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Simulation of High-Intensity Mercury Jet Targets

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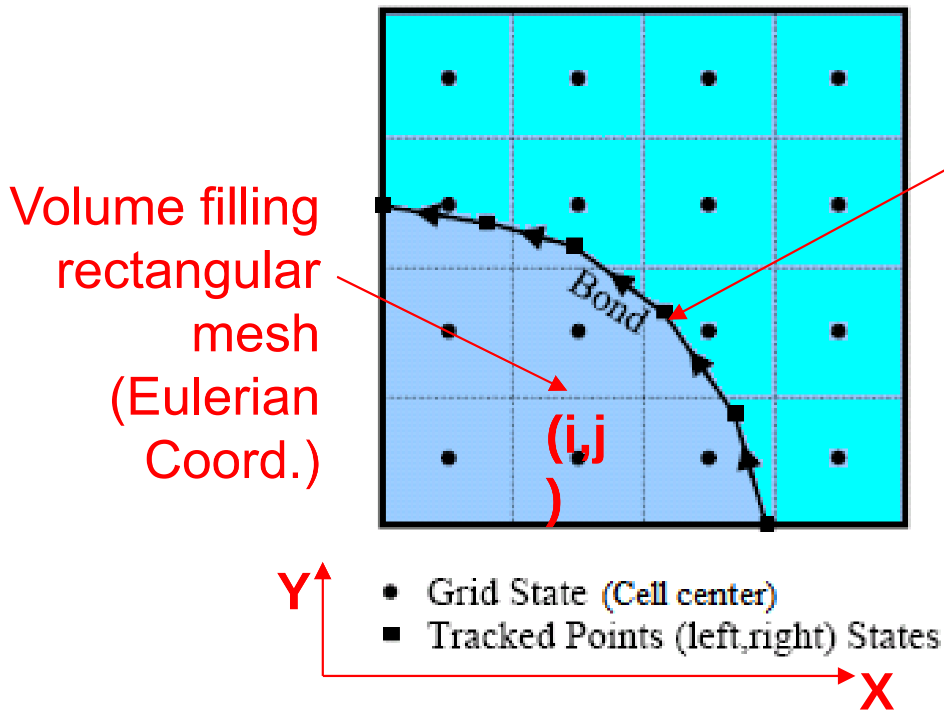
Talk Outline

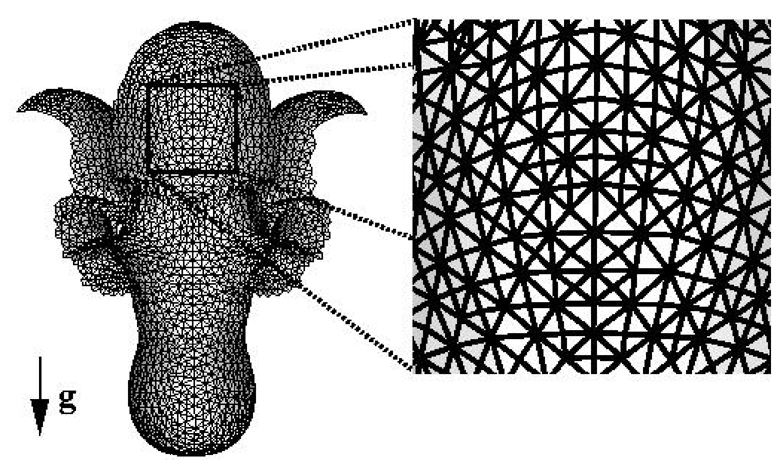
- FronTier simulations (grid-based simulations with explicitly tracked surfaces)
- SPH simulations (mesh-free simulations based on particles)
- Comparative analysis
- Summary and future plans

Main Idea of Front Tracking

- Front tracking is a hybrid Lagrangian-Eulerian method for systems with sharp discontinuities in solutions or material properties



2D Interface

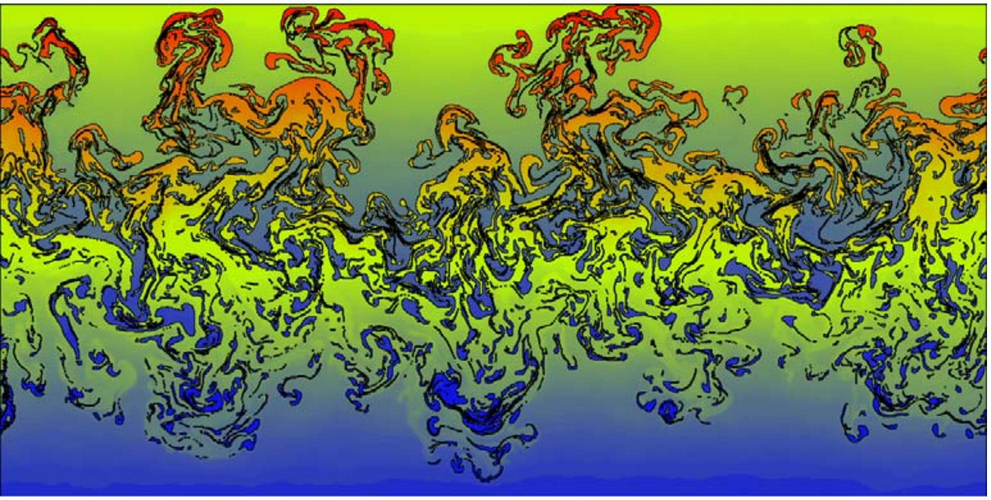


3D Interface

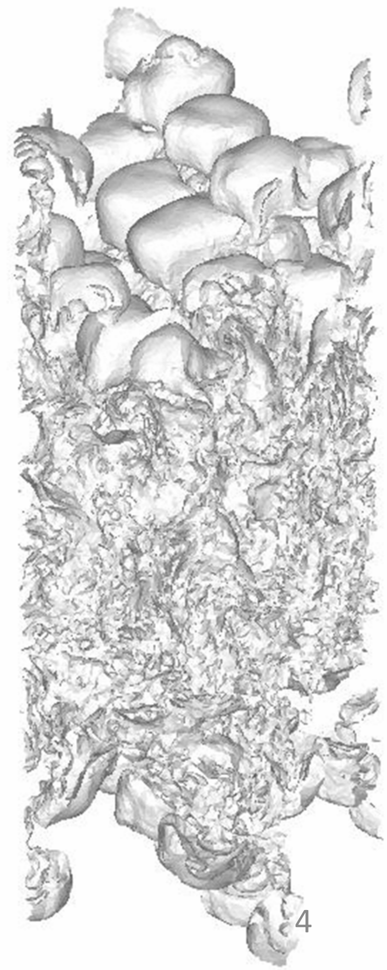
The *FronTier* Code (SciDAC ITAPS Software)

FronTier is a parallel 3D multiphysics code based on front tracking

- Physics models include
  - Compressible and incompressible fluid dynamics
  - MHD in low magnetic Reynolds number approximation
  - Flow in porous media
- Realistic EOS models, phase transition models
- Large selection of solvers
- Adaptive mesh refinement
- Under ITAPS, interoperable front tracking library (geometry package) has been developed



Turbulent fluid mixing.
Left: 2D
Right: 3D (fragment of the interface)



Main Approach of SPH

- Kernel approximation: replace the delta-function with a smooth kernel function

$$A(\vec{r}) = \int A(\vec{r}\,')\, W(\vec{r} - \vec{r}\,', h)\, d\vec{r}\,'$$

- Approximate this integral using some particle distributions

$$A(\vec{r}) = \sum_b m_b \frac{A_b}{\rho_b} W_{ab}$$

- Discretize Navier-Stokes (or MHD) equations in Lagrangian form

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\vec{\nabla} P + \vec{g} + \vec{\Theta}$$

Momentum PDE in Lagrangian system

Discretized Momentum Equation

$$\frac{d\vec{v}_a}{dt} = -\sum_b m_b \left(\frac{P_b}{\rho_b^2} + \frac{P_a}{\rho_a^2} + \Pi_{ab} \right) \vec{\nabla}_a W_{ab} + \vec{g}$$

Benefits of SPH

- A parallel SPH hydro / MHD code has been developed
  - Collection of solvers, smooth kernels, EOS and other physics models

- Exact conservation of mass (Lagrangian code)
- Natural (continuously self-adjusting) adaptivity to density changes
- Capable of simulating extremely large non-uniform domains
- Ability to robustly handle material interfaces of any complexity
- Scalability on modern multicore supercomputers

FronTier Simulations

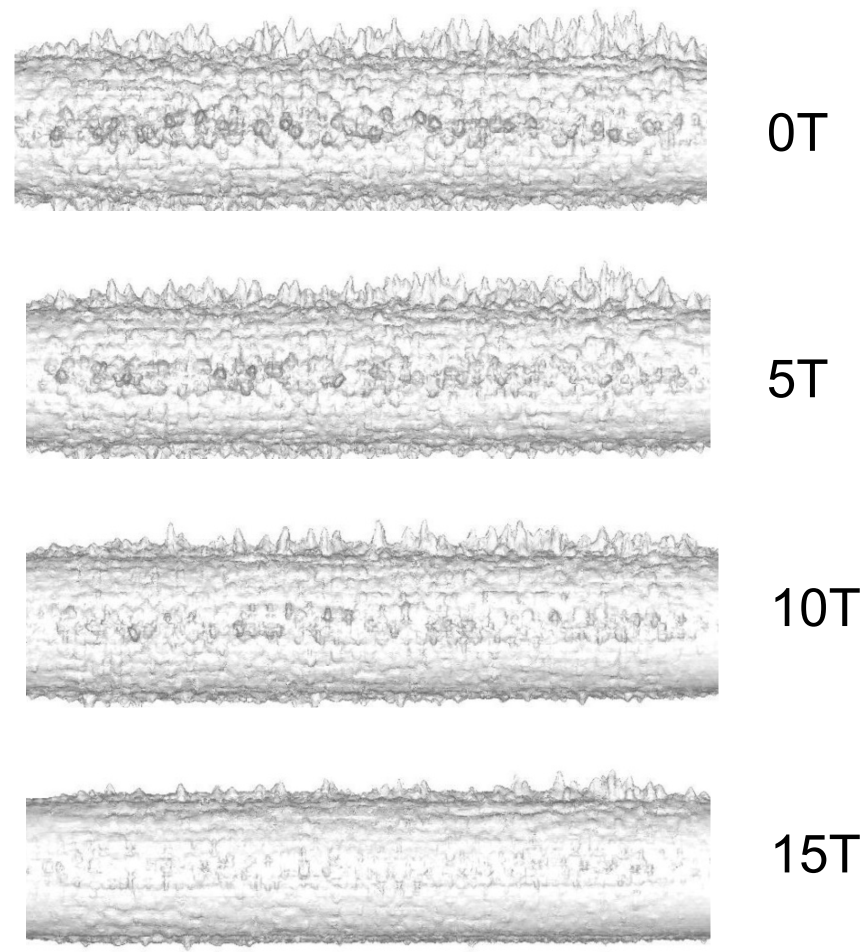
- Distortion of mercury jets entering solenoid magnets
- Disruption of mercury targets interacting with proton pulses
- Benchmark with MERIT experimental data

FronTier simulation of high speed jet cavitation and breakup

MHD Simulation of the mercury jet interaction with proton pulses

- Simulations predicted cavitation and surface filamentation
  - Cavitation is critical for the explanation of target behavior
  - Discrete bubble cavitation model
- Demonstrated stabilizing effect of the magnetic field
  - Magnetic field reduces the amount of cavitation and velocity of filaments
- Reasonable agreement with MERIT experiments on disruption velocities

- Only low time dynamics has been successfully achieved



Mercury jet surface at 150 microseconds after the interaction with 12 teraproton pulse

SPH Simulations

- Disruption of mercury targets interacting with proton pulses
- Entrance of spent mercury jets into the mercury pool

Muon Collider vs Neutrino Factory

Beam: 8 GeV, 4 MW, 3.125e15 particles/s, r.m.s. rad = 1.2 mm

Muon Collider:

15 bunches / s

66.7 ms interval

208 teraproton per bunch

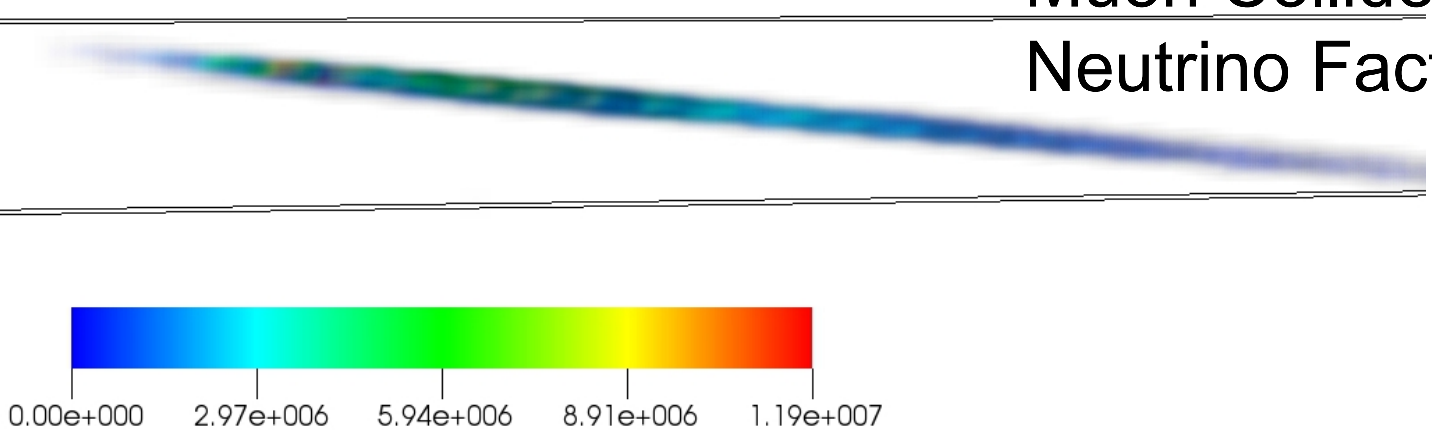
Neutrino Factory:

150 bunches / s

6.67 ms interval

20.8 teraproton per bunch

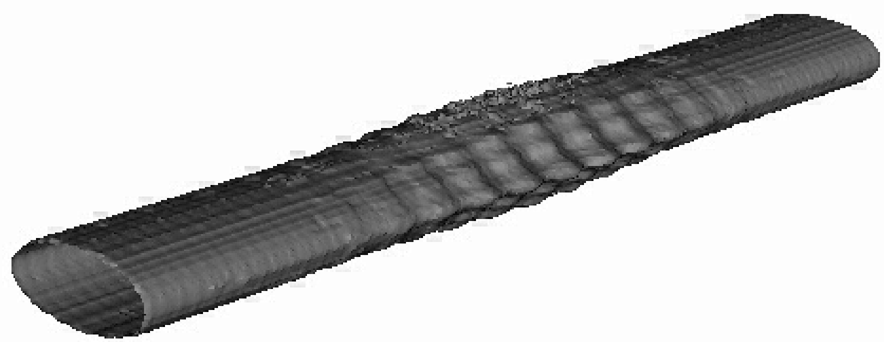
Maximum pressure (estimate):
Muon Collider: Pmax = 110 kbar
Neutrino Factory: Pmax = 11 kbar



Elliptical Mercury Jet after Interaction with Proton Pulse (I)

Orientation of the energy deposition profile is across the jet elliptic profile

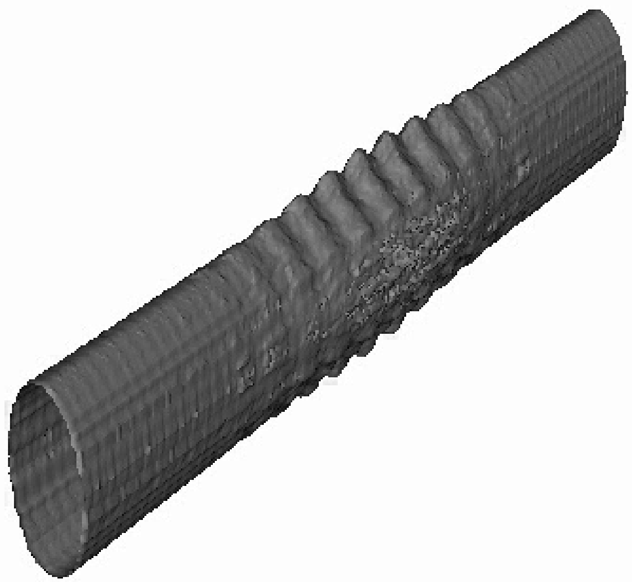
Velocities: 100 m/s (shorter axis), 20 m/s (longer axis)



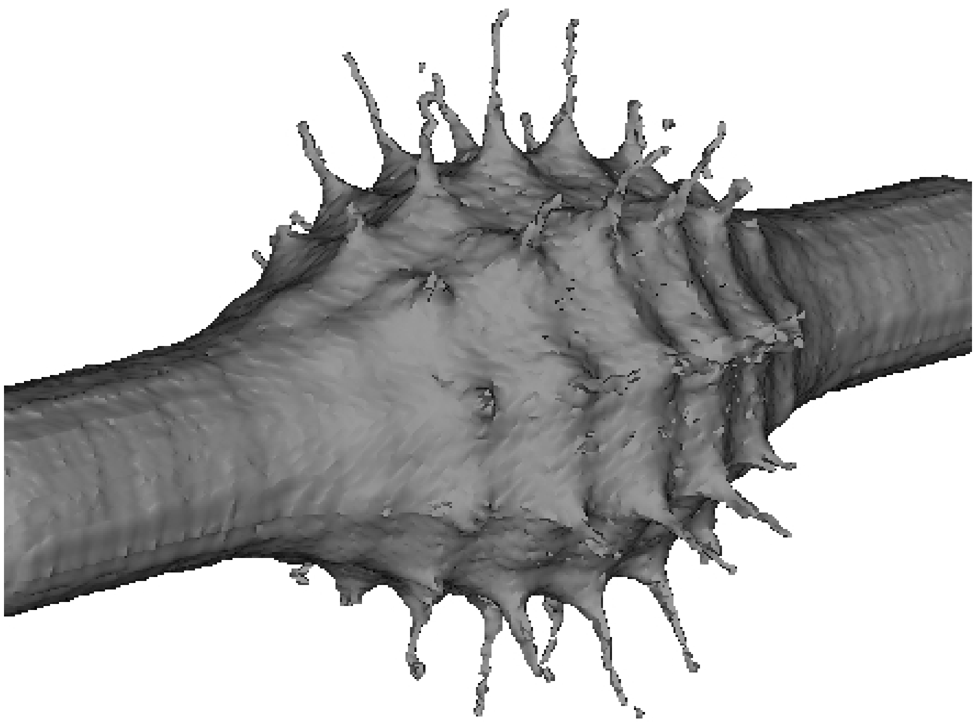
Elliptical Mercury Jet after Interaction with Proton Pulse (II)

