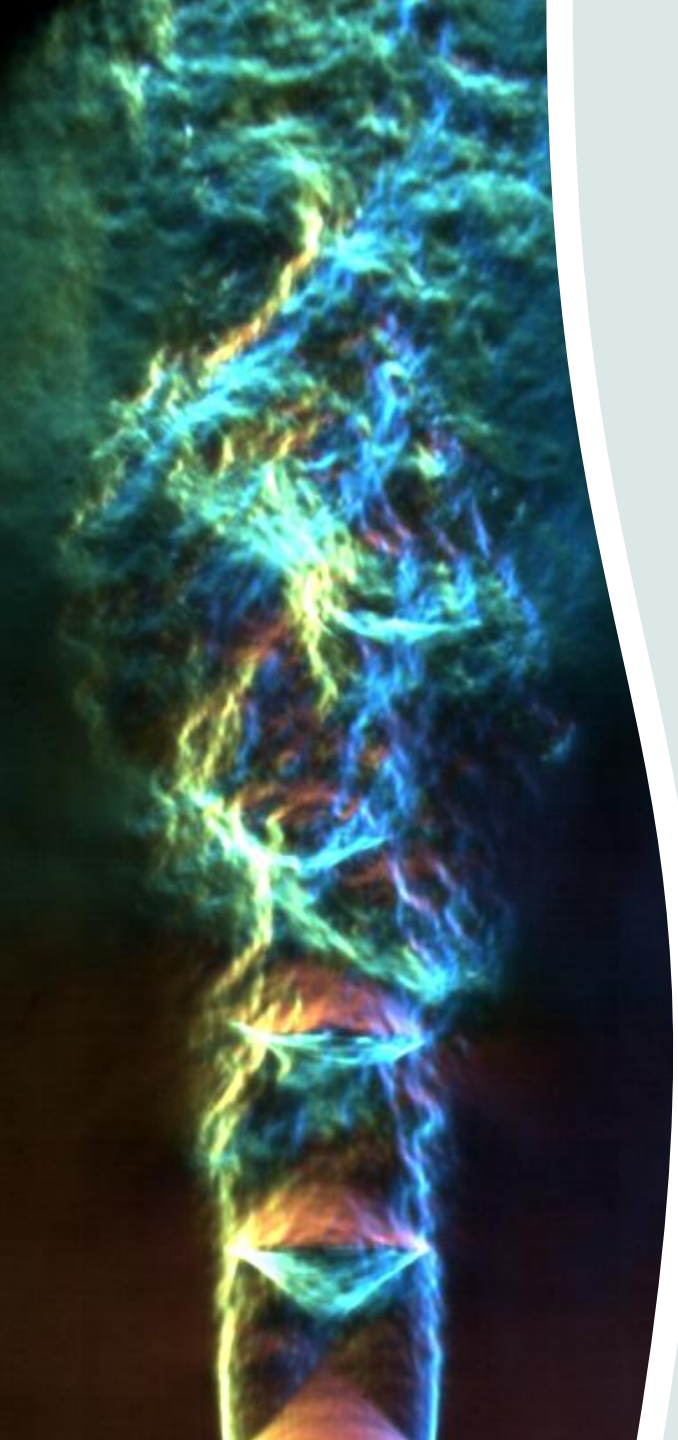


Overexpanded Glass Planar Rocket Nozzle

By Tom Russell.

Logo for Affiliations

MONASH University

SHOCK LAB

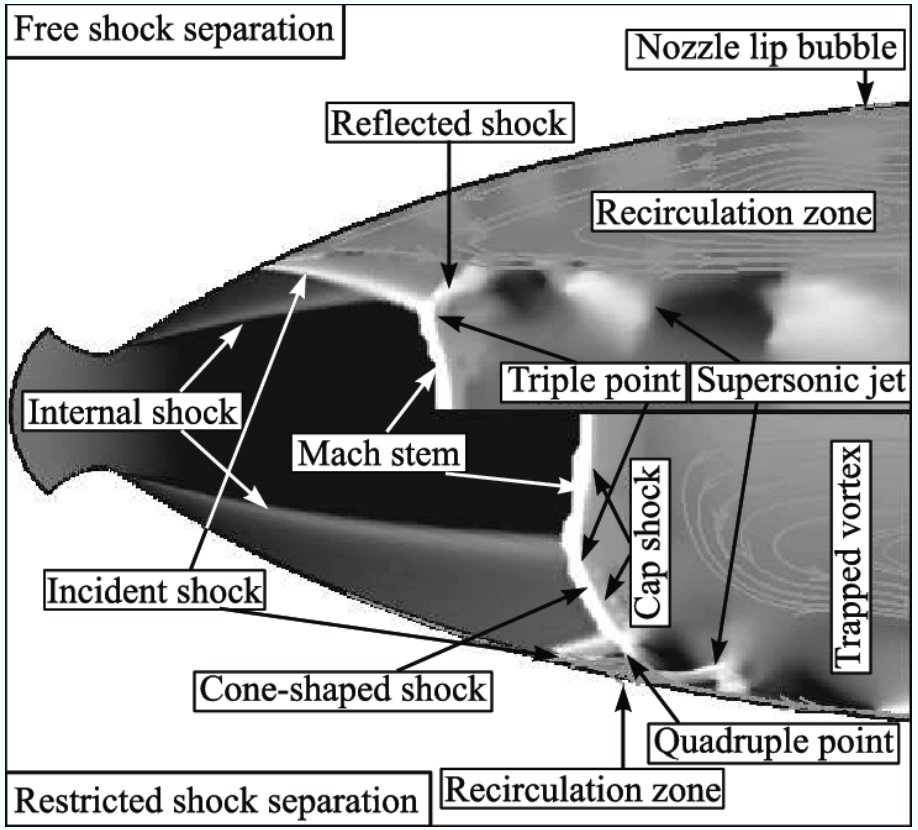
Logo for Affiliations

Project scope

- Create a glass walled planar nozzle
- Image with Schlieren to investigate FSS and RSS
- Perform SPOD and investigate underlying mechanism and feedback loop

Why? What is FSS and RSS and why do we care

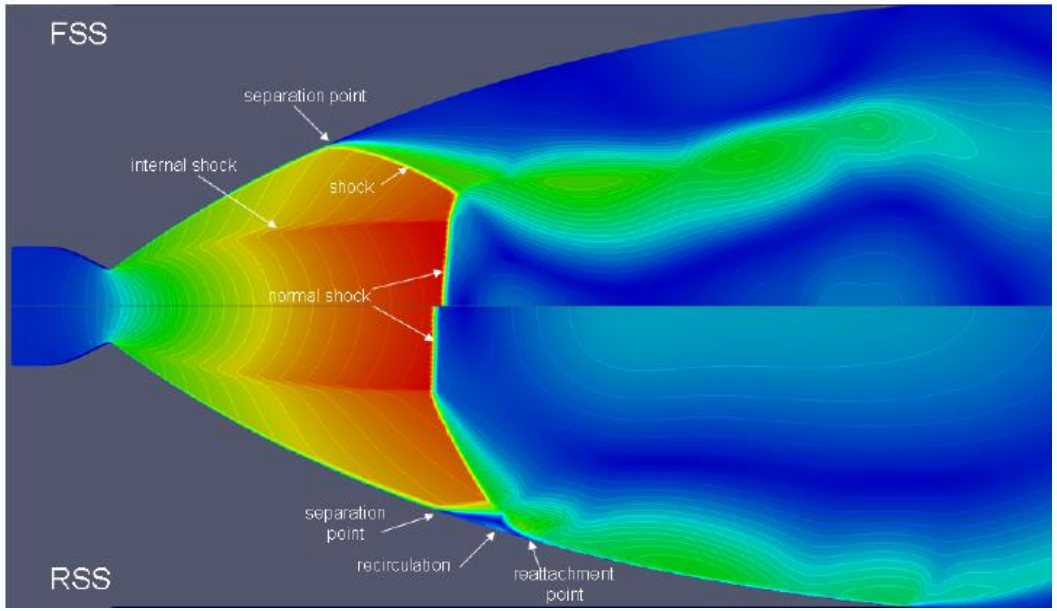
- FSS – Free Shock Separation
- RSS – Restricted Shock Separation



Why? What is FSS and RSS and why do we care

- FSS – Occurs in all types of rocket nozzle – Conical, TIC, TOP, TOC

- RSS – Only occurs in TOC and TOP nozzles
  - Characterised by an internal shock that meets the triple point

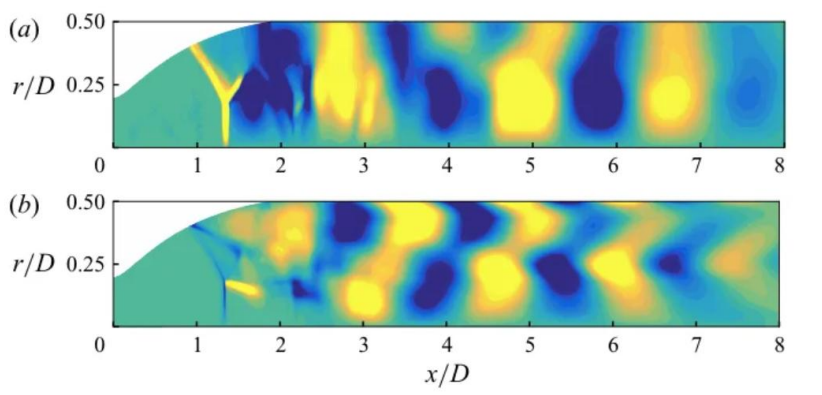


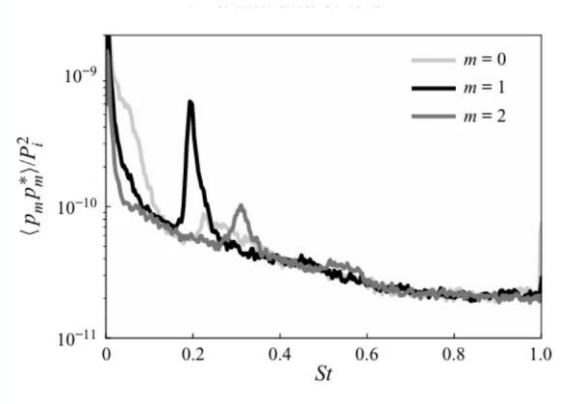
Why? What is FSS and RSS and why do we care

- These cause unwanted side loadings in nozzles, this is bad
  - These loadings are caused by azimuthal modes from a resonant feedback loop
- The underlying mechanism is not entirely understood
- A step in solving this is looking inside the nozzle to see where the source is

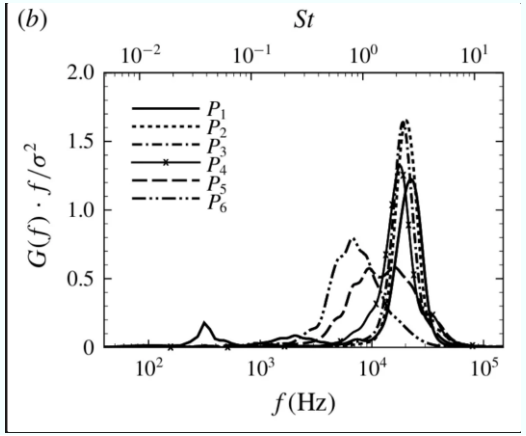
Prior research

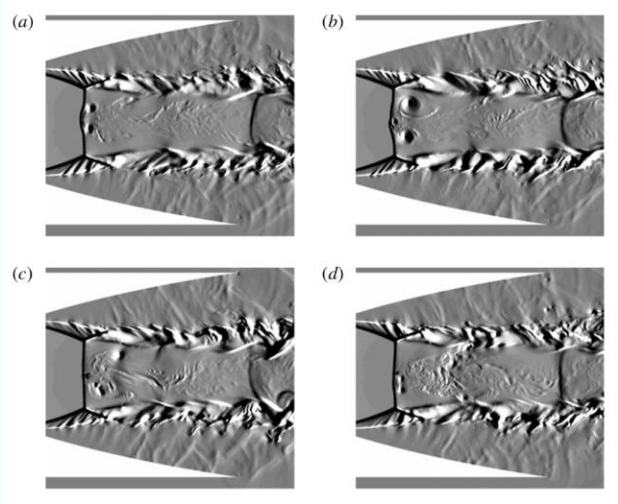
Bakalu (Mj 2.09)



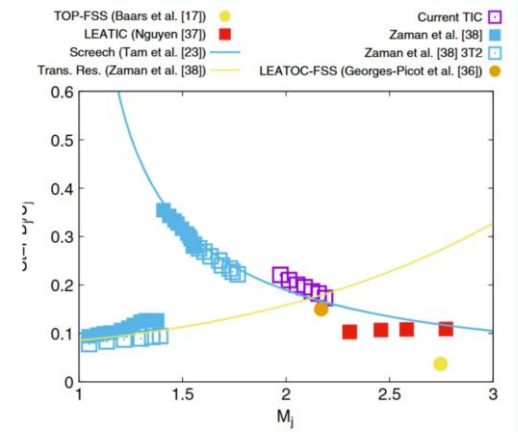


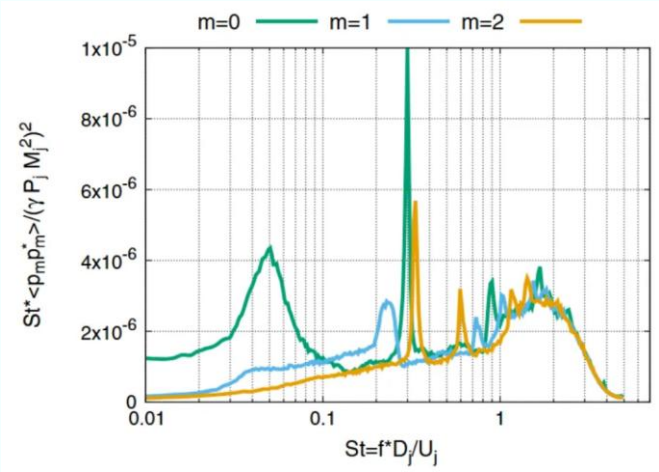
Martelli (Mj 2.8)





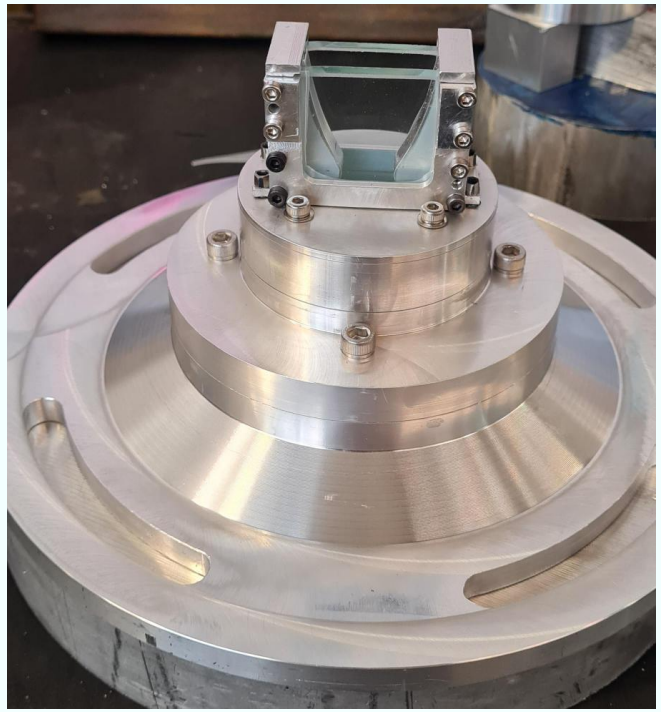
Jaunet (Mj 1.9-2.2)

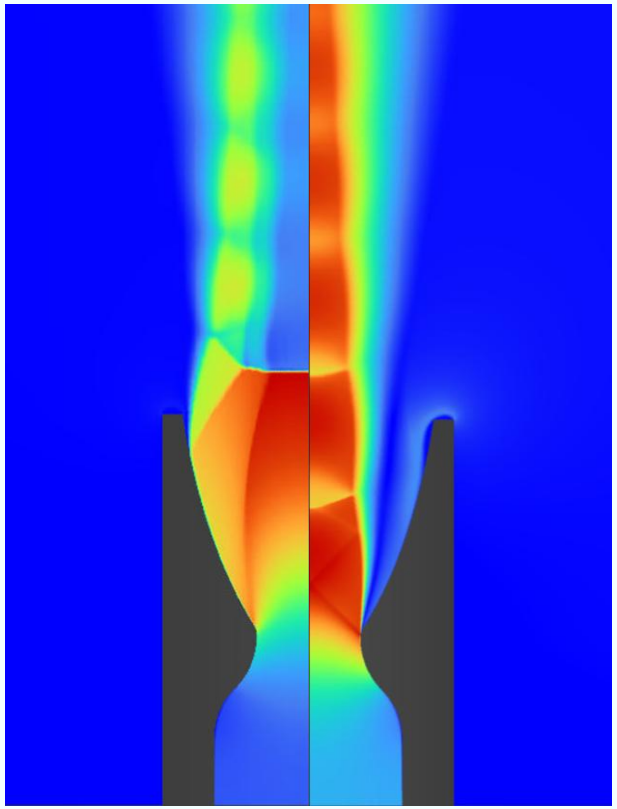




My Nozzle

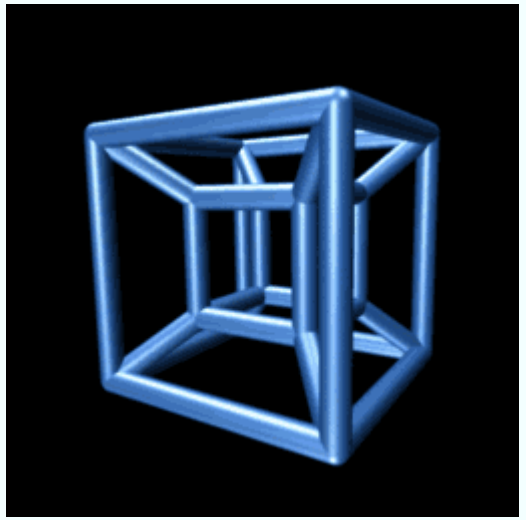
- Planar nozzle
- Contour based on axisymmetric TOP nozzle
- Area ratio of 2.45 (6 for axisymmetric)
  - Nozzle C (AR 6 80% length)
- Throat diameter of 15 mm
- 9mm thick



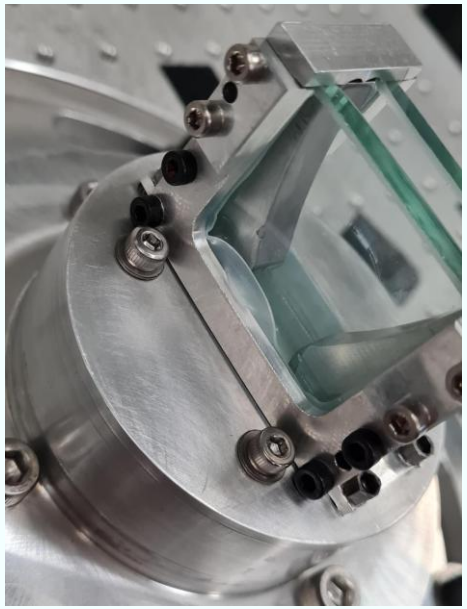


First Attempt

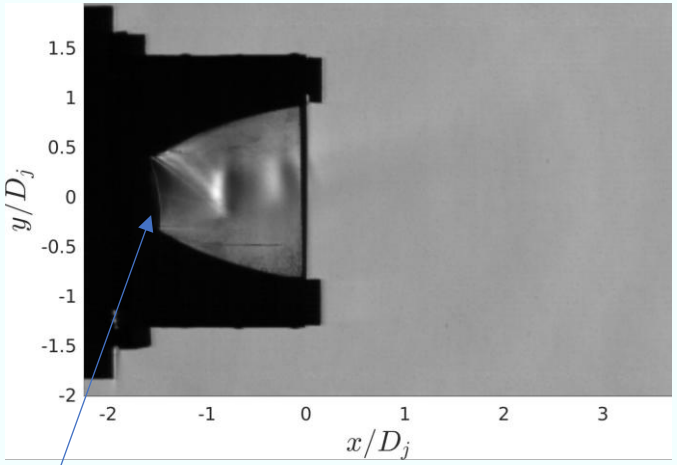
- NPR 2.0 – 6.0 @0.1 150k FPS 125mm
- Leaking in multiple places and poor gasket seal interfering with visuals and flapping throughout experiment



