High-Performance Computing in Magnetic Fusion Energy Research

Presented by

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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.
The simplest fusion reaction—deuterium and tritium.

$E_n = 14 \text{ MeV}$
Deposited in heat exchangers containing lithium for tritium breeding.

$E_\alpha = 3.5 \text{ MeV}$
Deposited in plasma; provides self-heating.

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

Remember this guy?
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.
  ⇒ **PLASMA: electrons + ions**

- Then we hold the fuel particles and energy long enough for many reactions to occur.

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

**Lawson breakeven criteria:**
- High enough temperature—T (~ 10 keV).
- High particle density—n.
- Long confinement time—τ.

\[n_e \tau_E > 10^{20} \text{ m}^{-3} \text{s}\]
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.
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 \( \sim 500 \text{ MW} \).
- \( I_{\text{plasma}} = 15 \text{ MA}, B_0 = 5 \text{ Tesla} \), \( T \sim 10 \text{ keV}, \tau_E \sim 4 \text{ s} \).
- Large – 30 m tall, 20 ktons.
- Expensive \( \sim 10\text{B}+ \).
- Project staffing, administrative organization, environmental impact assessment.
- First burning plasmas \( \sim 2018 \).

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

**Center for Simulation of Wave-Plasma Interactions**
- AORSA
- TORIC
- CQL3D
- ORBITRF
- DELTO5D

**Gyrokinetic Particle Simulation Center**
- GTC code
- GYRO

**Edge Simulation Projects**
- XGC code
- TEMPEST
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.
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 parallelization, 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.

<table>
<thead>
<tr>
<th></th>
<th>TODAY</th>
<th>Large present-day tokamak (DIII-D)</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative volume</td>
<td>1</td>
<td>50</td>
<td>1,500</td>
</tr>
<tr>
<td>Space-time pts.</td>
<td>$2 \times 10^{11}$</td>
<td>$1 \times 10^{13}$</td>
<td>$3 \times 10^{14}$</td>
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<tr>
<td>Actual speed</td>
<td>100 GF</td>
<td>5 TF</td>
<td>150 TF</td>
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<tr>
<td>No. processors</td>
<td>500</td>
<td>10,000</td>
<td>100,000</td>
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<tr>
<td>Rel. proc. speed</td>
<td>1</td>
<td>2.5</td>
<td>7.5</td>
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</tbody>
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