Simulation of High-Intensity Pulsed Beam Targeting

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Talk Overview

- Simulation of mercury jet target: main goals
- FronTier code for multiphase, multiphysics simulations
    - Typical applications of the FronTier code related to energy research
- Simulation of liquid mercury jet target for Neutrino Factory / Muon Collider and comparison with MERIT experiment

Motivation of the Present Study of the Mercury Target

- Understanding of the hydrodynamic response of the mercury target and explanation of all details of MERIT data is necessary for the future target design

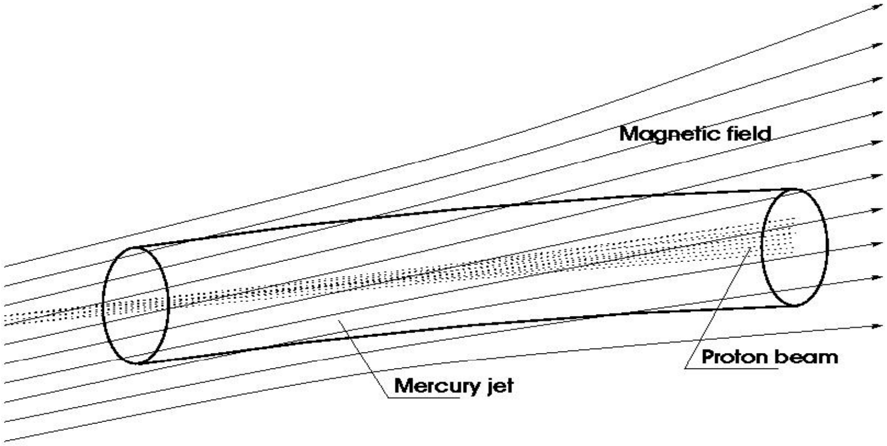
- Using improved 3D FrontTier capabilities, perform new series of full 3D simulations of the mercury target with resolved all relevant physics processes

- Perform full benchmark of simulations with MERIT data and fine-tune FronTier models

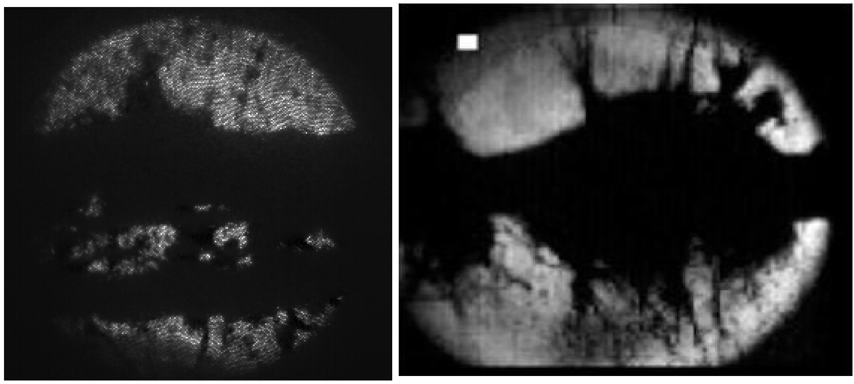
- After the benchmark, FronTier can be used for reliable predictions of future targets.

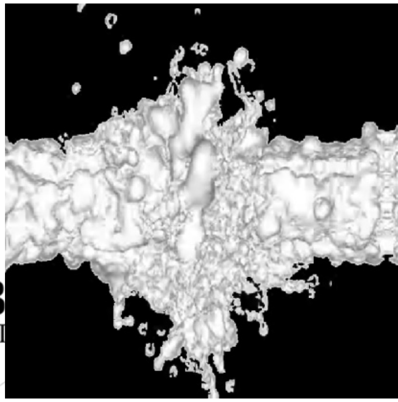
Mercury Jet Target for Neutrino Factory / Muon Collider

- Target is a mercury jet interacting with a proton pulse in a magnetic field
- Target converts protons to pions that decay to muons and neutrinos or to neutrons (accelerator based neutron sources)
- Understanding of the target hydrodynamic response is critical for design
    - Studies of surface instabilities, jet breakup, and cavitation
    - MHD forces reduce both jet expansion, instabilities, and cavitation



Target schematic

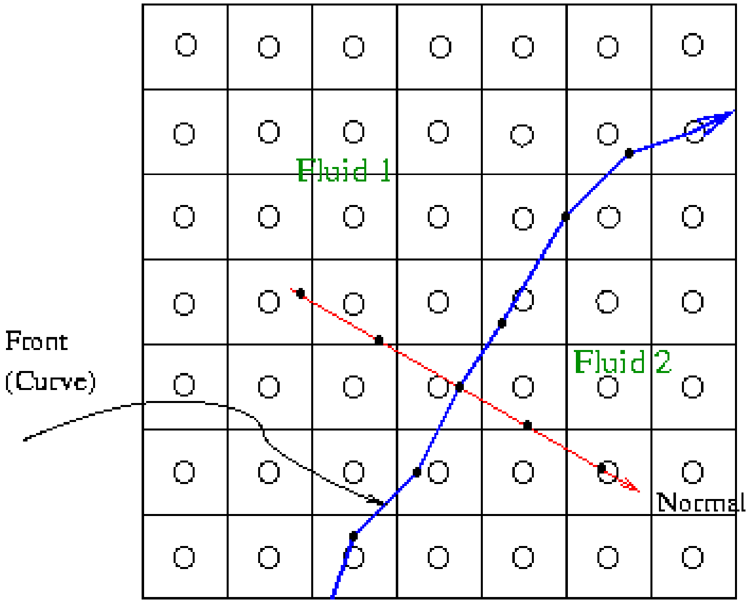




Jet disruptions
Top: experiment
Bottom: simulation

Main Ideas of Front Tracking

Front Tracking: A hybrid of Eulerian and Lagrangian methods



Two separate grids to describe the solution:

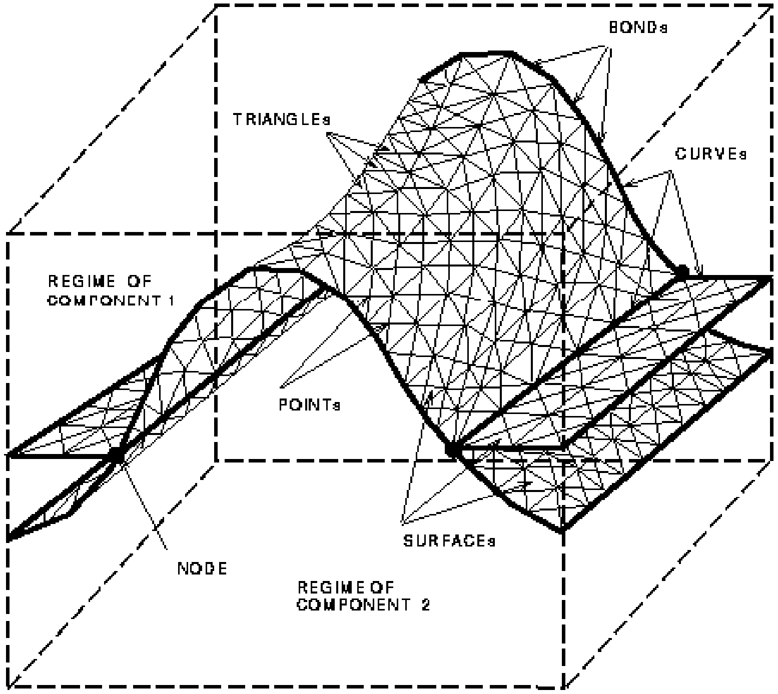
1. A volume filling rectangular mesh
2. An unstructured codimension-1 Lagrangian mesh to represent interface

Major components:

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

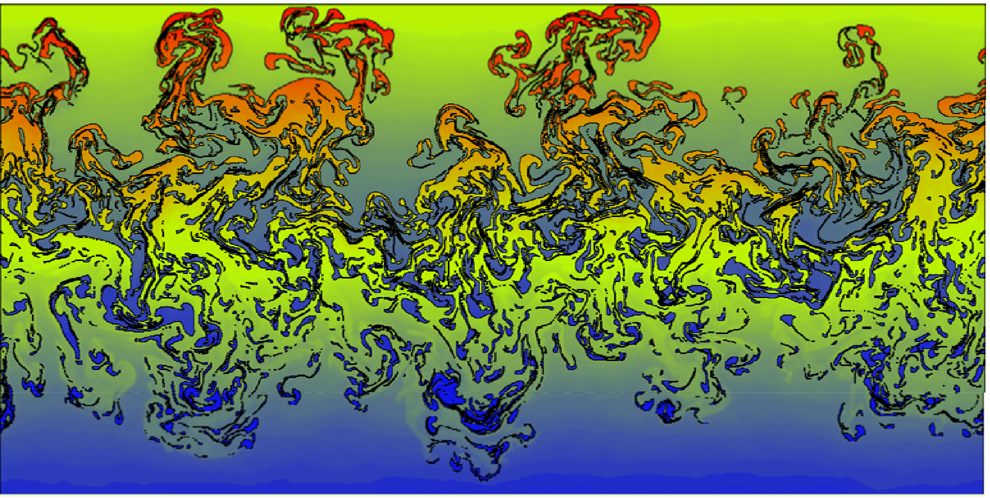
Advantages of explicit interface tracking:

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

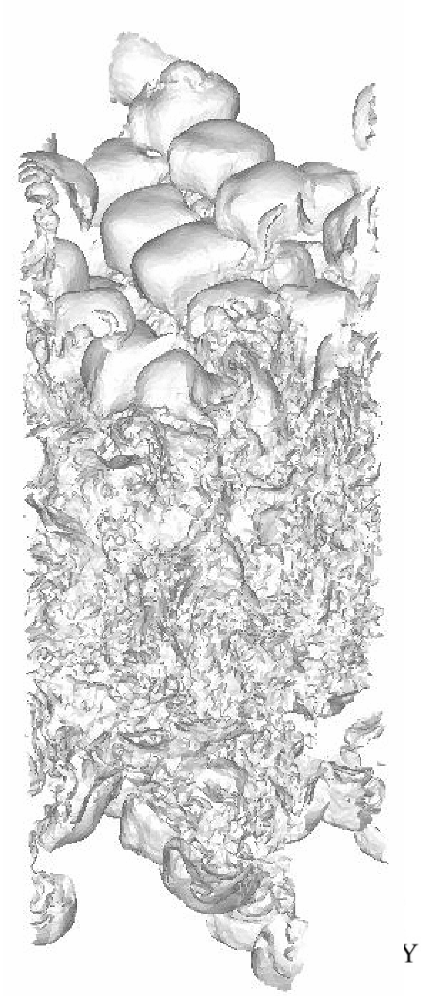


The ***FronTier*** Code

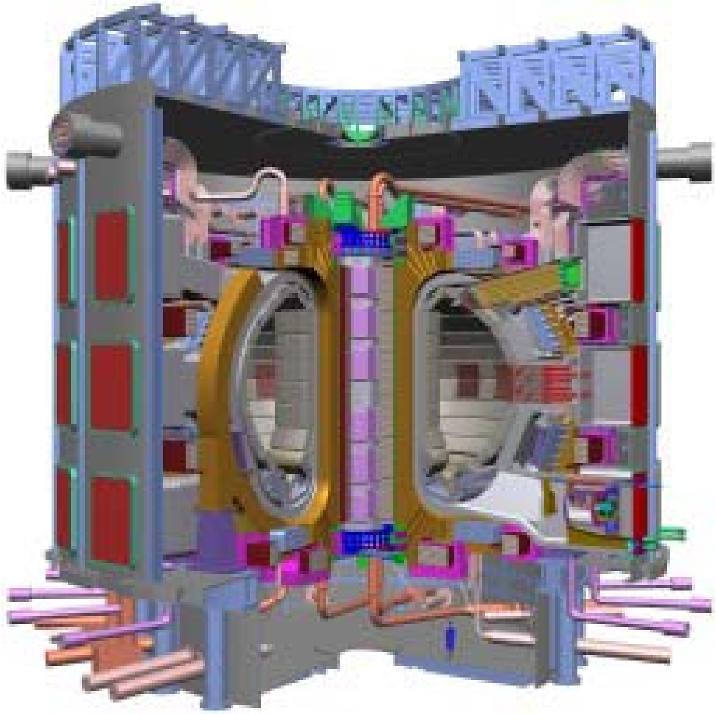
- FronTier is a parallel 3D multiphysics code based on front tracking
- Being developed within DOE SciDAC program
- Adaptive mesh refinement
- Physics models include
  - Compressible and incompressible fluid dynamics, MHD
  - Flows in porous media
  - Phase transitions and turbulence models



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



Fusion Energy. ITER project: fuel pellet ablation

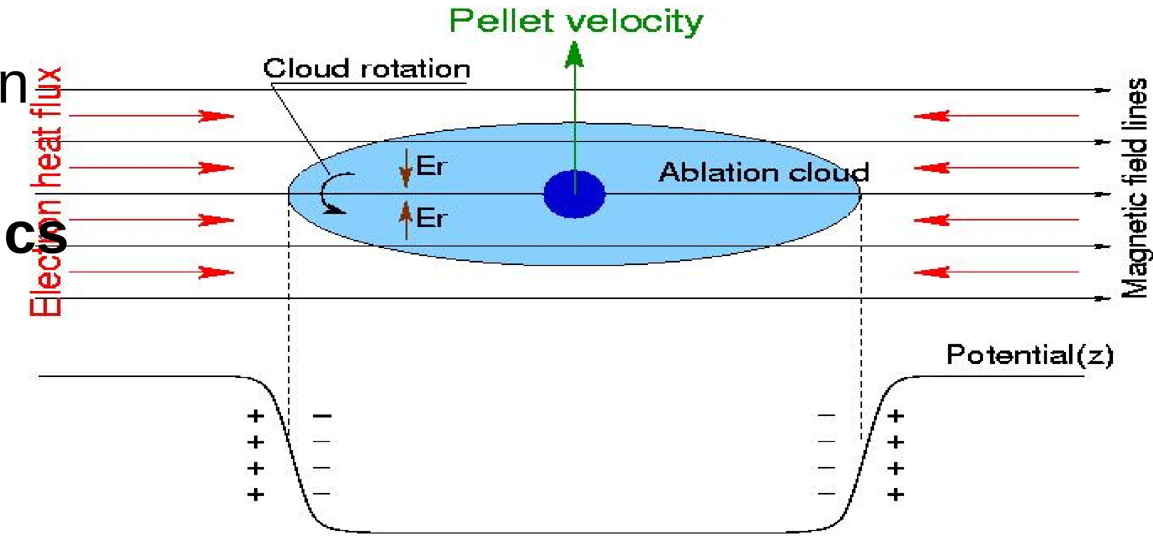


- ITER is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power
- ITER will be constructed in Europe, at Cadarache in the South of France in ~10 years

Our contribution:

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

Collaboration with General Atomics



New Ideas in Nuclear Fusion:
Palsma Jet Induced Magneto Inertial Fusion

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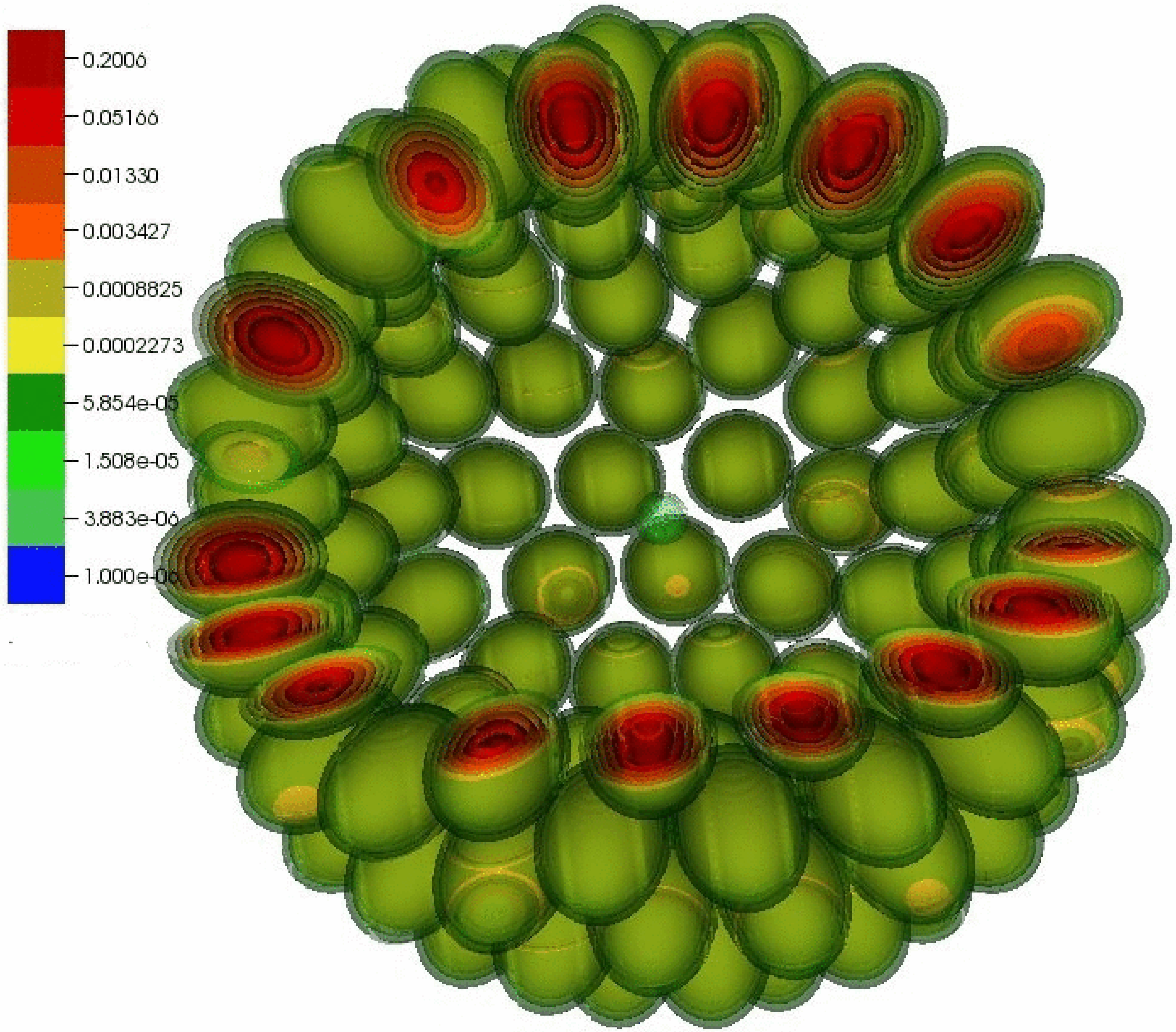
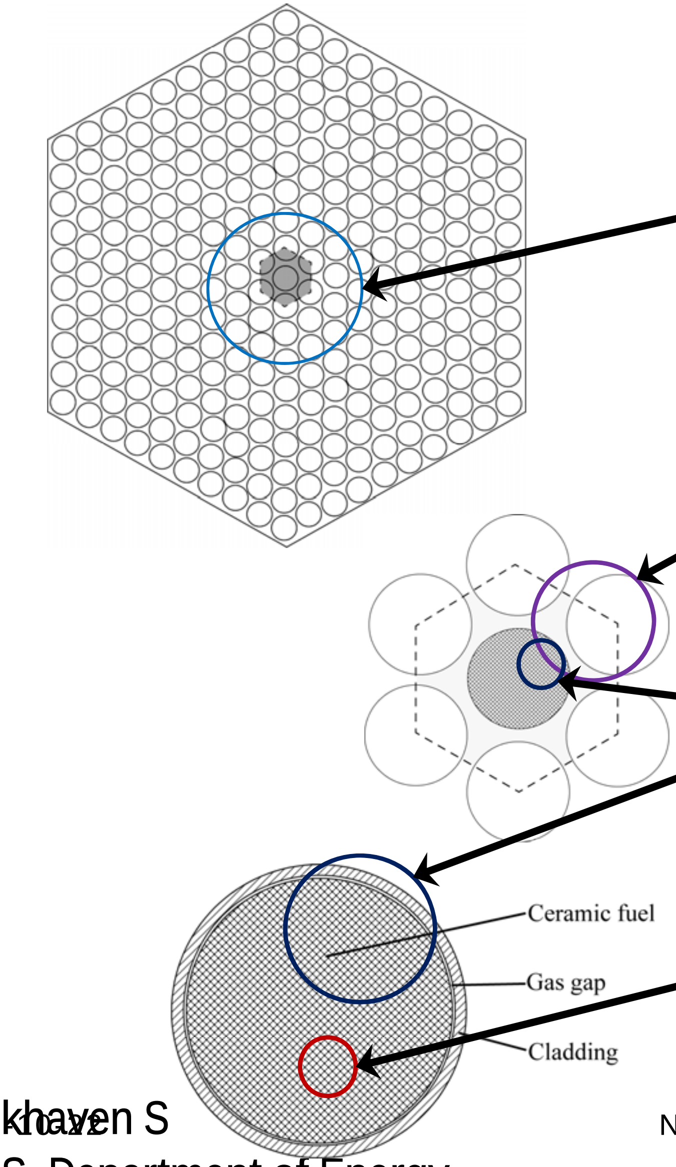
are needed to see



