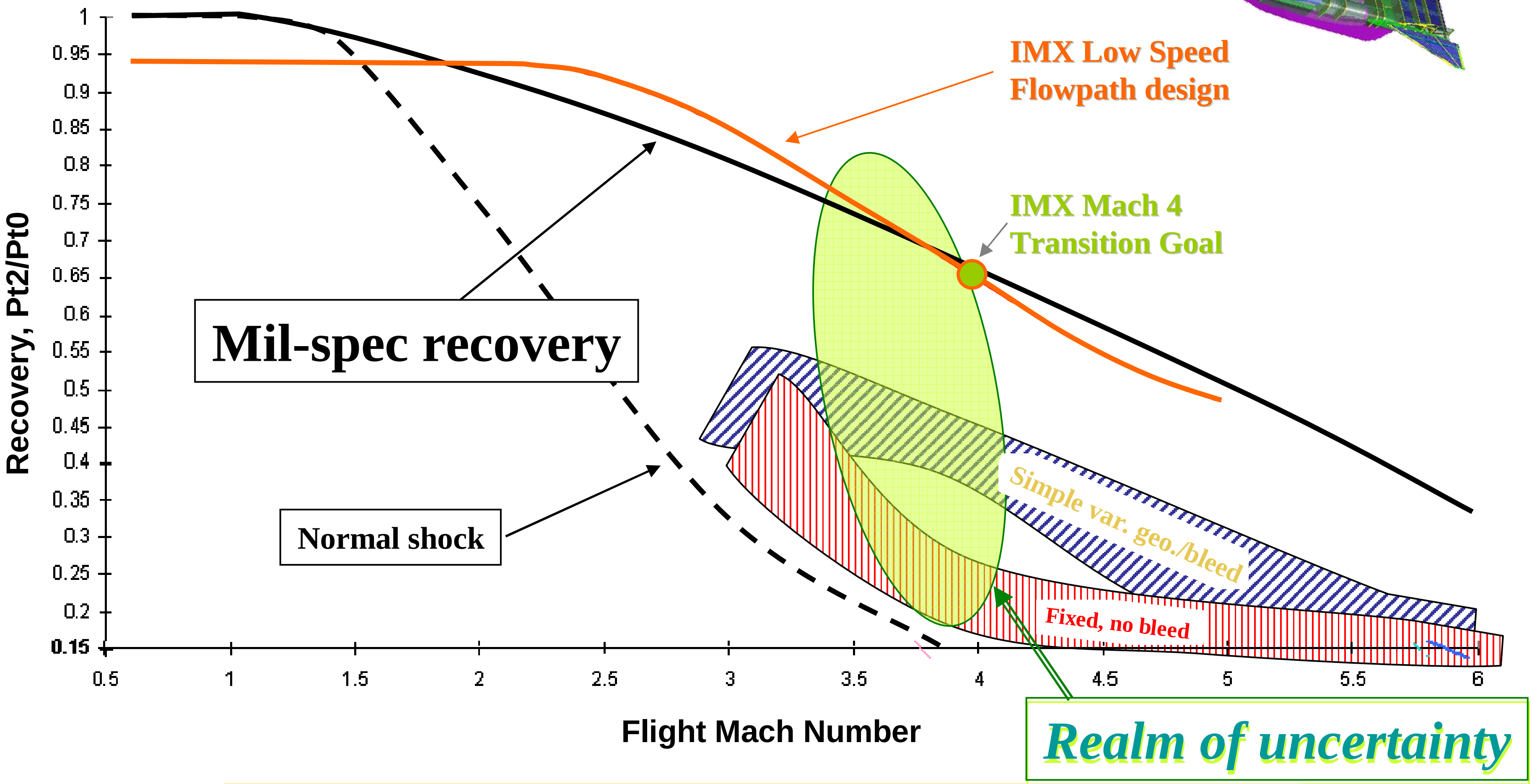


Inlet design driven by TBCC studies, CFD tools, and physical constraints

TBCC Inlet Experiments and Analysis

Inlet Pressure Recoveries for TBCC, ?s

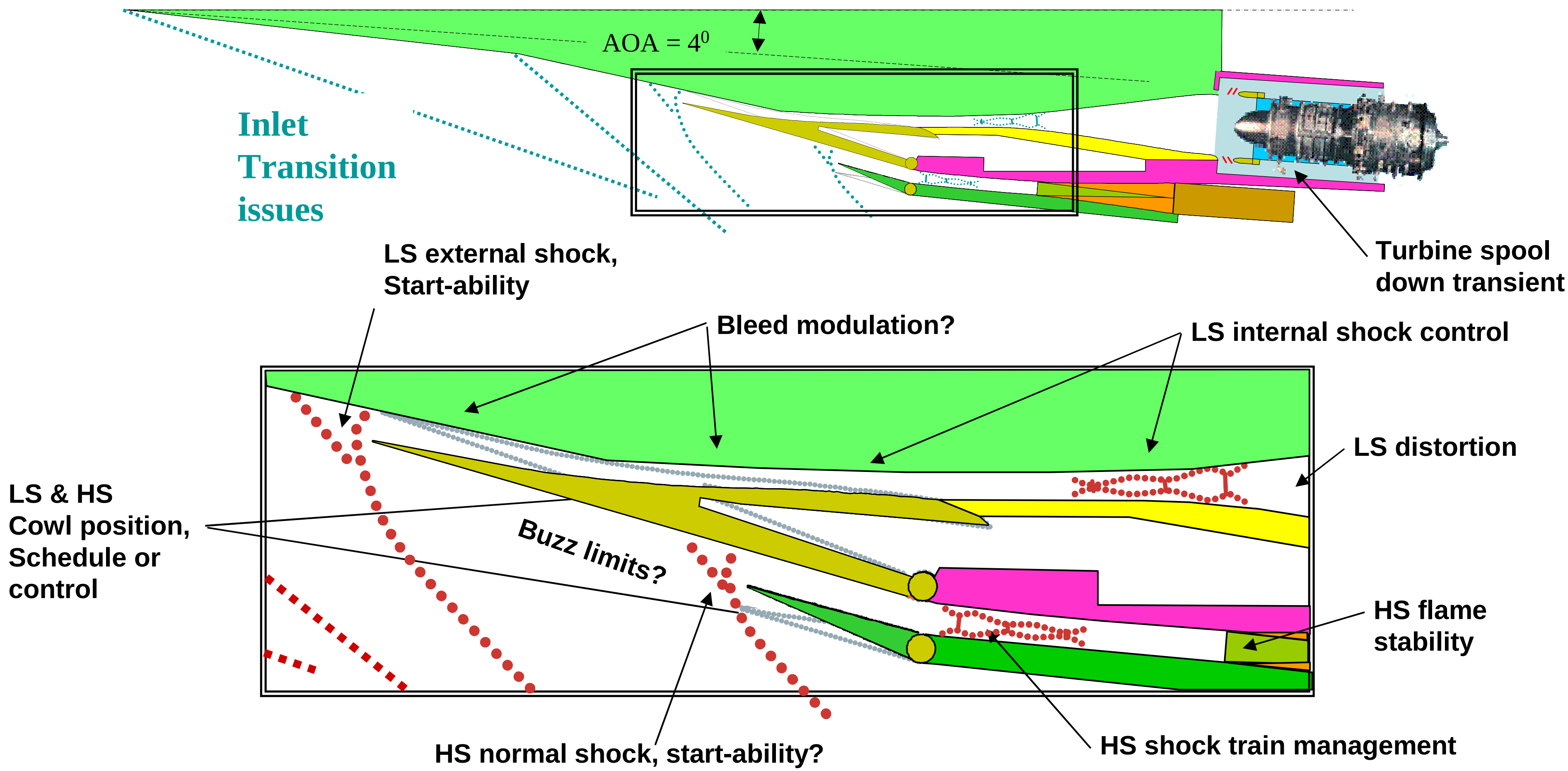




Inlet performance can vary by 4x depending on inlet design

TBCC Inlet Experiments and Analysis

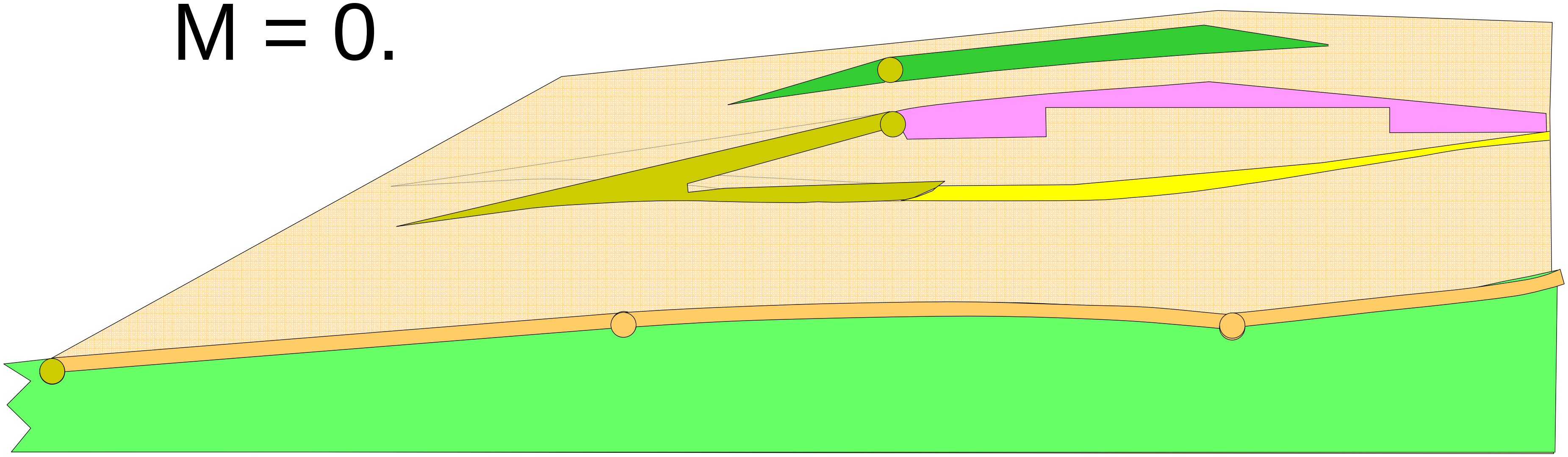
Mode transition sequences: *Mach 4 shock scenarios*



Mode transition design at Mach 4 has complex interations

TBCC Inlet Experiments and Analysis

M = 0.



