



# *On the FES Vision*

*Presented by:*

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For Fusion Energy Sciences  
U.S. Department of Energy*

*For the International Symposium on Fusion Nuclear Technology  
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## ***Our immediate challenge is about establishing scientific credibility***

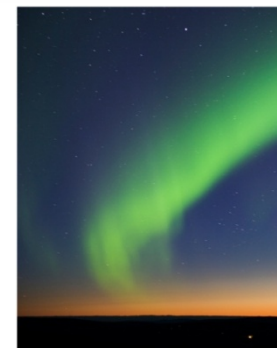
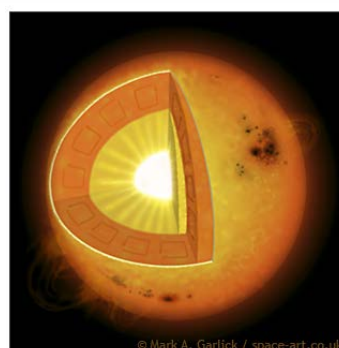
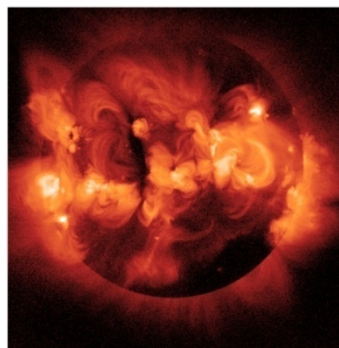
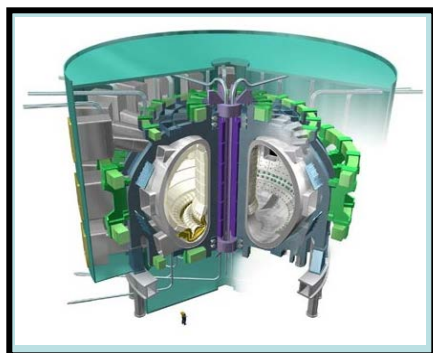
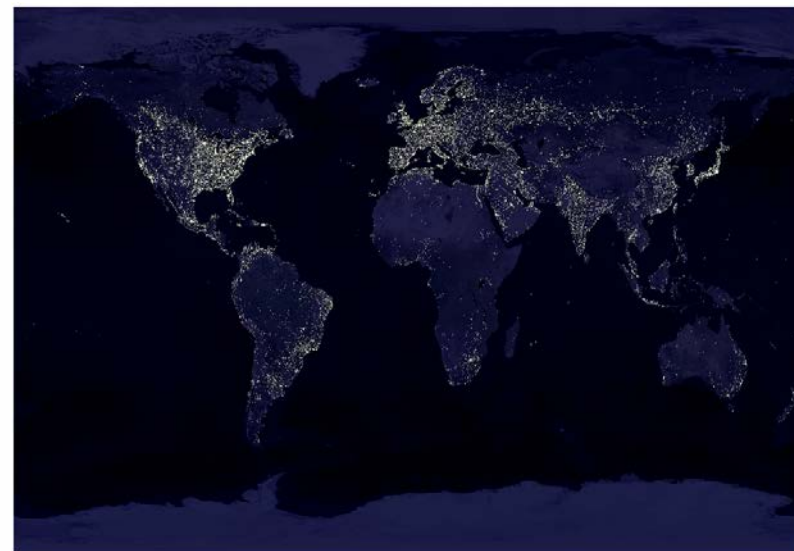
- Consistent with the mandate of the Office of Science.
- Many elements we need to pursue, but have not pursued yet, are deeply scientific opportunities.

*The times call for moving smartly, and bringing forward energy in our lexicon. Establishing scientific credibility is fully consistent with pursuing the energy goal.*



# *The science at the heart of fusion energy is far-reaching and is poised for a transformation*

- *Stewarding plasma science as a broad enterprise is fully consistent with the leading ambition of powering the planet*



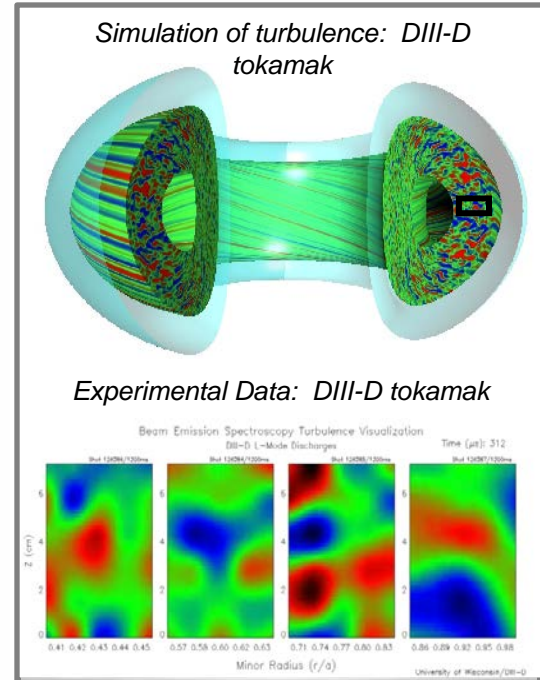
**The U.S. program in the fusion sciences is strongly oriented towards detailed physics understanding and developing predictive capability**

**Burning plasma science**

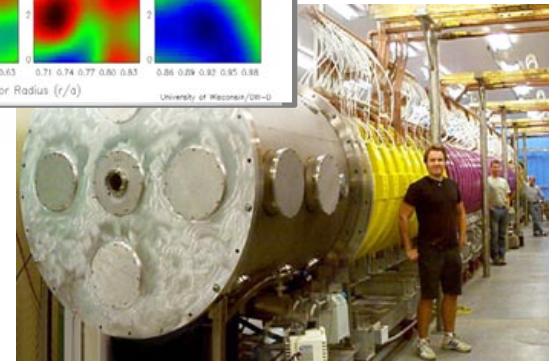
**Experimental tests**

**Theory**

**Simulation and prediction**



*LAPD, a user facility at UCLA for basic plasma science*





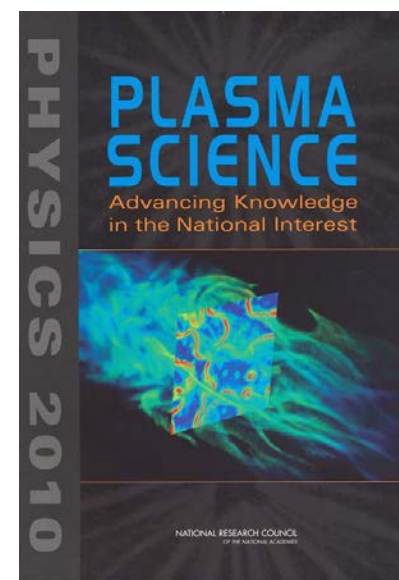
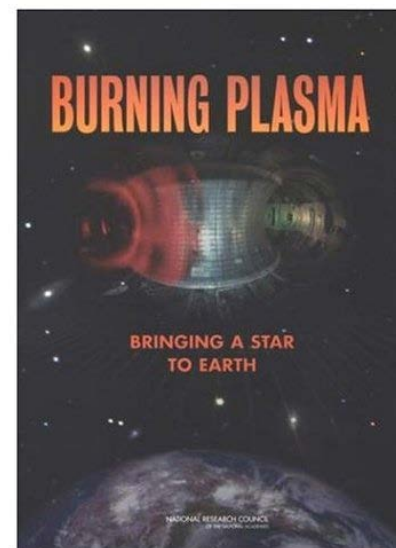
*... but we need to develop our path forward  
in a most challenging environment*

