Center for Integrated Computation and Analysis of Reconnection and Turbulence (CICART)

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CICART
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University of New Hampshire

CICART

Outline

Project Information

Center for Integrated Computation and Analysis of Reconnection and Turbulence

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CICART has a dual mission in research: it seeks fundamental advances in physical understanding, and works to achieve these advances by means of innovations in computer simulation methods and theoretical models, and validation by comparison with laboratory experiments and space observations. Our research program has two elements: niche areas in the physics of magnetic reconnection and turbulence which build on past accomplishments of the CICART group and to which the group is well-positioned to contribute, and high-performance computing tools needed to address these topics.

Objectives

Magnetic Reconnection

- Reconnection and secondary instabilities in large, high-Lundquist-number plasmas
- Particle acceleration in the presence of multiple magnetic islands
- Gyrokinetic reconnection: comparison with fluid and particle-in-cell models

Turbulence

- Imbalanced turbulence
- Ion heating
- Turbulence in laboratory (including fusion-relevant) experiments

Onset of fast reconnection and its long-time behavior

Magnetic reconnection is ubiquitous in laboratory (incl. fusion) devices as well as space and astrophysical plasmas.

Our research addresses fundamental questions underlying the onset of fast reconnection and its long-time behavior, in particular representation of kinetic effects in fluid codes through closure relations, which aids in global modeling of laboratory and space plasmas.

Important applications:

- sawtooth crashes in tokamaks and RFPs
- substorms, solar flares

High-Lundquist number plasmas

The classical Lundquist number in systems of interest is typically very high. Plasmas tend to develop thin, intense current sheets. Resistive MHD gets replaced by extended MHD (XMHD) with a generalized Ohm's Law:

$$\vec{E} = \vec{v} \times \vec{B} = \frac{1}{S}\vec{j} + \frac{d_e^2}{n}\frac{d\vec{j}}{dt} + \frac{d_i}{n}(\vec{j} \times \vec{B} - \nabla \cdot \overleftrightarrow{p}_e)$$

"Trigger problem": Magnetic configuration evolves slowly over a long period of time, only to undergo a sudden dynamic change over a much shorter period of time.

$m = 1$ resistive kink mode, resistive MHD

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$m = 1$ resistive kink mode, XMHD

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$m = 1$ resistive kink mode, XMHD w/pressure gradient

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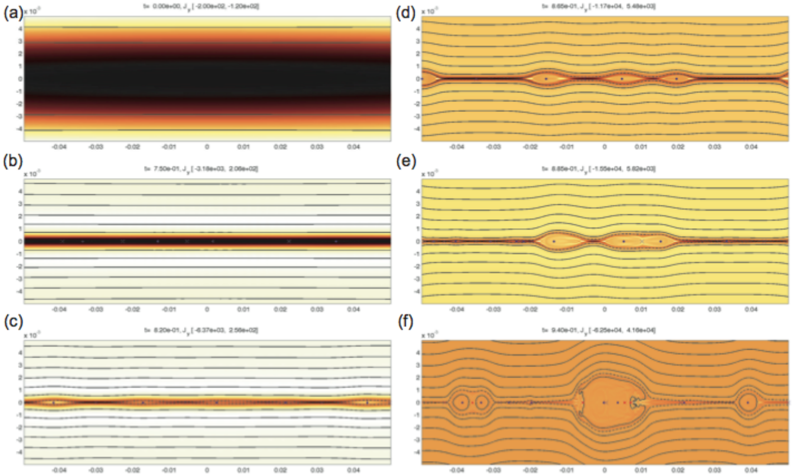
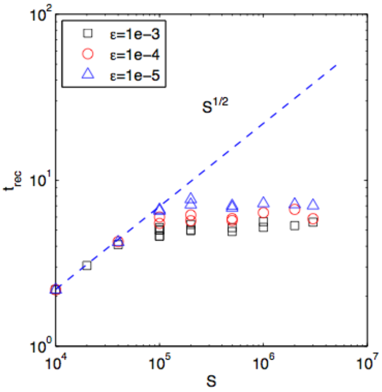
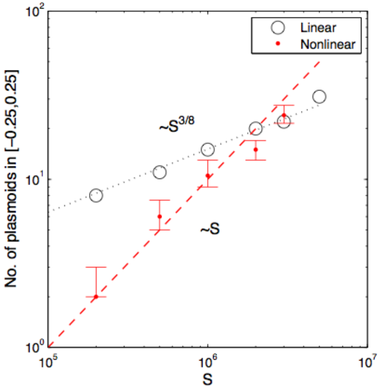
Plasmoid instability



