Real-Time Background Oriented Schlieren with Self-Illuminated Background

Mark Wernet
NASA
Glenn Research Center

January 7, 2022

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

Background Oriented Schlieren

- Background Oriented Schlieren (BOS) is a relatively simple technique which provides the derivative of the density field along the integrated path
- Much simpler to implement than conventional Schlieren systems
- More robust to vibration and can tolerate low quality windows (even Plexiglas)
- BOS provides the same information as conventional Schlieren – the derivative of density along the integrated path
  - BOS actually provides both the x- and y-components of the derivative of density
  - Conventional Schlieren typically yields only a single component of the density derivative

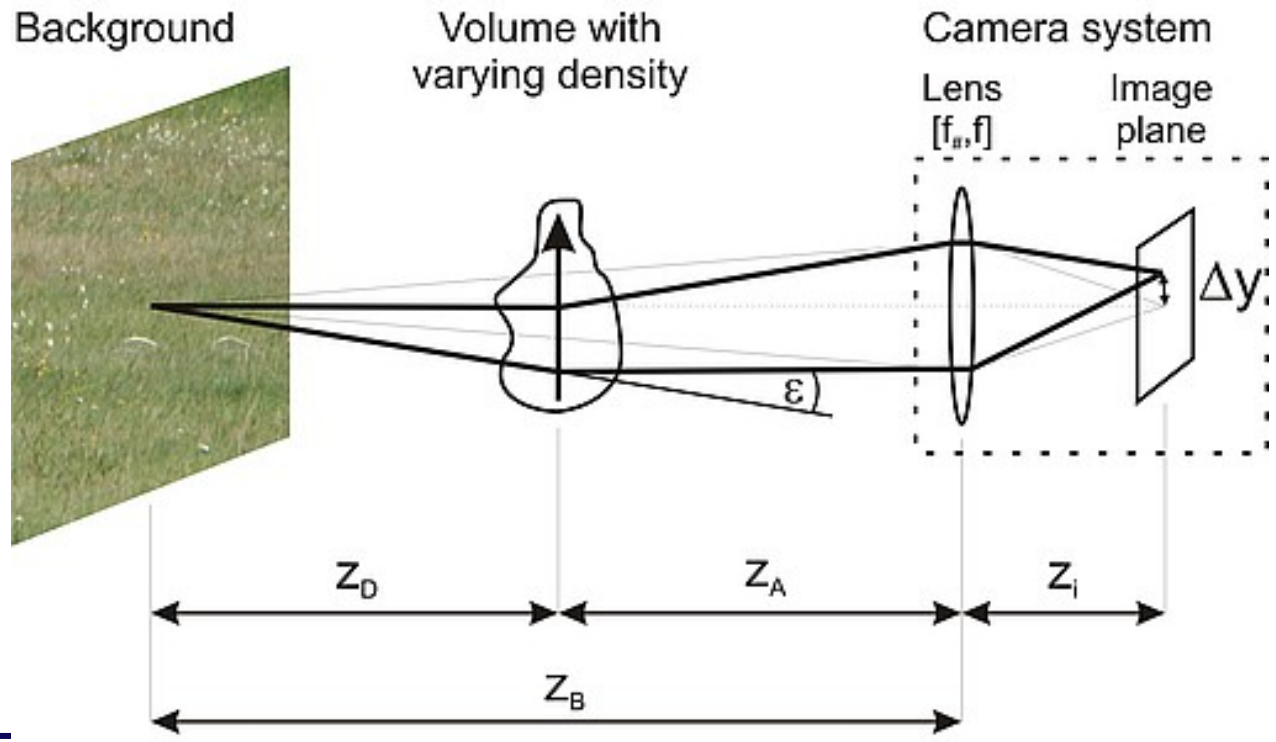


Image from DLR, Rafel

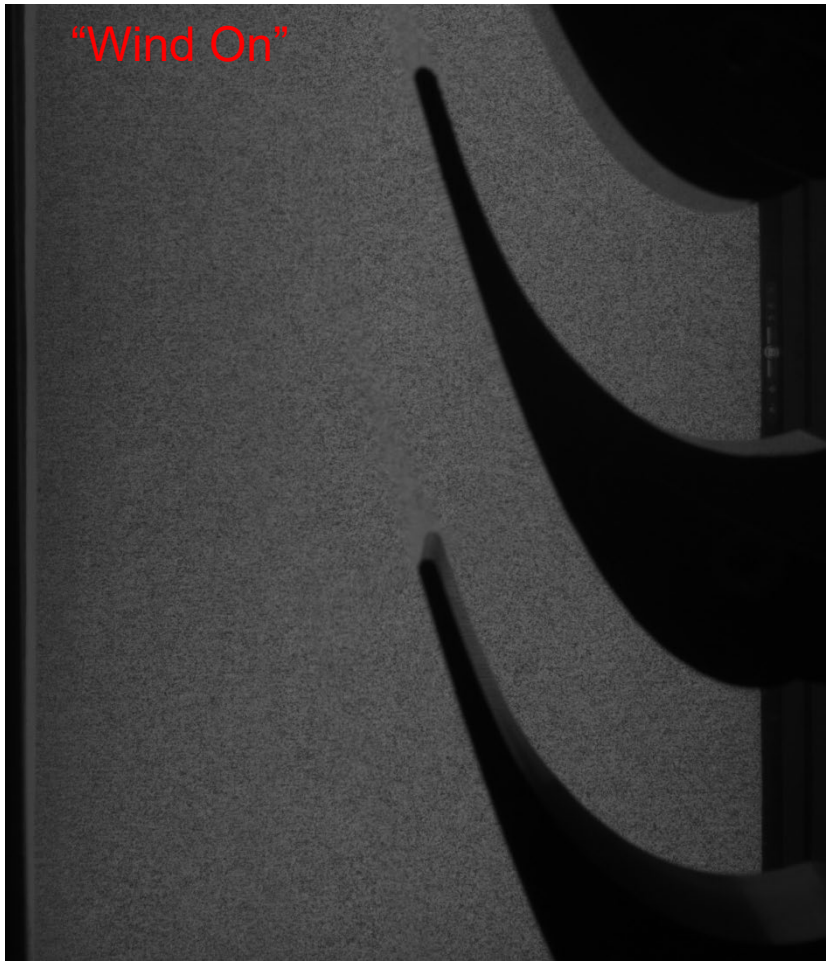
Background Oriented Schlieren

- In BOS, a camera images a speckle image or background scene
- A “wind off” image is acquired (reference)
- A density variation is placed between the camera and the speckled screen
- The flow is turned on and image data are acquired
- The acquired image data are then processed similar to conventional Particle Image Velocimetry (PIV) data
  - The images are divided up into small interrogation regions
  - Subregions from the reference image are cross-correlated with subregions from the “wind on” images
  - The measured displacement is proportional to the integrated density gradient across the density disturbance

Background Oriented Schlieren Images

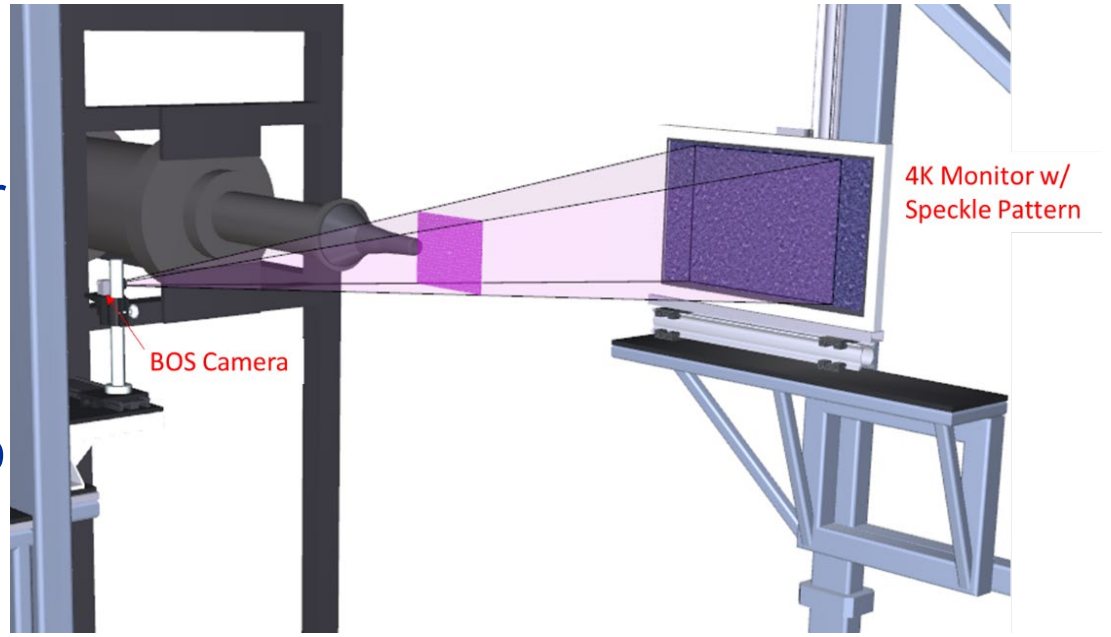
- A reference and “wind-on” image are shown
- Not really able to discern any flow features





