Neutrino Factory / Muon Collider Target Meeting

Numerical Simulations for Jet-Proton Interaction

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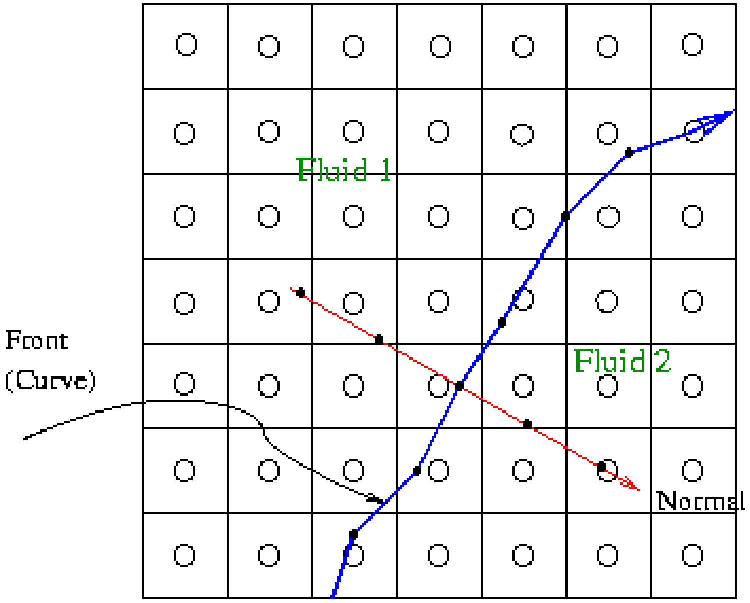
Outline

- FronTier code
- Simulations of the mercury jet – proton interaction.
- Conclusions and future plans

Main Ideas of Front Tracking

Front Tracking: A hybrid of Eulerian and Lagrangian methods



Two separate grids to describe the solution:

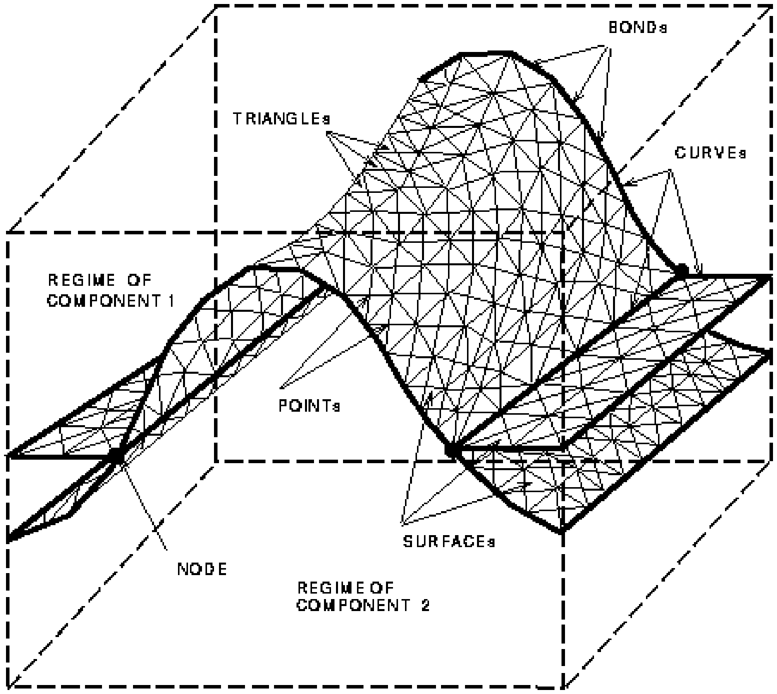
1. A volume filling rectangular mesh
2. An unstructured codimension-1 Lagrangian mesh to represent interface

Major components:

1. Front propagation and redistribution
2. Wave (smooth region) solution

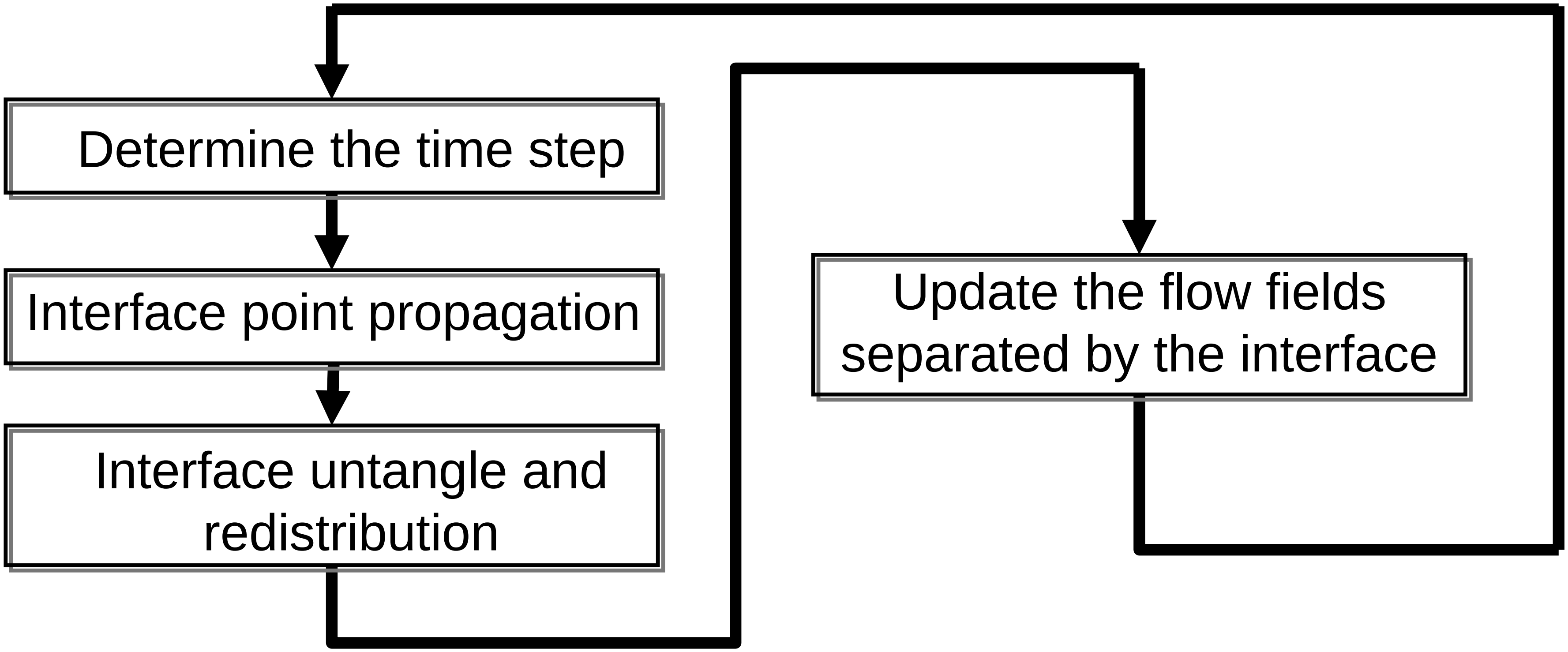
Advantages of explicit interface tracking:

- No numerical interfacial diffusion
- Real physics models for interface propagation
- Different physics / numerical approximations in domains separated by interfaces



Flow Chart of FronTier

Front tracking method is implemented in the code FronTier developed by AMS in Stony Brook university in collaboration with LANL and BNL. The following is the control flow for time stepping in FronTier.



