MHD Studies of Mercury Jet Target

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Talk Outline

- Brief summary of modeling and simulation of hydro and MHD processes in the mercury jet target

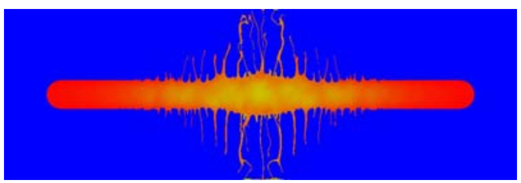
- Studies of the distortion of the mercury jet entering a 15 T magnetic solenoid

- Collaboration with UCLA computational MHD group

- Conclusions and future plans

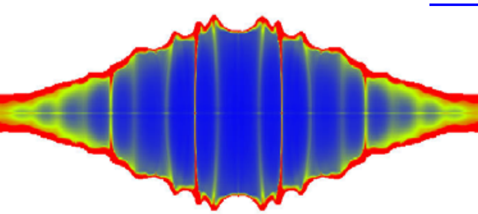
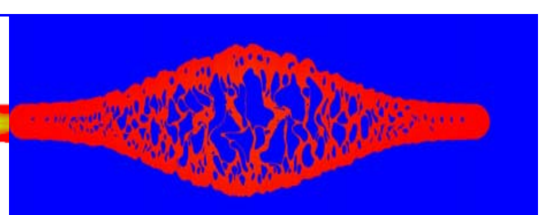
Brief summary of modeling and simulation

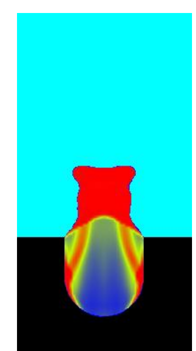
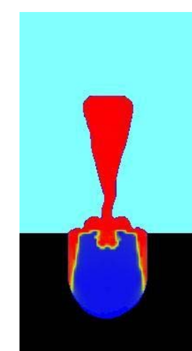
- Developed MHD code for compressible multiphase flows (more details in Jian Du's talk)
- Developed EOS homogeneous and heterogeneous models for phase transition (cavitation) and the Riemann solver for the phase boundary
- Studied surface instabilities, jet breakup, and cavitation
- MHD forces reduce both jet expansion, instabilities, and cavitation (will be discussed in Jian Du's talk)