- The U.S. budget challenge places enormous pressure on all of our scientific endeavors. There are large, not completely known moving parts that may collide as U.S. science budgets are developed.
  - ➔ very tough competition between science and energy with other national interests
  - ➔ very tough competition within the Office of Science
- The scrutiny on fusion's budgets will increase sharply as the program becomes more conspicuous and ambitious, especially in such times
  - ➔ the quality of fusion science has to be of the highest order in order to compete successfully

# Choices are driven by values

- This budget cycle may drive hard choices. The outcome is not known
- Values and priorities that govern FES's input into the budget process, and our actions in the Office, include
  - **Advance burning plasma science:** Essential for establishing fusion's credibility. ITER's success as a project and meeting our commitments. Complement ITER with science from our facilities, computation, and new opportunities internationally.
  - **Position the U.S.** to assert leadership in gaps that now exist worldwide
  - **Steward the plasma sciences:** Pursue our obligation regarding stewarding a broad class of plasma science

**Overarching themes:** utilize leverage between offices and agencies, and create opportunities to execute the best fusion and plasma science in the world for our students and researchers

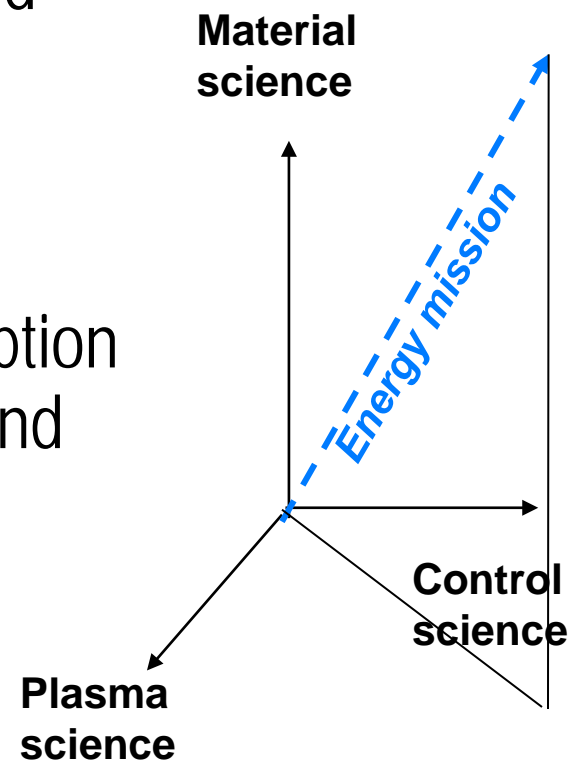


# *Much of the science we need to develop can be represented in a fairly simple scientific space*

Imagine our scientific credibility to be represented by a vector

There are many “frames of reference” we could choose, but this seems fairly complete

Scientific credibility for fusion → forming a complete enough basis set to enable a description of the requirements for energy development and the accompanying risks





# **High level goal #1:** **Plasma dynamics and control**

*Plasma dynamics and control frames the science questions of both magnetic and inertial fusion energy, industrial applications, and of nature*

- **Fusion**: understanding the dynamics and stability of the burning plasma state. Developing a robust control strategy
- **Non-fusion applications**: understanding the requirements and impact of being able to manipulate the distribution function of low temperature plasmas
- **Mysteries of nature**: understanding the physics of self-organization comprising phenomena such as plasma jets, dynamos, accretion disks, and supernova





## ***Regarding plasma dynamics and control in fusion...***

- *Plasma dynamics and control is our defining research area now, and we arguably are or are among world leaders in terms of detailed measurement of underlying processes, connection to theory, developing an integrated understanding, and demonstration of advanced scenarios in tokamaks. However,*

*At present world-wide investment and approach, it will not provide the validated predictive capability we need to take a confident step beyond ITER and its geometry*

*International commitment in plasma control is impressive and worth capturing. In fact, we will need to if we are to remain at the forefront*



## **High level goal #2:** **Materials in a fusion environment**

- **Plasma/surface interactions**: establishing boundary of a fusion plasma. Plasma facing surface survival, renewal: cracking, annealing. Fuel retention. Important for industrial, non-energy applications as well
- **Nuclear effects on materials and structures**, including the effects of  $> 100$  dpa on structure integrity, helium creation in situ, and time evolving properties
- **Harnessing fusion power** depends on the nuclear material science above and is extended to tritium breeding and extracting fusion power

*This requires the launching of a vigorous materials and nuclear science program that will be part of defining and constructing a fusion nuclear science facility, and will fill gaps en route to a DEMO.*



U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

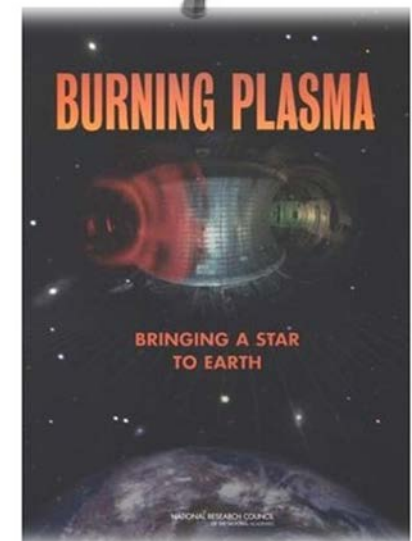
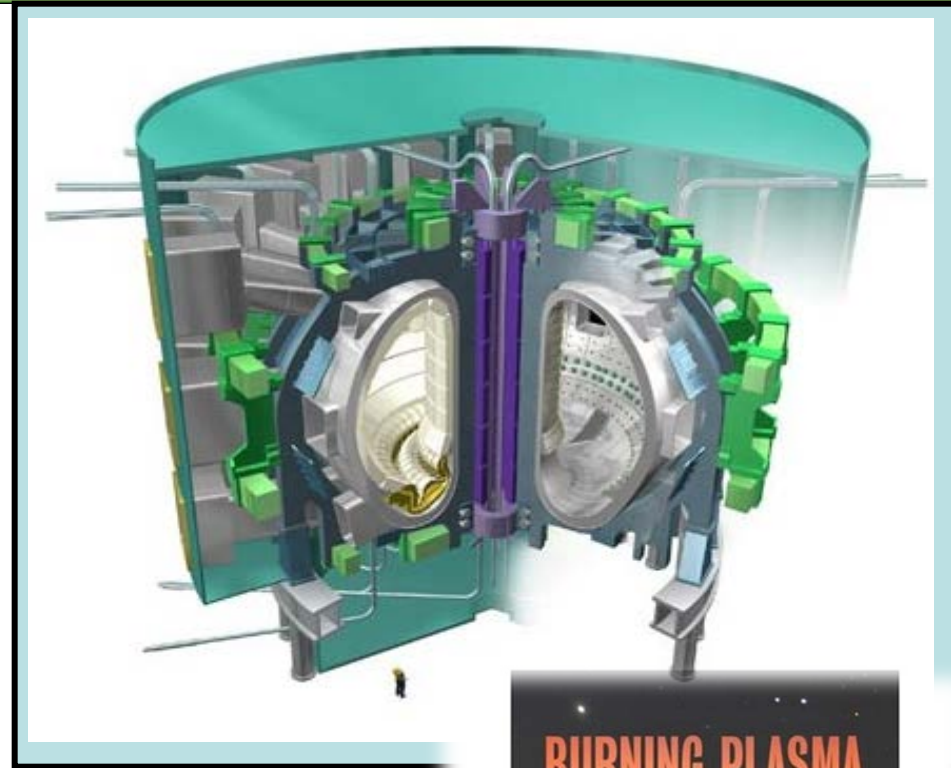
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*On ITER*



