Perspective on Fusion Energy Strategy

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With
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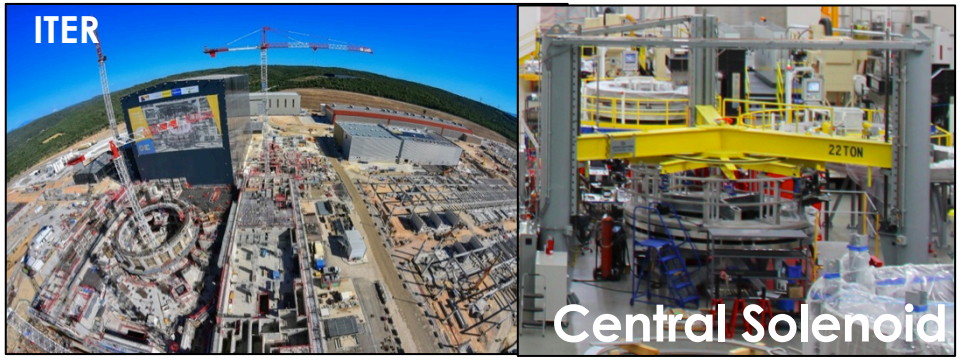
Presented at
NAS Committee for a Strategic Plan for U.S. Burning Plasma Research

August 29, 2017

Fusion Energy is at a Crossroads in the U.S.

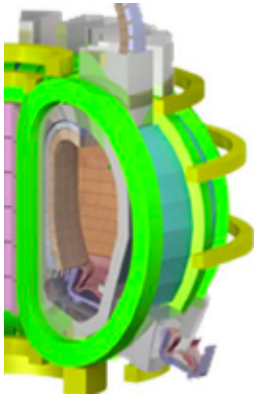
- **ITER construction underway**
  - Exciting and vital validation of the fusion energy concept

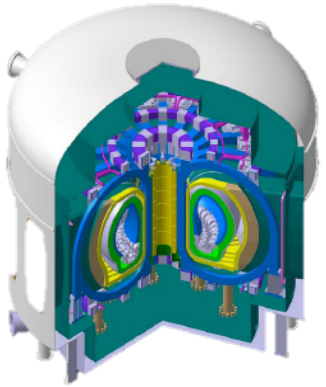


- **World program considering major facilities beyond ITER**

EU DEMO

K-DEMO


Japan DEMO


CFETR

World program is moving ahead aggressively with fusion energy development. What path with the U.S. take?

Your Charge to Me

We would especially appreciate learning your views on:

1) **The importance of U.S. burning plasma research to the development of fusion energy,**

2) **The scientific and technical developments since the 2004 report of the NAS Burning Plasma Assessment Committee**

3) **The current status of U.S. research that supports burning plasma science including U.S. scientific support for ITER**

4) **Any strategic elements that might strengthen or accelerate U.S. burning plasma research given that economical fusion energy within the next several decades is a U.S. strategic interest.**

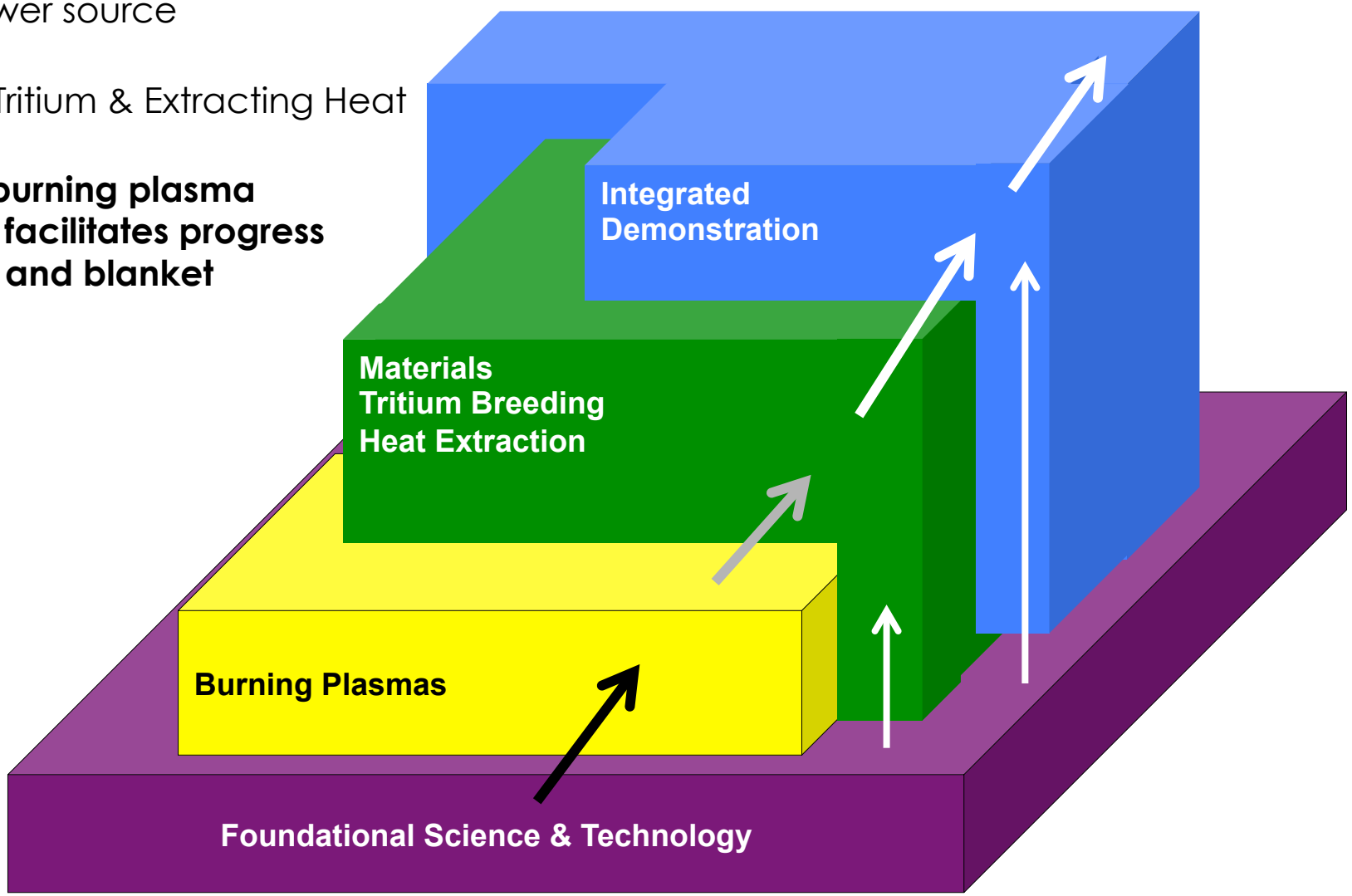
Importance of Burning Plasmas

Executive Summary:

- Burning plasmas are a critical next step towards the realization of fusion energy
- Tokamak physics is sufficiently advanced to support burning plasma step, and the tokamak remains the only fusion concept mature enough to proceed to the burning plasma step
- Strongly recommend that this committee reaffirm the importance of burning plasmas in fusion energy development, the highly developed status of tokamak plasma science, and the unique opportunity that ITER provides the U.S.

Burning Plasma: First Major Step on Path to Fusion Energy
Other Steps: Build on a Burning Plasma to Complete

- **For DEMO, technical readiness must be established for:**
  - Fusion power source
  - Materials
  - Breeding Tritium & Extracting Heat
- **Successful burning plasma experiment facilitates progress in materials and blanket technology**



A Burning Plasma Will Enable Frontier Fusion Science

- **Self-sustained fusion plasma is a highly nonlinear system**
  - Self-generated heating & magnetic fields → complex behavior
  - "Grand Challenge" for theory and numerical modeling

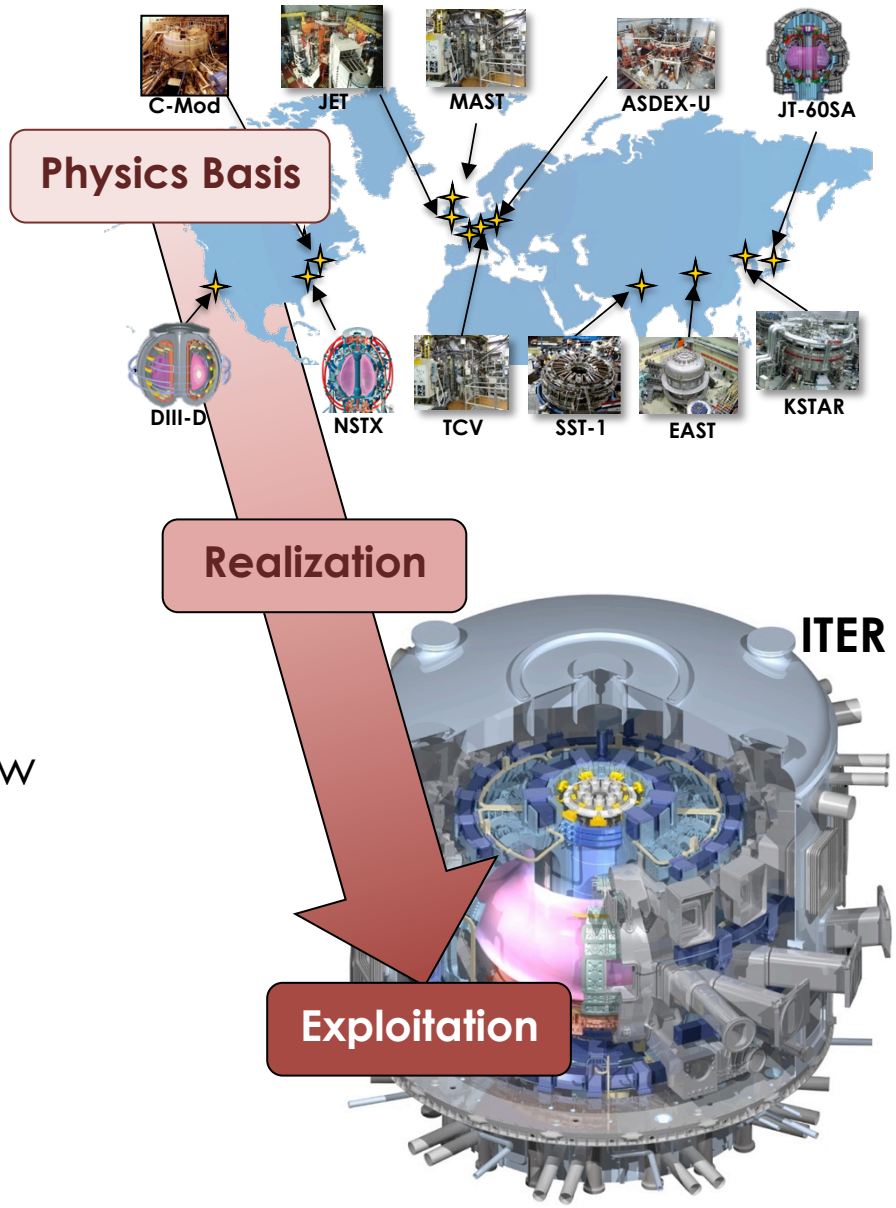
- **A burning plasma experiment and the supporting scientific program will advance basic plasma science**
  - Plasma turbulence, magnetic field line reconnection, wave-particle interactions, …
  - Applicable in other regimes (e.g. astrophysical plasmas)

"A burning plasma experiment can offer substantive and important contributions to other fields of science connected to plasma physics, primarily through experimental access to the fundamental and/or extreme conditions offered by such a state."

