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Mercury Jet Target Simulations

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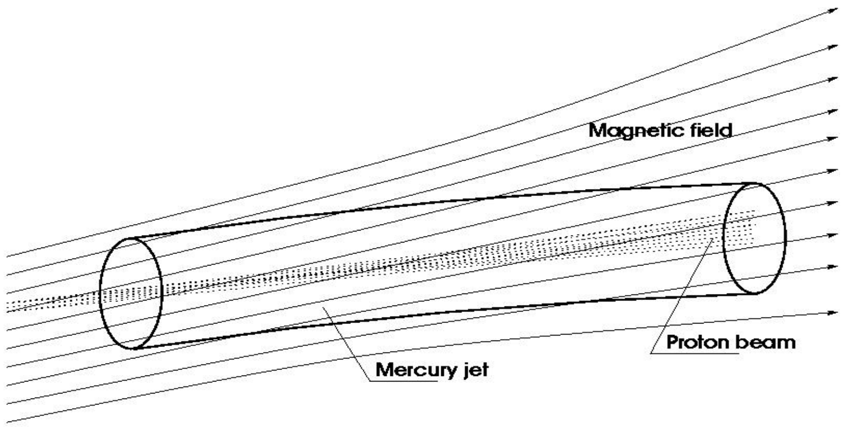
James Glimm, Xiaolin Li (numerical methods), P. Parks (MHD)

Talk Outline

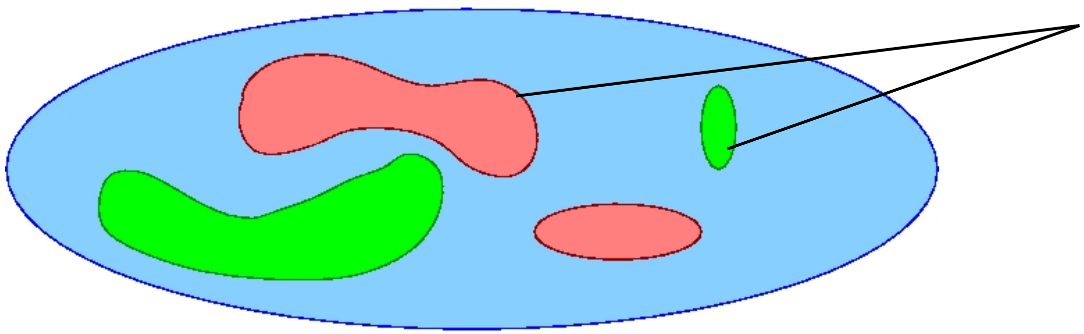
- Numerical methods. FronTier code and its typical applications.
- Distortion of the mercury jet entering magnetic field
- Simulation of the mercury jet – proton pulse interaction.
- Conclusions and future plans

Target simulation requires multiphase / free surface MHD



Target schematic

Solving MHD equations (a coupled hyperbolic – elliptic system) in geometrically complex, evolving domains subject to interface boundary conditions (which may include phase transition equations)



Material interfaces:
- Discontinuity of density and physics properties (electrical conductivity)
- Governed by the Riemann problem for MHD equations or phase transition equations

MHD equations and approximations

Full system of MHD equations

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

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

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)e = -P\nabla\cdot\mathbf{u} + \frac{1}{\sigma}\mathbf{J}^2$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) - \nabla\times\left(\frac{c^2}{4\pi\sigma}\nabla\times\mathbf{B}\right)$$

$$P = P(\rho, e), \qquad \nabla\cdot\mathbf{B} = 0$$

Low magnetic Re approximation

$$\mathrm{Re}^M = \frac{uL\sigma}{c^2} << 1, \quad \frac{\delta B}{B} << 1$$

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

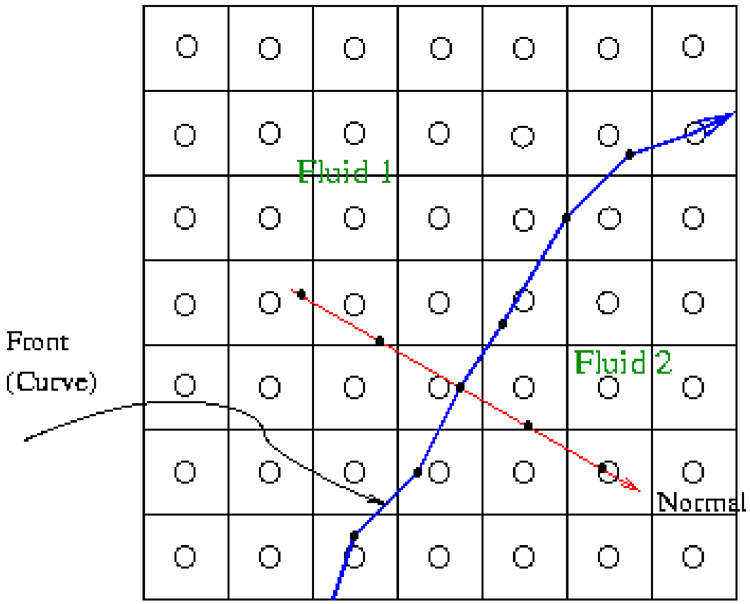
$$\nabla\cdot\sigma\nabla\phi = \frac{1}{c}\nabla\cdot(\mathbf{u}\times\mathbf{B}),$$

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

$$\mathbf{B} = \mathbf{B}_{\mathrm{ext}}(x,t), \quad \nabla\cdot\mathbf{B}_{\mathrm{ext}} \equiv 0$$

Main Ideas of Front Tracking

Front Tracking: A hybrid of Eulerian and Lagrangian methods



Two separate grids to describe the solution:

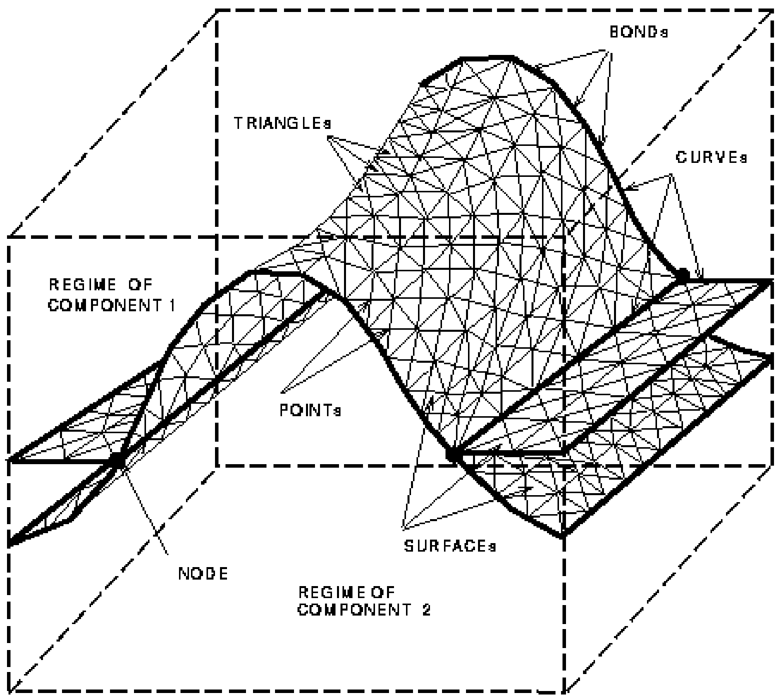
1. A volume filling rectangular mesh
2. An unstructured codimension-1 Lagrangian mesh to represent interface

Major components:

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

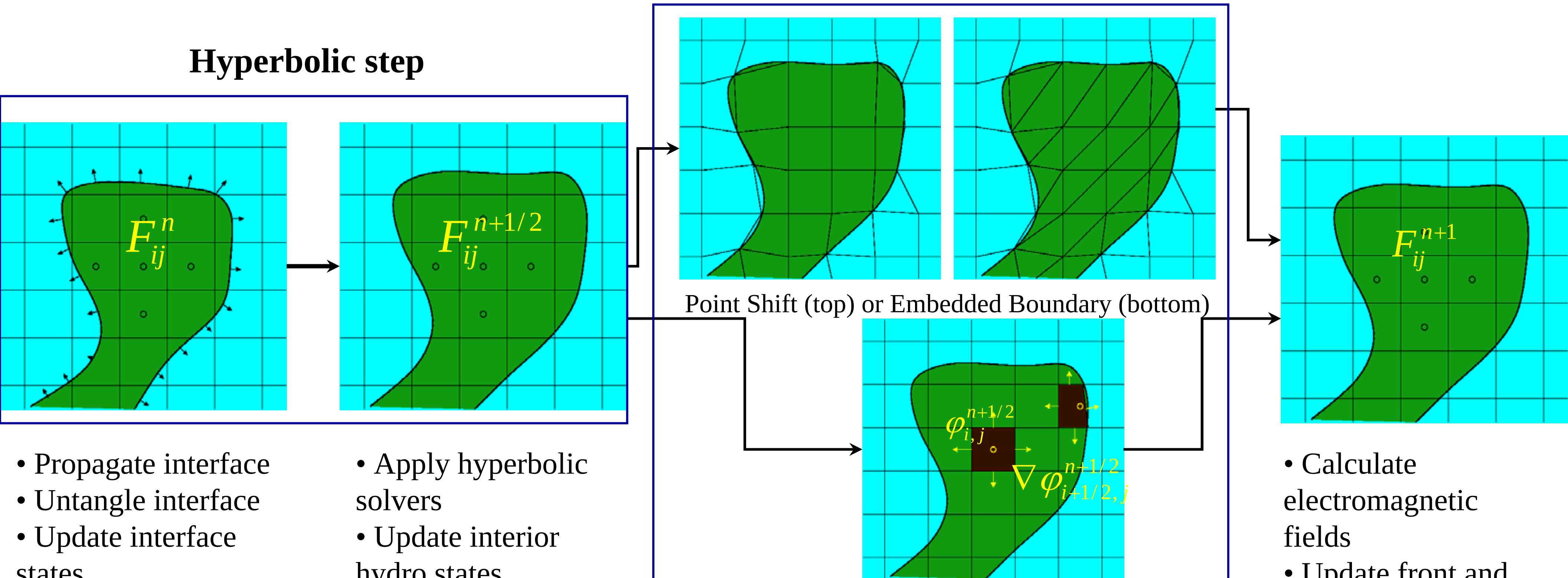
Advantages of explicit interface tracking:

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



FronTier-MHD numerical scheme

Elliptic step



- Propagate interface
- Untangle interface
- Update interface states

- Apply hyperbolic solvers
- Update interior hydro states

- Generate finite element grid
- Perform mixed finite element discretization

or

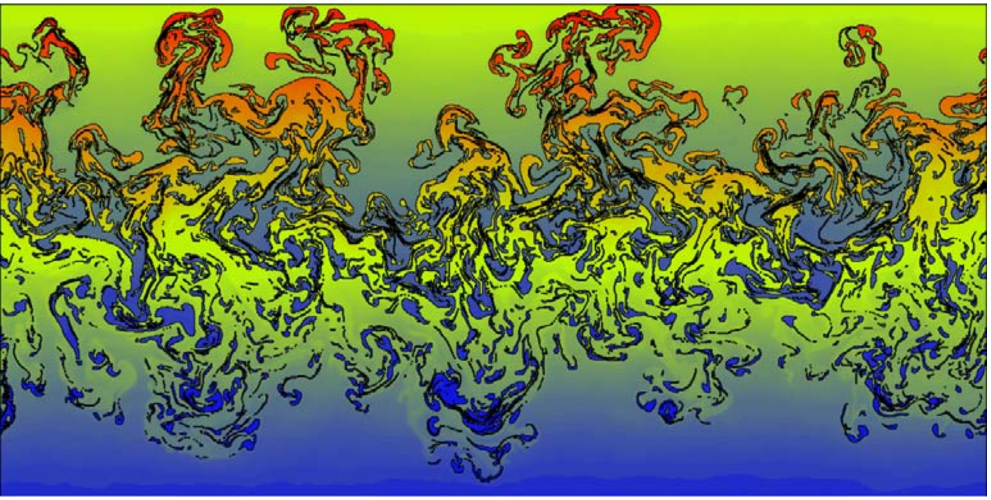
- Perform finite volume discretization
- Solve linear system using fast Poisson solvers

