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Target Simulation

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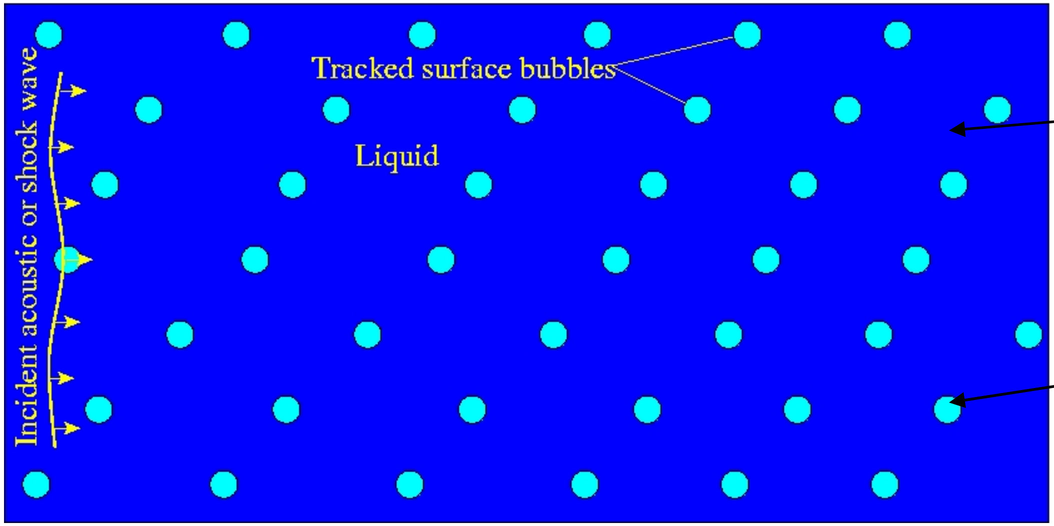
Talk Outline

- New matematical models and numerical algorithms for the simulation of cavitating and bubbly fluids and applications to mercury targets
- Mercury jet entering a 15T magnetic solenoid
- Conclusions and future plans

We have developed two models for cavitating and bubbly fluids

- **Heterogeneous Model (Direct Numerical Simulation):** Each individual bubble is explicitly resolved using FronTier interface tracking technique.



Stiffened Polytropic EOS for liquid

Polytropic EOS for gas (vapor)

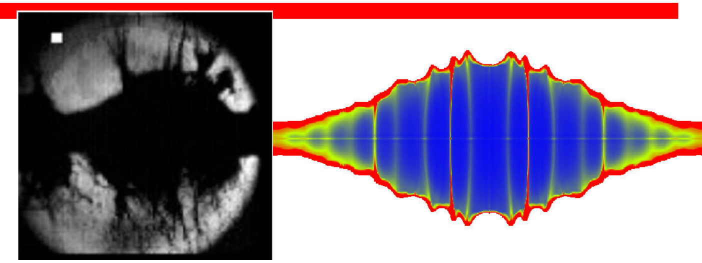
- **Homogeneous EOS Model.** Suitable average properties are determined and the mixture is treated as a pseudofluid that obeys an equation of single-component flow.

Homogeneous isentropic two phase EOS model (summary)

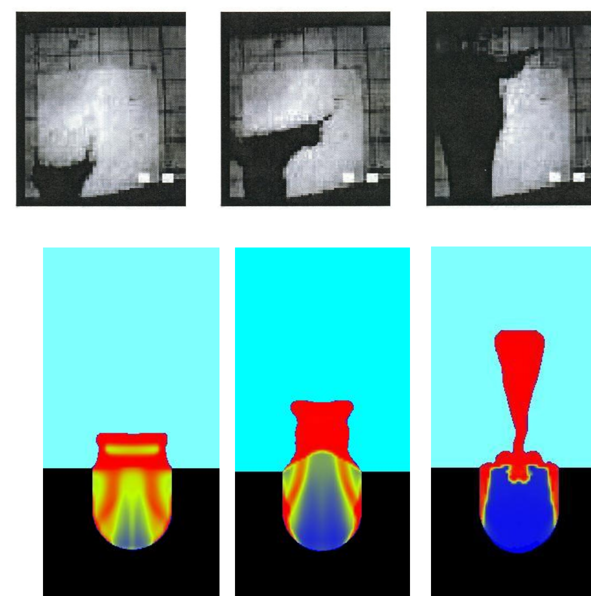
- Correct dependence of the sound speed on the density (void fraction). The EOS is applicable if properties of the bubbly fluid can be averaged on the length scale of several bubbles. Small spatial scales are not resolved.