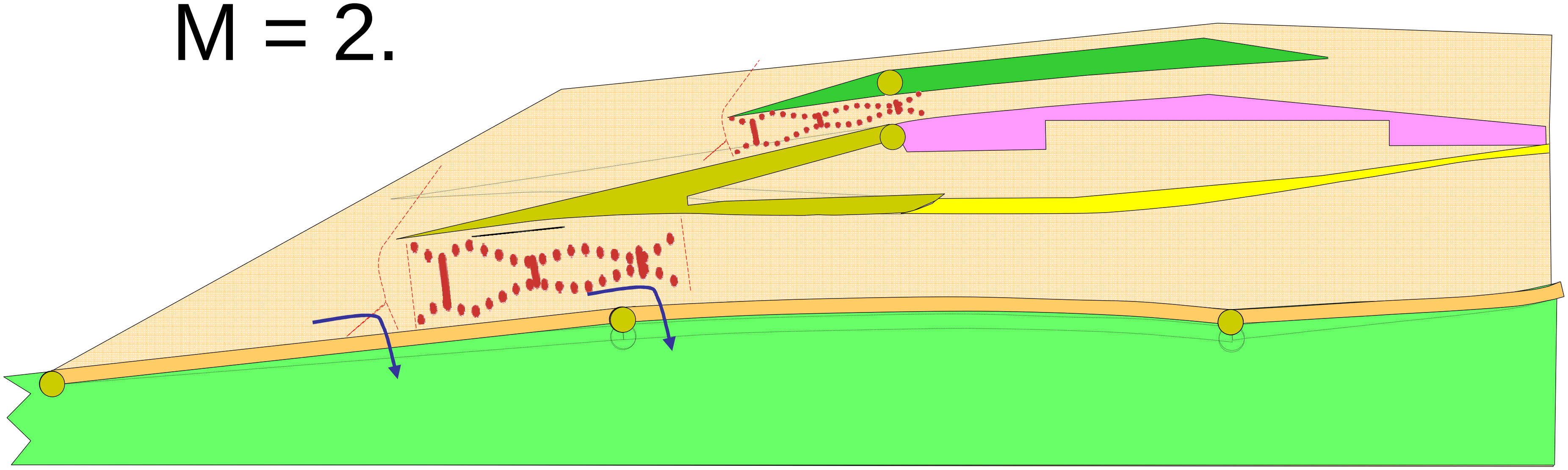
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis

M = 2.

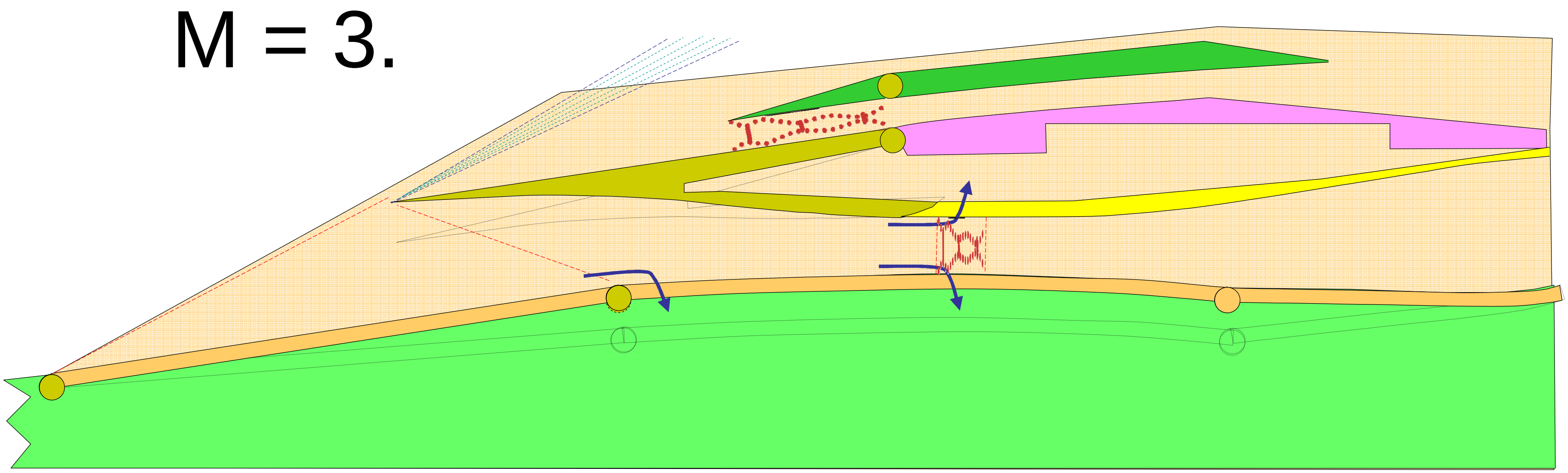


Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis



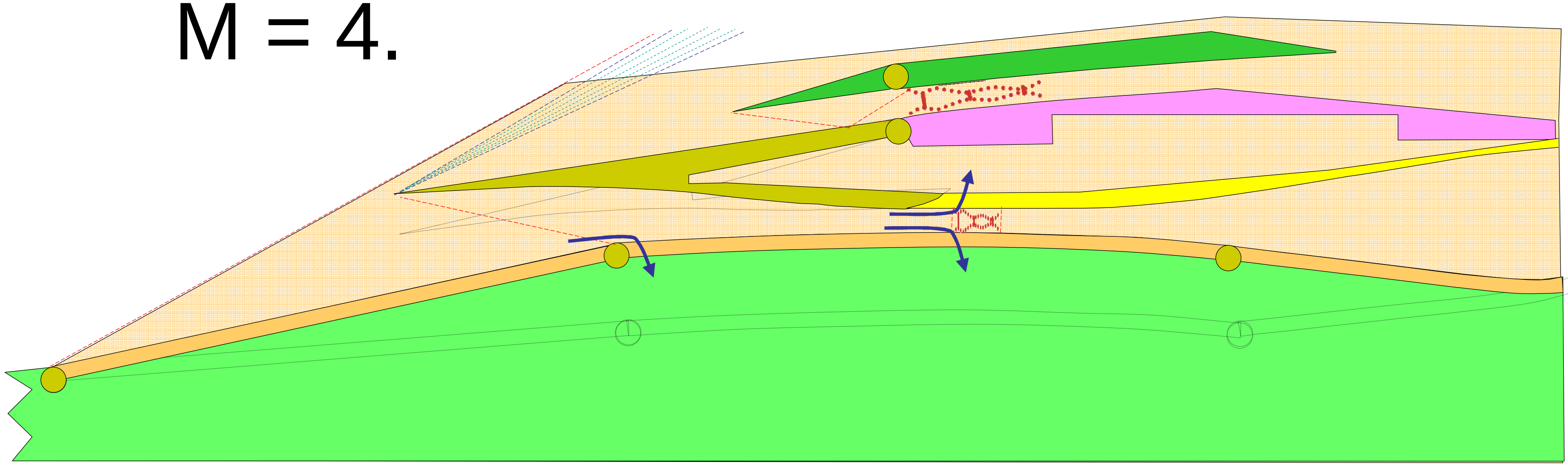
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis

M = 4.