- Calculate electromagnetic fields
- Update front and interior states

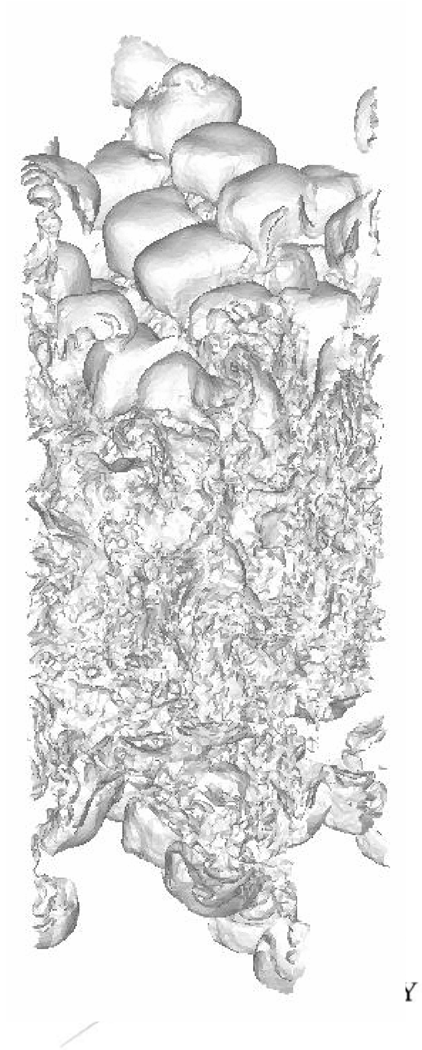
The ***FronTier*** Code (SciDAC ITAPS Software)

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

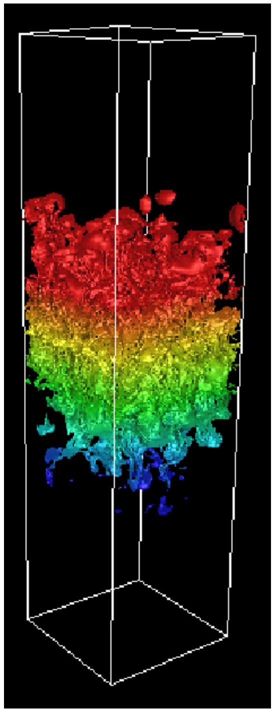
- Physics models include
  - Compressible fluid dynamics
  - MHD
  - Flow in porous media
  - Elasto-plastic deformations
- Realistic EOS models, phase transition models
- Exact and approximate Riemann solvers
- Adaptive mesh refinement



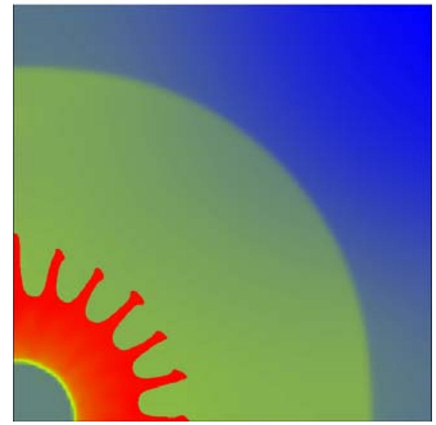
Turbulent fluid mixing.
Left: 2D
Right: 3D (fragment of the interface)



Main *FronTier* Applications

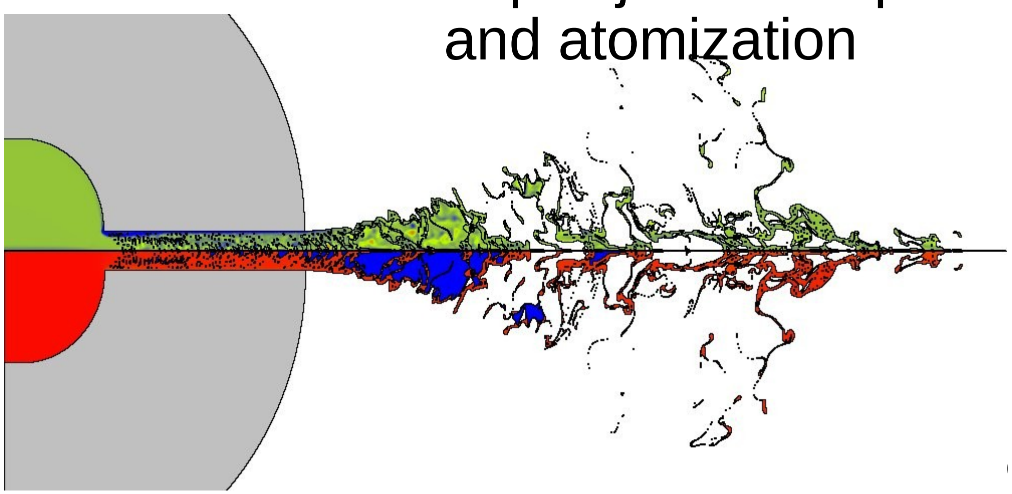


Rayleigh-Taylor instability



Richtmyer-Meshkov instability

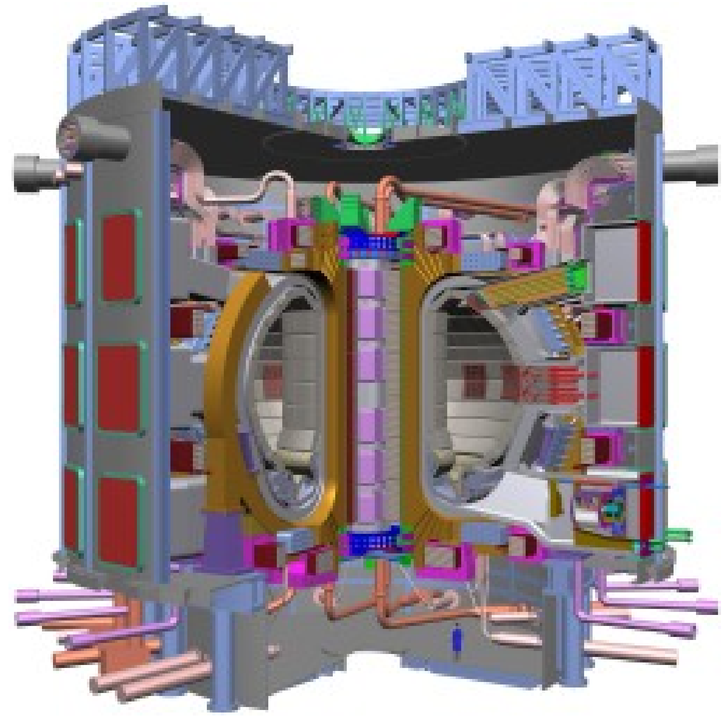
Liquid jet breakup and atomization



Fusion Energy. ITER project: fuel pellet ablation

• ITER is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power

• ITER will be constructed in Europe, at Cadarache in the South of France in ~10 years

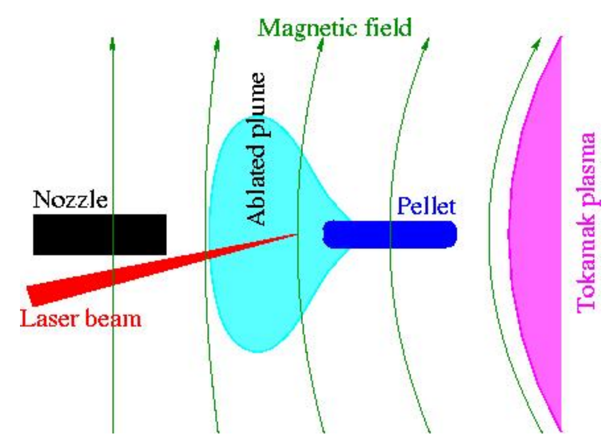


Our contribution to ITER science:

Models and simulations of tokamak fueling through the ablation of frozen D_2 pellets

Collaboration with General Atomics

Laser driven pellet acceleration



New Ideas in Nuclear Fusion: Magnetized Target Fusion (MTF)

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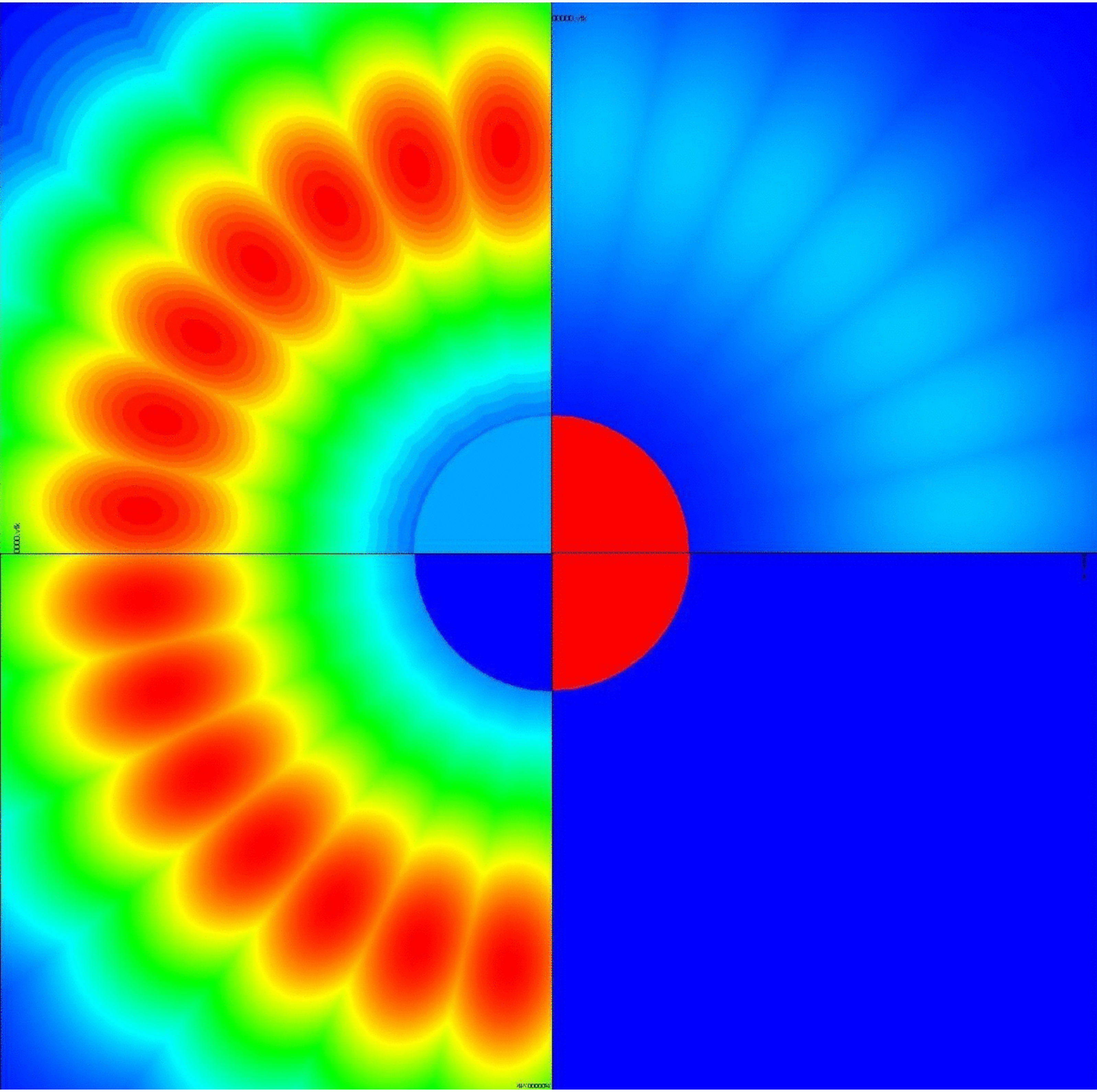

