MUTAC Review
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Target Simulations

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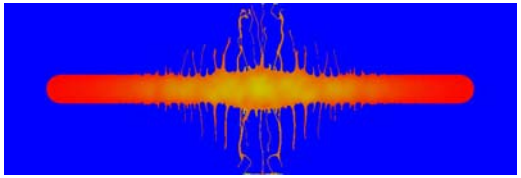
Talk Outline

- Brief summary of previous results
- New development of FronTier MHD code
- Studies of the distortion of the mercury jet entering a 15 T magnetic solenoid. Comparison with HIMAG simulations (UCLA computational MHD group)
- Simulation of droplets in magnetic fields
- Simulation of the mercury jet – proton pulse interaction. Electrical conductivity models for multiphase systems (cavitating fluids).
- Conclusions and future plans

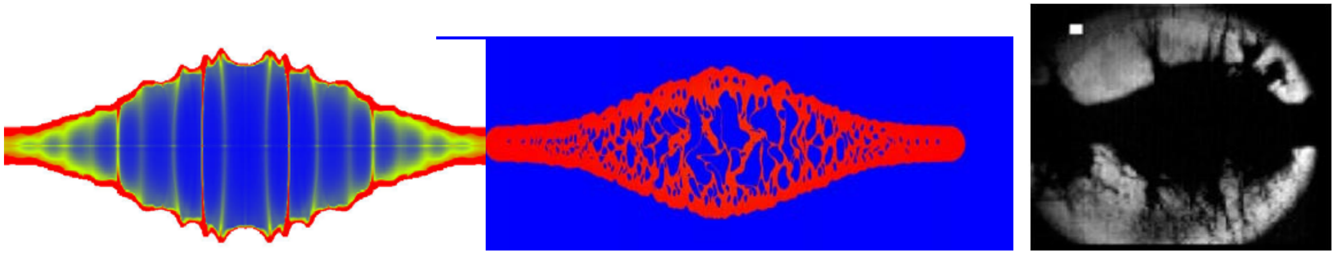
Brief summary of previous results

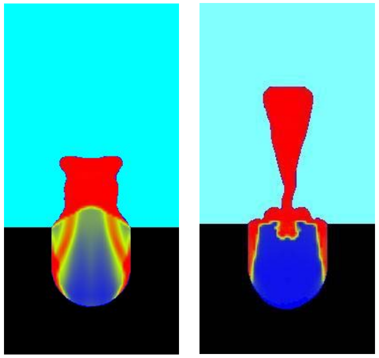
- Developed MHD code for compressible multiphase flows
- Developed EOS homogeneous and heterogeneous models for phase transition (cavitation) and the Riemann solver for the phase boundary
- Studied surface instabilities, jet breakup, and cavitation
- Found that MHD forces reduce both jet expansion, instabilities, and cavitation



Jet surface instabilities

Cavitation in the mercury jet and thimble





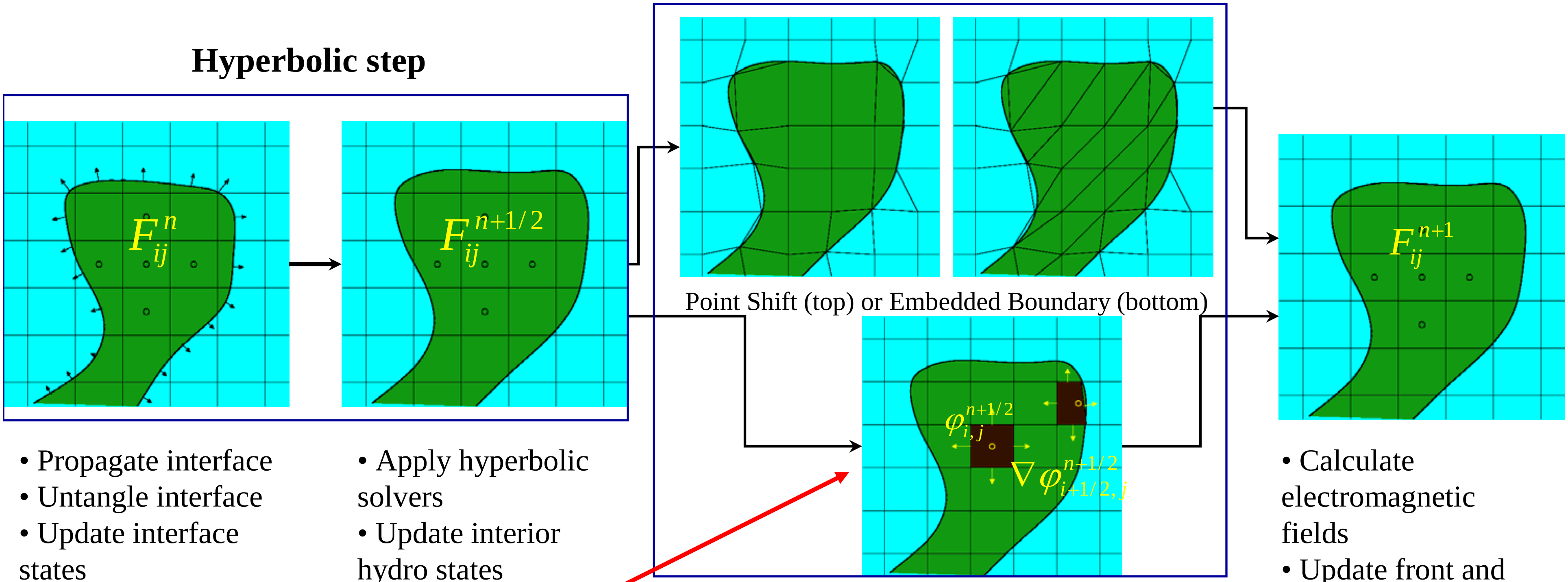
New elliptic solvers for MHD implemented in FronTier

- To improve robustness of the code with complex 3D interfaces, a new solver based on the Embedded Boundary method has been implemented and tested.
- The new code has been used for 3D jet and droplet simulations.

