Numerical Analysis of Vacuum Vessel Pressurisation in ITER Fusion Reactor

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Numerical Flow Models for Controlled Fusion

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Context of the study

- Numerical analysis of dust transport behaviour in Vacuum Vessel of a fusion reactor in case of Loss Of VAcuum event (LOVA)
- The simulation of LOVA scenario is a challenging task for today numerical methods and models:
  - ✔ Three dimensional geometry with large dimensions
  - ✔ Required computational ressources only available on large parallel platforms
  - ✔ Computing near vacuum flows ranging from highly supersonic to nearly incompressible
- Objective of the present work:
  - ✔ Presentation of basics numerical methods
  - ✔ Preliminary computations using parallel solutions

Outline of the presentation

1. The dusty Gas Model
    - Assumptions
    - Equations for the gas phase
    - Equations for the dust phase
    - Interactions terms
2. Treatment of the vacuum for the gas phase
    - What is vacuum?
    - The Riemann problem in presence of vacuum
    - Numerical results
3. Numerical scheme for the dust phase
    - The Riemann problem
    - A Godunov type scheme
    - Numerical experiments
4. Numerical results using the dusty gas model
    - Saito shock tube
    - Preliminary calculation of the VV pressurisation

Conclusions and Prospects

The Dusty-Gas Model

1. Assumptions

- High dilute and gas mixture

$$\alpha_d = \text{ Volumic fraction of the dust phase}$$

$$\alpha_g = \text{ Volumic fraction of the gas phase}$$

$$\alpha_d \ll \alpha_g \qquad \text{and} \qquad \alpha_g \approx 1$$

- This model leads to simplifications
  - Standard Euler equations can be considered for the gas phase
  - The solid phase can be modelled using pressureless gas equations

The Dusty-Gas Model

2. Euler equations for the Gas phase

$$\frac{\partial \rho_g}{\partial t} + \vec{\nabla} \cdot (\rho_g \cdot \vec{u}_g) = 0$$

$$\frac{\partial \rho_g \cdot \vec{u}_g}{\partial t} + \vec{\nabla} \cdot (\rho_g \vec{u}_g \otimes \vec{u}_g + p) = \rho_g \cdot \vec{g} + \vec{F}_{dg}$$

$$\frac{\partial \rho_g E_g}{\partial t} + \vec{\nabla} \cdot (\rho_g \vec{u}_g H_g) = \rho_g \vec{u}_g \cdot \vec{g} + \vec{F}_{dg} \cdot \vec{u}_g + Q_g$$

- These equations can be solved independently from the dust equations except for the interation terms detailed further.
- The treatment of the vacuum problem will lead us to a specific numerical scheme

The Dusty-Gas Model

3. The equations for the dust phase

$$\frac{\partial \sigma}{\partial t} + \vec{\nabla} \cdot (\sigma \cdot \vec{u}_d) = 0$$

$$\frac{\partial \sigma \cdot \vec{u}_d}{\partial t} + \vec{\nabla} \cdot (\sigma \, \vec{u}_d \otimes \vec{u}_d) = \sigma \cdot \vec{g} - \vec{F}_{dg}$$

$$\frac{\partial \sigma E_d}{\partial t} + \vec{\nabla} \cdot (\sigma \, \vec{u}_d E_d) = \sigma \, \vec{u}_d \cdot \vec{g} - \vec{F}_{dg} \cdot \vec{u}_d - Q_g$$

- where σ denotes the particle concentration.
- This system corresponds to the so-called pressureless gas equations in which the collisions between particles are neglected
- Dust system is degenerately hyperbolic with one multiple eigenvalue
- The Jacobian matrix is a Jordan block not diagonalizable
- Special properties such as the delta-shock waves

The Dusty-Gas Model

4. The interaction terms

- Hard to define in an unique way because case dependant
- Main actions of the gas on the particles
  - The drag force

$$\vec{D} = \rho_g C_D \cdot \frac{\pi d_p^2}{8} \cdot (\vec{u}_g - \vec{u}_d) \| \vec{u}_g - \vec{u}_d \|$$

  - The lift force (usually neglected)

- Heat transfert

$$Q = \pi d_p \frac{\mu C_p}{Pr} (T_g - T_d) Nu$$

Outline of the presentation

1. The dusty Gas Model

2. Treatment of the vacuum for the gas phase
   - What is vacuum?
   - The Riemann problem in presence of vacuum
   - Numerical results

3. Numerical scheme for the dust phase

4. Simulation of the pressurisation of the VV

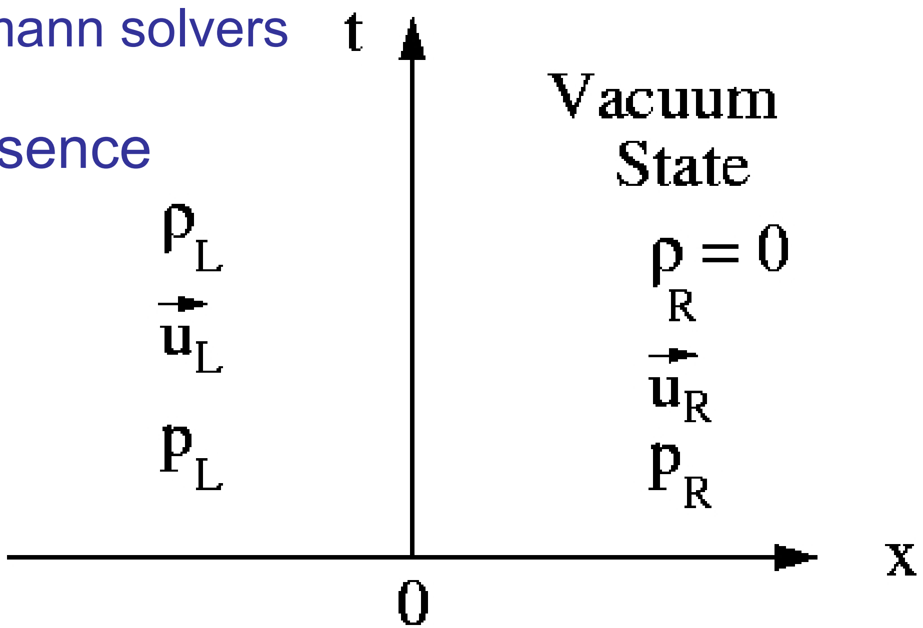
Conclusions

Treatment of the vacuum

1. Definition of the vacuum state

- Vacuum $\Leftrightarrow \rho_g = 0 \Rightarrow \rho_g E_g = 0$
- The continum assumption is no longer valid
- Necessity to adapt the Riemann solvers

2. The Riemann problem in presence of vacuum



Treatment of the vacuum

2. The Riemann problem in presence of vacuum

- A shock wave cannot be adjacent to a vacuum region
  - Proof: application of the Rankine-Hugoniot conditions

$$\rho_L u_L - \rho_R u_R = S(\rho_L - \rho_R)$$

$$\rho_L u_L^2 - \rho_R u_R^2 = S(\rho_L u_L - \rho_R u_R)$$

$$u_L(\rho_L E_L + p_L) - u_R(\rho_R E_R + p_R) = S(\rho_L E_L - \rho_R E_R)$$

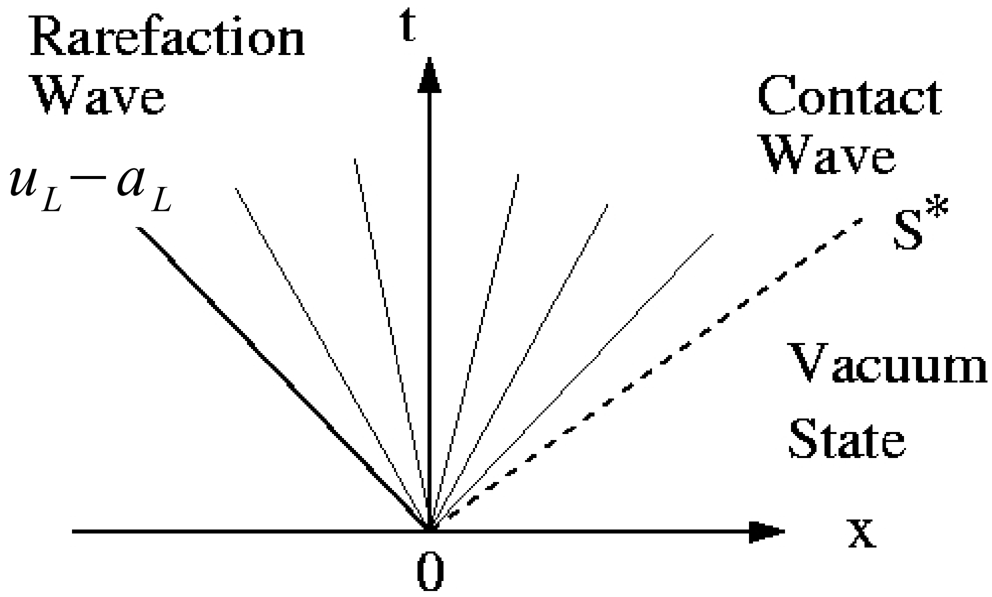
$$\left[\begin{array}{r} \rho_R = 0 \\ \rho_R E_R = 0 \end{array}\right. \Rightarrow \left[\begin{array}{l} u_L = u_R = S \\ p_L = p_R \end{array}\right. \Rightarrow \text{No shock wave}$$

- A contact discontinuity can be adjacent to the vacuum aera

Treatment of the vacuum

2. The Riemann problem in presence of vacuum

- As the gas particles fill the vacuum region, the pressure decreases behind them. The tail of the rarefaction wave thus coalesces with the contact wave.



Treatment of the vacuum

2. The Riemann problem in presence of vacuum

- The speed of the contact wave is then given by the left Riemann Invariant:

$$S^* = u_L + \frac{2 a_L}{\gamma - 1}$$

- The complete solution reads:

$$W(x,t) = \begin{cases} W_L & \text{if} \quad x/t < u_L - a_L \\ W_{Fan} & \text{if} \quad u_L - a_L < x/t < S^* \\ W_{Vac} & \text{if} \quad x/t > S^* \end{cases}$$

- An exact Godunov solver has been designed to deal with the vacuum case

Treatment of the vacuum

2. The Riemann problem in presence of vacuum

- When left state is at rest $u_L = 0$
  - A direct calculation of the Mach number yields:

$$M^2 = \left(\frac{a_L + x/t}{a_L - \frac{\gamma - 1}{2} \cdot x/t} \right)^2$$

  - For the air, the Mach number is greater than unity in the region originally at vacuum state

