3rd Year Project Summary

A new beam-profile monitor for the Large Hadron Collider at CERN

Project: Viscous Flow Analysis for Gas Curtain Formation

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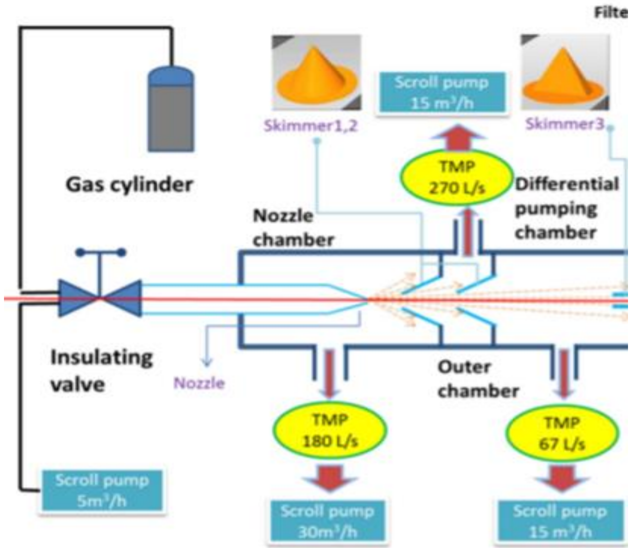
Philippe Rottner

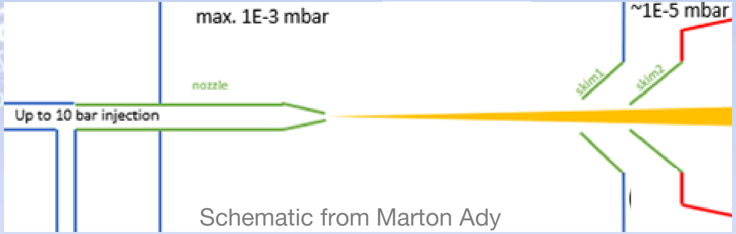
Project Aims and Definition

↦ Collectively our aims are centered around the gas initialization:

- ↳ **Ben** - Compressible flow
- ↳ **Philippe** - Condensation
- ↳ **Matthew** - Gas jet/curtain modelling and optical instrument design

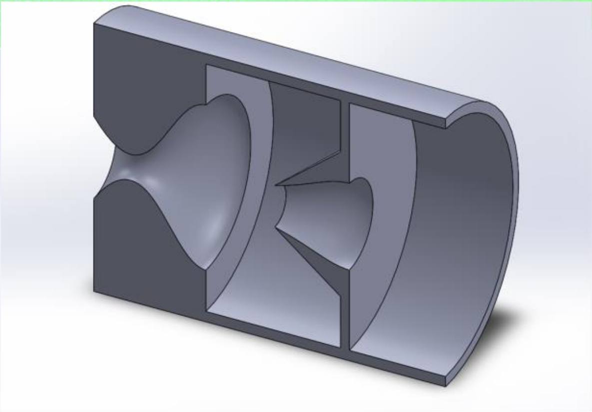


Base diagram: **Schematic of the supersonic gas jet beam profile monitor based on BIF** - H. D. Zhang et al. "A Supersonic Gas-Jet Based Beam Induced Fluorescence Prototype Monitor for Transverse Profile Determination" (2017).



Compressible Flow

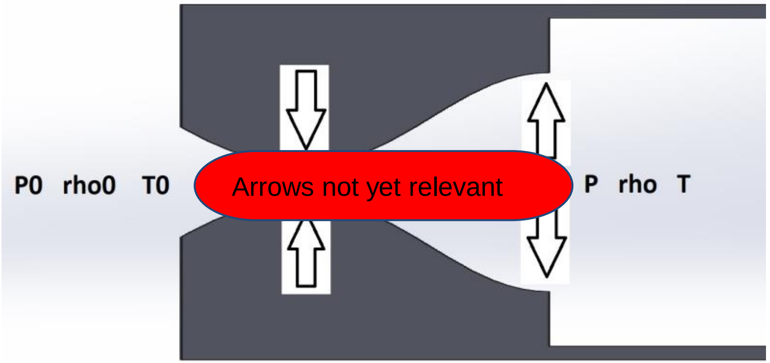
- Relations
- Basic Converging-Diverging (CD) Nozzle
- Design matched CD Nozzle



Compressible Flow: Relations

$$\frac{T_0}{T} = \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{\rho_0}{\rho}\right)^{\gamma-1} = 1 + \frac{\gamma-1}{2}M^2 \qquad (1)$$

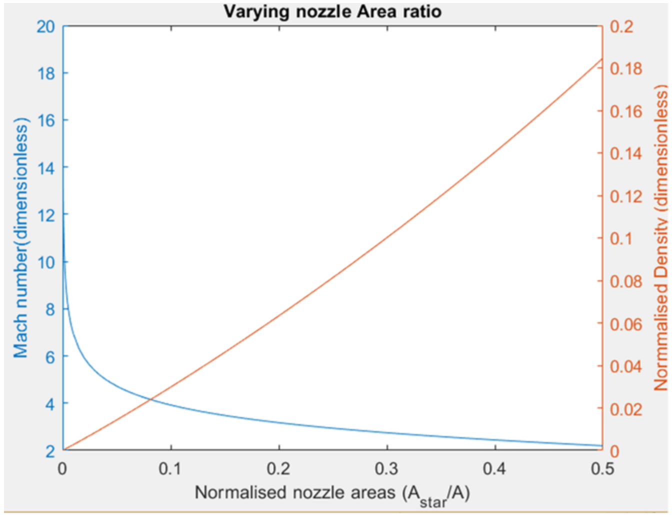
- ↦ The above equation is the basis for idealised compressible flow calculations.
- ↦ Terms and their relevance:
  - ↳ Pressure ratio - predefined and therefore drivers the equation.
  - ↳ Density ratio - output to be minimised.
  - ↳ Mach number - output to be maximised.
  - ↳ Temperature ratio - a constraint.

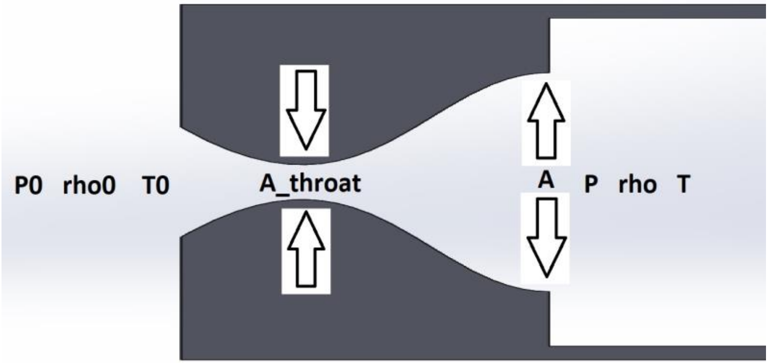


Compressible Flow: Relations

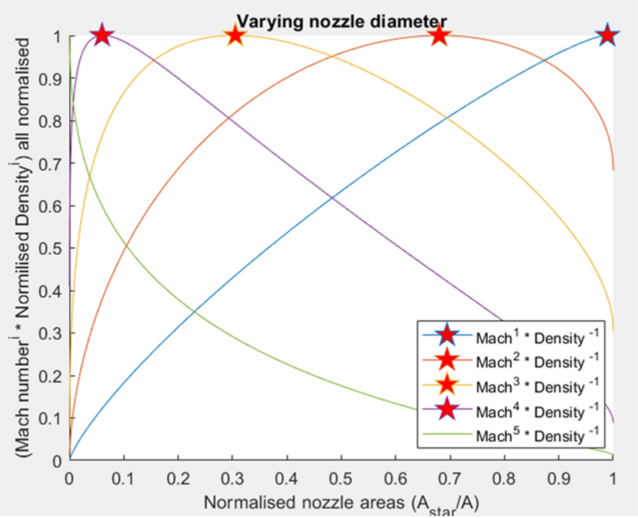
$$\frac{A}{A_t} = \frac{M_1}{M_2}\left(\frac{1+\frac{\gamma-1}{2}{M_2}^{2}}{1+\frac{\gamma-1}{2}{M_1}^{2}}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \qquad (2)$$

- ↦ Converging-Diverging nozzles Area ratio drives the Mach number of the flow.
- ↦ The leads to relations between Area ratio vs. Density ratio and Area ratio vs. Mach no.