Schematic of FronTier-MHD

Elliptic step

Hyperbolic step



Point Shift (top) or Embedded Boundary (bottom)

- Propagate interface
- Untangle interface
- Update interface states

- Apply hyperbolic solvers
- Update interior hydro states

- Generate finite element grid
- Perform mixed finite element discretization

or

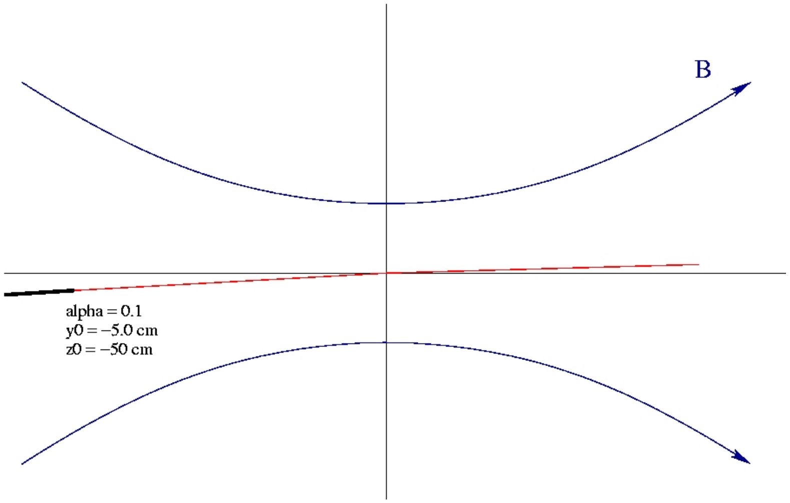
- Perform finite volume discretization
- Solve linear system using fast Poisson solvers

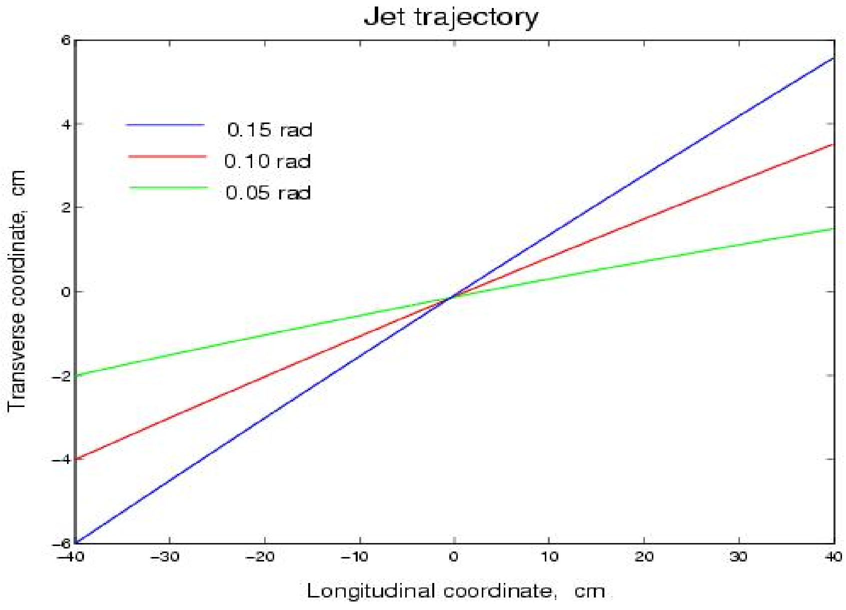
- Calculate electromagnetic fields
- Update front and interior states

New method added:

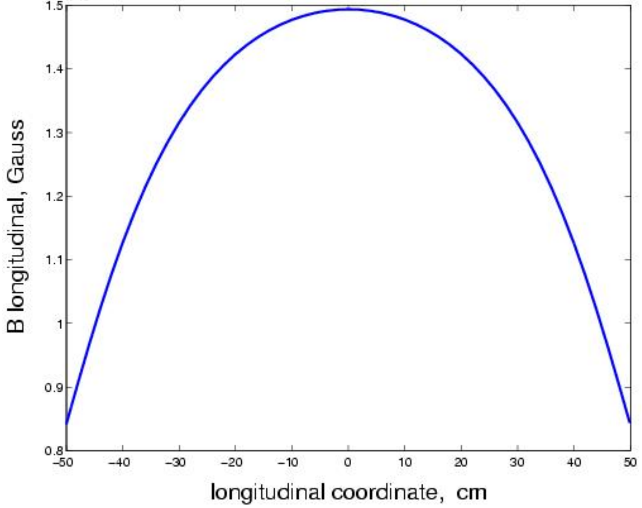
Mercury jet entering magnetic field.

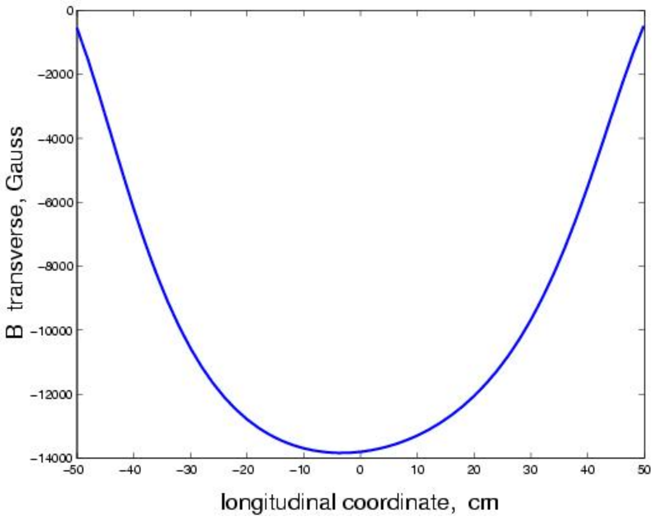
Schematic of the problem.





