High-Performance Computing in Magnetic Fusion Energy Research

Presented by

Donald B. Batchelor

RF Theory
Plasma Theory Group
Fusion Energy Division

SC07

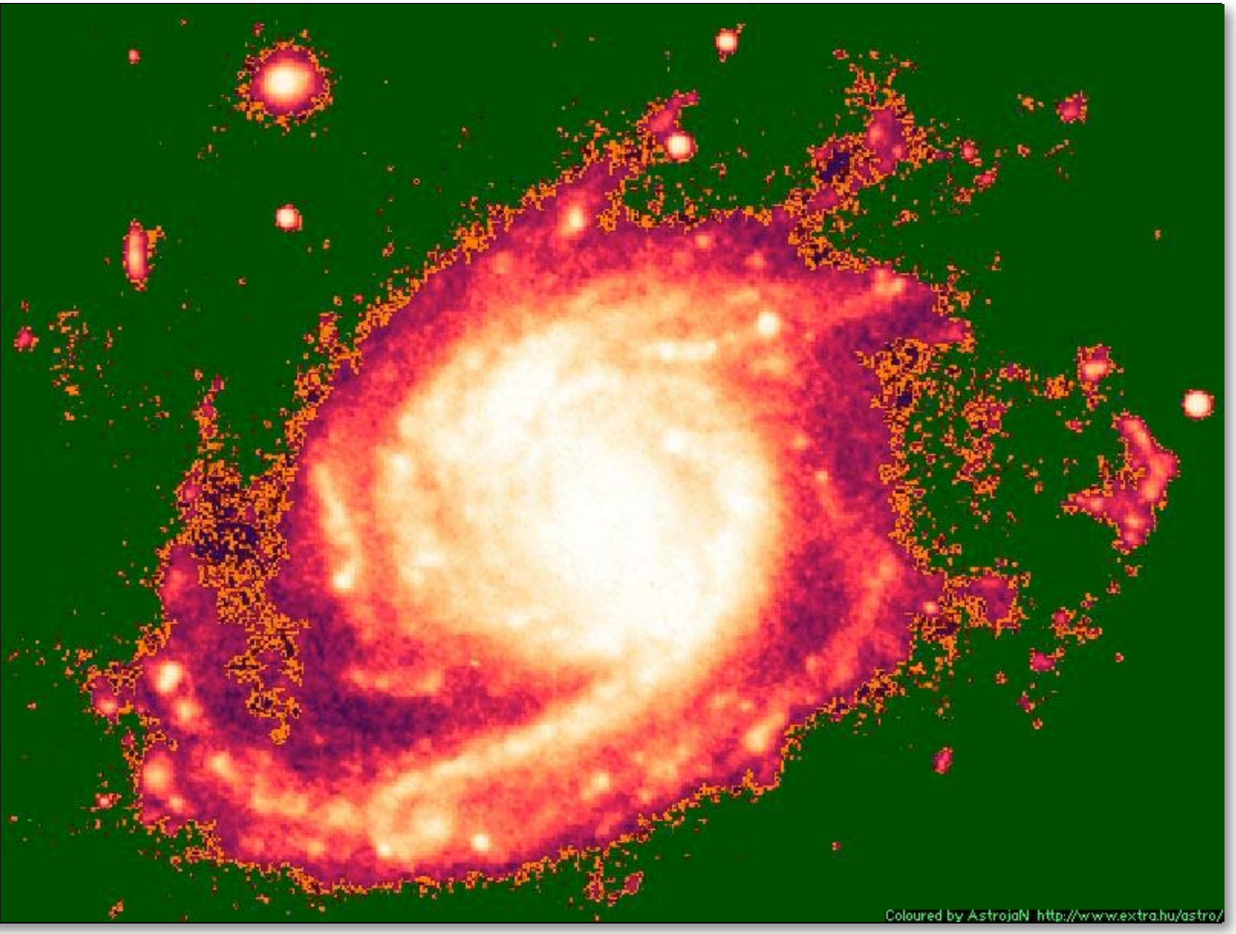
Office of Science
U.S. DEPARTMENT OF ENERGY