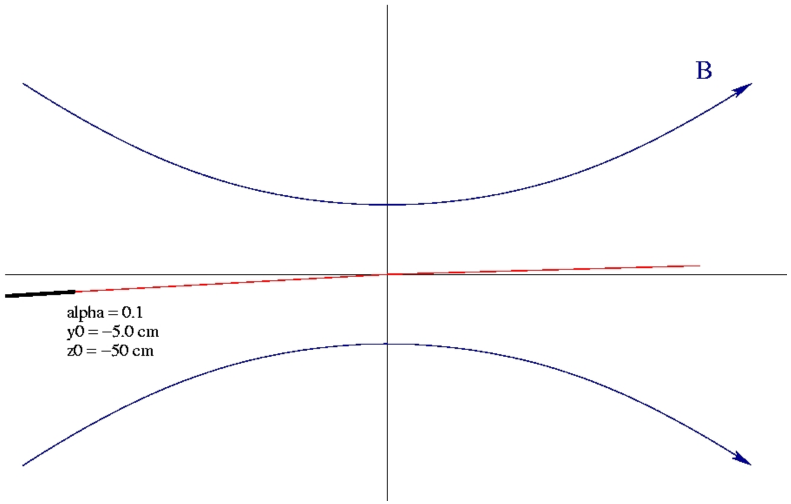
Jet surface instabilities

Cavitation in the mercury jet and thimble

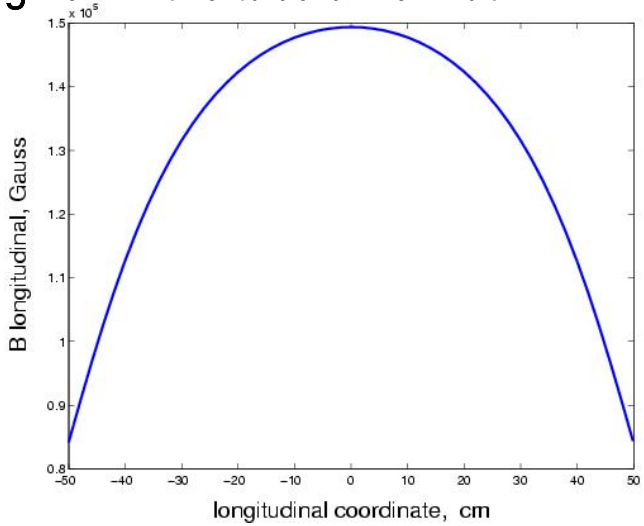



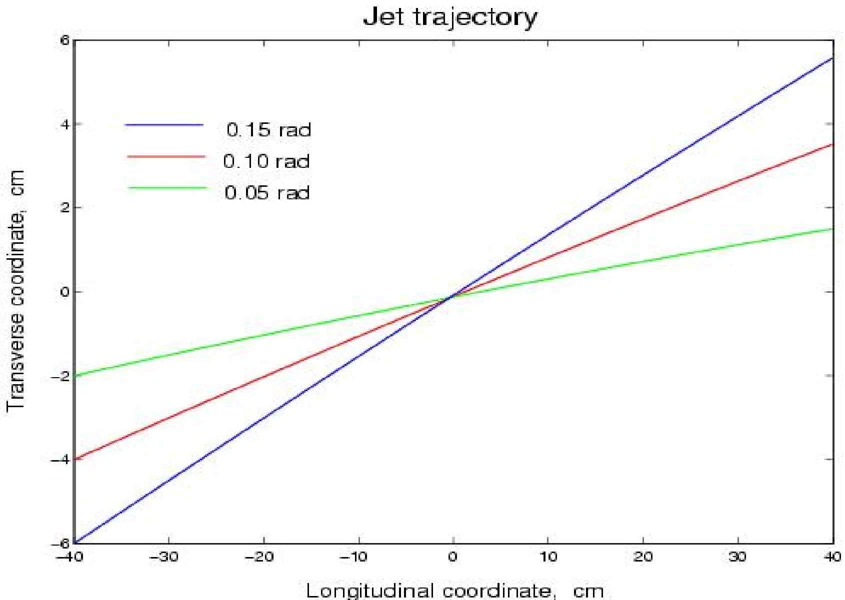



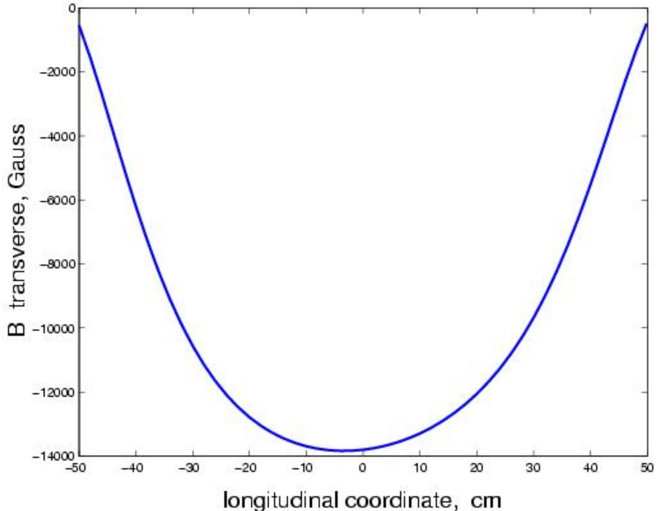
Mercury jet entering magnetic field.
Schematic of the problem.



Magnetic field of the 15 T solenoid is given in the tabular format







Incompressible steady state formulation of the problem

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

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

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

$$B.C.:$$

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

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

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

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

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

Direct numerical simulation approach (FronTier):