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





Two independent studies

- Direct numerical simulations (FronTier and HIMAG)

- Perturbation series semi-analytical/semi-numerical studies of incompressible MHD system.

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

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

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

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

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

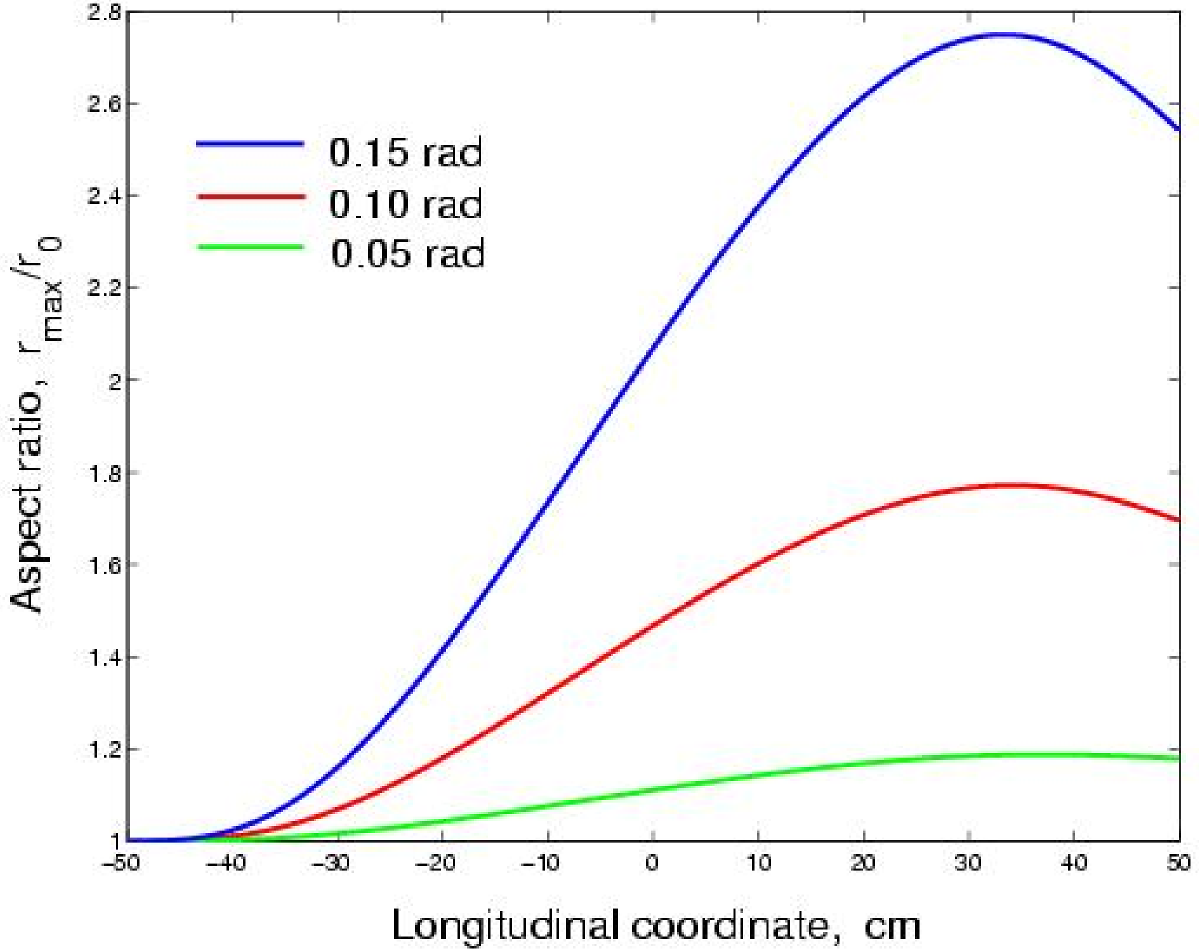
$B.C.:$

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

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

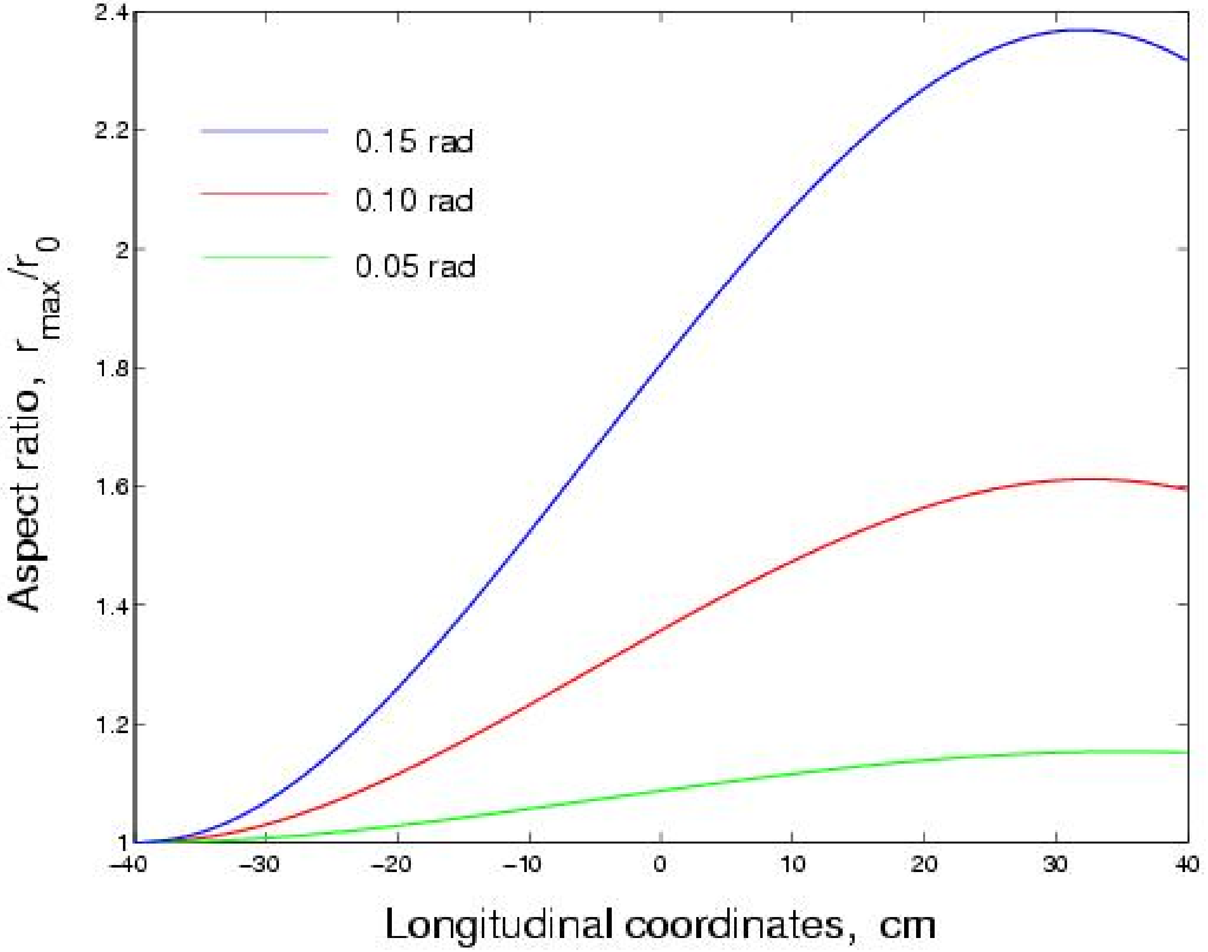
$$\mathbf{u}_\Gamma\cdot\mathbf{n} = 0$$

Results: Aspect ratio of the jet cross-section. I



B = 15 T
V0 = 25 m/s

Results: Aspect ratio of the jet cross-section. II



B = 15 T
V0 = 25 m/s

Summary of results

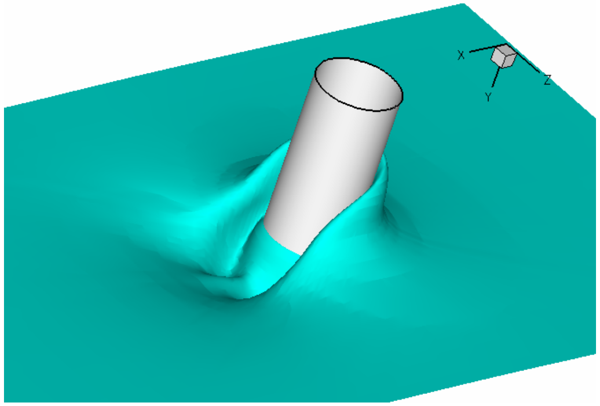
- Jet distortion (aspect ratio) strongly depends on the angle with the solenoid axes (it increases at larger angles)
- Jet aspect ratio increases at smaller jet velocities (at least if the change of velocity is small compared to the reference velocity of 25 m/s)
- Jet aspect ratio increases in nozzle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

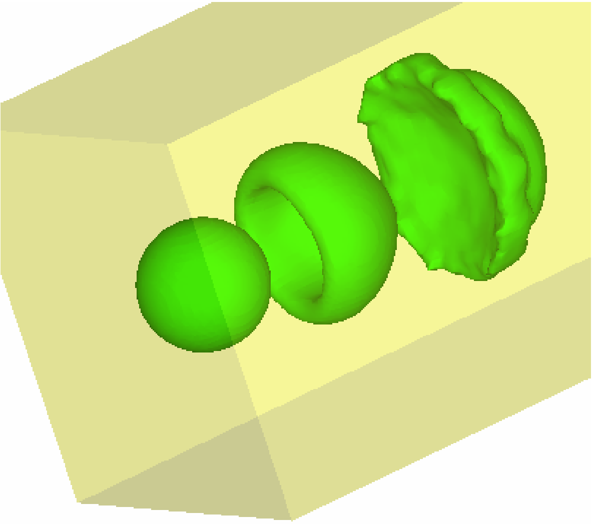
Typical values of the jet aspect ratio in the center of the soleniod:

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

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.