SciDAC
Scientific Discovery through Advanced Computing

Oak Ridge National Laboratory

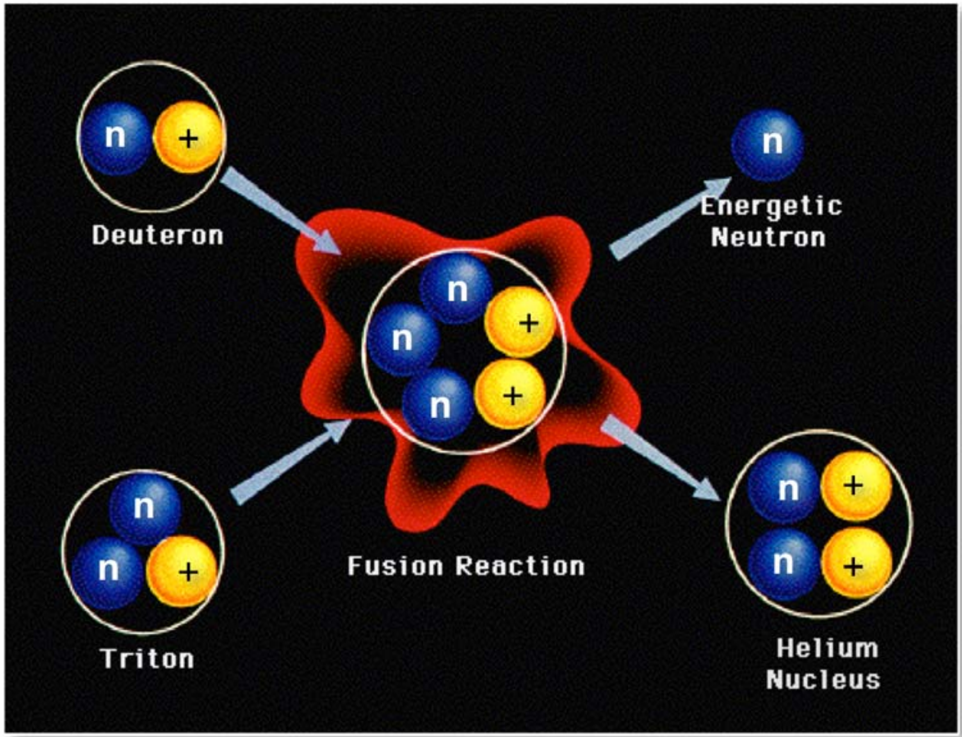
Nuclear fusion is the process of building up heavier nuclei by combining lighter ones.

It is the process that powers the sun and the stars and that produces the elements.



OAK RIDGE National Laboratory

The simplest fusion reaction—deuterium and tritium.



$E_n = 14$ MeV

Deposited in heat exchangers containing lithium for tritium breeding.

$E_\alpha = 3.5$ MeV

Deposited in plasma; provides self-heating.

About 1/2% of the mass is converted to energy ($E = mc^2$).

Remember this guy?

Oak Ridge National Laboratory

We can get net energy production from a thermonuclear process.

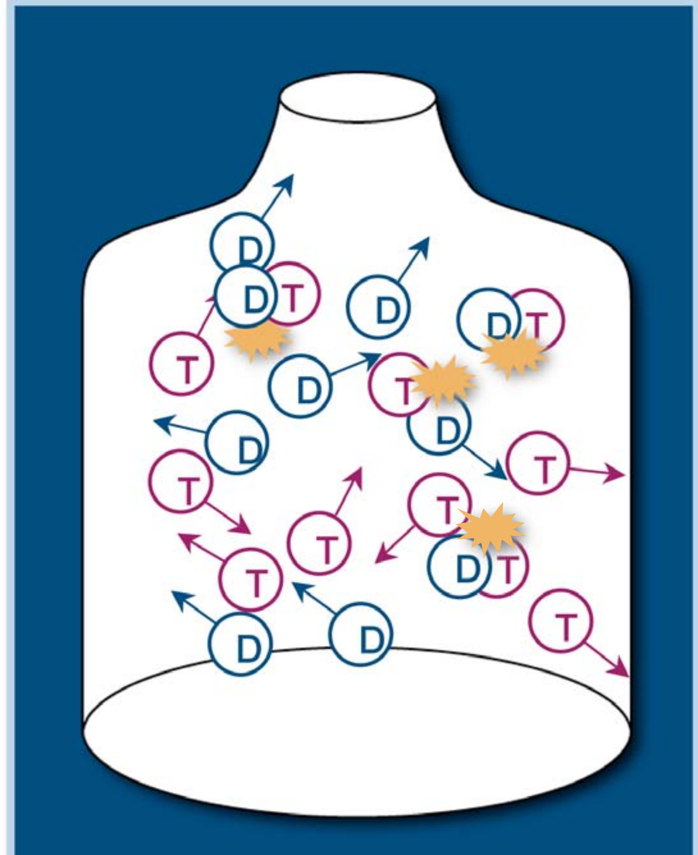
- We heat a large number of particles so the temperature is much hotter than the sun, ~100,000,000°F.
  $\Rightarrow$ PLASMA: electrons + ions
- Then we hold the fuel particles and energy long enough for many reactions to occur.