Real-Time Background Oriented Schlieren

- RT-BOS enables on-line visualization of density gradients in the flow
- A single program is used for BOS image acquisition and real-time display
- A 4k monitor used to display speckle pattern
  - Self-illuminating speckle background
  - Easy to generate speckle backgrounds on computer
- Both multi-core Intel processing or GPU processing of images in real-time
- Real-time live image-shifting also supported to compensate for rig vibrations or camera movement in real world test facilities



- RT-BOS images are then processed off-line to provide higher resolution & quality density gradient maps using commercial software

GPU Parallel Architecture

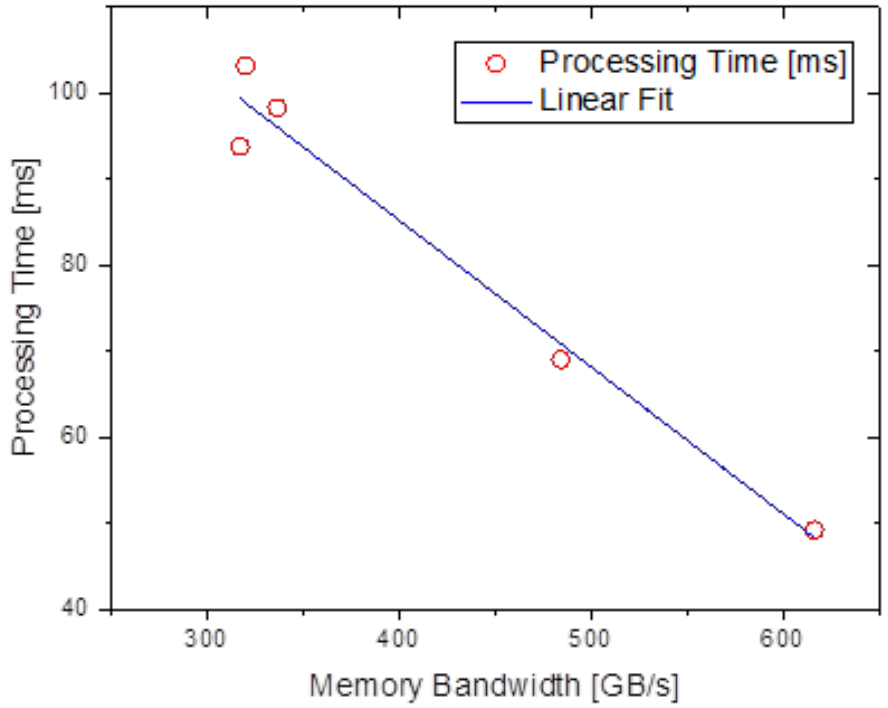
- Use the Compute Unified Device Architecture (CUDA) language
- Max performance by minimizing data uploads and downloads to the GPU
- Need to compute FFTs to perform cross-correlation operation
- Use cuFFT library from nVidia
  - Batch mode: cuFFT can operate on an array of subregions
  - Actually computes all FFTs across entire image in one step
- Write custom routines to:
  - Divide image data up and organize it for the Batch cuFFT operation
  - Complex math multiplication
  - Find correlation-peaks to sub-pixel accuracy (in-parallel)
  - Real-time sub-pixel shifting of live image versus reference image
- Transfer measured displacements back to Host PC for display

Performance Comparison: GPU vs Multi-Core Intel

	Subregion Size on 16x16 grid	# Subregions	Processing Platform	# of Threads	Total Processing Time [millisec]
Test1	64x64	40,098	PC	1	1904
Test2	64x64	40,098	PC	22	149
Test3	64x64	40,098	GPU	4352	49

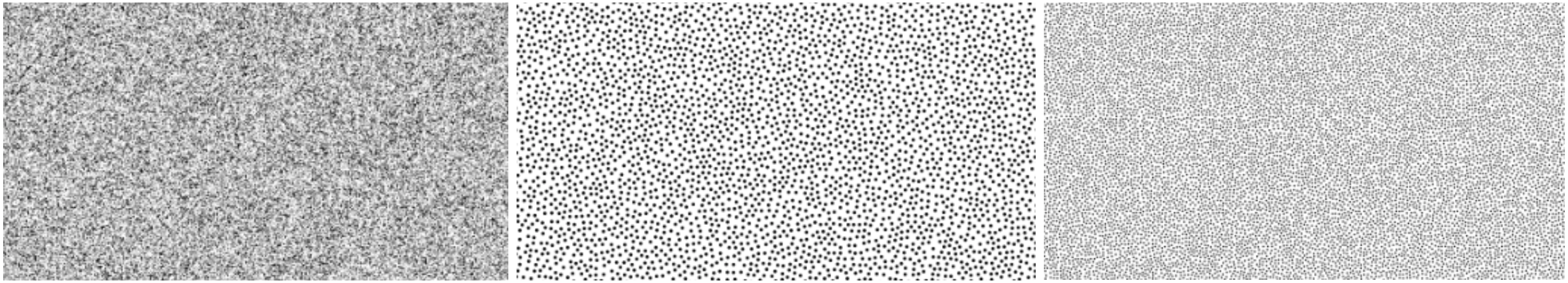
	GTX 980 ti	GTX 1080	Quadro M6000	GTX 1080 ti	RTX 2080 ti	Xeon 2699-v4
Compute Capability	5.2	6.1	5.2	6.1	7.5	
Memory [GB]	6	8	24	11	11	
Memory Type	GDDR5	GDDR5X	GDDR5	GDDR5X	GDDR6	
Mem Bandwidth [GB/s]	336.5	320	317	484	616	
# Cores	2816	2560	3072	3584	4352	44
Base Frequency [MHz]	1000	1607	1506	1480	1350	
Architecture	Maxwell	Pascal	Maxwell	Pascal	Turing	
Processing time [ms]	98.3	103.2	93.8	69	49.17	149

GPU Performance



Speckle Backgrounds

- Computer generated, complete flexibility over contrast ratio and speckle size
- Can use several programs already available, Matlab, LaVision…
- Single PC drives the external 4K monitor and displays the processed results
- The nVidia card performs all of the processing
- RT-BOS system performs self-optimization
  - Runs through a set of predesigned backgrounds
  - Acquires images and correlation processes them to find the background with the lowest noise floor for the configured optical system