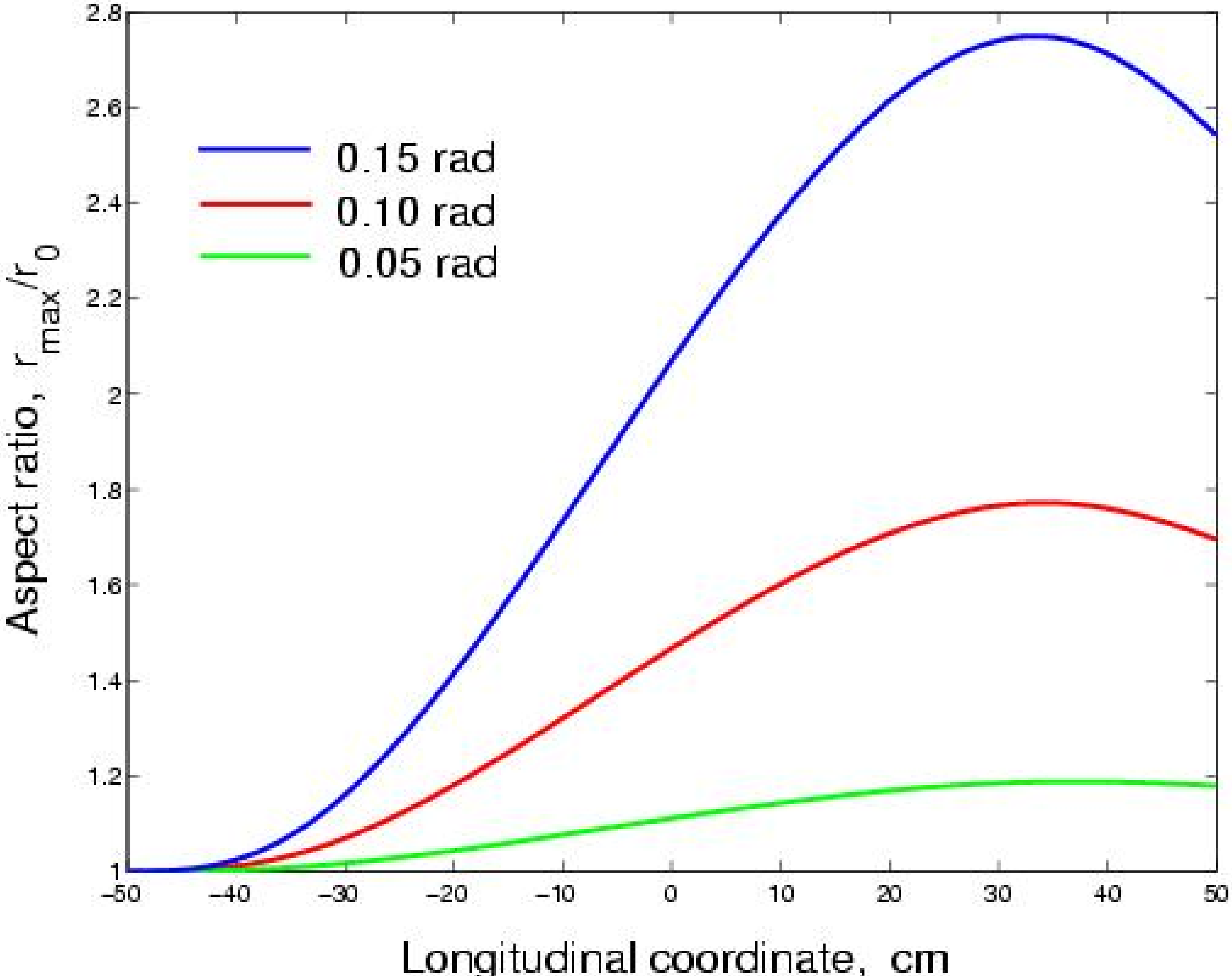
- Construct an initial unperturbed jet along the B=0 trajectory
- Use the time dependent compressible code with a realistic EOS and evolve the jet into a steady state

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

Ref.: S. Oshima, R. Yamane, Y. Mochimary, T. Matsuoka, JSME International Journal, Vol. 30, No. 261, 1987