$$M^2 \geqslant 1 \iff x \geqslant 0$$

  - Mach number increases with the distance from the original separation

Treatment of the vacuum

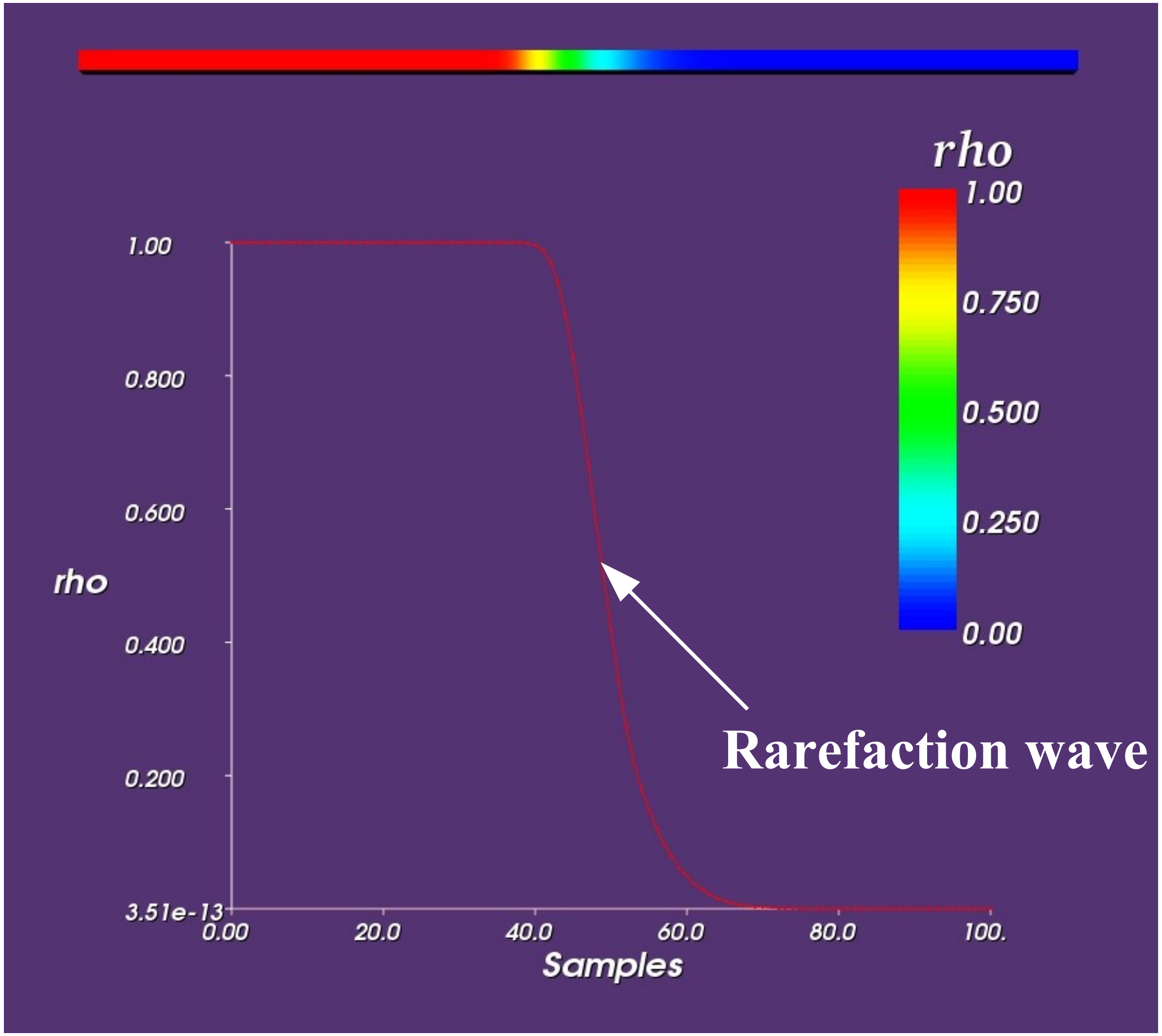
3. Numerical results

- Implementation of the designed Godunov scheme into the parallel code NUM3SIS
- Shock tube problem
  - Initial data

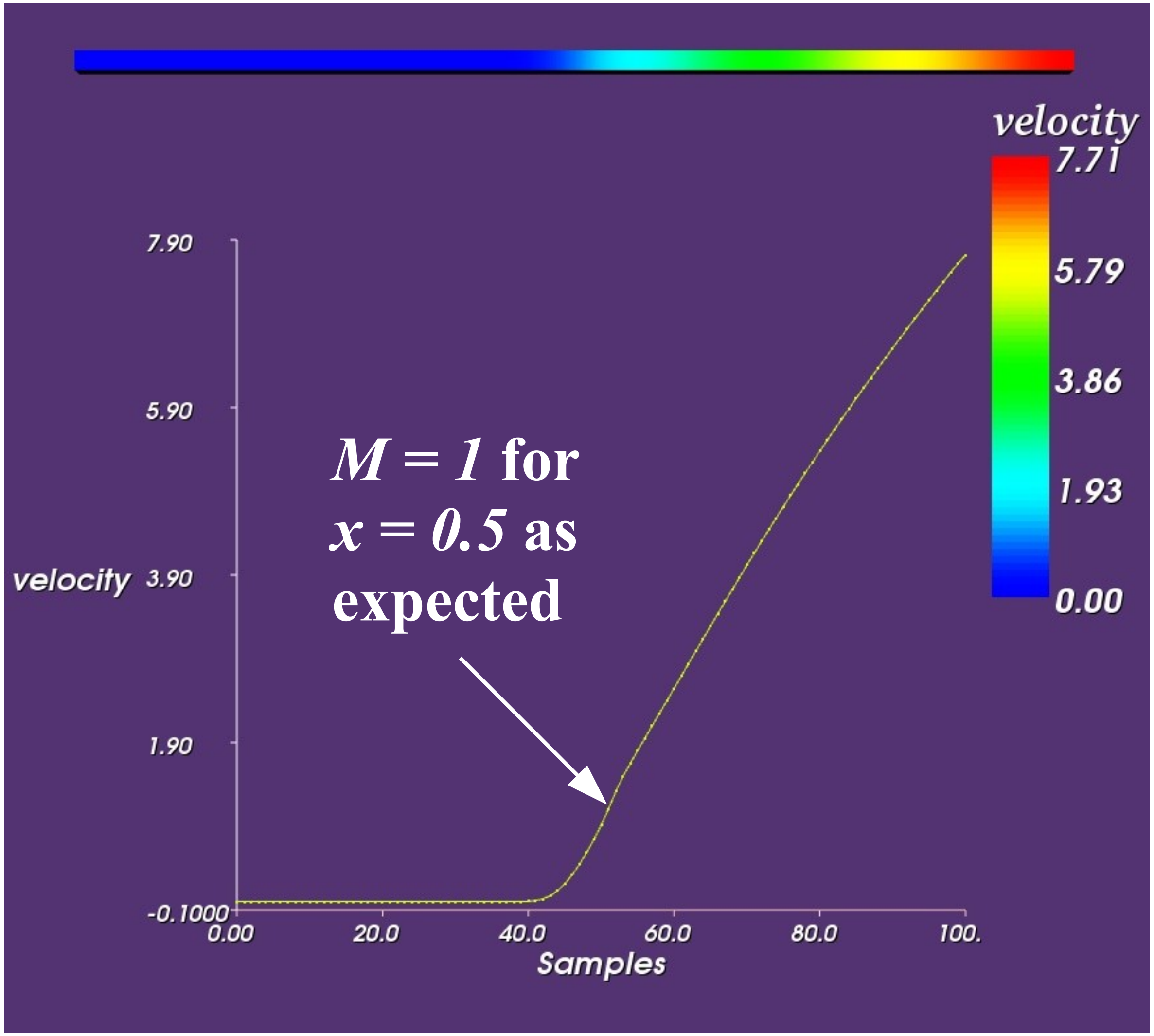
$$\begin{array}{l|l} \rho_L = 1 & \rho_R = 0 \\ u_L = 0 & u_R = 0 \\ p_L = 1 & p_R = 0 \end{array}$$

  - $L=1$, 200 points in the x-direction
  - Explicit scheme and 1st order space accuracy
  - Solved on 8 processors until time $t=0.05$

Treatment of the vacuum



Treatment of the vacuum



Outline of the presentation

1. The dusty Gas Model

2. Treatment of the vacuum for the gas phase

3. Numerical scheme for the dust phase
    - The Riemann problem
    - A Godunov type scheme
    - Numerical experiments

4. Simulation of the pressurisation of the VV

Conclusions

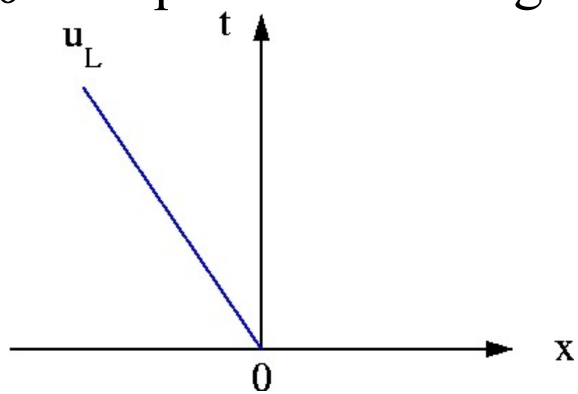
Numerical scheme for the dust phase

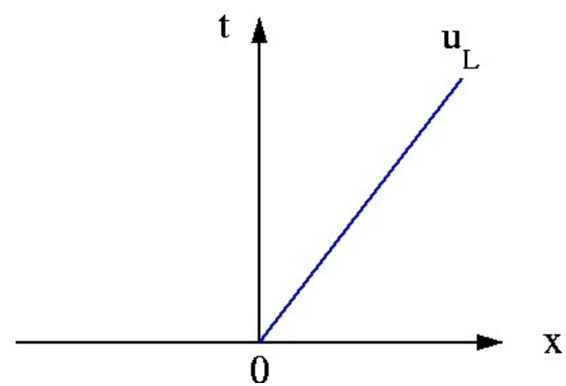
1. Resolution of the Riemann problem for pressureless system

- There is vacuum (on at least one side of the discontinuity)
  - If both states are vacuum, vacuum remains
  - If right state is vacuum:

$$u_L < 0 \;\Rightarrow\; \text{no particle goes through the interface} \quad \begin{cases} \rho^* = 0 \\ u^* = 0 \end{cases}$$

$$u_L > 0 \;\Rightarrow\; \text{particles coming from left go through the interface} \quad \begin{cases} \rho^* = \rho_L \\ u^* = u_L \end{cases}$$





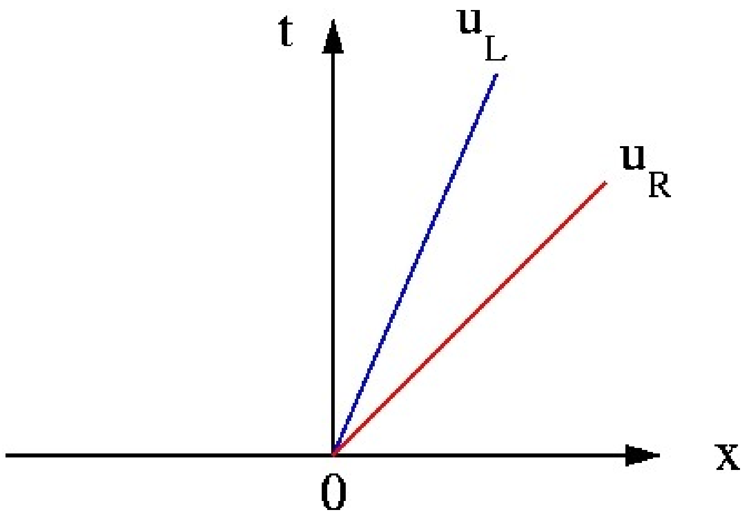
  - If left state is vacuum (reverse of the previous one)

Numerical scheme for the dust phase

1. Resolution of the Riemann problem for pressureless system
   - There is no vacuum

if $u_L < u_R \Rightarrow$ no collision, else $u_L > u_R \Rightarrow$ collision and delta wave

