U.S. Department of Energy
Office of Science

Fusion Energy Sciences Update

Presented to
NRC Board on Physics and Astronomy
April 25, 2008

Raymond Fonck
Associate Director
of Fusion Energy Sciences

www.science.doe.gov/ofes

Questions to Address

- **Agency Specific**
  - Response to Plasma 2010 (& other NRC) Reports
  - ITER: status and US Contributions, funding
  - Priorities for the US domestic fusion research program

- **General**
  - Most significant issues over the next year
  - Volatility in funding process and effects on program
  - Where can Academy add value

Mission: Generate the knowledge needed for fusion energy sources, and understand general plasma science

- **Program Elements:**
  - Magnetic Fusion Energy Sciences:
    - *Burning Plasma Science*
    - *Advanced Tokamak Physics*
    - *Toroidal Confinement Physics*
    - *ITER Project and Program*
    - *Theory and Computation*
    - *Plasma and Fusion Technologies*
    - *Diagnostics*
    - *Fusion Materials*
  - Plasma Sciences:
    - *Fundamental Properties of Plasmas*
    - *High Energy Density Laboratory Physics*
    - *Atomic Processes*
    - *Electromagnetic Confinement*
    - *Low-Temperature Plasmas*

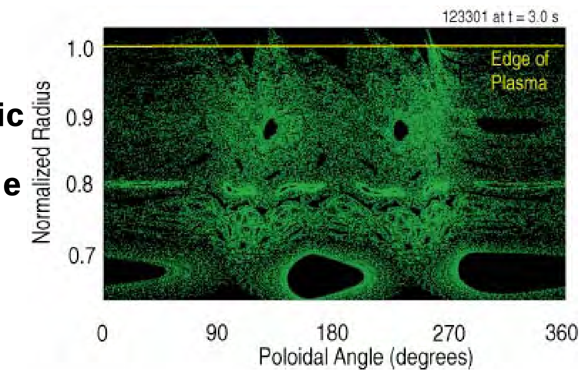
- **National/Shared Facilities:**
  - DIII-D Advanced Tokamak (GA)
  - C-Mod Advanced Tokamak (MIT)
  - NSTX Spherical Torus (Princeton)
  - NCSX Stellarator (Princeton – under construction)
  - MST Reverse Field Pinch (CMSO - WI)
  - Large Area Plasma Device (UCLA)

Magnetic Fusion Sciences:
Controlling Instability @ Plasma Edge

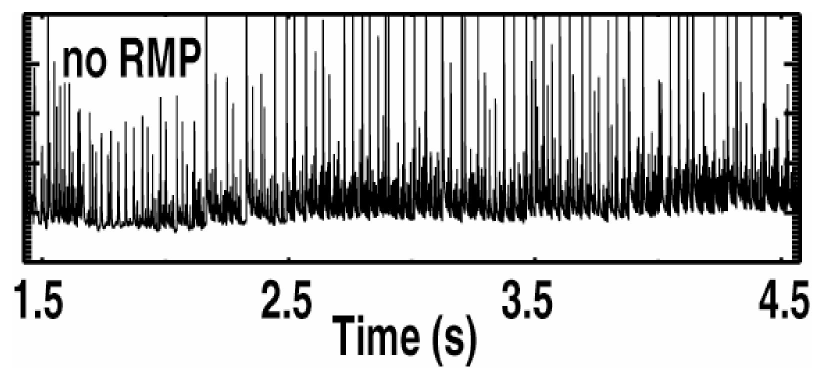
DIII-D Advanced Tokamak (General Atomics)

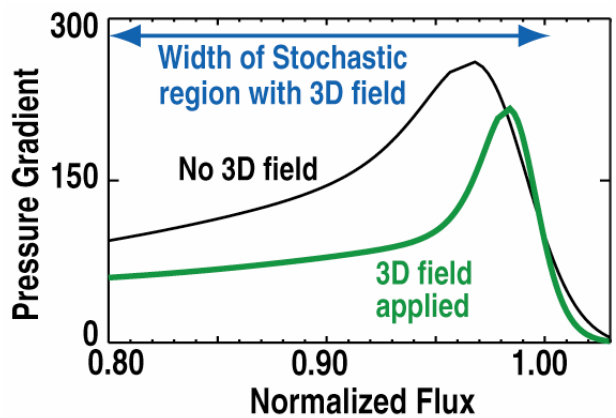
Critical Edge Instability Controlled by Purposefully Degrading Magnetic Surfaces

Applying 3D fields produces Stochastic region leading to stabilization of edge instabilities

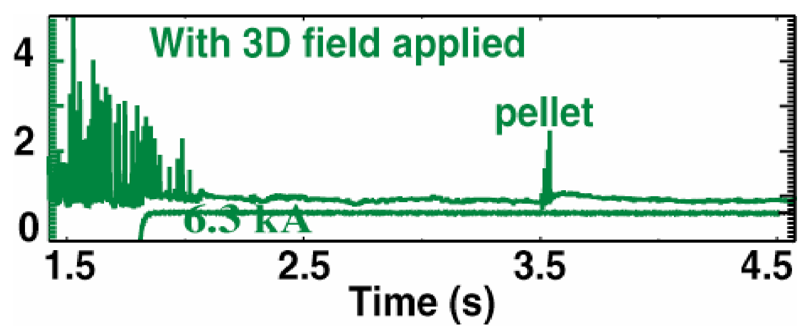


Unstable with high edge pressure gradients: sharp spikes in heat loss





Stable with relaxed edge pressure gradients



MFES: Understanding an Effective Disruption Mitigation Technique

Injection of massive gas puff dissipates energy through radiation:

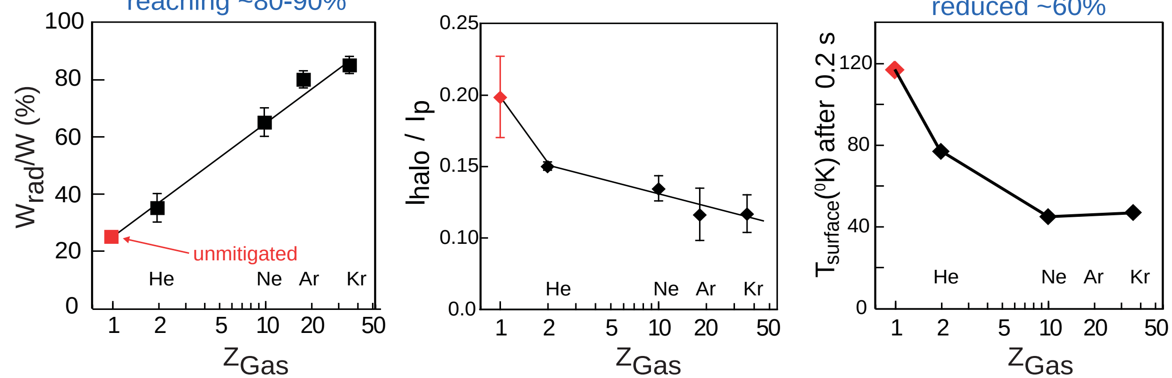
Alcator C-Mod (MIT)

3-D MHD Numerical Model (NIMROD + Radiation Package) gives quantitative agreement with detailed experimental results.