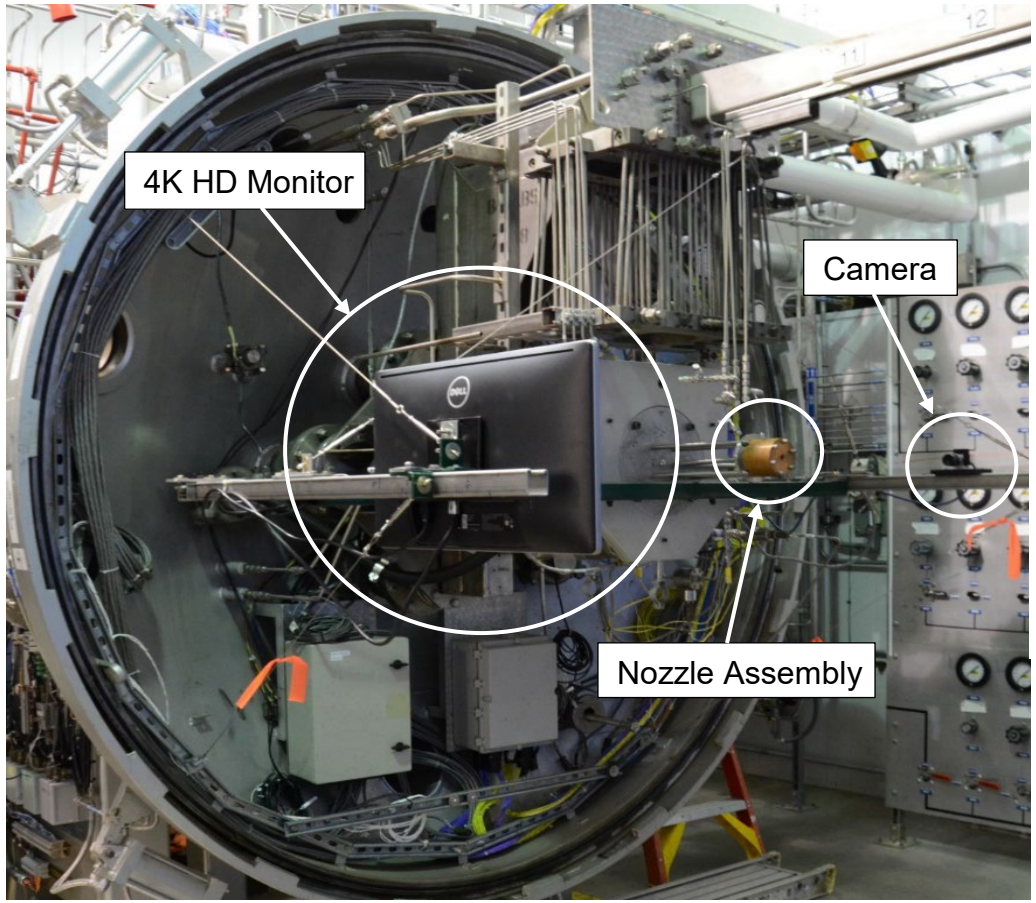


RT-BOS Supported Cameras

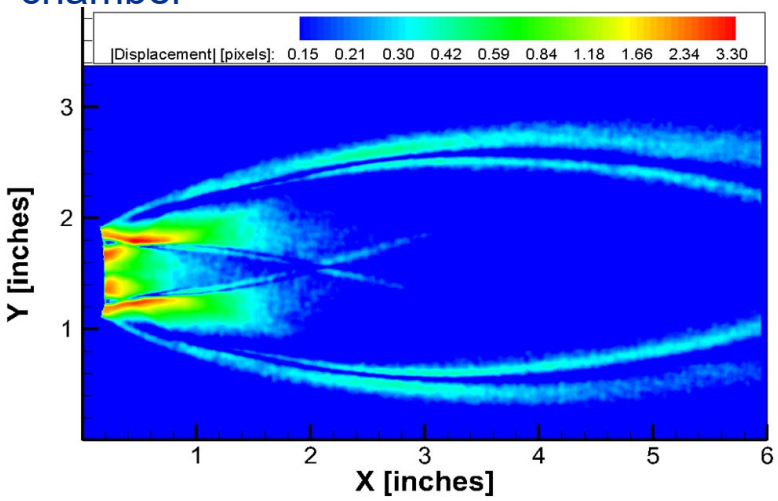
- Images can be acquired from USB3, GigE and CameraLink cameras
- 5 Mpixel cameras (1GB GigE) processed at 68 fps
- 29 Mpixel camera images (CameraLink) processed at full frame rate of 5 Hz
- 12 Mpixel cameras (10GB GigE) processed >20Hz

Altitude Combustion Stand (ACS)

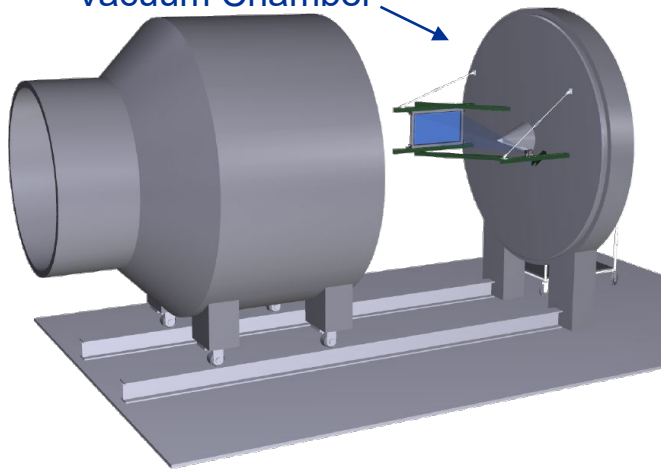
- Vacuum chamber facility with a single optical access port
- Traditional Schlieren not feasible
- Camera and 4K monitor placed inside vacuum chamber



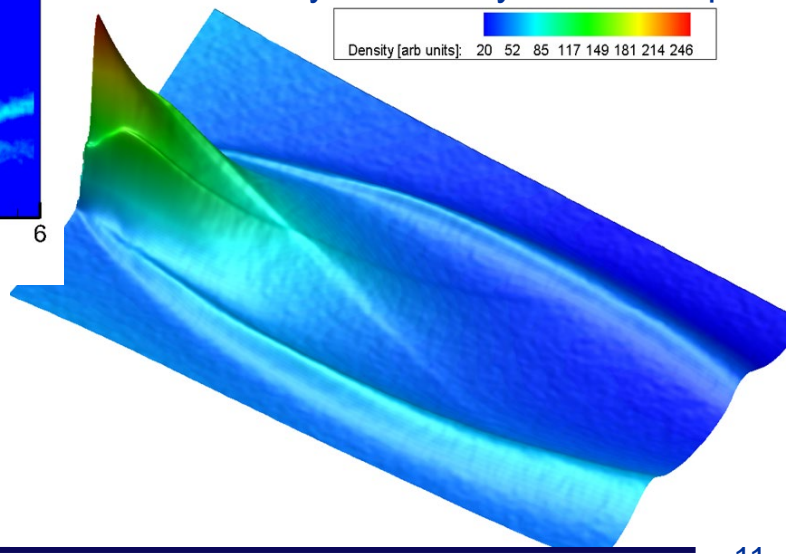
1000 psi plenum pressure through 0.105” diameter nozzle into 0.3 psia ambient chamber



