Scientific and Computational Advances in Fusion Energy Research & Key Partnerships with NERSC

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Fusion Energy: Burning plasmas are self-heated and self-organized systems



Deuterium-Tritium Fusion Reaction

 $D^{+} + T^{+} \rightarrow {}^{4}He^{++} (3.5 \text{ MeV}) + n^{\circ} (14.1 \text{ MeV})$

Fusion: an Attractive Energy Source

- Abundant fuel, available to all nations
 - Deuterium and lithium easily available for millions of years
- Environmental advantages
 - No carbon emissions, short-lived radioactivity
- Cannot "blow up or melt down," resistant to terrorist attack
 - Less than a minute's worth of fuel in the chamber
- Low risk of nuclear materials proliferation
 - No fissile materials required
- Compact relative to solar, wind and biomass
 - Modest land usage
- Not subject to daily, seasonal or regional weather variation; no requirement for local CO₂ sequestration
 - Not limited in its application by need for large-scale energy storage nor for long-distance energy transmission
- Fusion is complementary to other attractive energy sources

Progress in Magnetic Fusion Energy (MFE) Research



ITER Goal: Demonstration of the Scientific and Technological Feasibility of Fusion Power

ITER is an ~\$20B facility located in France & involving 7 governments representing over half of world's population

 → dramatic next-step for Magnetic Fusion Energy (MFE)

producing a sustained burning plasma

- -- Today: 10 MW(th) for 1 second with gain ~1
- -- ITER: 500 MW(th) for >400 seconds with gain >10
- <u>"DEMO"</u> will be demonstration fusion reactor after ITER
 <u>2500 MW(th) continuous with gain >25,</u> in a device of similar size and field as ITER
- Ongoing R&D programs worldwide [experiments, theory, <u>computation</u>, and technology] <u>essential to provide growing</u> <u>knowledge base for ITER operation targeted for ~ 2020</u>

Realistic HPC-enabled simulations required to costeffectively plan, "steer," & harvest key information from expensive (~\$1M/long-pulse) ITER shots ITER



Magnetically confined plasmas in a tokamak are complex and demand integrated analysis



Modern HPC-enabled simulations open opportunities for "transformational" science to accelerate understanding in fusion energy research

Though equations are well-known (Boltzmann-Maxwell), the problem is a physics grand challenge



Advanced Scientific Codes --- "a measure of the state of understanding of

natural and engineered systems" (1st SciDAC Director T. Dunning)



Fusion SciDAC Projects (2001-2004 → present)

Extended MHD Modeling



<u>PPPL,</u> SAIC, U. Wisconsin, NYU, U. Colorado, MIT, Utah State U., GA, LANL, U. Texas

Internal Magnetic Reconnection

RF/Wave Plasma Interactions

<u>ORNL</u>, PPPL, MIT, Lodestar



Plasma Microturbulence

<u>LLNL</u>, GA, PPPL, U. Maryland, U. Texas, U. Colorado, UCLA



Turbulent Eddies in Plasmas

Tremendous reliance on NERSC computational resources support !

MHD Simulation* of Internal Reconnection Event

Hot Inner Region Interchanges with Colder Outer Region via Magnetic Reconnection



*Simulation with M3D code carried out by W. Park (PPPL) <u>carried out at NERSC!</u> → Associated Movie shown by <u>DoE-SC Director Raymond Orbach</u> in plenary presentation on "High End Computation & Scientific Discovery" @ <u>SC'02, Baltimore, MD</u> M3D simulation of NSTX W. Park et al. Visualization

S. Klasky et al.



More recent Fusion SciDAC Projects (present)

Energetic Particles (EP) in Burning Plasmas

<u>Princeton Plasma Physics Laboratory</u> IFS, University of Texas @ Austin University of Colorado Oak Ridge National Laboratory



Alpha Particle–Driven Toroidal Alfven Eigenmode (TAE) Mode Structure in ITER

GK Simulations of EP Turbulence & Transport

<u>University of California @ Irvine</u> General Atomics Oak Ridge National Laboratory Lawrence Livermore National Laboratory



Validation of TAE GK Simulation with ECEI measurement in DIII-D plasma

→ Dominant reliance on NERSC computational resources support !