Results: Aspect ratio of the jet cross-section



B = 15 T
V0 = 25 m/s

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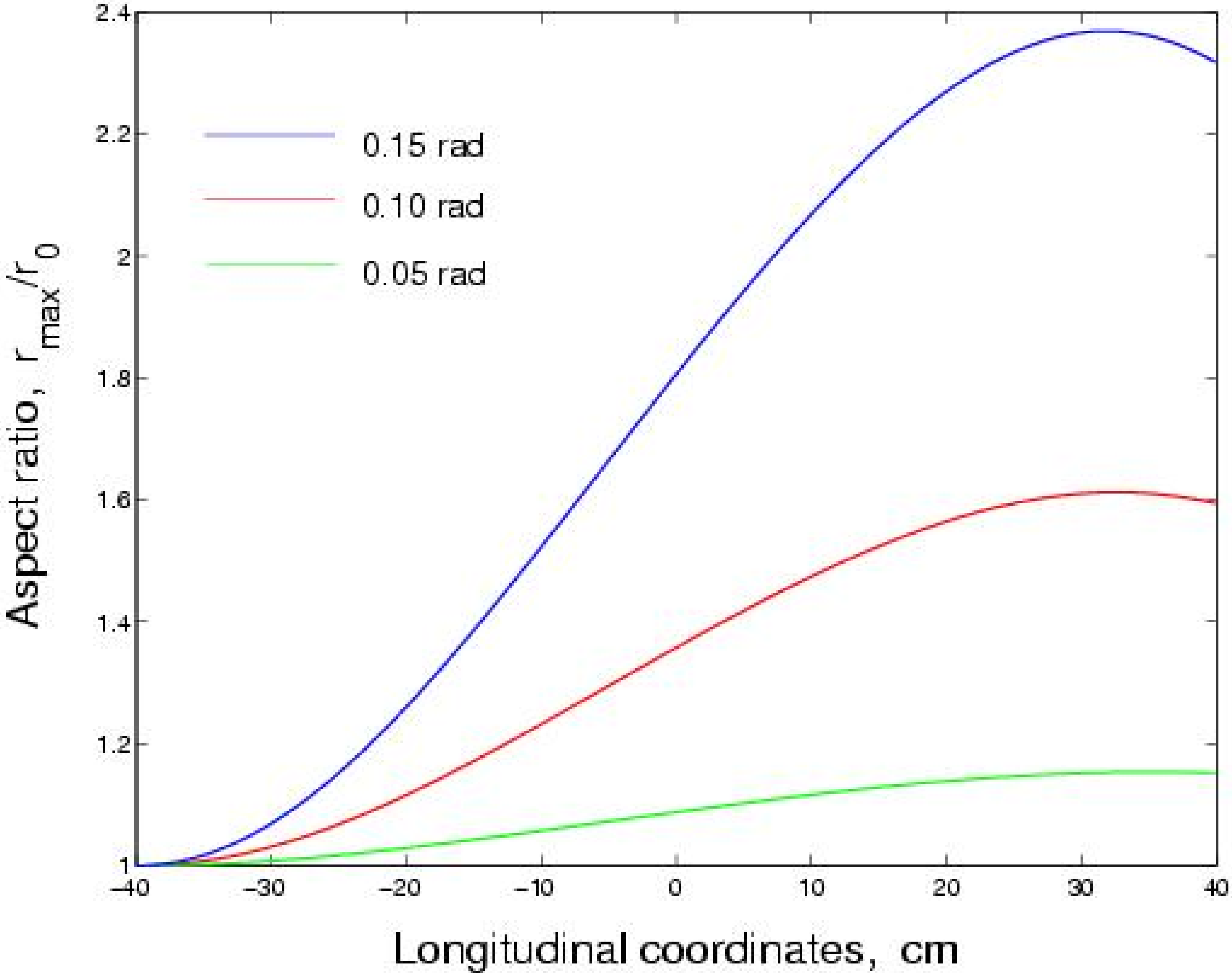
Results: Aspect ratio of the jet cross-section



B = 15 T
V0 = 25 m/s

Summary of results

• Jet distortion (aspect ratio) strongly depends on the angle with the solenoid axes (it increases at larger angles)
• Jet aspect ratio increases at smaller jet velocities (at least if the change of velocity is small compared to the reference velocity of 25 m/s)
• Jet aspect ratio increases in nozzle is placed further from the solenoid center

Typical values of the jet aspect ratio in the center of the soleniod:

Rmax/R0 = 1.35 at V = 25 m/s, alpha = 100 mrad, B = 15 T
Rmax/R0 = 1.09 at V = 25 m/s, alpha = 50 mrad, B = 15 T

Consequences of the jet distortion

• The cross-section of the mercury jet interaction with the proton pulse is significantly reduced. This reduces particle production rate

• In order to avoid these undesirable consequences, the angle between the magnetic field and the solenoid axes needs to be reduced. This imposes new hardware design constraints.

• Verification of results by an independent method. Collaboration with Neil Morley of UCLA computational MHD group.

UCLA code: HIMAG

- HIMAG is a parallel, second order accurate, finite volume based code for incompressible MHD and Navier-Stokes equations.

- The code has been written for complex geometries using unstructured meshes. Flexibility in choosing a mesh: Hexahedral, Tetrahedral, Prismatic cells can be used.

- An arbitrary set of conducting walls maybe specified. Free surface flows are modeled using the Level Set method. **Multiple solid materials** can be simulated

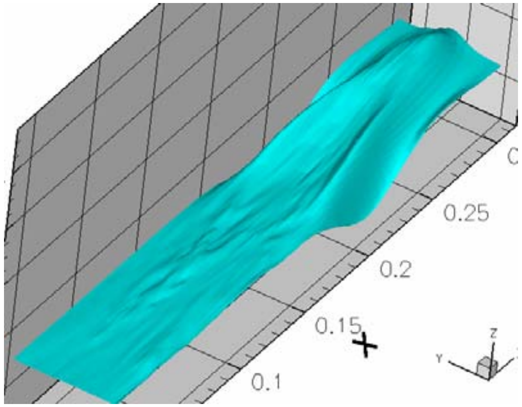
- Graphical interfaces are available to assist users from problem setup to post-processing.

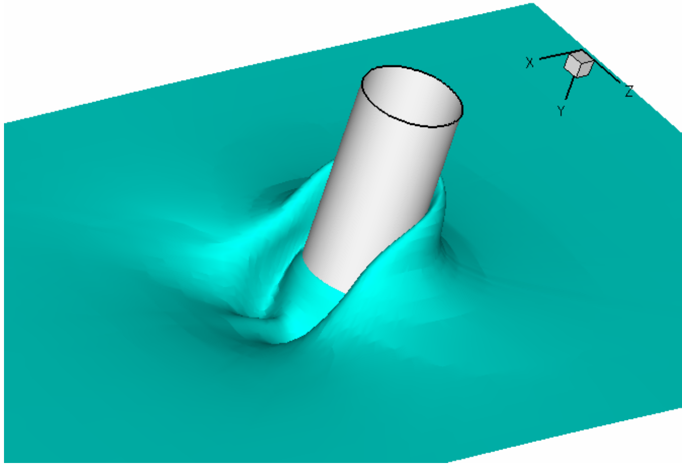
- A preliminary turbulence and heat transfer modeling capability now exists.

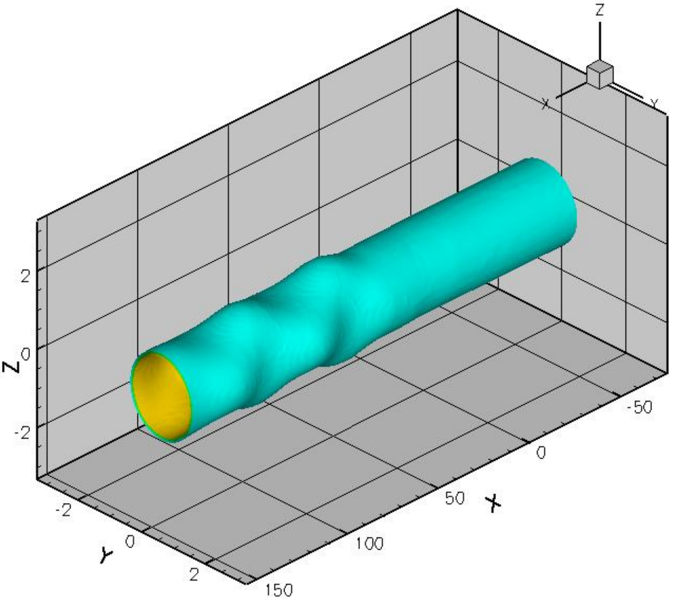
Simulation of free surface flows

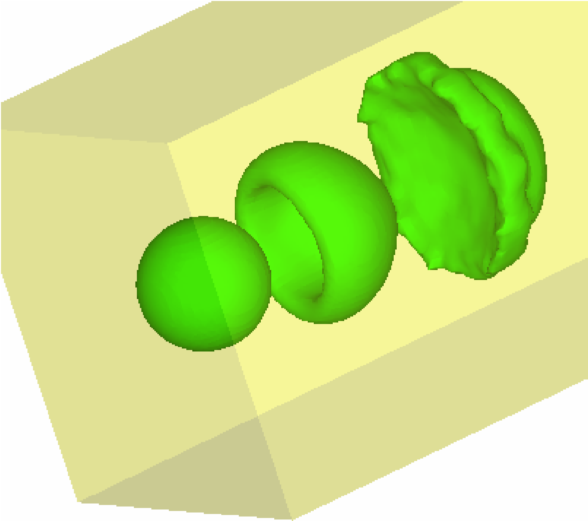
HIMAG uses the Level Set method to capture free surfaces

Examples of HIMAG simulations:





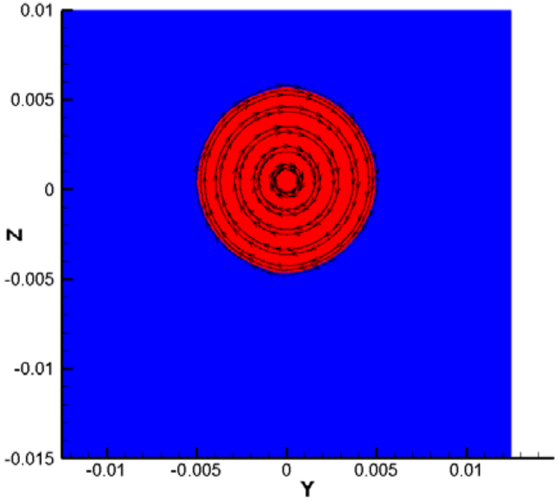




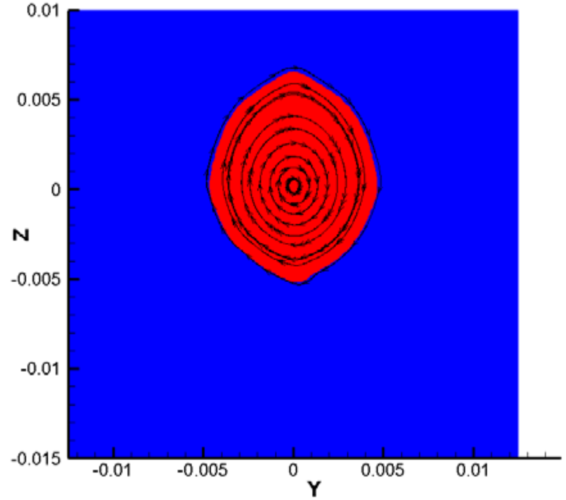
UCLA jet simulation setup

- The magnetic axis of the solenoid is horizontal. Magnetic field simulated as 24 x 78 windings with 7200 A spaced uniformly in ID 20 cm and OD 80 cm and axial length 1 m
- 100 mrad and 33 mrad tilt angle
- Inlet velocity 20 m/s
- Injection point of the jet is located at -5cm below the magnetic axis and -50cm from the solenoid center.
- The inlet electric potential condition is Phi = 0, trying to simulate disturbances from a perfectly conducting nozzle
- MHD forces are turned off at the exit two diameter before the computational boundary
- Computational area 2.5 x 2.5 x 100 cm with 100 x 100 x 200 computational cells.

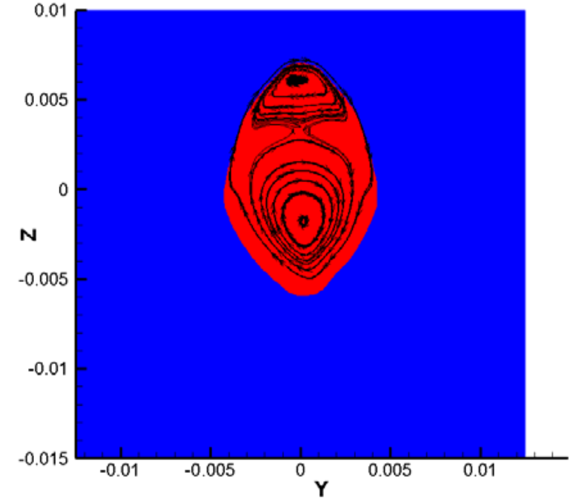
100 mrad tilt angle



z = 0 cm



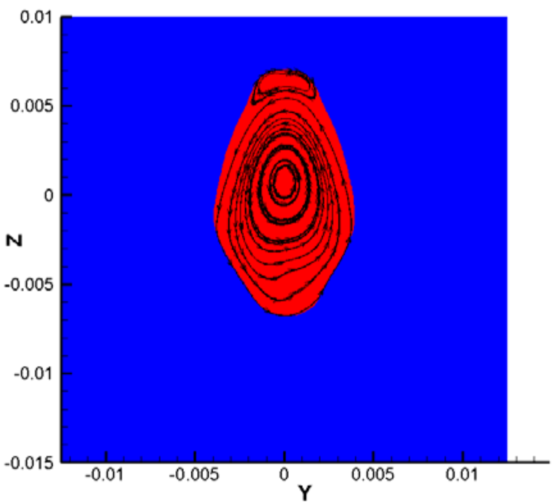
z = 20 cm



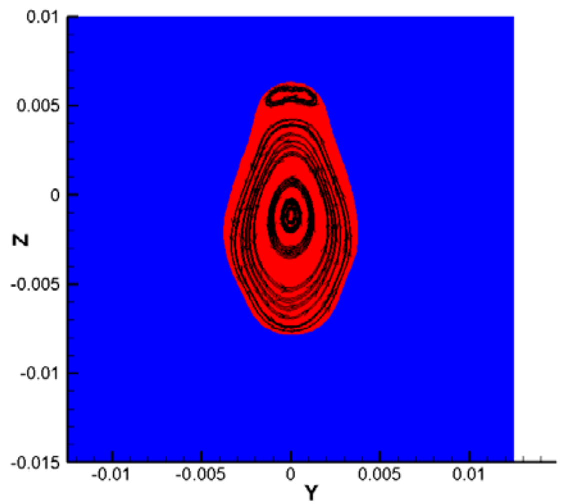
z = 30 cm

Aspect ratio = 1.4 in the solenoid center

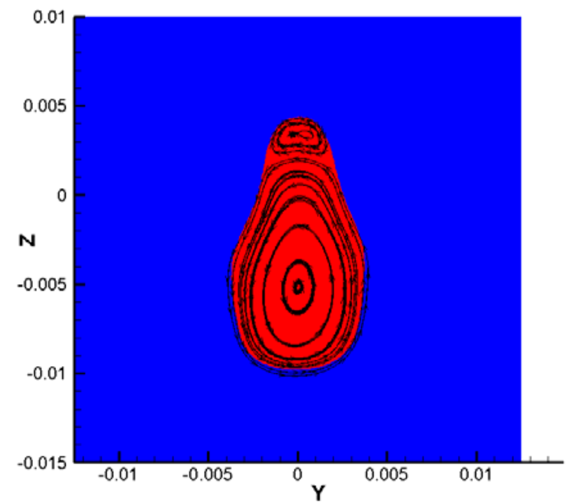
z = 40 cm



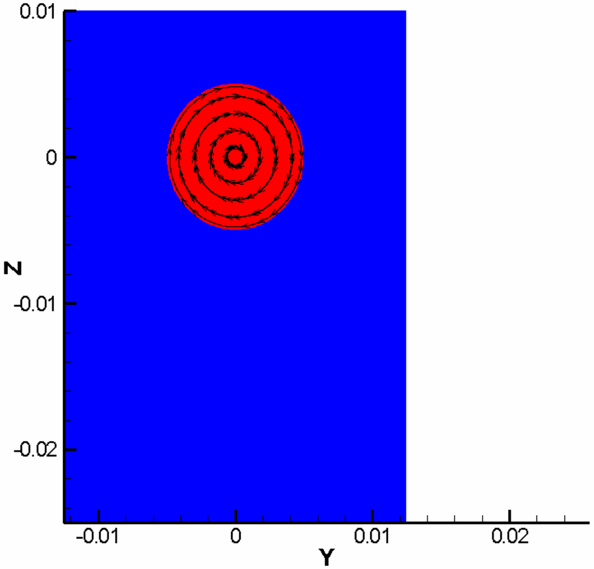
z = 50 cm



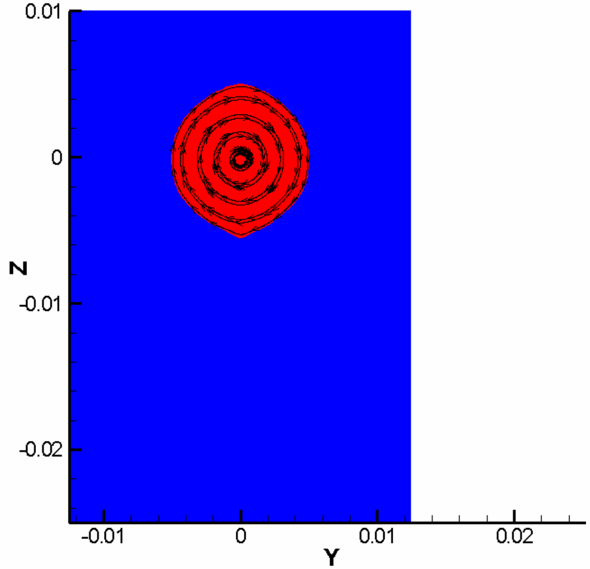
z = 60 cm



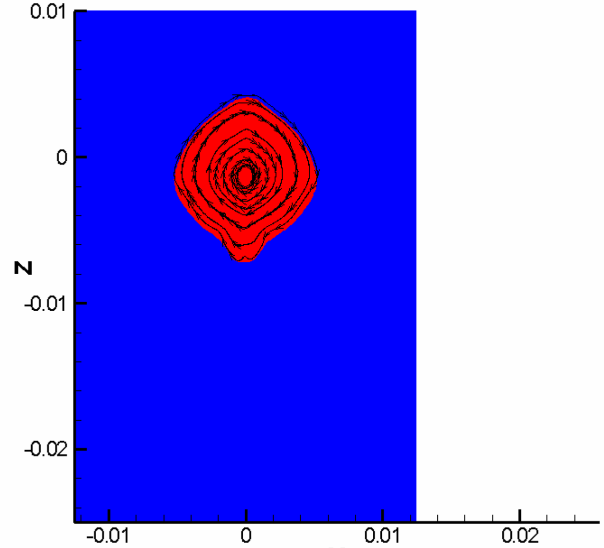
33 mrad tilt angle



z = 2.5 cm

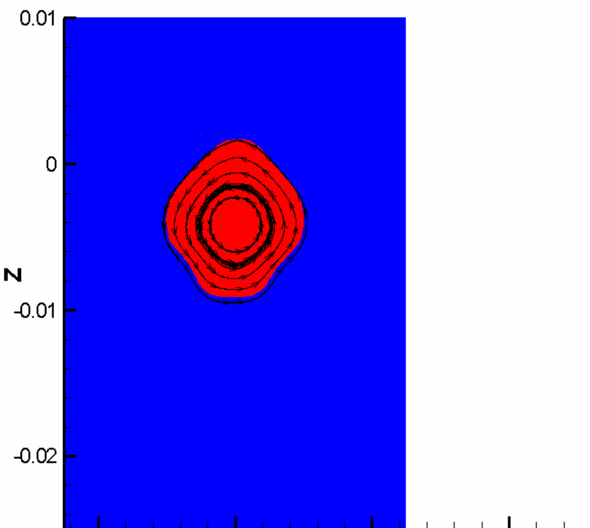


z = 20 cm

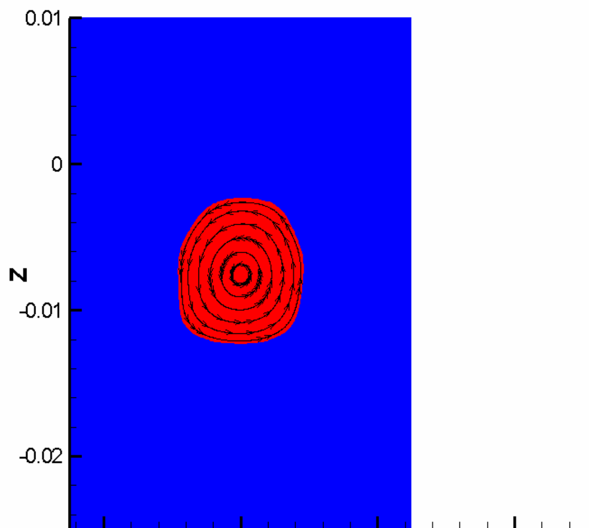


z = 40 cm

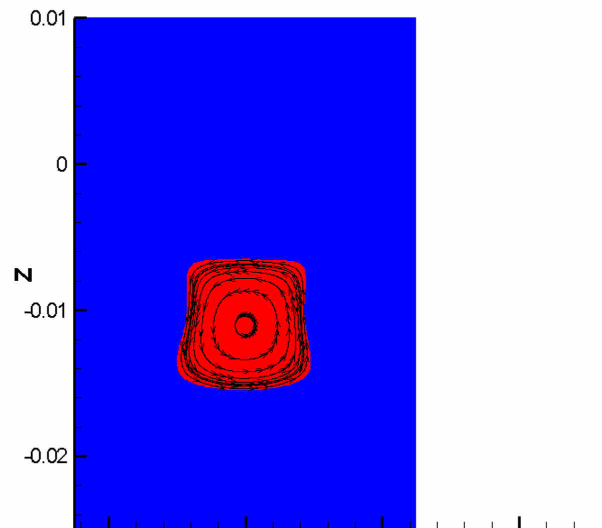
z = 60 cm



z = 80 cm



z = 98 cm



Summary of Neil Morley's results and design parameters change

• Confirmed the distortion of the jet in the 15 T solenoid. Jet evolution exhibited the same features: reduction of the aspect ratio with the increase of the jet velocity, sensitivity to the nozzle placement, and the angle of the jet with the solenoid axis.
• Good quantitative agreement was achieved by independent studies.

• **In order to reduce the jet distortion, the angle between the magnetic field and the solenoid axes for future experiments has been reduced to 33 mrad.**

• Another possible solution is the use of an elliptic nozzle to compensate for the MHD distortion. This option must be investigated by means of numerical simulation.

Conclusions and Future Plans

- Deformation of the mercury jet entering a magnetic field has been studied
- Collaboration with Neil Morley on studies of incompressible free surface jets flows in pipes in the magnetic field

- Further development of mathematical models and software libraries for the FronTier-MHD code
- Study the jet splash in the magnetic field using the heterogeneous (discrete bubble model) for cavitation
- 3D numerical simulations of the mercury jet interacting with a proton pulse in a magnetic field will be continued using the FronTier-MHD code