# *The National Academies underscores the urgency for a burning experiment for fusion, and ITER has been identified as the vehicle*

- The National Academies of Science concluded that a magnetically confined burning plasma experiment is the next step for fusion research, and that the world fusion community has established the scientific basis for taking this step
- The U.S. concluded that ITER is the most scientifically and technically compelling step to take (Snowmass 2002 Study)

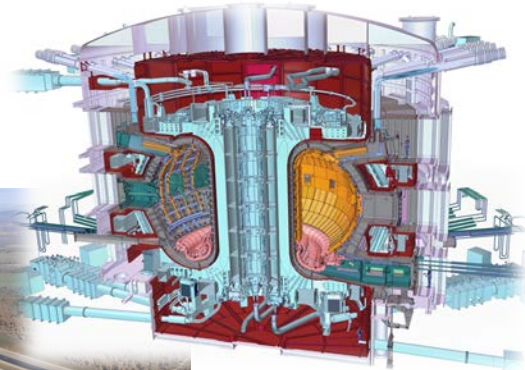


# There has been important progress in constructing ITER



*Poloidal winding building construction*

*The ITER Device*



*Site construction is underway*



*New project leadership*



*Director General Motojima*



*Rich Hawryluk (U.S., from PPPL); new Deputy Director General for Administration*



*Rem Haange (Netherlands), new Deputy Director General for ITER Construction*



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Science

*Work advances on schedule on the upper floors of the future ITER Headquarters building in July 2011.*





At 5:00 a.m. on Tuesday, 9 August, operations began to create the lower basemat of the Tokamak Complex



Steel reinforcement bars—each one weighing nearly 100 kilos—are built up to 1.5 meters on the floor of the Seismic Pit. In the distance, the future ITER Headquarters buildings rises above the platform. (August 2011).



Sitting atop the lower basemat, 500 of these 1.8 metre concrete columns will support the seismic pads. These, in turn, will support the upper basemat of the Tokamak Complex—the actual "floor" of the installation (August 2011).



Work advances rapidly on the Poloidal Field Coils Winding Facility in August 2011: the cladding is nearly finished, the three-floor office building is in place.



*Research beyond the last  
closed flux surface*





## ***On the scope of this area...***

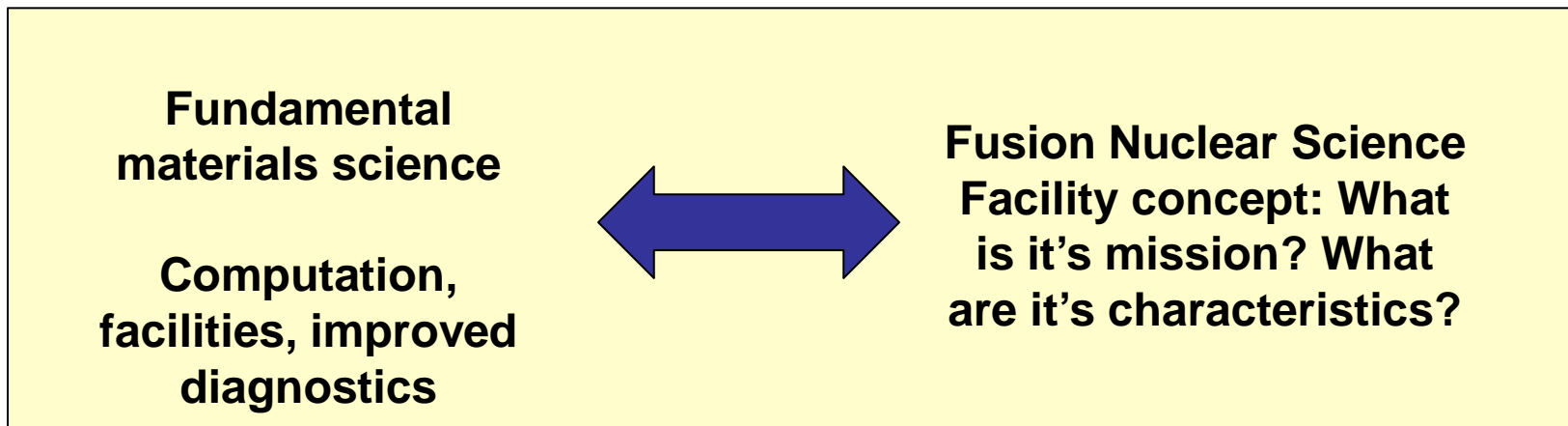
- In discussions with Office of Science leadership, I have defined a major leading challenge as being quite broad, but I think you may agree with my intent: *building on Greenwald and the MFE ReNeW, a leading challenge for fusion, and an opportunity for the U.S., pertains to understanding and controlling*
  - the processes beyond the last closed flux surface, including the open field line plasma physics, the plasma/material science governing the plasma-surface interactions, and how these processes couple to define the close flux surface boundary, and
  - the nuclear science related to structural evolution, integrity, and harnessing fusion power
  - the coupling of these non-nuclear and nuclear elements
- The materials science per se represents the most urgent need, but the open field line science/divertor issues are quite urgent
- Overall, this represents a major, leading challenge for the field, an opportunity for U.S. leadership, and a significant responsibility



***The materials challenge is enormous, both non-nuclear and nuclear, and the program needs to be carefully thought out***

We need to construct a sensible program: deeply scientific as well as directed

- ➔ What does a sensible program look like that advances materials science efficiently and effectively, towards a facility to investigate volume neutron effects on structures and materials and for harnessing fusion power?