Muon Collaboration

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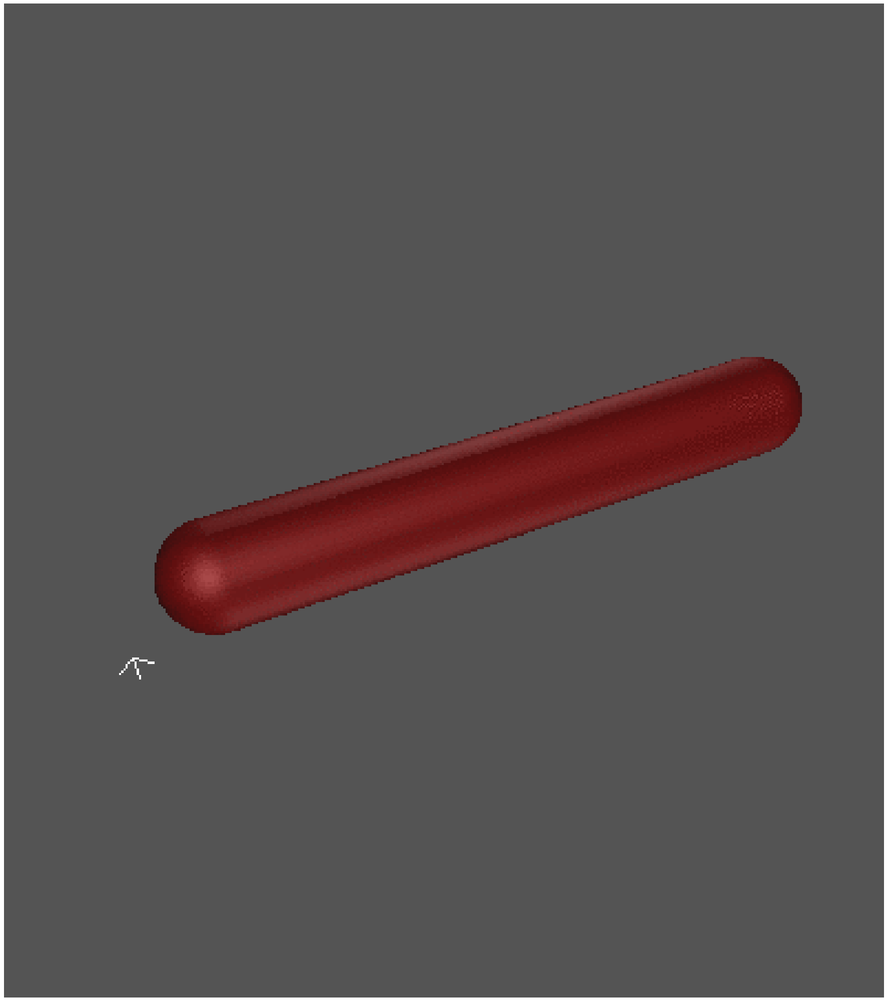
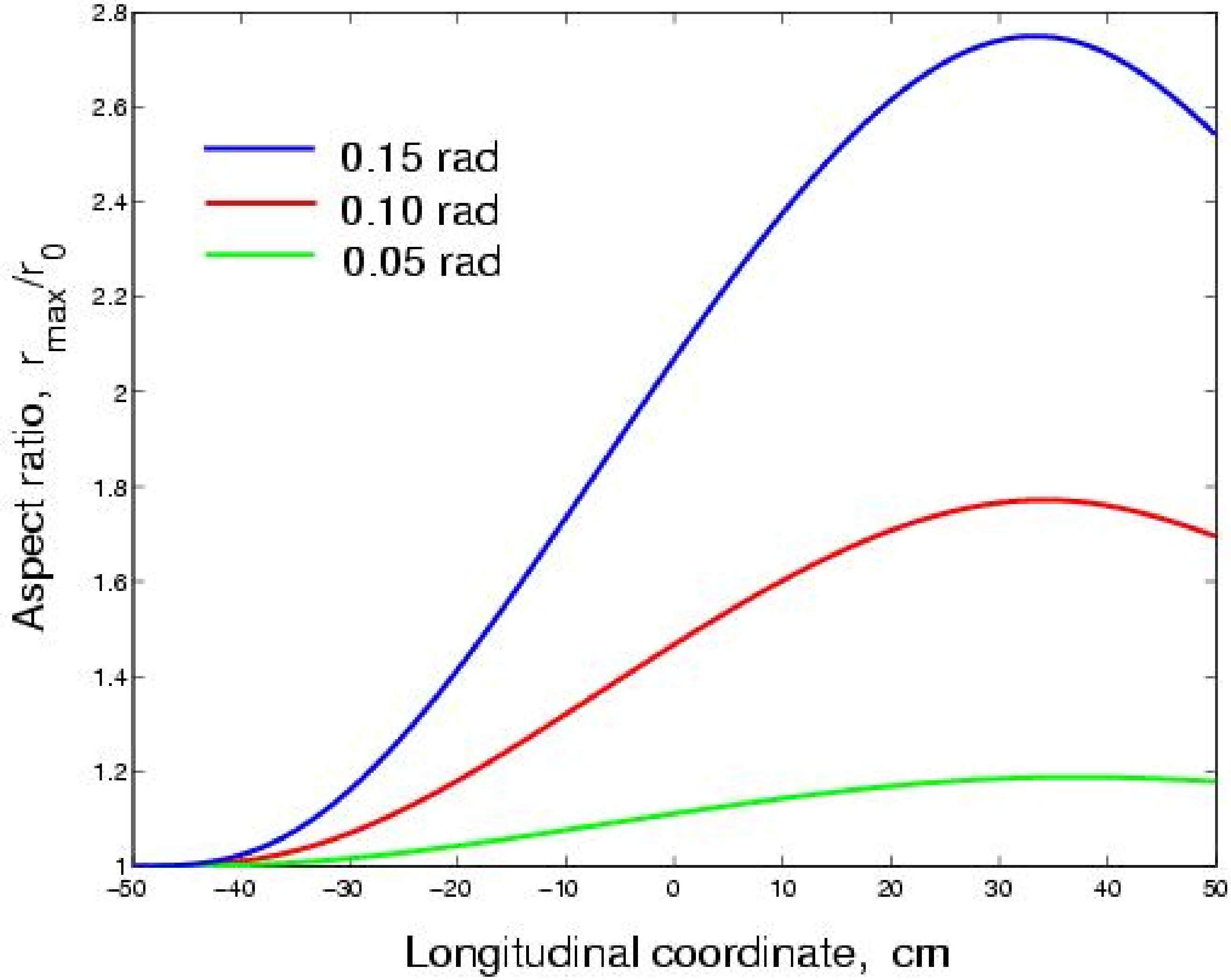
Jet entering 15 T solenoid

FronTier code:

- Explicitly tracked material interfaces
- Multiphase models
- MHD in low magnetic Reynolds number approximation

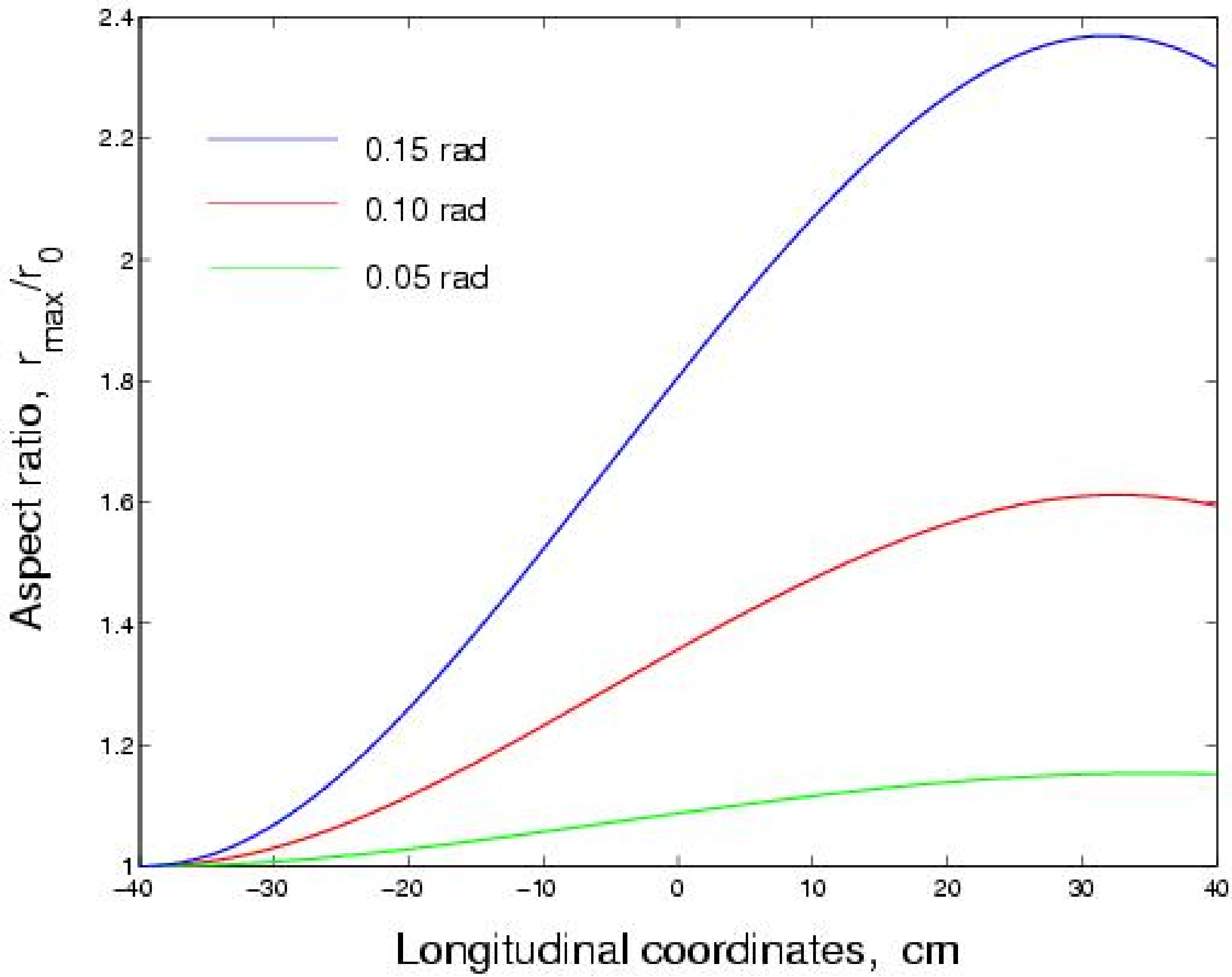


Previous Results (2005)
Aspect ratio of the jet cross-section. I



B = 15 T
V0 = 25 m/s

Previous Results (2005)
Aspect ratio of the jet cross-section. II

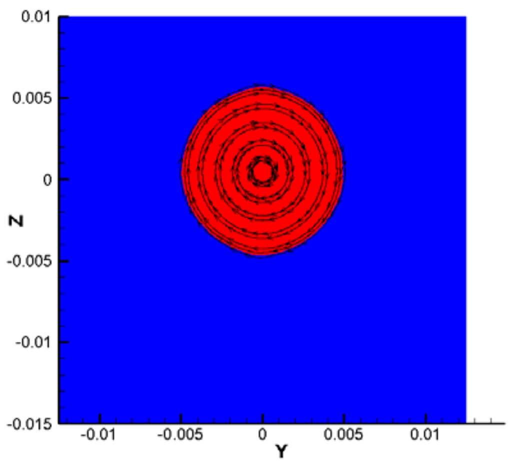


B = 15 T
V0 = 25 m/s

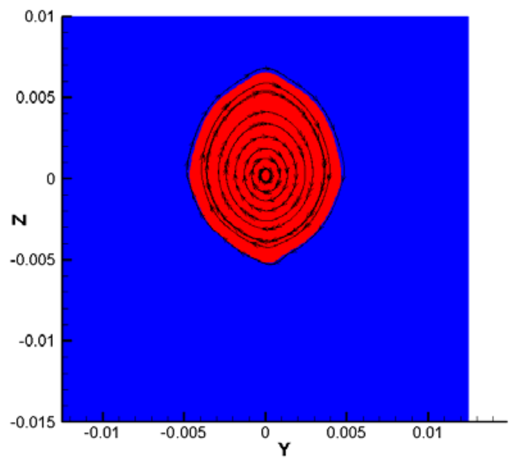
0.10 rad, z = 0:
Aspect ratio = 1.4

Confirmation: Independent studies by Neil Morley, UCLA, HiMAG code

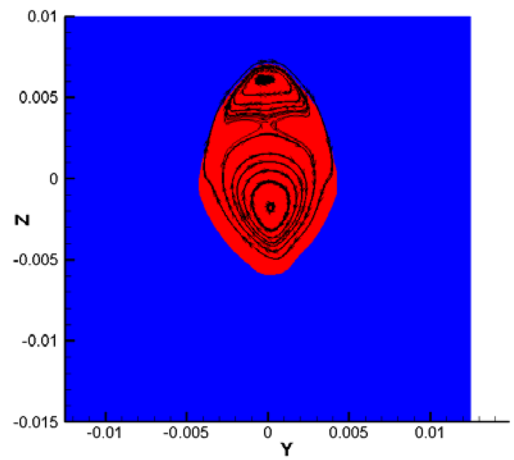
100 mrad tilt angle



z = 0 cm



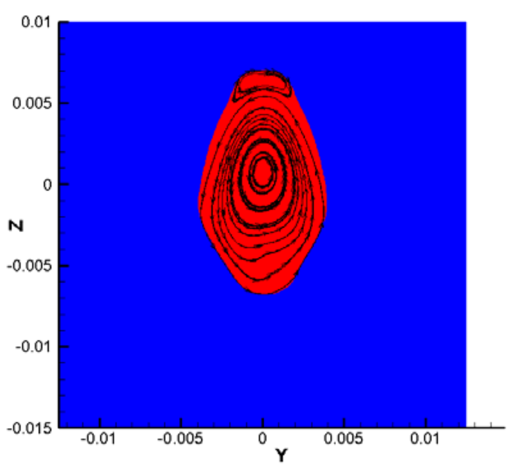
z = 20 cm



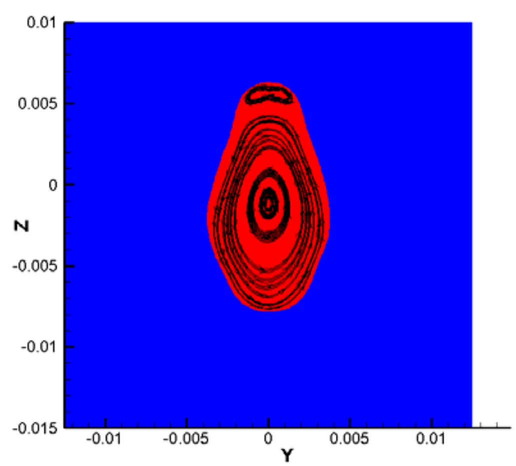
z = 30 cm

Aspect ratio = 1.4 in the solenoid center

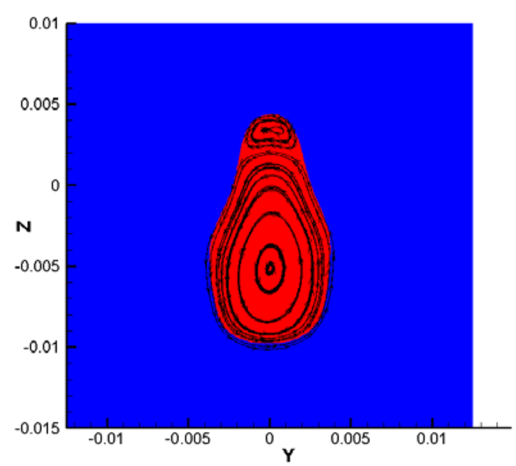
z = 40 cm



z = 50 cm



z = 60 cm



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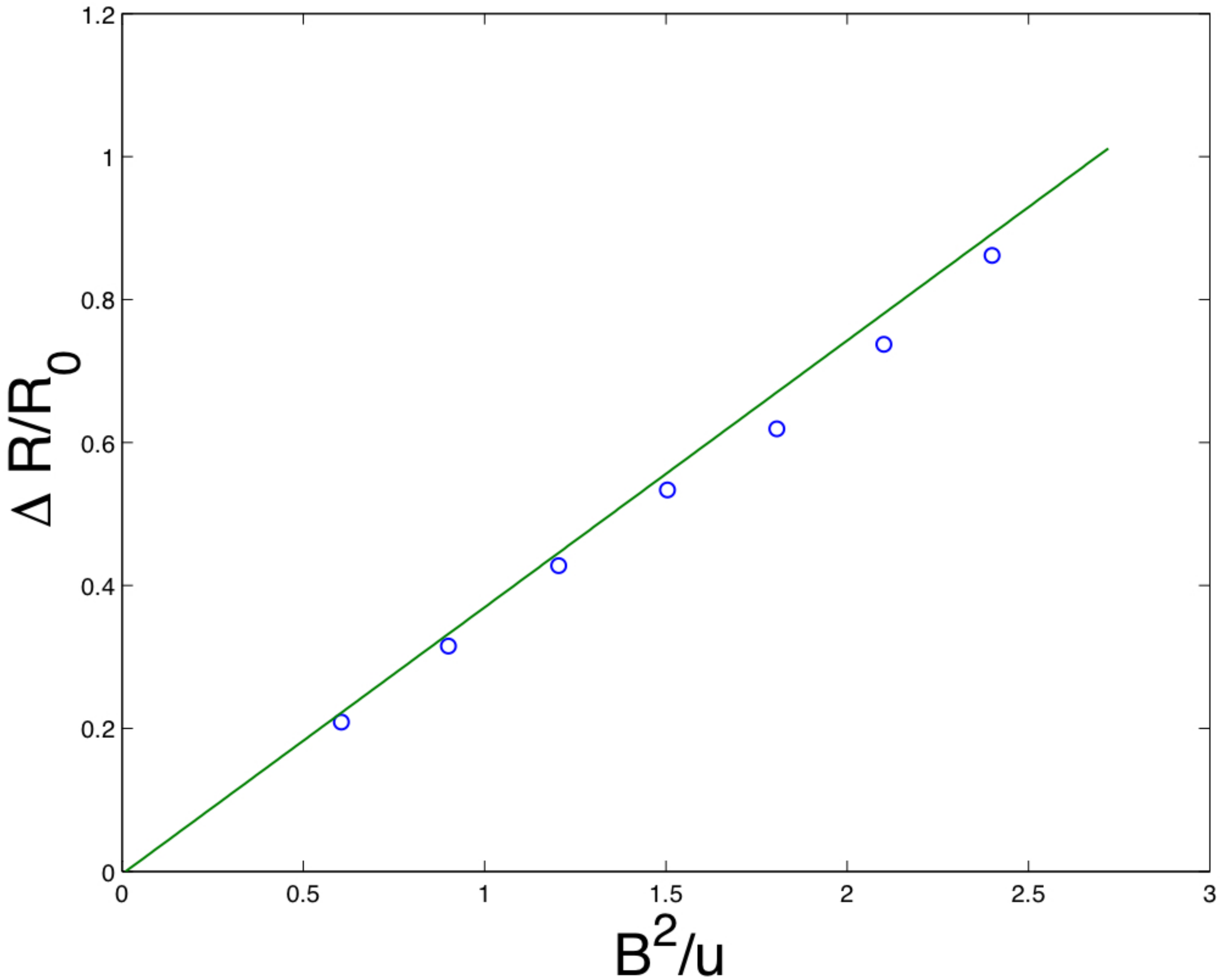
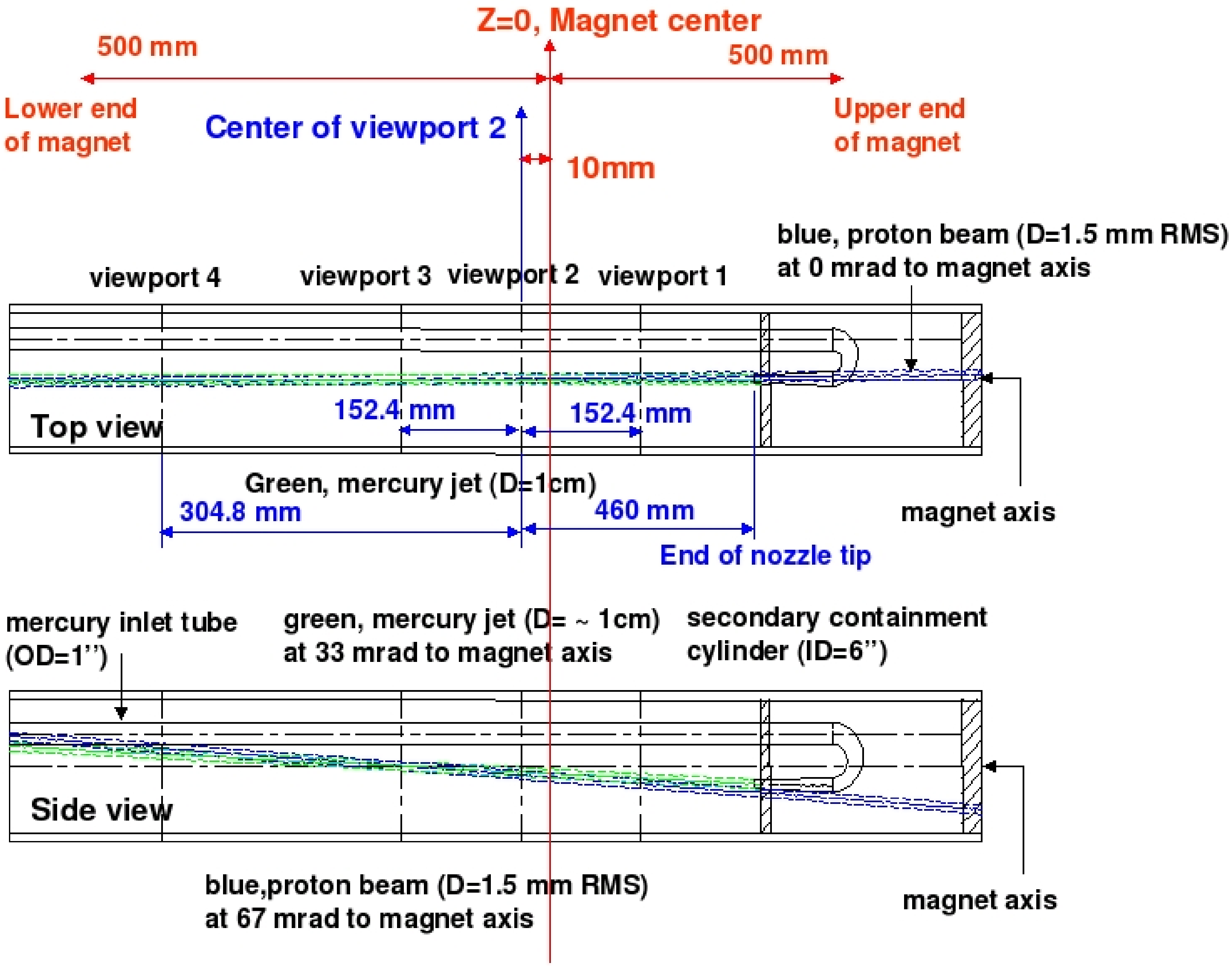
Comparison with the theory