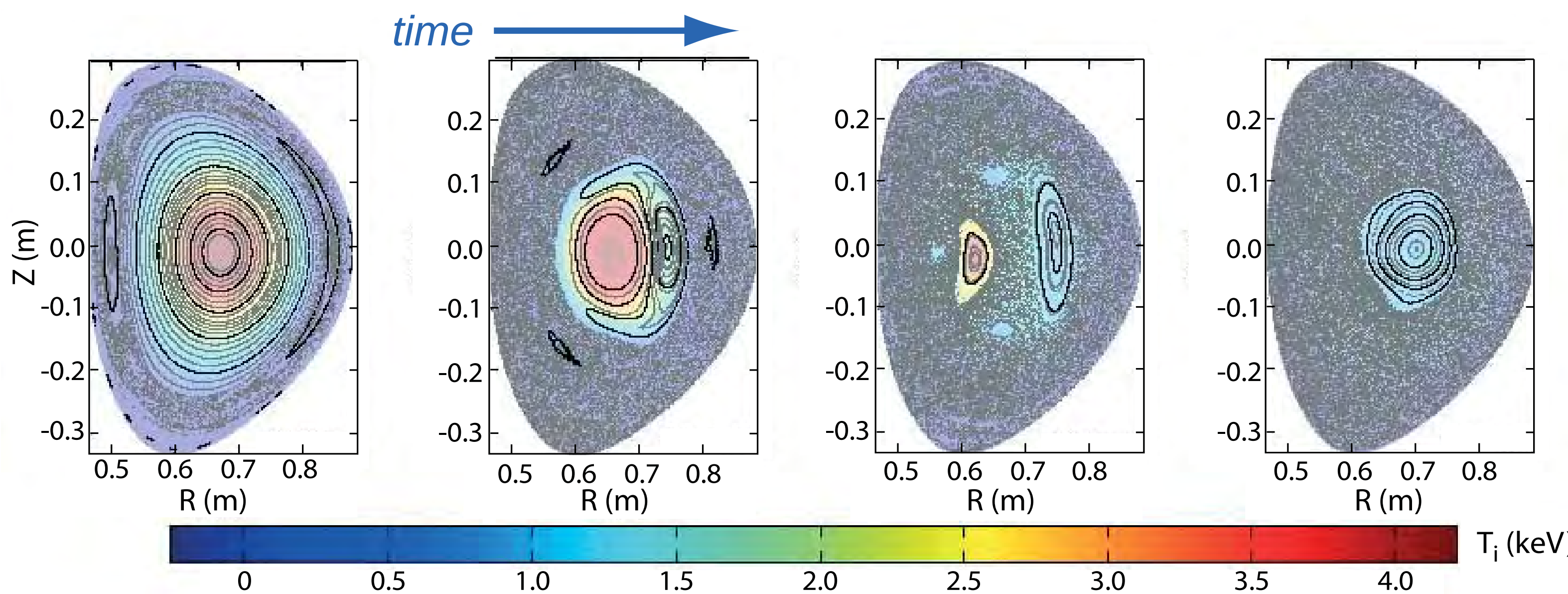
Radiated energy fraction increases with Z_{gas}, reaching ~80-90%

Halo currents reduced ~50%

Divertor tile heating reduced ~60%



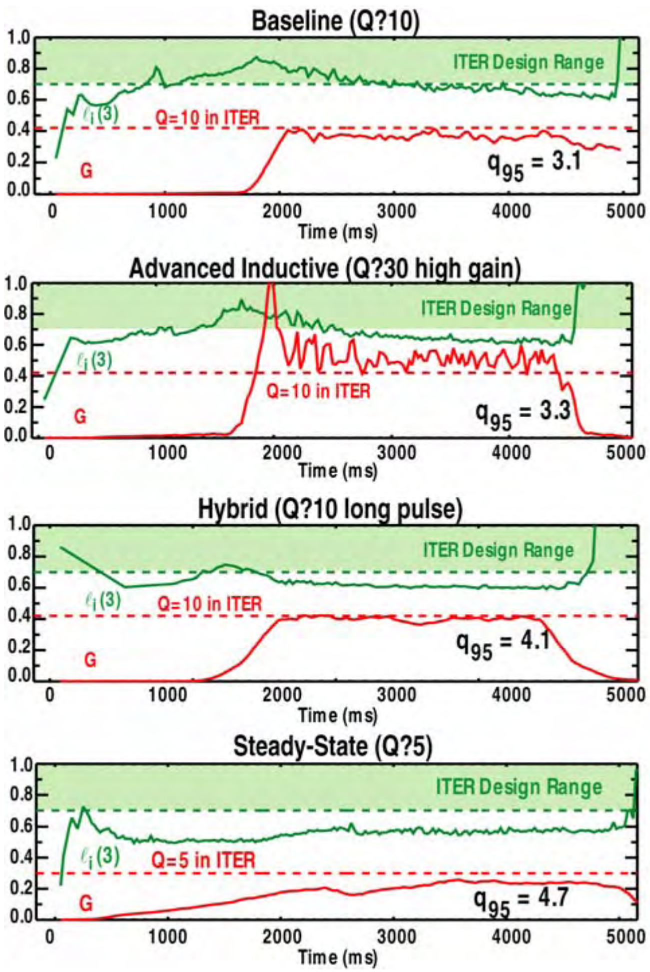
Fully 3-D simulation shows rapid destruction of flux surfaces:



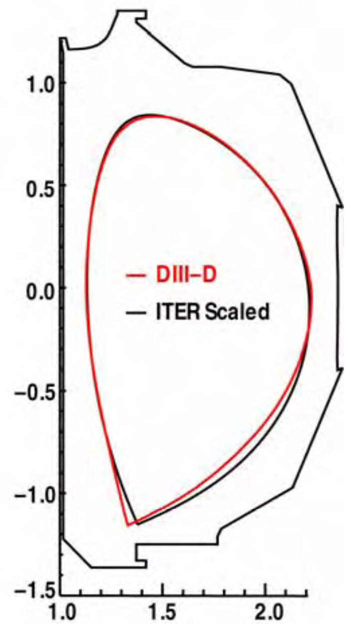
MFES: Similarity Experiments Enable Development of a Detailed Physics Basis for ITER

DIII-D Advanced Tokamak (General Atomics)

- **DIII-D can simulate ITER scenarios ...**

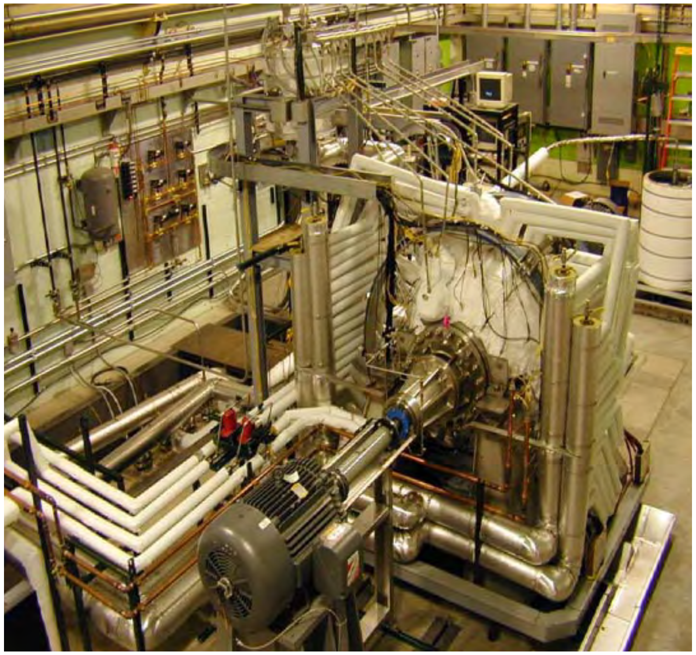


In the ITER shape and aspect ratio...



- **Baseline (ITER Scenario 2)**
  - Reference operating case
  - Q≈10 operation at full current (15 MA)
- **Advanced Inductive (AI)**
  - High fusion gain scenario
  - Q>10 at full current (15 MA)
- **Hybrid (ITER Scenario 3)**
  - Long pulse, high fluence mission
  - Q≈10 at reduced current (~12 MA)
- **Steady-state (ITER Scenario 4)**
  - Advanced Tokamak (AT) scenario targets steady-state objective
  - Above no-wall pressure limit
  - Q≈5 at reduced current (~9 MA)
- **Broad experimental current profiles (low ℓ_i) impact ITER coil design**

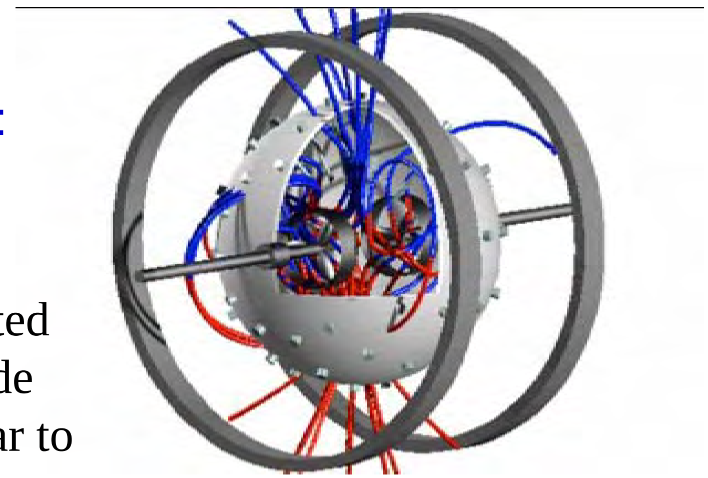
Dynamo Experiment: self-generation of magnetic fields in turbulent flows of liquid metal



The Madison Dynamo Experiment (WI)

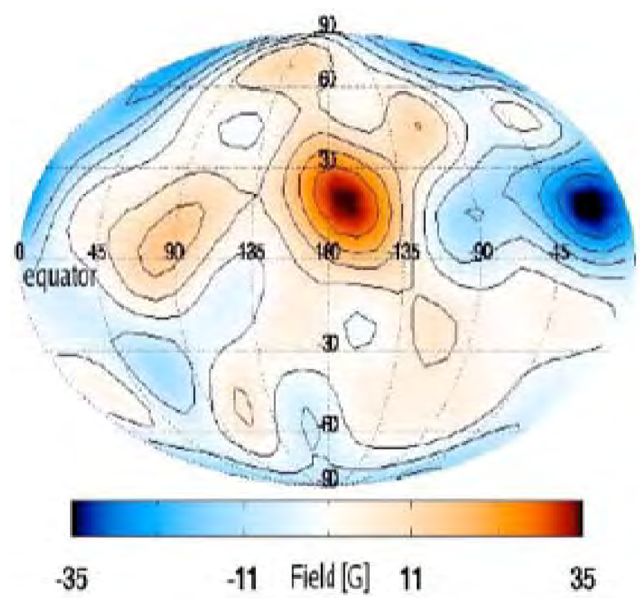
300 gallons of liquid sodium
150 kW of mechanical power
Rm/Re=10-5 (always turbulent)
Confinement is simple, and conductivity is uniform

Predicted:



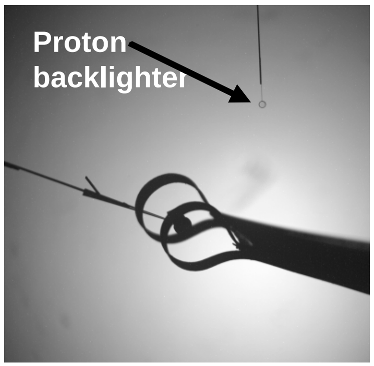
Intermittently excited magnetic eigenmode has structure similar to that predicted for the mean-flow, self-generated dynamo

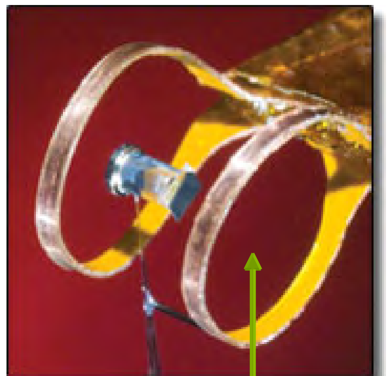
Observed:



Magnetic flux compression in implosion experiments on OMEGA produce MegaGauss Fields

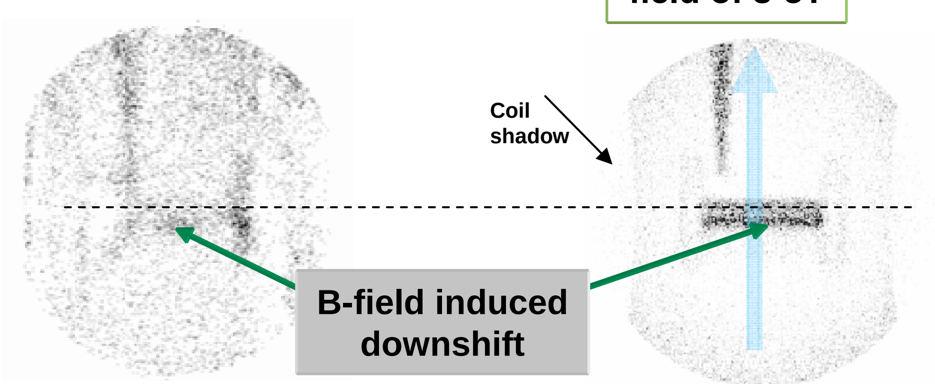
Compression of magnetized ICF targets produces magnetic fields of 13 MG and 10-fold increase in fusion yield





Initial seed field of 3-5T

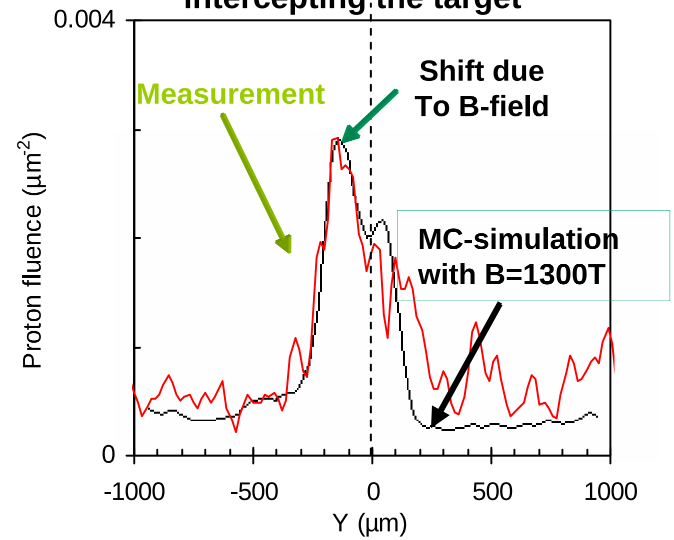
Proton deflectrometry measurements show B-field compressed to ~1300T, a first in a dense, fusing deuterium plasma with a neutron yield exceeding 5×10^8



Proton density map (E_{kin} < 14.8 MeV) at the detector surface

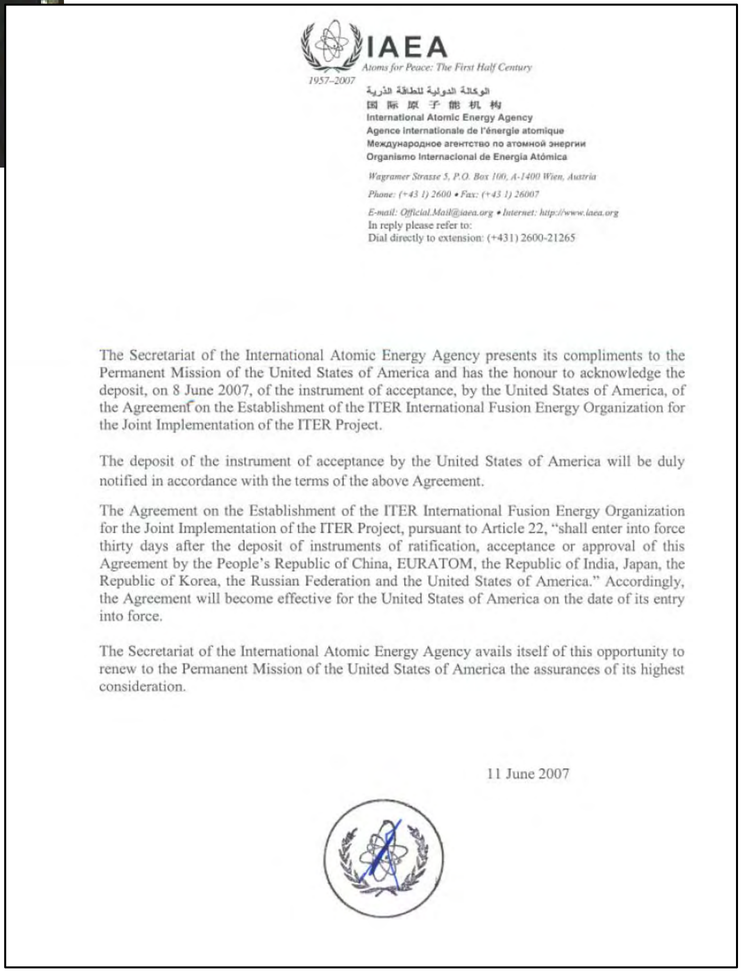
Simulated proton density map (E_{kin} < 14.8 MeV) at the detector surface

Fluence of protons intercepting the target



ITER Agreement Ratification Process Complete

- November 21, 2006 – the ITER Agreement was signed by the seven Members.
- October 24, 2007 – the ITER Agreement entered into force and the ITER Organization became a legal entity.
- November 27-28, 2007 - with completion of the above milestones, the first official ITER Council Meeting was held.



IAEA
Atoms for Peace: The First Half Century
1957–2007
الوكالة الدولية للطاقة الذرية
国 际 原 子 能 机 构
International Atomic Energy Agency
Agence internationale de l'énergie atomique
Международное агентство по атомной энергии
Organismo Internacional de Energía Atómica

Wagramer Strasse 5, P.O. Box 100, A-1400 Wien, Austria
Phone: (+43 1) 2600 • Fax: (+43 1) 26007
E-mail: Official.Mail@iaea.org • Internet: http://www.iaea.org
In reply please refer to:
Dial directly to extension: (+431) 2600-21265

The Secretariat of the International Atomic Energy Agency presents its compliments to the Permanent Mission of the United States of America and has the honour to acknowledge the deposit, on 8 June 2007, of the instrument of acceptance, by the United States of America, of the Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project.

The deposit of the instrument of acceptance by the United States of America will be duly notified in accordance with the terms of the above Agreement.

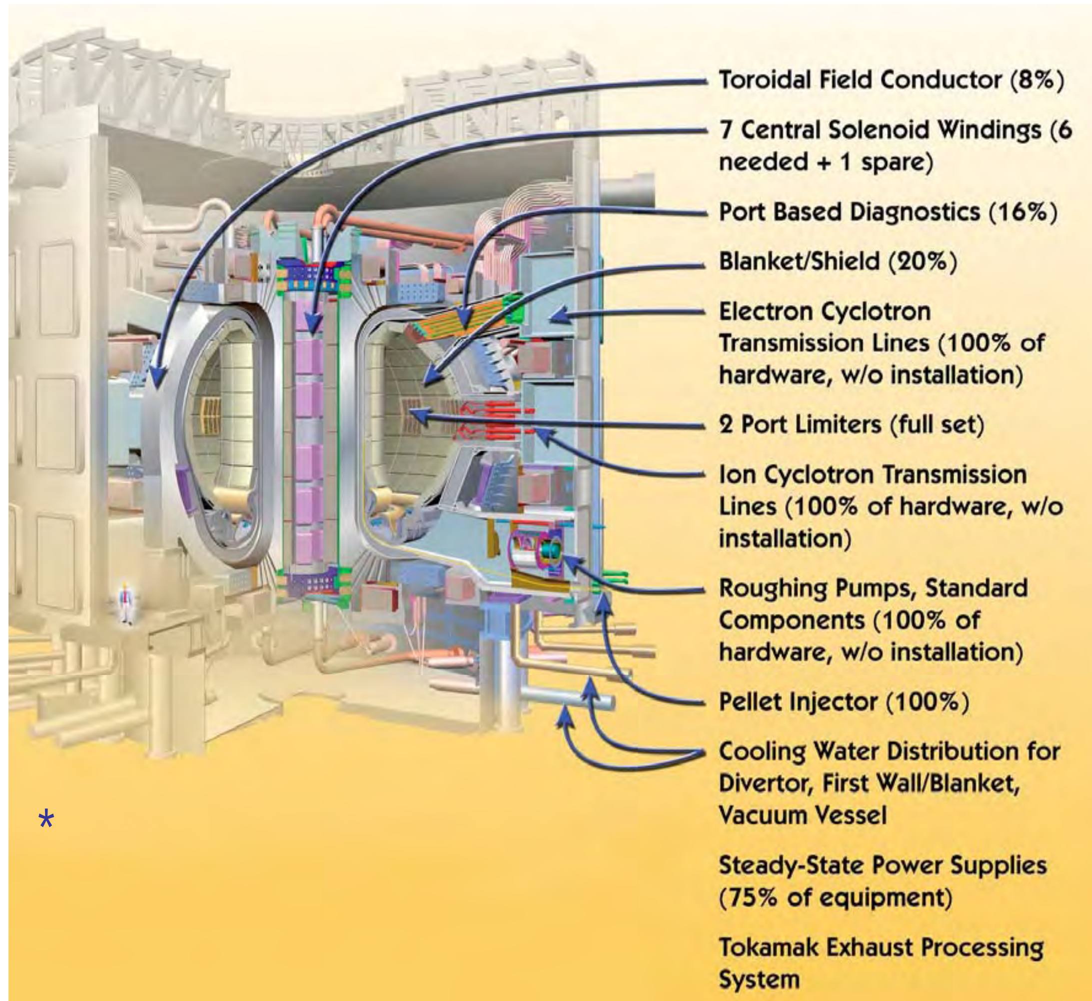
The Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project, pursuant to Article 22, "shall enter into force thirty days after the deposit of instruments of ratification, acceptance or approval of this Agreement by the People's Republic of China, EURATOM, the Republic of India, Japan, the Republic of Korea, the Russian Federation and the United States of America." Accordingly, the Agreement will become effective for the United States of America on the date of its entry into force.

The Secretariat of the International Atomic Energy Agency avails itself of this opportunity to renew to the Permanent Mission of the United States of America the assurances of its highest consideration.

11 June 2007

U.S. ITER Project Scope

- **In-kind contributions of hardware and its delivery to France,**
- **In-kind contribution of staff (secondees) to IO**
- **Cash contributions for**
  - R&D and Common Fund expenses (e.g., direct staff, IO services, machine assembly/installation/ commissioning)
  - the Central Reserve
- **Operation of the US ITER Project Office at ORNL in conjunction with partner Labs PPPL and SRNL**



Overall Status of ITER

- International
  - **ITER Organization (IO) staffed to ~ 300 including contractors; employees are under 5-year contracts**
  - **ITER Council's S&T and Management Advisory Committees are operational and engaged. Financial Audit Board is performing its first audit in April 2008.**
  - **Members' Domestic Agencies are becoming fully operational and developing Procurement Arrangements for hardware contributions**
  - **IO submitted the Preliminary Safety Report to the French regulatory authorities**
  - **Construction Site Preparations:**
    - ***Platform leveling (major earthmoving) underway***
    - ***Excavation for Buildings to begin in early 2009***
  - **ITER Organization is developing a bottoms-up Integrated Project Schedule and detailed resource estimates for their scope. Indications are that construction completion will slip to 2018-19.**
  - **Design Review concluded in 2007, but STAC identified several key design issues requiring additional work. IO & Members have made good progress in finding solutions. U.S. has been a major contributor.**
    - ***Goal = have overall design, schedule approved by Council by end of 2008.***

Overall Status of ITER

- Domestic (U.S. ITER Project)
  - **Achieved Critical Decision 1 (Approve Alternative Selection and Cost Range) in January 2008.**
    - ***Total Project Cost (TPC) range set at $1.45B - $2.2B based on analysis of risks and present market environment.***
    - ***This range supercedes the previous OMB cap of $1.122B.***
  - **Critical Decision 2 (Approve Performance Baseline) is projected to occur in FY2009-10**
    - ***Depending on how soon the ITER Organization can establish their own baselines for the entire construction phase of ITER.***
    - ***DOE will conduct Lehman reviews and an External Independent Review at the appropriate times to validate schedule and cost estimates for the U.S. ITER Project.***
    - ***Baseline funding profile will be set.***