- Enough input parameters (thermodynamic/acoustic parameters of both saturated points) to fit the sound speed in all phases to experimental data.

- Absence of drag, surface tension, and viscous forces. Incomplete thermodynamics.



Experimental image (left) and numerical simulation (right) of the mercury jet.



Features of the heterogeneous method

- Accurate description of multiphase systems limited only by numerical errors.

- Resolves small spatial scales of the multiphase system

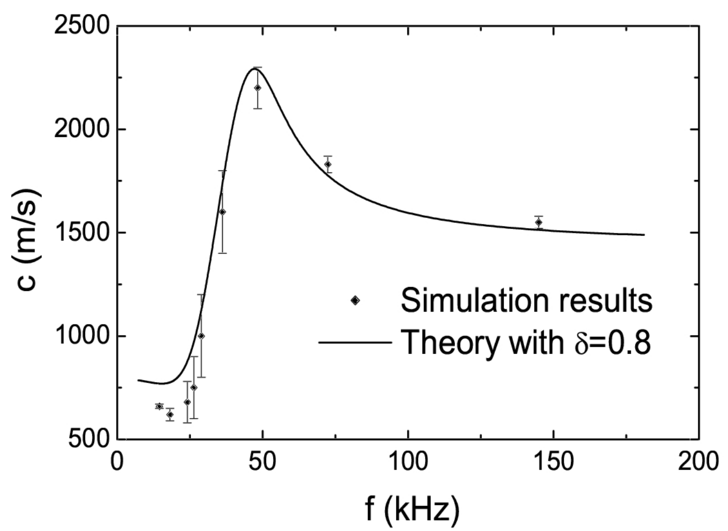
- Accurate treatment of drag, surface tension, viscous, and thermal effects.

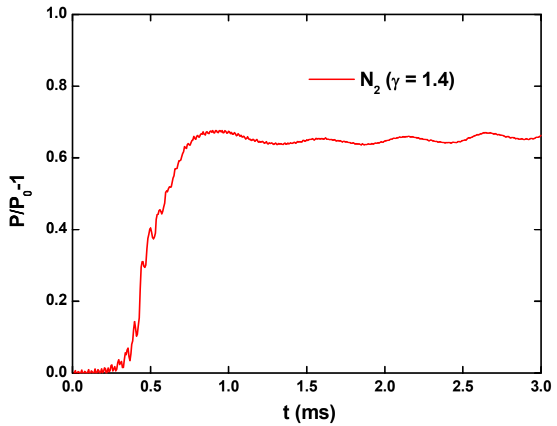
- Mass transfer due to phase transition (Riemann problem for the phase boundary)

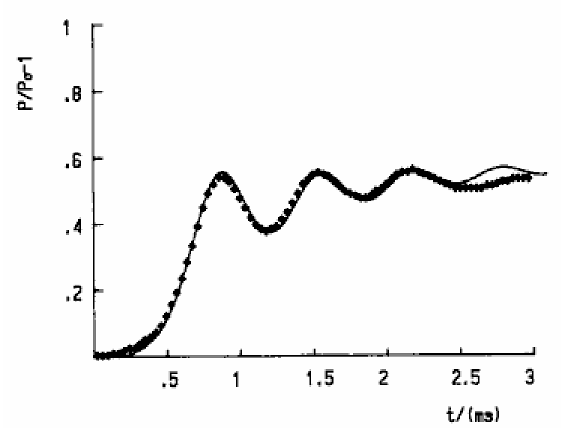
- Models some non-equilibrium phenomena (critical tension in fluids)

Validation of the direct method: linear waves and shock waves in bubbly fluids

- Good agreement with experiments (Beylich & Gülhan, sound waves in bubbly water) and theoretical predictions of the dispersion and attenuations of sound waves in bubbly fluids
- Simulations were performed for small void fractions (difficult from numerical point of view)
- Very good agreement with experiments of the shock speed
- Correct dependence on the polytropic index





