The evolution and interaction of two shock-accelerated, unstable gas cylinders

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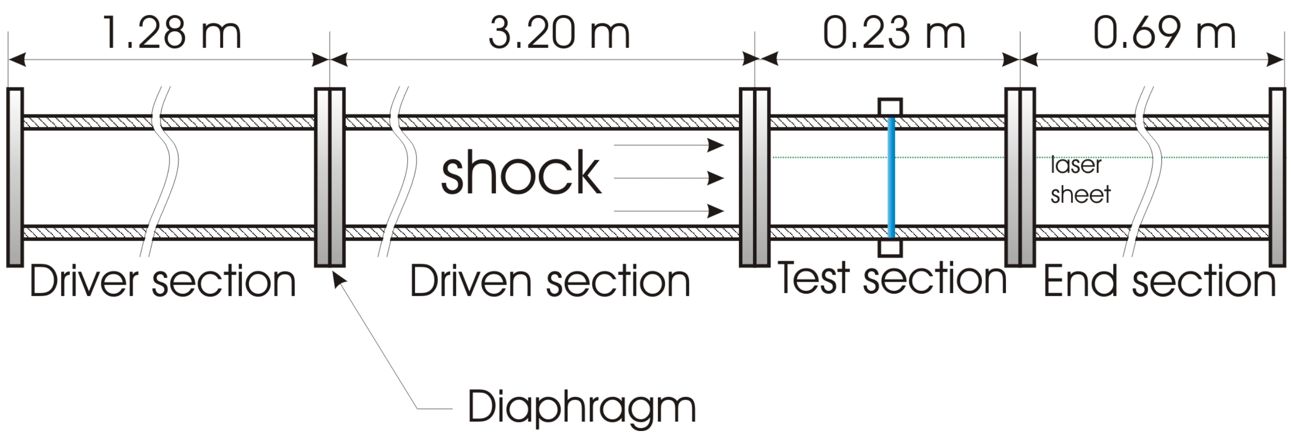
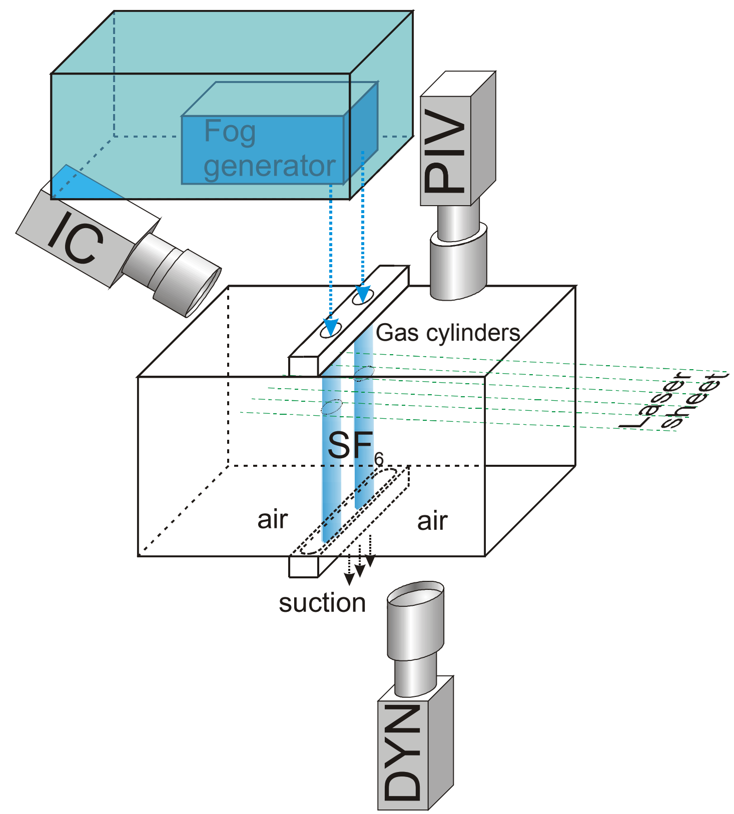


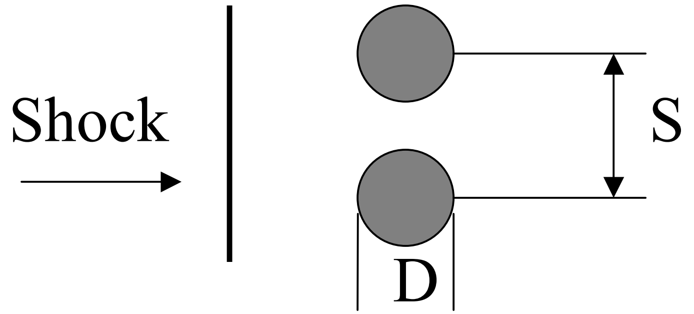
Experimental setup: shock tube



Overview

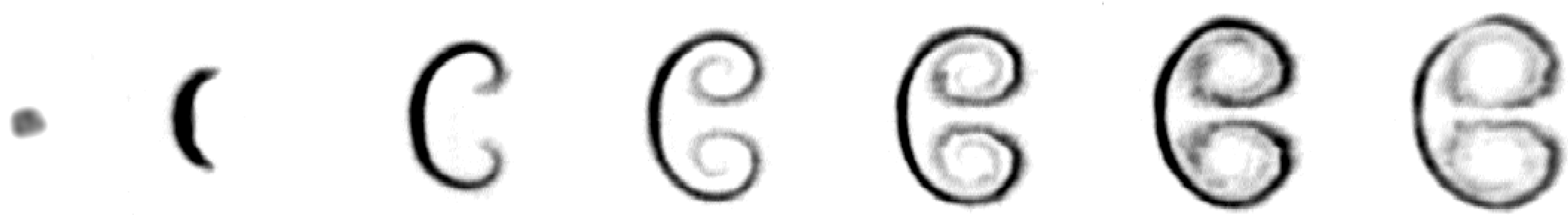
- Examine interaction of planar shock with 2 gas cylinders, separated spanwise.
- S = 1.2D to 2.0D.