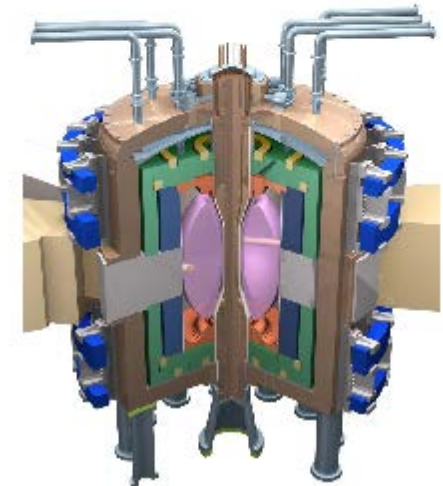
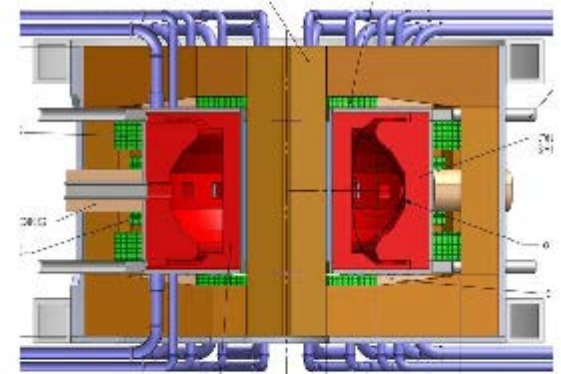
**“A tightening spiral of research and concept definition”**

# ***Towards a fusion nuclear science facility (FNSF)***

**Objective:** Develop experimental data base for all fusion reactor internals and, in parallel with ITER, provide the basis for DEMO.

- Our programs must be smartly directed to inform critical decisions:
  - Determine the FNSF Geometry.
  - Determine the materials the FNSF will be made from and should test
- International Collaborations with Asian tokamaks will support physics data base for non-nuclear plasma-wall science and operational scenarios.
- We need to sharpen our understanding of the metrics we must meet in order to justifiably advance into this class of research.

**FDF: standard aspect ratio**



**CTF: lower aspect ratio**

# ***There is a FESAC charge on materials research being addressed***

“What areas of research in materials science and technology provide compelling opportunities for U.S. researchers in the near term and in the ITER era? Please focus on research needed to fill gaps in order to create the basis for a DEMO, and specify technical requirements in greater detail than provided in the MFE ReNeW (Research Needs Workshop) report. Also, your assessment of the risks associated with research paths with different degrees of experimental study vs. computation as a proxy to experiment will be of value.”

Consider near- and long-term (~0-5; 5-15; 15+ years); what can be done with existing facilities, new facilities, and emergent international facilities

Experiment & the role of computation: Identify 2-3 paths with varying emphases on massively parallel computing – what are the risks associated with each path?

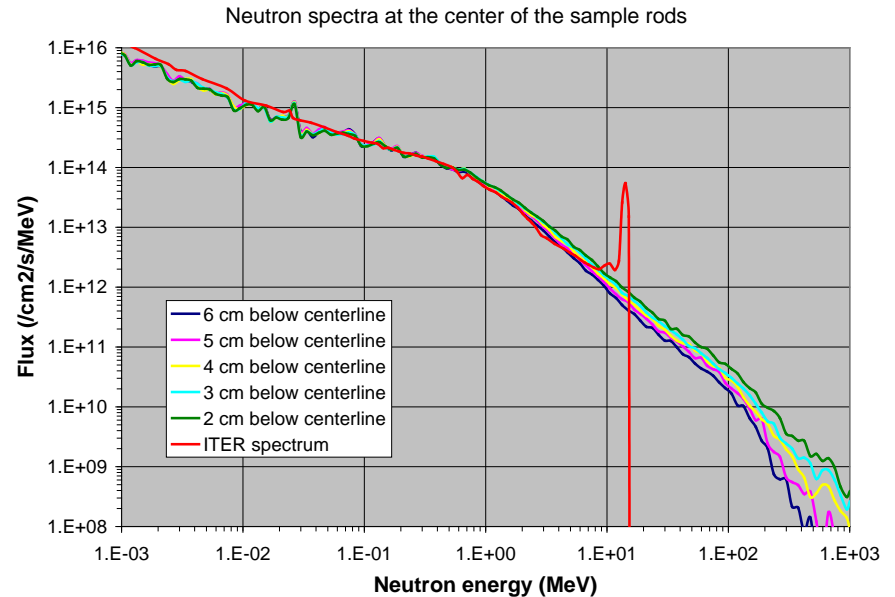
Materials = nuclear (dpa's); non-nuclear (pmi); differential and integrated; harnessing fusion power

# *A spallation source may provide a cost-effective entrance to fusion nuclear science*

Great scientific question of practical import: Can massively parallel computing build a credible bridge regarding the materials effects of a pure fusion vs spallation neutron spectrum?



