Directing transformation:
The science of fusion energy and striving towards a validated predictive capability

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We live in an unprecedented era of transformation: with benefit, burden, and promise.
Plentiful energy has been utterly transformative.

For the first time in history, we have an understanding of:

- the linkage between quality of life and energy availability
- our impacts on the globe of the drive to improve life quality
- that range of possibilities for our path forward

We have also come to understand that fusion energy, in step with high performance computing, can be a transformative clean energy source enabled by frontier science.
Fusion has transformative potential: plentiful, carbon-free, base-load energy

Create a star on earth. A hot plasma, or ionized gas, is the vehicle: isotopes of hydrogen collide hard and often to fuse into a helium nucleus and a neutron, with large net energy gain and self-heating the plasma (“burning plasma”).

Fusion is ready for a major step - A National Academies assessment: fusion is ready and must advance to the major next step in demonstrating net fusion power. ITER represents that step.

Fusion science is exciting and broad - The US has been a (or the) intellectual leader in creating a mature, exciting scientific endeavor that includes fusion and extends well beyond it.
A great intellectual framework has been developed, with rich and complex interplay. Energy-directed research spawns great science.

Reminding ourselves of the evolution of the field can inspire regarding its potential
“All fusion reactors require a burning plasma. The key challenge is to confine the hot and dense plasma while it burns.”

_Burning Plasma: Bringing a Star to Earth, p. 1_
National Research Council
Scientific advance has made fusion an option: the fusion reactor regime is within striking distance.
Scientific advance has made fusion an option: fusion’s progress rivals computer chips.
ITER, together with a vigorous world program in fusion science, can be a truly transformative scientific instrument.
Consider the airline industry:

10-fold reduction in prototyping of wing designs

“By using supercomputers to simulate the properties of the wings on recent models such as the 787 and the 747-8, we only had to design seven wings, a tremendous savings in time and cost, especially since the price tag for wind tunnel testing has skyrocketed over the past 25 years.”

- Doug Ball, Boeing (chief engineer for enabling technology and research)
Some FES background
FES research is carried out at a diversity of US institutions.

- **53 universities**
- **12 businesses**
- **10 laboratories**

Spending $M

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<th>FY 2015</th>
<th>142</th>
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<td>250</td>
<td>90</td>
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<td>300</td>
<td>71</td>
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Map showing research locations in the US.
Burning Plasma Science in the U.S.: Foundations

Science that will drive economics of fusion:
Heating efficiency and containment, maximum fuel pressure
→ confinement system size and complexity
→ attractiveness and cost
DIII-D and NSTX are flagships of a scientifically powerful combination

- The aspect ratio is central to much of toroidal confinement science
- It is also a driver in the ultimate cost and viability of a fusion power plant
- Smaller university scale facilities of varying magnitude support each
- V&V: increasingly the goal is detailed comparison of detailed measurement with theory-based computation
DIII-D and NSTX-U are both highly flexible and world-leading in measurement capability and impact.

Comparative research between facilities, and in concert with overseas experiments, are hallmarks.

Both have been highly impactful regarding burning plasma science fundamentals.
My own brush with computing as an experimentalist
A personal view of the evolution of a slice of fusion science...

**TFTR (‘82 - ‘97)**

Extraordinary dependence of confinement on boundary conditions (Li on carbon walls)

Experimental $\chi_i$, $\chi_\phi$

Scott et al., Phys. Fluids B 1990

... a taste of the early theory-experiment comparisons in thermal conduction
Mid 90’s: IFS-PPPL model gets $T_i(r)$ in very different confinement regimes about right
Linear gyrokinetics identify critical gradients.
Nonlinear gyrofluids map out parametric shape of $\chi_i$.

I (spectroscopist) hear for first time from theorists: “We think your $T_i$ data are incorrect in some cases - can you reanalyze these shots?”

→ Theorists were right: the measurement was wrong

→ Realization that simulation at the level of the turbulence had to be part of future predictions

Physical processes in a tokamak discharge span multiple time and spatial scales.

