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A vision for fusion research in the coming decade, and perspectives on university engagement

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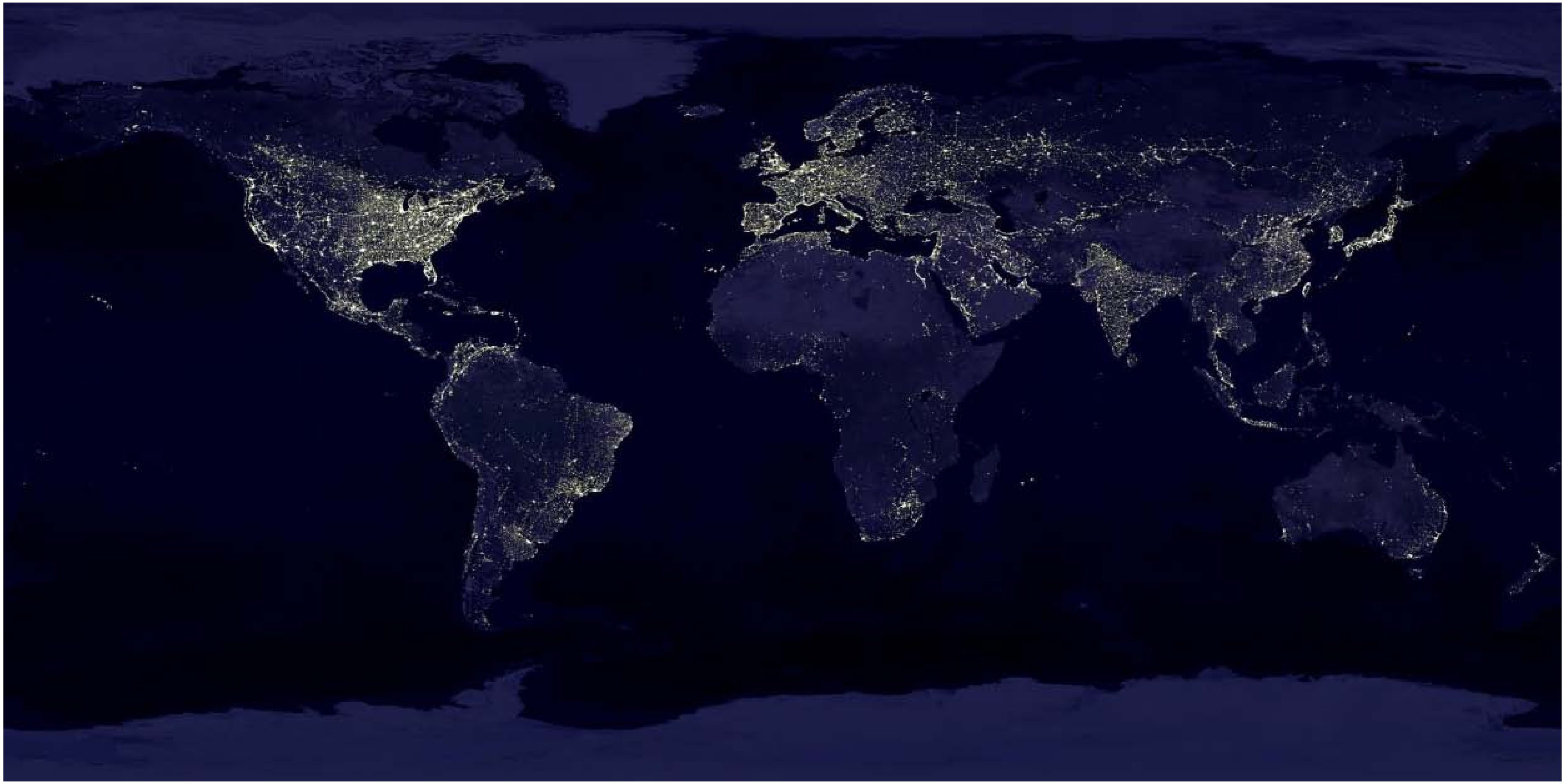
We need to have a shared sense of opportunity and urgency

- In the coming decade, the fusion energy sciences must undergo a transformation

- Here: comments on strategic priorities for the next decade, including risks, some aspects of change we need to manage, all with an emphasis on perspectives on university engagement