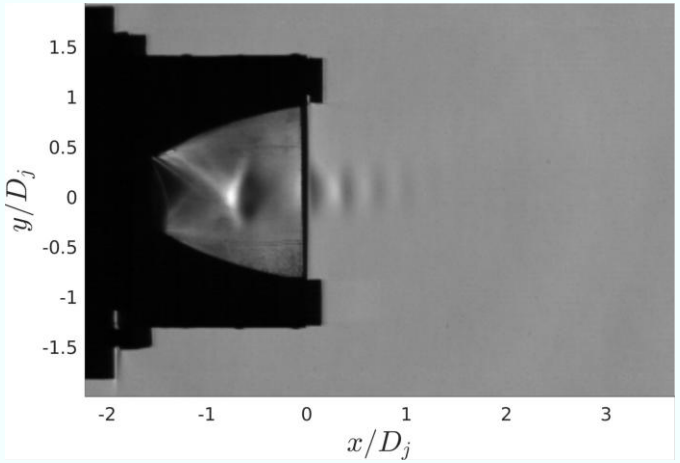
How it felt trying to seal this



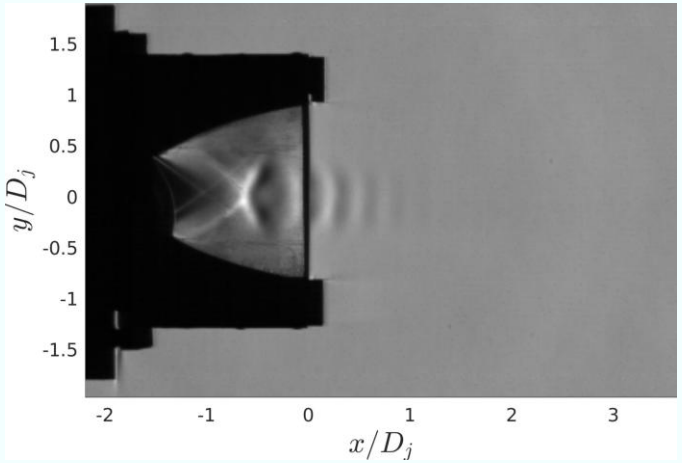
NPR 2.0 – 2.7: Free Jet



NPR 2.0



NPR 2.3

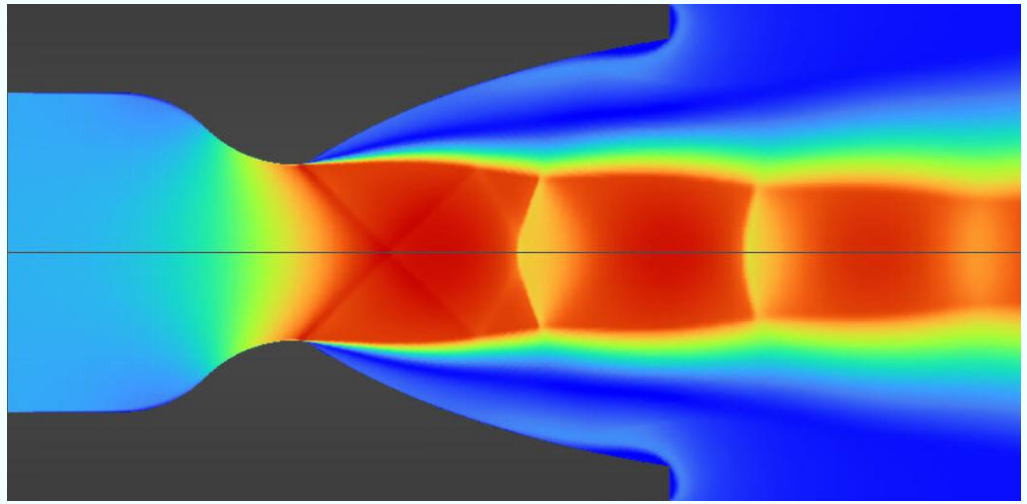


NPR 2.6

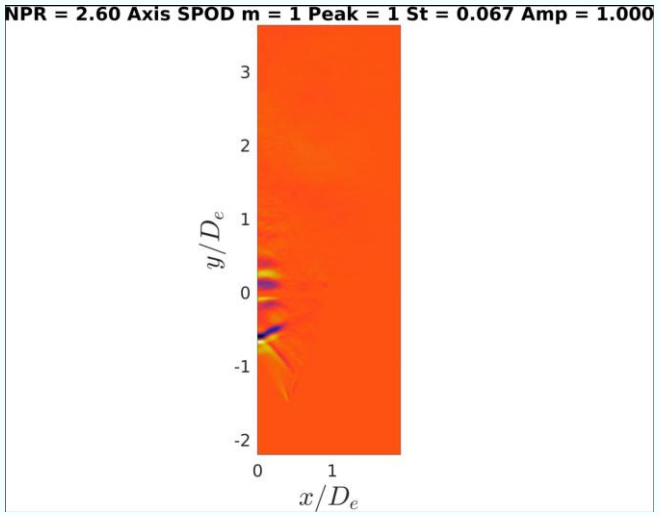
Gasket

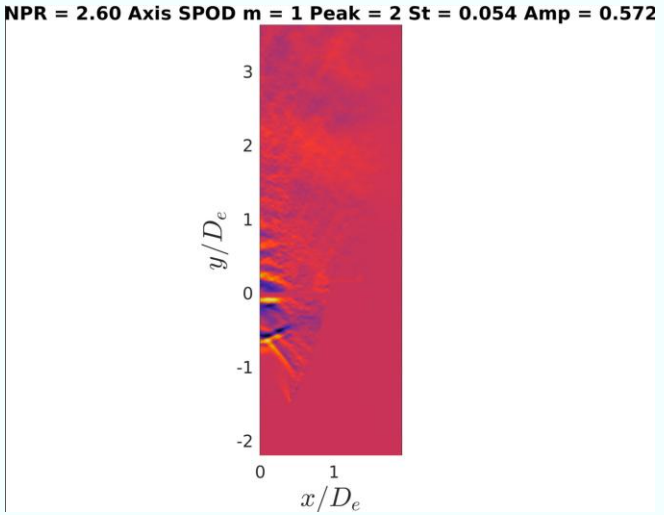
NPR 2.5 CFD Planar

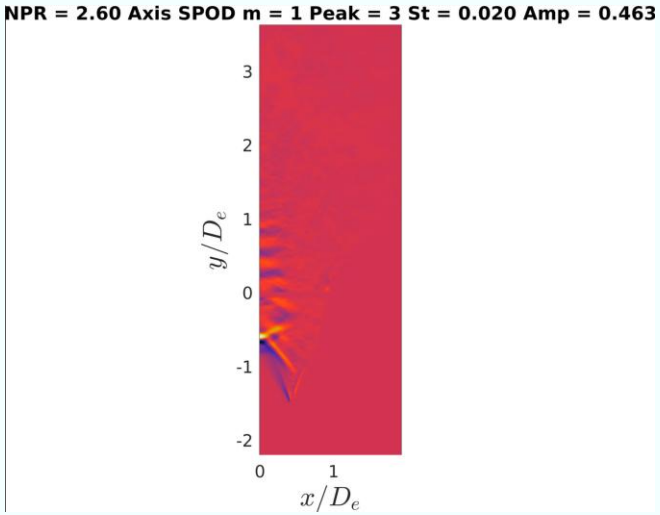
Nozzle C

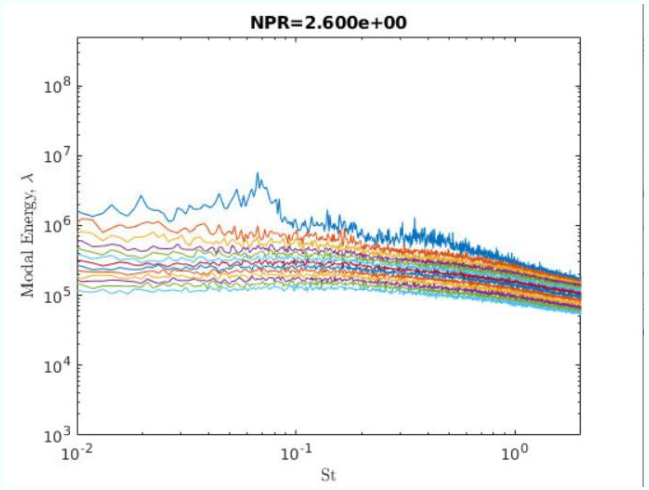


NPR 2.0 – 2.7: Free Jet

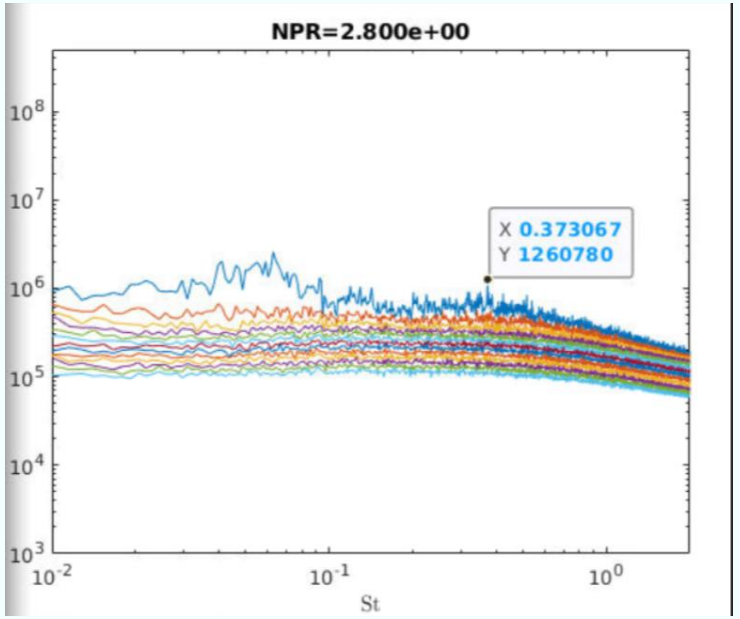


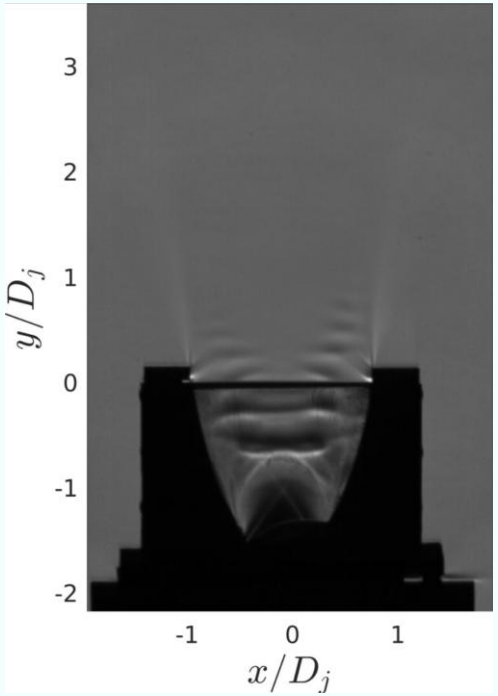


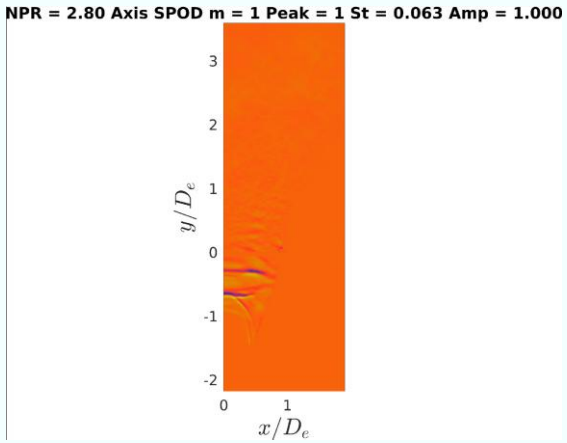


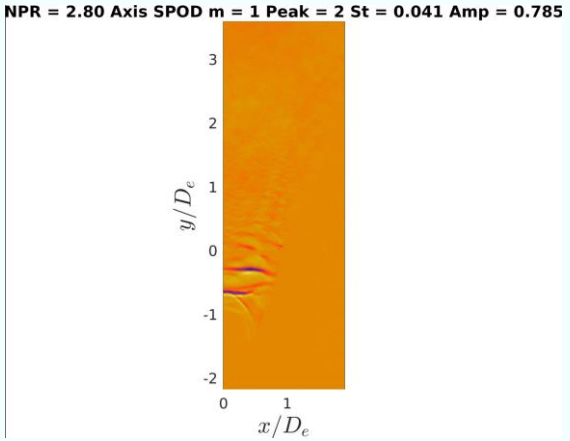


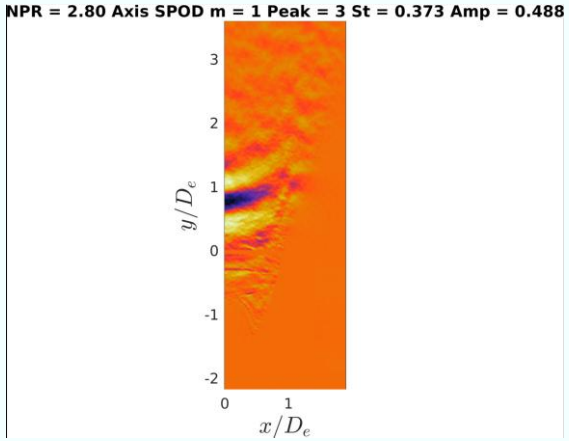
NPR 2.8: Transition Point



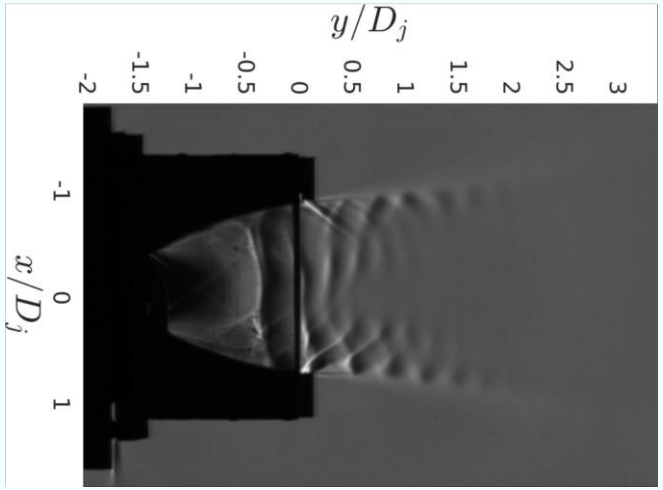




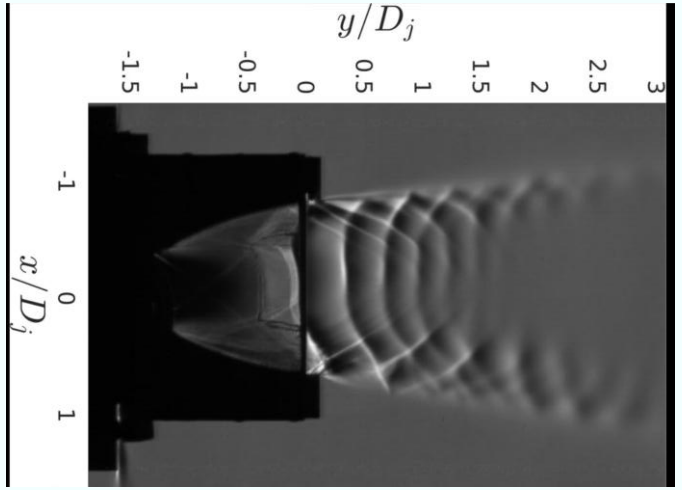




NPR 3.0 – 6.0: Attachment

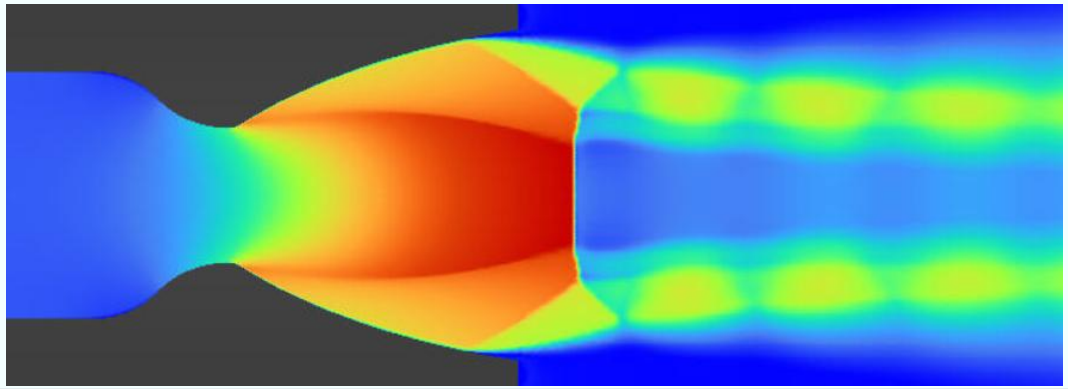


NPR 4.0

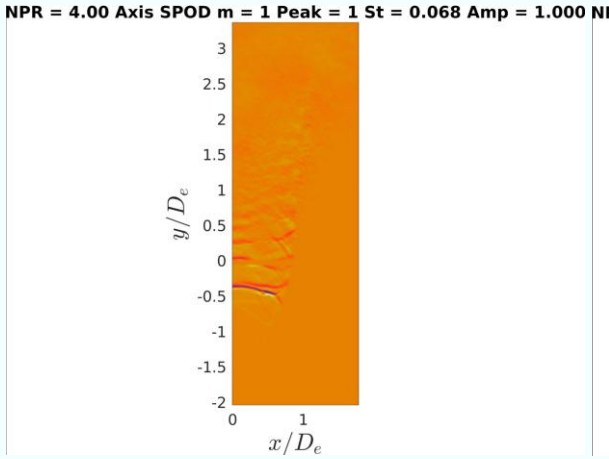


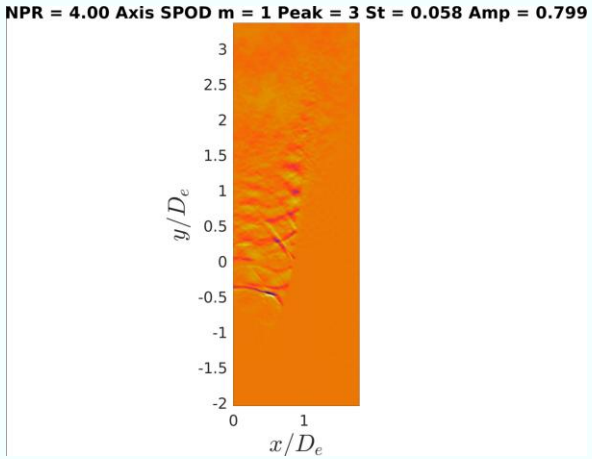
NPR 5.9

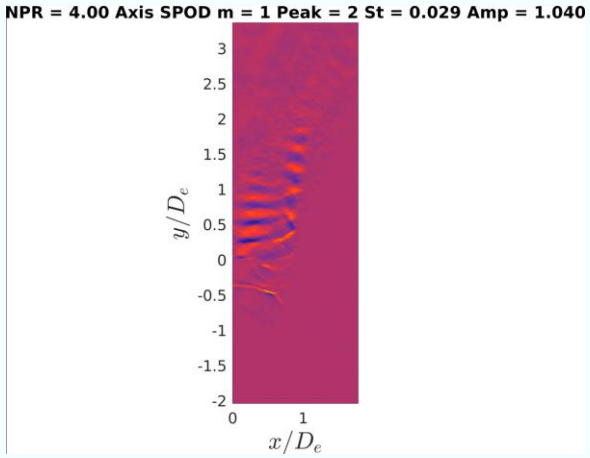
NPR 4.0 CFD Planar Nozzle C

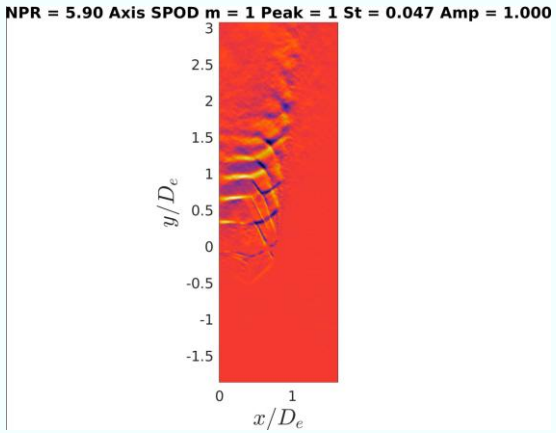


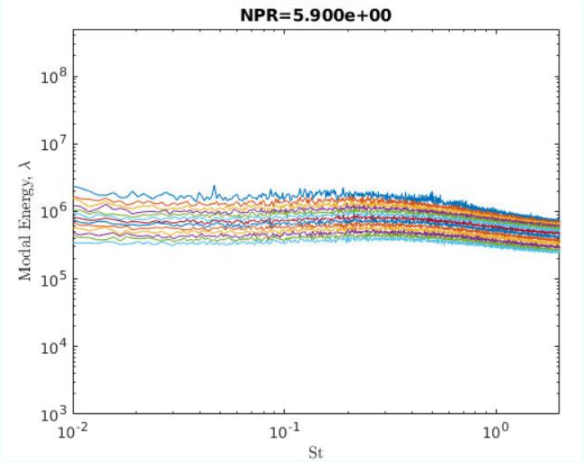
NPR 3.0 – 6.0: Attachment

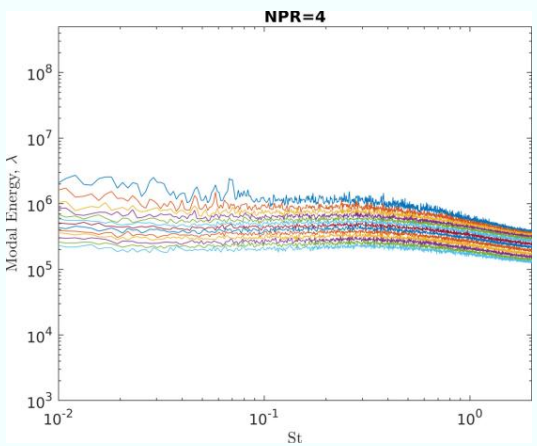


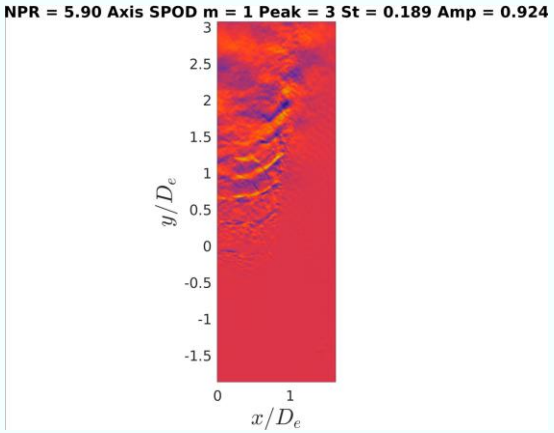


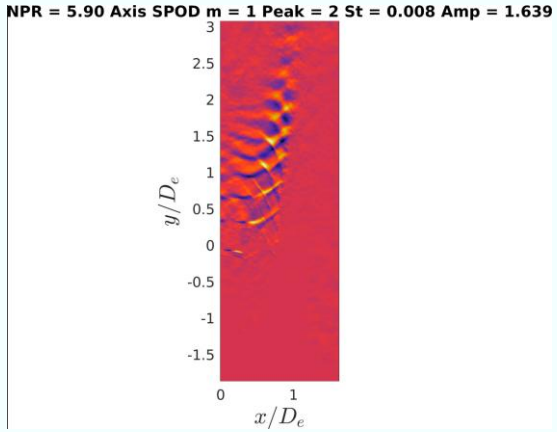




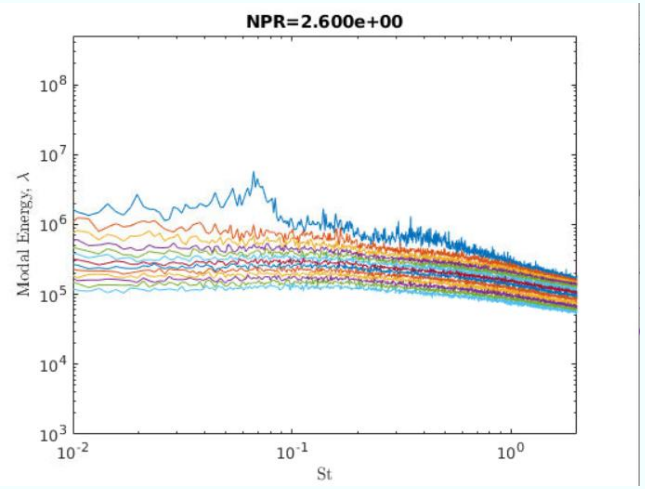








Comparison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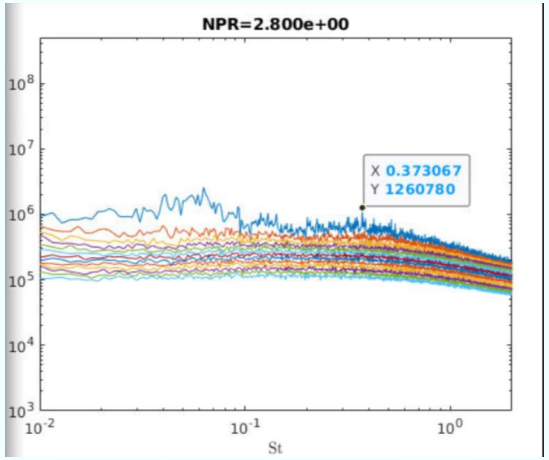
Modal Energy, λ
St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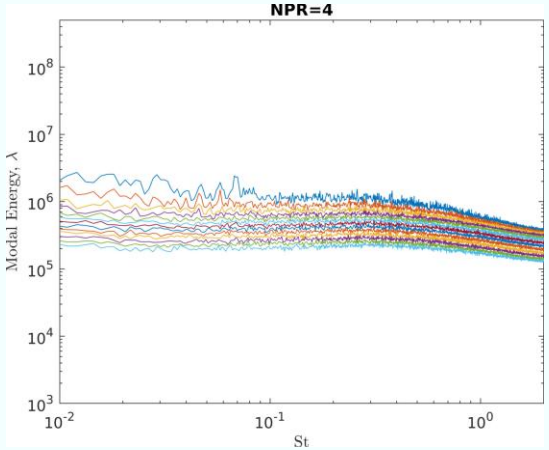
Y 1260780
St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Modal Energy, λ
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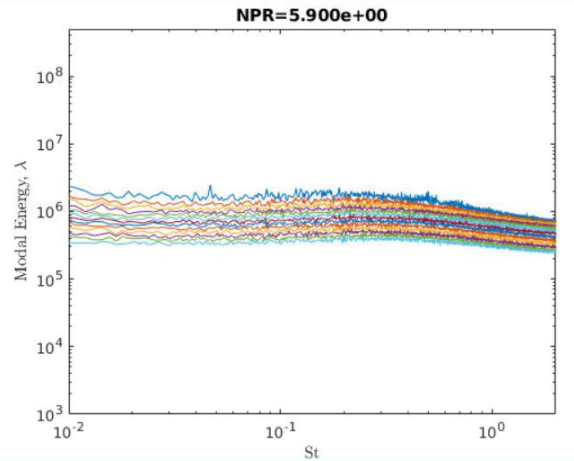

NPR=5.900e+00
Modal Energy, λ
St

What did I learn

- It is very poorly sealed
- The Coandă effect is real
- The lip of my brackets need to be further back to not disturb flow
- Free jet looks similar to CFD, there seems to be some vague broad peak
- When the flow attaches it seems to completely attach and not partially attach like we would expect from FSS

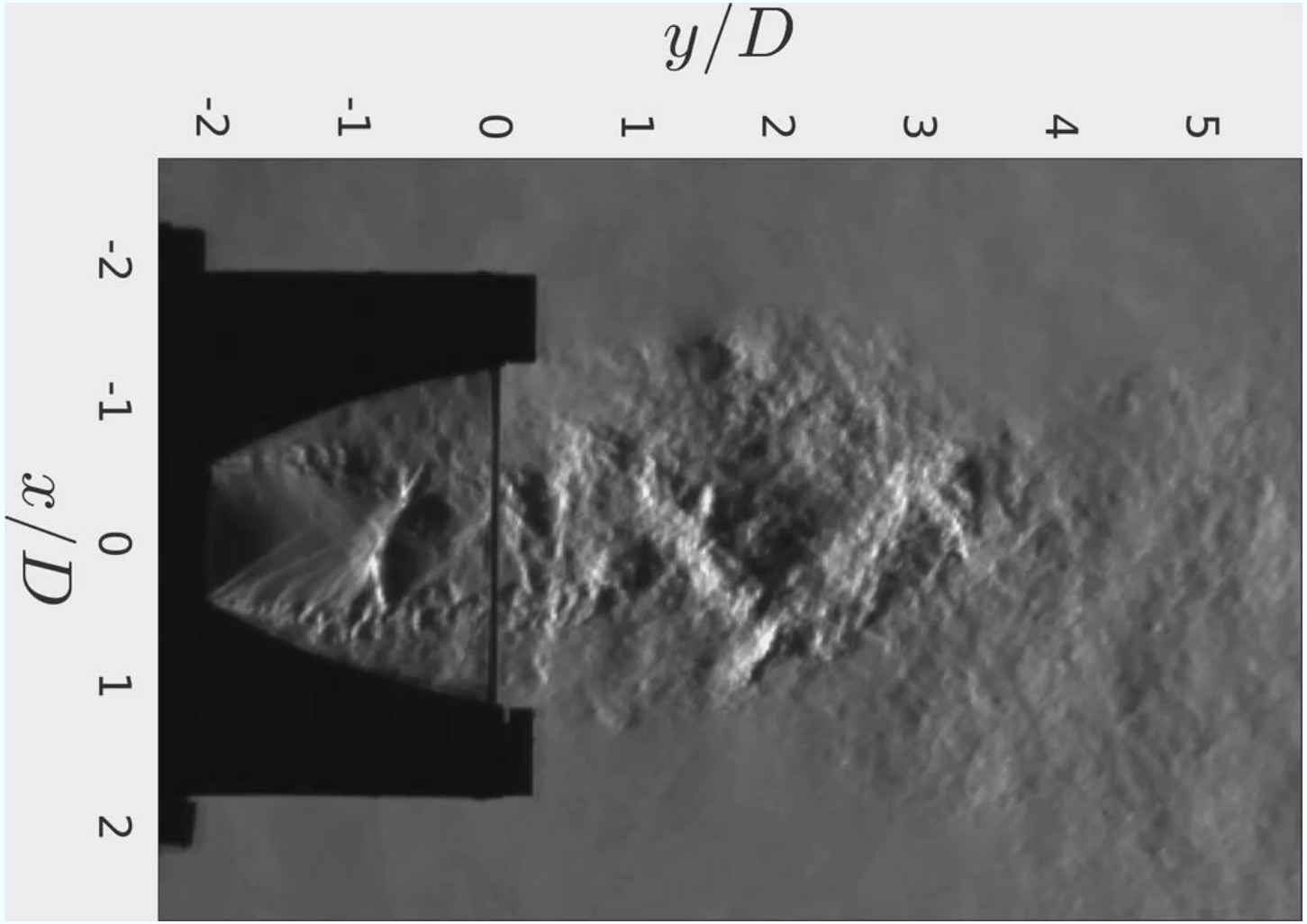
What next?

- Silicone
- Wasn’t expecting for sealing to greatly improve things or fundamentally change the flow
- Just for the sake of completion I proceeded to cover every crevice with silicone from a caulking gun
- And its back to the lab…

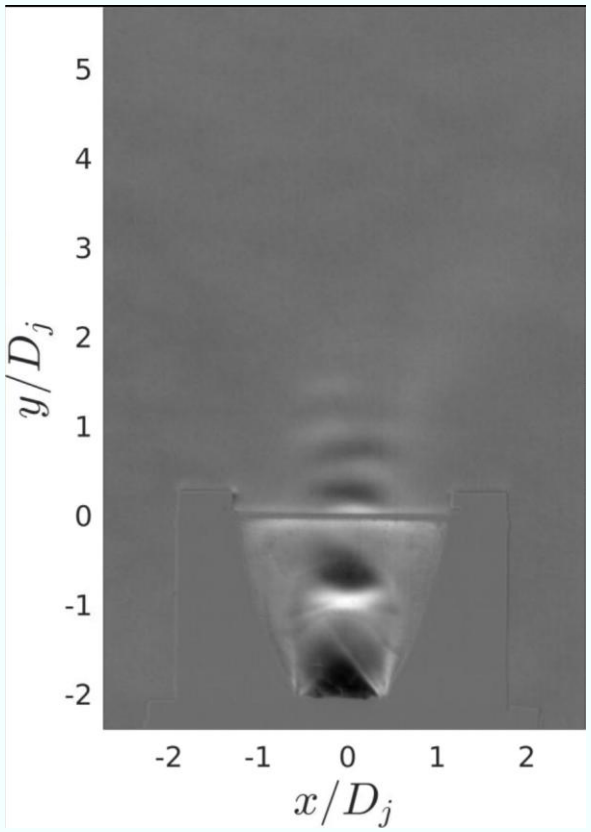
Second Attempt

- NPR 2.3, 2.48, 2.7, 2.77, 3, 4, 5, 6
- 125 mm and 300 mm focal length
- 125mm at 150k FPS
- 300mm at 120k FPS
- Initial tests showed it was sealing very well
  - There was some draft when we were feeling it but believe its highly probably that's the entrainment flow