$$Q = \frac{P_{fusion}}{P_{heating}} \Rightarrow \begin{cases} = 1 \rightarrow \text{breakeven} \\ > 20 \rightarrow \text{energy-feasible} \\ \infty \rightarrow \text{ignition} \end{cases}$$

Lawson breakeven criteria:

- High enough temperature—T (~ 10 keV).
- High particle density—n.
- Long confinement time—τ.

$$n_e \tau_E > 10^{20} \text{ m}^{-3}\text{s}$$

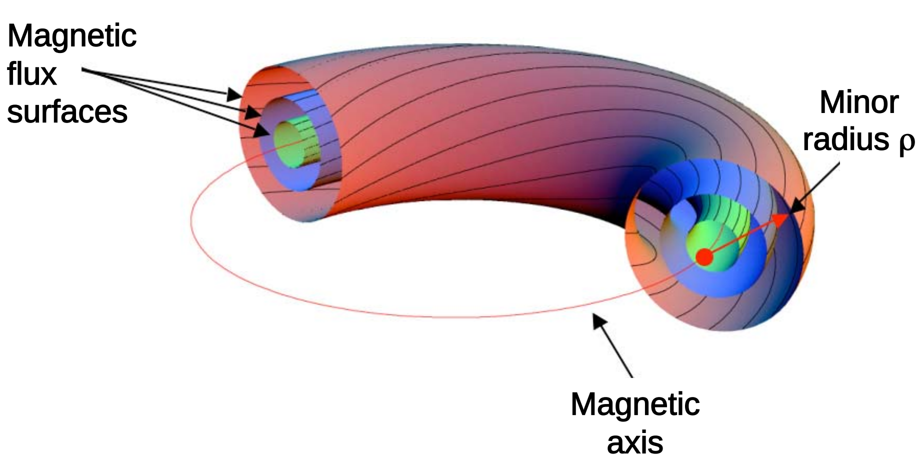


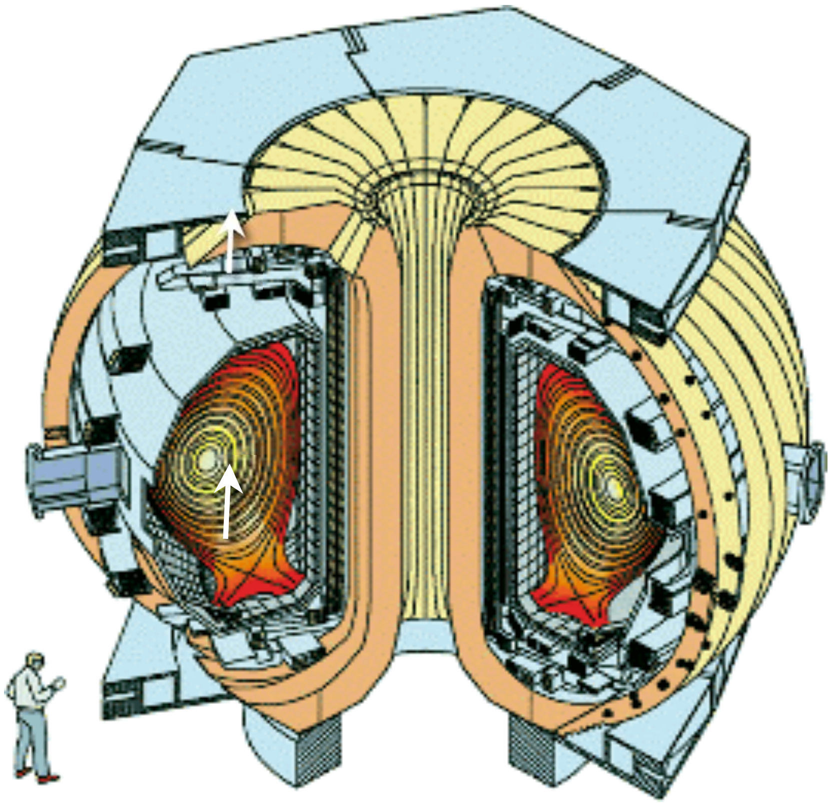
Nuclear thermos bottle

Oak Ridge National Laboratory

We confine the hot plasma using strong magnetic fields in the shape of a torus.

- Charged particles move primarily along magnetic field lines. Field lines form closed, nested toroidal surfaces.
- The most successful magnetic confinement devices are tokamaks.



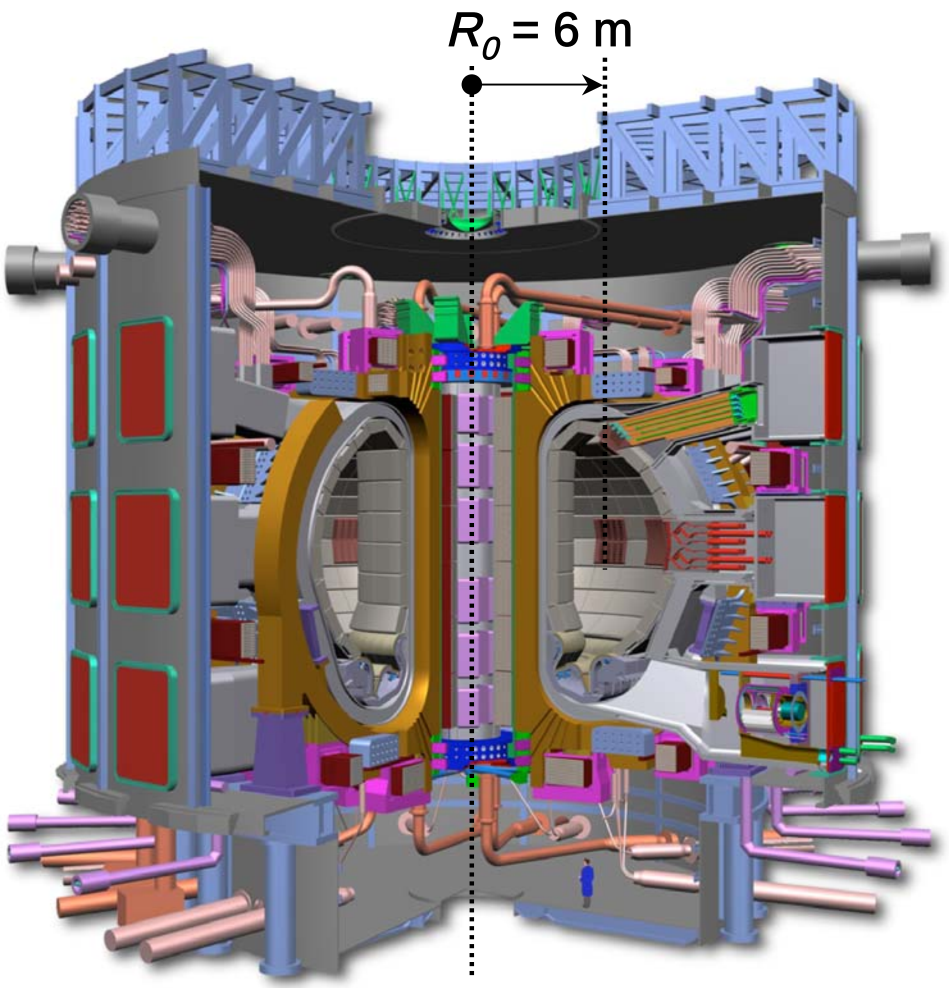


DIII-D Tokamak

ITER will take the next steps to explore the physics of a “burning” fusion plasma.

An international effort involving Japan, Europe, U.S., Russia, China, Korea, and India.

- Fusion power ~500 MW.
- I_{plasma} = 15 MA, B_0 = 5 Tesla
  T ~10 keV, τ_E ~4 s.
- Large – 30 m tall, 20 ktons.
- Expensive ~10B+.
- Project staffing, administrative organization, environmental impact assessment.
- First burning plasmas ~2018.



Latest news: http://www.iter.org.

OAK RIDGE National Laboratory

What are the big questions in fusion research?

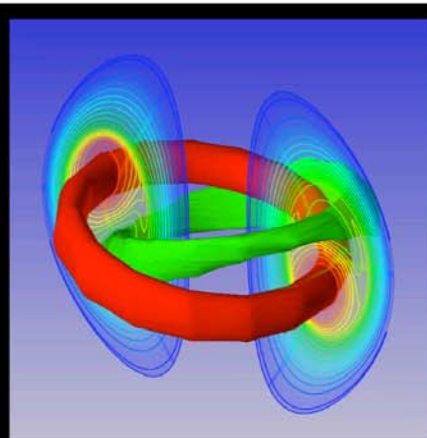
- How do you heat the plasma to 100,000,000°F, and once you have done so, how do you control it?
  - We use high-power electromagnetic waves or energetic beams of neutral atoms. Where do they go? How and where are they absorbed?
- How can we produce stable plasma configurations?
  - What happens if the plasma is unstable? Can we live with it? Or can we feedback control it?
- How do heat and particles leak out? How do you minimize the loss?
  - Transport is mostly from small-scale turbulence.
  - Why does the turbulence sometimes spontaneously disappear in regions of the plasma, greatly improving confinement?
- How can a fusion-grade plasma live in close proximity to a material vacuum vessel wall?
  - How can we handle the intense flux of power, neutrons, and charged particles on the wall?

Supercomputing plays a critical role in answering such questions.

We have SciDAC and other projects addressing separate plasma phenomena and time scales.

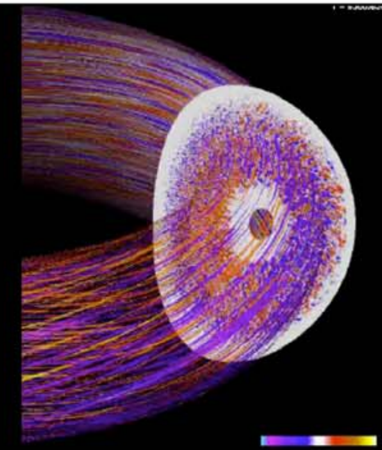
Center for Extended MHD Modeling

- M3D code
- NIMROD



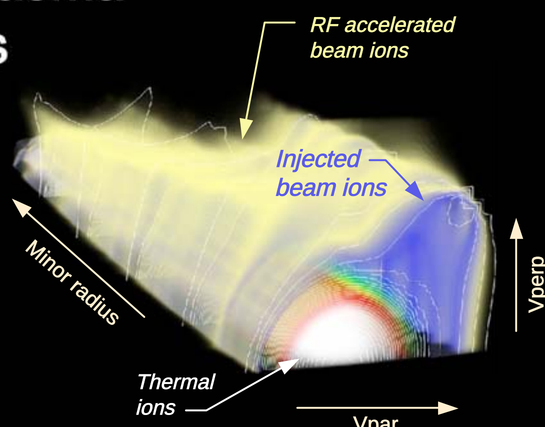
Gyrokinetic Particle Simulation Center

- GTC code
- GYRO



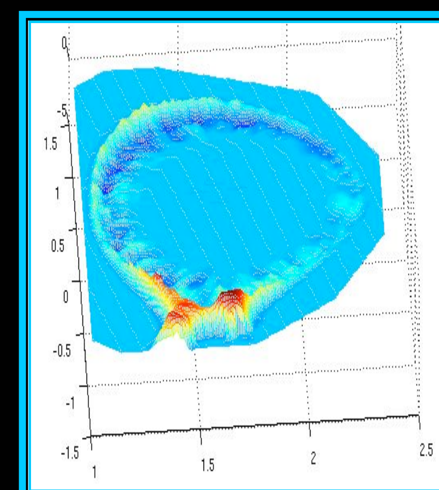
Center for Simulation of Wave-Plasma Interactions

- AORSA
- TORIC
- CQL3D
- ORBITRF
- DELTO5D



Edge Simulation Projects

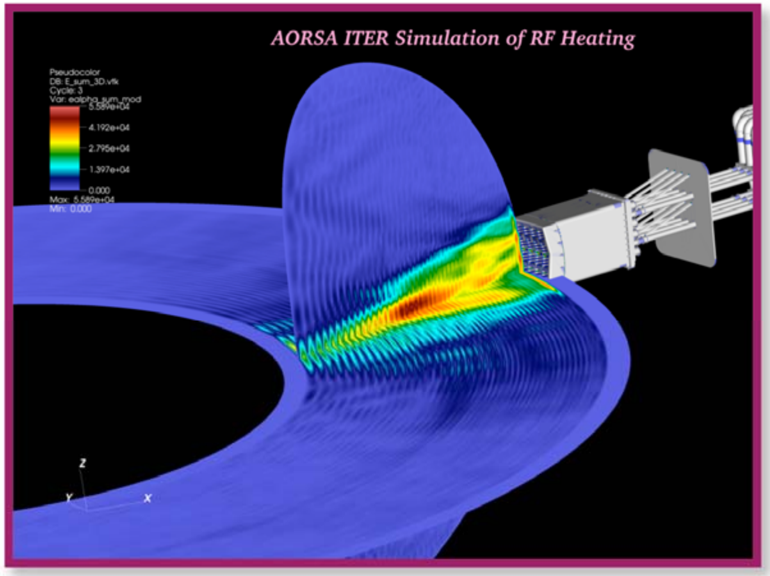
- XGC code
- TEMPEST



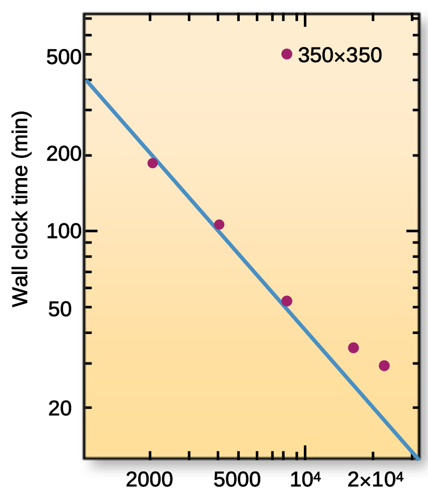
Petascale problems in wave heating and plasma control—GSWPI/SWIM project.

Objectives: Understand heating of plasmas to ignition, detailed plasma control through localized heat, current, and flow drive.

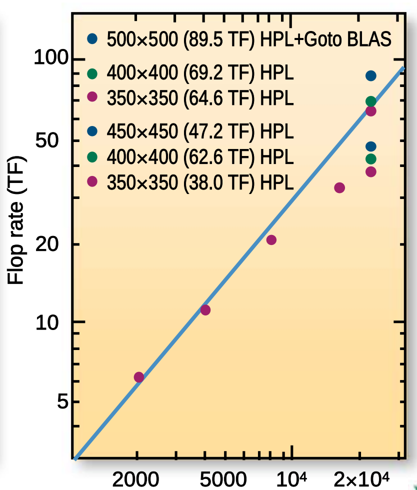
- The peak flop rate achieved so far is 87.5 TF using 22,500 processors with High Performance Lapack (HPL) and Goto BLAS.
- AORSA has been coupled to the Fokker-Planck solver CQL3D to produce self-consistent plasma distribution functions. TORIC is now being coupled to CQL3D.



Wall clock time (min)



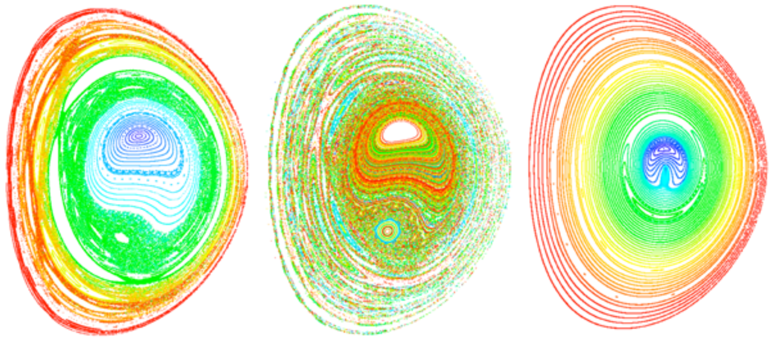
ScaLAPACK flop rate (TF)



Petascale problems in extended MHD stability of fusion devices (M3D and NIMROD codes)—CPES/SWIM.

Objectives: To reliably simulate the sawtooth and other unstable behavior in ITER in order to access the viability of different control techniques.

- M3D uses domain decomposition in the toroidal direction for massive parallization, partially implicit time advance, and PETc for sparse linear solves.
- NIMROD uses spectral in the toroidal dimension, semi-implicit time advance, and SuperLU for sparse linear solves.



NIMROD simulation of sawtooth crash

	TODAY Small tokamak (CDX-U)	Large present-day tokamak (DIII-D)	ITER
Relative volume	1	50	1,500
Space-time pts.	2×10^{11}	1×10^{13}	3×10^{14}
Actual speed	100 GF	5 TF	150 TF
No. processors	500	10,000	100,000
Rel. proc. speed	1	2.5	7.5

Oak Ridge National Laboratory

Contact

Donald B. Batchelor

RF Theory
Plasma Theory Group
Fusion Energy Division
(865) 574-1288
batchelordb@ornl.gov