Typical Time Scales in a next step experiment with $B = 10$ T, $R = 2$ m, $n_e = 10^{14}$ cm$^{-3}$, $T = 10$ keV

- Electron Transit
- SAWTOOTH CRASH
- Energy Confinement
- Turbulence
- Island Growth
- Current Diffusion

Single frequency and prescribed plasma background

RF Codes wave-heating and current-drive

Neglect displacement current, average over gyroangle, (some) with electrons

Gyrokinetics Codes turbulent transport

Neglect displacement current, integrate over velocity space, neglect electron inertia

Extended MHD Codes device scale stability

Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia

Transport Codes discharge time-scale
Meeting the challenge of validated predictive capability through partnership
Partnerships between fusion scientists and computational scientists, under the auspices of SciDAC, have accelerated the rate of scientific discovery in fusion plasma science by improving the performance of fusion codes on leadership computing facilities and by addressing challenging data management and visualization issues associated with high-performance computing.
There has been significant progress in understand how the fusing plasma interacts with the material boundary

**the Science:**

Helium bubbles are detrimental to plasma-facing materials such as tungsten. Understanding how helium bubbles form and grow is important for predicting large-scale material response to the extreme fusion environment. The helium simulations find a qualitatively different growth mode when helium arrival rates approach experimental values. When simulated helium bubbles grow quickly, the surrounding tungsten cannot respond, leading to over-pressurized bubbles that burst violently when they reach the surface. When the bubbles grow more slowly, the tungsten atoms pressed against the bubble’s surface can diffuse around it, leading to a smaller bubble when it ultimately bursts.

**the Impact:**

These results highlight the importance of accounting for all relevant kinetic processes and how these kinetic processes enhance the interaction of, in this case, the helium bubble with the local microstructure. The results further have consequences for the nucleation of surface morphology on the tungsten, which is ultimately the source of fuzz, a nanostructured “steel wool”-like structure that causes significant degradation in performance of the material.
Major themes of the FES strategic plan

- **Massively parallel computing** with the goal of validated whole-fusion-device modeling will enable a transformation in predictive power, which is required to minimize risk in future fusion energy development steps.

- **Materials science** as it relates to plasma and fusion sciences will provide the scientific foundations for greatly improved plasma confinement and heat exhaust.

- Research in the prediction and control of **transient events** that can be deleterious to toroidal fusion plasma confinement will provide greater confidence in machine designs and operation with stable plasmas.

- Continued stewardship of **discovery in plasma science** that is not expressly driven by the energy goal will address frontier science issues underpinning great mysteries of the visible universe and will help attract and retain a new generation of plasma/fusion science leaders.

- **FES user facilities** will be kept world-leading through robust operations support and regular upgrades.

- The strategic plan responds to several recent Congressional requests, viz., concerning a strategic plan (FY14), a fusion simulation program (FY14), and community workshops (FY15).

The plan has just been delivered to Congress.
Recent efforts continue a strong tradition of planning and working together. Our challenges are significant. Joint program review meetings and workshops shape future directions and provide unique opportunities to exchange information with all stakeholders.
Flexibility envisioned for the WDM is embodied in the use of both Advanced Reduced models and Extreme Scale Simulations.

WDM framework provides verification and validation technology (UQ workflows) plus connection to experimental data (both raw and processed).

From WDM Workshop Summary, Bonoli and McInnis
Vision for integrated extreme-scale simulations

Disruption prediction, avoidance, and mitigation:
Extended MHD analysis of NTM island growth, locking, and disruption

Embedded GK turbulence in transport solver for burning plasma:
Multiple ion species [10^7 CPU-hours @200,000 cores]

Multiphysics and multiscale coupling

Verification, validation, UQ, optimization, inverse problems

Continuum simulations of PSI for reactor-scale divertor surface (100 m^2) to predict PFC performance & tritium retention
> 120,000 cores

Software integration and performance

From WDM Workshop Summary, Bonoli and McInnis
Computational and enabling technologies in integrated fusion simulations

- Multiphysics Coupling
- Uncertainty Quantification
- Data Management
- Scientific Inference
- Fusion Processes
- Engineering Design
- Data Analysis & Assimilation
- Multiscale Coupling
- Numerical Optimization
- Software Performance
- Software Integration

Modeling & Simulation

Experiment
Opportunity and challenge for computing and fusion: global cooperation
GA Remote Control Room:
Display hardware and software to provide control room experience remotely.
Accommodates 8 scientists & remote support staff.
Real-time audio/video, streaming of data during shot, display of real-time boundary/ signal traces.