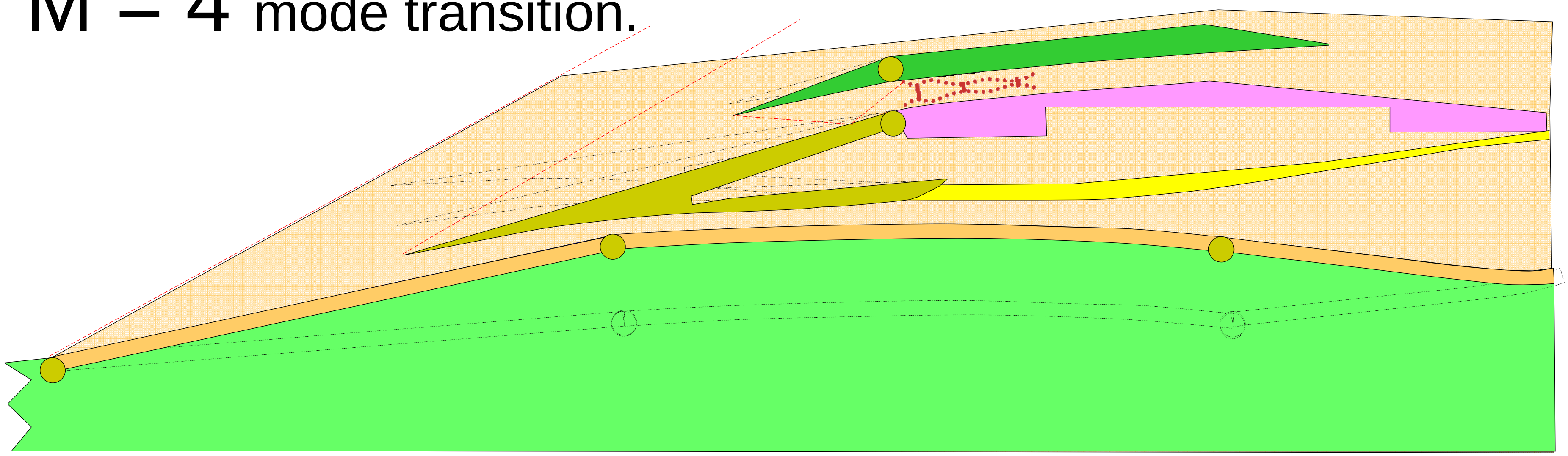
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis

M = 4 mode transition.



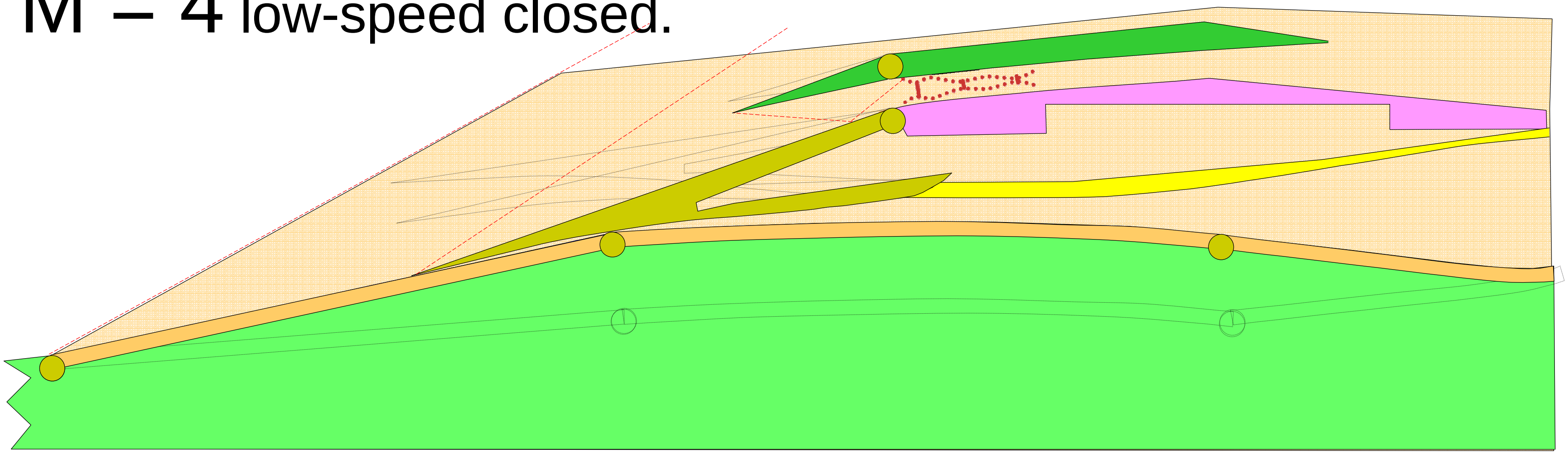
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis

M = 4 low-speed closed.



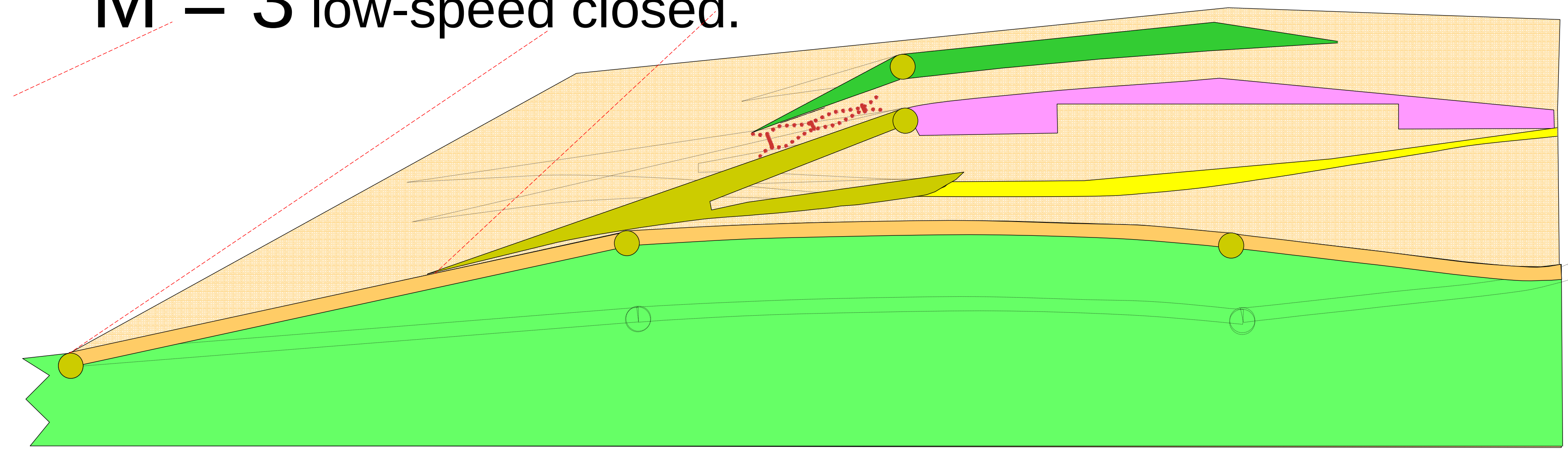
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis

M = 3 low-speed closed.

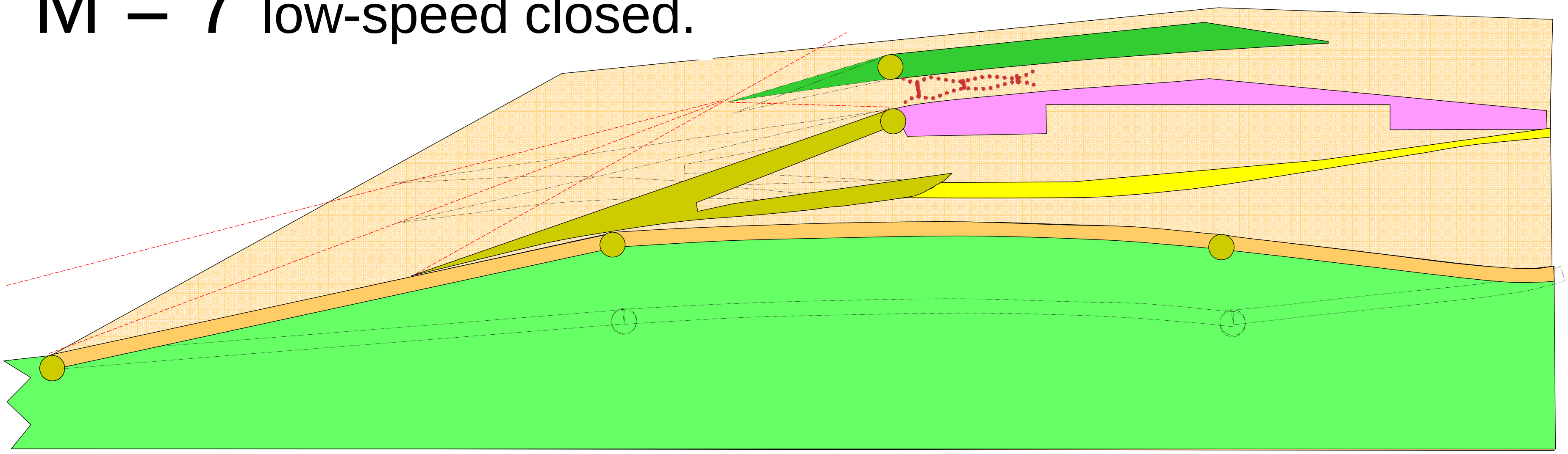


Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

M = 7 low-speed closed.