Plasmoid instability



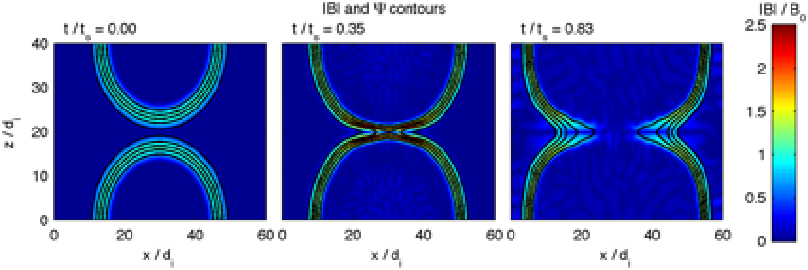


Bubble reconnection

Recently, magnetic reconnection has been observed to occur in high-density laser-produced plasmas, in the presence of extremely high magnetic fields. TW class lasers are focused onto plastic or metallic foils, creating supersonically expanding bubbles with a self-generated magnetic field of $\approx 1MG$. Multiple bubbles expand into each other and reconnect.

It is now becoming feasible to directly simulate these laser-plasma systems with plasma parameters and global geometry close to the actual experiment.

Bubble reconnection



Current HPC usage

We used to run most simulations on a local Opteron cluster. We have been moving to NERSC in recent years, increasing our allocation quickly.

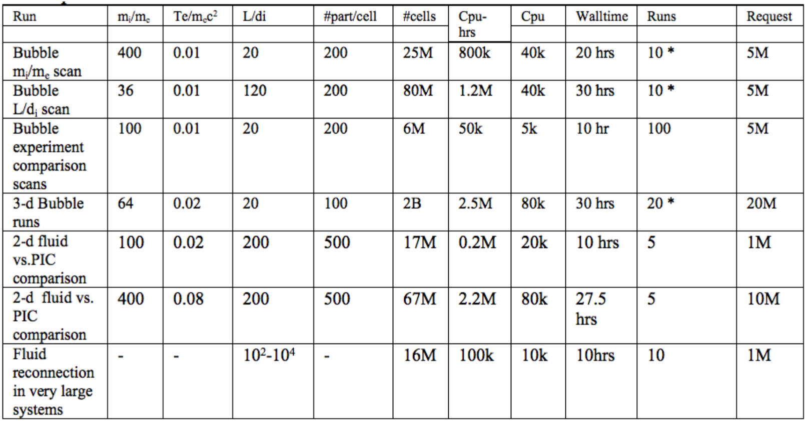
Usage 2009

- NERSC: 500,000 hrs
- local cluster: 1,400,000 hrs

Usage 2010

- NERSC: 1,600,000 hrs
- local cluster: 2,000,000 hrs

Runs within next 3 years



Run	m_i/m_e	Te/m_ec^2	L/di	#part/cell	#cells	Cpu-hrs	Cpu	Walltime	Runs	Request
Bubble m_i/m_e scan	400	0.01	20	200	25M	800k	40k	20 hrs	10 *	5M
Bubble L/d_i scan	36	0.01	120	200	80M	1.2M	40k	30 hrs	10 *	5M
Bubble experiment comparison scans	100	0.01	20	200	6M	50k	5k	10 hr	100	5M
3-d Bubble runs	64	0.02	20	100	2B	2.5M	80k	30 hrs	20 *	20M
2-d fluid vs.PIC comparison	100	0.02	200	500	17M	0.2M	20k	10 hrs	5	1M
2-d fluid vs. PIC comparison	400	0.08	200	500	67M	2.2M	80k	27.5 hrs	5	10M
Fluid reconnection in very large systems	-	-	10^2-10^4	-	16M	100k	10k	10hrs	10	1M