**Location for sample tubes**



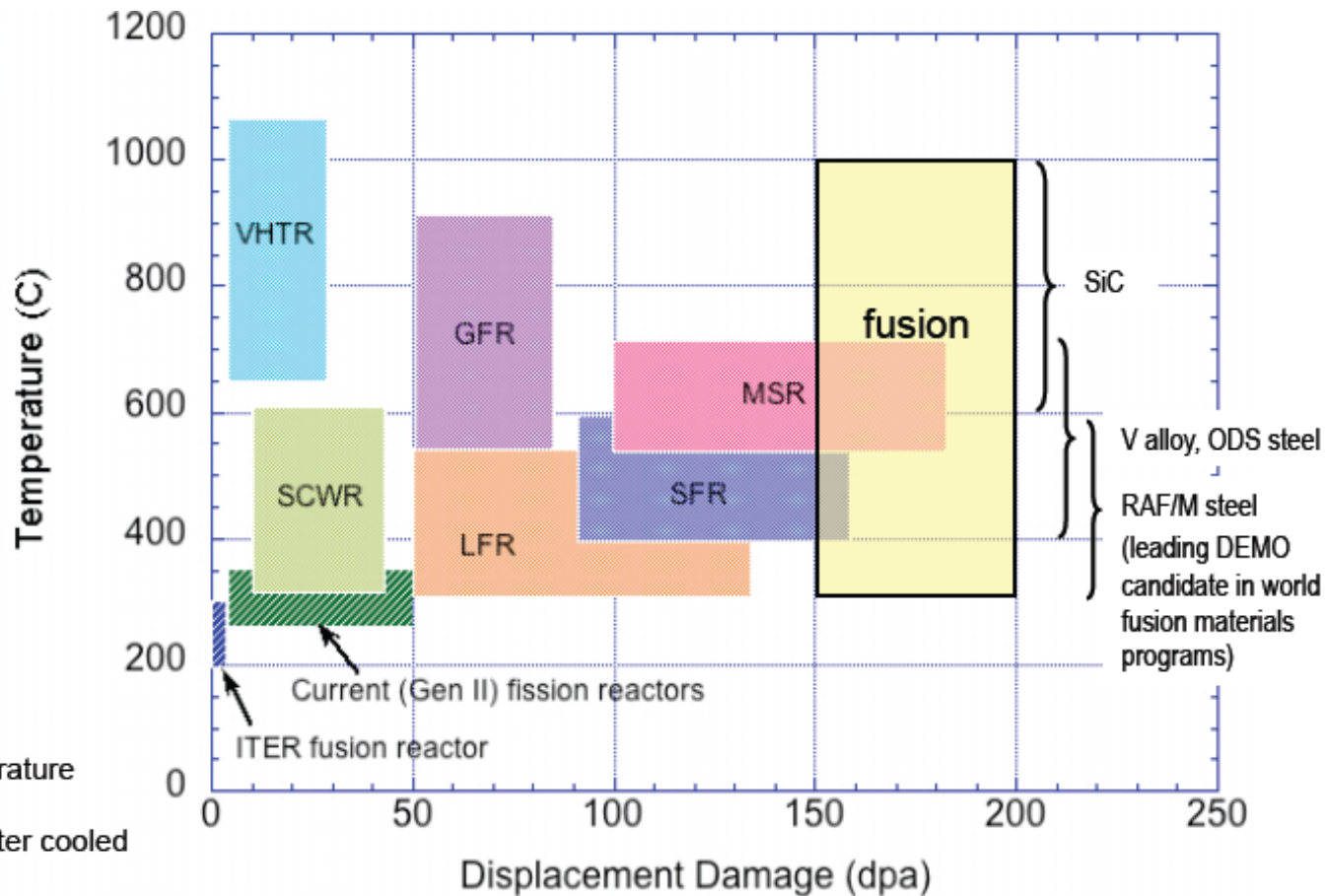
**Modified target regions**





# Opportunities for leverage: good scientific sense, good politics

S.J. Zinkle, 2007



- VHTR: Very High temperature reactor
- SCWR: Super-critical water cooled reactor
- GFR: Gas cooled fast reactor
- LFR: Lead cooled fast reactor
- SFR: Sodium cooled fast reactor
- MSR: Molten salt cooled reactor

*A common theme for fusion and advanced fission is the need to develop high-temperature, radiation resistant materials.*



*In the remainder of the talk:  
other aspects of the program...*

*Validated predictive  
capability*

*Engineering vs.  
physics complexity:  
3-D plasma physics*

*High energy density  
laboratory plasma  
physics*

*High performance  
steady-state research*

*General plasma  
science*



*1. On high performance steady-state research*

*and*

*2. Engineering vs. physics complexity:  
3-D plasma physics*



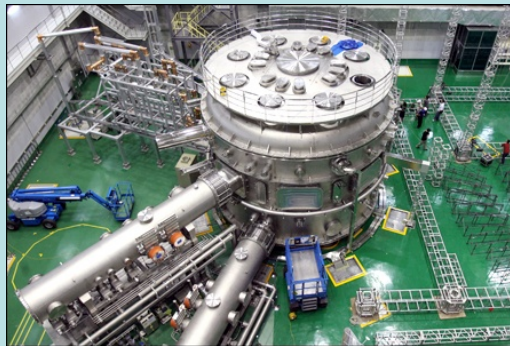


# *There have been large investments in the steady-state tokamak arena*

*U.S researchers have been pivotal in enabling early access to plasma regimes of high interest . . .*

## **K-STAR**

*Daejon, S. Korea  
Goal: 300 s pulse  
2 MA*

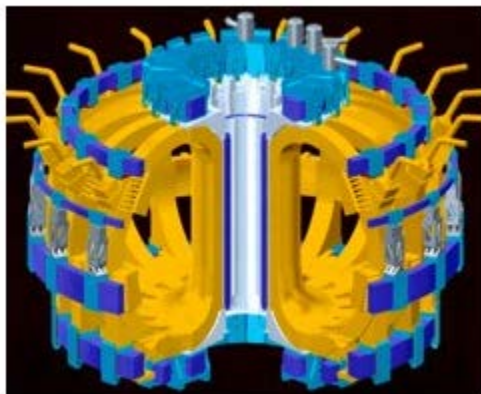


## **EAST**

*Hefei, China  
Goal: 1000 s  
1 MA*



# *While stellarators are complex, they may address some Achilles' heels of tokamaks. Facilities overseas are impressive*

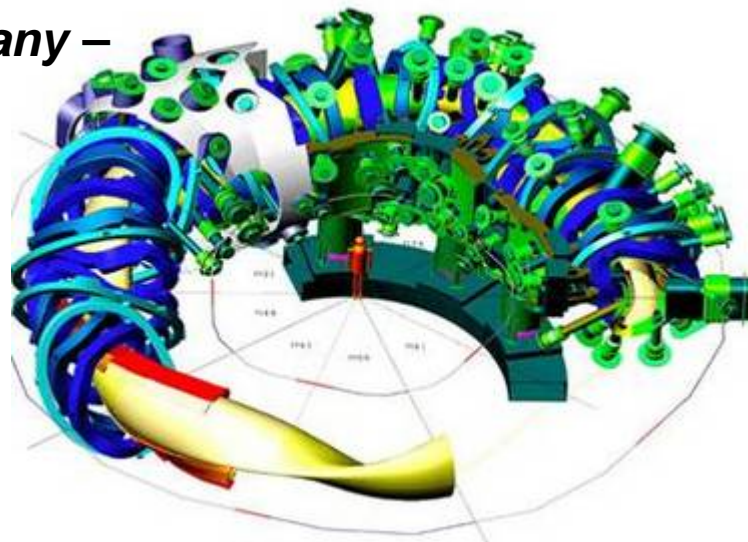


**ITER**



**LHD (Japan; operating)**

**W7-X  
(Germany –  
2016)**



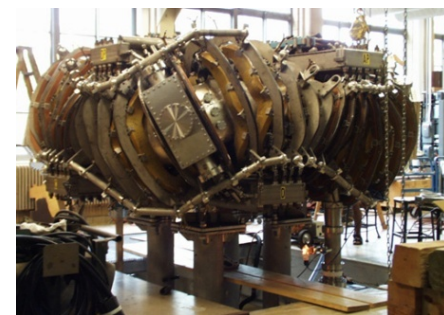


# *There may be an optimization between very small and very large deviations from a tokamak*

- ELM coils: perturb B about  $10^{-3}$  → ELMs can (may) be controlled. No influence in disruptions
- Stellarator: perturb B ~ 0.1 - 1 : disruptions *may robustly disappear*.  
In the limit of a “pure” stellarator, need for auxiliary current drive systems can be eliminated

Stellarators are complex and expensive

*HSX  
(Wisconsin)*



- Need to participate in stellarator research globally
- University-scale can address targeted physics challenges
- 3-D theory research; ensure that FSP can capture this physics