Our ambition is commensurate with the challenges of the times



- We are talking about *powering the planet* with a carbon-free energy source

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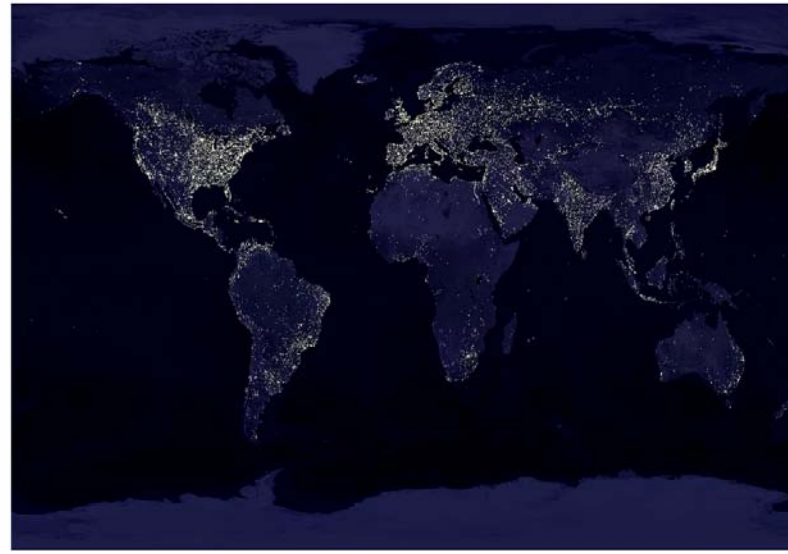
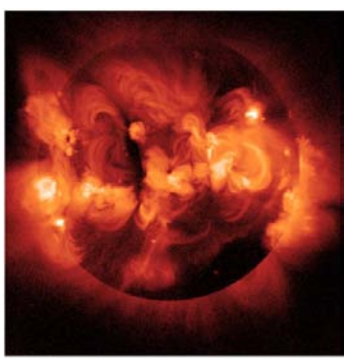
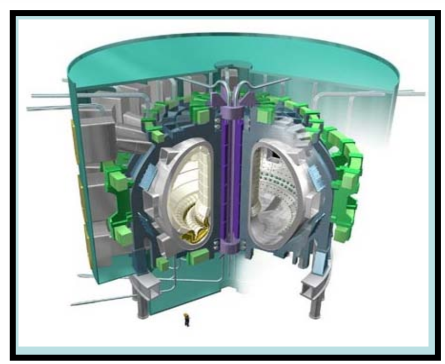
… and to get there, we are talking about fantastic science

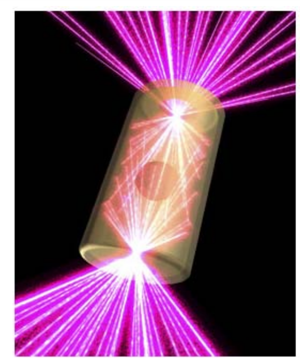
- *The science pursued by FES may form the basis for powering the planet through fusion energy: bringing a star to earth.*

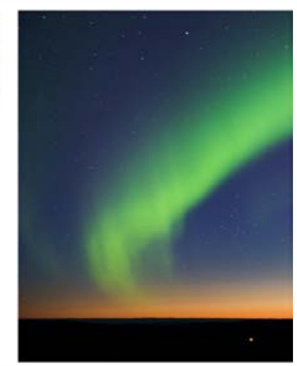
- *This science enables a deeper understanding of our universe and has a wide range of practical applications.*











We need to develop our path forward in a most challenging environment

- Budget deficits are enormous, which implies an all-too-interesting tension between the Administration's commitment to science vs. managing deficits
- The impact of the next Congress is far from clear
- Scrutiny of ITER and fusion is **very** high, and navigating the project and budget waters is a challenge of supreme importance to the field
  - ➔ exceedingly tough competition between science and energy with other national interests
  - ➔ tough competition within the Office of Science
  - ➔ our project office has to perform to the highest standards, and weak international project execution will not be acceptable to any of the U.S. stakeholders

The fortunes of university research in fusion and plasma science are coupled to fusion's overall fortunes, which is inseparable from the fortunes of U.S. government-sponsored science

High level goals

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, it will not provide the validated predictive capability we need to take a confident step beyond ITER and it's geometry

  International commitment in this research is impressive and worth capturing. We will need to if we are to remain at the forefront

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,*

Questions and challenge for universities include:

What are the opportunities for universities to lead in validation and verification of theory **central to how we predict and control plasma dynamics?**

As we extend our reach internationally and prepare for the ITER era, what is the place for university-based engagement?