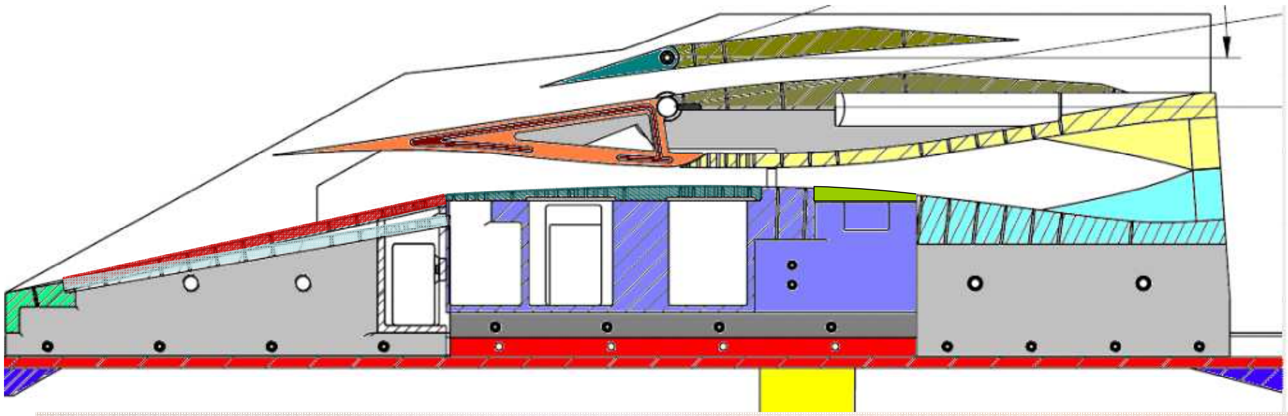


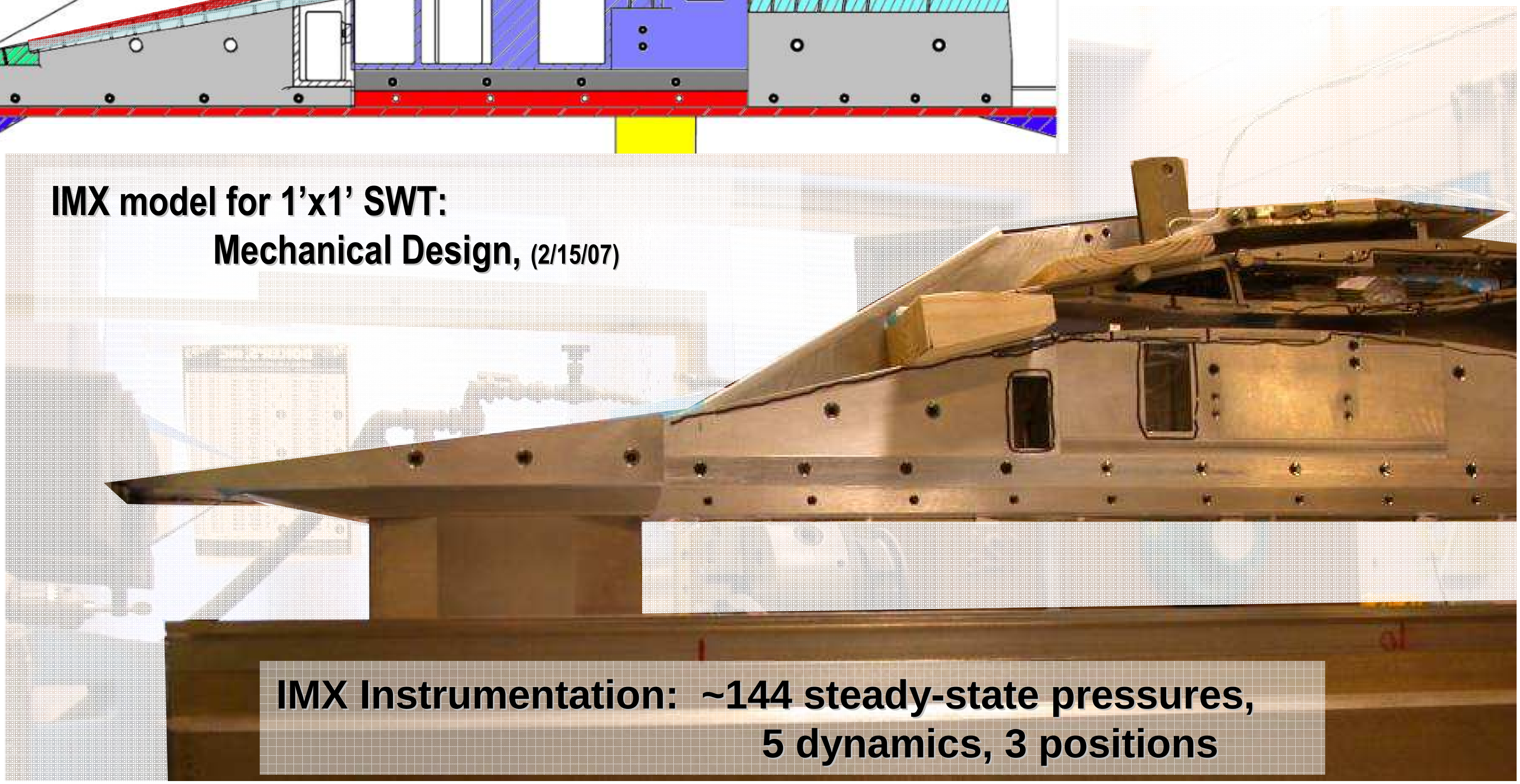
Mode transition sequences

Variable geometry ramp inlet configurations.

Mach number / mode transition with shocks

TBCC Inlet Experiments and Analysis





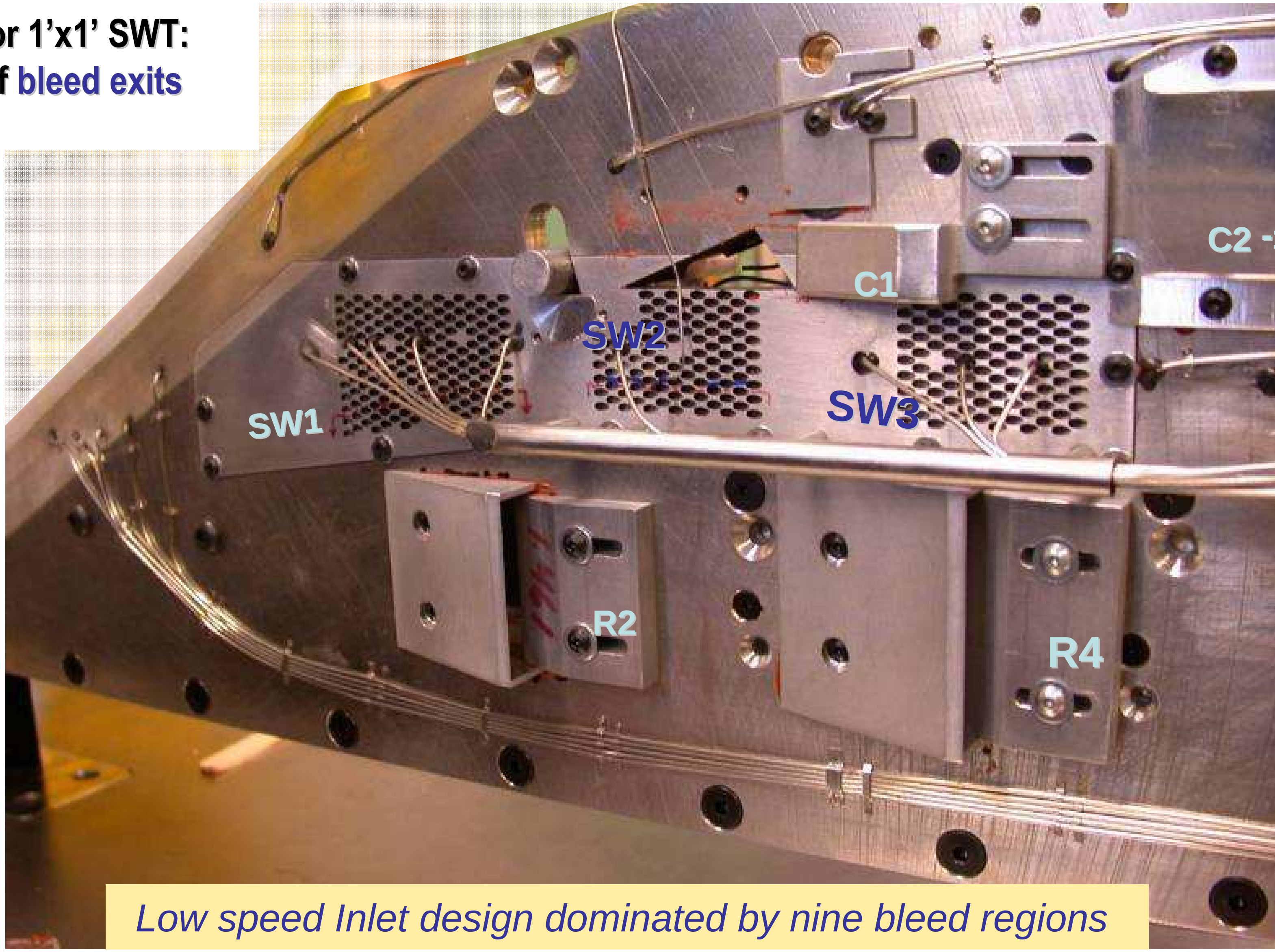
IMX model for 1'x1' SWT:

Mechanical Design, (2/15/07)

