Directing transformation:

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

Ed Synakowski
Associate Director, Office of Science

Fusion Energy Sciences

U.S. DEPARTMENT OF
ENERGY
Office of Science

For the Advanced Scientific Computing
Advisory Committee
December 9, 2015

We live in an unprecedented era of transformation:
with benefit, burden, and promise

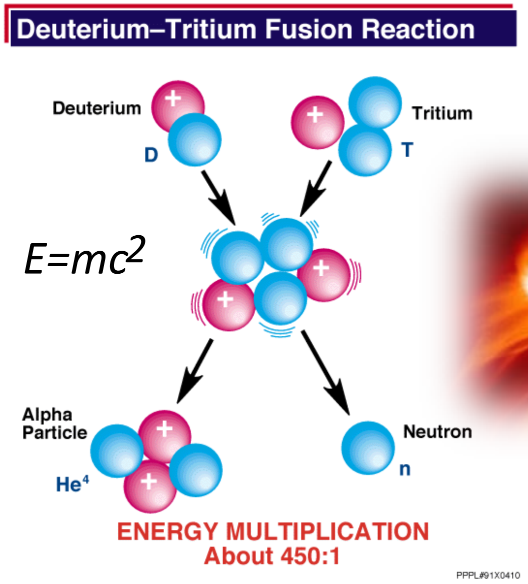
Plentiful energy has been utterly tranformative

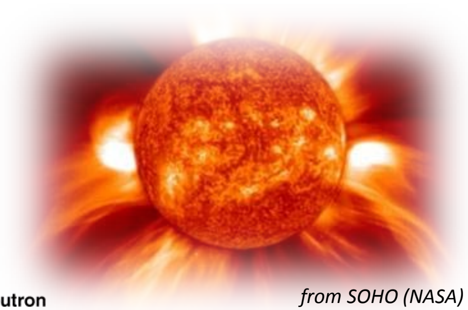
For the first time in history, we have an understanding of

- 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



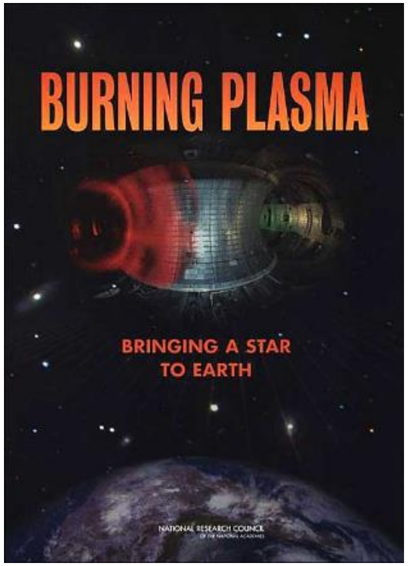


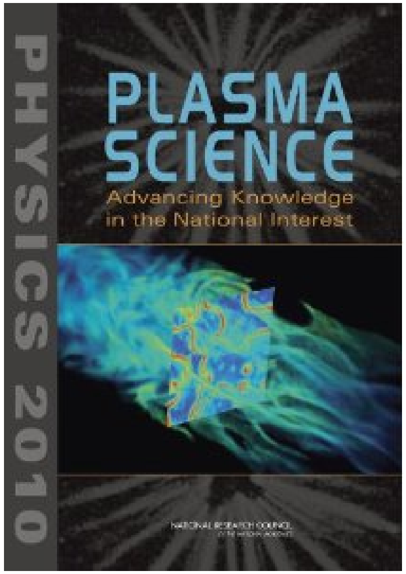
from SOHO (NASA)

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





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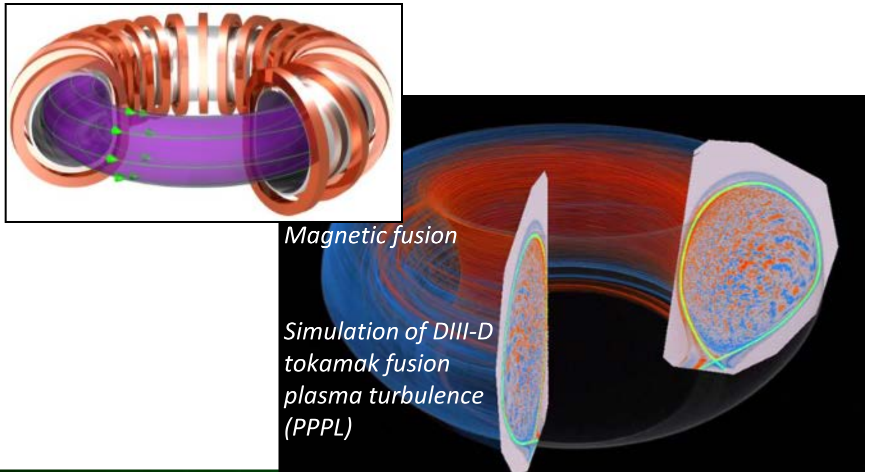
The fusion and plasma sciences are broad and tremendously rich

- A great intellectual framework has been developed, with rich and complex interplay. Energy-directed research spawns great science

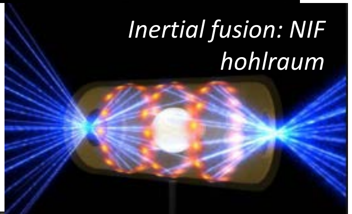
- Reminding ourselves of the evolution of the field can inspire regarding its potential



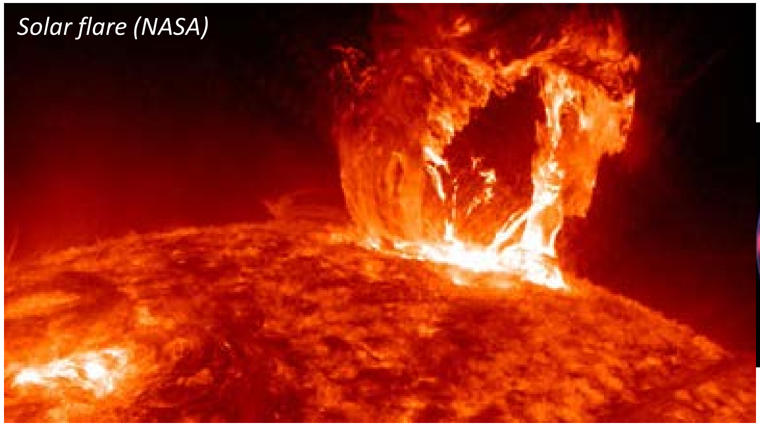
Magnetic fusion

Simulation of DIII-D tokamak fusion plasma turbulence (PPPL)

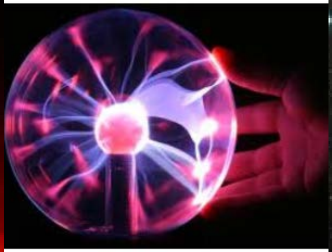
Aurora



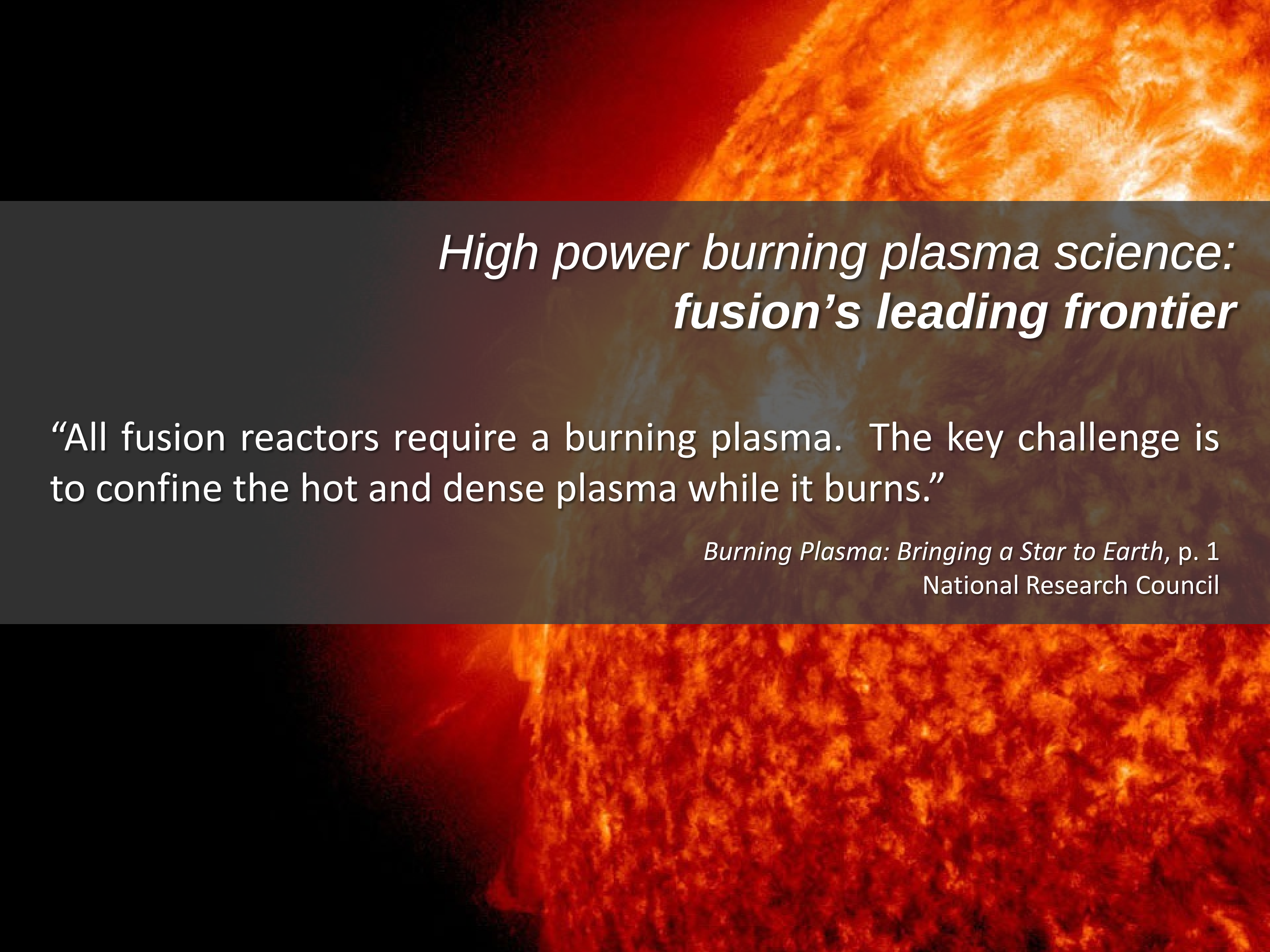
Inertial fusion: NIF hohlraum



Solar flare (NASA)



Centaurus A with plasma jets from central black hole (NASA)

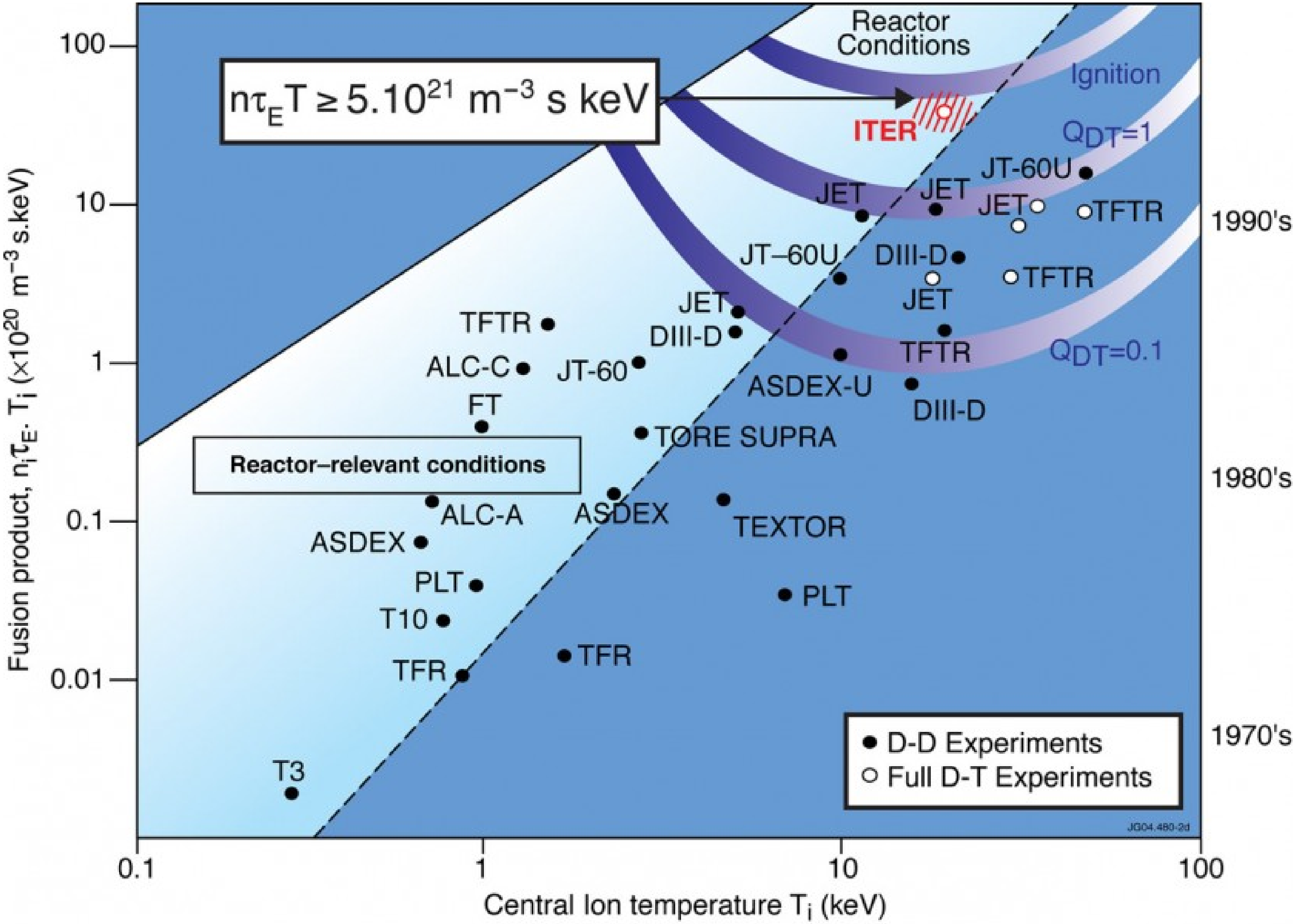


High power burning plasma science: ***fusion's leading frontier***

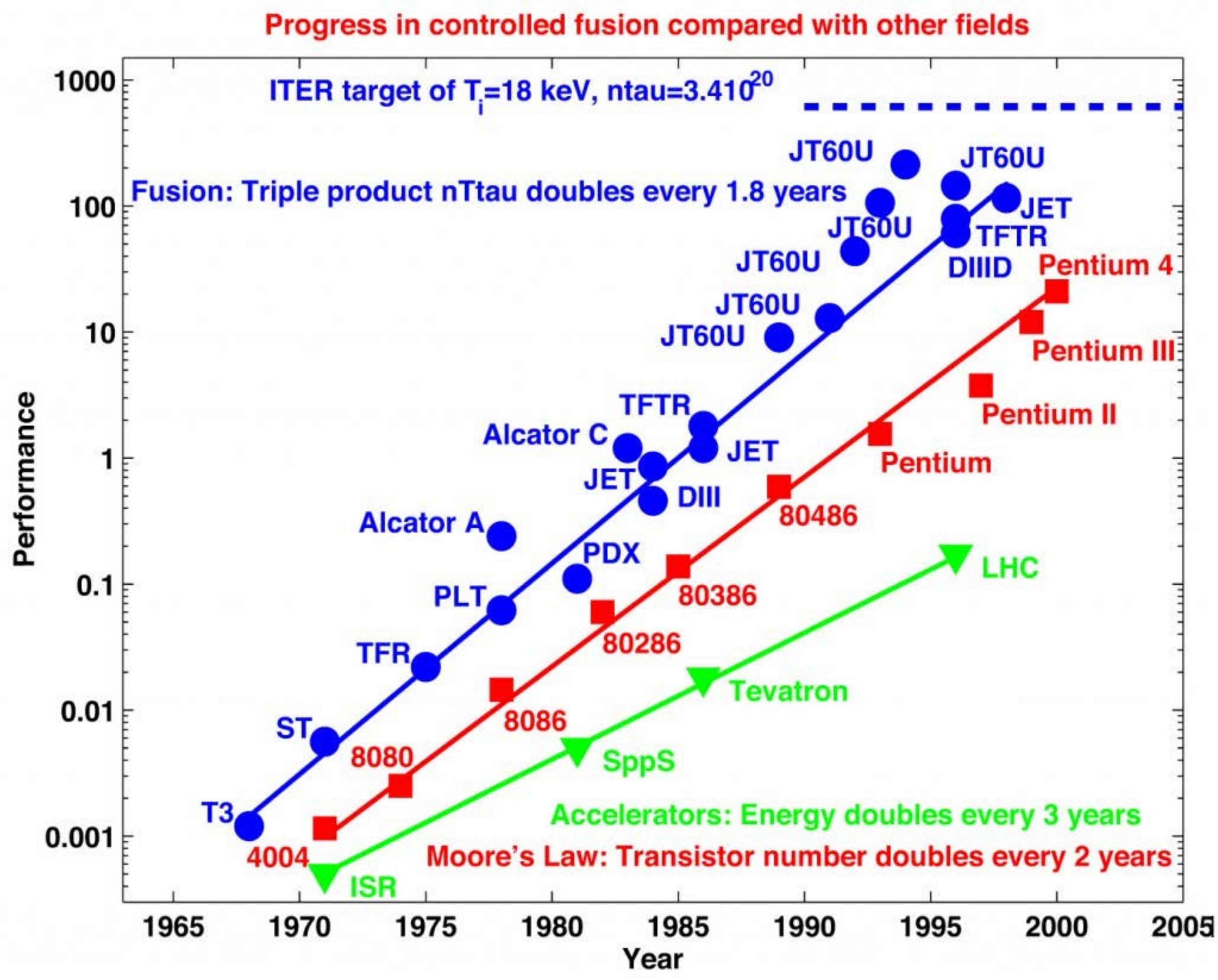
> "All fusion reactors require a burning plasma. The key challenge is to confine the hot and dense plasma while it burns."