(D = cylinder diameter)

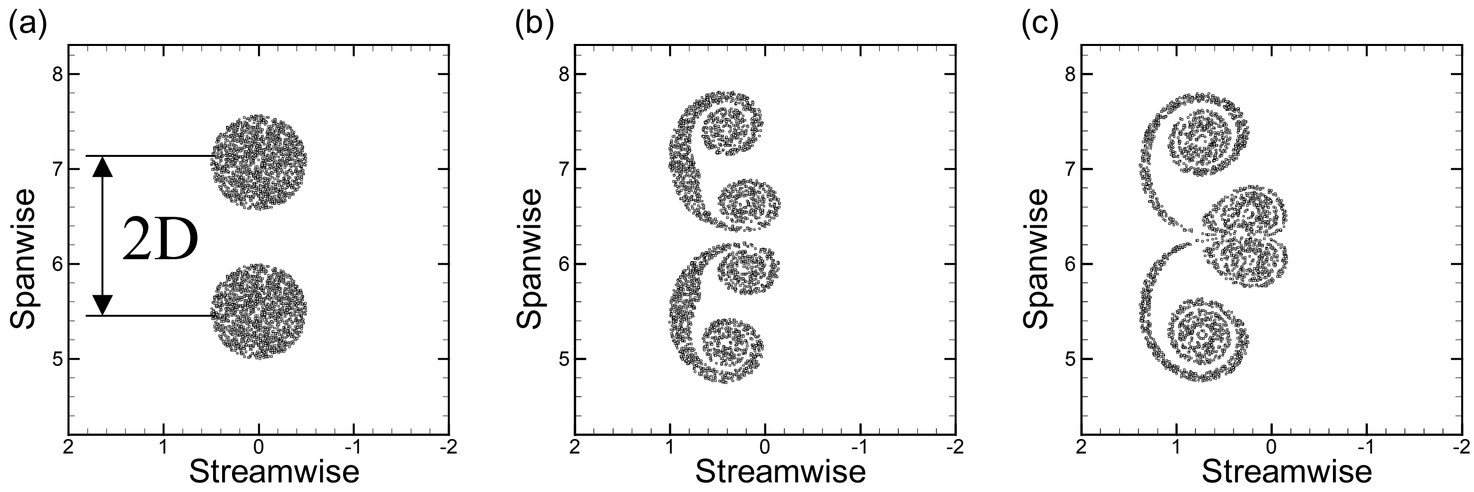


- Goal: Investigate the evolution of the interacting, RM-unstable cylinders. Issues of interest include:
  - What is the effect of the interaction on the resulting flow morphologies? On the initial vorticity deposition? On the post-shock vortex development?
  - How sensitive is the flow evolution to the initial separation S?

Single shock-accelerated cylinder

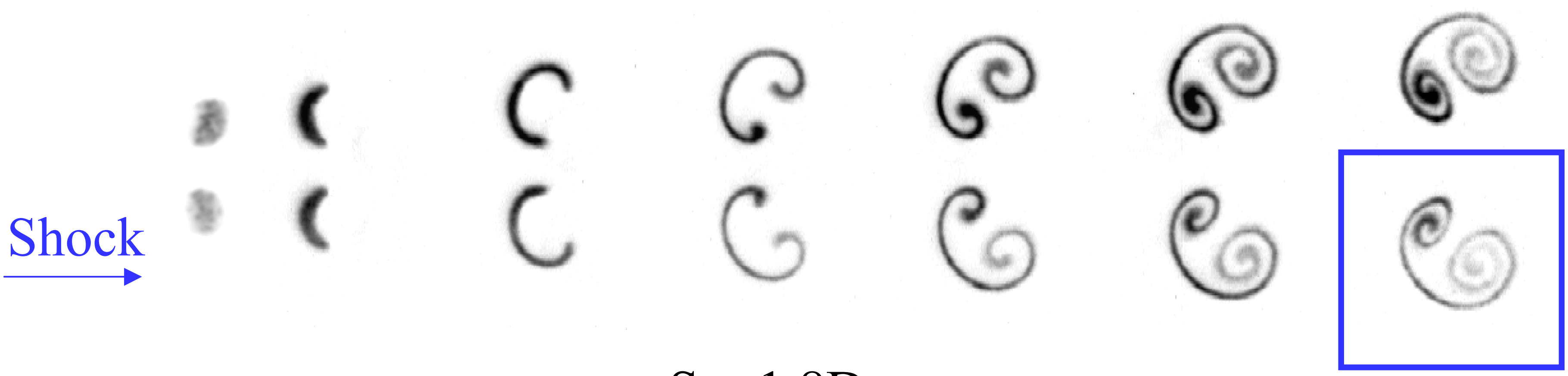


Double-cylinder “vortex blob” simulation

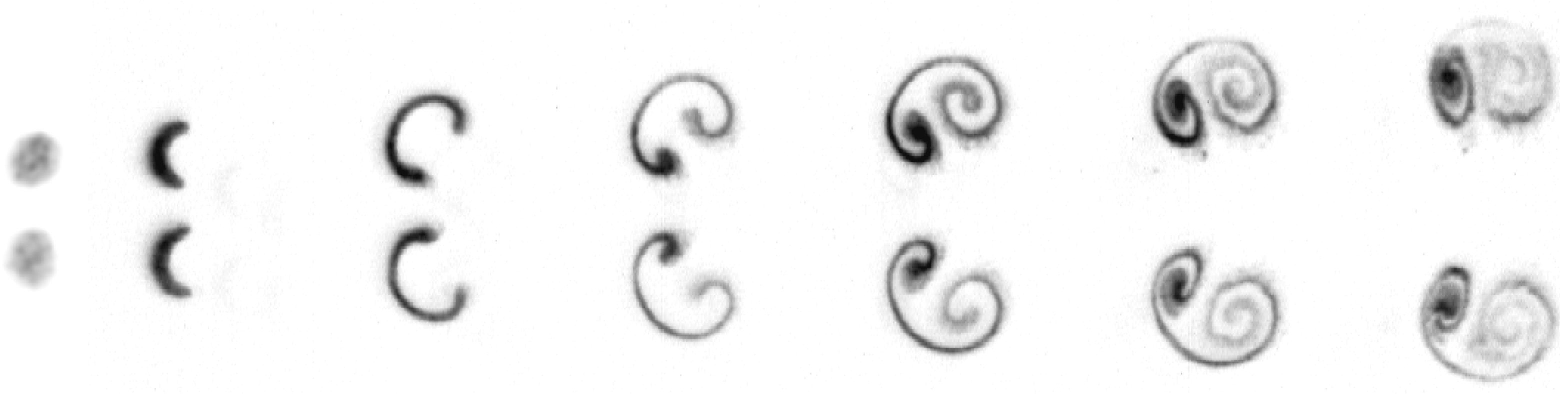


Double-cylinder interaction: weak

$S \approx 2.0D$

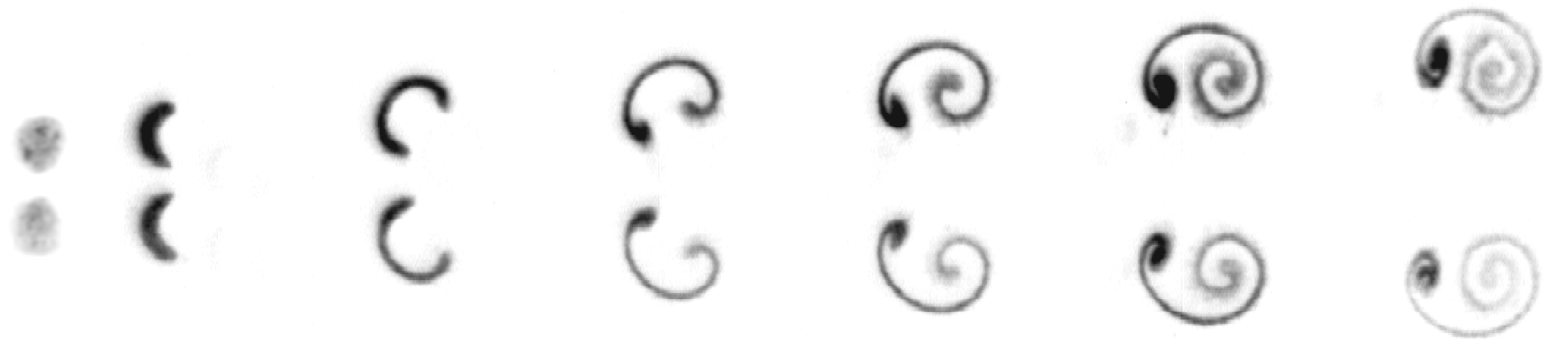


$S \approx 1.8D$



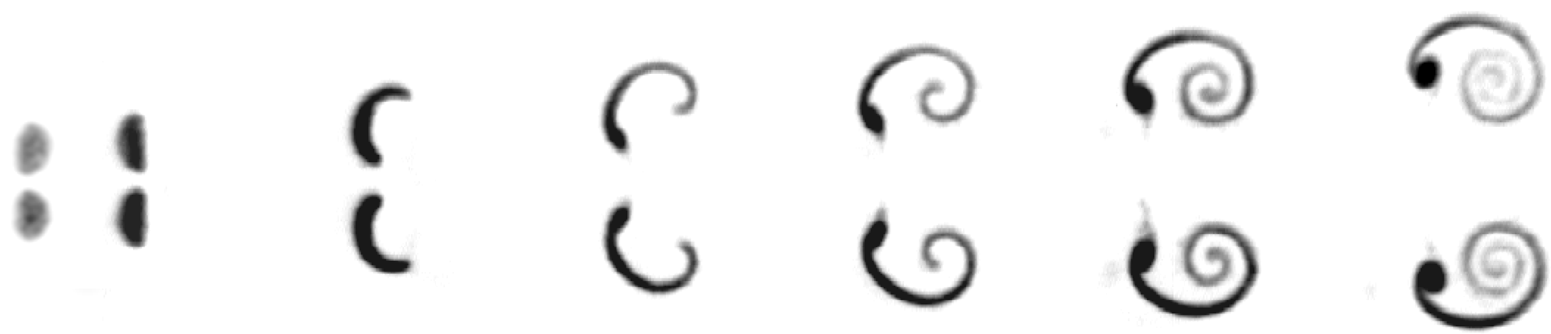
Double-cylinder interaction: moderate

$S \approx 1.6D$



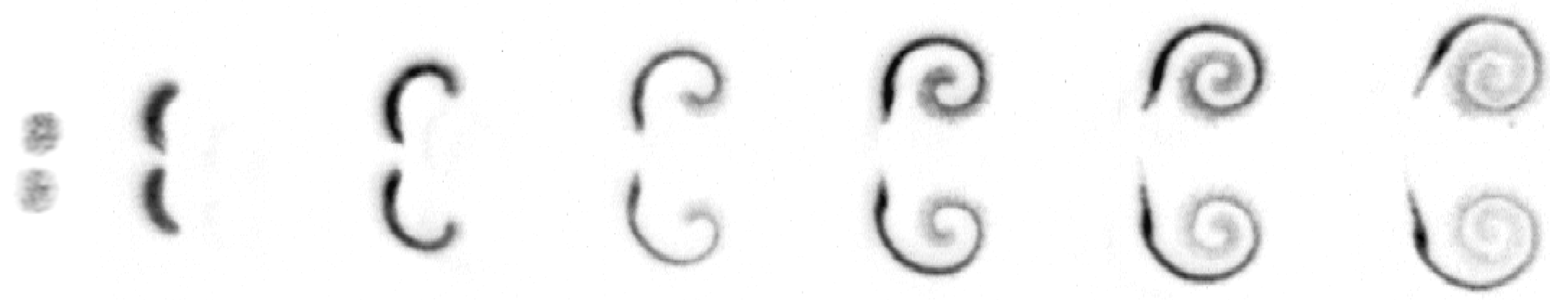
Shock →

$S \approx 1.5D$



Double-cylinder interaction: strong

S ≈ 1.4D

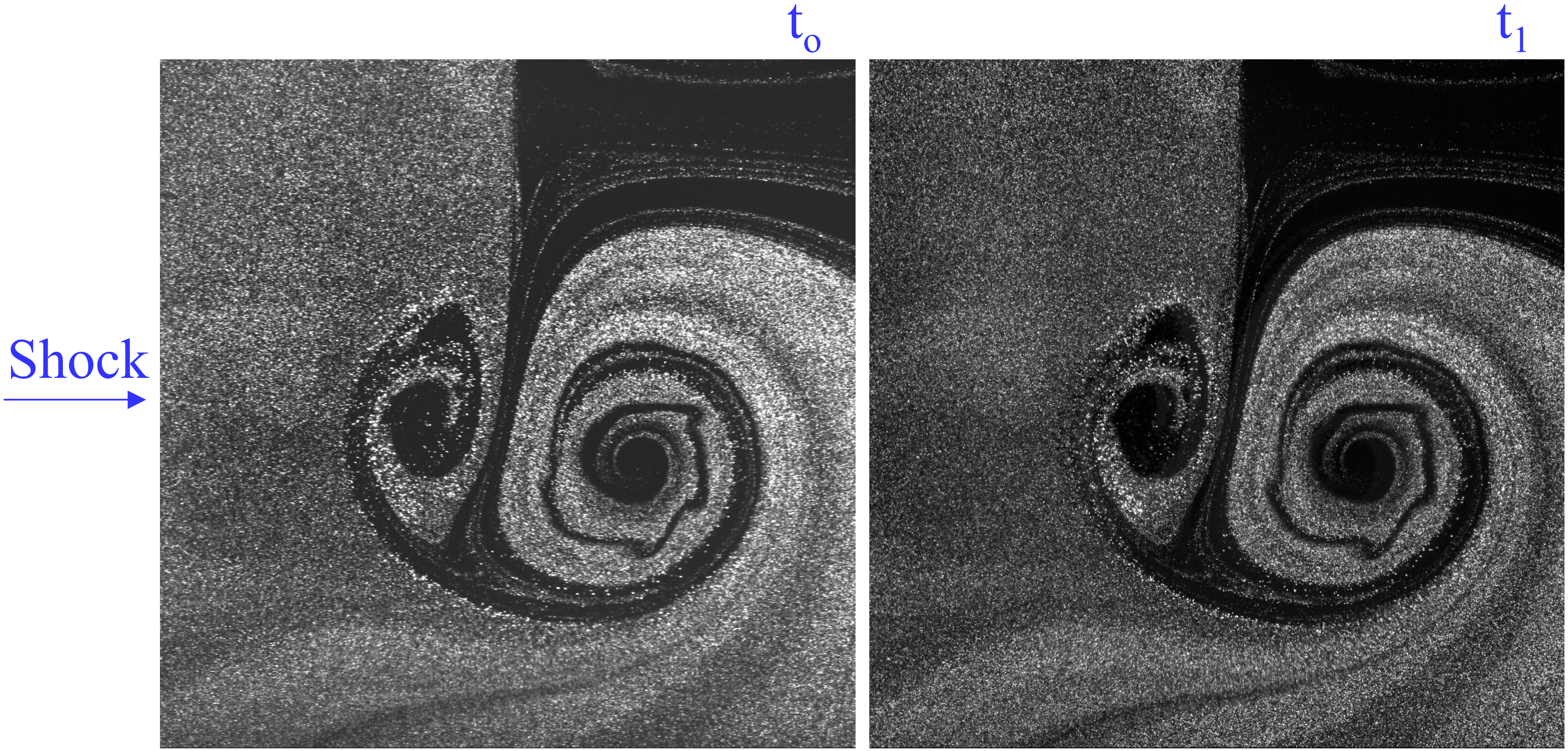


Shock

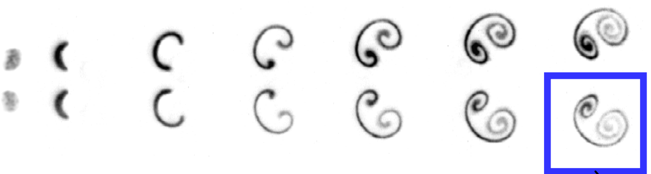
S ≈ 1.2D

PIV images: double cylinder

- Two-frame cross-correlation, flow left to right, 6th pulse
- S = 2.0D. Note non-uniform seeding.

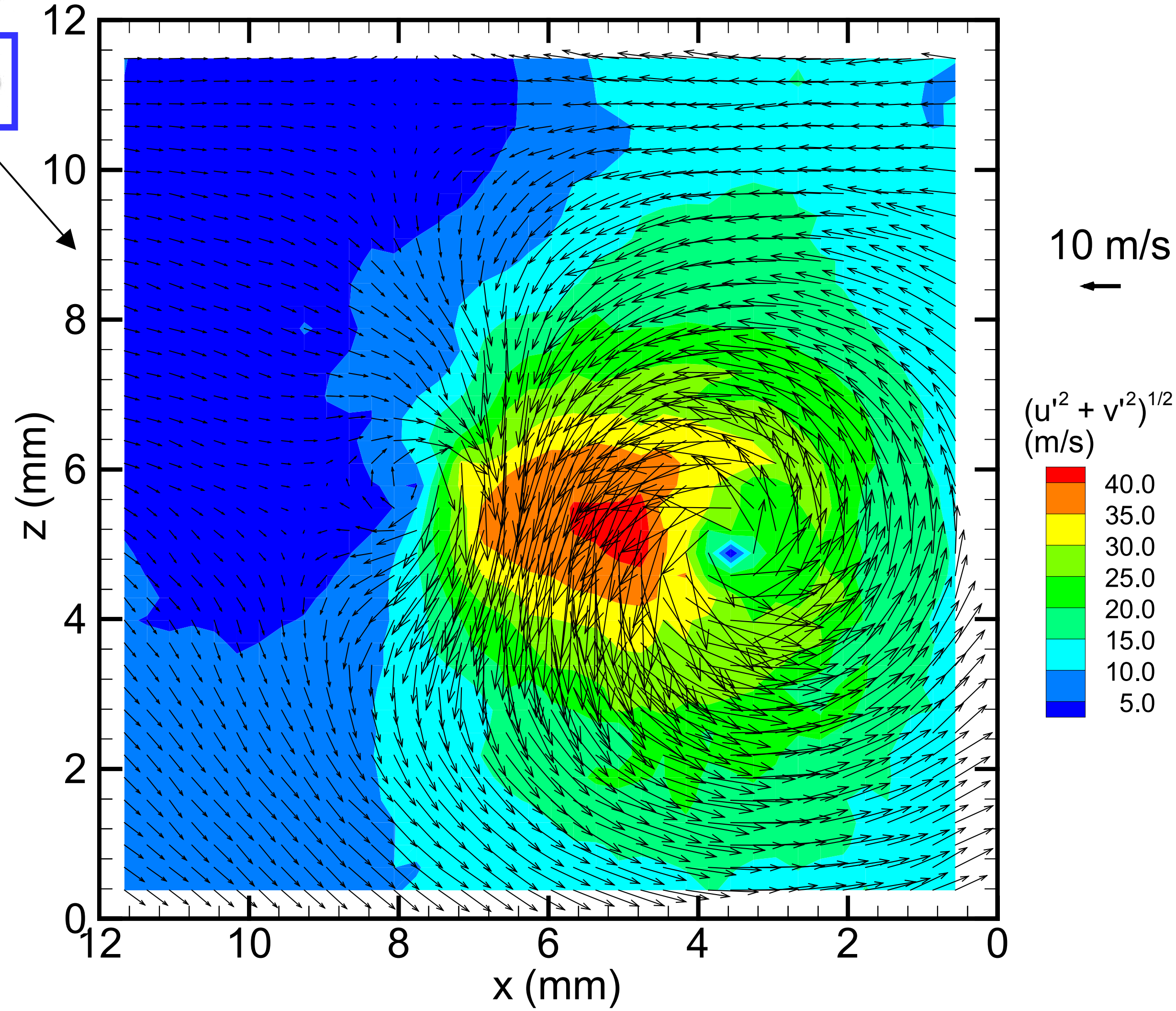


Double-cylinder velocity field: PIV



- Double-cylinder data, 6th pulse, S = 2.0D
- Two-frame cross-correlation (Christensen et al., 2000)
- Not smoothed
- Contours are fluctuating velocity magnitude

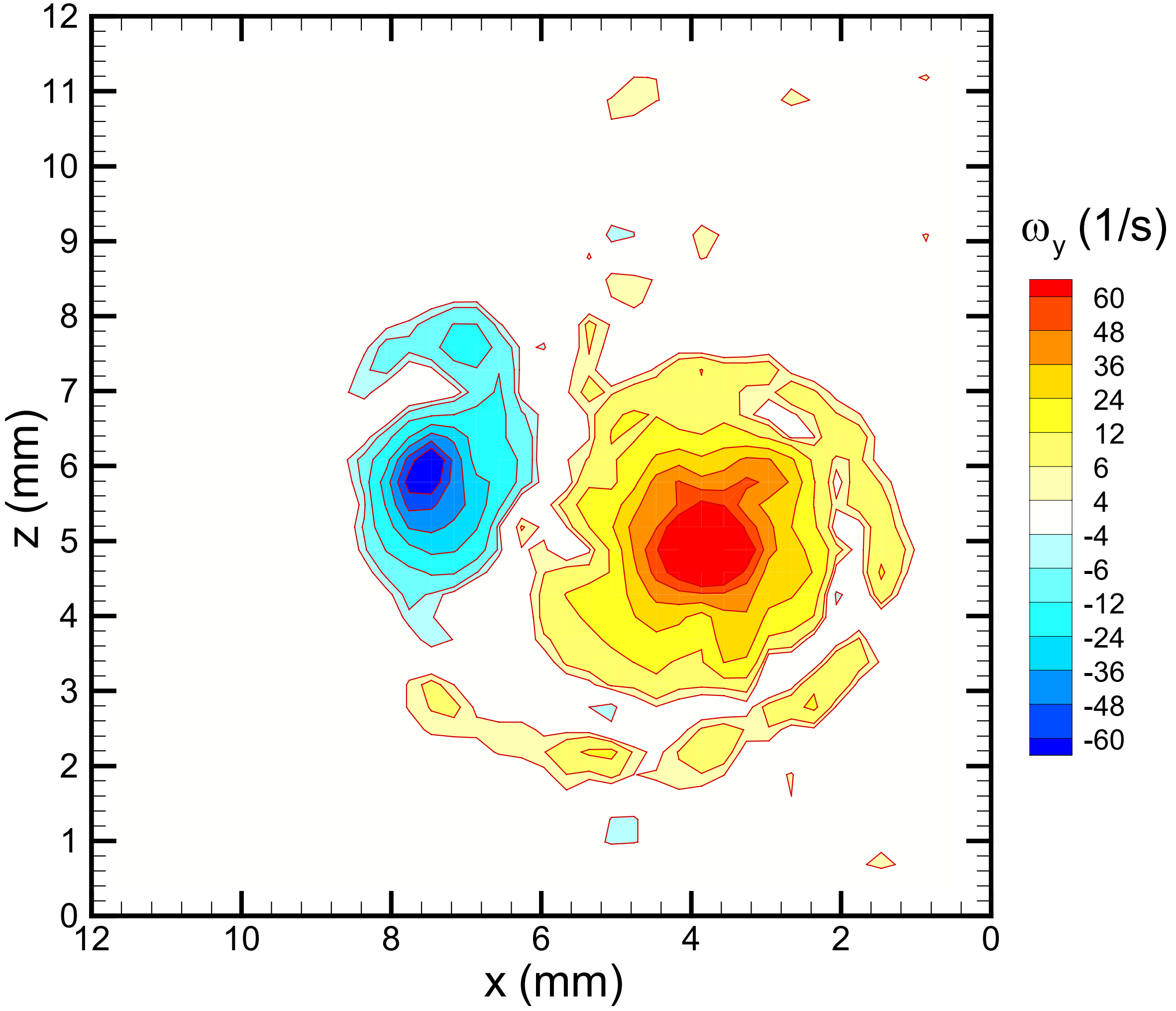
Shock →



Double-cylinder vorticity field

- Same realization
- Vorticity contours
- Not smoothed

Shock →



- And the ratio of circulations is

$$\frac{\Gamma_{outer}}{\Gamma_{inner}} \approx 3$$

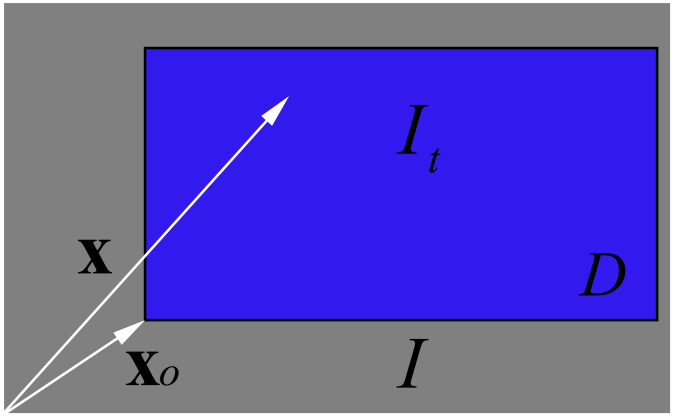
Correlation-based ensemble averaging

Match one image (template) to each individual realization.
Desire optimum match between template and image, i.e. minimize mean sq. error: $e = \int \left| I(\underline{x}) - I_t(\underline{x} - \underline{x}_o) \right|^2 dA$

This requires maximizing $\int_D I(\mathbf{x}) \bullet I_t(\mathbf{x} - \mathbf{x}_o)\, dA$ w.r.t. $\mathbf{x}_o$

Do for each realization, then extract and average (Soloff, 1997)
Yields cond. avg.: $< I(\mathbf{x} - \mathbf{x}_o) \mid \mathbf{x}_o >$

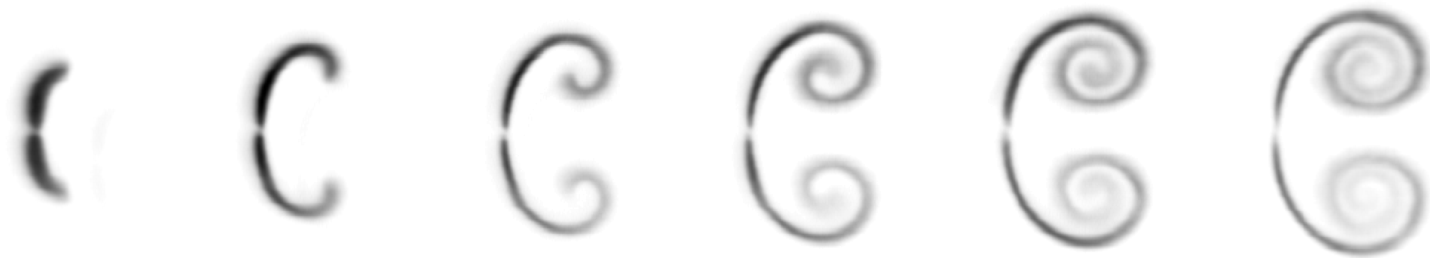
This avg. becomes the new template.



Properties:
- Minimizes dependence on initial choice of template.
- Converges quickly.

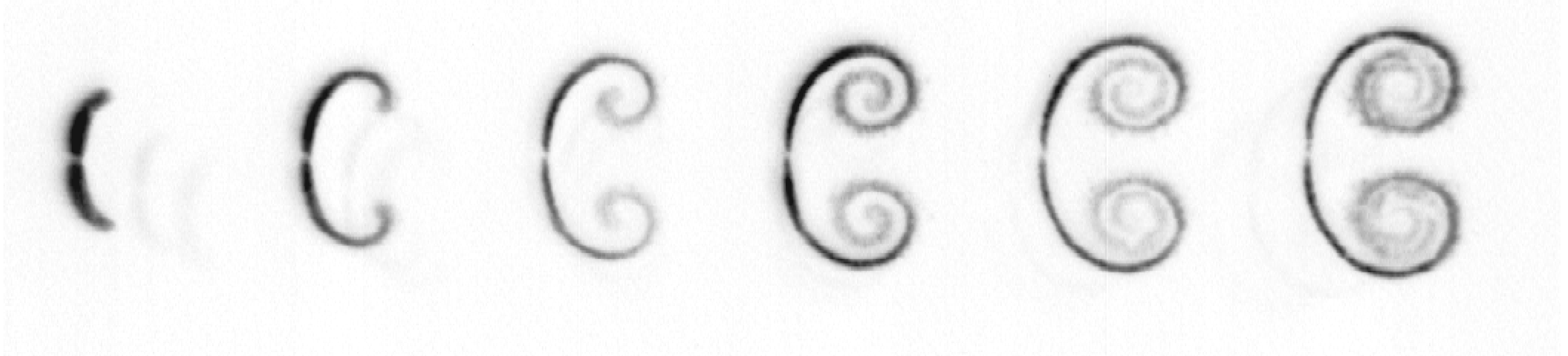
Correlation-based ensemble average

S ≈ 1.2D, Ensemble average



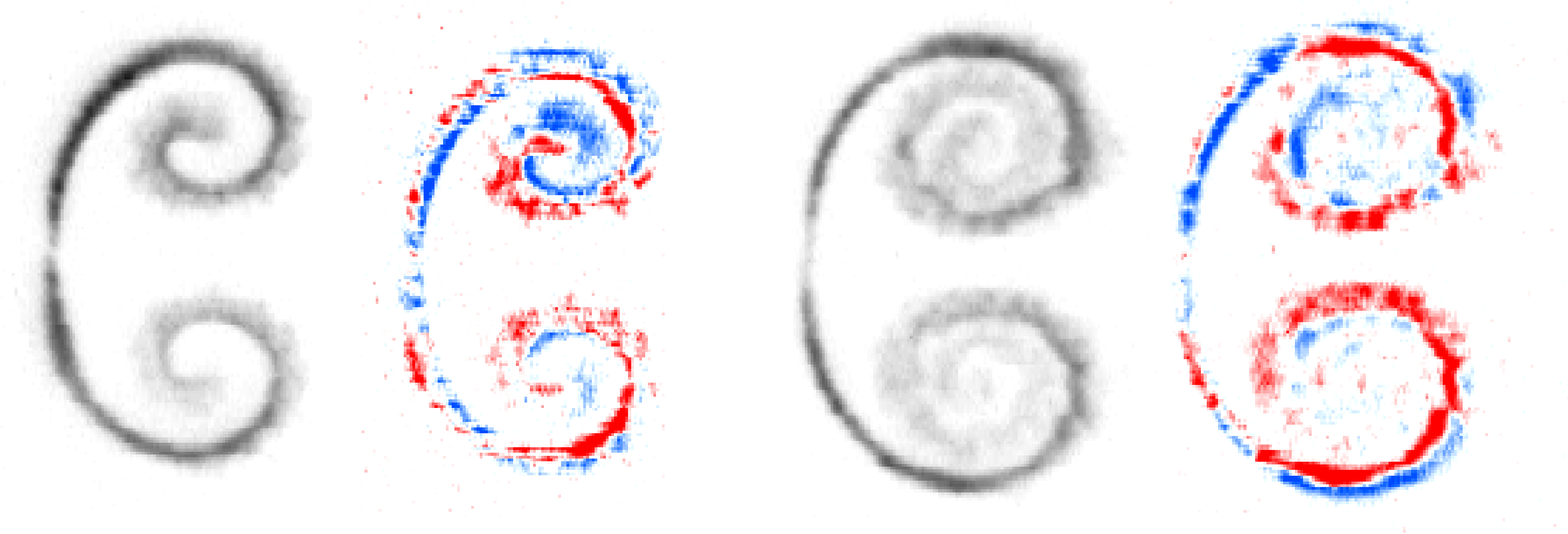
Shock →

S ≈ 1.2D, Individual realization



Fluctuating intensity fields, S = 1.2D

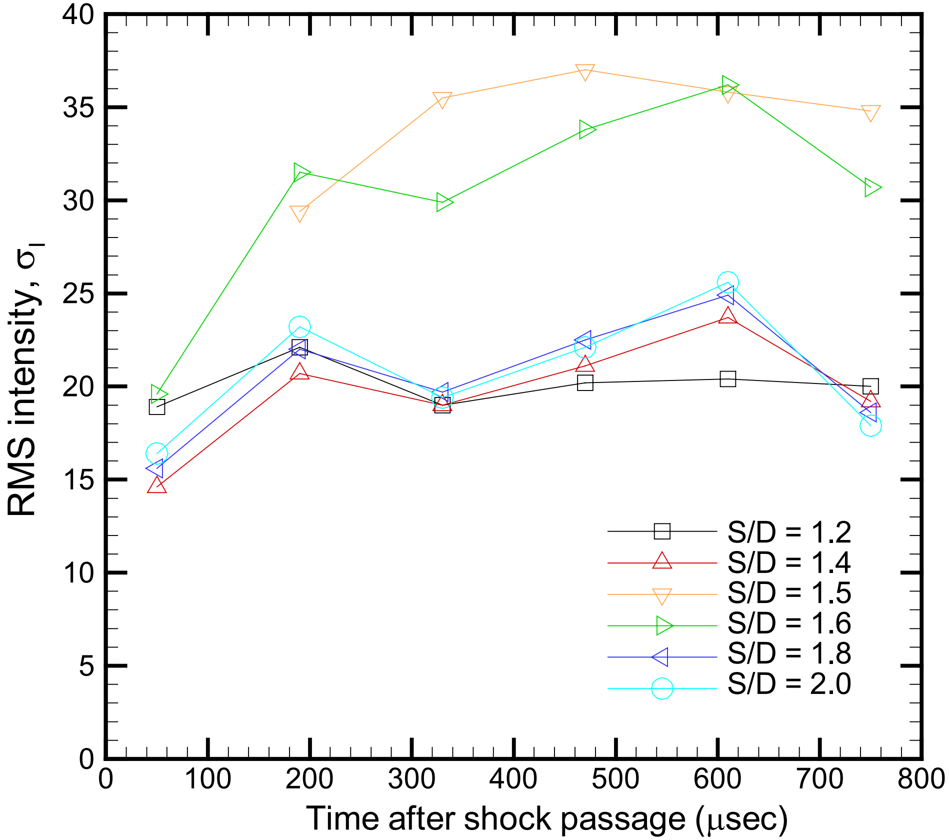
$t = 470\,\mu s$ $t = 750\,\mu s$



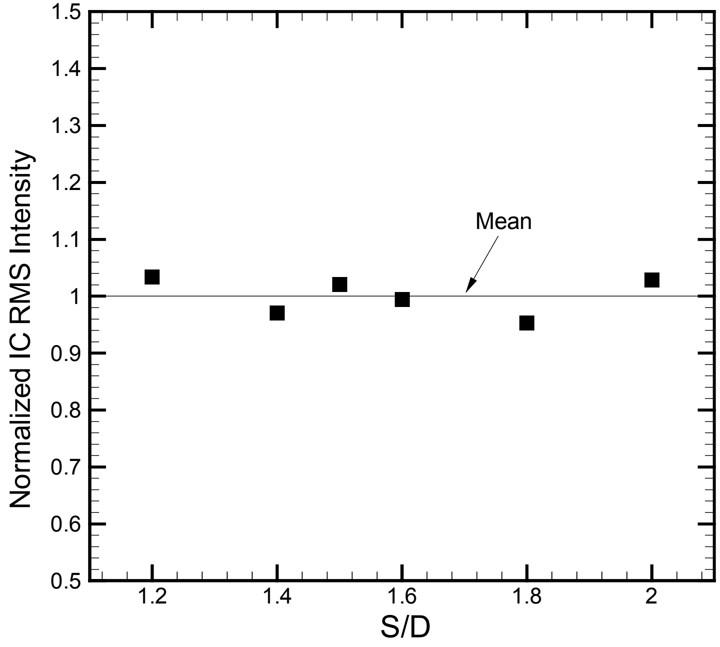
Total Fluctuating Total Fluctuating

RMS of fluctuating intensity

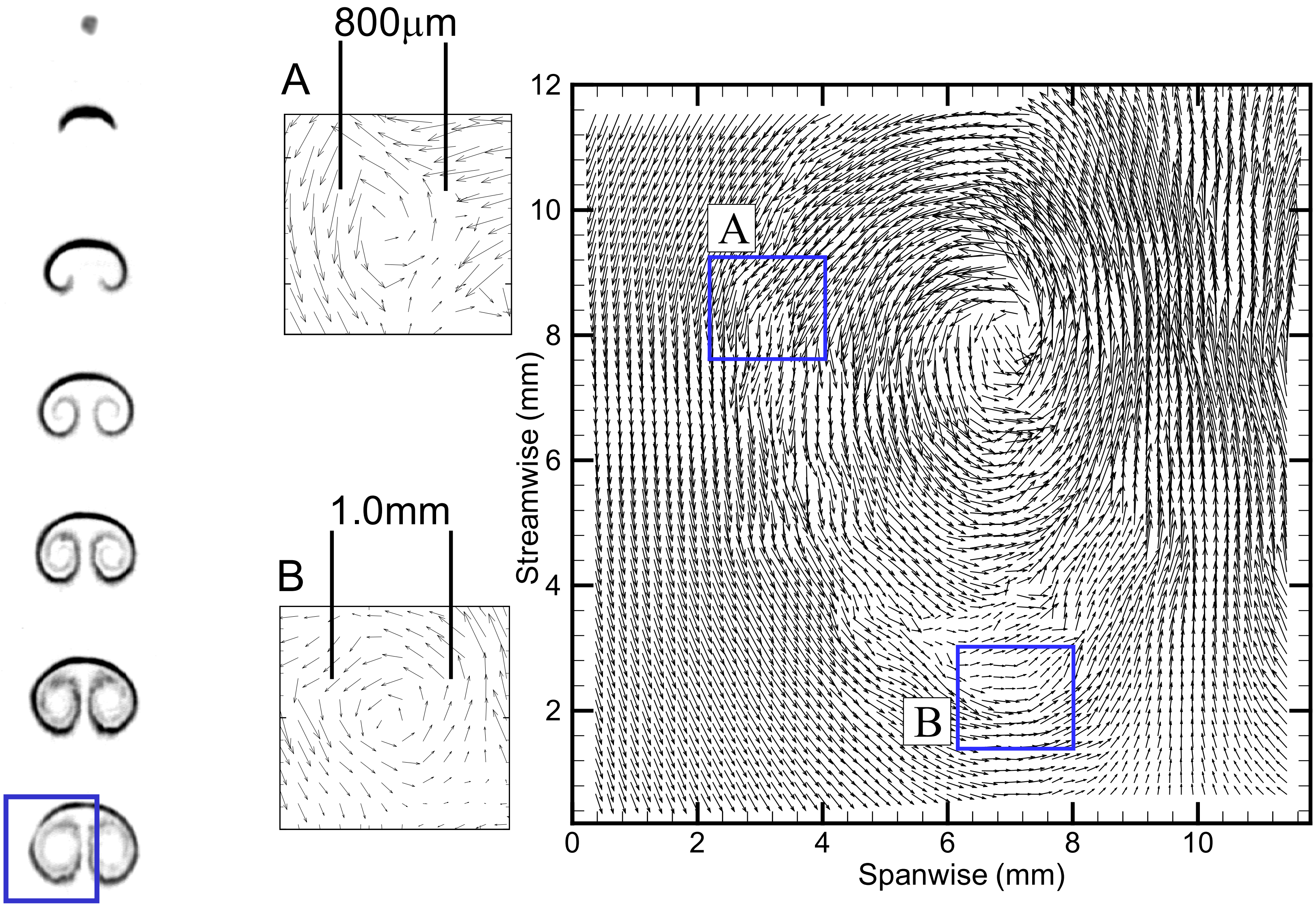
RMS Intensity vs. Time for several values of S/D.



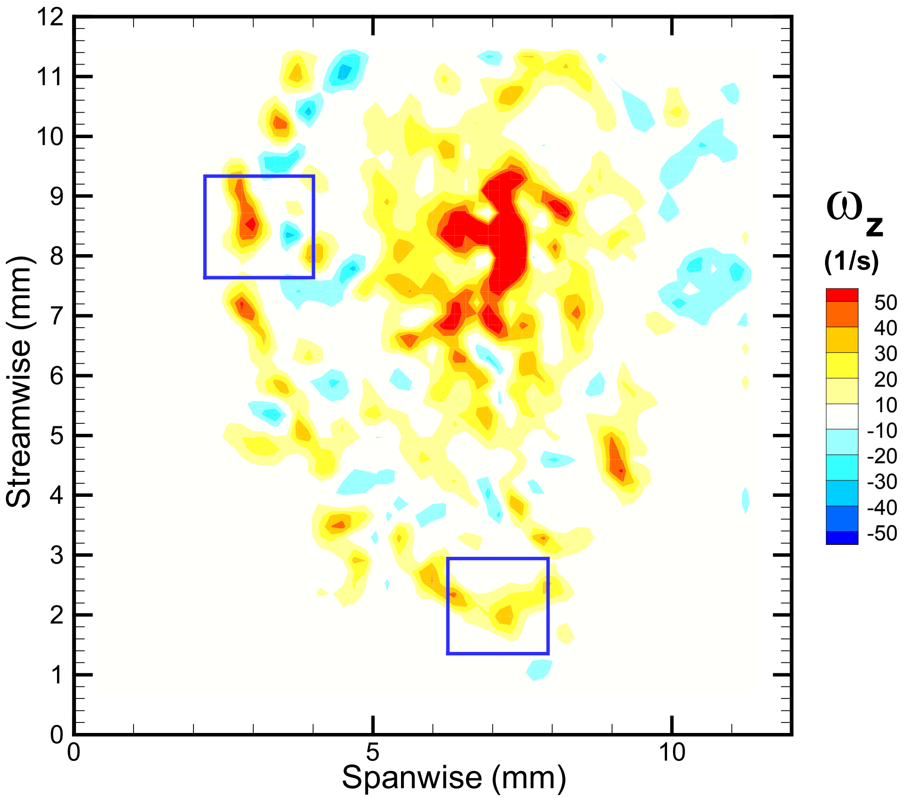
RMS of Initial Conditions

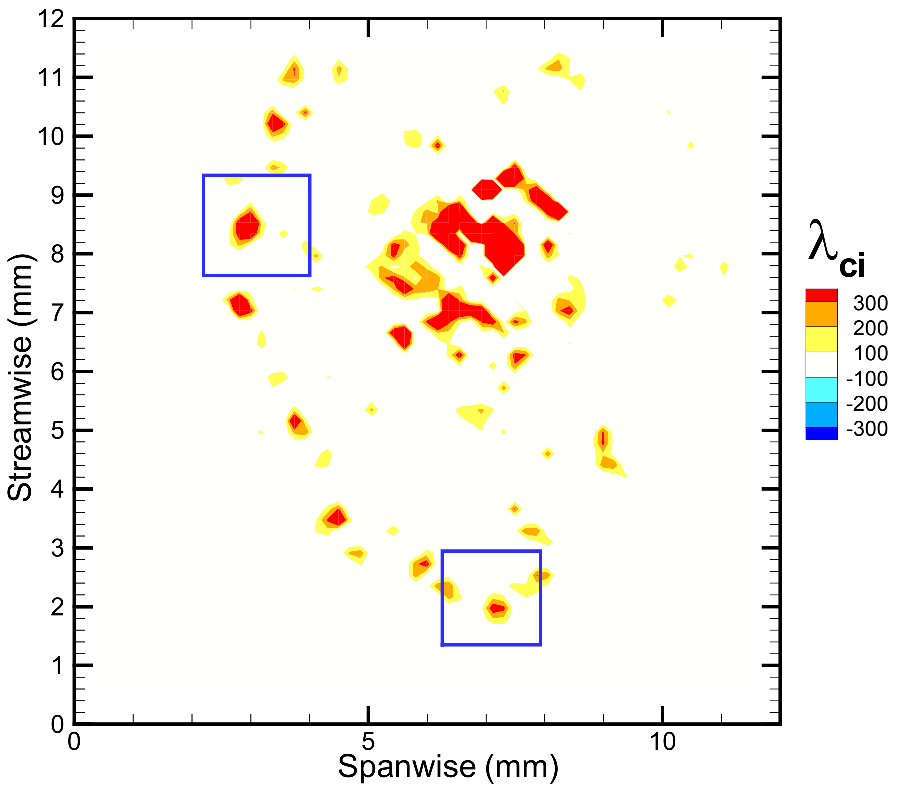


Small-scale activity: single cylinder



Vorticity and swirling strength





Conclusions

- The degree of cylinder-cylinder interaction, and hence the resulting flow morphology, is highly sensitive to the initial cylinder separation.
  - Different separations may lead to weak, moderate, or strong interactions.
- An idealized “vortex blob” simulation leads to very different flow morphologies than experiment, suggesting that the inner vortices are weakened by interaction.
- Vorticity fields calculated from high-resolution PIV measurements confirm that the inner vortices are significantly weaker, even for S/D = 2.0:
  $\Gamma_{outer} / \Gamma_{inner} \approx 3$

Conclusions

- A correlation-based ensemble averaging procedure effectively captures the large and intermediate scales of the flow, providing confirmation of the experimental repeatability, and permitting decomposition of the density field into mean and fluctuating components.
- The RMS intensity fluctuations based on this decomposition are substantially greater for the case of “moderate” interaction than for the “strong” or “weak” interaction cases, despite comparable initial RMS values.
- High-resolution PIV data resolves mm-scale vortices being convected around the vortex cores.