How do we best engage the intellectual power at universities in our upcoming efforts in large-scale simulation of future fusion systems?

Overall: How do we engage and interest campus leadership and deliver a vision for the research they nurture that offers as direct a link as possible to where the world is going in fusion in the burning plasma era?

High level goal #2: Materials in a fusion environment and harnessing fusion power

- 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 from the burning plasma

Present investment is a fraction of what is needed. This requires the development of a new fusion materials science program for materials to define and construct a fusion nuclear science facility: benefits MFE, IFE, and other disciplines

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- … materials to define and construct a fusion nuclear science facility: benefits MFE, IFE, and other disciplines

Questions and challenge for universities include:

What are the opportunities for universities to lead in materials science? What is the role of test stands? Computation? Participation in off-site facilities?

Are there synergies to be levered in universities with departments that aren't traditionally sponsors of fusion or plasma science?

On the ITER project

ITER represents an extraordinary commitment of funding and effort

- The U.S. contribution to ITER represents an enterprise that **will cost more than anything the Office of Science has ever undertaken**

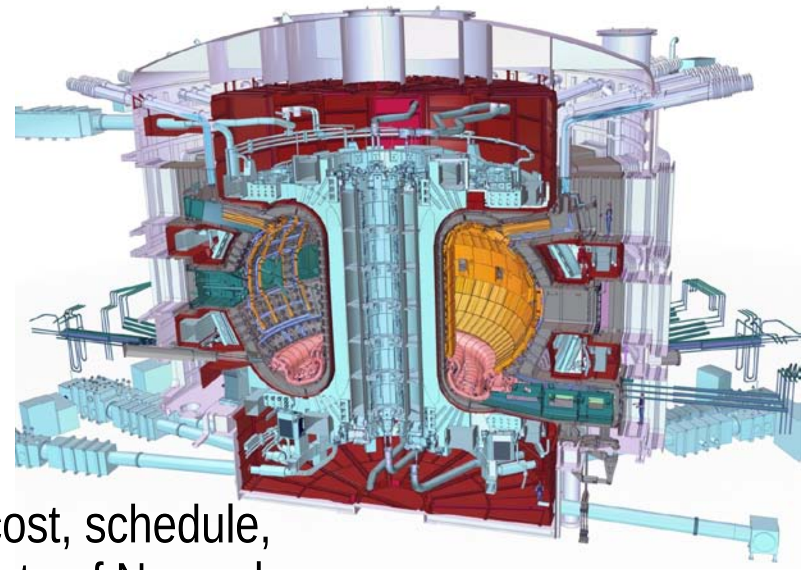
  U.S. contribution will be capped at $2.2B. Annual U.S. effort will expend over $300M/year at peak, which is a *big and constraining perturbation on the Office of Science*, not just FES

- It represents our choice for pursuing the science of burning plasmas and burning plasma control

- We have been working hard at ensuring that the ITER project meets U.S. project management standards and expectations

There have been major developments regarding ITER's baseline and leadership

CAD drawing of the baselined device. ITER is a seven nation endeavor being built in Cadarache, France. 50% of the world's population is represented at the ITER table



Baseline: The seven members have agreed on a cost, schedule, and project baseline, with an early first plasma date of November 2019

Leadership: Director General, O. Motojima (Japan) - strong leadership as ITER enters the project stage

Each of these represents *major* progress

Director General Motojima

Office of Science and DOE leadership have been absolutely critical in enabling this progress

Present Construction on ITER Site

The concrete foundation for the Poloidal Field Coil Winding Facility is being put in place

Excavation of the Tokamak Building

Construction of the Annex Office Building

But consider where we have to be to get the best science out of ITER…

- We need to be hitting the ground running with a vibrant, front-line research team in Cadarache in less than a decade

→ this is one key motivation for learning how to execute research internationally sooner than that

Engagement in our major facilities is certainly one path for university students to ITER research, but we need to develop a path for university engagement in non-ITER international research as well so that young researchers are at the front lines of developing our overseas research approaches

Research beyond the last closed flux surface

On definitions of terms…

- 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 closed 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
- This represents a major, leading challenge for the field, an opportunity for U.S. leadership, and a significant responsibility

Goals of the fusion nuclear science pathways activity

- Identify research and development activities in a series of topical areas representing fusion nuclear science
  - Materials science and technology
  - Plasma facing components and plasma material interface
  - Power extraction and tritium sustainability
  - FNSF/DEMO detail design studies
  - Enabling technologies
  - Plasma duration and sustainment
  - Reliability, maintainability, availability, and inspectability
  - Safety and environment

- Motivate these R&D activities by rolling back from DEMO and FNSF definitions, and from rolling forward from scientific needs studies (ReNeW)

- Establish what is to be done, why it must be done, how it will be done and when it needs to be done.

