Single Source/Cutoff Grid, Self-Aligned Focusing Schlieren System

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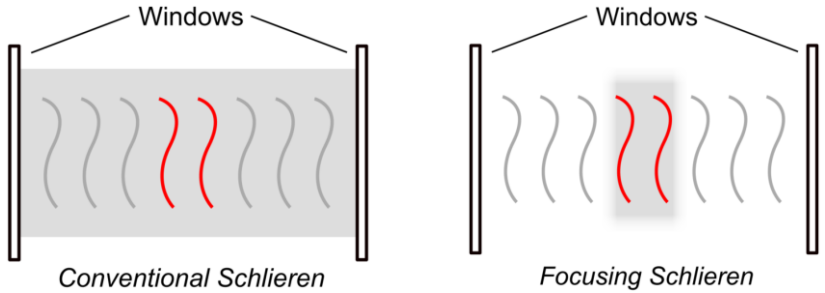
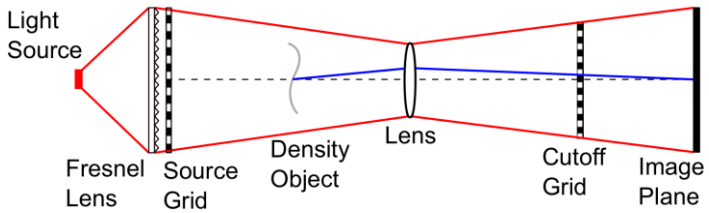
Weisberger and Bathel, "*Single source/cutoff grid, self-aligned focusing schlieren system*," Experiments in Fluids, Vol. 63, No. 8, 2022.

Motivation for New Focusing Schlieren System

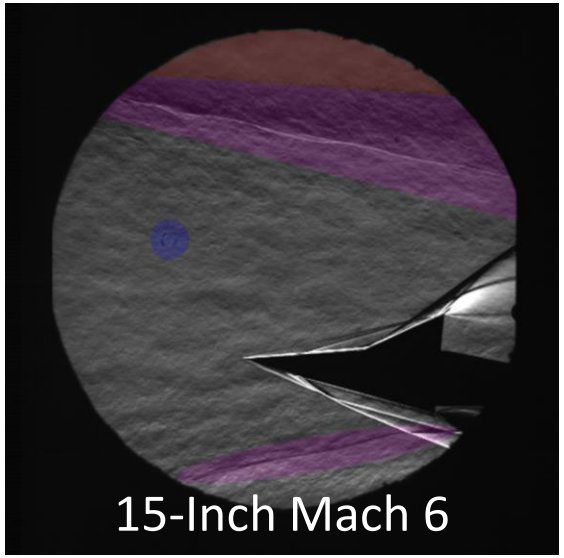
- Conventional schlieren has been a staple flow visualization tool for researches for decades, but has several drawbacks:
  - Window defects (scratches, chips, etc.)
  - Thermal air currents outside wind tunnel
  - Turbulent wall boundary layer
  - Shear layer between free-jet core and ambient tunnel cabin
- Focusing schlieren first reported in the early 40s to isolate flow imaging in a narrow depth-of-field

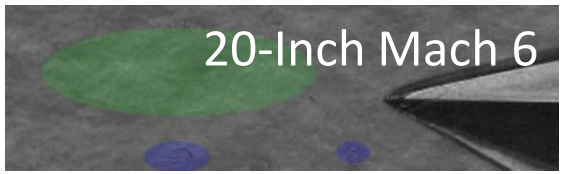


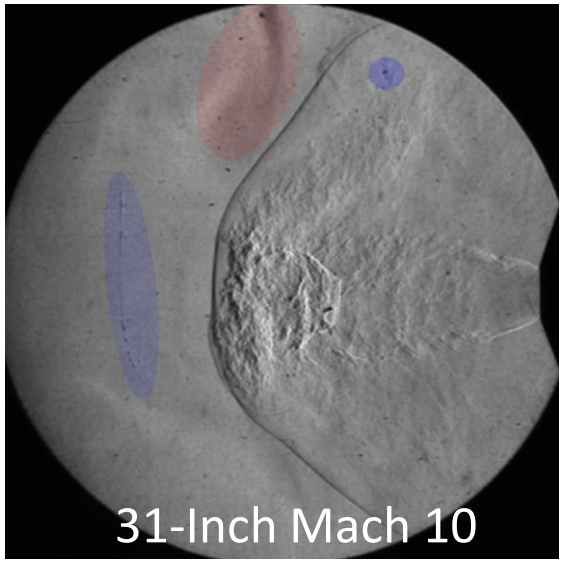


- Historically, focusing schlieren has been <u>difficult</u> and <u>time-consuming</u> to set up, limiting its practical use

- **<u>Our main motivating factors:</u>**
  - Does not require the fabrication and precise alignment of a source-matched cutoff grid
  - Single-sided imaging, does not require optical through-access in a wind tunnel

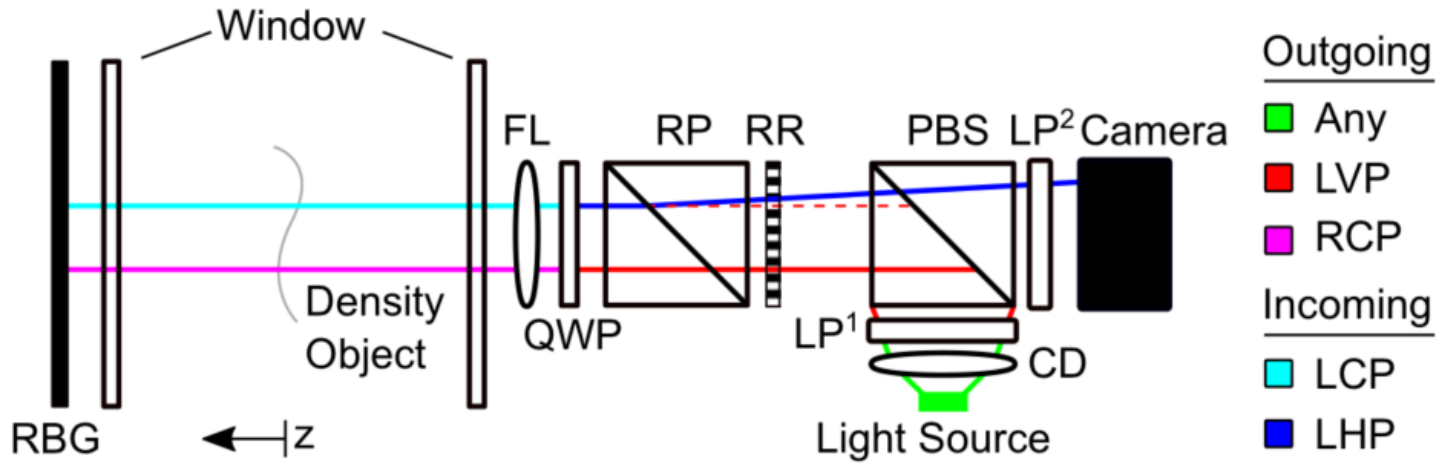






Experimental Setup

- Linearly polarized light reflected onto main optical axis
- Image of Ronchi ruling (RR) projected onto a retroreflective background (RBG) by field lens (FL)
- RBG alters polarization of light upon reflection



- Light is slightly refracted through Rochon prism (RP) before passing through RR
  - Provides cutoff akin to conventional schlieren knife-edge cutoff