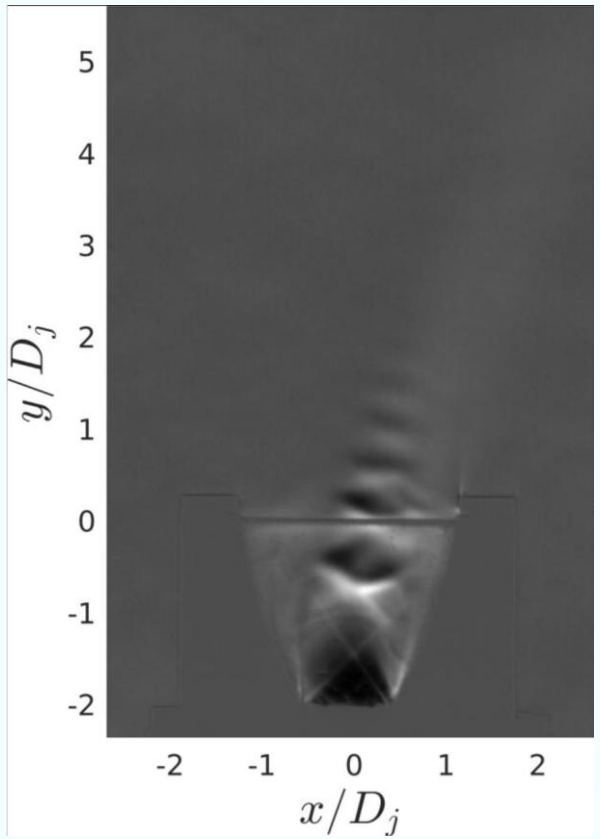
NPR 2.3



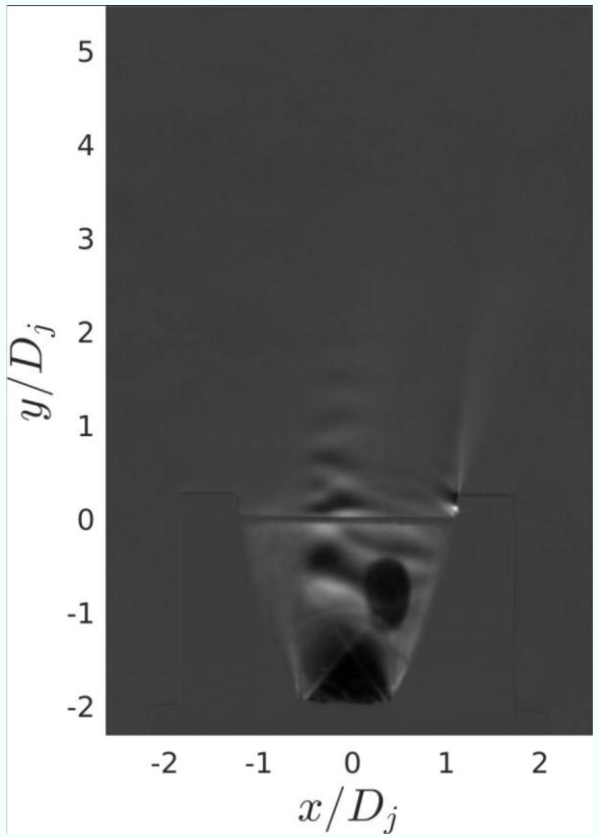
Mean flows



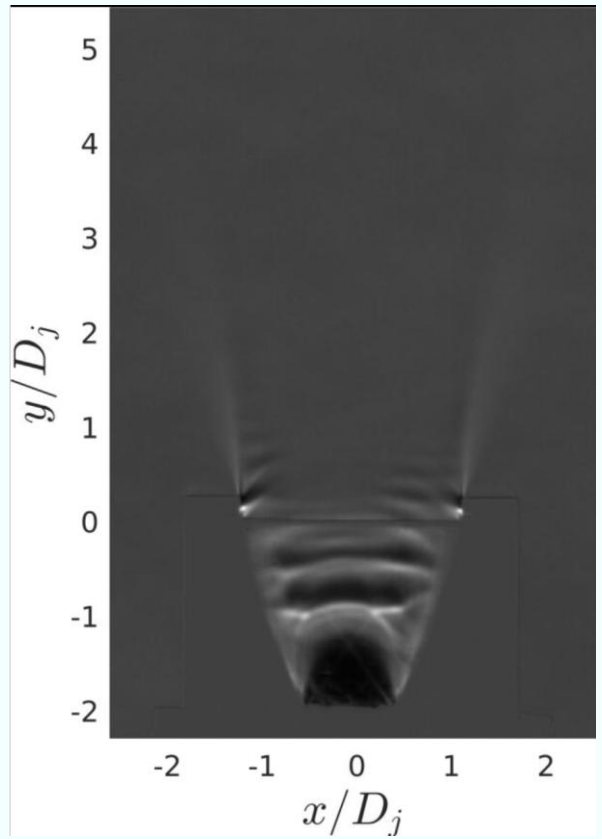
NPR 2.3



NPR 2.48

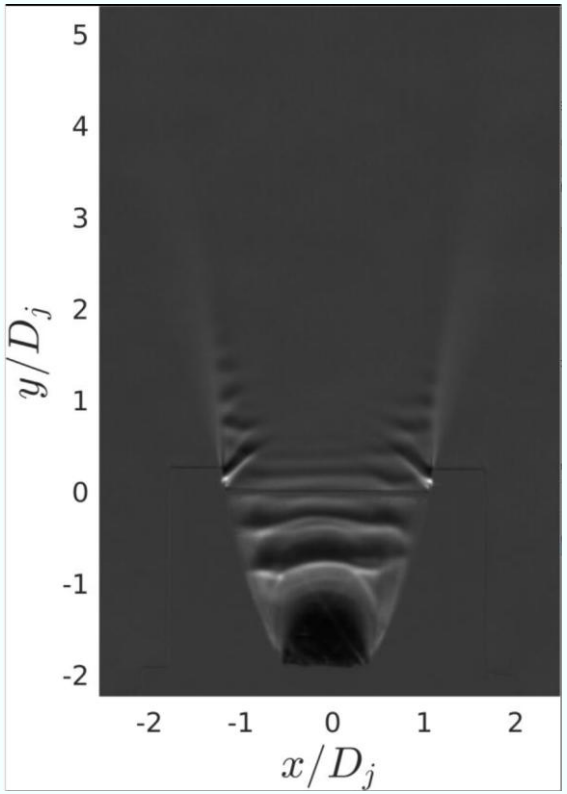


NPR 2.7

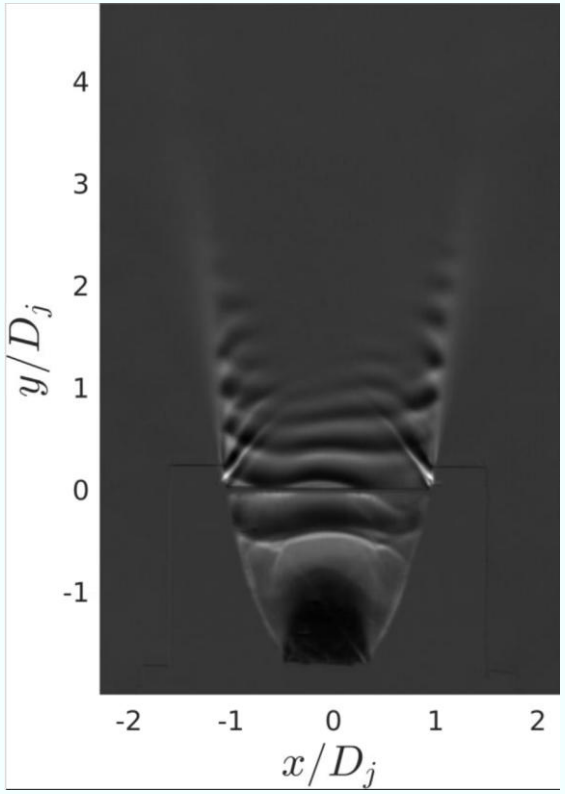


NPR 2.77

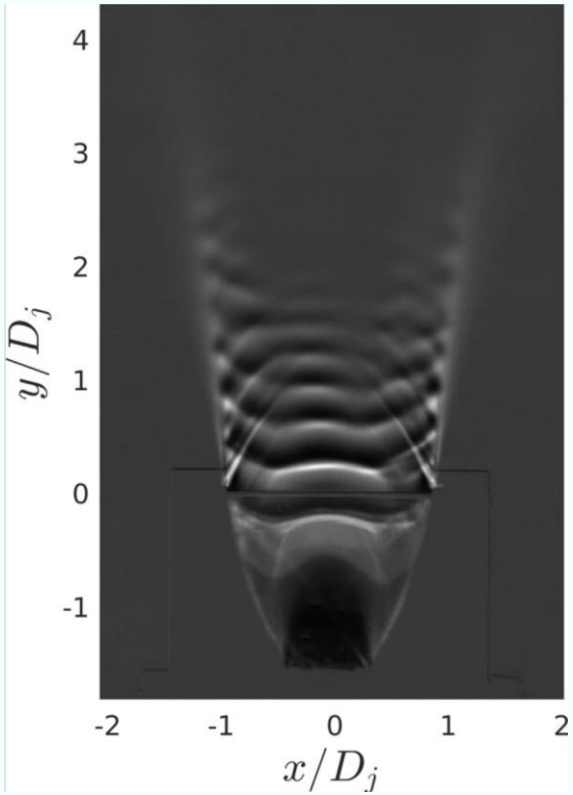
Mean flows



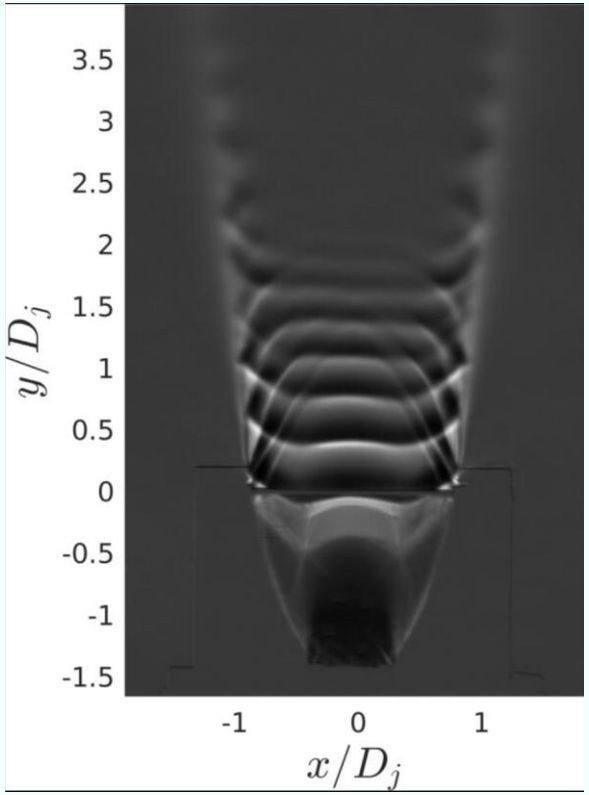
NPR 3.0



NPR 4.0

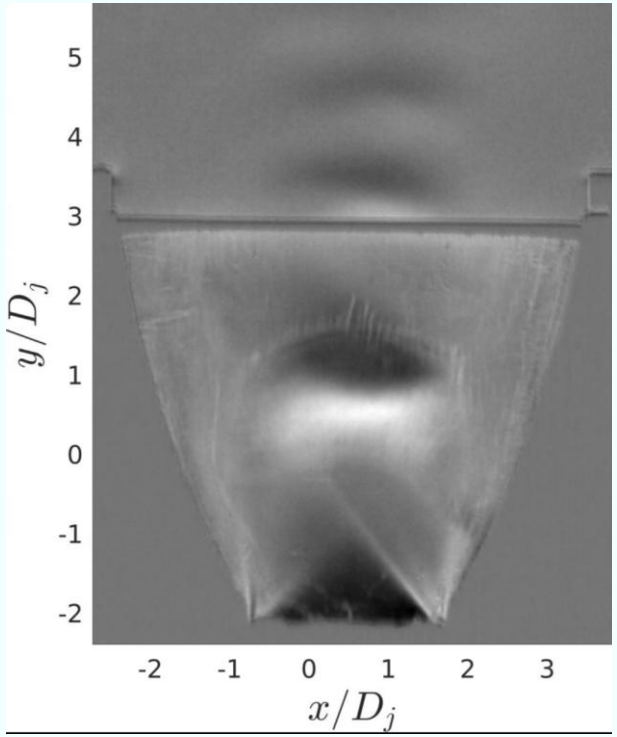


NPR 5.0

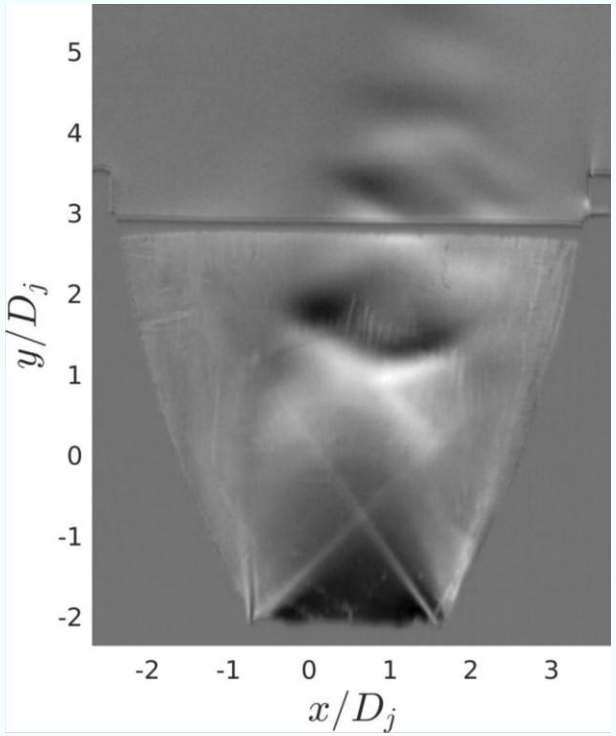


NPR 6.0

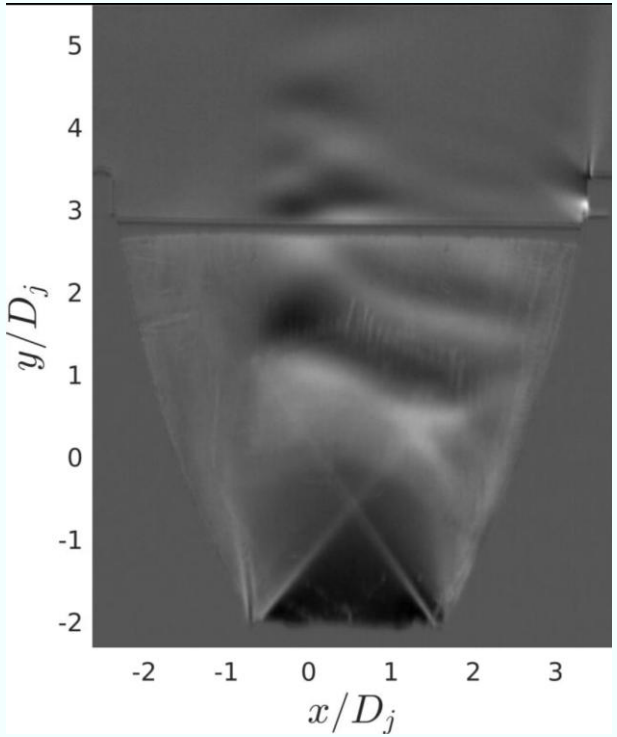
Zoom and Enhance



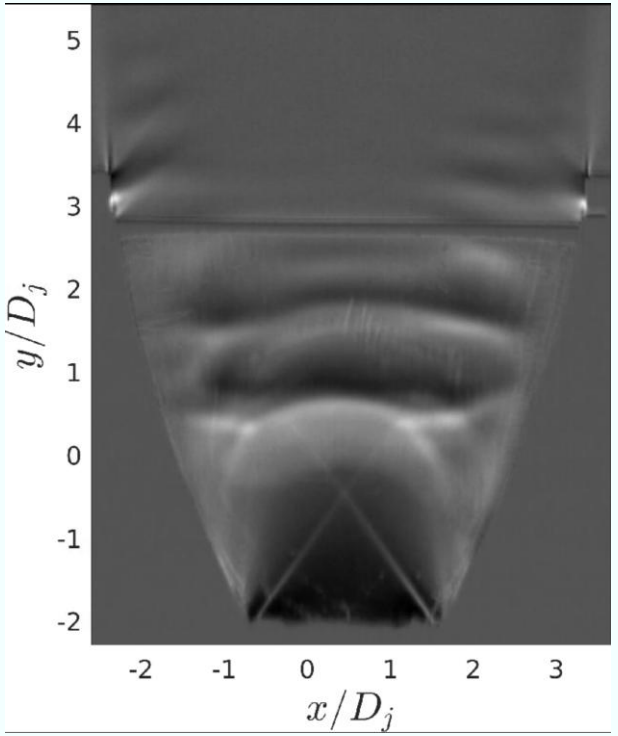
NPR 2.3



NPR 2.48

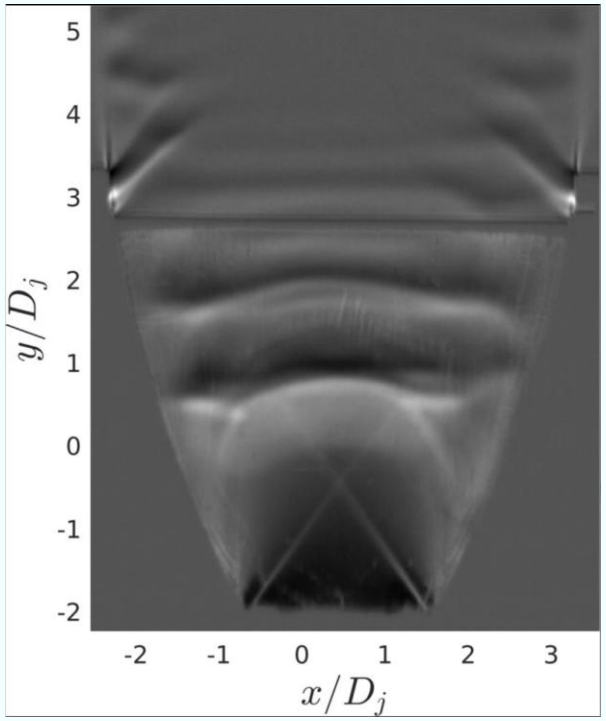


NPR 2.7

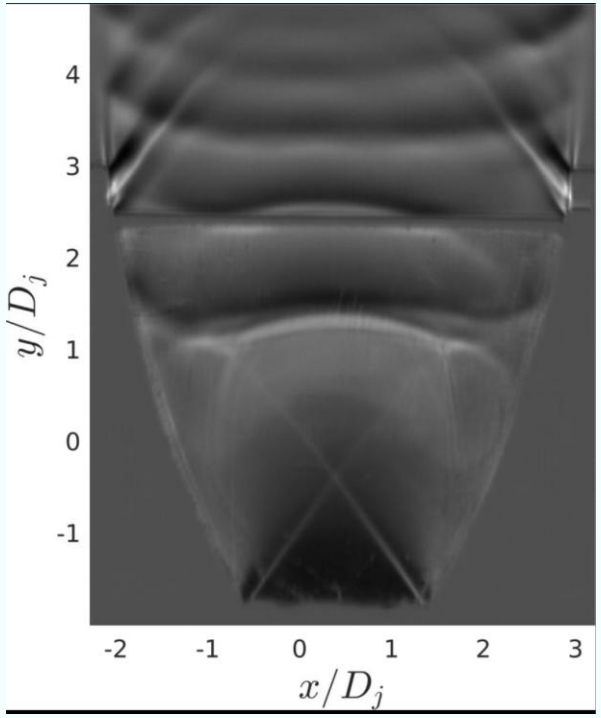


NPR 2.77

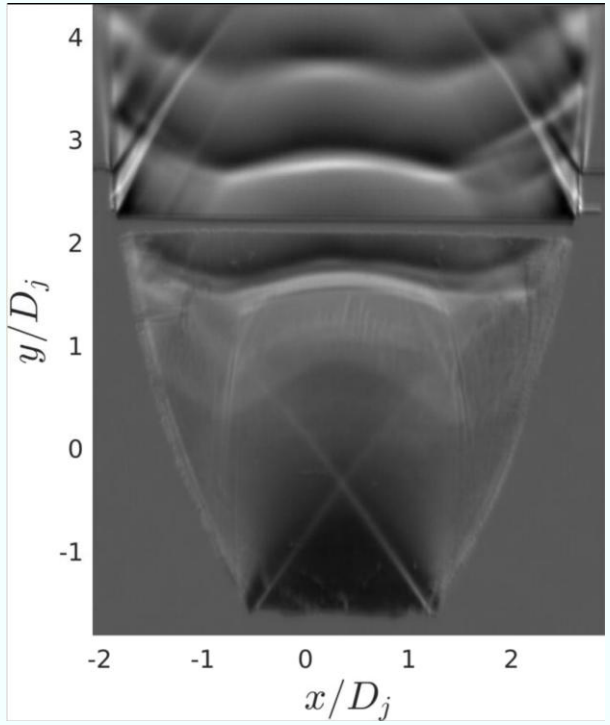
Zoom and Enhance



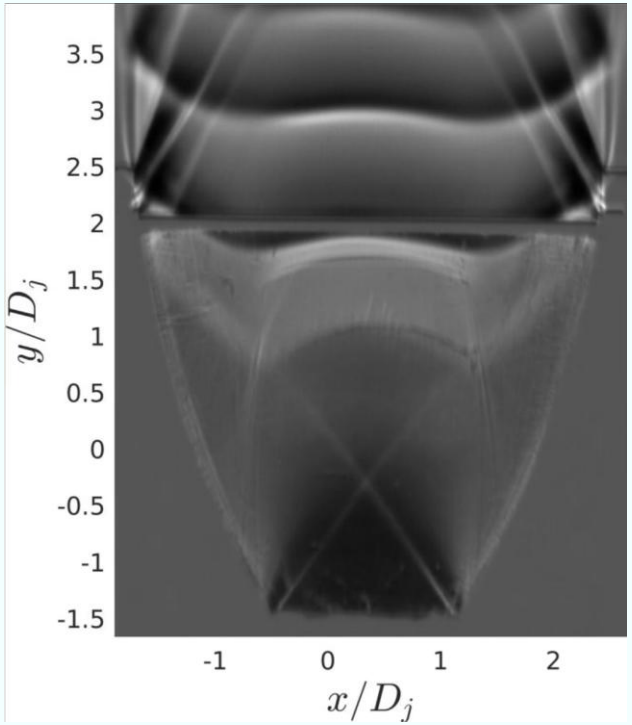
NPR 3.0



NPR 4.0

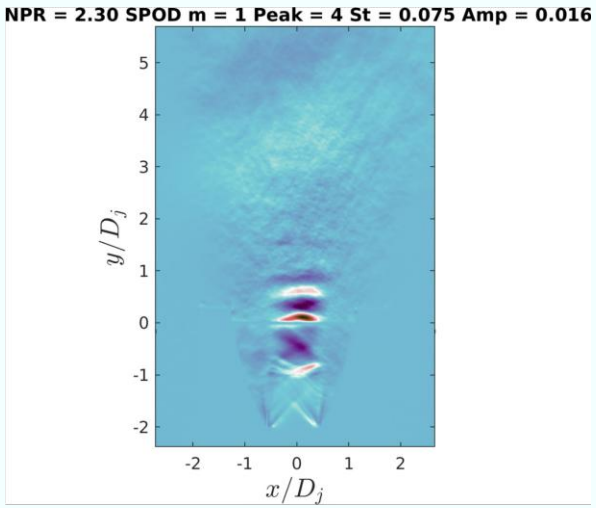


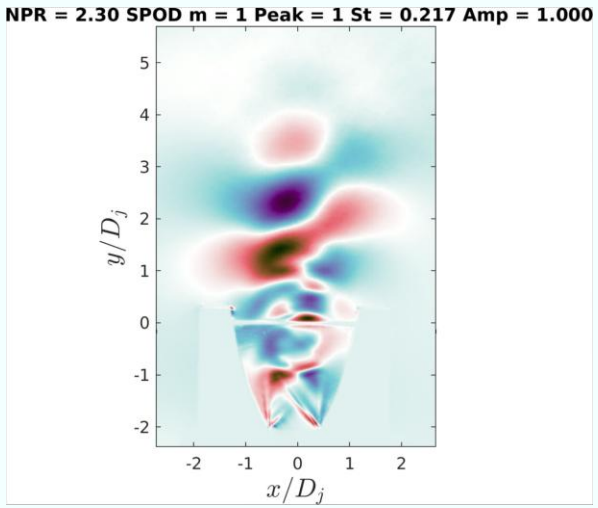
NPR 5.0

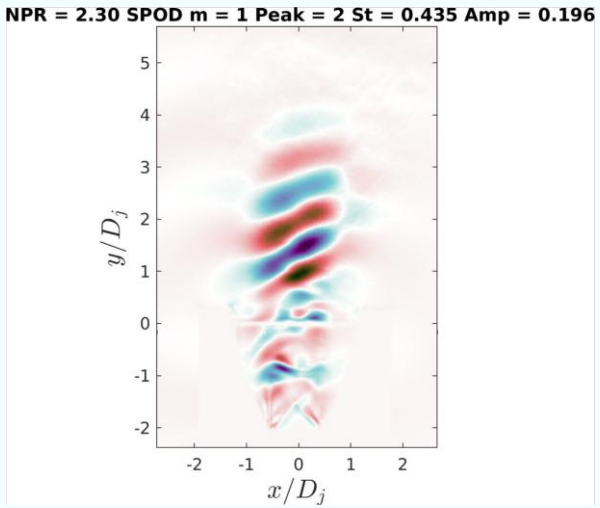


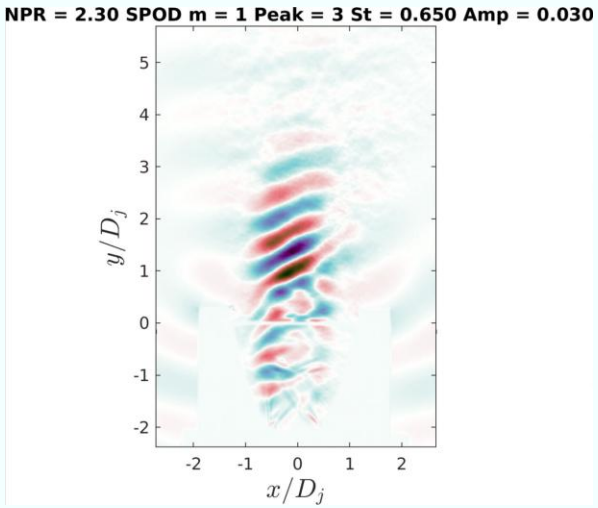
NPR 6.0

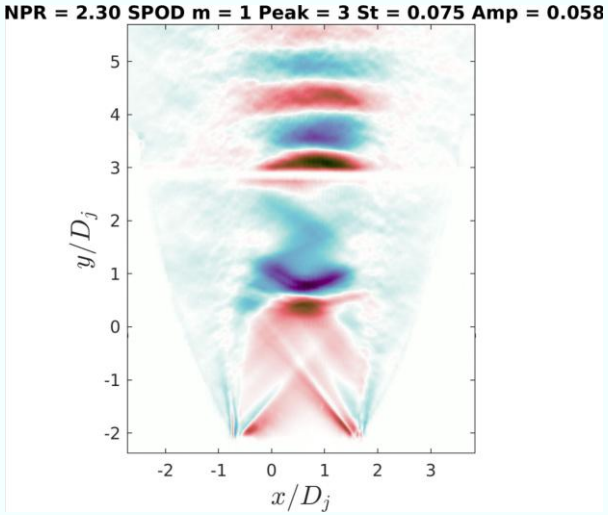
NPR 2.3 – Free Jet

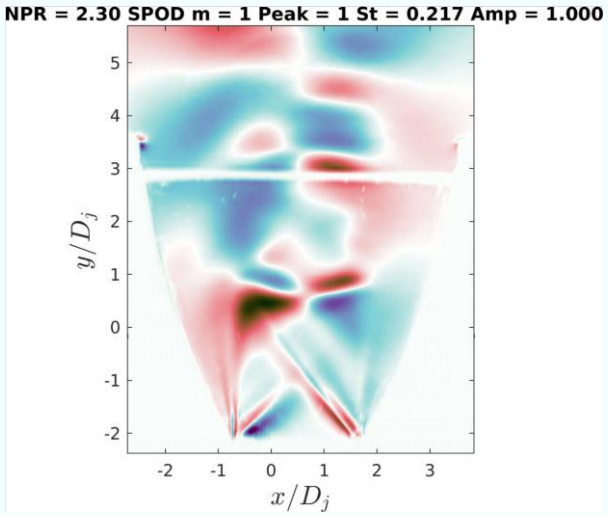


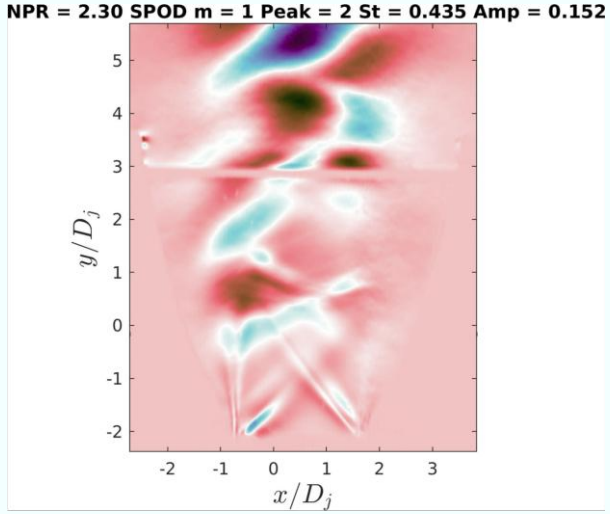


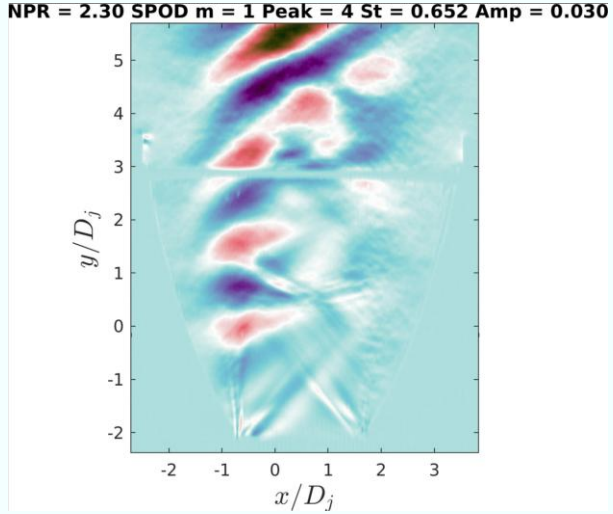