R. Samulyak et. al, Journal of Computational Physics, 226 (2007), 1532 - 1549.

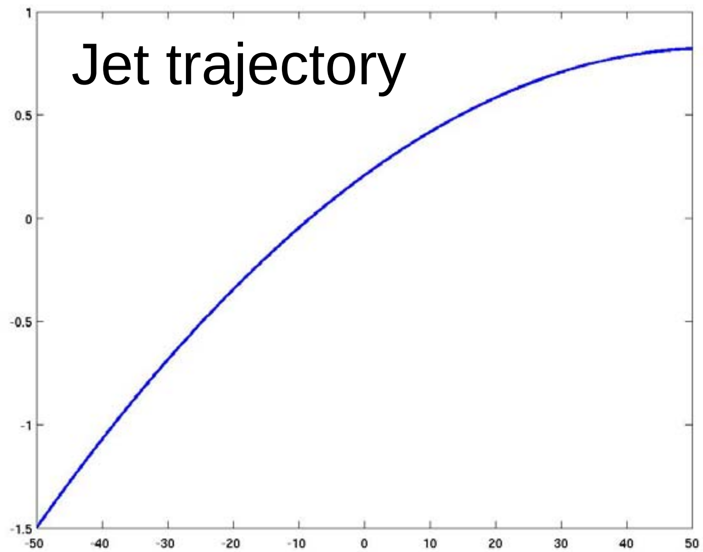


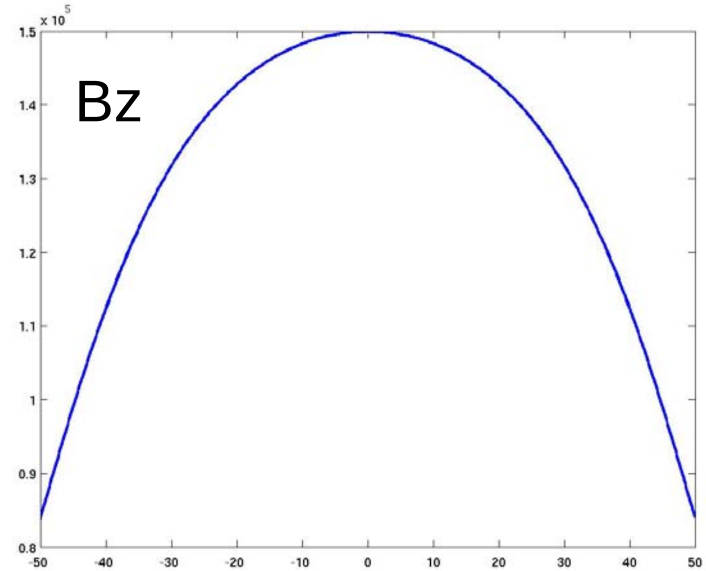
MERIT setup

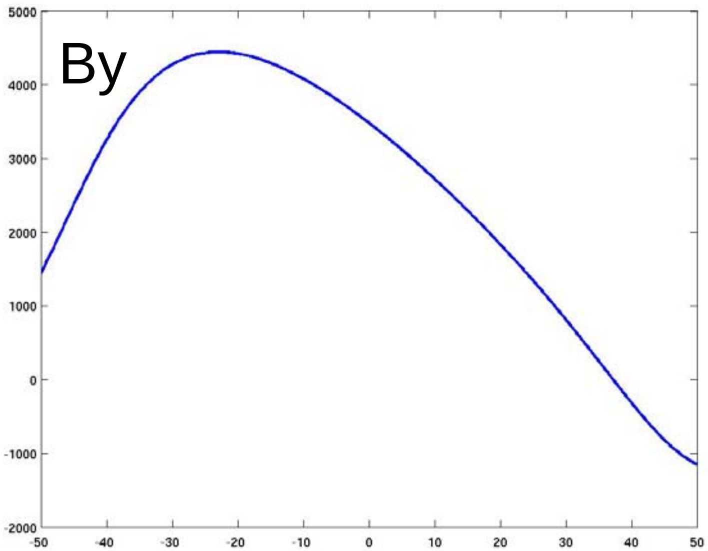
Geometry of Hg system in Magnet

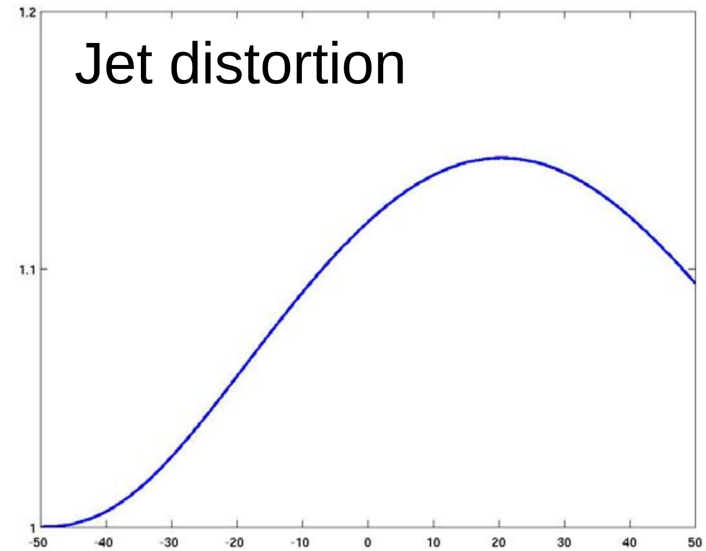


V = 15 m/s, B = 15 T

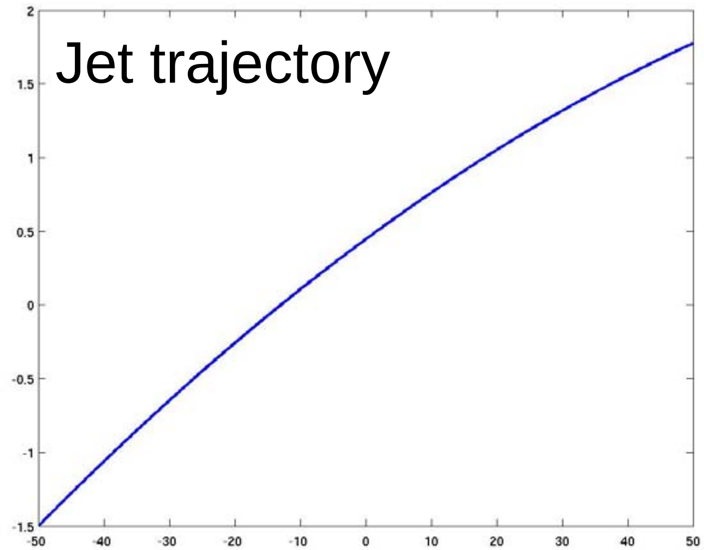


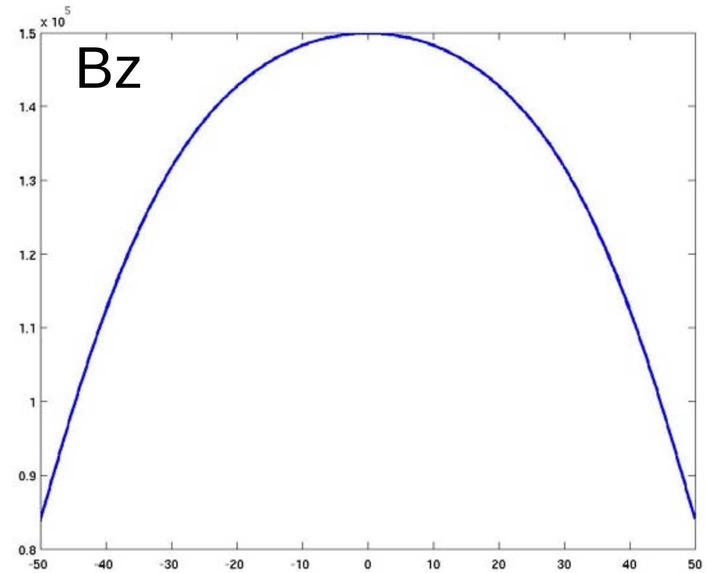


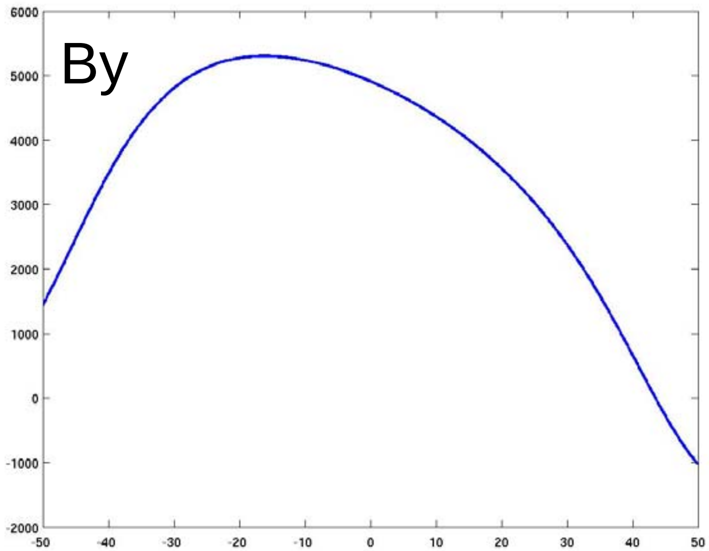


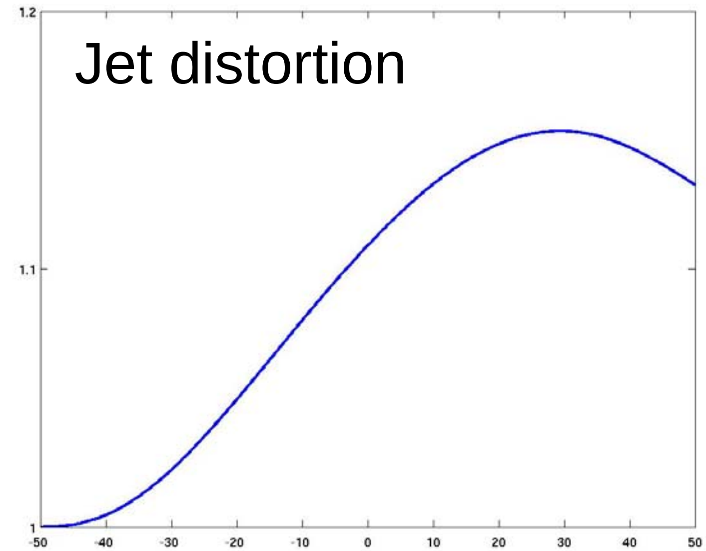


V = 20 m/s, B = 15 T

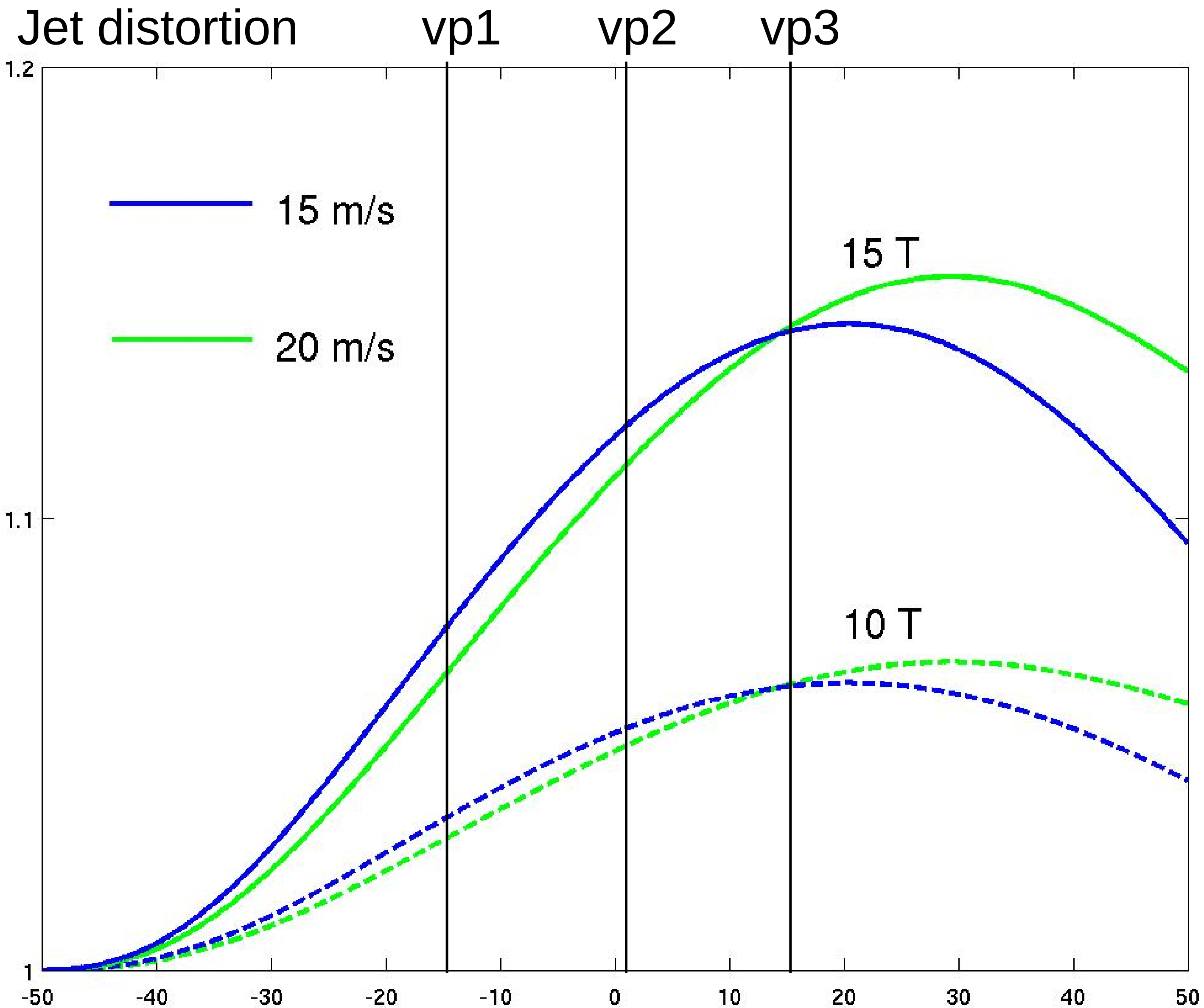

Jet trajectory
2
1.5
1
0.5
0
-0.5
-1
-1.5
-50 -40 -30 -20 -10 0 10 20 30 40 50


Bz
x 10^5
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
-50 -40 -30 -20 -10 0 10 20 30 40 50


By
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-50 -40 -30 -20 -10 0 10 20 30 40 50


Jet distortion
1.2
1.1
1
-50 -40 -30 -20 -10 0 10 20 30 40 50

Comparison: V = 15 and 20 m/s, B = 10 and 15 T



Experimental data

V = 15 m/s, B = 10T

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V = 20 m/s, B = 10T

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B = 15T

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B = 15T

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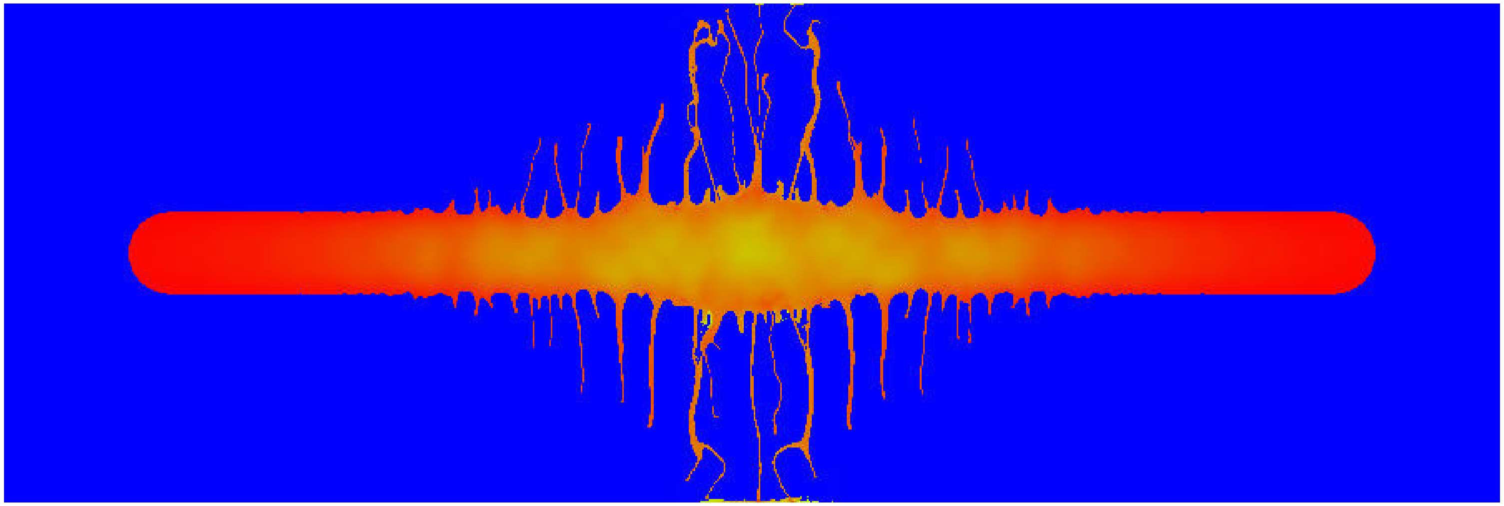