FY 2009 Fusion Energy Sciences Budget Request Restores ITER Funding

	FY 2007 Actual	FY 2008 CONG	FY 2008 Jan AFP	FY 2009 CONG
	($ Millions)			
Science	144.6	159.5	163.9	168.4
Facility Operations	146.3	247.5	100.8	301.9
Enabling R&D	20.8	20.8	21.8	22.7
OFES Total	**311.7**	**427.8**	**286.5**	**493.1**
Research:				
Burning Plasma/Tokamak	85.7	89.7	93.8	88.1
Alternate Toroidal Configs	52.7	55.7	57.7	50.1
Plasma Science	28.7	25.6	29.5	38.4
MIE Projects:				
ITER MIE	60.0	160.0	10.6	214.5
NCSX MIE	15.9	15.9	15.9	19.6

DOE Perspective on ITER Funding

- **Despite the FY2008 Budget shortfall, the U.S. ITER Project remains the highest priority in the DOE Office of Science's Facilities for the Future of Science: A Twenty-Year Outlook.**
  - See Dr. Ray Orbach, DOE Under Secretary for Science, March 5, 2008 Congressional Testimony

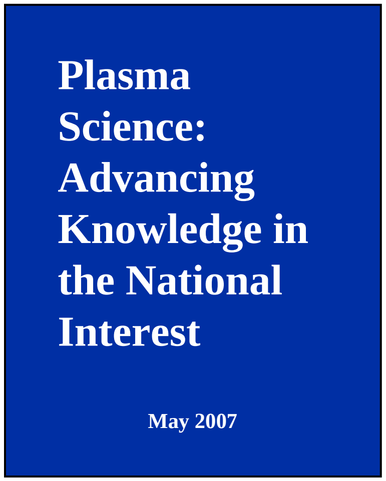
- **Using uncosted prior year funds and the $10.6M FY2008 appropriation for ITER**
  - the U.S. ITER Project has retained a core team
  - remained engaged with the ITER Organization in finalizing the ITER design and establishing a credible construction schedule.
  - U.S. secondees remain on assignment in France.
  - Our cash contributions and long-lead procurements, however, are being deferred until additional funds become available.

- **President's FY2009 Budget Request calls for $214.5M**
  - Consistent with previous funding projections
  - Enables U.S. to meet 2008 – 09 funding commitments to the ITER Organization
  - U.S. ITER Project staffing will be reconstituted
  - Permits U.S. design and R&D activities to move forward, and allows long-lead hardware procurements to be initiated
  - Helps restore international confidence in U.S. commitment

- **Realization of the FY2009 request is crucial for the success of ITER and for the future health of the U.S. Fusion Program.**

Recommendations from Recent National Academies Studies

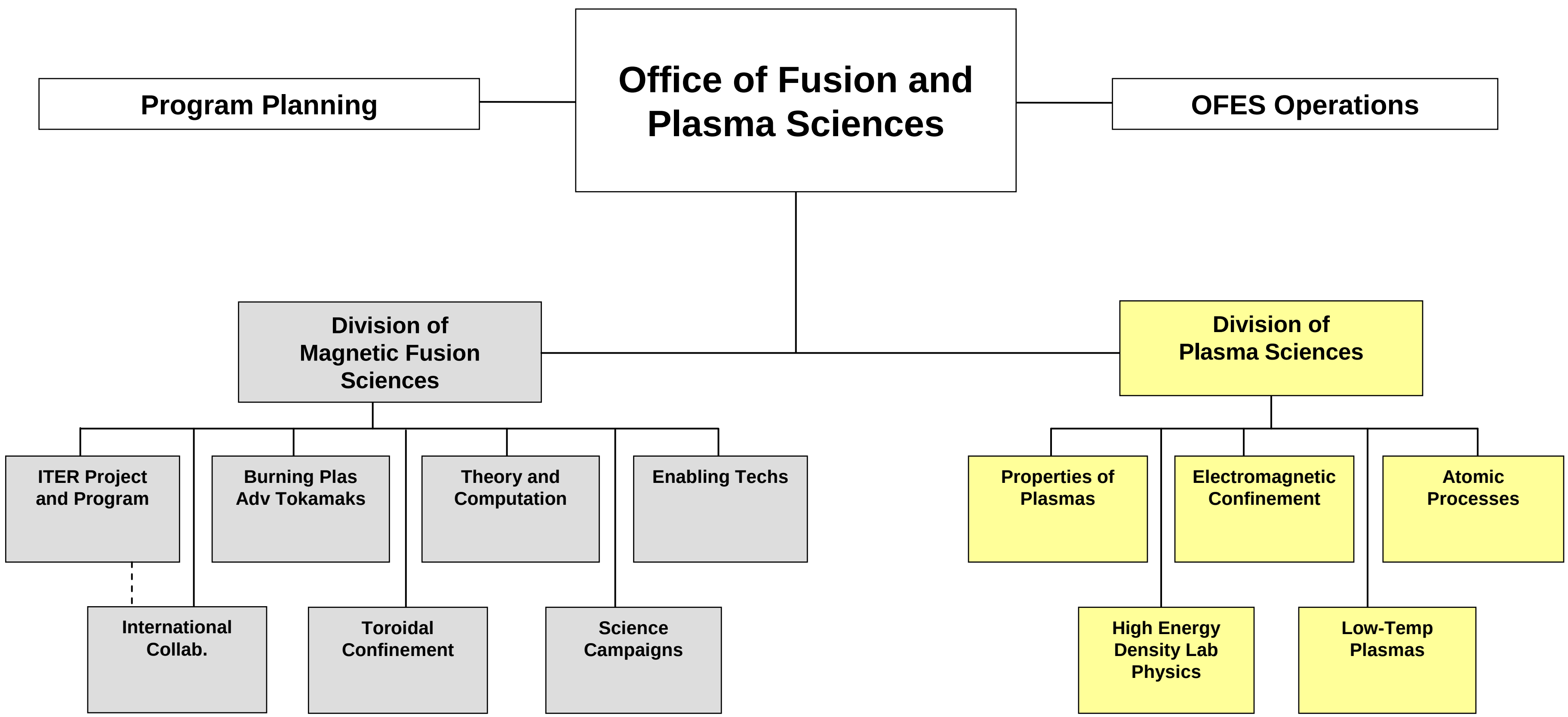
- **Plasma Science: Plasma 2010 Decadal Study (2007)**
  - Central recommendation:
  - “To fully realize the opportunities in plasma research, a unified approach is required. Therefore, the Department of Energy’s Office of Science should reorient its research programs to incorporate magnetic and inertial fusion energy sciences, basic plasma science, non-mission-driven high-energy density plasma science, and low-temperature plasma science and engineering.”