Burning Plasma: Bringing a Star to Earth, p. 1
National Research Council

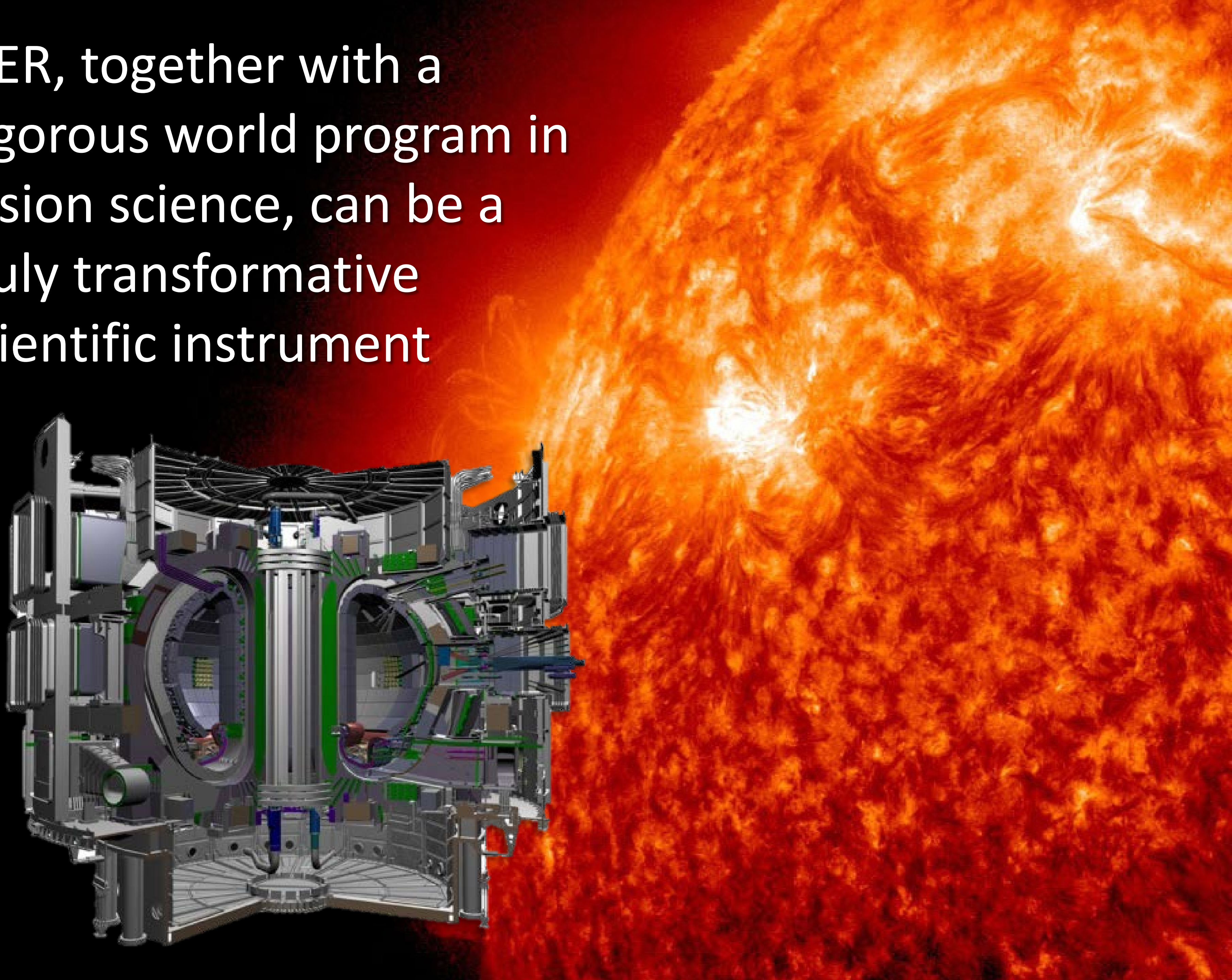
*Scientific advance has made fusion an option: **the fusion reactor regime is within striking distance***



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



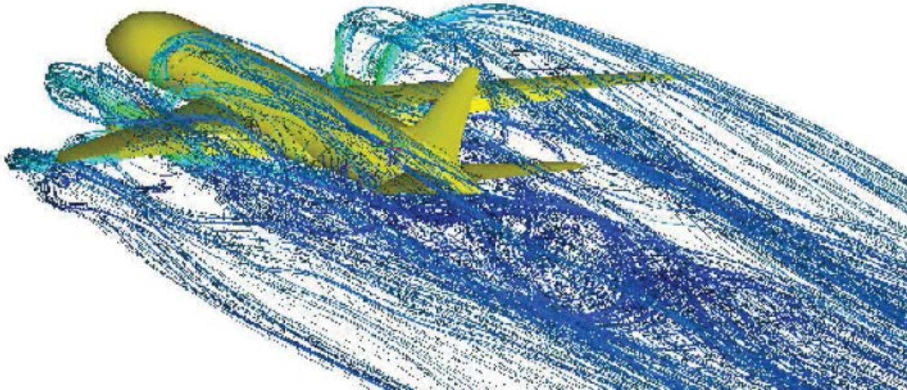
To reduce development costs, how fusion science relies on computing has to evolve

Consider the airline industry:

10-fold reduction in prototyping of wing designs

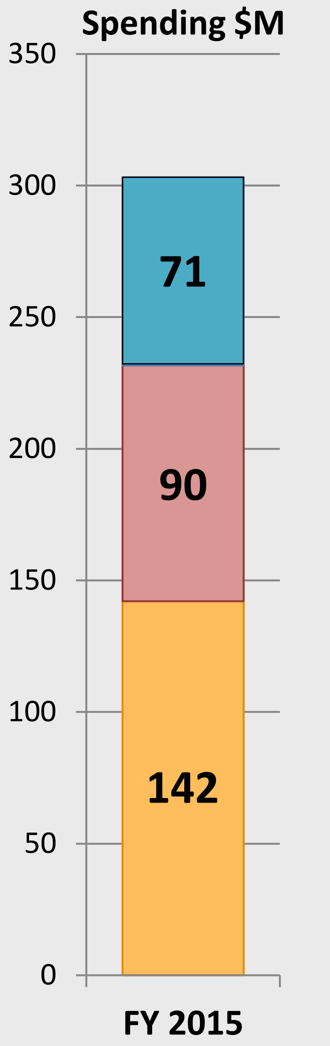
“ By using supercomputers to simulate the properties of the wings on recent models such as the 787 and the 747-8, we only had to design seven wings, ***a tremendous savings in time and cost***, especially since the price tag for wind tunnel testing has skyrocketed over the past 25 years.”

- Doug Ball, Boeing (chief engineer for enabling technology and research)



Some FES background

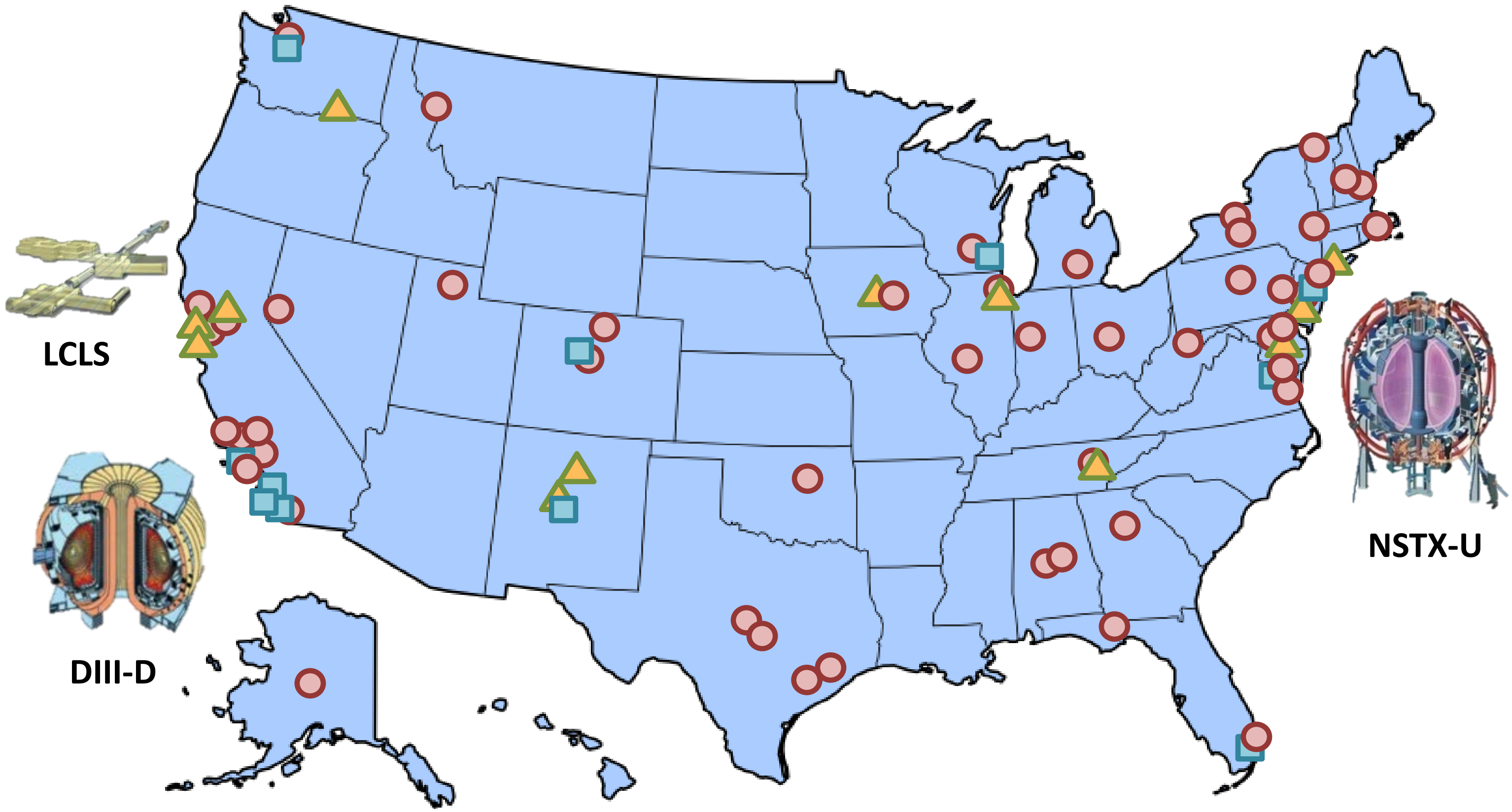
FES research is carried out at a diversity of US institutions



53 universities

12 businesses

10 laboratories



Burning Plasma Science in the U.S.:

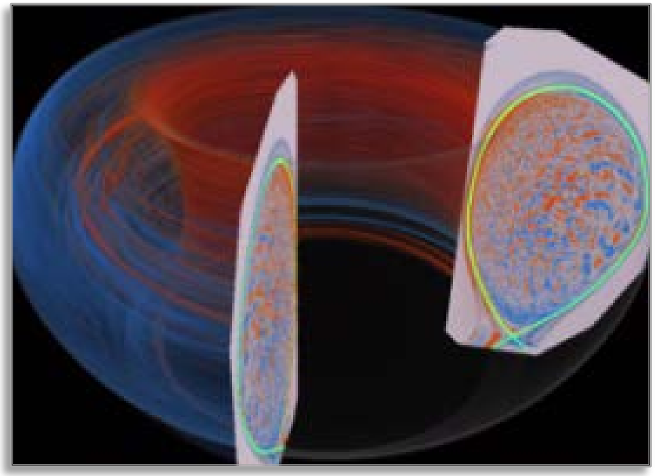
Foundations

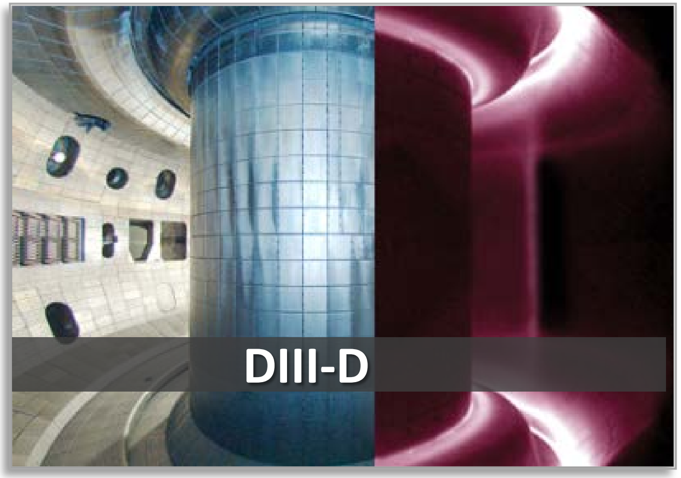
Science that will drive economics of fusion:

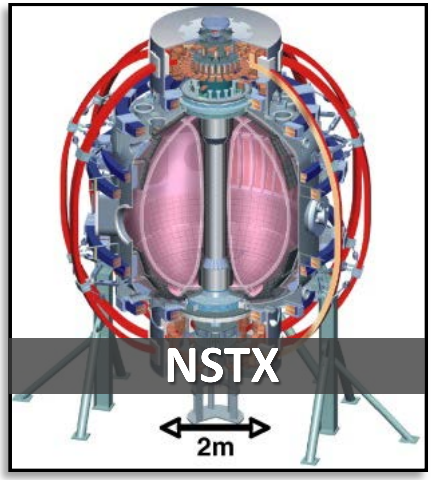
Heating efficiency and containment, maximum fuel pressure

→ confinement system size and complexity

→ attractiveness and cost







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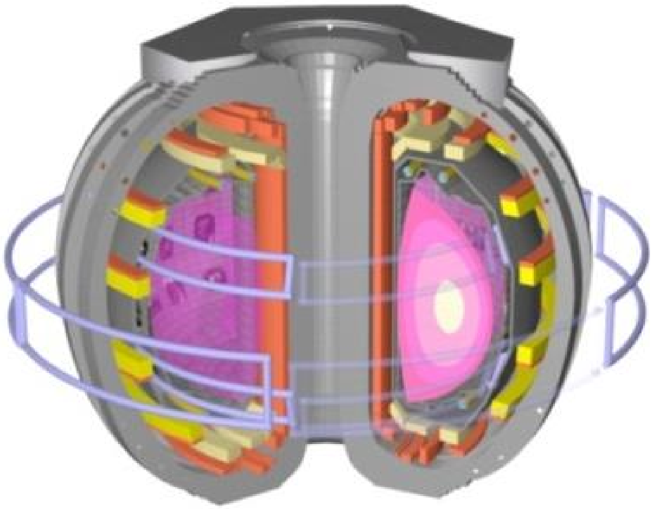
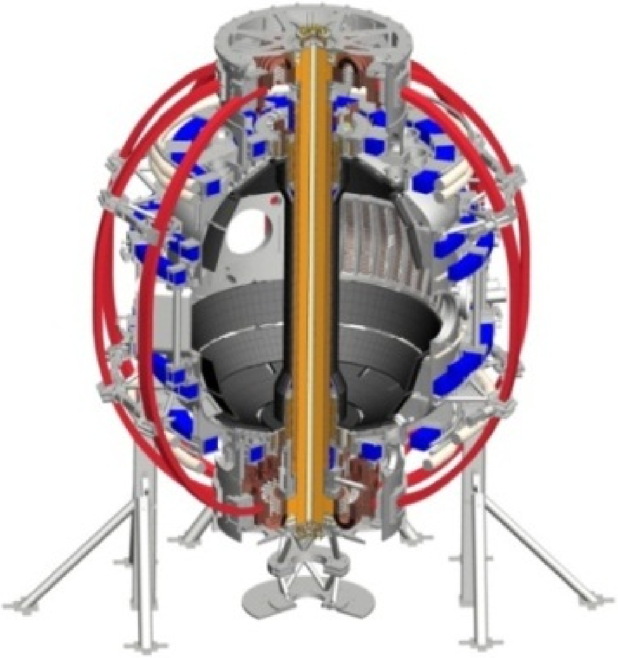
DIII-D and NSTX are flagships of a scientifically powerful combination

DIII-D NATIONAL FUSION FACILITY

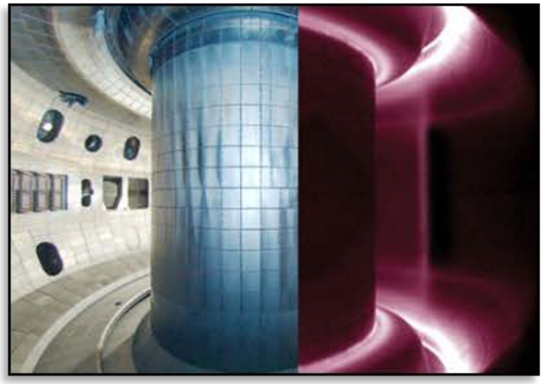


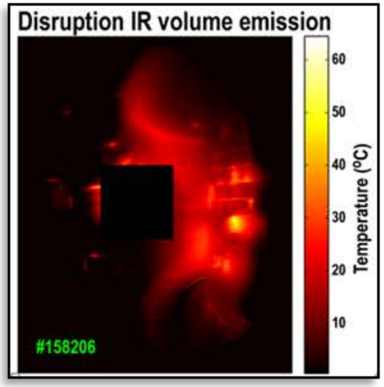
NSTX-U

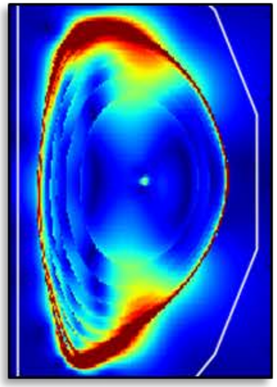


- *The **aspect ratio** is central to much of toroidal confinement science*
- *It is also a driver in the ultimate cost and viability of a fusion power plant*
- *Smaller university scale facilities of varying magnitude support each*
- *V&V: increasingly the goal is detailed comparison of detailed measurement with theory-based computation*