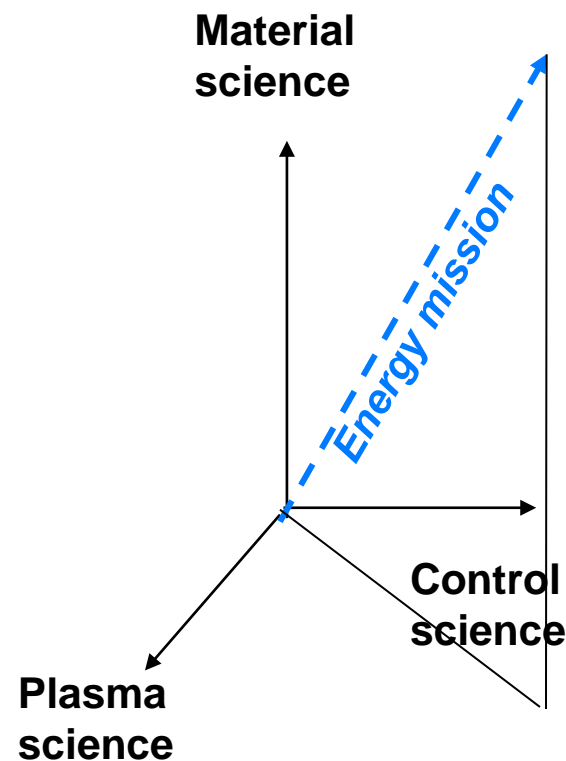
*Simulation has to be sophisticated enough to predict between pure tokamaks and full blown stellarators to find an optimum. We need to account for both physics and engineering complexity.*



# ***Consider these new superconducting devices regarding the space that describes our science***

■ The potential long pulse capabilities in Asia and Europe present opportunities for the world in all aspects of

- plasma control science, complementing our own mature capabilities and extending pulses towards hundreds of current relaxation times) and
- plasma-wall interaction science ( $\sim 10$  MW/m<sup>2</sup> for  $\sim 1000$  s), with the exception of fusion nuclear science





# ***There are FESAC charges on international collaboration opportunities being addressed***

“What areas of research on new international facilities provide compelling scientific opportunities for U.S. researchers over the next 10 – 20 years? Look at opportunities in long-pulse, steady-state research in superconducting advanced tokamaks and stellarators; in steady-state plasma confinement and control science; and in plasma-wall interactions.”

- The explicit aim is to focus on the superconducting facilities in Asia and Europe, both existing and emergent



## ***There are FESAC charges on international collaboration opportunities being addressed***

“What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.”

What lessons can we learn from other scientific fields, e.g. high energy physics, nuclear physics, others, that have had to undergo a transition and take on off-shore research significantly or nearly entirely

FESAC is encouraged to engage members of those fields and representatives from universities where international research efforts are successful, as well as where transitions to an off-shore emphasis have failed

Observations about national lab/university partnerships in new international collaborations will be highly valued. Again, what can other fields teach us?



*On validated predictive  
capability*



***Massively parallel computing is critical to  
our predictive science effort, but it is only  
part of it***

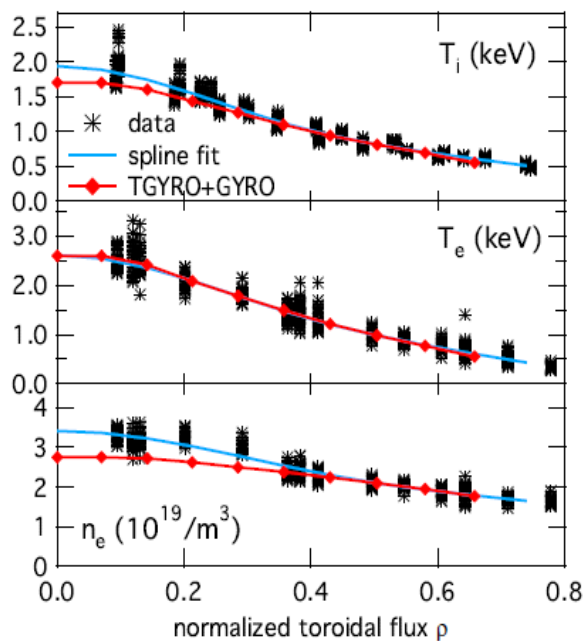
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- Fusion simulation will only be as good as the physics models that go into it
- Our reliance on validated prediction to fill gaps will demand a kind of confidence we don't yet appreciate
- Plan: grow our emphasis on validation of physics models that are incorporated in fusion simulation



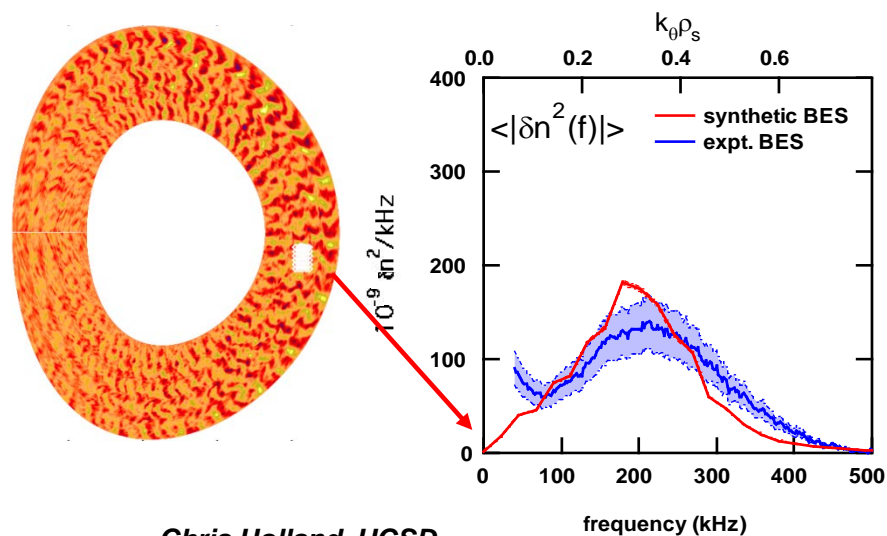
# Predictions of the plasma profiles based on detailed understanding of non-linear physical processes are emerging

*Predicted and measured temperatures and densities...*



Simulation results (red) versus experimental data (blue) for ion temperature (top), electron temperature (middle) and electron density (bottom) and electron (right) for DIII-D L-mode discharge 128913. The TGYRO solutions in red represent a steady-state scenario in which measured input power and particle source balances the neoclassical and turbulent fluxes.