IMX Instrumentation: ~144 steady-state pressures, 5 dynamics, 3 positions

TBCC Inlet Experiments and Analysis

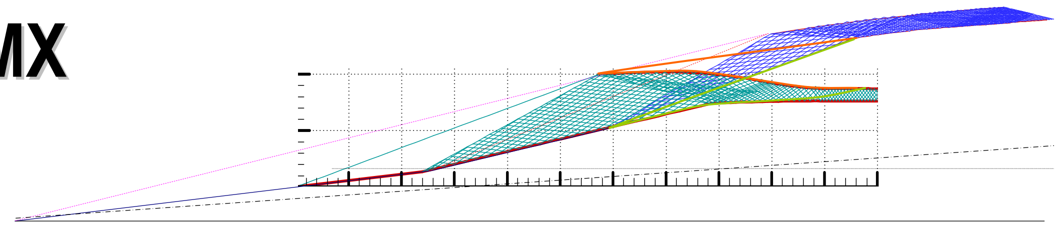
IMX model for 1'x1' SWT:
Photo of bleed exits



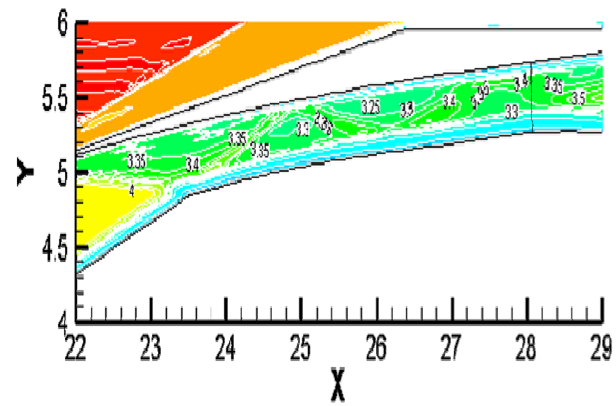
Low speed Inlet design dominated by nine bleed regions

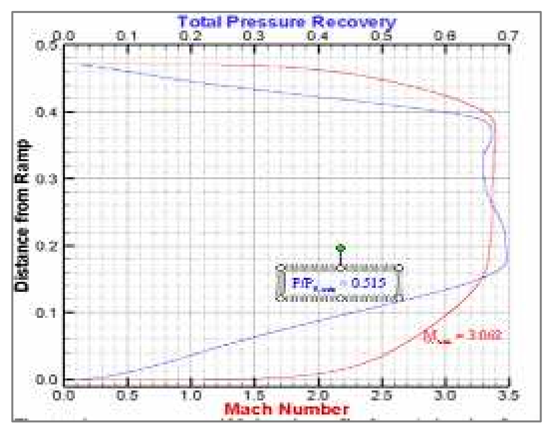
TBCC Inlet Experiments and Analysis

CFD Analyses of IMX



- Design validation: MOC/Euler/RANS
  - Shock wave structure
  - Boundary Layers
  - Throat Mach number
- Inlet performance
  - Integrated back-pressure (cane curves)
- Testing guidance:
  - Bleeds – 9 regions: extents and flow amounts,
    - ➢ CFD derived bleed
  - Throat Mach number (or contraction ratio),
    - ➢ Cowl contour
  - Shoulder interaction,
    - ➢ Cutback cowl

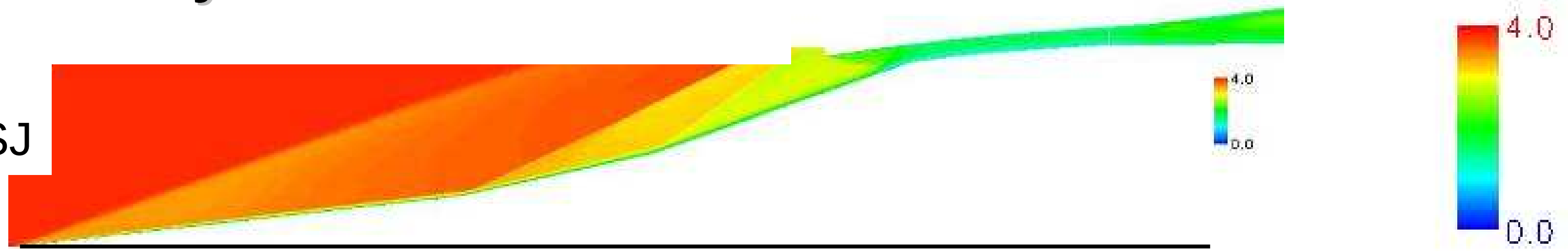




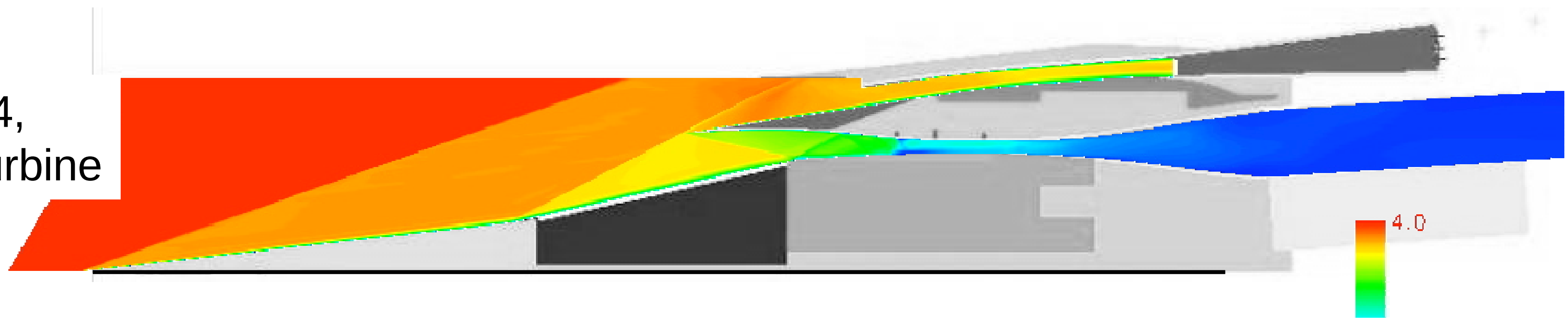
CFD has been an integral tool throughout IMX project