DIII-D and NSTX-U are both highly flexible and world-leading in measurement capability and impact







DIII-D
NATIONAL FUSION FACILITY

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

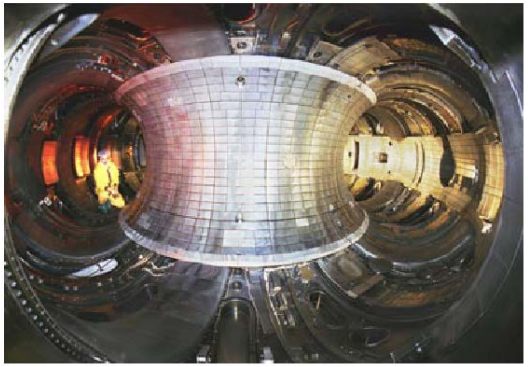
Both have been highly impactful regarding burning plasma science fundamentals

NSTX-U

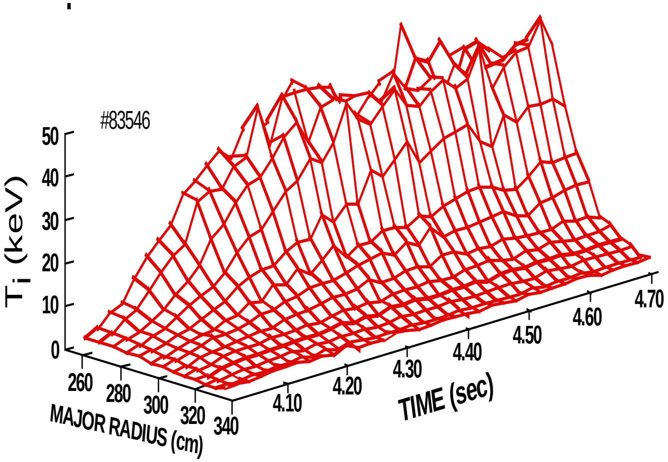
My own brush with computing as an experimentalist

A personal view of the evolution of a slice of fusion science…

TFTR ('82 - '97)

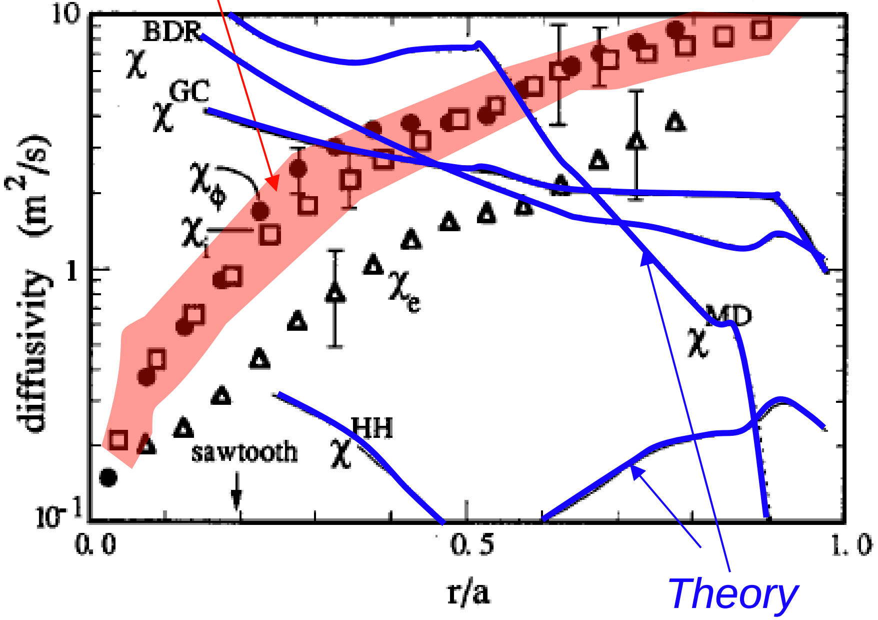


Extraordinary dependence of confinement on boundary conditions (Li on carbon walls)



Experimental χ_i, χ_ϕ

Scott et al., Phys. Fluids B 1990



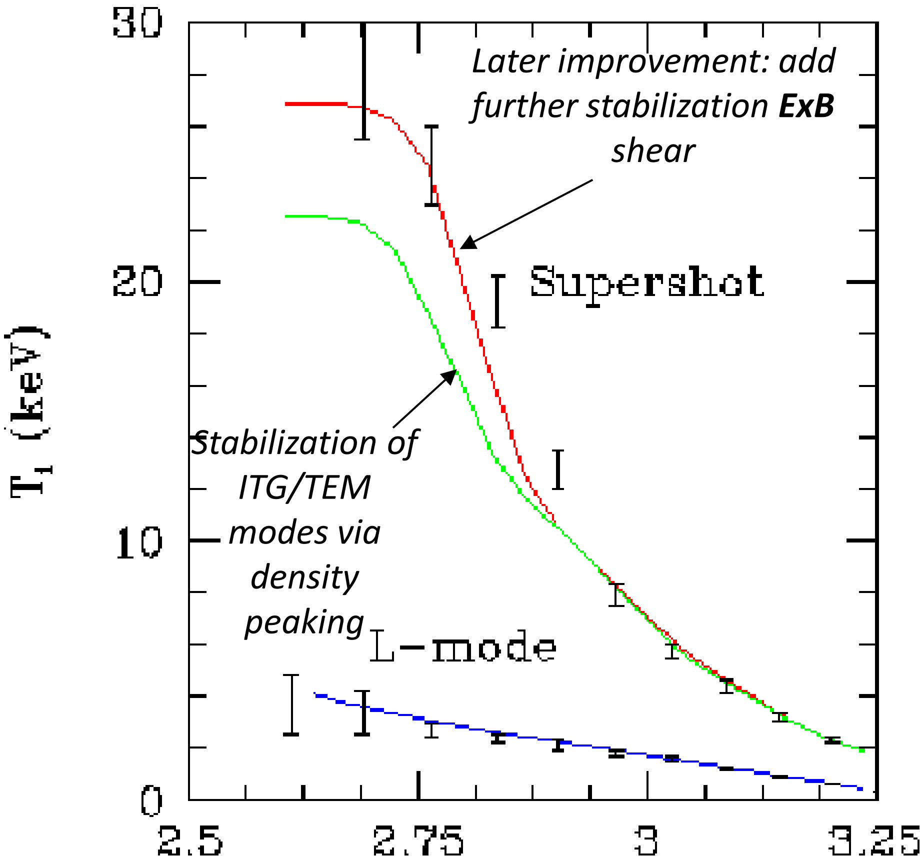
… a taste of the early theory-experiment comparisons in thermal conduction

Mid-90's example of a transformation: turbulence theory-based model challenges experimentalists

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 χ_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

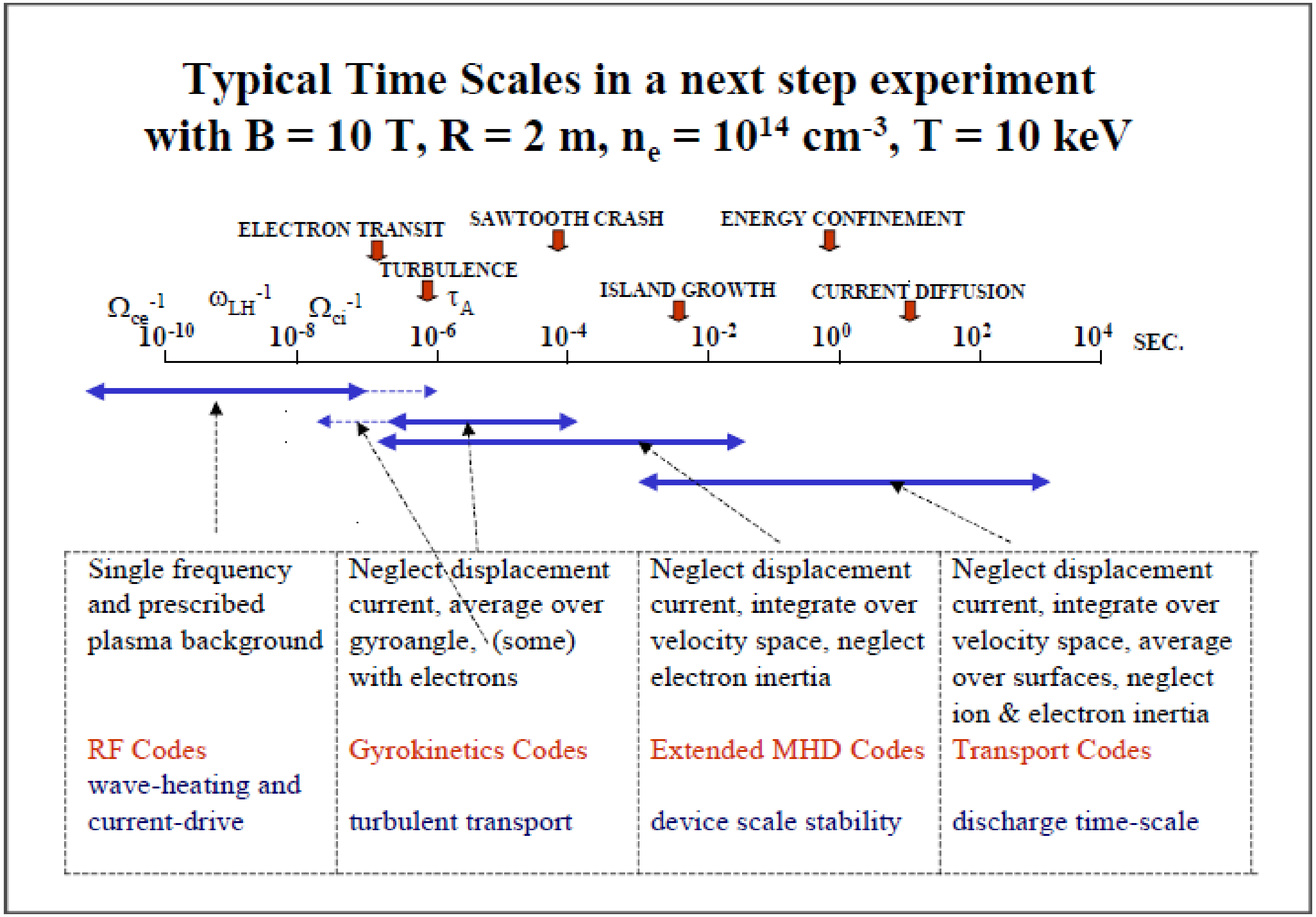


Later improvement: add further stabilization ***ExB*** *shear*

Stabilization of ITG/TEM modes via density peaking

Kotschenreuther, Dorland, Hammett, Phys. Plasmas 2 (1995)

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

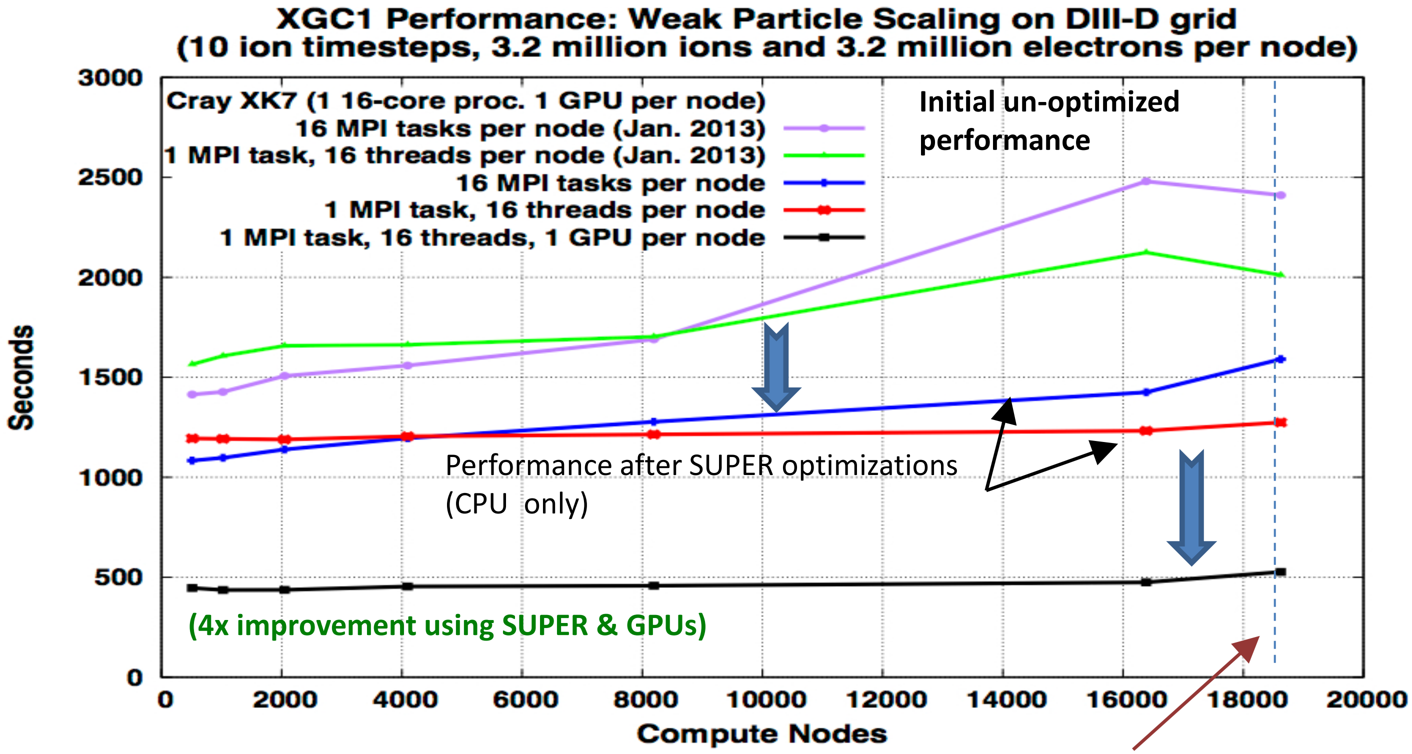
Single frequency and prescribed plasma background	Neglect displacement current, average over gyroangle, (some) with electrons	Neglect displacement current, integrate over velocity space, neglect electron inertia	Neglect displacement current, integrate over velocity space, average over surfaces, neglect ion & electron inertia
RF Codes	Gyrokinetics Codes	Extended MHD Codes	Transport Codes
wave-heating and current-drive	turbulent transport	device scale stability	discharge time-scale

2002 FESAC ISOFS Report

Meeting the challenge of validated predictive capability through partnership

FES – ASCR partnerships are impactful

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.



Initial un-optimized performance

Performance after SUPER optimizations (CPU only)

(4x improvement using SUPER & GPUs)

Maximum # of Titan cores

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There has been significant progress in understand how the fusing plasma interacts with the material boundary

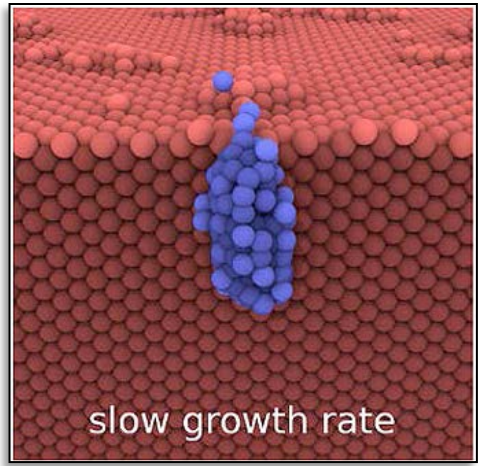
the Science:

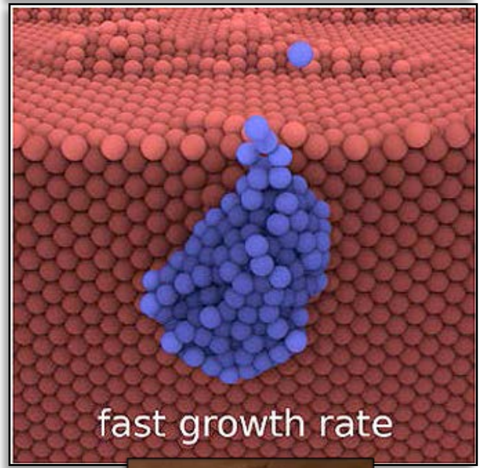
Helium bubbles are detrimental to plasma-facing materials such as tungsten. Understanding how helium bubbles form and grow is important for predicting large-scale material response to the extreme fusion environment. The helium simulations find a qualitatively different growth mode when helium arrival 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.