*... based on validated understanding of the detailed processes*



Chris Holland, UCSD

Visualization of turbulent density fluctuations from a first-principles gyrokinetic simulation of plasma turbulence and predicted fluctuation spectra

- These kinds of measurements are made on all three major devices in complementary physics regimes. FES also has dedicated experiments designed for isolated physics studies of particular phenomena, and seeks to grow these

# ***University-scale research is well-suited for critical tests of fundamental physics and discovery***

- Plasma Science Centers

Predictive Control of Plasma Kinetics: Multi-phase and bounded systems (U. Michigan)

Momentum Transport and Flow Self-organization in Plasma (UCSD)

Bridging the PSI Knowledge Gaps - A Multiscale Approach (MIT)

Also a joint Frontier Science Center with NSF: Magnetic Self-Organization (U. Wisconsin)

- Basic Plasma Science Facility (UCLA) (with NSF)

User facility for Alfvén-wave physics and plasma-current dynamics, relevant to geospace plasmas, fusion and astrophysics.

***What is the potential role of universities for testing physics models in an expanded materials science program for fusion?***

PHYSICS OF PLASMAS 15, 062503 (2008)

### **Validation in fusion research: Towards guidelines and best practices**

P. W. Terry,<sup>1</sup> M. Greenwald,<sup>2</sup> J.-N. Leboeuf,<sup>3</sup> G. R. McKee,<sup>4</sup> D. R. Mikkelsen,<sup>5</sup>  
W. M. Nevins,<sup>6</sup> D. E. Newman,<sup>7</sup> D. P. Stotler,<sup>5</sup> Task Group on Verification and Validation,  
U.S. Burning Plasma Organization, and U.S. Transport Task Force

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<sup>2</sup>Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

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<sup>4</sup>Department of Engineering Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

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<sup>7</sup>Department of Physics, University of Alaska at Fairbanks, Fairbanks, Alaska 99775, USA

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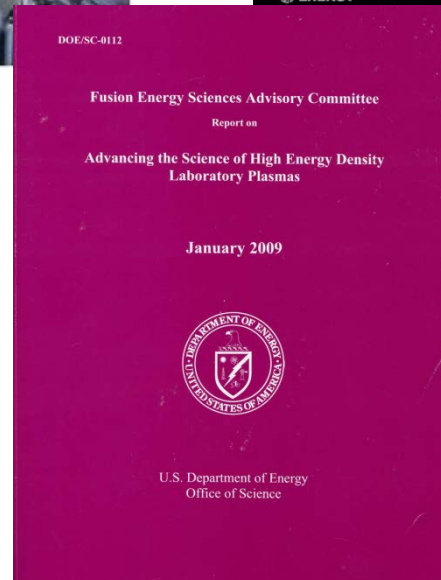
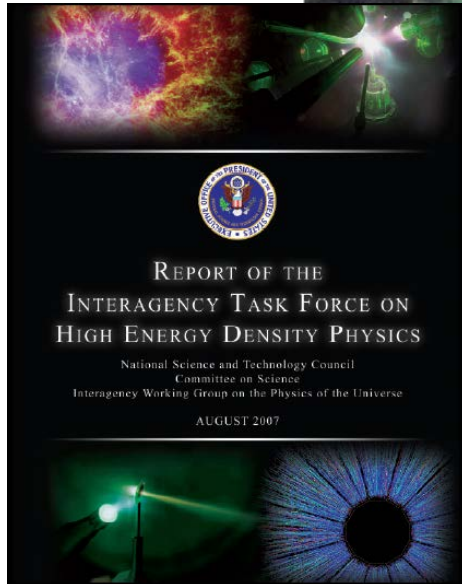
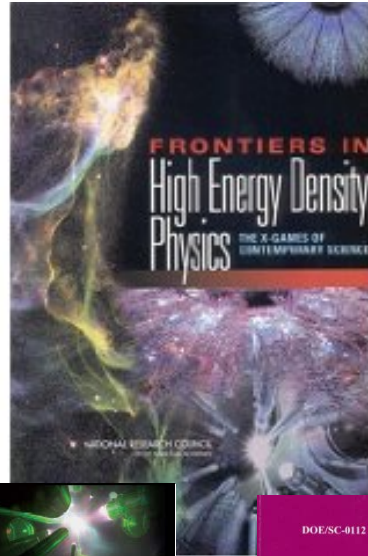


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*High Energy Density  
Laboratory Plasmas (HEDLP)  
and General Plasma Science*



Elements of a path forward in HEDLP and IFE science are being informed by many high-level panel and community assessments

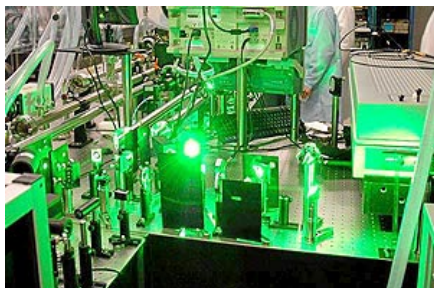
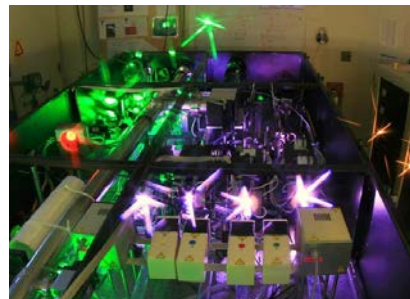


National Academies Study on IFE underway

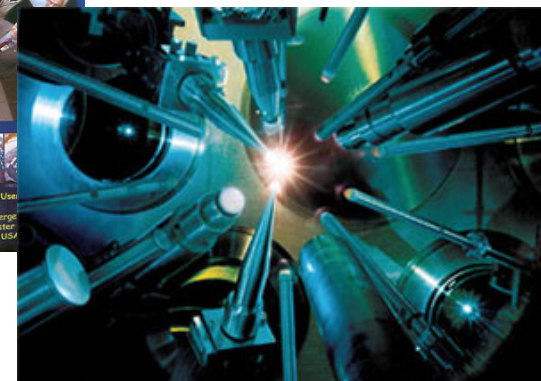


# Range of facilities on the NNSA side is impressive: scientific leverage opportunity

e.g. Petawatt lasers at Texas, LLNL, Michigan, Rochester...



*Omega-EP (Rochester) has a well-run Users Group*



Executive Committee: (l-r) Paul Drake, Jim Berger, Jim Gibble, Rich Petráň (Chair), Peter Norreys, Marilyn Schneider, Hector Baldis, Roberto Mariani  
First Omega Laser Facility Users Workshop  
Laboratory for Laser Energetics  
University of Rochester  
Rochester, New York, USA  
24 April - 1 June 2009