- There is no collision $u_L < u_R$



$u_L > 0 \Rightarrow$ only left particles go through the interface

$$\begin{cases} \rho^* = \rho_L \\ u^* = u_L \end{cases}$$

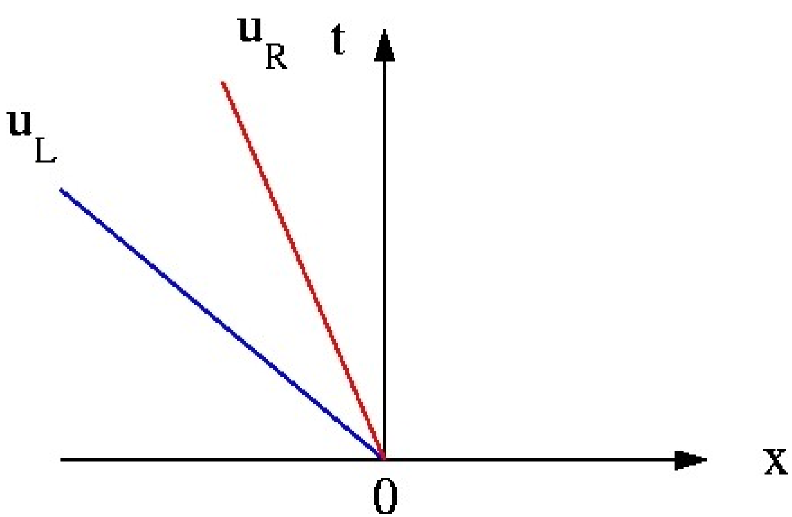
Numerical scheme for the dust phase

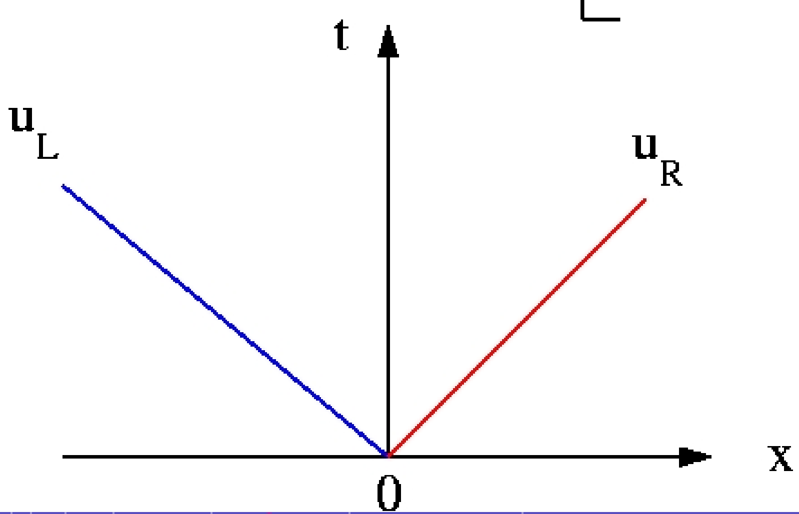
1. Resolution of the Riemann problem for pressureless system

- There is no collision $u_L < u_R$

$u_R < 0 \;\Rightarrow\;$ only right particles go through the interface $\begin{cases} \rho^* = \rho_R \\ u^* = u_R \end{cases}$

$u_L \cdot u_R < 0 \;\Rightarrow\;$ no particle goes through the interface $\begin{cases} \rho^* = 0 \\ u^* = 0 \end{cases}$

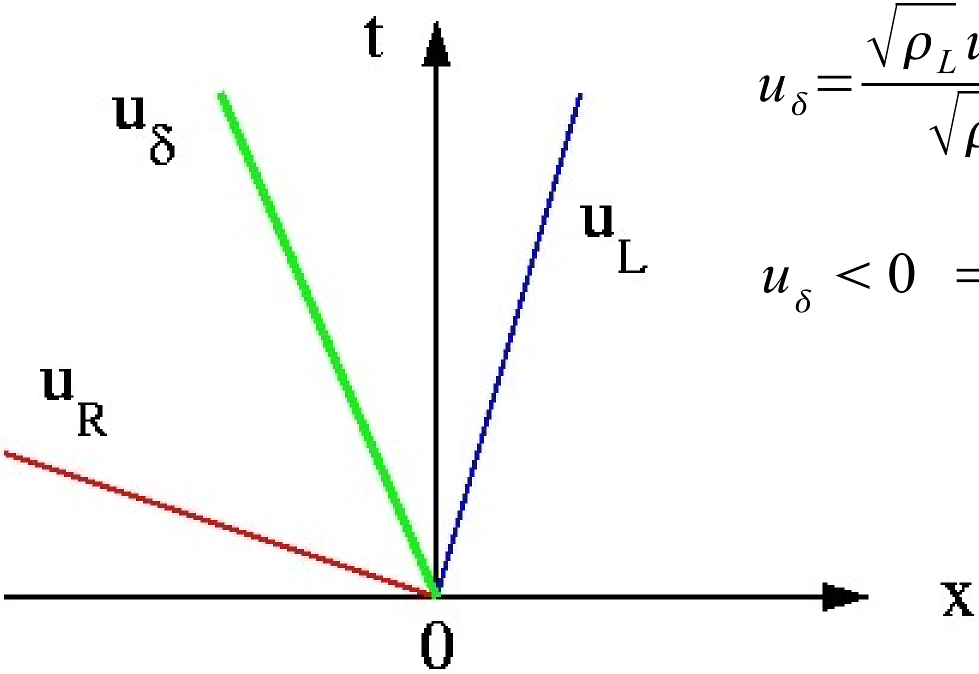




Numerical scheme for the dust phase

1. Resolution of the Riemann problem for pressureless system

- There is collision $u_L > u_R$
  - A delta wave is generated and its speed is given by:



$$u_\delta = \frac{\sqrt{\rho_L} u_L + \sqrt{\rho_R} u_R}{\sqrt{\rho_L} + \sqrt{\rho_R}}$$

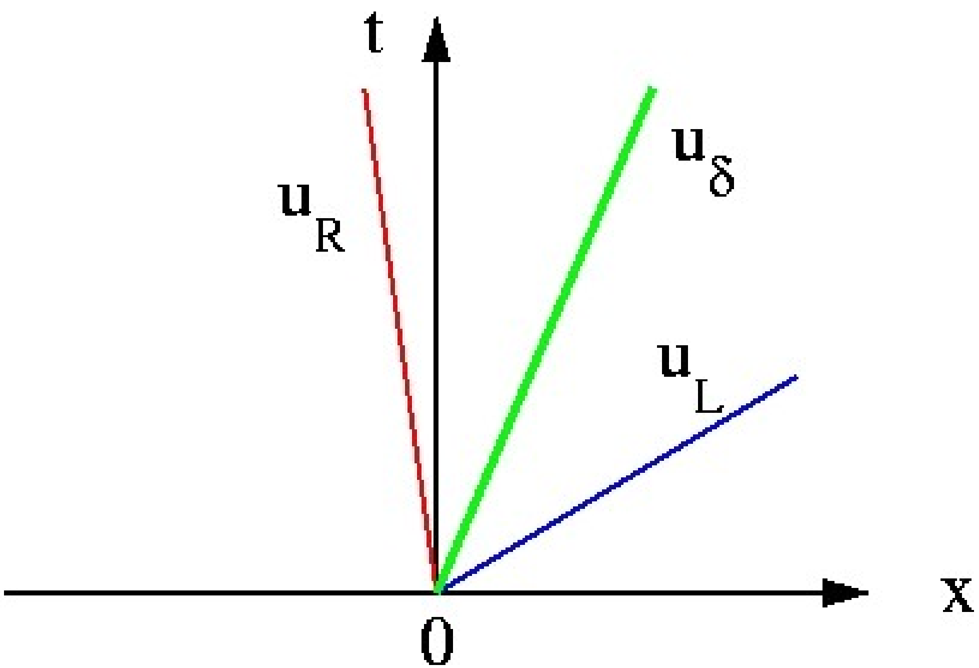
$u_\delta < 0 \Rightarrow$ only right particles go through the interface

$$\begin{cases} \rho^* = \rho_R \\ u^* = u_R \end{cases}$$

Numerical scheme for the dust phase

1. Resolution of the Riemann problem for pressureless system

- There is collision $u_L > u_R$



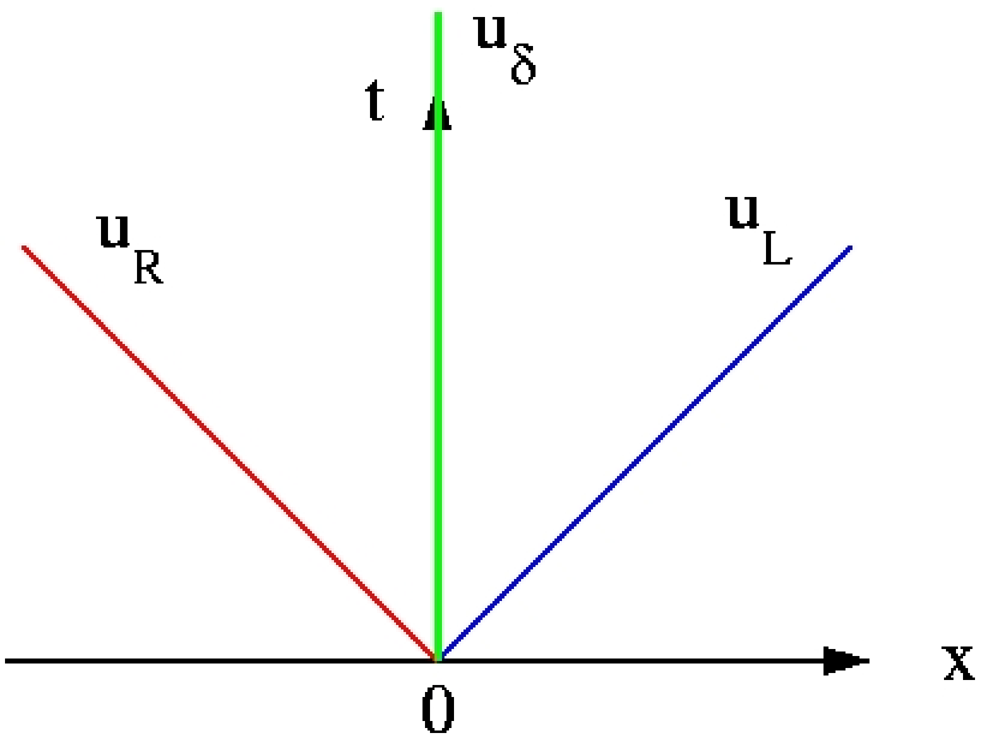
$u_\delta > 0 \;\Rightarrow$ only left particles go through the interface

$$\begin{cases} \rho^* = \rho_L \\ u^* = u_L \end{cases}$$

Numerical scheme for the dust phase

1. Resolution of the Riemann problem for pressureless system

- ✗ There is collision $u_L > u_R$



$u_\delta = 0 \Rightarrow$ particles are stuck on the interface, the delta shock is on the interface

Numerical scheme for the dust phase

2. A Godunov type scheme

- In all previous cases except the one for which $u_\delta = 0$, the numerical flux reads:

$$F = F\left(W^*\right) = \begin{bmatrix} \rho^* u^* \\ \rho^* u^{*\,2} \\ \rho^* E^* \end{bmatrix}$$

- When $u_\delta = 0$, the numerical flux is taken as the average between the left and right fluxes:

$$F = \frac{1}{2} \cdot \left(F\left(W_L\right) + F\left(W_R\right) \right)$$

- The scheme has been implemented in NUM3SIS

Numerical scheme for the dust phase

3. Collision between two finite clouds

- Initial data

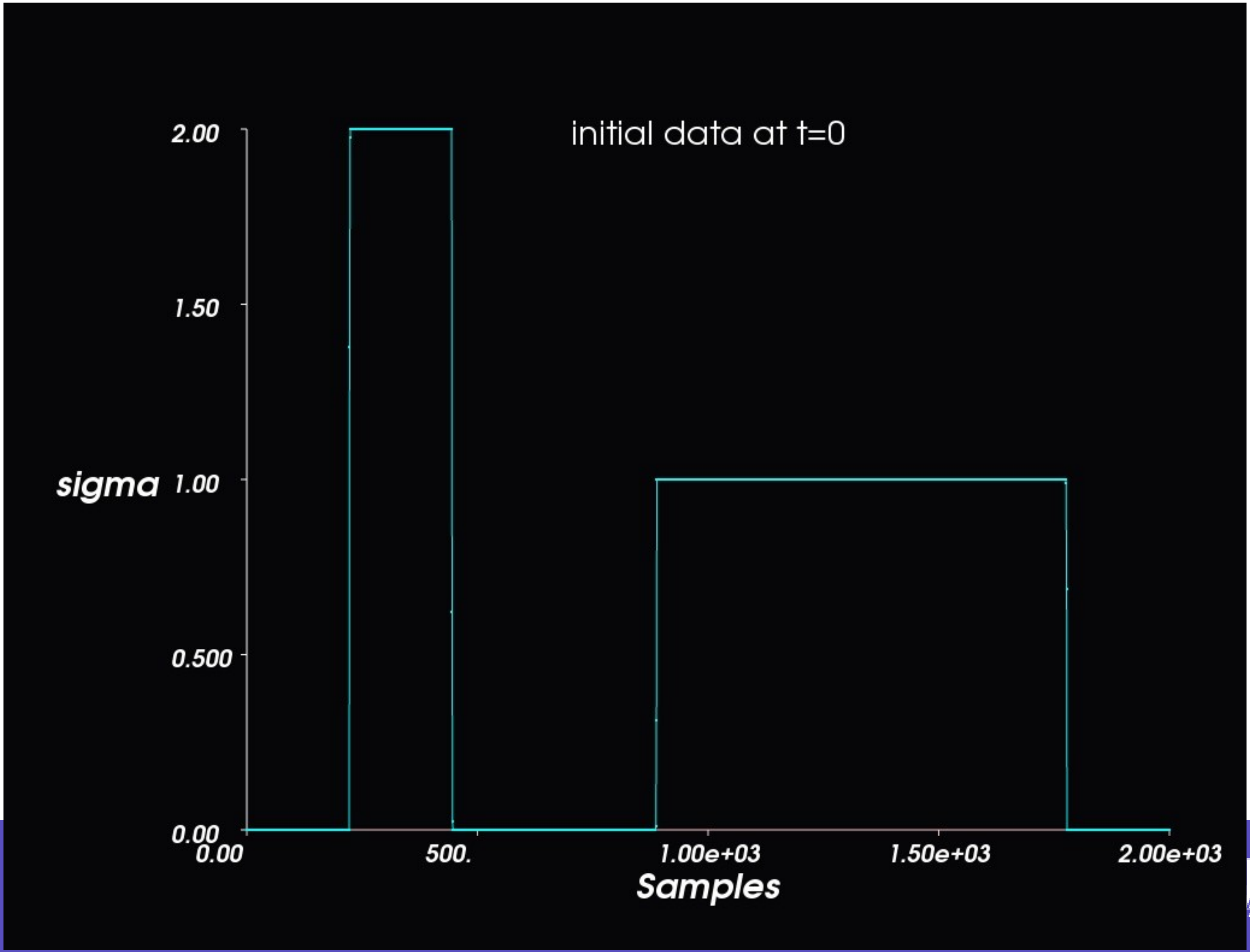
$$\sigma(x,0)=\begin{cases} 2 & if \quad 5/9 < x < 10/9 \\ 1 & if \quad 20/9 < x < 40/9 \\ 0 & else \end{cases} \qquad u(x,0)=\begin{cases} 1 & if \quad 5/9 < x < 10/9 \\ -1 & if \quad 20/9 < x < 40/9 \\ 0 & else \end{cases}$$

- Domain length L=5, 2000 points in the x-direction
- Runge-Kutta scheme (RK2), 2^{nd} order space accurate scheme (Barth-Jespersen reconstruction)
- Solved using 80 processors (Cluster bi-opteron 2GHz)