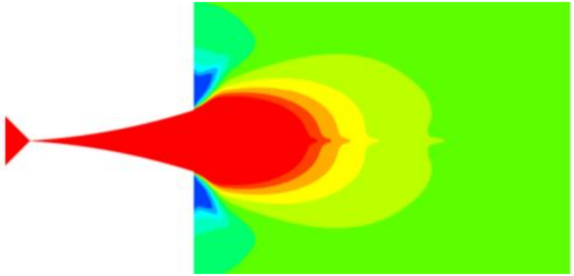




Compressible Flow: Basic Converging-Diverging (CD) Nozzle

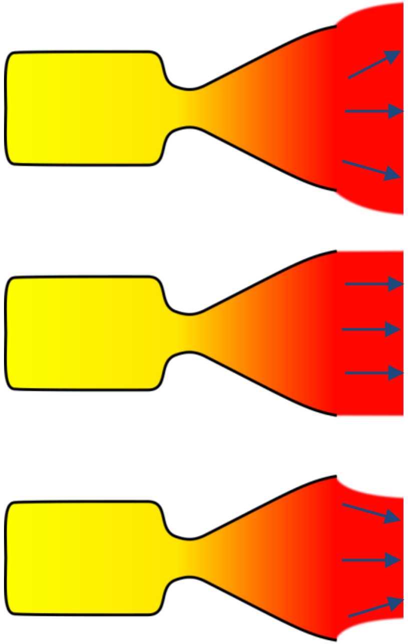


- ↦ An optimal Area ration can therefore be found if the importance of Mach number relative to density is known
- ↦ Draw back
  - ↳ the shape/flow field direction is not factored in



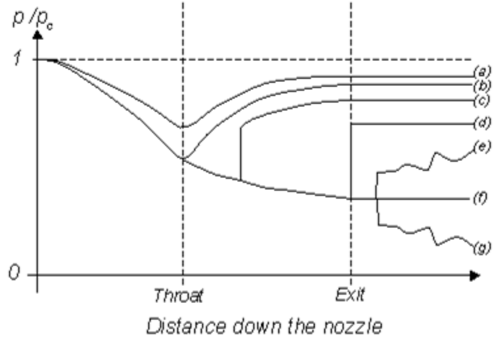
indico.cern.ch/event/712498/contributions/2926528/attachments/1619269/2575222/Nozzle_HighPressure_BGCMeeting_PS.pdf

Compressible Flow: Design matching CD Nozzle



https://en.wikipedia.org/wiki/Rocket_engine_nozzle#/media/File:Rocket_nozzle_expansion.svg

- ↦ Fully developed, non-choked flow falls into three categories:
  - ↳ Over expanded (e)
  - ↳ Design condition (f)
  - ↳ Under expanded (g)



http://www.engappiets.vt.edu/fiuids/CDnozzle/cdinfo.html

- ↦ All nozzles seen in papers are Over expanded
- ↦ Here the aim will be to achieve design condition
  - ↳ This will allow the flow field to be independent of distance between nozzle and skimmer

Compressible Flow: Design matching CD Nozzle (1-Dimensional)

1

P0 = 1e6Pa	P = 0.1Pa

2

M	22.25
rho/rho0	1e-5
P/P0	1e-7
T/T0	1e-2
A/At	26010

↦ Idealised design condition values

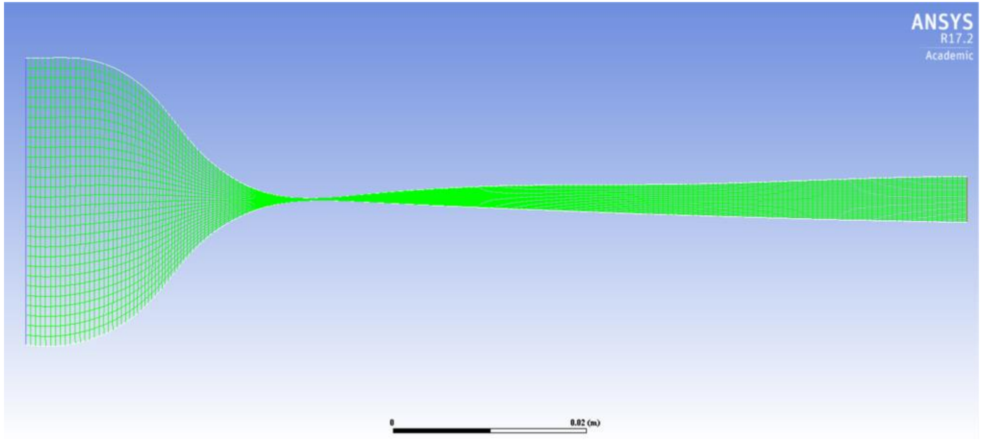
1. The inlet (P0) and outlet/chamber (P) pressure is used to drive the equations
2. Non-dimensional results
3. Dimensionalised results based on initial temperature (T0) and throat diameter (Dt)

3

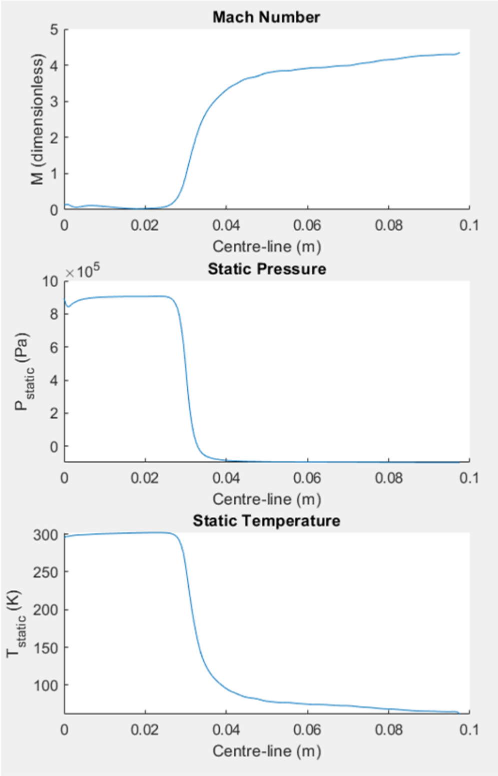
T0 = 300K	**T = 3K**
Dt = 30e-3mm	**De = 4.8mm**

Compressible Flow: Design matching CD Nozzle (ANSYS Fluent Model)

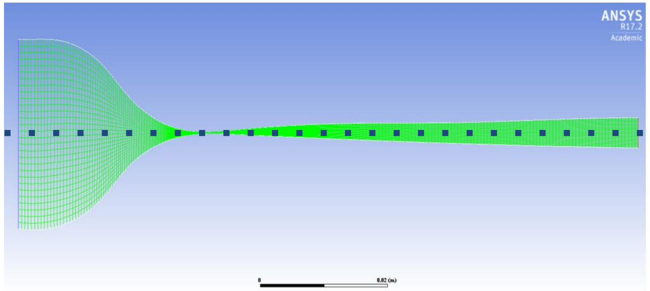
- 2-Dimensional nozzle with with geometry defined by equation 1 & 2
- Length of nozzle = 10 cm to encourage fully developed flow
- Mesh build in ANSYS ICEM, model run in ANSYS FLUENT

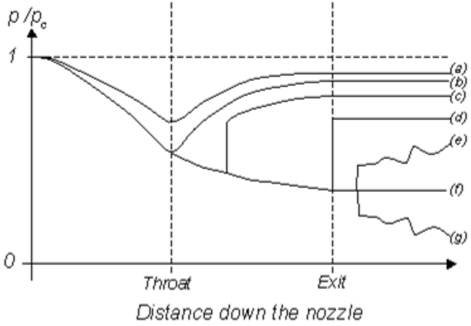


Compressible Flow: Design matching CD Nozzle (ANSYS Fluent Model)