- Recognizing that we cannot do everything, develop possible paths and an initial statement of technical risks associated with each path

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The FNS-PA group

<u>Community members:</u>
M. Abdou (UCLA)
V. Chan (GA)
R. Fonck (Univ. WI)
R. Kurtz (PNL)
S. Milora (ORNL)
J. Minervini (MIT)
N. Morley (UCLA)
F. Najmabadi (UCSD)
H. Neilson (PPPL)
R. Nygren (Sandia)
M. Peng (ORNL)
D. Rej (LANL)
R. Stambaugh (GA)
M. Tillack (UCSD)
G. Tynan (UCSD)
J. VanDam (Univ. TX, USBPO)
D. Whyte (MIT)
S. Willms (LANL)
B. Wirth (Univ. TN)

<u>DOE members</u>:
S. Eckstrand
C. Kessel (PPPL)
M. Koepke
G. Nardella
E. Oktay
A. Opdenaker
E. Synakowski

<u>Others presently contributing in expert groups:</u>

L. Bromberg (MIT)
R. Maingi (ORNL)
C. Skinner (PPPL)
C. Wong (GA)
A.Garofalo (GA)
M. Sawan (Univ. WI)
ARIES team members
M. Baldwin (UCSD)
R. Doerner (UCSD)
D. Youchison (Sandia)
M. Ulrickson (Sandia)

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Elements of what we need to do in materials research in the coming decade

- Growth Areas and Needs

  - Expand R&D efforts on all aspects of plasma facing, structural, and blanket materials

  - Upgrade/build testing capabilities to address both single and multiple effects.

  - Enhance modeling and simulation capabilities in parallel with both activities above.

  - Increase both domestic and international collaborative activities on ITER Test Blanket Modules.

  - Exploit synergies with IFE and NNSA for both technical and political support

Plasma physics will always be an important part of FES, but broadening our portfolio to include understanding the plasma/material interface and materials in a high heat flux, nuclear environment is a goal for this decade and an area where universities can play an increasingly important role

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.

The standards we must reach in making a sensible decision on the best geometry and operating scenario of an FNSF are higher than we presently employ.

Potential example of university engagement: can university experiments address key questions that an FNSF must master for robust operations?

We need to help universities forge partnerships with our labs in forming national teams on critical questions that need to be answered to make an FNSF credible

On high performance steady-state tokamak research

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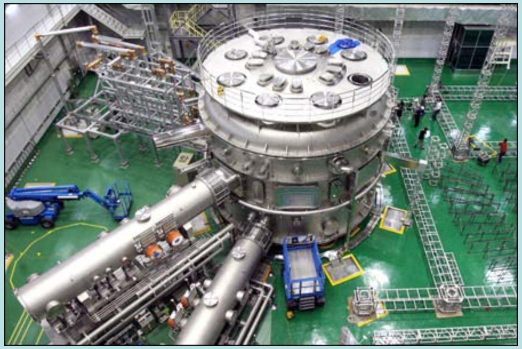
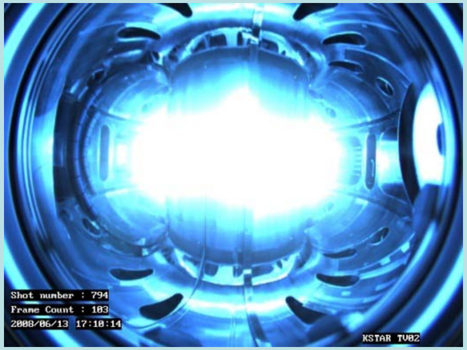
There have been large investments in the steady-state tokamak arena