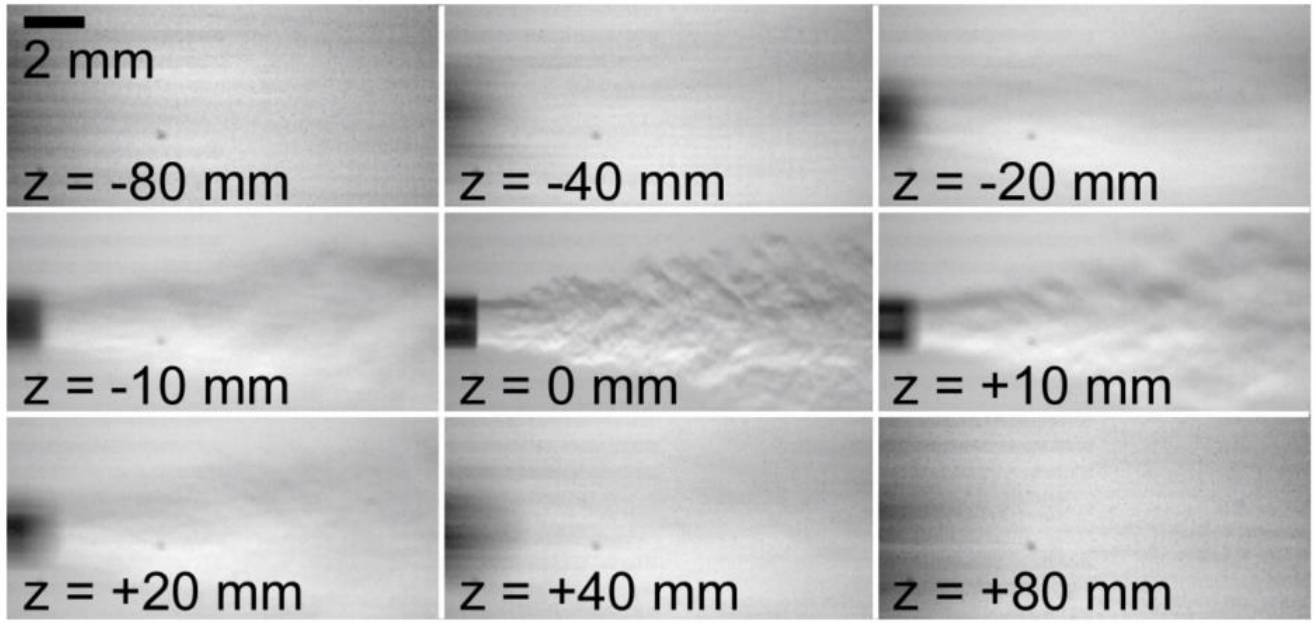
- Two important optic positioning pairs:
  1. RR placement relative to FL to image onto RBG
  2. Camera placement relative to FL to image density object of interest

[1] Bathel and Weisberger, "*Compact, self-aligned focusing schlieren system*," Optics Letters, Vol. 46, No. 14, 2021.

[2] Bathel and Weisberger, "*Development of a Self-Aligned Compact Focusing Schlieren System for NASA Test Facilities*," AIAA 2022 SciTech Forum, AIAA-2022-0560.

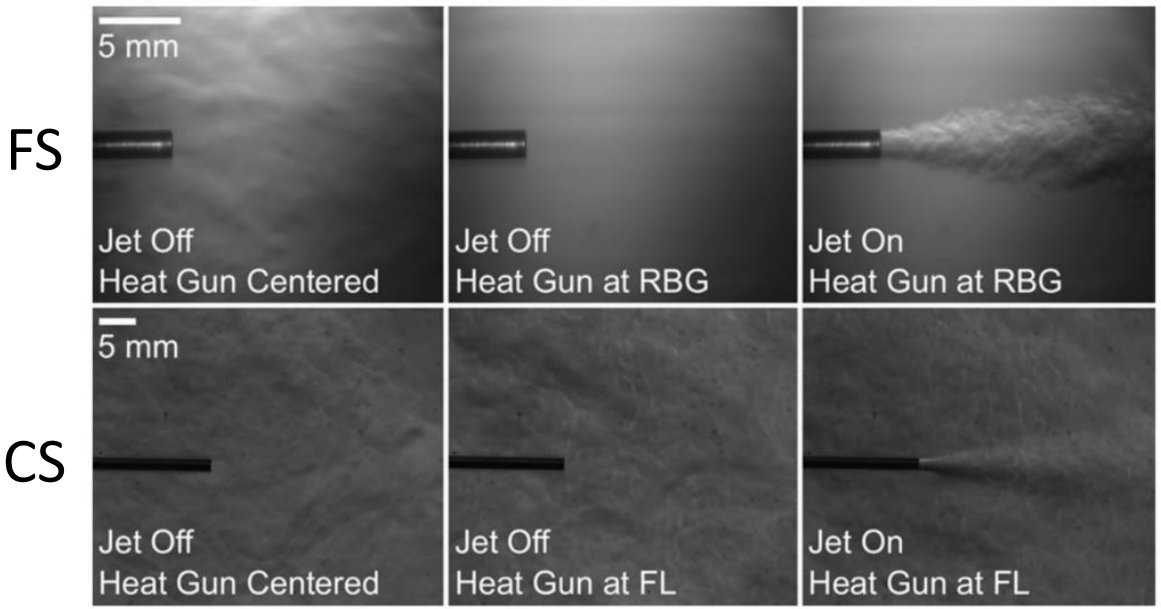
Initial System Testing

Does this system work as intended, and what is its depth-of-field?



- Distance between field lens and background is 750 mm
- Helium jet (1.7 mm outer diameter) halfway between field lens and background

- Narrow depth-of-field, good defocusing, strong schlieren signal



How does it compare to equivalent conventional schlieren?

- Lens-based conventional schlieren (CS) system with same working distances as focusing schlieren (FS) system