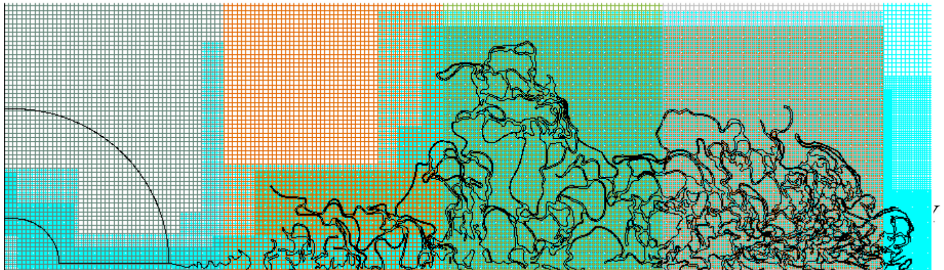


Dynamic cavitation

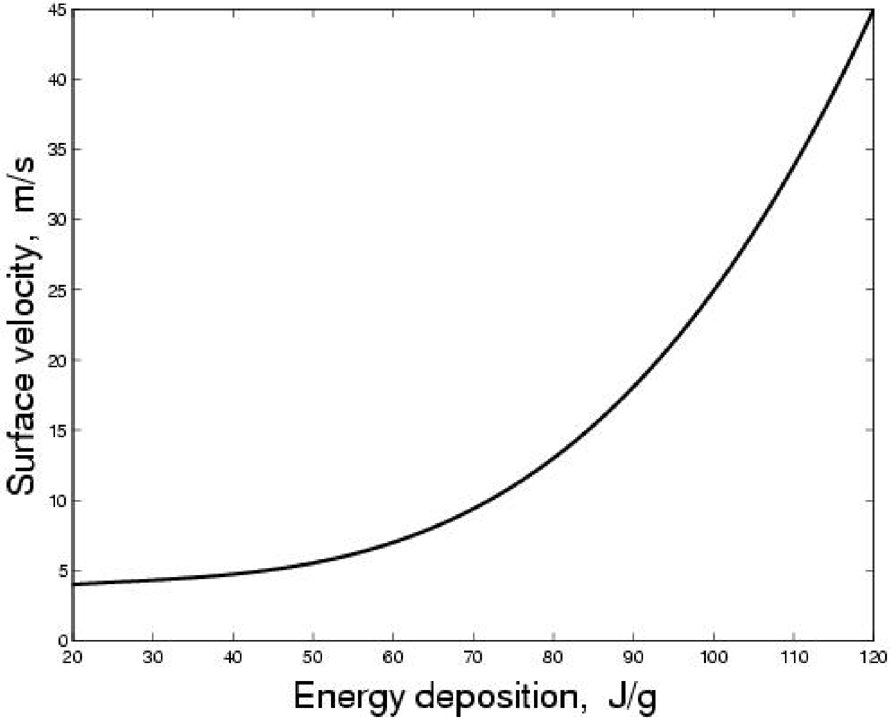
- A cavitation bubble is dynamically inserted in the center of a rarefaction wave of critical strength
- A bubbles is dynamically destroyed when the radius becomes smaller than critical. In simulations, critical radius is determined by the numerical resolution. With AMR, it is of the same order of magnitude as physical critical radius.
- Modeling of the distribution of cavitation centers and critical parameters