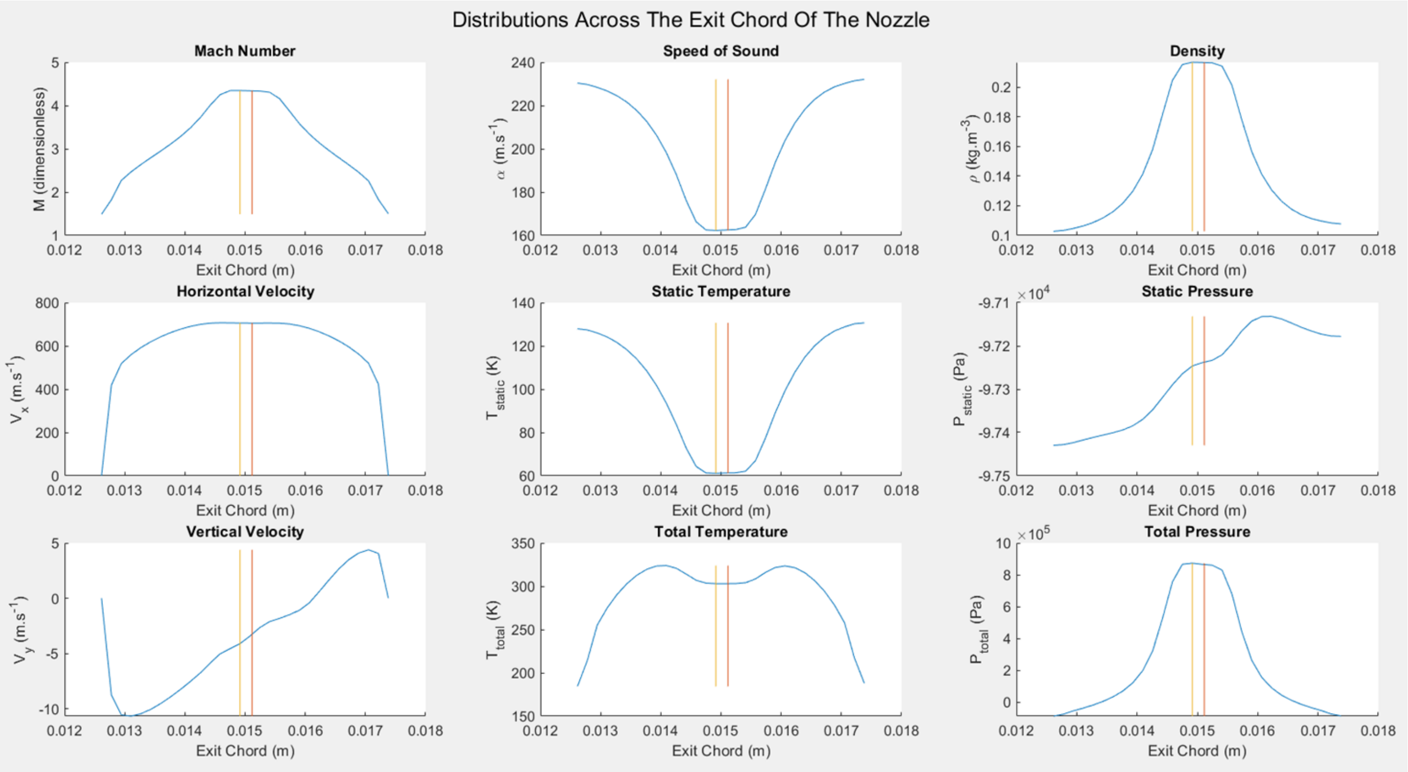
- ↦ Distributions across the centre-line of the nozzle
  - ↳ Shape of static pressure curve indicates design condition being met
  - ↳ Mach number is significantly lower at exit M = 4.3
  - ↳ Cluster formation is a function of static Temperature and Pressure





http://www.engapplets.vt.edu/fluids/CDnozzle/cdinfo.html

Compressible Flow: Design matching CD Nozzle (ANSYS Fluent Model)



Compressible Flow: Possible Further Work

- ↦ Investigate further the boundary at which compressible flow breaks down and molecular flow begins
  - ↳ Knudsen number
- ↦ Model the flow through the first chamber in ANSYS Fluent to validate prediction of parallel streamlines

Condensation

- Phase diagram analysis
- Hypersonic flow considerations

When does condensation occur?

Phase Diagram Analysis:

- ↦ Is pressure and temperature above saturation line as seen in a phase diagram?
- ↦ Condensation only initiated through formation of clusters or nucleation sites

Hypersonic Flows Considerations:

- ↦ Saturation line can be crossed without a change of state
- ↦ Condensation can influence free-stream pressure, velocity and temperature
- ↦ Design of nozzle is a factor due to nozzle expansion effects

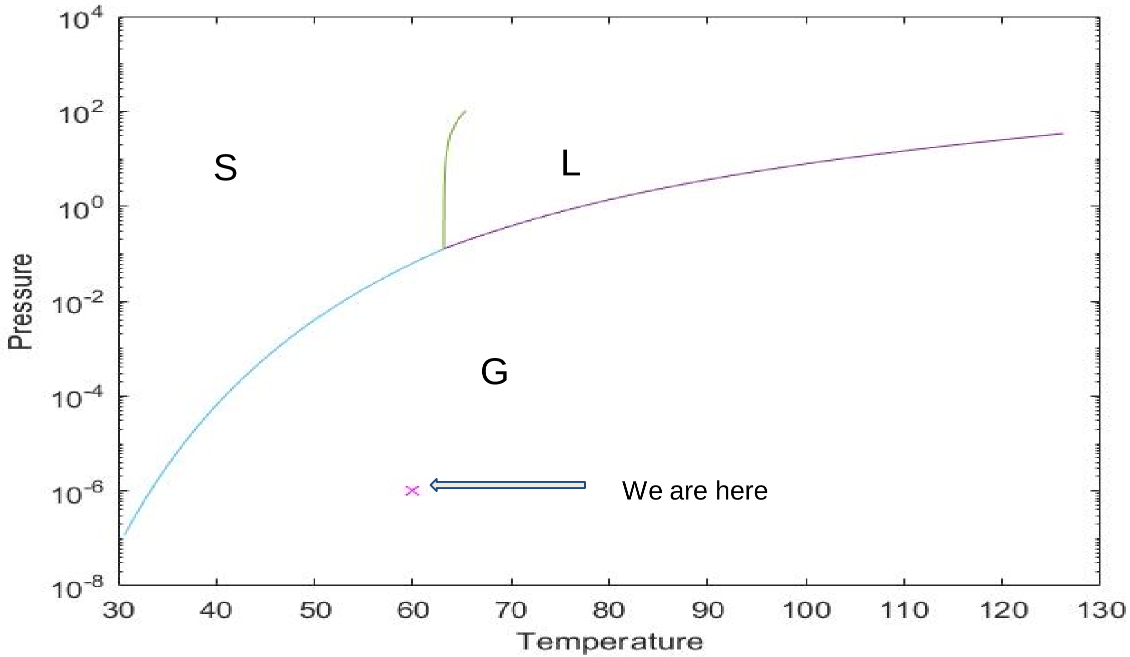
What is a phase diagram?

- ↦ Diagram of Temperature vs Pressure indicates the difference between states
- ↦ Separate regions represent different phases: solid, liquid and gas
- ↦ Saturation line/Phase boundary: denotes where 2 different phases meet
  - ↳ Can be expressed using Clausius-Clapeyron equation:

$$\ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \tag{3}$$

- ↦ Triple point: where unique combination of pressure and temperature means that all three phases are present

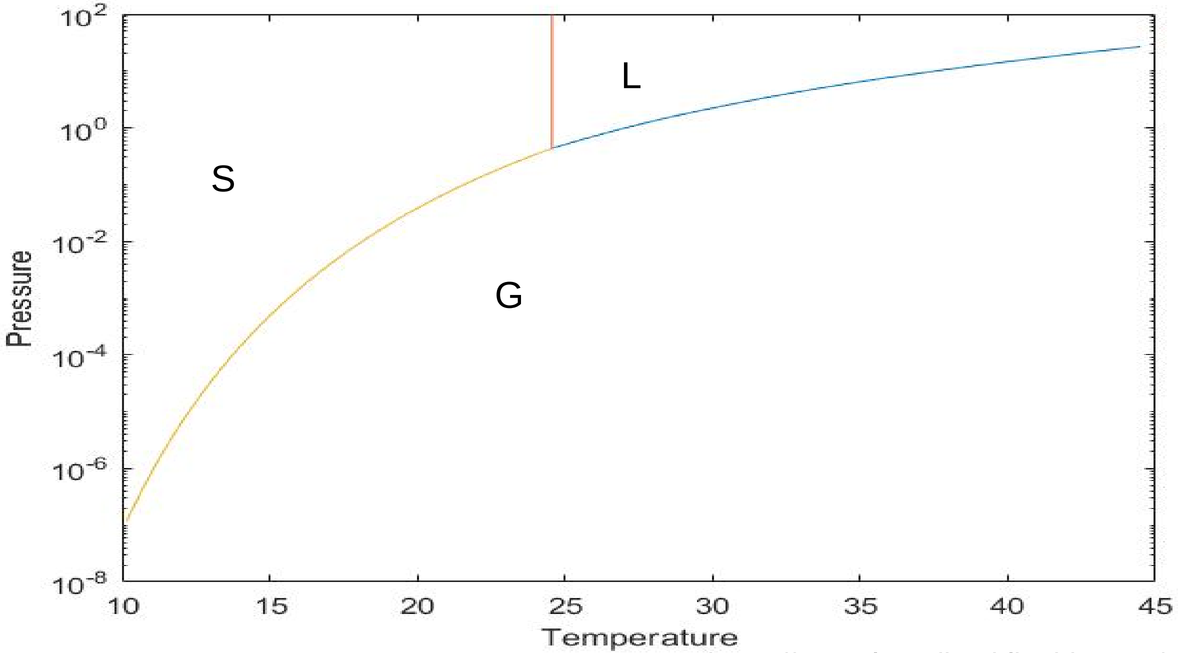
Phase Diagram: Nitrogen



Phase diagram of nitrogen with logarithmic y-axis. Data from https://encyclopedia.airliquide.com/nitrogen

No condensation

Phase Diagram: Neon



No condensation

Phase diagram of neon with logarithmic y-axis. Data from https://encyclopedia.airliquide.com/neon

Is the flow hypersonic?