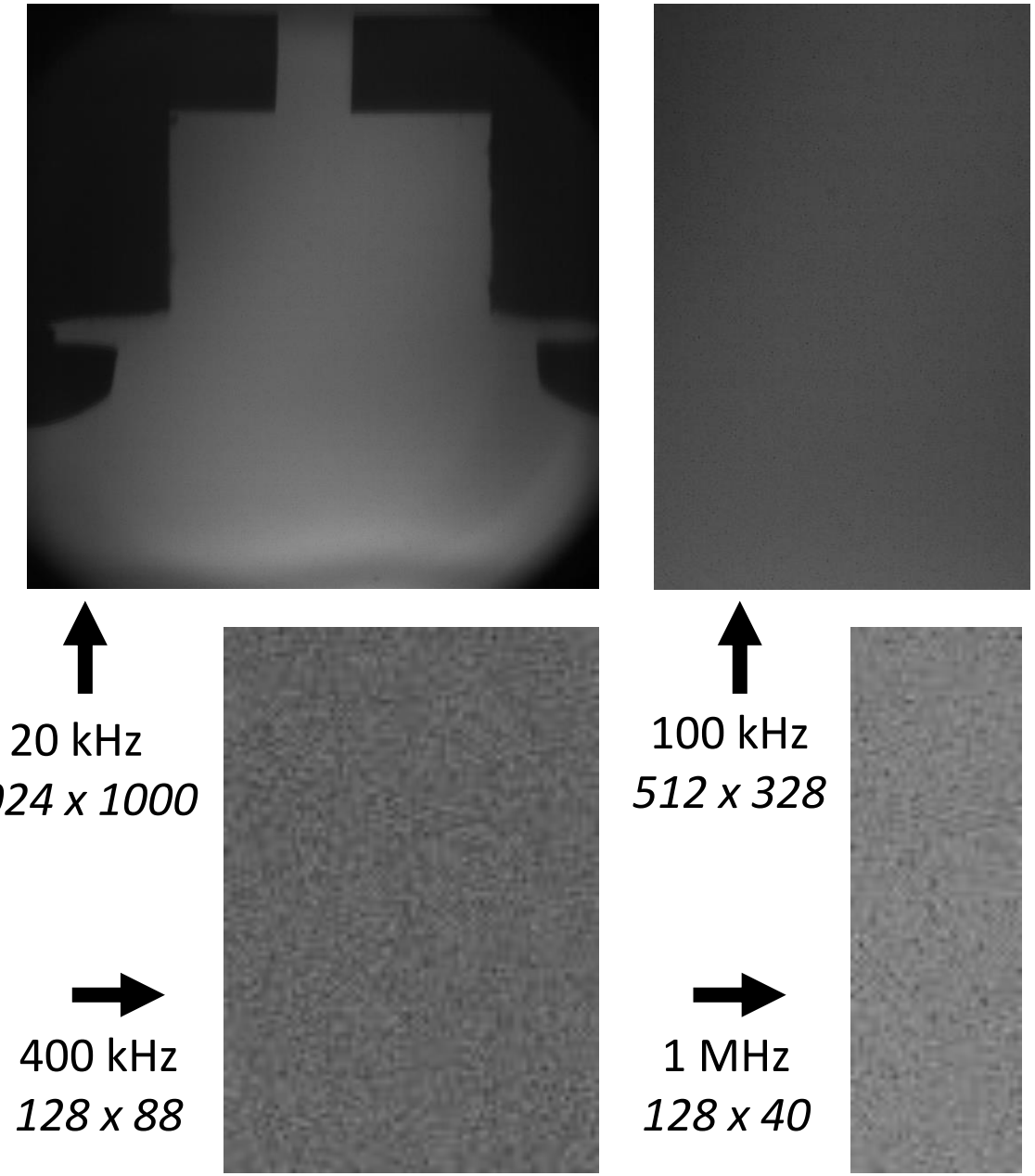
- CS: heat gun thermal plume overwhelms helium jet flow structure
- FS: heat gun thermal plume does not interfere with helium jet flow of interest

High-Speed Imaging Capability

Using retroreflective material, will we have enough light intensity for high-speed imaging?

- Electrode spark generates shock wave
- Cavilux Cavitar HF 640 nm laser with UHS unit
- Photron SA-Z with four camera frame rates
  - 20 kHz, 100 kHz, 400 kHz, 1 MHz

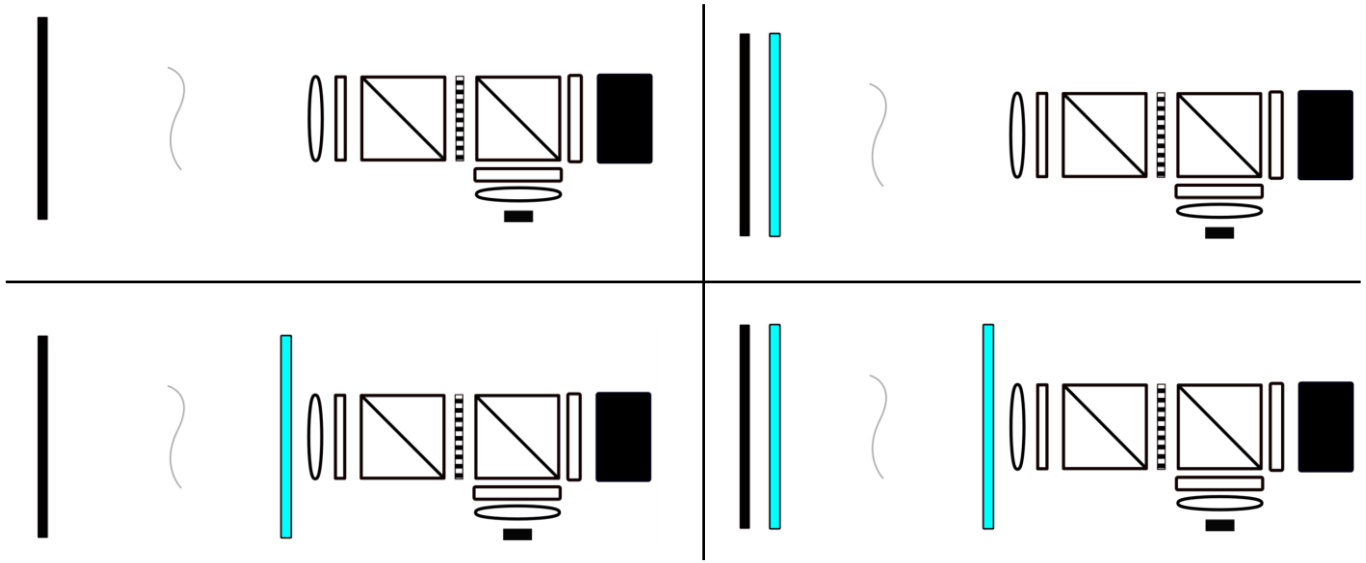
- High-quality high-speed images comparable to conventional schlieren
- Sufficient light return for camera framing rates up to at least 1 MHz
- Limitation for higher framing rates will be usable camera region-of-interest



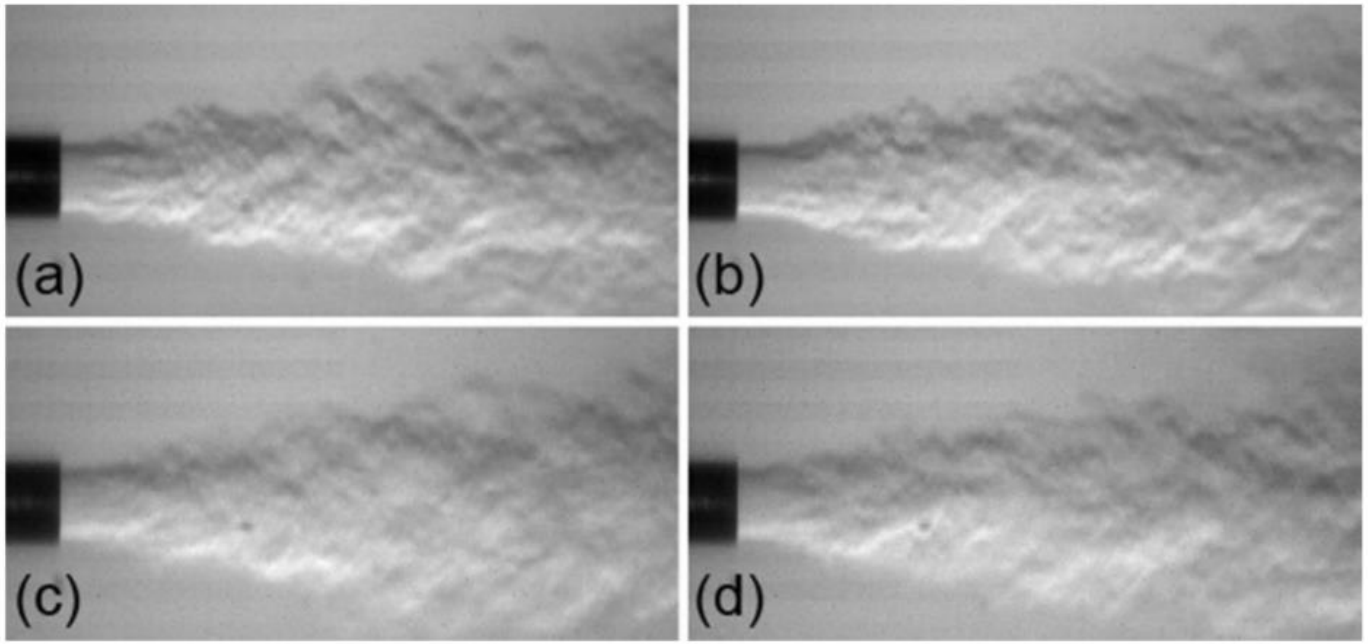
Influence of Windows

What influence do windows have on images?

- (**a**) Baseline system without windows
- (**b**) Window only in front of retro background
- (**c**) Window only after field lens
- (**d**) Windows after field lens and in front of retro background
- Windows placed at normal incidence to optical axis

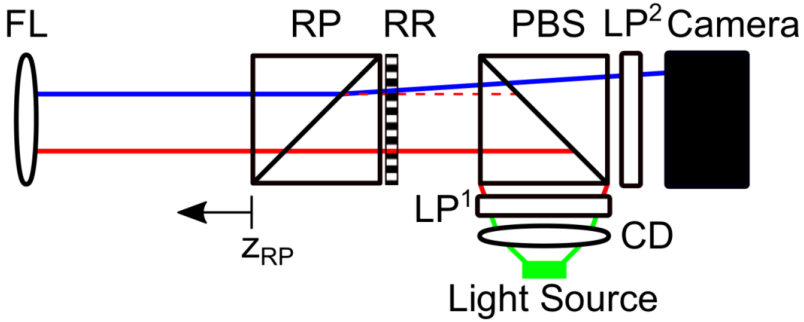


- Window in front of retro background (**b**) does not change image quality from baseline (**a**)
- Window after field lens (**c**) slightly reduces contrast of images
- Typical wind tunnel configuration (**d**) slightly reduces contrast of images
- Can use system at normal incidence to wind tunnel windows without noticeable reflections or glare



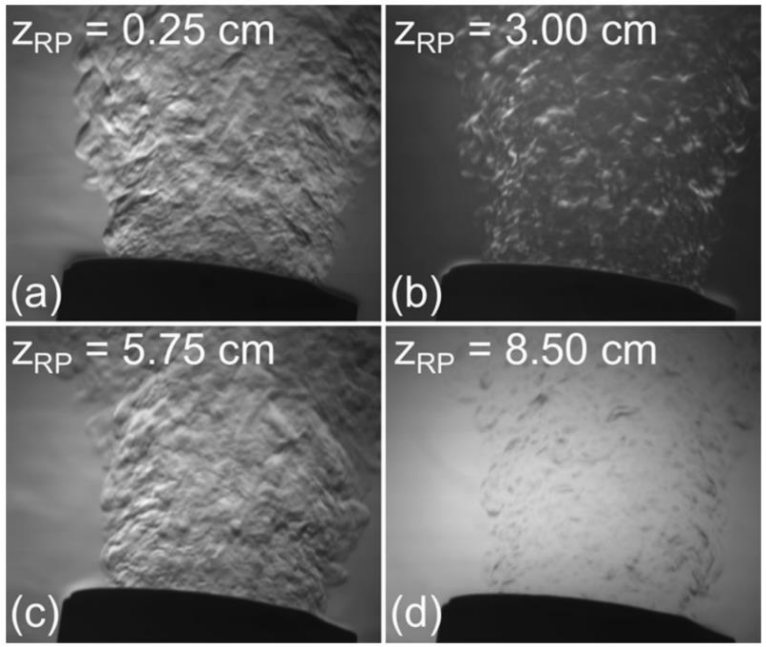
Adjustable Sensitivity using Rochon Prism

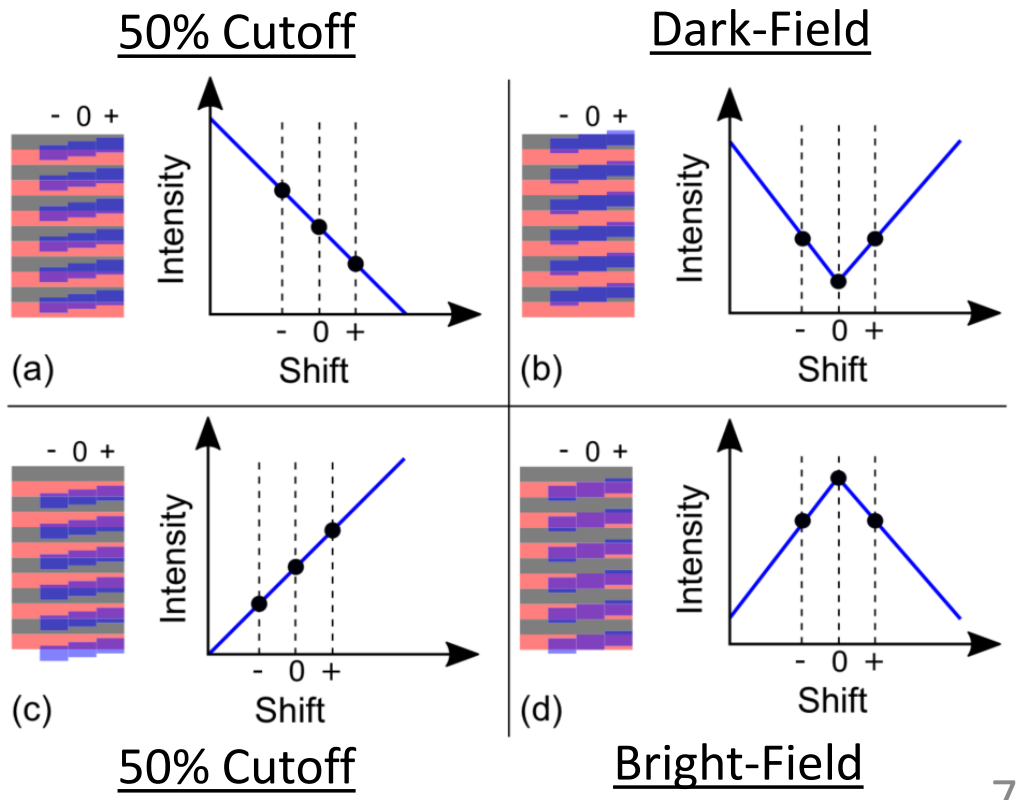
Can we adjust the sensitivity of the system, similar to the adjustment of a conventional schlieren knife-edge cutoff percentage?



- Move polarizing prism relative to Ronchi ruling to adjust cutoff percentage
- Schematics (bottom-right) show four distinct cutoff scenarios
  - 50% cutoff (two directions), dark-field, bright-field
- Near 50% cutoff is preferred for schlieren imaging

- Movement of Rochon prism along optical axis allows for adjustment of cutoff
- Level of adjustment depends on:
  1. Prism refraction angle
  2. Ronchi grid spacing (lp/mm)
  3. Separation distance



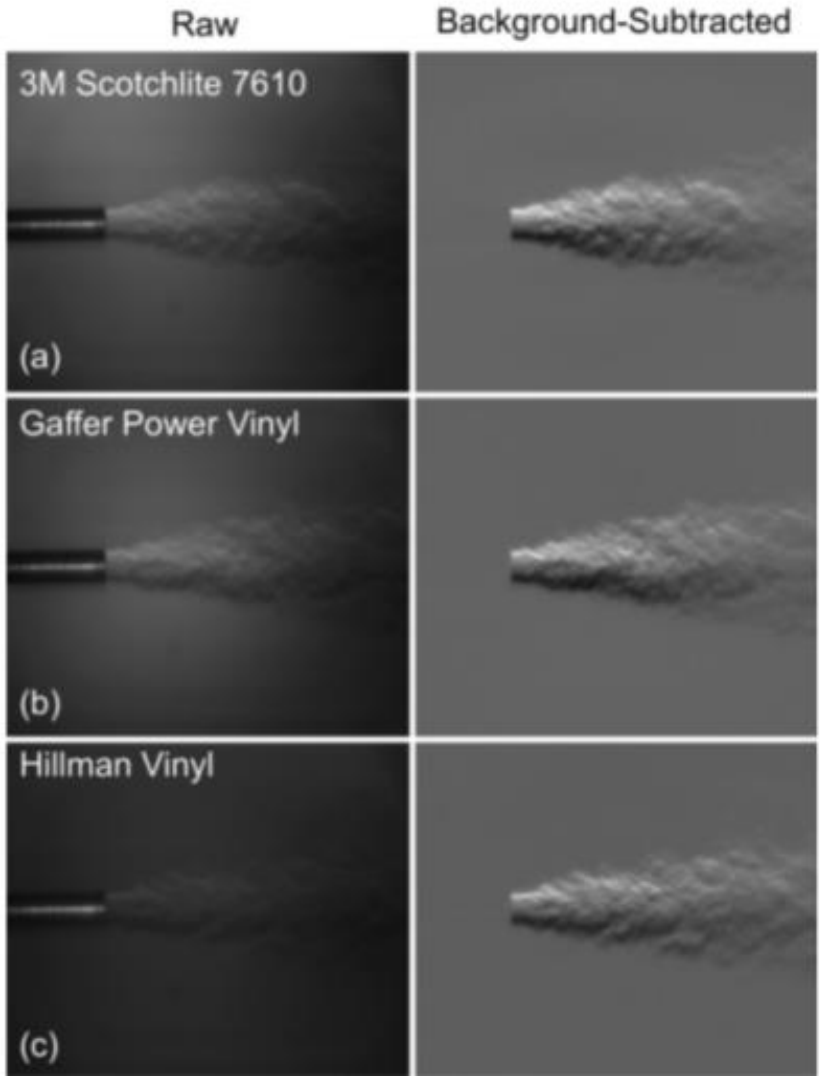


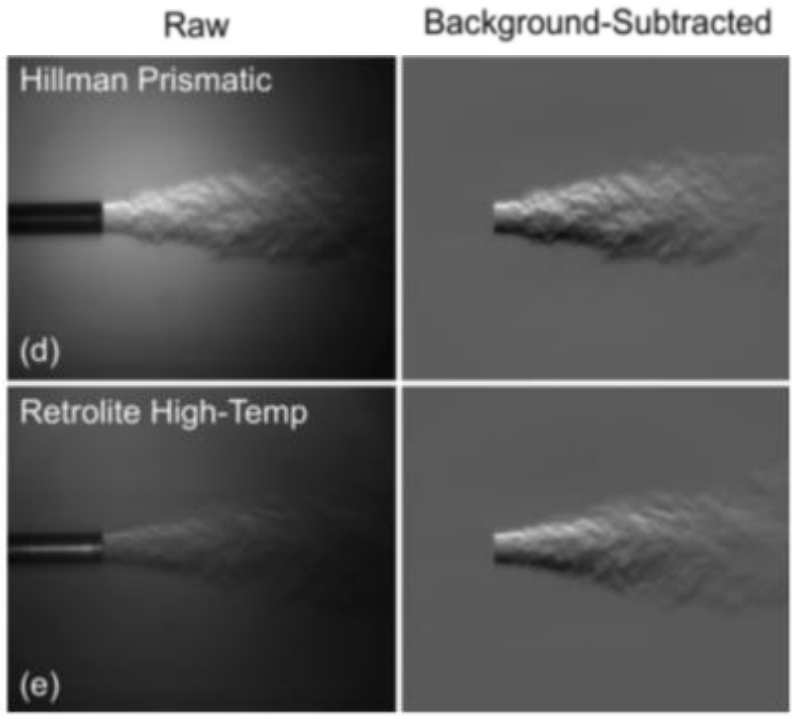
Retroreflective Background Material Selection

Does the type of retroreflective background (RBG) affect the images?

- Only change to FS system between tests is replacing the RBG material
- All images are scaled to the same bounds for qualitative comparison

- Raw images (left columns) show different levels of intensity return for different RBG materials
- Prismatic (**d**) has highest intensity return
- Background-subtracted images (right column) all show similar levels of detail in turbulent structure
- Can use any retro material (that we have tested) depending on intensity required



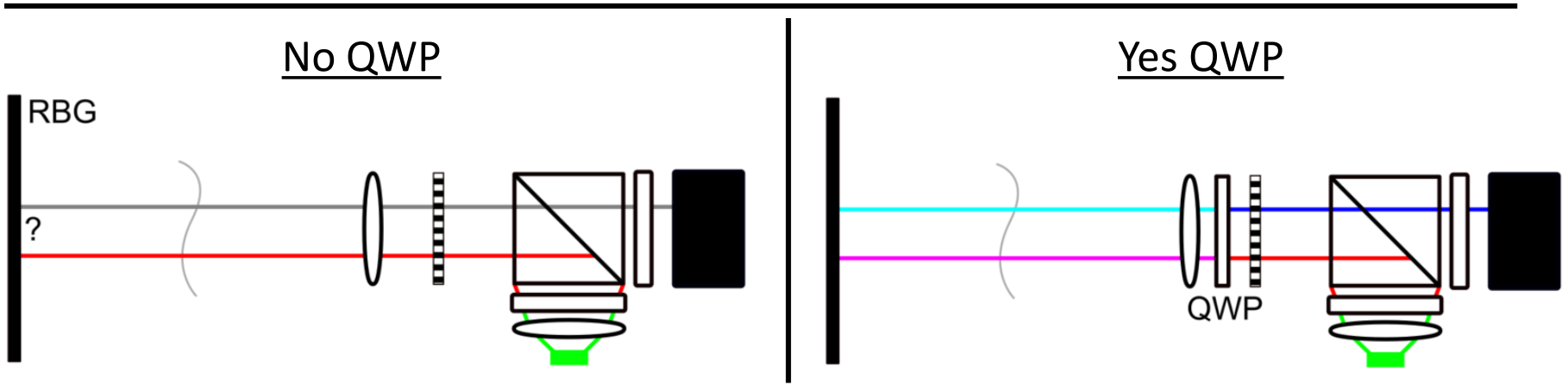


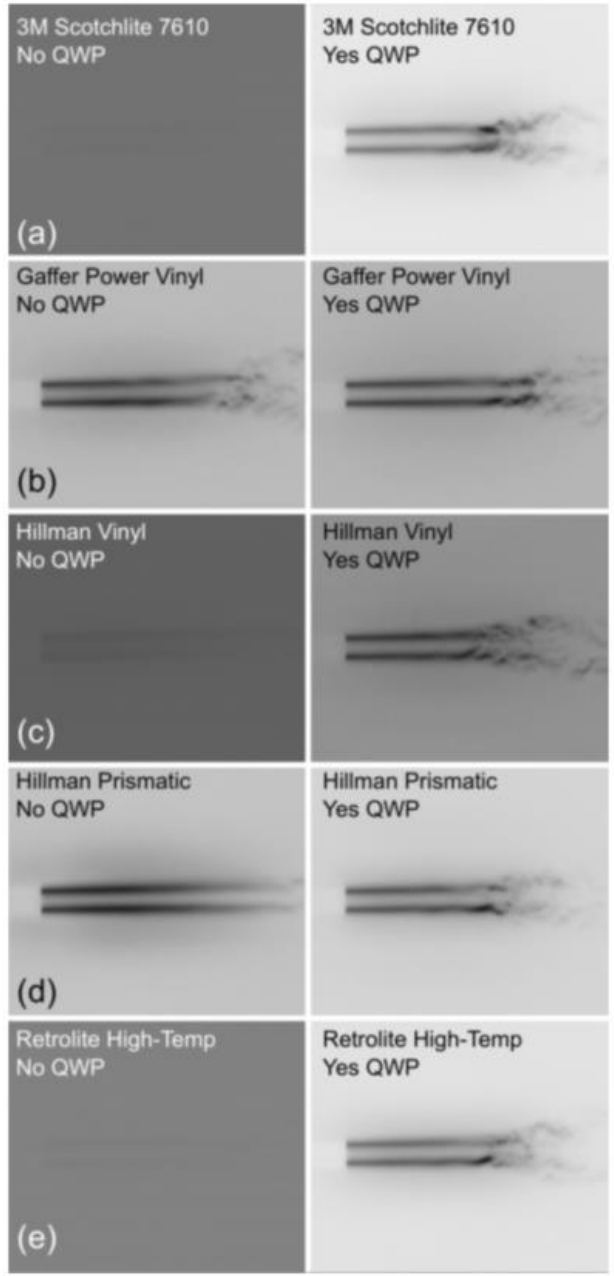
Quarter-Wave Film Polarization State Alteration

What influence does the retroreflective material have on polarization state of the light, and can we use that to our advantage?

- Removed the Rochon prism from the system
- Images with every retro material, both without (left column) and with (right column) the quarter-wave plate (QWP)

- (**a**, **c**, **e**): Three retro materials do not alter polarization state of light upon reflection
- (**b**, **d**): Two retro materials act as if they have a built-in retarder
  - Do not need to include QWP for imaging
- Can obtain focusing bright-field schlieren with minimal optics if cost-limited
  - No Rochon prism, no quarter-wave plate, no linear polarizers

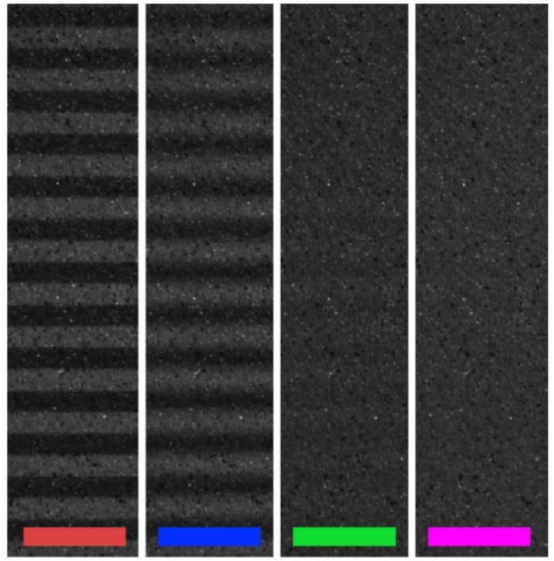


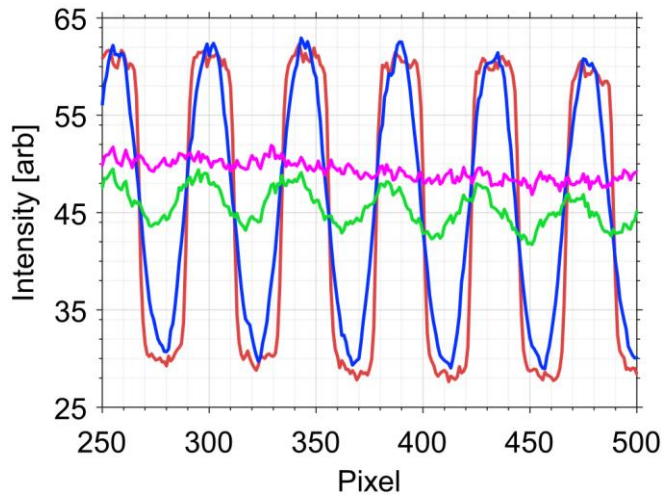


Influence of Projected Grid Focus on Background

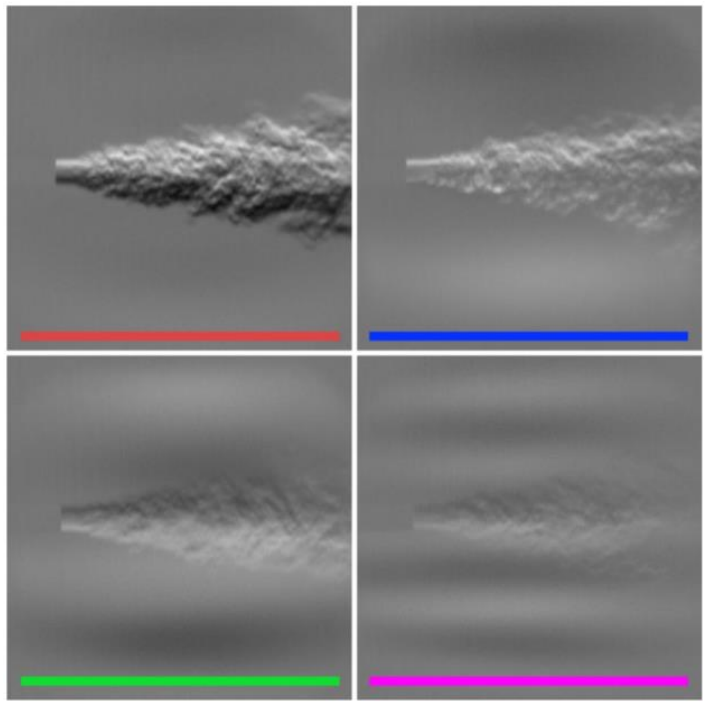
How much can the grid be de-focused from the background before we lose meaningful sensitivity?

- External camera imaging the focus of the grid pattern on retro background
- Four levels of grid focus tested
  - Sharp focus, two intermediate focus, near-total defocus





- Sharply focused grid provides high-contrast image
- Intermediately focused grid shows structure of the jet, but contrast is reduced
- Near-total defocused grid still images faint jet, but not useful
- Vibrations at wind tunnel facility causing defocusing of grid will reduce contrast slightly, but useful imaging still possible