Simulations only qualitatively explain the width of the jet in different view ports.

Jet - proton pulse interaction. Evolution of models.
Phase I: Single phase mercury (no cavitation)

- Strong surface instabilities and jet breakup observed in simulations

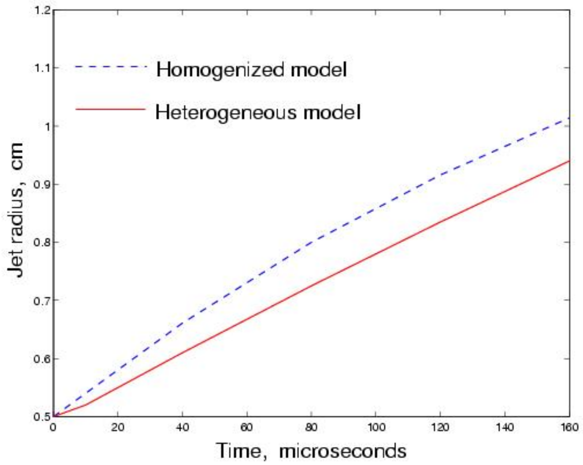
- Mercury is able to sustain very large tension
- Jet oscillates after the interaction and develops instabilities

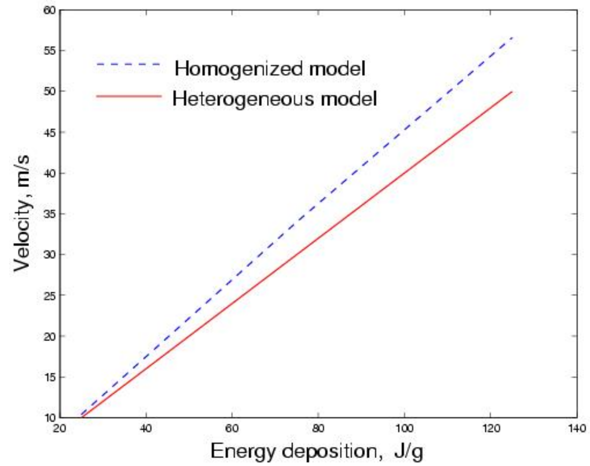
Jet surface instabilities

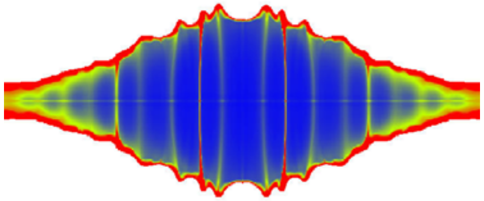


Jet - proton pulse interaction.
Phase II: Cavitation models

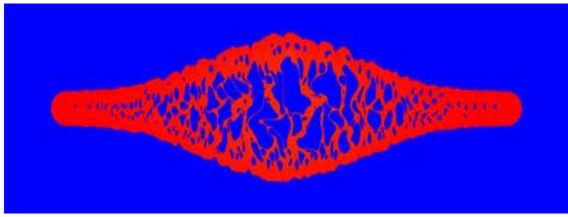
• We evaluated and compared homogeneous and heterogeneous cavitation models:



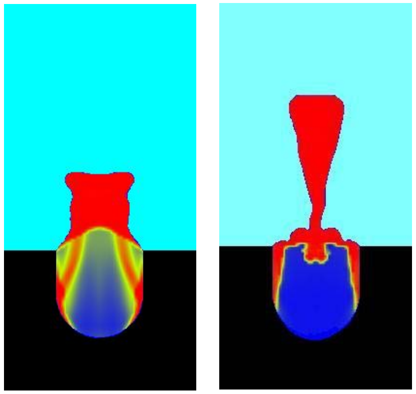




Homogeneous model



Heterogeneous model (resolved cavitation bubbles)



• Two models agree reasonably well
• Predict correct jet expansion velocity
• Surface instabilities and jet breakup not present in in simulations
• Delay and reduction of jet disruptions by the magnetic field

Jet - proton pulse interaction
Phase III: Search of missing physics phenomena

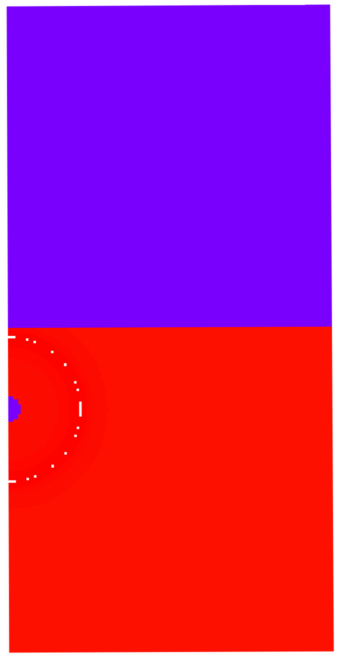
Surface instabilities and jet breakup were not observed in simulations with cavitation.

Possible Cause:

- **Turbulence nature of the jet**
- **Microscopic mixture and strong sound speed reduction of the homogeneous model (separation of phases is important)**
- **2D vs 3D physics**
- **Unresolved bubble collapse in the heterogeneous model**
  - **Bubble collapse is a singularity causing strong shock waves**
- **Other mechanisms?**

Multiscale approach to bubble collapse

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



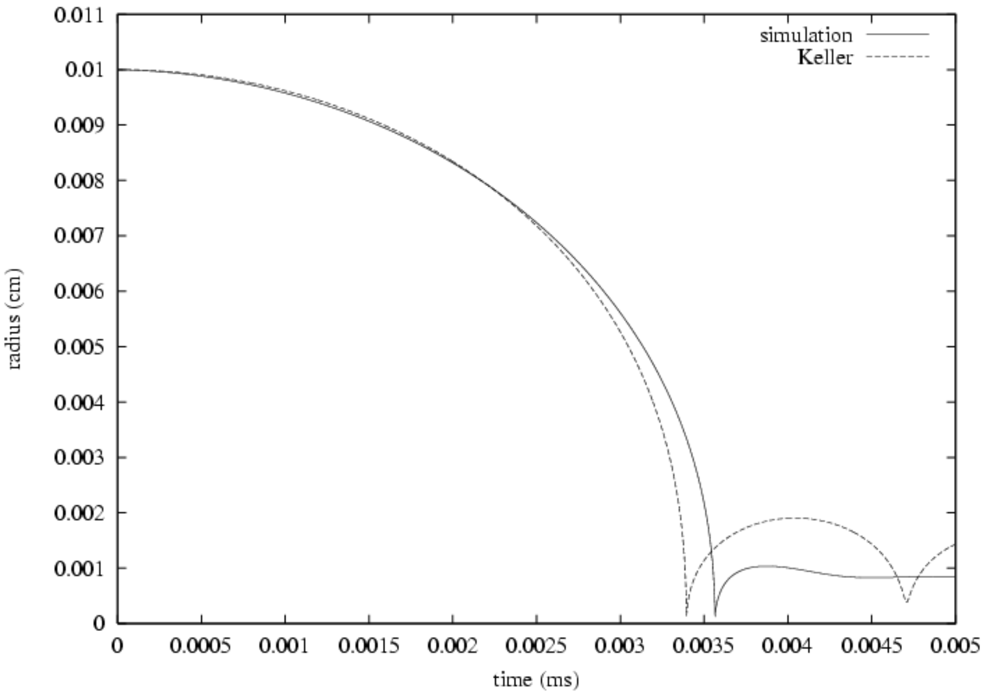
Multiscale approach:

Step 1: Accurate local model precomputes the collapse pressure

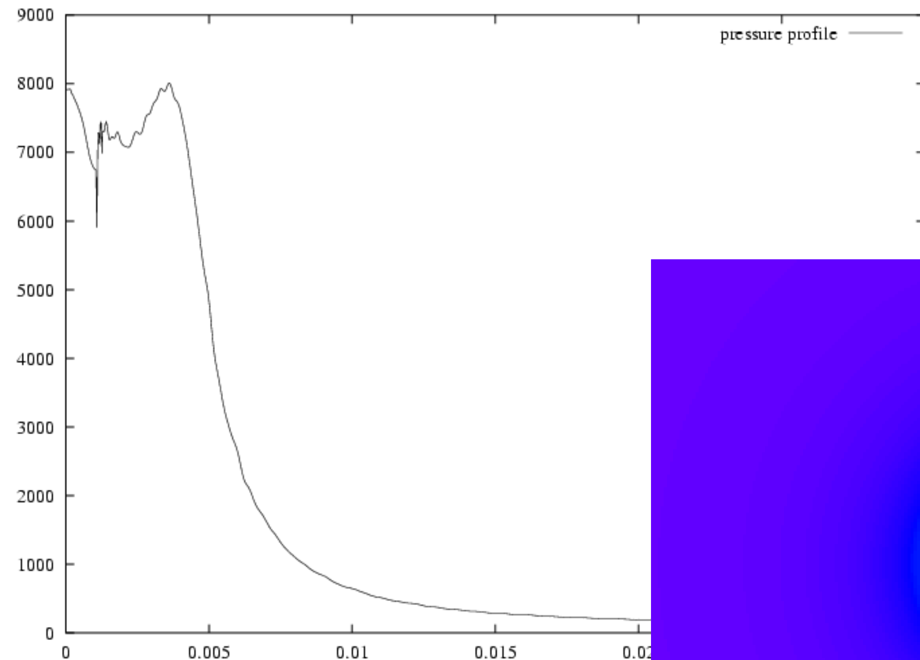
Step 2: Output of the local model serves as input to the global model

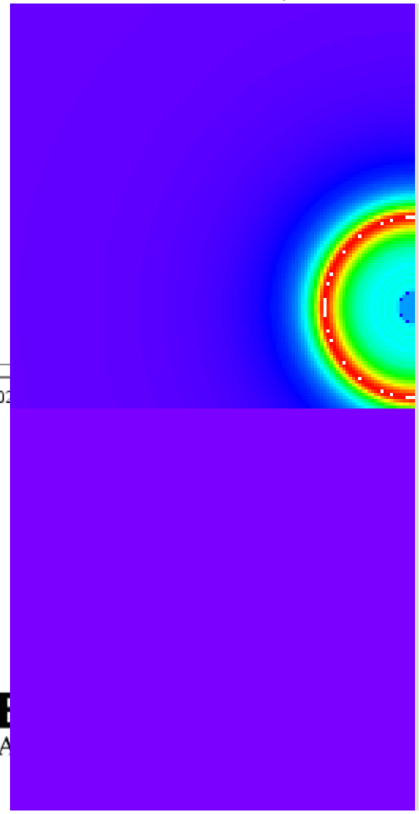
Step 1: 1D bubble collapse

Radius vs. Time



Pressure Profile at t =0.0035 ms





Step 2: 2D and 3D simulations of the collapse induced spike

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t = 0 t = 0.0035 ms t = 0.0070 ms

- 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

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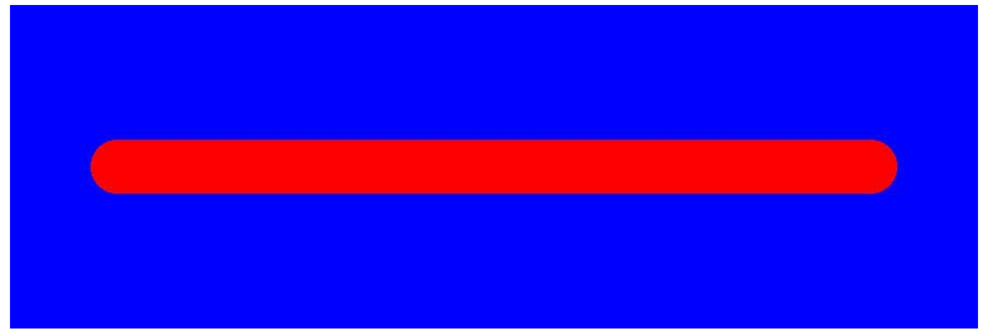


This was the real state of the jet before the interaction with protons

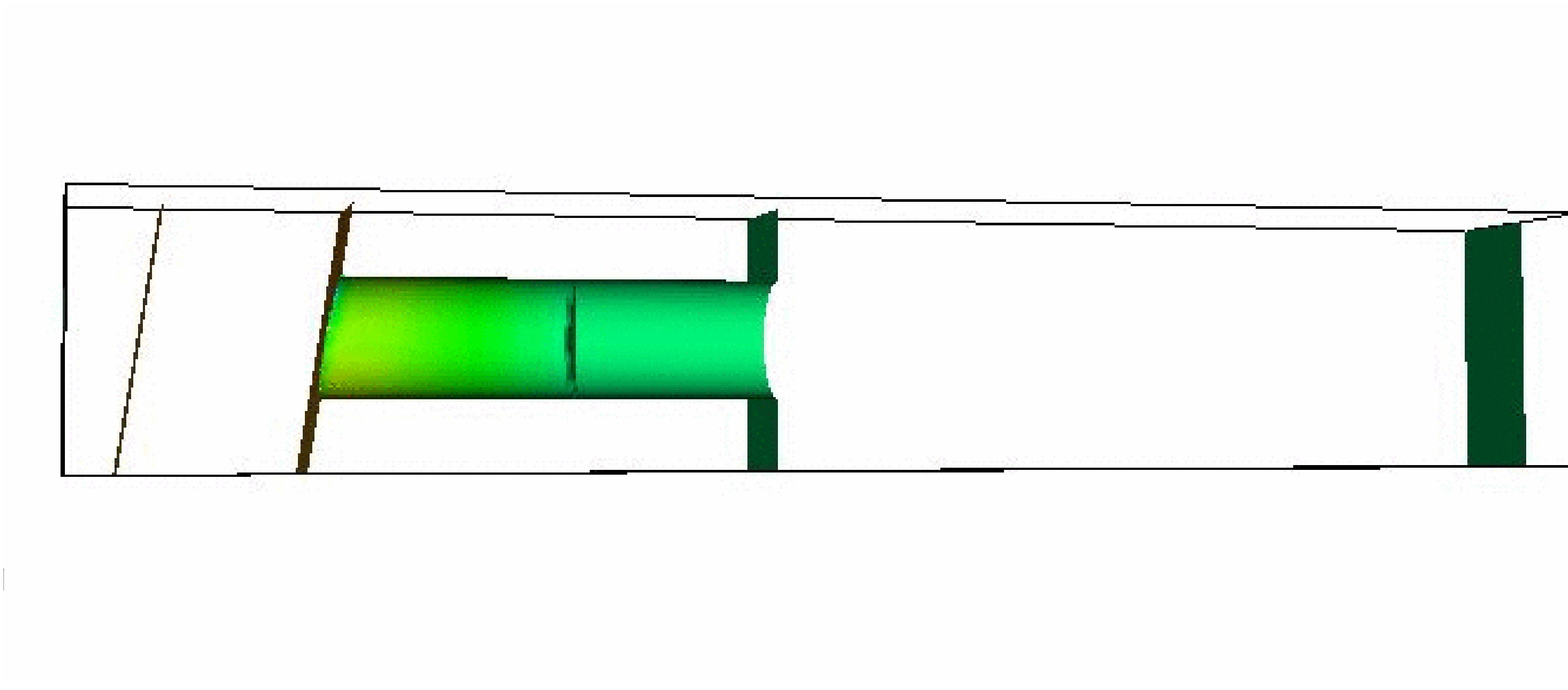
This was initial jet in previous numerical simulations (in 2D and 3D)

The obvious difference might be an important missing factor for both the jet flattening effect and interaction with the proton pulse.