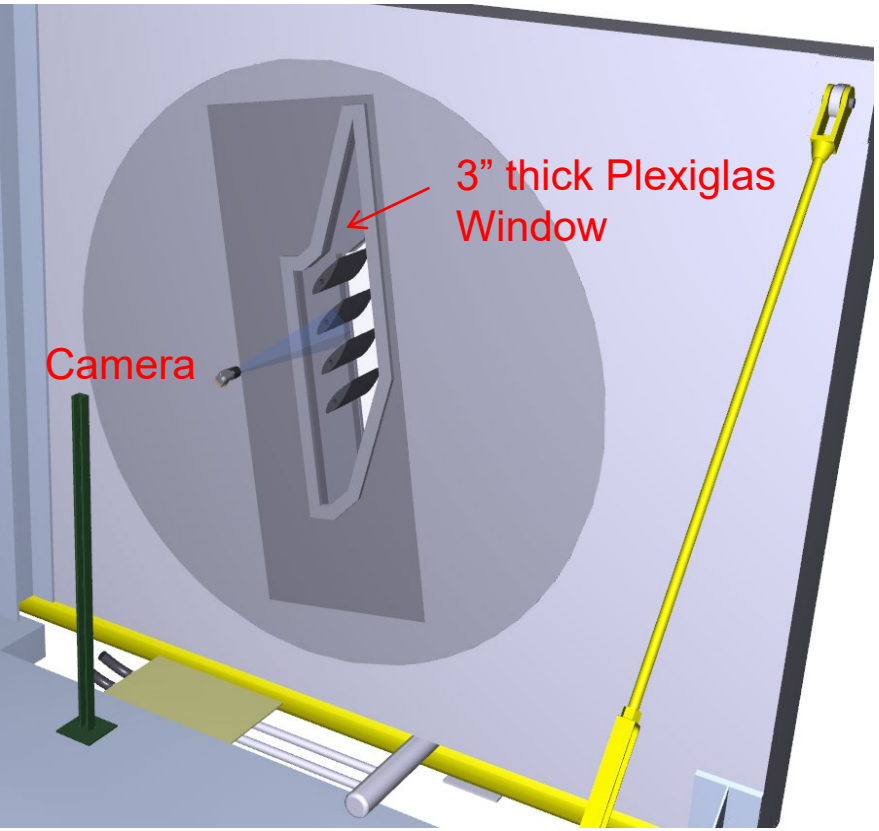
Vacuum Chamber

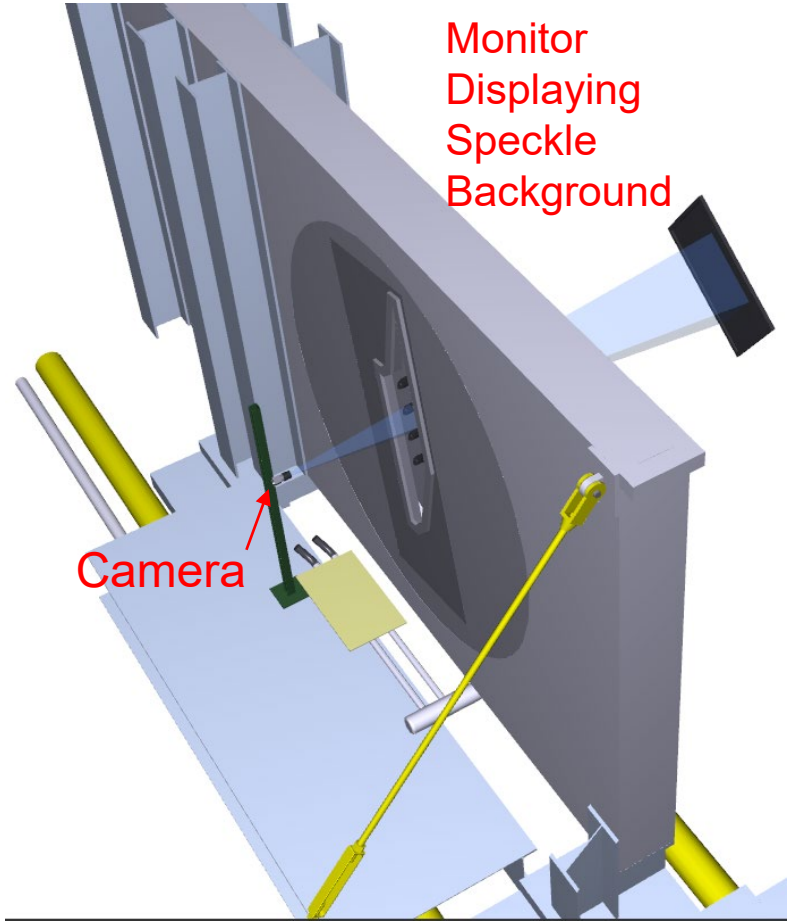


Same data set integrated to yield density surface map

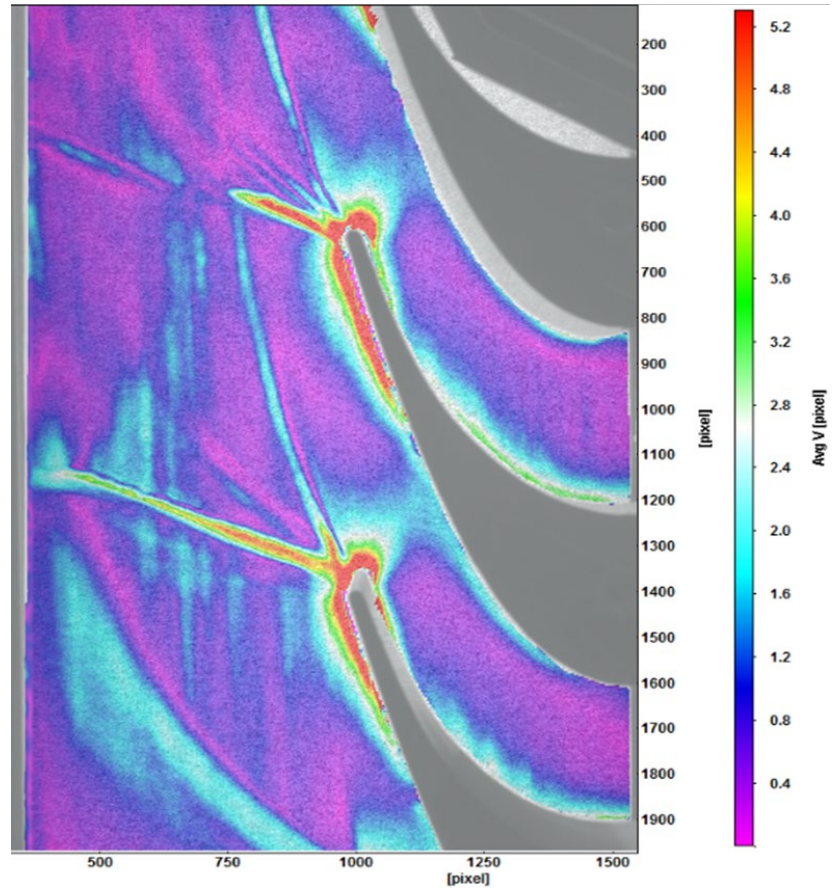


RT-BOS Installation in Turbine Cascade Rig



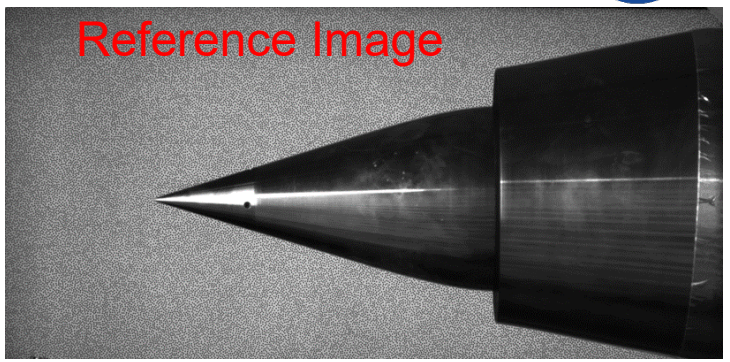


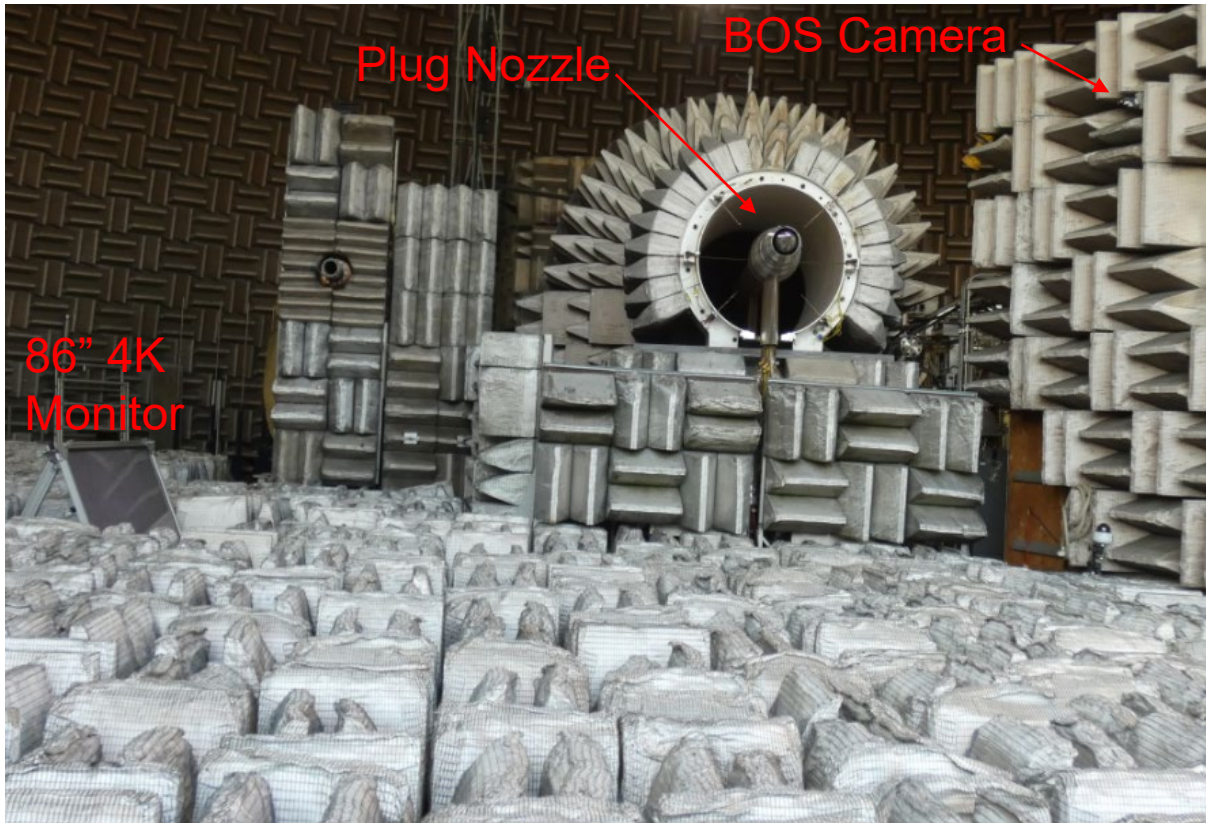
Processed Image, 100 Frame Average

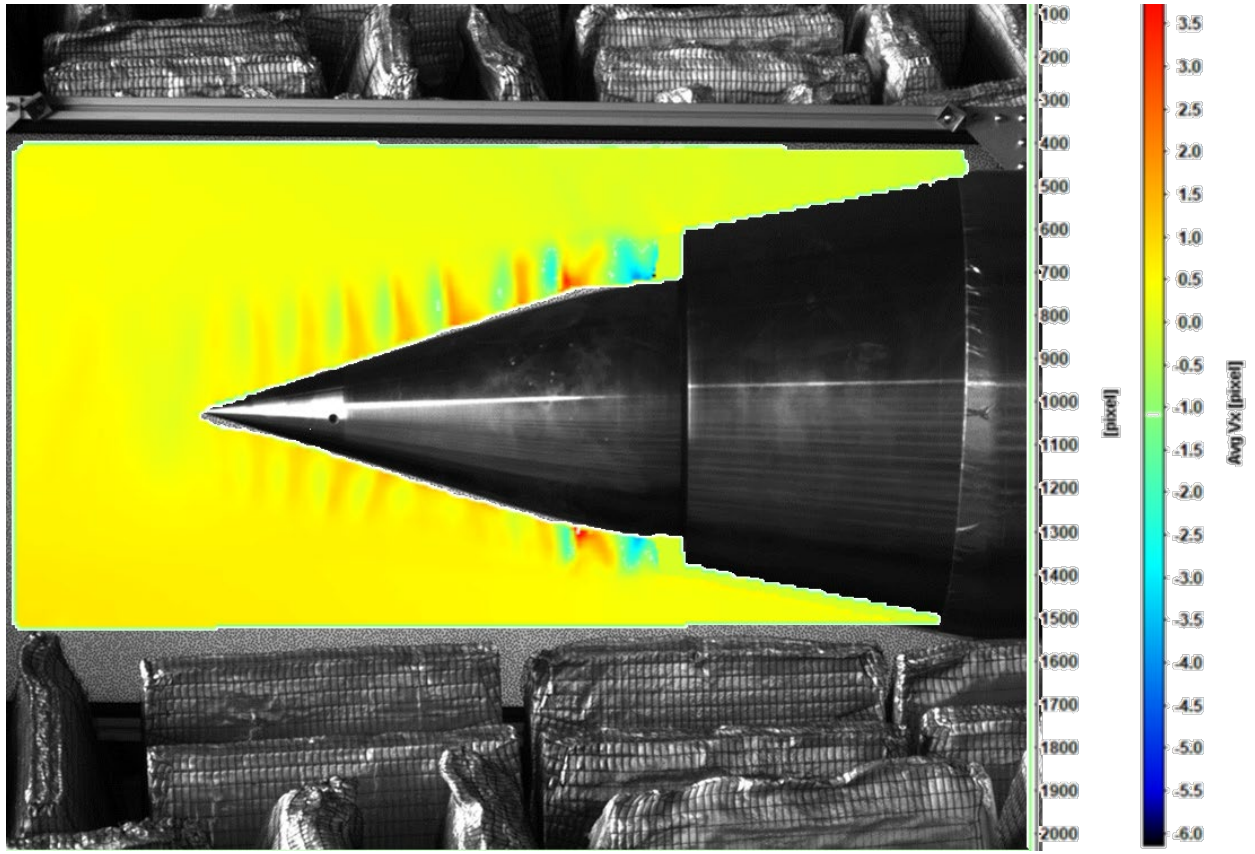


RT-BOS in a CST Plug Nozzle Acoustic Test

- Real-Time BOS displaying density gradient data while acoustic data were being acquired
- Speckle pattern displayed on 4K monitor
- 86” monitor was located 27’ from BOS camera, yielding 25x14” FOV