– Burning Plasma, NRC Report

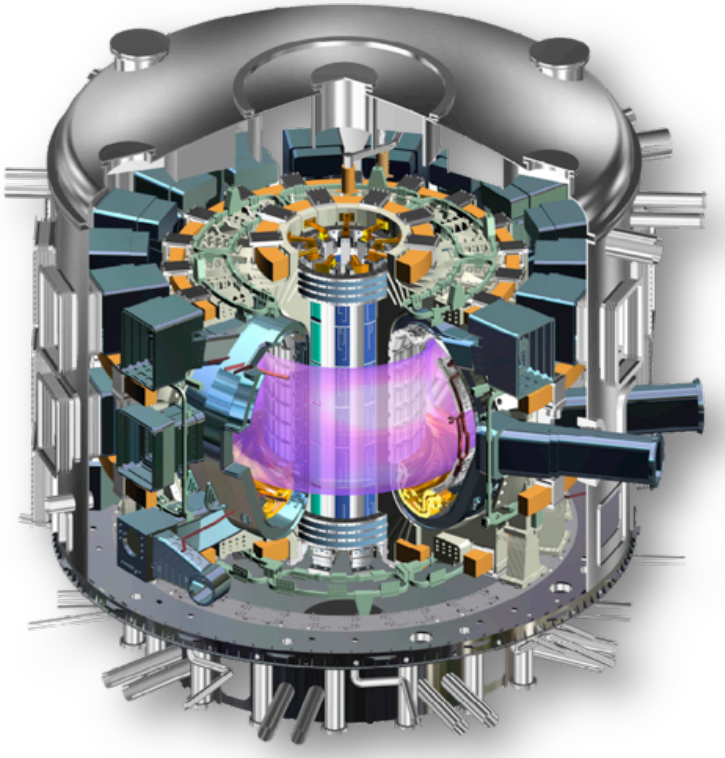
Burning Plasmas are both a Challenge and an Enormous Scientific Opportunity

- **Challenge: Produce burning plasma conditions and then maintain them**
  - Achieve necessary density/ temperature/ confinement (n T τ)
  - Operate safely at high plasma pressure
  - Handle concomitant heat/particle flux
  - Minimize/Eliminate effect of transients
- **Opportunities enabled:**
  - Alpha-particle impact on stability & turbulence
  - Turbulent transport and resistive MHD at low ρ^* (relative gyroradius) and rotation
  - Fusion burn stability, control, and propagation
  - Strong, non-linear coupling of heating, current drive, turbulent transport, MHD stability and boundary plasma



A Burning Plasma Experiment Drives Advances in Fusion Technologies

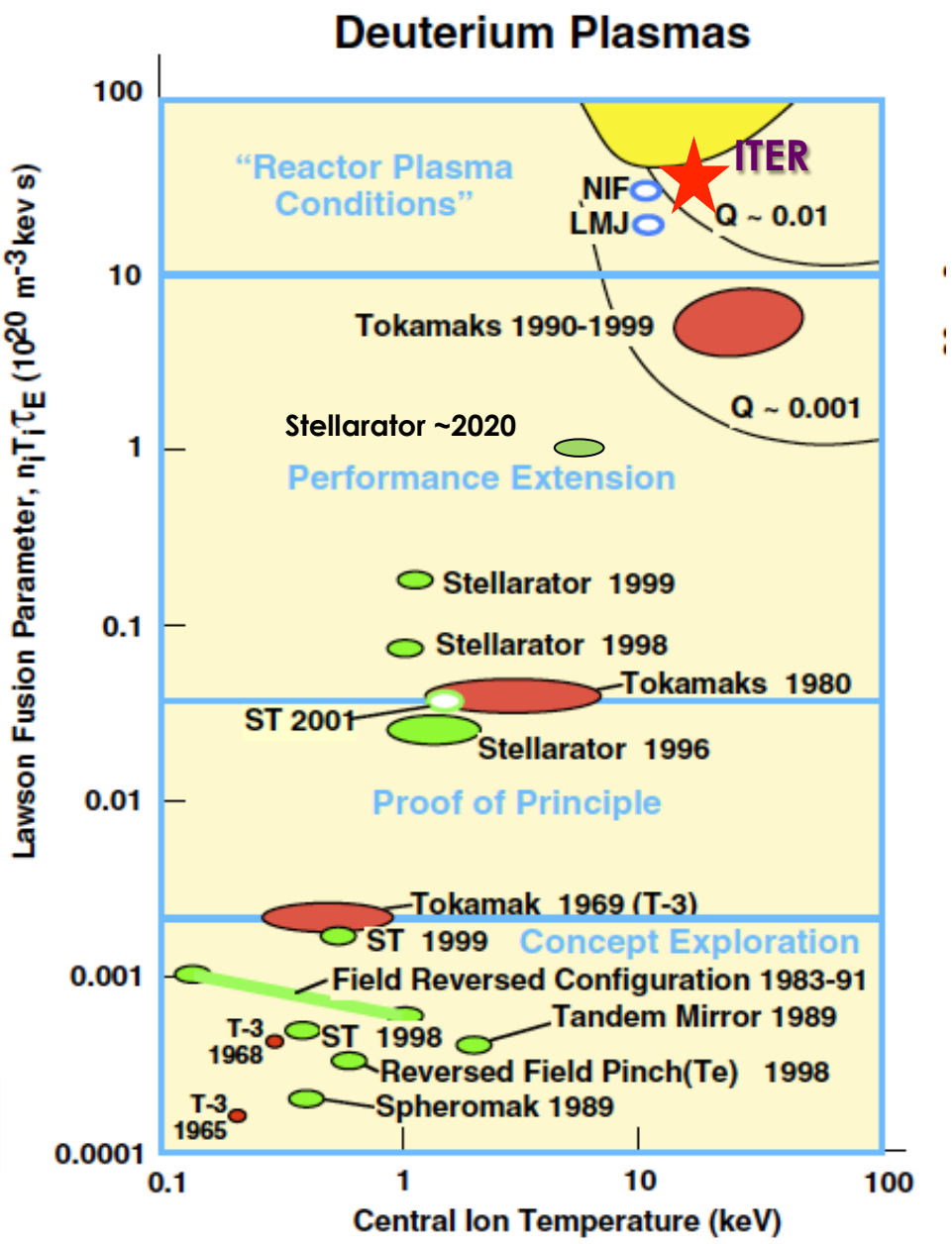
- **Large, high field magnets**
  - superconducting if long pulse
- **Remote maintenance and handling**
- **Tritium processing systems**
- **Hardened diagnostics**
- **High heat flux energy removal systems**
- **Long pulse, high power density heating and current drive systems**
- **Plasma current quench detection/ remediation systems**
- **Integrated control systems for the nuclear plant and plasma, including burn control**
- **Desired: test blankets for tritium breeding**
- **…**



Tokamaks Presently at Highest Level of Readiness of Any Concept to Exploit Burning Plasmas

- **Achieved tokamak performance is two orders of magnitude above other concepts**
- **Physics basis is well established (ITER Physics Basis in NF 1999, 2007)**
  - Recent advances in later section
- **Strong Worldwide Research Program**
  - Complementary and versatile facilities
  - Well diagnosed → solid science
  - Theory & simulation → prediction
  - Advanced plasma control
  - Large, capable work force

Tokamak is well positioned for continued scientific advances and innovation



Previous Panels Have Affirmed the Importance of Burning Plasmas and Opportunity to Participate in ITER

NRC Burning Plasma Report 2004

- **"Participation in a burning plasma experiment is a critical missing element in the U.S. fusion science program".**
- **"The United States should participate in the International Thermonuclear Experimental Reactor (ITER) project"**
- "Progress toward the fusion energy goal requires this step"
- **"**There is now high confidence in the readiness to proceed to the burning plasma step."
- "The tokamak is the only fusion configuration ready for implementing such an experiment."

NAS Decadal Study 2010

- "**It is clear that the next critical step in the development of fusion power is a burning plasma experiment. ITER is that step."**

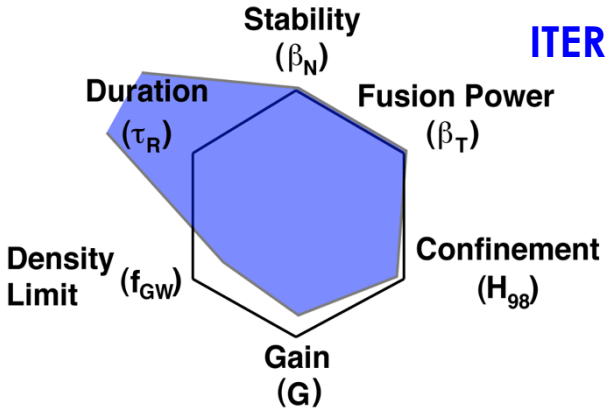
Strongly recommend that this NAS committee reaffirm the importance of burning plasmas and the unique opportunity of ITER

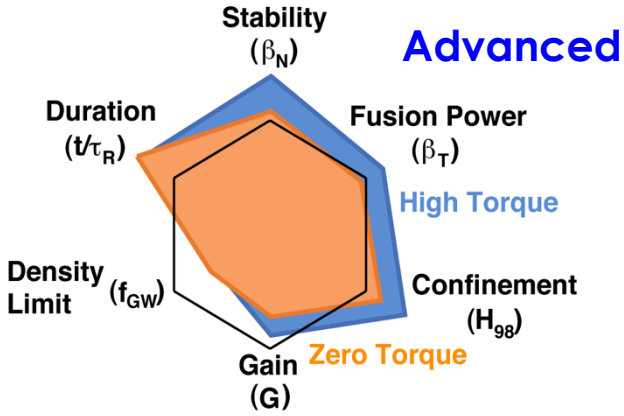
Scientific Developments since 2004 NAS Report

Executive Summary:

- The understanding of key physics governing underlying performance has advanced dramatically
- The U.S. fusion program remains at the forefront of fusion science.
- Research since the NAS Burning Plasma Report (2004) has strengthened our confidence in burning plasma (ITER) performance.

Scenarios Match ITER Q=10 Dimensionless Parameters Relevant to Fusion Power & Gain in Present-Day Expts





Issue	ITER Physics Basis (1998, 2007)	Present
Rotation	Co-NBI, high rotation	Zero applied torque solutions found
Electron heating	Ion dominant	Electron dominant heating explored
Operational issues	Basic EC/low voltage startup, rampdown in constant shape	Integrated tests of EC startup and rampdown with shape control
ELM mitigation	First indications of mitigation by RMP	RMP ELM suppression in baseline and advanced scenario, pellet pacing
Heat flux mitigation	Basic radiative divertor demonstration	Radiative divertor in operating scenario
Disruption mitigation	Basic physics understood	MGI and SPI tested
PMI	Mostly in graphite walls	Direct tests of ITER-like wall

Theory-Experiment Validation Has Increased Confidence in ITER Achieving its Q=10 mission

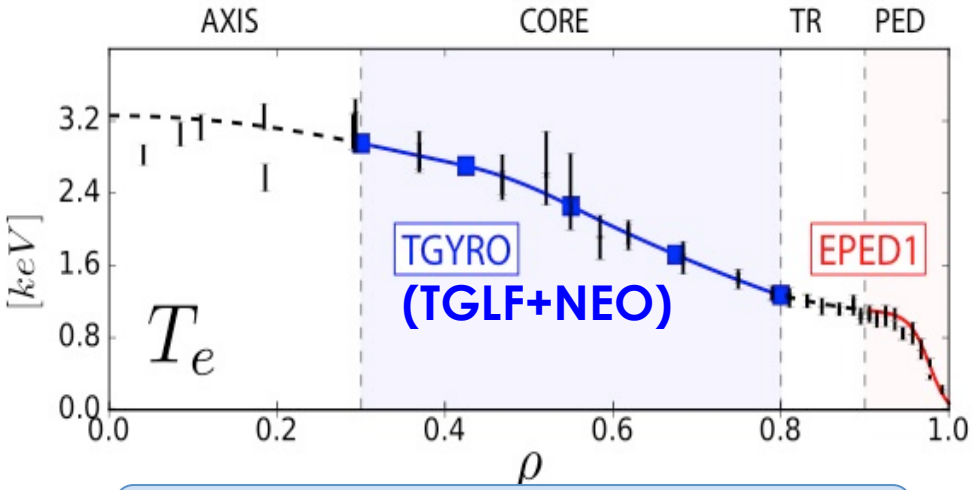
2004 status:

- **Manually-intensive "Herculean" simulations. Missing first principle pedestal model, rotation etc**

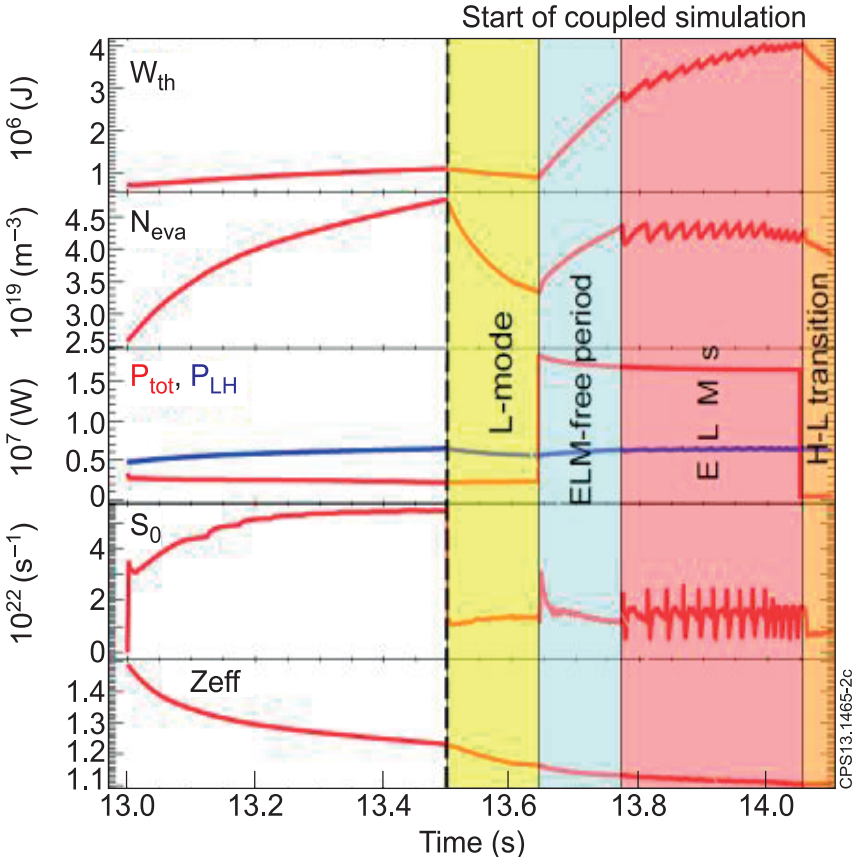
2017 status:

- **Self-consistent coupling of core & pedestal theoretical models**
- **Enables prediction and optimization of ITER fusion gain: Q~12 possible**

Profile Prediction (OMFIT, IPS, TRANSP, TGYRO using TGLF, NEO, EPED)



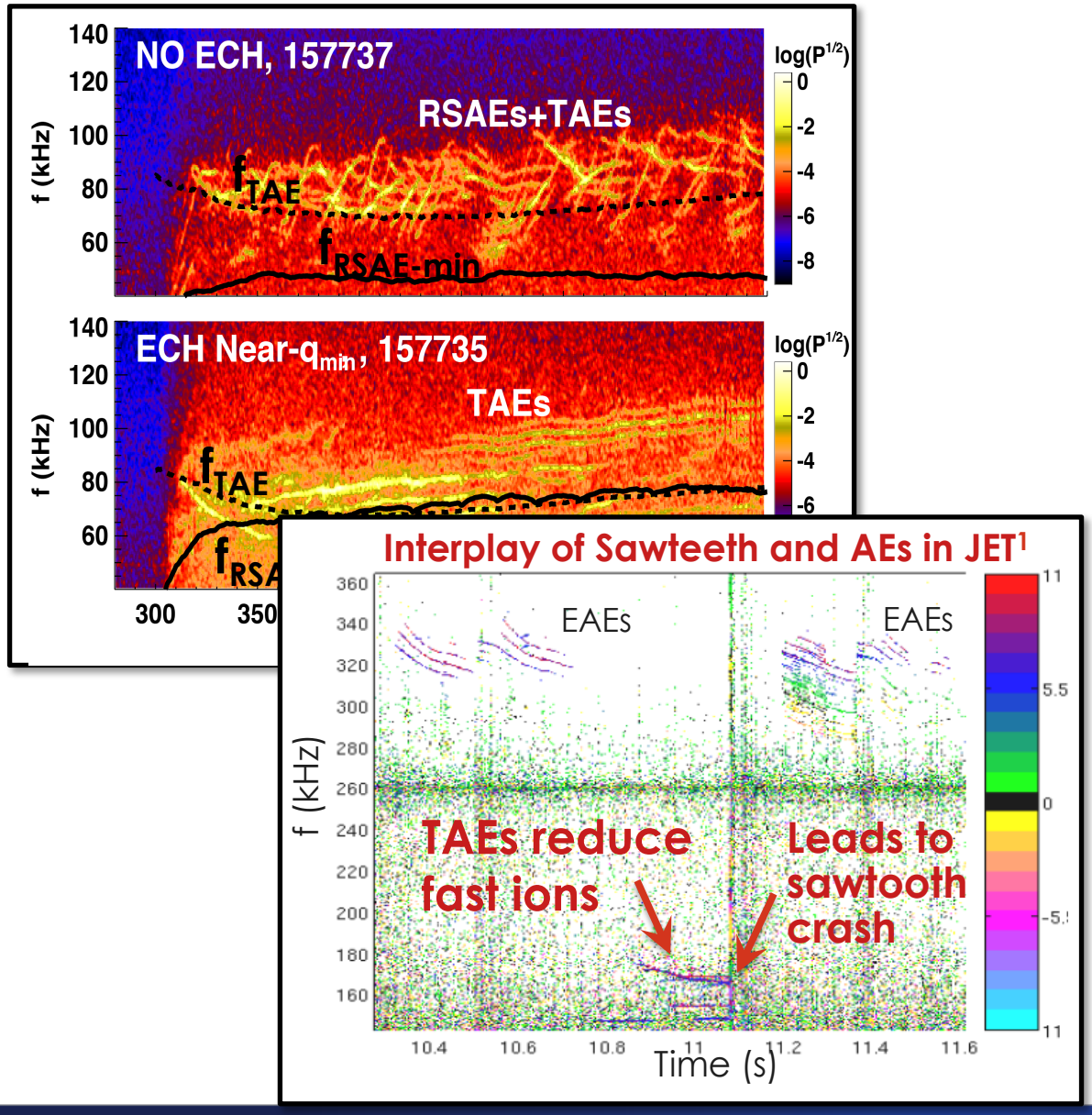
Meneghini Nucl. Fusion 2017, Snyder Nucl. Fusion Award 2014



Romanelli Plasma Fus. Res 2014

Major Advancement in Core Fluctuation Diagnostics Have Enabled Detailed Validation of Fast Ion Transport Models

ECH modification of RSAEs in DIII-D



2004 status:

- Alfven Eigenmodes and associated transport observed and characterized

2017 status:

- Fast-ion instability control tools show promise
- First principles simulations reproduce measured modes & transport (MEGA)
- Reduced predictive models based on critical gradient

Van Zeeland Nucl. Fusion 2016
Y. Todo Nucl. Fusion 2016
Sharapov IAEA 2016

ELM Suppression Achieved in Fully Non-Inductive Hybrid Plasma with Minimal Impact on Performance

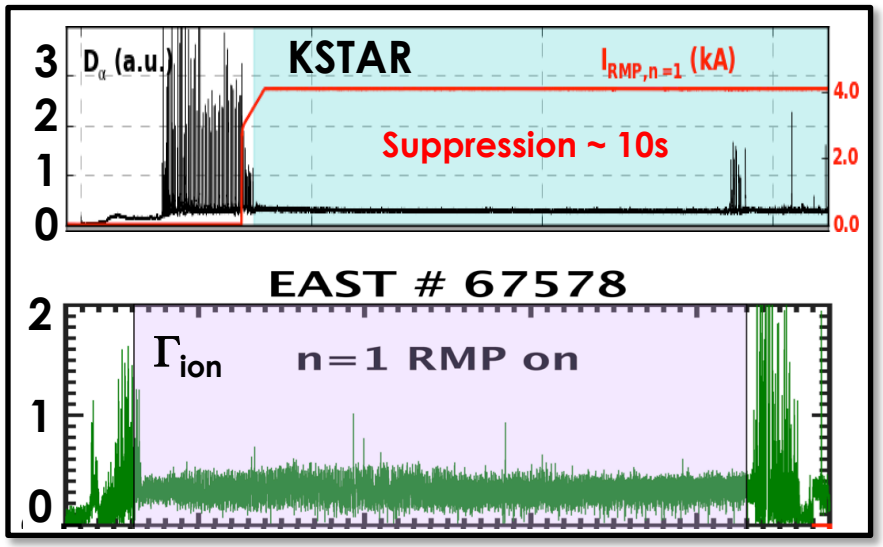
2004 status:

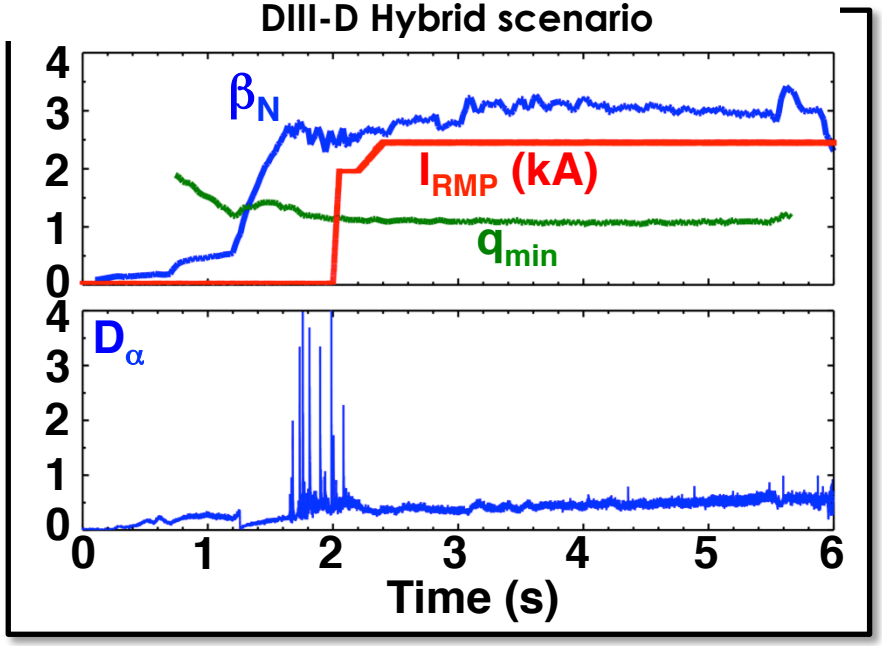
- Proof-of-principle demonstrations of RMP ELM suppression, pellet pacing, and QH-mode

2017 status:

- Extension of all technique towards ITER conditions
- Long-pulse ELM suppression
- I-mode developed, QH-mode operation expanded
- Role of plasma response and field penetration