CFD Analyses of IMX

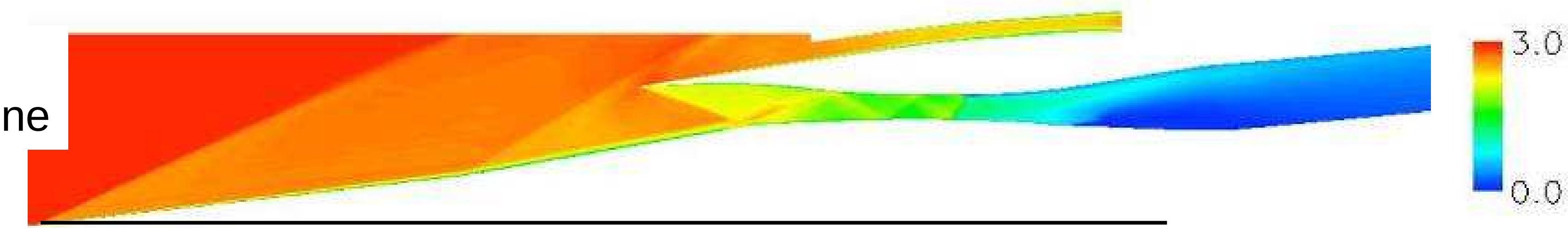
M4, DMRSJ



M4, Turbine



M3, Turbine

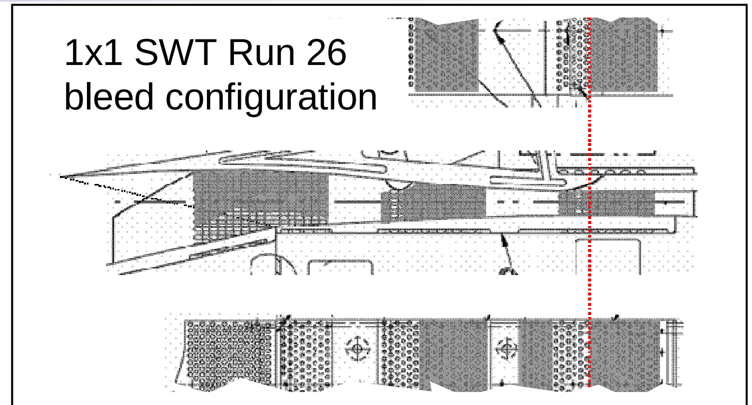


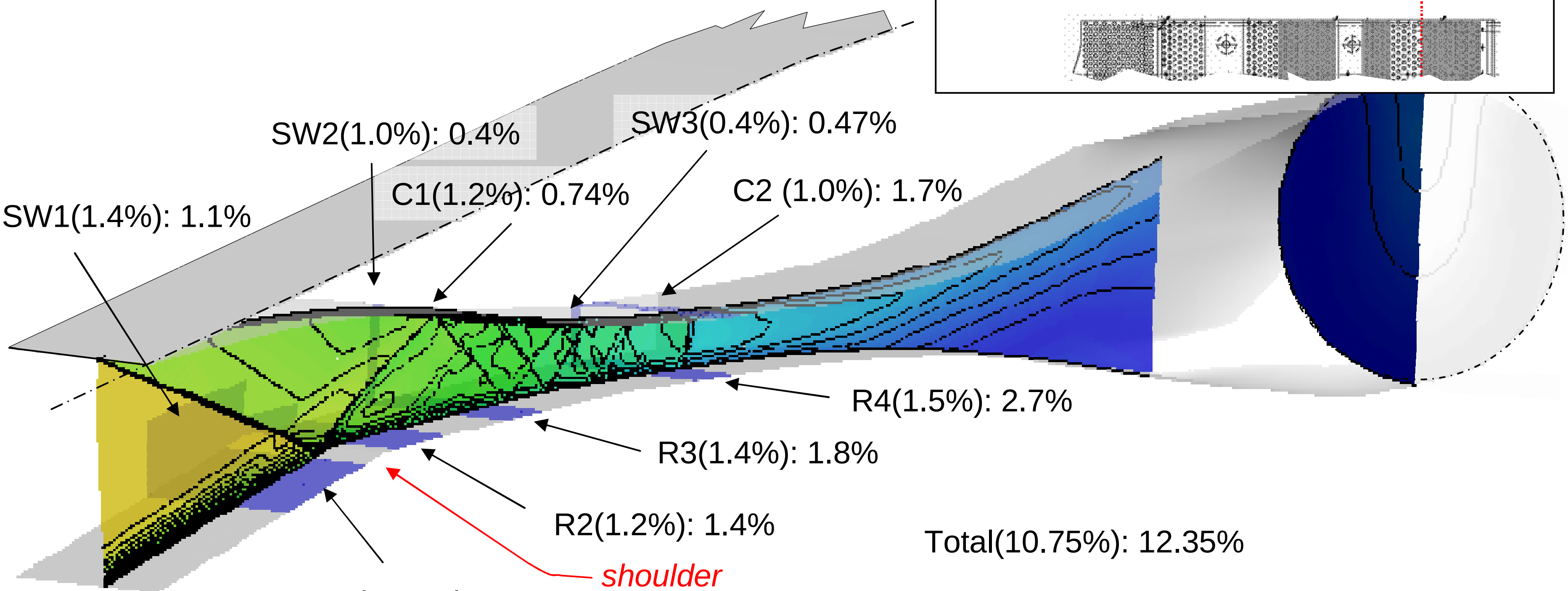
Early CFD showed expected flowfields through mode transition

TBCC Inlet Experiments and Analysis

Low-Speed Inlet Bleed Study

- Bleed Model
- Adjust bleed plenum static pressures
- Match design bleed rates





Total(10.75%): 12.35%

Values in (parentheses) are design goals
Bleed rates are at supercritical flow
3D oblique perspective view shown (1/2 plane)

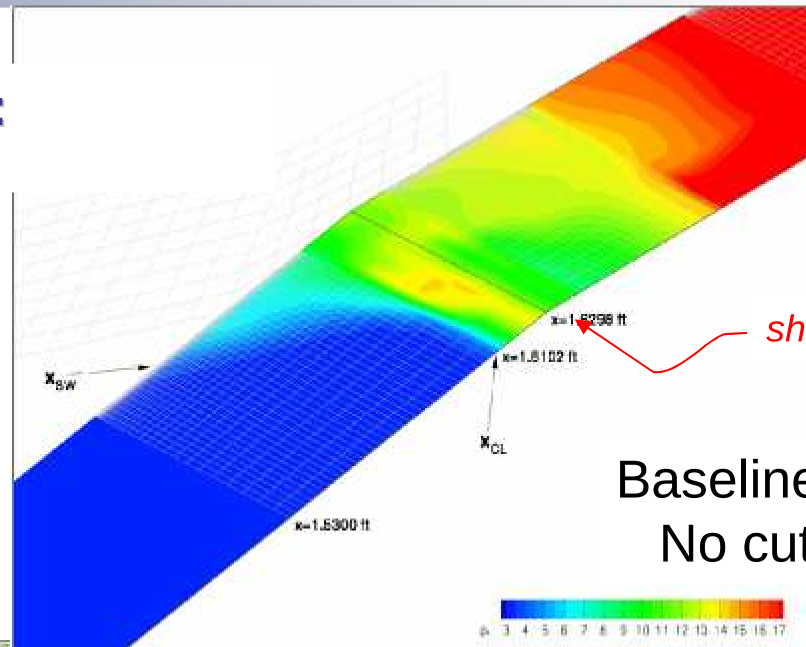
CFD able to model complexity of inlet bleed design

TBCC Inlet Experiments and Analysis

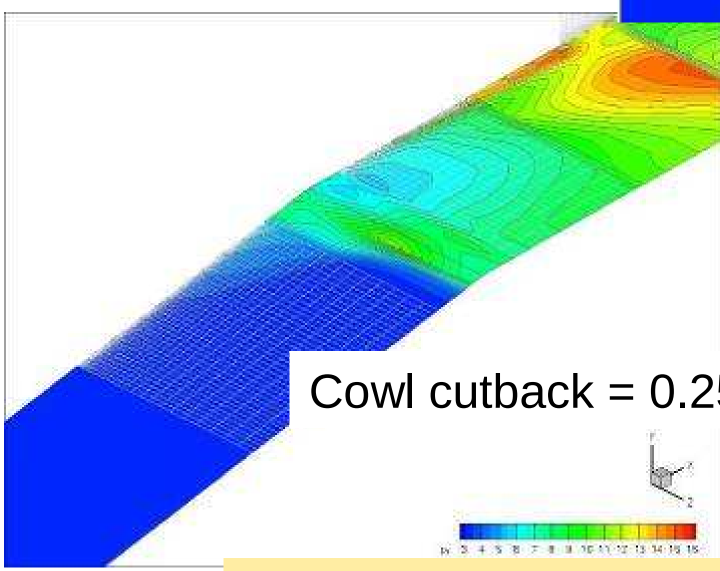
Low speed Inlet Bleed Study:

Cowl shock cancellation / Shoulder interaction

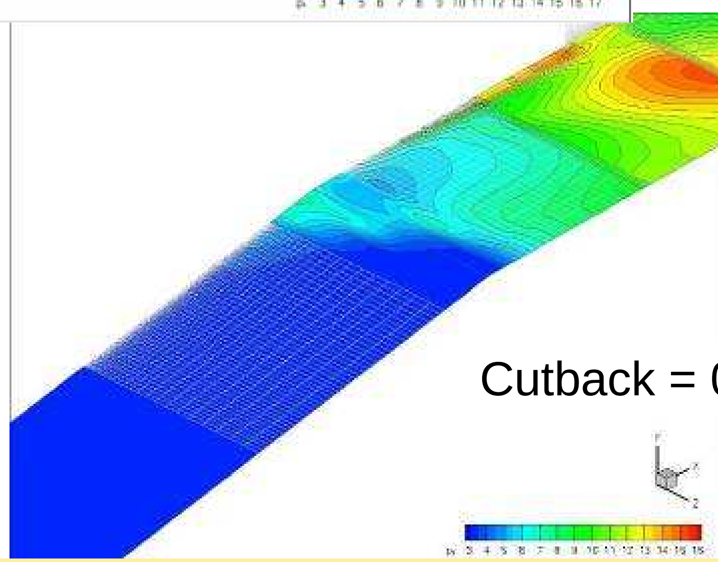
Effect of cutting back cowl leading edge on static pressures near the ramp shoulder



Baseline Cowl, No cutback



Cowl cutback = 0.25”