Numerical scheme for the dust phase

3. Collision between two finite clouds

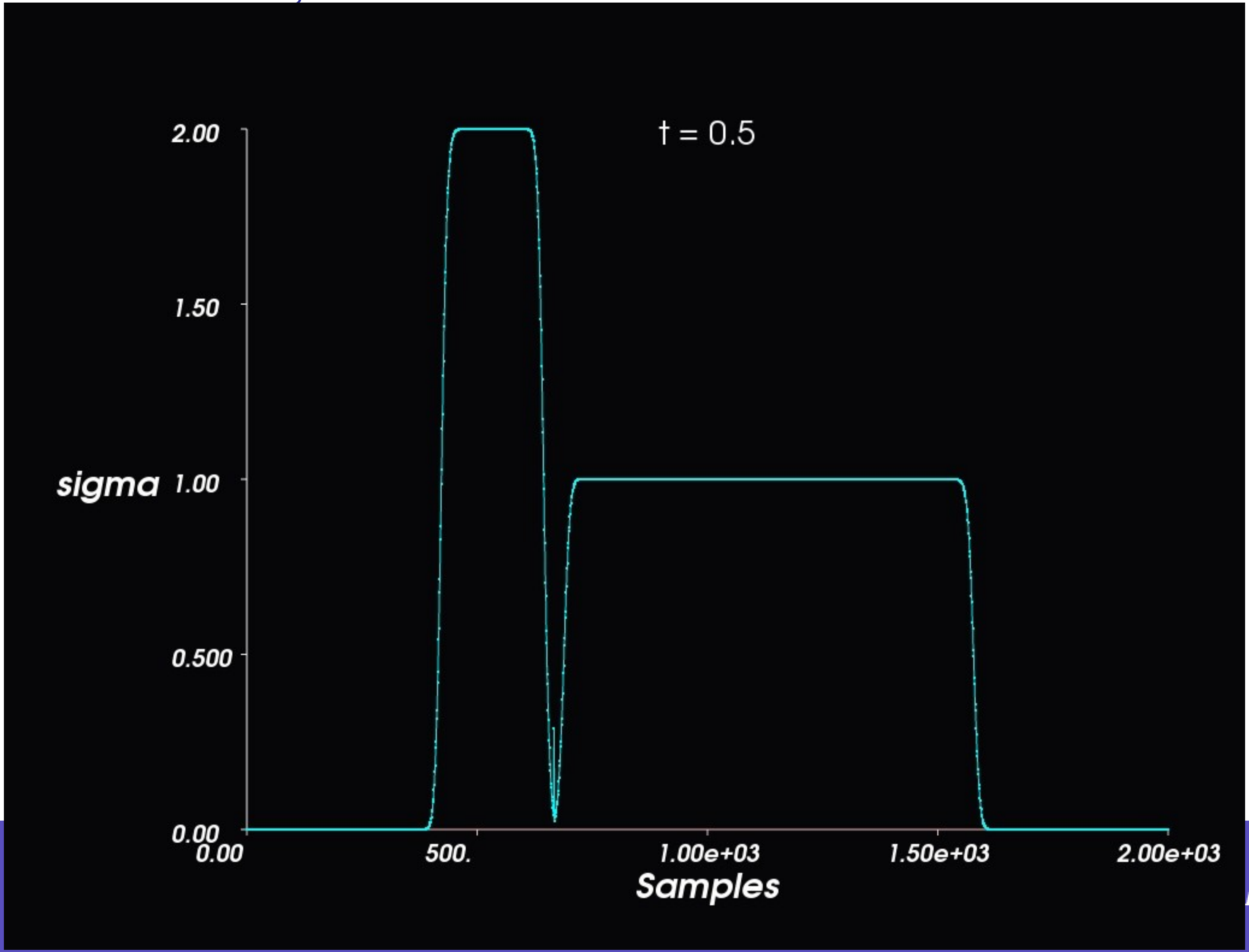
- Initial data



Numerical scheme for the dust phase

3. Collision between two finite clouds

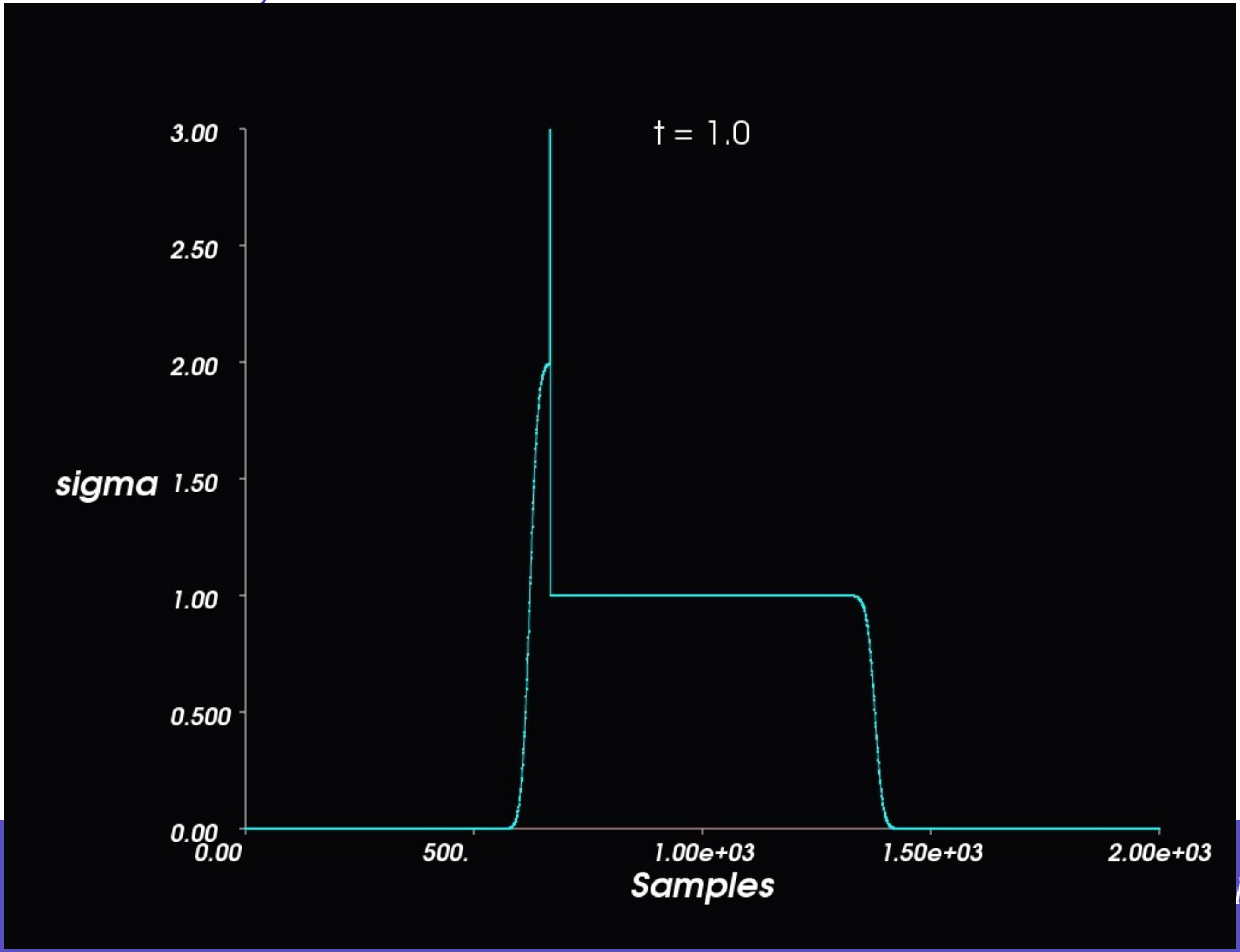
- Time, t=0.5



Numerical scheme for the dust phase

3. Collision between two finite clouds

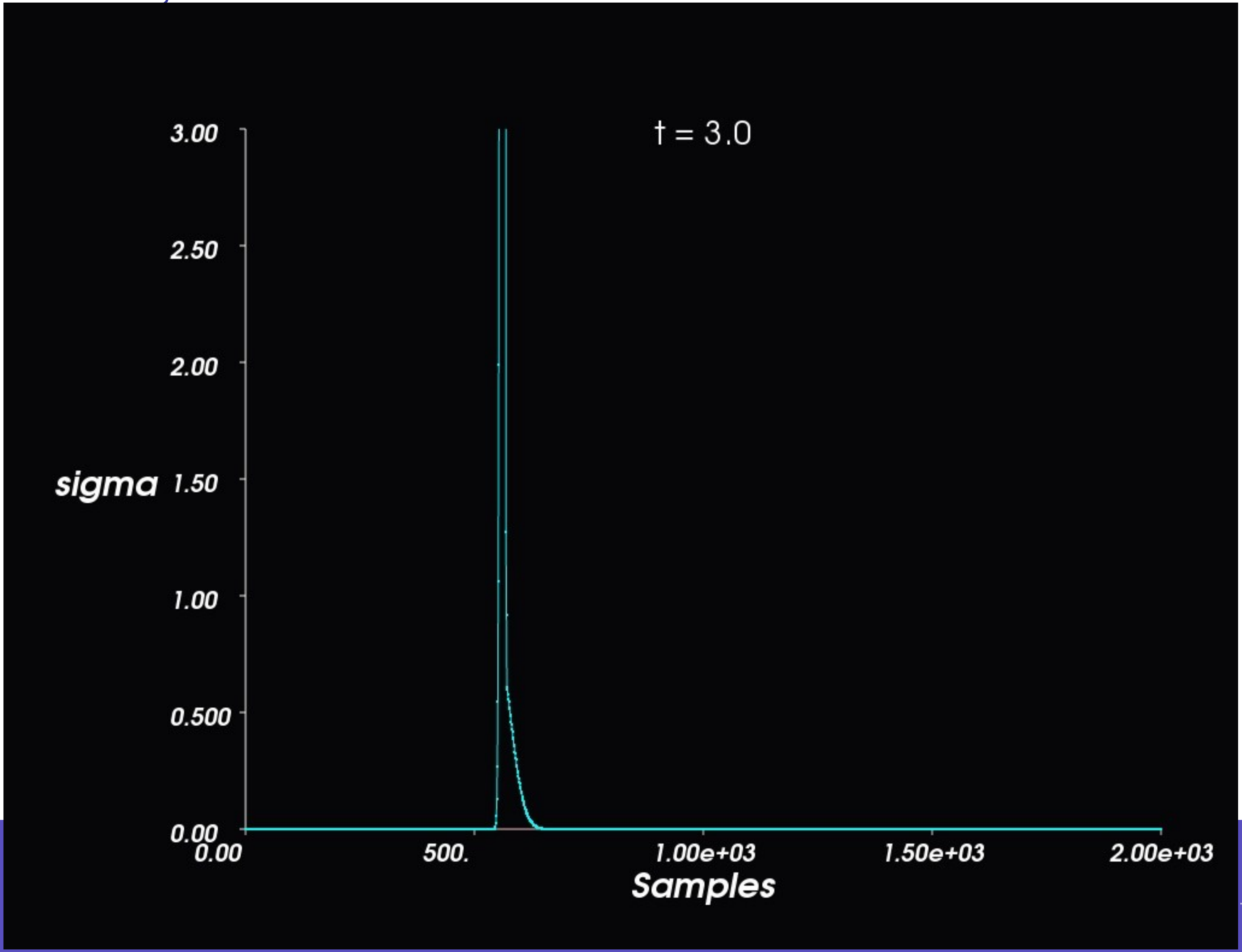
- Time, t=1.0



Numerical scheme for the dust phase

3. Collision between two finite clouds

- Time, t=3.0



Outline of the presentation

1. The Dusty-Gas Model

2. Treatment of the vacuum for the gas phase

3. Numerical scheme for the dust phase

4. Numerical results with the dusty gas model
    - Saito shock-tube
    - Preliminary calculation of the VV pressurisation

Conclusions

Numerical results with the dusty-gas model

1. The Saito shock-tube (with crown glass)

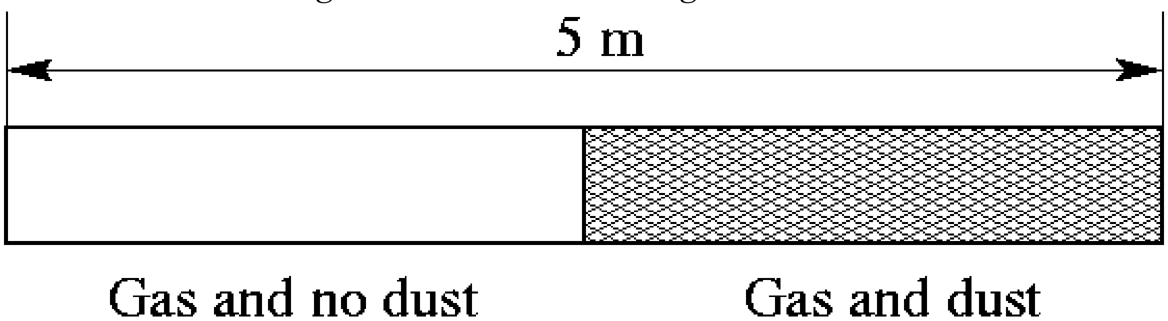
$$T_g = 300\text{K} \qquad u_g = 0 \qquad p_g = 10^6\,Pa \qquad \sigma = 0$$

$$T_g = T_d = 300\text{K} \qquad u_g = u_d = 0 \qquad p_g = 10^5\,Pa \qquad \sigma = \rho_g(p = 10^5\,Pa,\, T_g = 300\text{K})$$

$$\rho_d = 2500\,kg/m^3$$

$$d_d = 10\,\mu m$$

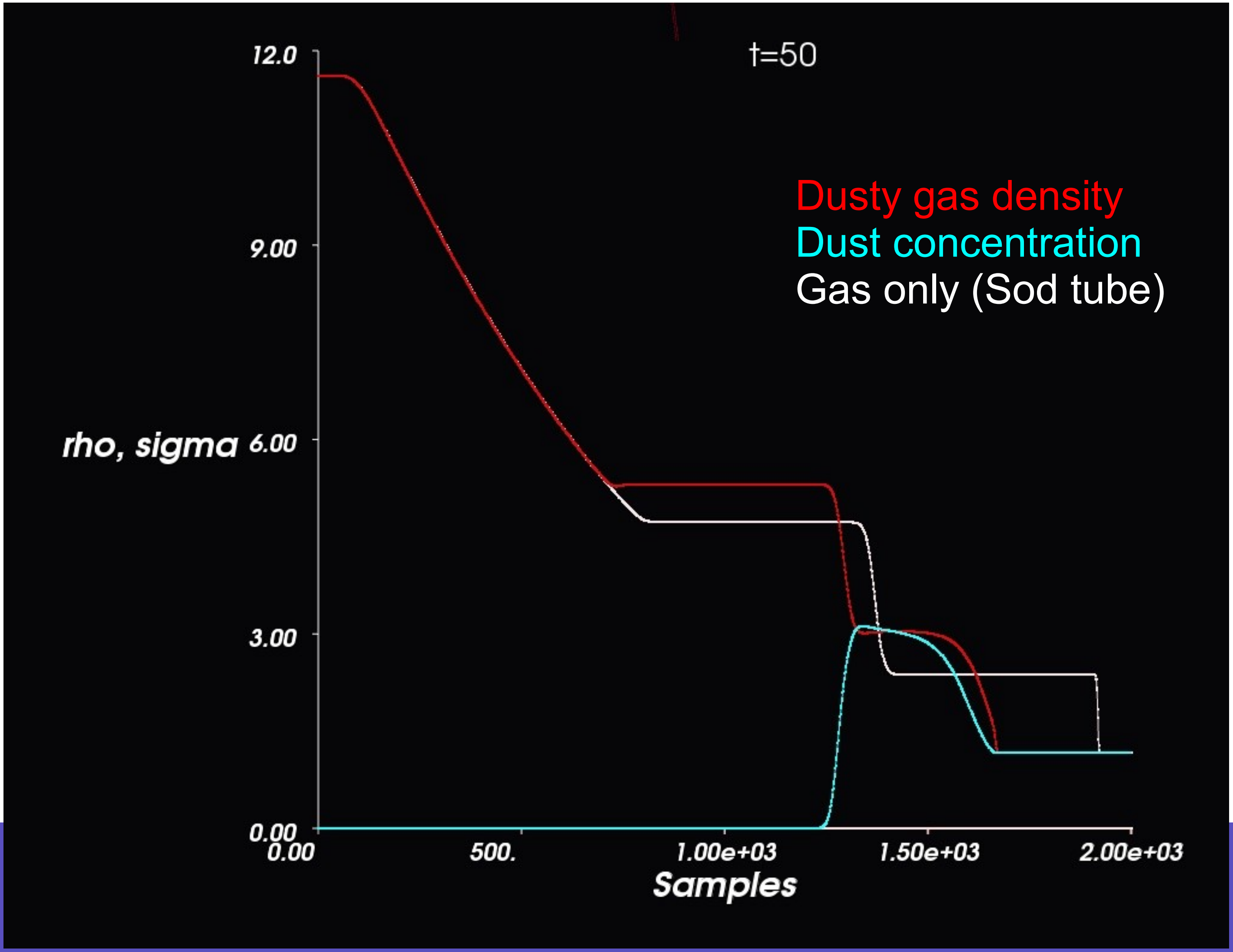
$$\mu_g = 1.71 \cdot 10^5 \cdot \left(\frac{T_g}{273}\right)^{0.77}$$



- Tube length L=5, 2000 points in the x-direction
- Runge-Kutta scheme (RK2), 2nd order space accurate scheme (Barth-Jespersen reconstruction)
- Solved using 80 processors (Cluster bi-opteron 2GHz)

Numerical results with the dusty-gas model

1. The Saito shock-tube
   - Time, t=50



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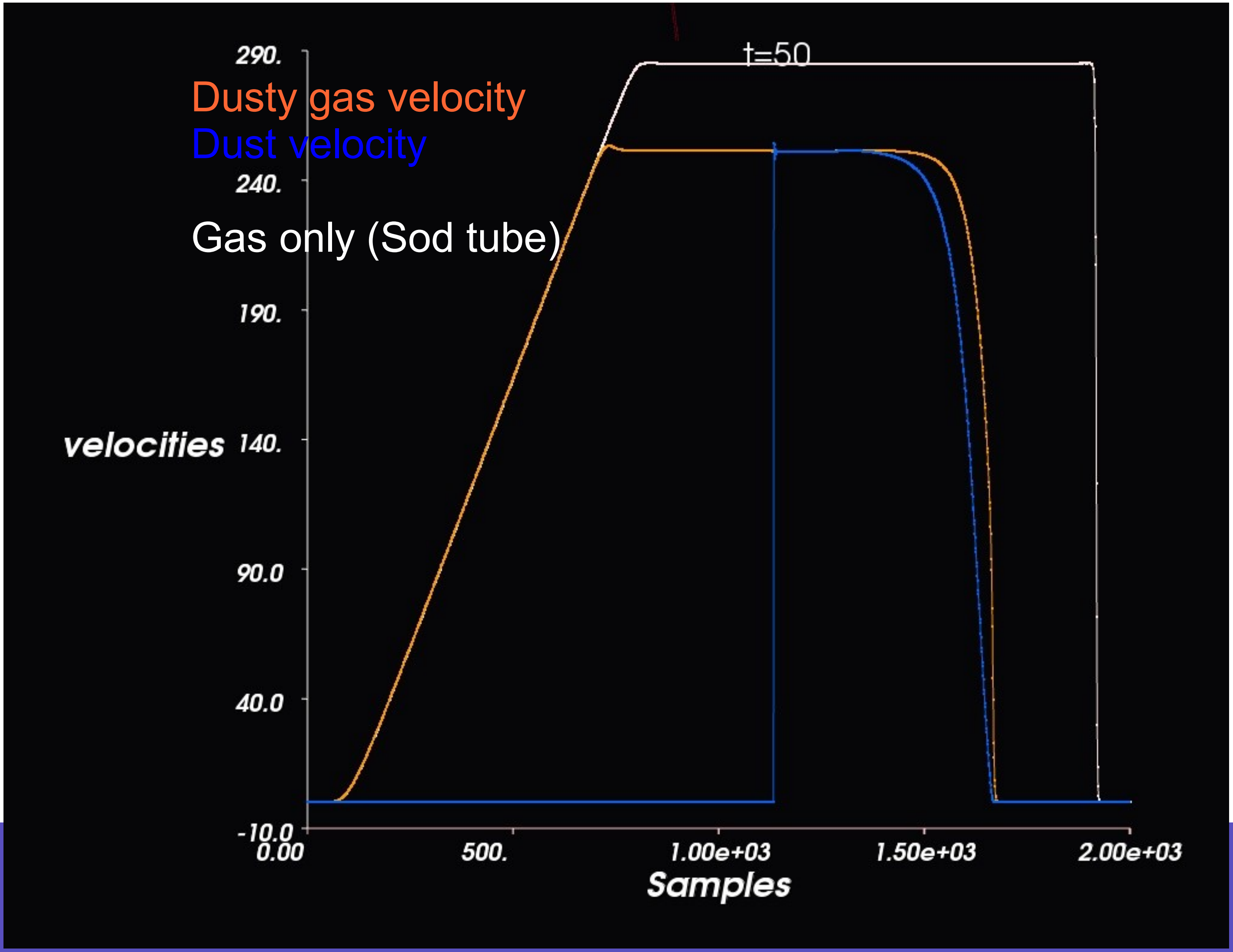
Numerical results with the dusty-gas model