- **Burning Plasmas and Fusion: Burning Plasma (2004)**
  - Participate in ITER
  - Integrate burning plasmas/ITER and rest of program
  - Develop cross-cutting science campaigns
  - Prioritize magnetic fusion program activities

- **High Energy Density : X-games (2003), Interagency Task Force**
  - Work with NNSA to steward High Energy Density Laboratory Physics - HEDLP

Draft, Conceptual, etc. Reorganization to Address NRC Recommendations

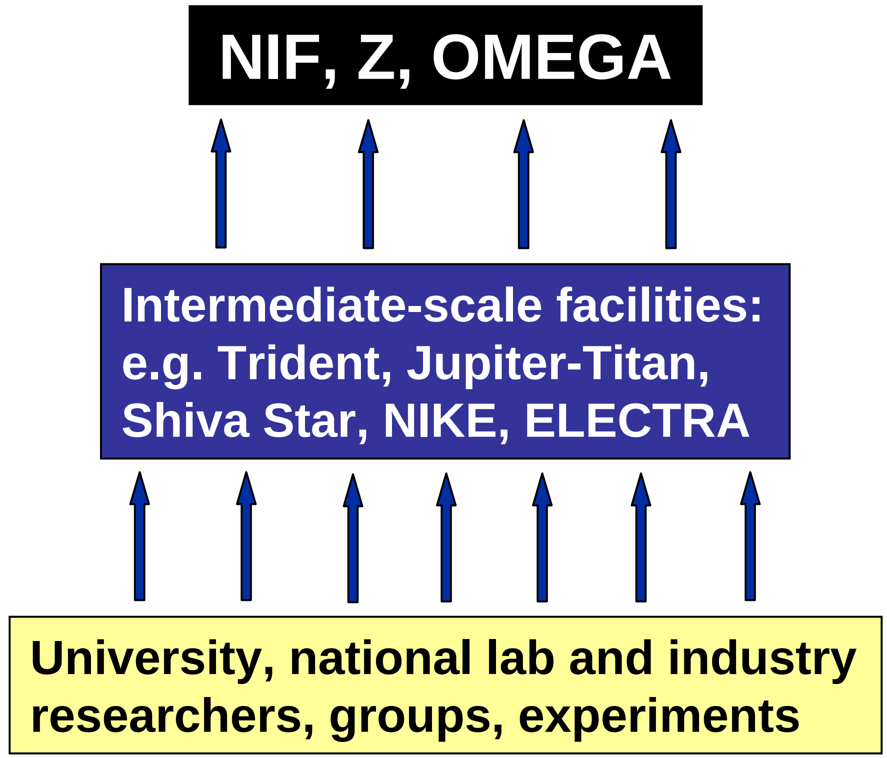


The Joint Program in HEDLP

- **OFES and NNSA ICF Office establishing a joint program in High Energy Density Laboratory Plasmas (HEDLP)**
  - *Addressing the finding of the interagency TF-HEDP*
  - *The joint program will provide stewardship of HEDLP while maintaining the interdisciplinary nature of this area of science*
- **Topical research areas include:**
  - *Laboratory astrophysics*
  - *Compressible dynamics and radiative hydrodynamics*
  - *Heavy ions, warm dense matter and strongly coupled plasmas*
  - *Dense plasmas in ultrahigh magnetic fields*
  - *Laser-plasma interactions*
  - *Inertial confinement fusion and fast ignition*
  - *HEDLP with ultra-fast and ultra-intense lasers*

Current SC/NNSA Joint Program in HEDLP

- **Initial main scientific themes[1]:**
  - Create, probe, and control new states of matter in HEDLP
  - Laboratory Astrophysics
  - Challenges in inertial fusion energy sciences
- **Program evolution will be guided by Advisory Committee and planning exercises**
- **First joint solicitation planned for 2008-2009**
  - Requesting + $5M for FY 2009
  - Details coming soon