GA Science Collaboration Zone:
Dedicated network and cyberspace for between-shot transfer of data to GA.
DIII-D provides EAST data repository for all U.S. collaborators.
Data mirror at GA serves all US collaborators.

First full 3rd shift remote operation July 22 and 23:
Two 3rd shift periods (overnight in China)
Executed vertical controllability experiments
Enables US to use entire third shift (2016)
Thank you
$\lambda_q$ is dominated by ions in this DIII-D like edge plasma for $I_p=0.97\text{MA}$.

$\lambda_q = 5.1\text{ mm}$ at $I_p=0.97\text{MA}$.

Enhancement by neutral particles is only $\sim 10\%$.

$\lambda_q$ is closer to ion orbit spreading width than the radial blob size ($\geq 1\text{ cm}$).

Heat-load spreading by blobs (represented by $\lambda_{qe} \sim 2\text{mm}$ in the figure) is masked by the ion orbital spreading.
An exciting period scientifically and with respect to the community. The theoretical minimum in core transport can be realized.

Scientific cross-connects: core and edge physics. ExB shear, a bifurcating core joins the bifurcating edge, the language of phase transitions enters the lexicon...

Institutional cross talk/stimulation/competition was vibrant.
Foundations

Focuses on U.S. capabilities targeting key scientific issues.

Long Pulse

Building on U.S. capabilities furthered by international partnership

High Power

ITER is the keystone
Global Average Temperature

http://www.epa.gov/climatechange/science/future.html
International partnership is essential

• Challenges are too big, too complex to go it alone; and major steps are expensive

• Grand challenge is optimizing the complex sociology of seven Members operating as a smartly functioning, directed whole
The science of fusion and plasmas extends from the laboratory to the stars and beyond.

Magnetic confinement

The tokamak is the leading magnetic confinement concept for fusion.

Gravitational confinement

Inertial confinement

Sun: interior... and in x-rays

ITER

NIF hohlraum

Aurora

The tokamak is the leading magnetic confinement concept for fusion.
The FES magnetic fusion energy sciences program is organized along the following lines:

**Foundations**

**Long pulse**

**High Power**
Burning Plasma Science in the U.S.: Long pulse

Science that will drive economics:

Maintaining the magnetic cage:
External + internal $B$ (tokamak) vs. externally imposed $B$ (stellarator)

Fusion materials:
Solid vs liquid, tritium breeding, closing the fuel cycle
ITER is the scientific vehicle for the science of burning plasmas for the world

- ITER will establish the science of robustly and attractively controlling fusion plasmas that heat themselves
- Test the fundamentals and long pulse science at reactor scale
ITER:
The fundamental science of a burning plasma. ITER will establish the science of robustly and attractively controlling fusion plasmas that heat themselves.

High power burning plasma science is essential for establishing fusion’s science basis and thus its credibility.
Photovoltaic Cost of Energy

This is an age of transformation: energy science increases options

http://www1.eere.energy.gov/tribalenergy/guide/costs_solar_photovoltaics.html
10% improvement in fuel efficiency has a powerful effect

- 2.5 million tons annual CO2 reduction
- 2.8 billion annual diesel fuel savings
- $8.3 billion annual fuel cost savings
NERSC roots in magnetic fusion research underline the deep connection between fusion research and high performance computing

How a computer center dedicated to fusion research became the primary scientific computing facility for the Office of Science:

• **1974**: AEC establishes the Controlled Thermonuclear Research (CTR) center at LLNL (first computer: CDC 6600)

• **1976**: CTR is renamed the National Magnetic Fusion Energy Computer Center or NMFECC (first computers: CDC 7600; Cray-1)
  - Access to remote facilities is provided via the Magnetic Fusion Energy Network (MFEnet) which will evolve to today’s ESnet