Orientation of the energy deposition profile is along the jet elliptic profile

Velocities: ~80 m/s (shorter axis), ~30 m/s (longer axis)



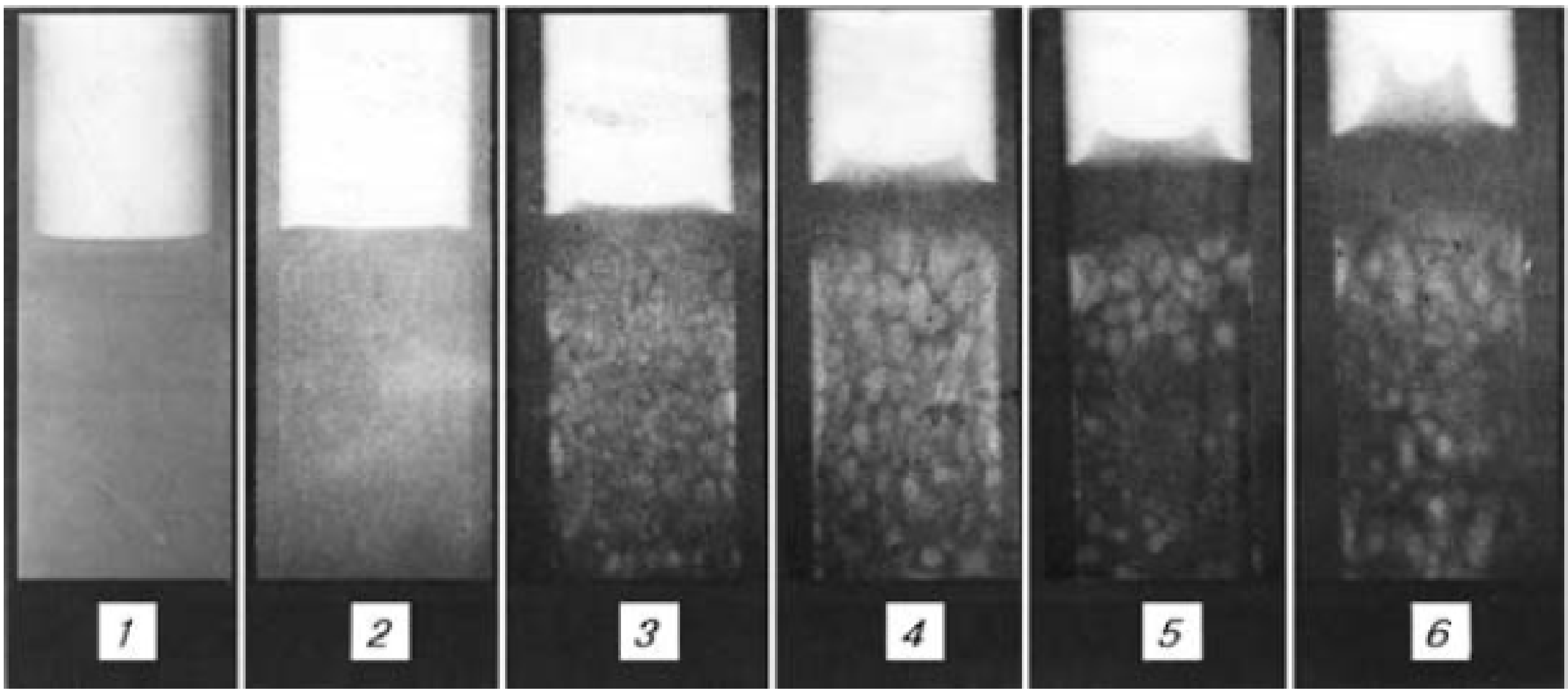
Cylindrical Mercury Jet after Interaction with Proton Pulse



Velocities: ~90 m/s

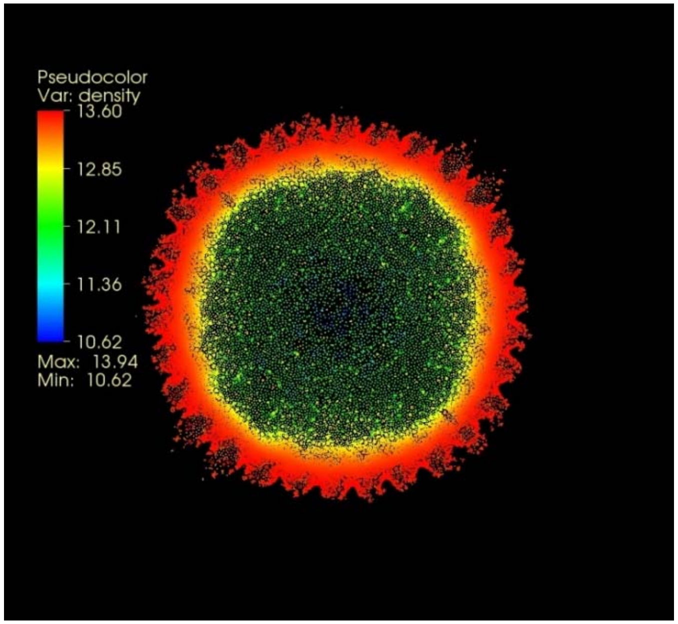
- **Simulations critically depend on the state of mercury inside the jet (on cavitation models)**

But what is the internal structure of the cavitation zone?

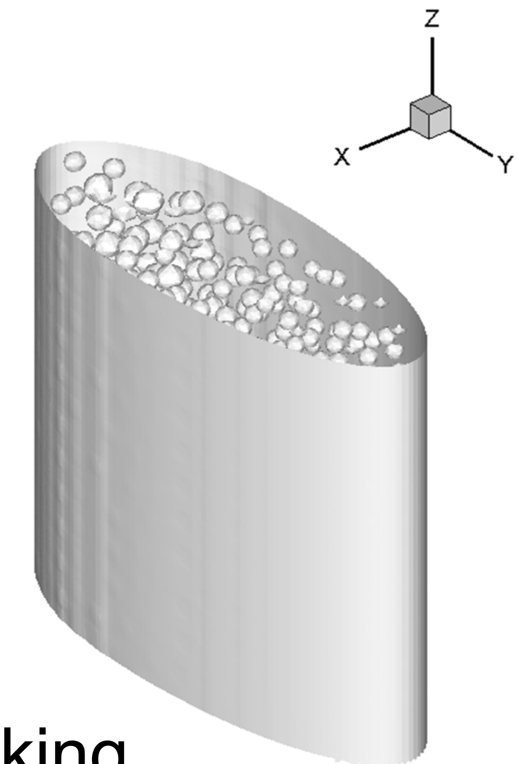


X-ray images of the dynamics of the cavitation zone in water
(the interval between frames is 200 μs)

Interior mercury state / cavitation with front tracking and SPH



SPH



Front tracking

- SPH is capable of making a transition to mesoscale
- Under high-energy impact, numerous microcracks in mercury are better modeled by particles compared to grid-based simulations with explicit cavitation bubbles

SPH Simulation of Mercury Jet Dump: Surface Visualization

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Summary

- Developed new smoothed particle hydrodynamics code for free surface / multiphase flows
  - Modular C++ design; the code is very stable
- Preformed simulations of targets interacting with proton pulses and jets entering a mercury pool, benchmarks with MERIT experiments
- Future plans: code development
  - Improve current interior solvers by using Riemann problem based solvers
  - Cavitation and breakup modeling, MHD
- Future plans: target studies
  - Perform comprehensive studies of mercury (and lighter Z) targets under various scenarios
- Release the code