Petty Nucl. Fusion 2017
Oh IAEA 2016
Sun IAEA 2016





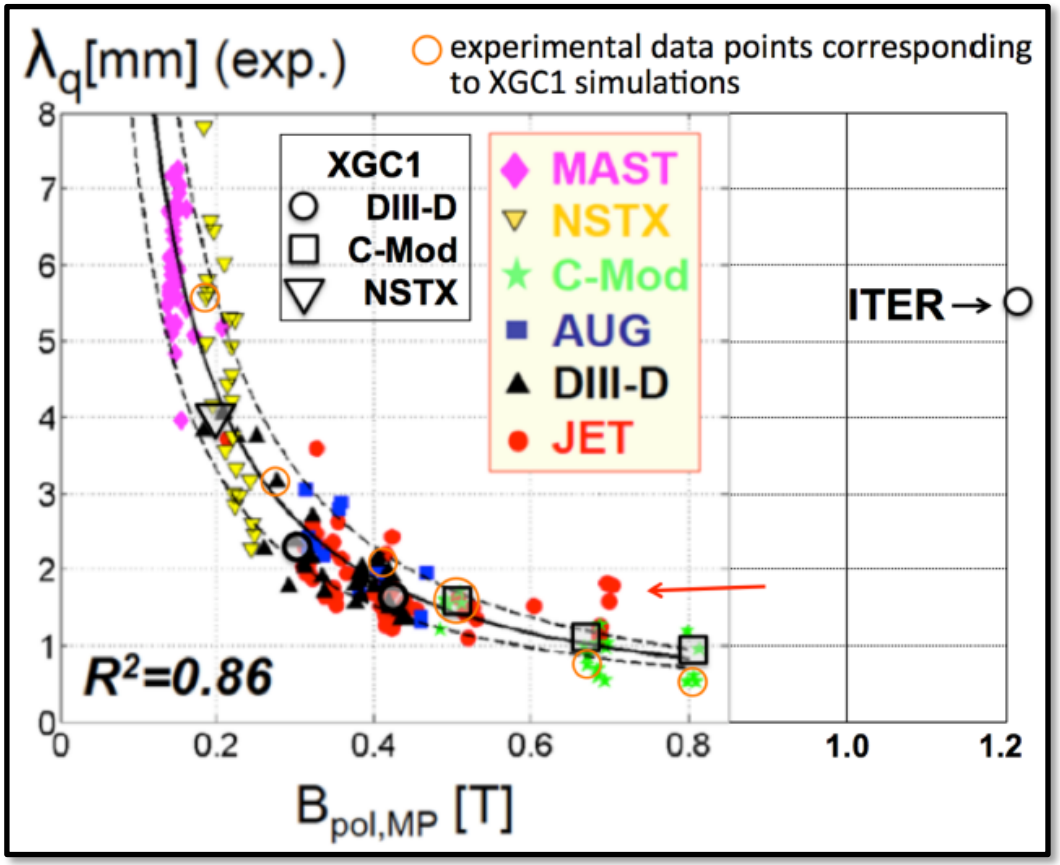
Major New Understanding in SOL Heat Flux Channel Width Developed Through Joint Experiments

2004 status:

- Conflicting experimental data on heat flux width; large experimental uncertainties

2017 status:

- ITPA empirical scaling developed setting potential challenge for 15 MA ITER discharges (λ_q ~ 1mm)
- High performance computing enabling gyrokinetic simulations of heat flux width
- New role of electron turbulence found in simulations which may significantly broaden heat flux



Goldston Nucl Fusion, 2012
Eich, Nucl. Fusion, 2013
Chang, Nucl. Fusion, 2017,

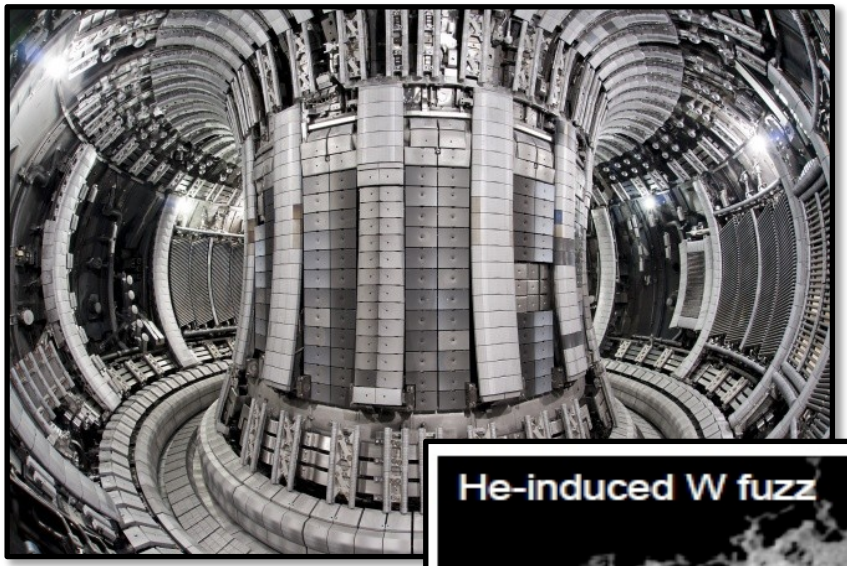
Major Advances Have Been Made to Understand Tungsten Behavior Under Extreme Conditions

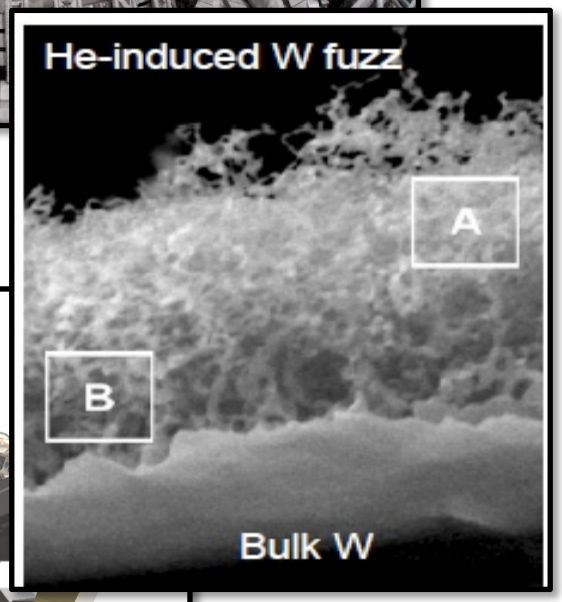
2004 status:

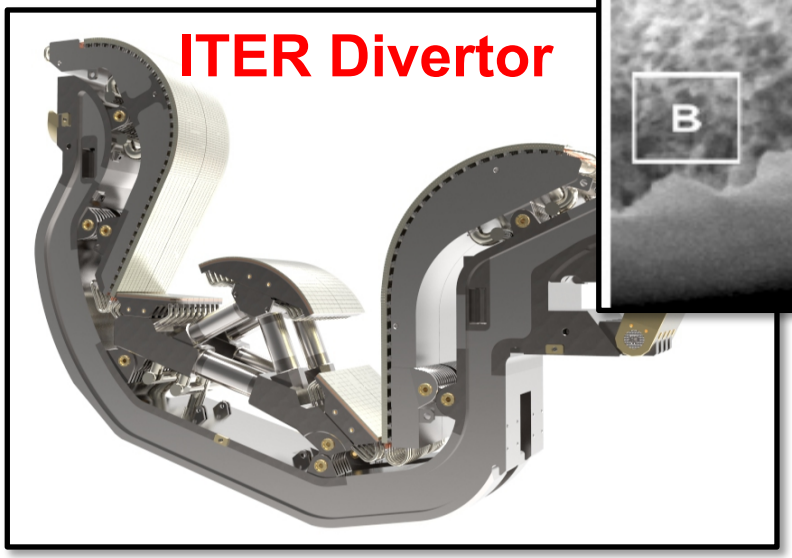
- Most devices favor low-Z wall for plasma performance

2017 status:

- ITER to start operation with full-W divertor
- JET ITER-like-wall (ILW) used to characterize tritium retention, fuel removal, cracking, melting, dust, plasma performance
  - Low T retention (0.3%)
  - Similar core confinement, pedestal Te reduced
- Surface modifications (He-fuzz)



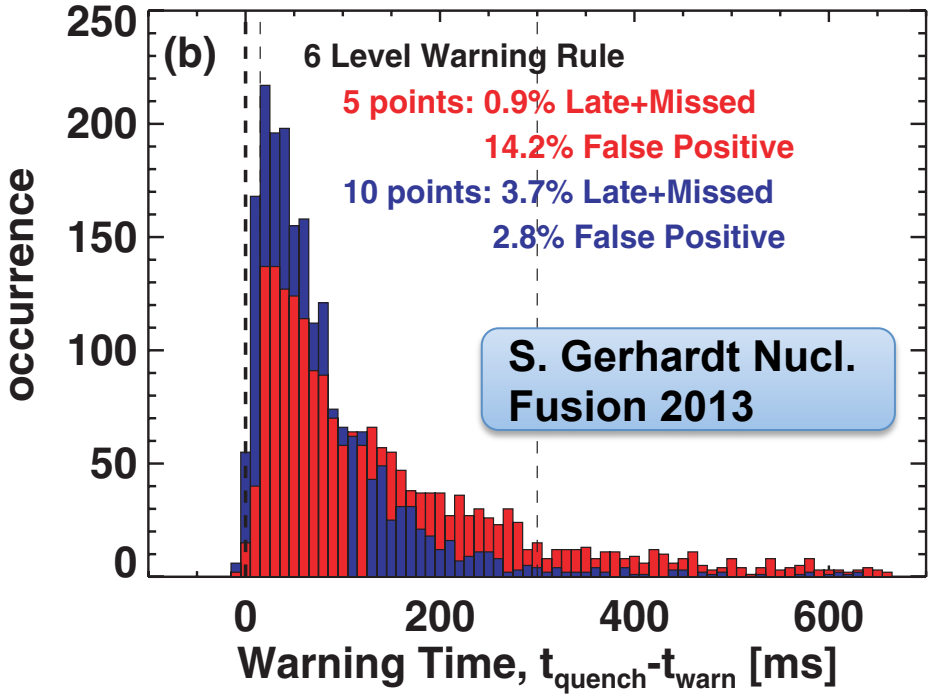


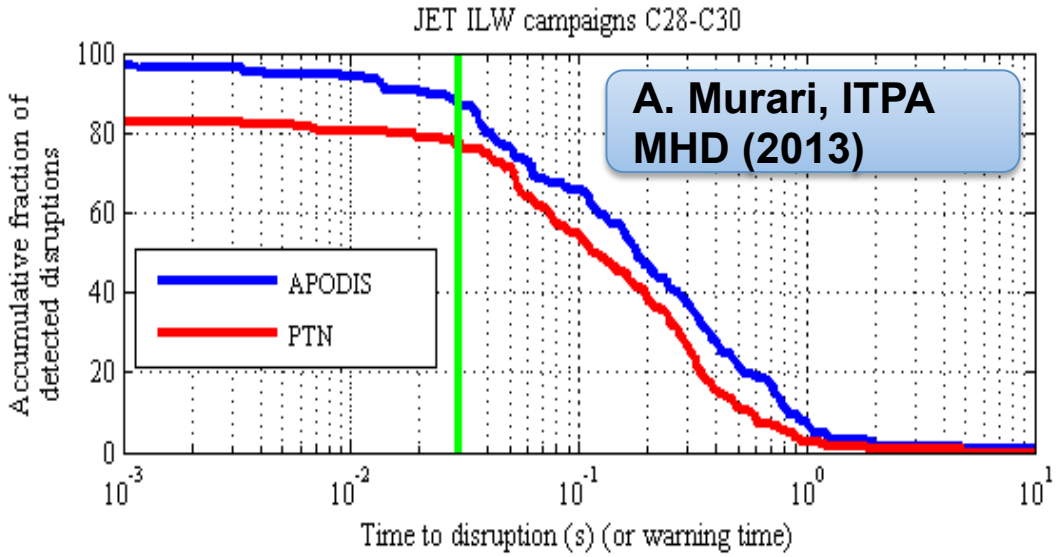


Litaudon Nucl. Fusion 2017
Baldwin Nucl. Fusion 2008

Powerful Tools Have Been Developed to Predict and Avoid Disruptions

- **Advanced disruption warning systems predict oncoming disruptions**
  - **NSTX: > 96% disruptions caught, < 3% false alarm**
  - **JET: > 98% disruptions caught, < 1% false alarm**