• **1983**: Access to NMFECC is extended to other ER (now SC) programs

• **1990**: The center is renamed the National Energy Research Supercomputer Center (NERSC) to reflect its broader mission*

*Now known as the National Energy Research Scientific Computing Center*

NERSC, along with the Oak Ridge and Argonne Leadership Computing Facilities, represent a critical resource for FES in its quest to develop a predictive capability for fusion plasmas.
The FES SciDAC program:

- The FES Scientific Discovery through Advanced Computing (SciDAC) program advances scientific discovery in fusion plasma science by exploiting SC leadership class computing resources and associated advances in computational science.

- Addresses grand challenges in burning plasma science and materials science.

- Highly collaborative program, leverages strengths of FES and ASCR.
## Prioritization of multi-x topics in physics areas

### Near-term
- Integrated models: Two-fluid solver + discretization
- Integrated models: Fluid-kinetic coupling (runaway $e$, energetic particles)
- Integrated models: Coupling with wall dynamics (melting, ionization, multiphase, radiation)
- Parameterized assessment: Model hierarchy to quantify errors in sampling of parameter space

### Mid-term
- Pedestal characterization
- Detached divertor plasmas: Fast collisional algorithms (neutrals, plasma)

### Long-term
- Detached divertor plasmas: Plasma + neutrals + radiation coupling strategies
- Detached divertor plasmas: Kinetic + fluid coupling
## Prioritization of multi-x topics in physics areas

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<th>Multi-X Topics</th>
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<td>C.1.1 Time-dependent baseline: Coupling 1D + fast dynamics components</td>
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<td>C.2.2 ELMs, sputtering, impurity transport: Kinetic high-Z impurity transport</td>
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<td>C.3.2 ITER core transport and ITBs: Coupling with edge (HMM, projective integration)</td>
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<td>C.3.3 ITER core transport and ITBs: Reduced models for ITB triggers</td>
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<td>C.3.5 ITER core transport and ITBs: Sensitivity studies in high-D (&gt; 20) space</td>
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<td>C.4 Q=10 ITER scenario: Coupling MHD + EP + transport</td>
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<td>C.5.1 Steady-state ST: Global GK simulations</td>
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<td>C.5.2 Steady-state ST: Coupled ions-electrons, realistic mass ratios</td>
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<td>C.5.3 Steady-state ST: EM effects (high-(\beta))</td>
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This is an age of transformation: energy transforms economies

US Consumption by Source v. Real GDP
1845-2001

This is an age of transformation: energy transforms life quality

U.S. Life Expectancy vs. Real GDP per Capita (log)
1929 to 2007
This is an age of transformation: global impacts are measurable.
The MFE Theory program:

Focuses on fundamental plasma science of magnetic confinement with emphasis on burning plasma science

Supported areas include macroscopic stability, confinement and transport, interaction of RF waves with plasmas, energetic particle physics, and plasma boundary physics

- Efforts range from small single-investigator grants, mainly at universities, to large coordinated teams at national laboratories, universities, and private industry
- Provides theoretical underpinning for advanced simulation codes (SciDAC) and supports validation efforts at major experiments

The FES SciDAC program:

- The FES Scientific Discovery through Advanced Computing (SciDAC) program advances scientific discovery in fusion plasma science by exploiting SC leadership class computing resources and associated advances in computational science
- Addresses grand challenges in burning plasma science and materials science
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This is an age of transformation: we now understand the scale of the solution to climate change that is required.

**CO₂ concentration, temperature, and sea level continue to rise long after emissions are reduced.**

<table>
<thead>
<tr>
<th>Magnitude of response</th>
<th>Time taken to reach equilibrium</th>
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<tr>
<td>CO₂ emissions peak</td>
<td>Sea-level rise due to ice melting: several millennia</td>
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<tr>
<td>0 to 100 years</td>
<td>Sea-level rise due to thermal expansion: centuries to millennia</td>
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- Temperature stabilization: a few centuries
- CO₂ stabilization: 100 to 300 years