Target Simulations

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Talk Outline

- FronTier code
- Distortion of the mercury jet entering magnetic field
- Simulation of the mercury jet – proton pulse 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
The *FronTier* Code

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

- Physics models include
  - Compressible fluid dynamics
  - MHD
  - Flow in porous media
  - Elasto-plastic deformations
- Realistic EOS models
- Exact and approximate Riemann solvers
- Phase transition models
- Adaptive mesh refinement

Interface untangling by the grid based method

(a)  (b)  (c)
Hyperbolic step

- Propagate interface
- Untangle interface
- Update interface states
- Apply hyperbolic solvers
- Update interior hydro states

Elliptic step

- Generate finite element grid
- Perform mixed finite element discretization or
- Perform finite volume discretization
- Solve linear system using fast Poisson solvers
- Calculate electromagnetic fields
- Update front and interior states

Point Shift (top) or Embedded Boundary (bottom)
Main Frontier Applications

Rayleigh-Taylor instability

Richtmyer-Meshkov instability

Liquid jet breakup and atomization

Tokamak refueling through the ablation of frozen D$_2$ pellets
Jet entering 15 T solenoid

FronTier code:

- Explicitly tracked material interfaces
- Multiphase models
- MHD in low magnetic Reynolds number approximation
Previous Results (2005)
Aspect ratio of the jet cross-section. I

\[ B = 15 \text{T} \]
\[ V_0 = 25 \text{ m/s} \]
Previous Results (2005)
Aspect ratio of the jet cross-section. II

B = 15 T
V0 = 25 m/s

0.10 rad, z = 0:
Aspect ratio = 1.4
Confirmation: Independent studies by Neil Morley, UCLA, HiMAG code

100 mrad tilt angle

z = 0 cm
z = 20 cm
z = 30 cm

z = 40 cm
z = 50 cm
z = 60 cm

Aspect ratio = 1.4 in the solenoid center
Comparison with the theory

Geometry of Hg system in Magnet

MERIT setup

- Lower end of magnet
- Center of viewport 2
- Upper end of magnet
- Viewports 1, 2, 3, 4
- Top view
- Side view
- Green, mercury jet (D=1 cm) at 33 mrad to magnet axis
- Mercury inlet tube (OD=1")
- Blue, proton beam (D=1.5 mm RMS) at 67 mrad to magnet axis
- Secondary containment cylinder (ID=6")
- End of nozzle tip
- Magnet axis
- Z=0, Magnet center
- 500 mm
- 10 mm
- 304.8 mm
- 460 mm
- 152.4 mm
$V = 15 \text{ m/s}, \quad B = 15 \text{ T}$
$V = 20 \text{ m/s}, \ B = 15 \text{ T}$

Jet trajectory

Bz

By

Jet distortion
Comparison: $V = 15$ and $20$ m/s, $B = 10$ and $15$ T
Experimental data

<table>
<thead>
<tr>
<th>V = 15 m/s, B = 10T</th>
<th>V = 20 m/s, B = 10T</th>
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<tbody>
<tr>
<td><em>QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.</em></td>
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Simulations only qualitatively explain the width of the jet in different view ports.
Jet - proton pulse interaction. Evolution of models.
Phase I: 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 - proton pulse interaction.
Phase II: 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 not present in simulations
Jet - proton pulse interaction
Phase II: Cavitation models in magnetic field

- The linear conductivity model predicts strong stabilizing effect of the magnetic field

- Stabilizing effect of the magnetic field is weaker if conductivity models with phase transitions are used (~ 20 % for Bruggeman’s model)

- If jet does not develop surface instabilities, the jet expansion is strongly damped in 15 T magnetic field (radial current are always present). Experimentally confirmed in MERIT.
Jet - proton pulse interaction
Phase III: Search of missing physics phenomena

Why surface instabilities and jet breakup are not observed in simulations with cavitation?

Possible Cause:

• Turbulence nature of the jet

• Microscopic mixture and strong sound speed reduction of the homogeneous model (separation of phases is important)

• Unresolved bubble collapse in the heterogeneous model
  • Bubble collapse is a singularity causing strong shock waves

• Other mechanisms?
• Bubble collapse (singularity) is difficult to resolve in global 3D model.

Multiscale approach:

Step 1: Accurate local model precomputes the collapse pressure

Step 2: Output of the local model serves as input to the global model
Step 1: 1D bubble collapse

Radius vs. Time

Pressure Profile at \( t = 0.0035 \text{ ms} \)
Step 2: 2D and 3D simulations of the collapse induced spike

- Bubble collapse near the jet surface causes surface instability
- The growth of the spike is not stabilized by the magnetic field
- This is unlikely to be the only mechanism for surface instabilities
Initial instability (turbulence) of the jet

This was the real state of the jet before the interaction with protons

This was initial jet in previous numerical simulations (in 2D and 3D)

The obvious difference might be an important missing factor for both the jet flattening effect and interaction with the proton pulse.
3D jet naturally growing from the nozzle

• Major numerical development allowed us to obtain the state of the target before the interaction by “first principles”

• Simulation of the jet - proton pulse interaction is in progress
Mercury jet before the interaction with proton pulse. No magnetic field.