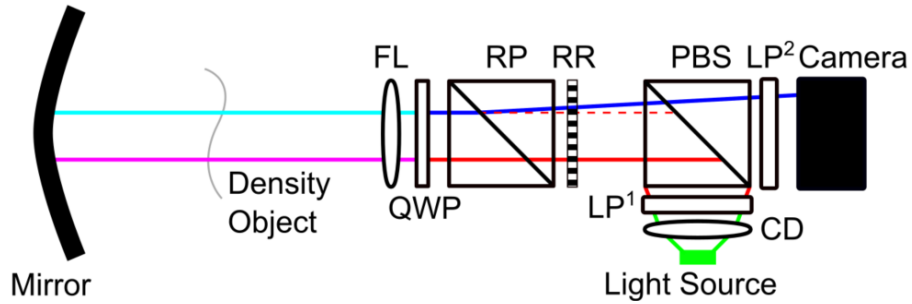
Images are background-subtracted

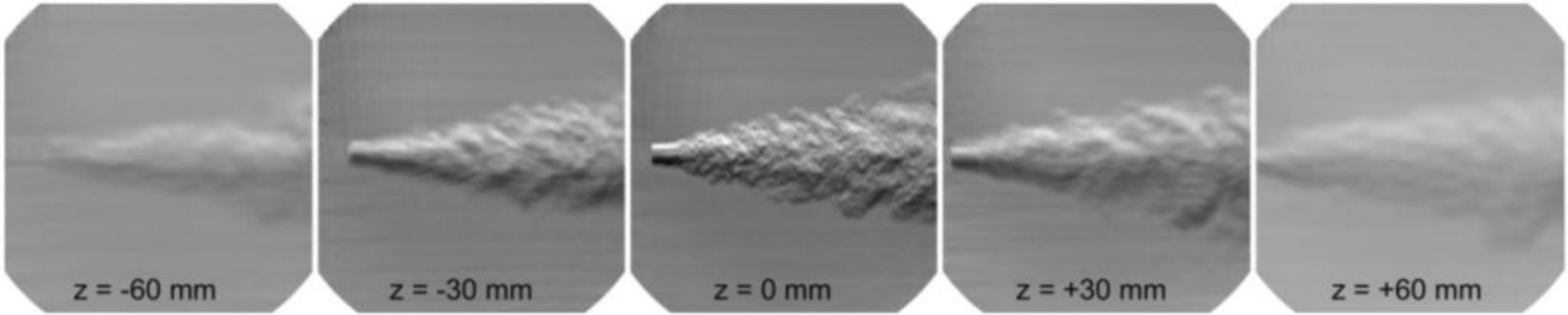
Using a Mirror as a Reflector

Do we need to use retroreflective material as the background, or can we use a mirror?

- In place of RBG, placed a concave parabolic mirror (f = 762 mm)
- Image the projected grid onto the mirror surface
- Also tested:
  - Parabolic concave mirror, f = 381 mm
  - Concave spherical mirror, R = 1524 mm

- Focusing ability of the system is retained
- Depth-of-focus is widened slightly
- Can use existing wind tunnel mirrors if optical through-access is available



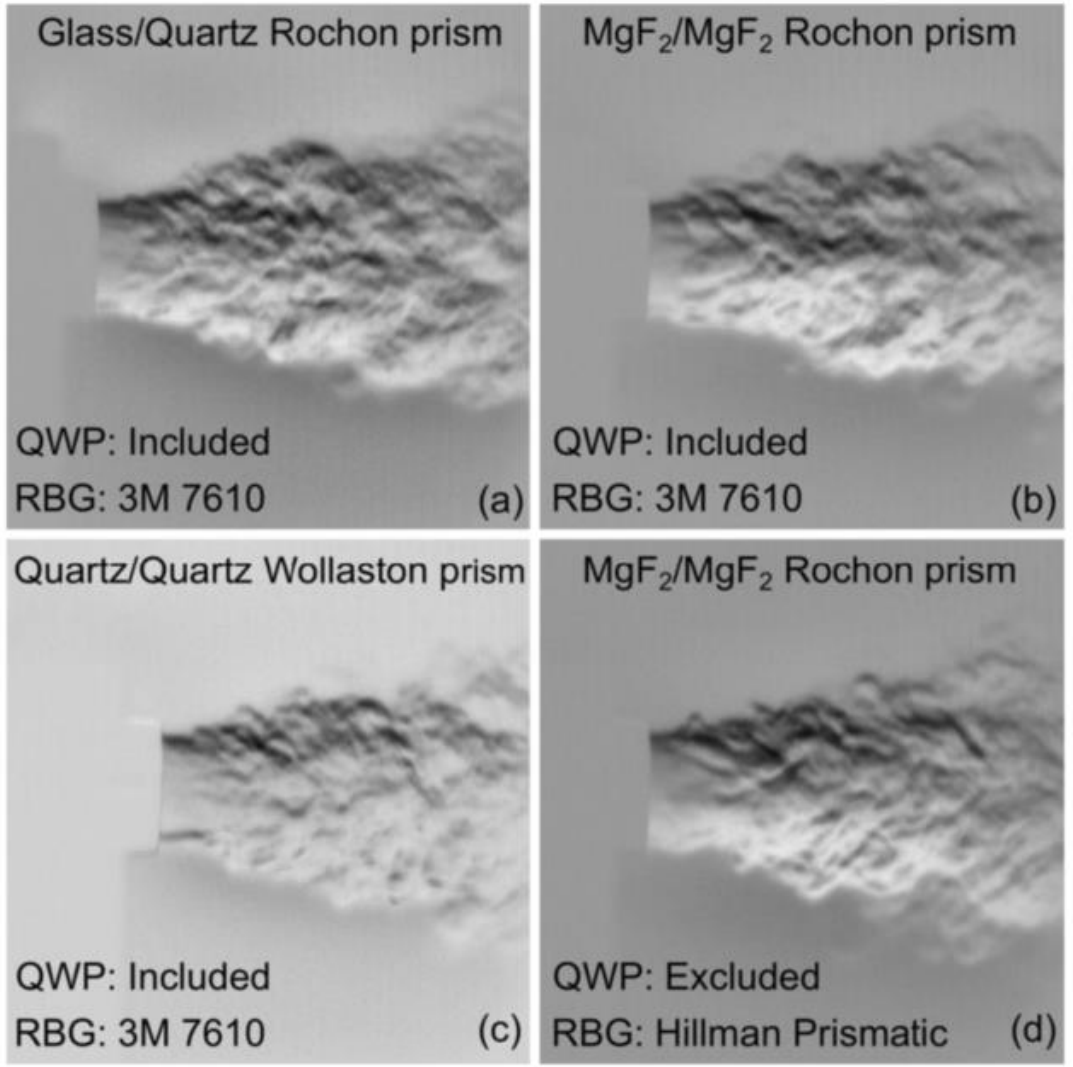


Alternative Polarizing Prism Options

Can we use Rochon prisms made from other materials? What about using a Wollaston prism?

- Quartz/quartz Rochon prism used for all previous results
  - Polarization properties differ in forward and backward directions (Ref. [1]) due to optical activity of quartz
- Testing three other prisms for potential use:
  - Glass/quartz Rochon prism (Refs. [2,3,4])
  - MgF_2/MgF_2 Rochon prism
  - Quartz/quartz Wollaston prism

- All three alternative prism options can be used in this system
- MgF2/MgF2 experiences non-ideal polarization characteristics when light is not collimated
- *Suggested prism for this system is glass/quartz Rochon prism*



[1] Weisberger and Bathel, "*Characterization of Rochon Prisms for Bi-Directional Imaging Applications*," NASA Technical Memorandum, 20210026232, 2022.

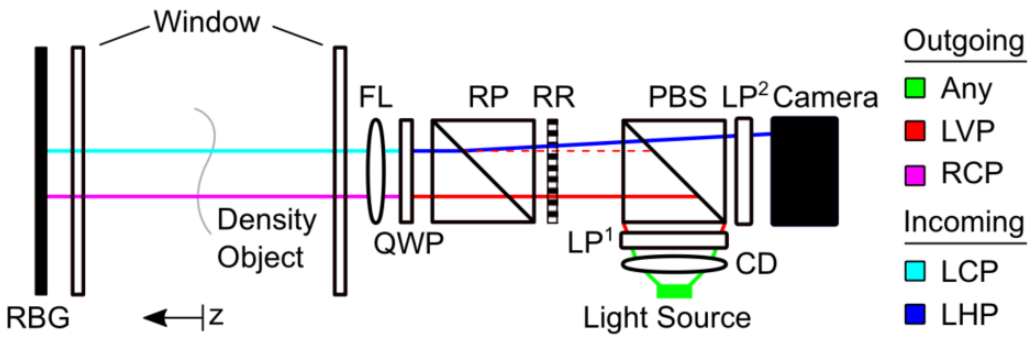
[2] Ammann and Massey, *"Less-expensive Rochon prisms,"* NASA Tech Brief, 70-10681, 1970.