- **Extensive suite of disruption avoidance techniques**
  - NTM control by ECCD, MHD instability control, MHD spectroscopy

Strong Progress in Explaining Fast Dissipation of 'Runaway' Electrons at Plasma Termination

2004 status:

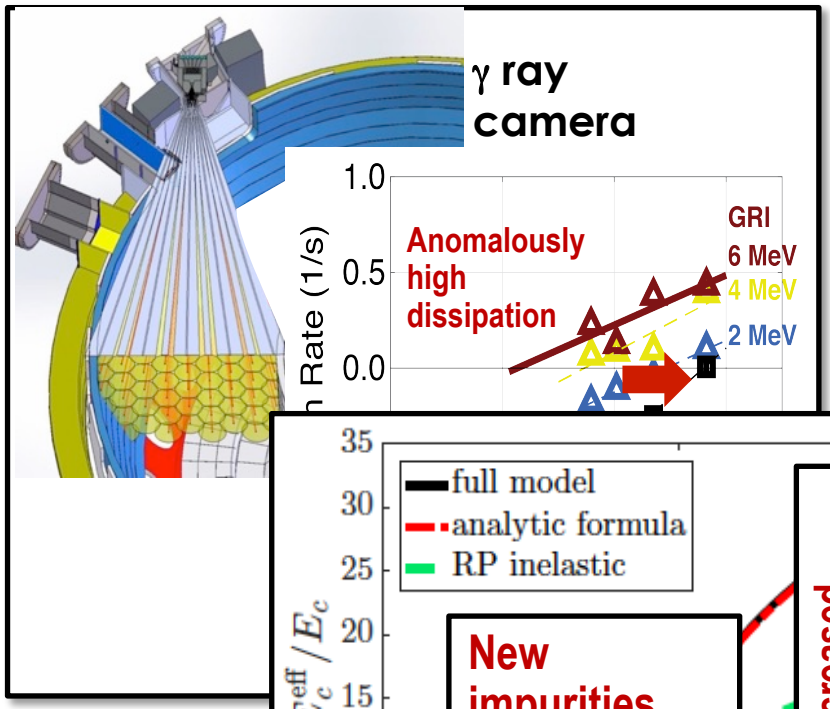
- Critical electric field quantified, additional terms starting to be explored

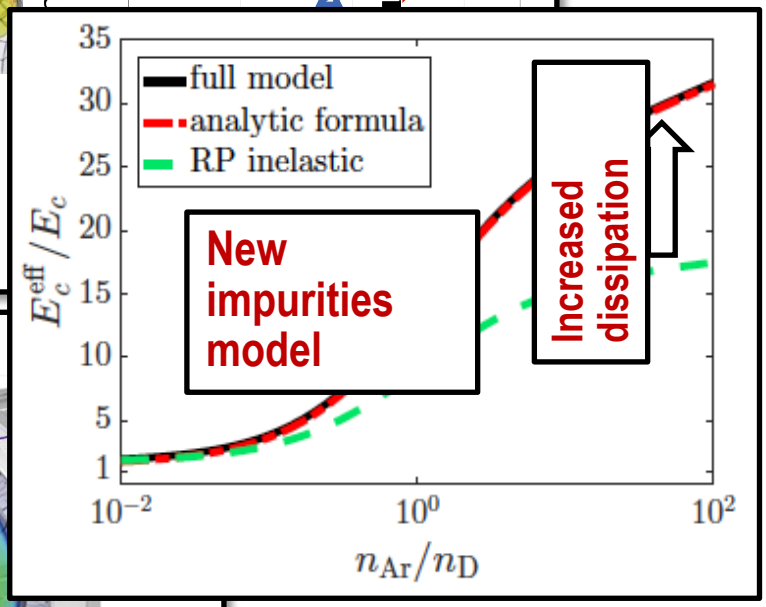
2017 status:

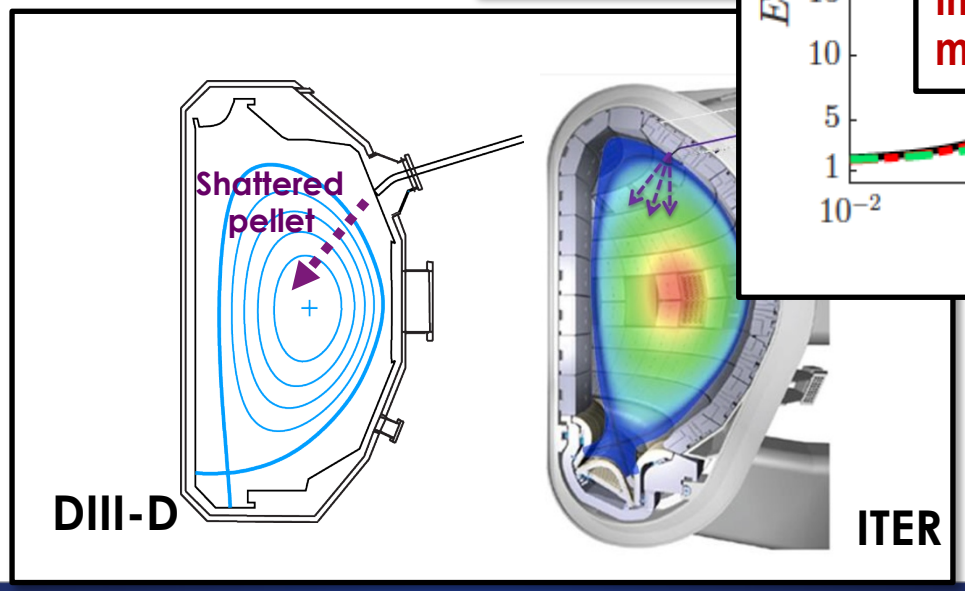
- Simulations capture underlying dissipation mechanisms
- Dominant RE seed processes discovered (hot tail)
- RE control developed

Strong U.S. focus

- Experiment
- SciDAC SCREAM
- BPO task group
- ORNL/DIII-D pellets







Paz-Soldan PRL 2017
Hesslow PRL 2017

Progress Since the 2004 Burning Plasma Report Has Strengthened Our Confidence in BP Performance

Topic (example)	2004	2017
ITER Operational Scenarios	Isolated examples of performance, high rotation, ion heating	• Integrated solutions • Extended toward ITER conditions (low rotation, e-heating) • JET ILW
Pedestal	Peeling-ballooning theory developed	• Predictive model of pedestal performance validated against experiments
Energetic particles	AEs observed, basic mode properties and associated transport characterized	• Advanced fluctuation and fast ion distribution measurements • First gyro-kinetic simulations reproduce measurements • Reduced predictive models based on critical gradient
Disruption mitigation and avoidance	Massive gas injection for fast shutdown, limited capabilities on disruption avoidance & mitigation characterization	• SPI technique • Understanding of radiation asymmetries • Real-time stability calculations & disruption predictors

Progress Since the 2004 Burning Plasma Report Has Strengthened Our Confidence in BP Performance

Topic (example)	2004	2017
Runaway electrons	Critical electric field quantified + other terms being explored	• Simulations capture underlying dissipation mechanisms • RE control developed
ELM control	Proof-of-principle demonstrations of RMP ELM suppression, pellet pacing, and QH-mode	• Extension towards ITER conditions • Understanding of stability limits
Error Fields	Simple vacuum field understanding	• Predictive models with plasma response and field penetration
Transport	Gyrokinetic codes and reduced transport models being developed	• Multi-field, multi-scale simulations compared with data • Improved fidelity reduced models
Integrated modeling	Manually intensive “Herculean” simulations. Missing first principle pedestal model, rotation etc	• General frameworks developed for streamlined integrated workflows • High fidelity models using high performance computing

Progress Since the 2004 Burning Plasma Report Has Strengthened Our Confidence in BP Performance

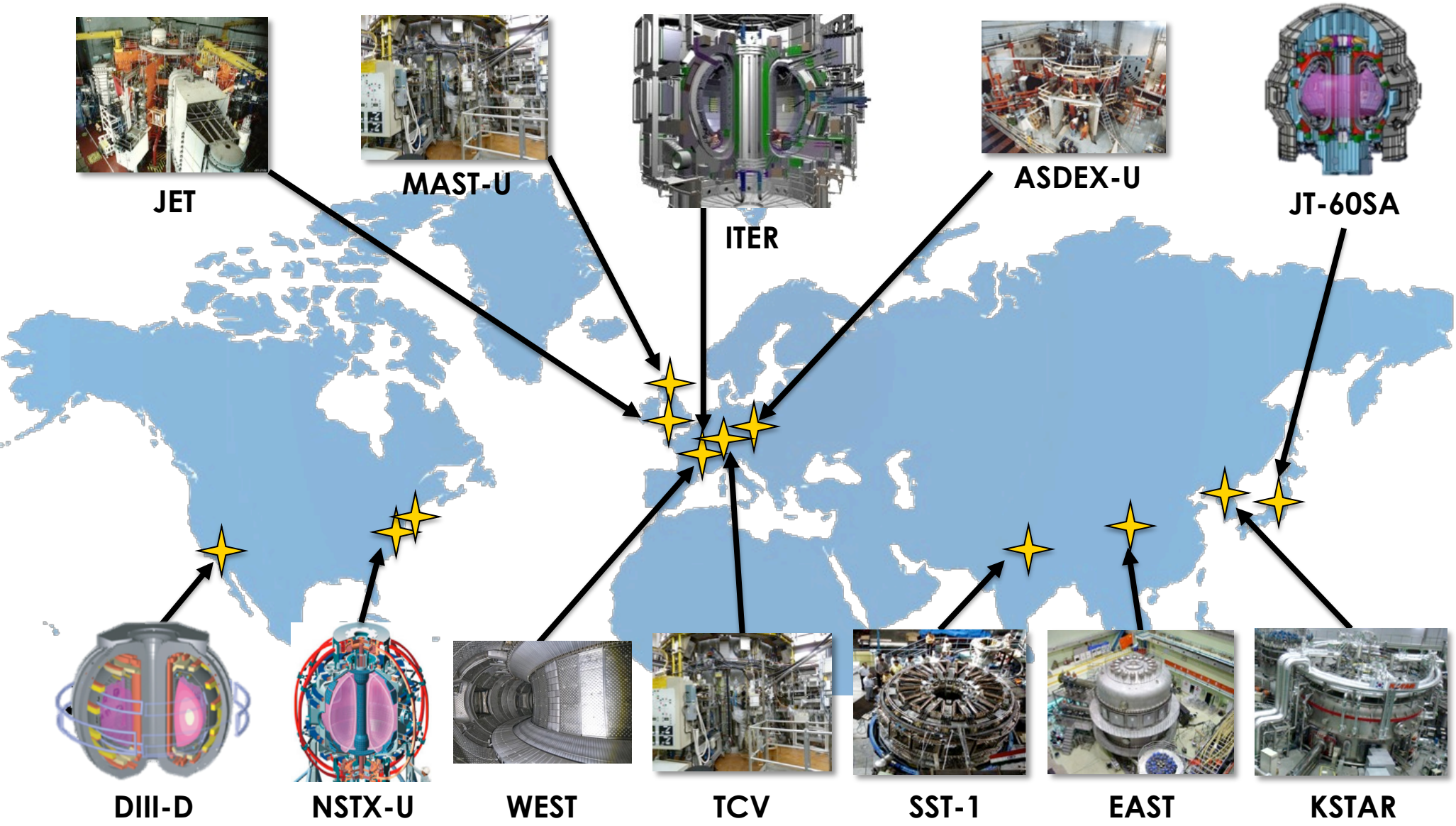
Topic (example)	2004	2017
Plasma control	Feedback control of 0D plasma parameters	• Profile control • Offline control developed by simulation
Divertor power handling	Demonstration of heat flux reduction in low-Z tokamaks	• Extended to metal walls • Feedback control of divertor heat flux
SOL heat flux width	Conflicting experimental data on heat flux width	• ITPA empirical scaling developed • New role of electron turbulence predicted in gyrokinetic simulations
Divertor geometry	Standard configurations with limited poloidal flux expansion	• Advanced divertor configurations with increased poloidal/toroidal flux expansion
PMI	Individual research on local surface, global migration, SOL transport	• Integrated studies between core/edge/wall • Mixed wall and ITER-like wall material studies