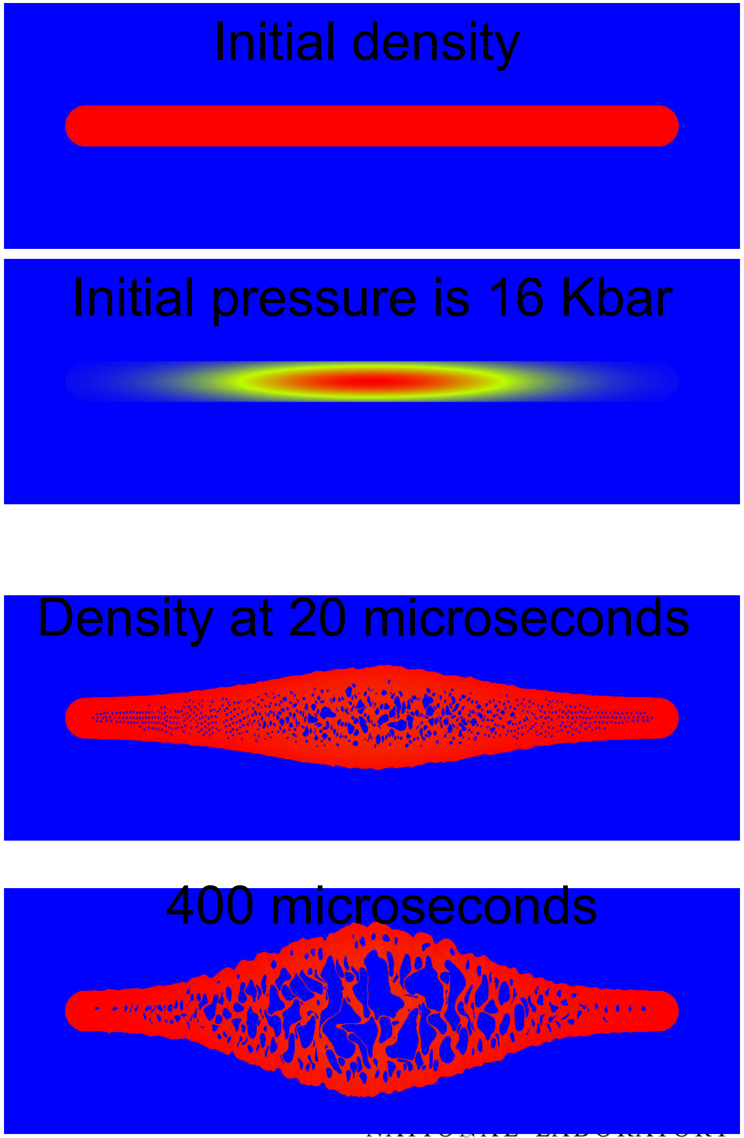
$$P_c \cong -\left(\frac{16\pi S^3}{3kT\ln\left(J_0 V dt\right)}\right) \qquad R_C = \frac{2S}{\Delta P_C}$$

- AMR: Adaptive Mesh Refinement
- Riemann problem for the phase boundary

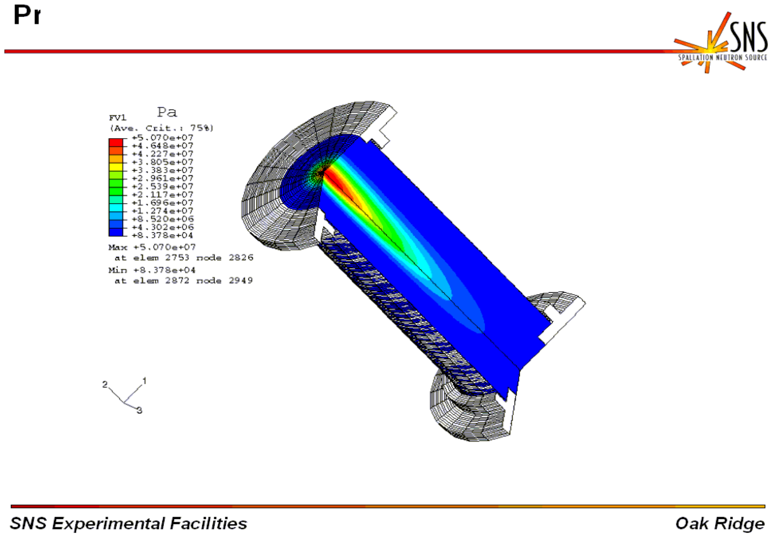


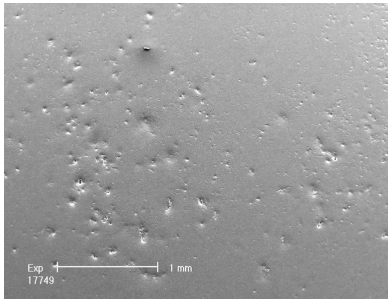
Cavitation in the mercury jet interacting with the proton pulse