Cavitation and instabilities of 3D jet emerging from the nozzle

- Major numerical development allowed us to obtain the state of the target before the interaction by "first principles"

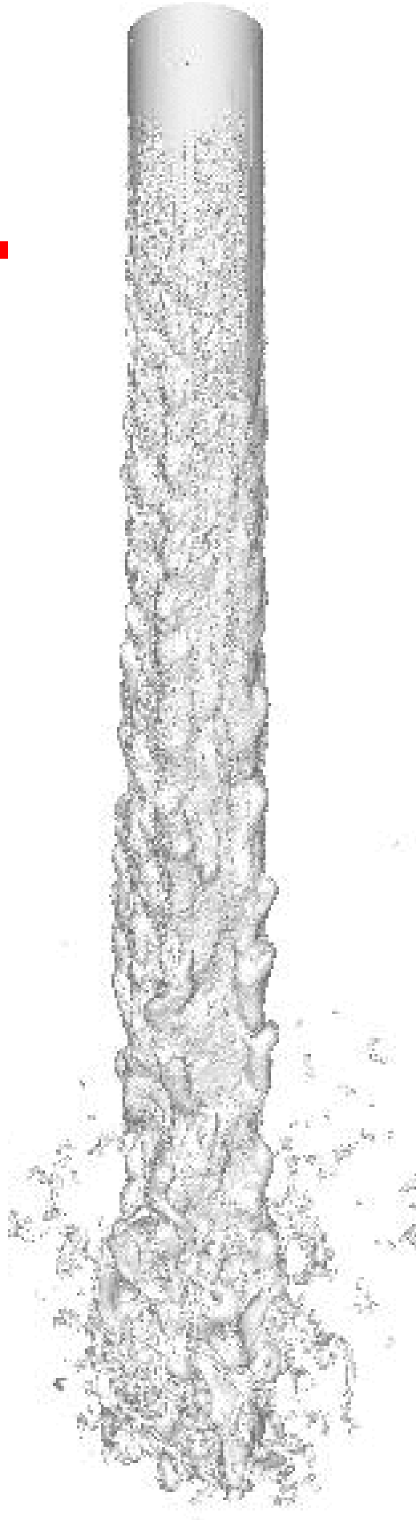
- Simulation of the jet - proton pulse interaction is in progress

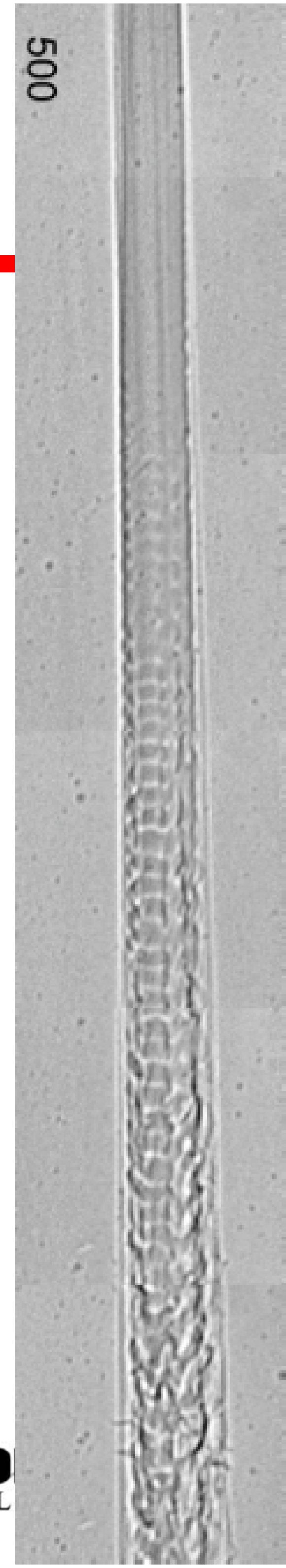


3D (fuel) jet breakup and atomization

Left: FronTier simulations

Right: ANL experiment





3D jet cavitation

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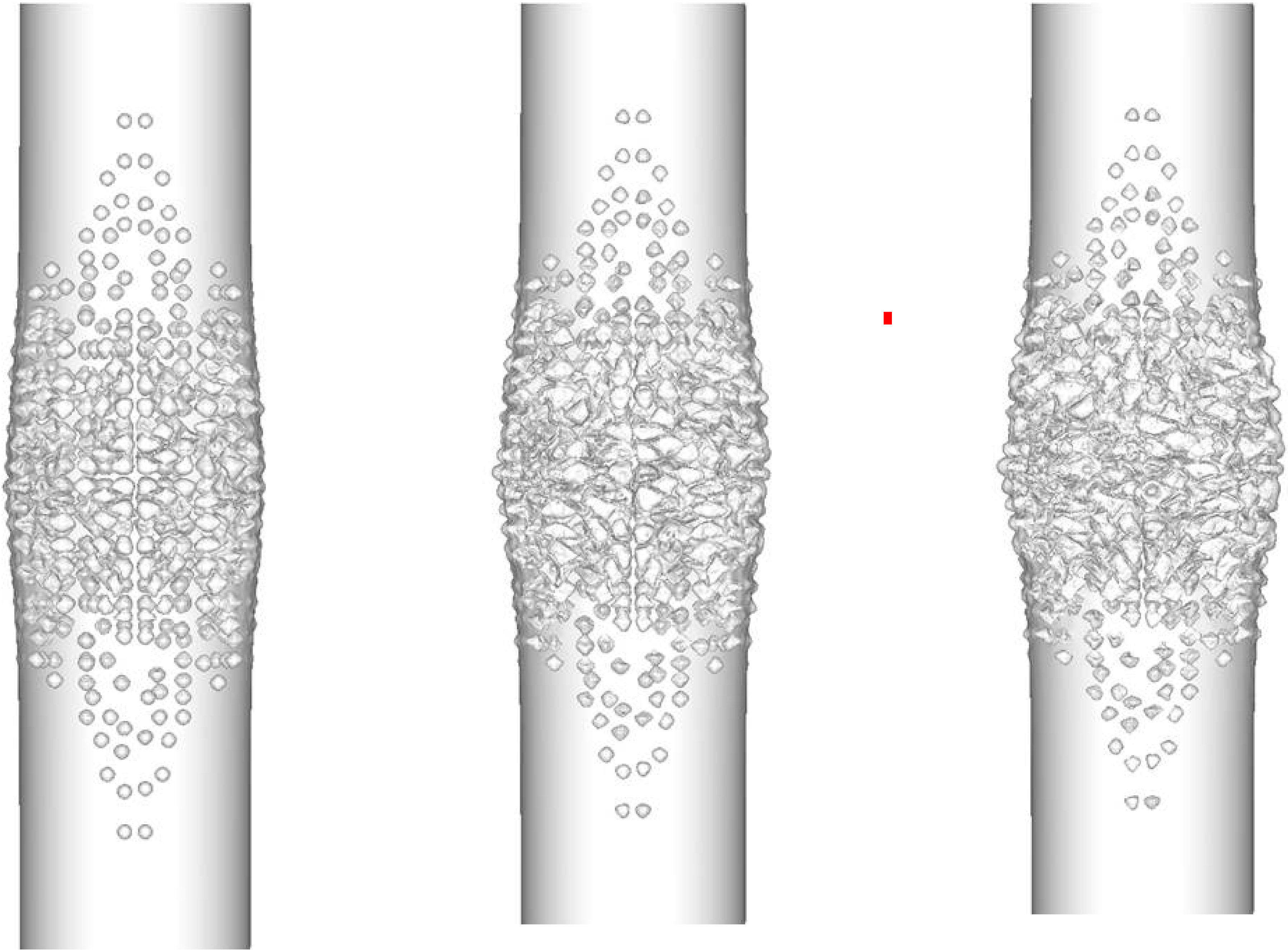
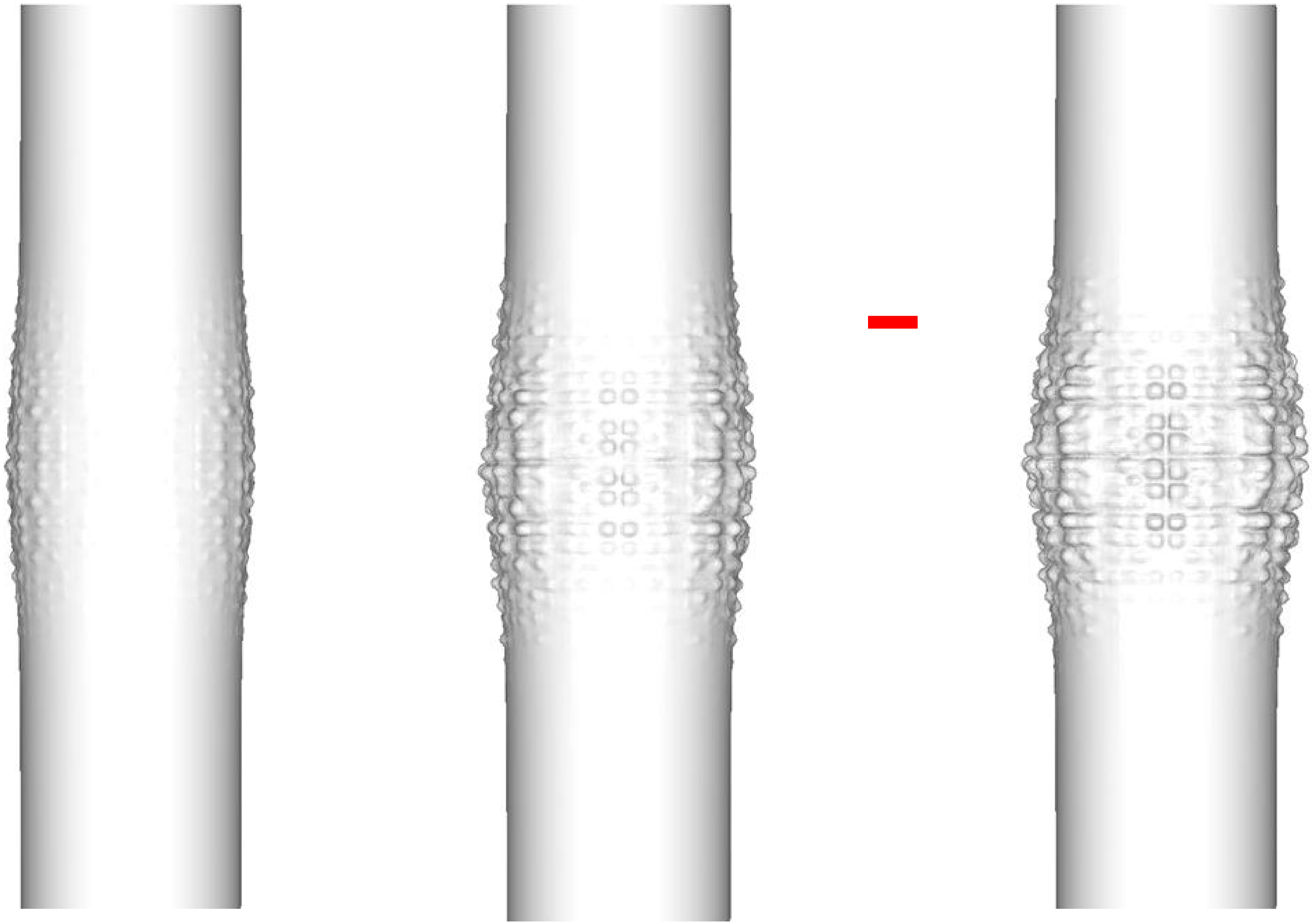


14.8 31.4 45.4 microseconds



14.8 31.4 45.4 microseconds

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