ITAPS Tools in Computational Evaluation of Alternative Methods of Nuclear Fusion

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Front tracking team led by Jim Glimm and Xiaolin Li
Inertial Confinement Fusion and NIF

National Ignition Facility
• Construction started in 1997
• Official opening ceremony: May 29, 2009
• 500 Terawatt flash of light within a few picoseconds
• 192 laser beams focused on the target
Magnetized Target Fusion (MTF)

- The NIF target loses energy during compression (alpha-particle emission etc.)
- If a magnetic field is embedded into a target, it can insulate target and greatly improve (relax) the confinement requirements
- MTF is a combination of inertial and magnetic confinement
- MFT has been studied using solid liners (LANL, Rochester U.)

MTF schematic (courtesy LANL)
Plasma Jet Induced Magnetoinertial fusion (PJMIF)

• “Stand-off problem” for MTF with solid liners
  • The liner has to be assembled near the center of nuclear reaction

• To solve the stand-off problem, Thio et al (1999) suggested that a plasma liner, formed by the merger of a large number of highly supersonic (M=60) plasma jets, can be used
Plasma Liner Experiment at Los Alamos

- Work on building a plasma liner experiment has been started at Los Alamos (PI: Scott Hsu)
- PLX will operate with 30 plasma jets (deuterium, argon, xenon)
- Goal of our work is to provide simulation support for PLX experiment
PJMIF: Most Important Simulation Problems

• Propagation of single, Mach 60 plasma jet (3D or 2D axisymmetric simulations)

• Jet merger and the formation of the plasma liner
  • Oblique shock waves (3D)

• Liner implosion; liner stability during implosion

• Compression of targets
  • Rayleigh-Taylor instabilities. Estimates of conditions at the maximum compression and the confinement time

• Study of multi-layered liners (heavy-Z (Xenon) pusher behind DT layer)

• Verification of theoretical scaling laws
Other applications: ITER Fueling and Plasma Disruption Mitigation

- 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

Using ITAPS Front Tracking technologies, we have been working on modeling and simulations of tokamak fueling through the ablation of frozen DT pellets and plasma disruption mitigation using pellets and dense gas jets

Collaboration with General Atomics
Schematic of pellets and gas jets in tokamaks

- Pellet temperature is \( \sim 4K \)
- Plasma temperature is \( \sim 4 \text{ keV} \sim 5 \times 10^6 \text{ K} \)
- Fast ablation, atomic physics processes, extreme thermodynamic conditions
- New multiscale models and algorithms
ITAPS Technologies for nuclear fusion simulations

Common features of all applications:

- Multiphase hydro and MHD flows interacting with external energy sources
- Extreme gradients of physics properties
- Phase transitions

They require:

- Explicitly resolved multiphase (free surface) flows
  - Our choice is ITAPS Front Tracking
- Numerical algorithms for coupled systems of PDEs in geometrically complex domains
- Large scale computing
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:
• Negligible numerical interfacial diffusion
• Real physics models for interface propagation
• Different physics / numerical approximations in domains separated by interfaces
FronTier is a parallel 3D multiphysics code based on front tracking

- Physics models include
  - Compressible fluid dynamics
  - MHD
  - Flow in porous media
- 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)
Example of interface topological changes: 3D liquid jet breakup and atomization

Simulations performed by Wurigen Bo
MHD equations and approximations

**Full system of MHD equations**

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

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

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

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

\[P = P(\rho, e), \quad \nabla \cdot \mathbf{B} = 0\]

**Low magnetic Re approximation**

\[\text{Re}^M = \frac{uL\sigma}{c^2} \ll 1, \quad \frac{\delta B}{B} \ll 1\]

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

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

with \[\left. \frac{\partial \phi}{\partial \mathbf{n}} \right|_r = \frac{1}{c} (\mathbf{u} \times \mathbf{B}) \cdot \mathbf{n}\]

\[\mathbf{B} = \mathbf{B}_{\text{ext}}(x, t), \quad \nabla \cdot \mathbf{B}_{\text{ext}} \equiv 0\]
FronTier-MHD numerical scheme

**Hyperbolic step**
- Propagate interface (contact or phase transition equations)
- Untangle interface
- New interface states

**Elliptic step**
- Apply hyperbolic solvers
- Update interior hydro states
- Perform finite volume discretization
- Solve linear system

**External fields and coupling**
- Calculate external and electromagnetic fields
- Update front and interior states
Application to Plasma Jet Induces Magnetoinertial Fusion
Stages of PJMIF Simulation

• Understanding of the PJMIF concept via spherically-symmetric simulations, verification of scaling laws, and comparison with the theory