Status of *World-Wide* Research That Supports Burning Plasma Science

Executive Summary:

- The world program is focused on preparing for burning plasmas in ITER
- ITER has been highly effective as a forcing function for driving progress in fusion science and technology.
- World tokamak program is well positioned to address any emerging issues with regard to ITER operations and successful attainment of Q=10
- U.S. facilities are highly capable research platforms for innovation and understanding

The World Program Is Focused on Preparing for Burning Plasmas in ITER

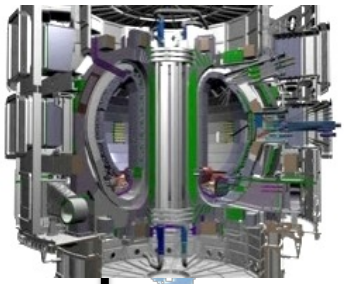


U.S. is a major contributor, and benefits greatly from participation

The World Program Is Focused on Preparing for Burning Plasmas in ITER

JET

MAST-U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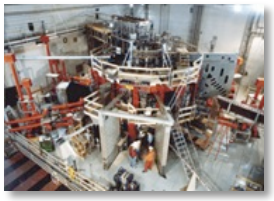
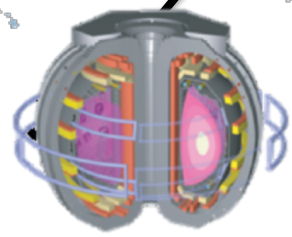
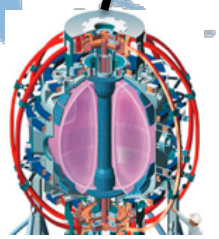

ASDEX-U

JT-60SA

International partners provide

- Stronger scientific basis
- Broad team, range of facilities, tools, and experience
- Industrial fabrication capabilities
- Shared costs


DIII-D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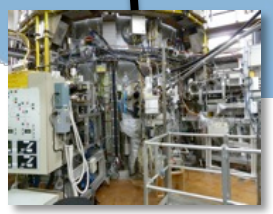
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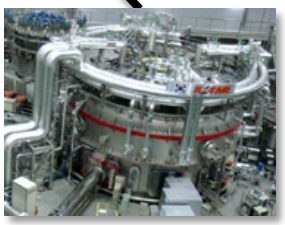
SST-1

EAST

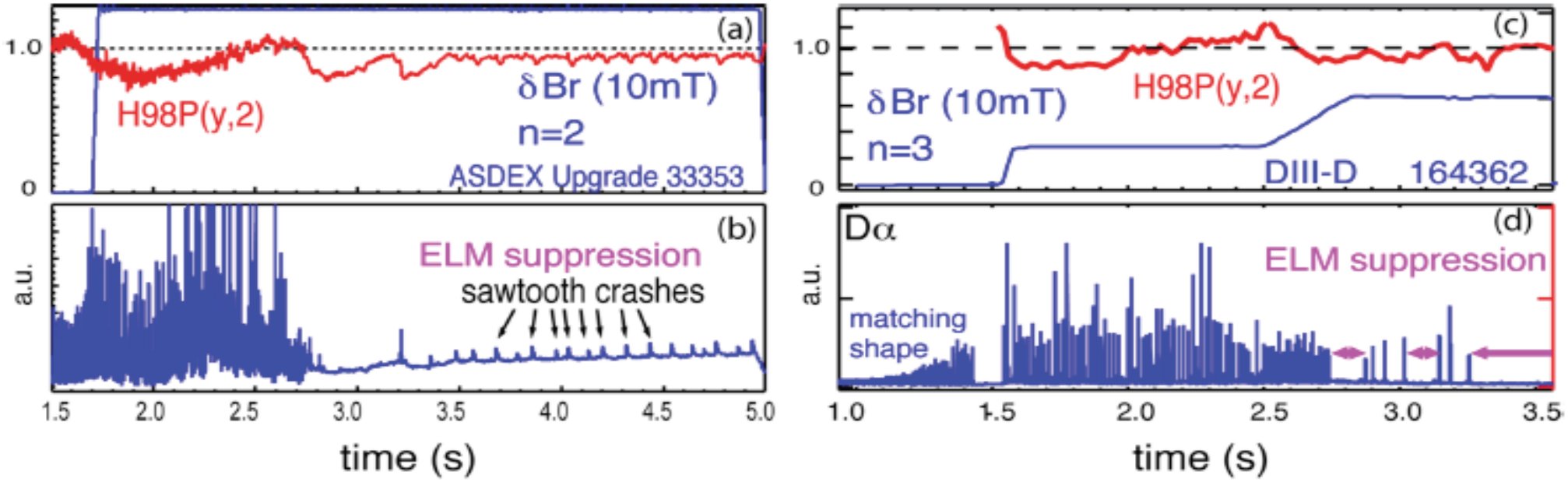

KSTAR

U.S. is a major contributor, and benefits greatly from participation

The World Fusion Community is Organized to Carry Out Burning Plasma Research

- **International Tokamak Physics Activity (ITPA) makes key contributions to coordinating worldwide burning plasma research through joint experiments on multiple devices**
  - ~ 850 scientists from all 7 ITER parties (US, China, EU, India, Japan, Korea, Russia) plus Australia
  - 7 Topical Groups focus research in key areas
    - Diagnostics, Divertor-Scrape-Off-Layer, Energetic Particles, Magnetohydrodynamic Instabilities, Pedestal & Edge Physics, Transport and Confinement, Integrated Operating Scenaros
  - Semi-annual meetings convene 30-40 members and other experts
    - State of the art burning plasma research discussed
    - Multi-machine joint research proposals generated
    - Recommendations for ITER generated
  - Over 100 refereed journal publications produced directly from ITPA topics in last 5 years
- **The US plays a substantial role in ITPA experiments and documentation activities**
  - Over 200 US scientists

ITPA Success Story: ELM Suppression by Magnetic Perturbations Verified on US and EU Tokamaks



- **ELM Suppression using internal coils on DIII-D initially formed the basis for adding 3D coils to the ITER design**
- **ITPA Joint Experiment organized to reproduce ELM suppression on other tokamaks**
- **DIII-D and ASDEX-Upgrade joint experiment led to the first observation[1-3] of ELM suppression in AUG, confirming basis for ITER**

1. R. Nazikian, W. Suttrop et al. Proc. 26th IAEA Fusion Energy Conf., Kyoto, Japan (2016), to be submitted to Nuc. Fusion
2. W. Suttrop, R. Nazikian et al., submitted to Phys. Rev. Lett. (Nov 2016)
3. W. Suttrop, R. Nazikian et al., Proc 44th European Phs. Soc. Conf., Belfast, N. Ireland (July 2017), to be submitted to Plas. Phys. Control. Fusion

ITER Project is Coordinating Additional Research Activities Involving World Community

- **ITER Research Plan**
  - Developed in collaboration with community experts worldwide, this document outlines the anticipated content and schedule for research activities on ITER
- **ITER Integrated Modeling Expert Group**
  - Help guide the ITER integrated modeling program and to act as an interface between member physics modeling programs and the ITER organization.
- **ITER Scientist Fellow**
  - Prepare for the scientific exploitation phase of the device by strengthening the involvement of the fusion community directly with ITER. Interact closely with the ITER Science & Operations Department in the definition of a research program
- **ITER Operations Network**
  - Provide advice and feedback to the ITER project in the Operations area…"

Complementarity/Uniqueness of World Tokamak Facilities Continue to Advance Fusion Toward Burning Plasmas

- Complementarity enables multi-platform development and evaluation of key physics
- Uniqueness promotes evaluation of new ideas that emerge from synergistic collaborations across facilities

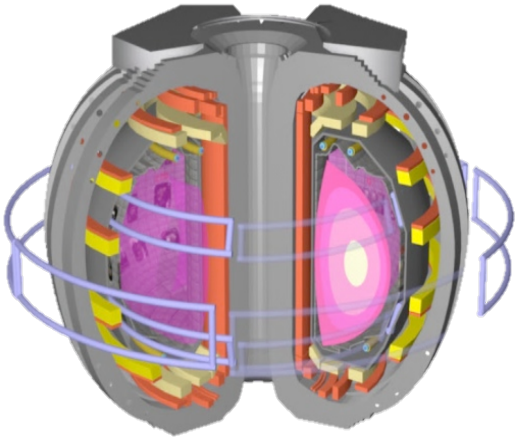
Well positioned to advance burning plasma science in preparation for and in concert with ITER

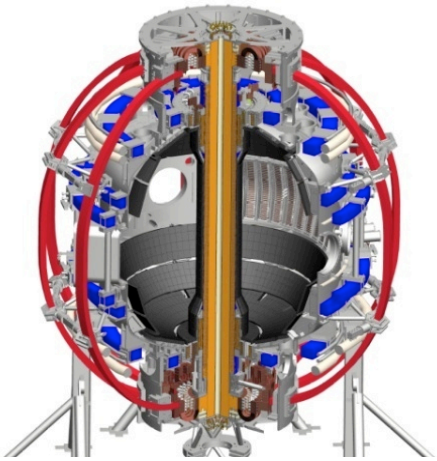
Tokamak	Key Contributions to Burning Plasma Science
DIII-D	Scenarios, transients, control, EPs
NSTX-U	Low R/a physics, EPs, transients
JET	Tritium, size scaling, ITER-like wall
AUG	Transport, divertor, tungsten wall
TCV	Shaping effects on core and divertor
MAST-U	Low R/a physics, advanced divertor
WEST	Long-pulse tungsten divertor
EAST	Long-pulse scenarios, core/edge compatibility, metal walls
KSTAR	Long-pulse physics, 3D fields, H&CD technology
JT-60SA*	H&CD technologies, advanced scenario demonstration
ITER*	Integrated burning plasma demonstration

*under construction

U.S. Facilities: Excellent, Cost-Effective Research Tools to Provide World-Leading Fusion Science

DIII-D





NSTX-U

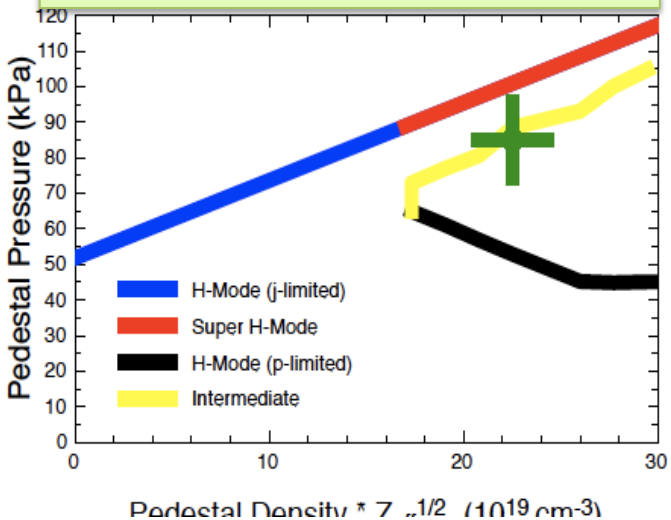
- **DIII-D and NSTX-U provide world-leading and complementary capabilities to resolve scientific Issues for fusion energy**
  - Mature facilities with established infrastructure and experienced staff
  - Highly flexible, 2D shaping, controlled 3D magnetic perturbations,
  - Well diagnosed: in-depth scientific investigations and model validation
  - Divertor structures top and bottom, easily modified
  - National and international research teams
  - Low vs high torque and ρ_e
  - Complementary current drive (ECCD, Helicon vs HHFW, helicity injection)
  - Complementary boundary approach (cryopump vs lithium, solid vs liquid)