- BOS data are being used to validate CFD predictions of the shock locations







Summary

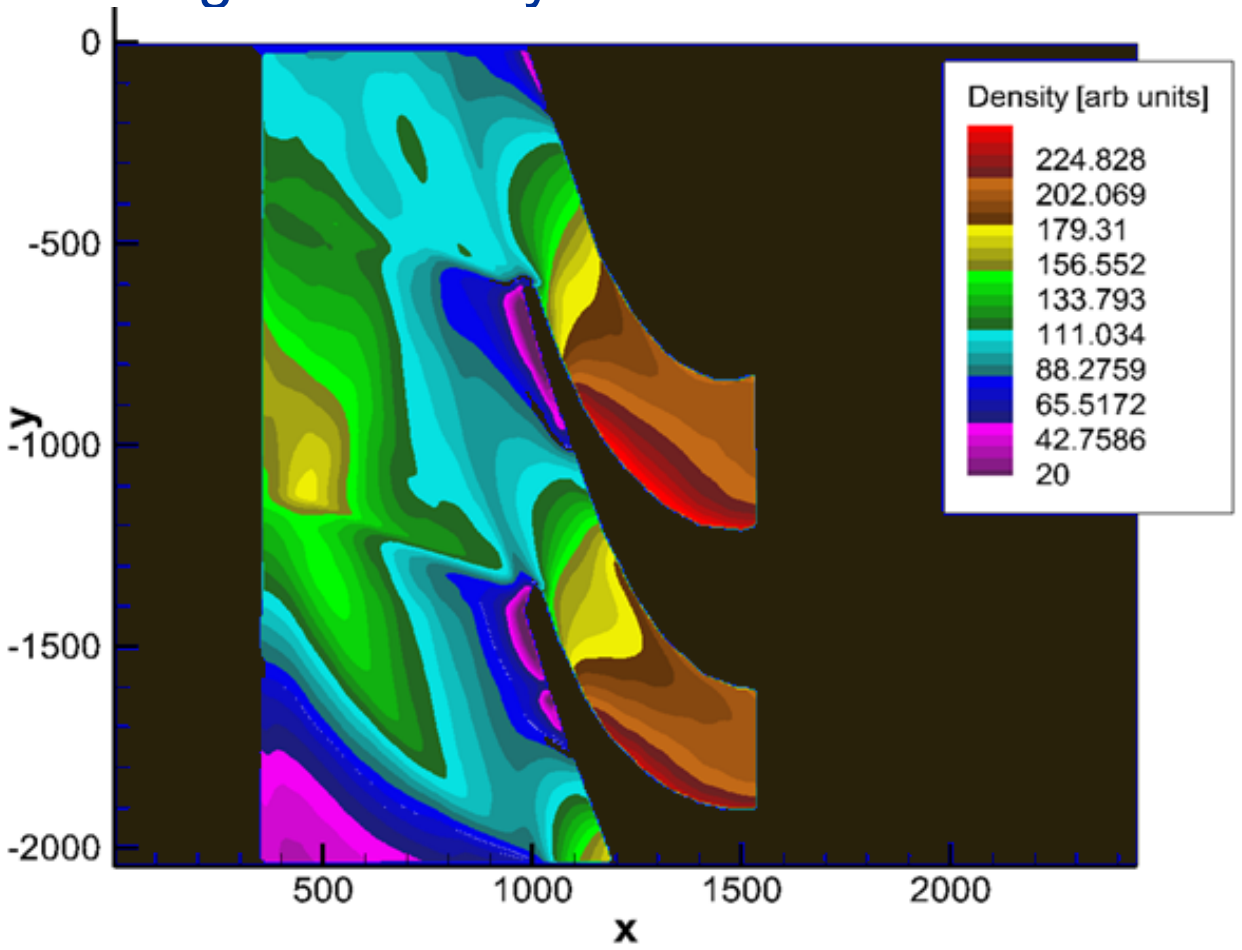
- RT-BOS is a simple diagnostic which is easy to setup using the 4K monitor for self-illuminated speckle backgrounds
  - Operates either on multi-core PC or GPU based system
  - Robust against vibration using real-time image shifting
- Enables optimization of the BOS system as configured for the experiment
- Cameras are inexpensive and easy to integrate into the experiment
  - Recent acoustic test with simultaneous RT-BOS measurements
- Very useful for providing on-line monitoring of the rig set point conditions

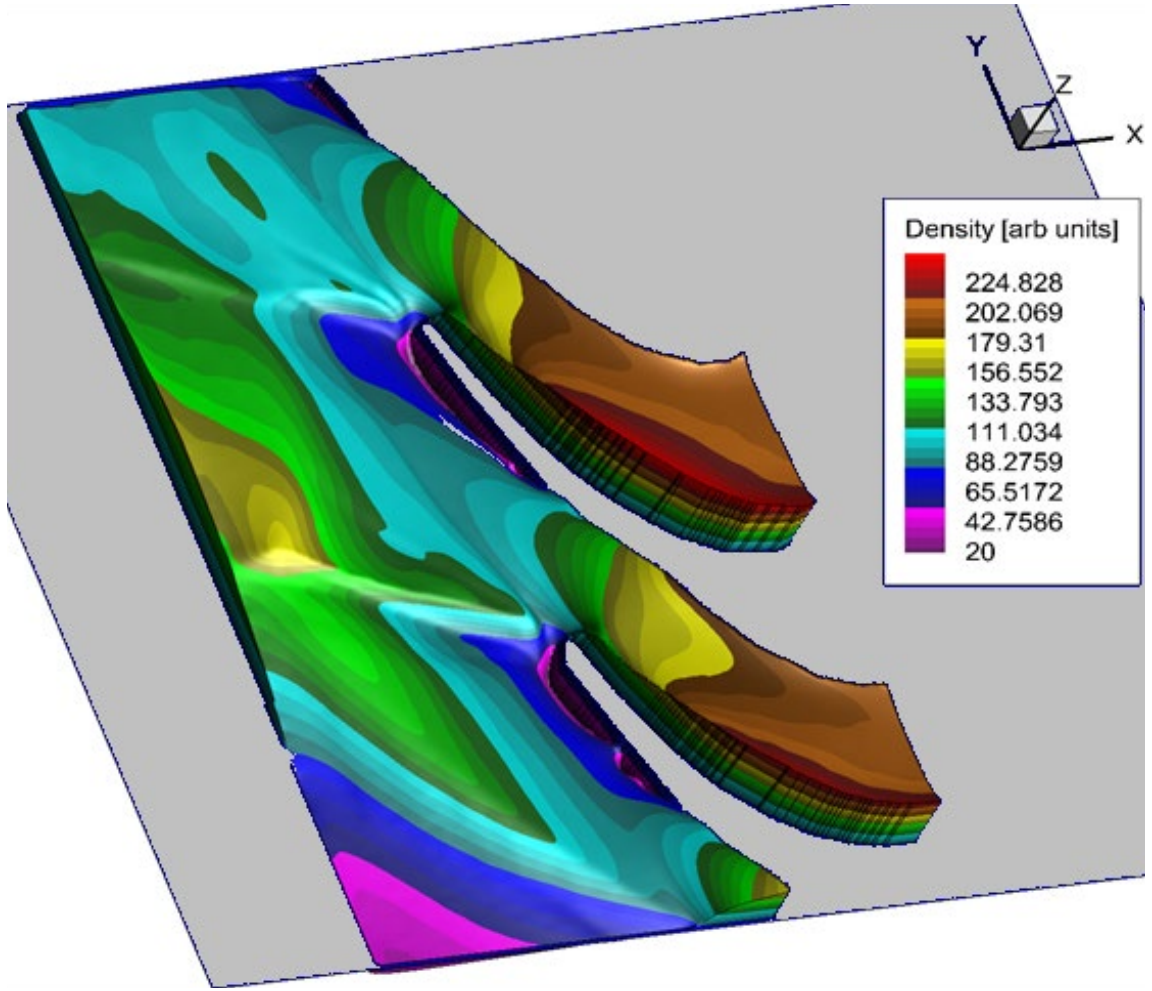
RT-BOS Active Stabilization

- In a recent test in AAPL, the camera was mounted on the large traverse, 4K monitor mounted on the floor
  - Probe based temperature surveys were also required during the testing.
  - Traverse system had to be moved after the BOS reference image was acquired, which was before the BOS data needed to be acquired.
  - Since the traverse does not always go back to the exact location – the BOS image correlation failed
  - Vibration of the BOS camera due to the high acoustic noise in the AAPL facility, again can yield a loss of correlation between the reference image and the live camera image
- Implemented an adaptive image-shifting correction for real-time alignment of the reference image with the current acquired image.
  - Used a point on the speckle background that does not have flow on it to compute the required shift to realign the reference and current images.
  - The shift correction is applied and then the RT-BOS processing is conducted – yielding real-time shock visualization in the flow that is tolerant to facility vibrations, and/or misalignment of the camera

Density Reconstruction

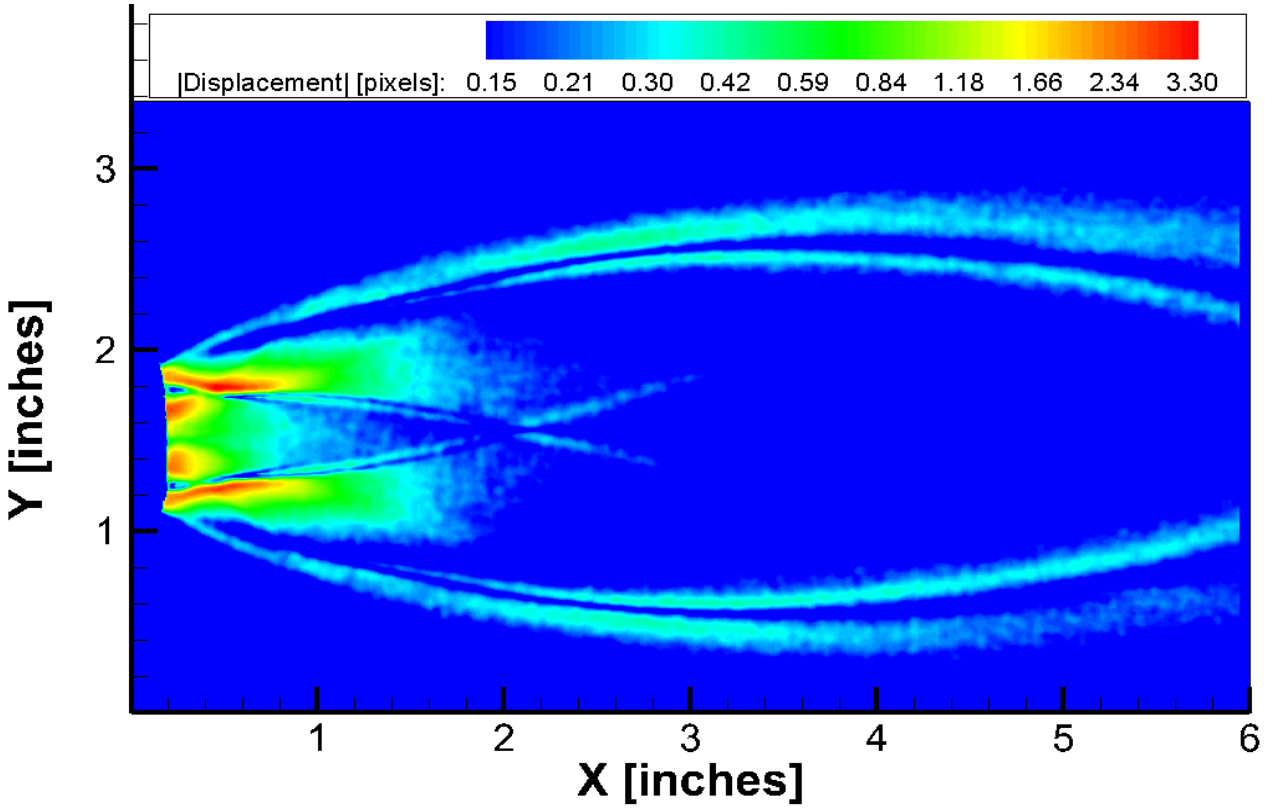
- The 2-Dimeneional gradient field of density can be integrated to reconstruct the original density field



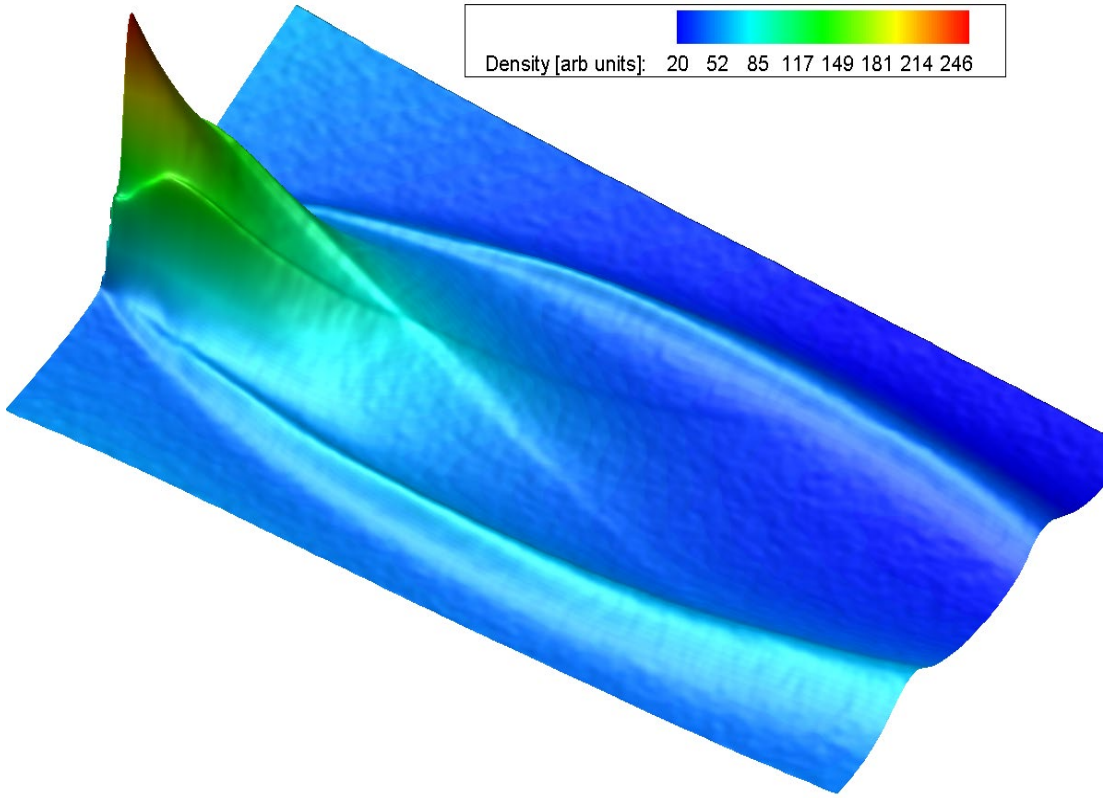


ACS Results

- 1000 psi plenum pressure through 0.105” diameter nozzle into 0.3 psia ambient chamber