FronTier Application: NERI Collaboration of RPI, SBU, Columbia, and BNL. Fuel Rod Failures in Sodium Coled Reactors



NPHASE-CMFD code uses Reynolds-Averaged Navier Stokes (RANS, e.g. k-ε model) approach to multiphase modeling

Flow of liquid sodium coolant and fission gas around I reactor fuel rods

PHASTA uses direct numerical simulation (DNS) with Level Set method to track the interface between gas and liquid phases

Jet of high pressure fission gas entering coolant channels

FronTier is a front tracking code capable of simulating multiphase compressible fluid dynamics

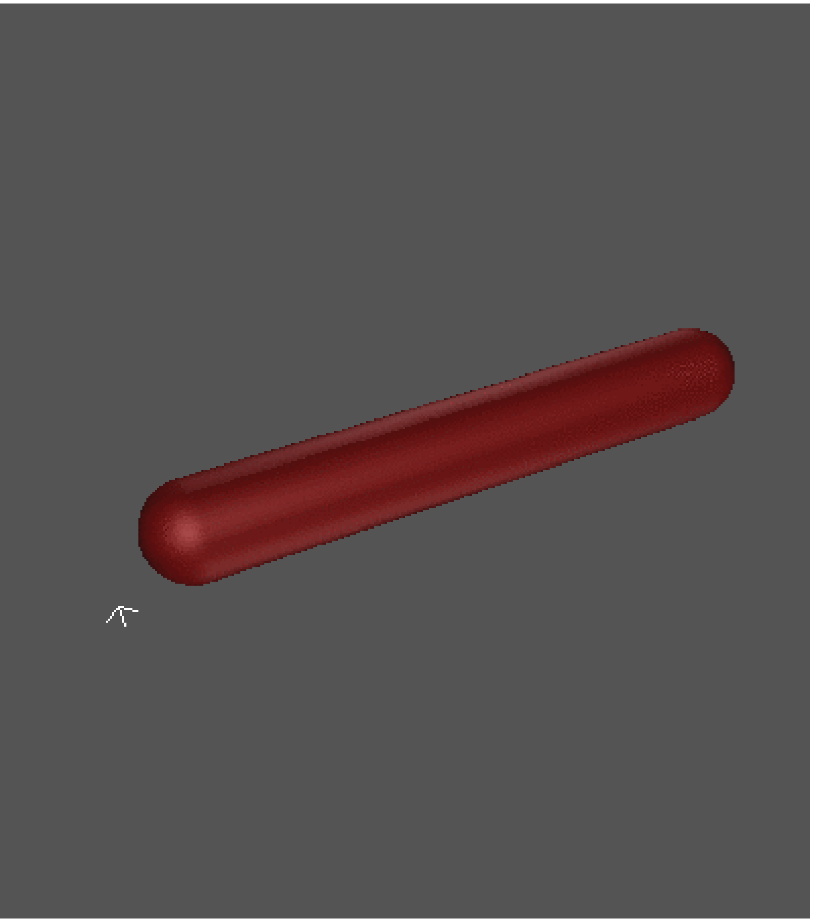
Fuel rod overheating and melting of cladding in case of coolant-blockage accident