Train the next generation of scientists and engineers

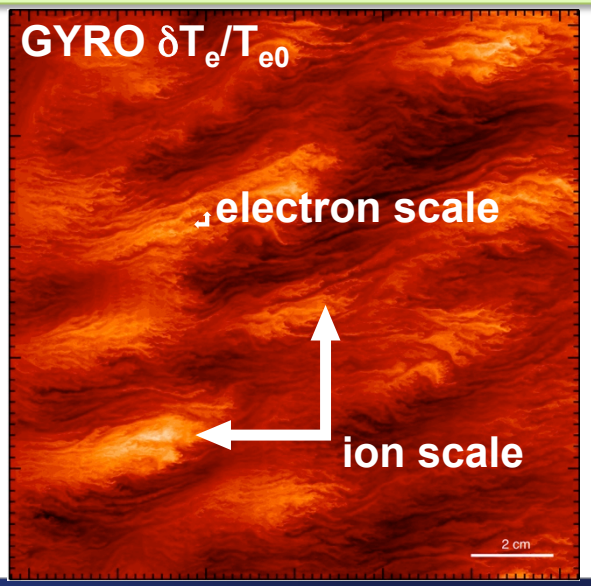
US Theory and SciDAC Burning-Plasma Research: Rapid World-Leading Advances in Predictive Capability

- **Develop and support world-class numerical tools**
  - GYRO, GS2, GTC, GEM: electromag. turbulence
  - M3D-C1, NIMROD; nonlinear extended MHD
  - BOUT, ELITE, XGC1, COGENT, UEDGE: bound. & PMI
  - TGLF, NEO, EPED: core/pedestal prediction
  - OMFIT, TRANSP, ISP: integrated simulation
  - AORSA, NuBEAM, CQL3D: RF sources
- **Address important burning plasma issues**
  - Performance prediction with coupled core & pedestal → higher confidence, optimization
  - Pedestal transport and L-H transiton
  - Plasma response to 3D fields →ELM suppression
  - Simulation of RE dynamics and disruption mitigation scenarios
  - Critical gradient and resonance broadening EP transport models
- **Strong U.S. partnership between theory & experiment**
  - Model validation
  - Interpret, direct, and predict experiment →discovery and innovation in fusion research

EPED Super H-Mode Prediction
Theory → experiment



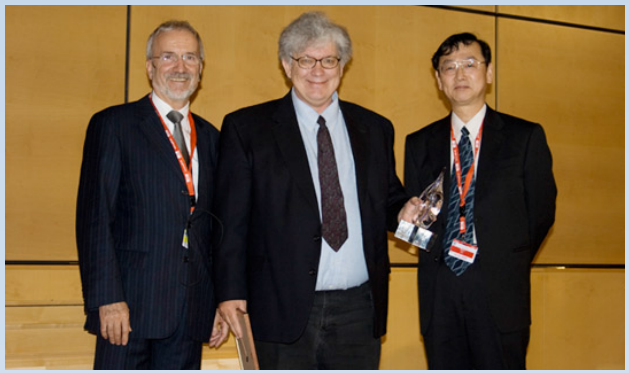
Multi-Scale Turbulence (GYRO)



U.S. Leadership In Burning Plasma Research Evidenced By Nuclear Fusion Prize Recipients (won 8 of 11)

Luce, Scenarios, 2006

Evans, ELM Suppression, 2008



Sabbagh, Stability, 2009

Rice, Intrinsic Rotation, 2010

Diamond, Rotation Theory, 2012

Snyder, Pedestal, 2014

Whyte, Scenarios, 2013

Goldston, SOL physics, 2015

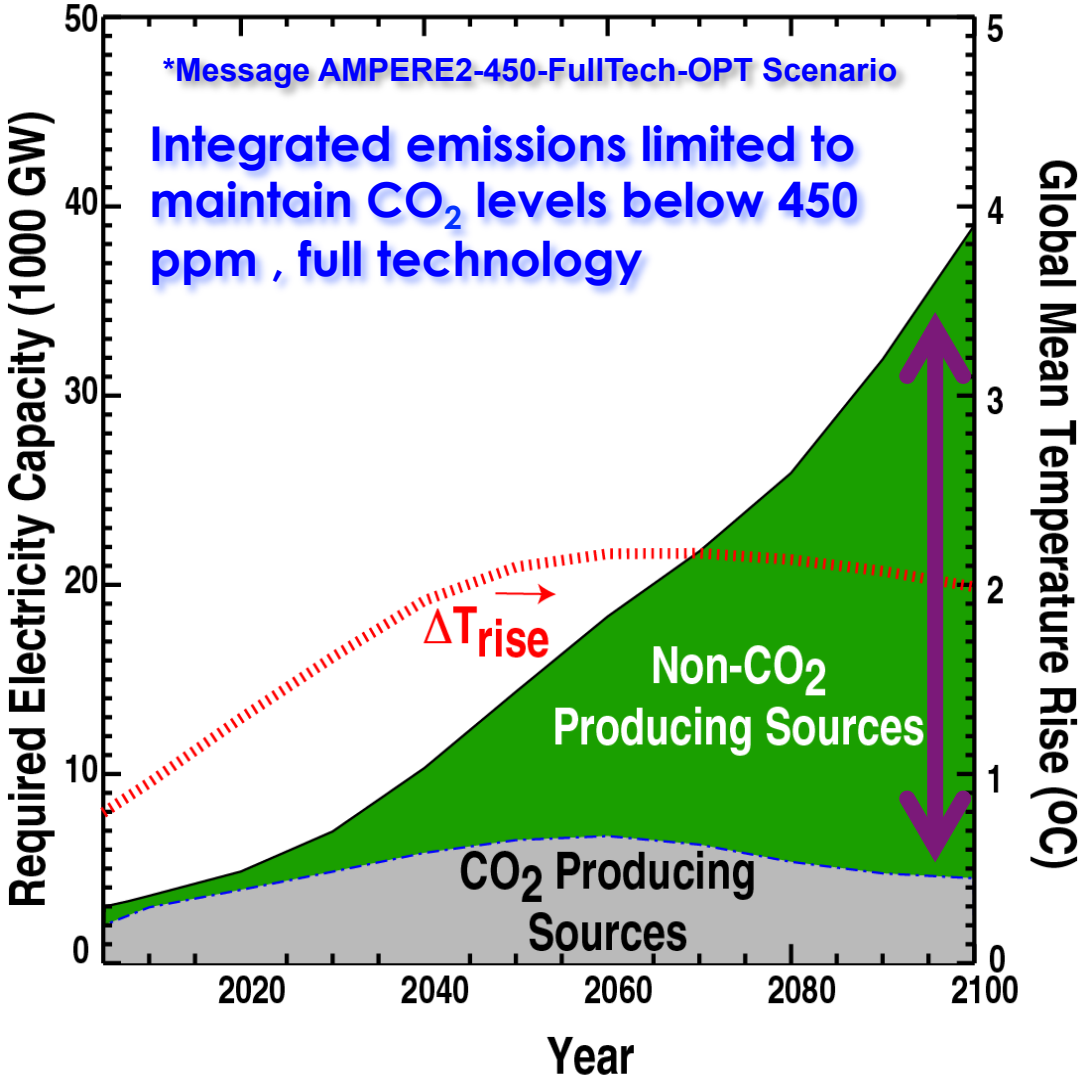
Strategic Elements to Strengthen or Accelerate U.S. Burning Plasma Research

Executive Summary:

- Realizing fusion energy within the next several decades will require increased funding and reduced costs.
- ITER provides the most timely and capable option for the U.S to exploit burning plasmas.
- The U.S. should develop a strategic plan with exciting stage milestones targeting a U.S. cost-attractive DEMO in the next several decades
- Fusion energy development requires an increasing effort in fusion materials and fusion nuclear science

Strategic elements in mostly considering the United states is a partner in ITER

Electricity Demand in Next 100 Years Presents Major Challenges and Also Tremendous Opportunity



Strategic Interest for the U.S. and the World

- **Projected need for ~ 35,000 GW from non-CO2 producing sources**

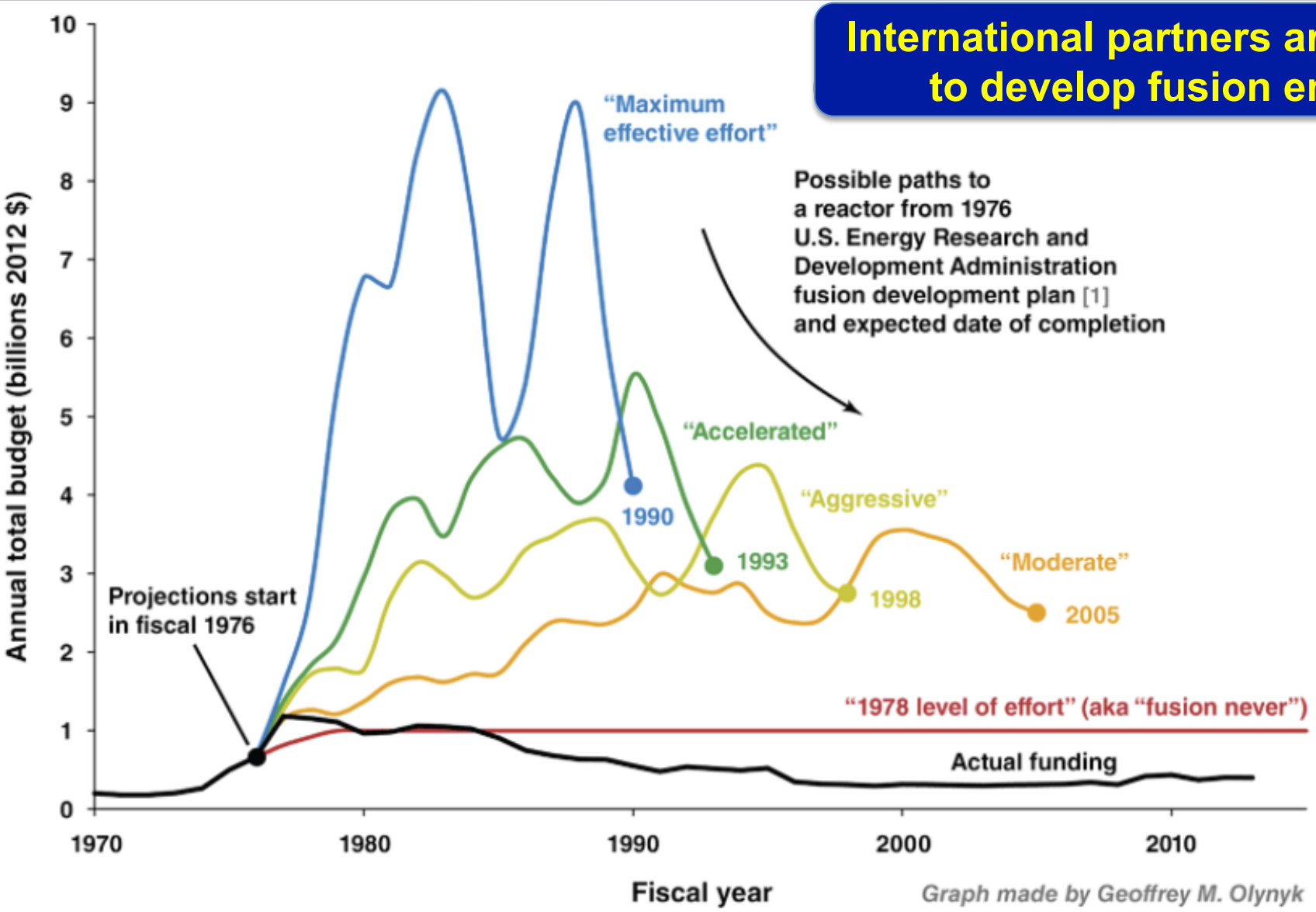
35,000 1 GW-e plants !!!