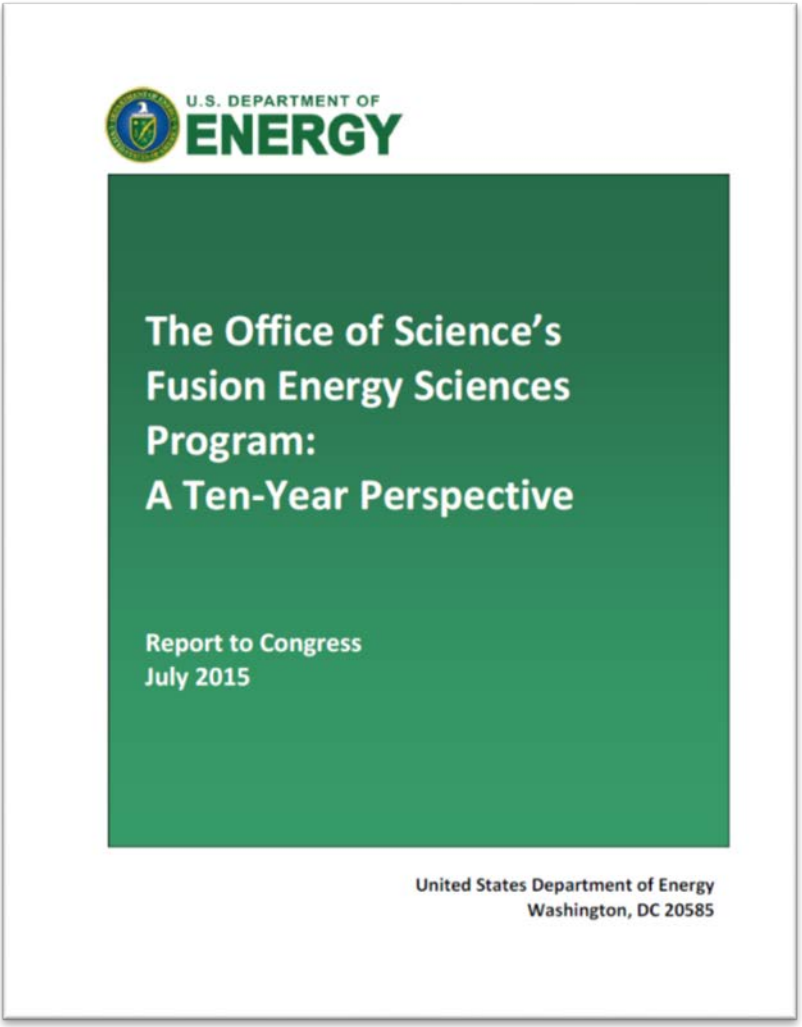




FES strategic plan places a strong emphasis on high performance computing

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.



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The Office of Science's
Fusion Energy Sciences
Program:
A Ten-Year Perspective

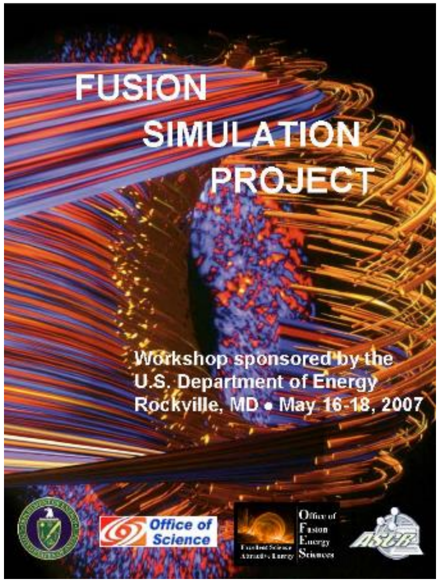
Report to Congress
July 2015

United States Department of Energy
Washington, DC 20585

- 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

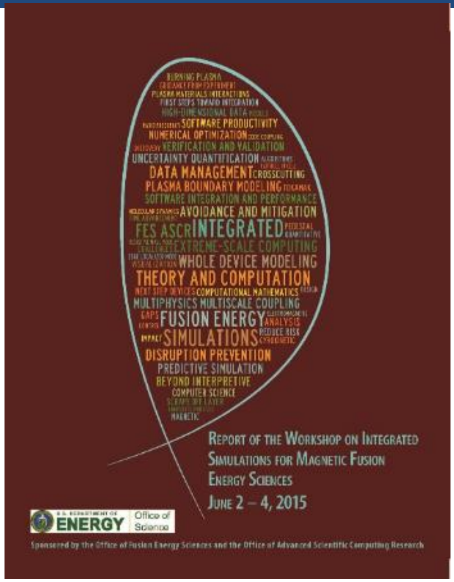
Recent efforts continue a strong tradition of planning and working together

Our challenges are significant.
Joint program review meetings and workshops shape future directions and provide unique opportunities to exchange information with all stakeholders.


FUSION SIMULATION PROJECT

Workshop sponsored by the
U.S. Department of Energy
Rockville, MD • May 16-18, 2007

Office of Science
Office of Fusion Energy Sciences

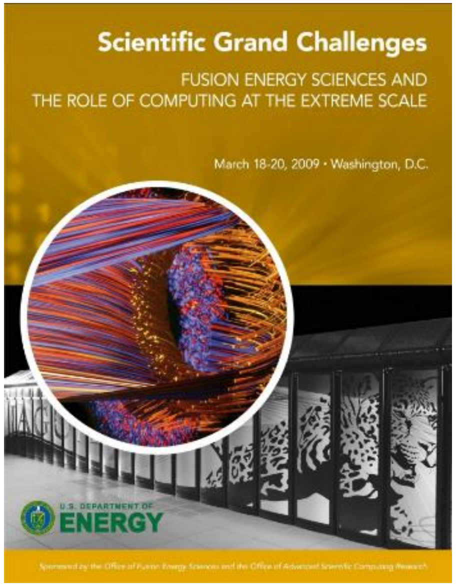


REPORT OF THE WORKSHOP ON INTEGRATED SIMULATIONS FOR MAGNETIC FUSION ENERGY SCIENCES

JUNE 2 – 4, 2015

U.S. DEPARTMENT OF ENERGY | Office of Science

Sponsored by the Office of Fusion Energy Sciences and the Office of Advanced Scientific Computing Research


Scientific Grand Challenges

FUSION ENERGY SCIENCES AND THE ROLE OF COMPUTING AT THE EXTREME SCALE

March 18-20, 2009 • Washington, D.C.

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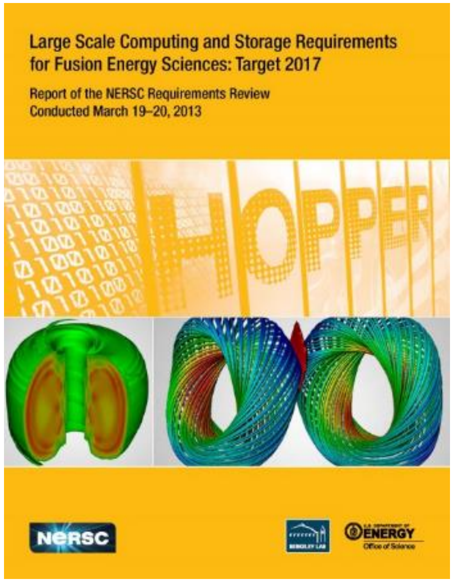
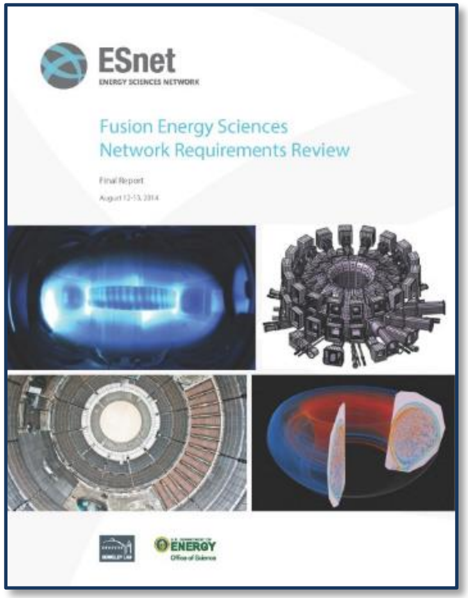

Large Scale Computing and Storage Requirements for Fusion Energy Sciences: Target 2017

Report of the NERSC Requirements Review Conducted March 19–20, 2013

NERSC
U.S. DEPARTMENT OF ENERGY Office of Science

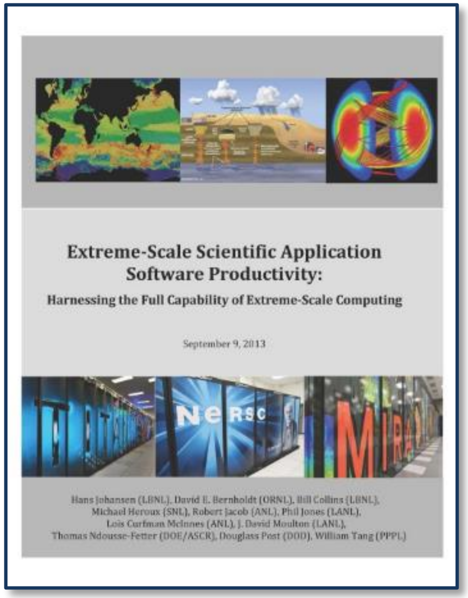

ESnet
ENERGY SCIENCES NETWORK

Fusion Energy Sciences Network Requirements Review

Final Report

August 12-13, 2014

ENERGY Office of Science

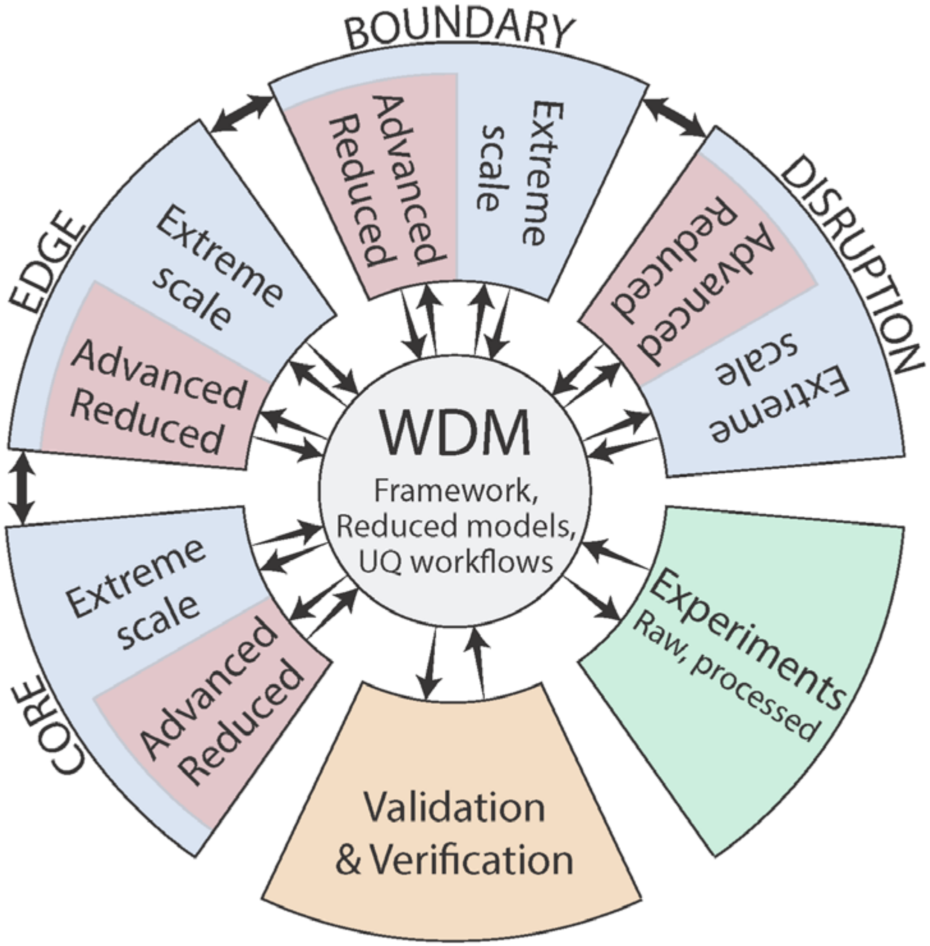

Extreme-Scale Scientific Application Software Productivity:

Harnessing the Full Capability of Extreme-Scale Computing

September 9, 2013

Hans Johansen (LBNL), David E. Bernholdt (ORNL), Bill Collins (LBNL),
Michael Heroux (SNL), Robert Jacob (ANL), Phil Jones (LANL),
Lois Curfman McInnes (ANL), J. David Moulton (LANL),
Thomas Ndousse-Fetter (DOE/ASCR), Douglass Post (DOD), William Tang (PPPL)

Schematic overview envisioned for the WDM showing the interaction between topical areas

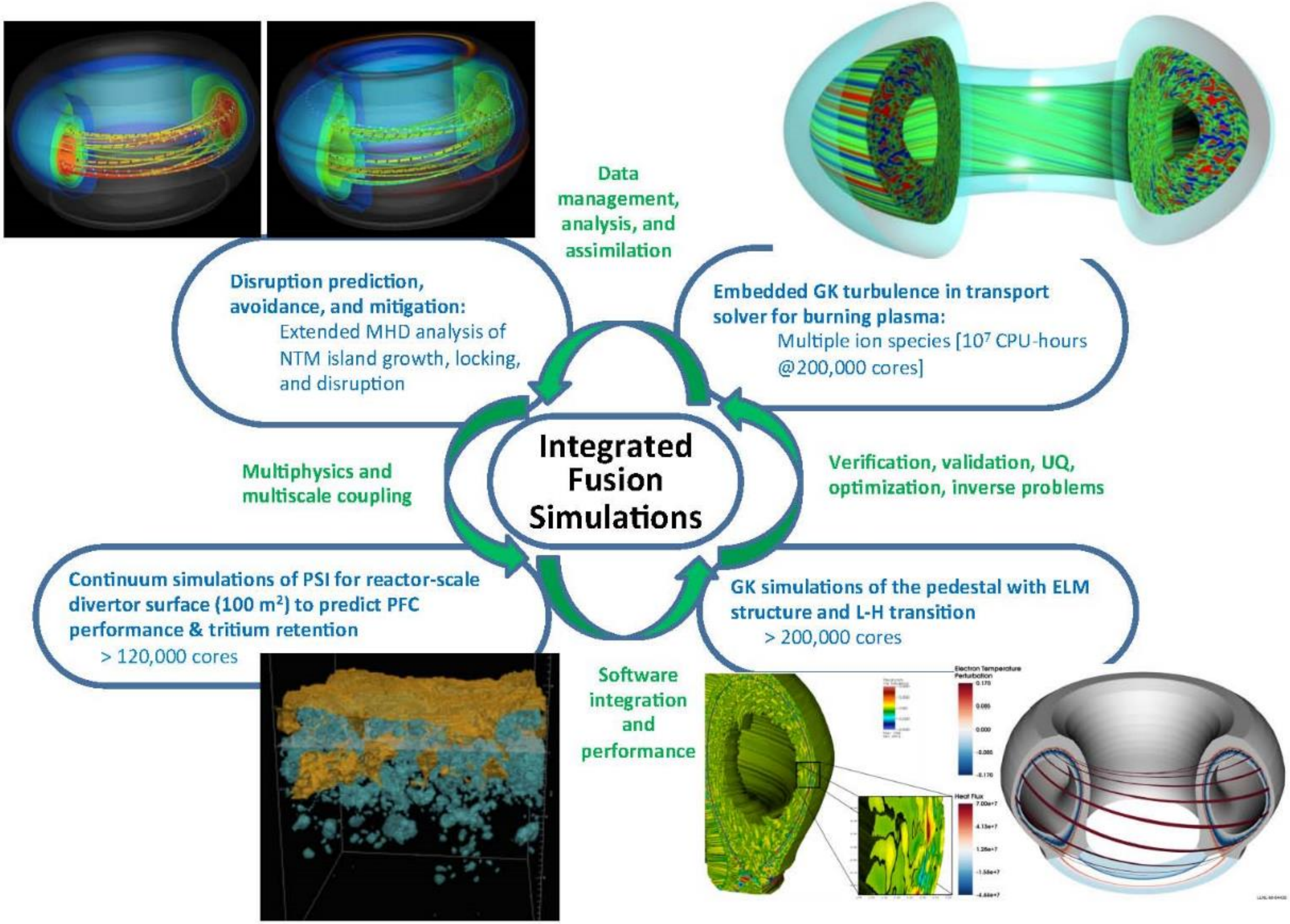


Flexibility envisioned for the WDM is embodied in the use of both Advanced Reduced models and Extreme Scale Simulations.