- ↦ Results from Fluent indicate supersonic flow since M<5
- ↦ Nevertheless hand calculations indicate we may be in hypersonic flow regime

In this case

- ↦ For a fast enough flow expansion some non-equilibrium effects occur such as supercooling
- ↦ Supercooling: gases at temperatures below equilibrium saturation, but no condensation
- ↦ Study by Grossir and Rambaud helps us

Study by Grossir and Rambaud for hypersonic flows

- ↦ All points are places where condensation is detected for different fluids and nozzle shapes - inside solid regions
- ↦ Dashed curve is minimum temperature that can be achieved for condensation-free flows
- ↦ There are points before the saturation line in gas region where condensation occurs BUT, the pressures are too high compared with what we have calculated

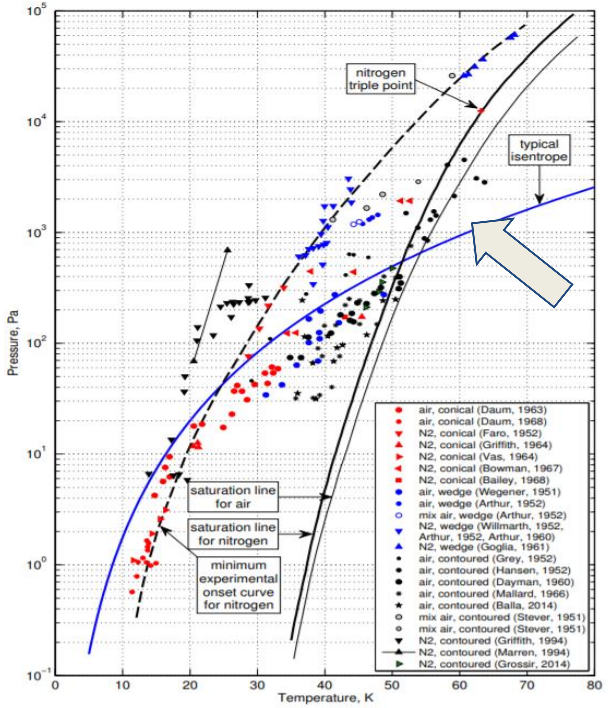
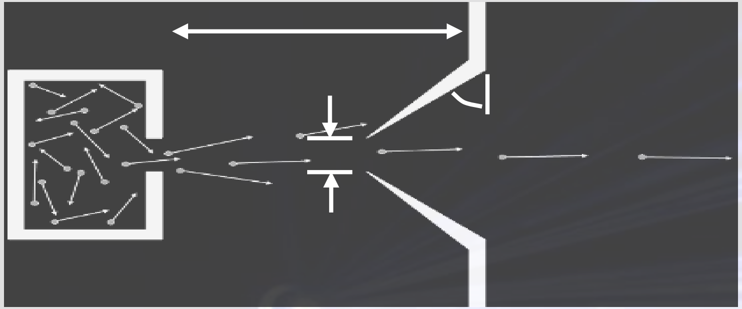
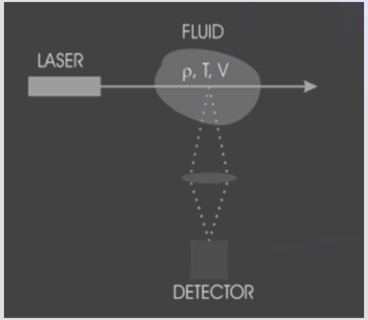


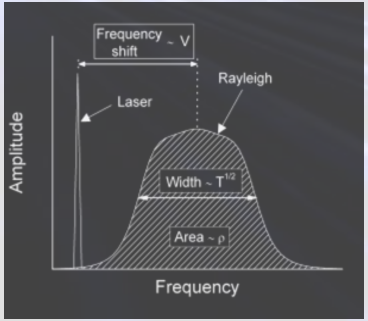
Image: Comparison of air and nitrogen condensation onset. From G Grossir's thesis: URL:https://www.researchgate.net/profile/Guillaume_Grossir/publication/281523360_Longshot_Hypersonic_Wind_Tunnel_Flow_Characterization_and_Boundary_Layer_Stability_Investigations/links/55ec23dd08ae21d099c5f418.pdf



Gas Jet/Curtain Simulation

- Model Description
- Model Results



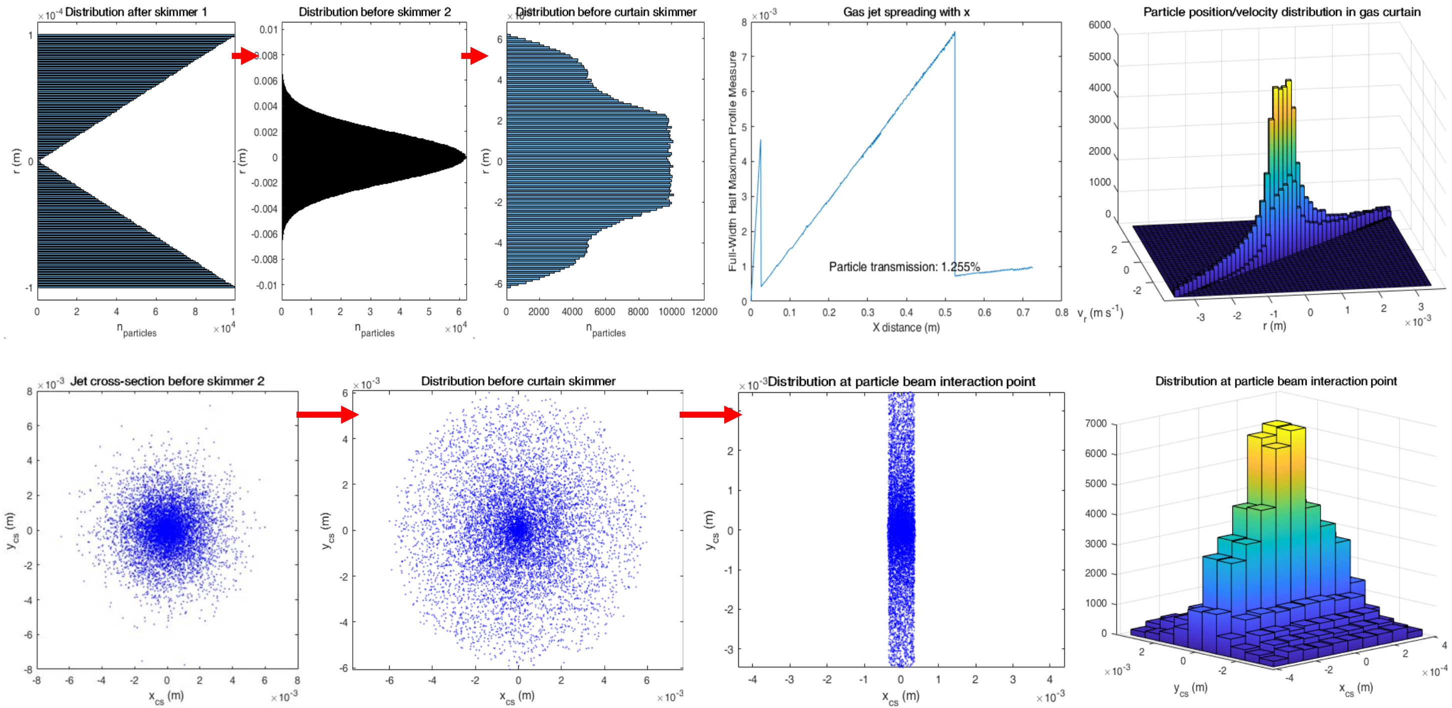


Optical State Measurement

- Scattering Types and Cluster Detection
- Wavelength/Power Optimisation
- Optical Instrument Design
- Performance Analysis

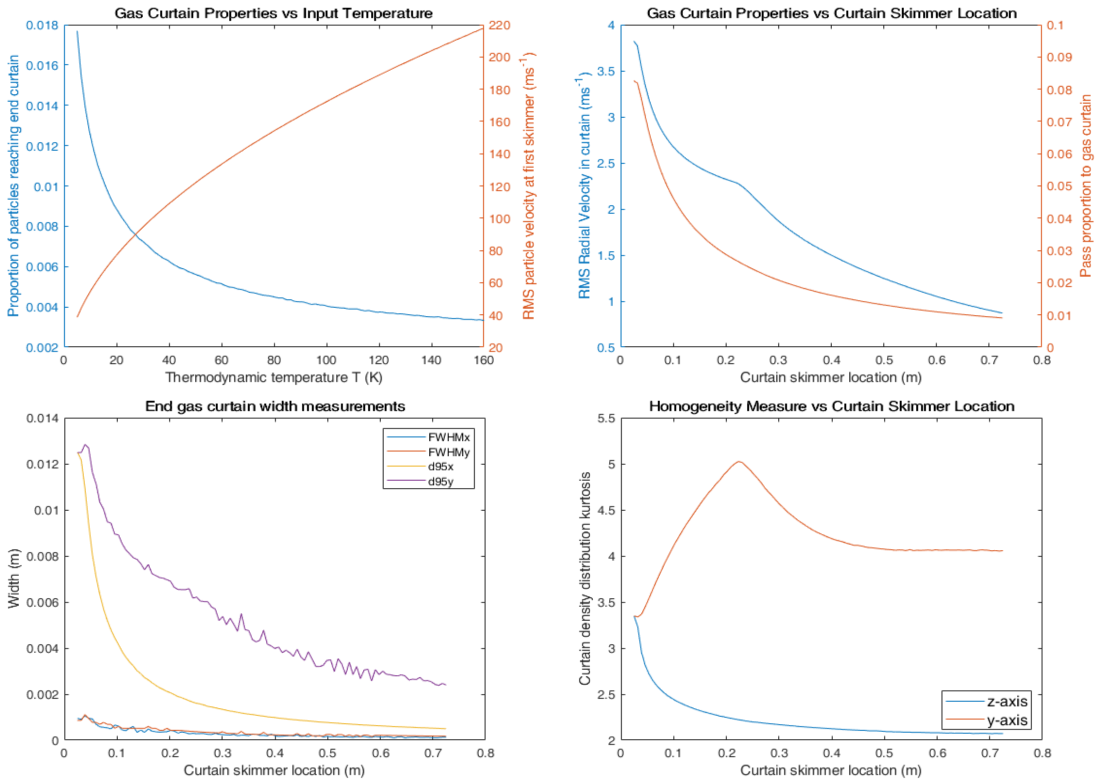
Top: Supersonic jet expansion schematic view, Heriot Watt University. http://dynamics.eps.hw.ac.uk/Molecular_Beams.php
Bottom LHS and RHS: https://www.grc.nasa.gov/WWW/OptInstr/rayleigh.html

Gas Jet/Curtain Simulation: Model Description



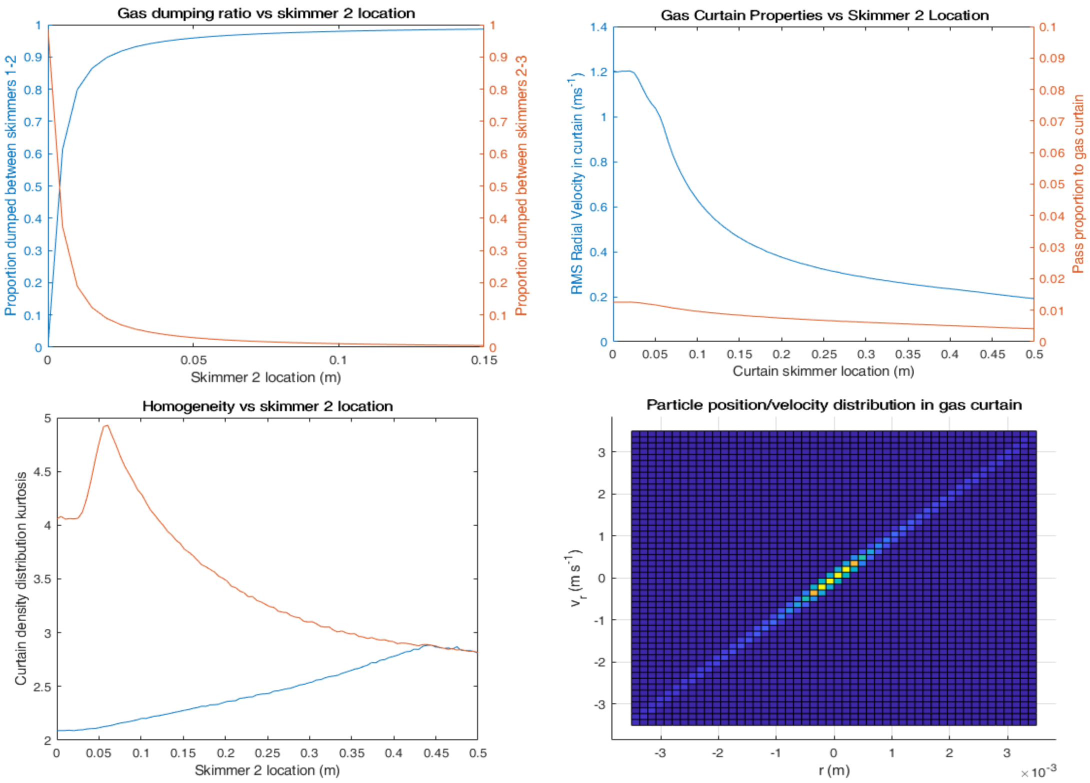
- ↦ Model quantifies gas apparatus design trade-offs.
- ↦ Exploits θ-symmetry and parallel operations on large numbers (>10^7) of particles per simulation run.
- ↦ Multiple runs to produce graphs.

Gas Jet/Curtain Simulation: Results

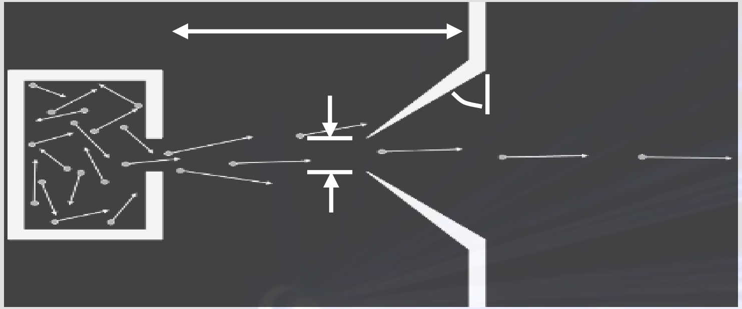


- ↦ Dimensions similar to Cockcroft apparatus, input density/velocity from ANSYS Fluent.
- ↦ Input thermodynamic temperature:
  - ↳ Inverse relationship between input T and gas transmission.
  - ↳ No effect on density homogeneity.
- ↦ End skimmer position:
  - ↳ Sets solid angle ∴ sets pass proportion and velocity dist.
  - ↳ Some effect on homogeneity, but whole density distribution is never very rectangular.

Gas Jet/Curtain Simulation: Results



- ↦ Repositioning second skimmer changes chamber extraction ratio.
- ↦ Gas jet unaffected as long as laser power is kept under ~100W.
- ↦ Ability to predict radial velocity from reading in the gas curtain:
  - ↳ Velocity differences in bulk direction will have the greatest uncertainty contribution.
  - ↳ There may be more complex effects due to particle collisions before skimmer 1.



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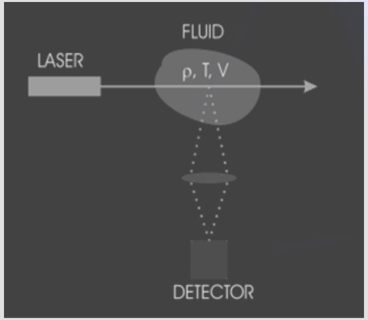

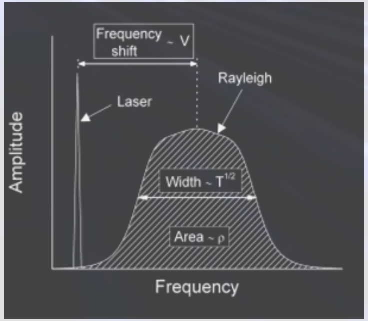

Optical State Measurement

- Scattering Types and Cluster Detection
- Wavelength/Power Optimisation
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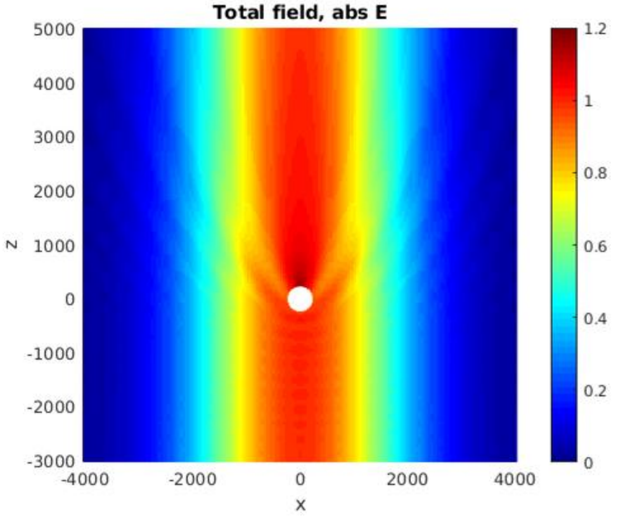
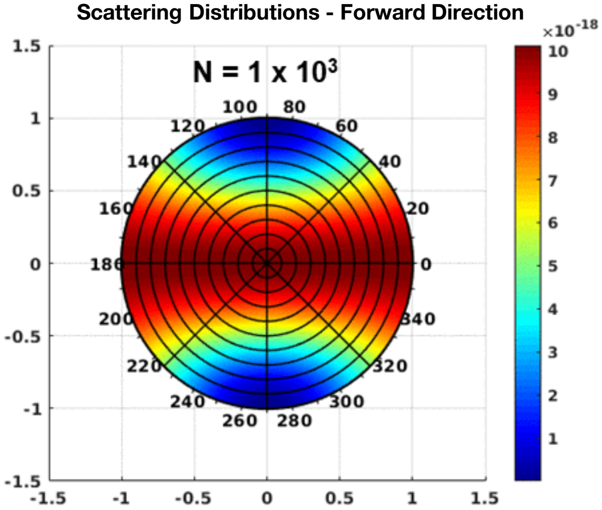
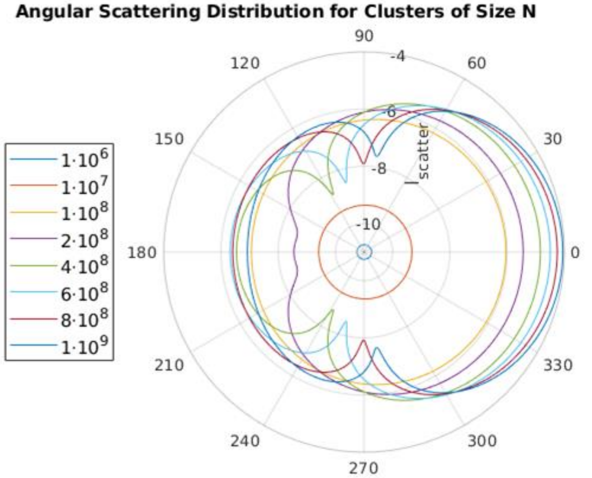
Top: Supersonic jet expansion schematic view, Heriot Watt University. http://dynamics.eps.hw.ac.uk/Molecular_Beams.php
Bottom LHS and RHS: https://www.grc.nasa.gov/WWW/OptInstr/rayleigh.html

Optical State Measurement: Scattering Types and Cluster Detection

- ↦ Rayleigh scattering: from individual molecules and small clusters. Analytic scattering distribution.
- ↦ Mie scattering: from large clusters of molecules. Scattering distribution computationally difficult.







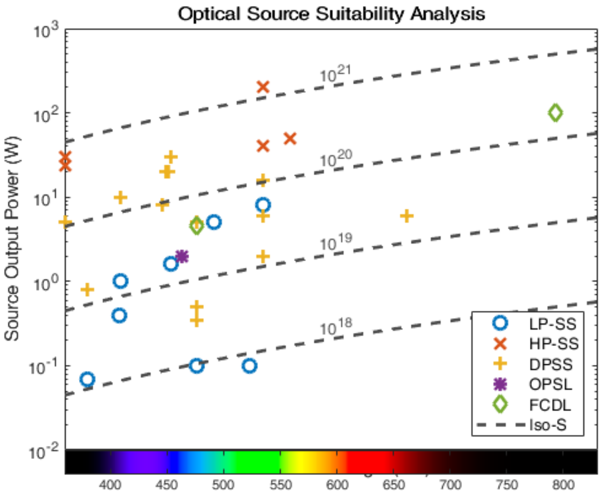
Simulations run with CELES: CUDA-accelerated electromagnetic scattering by large ensembles of spheres. Egel A, Pattelli L, Mazzamuto G, Wiersma DS, and Lemmer U., Journal of Quantitative Spectroscopy and Radiative Transfer 199C (2017) pp. 103-110.

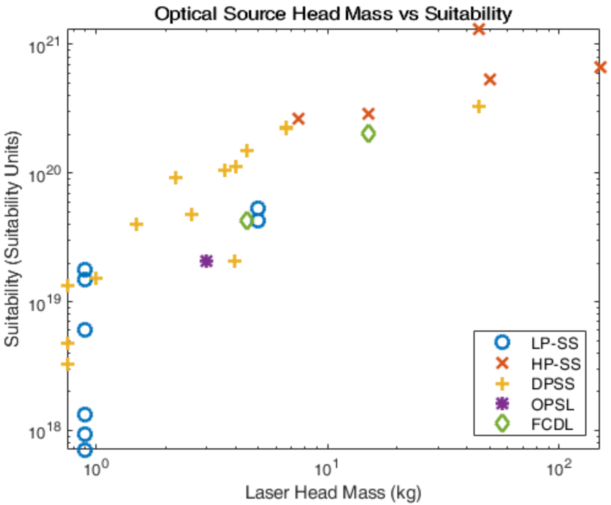
Optical State Measurement: Wavelength / Power Optimisation

↦ Maximising the number of detected scattered photons minimises measurement uncertainty.

$$\frac{\sigma(\rho)}{\rho} = \left(\frac{1}{\langle N_R \rangle}\right)^{\frac{1}{2}} \qquad \langle N_R \rangle = \varepsilon \cdot \frac{P_0 \lambda}{hc} \cdot n L_x \cdot \sin^2 \beta \left(\frac{d\sigma}{d\Omega}\right) \Omega \qquad \left(\frac{\partial \sigma}{\partial \Omega}\right)_j = \frac{4\pi^2 (n_j - 1)^2}{N_0^2 \lambda^4} \rightarrow S = P_0 \lambda^{-3} \quad (5)$$

↦ N_2 absorption is negligible above ~350nm.





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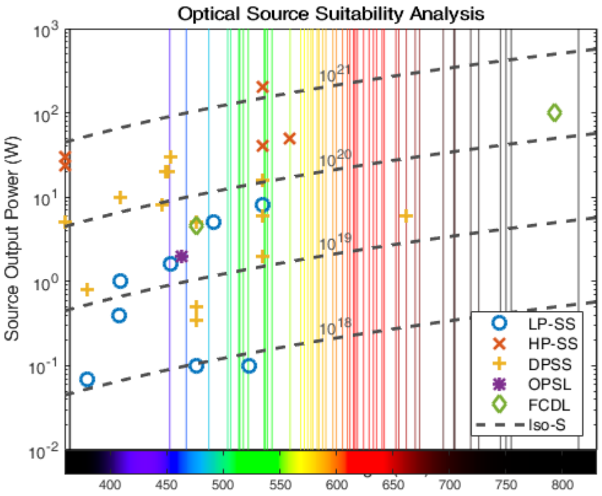
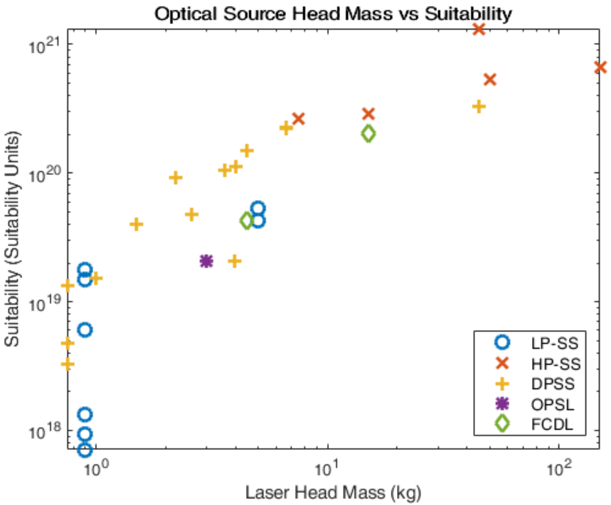
↦ Ne absorption lines occur across the spectrum.

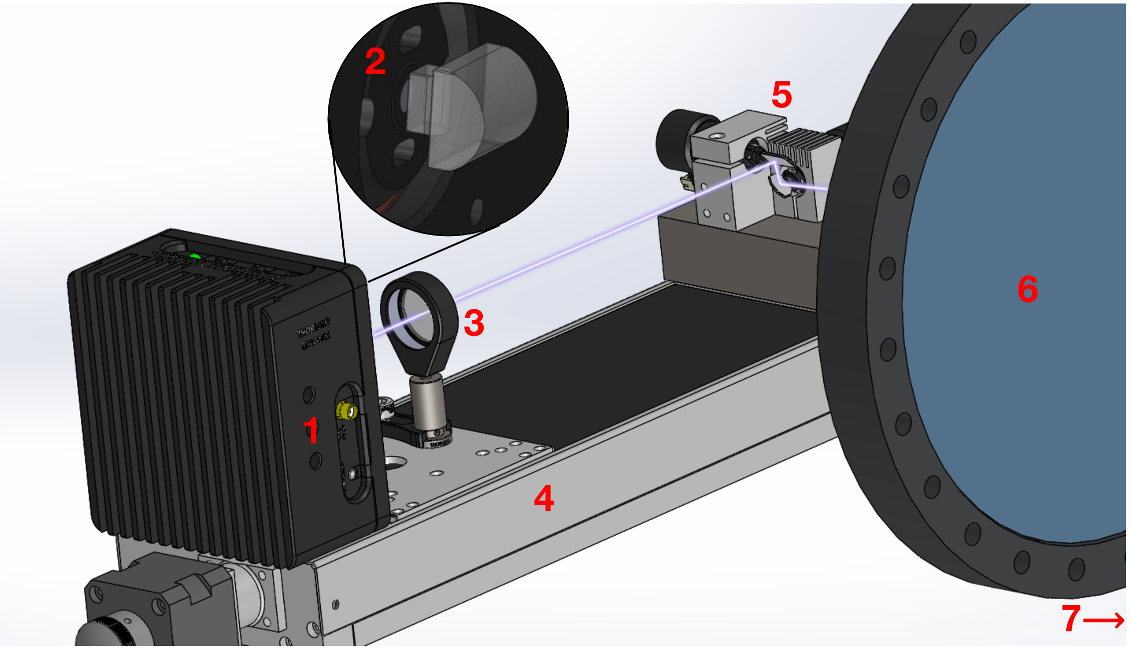




Ne absorption spectrum information:
NIST Atomic Spectra Database (v5.6.1)
https://physics.nist.gov/asd

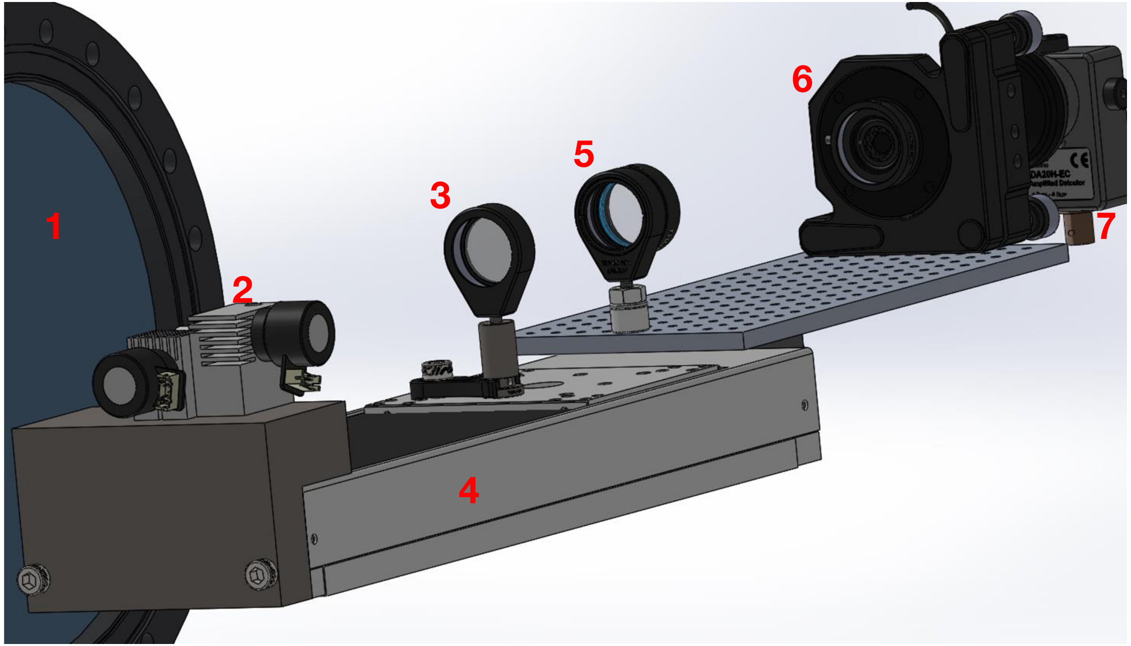
Optical State Measurement: Optical Instrument Design, Laser Side

1. 405nm 1200mW laser diode in temperature controlled mount.
2. 2x cylindrical lens beam collimator for 3mm diameter.
3. Beam focus lens, *f=300.0mm.*
4. Translation stage, 0-150mm.
5. Laser steering 2-axis mirror galvanometer.
6. Gas apparatus laser-in viewport.
7. Class-4 beam dump.



Optical State Measurement: Optical Instrument Design, Receiver Side

1. Gas apparatus scattering-out viewport.
2. FoV steering 2-axis mirror galvanometer.
3. FoV focus lens, *f=300.0mm.*
4. Translation stage, 0-150mm.
5. FPI alignment lens, *f=200.0mm.*
6. Scanning Fabry-Perot interferometer, 350-450nm.
7. Amplified / Avalanche Photodetector.



Optical State Measurement: Performance Analysis

- **Core:** Velocity(±5%), Density (±5%), Temperature (±5K)
  - 4s sample time with 1mm^3 resolution - 4s per mm^3
  - 40s sample time with (0.1mm)^3 - 40000s per mm^3
  - Scanning Fabry-Perot interferometer would increase by a factor dependent on fabry-perot resolution/finesse.
- These figures can be improved by a factor of 10-100 with more in-depth optical design to increase the solid angle of detection.
- Measurement with Mie scattering-based cluster measurement:
  - Multiple measurement points required - at least 2.
  - Solving matrix equation with non-negative least squares.

$$x = \frac{2\pi r n}{\lambda} \tag{6}$$

$$I(\theta) = F(\theta, x) q(x) \tag{7}$$

$$F(\theta, x) = \theta \updownarrow \overset{\longleftarrow\; x \;\longrightarrow}{\begin{bmatrix} A & \cdots & B \\ \vdots & \ddots & \vdots \\ C & \cdots & D \end{bmatrix}}$$

$$q = (F^{\mathrm{T}} W F + \gamma E)^{-1} F^{\mathrm{T}} W I. \tag{8}$$

Optical State Measurement

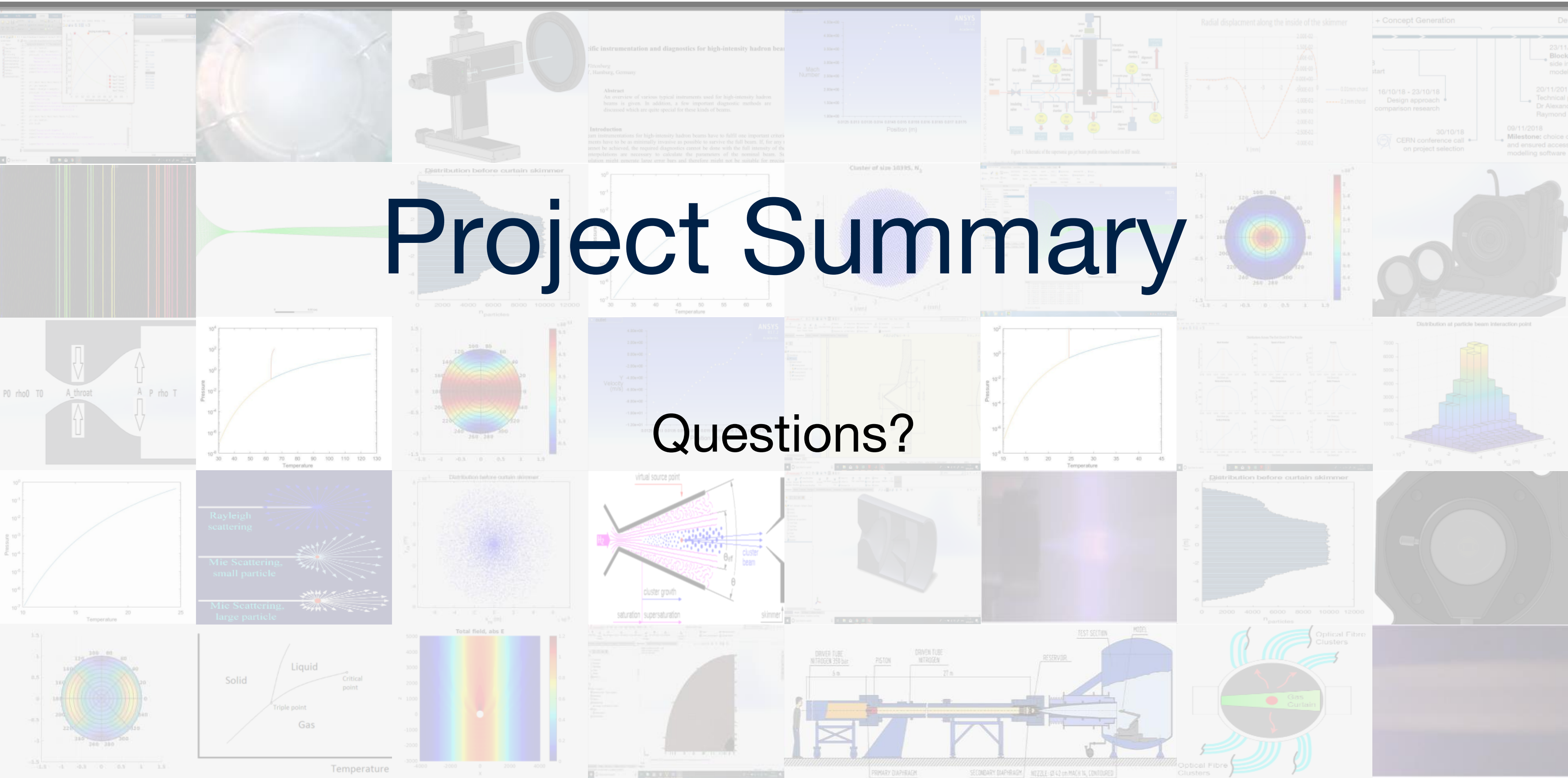
Collider*-scope

*Cannot actually measure the collider itself, just the gas jet and curtain.

Optical State Measurement: Possible Future Work

- ↦ In-depth optical design taking into account available equipment, exact apparatus dimensions and the measurement areas of highest interest.
- ↦ Gather more cluster scatter simulation data - more combinations of angles and particle sizes.
  - ↳ Ideally >100 cluster sizes ($10^6 \sim 10^9$) - 100 runs.
  - ↳ Distribution of molecules in cluster - more in-depth than simple cubic packing.
- ↦ Build and run experimental setup to verify computer models.

Project Summary



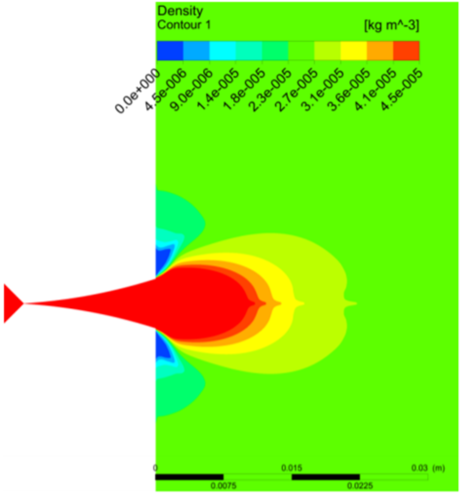
Questions?

Appendix I: Przemysław Smakulski's data

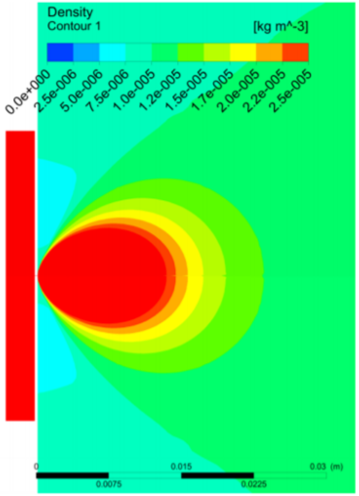
Density Profile – comparison of the nozzle design

nozzle throat 30 μm

De Laval



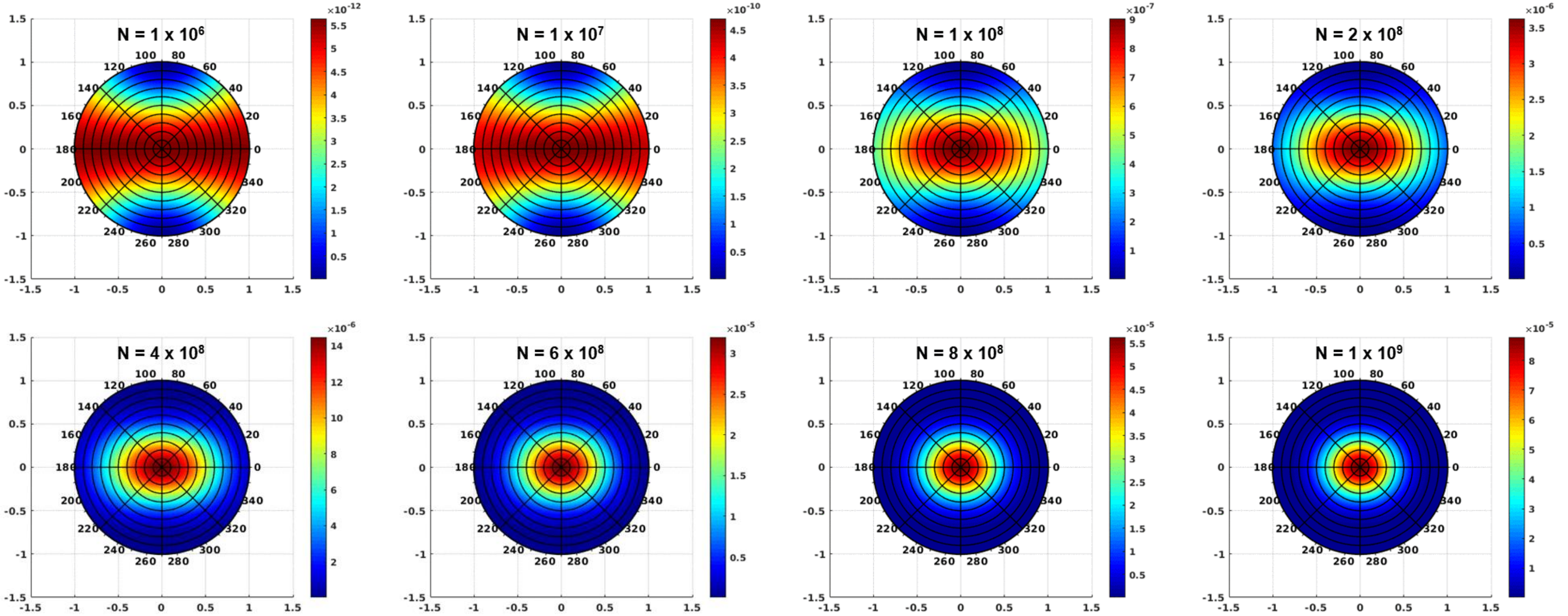
Simple Geometry



Taking into consideration the same boundary conditions, the de Laval (convergent-divergent) nozzle shows higher density profile, which is around 2 times higher in comparison to simple geometry nozzle.

indico.cern.ch/event/712498/contributions/2926528/attachments/1619269/2575222/Nozzle_HighPressure_BGCMeeting_PS.pdf

Appendix II: Scattering Distribution Graphs



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Appendix III: Study by Grossir and Rambaud

- ↦ Demonstrates condensation detection for different expansion rates
- ↦ Expansion rates given by:

$$\dot{P} = -\frac{dp/dt}{p} = -\frac{dp/dx}{p/u}. \qquad (4)$$

- ↦ Conical nozzles with high expansion rates experience less supercooling that contoured nozzles

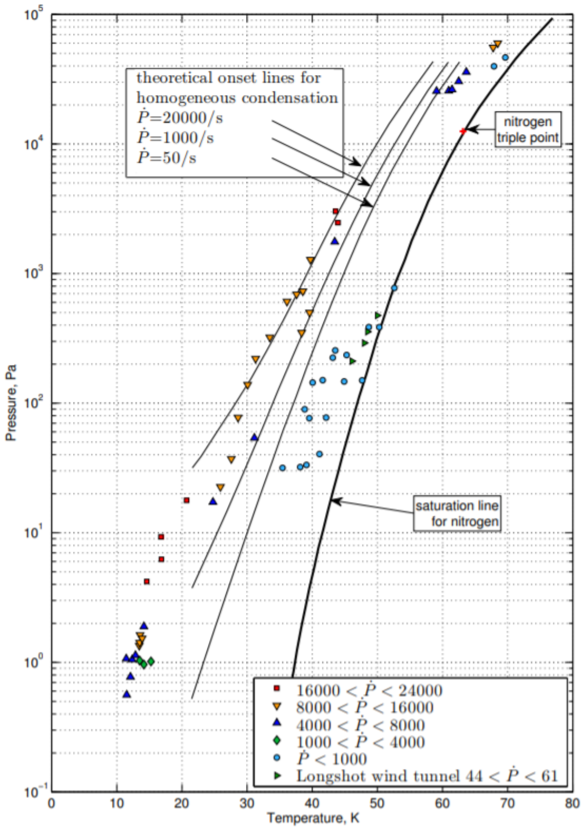

Image: Expansion rate effects on condensation. From G Grossir's thesis: URL:https://www.researchgate.net/profile/Guillaume_Grossir/publication/281523360_Longshot_Hypersonic_Wind_Tunnel_Flow_Characterization_and_Boundary_Layer_Stability_Investigations/links/55ec23dd08ae21d099c5f418.pdf