- **Consequently, annual investment in energy projected to explode**
  - $0.8T by 2050
  - $2.5T by 2100

→ ***Timely positioning is key***

Substantive Progress Towards Fusion Energy Requires a) Increased Funding and/or b) Reduced Costs

International partners are needed to develop fusion energy



[1] U.S. Energy Research and Development Administration, 1976. "Fusion power by magnetic confinement: Program plan" ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

Koepke, 2014

What is Required to Increase Funding

- **Provide an exciting vision for the future to motivate increased public and political support, funding and attract the brightest and best researchers**
- **Work to unify the community, get the community working together**
  - Requires community leadership and engagement, perhaps a process similar to that of 1998 - 2004
- **Establish a partnership between the Feds (OFES, OS) and the community**
- **Resolve to maintain a strong U.S. commitment to the path forward**
- **Engage the entire U.S. fusion community in burning plasma research: planning, preparing, and execution.**
  - Community must own the path forward as <u>their</u> path forward
  - Required to maintain community unity and commitment
- **Recommendation: FES and the U.S fusion community should begin a process to develop a roadmap and strategic plan**

Accelerating the Path to Burning Plasmas and Fusion Energy Development

Ages-old quip: ***"Fusion is 50 years away and always will be."***

NAS charge: ***"given that economical fusion energy within the next several decades is a U.S. strategic interest"***

Accelerating the Path to Burning Plasmas and Fusion Energy Development

- **The Challenge**
  - Very challenging problem → Robust funding required
  - Multiple challenges must be resolved→ Strategic plan required
  - Staging of elements essential → Community consensus needed

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- **The Solution**
  - Compelling vision for energy mission → Increase available funding
  - Vetted strategic plan → Inform prioritization of available funding
  - Broad community consensus → Unified purpose and messaging
  - Bold leadership → Implement & execute difficult priority choices

--- All done in partnership with Office of Science and FES ---

Accelerating the Path to Burning Plasmas and Fusion Energy Development

- **The Challenge**
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How to reconcile?

NAS charge: ***"given that economical fusion energy within the next several decades is a U.S. strategic interest"***

- **The Solution**

My recommendation:

- **Fully participate in ITER as the U.S. Burning Plasma Experiment**
- **Develop a strategic plan with exciting staged milestones targeting a U.S. cost-attractive DEMO in the next several decades**

U.S. Should Fully Participate in ITER as the Most Direct and Fastest Path to a Burning Plasma

Observations

- **All fusion programs worldwide have chosen ITER as the most expedient means to burning plasmas on their path to fusion energy development**
  - ✓ Broad consensus on goals, responsibilities, and ownership
  - ✓ Broad worldwide participation in burning plasma research
- **The framework for pursuing a project of this magnitude is now in place with established management, design and construction teams; infrastructure; nuclear license…**
  - ✓ Established mechanisms for timely resolution of emerging issues
- **ITER construction is progressing rapidly under new management**
  - ✓ Clear communication, responsibility, and accountability structure
- **Planning and preparation for operations and exploitation are beginning**

These efforts/activities take time and money

Recommendation: Fully fund U.S. contributions to ITER

- Guarantee on-time, on-spec delivery of U.S. in-kind contributions
- Enable ITER IO to address emerging issues in timely, efficient manner
- Expand breadth of U.S. community efforts in burning plasma research

Strategic Plan
Assertions and Principles

Assertions

- Burning plasma R&D is the next major step for fusion development
- ITER represents the most timely, capable option for a U.S. burning plasma experiment
- Materials and nuclear science challenge is formidable and early resolution of key challenges is critical for timely delivery of fusion energy
- Tokamak is the most expedient path to fusion energy

Principles

- Enable development of attractive fusion energy as soon as possible
- Timeliness over attractiveness of end product (power plant)
- Build on existing strengths
- Maintain high level of scientific excellence
- Value innovation
- Leverage capabilities of international partners

Realization of Attractive DEMO Will Require Closing the Feasibility Gap in Three Areas Required for Fusion Energy*

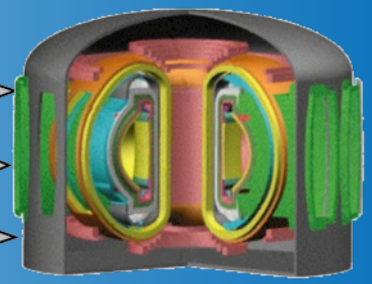
* Priorities, Gaps, Opportunities … 2004

Fusion Power Source (Neutrons)

Materials for Fusion Environment

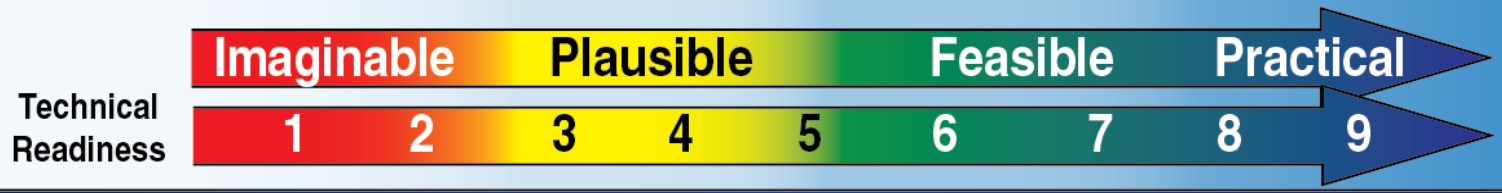
Harnessing Fusion Power

A successful burning plasma experiment will leave significant gaps in fusion materials and blankets



DEMO

Approximate Technical Readiness Level



Developing Key Elements of a Strategic Plan

- **Support a significant community effort to provide a more in-depth evaluation of opportunities for a more cost attractive DEMO or power plant. (systems studies)**
  - Define domestic R&D needed to validate opportunities
- **Support a community/FES process (follow-on to present community workshops) to develop a long term fusion strategy/roadmap targeting a U.S. cost-attractive DEMO in the next several decades.**
  - Include exciting staged milestones
- **Strategy should include**
  - Robust support for engaging in burning plasma physics
  - Plans for solid foundational physics; engaging universities, industry, and national labs
  - A strong theory and computation program
  - Plans for new U.S. fusion facilities
  - Plan (how/when) to transition from existing facilities to new facilities
  - A growing effort in fusion material development and testing
  - A growing effort in developing fusion blanket research

Challenge: broad effort is needed, requiring significant funding
➜ Difficult priority choices are required

The U.S. Strategic Plan Must Include a Robust Tokamak Effort

- **To support and prepare for burning plasma research (ITER) → exploitation**
- **To prepare for a cost effective DEMO**
- **To train fusion scientists and engineers for the future**

Key elements of a tokamak program should include

- **Plasma exhaust (divertor, materials)**
- **Disruption prediction and avoidance**
- **Steady-state**
- **Predictive capability**
- **Optimize performance ($nT\tau$/RB)**
  - Proposals for cost effective Demos include significantly improved confinement (~ 1.6 - 1.8) and stability.
- **Enabling Technologies**
  - Magnet Development program -> demonstrate large, high field magnet with high temperature superconductors
  - Current drive?

Facility: new tokamak facility or upgrade of existing facility

A Growing Effort in Fusion Materials and Fusion Nuclear Science is Required to Advance Fusion Energy

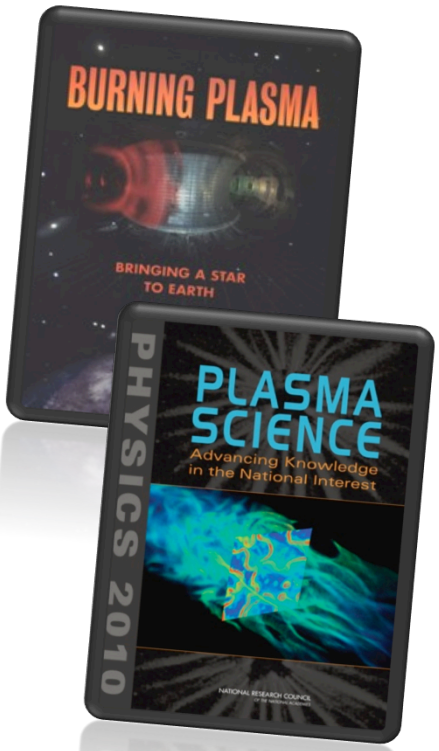
- **Materials**
  - Develop new materials (BES: materials by design); plasma facing, structural
  - Test materials in a plasma environment
    - Linear devices, such as MPEX
    - Fusion facility environment (tokamak, …) effect of material response on plasma performance is critically important
  - Test material in high energy neutron environment
    - Gap in the world program
    - Potential opportunity for cost effective volume neutron source (Gas dynamic Trap), or integrated nuclear science test facility (FNSF)

- **Fusion Blankets**
  - Propose next step is a multi-effect, non-nuclear blanket test facility
  - Develop a long term strategy and plan for U.S. fusion blanket development, in the context of the international program.

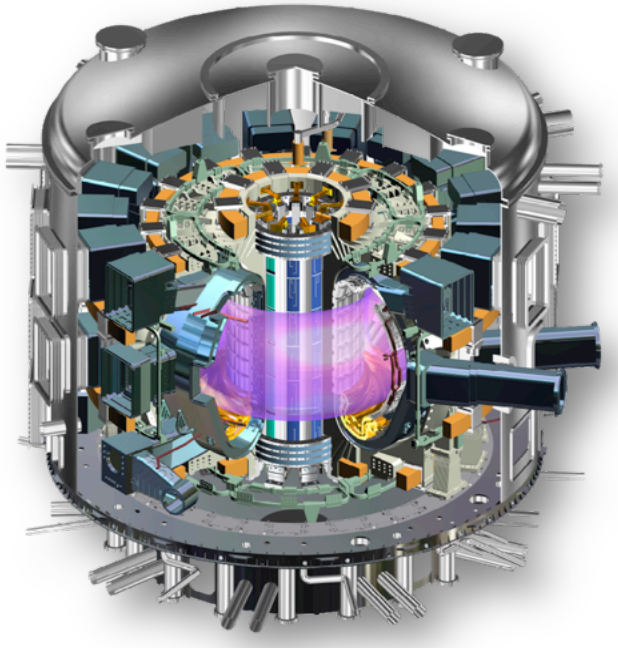
- **We will require a growing workforce of scientists and engineers with expertise in materials and fusion nuclear science**

Summary

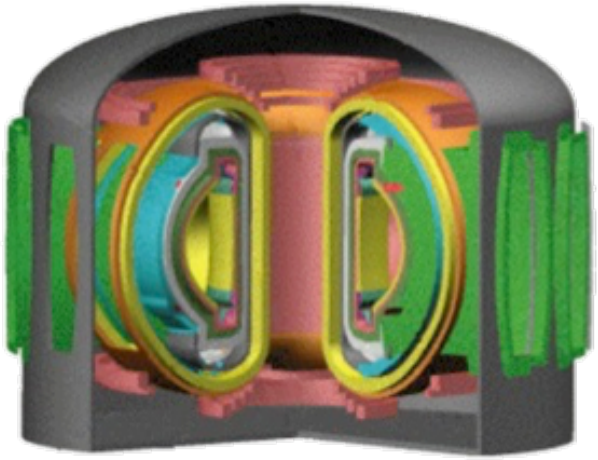
Burning plasmas are the next step in fusion energy development



ITER represents a unique opportunity for the U.S. to pursue burning plasmas



Feasibility gaps in materials and blanket technology offer rich scientific opportunities



Recommended Actions:

Reaffirm previous panel reports stressing the importance of burning plasmas

Capitalize on the substantial human, technical and fiscal investment made in ITER

Develop a strategic plan with exciting staged milestones leading to a cost-attractive DEMO