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



Data management, analysis, and assimilation

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]

Integrated Fusion Simulations

Multiphysics and multiscale coupling

Verification, validation, UQ, optimization, inverse problems

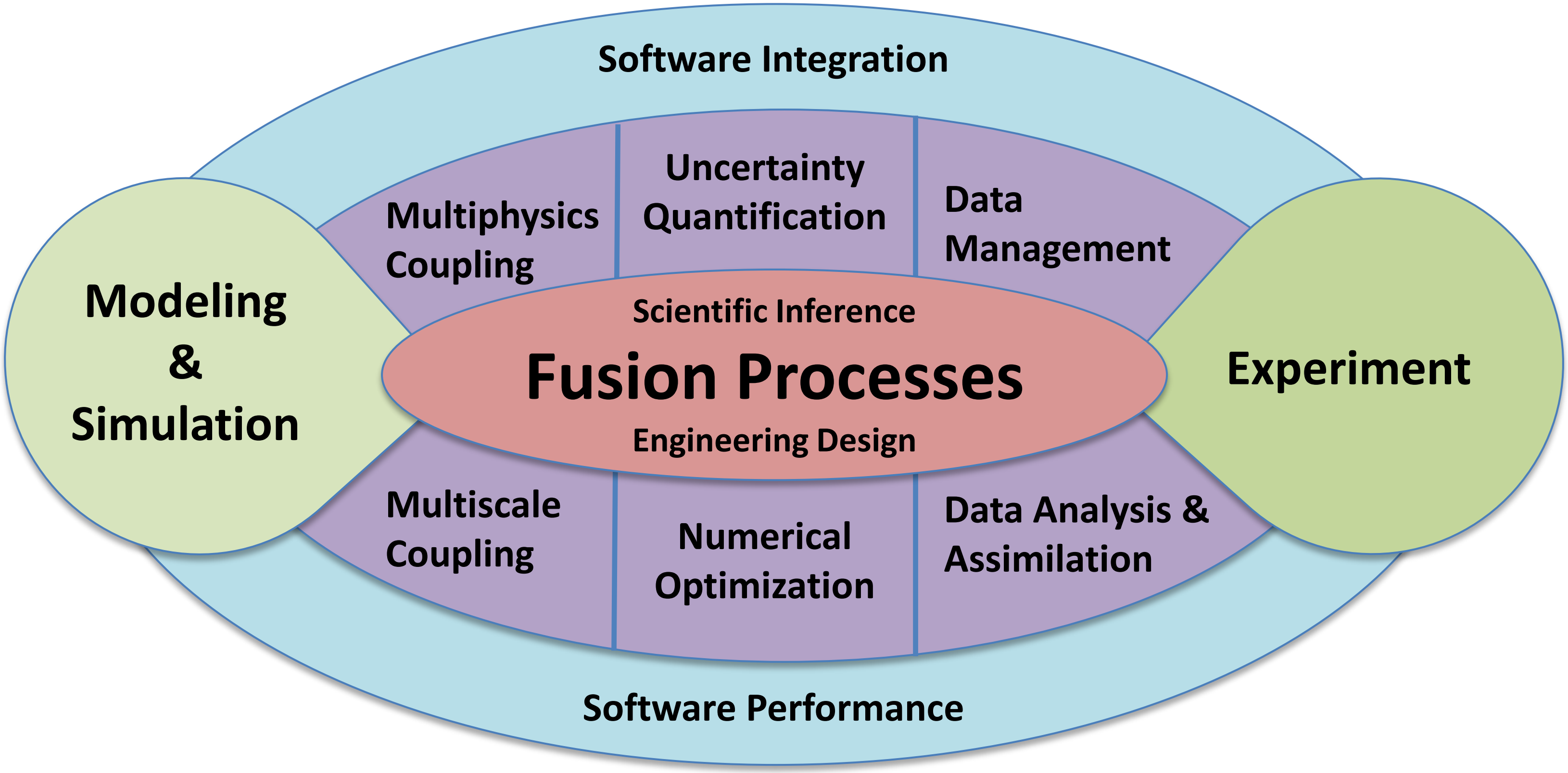
Continuum simulations of PSI for reactor-scale divertor surface (100 m^2) to predict PFC performance & tritium retention
> 120,000 cores

GK simulations of the pedestal with ELM structure and L-H transition
> 200,000 cores

Software integration and performance

From WDM Workshop Summary, Bonoli and McInnis

Computational and enabling technologies in integrated fusion simulations



Software Integration

Multiphysics Coupling

Uncertainty Quantification

Data Management

Modeling & Simulation

Scientific Inference

Fusion Processes

Engineering Design

Experiment

Multiscale Coupling

Numerical Optimization

Data Analysis & Assimilation

Software Performance

Opportunity and challenge for computing and fusion: global cooperation

OAK RIDGE National Laboratory

GENERAL ATOMICS

PPPL

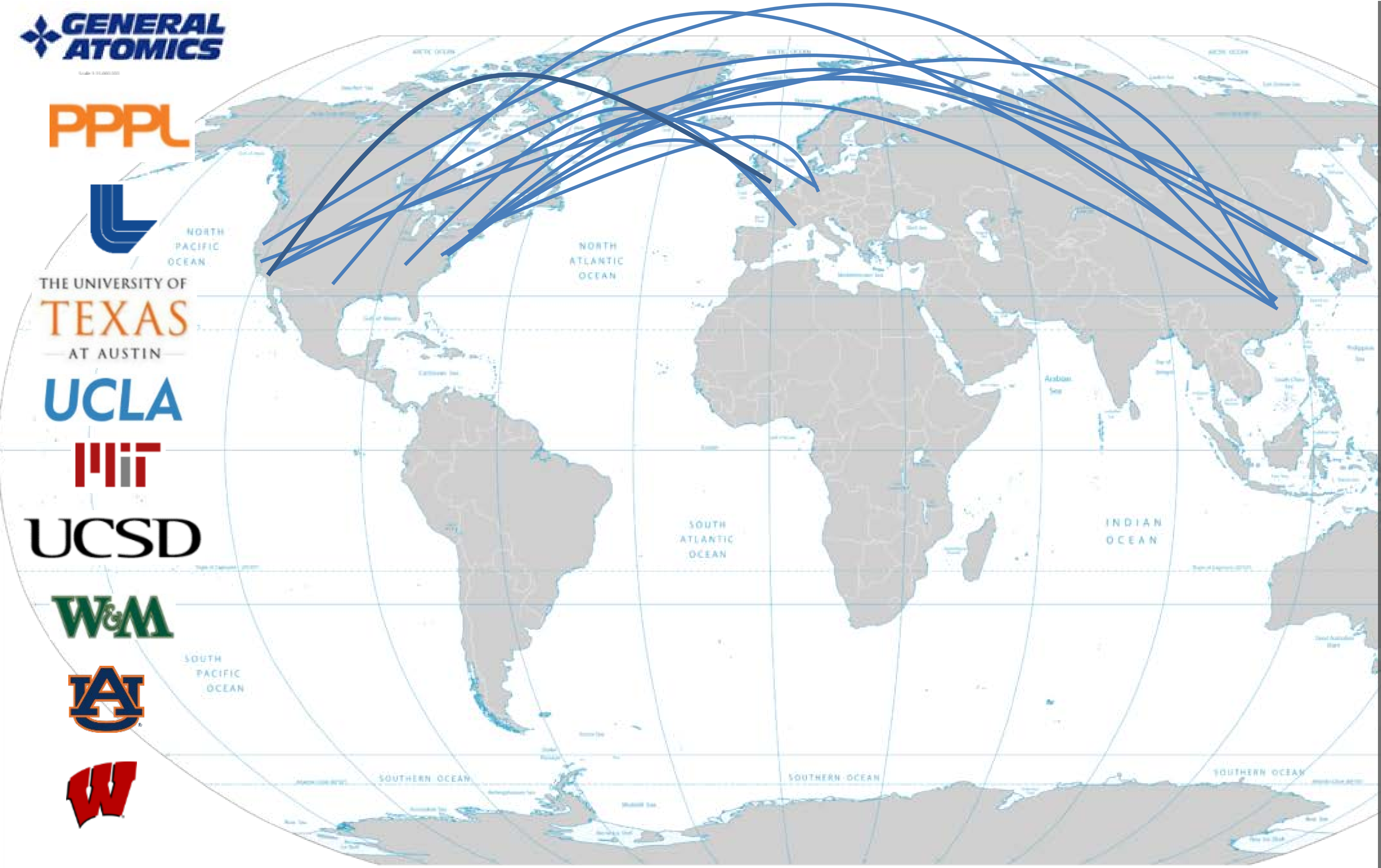
THE UNIVERSITY OF TEXAS AT AUSTIN

UCLA

MIT

UCSD

W&M



EAST/DIII-D partnership: Joint teams execute research on both DIII-D & EAST

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

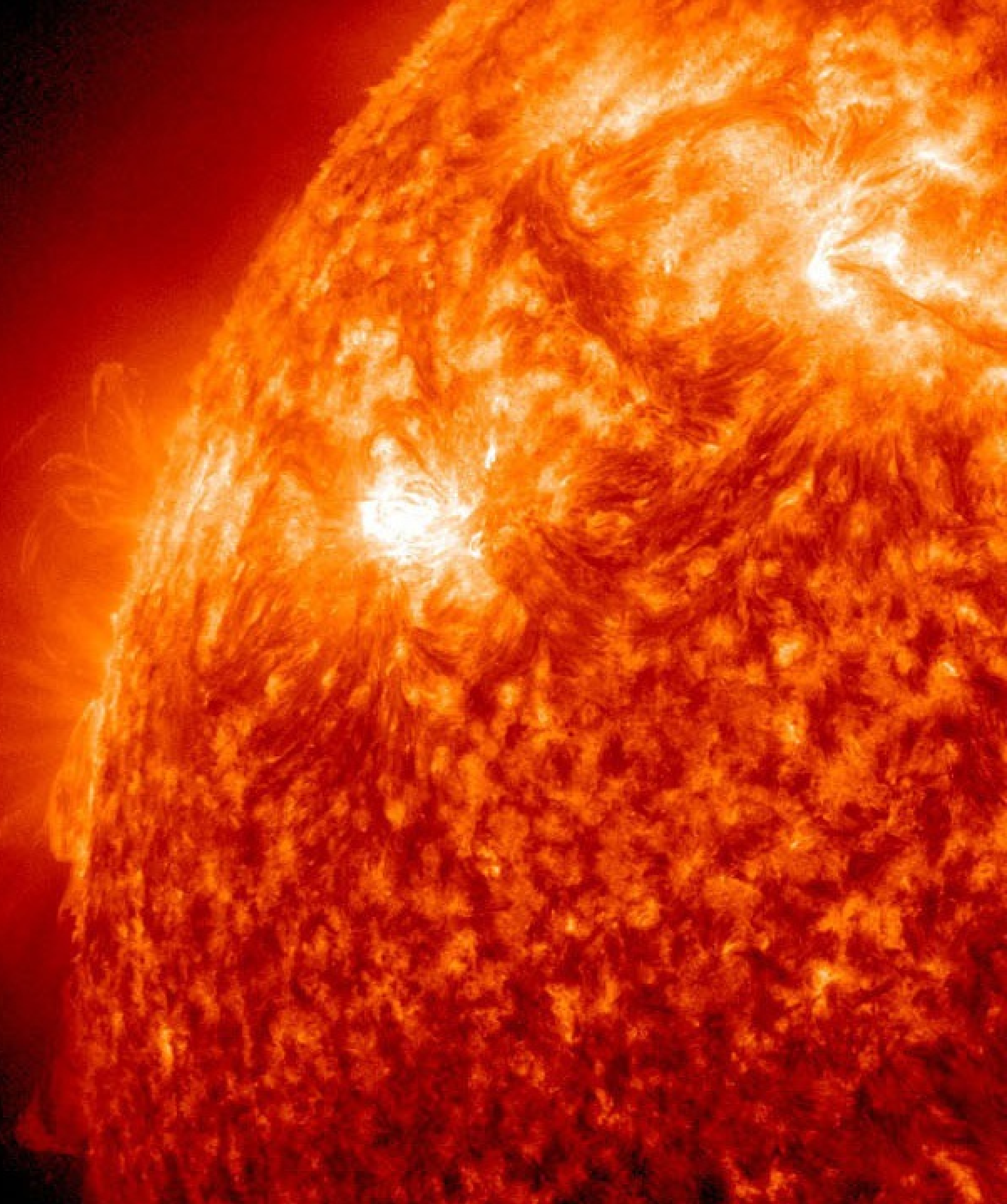
- Two 3rd shift periods (overnight in China)
- Executed vertical controllability experiments
- Enables US to use entire third shift (2016)

General Atomics Remote Control Room supports 3rd shift operation of EAST by US scientists

ITER construction site

ITER construction site

Thank you



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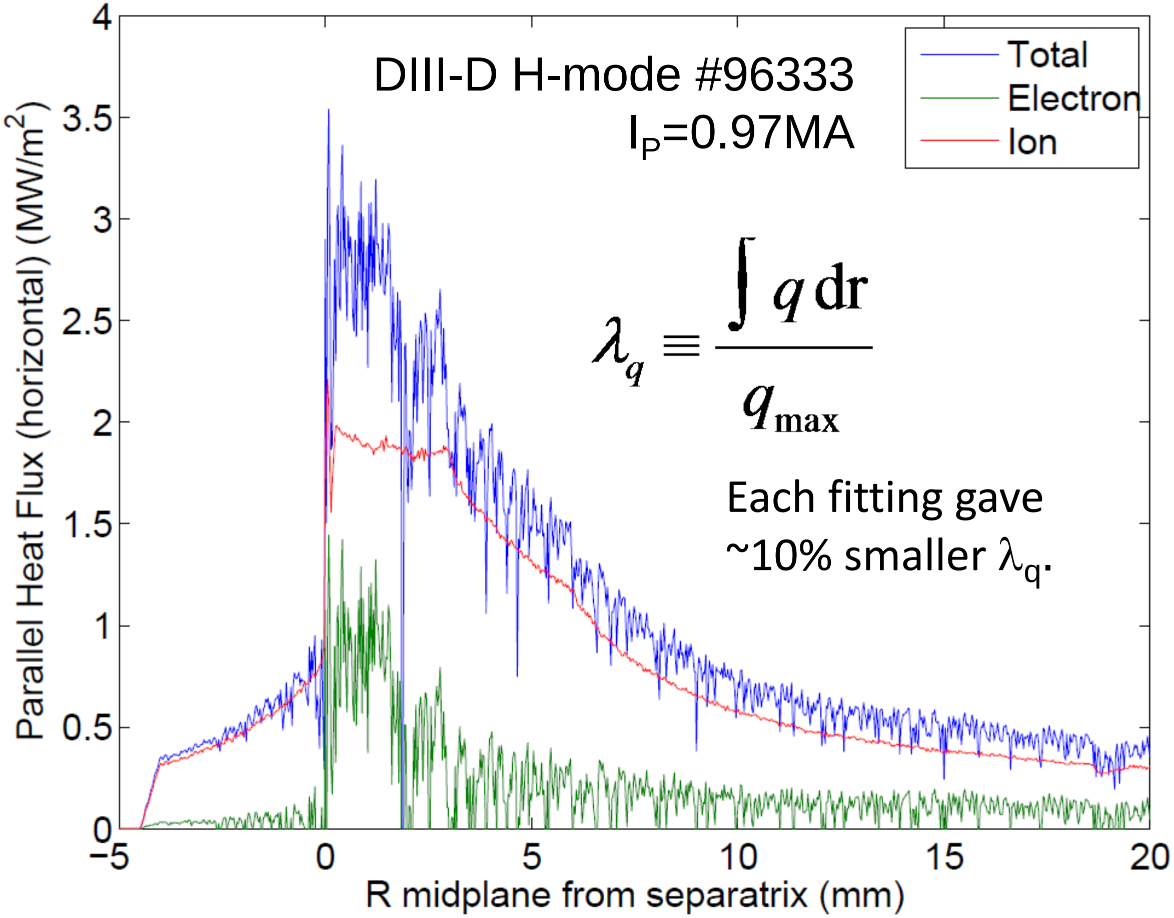
λ_q is dominated by ions in this DIII-D like edge plasma

$K_e < K_i$ in scrape-off, and ions (electrons) gain (lose) kinetic energy in the pre-sheath



$$\lambda_q \equiv \frac{\int q\,dr}{q_{\max}}$$

Each fitting gave ~10% smaller λ_q.

λ_q =5.1 mm at I_P=0.97MA

Enhancement by neutral particles is only ~10%

λ_q is closer to ion orbit spreading width than the radial blob size (≳1cm)

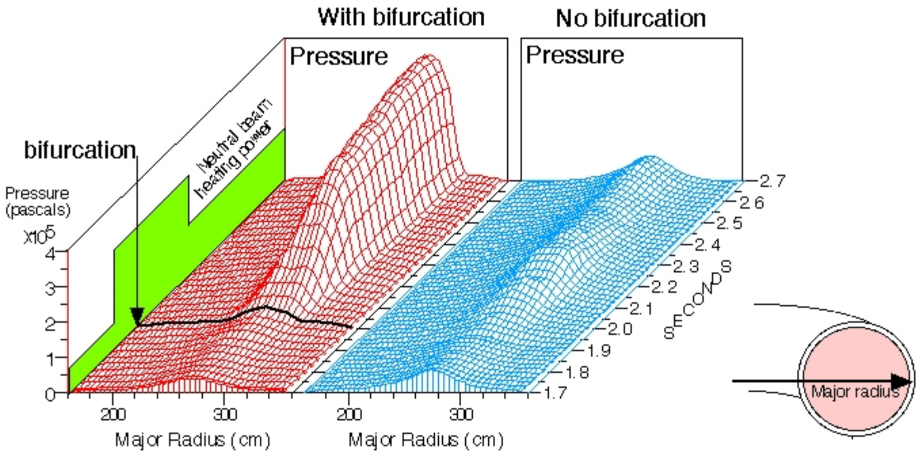
Heat-load spreading by **blobs** (represented by λ_{qe} ~2mm in the figure) is masked by the ion orbital spreading.