Microturbulence in Fusion Plasmas – Mission Importance: <u>Fusion reactor size & cost</u> <u>determined by balance between loss processes & self-heating rates</u>



 BUT, compelling understanding of plasma size scaling demands higher physics fidelity requiring <u>much greater</u> computational resources + <u>new algorithms</u> & modern diagnostics for VV&UQ

→ Excellent Scalability of Global PIC Codes on modern HPC platforms <u>enables much greater resolution/physics</u> <u>fidelity to improve understanding</u>

→ BUT - further improvements for efficient usage of current LCF's <u>demands code re-write featuring modern</u> <u>CS/AM methods addressing locality, low-memory-per-</u> <u>core,</u>



SciDAC-2 & 3 Integrated Plasma Edge-Core Petascale Studies



XGC1 performance on 3mm ITER grid

• <u>C.S. Chang, et al.</u>, <u>SciDAC-2 "CPES"</u> <u>Project</u>: petascale-level production runs with XGC-1 global PIC code \rightarrow 24M CPU hours (100K cores x 240 hours)



• XGC1 scales efficiently to full Jaguar petaflop capability (with MPI+ OpenMP) & can routinely use >70% of maximum – <u>key developmental phase carried out at NERSC!</u>

<u>Current SciDAC-3</u> "EPSi" Project: focus on XGC1 conversion to GPU architecture of Titan

FSP -- A Strategic **Opportunity** to Accelerate Scientific Progress in FES

• Need for reliable predictive simulation capability for BP/ITER

• Powerful ("Leadership Class") Computational Facilities moving rapidly beyond petascale

• Interdisciplinary *collaborative experience*, knowledge, & software assembled over the course of nearly a decade under SciDAC plus OFES and OASCR base research programs in the US



FSP Plan: U.S. National Website at \rightarrow http://www.pppl.gov/fsp

FSP Program Plan



Posted: July, 2011

FSP U.S. National Website:

http//www.pppl.gov/fsp

Image from Microturbulence Simulation with GTS code by W. Wang of PPPL carried out at NERSC!

FINAL U.S. SENATE APPROPRIATIONS LANGUAGE July, 2013

The Committee *recommends* \$12,000,000 for the Fusion Simulation Program to provide experimentally validated predictive simulation capabilities that are critical for ITER and other current and planned toroidal fusion devices. The Committee is concerned that the fusion energy program is not taking full advantage of high performance computing to address scientific and technical challenges on the path to fusion energy. Given current and future budget constraints, the Committee views this initiative as critical to maintain U.S. world leadership in fusion energy sciences in a costeffective manner. The Committee directs the Office of Science to develop a plan on the use of these simulation capabilities based on the results of a 2-year planning effort recently funded by the Department.



Fusion Energy Data Management and Visualization Challenges



* <u>Petabytes of data expected in future – especially for ITER/Burning Plasmas</u>

Prioritized Magnetic Fusion Energy Science Drivers in FSP Plan

#1 PRIORITY: Disruptions → Large-scale macroscopic events leading to rapid termination of plasma discharges

Goal: Need to avoid because ITER can sustain only a limited number of full-current disruptions with **severe heat loads**, **JxB forces**, **run-away electron generation**

<u>Current Situation Analysis</u>: <u>First principles-based codes are not deployable to avoid/</u> <u>mitigate disruptions on JET now – and probably on ITER in the future</u>

[P. C. DeVries, 2013 APS-DPP Invited Presentation]

→ Viable Alternative: Large-data-driven "machine-learning" kinds of statistical approaches

-- Some early successes evident in applications of such methods [A. Murari, J. Vega, ...]

-- Deterministic response potentially achievable to satisfy real-time needs of fusion systems

-- ITER will need a reliable disruption avoidance capability of over 95% !!

• Requirement: <u>early recognition of disruption onset while avoiding "false alarms" that</u> <u>interrupt experimental operations</u>

Future Challenges and Opportunities in FES

- (1) Energy Goal in FES application domain is to increase availability of clean abundant energy by first moving to a burning plasma experiment on the ITER facility & moving on to DEMO
 -- ITER targets 500 MW for 400 seconds with gain > 10 to demonstrate technical feasibility & DEMO (demonstration power plant) will target 2500 MW with gain of 25
- (2) <u>HPC-Driven Modeling Goal</u> is to harness continuing rapid increase of HPC capability by improving the ability of advanced codes to utilize increasingly powerful HPC systems worldwide to help accelerate *progress toward much improved reliability of predictive tools.*
- (3) Experimental Validation Goal is to engage FES experimental facilities worldwide to: (i) provide key data bases & develop and deploy accurate new diagnostics to test the reliability of advanced simulation codes via <u>sensitivity studies</u> to support quantification of uncertainties.
- (4) <u>Large-Data-driven Goal</u> engage, develop, & incorporate new statistical methods enabled by modern HPC capabilities to complement/replace (as needed) the existing first-principles-based & empirical approaches
- Overall Goal of Fusion Simulation & Modeling: → will continue to involve key FES partnerships with <u>NERSC!</u>

Accelerate progress in delivering reliable integrated predictive capabilities – benefiting from access to <u>HPC resources at extreme scale</u> -- together with a vigorous verification, validation, & uncertainty quantification program – and modern HPC-enabled large-data driven tools.