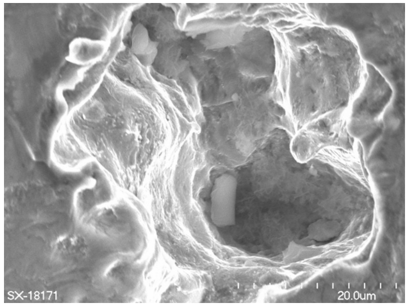




Application to SNS target problem



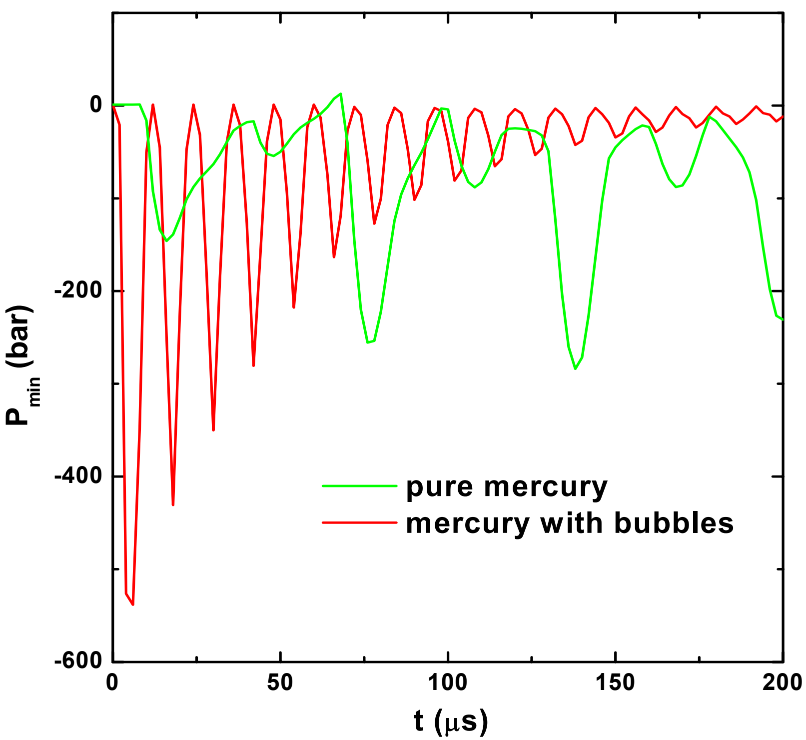




Left: pressure distribution in the SNS target prototype. Right: Cavitation induced pitting of the target flange (Los Alamos experiments)

- Injection of nondissolvable gas bubbles has been proposed as a pressure mitigation technique.
- Numerical simulations aim to estimate the efficiency of this approach, explore different flow regimes, and optimize parameters of the system.

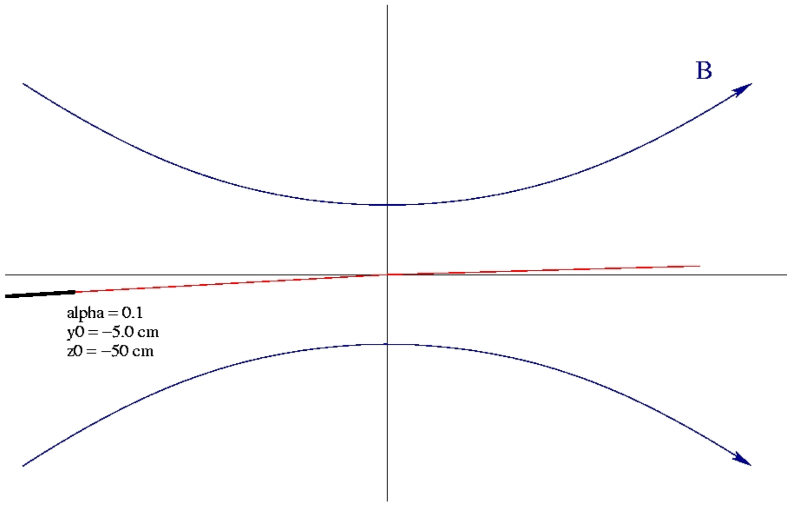
Application to SNS: gas bubble mitigation