Current computational methods

Magnetic Reconnection Code (MRC)

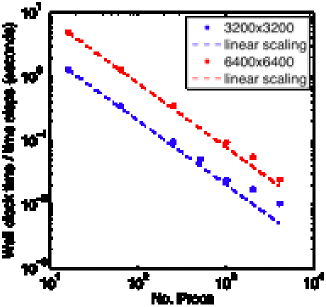
- solves XMHD: Generalized Ohm’s Law with Hall term, electron pressure gradient
- finite-volume, div B = 0
- arbitrary curvilinear grids
- explicit, implicit time integration through PETSc (Newton-Krylov, Newton-direct solver)
- automatic code generator generates r.h.s., Jacobian
- parallelized by domain decomposition / MPI

Current computational methods

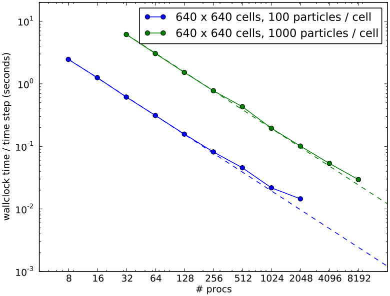
Particle Simulation Code (PSC)

- solves Vlasov-Boltzmann equations, in 1D/2D/3D
- EM fields: FDTD
- boundary conditions: periodic, wall, radiating
- second order shape functions
- binary collisions
- modular design, e.g. particle pusher available in Fortran, SIMD/SSE2, nvidia GPU (wip)
- explicit timestepping, parallelized by domain decomposition / MPI

Parallel Scaling



HMHD



PSC

HPC requirements

PIC runs are by far most expensive.

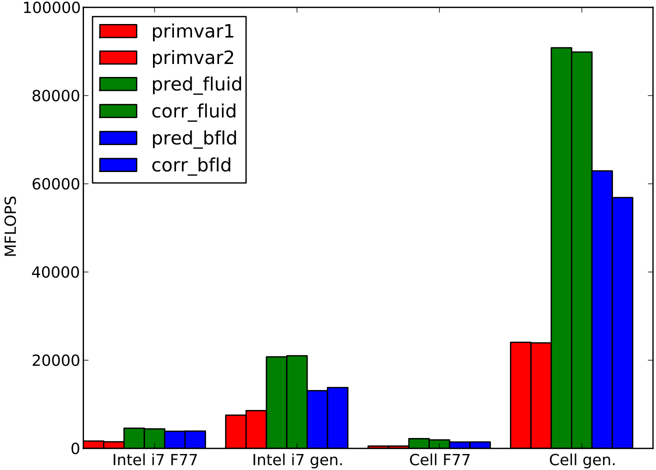
- Hours: 50,000,000
- nr cores: 50k, 1 GB / core
- wallclock: 100 hrs
- checkpoint: 50TB
- other I/O: 5GB
- online file storage: 55 TB
- offline file storage: 500 TB

Algorithmic/computational improvements

MRC will need an algorithmically scalable implicit time integration method in order to approach realistic parameter regimes for 3D runs, that is, an efficient preconditioner for the Newton-Krylov method. We recently implemented multi-block grid in the underlying framework and are working on porting the discretization to the "butterfly" grid.

- MRC: physics based preconditioning
- MRC: multi-block grid, (AMR)
- MRC: more physics (e.g., anisotropic heat conduction)
- PSC dynamic load-balancing
- parallel I/O, fault tolerance?
- automatic code generation / heterogeneous architectures

Automatic code generation for heterogeneous architectures



Potential Impact

1. enable the development of scaling relations in 2D for fast reconnection as a function of the Lundquist number, electron-to-ion mass ratio, plasma beta, and system size
2. identify 3D secondary instabilities that can alter qualitatively the predictions of 2D theory for the range of plasma parameters considered in item (1)
3. test closure relations for the pressure tensor that will enable the parameterization of kinetic effects in fluid codes
4. test the predictive capabilities of both the PSC and the HMHD codes in reproducing quantitatively the results of magnetic reconnection experiments in a novel, laser-driven, high-density plasma regime