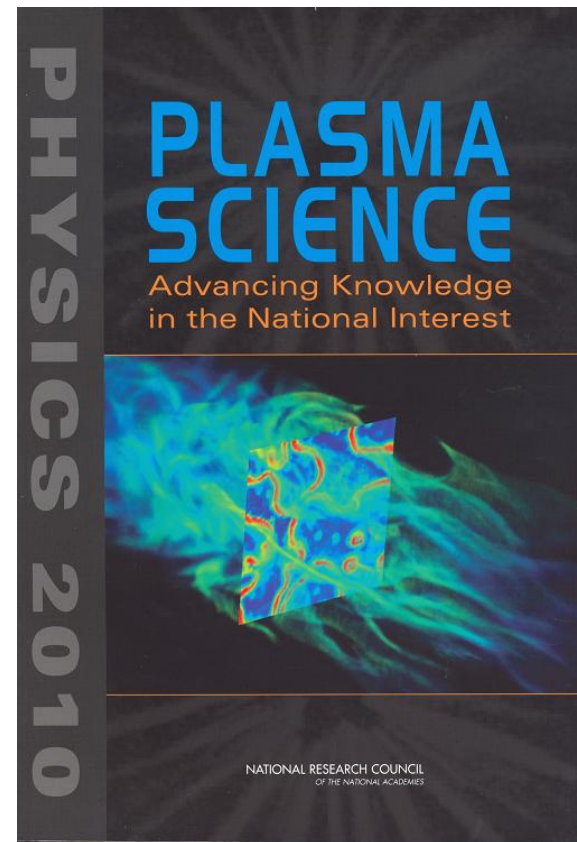


# ***Deepening credibility of plasma science as a discipline demands nurturing the field broadly***

**Principal Recommendation:** To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy's Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences; basic plasma science; non-mission-driven, high-energy-density plasma science; and low-temperature plasma science and engineering.

The new stewardship role for the Office of Science would extend well beyond the present mission and purview of the Office of Fusion Energy Sciences (OFES). It would include a broader portfolio of plasma science as well as the research OFES currently supports. Two of the thrusts in this portfolio would be new: (1) a non-mission-driven, high-energy-density plasma science program and (2) a low-temperature plasma science and engineering program. The stewardship framework would not replace or duplicate the plasma science programs in other agencies; based research. These changes would be more evolutionary than revolutionary, starting modestly and growing with the expanding science opportunities.

***FES can be the home for plasma science broadly. It makes scientific and political sense.***

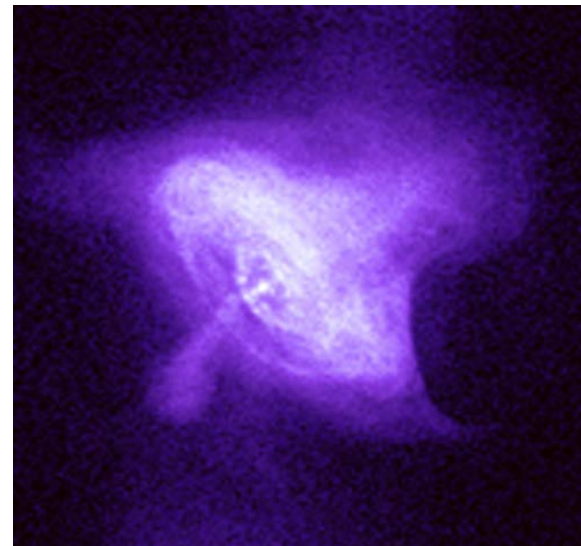


**([Science: June 4th, 2011; Vol.179 #12](#))**

The latest and greatest outbursts from the Crab Nebula — long known for its steady high-energy glow — are challenging theories about how the heavens accelerate charged particles to high energies.

Only last year, scientists were astonished to find that the nebula's gamma-ray flares fluctuated on time scales of only a few days. More recently, in April, the Crab hurled gamma-ray flares, more energetic and five times brighter than any previously recorded, that fluctuated over just one to three hours. Because no signal can travel faster than light, this variation indicates that the charged particles were accelerated within a tiny region of the vast Crab *no bigger than our solar system*.

It is proposed that the electron-positron plasma particles are accelerated near the nebula's center where rapid magnetic reconnection unleashes enormous amounts of energy in the presence of a strong electric field.



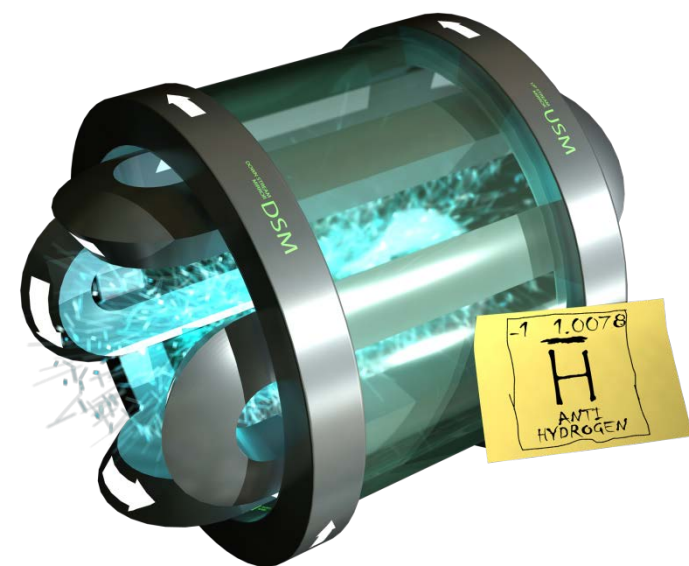
The project's theory is supported  
in part under the NSF/DOE  
Partnership in Basic Plasma  
Science and Engineering



# General Plasma Science: Non-neutral Plasma Antihydrogen Atoms Trapped for the First Time in the Laboratory

Much of the mysterious anti-matter universe is unknown to humankind . Therefore, trapping of antihydrogen atoms that are made from non-neutral antiproton and antielectron (positron) plasmas for the first time will open the door for measurements of critical properties of the antimatter.

By comparing matter to its counterpart, scientists can verify fundamental symmetries that lie at the heart of the standard model of particle physics, and look for hints of new physics beyond.



**“Top Breakthrough in 2010” -  
Physics World/Institute of  
Physics**

This project is supported under the Joint Program:  
NSF/DOE Partnership in Basic Plasma Science and Engineering



# ***Fusion needs to take on new classes of challenges; leverage can be key***

## Key elements of the vision: Plasma dynamics and control

- ITER success is critical: successful project execution, diagnostic development, training of students and young researchers towards an ITER research team.
- Seek to develop global scientific partnerships in steady-state tokamak and 3D **B** science.
- Validated predictive capability: support work to take our confidence to a much higher level to enable extrapolation that can improve the tokamak with reasonable risk. Leverage NNSA experience, learn/leverage experience from other offices (BER and climate, for example)
- HEDLP and IFE science: For IFES, emphasize multiscale physics questions. Leverage NNSA investments. Bring Recovery Act investments to scientific maturation. Coordinate HEDLP facilities to address great questions of nature. Await input from NAS study
- General plasma science for discovery and industrial applications: Cross-agency leverage is of high value.



## ***Fusion needs to take on new classes of challenges; leverage can be key***

### Key elements of the materials science vision

- Develop prerequisite programs in materials science, nuclear and non-nuclear, that inform the assessment of reasonable risks in FNSF design, construction and operation.
- Clarify the optimal geometry for an FNSF, informed by a much better understanding of the operating environment, which translates to a better understanding of risk tolerance
- Leverage cross-office opportunities: links with NE, BES, NNSA.



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*Thank you*