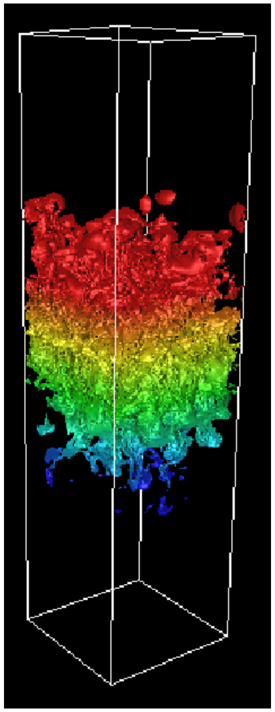
Determine the time step

Interface point propagation

Interface untangle and redistribution

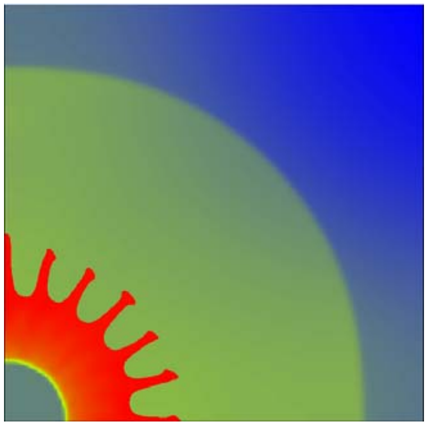
Update the flow fields separated by the interface