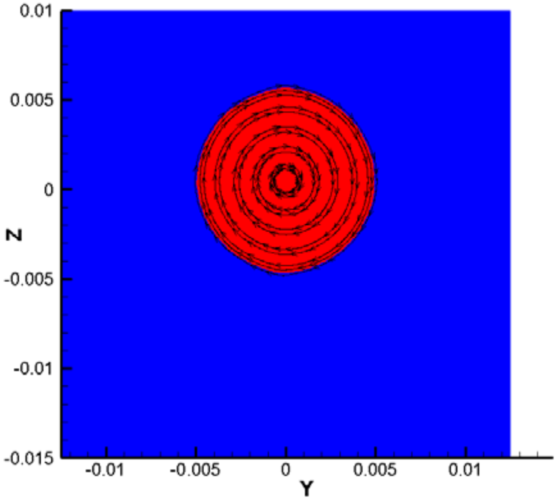




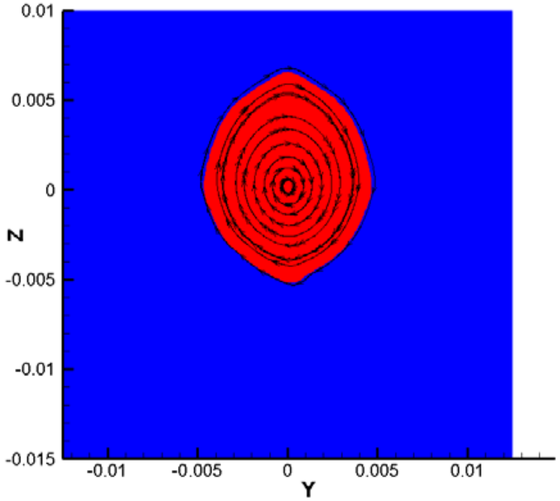
UCLA jet simulation setup

- 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.