Molecular Dynamics approach analyses the irradiated fuel properties

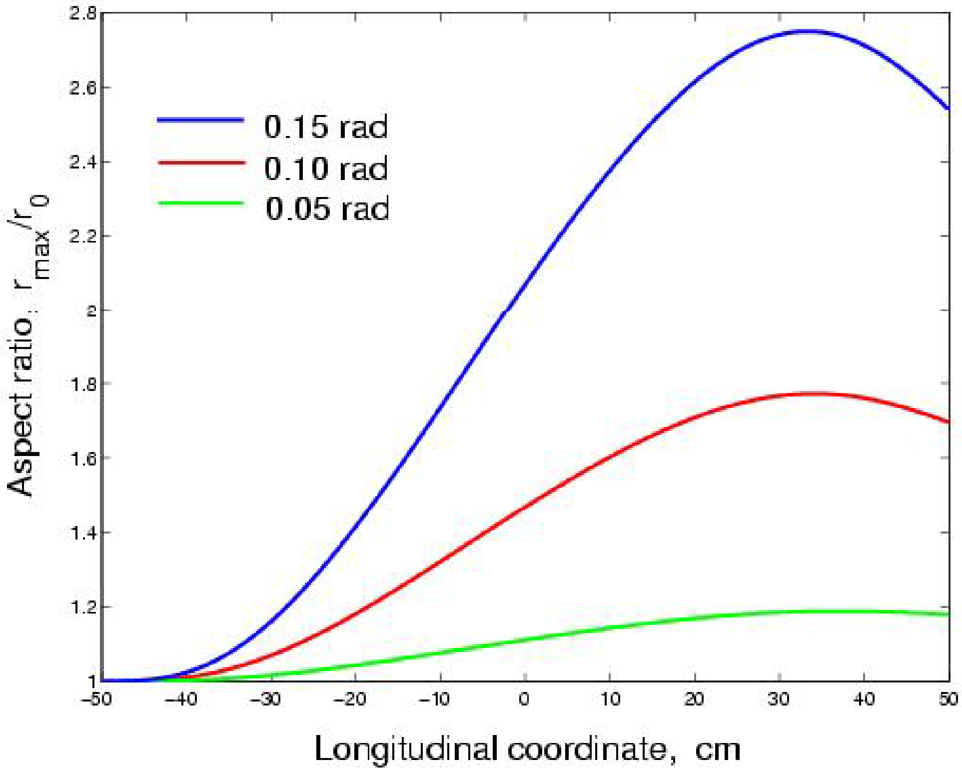
Prediction of fuel properties evolution

Simulations of the mercury jet entrance into the magnetic field

Distortion of the jet entering 15 T solenoid



B = 15 T
V0 = 25 m/s

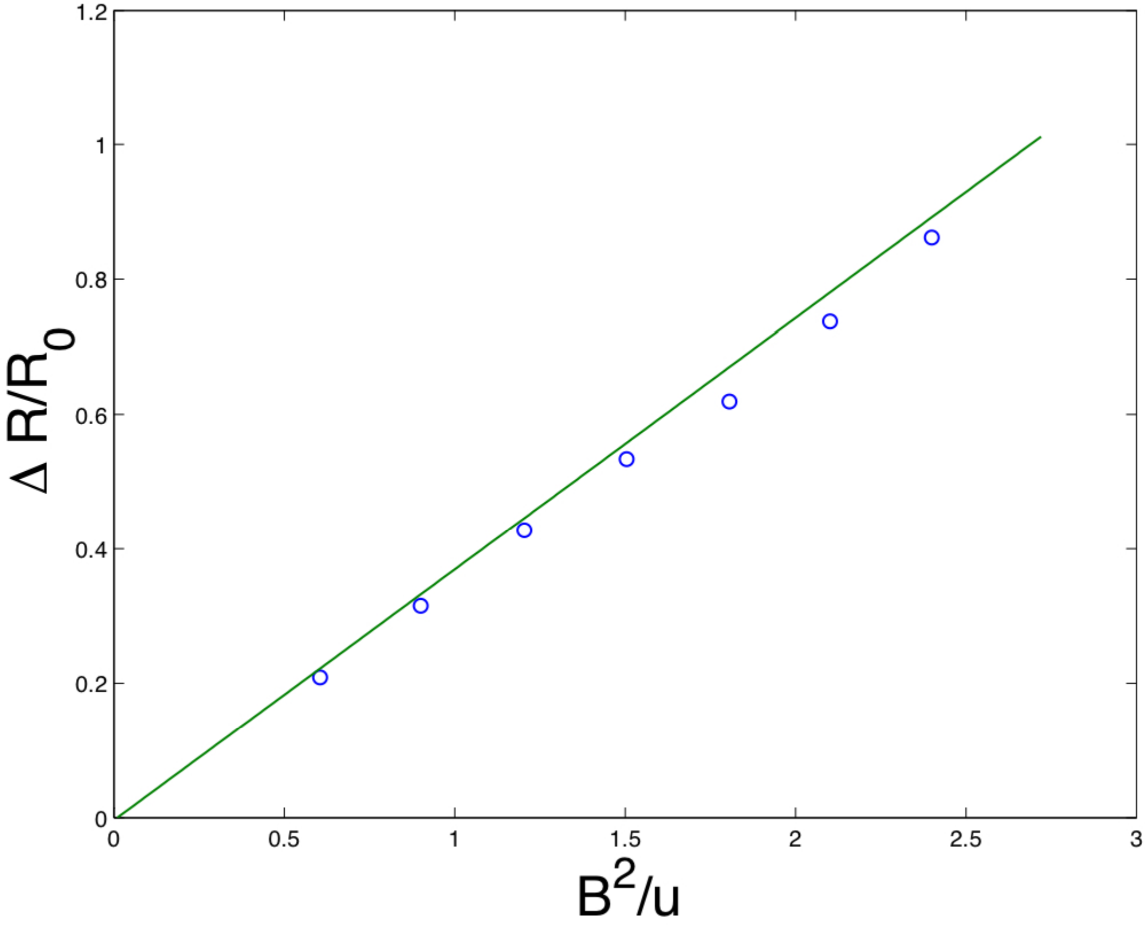


Top: Aspect ration of the jet entering 15 T solenoid

Comparison with the theory and other experiments (Oshima et al)

Obtained an excellent agreement with theory and experiments (Oshima at al) on the jet distortion

MERIT target simulations by FronTier agreed well with HyperMAG simulations (Neal Morley)



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

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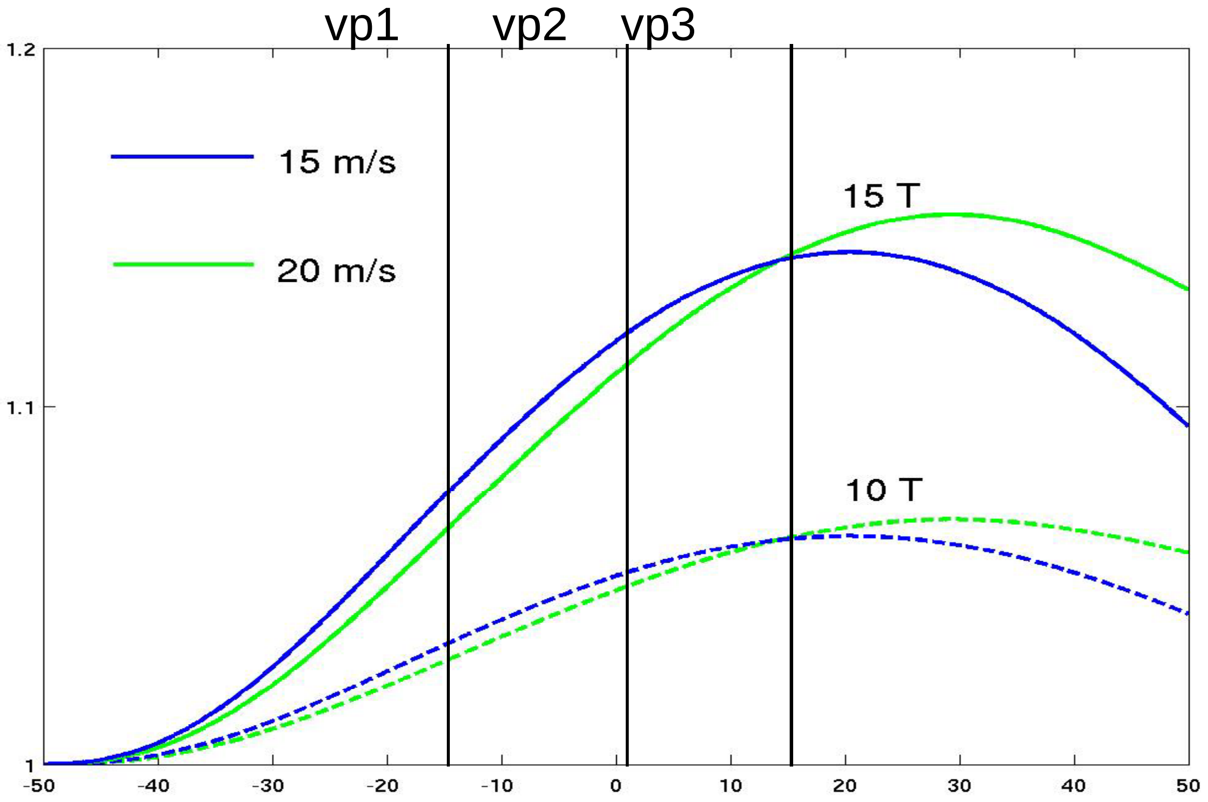
Predicted jet distortion in three view ports (MERIT experiment)



Our simulations underestimeted the jet distortion. Some other factors need to be resolved

Experimental data

V = 15 m/s, B = 10T

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TIFF (LZW) decompressor
are needed to see this picture.

V = 20 m/s, B = 10T

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

B = 15T

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

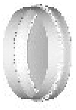
B = 15T

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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

Simulations of the mercury jet interaction with proton pulses

3D Simuation of Jet Ejection from a Nozzle.
High Speed Jet Cavitation, Breakup and Atomization

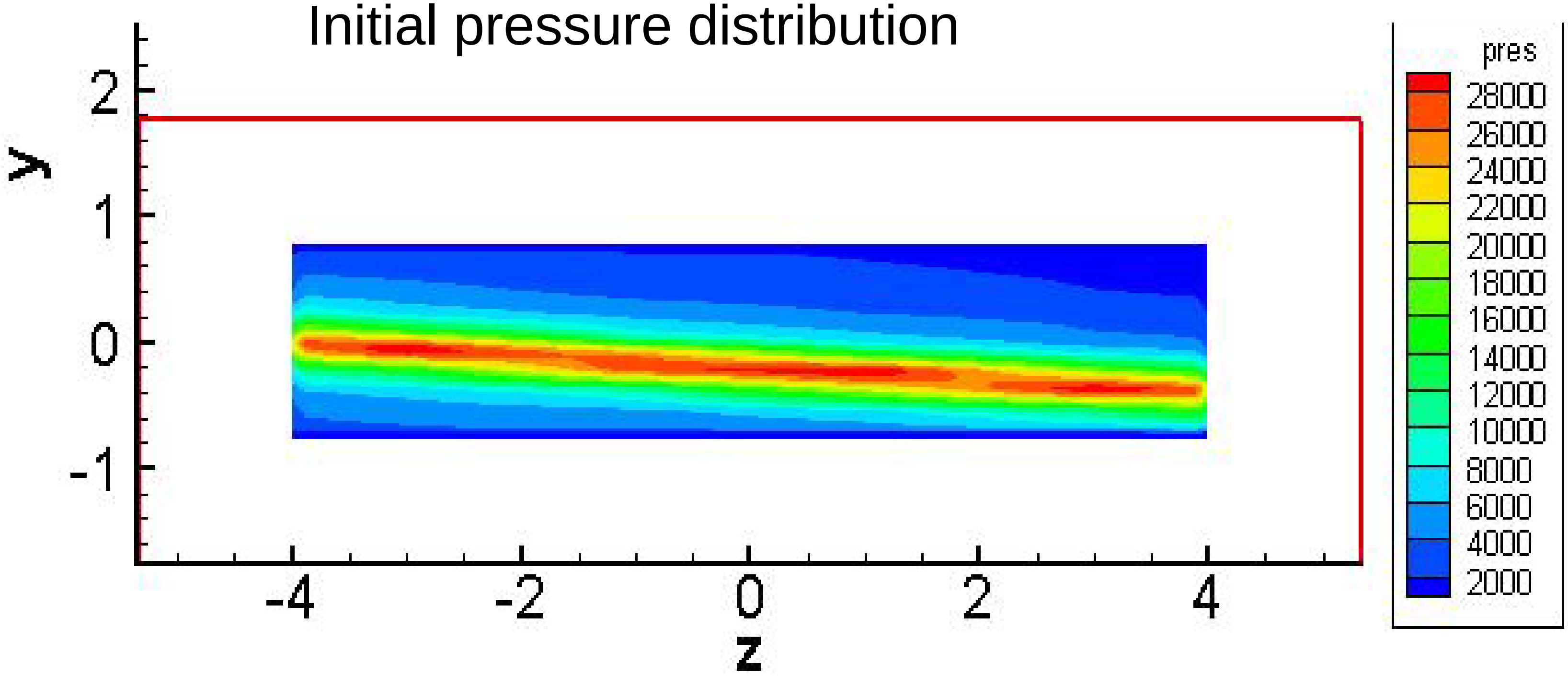


- We evaluated the influence of the initial jet turbulence on jet disruption due to the interaction with the proton pulse
- Initial turbulence is negligible compared to proton pulse induced instabilities
- As a result, most of runs are done with idealized initial jet