1. The Saito shock-tube
   - Time, t=50



Numerical results with the dusty-gas model

2. Preliminary calculation of the VV pressurisation

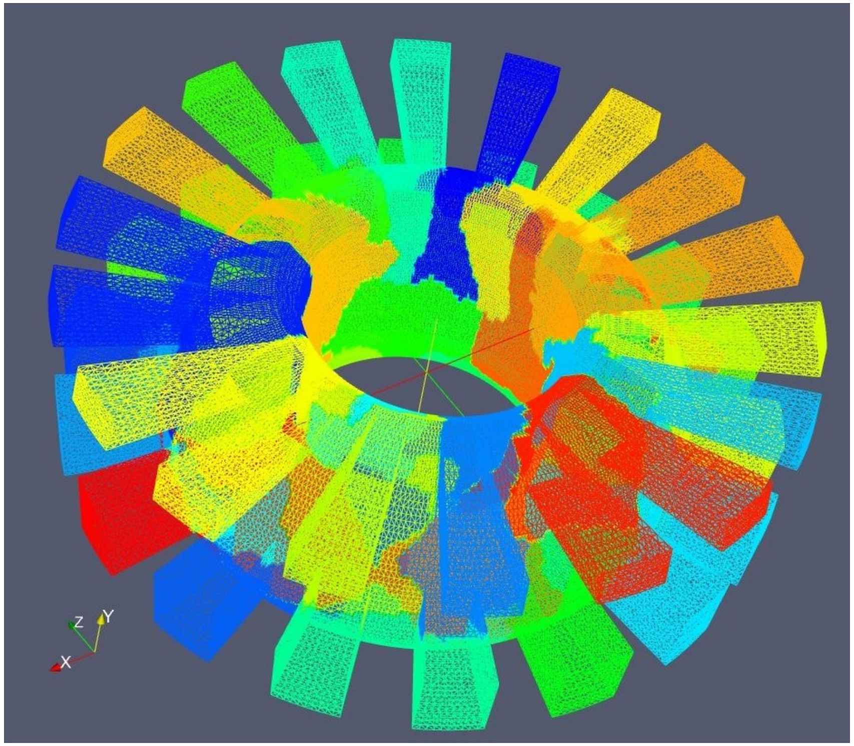
- Objective:
  - Testing the model on a realistic 3D problem
  - Proving the efficiency of the code for such geometries
  - Reporting difficulties to enhance model
- First step: Generating and partitioning the mesh
  - Geometry given by LTMF laboratory (CEA Saclay)
  - Extended to unstructured grid using CAST3M (CEA)
  - Mesh partitioning carried out using Meshmigration (CEMEF-INRIA)

Numerical results with the dusty-gas model

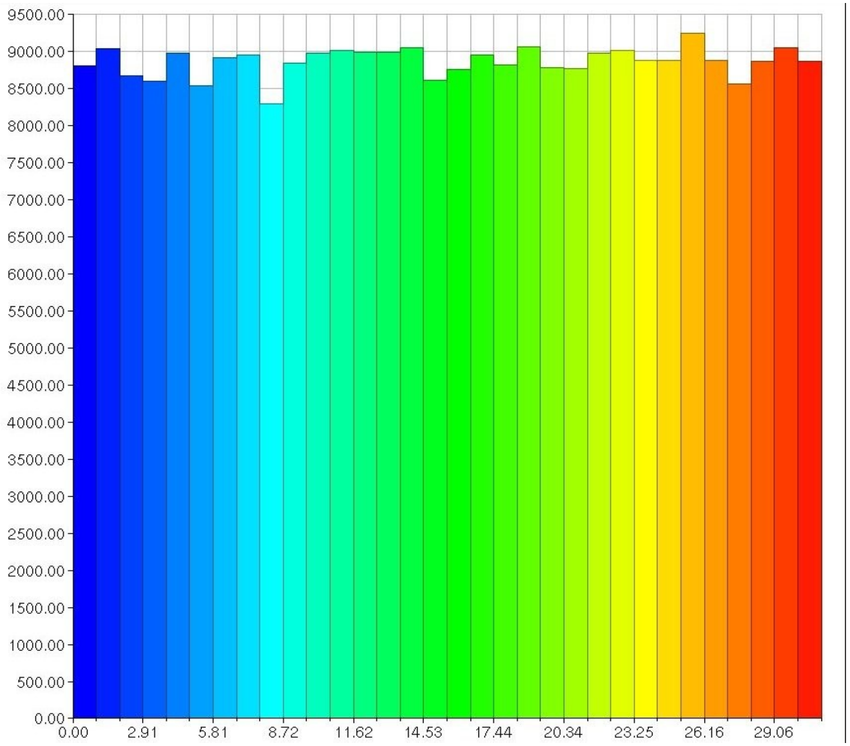
2. Preliminary calculation of the VV pressurisation

- First step: Generating and partitioning the mesh

283,747 nodes
1,468,537 elements



32 balanced partitions
(~ 9,000 nodes)

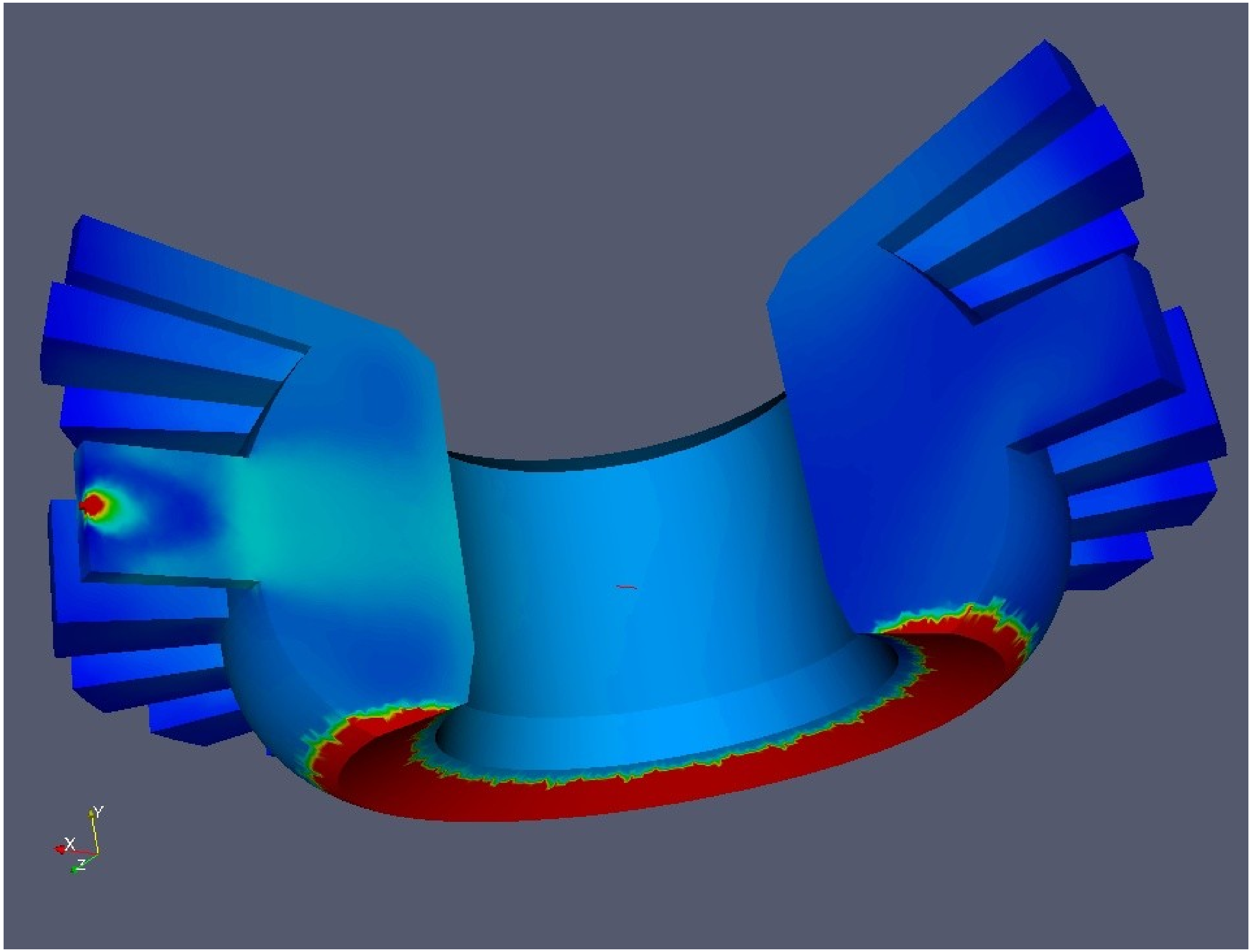


Numerical results with the dusty-gas model

2. Preliminary calculation of the VV pressurisation

- Second step: Initial and boundary conditions
  - Thin layer of beryllium oxide at the bottom of the vessel
    - Thickness = 2cm => volume ~ 1.4 m^3
    - Total mass mobilisable = 100 kg => $\sigma = 70\, kg/m^3$ in the layer
    - $\rho_d = 3{,}01 \cdot 10^3\, kg/m^3$ $d_d = 10\, \mu m$ $Cv_d = 900\, J/kg/K$
  - Vacuum state everywhere else ($\sigma = 0$ $\rho_g = 0$)
  - Pressurisation through a 10 cm^2 hole in one equatorial port
    - $p_g = 10^5\, Pa$ $T_g = 300\, K$ at the inlet

Numerical results with the dusty-gas model



Physical time = 1s

CPU time ~ 10h

Obviously, the computation has to be continued so as to observe dust mobilization.

The mesh is not fine enough

Conclusion

• The developped schemes and solvers for the dusty gas problems have been validated over reference test cases

• The preliminary calculations confirm that the simulation of the LOVA scenario is very costly in terms of CPU time

Prospect

• Mesh refinement

• Larger amount of partitions

• Experimental data to validate further the developped models

Thank you for your attention !

The Dusty-Gas Model

3. The equations for the dust phase

- The quantity $f(x, v, T, r, t)\,dx\,dv\,dT\,dr$ denotes the amount of particles which are contained in the volume *[x, x+dx]* and that have, at time *t* a velocity standing in the range *[v, v+dv]*, a temperature in *[T,T+dT]* and a radius in *[r,r+dr]*
- The distribution function *f* obeys a Liouville-Boltzmann equation

$$\frac{\partial f}{\partial t} + \sum_i \frac{\partial f \dot{q}_i}{\partial q_i} = \dot{f}_{coll}$$

$q_i =$ Phase variable (e.g. x, v, T or r)

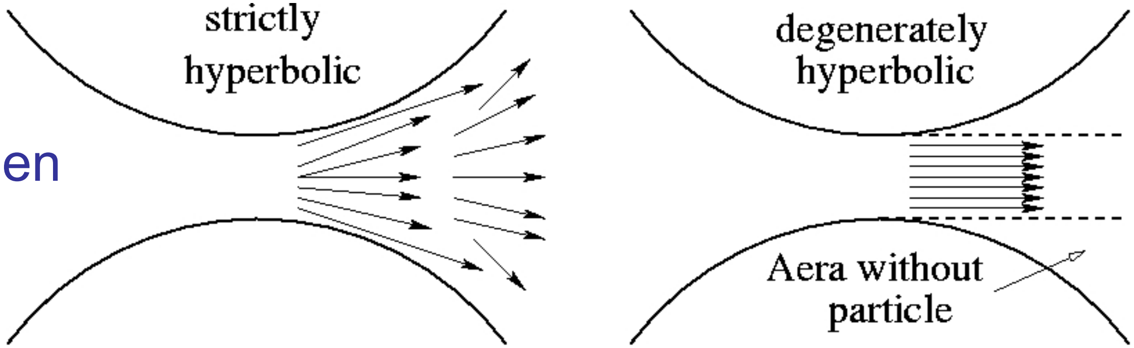
$\dot{f}_{coll} =$ Temporal variation due to collisions (neglected for high dilute mixture)

- Integrating this equation yields the system for the dust phase

The Dusty-Gas Model

5. Nature of the systems of equations

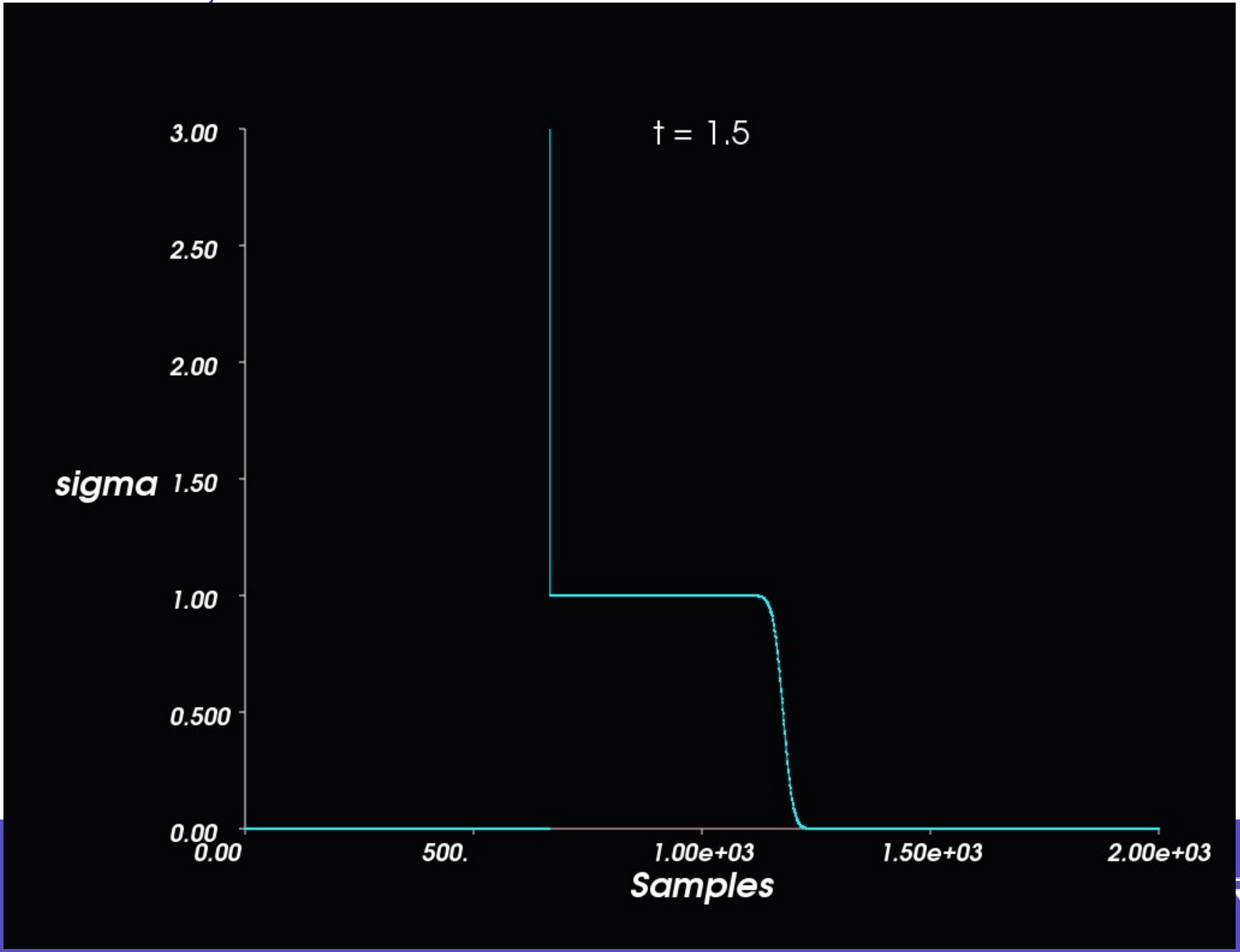
- Both systems are solved separately
- Gas system is strictly hyperbolic (use of Riemann solver)
- Dust system is degenerately hyperbolic with one multiple eigenvalue
- Consequences
  - ✗ Information only transmitted along streamlines in the direction of the velocity
  - ✗ Competition between inertial effects and exchange effects