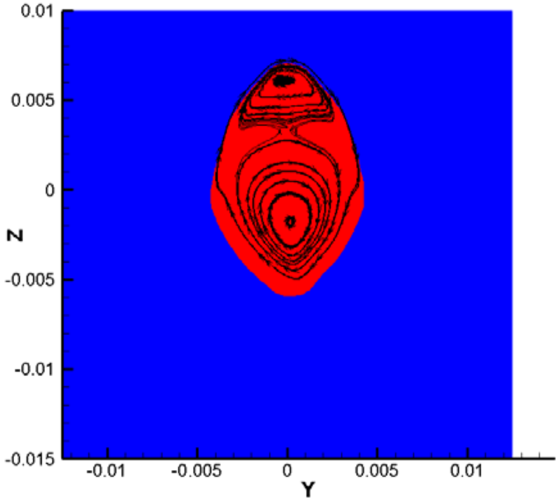
100 mrad tilt angle



z = 0 cm



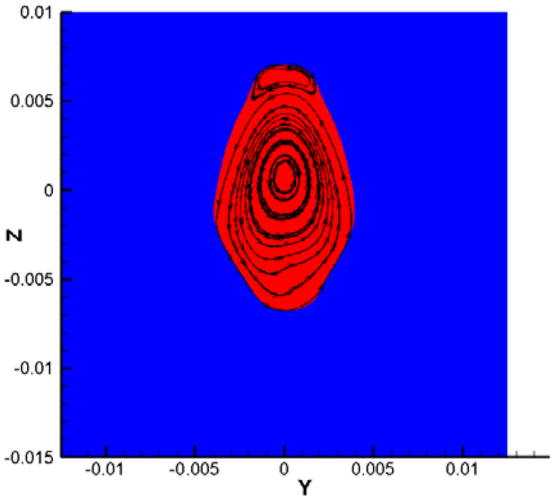
z = 20 cm



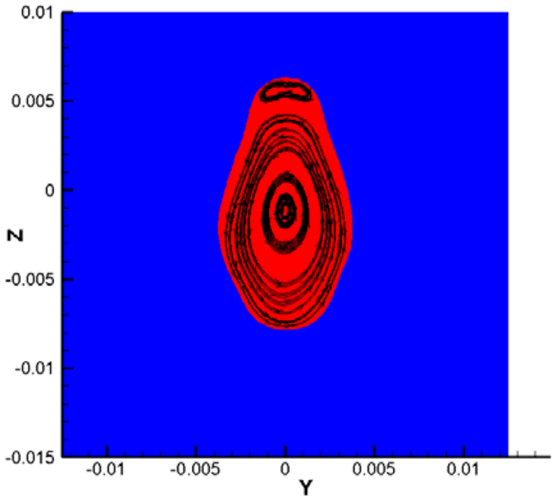
z = 30 cm

Aspect ratio = 1.4 in the solenoid center

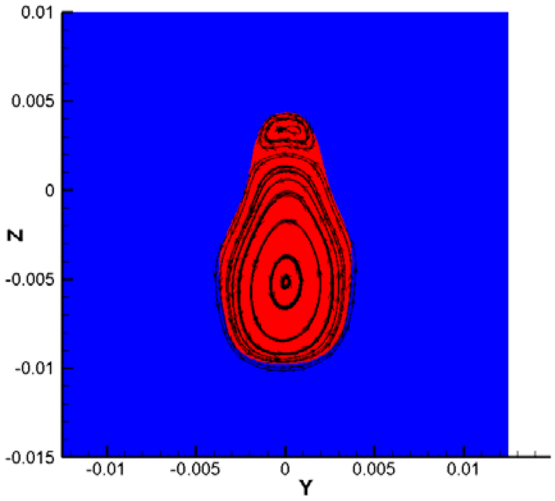
z = 40 cm



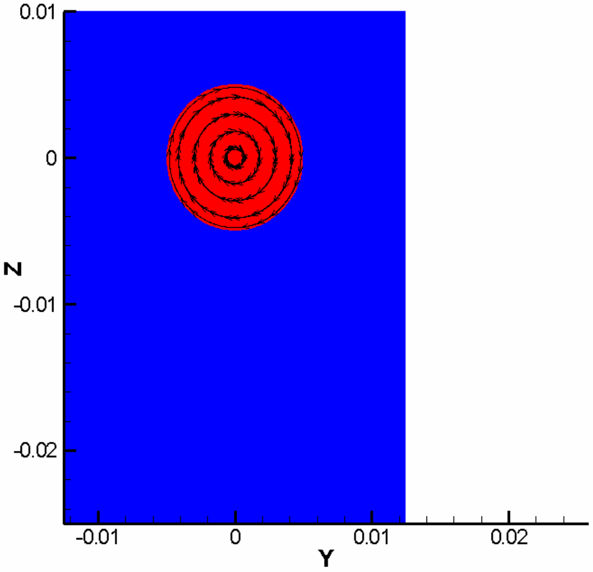
z = 50 cm



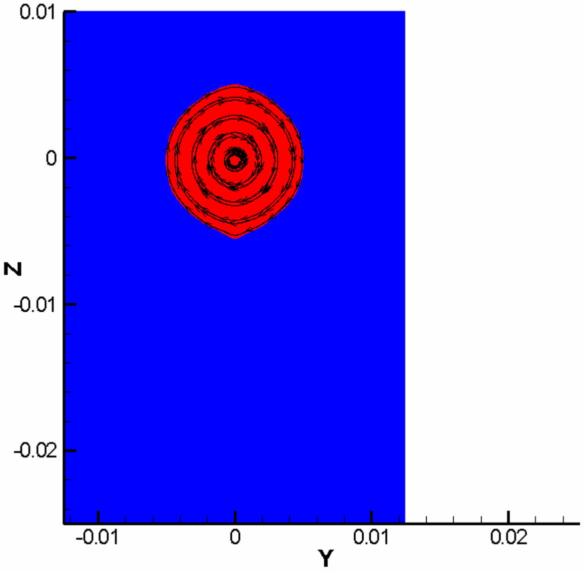
z = 60 cm



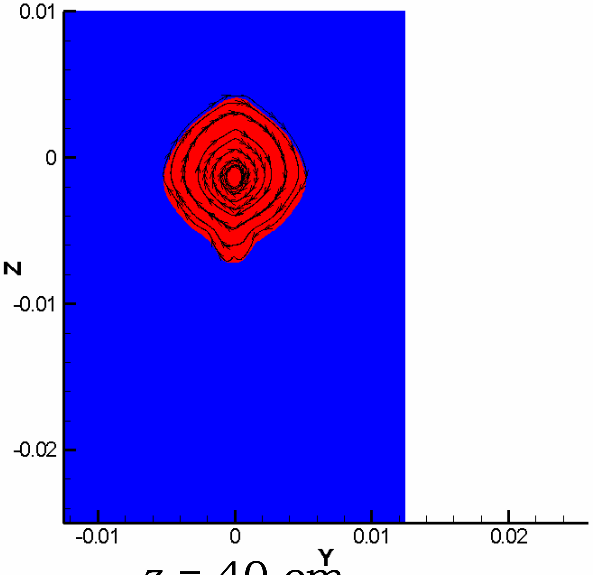
33 mrad tilt angle



z = 2.5 cm

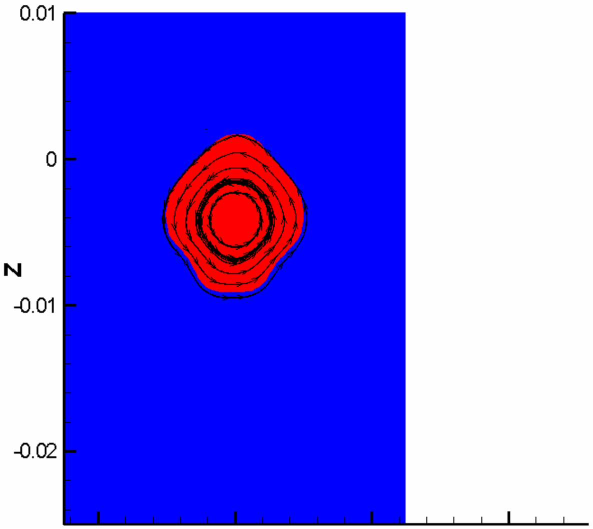


z = 20 cm

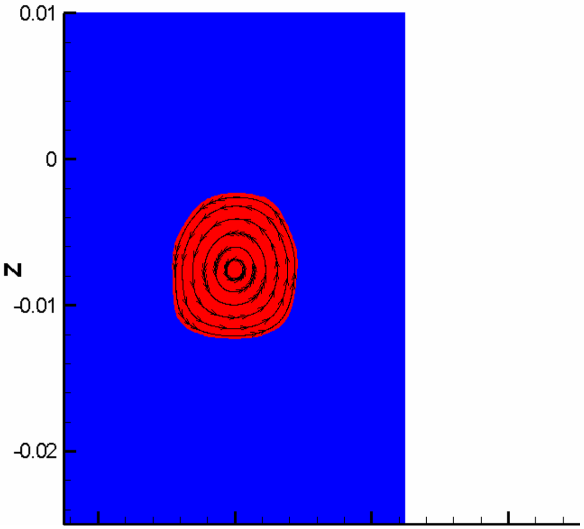


z = 40 cm

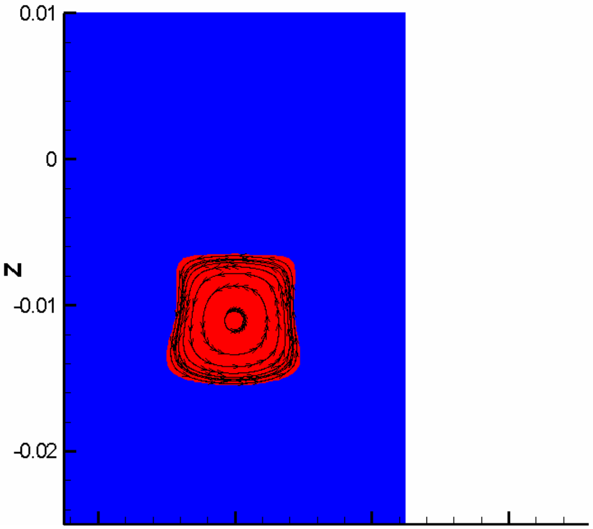
z = 60 cm



z = 80 cm



z = 98 cm



Consequences of the jet distortion

- 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.

- As a result of the jet distortion, the cross-section of the mercury jet interaction with the proton pulse is significantly reduced. This reduces particle production rate

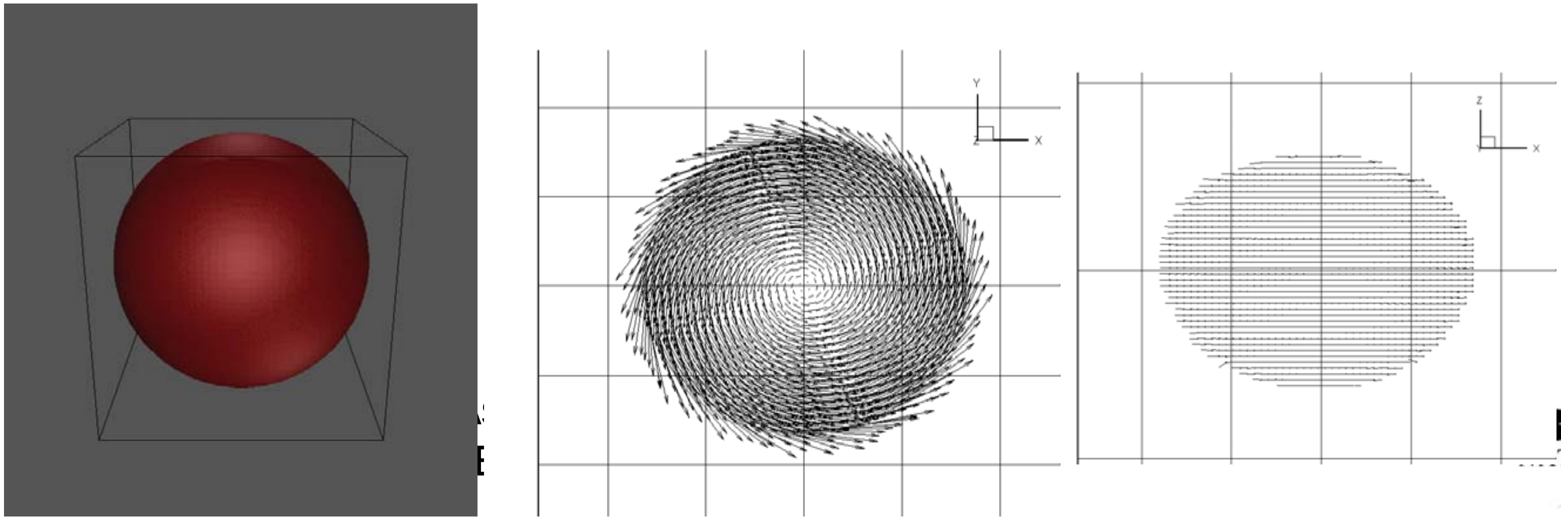
- **In order to reduce the jet distortion, the angle between the magnetic field and the solenoid axes for future experiments has been reduced to 33 mrad.**

Droplet studies in magnetic fields

- Studied the evolution of droplets (r ~ 1-3 mm) moving longitudinally and transversely in the 15 T solenoid with velocities ~ 10 – 100 m/sec.

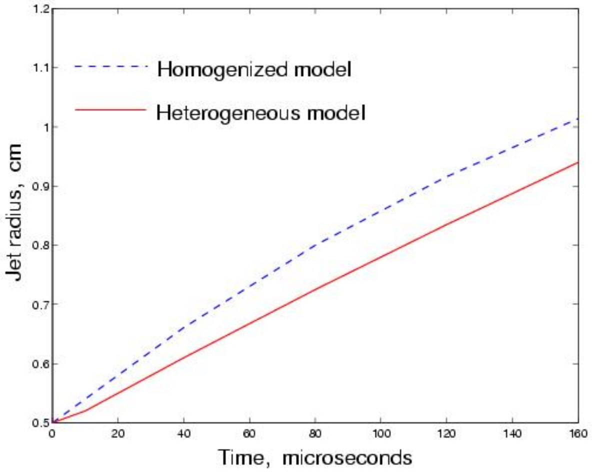
- Change of the velocity of droplets was **negligible**.

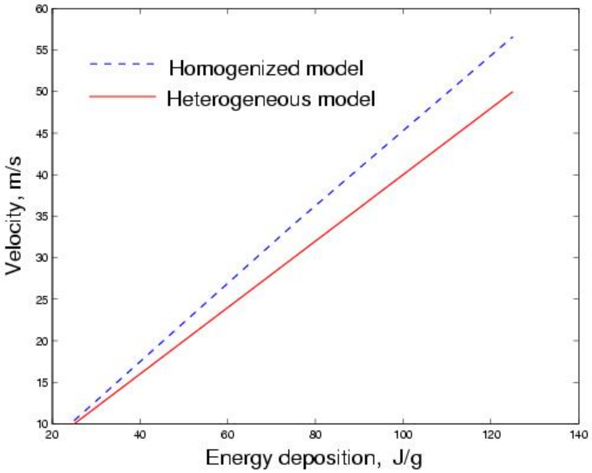
- Slight deformation of droplets traveling longitudinally in the high grad **B** region.

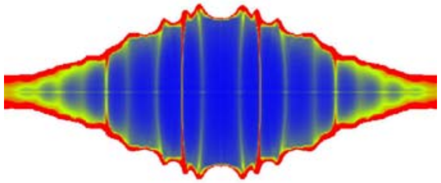


Mercury jet – proton pulse interaction using different EOS models

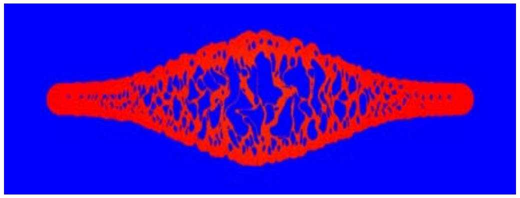
- We evaluated and compared homogeneous and heterogeneous cavitation models:







Homogeneous model



Heterogeneous model

- Two models agree reasonably well

- Since 3D direct numerical simulation of cavitation bubbles with the resolution of small scale effects still remain prohibitively expensive, the homogeneous model is currently used for 3D simulations

- Problem of electrical conductivity of multiphase domains within the homogeneous model.

Electrical conductivity models for multiphase mixtures (cavitating liquid)

- There are several models for the conductivity of multiphase mixtures (the original one proposed by Maxwell)
- Most of them predict phase transition (in the conductivity parameter at some critical volume fraction)

- Bruggeman's Symmetrical Effective Medium Theory

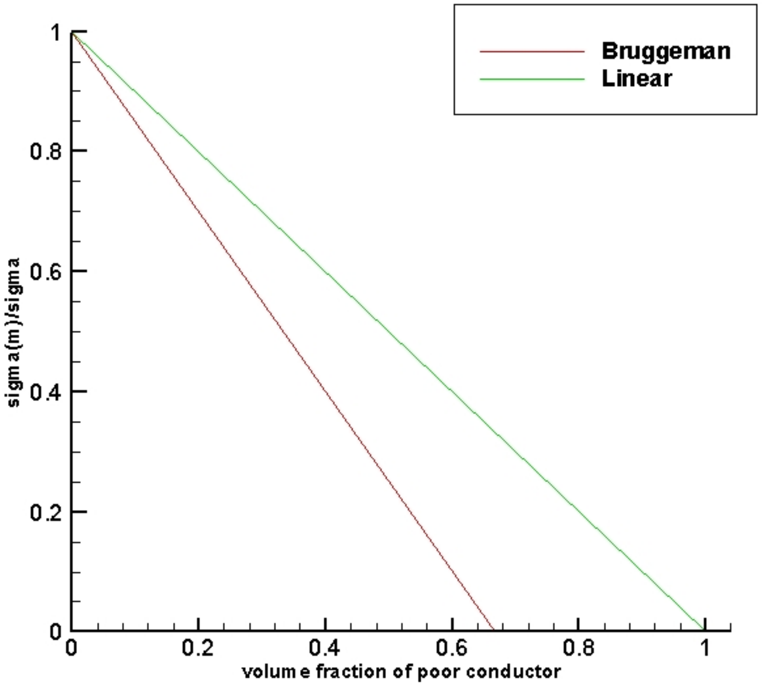
$$\delta_1 \frac{\sigma_1 - \sigma_m}{\sigma_1 + 2\sigma_m} + \delta_2 \frac{\sigma_2 - \sigma_m}{\sigma_2 + 2\sigma_m} = 0$$

$\delta(1,2)$ -- *volume fraction of components*

$\sigma(1,2)$ -- *conductivity of components*

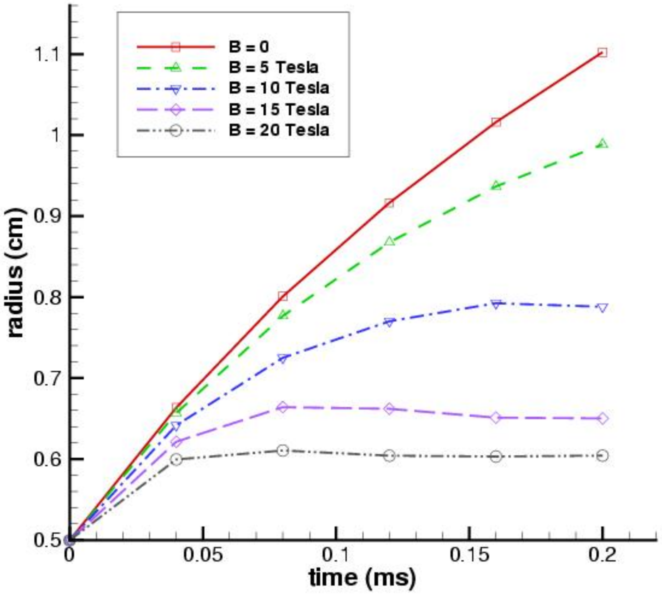
σ_m -- *effective conductivity of mixturer*

$$for\ \sigma_1 >> \sigma_2 \Rightarrow \sigma_m = \frac{\sigma_1}{2}(3\delta_1 - 1)$$



Numerical simulations

- 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)
- Influence of the droplet size on conductivity is being studied now.

Conclusions and Future Plans

- New developments of mathematical models, numerical algorithms, and software libraries for the FronTier-MHD code enabled simulations of 3D MHD with geometrically complex interfaces

- Deformation of the mercury jet entering 15 Tesla solenoid has been established. The design angle between the jet and solenoid axis has been changed to 33 mrad.

- Performed simulations of droplets. The calculated velocity change was negligible.

- Studies of the electrical conductivity for multiphase domains. Linear conductivity models predicts strong stabilizing effect of the magnetic field. Bruggeman's model predict 20% weaker effect.

- 3D numerical simulations of the mercury jet – proton pulse interaction using homogeneous cavitation models and new conductivity models.