… these platforms will be at the leading edge of plasma control science, and can also be leading contributors to PMI science given their pulse length and possible power density. Their leaders recognize U.S. scientific excellence and seek our partnership. We need to identify opportunities. First formal step: FES to receive assessment from Zarnstorff committee

K-STAR
Daejon, S. Korea
Goal: 300 s pulse
2 MA





EAST
Hefei, China
Goal: 1000 s
1 MA

Mid-decade vision: we should be well established in international research in steady-state tokamak physics

- Grow international research teams
  - Opportunities in core plasma control science as well as materials science
    - Some experiments seek all manner of expertise, especially boundary/divertor physics and, in the near term, plasma control
- Consider remote control rooms. University data nodes for diagnostics, perhaps
- FES needs to increase management staff with expertise in tokamak steady-state research, and an interest and ability to engage international programs
- Near-term: FES working with community to develop understanding of international research opportunities.

University engagement through diagnostics should continue. Are local data centers at universities viable and of interest?
Learn from other sciences as to how universities are engaged in international research platforms. Where would these models succeed for fusion, where would they fail?

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Engineering vs. physics complexity: 3-D effects

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There is 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

  But stellarators are complex and expensive, and we are not going to have new starts in U.S. stellarator projects in the foreseeable future

➔Need to participate in stellarator research globally

➔University-scale can address targeted physics challenges

➔3-D theory research: need to ensure that fusion simulation can capture this physics

Simulation has to be sophisticated enough to predict between pure tokamaks and full blown stellarators to find an optimum. This is a very high scientific standard. Ultimately, we need to account for both physics and engineering complexity when optimizing

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Mid-decade vision for 3D physics research

- Growth in theory of 3-D equiilbria, stability, and transport research
- Increase emphasis in 3-D fields near-term on domestic facilities
- Solicit theory/simulation proposals that have the potential for bridging the gap between small and large topological variations from a tokamak, aiming for inclusion in fusion simulation
- Build overseas partnerships

This arena ought to be ripe for university participation through existing experiments, development of international research teams, and participation in our domestic large-scale facilities

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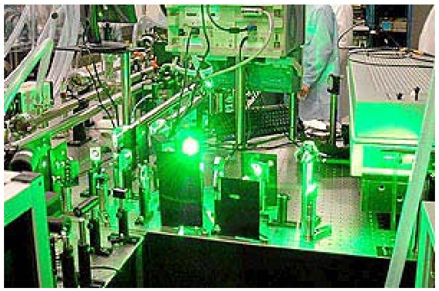
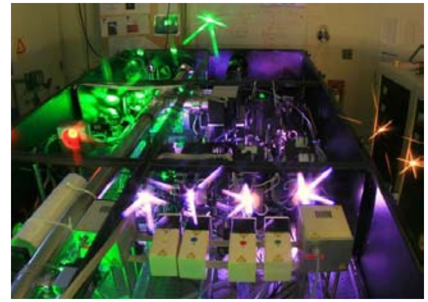
High energy density laboratory plasma physics and IFE

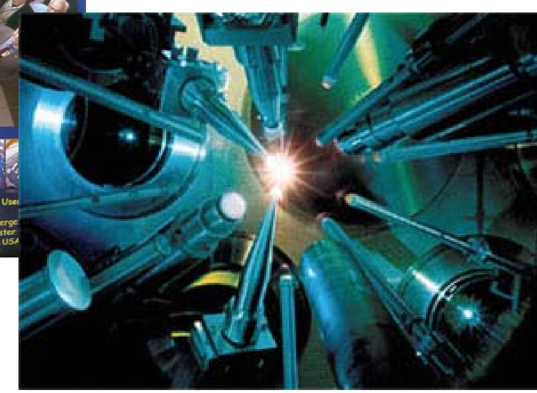
Range of facilities on the NNSA side is impressive

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





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



HEDLP/IFE outlook, 5 years

- NIF will have ignited. FES will have a leadership role in developing IFE and astrophysical science experiments on NIF and on HEDLP facilities, in partnership with NNSA, and a leadership role in a new IFE Technology effort.