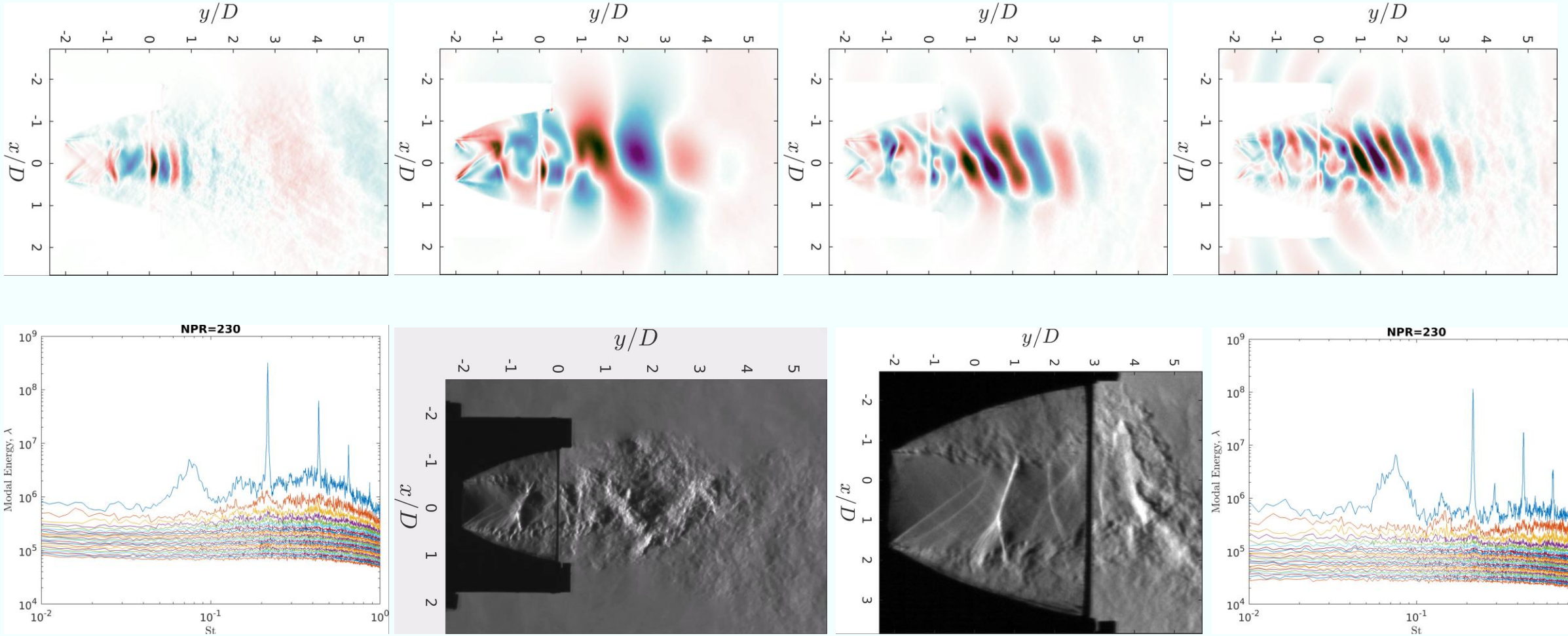




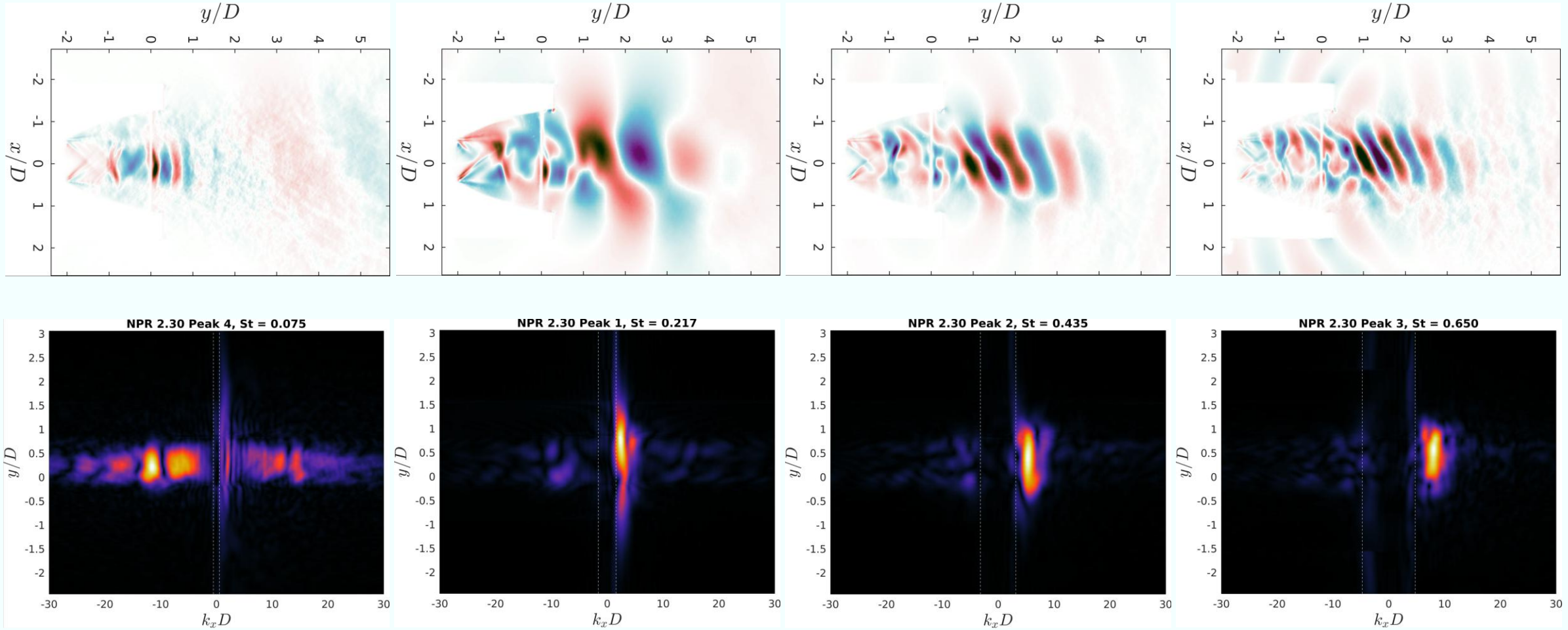




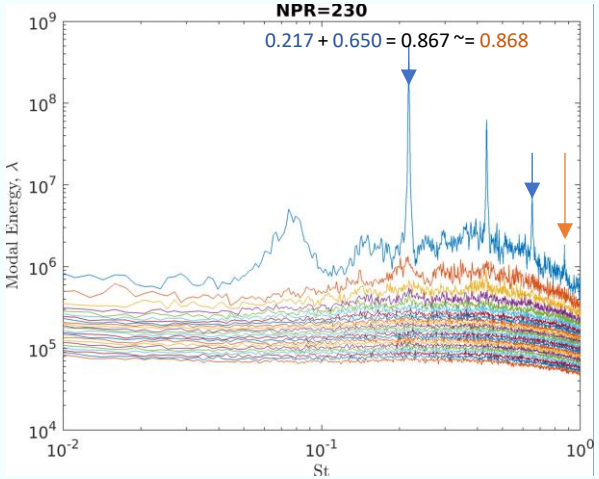
NPR 2.3 – Free Jet

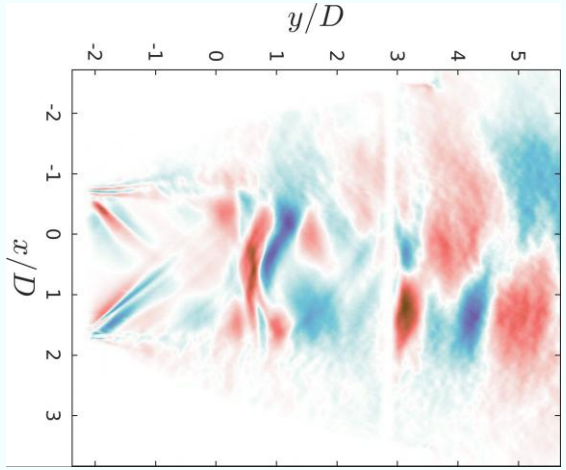


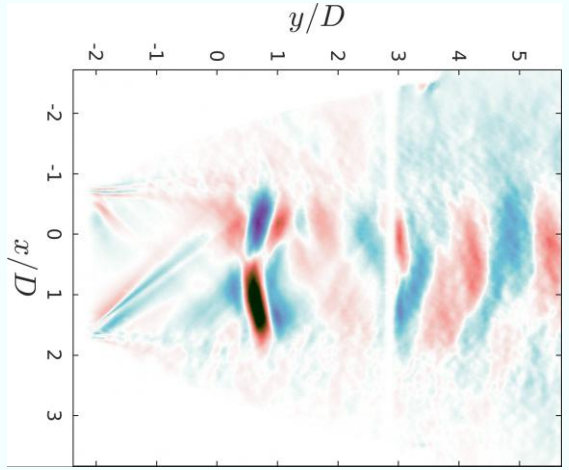
NPR 2.3 – Free Jet

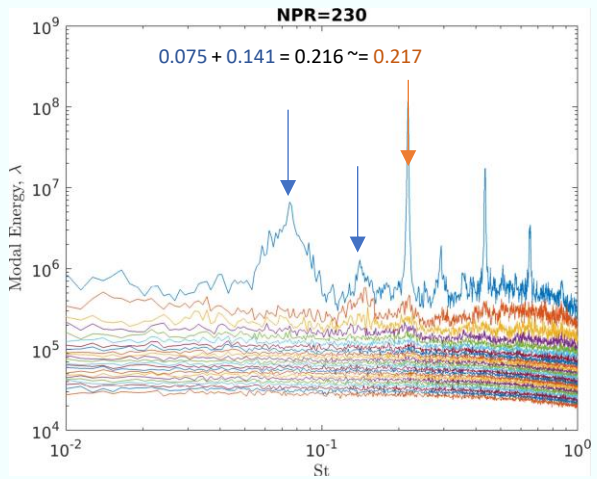


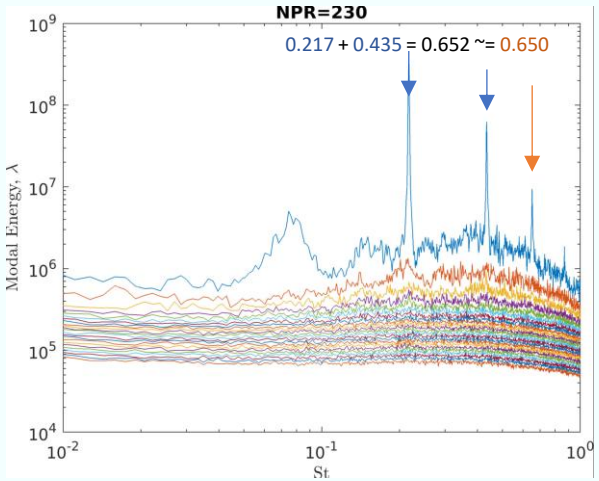
NPR 2.3 – Free Jet

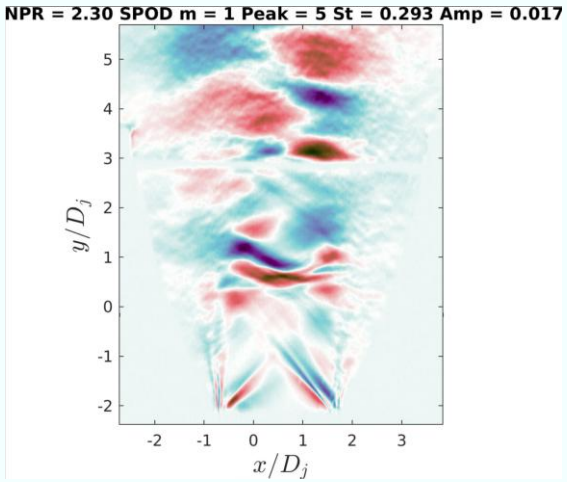


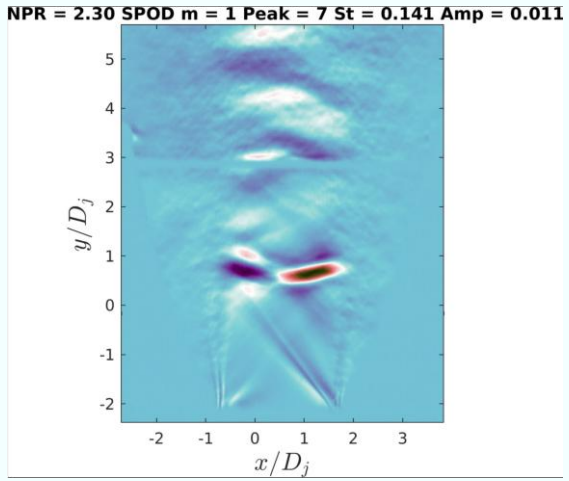


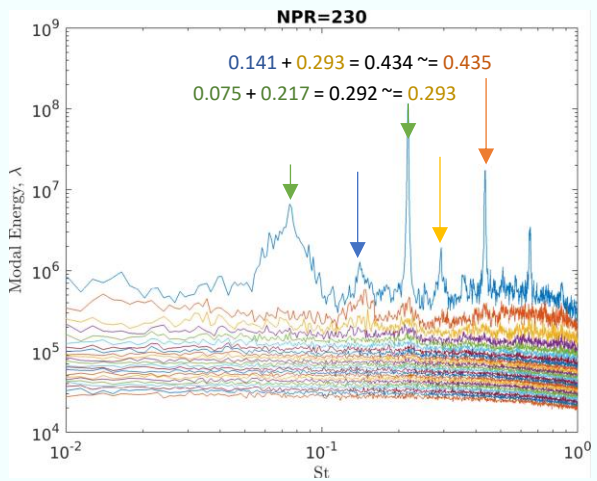




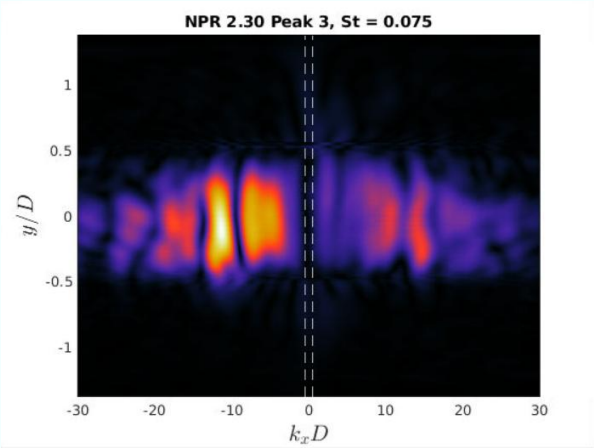


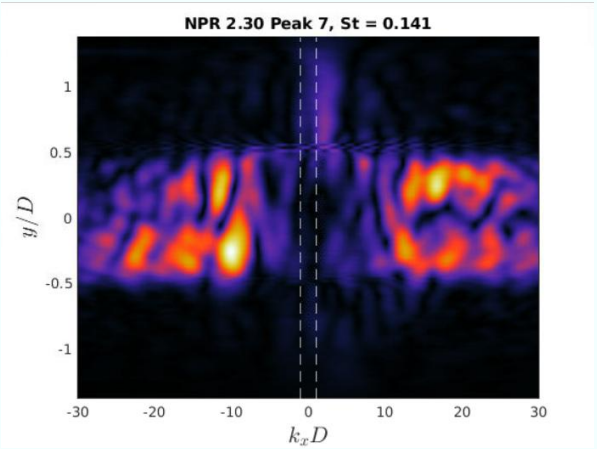


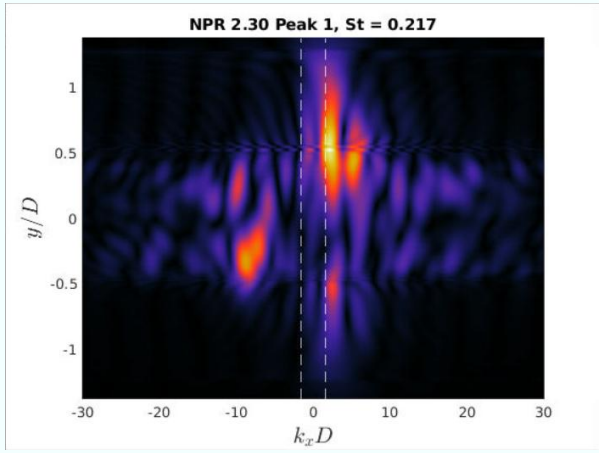


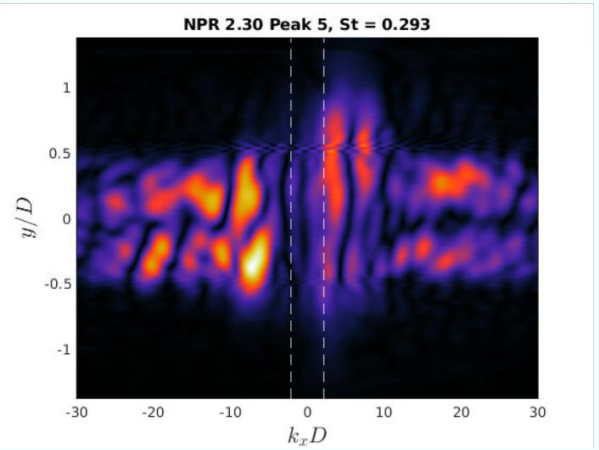


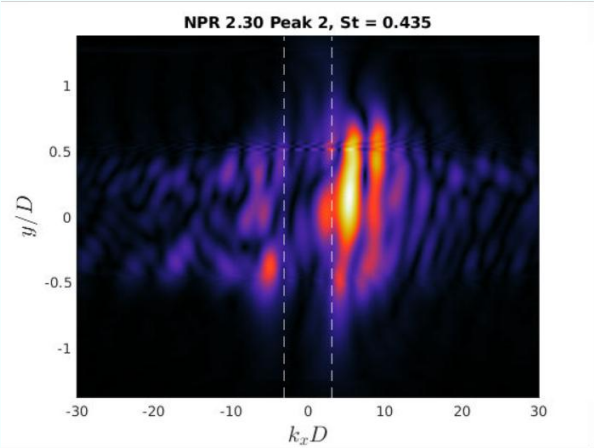
NPR 2.3 – Free Jet – 300 mm

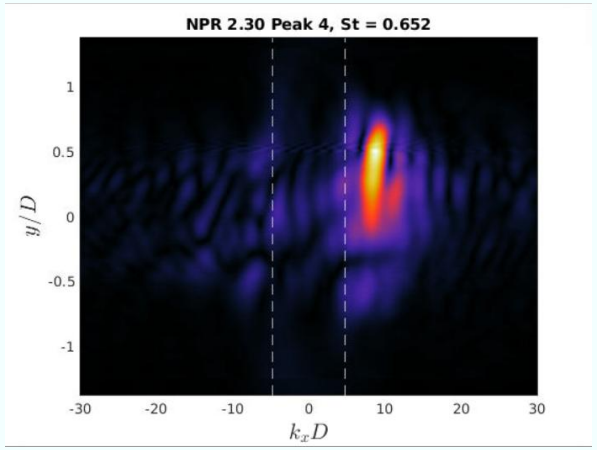


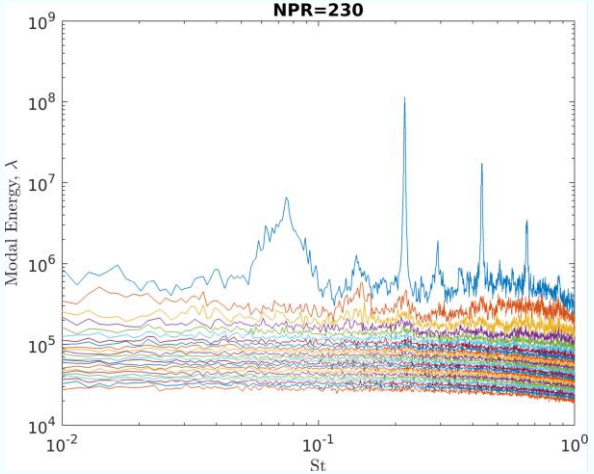




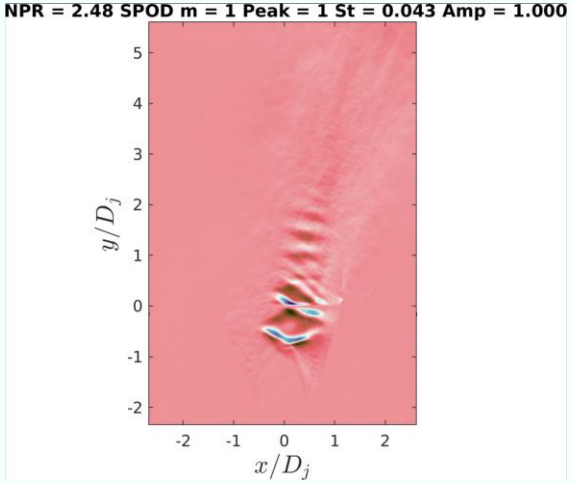


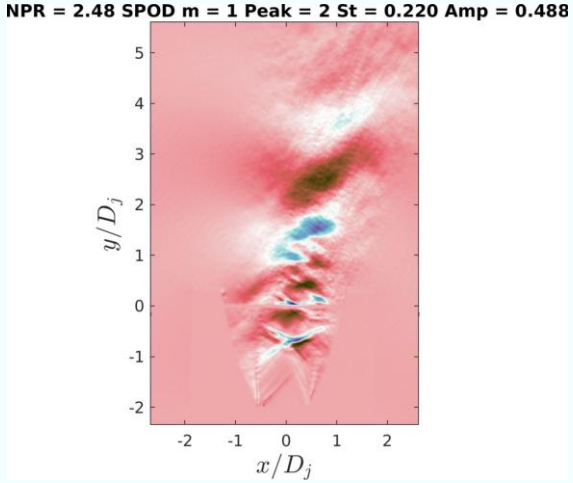


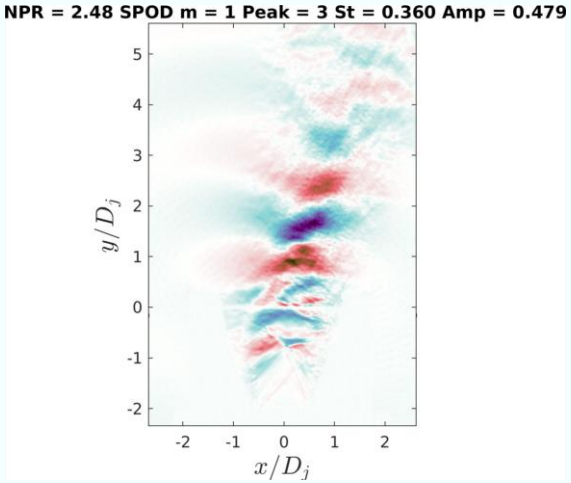


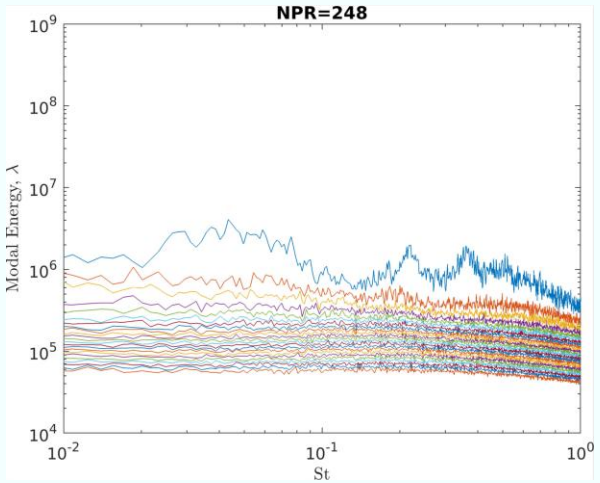


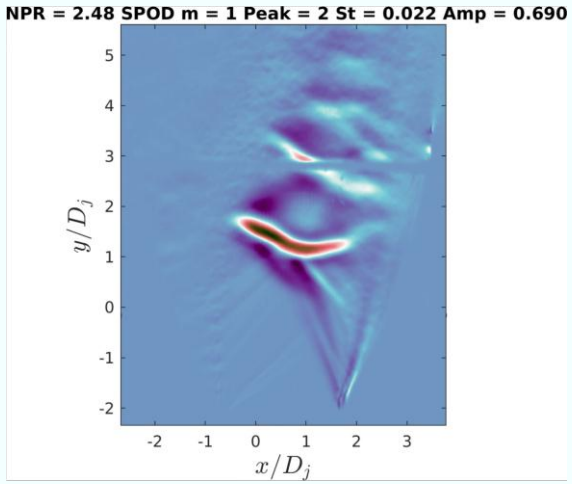
NPR 2.48 – Free jet

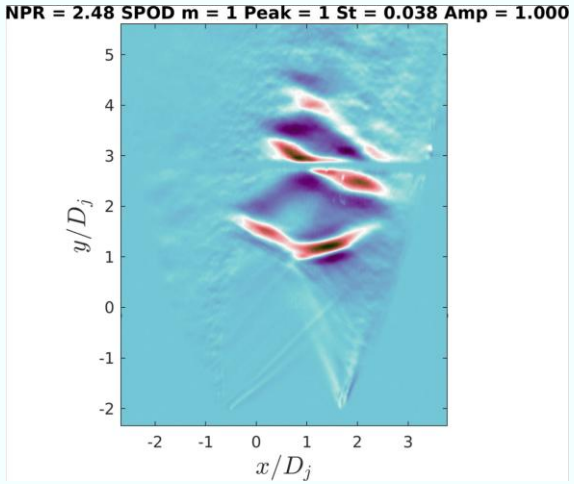


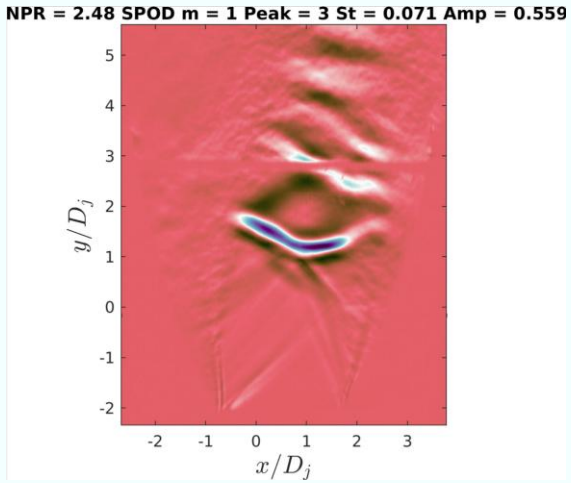


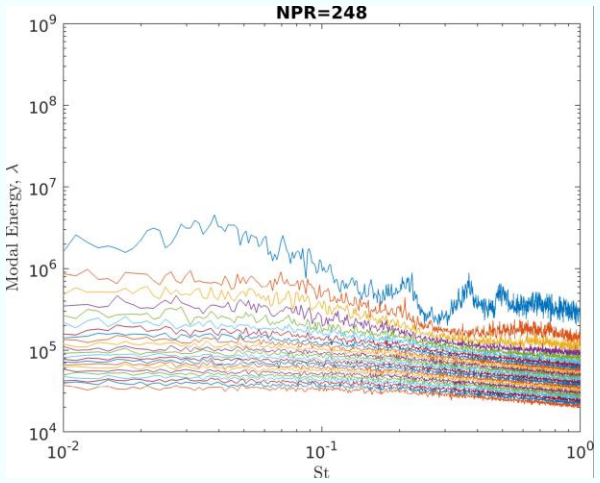




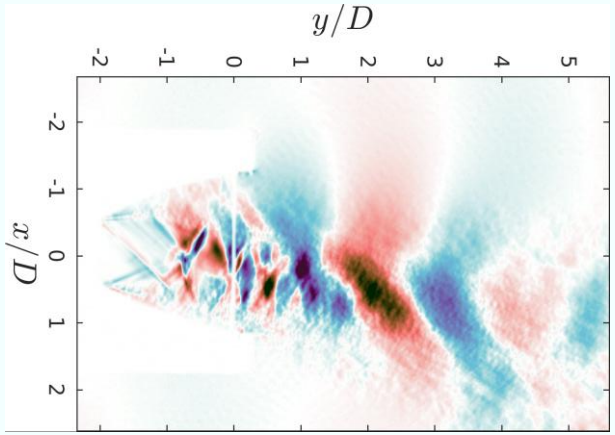