[3] Ammann, *"Optical polarizing prism,"* US Patent, US3511556A, 1970.

[4] Amman and Massey, *"Modified forms for Glan-Thompson and Rochon prisms,"* J. Opt. Soc. Am. 58:11, pp. 1427-1433, 1968.

What Was Accomplished

- New focusing schlieren system uses one optic as the source grid and cutoff grid
- Retroreflective background ensures system is self-aligned
- Extensive testing of optics and configurations has been performed



- Implementation:
  - –System has been successfully used at NASA Langley Research Center's 20-Inch Mach 6 and 31-Inch Mach 10 wind tunnels, as well as a large-scale arc-jet tunnel
- Our hope:
  - –This system lowers the barrier-to-entry for high-quality focusing schlieren imaging for researchers

[1] Bathel and Weisberger, "*Compact, self-aligned focusing schlieren system*," Optics Letters, Vol. 46, No. 14, pp. 3328-3331, 2021.

[2] Bathel and Weisberger, *"Development of a Self-Aligned Compact Focusing Schlieren System for NASA Test Facilities,"* AIAA SciTech 2022 Forum, AIAA-2022-0560.

[3] Weisberger and Bathel, "*Single source/cutoff grid, self-aligned focusing schlieren system*," Experiments in Fluids, 63:38, 2022.

BACKUP SLIDES

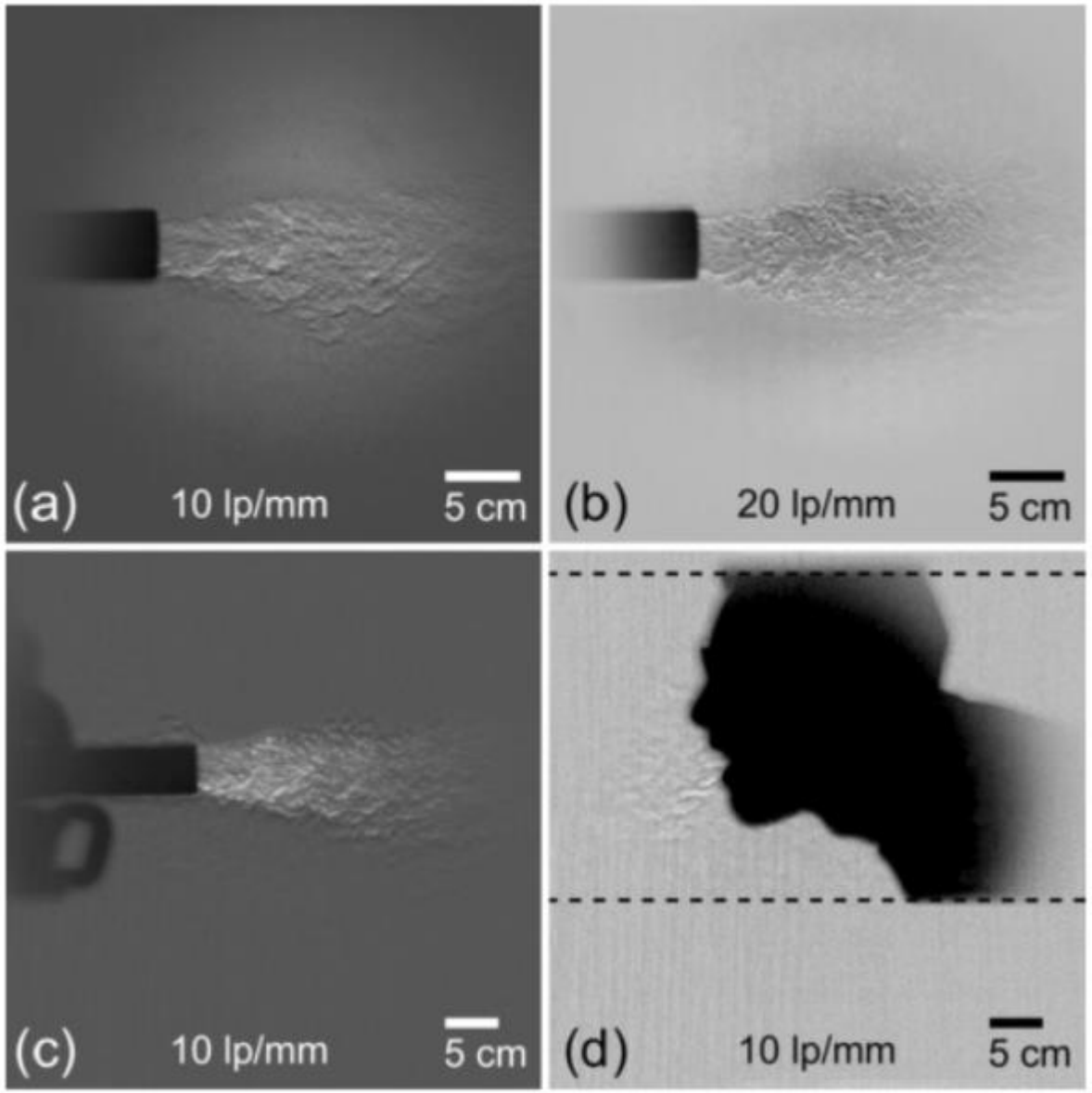
Large-Scale System Testing

Are we able to achieve large fields-of-view, comparable to conventional schlieren imaging?

- Lage-scale system to demonstrate capability in larger wind tunnel facilities
- Heat gun thermal plume (**a**, **b**, **c**) and human breath (**d**) used as density objects

- Large fields-of-view are possible
- The larger the FOV and throw distance, the wider the depth-of-field
- Still able to get sensitive schlieren measurements, as indicated by image of human breath (**d**)

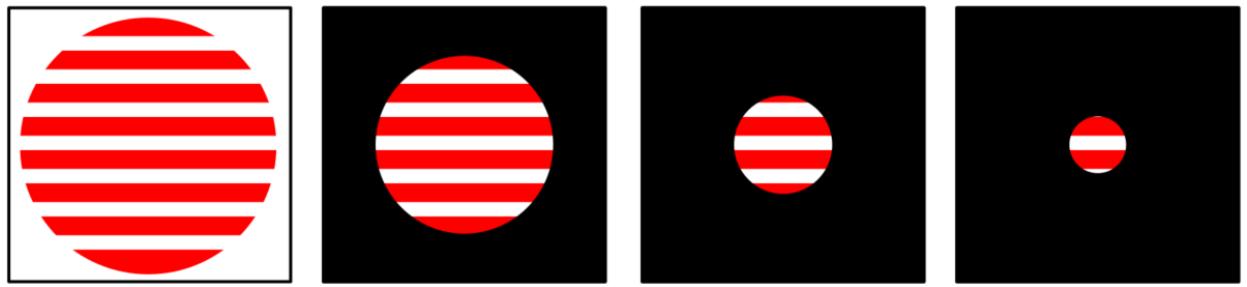
Version	FOV	FL-RBG	FL-DO	FL-RR	FL-Cam
LS-1	57.5	5486	2743	550	612
LS-2	350	1829	1219	111	115
LS-3	500	4318	2159	107	110



Background Size Requirements

To what extent can we reduce the amount of retroreflective material that we use?

- Place iris aperture directly in front of retro background
- Change iris diameter to cut down projected intensity of the grid on the background



- High-quality images with good focusing ability are possible for very small projected/reflected grids
- These results are only tested using the small-scale system, and may not hold for larger-scale system