Main *FronTier* Applications

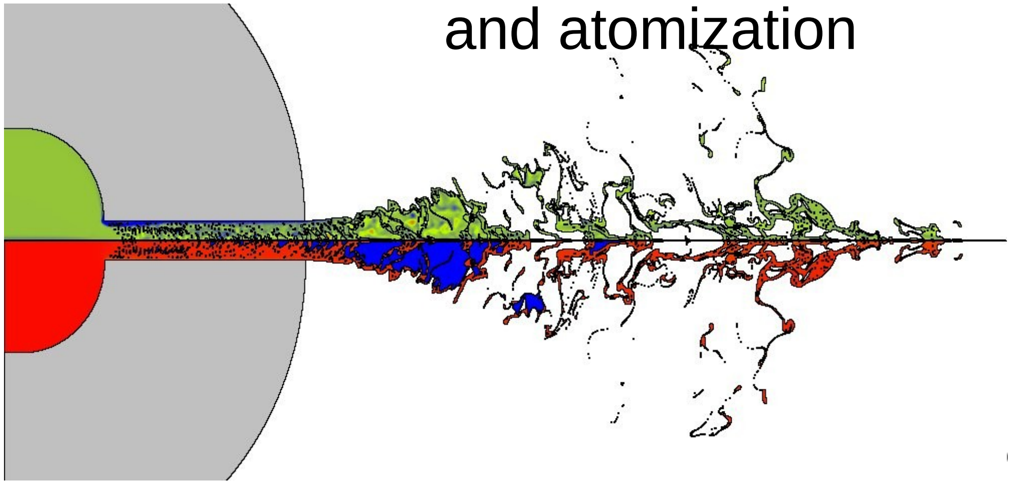


Rayleigh-Taylor instability

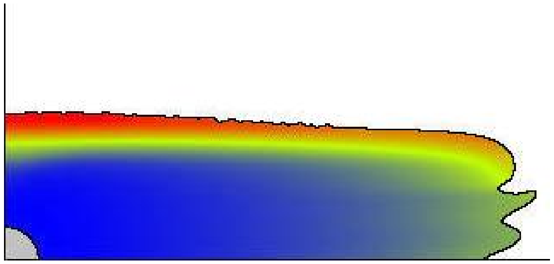
Richtmyer-Meshkov instability



Liquid jet breakup and atomization

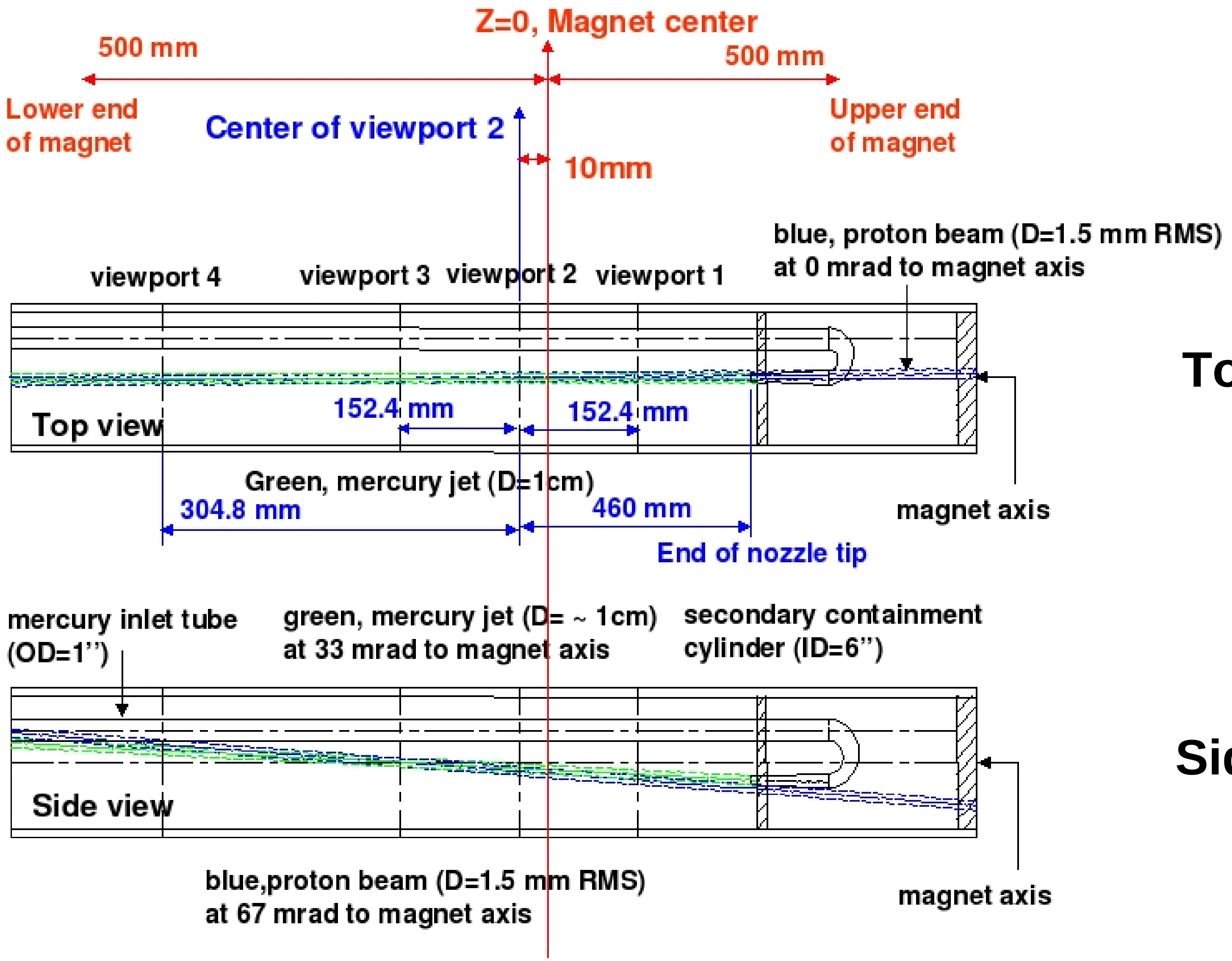


Tokamak refueling through the ablation of frozen D_2 pellets



MERIT setup

Geometry of Hg system in Magnet



Top view

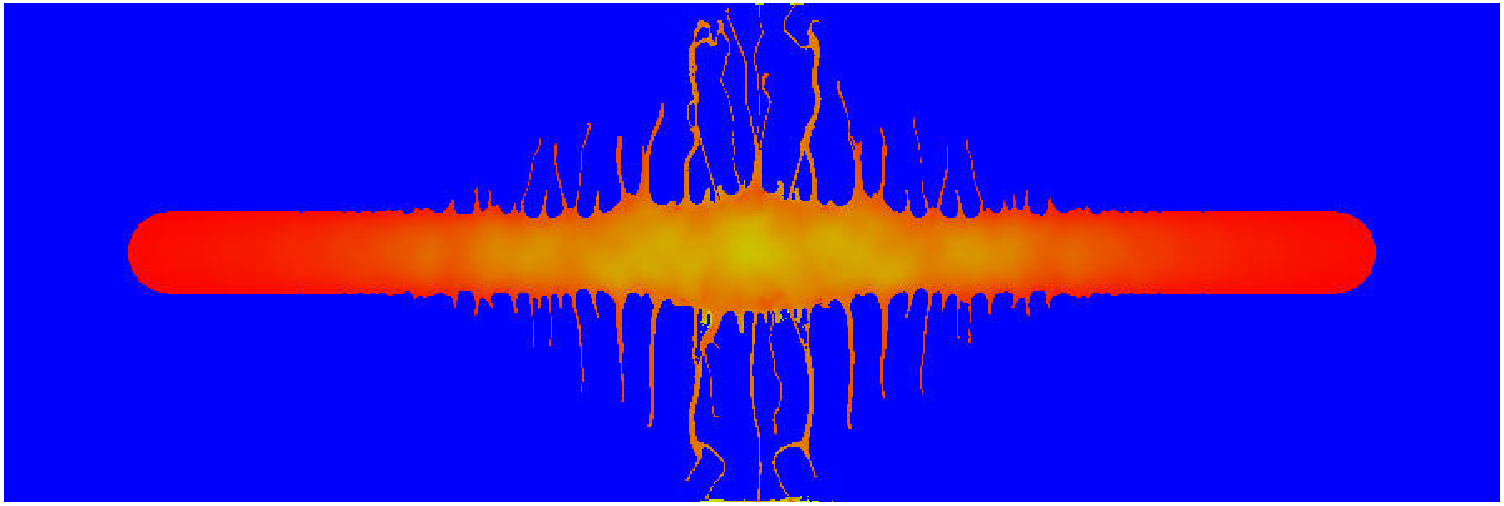
Side view

Previous Work: Single phase mercury (no cavitation)

- Strong surface instabilities and jet breakup observed in simulations

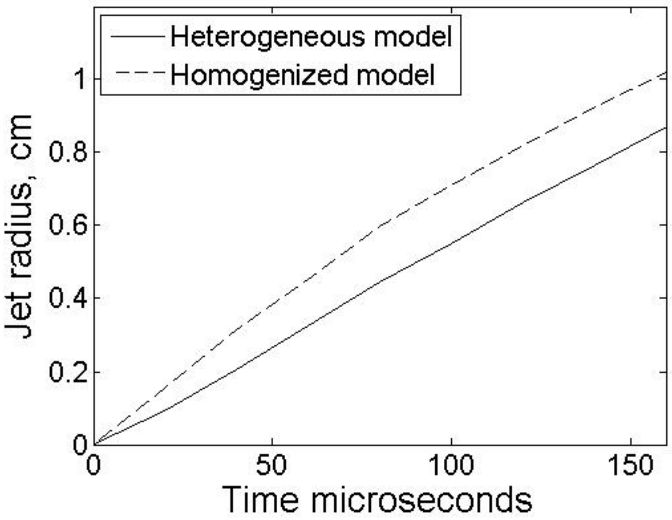
- Mercury is able to sustain very large tension
- Jet oscillates after the interaction and develops instabilities

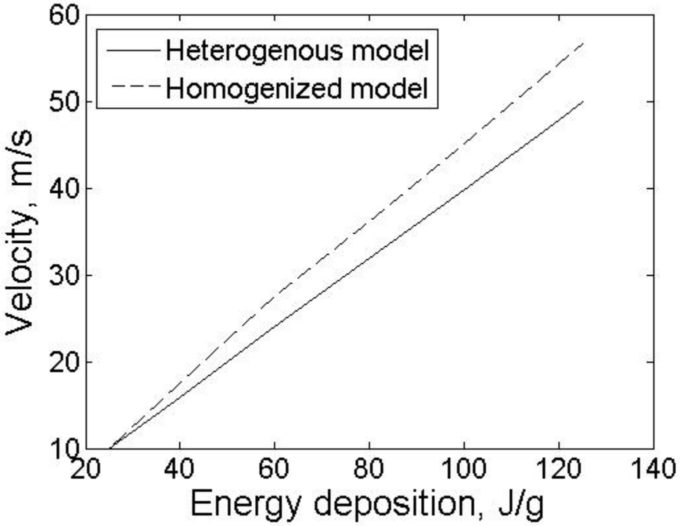
Jet surface instabilities



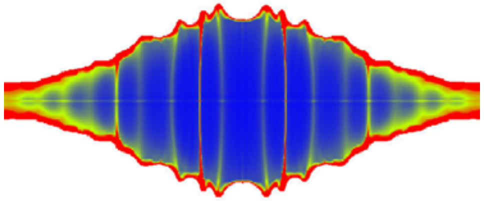
Previous Work: Cavitation models

- We evaluated and compared homogeneous and heterogeneous cavitation models:

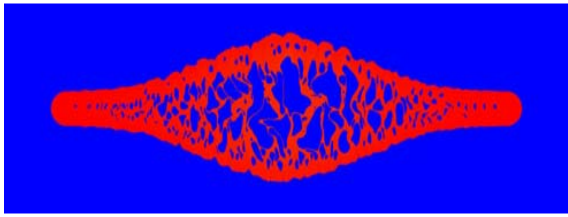




- Two models agree reasonably well
- Predict correct jet expansion velocity
- Surface instabilities and jet breakup is not present in simulations

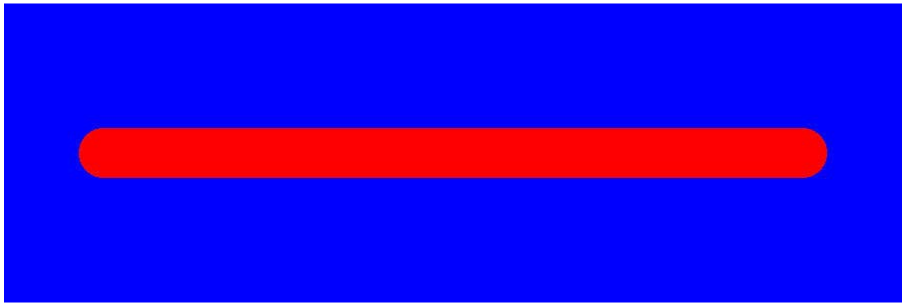


Homogeneous model

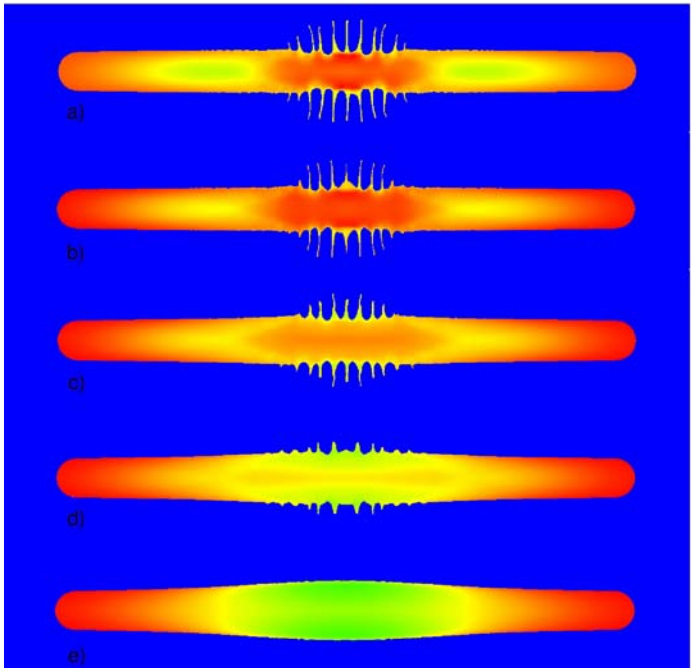


Heterogeneous model (resolved cavitation bubbles)

Previous Work: Effect of Magnetic Field



Initial surface



a) B = 0
b) B = 2T
c) B = 4T
d) B = 6T
e) B = 10T

Stabilizing effect of the magnetic field.

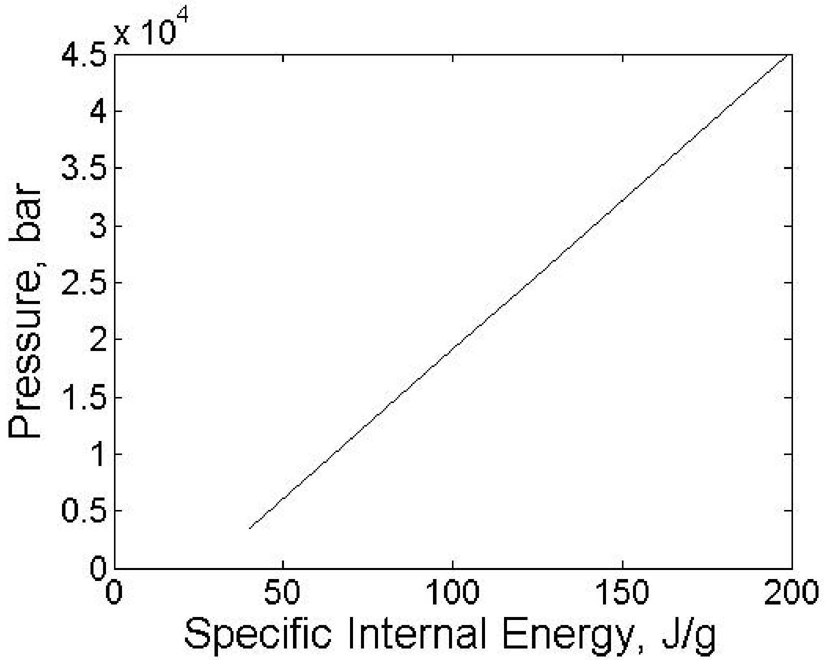
The Objectives of Current Work

- Perform 3D simulations which are comparable with those from 2D. Evaluate the jet expansion speed and surface instabilities and compare with experimental results.

- Obtain the state of the target before interaction from jet simulation. Study If the initial state has any effect on the evolution of mercury target after proton Interaction.

Energy Deposition by Proton Beam

- Peak density of energy deposition in Hg for a proton beam is 100J/g.
- It is an isochoric (constant volume) process, because the time scale for deposition is very short.
- Peak pressure can be estimated as

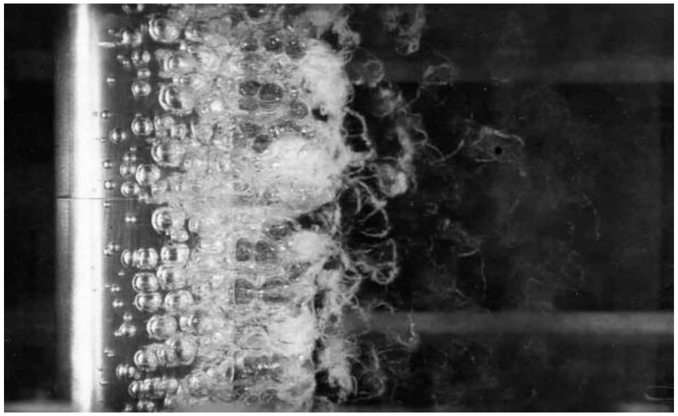


$$P \approx \frac{\alpha_v K}{c_p} E_{dep}$$

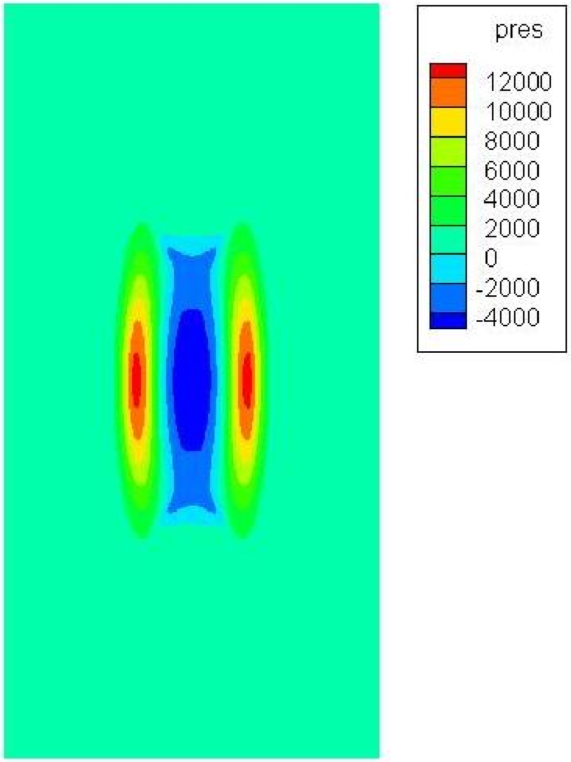
α_v	Thermal volumetric expansion coefficient	$1.8 \times 10^{-4} / K$
K	Bulk modulus	$2.85 \times 10^{8} Pa$
c_p	Specific heat capacity	$138 J / Kkg$
E_{dep}	density of energy deposition	

Cavitation Bubbles

- The high pressure induced by energy deposition leads to the production of large amplitude pressure waves in the mercury.
- Cavitation bubbles forms as the local tension exceeds the tensile strength of the liquid.



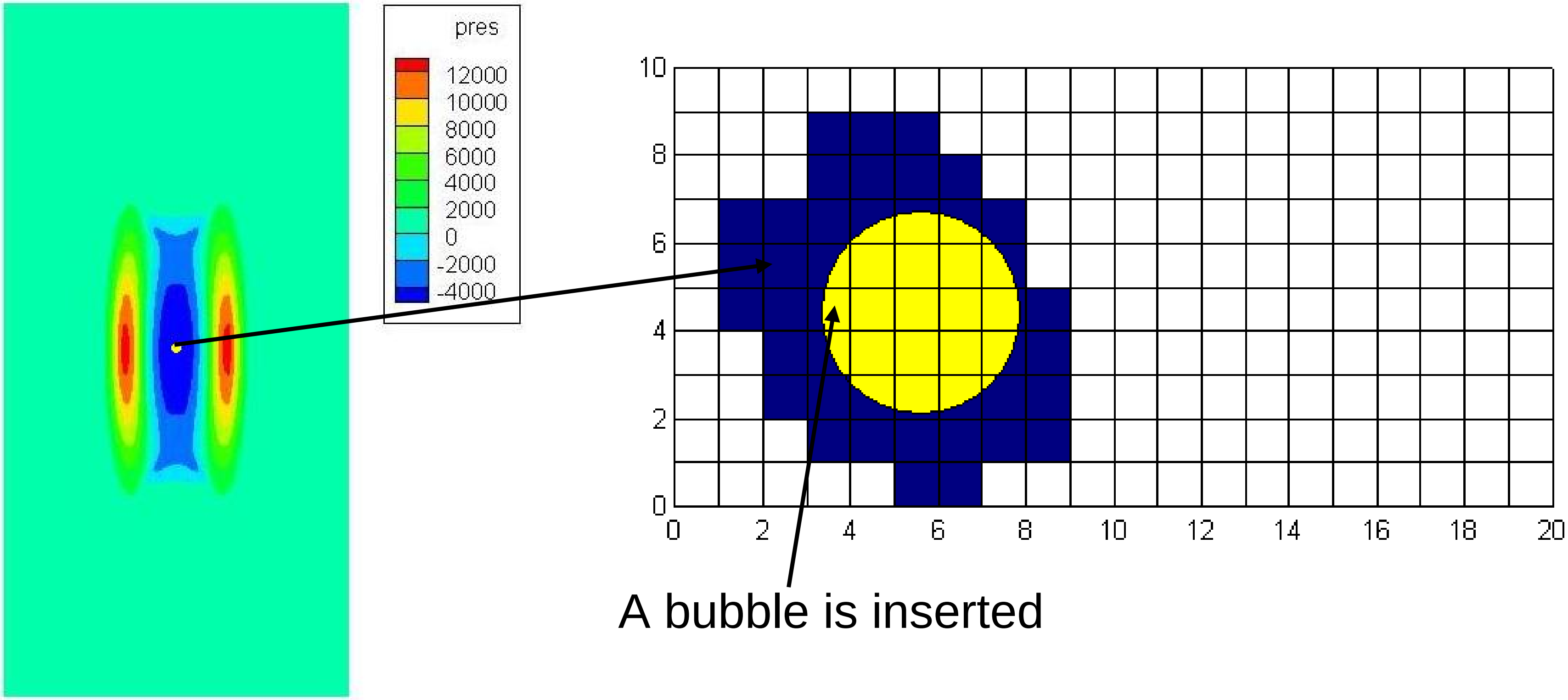
Cavitation bubbles on the surface of a hydrofoil



Pressure contour in mercury target.

The Bubble Insertion Model

- Numerical bubble insertion model models the bubble as a interface which separates the vapor and the fuel.
- As bubbles are inserted, the large tensile strength in mercury jet is released.



A bubble is inserted

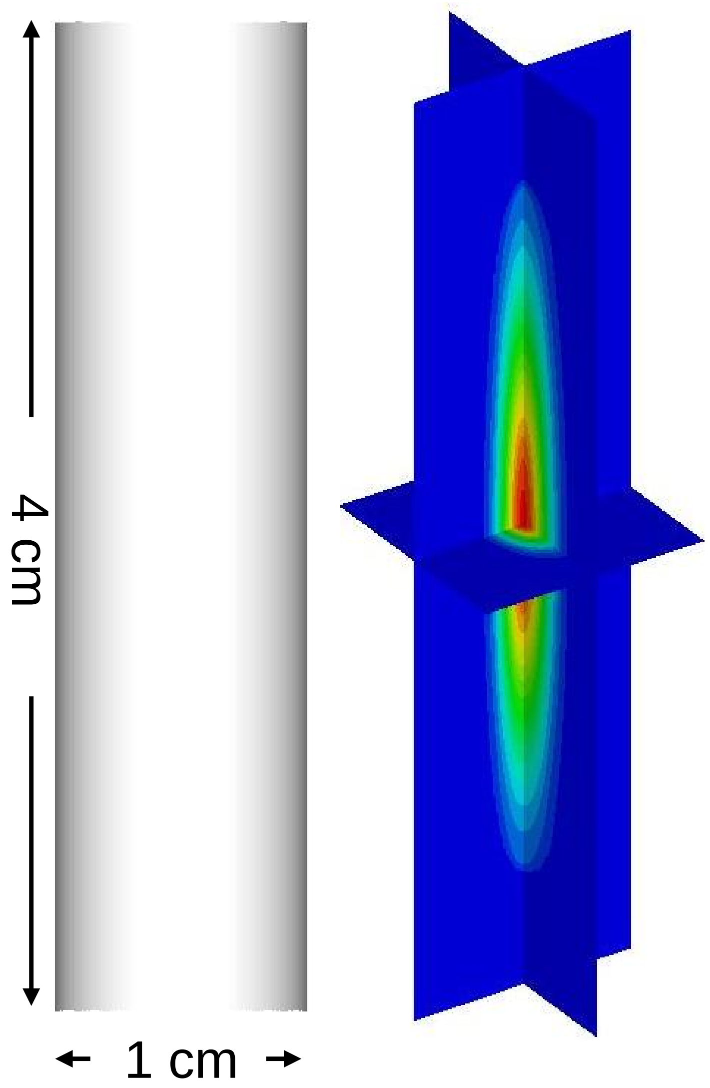
Setup of the Simulation for Testing

- Diameter of the cylinder: 1cm
- Height of the cylinder: 4cm
- Mercury is modeled by stiffened polytropic equation of states with $p_\infty = 8 \times 10^5 bar$
- Mesh: 160x160x320
- The distribution of the energy deposition is approximated by a 3D Gaussian distribution:

$$E_0 \exp(-(x/k_1)^2)\exp(-(y/k_2)^2)\exp(-(z/k_3)^2)$$

$$E_0 = 100 J/g$$

$$k_1 = 1.1mm \quad k_2 = 3.3mm \quad k_3 = 6.0mm$$



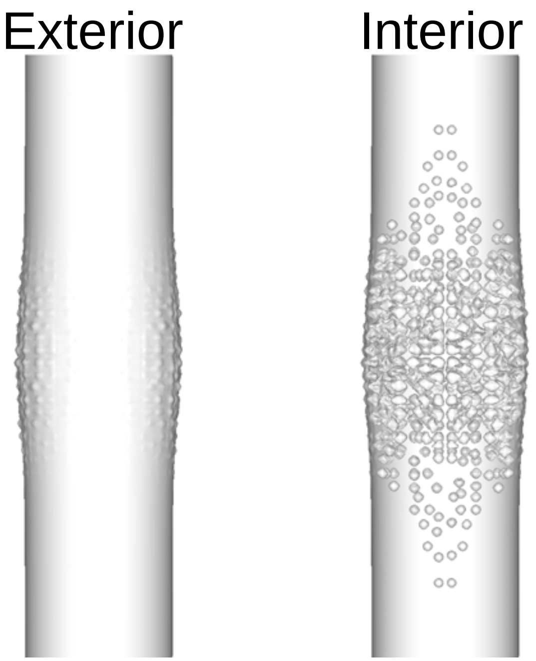
Evolution of the Jet with Bubble Insertion Model

Parameters:

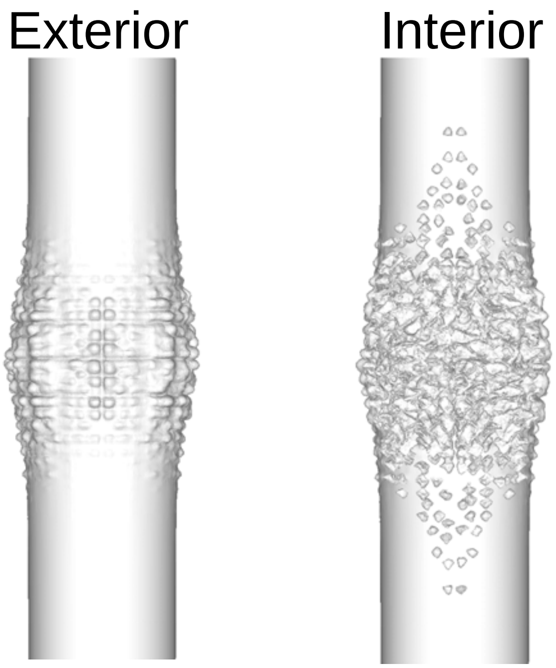
- The cavitation threshold $P_c = -1000$bar is estimated from thermodynamic equilibrium.
- The initial bubble size is 5dx=0.6mm.

Results:

- Bubble expansion near the surface can generate perturbation on the surface.
- Jet expansion velocity is about 30m/s.
- jet breakup is not present in simulations.



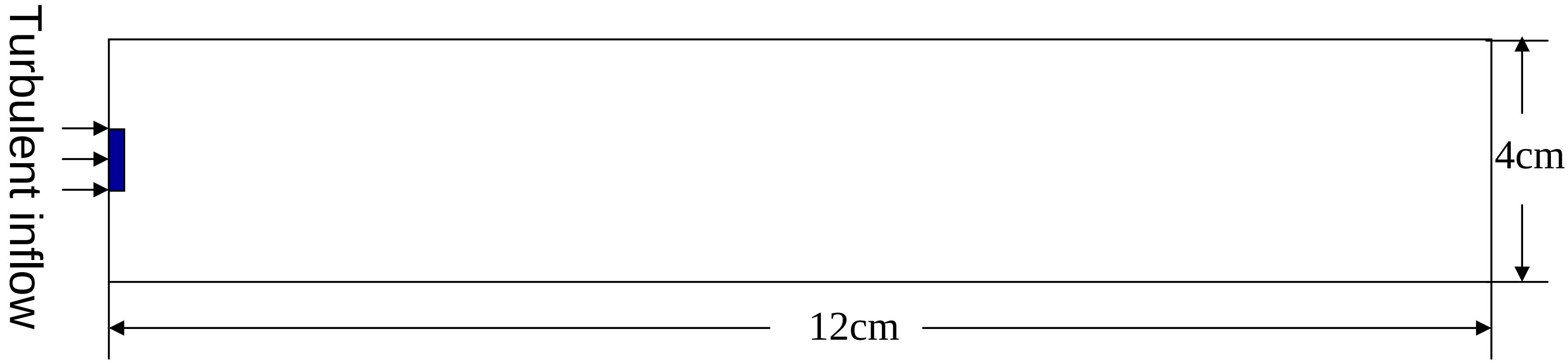
$15\mu s$



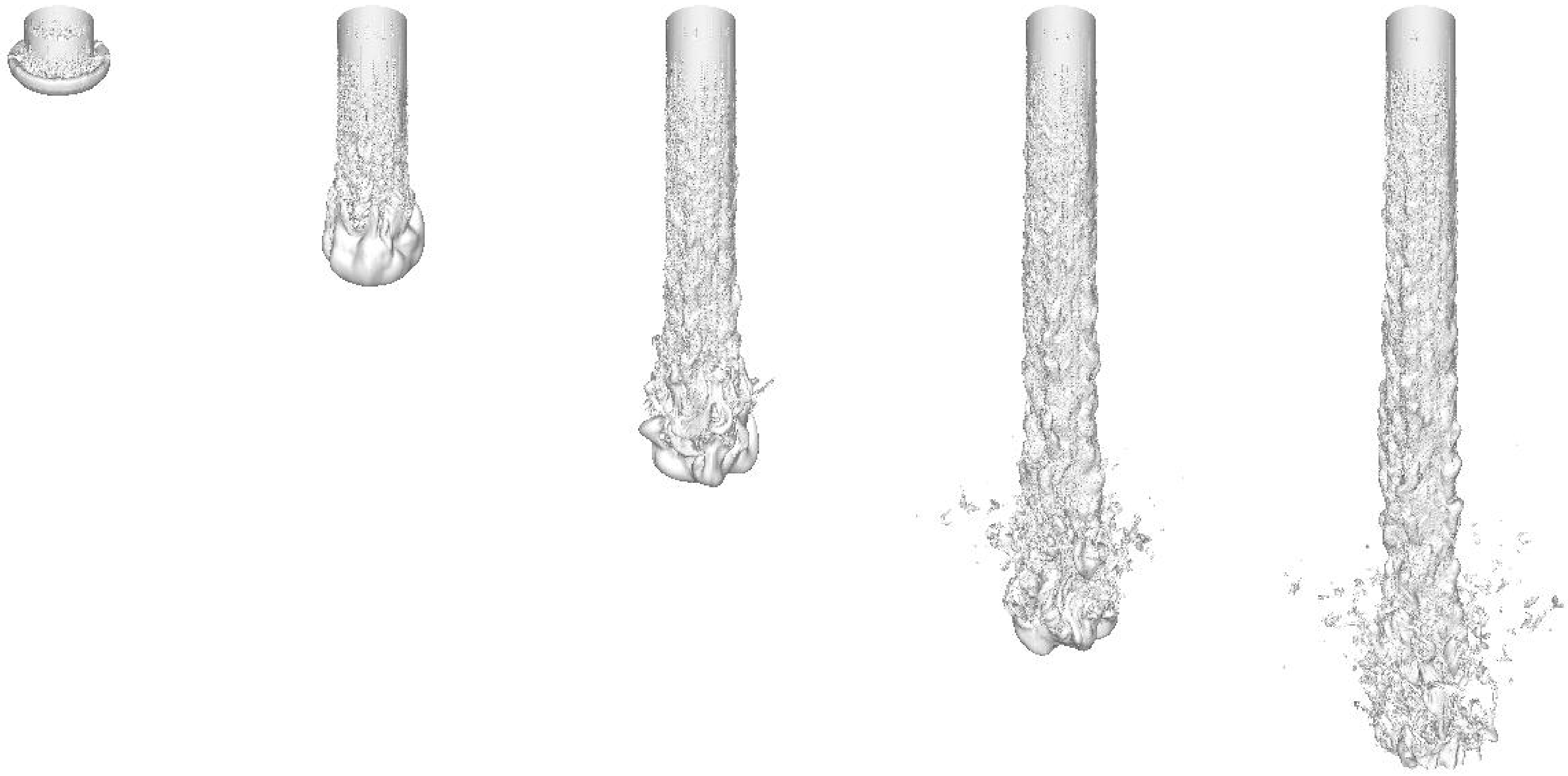
$50\mu s$

Jet Simulation(1)

- Jet simulation will provide surface instabilities and turbulence velocity which serve as the initial data for jet – proton interaction simulation.
- The pipe is long enough, the transition to fully developed turbulent flow is expected. The jet outside the pipe is simulated.
- The mean inflow speed is 50m/s, 40 cells across the nozzle diameter.

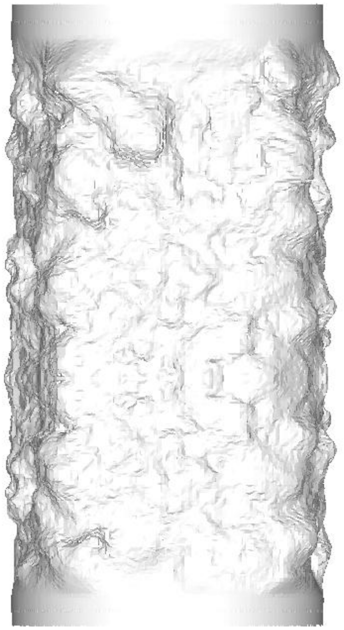


Jet Simulation(2)

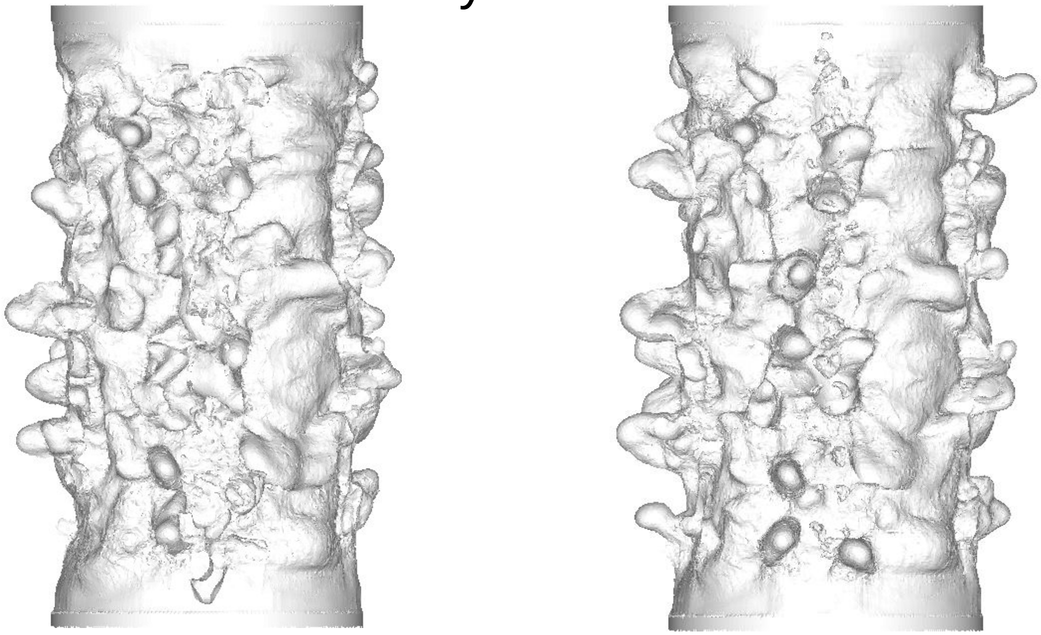


Simulation with Turbulent Jet

- One segment of the jet is cut and is used for the initial surface for target simulation.



Jet at t=0



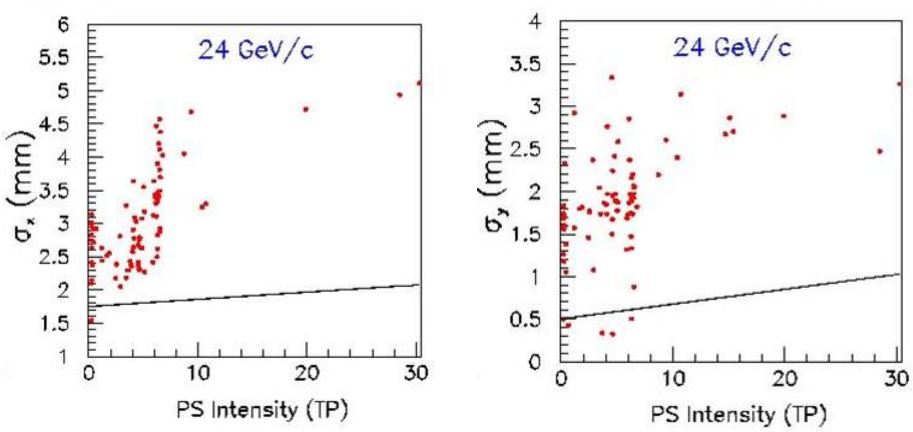
without turbulence velocity

with turbulence velocity

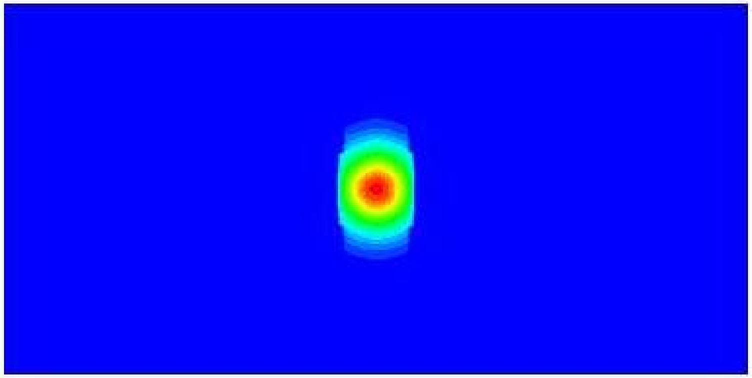
Jet at t=100 microseconds

Simulation with Elliptic Jet

- Under strong magnetic field, the cross-section of the jet becomes elliptical due to quadrupole effect.
- The energy deposition data comes from Goran Skoro’s measurement for peak energy 24Gev



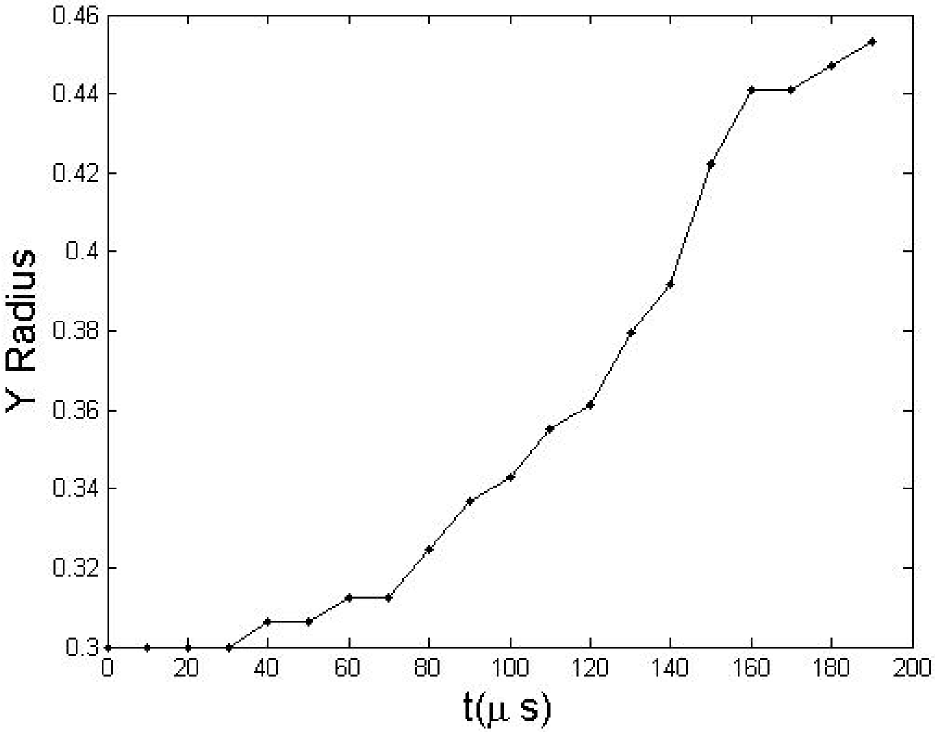
spot size data



Pressure contour in the initial time at plane z=0

Simulation with Elliptic Jet

- The jet expands along the minor axis.
- The velocity of expansion is about 11m/s.



Evolution of jet minor radius

Jet viewed from the minor radius.

Conclusions and Future Plans

Conclusions

- Qualitatively correct evolution of the jet surface due to the proton energy deposition.
- Initial instability of the jet surface is amplified by the pressure wave induced by energy deposition.
- The bubble expansion in 3D is not properly modeled due to the limitation of the code and the mesh resolution.

Future Plans

- Improve the model for bubble expansion so that correct physics can be captured.
- Perform 3D simulations considering magnetic field with fine grid.