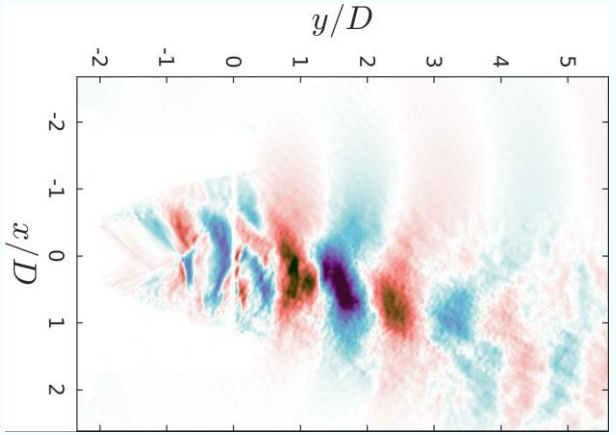


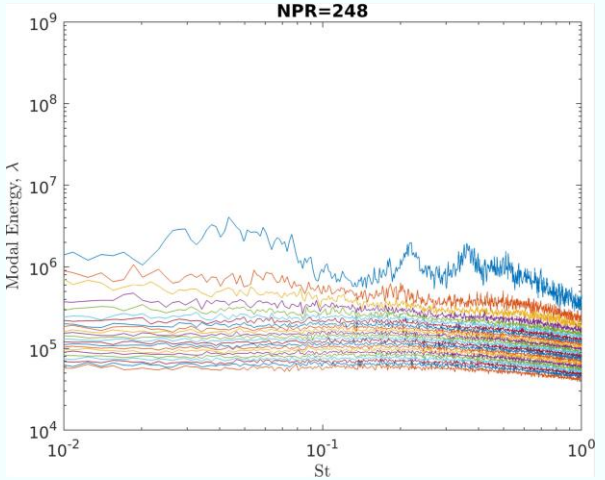


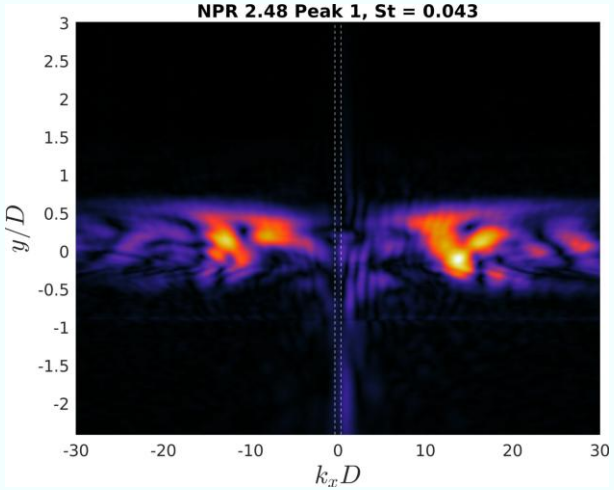


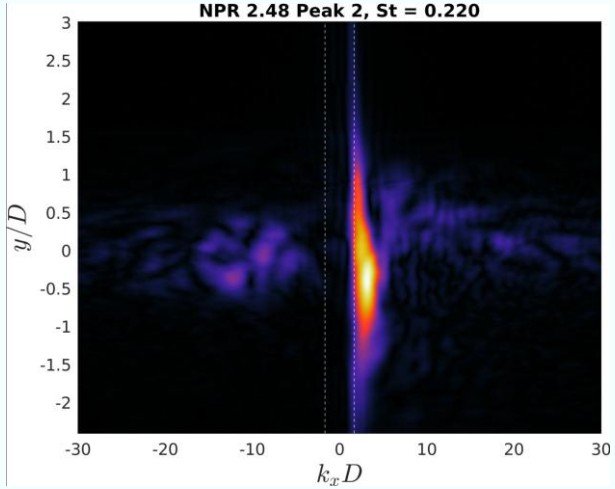
NPR 2.48 – Free jet

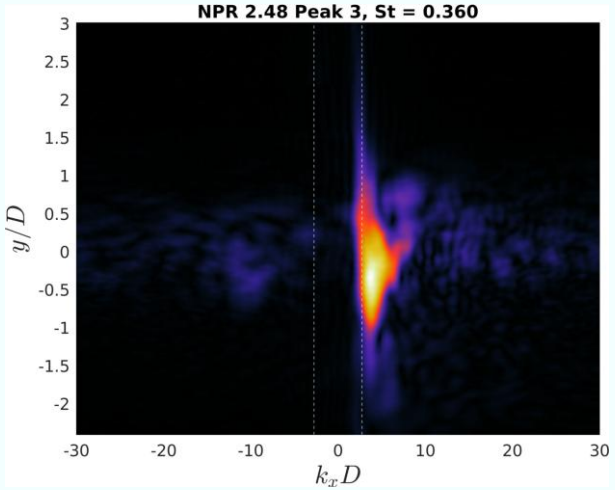


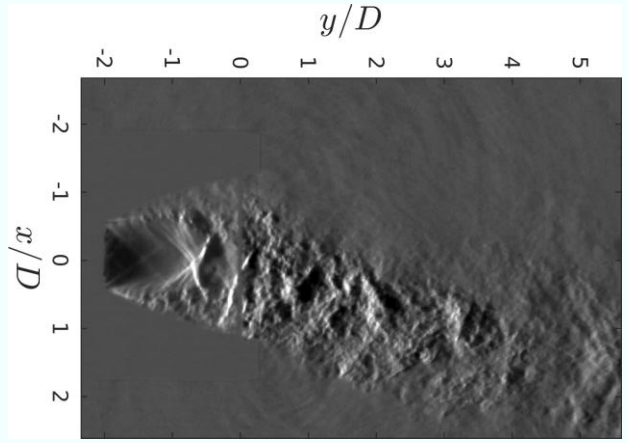




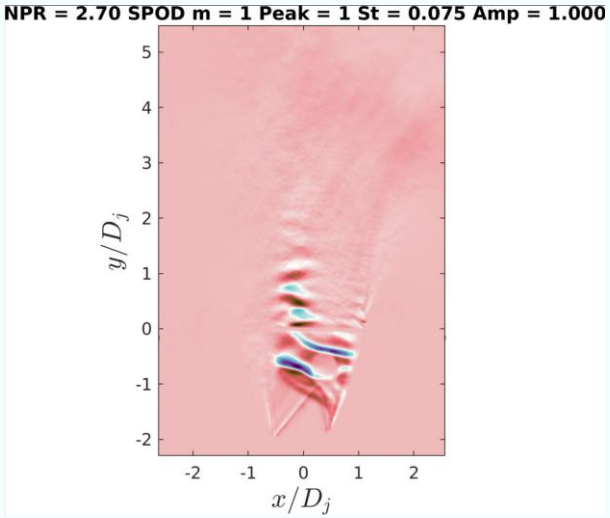


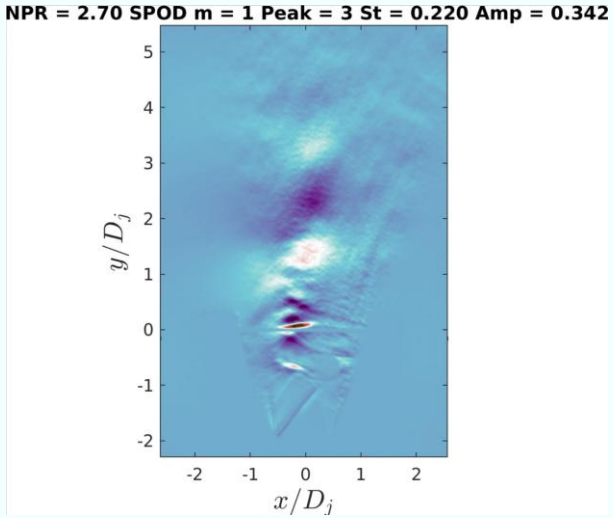






NPR 2.7 – ???


NPR = 2.70 SPOD m = 1 Peak = 1 St = 0.075 Amp = 1.000
y/D_j
x/D_j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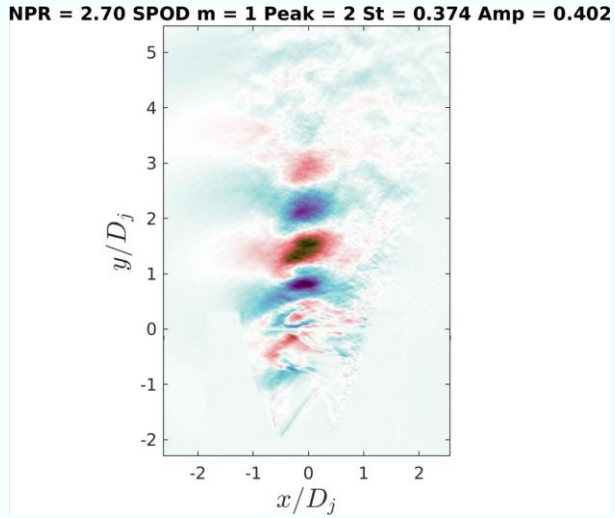
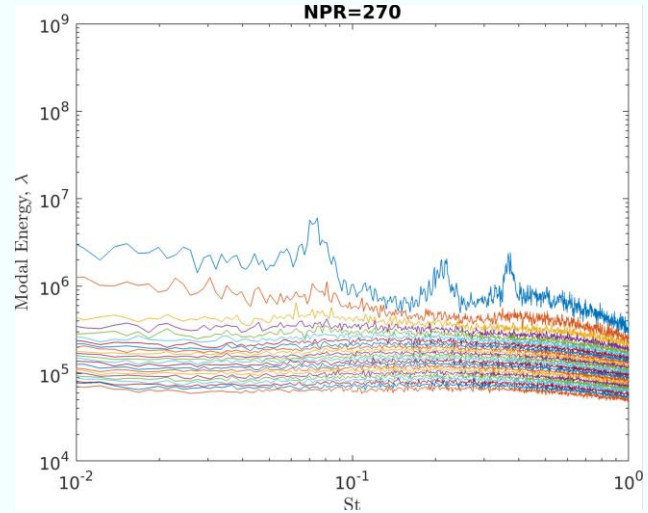
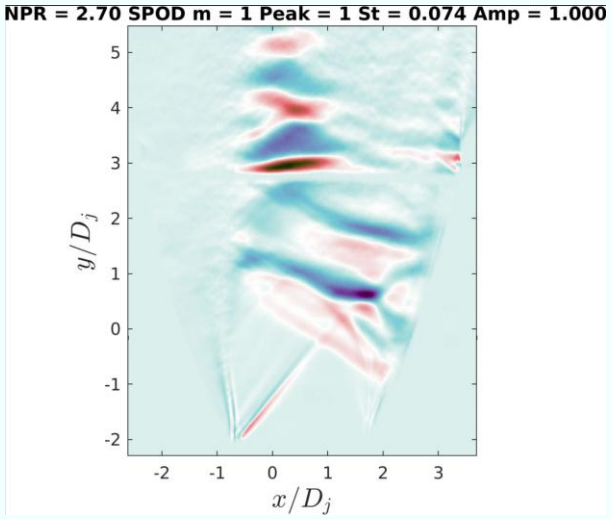
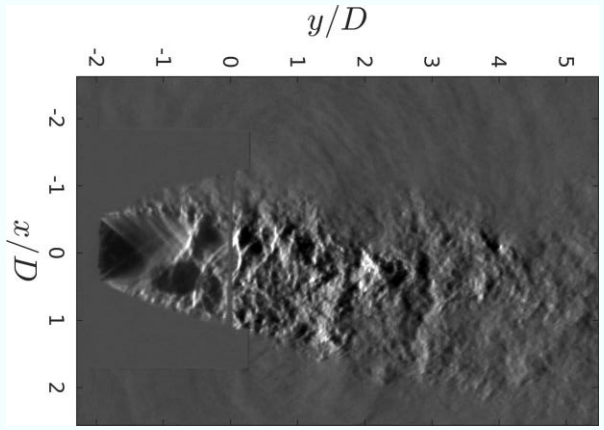
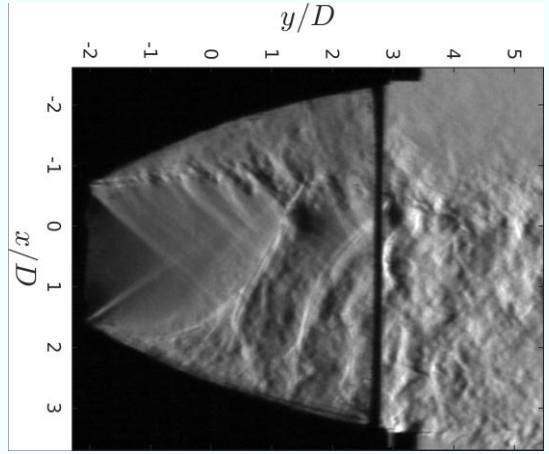
y/D_j
x/D_j

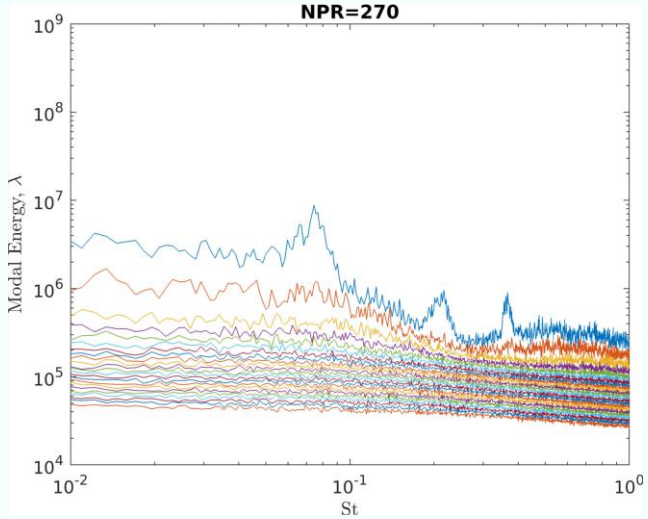

NPR = 2.70 SPOD m = 1 Peak = 2 St = 0.374 Amp = 0.402
y/D_j
x/D_j


NPR=270
Modal Energy, λ
St

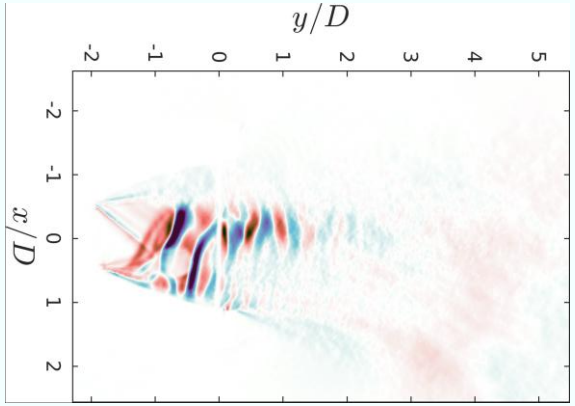

NPR = 2.70 SPOD m = 1 Peak = 1 St = 0.074 Amp = 1.000
y/D_j
x/D_j

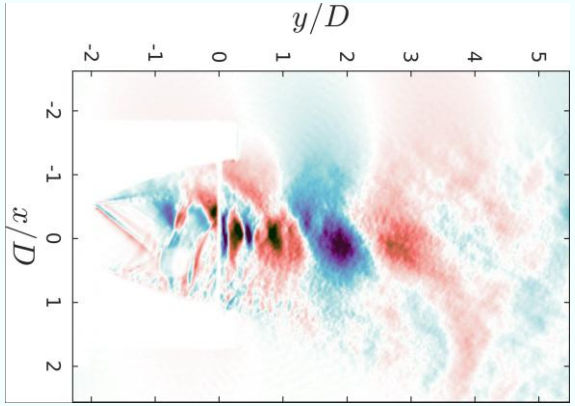

y/D
x/D

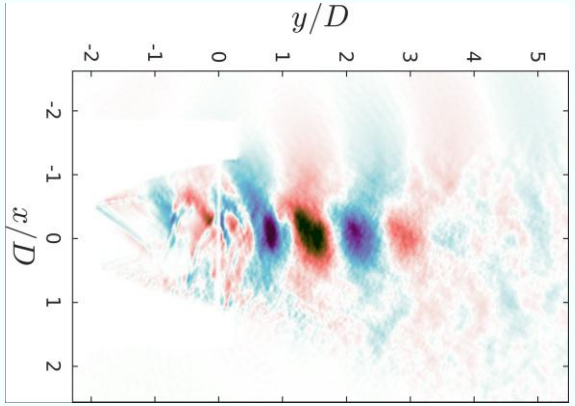

y/D
x/D

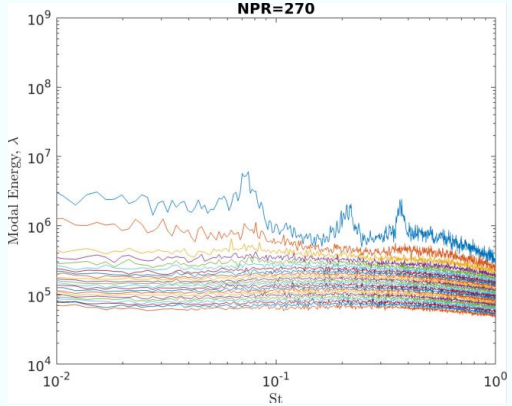

NPR=270
Modal Energy, λ
St

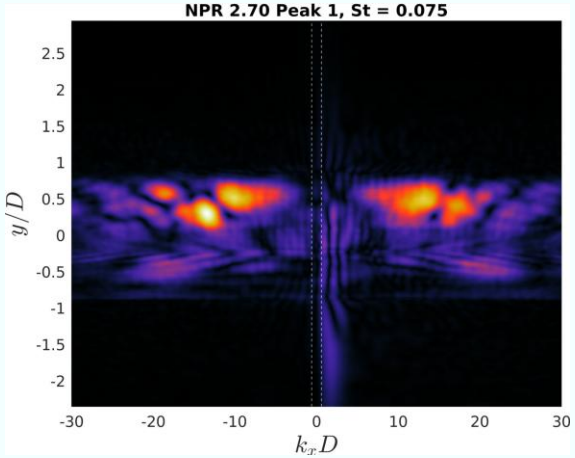
NPR 2.7 – ???