Transport barrier studies: exciting dynamics in the plasma drive important dynamics in the community

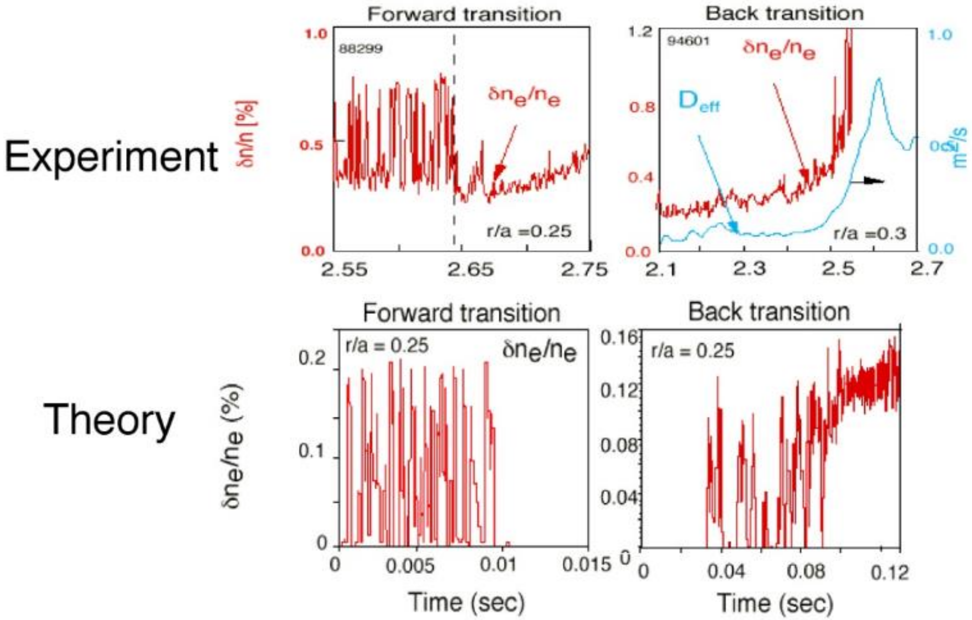
An exciting period scientifically and with respect to the community. The theoretical minimum in core transport can be realized

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

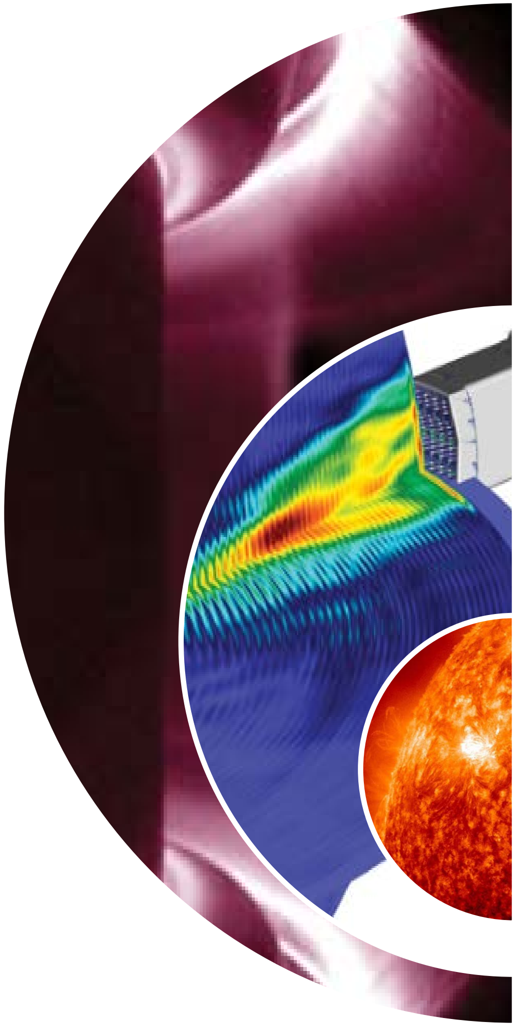
Institutional cross talk/stimulation/competition was vibrant



Density turbulence & confinement



U.S. Burning Plasma Science priorities:



Foundations

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

Long Pulse

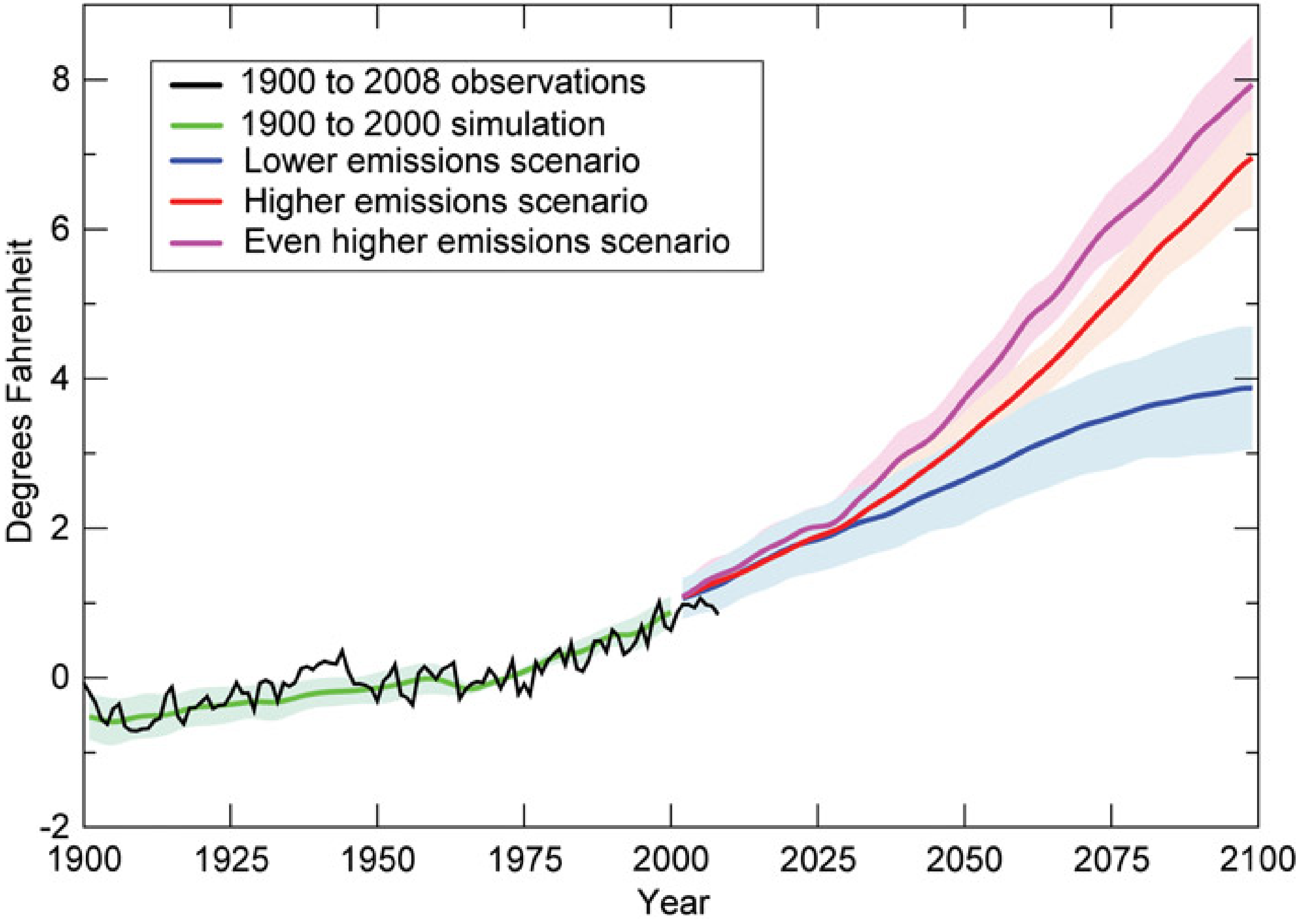
Building on U.S. capabilities furthered by international partnership

High Power

ITER is the keystone

This is an age of transformation: consequences are predictable

Global Average Temperature



http://www.epa.gov/climatechange/science/future.html

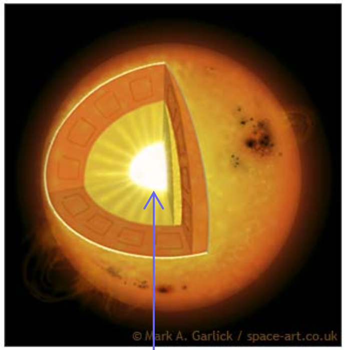
ITER can be a vehicle for transforming international cooperation

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

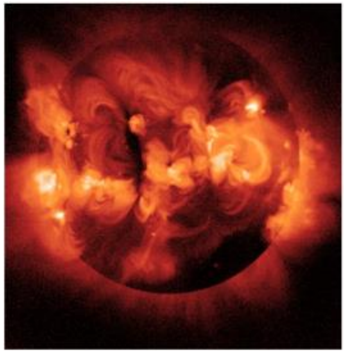
The science of fusion and plasmas extends from the laboratory to the stars and beyond

Sun: interior…

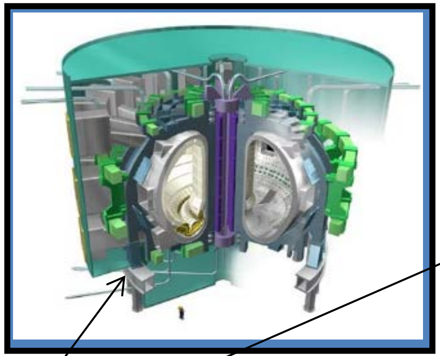


© Mark A. Garlick / space-art.co.uk

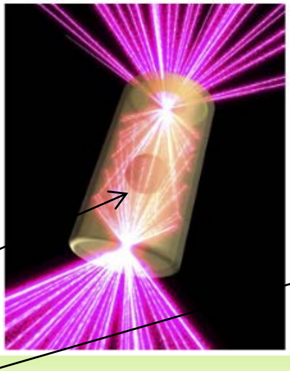
and in x-rays



ITER



NIF hohlraum

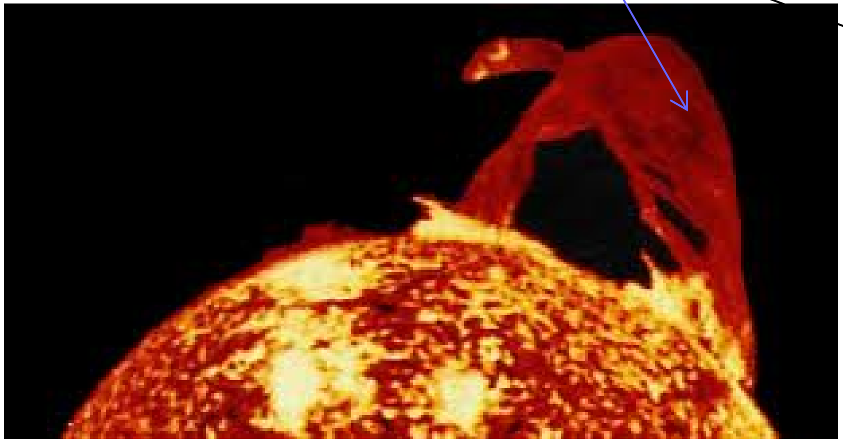


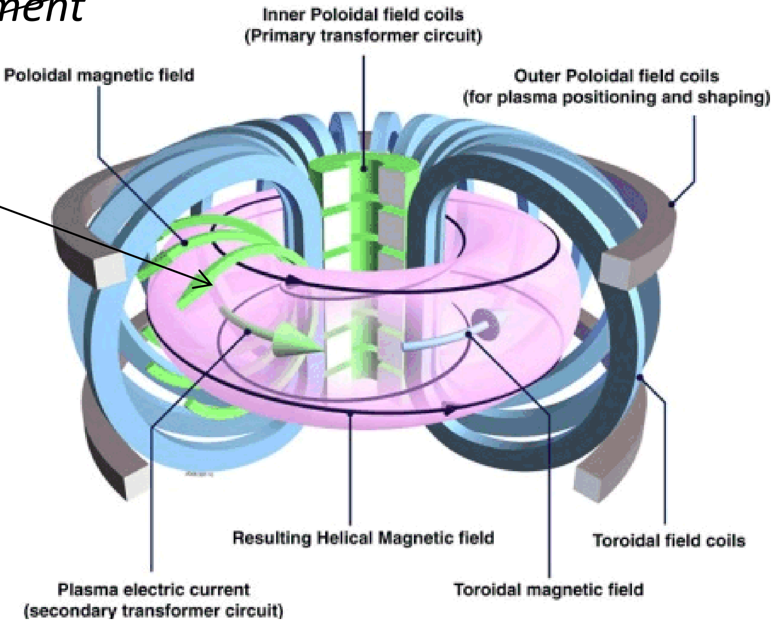
aurora

gravitational confinement

inertial confinement

magnetic confinement





*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

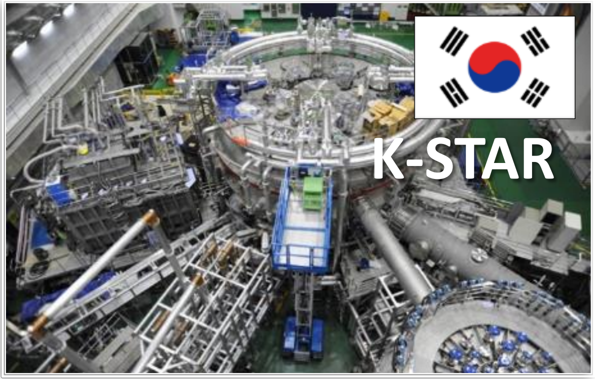
High Power

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



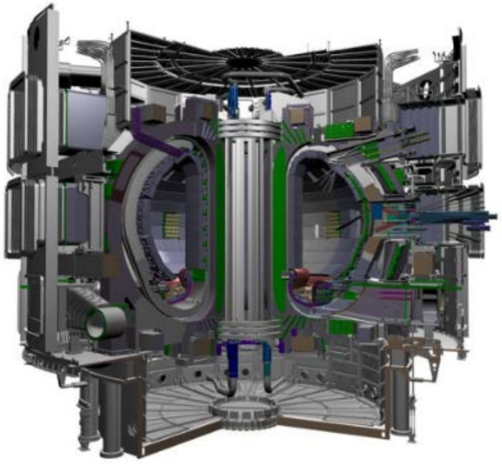
Burning Plasma Science in the U.S.:

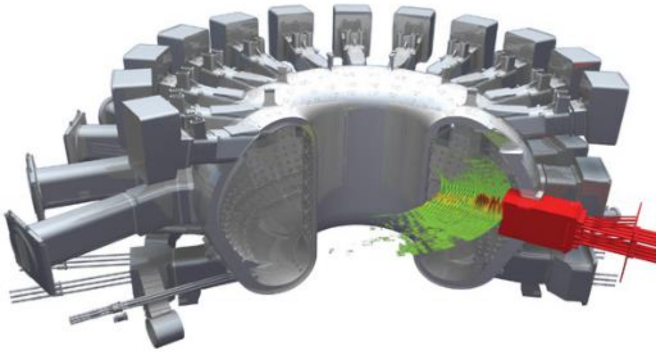
High Power

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
china eu india japan korea russia usa

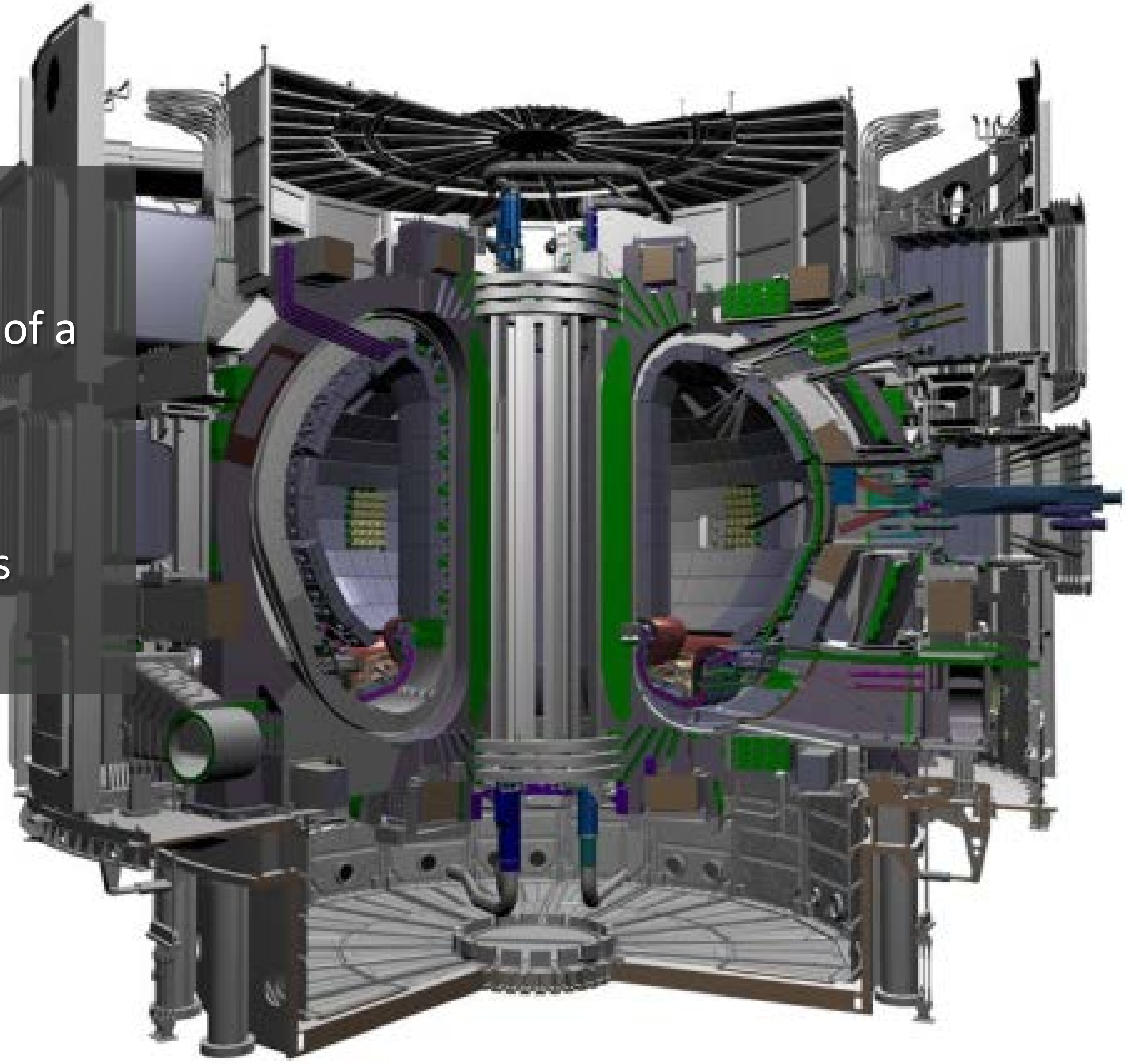




High power burning plasma science is essential for establishing fusion's science basis and thus its credibility