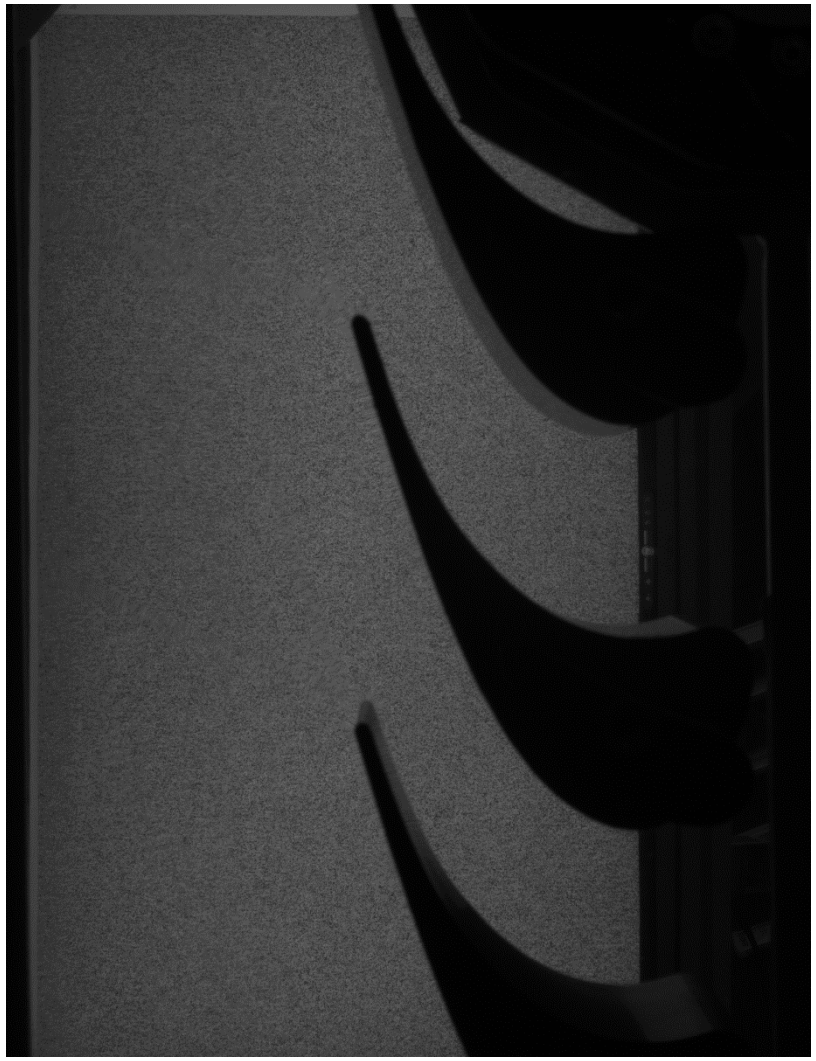


Same data set integrated to yield density surface map

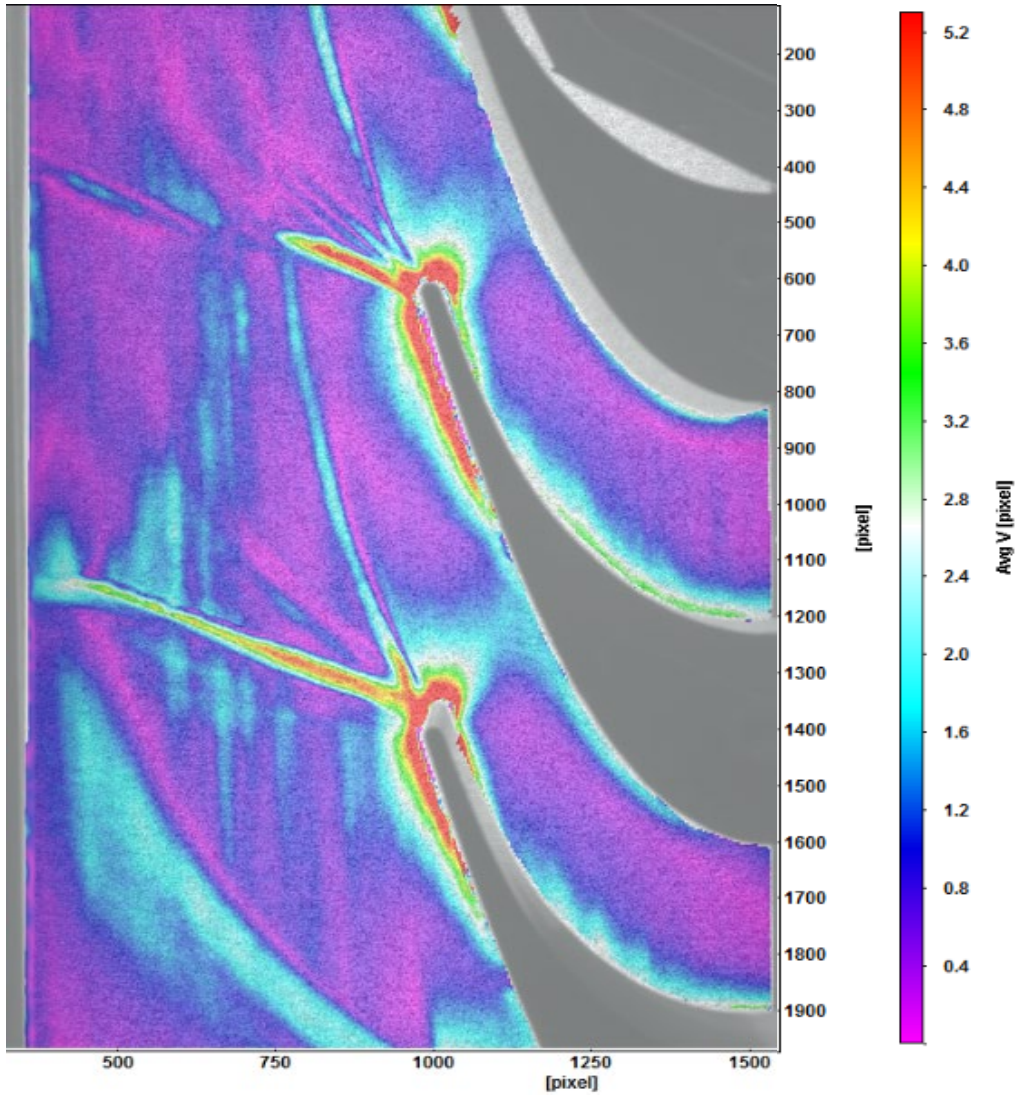


BOS Images

Raw Image

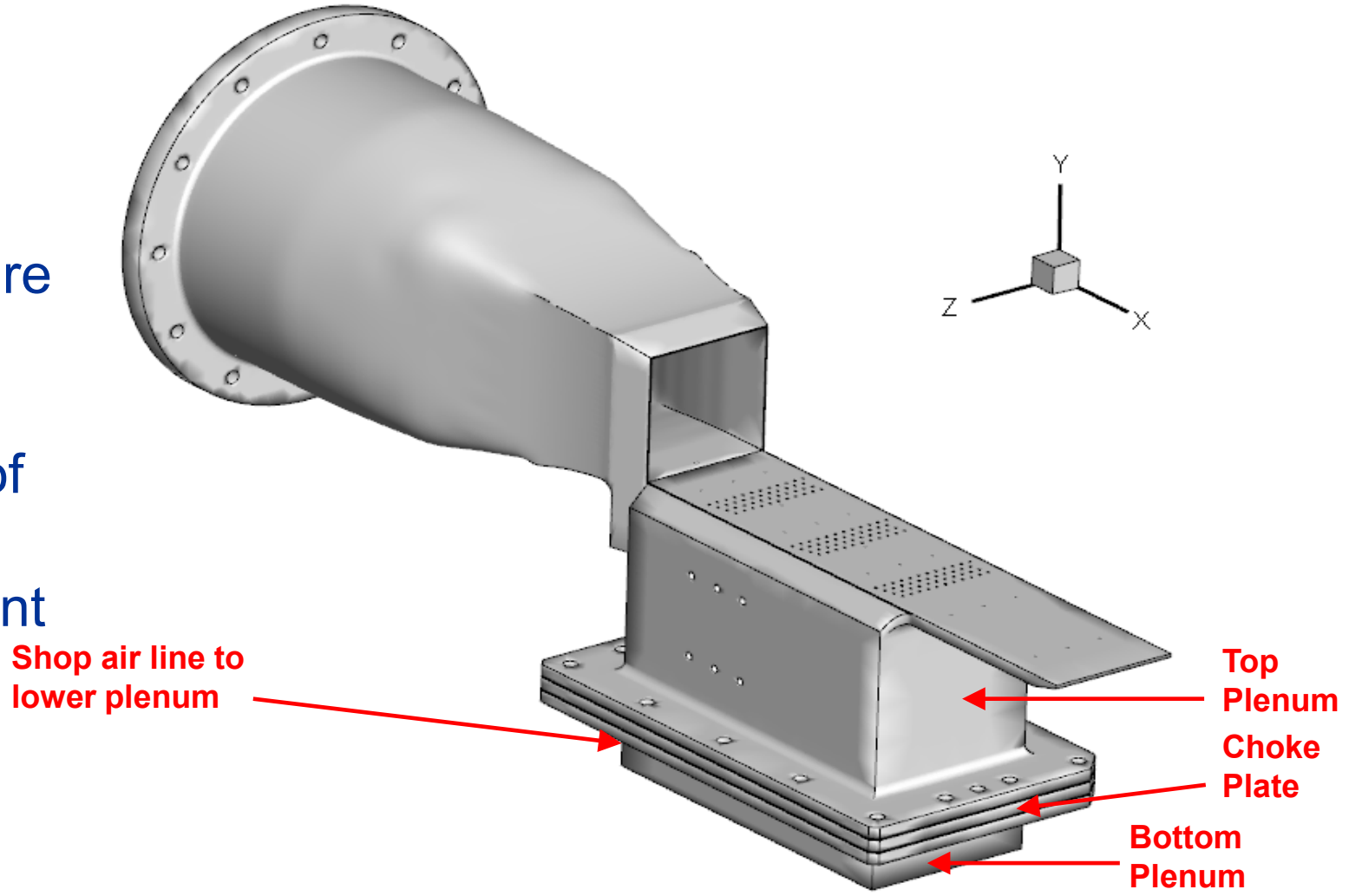


Processed Image, 100 Frame Average



Turbulent Heat Transfer (THX) – Porous plate geometry

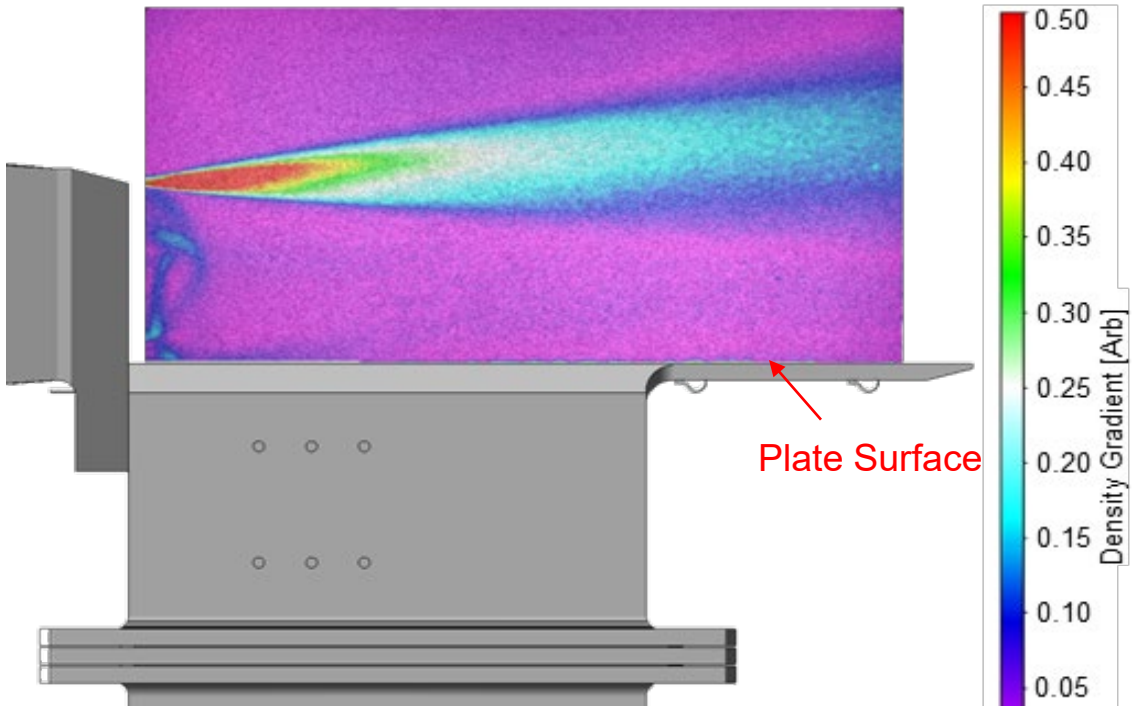
- TTT Program to obtain benchmark data for CFD validation
- Use Raman to get temperature and PIV to get velocity
- Used RT-BOS before the Raman to get the thickness of the film cooling layer to optimize Raman measurement grid

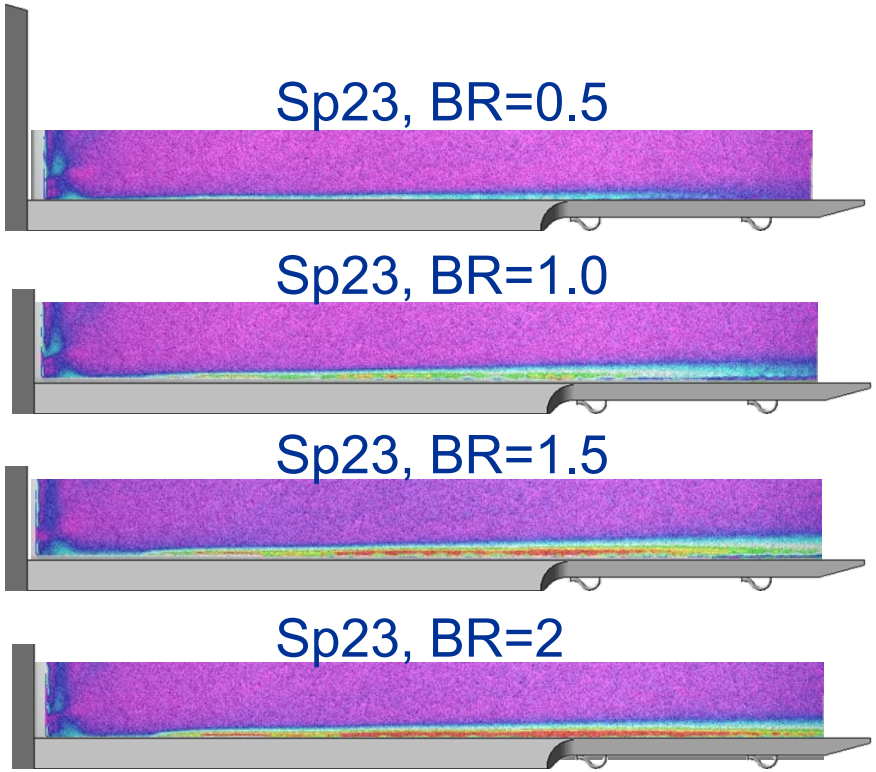


Background Oriented Schlieren on THX 4

- BOS displays the thickness of the film cooling layer
- From BR = 0 (no blowing) up to BR=2, the thickness and extent of the cooling film is observed

THX18 Sp23, BR=0





Background Oriented Schlieren

THX18 Sp9050, Br=0.5