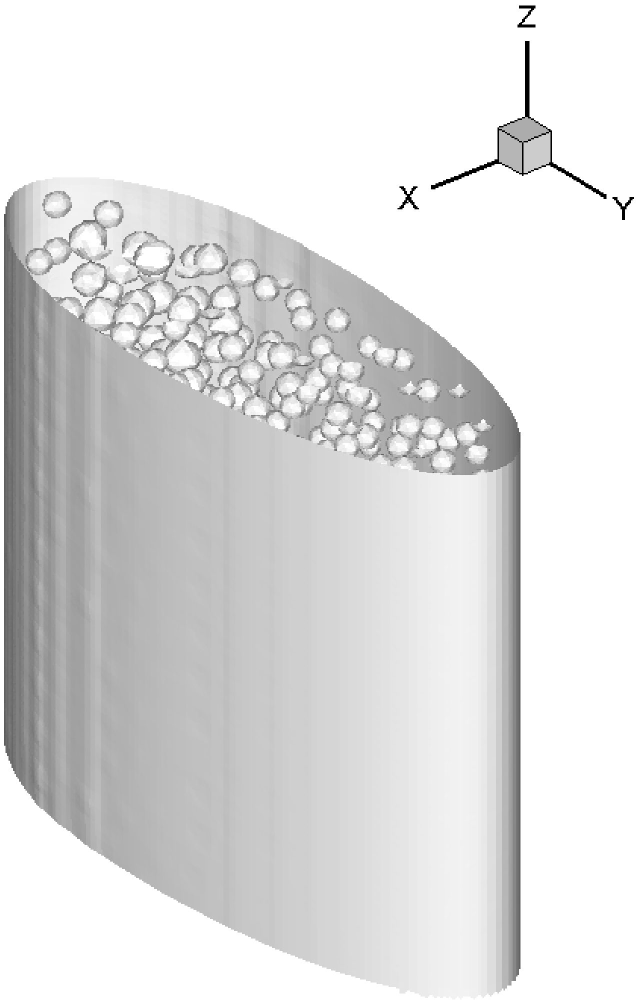
Simulation setup for proton-jet interaction

- Elliptic jet: Major radius = 0.8cm
- Minor radius = 0.3cm
- Striganov's Energy deposition calculation for 14Gev, 10T proton beam is used. The peak pressure is 12,050 bar.

Initial pressure distribution

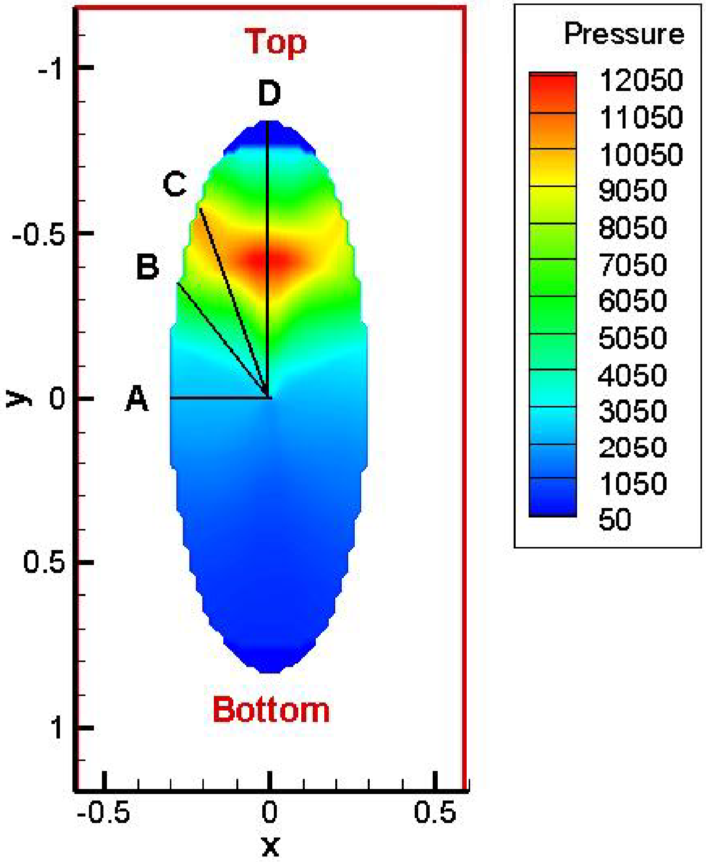


Evolution of the jet surface and cavitation bubbles for B=5T



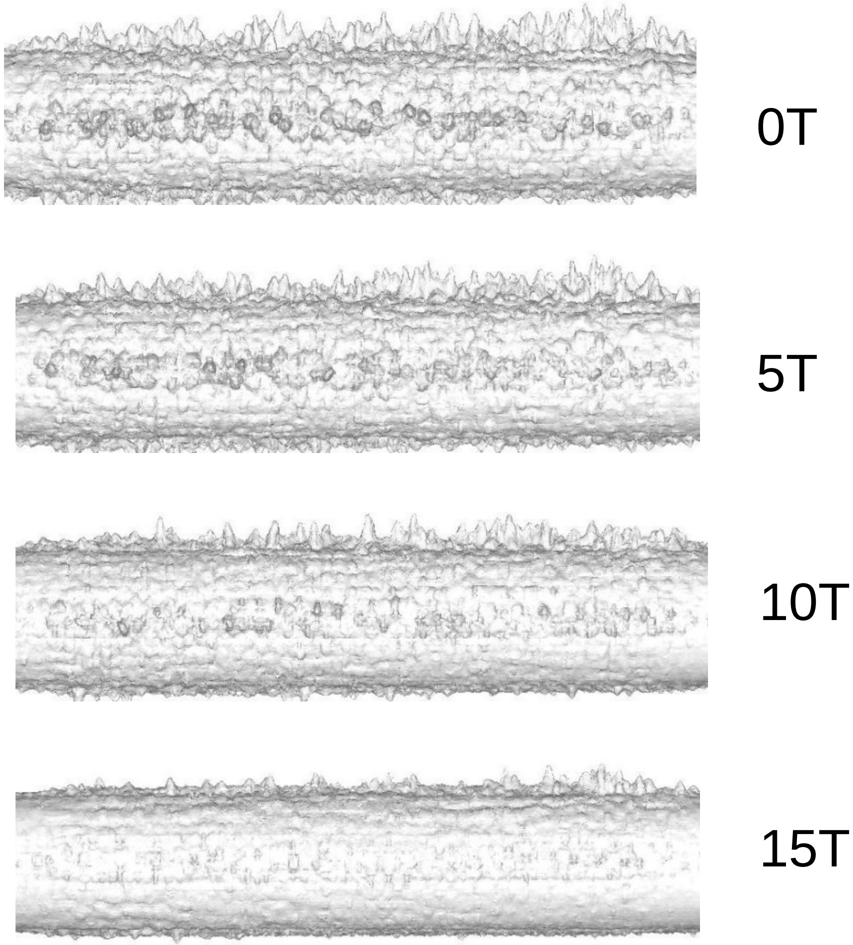
Positions for the filament length calculation

- To obtain the expansion velocity along the jet surface, we evaluate the expansion length in 4 typical positions.



MHD Stabilizing Effect

- Right: From top to bottom, the jet surface at 150 microsecond under longitudinal magnetic field.
- Both the interior velocity and the surface velocity of the jet are decreasing with the increasing magnetic field.
- The MHD stabilizing effect is weaker than in the corresponding 2D simulations where circular current exists in filaments.



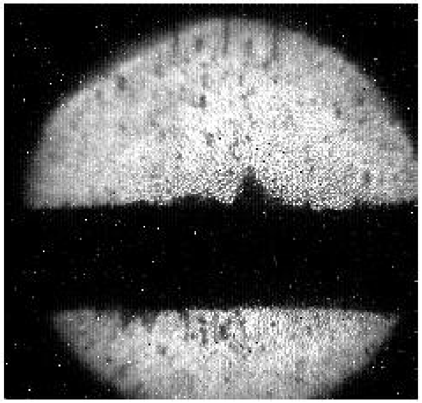
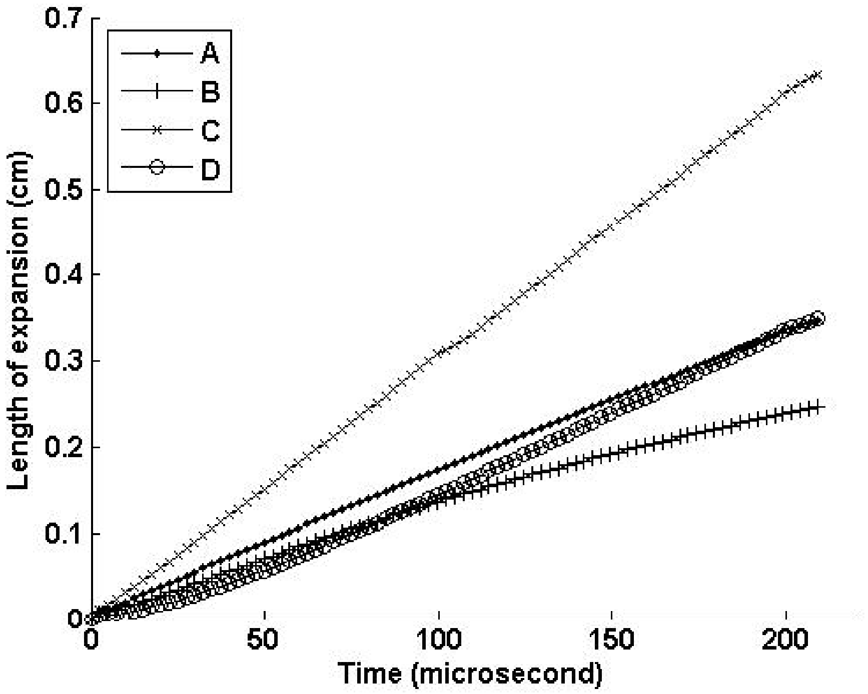
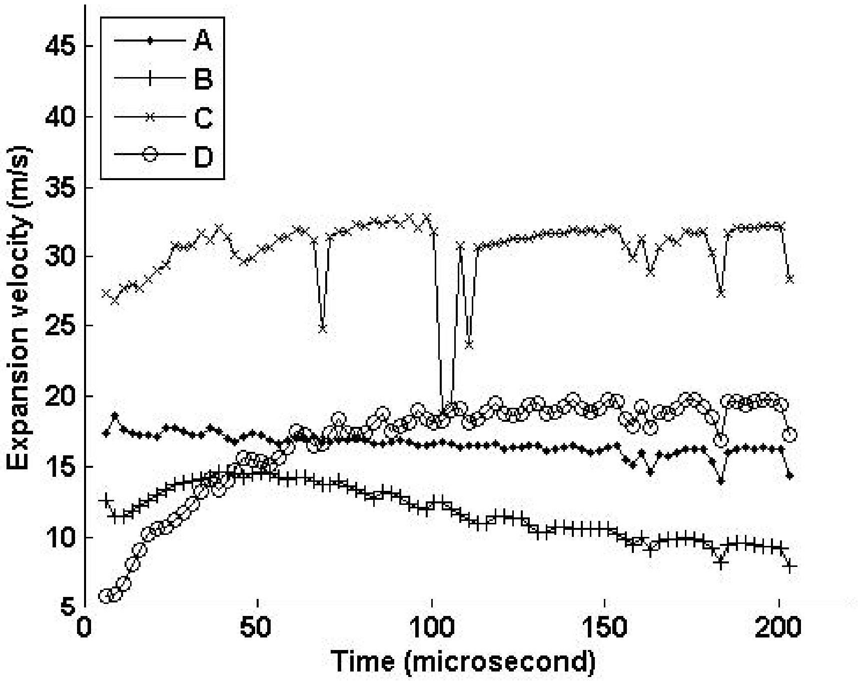