- IFE and MFE common interests in materials will support growth in this area

- In HEDLP, through its development of coordinated marches on the wide range of HEDLP facilities, universities will be key in resolving fundamental questions of nature and pursuing science essential to assessing the viability of IFE. The range of scales can be levered in a scientifically sensible way

- MEC End-station at SLAC will be producing one-of-a-kind WDM research

University-scale experiments have a natural scientific place in addressing questions on their own as well as within sensibly planned national activities linked to the largest facilities. FES looks forward to supporting access to the larger NNSA facilities through the joint development of user programs

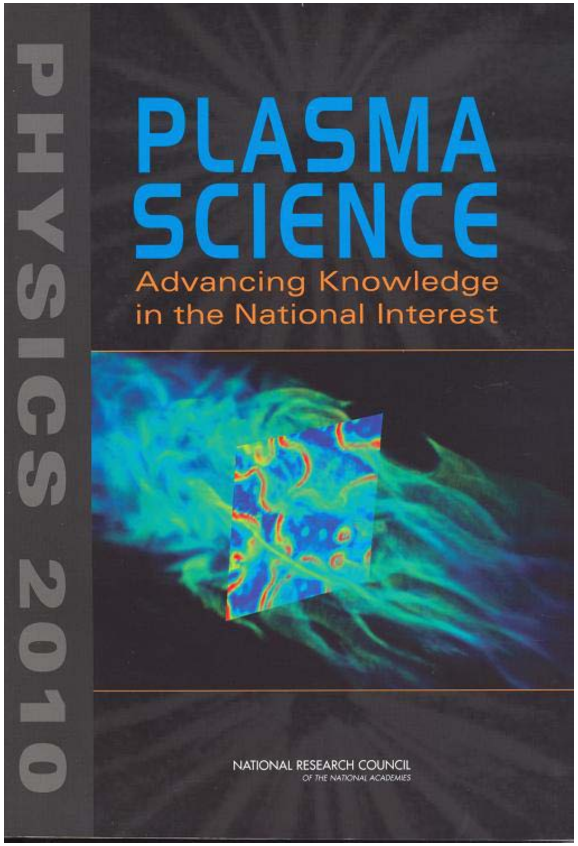
its ARRA upgrade

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. Leverage with other scientific institutions will be critical, especially with tight budgets in the near term. NSF/DOE partnership is a leading example. Universities have a natural place in this endeavor



On validated predictive capability

Fusion simulation is critical to our predictive science effort, but it is only part of it

- Massively parallel computing 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

By mid-decade, in validated predictive capability…

- In massively parallel, integrated computing, we will have developed an effective means of partnership between national labs and universities to enable universities to make leading contributions to this effort. This will require effective FES stewardship of the university theory/simulation community
- Potential leverage/collaborative opportunities with NNSA clarified and perhaps engaged: we can likely learn a great deal from each other
- SciDAC portfolio augmented to include materials science relevant to divertors and first walls.
- Stand-alone validation platforms have begun to mature

Interest in the sensible use of massively parallel computing and the role theory and experimental validation play is very high. These efforts are a natural for strong university engagement

We are at a turning point in fusion's development

Elements of a vision for 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
- HEDLP and IFE science: grow to capture NIF success. For IFE, plasma dynamics and control is about understanding and optimizing ignition scenarios. Lever NNSA investments. ARRA investments will be scientifically mature. Coordinated HEDLP facilities address great questions of nature. Take a strong role in IFE Technology

As we focus on increasing the chances of scientific success of ITER, position ourselves to become increasingly international, and strive for the strongest justification and best plans for an FNSF, we need to augment approaches for univeristy engagement

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Elements of the FES vision

Materials science

- Develop prerequisite programs that inform the assessment of reasonable risks in both FNSF operation as well as the choices of materials themselves.
- High metrics for our research on present devices will be established to guide our choices regarding the nature of a future fusion nuclear science facility
- Leverage will be sought with cross-office partnerships, links with nuclear, MFE and IFE, NNSA

What is the potential for university-based materials research, including test stands, engagement with nuclear engineering departments, and computation in materials-for-fusion research?

The vision for the next decade is defined by a great intellectual challenge

- In the last twenty years, our science has undergone a great shift: fusion plasmas are seen to be *knowable and controllable*

But can plasma and fusion science become a truly predictive enterprise?

- In the next ten years, we need to challenge ourselves with the question: can our knowledge evolve to the point where we can reduce the risks of development of new fusion systems through a deep confidence in our predictive capability? We need a heightened sense of urgency to answer these questions, and it needs to be reflected in the goals of both our experiment and theory & simulation programs

This challenge can resonate with the leadership on our campuses as to why their engagement with fusion and plasma science should deepen in the next decade

Thank you