Numerical scheme for the dust phase

3. Collision between two finite clouds

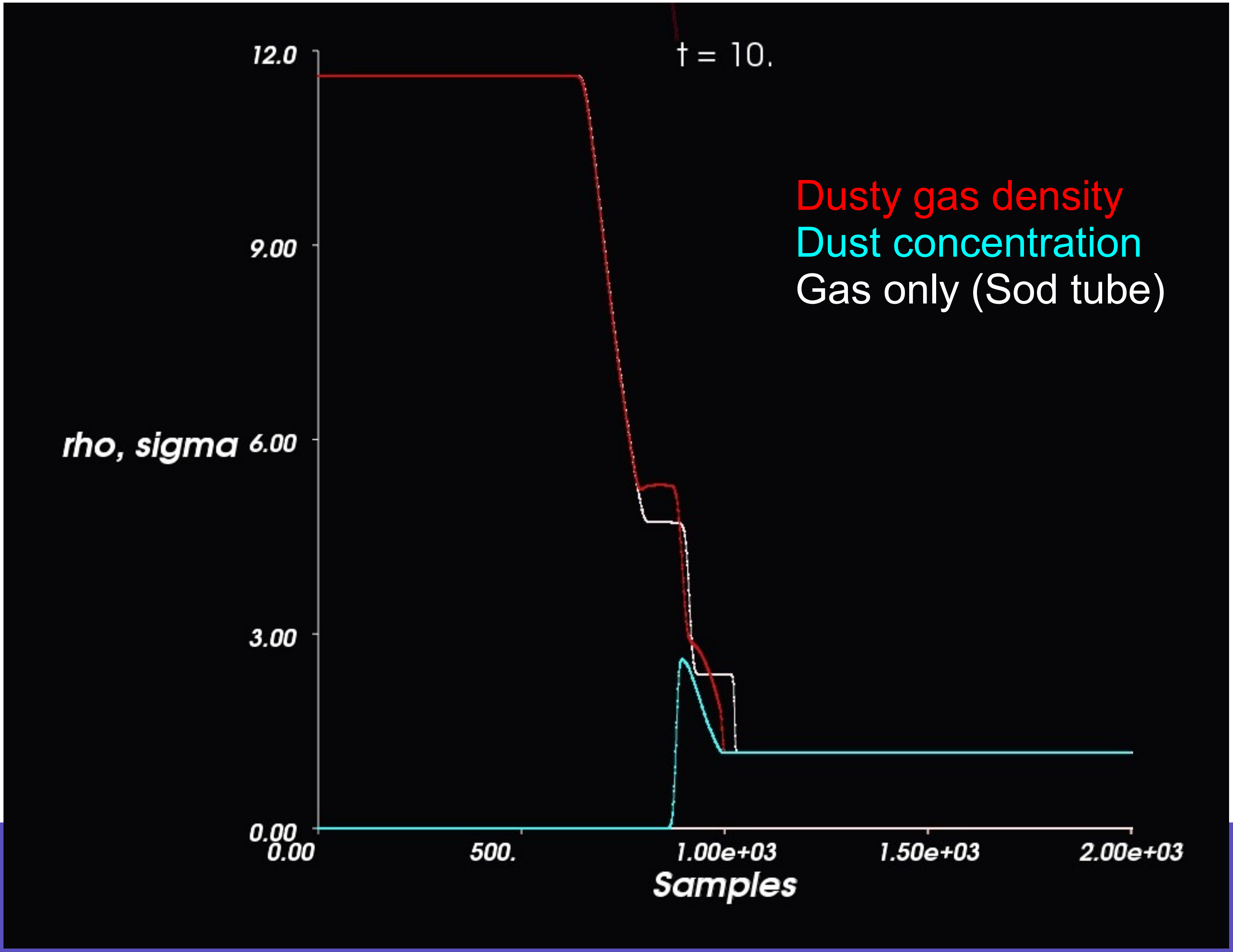
- Time, t=1.5



Numerical results with the dusty-gas model

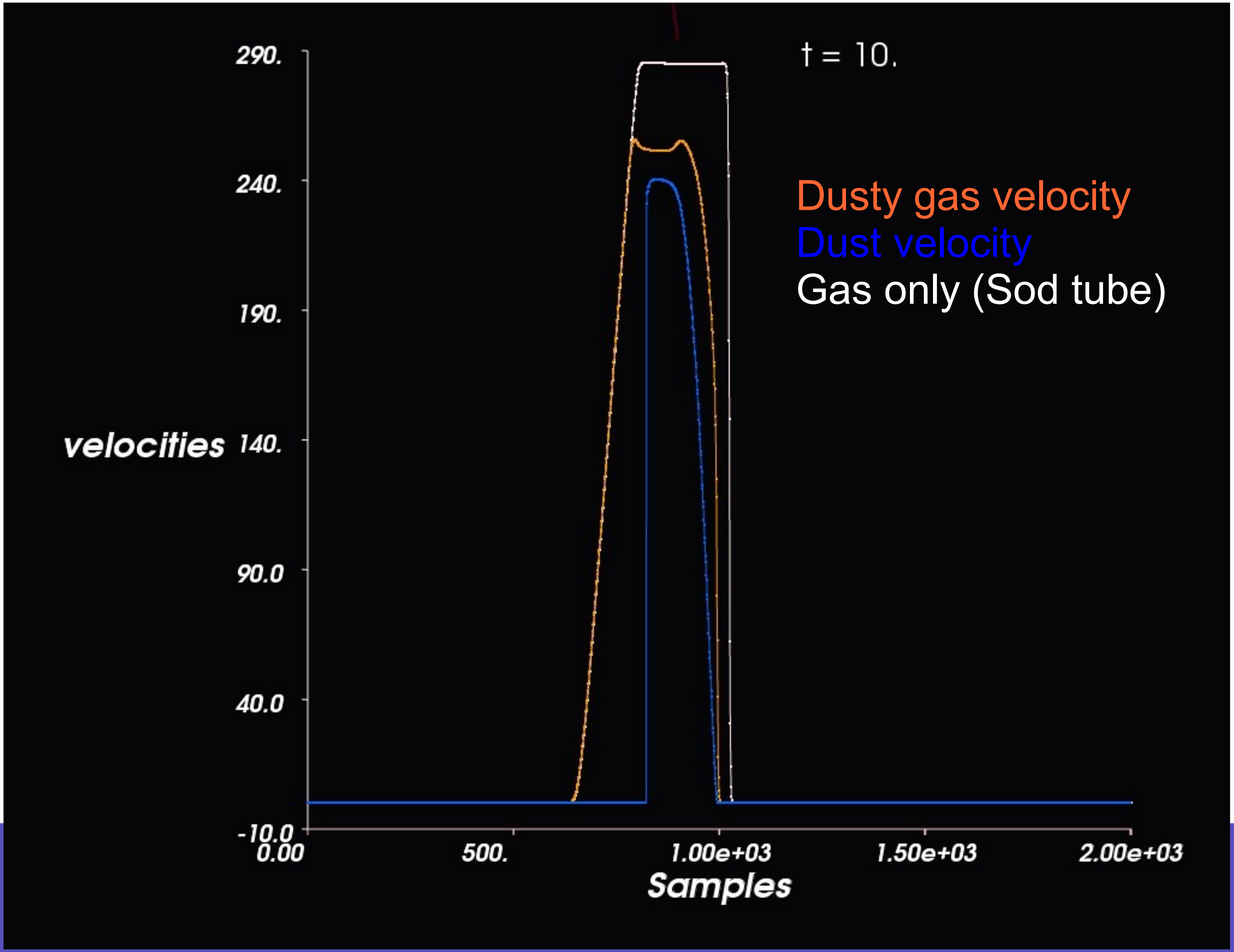
1. The Saito shock-tube

- Time, t=10



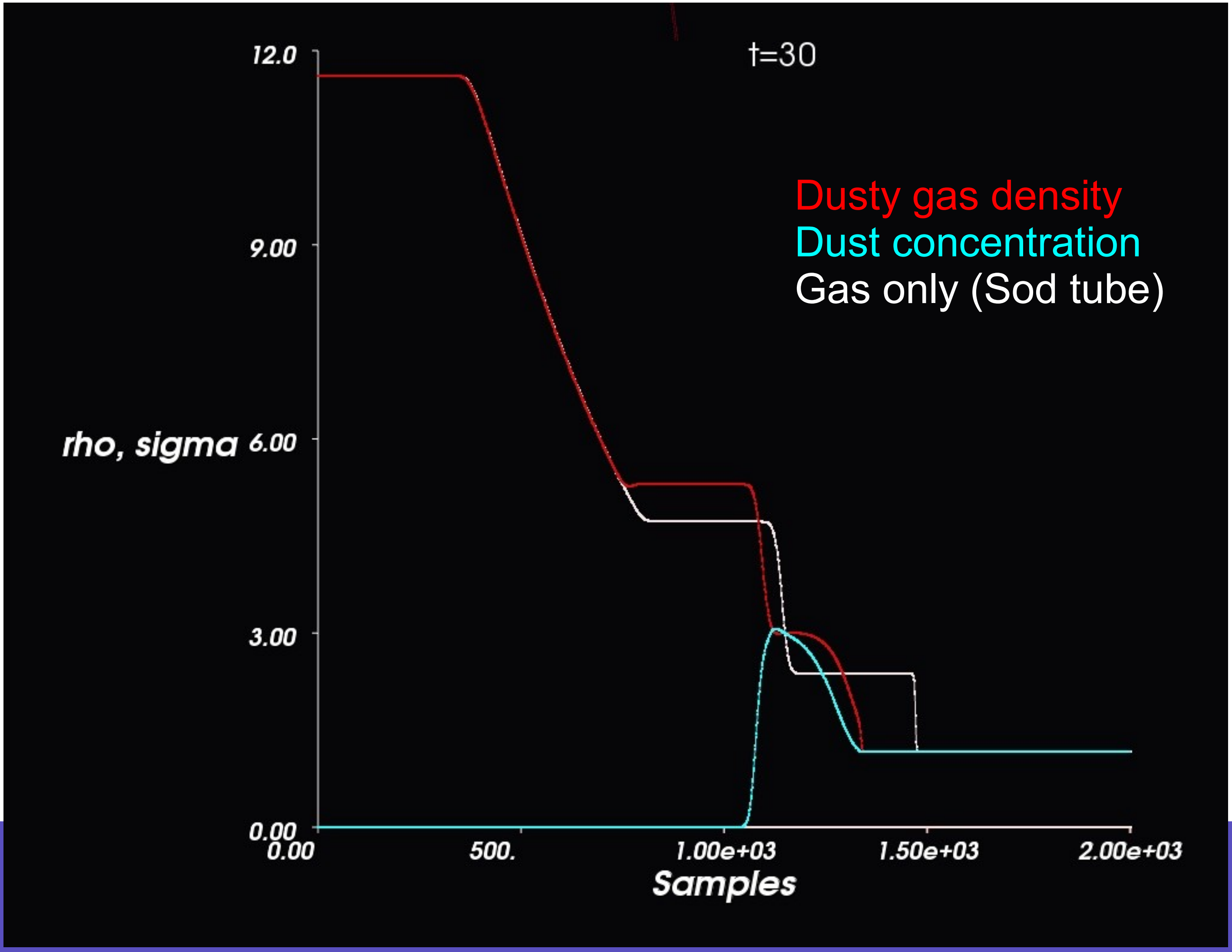
Numerical results with the dusty-gas model

1. The Saito shock-tube
   - Time, t=10



Numerical results with the dusty-gas model

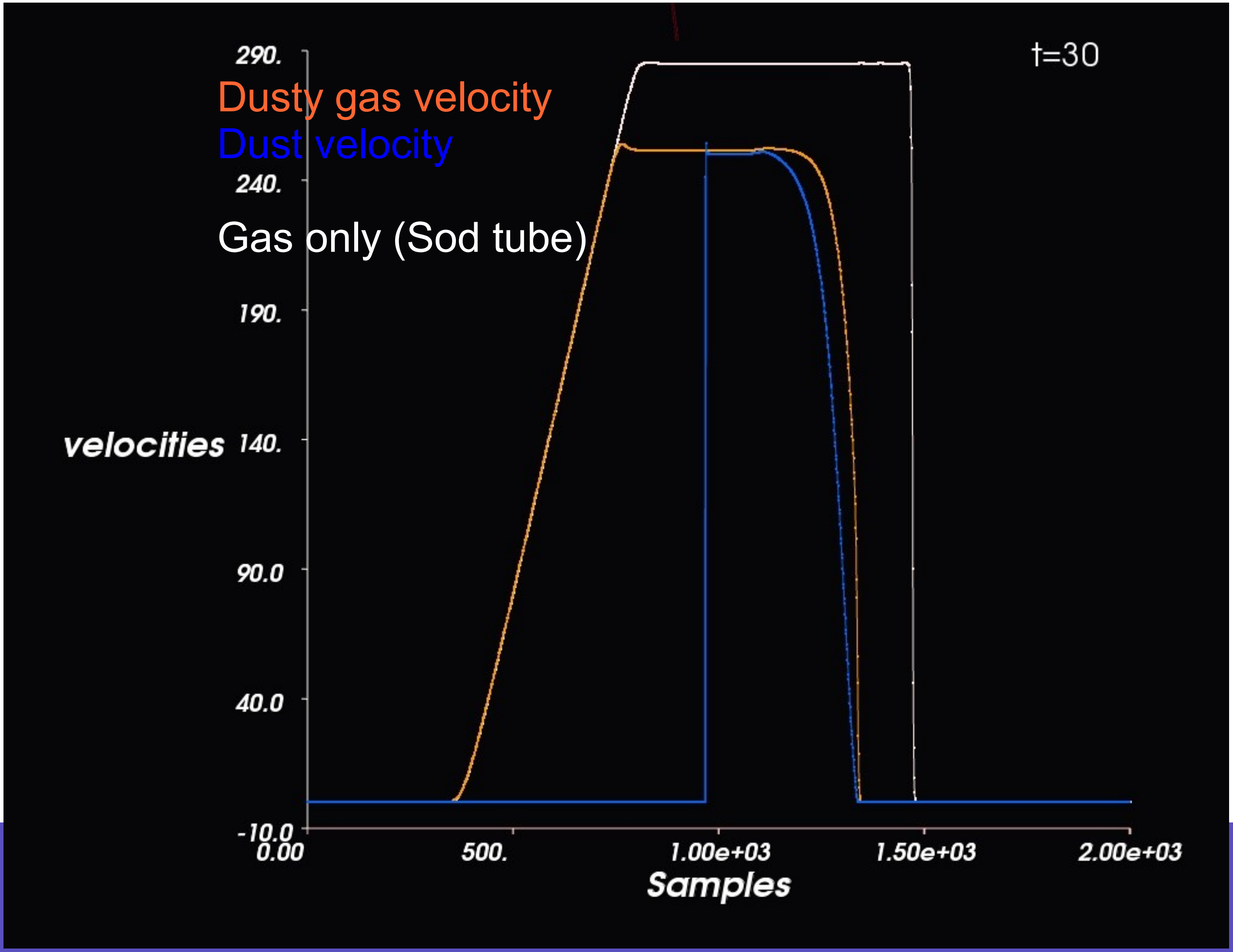
1. The Saito shock-tube
   - Time, t=30



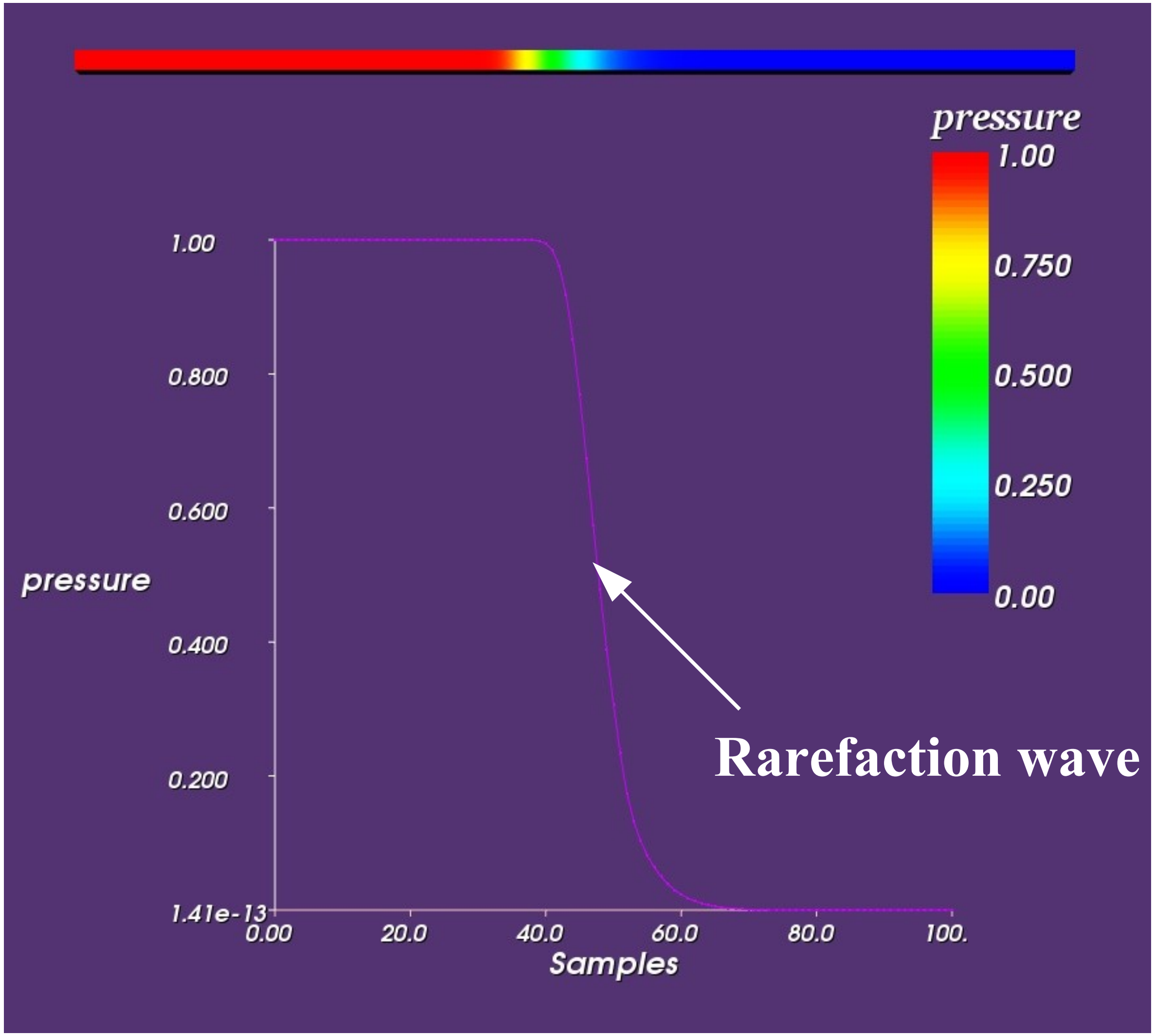
Numerical results with the dusty-gas model

1. The Saito shock-tube

- Time, t=30



Treatment of the vacuum



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