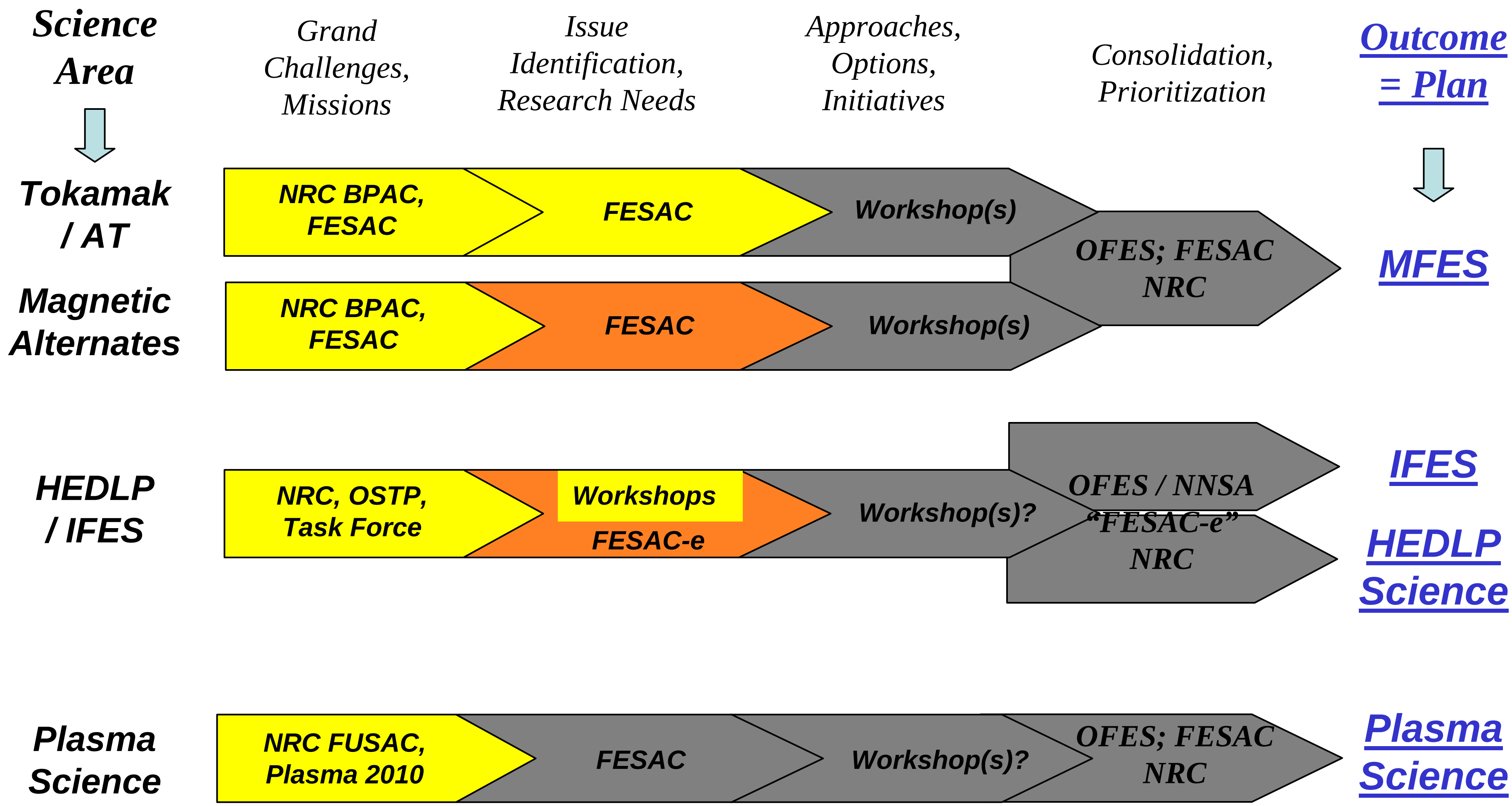


1. Recommended by community HEDLP Workshop at the Argonne National Lab (May 23–24, 2007)

Fusion Energy Sciences Program is Confronting Significant Issues

- **Support for ITER and the burning plasma program**
  - Integration of program vision
- **Addressing most issues in a flat-budget climate, at best**
  - Distribution of mission elements
  - Multi-year planning, despite single-year funding
- **New Initiatives needed, even on a flat budget**
  - Major Facilities utilization
  - ITER physics program and national research team
  - Fusion Simulation Project: the culmination of the MFES program
  - Future: confronting the fusion-plasma-materials challenges
  - HEDLP science needs
  - Plasma Sciences renewal (modest Plasma Science Initiative)
- **Need for strategic plans to guide decisions**
  - Resource redistribution inevitable
    - *E.g., near-term termination of major facility*

A Multi-year, Multi-Step Planning Process for ***Each*** Area of Responsibility



FESAC Gaps and Opportunities Study Already Suggests Basic Plan Structure

- **Address 4 major themes in establishing a basis for Fusion Energy**
  - Demonstrate control and understanding of burning plasma
    - *Issue: understanding high-gain, nonlinear burning plasma science*
    - *Initiative: ITER MIE, operations, and upgrades*
  - Creating predictable high-performance steady-state plasmas
    - *Issue: establish, control and sustain advanced tokamak scenarios*
    - *Initiatives: Fusion Simulation Project; off-shore tokamak collaborations*
  - Taming the plasma-material interface
    - *Issues: plasma-materials interactions*
    - *Initiative: domestic and international tokamak studies of plasma-wall*
  - Harnessing fusion power
    - *Issue: integrating the multiply nonlinear plasma-nuclear environment*
    - *Initiative: Materials Test Station; Fusion Nuclear Science Expt.*
- **Modest watch on alternative confinement concepts**
  - Expand knowledge base for toroidal confinement
  - Mitigate potential deficiencies in tokamak as reactor concept
- **Foster stewardship of plasma sciences**
- **Strengthen HEDLP and related inertial fusion energy sciences (IFES) to prepare for access to ignition studies on NIF**

Initial Prioritization of Issues Beyond Burning Plasmas:

Finding 3: Results of Prioritization

- **Tier 1:** *solution not in hand, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for both short and long term*
  - *Plasma Facing Components*
  - *Materials*
- **Tier 2:** *solutions foreseen but not yet achieved, major extrapolation from current state of knowledge, need for qualitative improvements and substantial development for long term*
  - *Off-normal events*
  - *Fuel cycle*
  - *Plasma-wall interactions*
- **Tier 2:** *(Continued)*
  - *Integrated, high-performance plasmas*
  - *Power extraction*
  - *Predictive modeling*
  - *Measurement*
- **Tier 3:** *solutions foreseen but not yet achieved, moderate extrapolation from current state of knowledge, need for quantitative improvements and substantial development for long term*
  - *RF launchers/internal components*
  - *Auxiliary systems*
  - *Control*
  - *Safety and environment*
  - *Magnets*

FESAC Planning Panel Final Report October 23, 2007

Questions to Address

- **Agency Specific**
  - Response to Plasma 2010 (& other NRC) Reports
    - *Most major recommendations adopted and are heavily influencing program*
  - ITER: status and US Contributions, funding
    - *FY 2009 is critical for US participation in ITER*
  - Priorities for the US domestic fusion research program
    - *Initial prioritization is emerging, but really needs boring down to extract scientific issues and needed initiatives; needs decoupling from near-term interests*

- **General**
  - Most significant issues over the next year
    - *Burning plasma future; strategic scientific planning*
  - Volatility in funding process and effects on program
    - *Obvious difficulties in plotting trajectories of programs over many years*
  - Where can Academy can add value
    - *Feedback during strategic planning process, and eventual review*
    - *Recognize differences between fusion sciences and plasma sciences; not zero-sum*

Summary

- **Detailed and exciting physics results from all areas of programs**
- **ITER growing from its “green-field” startup**
  - International Organization developing
  - Major Design review activity near completion
  - Cost and schedule will clarify over next year
- **Hoping to restore ITER funding in FY 2009**
  - Defunding in FY 2008 omnibus bill was an unfortunate surprise
  - Concerns on US reliability
  - US ITER Project Office surviving in minimal state
  - Attaining near President’s request in FY 2009 is needed for US participation in ITER
- **OFES responding to NRC recommendations**
  - Supporting several dedicated centers of excellence
  - Integrating burning plasma enterprise with other program activities
  - Stewardship of general plasma science and HEDLP are core interests
    - *General plasma science and DOE/NSF partnership (Plasma 2010)*
    - *New Joint Program for HEDLP (w/NNSA) (DOE Workshops)*
- **Embarking on extensive strategic planning and prioritization efforts for all lines of research**
  - NRC, FESAC studies; Reasearch Needs workshops; Consolidation to Integrated Plans