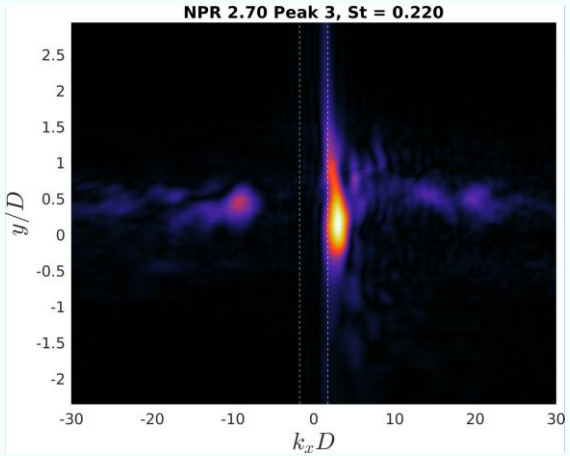

y/D
x/D

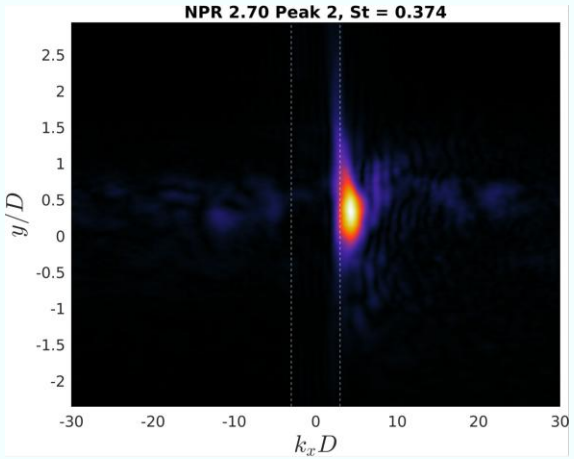

y/D
x/D


y/D
x/D


NPR=270
Modal Energy, λ
St


NPR 2.70 Peak 1, St = 0.075
y/D
$k_x D$


NPR 2.70 Peak 3, St = 0.220
y/D
$k_x D$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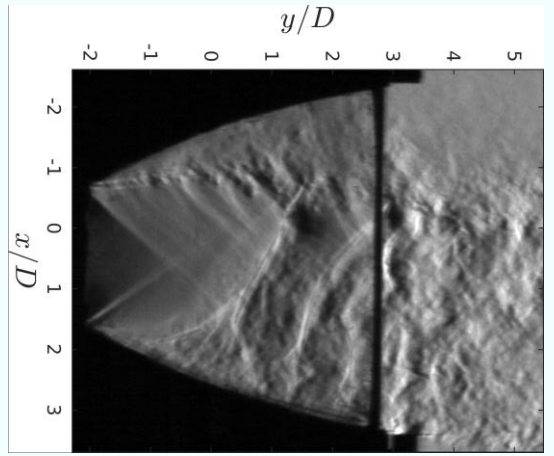
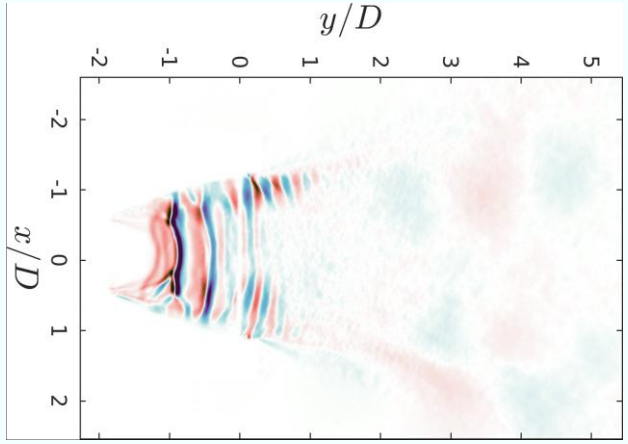
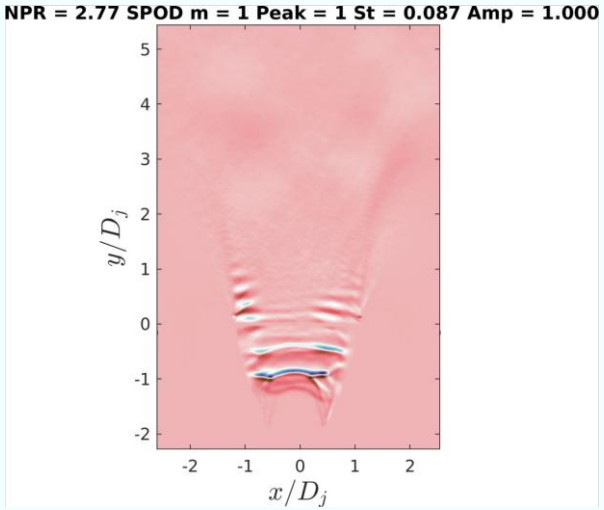
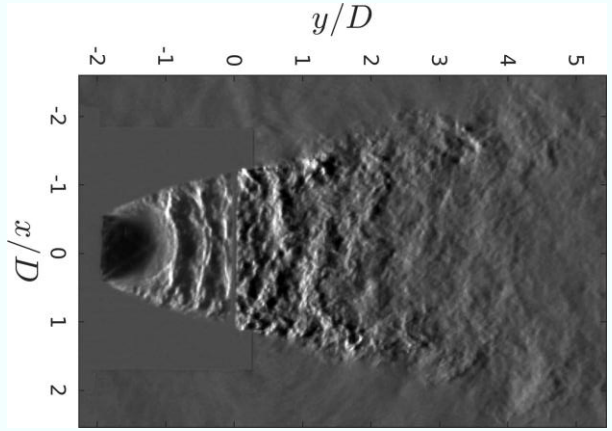
y/D
$k_x D$

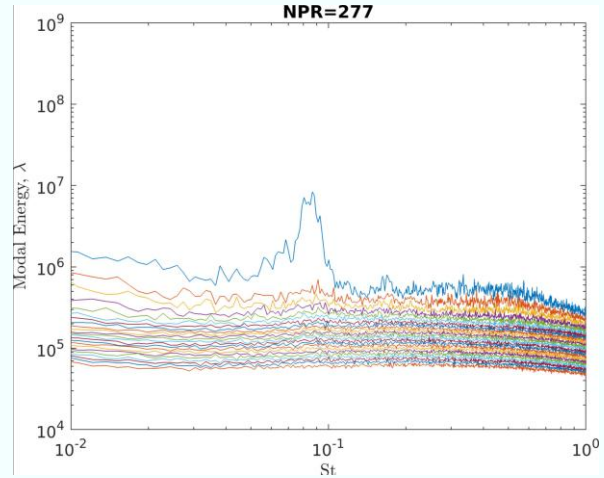

y/D
x/D

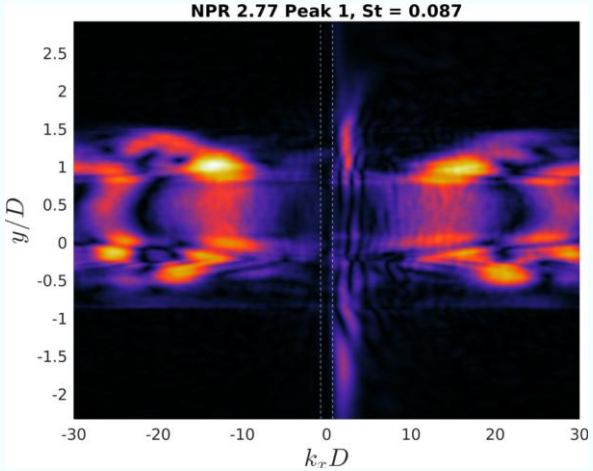
NPR 2.77 – Transition

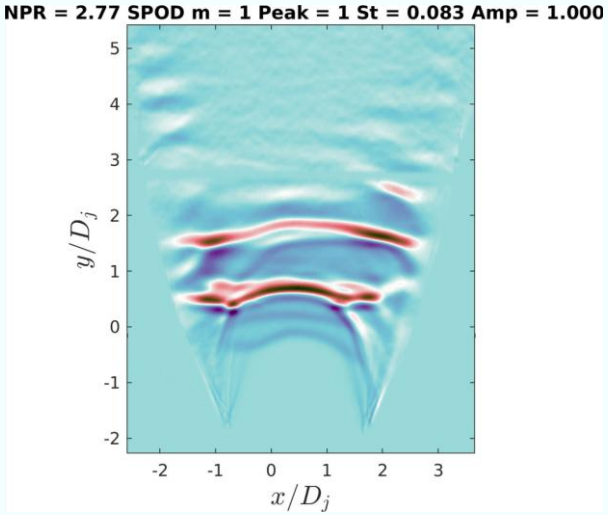


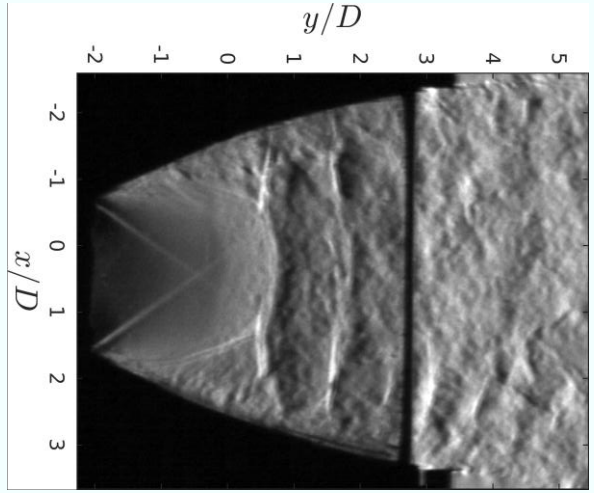


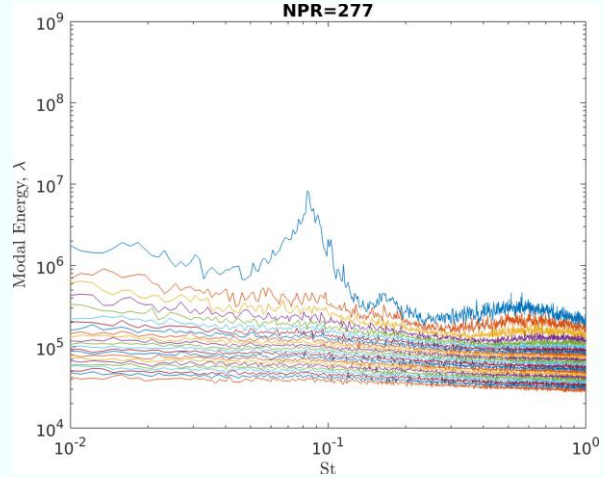




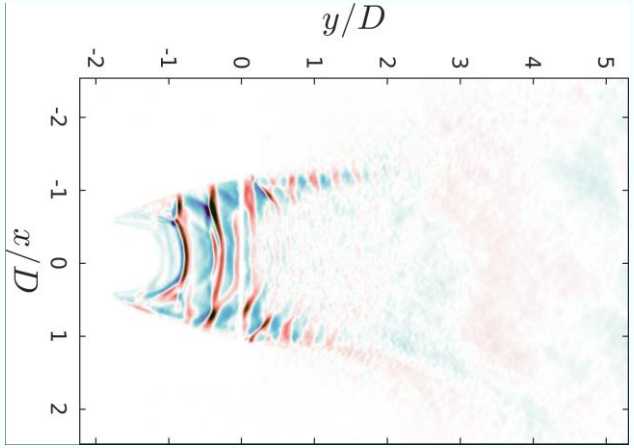


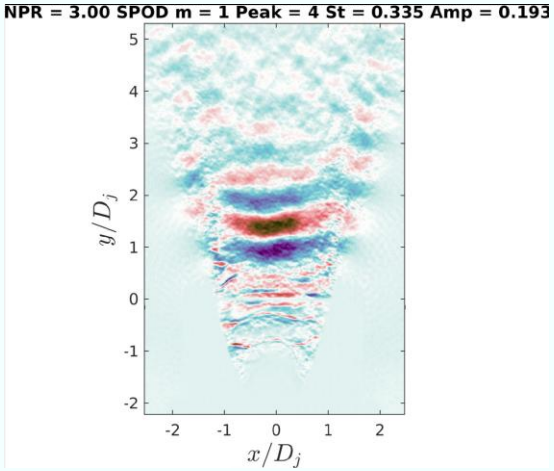


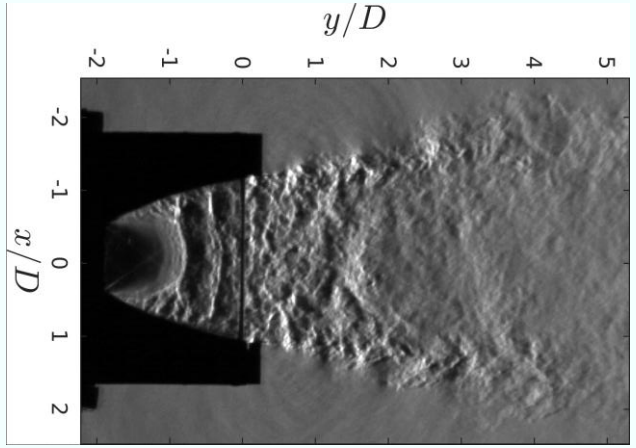


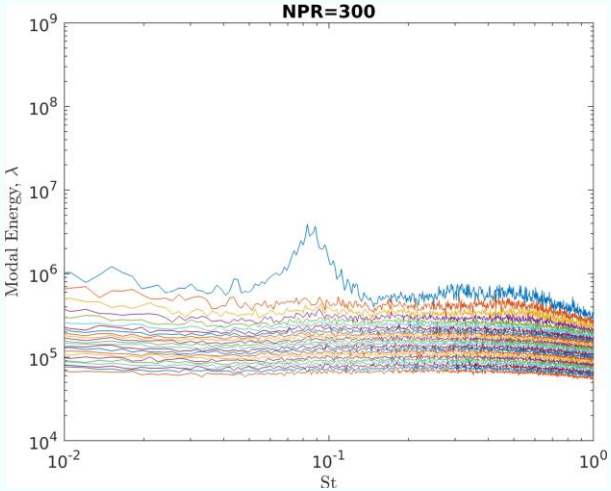


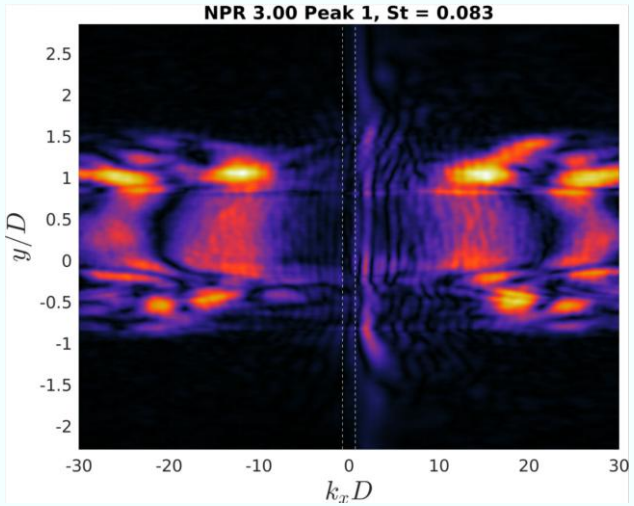
NPR 3.0 – Attached

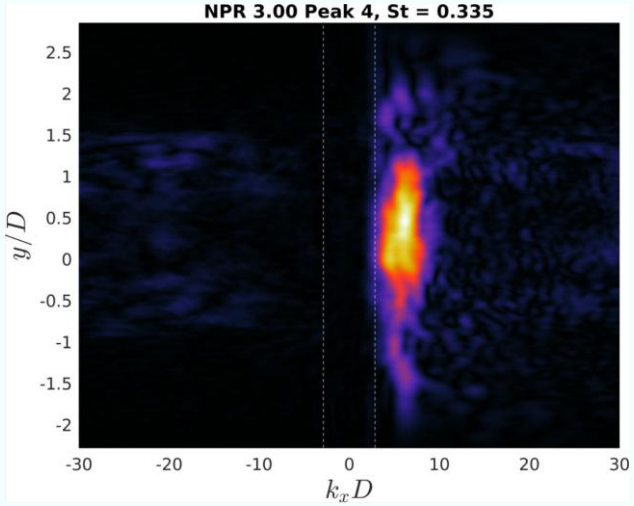


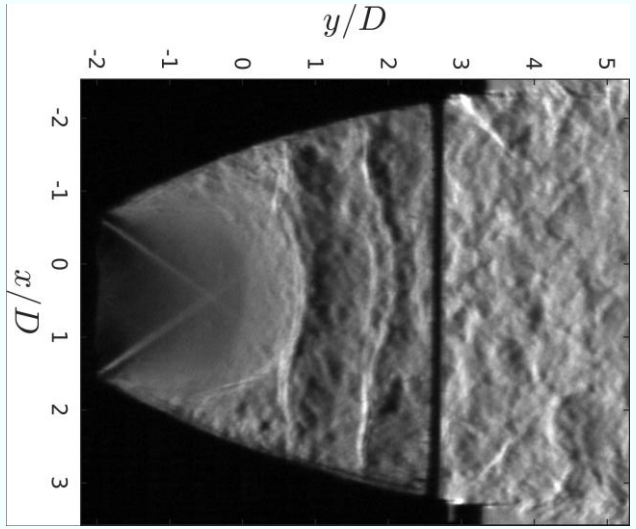


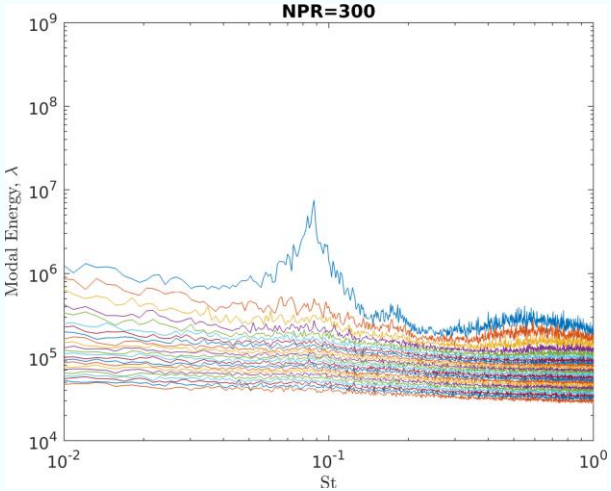




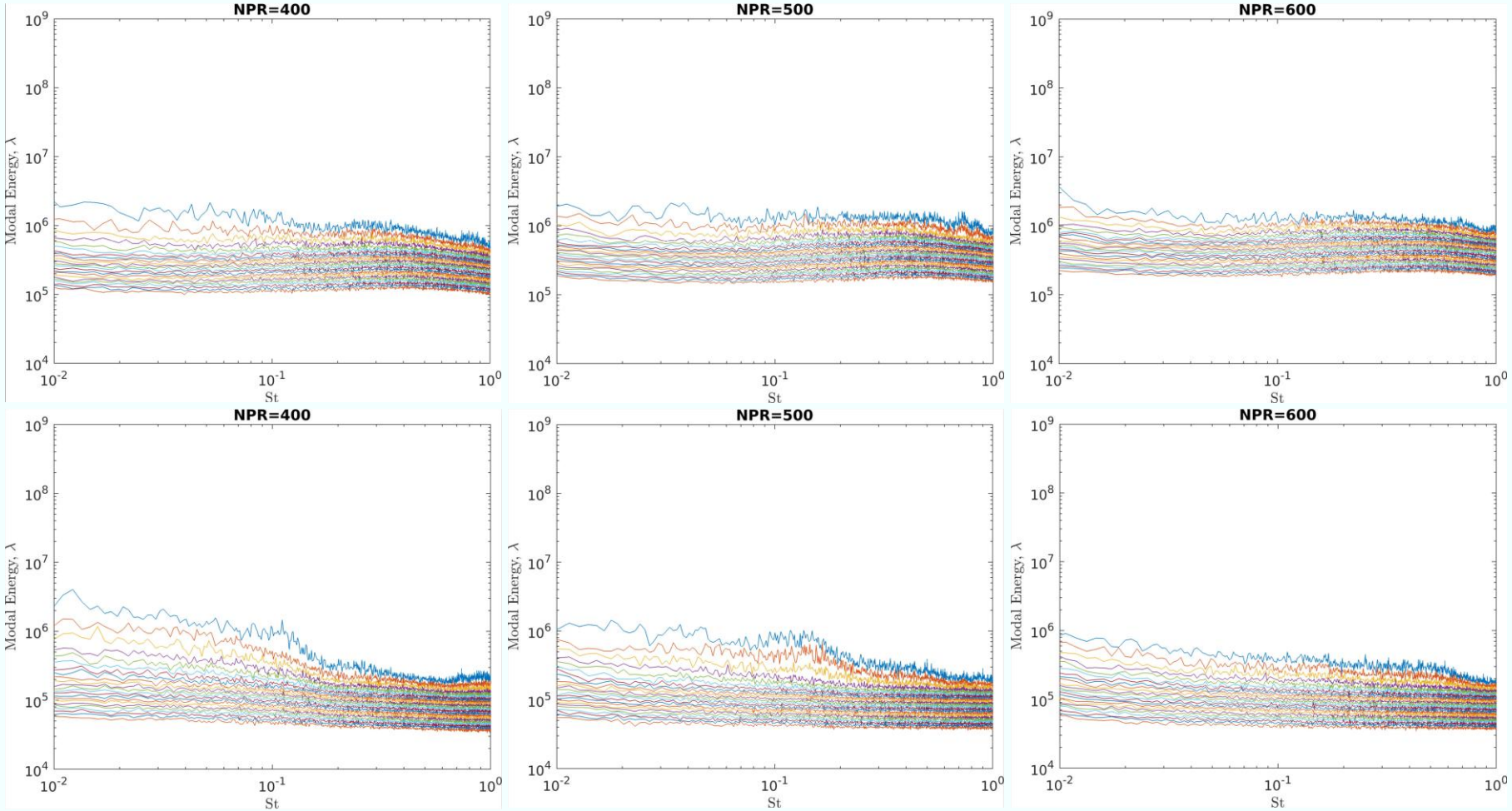




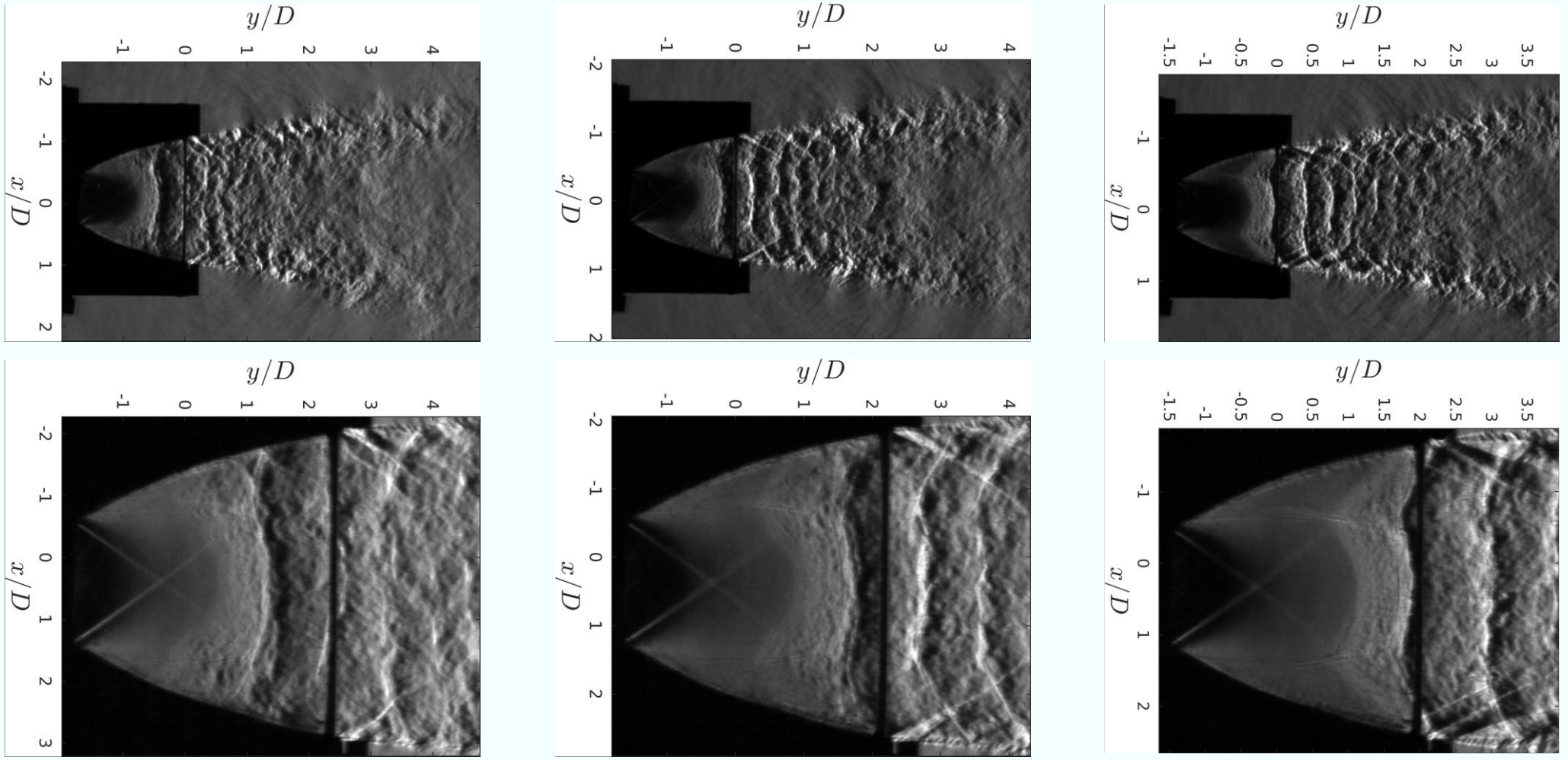




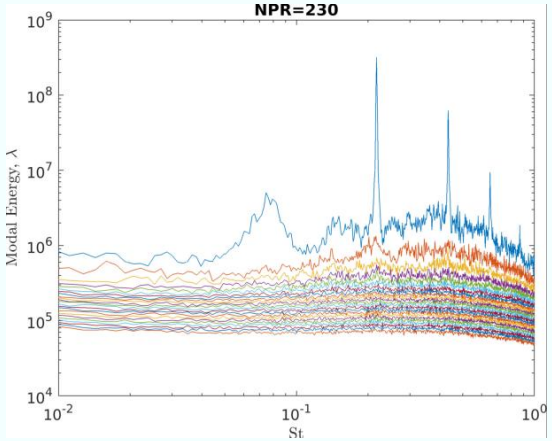
NPR 4.0, 5.0, 6.0 – Steady

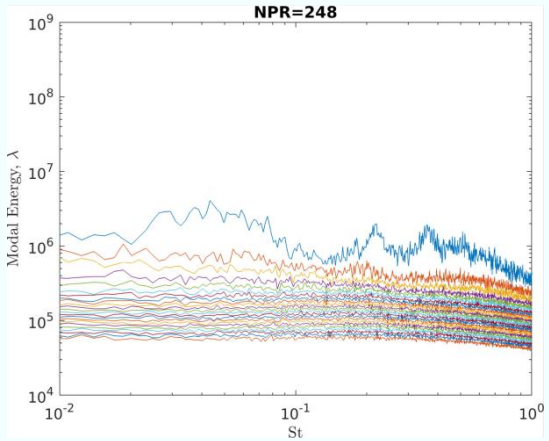


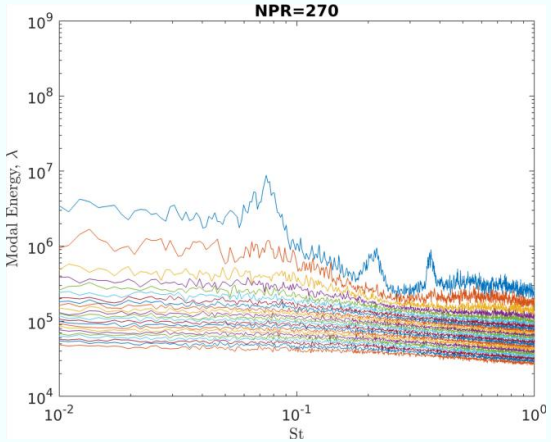
NPR 4.0, 5.0, 6.0 – Steady

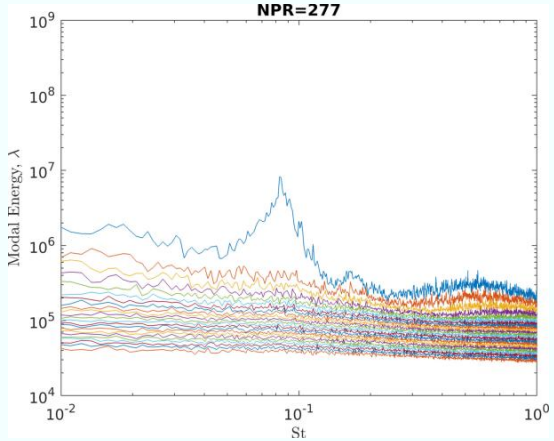


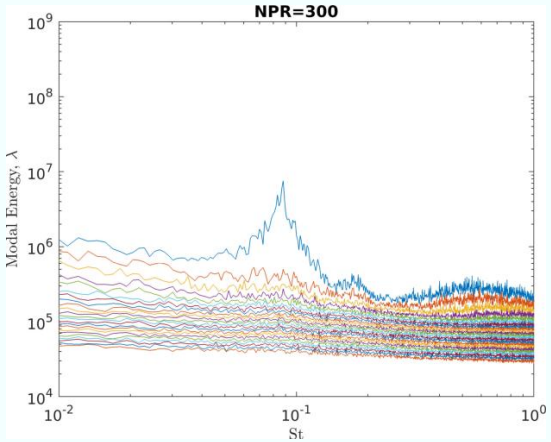
Comparison


NPR=230
Modal Energy, λ
St


NPR=248
Modal Energy, λ
St


NPR=270
Modal Energy, λ
St


NPR=277
Modal Energy, λ
St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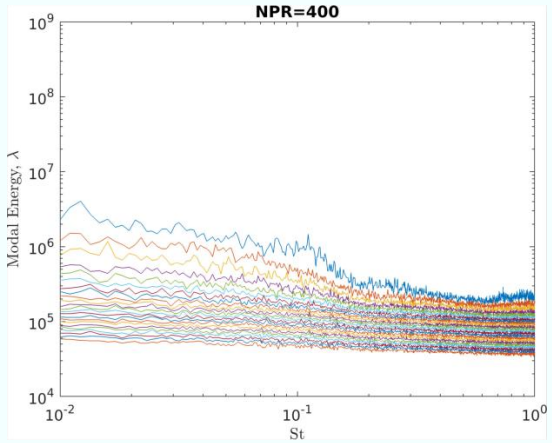
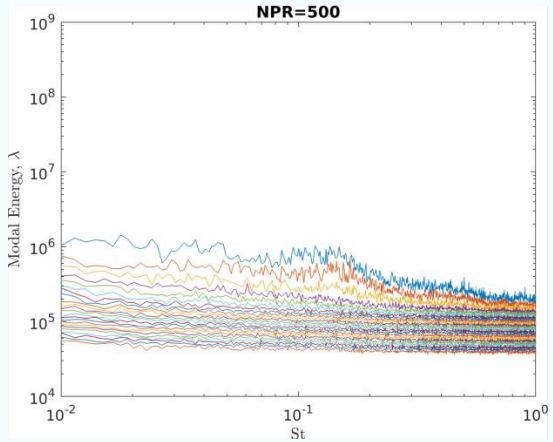
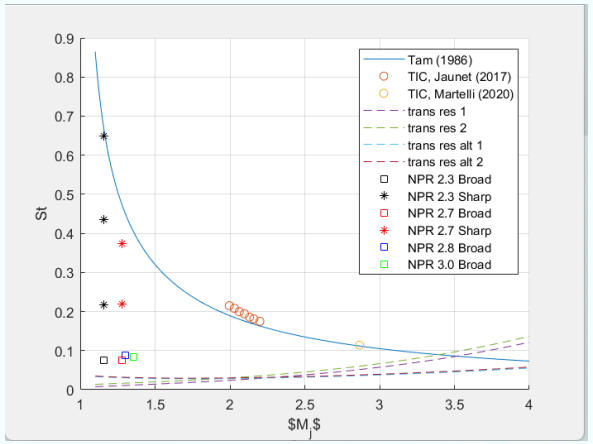
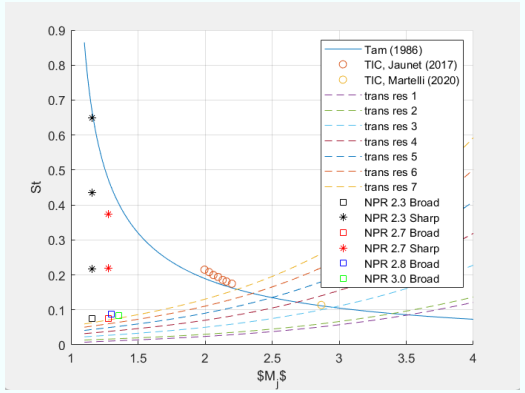
Modal Energy, λ
St

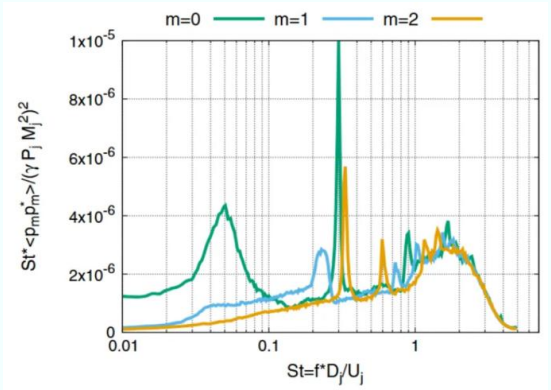

NPR=400
Modal Energy, λ
St

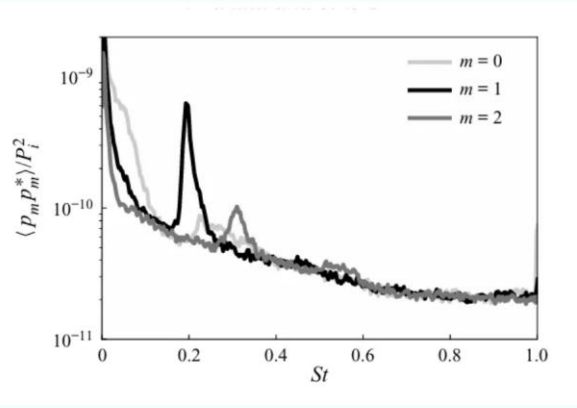

NPR=500
Modal Energy, λ
St

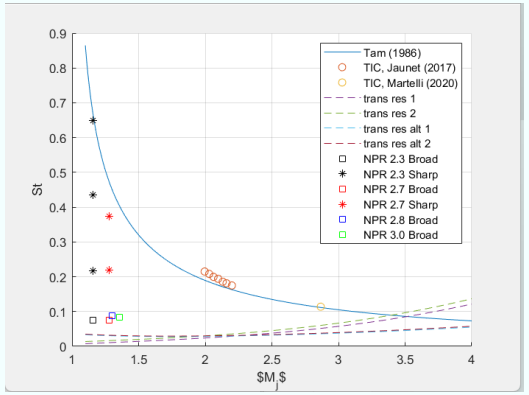

Tam (1986)
TIC, Jaunet (2017)
TIC, Martelli (2020)
trans res 1
trans res 2
trans res alt 1
trans res alt 2
NPR 2.3 Broad
NPR 2.3 Sharp
NPR 2.7 Broad
NPR 2.7 Sharp
NPR 2.8 Broad
NPR 3.0 Broad
St
M_J

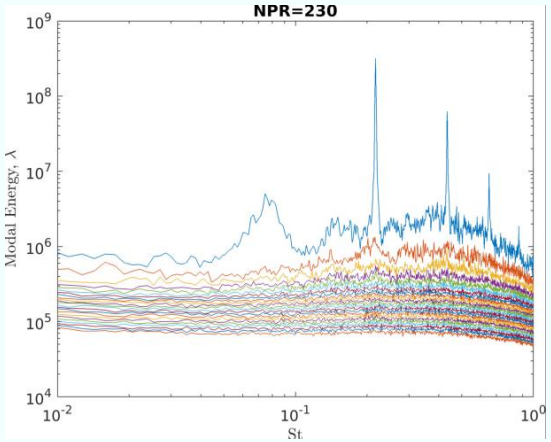
Agreement with prior literature

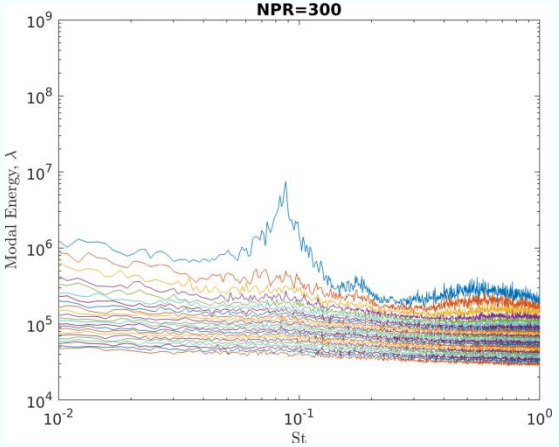










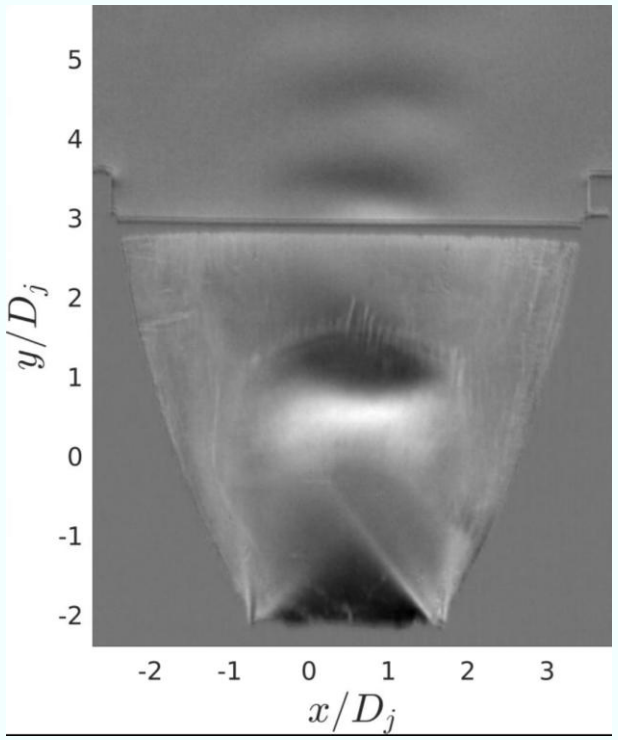


Discussion

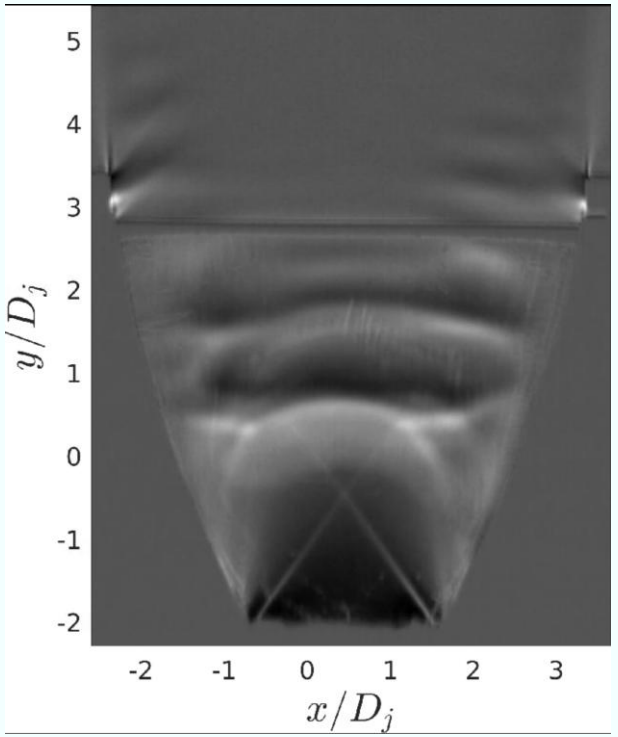
- Sharp peaks appear at low NPR and disappear and higher NPR once attachment occurs
- The broad peak disappears shortly after attachment
- Coanda effect is potentially playing a role in the odd flow that appears
  - The entrainment flow creates a negative pressure which causes attachment to the wall (this is the coanda effect). At low NPR this manifests as the flow bending to one side, potentially, when the flow splits (forks) the two separate flows are immediately attracted to the respective walls and stick when from CFD and prior understanding, they shouldn't. This could cause a stability in the flow since its fully attached and would explain why any tones disappear.

Discussion

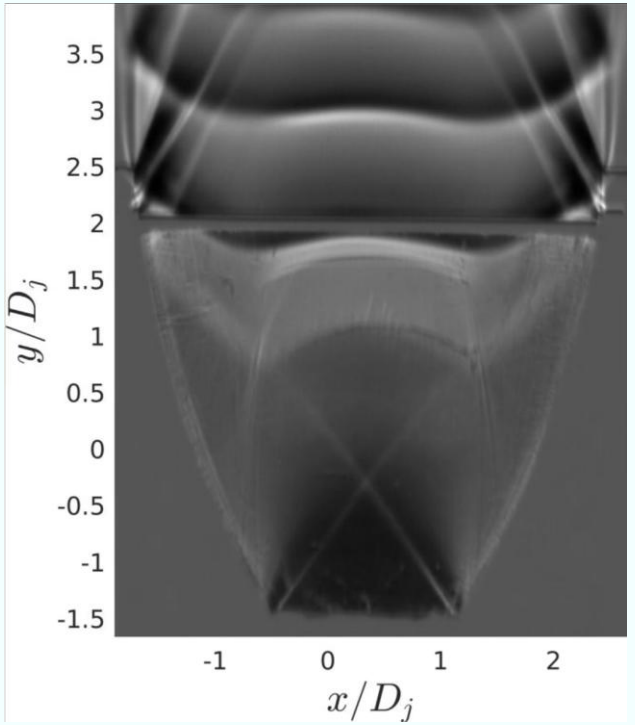
NPR 2.3



NPR 2.77



NPR 6.0



Discussion

- The broad and sharp peaks appear to be linked (the St values are additions of each other).
- Potentially indicated the wobbling of the mach disk (broad peak) is responsible or linked to the screech like peaks (sharp peaks)
- From the NPR 2.3 case at 300 mm, the wobbling of the mach disk has multiple modes.
- Broad peaks could be transonic resonance but don’t fit particularly well with current model, sharp peaks could be screech but not certain since nozzle is planar.
- Might need to linish the lip at the top of the nozzle because it is causing artifacts in the flow, its quite prominent but I actually think its not having an effect on the part of the flow we care about but its definitely worth making sure.

Further research

- Looking at the nozzle at 90 degrees could expose a flapping mode that might be completely invisible and disprove the theory of the flow attaching and causing steadiness.
- Axisymmetric glass nozzle (FYP?) would be useful to see the modes that have already been researched in depth and allow for better conclusions to be drawn
- Square or Octagonal (?) nozzle could be made which might be quasi-circular or at the very least minimise the Coanda effect which might be causing issues
- Re-do the nozzle contour with more aggressive angles and higher area ratio to increase the range at which FSS is expected and to minimise the chance of the flow fully attaching unwantedly

Personal takeaways

- Went from never hearing of FSS or RSS to having a solid base understanding and have learnt a lot about the physics.
- CFD
- Lab experience which I previously haven't had, learnt how to setup and run Schlieren, analyse the flow.
- Learnt about data analysis and how to read and understand SPOD mode shapes, spectra, wavenumber spectrums.
- Started looking at the relationship between the different coherent structures, transonic resonance, screech.
- Would like to further develop SPOD skills and learn it a deeper level, probably developing my own code. Would like to get better at interpreting the data, I know more than I did but I definitely feel like I know 1% of what there is to know

Acknowledgements

- Chi Tran
  - My king
- Dr. Joel Weightman
- A/Prof Daniel Edgington-Mitchell
- Dr. Petronio Nogueria
- Massive M3