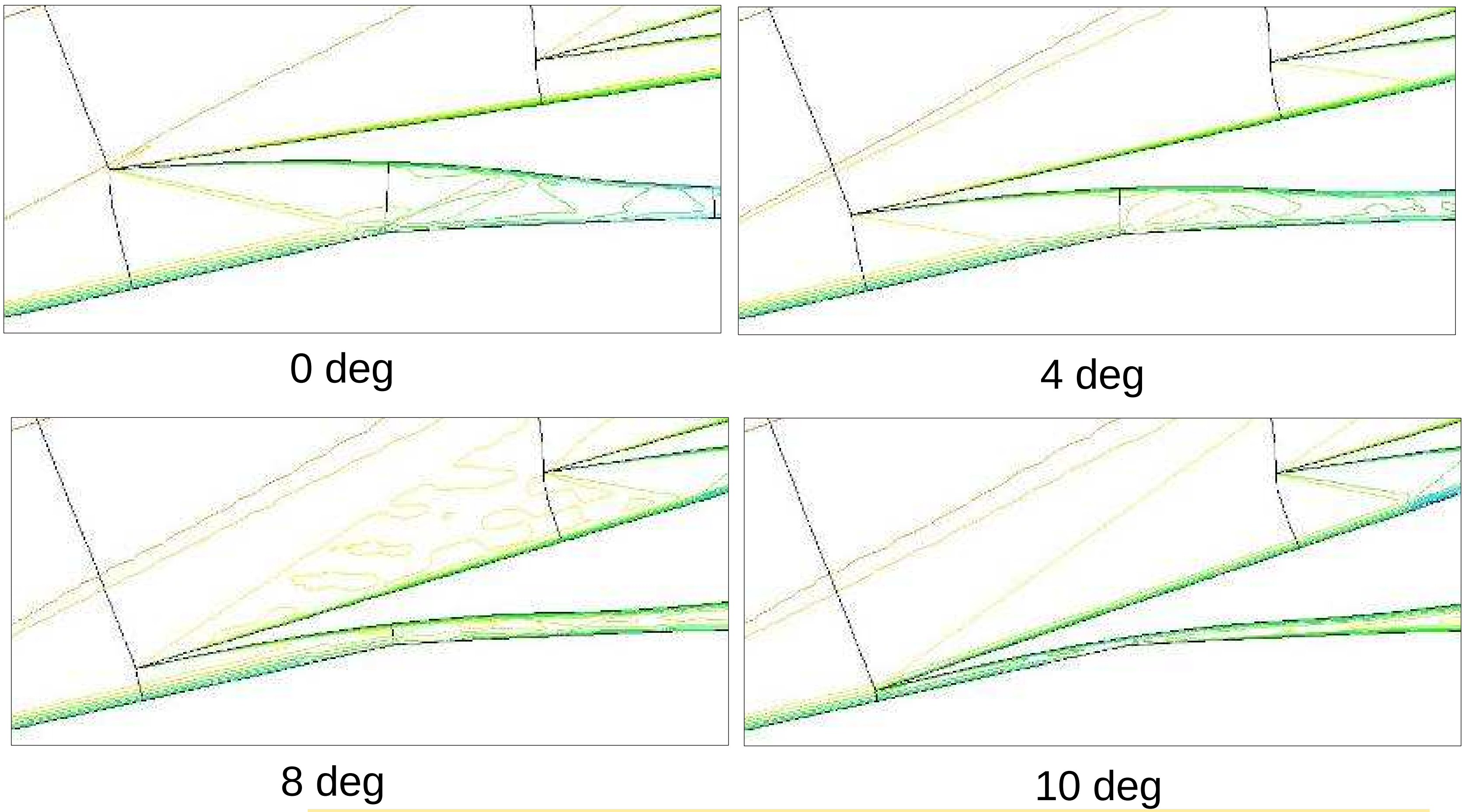


Cutback = 0.5”

Adverse shock interaction characterized at LS inlet ‘shoulder’

Mode Transition at Mach 4

Sequence of 2D steady-state solutions at 2-deg increments

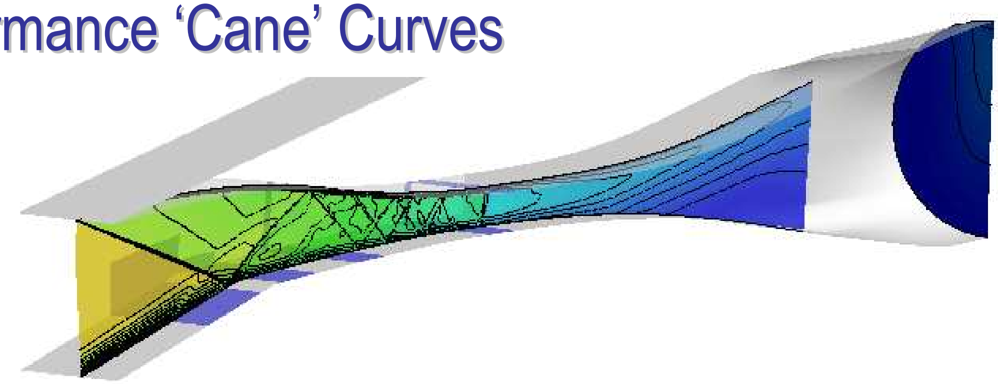


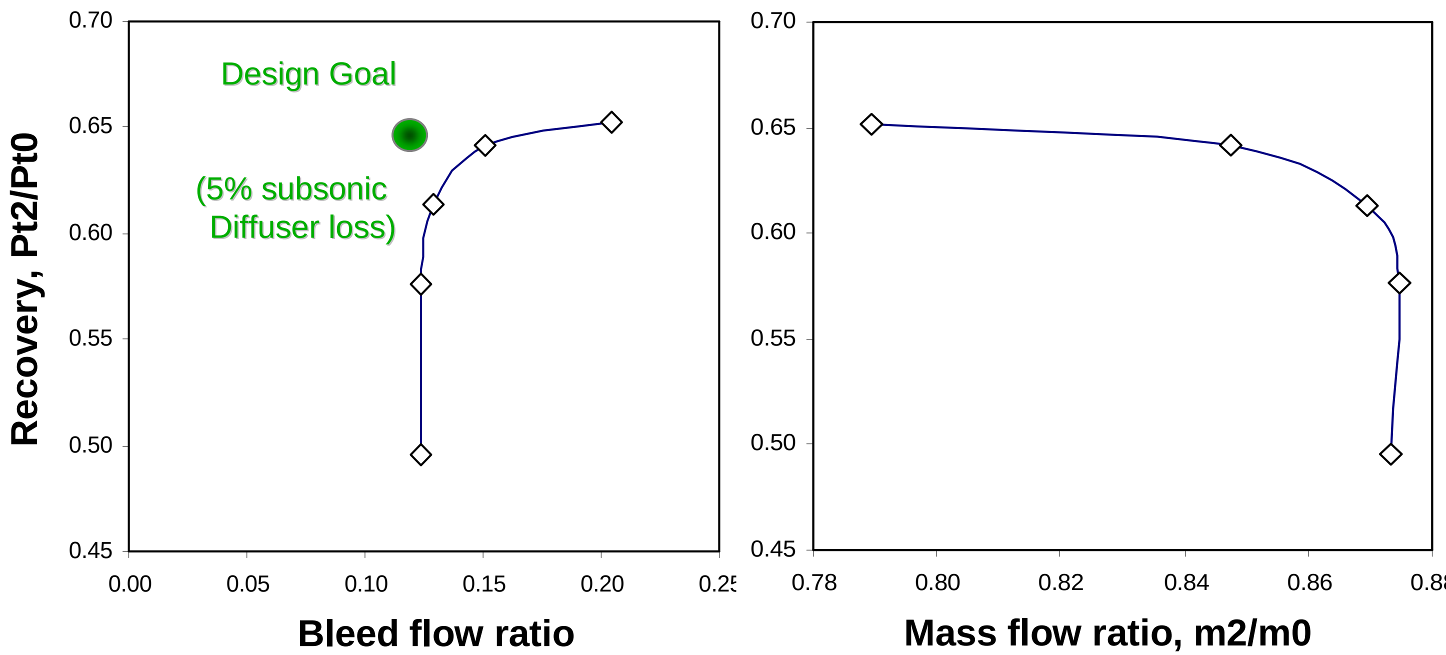
LS inlet mode transition screened by 2D CFD

TBCC Inlet Experiments and Analysis

Back-pressured CFD Study: Performance 'Cane' Curves

- Low-Speed Inlet Performance
- 1x1 SWT Run 26 bleed configuration
- Constant bleed plenum pressure b.c., (non-physical stability)





CFD suggests LS recovery performance obtainable

TBCC Inlet Experiments and Analysis

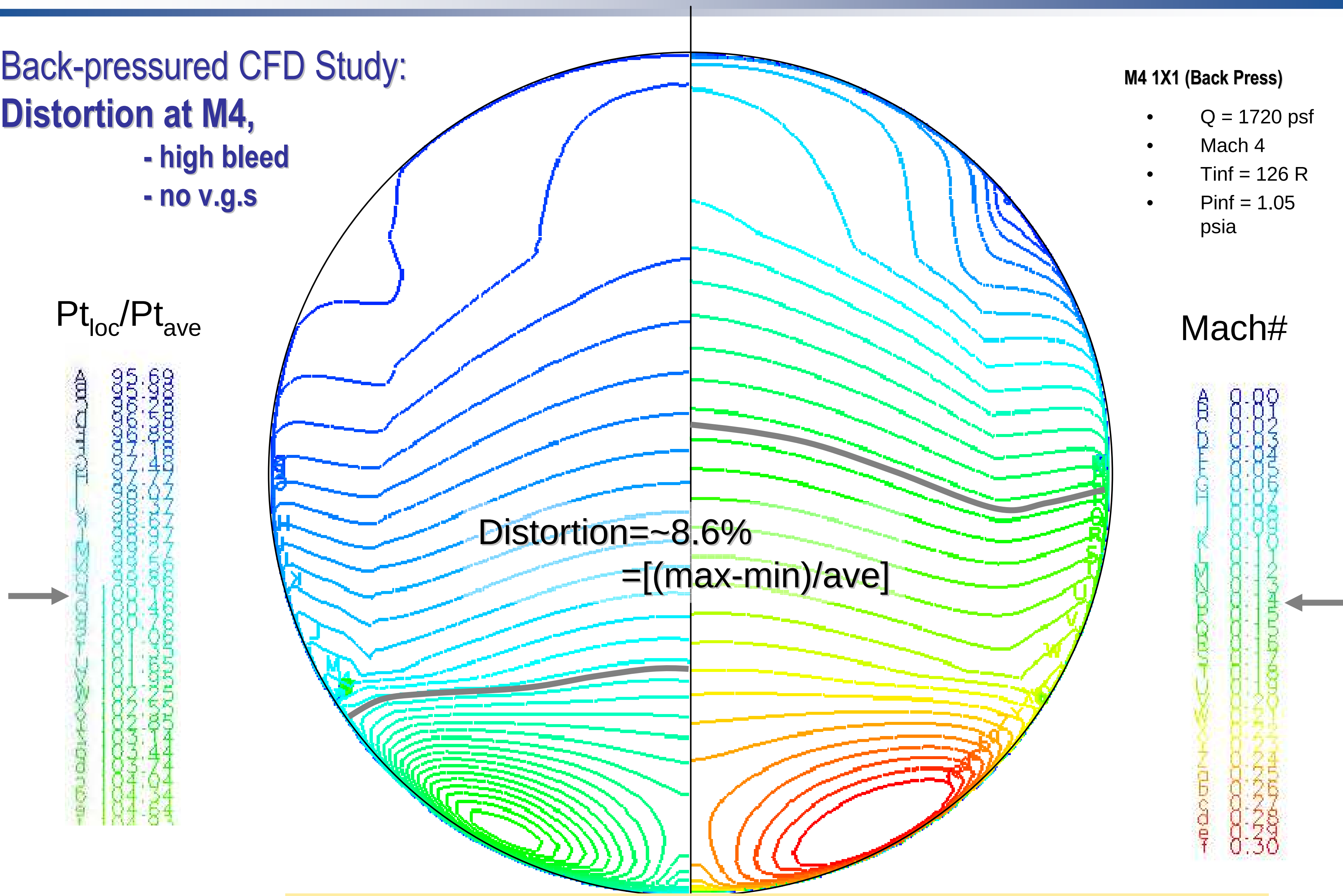
Back-pressured CFD Study:

Distortion at M4,

- high bleed
- no v.g.s

M4 1X1 (Back Press)

- Q = 1720 psf
- Mach 4
- Tinf = 126 R
- Pinf = 1.05 psia

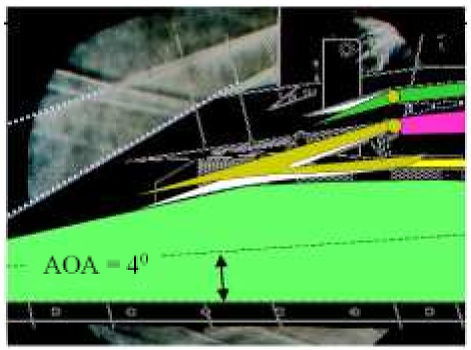


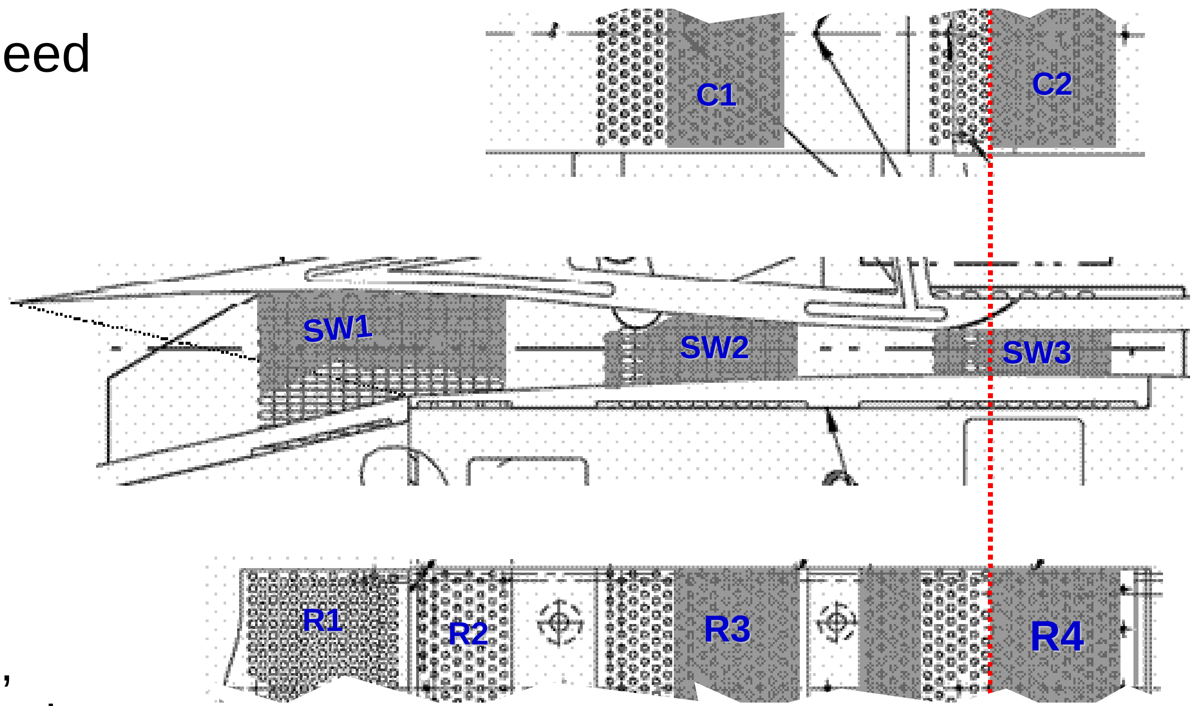
CFD indicates distortion without vortex generator may be high

TBCC Inlet Experiments and Analysis

1x1 SWT screening results, 50+runs to date

- Configurations / bleed



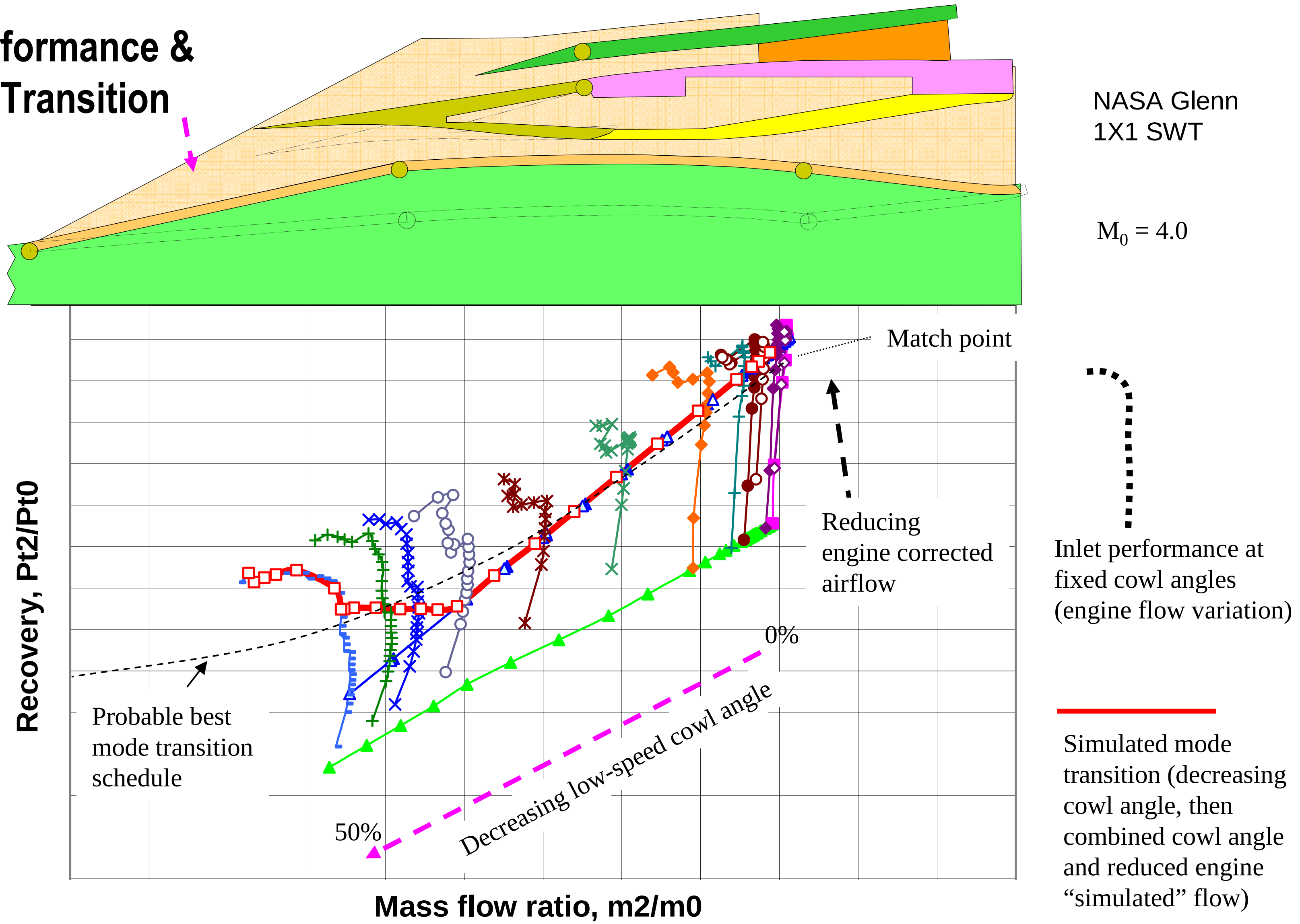


- M4 results:
  - performance,
  - popping behavior,
  - distortion,
  - Mode-x
- Off-design results: recovery and distortion

1x1 experiment underway, major objectives are complete

TBCC Inlet Experiments and Analysis

Mach 4 performance & Inlet Mode Transition Screening



Mach 4 performance is near design goal: mode transition smooth

Conclusions

- TBCC Inlet design approach is valid
- CFD as a toolset is becoming helpful in inlet design
  - and continues to be part of: *Visualize, Validate, Instrument, Test plan*
  - fixed exit bleed boundary conditions needs further modeling
- Small-scale Test Results: 1x1 SWT
  - near mil-spec recovery demonstrated
  - distortion effect must be investigated further
  - cowl contour / reduced throat Mach number is desirable
  - smooth mode-x is possible
- TBCC Inlet design verified for large-scale 10x10 SWT entry
  - Mechanical design nearly complete, hardware delivery in spring ’08
  - Results to date show confidence that larger-scale will perform as designed