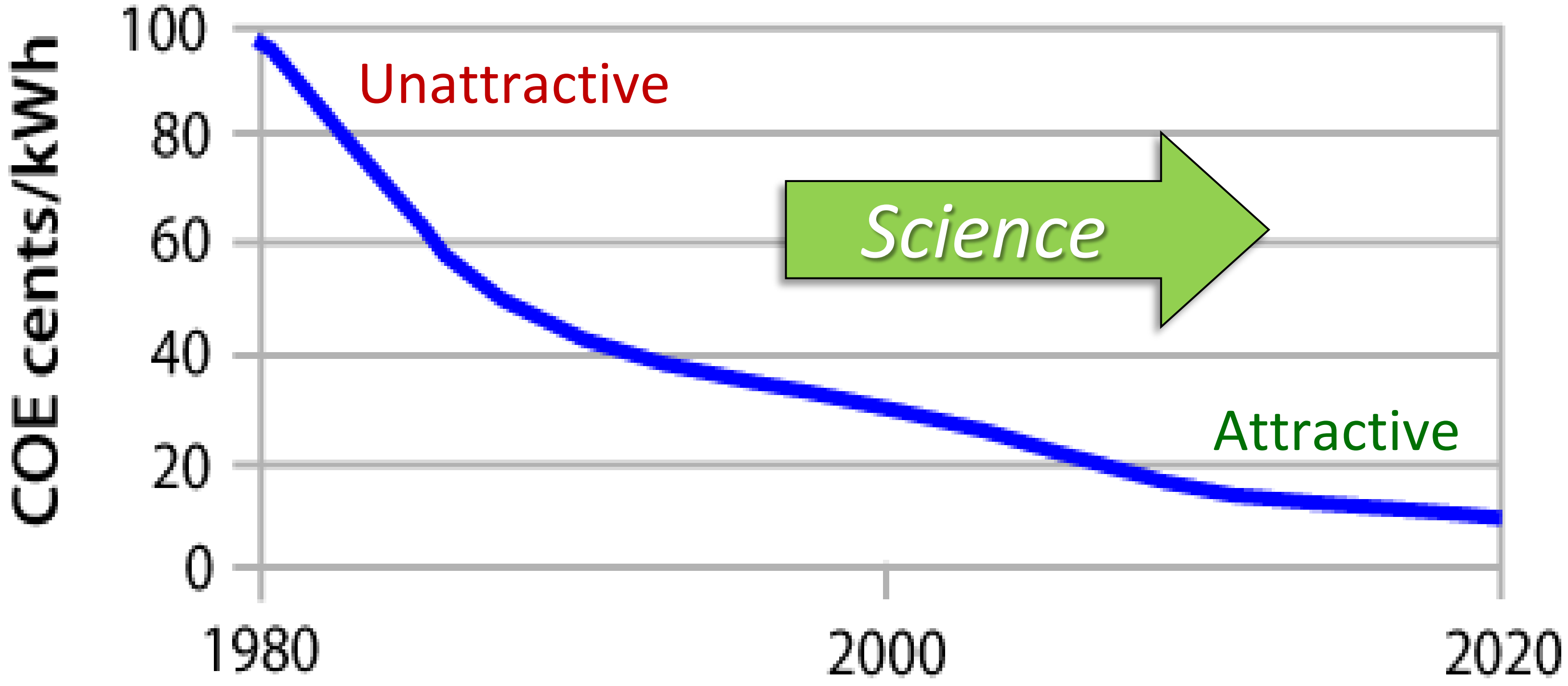
ITER:

The fundamental science of a burning plasma. ITER will establish the science of robustly and attractively controlling fusion plasmas that heat themselves



This is an age of transformation: ***energy science increases options***

Photovoltaic Cost of Energy



http://www1.eere.energy.gov/tribalenergy/guide/costs_solar_photovoltaics.html

This is an age of transformation:
science improves performance

10% improvement in fuel efficiency has a powerful effect

2.5 million tons

annual C02 reduction

2.8 billion

annual diesel fuel savings

$8.3 billion

annual fuel cost savings

NAVISTAR®

U.S. DEPARTMENT OF ENERGY

Office of Science

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:

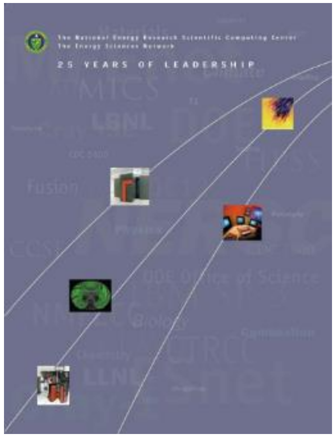
- **1974:** AEC establishes the Controlled Thermonuclear Research (**CTR**) center at LLNL (first computer: CDC 6600)
- **1976**: CTR is renamed the *National Magnetic Fusion Energy Computer Center* or **NMFECC** (first computers: CDC 7600; Cray-1)
    - *Access to remote facilities is provided via the 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*

> *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.*

NATIONAL MFE COMPUTER CENTER

1976: CDC 7600 at MFECC

NERSC



The National Energy Research Scientific Computing Center
The Energy Sciences Network

25 YEARS OF LEADERSHIP

2013: Edison, CRAY XC30

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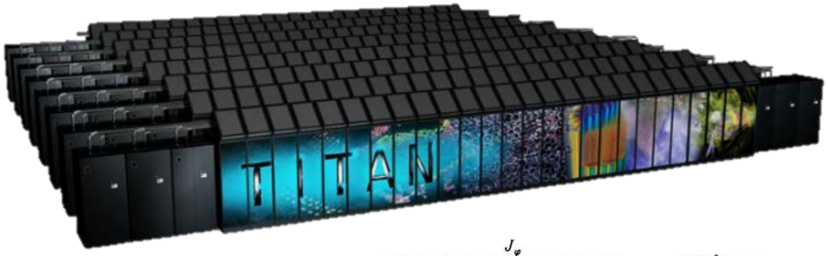
* *Now known as the National Energy Research Scientific Computing Center*

Burning Plasma Foundations: SciDAC

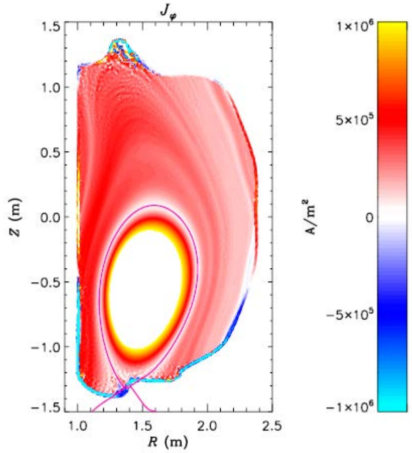


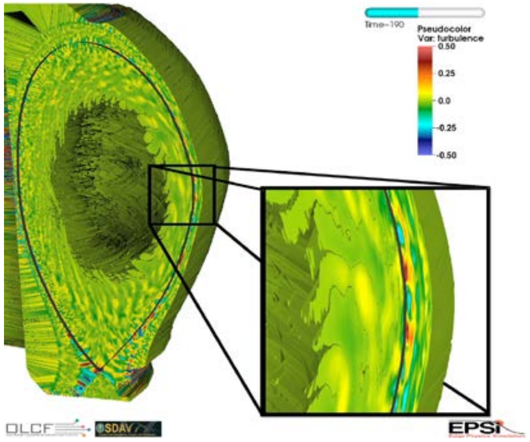
The FES SciDAC program:

- 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

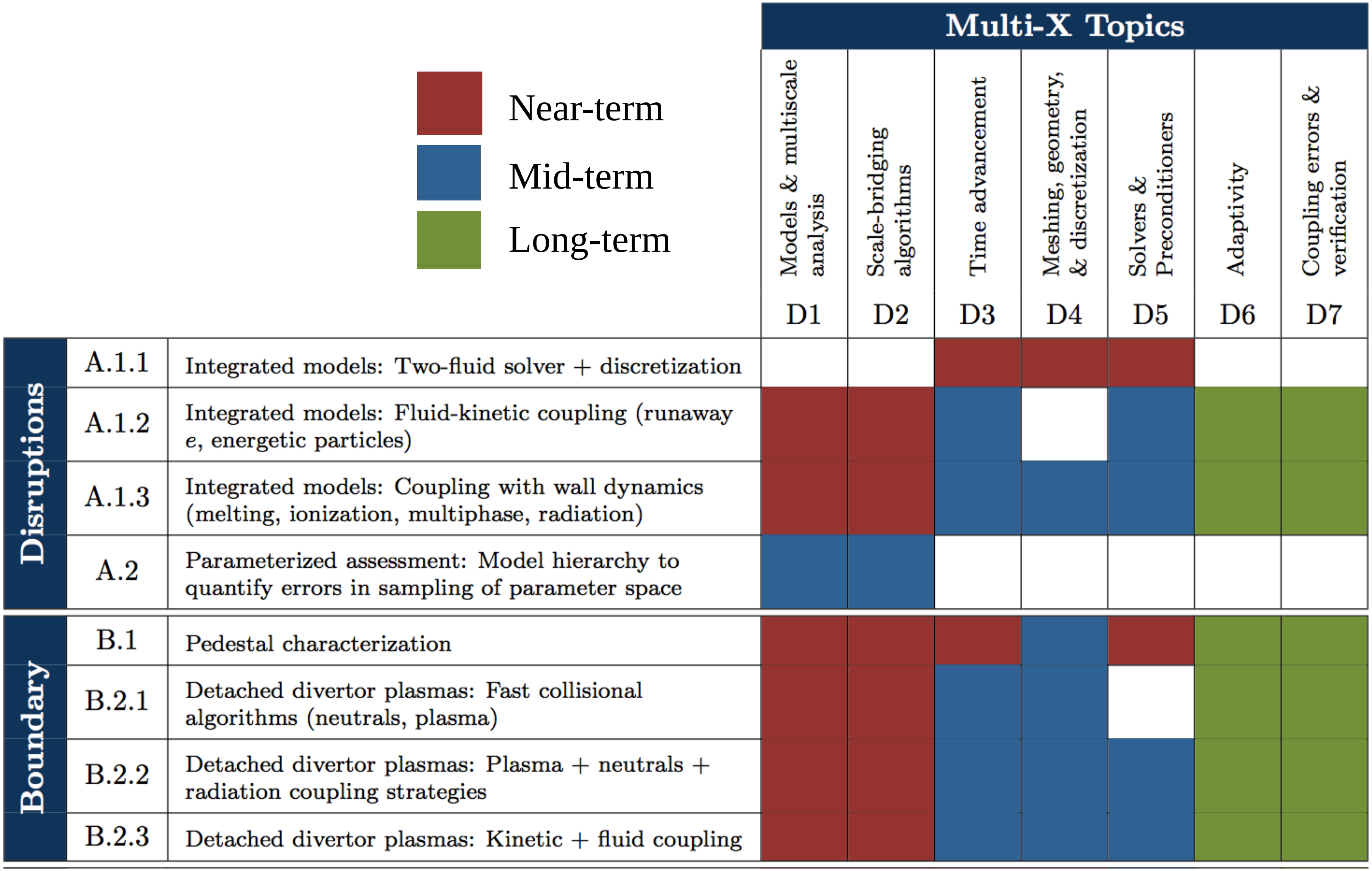
- Addresses grand challenges in burning plasma science and materials science

- Highly collaborative program, leverages strengths of FES and ASCR





Prioritization of multi-x topics in physics areas



🟥 Near-term

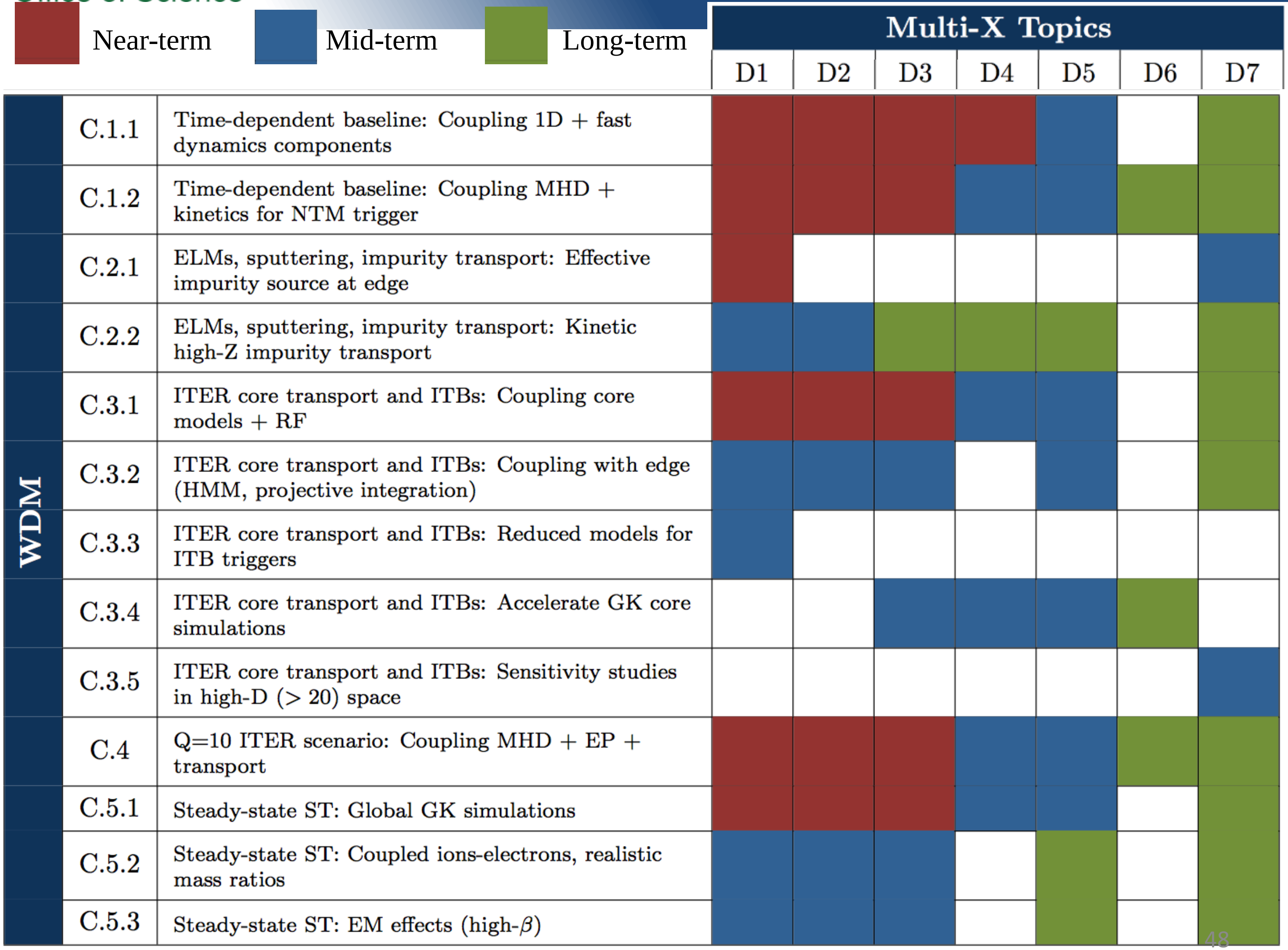
🟦 Mid-term

🟩 Long-term

			Multi-X Topics						
			Models & multiscale analysis D1	Scale-bridging algorithms D2	Time advancement D3	Meshing, geometry, & discretization D4	Solvers & Preconditioners D5	Adaptivity D6	Coupling errors & verification D7
Disruptions	A.1.1	Integrated models: Two-fluid solver + discretization			🟥	🟥	🟥		
	A.1.2	Integrated models: Fluid-kinetic coupling (runaway *e*, energetic particles)	🟥	🟥	🟦		🟦	🟩	🟩
	A.1.3	Integrated models: Coupling with wall dynamics (melting, ionization, multiphase, radiation)	🟥	🟥	🟦	🟦	🟦	🟩	🟩
	A.2	Parameterized assessment: Model hierarchy to quantify errors in sampling of parameter space	🟦	🟦					
Boundary	B.1	Pedestal characterization	🟥	🟥	🟥	🟦	🟥	🟩	🟩
	B.2.1	Detached divertor plasmas: Fast collisional algorithms (neutrals, plasma)	🟥	🟥	🟦	🟦		🟩	🟩
	B.2.2	Detached divertor plasmas: Plasma + neutrals + radiation coupling strategies	🟥	🟥	🟦	🟦	🟦	🟩	🟩
	B.2.3	Detached divertor plasmas: Kinetic + fluid coupling	🟥	🟥	🟦	🟦	🟦	🟩	🟩