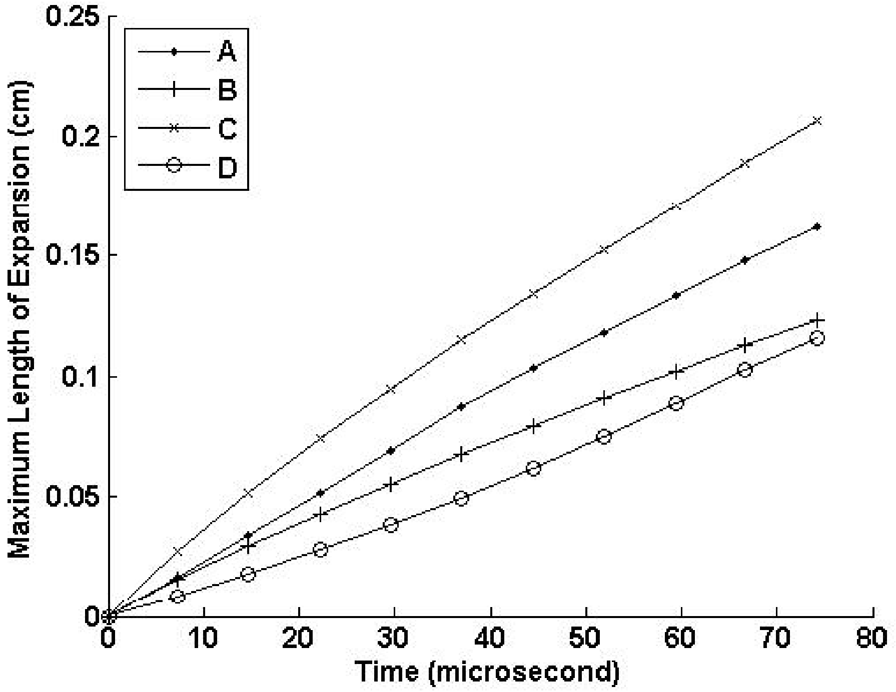
Image from the experiment, B=10T

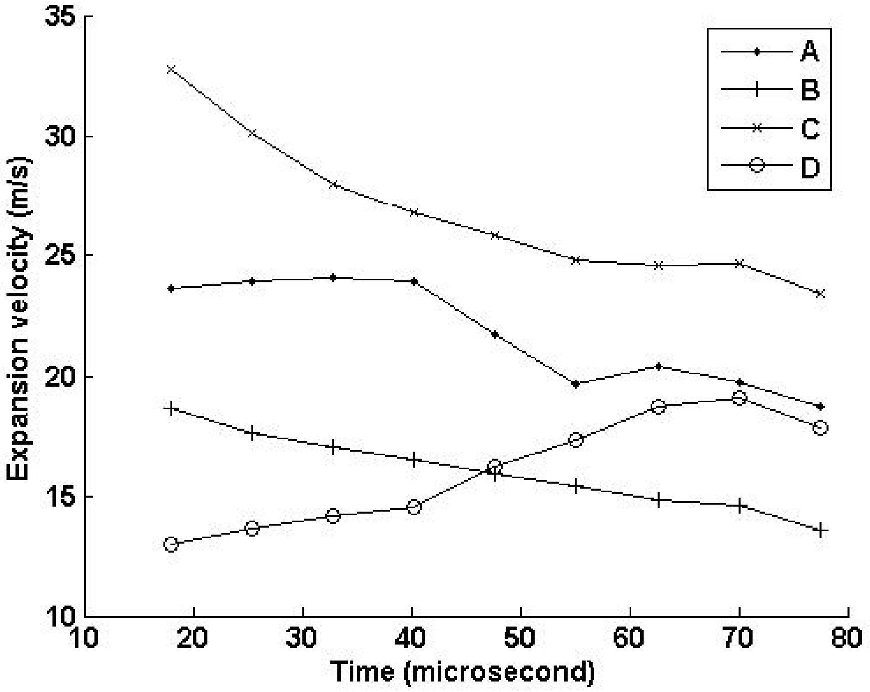
No magnetic field



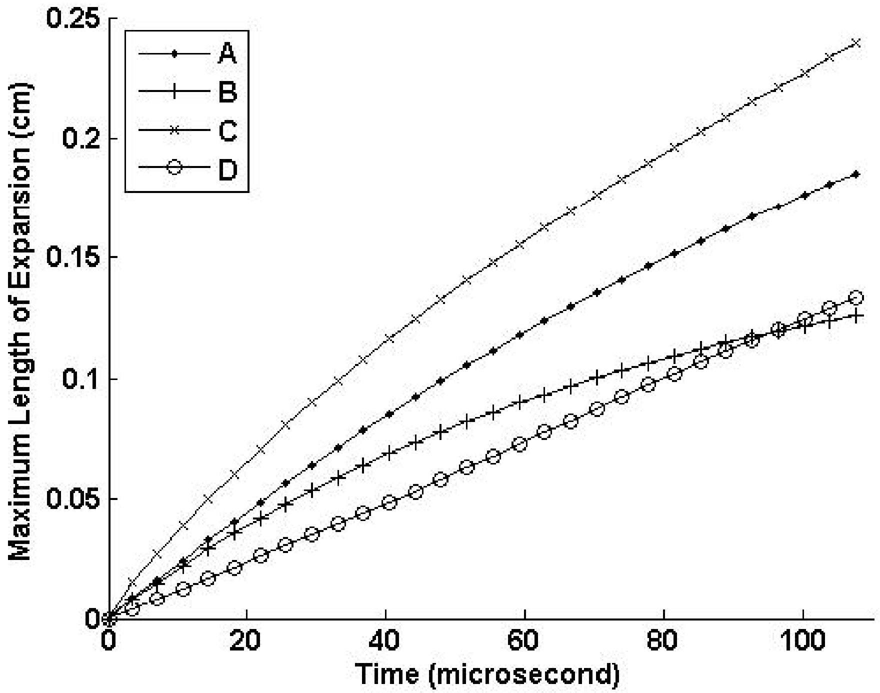


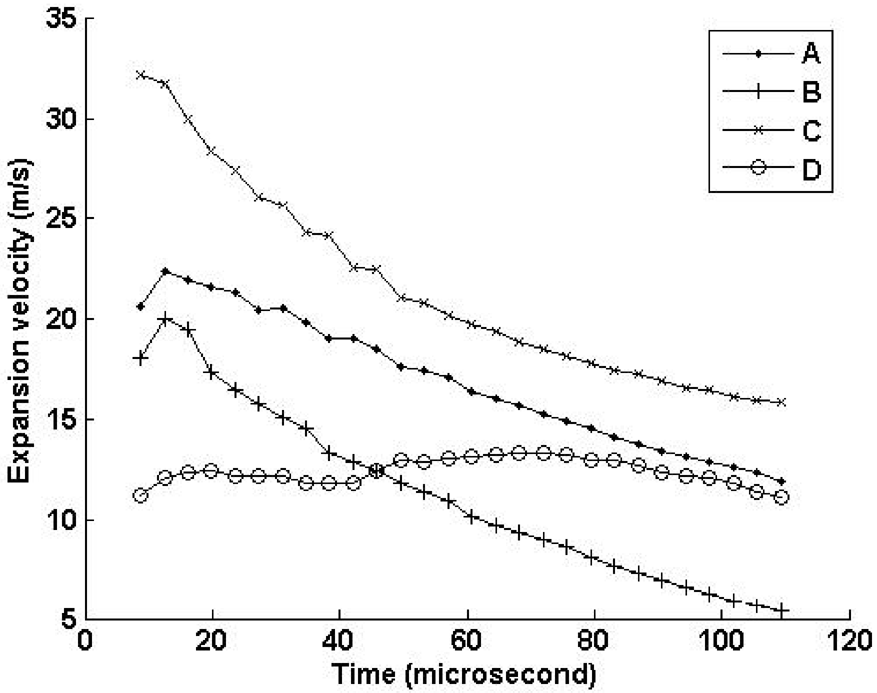
B=5T


Maximum Length of Expansion (cm)
0.25
0.2
0.15
0.1
0.05
0
Time (microsecond)
0
10
20
30
40
50
60
70
80
A
B
C
D

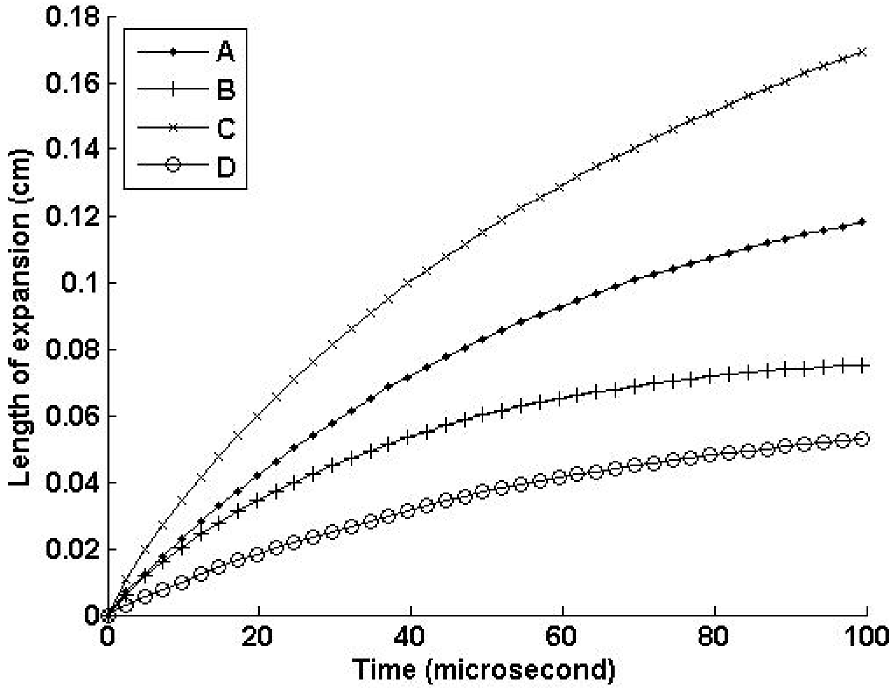

Expansion velocity (m/s)
35
30
25
20
15
10
Time (microsecond)
10
20
30
40
50
60
70
80
A
B
C
D

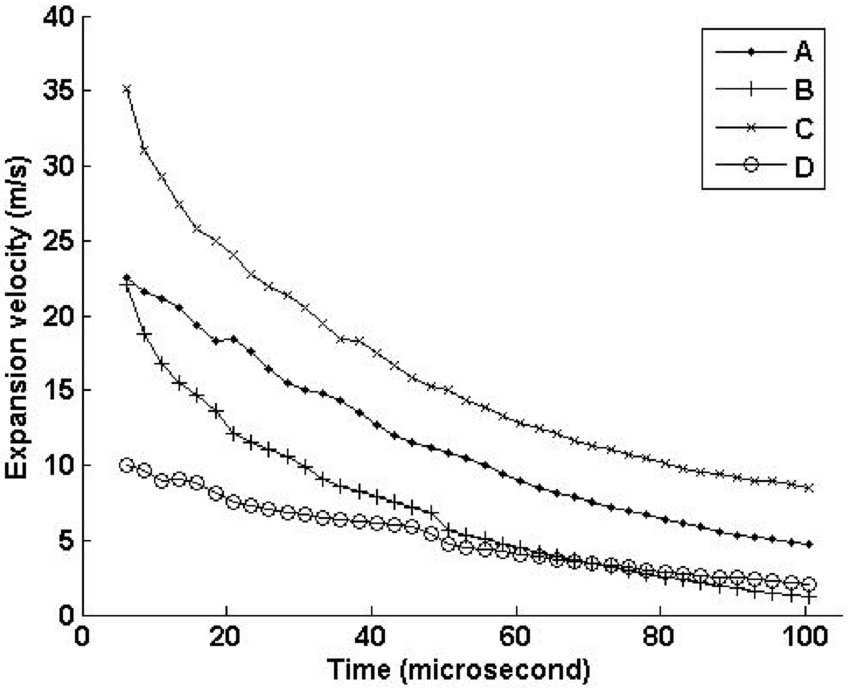
B=10T


Maximum Length of Expansion (cm)
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
Time (microsecond)
A
B
C
D


Expansion velocity (m/s)
35
30
25
20
15
10
5
0
20
40
60
80
100
120
Time (microsecond)
A
B
C
D

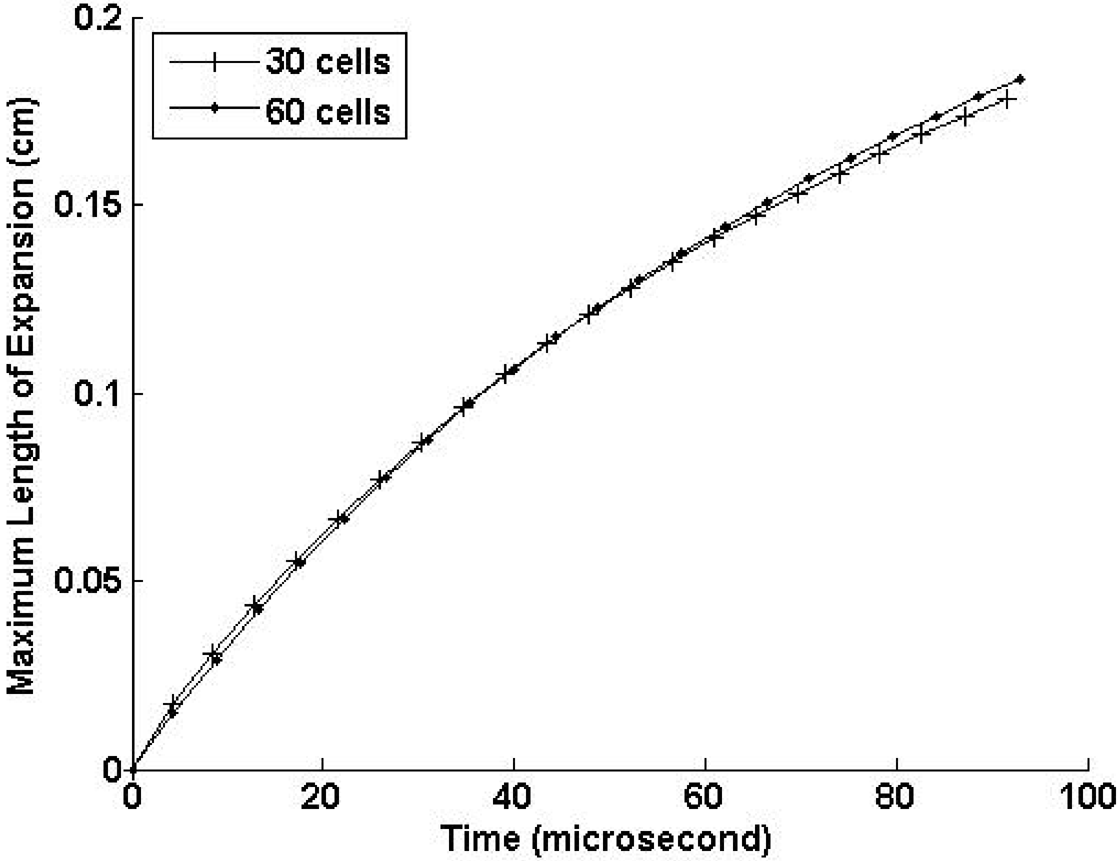
B=15T


Length of expansion (cm)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
Time (microsecond)
0
20
40
60
80
100
A
B
C
D

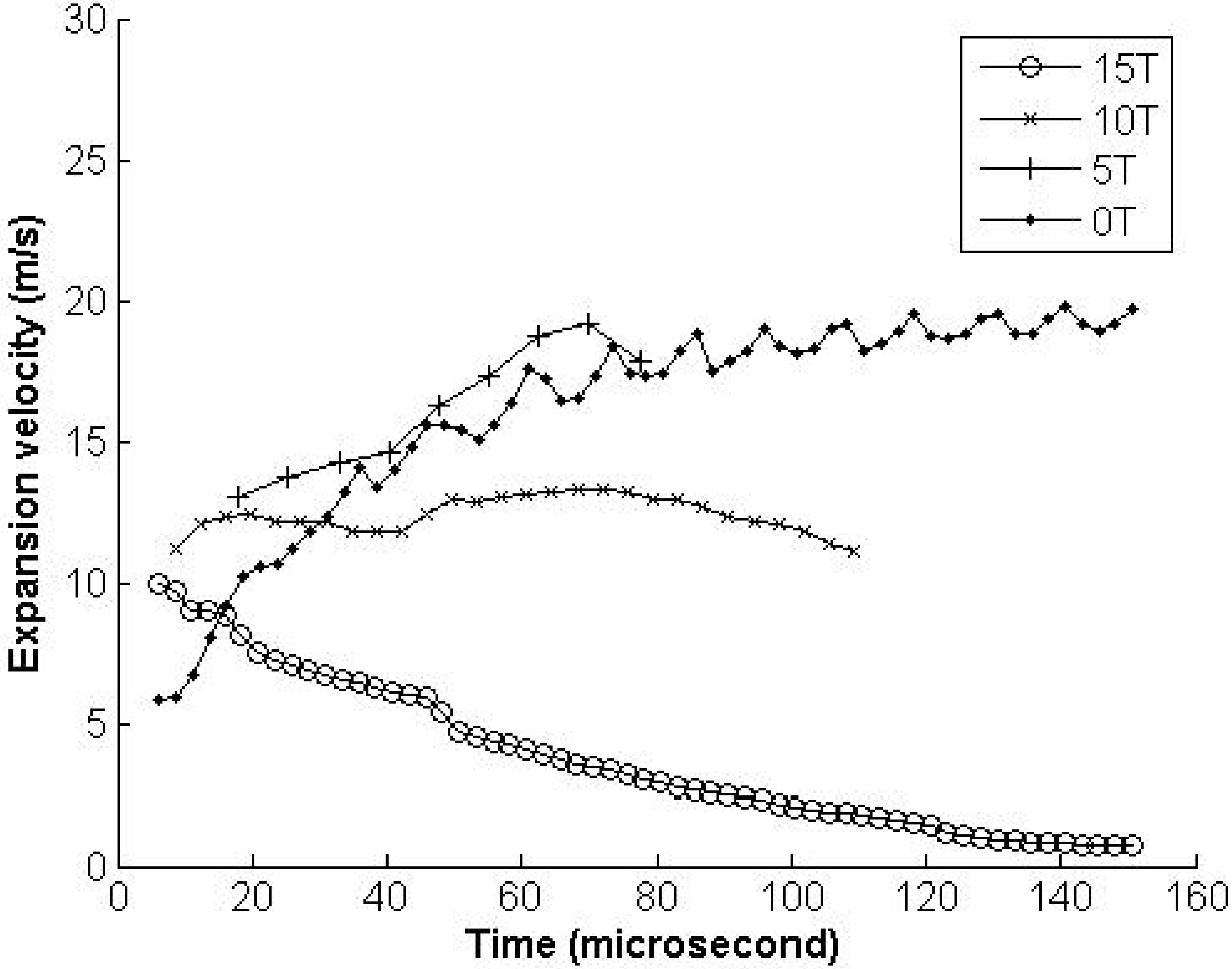

Expansion velocity (m/s)
0
5
10
15
20
25
30
35
40
Time (microsecond)
0
20
40
60
80
100
A
B
C
D

Mesh refinement

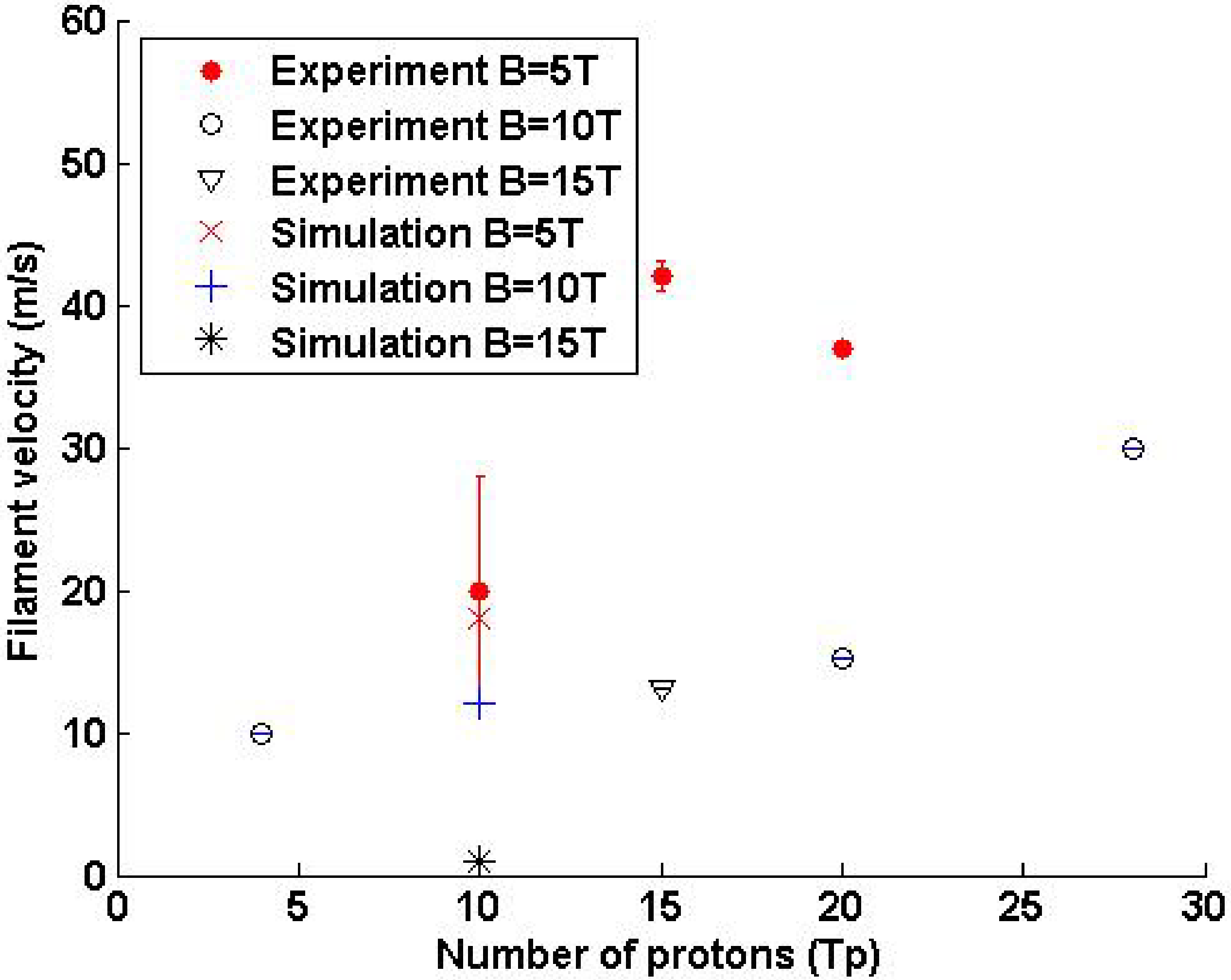
- Maximum length of expansion for B=15T under mesh refinement.



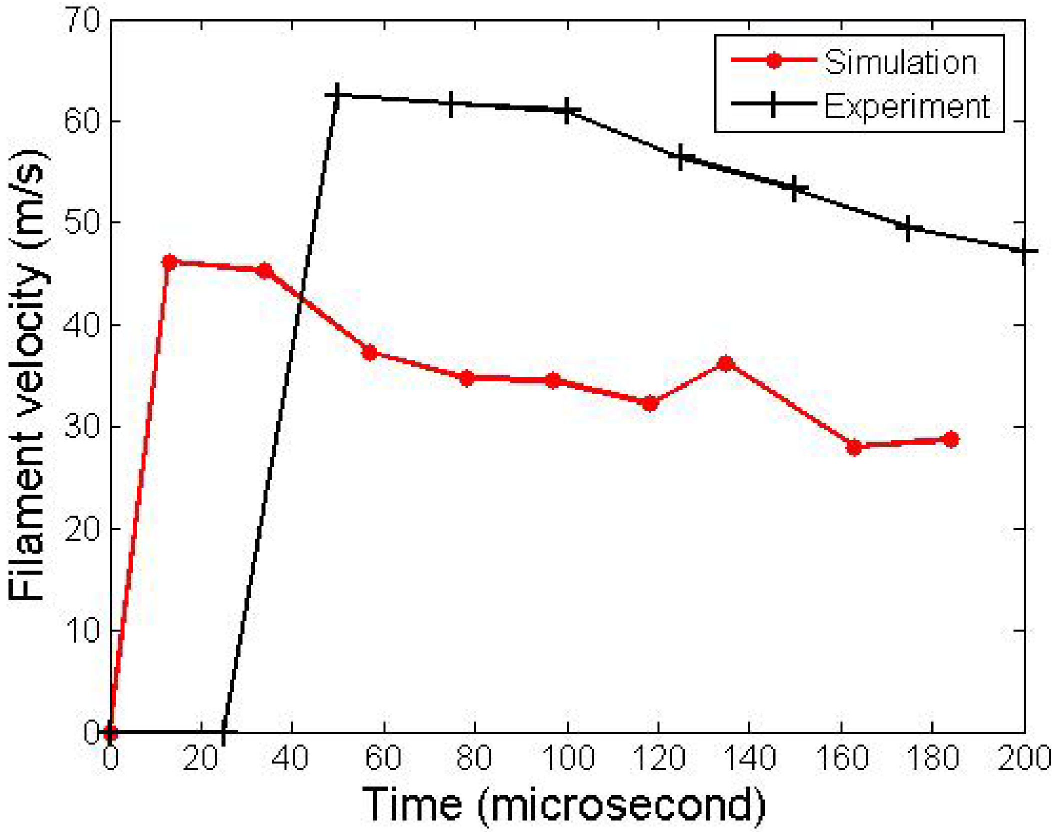
The velocity of filaments in the major axis of the ellipse for different magnetic fields.



The velocity of filaments in the major axis of the ellipse for different magnetic fields: comparison of experiments and simulations



Delay in the formation of filaments



Large (~25 microsecond) delay in the formation of filaments was not observed in simulations.

Currently the nature of this delay is not understood.

Conclusions and Future Plan

- New robust algorithm for topological change of 3D surface, 3D bubble insertion method coupling with the MHD code enabled large scale 3D simulations with complex geometry.
- Performed simulations of mercury jets interacting with magnetic fields
- Observed good agreement with experiments on the filament velocity
- The delay of the filament formation was not observed in simulations.

- Need to clarify the physics of the observed delay of the jet disruption
- Further study of the jet entrance in the magnetic field will be performed and the contribution of several factors (velocity profile, turbulence etc) will be tested
- Comprehensive benchmark with MERIT experiments
- Simulations of mercury target at higher beam intensities
- Simulations of the mercury damp process
- Studies relevant to other target concepts (waterfall etc.)