• 2D axisymmetric simulations of the propagation of a single high Mach number plasma jet

• 3D Initialization of plasma jets before their merger
  • Positions are given by the Spherical Centroidal Voronoi Tesslation
  • States are obtained using the output of 2D single jet simulations

• 3D simulations of the jet merger, liner implosion and target compression
  • Comparison with theory and 1D simulations
Spherically Symmetric Simulations

• Single deuterium liner compressing 5 cm target
  • Study of the deconfinement time, hydrodynamic efficiency, fuel burn-up fraction, and fusion energy gain
  • Comparison with Parks’ theory [P. Parks, Phys. Plasmas, 15 (2008), 062506]

• Optimization of parameters for maximum fusion gain
  • Heavy xenon liners
  • Larger targets
  • Alpha-particle heating

• Study of double-layer Xenon - DT liners
Logarithm of the ram pressure amplification factor vs logarithm of the radial compression

(1) : the ideal model $A=C^2$
(2) : $M = 60$ and gamma = 1.3
(3) : $M = 60$ and gamma = 5/3
(4) : $M = 20$ and gamma = 1.3
(5) : $M = 20$ and gamma = 5/3
Evolution of normalized pressure and normalized fusion energy

- Simulation show that time during which pressure reduces by the factor of two should be used as the deconfinement time
- Fusion gain achieved in simulation was 0.012
- For fusion gain, the discrepancy between the theory and simulation in the sense of scaling law is 1.7
- DT liners are not able to achieve significant fusion gains
Finding ways to improve fusion energy gain

• Heavy Z (xenon) liners
• Composite xenon – DT liners
• Larger targets
• Alpha particle heating
• Atomic processes in the liner
Fusion gain of targets compressed by 5 cm thick single layer xenon liner. Initial target radii are: 10 (1), 15 (2), 20 (3), 25 (4), and 30 cm (5).
Influence of atomic processes in the target and liner on the fusion gain

Influence of alpha-heating

Influence of dissociation and ionization
2D cylindrically symmetric simulation of the propagation of detached jets

- The purpose of this simulations is to obtain data for the initialization of the 3D jet merger simulation
- Initial jet velocity is 100 km/s and the Mach number is 60

Density of the detached jet at initial time and 40 microseconds

Pressure in the transverse plane

Radius, cm
3D Jet Merger Problem Setup

• Output of the detached jet simulation was used as input to the 3D jet merger problem

• 144 jets in 6m radius chamber merging at the radius of 60 cm

• 125 and 625 jets in 3m radius chamber merging at the radii of 50 cm and 100 cm, correspondingly

• Simulations performed on 4000 processors of the BluGene supercomputer

Initial locations of jets obtained via SCVT
The Jet Merger Process

\[ \rho_{\text{max}} = 1.3e^{-5} \]

\[ \rho_{\text{max}} = 1.0e^{-5} \]

\[ \rho_{\text{max}} = 1.6e^{-5} \]

\[ \rho_{\text{max}} = 6.2e^{-5} \]

\[ \rho_{\text{max}} = 9.3e^{-4} \]
Formation of Oblique Shock Waves
Reduction of the Mach Number during the liner Implosion
Merger of 125 and 625 jets in a 3-meter chamber

- A series of simulations have been performed for 3 m chamber
- Merging radii are: 50 cm for 125 jets and 100 for 625 jets
- Investigation of the peak pressure dependence on the liner uniformity and longitudinal density spread

FronTier simulation of the implosion of plasma liner formed by the merger of 625 jets
125 and 635 jets in a 3m chamber and the liner uniformity

<table>
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<th>Number of jets</th>
<th>P/ Density</th>
<th>Sigma</th>
<th>Max value</th>
<th>Relative Sigma</th>
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Summary of code development

• Using ITAPS front tracking libraries, built a multiphase MHD code for the simulation of processes in nuclear fusion
  • Plasma jet induced magnetoinertial fusion
  • Pellet fueling of tokamaks
  • Plasma disruption mitigation by pellets and high density jets (in progress)
Summary of PJMIF study

• Verified scaling laws
• Defined the deconfinement time for PJMIF
• Showed that DT liners are unable to achieve fusion gains
• Explored ways to improve fusion energy gain
  • Heavy-Z liners
  • Optimized target and chamber parameters
  • Refined physics models
• Performed 3D simulations of the formation and evolution of plasma liners
  • Oblique shock waves do not significantly reduce the Mach number and peak pressures
  • Longitudinal density spread of the liner is critical in the reduction of peak pressures
  • Low vacuum typical for such chambers greatly influences the liner / target interaction