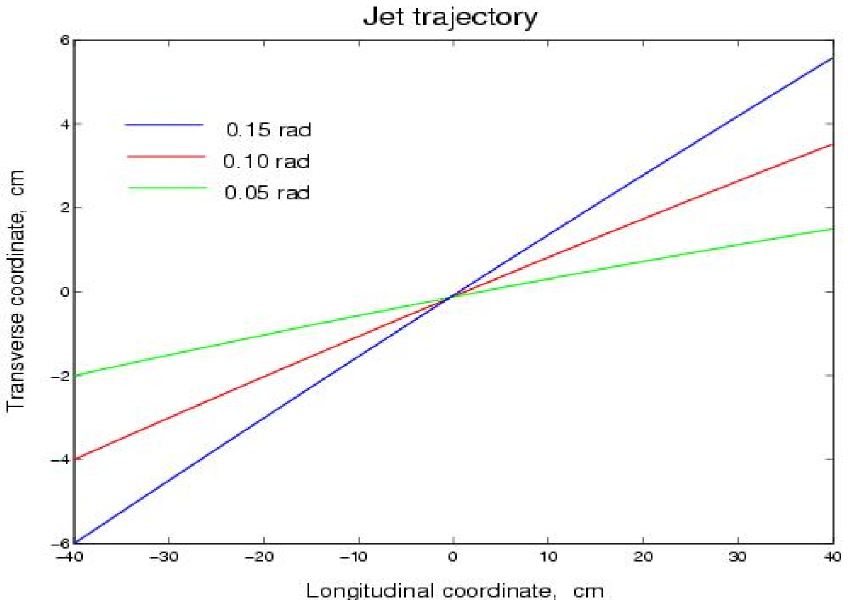


Effect of the bubble injection:

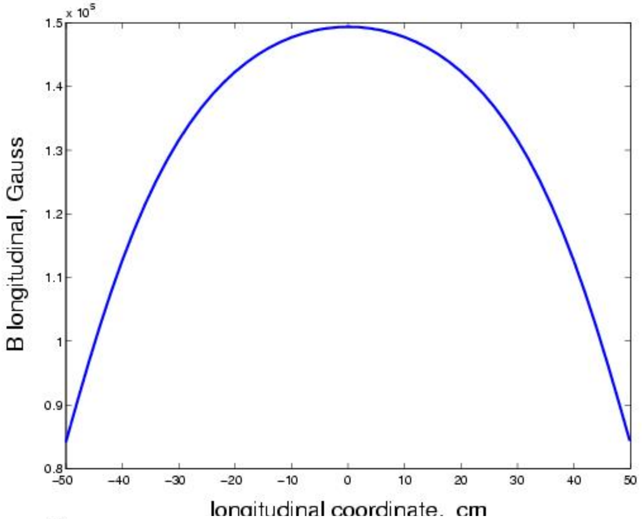
- Peak pressure decreases within 100 µs
- Fast transient pressure oscillations. Minimum pressure (negative) has larger absolute value.
- Formation and collapse of cavitation bubbles in both cases have been performed.
- The average cavitation damage was estimated to be reduced by > 10 times in the case of the bubble injection

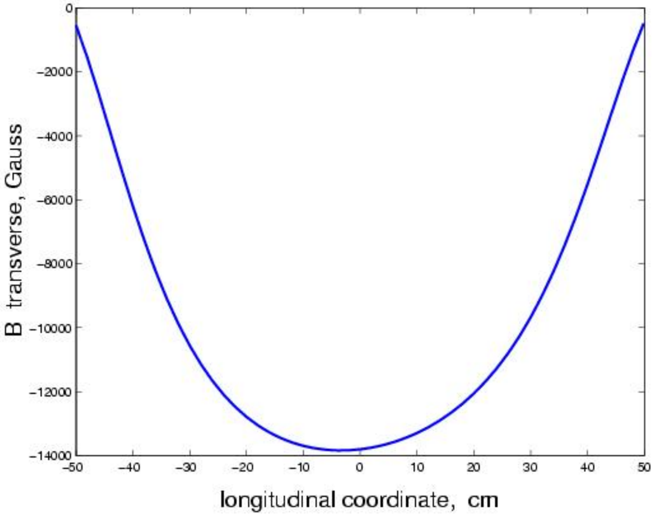
Mercury jet entering magnetic field.
Schematic of the problem.





Magnetic field of the 15 T solenoid along the jet trajectory





Incompressible steady state formulation of the problem

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P + \frac{1}{c}\left(\mathbf{J} \times \mathbf{B}\right)$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\left.\begin{array}{l} \mathbf{J} = \sigma\left(-\nabla \phi + \dfrac{1}{c}\mathbf{u} \times \mathbf{B}\right) \\ \nabla \cdot \mathbf{J} = 0 \end{array}\right\} \Rightarrow \Delta \phi = \frac{1}{c}\nabla \cdot \left(\mathbf{u} \times \mathbf{B}\right)$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = 0$$

$B.C.:$

$$\left.\frac{\partial \phi}{\partial \mathbf{n}}\right|_{\Gamma} = \frac{1}{c}(\mathbf{u} \times \mathbf{B}) \cdot \mathbf{n}$$

$$p_{\Gamma} - p_a = S\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

$$\mathbf{u}_{\Gamma} \cdot \mathbf{n} = 0$$

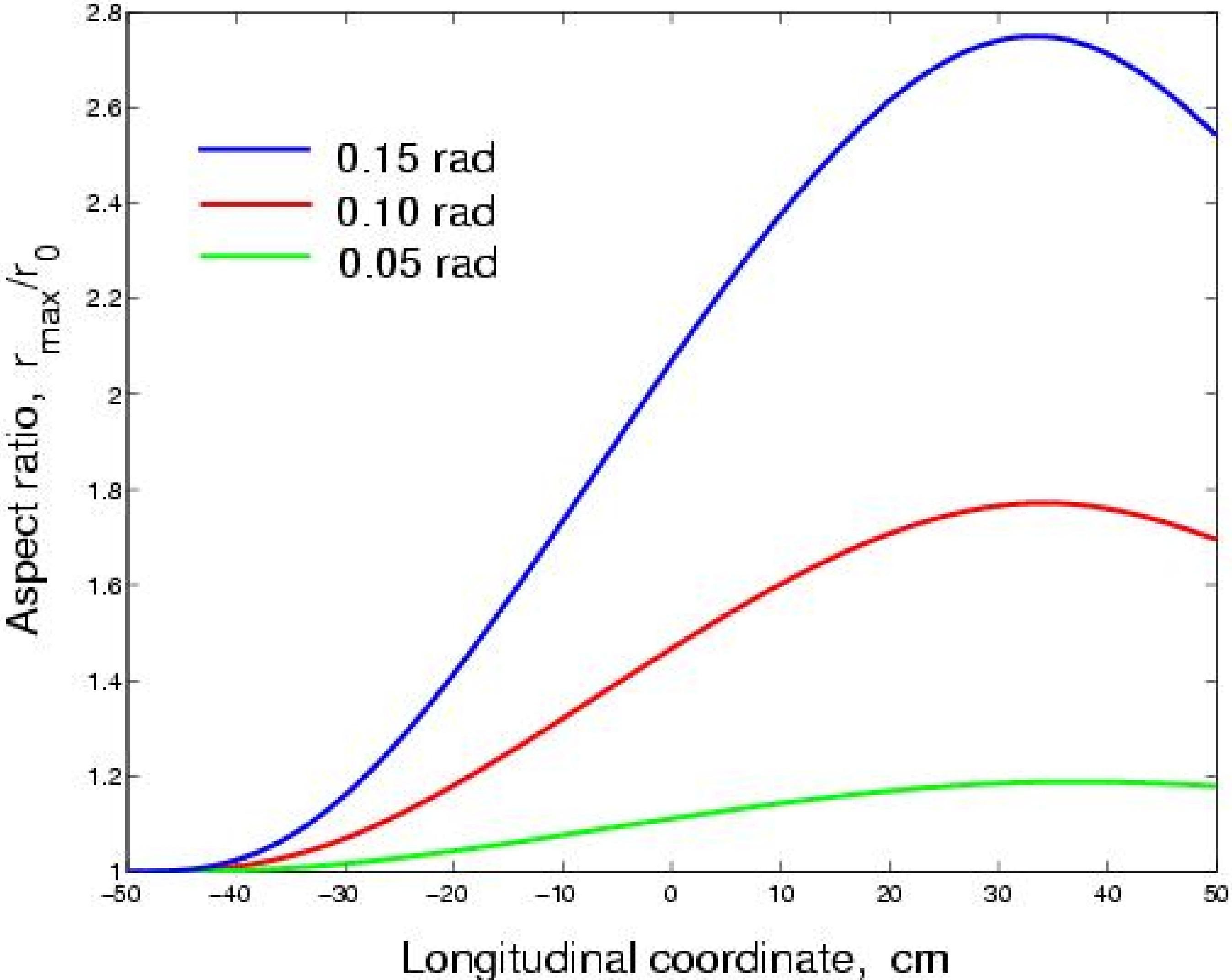
Direct numerical simulation approach (FronTier):

- Construct an initial unperturbed jet along the B=0 trajectory
- Use the time dependent compressible code with a realistic EOS and evolve the jet into the steady state

Semi-analytical / semi-numerical approach:

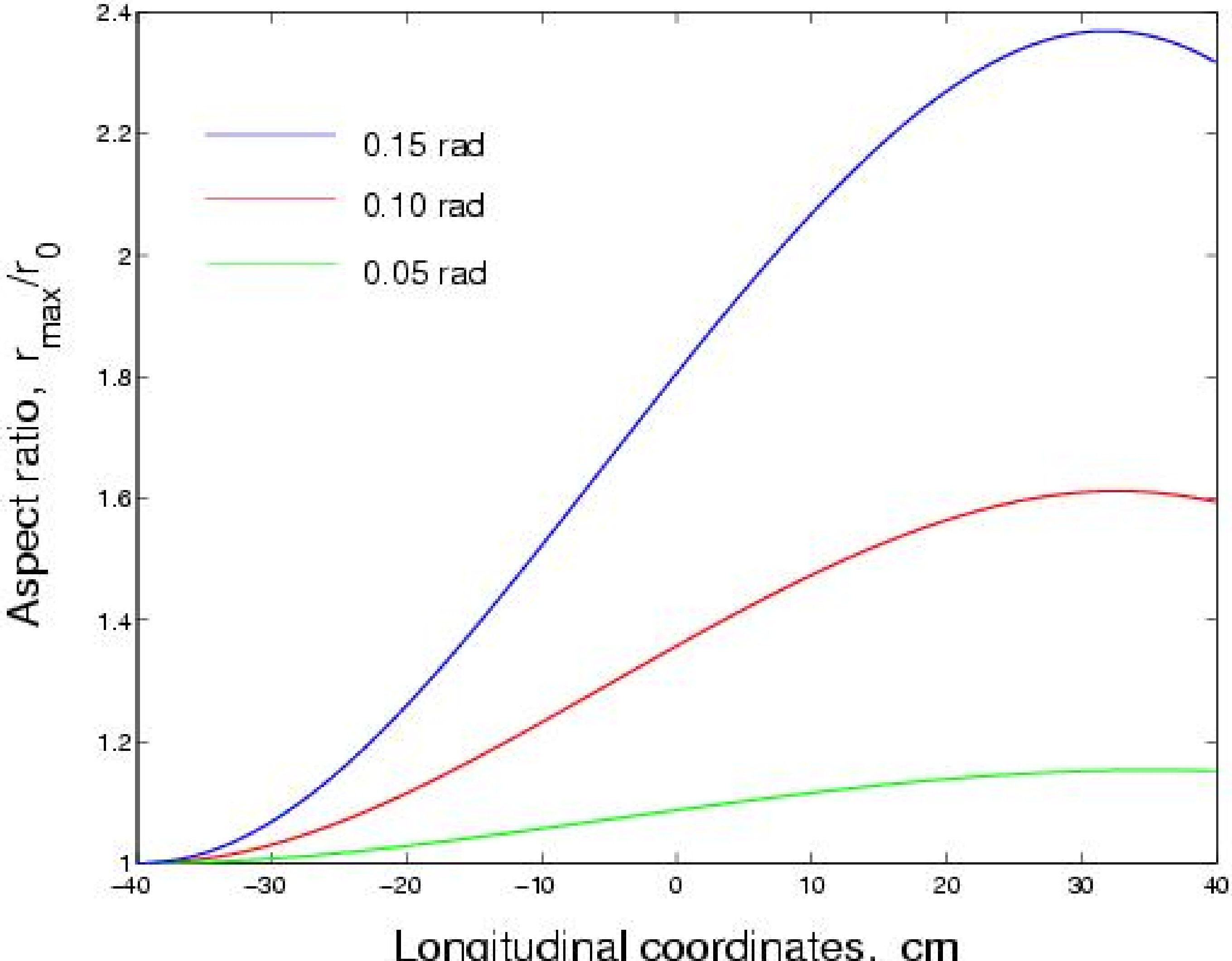
- Seek for a solution of the incompressible steady state system of equations in form of expansion series
- Reduce the system to a series of ODE’s for leading order terms
- Solve numerically ODE’s

Results: Aspect ratio of the jet cross-section



B = 15 T
V0 = 25 m/s

Results: Aspect ratio of the jet cross-section



B = 15 T
V0 = 25 m/s

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Conclusions and Future Plans

- New mathematical models and numerical algorithms for cavitation (phase transitions) have been developed
  - Heterogeneous method (Direct Numerical Simulation)
  - Riemann problem for the phase boundary
  - Dynamic cavitation algorithms based on the homogeneous nucleation theory
  - Adaptive mesh refinement
  - Applications to mercury targets
- Deformation of the mercury jet entering a magnetic field has been calculated
- 3D numerical simulations of the mercury jet interacting with a proton pulse in a magnetic field will be continued.