Prioritization of multi-x topics in physics areas

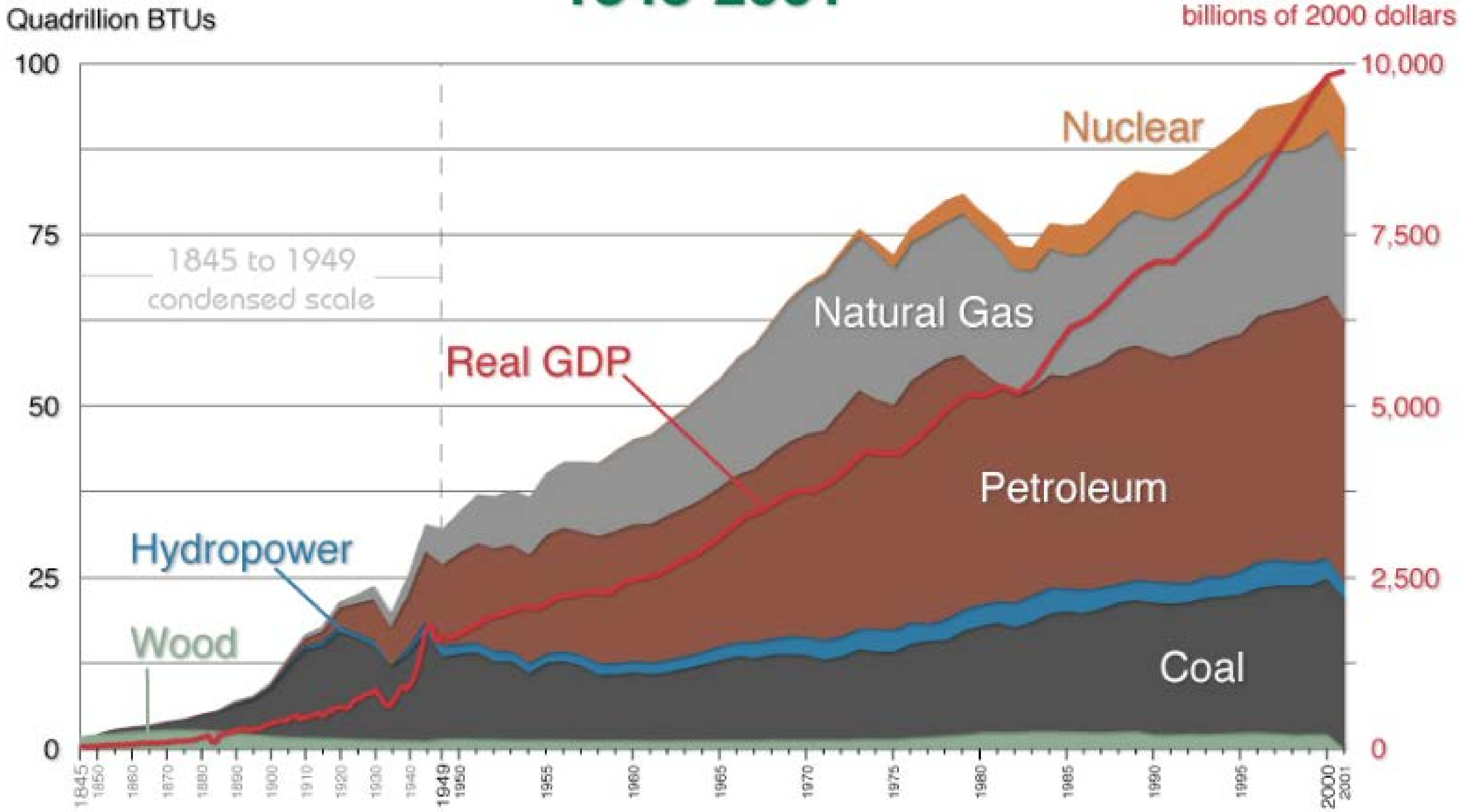
🟥 Near-term 🟦 Mid-term 🟩 Long-term



			Multi-X Topics						
			D1	D2	D3	D4	D5	D6	D7
WDM	C.1.1	Time-dependent baseline: Coupling 1D + fast dynamics components	🟥	🟥	🟥	🟥	🟦		🟩
	C.1.2	Time-dependent baseline: Coupling MHD + kinetics for NTM trigger	🟥	🟥	🟥	🟦	🟦	🟩	🟩
	C.2.1	ELMs, sputtering, impurity transport: Effective impurity source at edge	🟥						🟦
	C.2.2	ELMs, sputtering, impurity transport: Kinetic high-Z impurity transport	🟦	🟦	🟩	🟩	🟩		🟩
	C.3.1	ITER core transport and ITBs: Coupling core models + RF	🟥	🟥	🟥	🟦	🟦		🟩
	C.3.2	ITER core transport and ITBs: Coupling with edge (HMM, projective integration)	🟦	🟦	🟦		🟦		🟩
	C.3.3	ITER core transport and ITBs: Reduced models for ITB triggers	🟦						
	C.3.4	ITER core transport and ITBs: Accelerate GK core simulations			🟦	🟦	🟦	🟩	
	C.3.5	ITER core transport and ITBs: Sensitivity studies in high-D (>20) space							🟦
	C.4	Q=10 ITER scenario: Coupling MHD + EP + transport	🟥	🟥	🟥	🟦	🟦	🟩	🟩
	C.5.1	Steady-state ST: Global GK simulations	🟥	🟥	🟥	🟦	🟦		🟩
	C.5.2	Steady-state ST: Coupled ions-electrons, realistic mass ratios	🟦	🟦	🟦		🟩		🟩
	C.5.3	Steady-state ST: EM effects (high-β)	🟦	🟦	🟦		🟩		🟩

This is an age of transformation:
energy transforms economies

US Consumption by Source v. Real GDP 1845-2001



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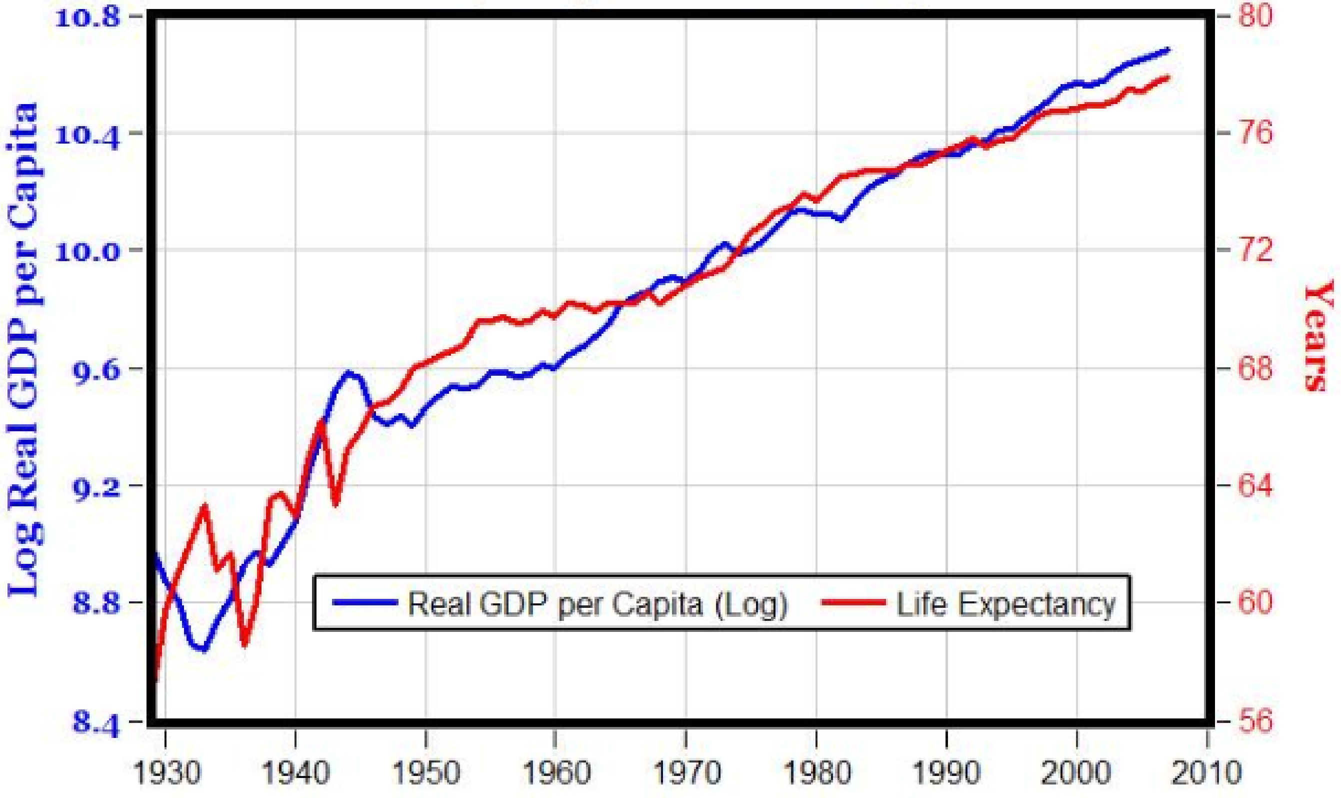
Sources: USDOE, EIA, Annual Energy Review 2001, Table F1a, F1b; and Real GDP data: Louis D. Johnston and Samuel H. Williamson, "The Annual Real and Nominal GDP for the United States,1790-Present" Economic History Services, Oct. 2005, http://www.eh.net/hmit/gdp

This is an age of transformation: ***energy transforms life quality***



U.S. Life Expectancy vs. Real GDP per Capita (log) 1929 to 2007

U.S. DEPARTMENT OF ENERGY

Office of Science

This is an age of transformation: ***global impacts are measurable***

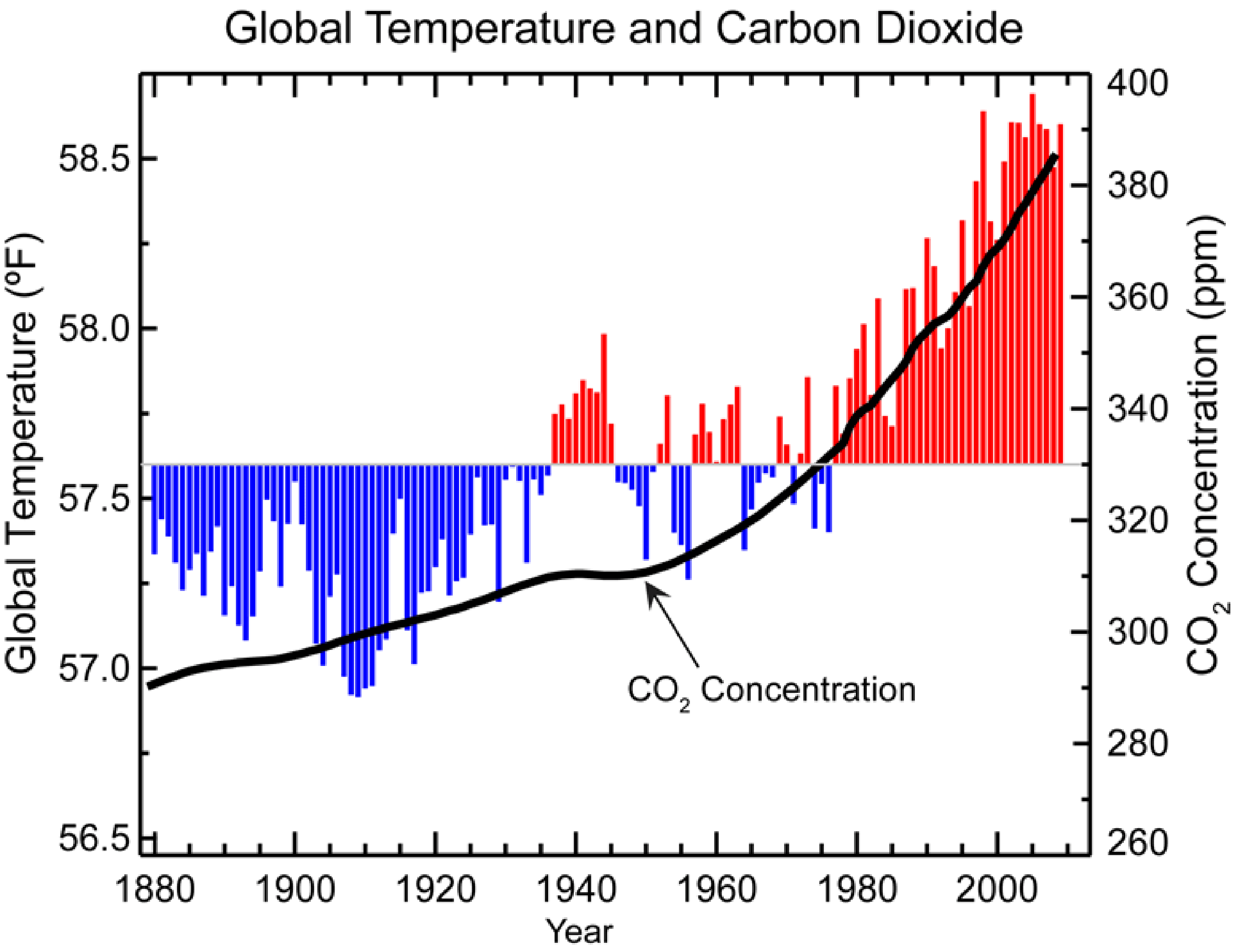


Figure from NOAA National Climate Data Center http://www1.ncdc.noaa.gov/pub/data/cmb/images/indicators/

Foundations: Fusion theory and computation are positioned to capture a computational revolution

The MFE **Theory** program:

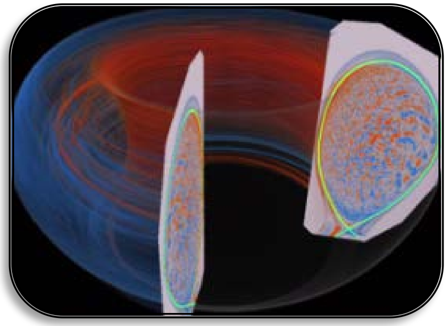
Focuses on fundamental plasma science of magnetic confinement with emphasis on burning plasma science

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:

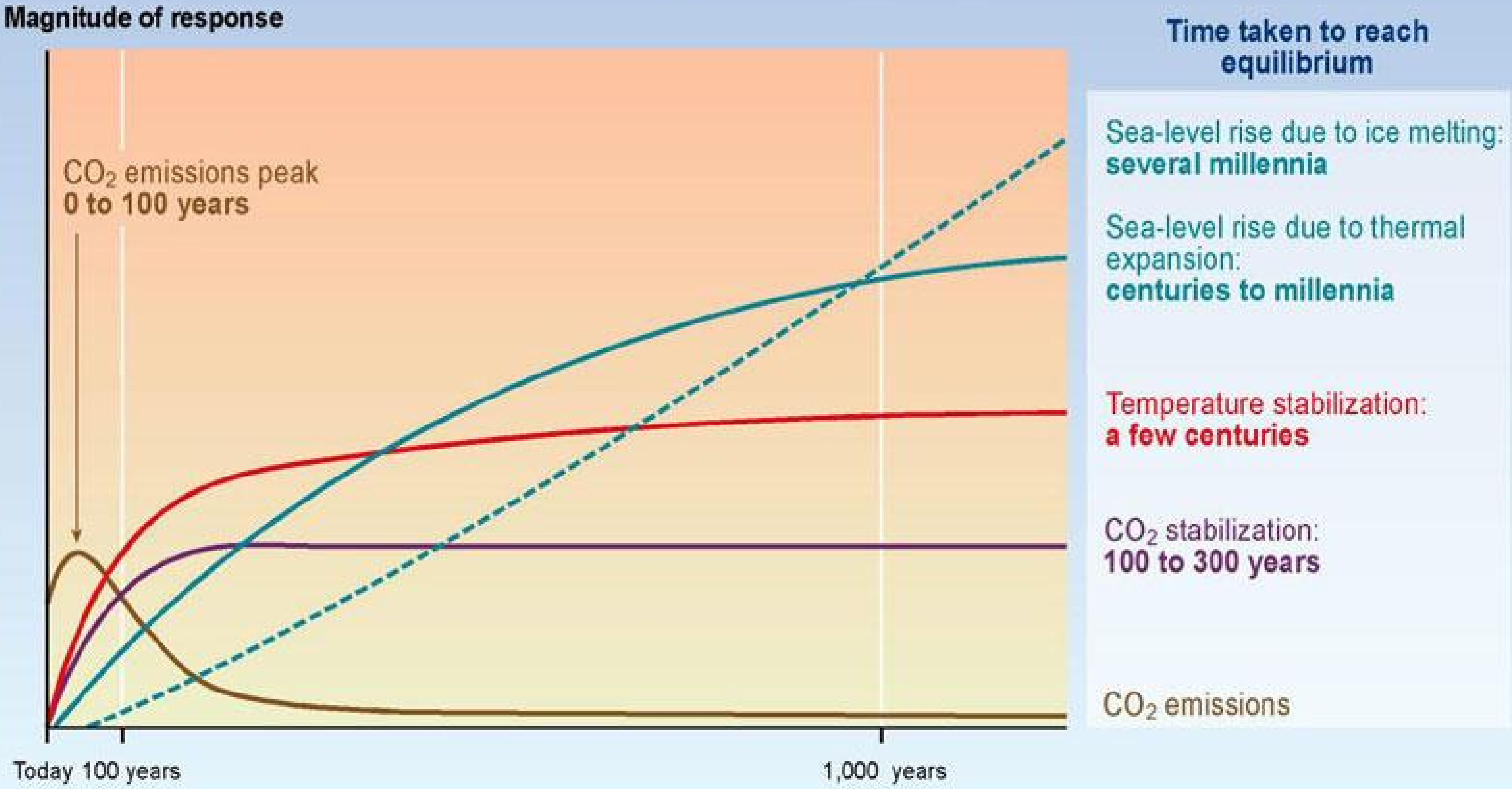
- The FES Scientific Discovery through Advanced Computing (SciDAC) program advances scientific discovery in fusion plasma science by exploiting SC leadership class computing resources and associated advances in computational science
- Addresses grand challenges in burning plasma science and materials science
- Highly collaborative program, leverages strengths of FES and ASCR



Supports: 60 graduate students, 29 postdocs

This is an age of transformation: ***we now understand the scale of the solution to climate change that is required***

CO_2 concentration, temperature, and sea level continue to rise long after emissions are reduced



INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE