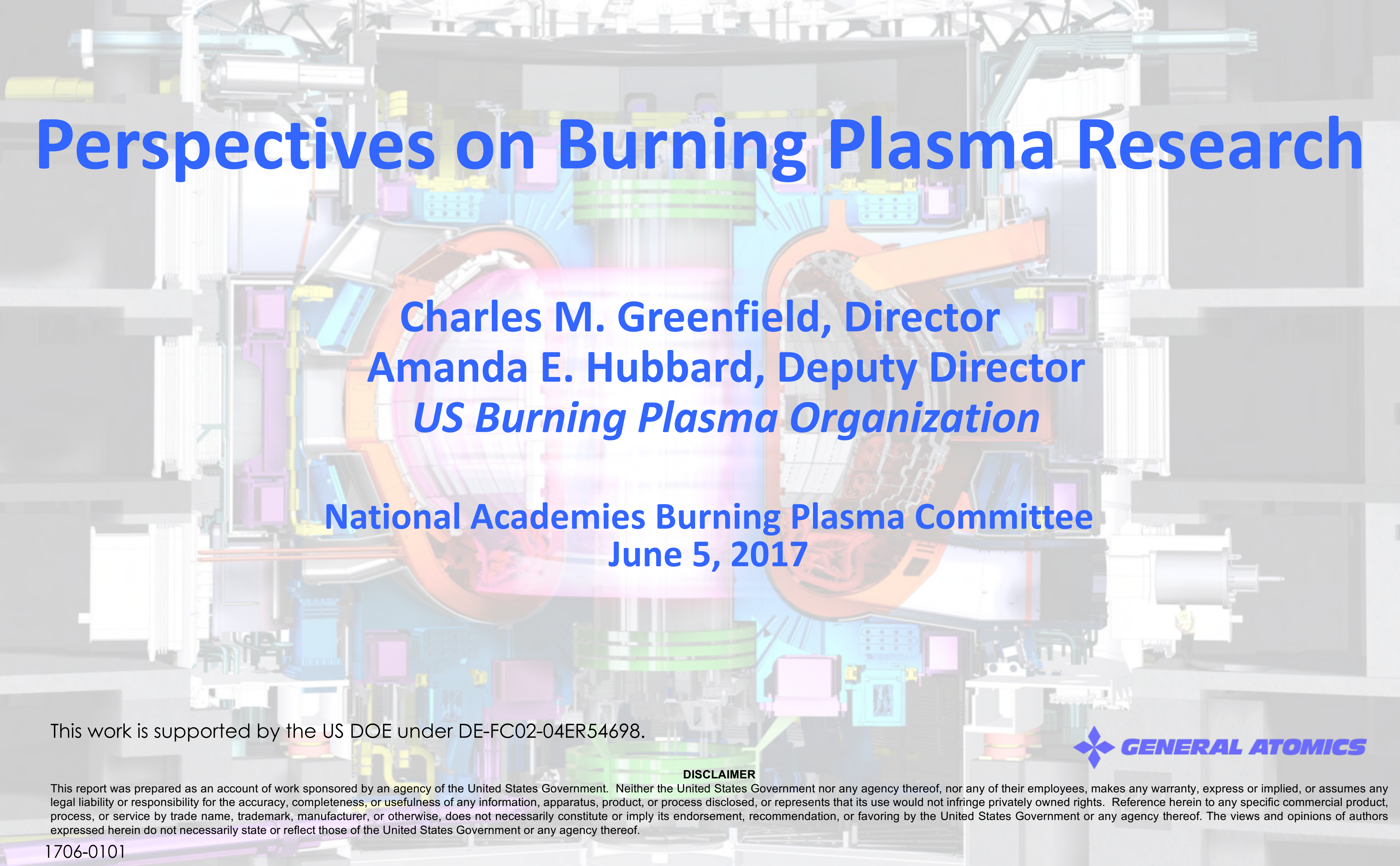
USBPO

United States
Burning Plasma Organization



# Perspectives on Burning Plasma Research

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***US Burning Plasma Organization***

**National Academies Burning Plasma Committee**
**June 5, 2017**

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GENERAL ATOMICS

1706-0101

# Disclaimer

- We would like to claim this talk is comprehensive, deep, and balanced. But we can't. *That talk would take weeks to prepare and hours to present.*

- We have not had time to solicit input from USBPO membership to prepare for this meeting, so this talk should be taken as our personal perspective.

- As you may know, we have been collecting input from USBPO membership with the intention of preparing one or more white papers for your committee. We hope to have an opportunity later to present and discuss that input.

# You asked us to address three questions

1. **What advancements in fusion science and technology have occurred since the release of the previous Burning Plasma Report (2004)?**

2. **Have any advancements or developments altered the importance of burning plasma research to the U.S. fusion research program?**

3. **During the next decade, what are the important scientific and technical problems to be addressed in the U.S. burning plasma research program?**

**We will focus our comments (mostly) on *fusion science* – the Virtual Laboratory for Technology (VLT) may be better positioned to brief you on *fusion technology*.**

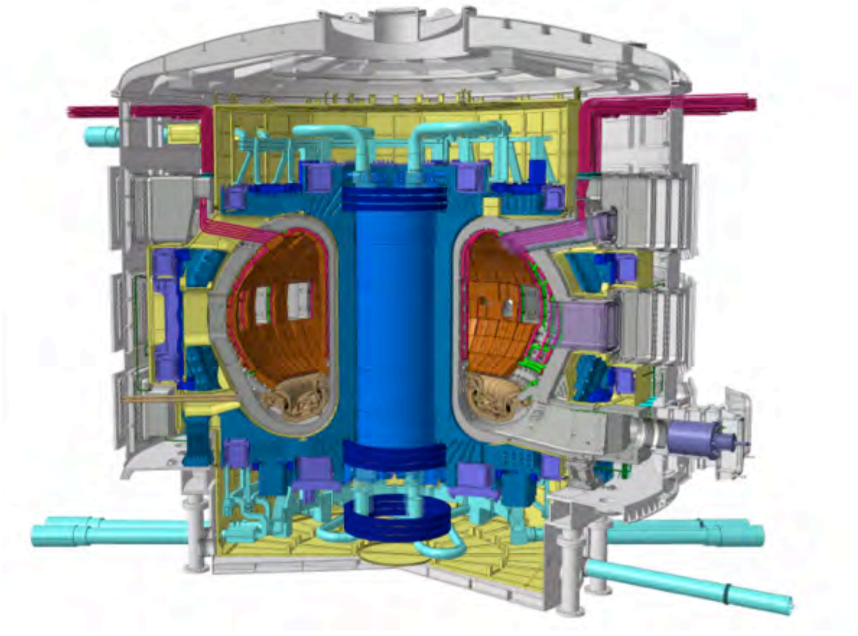
***We will give a more complete answer to #3 later, based on USBPO member input.***

# This talk will address advances since 2004, and those yet to be made, in fusion science

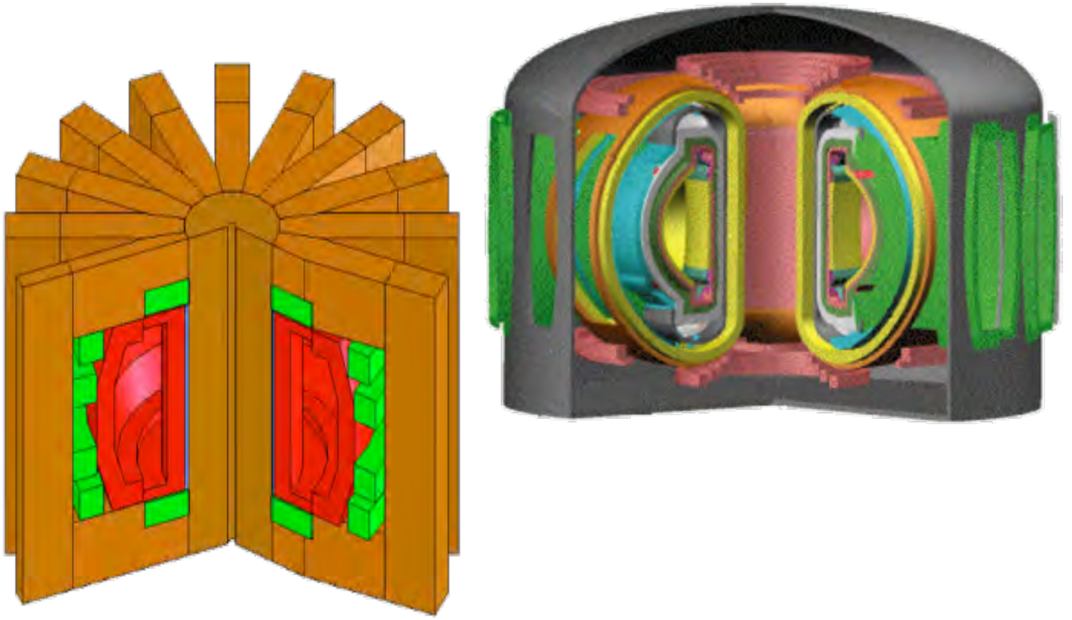
- **Advances since 2004 and next steps for burning plasma research**
  - Transients: ELMs and Disruptions
  - Plasma-material interactions: Power and particle exhaust, PFCs, core-edge coupling
  - Integrated simulations
  - Operating scenarios
  - Heating and current drive
  - Diagnostics
  - Plasma control
  - Energetic particles
  - Transport and confinement
- **The role of international collaboration**
- **Have any advancements or developments altered the importance of burning plasma research to the U.S. fusion research program?**
- **A few comments on ITER**

**Focusing on the tokamak, but most of this is applicable to other configurations, e.g. stellarator**

# Fusion Science and Technology Has a Medium-Term and a Long-Term Target



1. **Ensure that ITER can successfully carry out its mission.** *ITER is largely designed, with a rapidly closing window for design changes. Emphasis is needed on validating and optimizing use of the already specified hardware and to make the very few remaining hardware decisions.*



2. **Prepare for post-ITER devices** *that are still largely undefined. They will undoubtedly pose new and greater technical challenges than ITER, but also present unconstrained opportunities to develop new tools. Research will continue through the next decade or more.*

# The state of research in most of the highest priority areas was captured in the 2015 community workshops

- Workshops documented recent progress and identified near-term research opportunities

Fusion Energy Science Workshop

ON TRANSIENTS IN TOKAMAK PLASMAS

Report on Scientific Challenges and Research Opportunities in Transient Research
June 8-11, 2015

U.S. DEPARTMENT OF ENERGY | Office of Science | Fusion Energy Sciences

FUSION ENERGY SCIENCES WORKSHOP

ON PLASMA MATERIALS INTERACTIONS

Report on Science Challenges and Research Opportunities in Plasma Materials Interactions

MAY 4-7, 2015

U.S. DEPARTMENT OF ENERGY | Office of Science | Fusion Energy Sciences

Report of the Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences
June 2 – 4, 2015

RGY | Office of Science

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

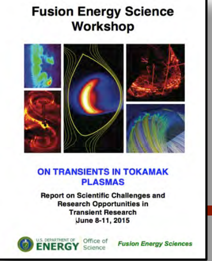
Report of the Panel on Frontiers of Plasma Science

Plasma: at the frontier of scientific discovery

US Department of Energy
Office of Science
Office of Fusion Energy Science

**Recommended reading!**

- Many, but not all, of the topics we will discuss today are described in more detail in these reports
- Other source material includes 2009 ReNeW and several recent FESAC studies



Fusion Energy Science Workshop

ON TRANSIENTS IN TOKAMAK PLASMAS

Report on Scientific Challenges and Research Opportunities in Transient Research
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# The Transients Workshop Addressed the Most Immediate Challenges for Burning Plasmas

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| Challenge | Approach |
|---|---|
| Edge-Localized Modes (ELMs) inflict a repetitive, pulsed heat load to the divertor in H-mode plasmas in tokamaks and stellarators | • Suppression with resonant magnetic perturbations (RMP)<br>• ELM pacing<br>• Naturally ELM-free operating scenarios (QH-mode, I-mode) |
| Disruptions can rapidly release all of the plasma's magnetic and kinetic energy during a fast termination, primarily in tokamaks | • Disruption prediction (proximity to stability limits)<br>• Active avoidance via plasma control<br>• Passively stable operating scenarios<br>• Mitigation by injecting impurities into the plasma core |

**These are areas in which the U.S. is a clear leader**

**There has been a great deal of progress in these areas since 2004, but additional work is still needed for ITER**

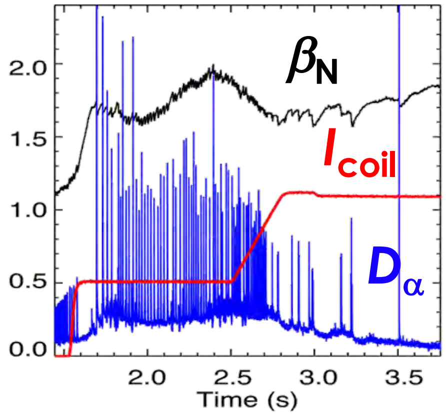
# ELM Mitigation Compatible with High Performance Operation is a Requirement for ITER and Future Reactors

**Requirements**

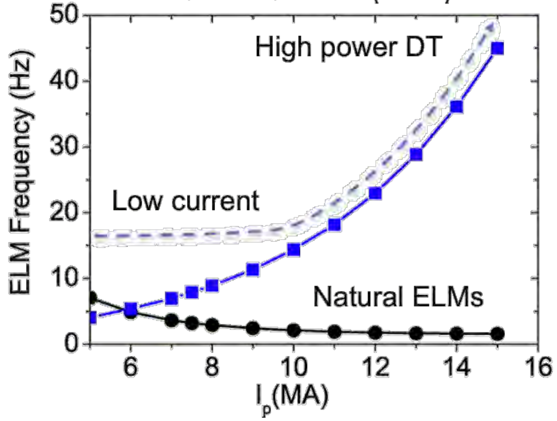
1. Reduce peak heat flux from ELMs by factor 50-100x
2. Replace ELM's impurity removal mechanism

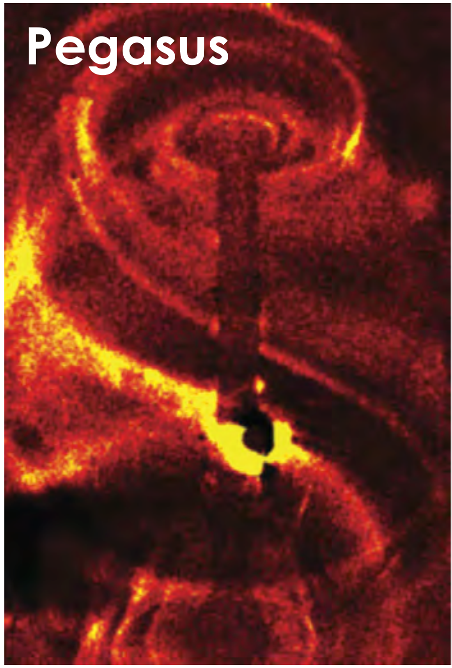
**Goals of current research**

- Demonstrate effective ELM control solutions in ITER & SS regimes
- Test and validate model predictions for extrapolation to reactors



A. Loarte, et al., NF **54** (2014) 033007



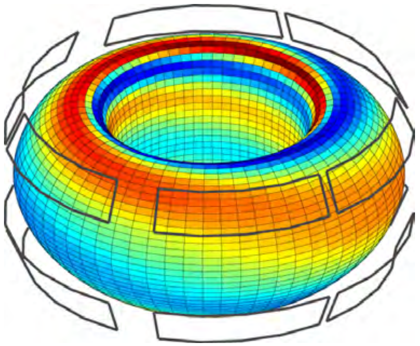


**2004:** Quantitative understanding of ELMs lacking, only rudimentary mitigation (pellet pacing) achieved, naturally ELM-free QH-mode obtained but required strong counter-NBI

**2017:** ELM limit understood and predictable as peeling-ballooning mode, several different approaches demonstrated to control. I-mode.

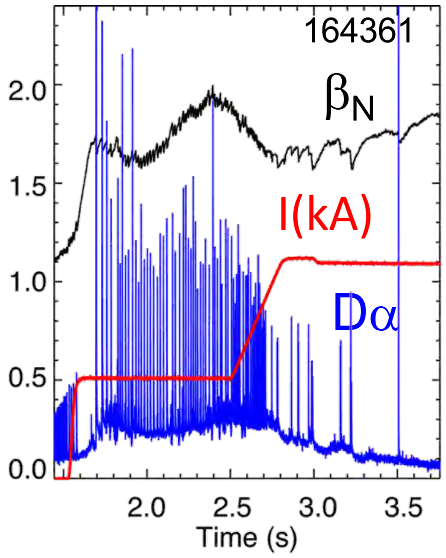
# RMP ELM suppression demonstrated in DIII-D and ASDEX-U

- First demonstrated in DIII-D in early 2000s
- Previous: ASDEX-U only able to access mitigation (decreased size) rather than ELM elimination as seen in DIII-D
- Result on DIII-D suggested lower collisionality on AUG is key
- Follow on experiment on AUG achieved ELM suppression
- Encouraging result for ITER
- Research carried out as ITPA joint experiment

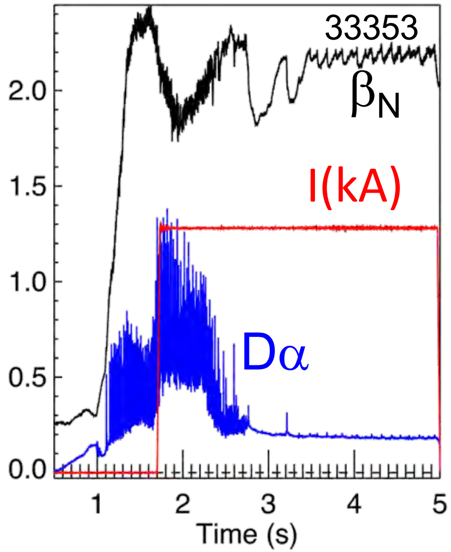


Internal coil (I-coil) in DIII-D produces n=3 RMP field

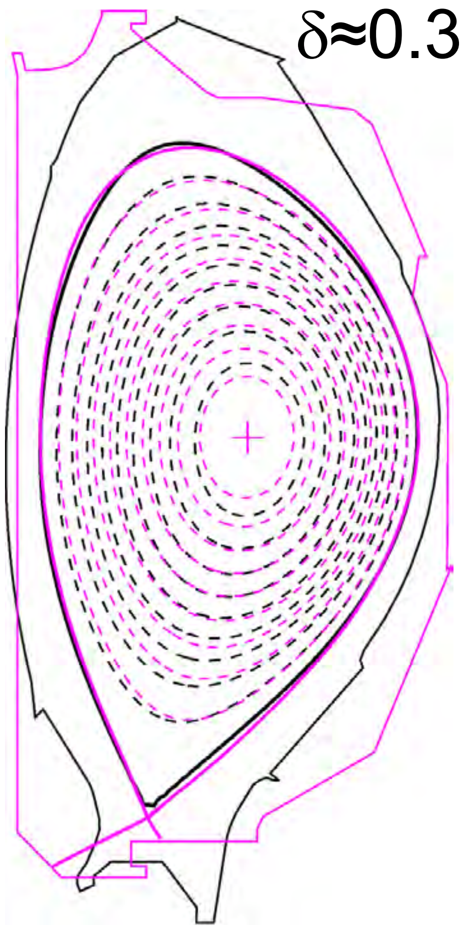
DIII-D n=3 RMP



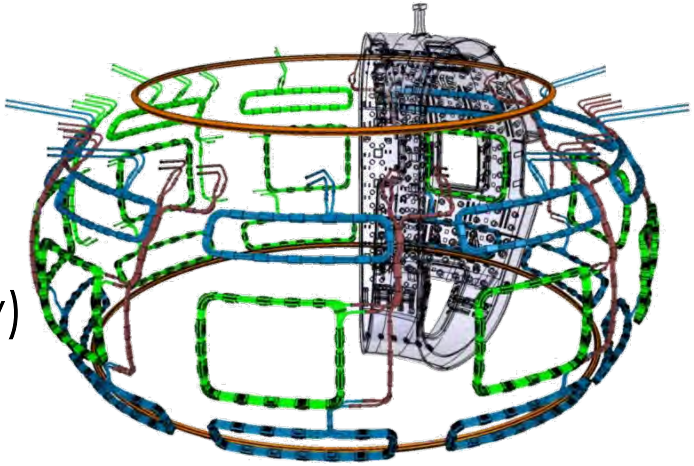
AUG n=2 RMP



Shape overlay
DIII_D/AUG



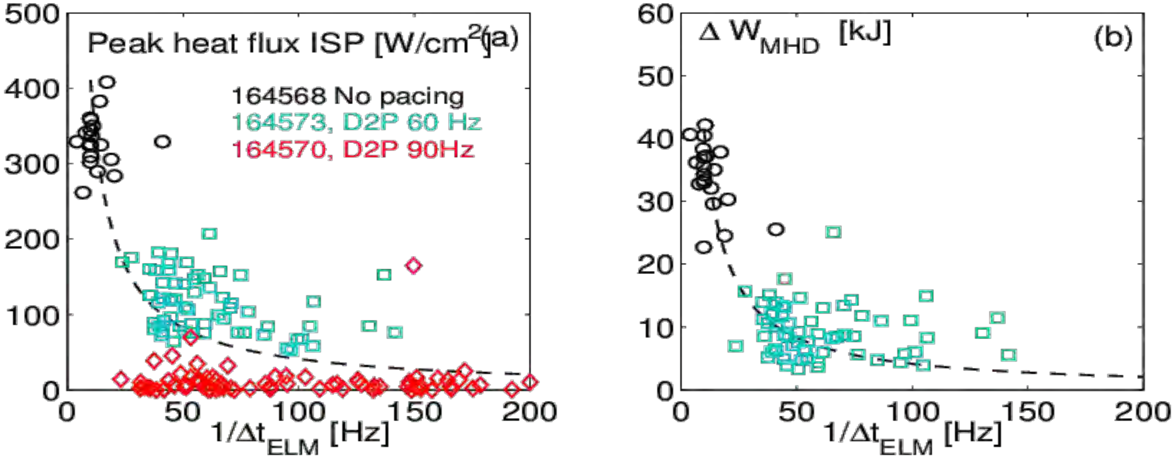
# ELM Control Coils for ITER are based on DIII-D experience



- **ELM control coils for ITER are based on empirical extrapolation from DIII-D**
  - water-cooled "picture frame" coils
    - mineral insulated conductor
  - Geometry : 9x3 coils (powered independently)
    - toroidal symmetry n=3 or 4
  - Current: max 90 kAturns (6 turns)
- **To do:**
  - Physics largely understood, but predictive capability not yet achieved
  - ELM suppression at ITER relevant low torque in baseline scenario remains elusive
    - Has been achieved in hybrid scenario
  - RMP ELM suppression in helium plasmas not well established
    - Question: Is the physics the same?
  - Reduced pedestal gradient ➔ reduced global confinement
    - Need to quantify and optimize.

# ELM mitigation with pellet pacing

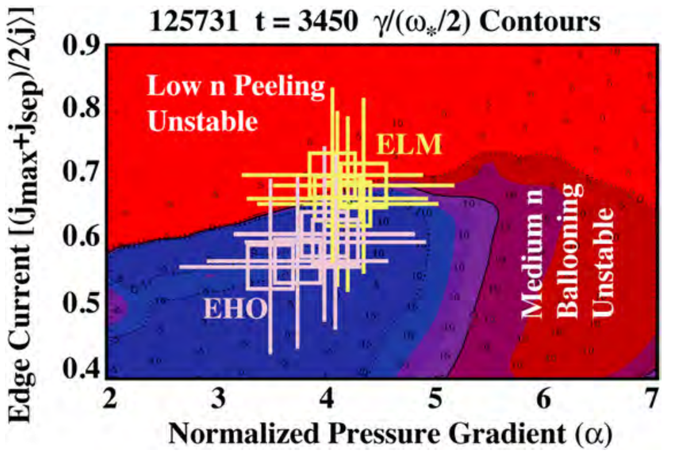
- **Inject pellets into pedestal at higher rate than natural ELM rate with expectation that ELM frequency increases with concomitant decrease in ELM size**
- **First demonstrations in early 2000s at ASDEX-U and others**
- **Recent results with fuel ($D_2$) pellets in DIII-D: Peak heat flux at or better than $1/f_{ELM}$ expectation**
- **Effect also seen with impurity pellets (carbon, lithium)**

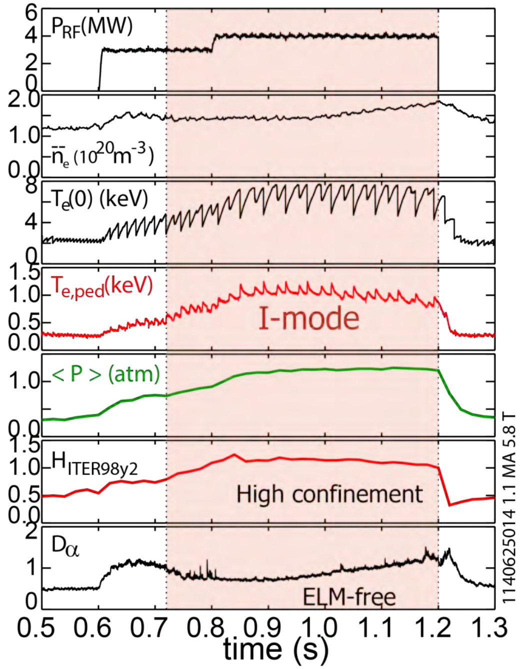


- **To do:**
  - Quantify dependencies, e.g. is divertor detachment and fueling affecting the ELMs?
  - Results across devices not consistent – need to understand why
  - How does this affect confinement?
  - Does this extrapolate to ITER? Beyond ITER??

# Naturally ELM-free operating scenarios offer the promise of a simplified solution

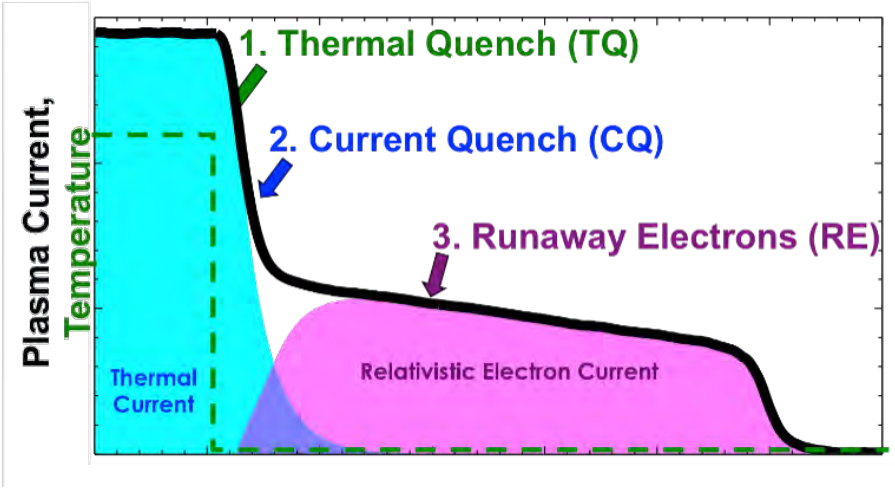
- **QH-mode discovered in 1999 in DIII-D**
  - Early results required strong counter-NBI
  - More recently, obtained with co-NBI and sustained (not yet accessed) with ITER-relevant low torque
- **I-mode more recently discovered in C-Mod**
  - Energy but not particle barrier.
  - Requires toroidal field oriented for the ∇B drift to point away from the active x-point
- **Both are sustained with MHD activity near the boundary that prevents access to the ELM limit**
- **To do:**
  - QH-mode is a candidate scenario for ITER, but access with little or no applied torque is still to be developed
  - I-mode requires reversed B, not in ITER plans
    - Subsequent devices could be designed to allow this.

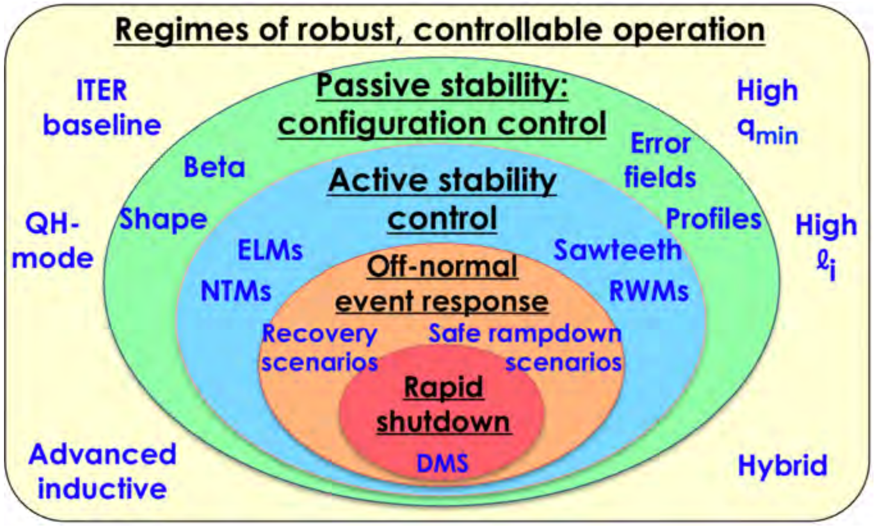




# Disruptions in tokamaks can release all of the plasma's thermal and magnetic energy

- **Anatomy of a disruption**
  - Can be triggered by crossing a stability limit or by hardware failure
  1. At the thermal quench (TQ), the plasma's kinetic energy is rapidly released
     →Localized heating of PFCs
  2. At the current quench (CQ), the plasma current ramps down, releasing magnetic energy and generating a large toroidal electric field
     →Large EM forces
  3. The toroidal electric field can accelerate electrons creating a multi-MeV runaway electron (RE) beam
     →Localized beam strike on PFCs
- **Each of these phases can cause device damage if not prevented or mitigated**
  - Requires a multi-layered strategy →





**Regimes of robust, controllable operation**

ITER baseline

High $q_{min}$

QH-mode

High $\ell_i$

Advanced inductive

Hybrid

**Passive stability: configuration control**

Beta

Error fields

Shape

Profiles

**Active stability control**

ELMs

Sawteeth

NTMs

RWMs

**Off-normal event response**

Recovery scenarios

Safe rampdown scenarios

**Rapid shutdown**

DMS

# MYTH: Disruptions are inevitable in tokamaks

- **Operating scenarios are characterized by their "safety factor" $q$, which varies as B/I.**
  - ITER baseline scenario operates at $q$~3
- **Passively stable operating scenarios can be achieved**
  - Higher $q$ → less likely to disrupt, **even at high $\beta$ (pressure)!**
  - High performance scenarios, such as Advanced Inductive ("Hybrid") and high $q_{min}$ steady-state scenarios rarely disrupt in present-day experiments
  - Note: This does not preclude a disruption caused by hardware failure (control fault, PFC breakage,…).
- **Active stability control → high performance operation near stability limits**
  - Plasma control system must be able to predict an oncoming disruption and take measures to restore stability or shift to a more stable (albeit lower performance) operating point
  - As a last resort, the PCS will need to trigger mitigation measures

**2004: Disruptions thought by many to be a random and unpreventable event**

**2017: Progress in understanding, prediction, avoidance, and mitigation**

# Disruption prediction and avoidance: Where we are, where we need to go

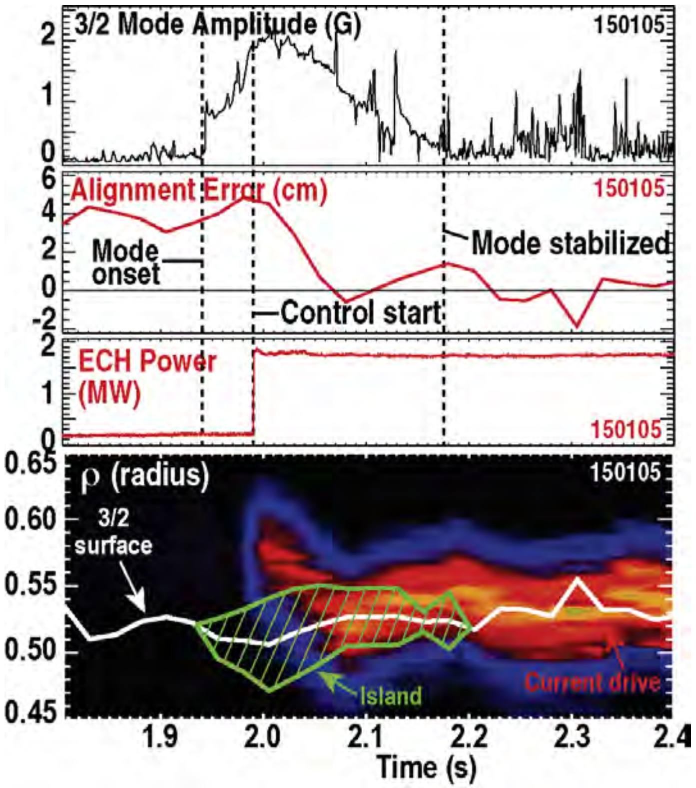
- **Empirical disruption predictors (including neural nets) have been developed on NSTX, JET, etc.**
  - Already in routine use in JET to protect "ITER-like" tungsten/beryllium first wall
- **Rudimentary disruption avoidance already a part of routine operation**
  - DIII-D "dud detector" can trigger safe rampdown or measures to suppress instabilities including neoclassical tearing mode or resistive wall mode
- **To do:**
  - Empirical approaches: Need to demonstrate portability, e.g. can an empirical predictor developed/trained on one device be ported to a new device with minimal new training or calibration?
  - Real-time stability calculations becoming a reality
  - Develop increased sophistication of PCS
    - Need to include off-normal ("not plasma physics") event response

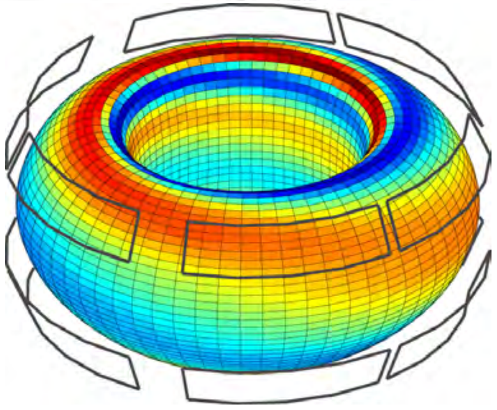
# We have active control techniques in hand for the most common instabilities

- **Neoclassical tearing modes (NTM)**
  - Magnetic islands form and locally depress bootstrap current
  - Can lead to mode locking and disruption
  - Successfully suppressed by replacing current in magnetic island with electron cyclotron current drive (ECCD)
- **Resistive Wall Mode (RWM)**
  - Instability occurs when above the "no wall" $\beta$ limit – most applicable to advanced/higher performance scenarios
  - **Rarely disruptive**, but can result in loss of a desirable operating point
  - Successfully suppressed with application of external magnetic fields (from same coil system used for RMP ELM suppression)
- **Error fields**
  - Can arise from tokamak assembly defects of application of external field perturbations
  - Can impact confinement and stability (interacts with above instabilities)
  - Correction of n=1 component of error field routinely done in tokamaks
  - Recent: Discovery that higher order error field components are important too – more advanced error correction techniques can address this

# Instability control, continued

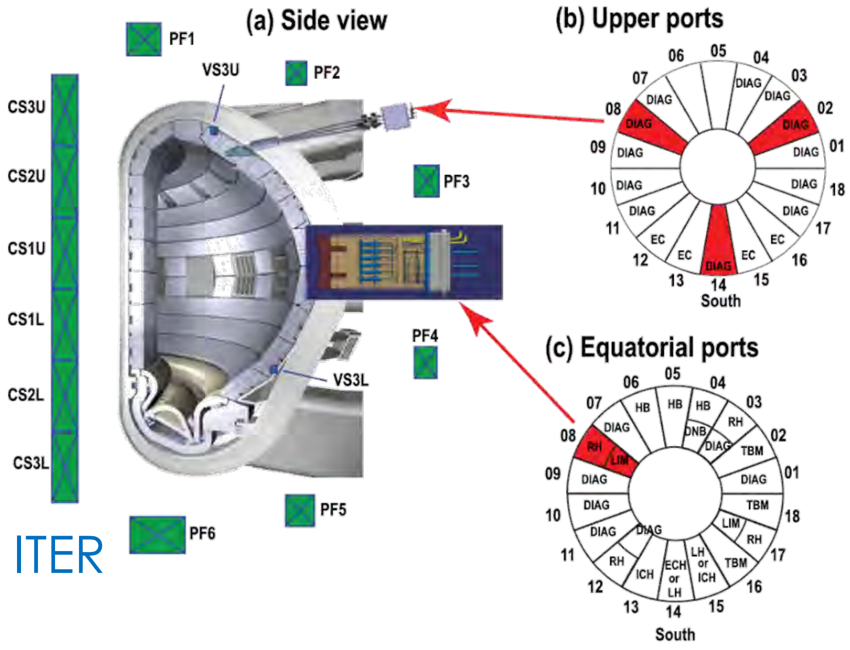
- **To do:**
  - NTM
    - Continue to develop “catch and subdue” technique that minimizes effect on Q by only applying ECCD when and where instability appears
  - Error fields and RWM
    - More work is needed to determine optimal use and placement of internal and external coils
    - Continue to develop techniques using these coils to correct error fields with n=1, 2, 3,…
    - Includes dynamic error field control applicable to RWM suppression





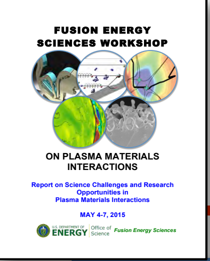
# The last resort: Radiate away the plasma's energy harmlessly (mitigation)

- **Usual approach: inject impurity particles during or before the TQ**
  - Massive Gas Injection (MGI): C-Mod, DIII-D,…
  - Shattered Pellet Injection (SPI): DIII-D; JET (2018)
    - Chosen for ITER Disruption Mitigation System (DMS)
  - Capable of mitigating the heat and electromagnetic loads of the TQ and CQ
    - Both theory and present experience suggest RE beam not solved



- **To do**
  - Complete testing to qualify SPI for ITER
    - DIII-D (2017): Use of multiple injectors, requirements for injection direction
    - DIII-D & JET (2018): Data to extrapolate to ITER
  - Develop solutions for RE beam
    - Requires advances in theory
    - ITER can accept alternative concepts with mature designs up to 2030
    - No shortage of ideas, but only a few being tested
      - Need international cooperation

**Not just an ITER issue – needed for all future tokamaks**



FUSION ENERGY SCIENCES WORKSHOP

ON PLASMA MATERIALS INTERACTIONS

Report on Science Challenges and Research Opportunities in Plasma Materials Interactions

MAY 4-7, 2015

U.S. DEPARTMENT OF ENERGY | Office of Science Fusion Energy Sciences

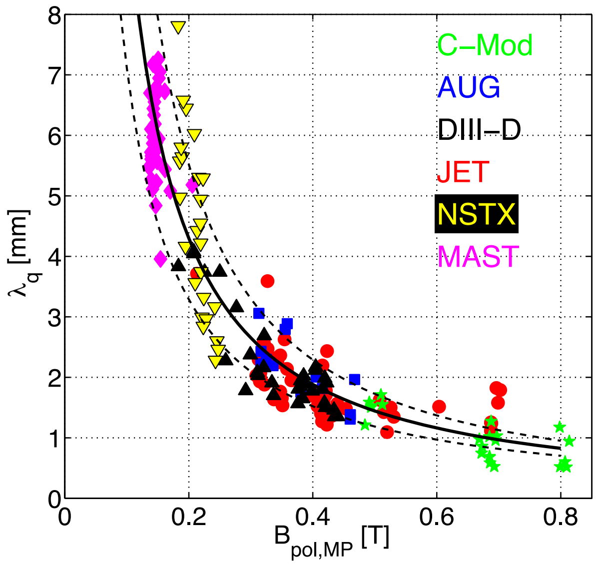
# The Plasma Materials Interactions Workshop Was More Future-Focused

| Challenge | Approach |
|---|---|
| Power exhaust and particle control | Understand, develop, and demonstrate innovative solutions for:<br>• Dissipative/detached divertor<br>• Main chamber wall components |
| Plasma facing components (PFCs) | • Develop understanding of material behavior under reactor conditions<br>• Identify limits for solid and liquid PFCs |
| Interplay between boundary conditions and core performance | • Develop understanding and control of core-edge coupling.<br>• Use to optimize scenarios (including ITER) |

# Plasma exhaust and particle control

**For ITER:**

- **Heat flux width characterized, but scaling to ITER is much narrower than had been expected, increasing the challenge.**
- **Progress made in understanding conditions for detachment.**
- **Diagnostics allowing increasingly sophisticated model validation exercises**
- **Heat fluxes studied at ITER level in C-Mod, reduction to need levels by seeding demonstrated**
- **To do:**
  - ITER hardware is set, but more progress in understanding detachment conditions and extrapolation of heat flux width is still needed
  - Model validation in present-day tokamaks



**2004: Radiative divertors assumed in future tokamaks, but not much detailed thought to how it could be achieved.**
**2017: Heat flux width characterized. Diagnostic sets primed to make progress.**

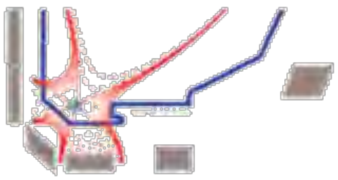
# Plasma exhaust and particle control

**Beyond ITER, to DEMO**

- Challenge is much greater, may well need new divertor geometries.
- Several divertor geometries have been tested or modifications are underway now
- Simulations of detachment predict detachment with much less impact on core plasma

To do: Validate models, optimize divertor geometry, test more options, at high heat flux.

Snowflake



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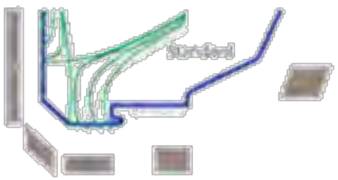
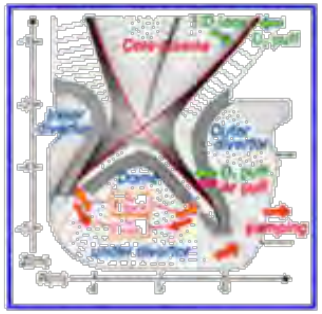


Deep Slot



XPT

**2004: Rudimentary comparisons of open and closed divertors carried out with sparse diagnostic sets**
**2017: Simulations and tests of several divertor configurations underway and planned.**

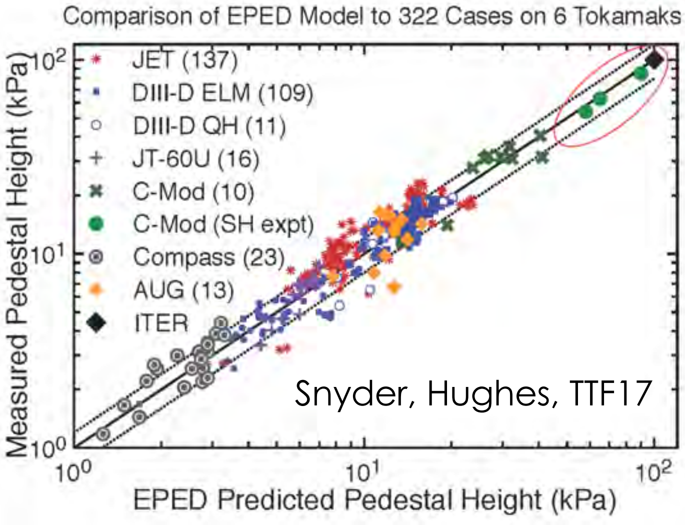
# Plasma-facing components

- **Most experience and databases gained with carbon-walled tokamaks. ITER will have tungsten divertor and beryllium main chamber**
  - Adopted by JET
- **Performance in metal-wall devices has not been as good as with carbon**
  - New optimizations being performed, e.g. impurity injection
- **To do:**
  - Optimize performance with metal walls (needed for ITER). JET is making progress.
  - For post-ITER devices, development of new materials may be required to meet reactor challenges
    - Simultaneously address tritium retention, heat flux tolerance, radiation tolerance,…

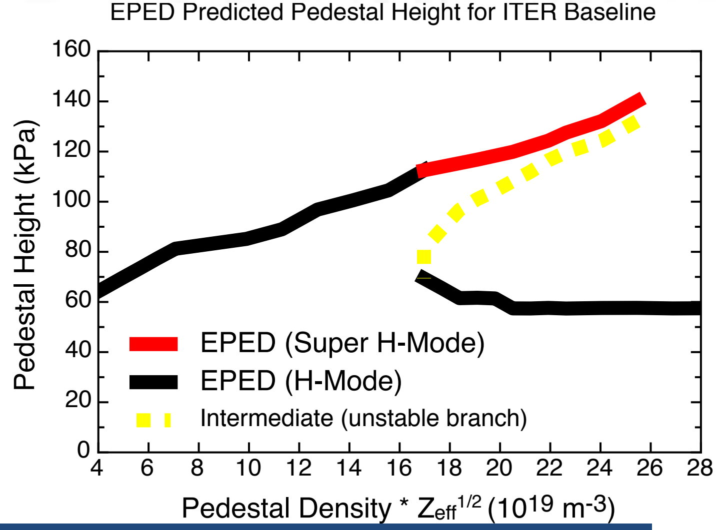
**2004: Carbon walls in most tokamaks (Mo in C-Mod)**
**2017: Several tokamaks changed to metal walls, especially JET with its "ITER-like" wall**

# Core-edge coupling

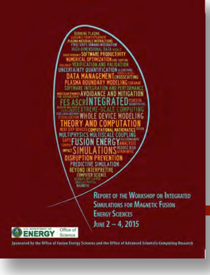
- **The core and edge communicate with each other through the H-mode pedestal**
- **EPED can predict the pedestal based on peeling-ballooning setting stability (ELM) limit and kinetic ballooning mode driving transport**
- **New C-Mod data, fills in to ~90% of ITER's expected pedestal pressure**
- **To do:**
  - Full pedestal still not predictable… EPED predicts pressure, but not density and temperature
  - Progress would greatly improve predictability ➞ shorten time (number of shots) to make progress in ITER and subsequent devices



Snyder, Hughes, TTF17



**2004: H-mode pedestal largest uncertainty in predicting performance**
**2017: Theoretical understanding makes many (but not all) features of the pedestal predictable, including ELM limits**



Report of the Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences

June 2 – 4, 2015

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

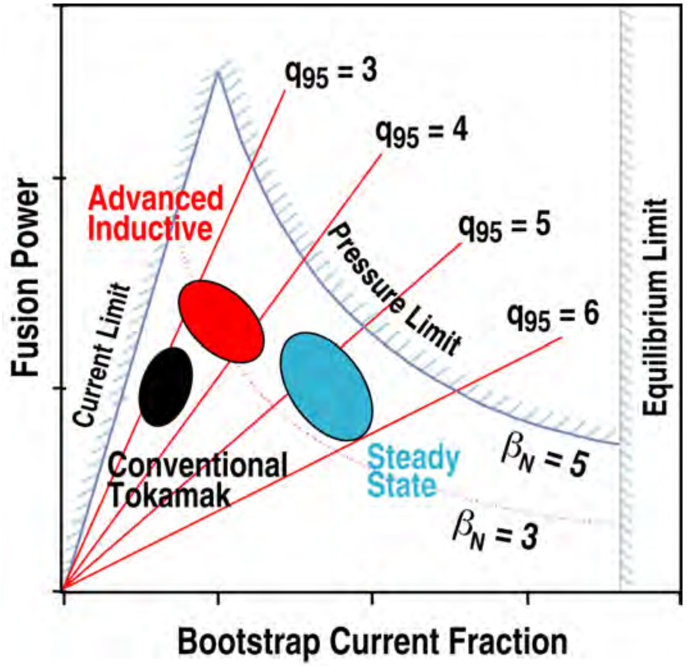
# The Integrated Simulations Workshop Identified Numerous Opportunities

- **Identified gaps and challenges in the areas of:**
  - Disruption physics, including prevention, avoidance, and mitigation
  - Plasma boundary, including the pedestal, scrape-off layer, and plasma-materials-interactions
  - Whole device modeling (WDM)
- **New opportunities identified in**
  - Interaction of fast particles with thermal plasma waves and instabilities
  - Steady-state plasma modeling with strong coupling of core transport to sources and MHD
  - Whole-device modeling (WDM)
    - Inclusion of multiscale turbulence
    - Development of a fast WDM capability for real-time simulation, numerical optimization, and uncertainty quantification
    - Use of probabilistic WDM to assess the likelihood of key physical transitions or states occurring

**Integrated simulation in concert with experimentation has been and will continue to be a hallmark of our burning plasma research**

# Operating scenario development is progressing with increasing fidelity to burning plasma conditions

- **Operating scenarios for burning plasmas (e.g. ITER) developed mostly in tokamaks with co-NBI**
  - Strong rotation and ion heating contrasts with expectations in BP
- **Recent research exploring access in more reactor-relevant conditions**



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- **Conventional tokamak**
  - ELMing H-mode – ITER baseline scenario
  - Stability at low rotation a concern
- **Hybrid/advanced inductive**
  - Self-organized core maintains $q_{axis}>1$ (avoids sawtooth instability)
  - Demonstrated with low torque and combined with RMP ELM suppression
  - Higher *q* → lower incidence of disruption
  - Projects to Q=10 in ITER at lower current
- **Steady-state**
  - Higher *q*, with all current provided by bootstrap and external sources
  - Confinement reduced in some recent experiments due to energetic particle instabilities
  - Rarely disrupts
  - Lower Q due to requirement for external current drive

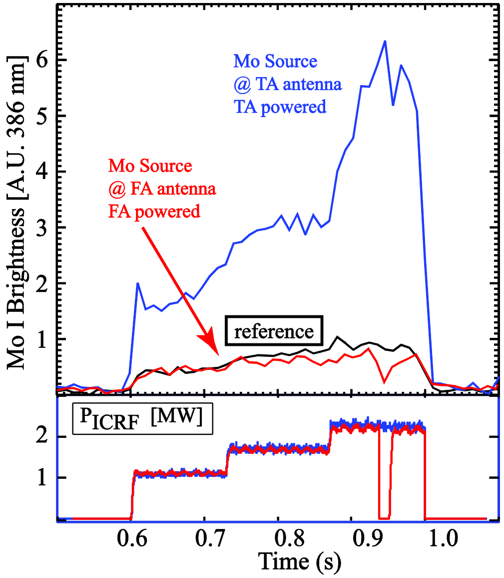
# Operating scenarios, continued

- **To do:**
  - All scenarios: Continue to work toward demonstrations that include:
    - Integration of first wall, boundary, pedestal, and core
    - Reactor-relevant applied torque and (primarily electron) heating
    - ELM control – via RMP, pacing, or coupling core scenario with QH-mode or I-mode edge
    - Heat flux within PFC limits.
  - Conventional tokamak ("ITER baseline")
    - Address instability at low rotation – some recent success in DIII-D
    - RMP ELM control needs to be established at low rotation and in helium plasmas (addresses ITER non-activated operational phase)
  - Hybrid/advanced inductive
    - Work to establish as viable alternative ITER baseline scenario
  - Steady-state
    - Address energetic particle instability issue
      - Broader issue in a burning plasma with alpha heating
    - Establish at low rotation and with ITER-relevant heating and current drive mix (for ITER Q=5 steady-state mission)
    - Scenario optimization to maximize bootstrap/minimize need for external current drive
    - Establish physics basis for steady-state DEMO operation

# Heating and current drive

- **Have made good progress, particularly in RF.**
- **Has become clear that electron heating (ECH or ICRH) is critical for controlling high Z impurities.**
- **ICRH:**
  - Impurity generation is a major issue. Now much better understood, and options demonstrated to greatly reduce source. Field-aligned (FA) antenna on C-Mod, new design on AUG.
  - Still some unanswered questions on physics mechanisms, impurity transport.
  - US leads in simulation, through SciDAC. New RF schemes, relevant to ITER, have been predicted and demonstrated. (eg 3-species, on C-Mod and JET, generates high energy ions). W7X will use.
- **LHCD:**
  - High CD efficiency demonstrated to ~$10^{20}$ $m^{-3}$ (C-Mod). Improved understanding of limiting mechanisms at higher density.

C-Mod, S. Wukitch



- **Much improved performance predicted with high field side launch, for both ICRF and LHCD.** (see PMI workshop) Requires testing as option for devices beyond ITER.

# Diagnostics

- **Status**
  - A steady progression of diagnostic developments accelerated in the 1990s, and continues to the present day
    - A hallmark of the US fusion program
  - To do:
    - Many present-day diagnostics will not work in a burning plasma environment due to radiation, heat, long-pulse operation, and access limitations
    - Work already in progress to develop new techniques for ITER
    - New classes of diagnostics needed for confined and lost alphas in ITER, including velocity space distribution
    - Post-ITER devices even more challenging
      - Example: Magnetic pickups, ubiquitous in present-day devices, may not be applicable in a reactor
    - Need to establish minimum set of diagnostics for reactor control

# Plasma Control

- **Status**
  - Real-time plasma control becoming increasingly sophisticated, including multiple sensors and multiple actuators
  - Real-time profile analysis allowing control of profile shapes (not just 0-D control anymore!)
- **To do:**
  - Include possibility of a single actuator doing multiple things
  - Burn control – alpha particles will be dominant source of heating power in a burning plasma
  - Determine minimum sets of measurements and actuators for a power plant

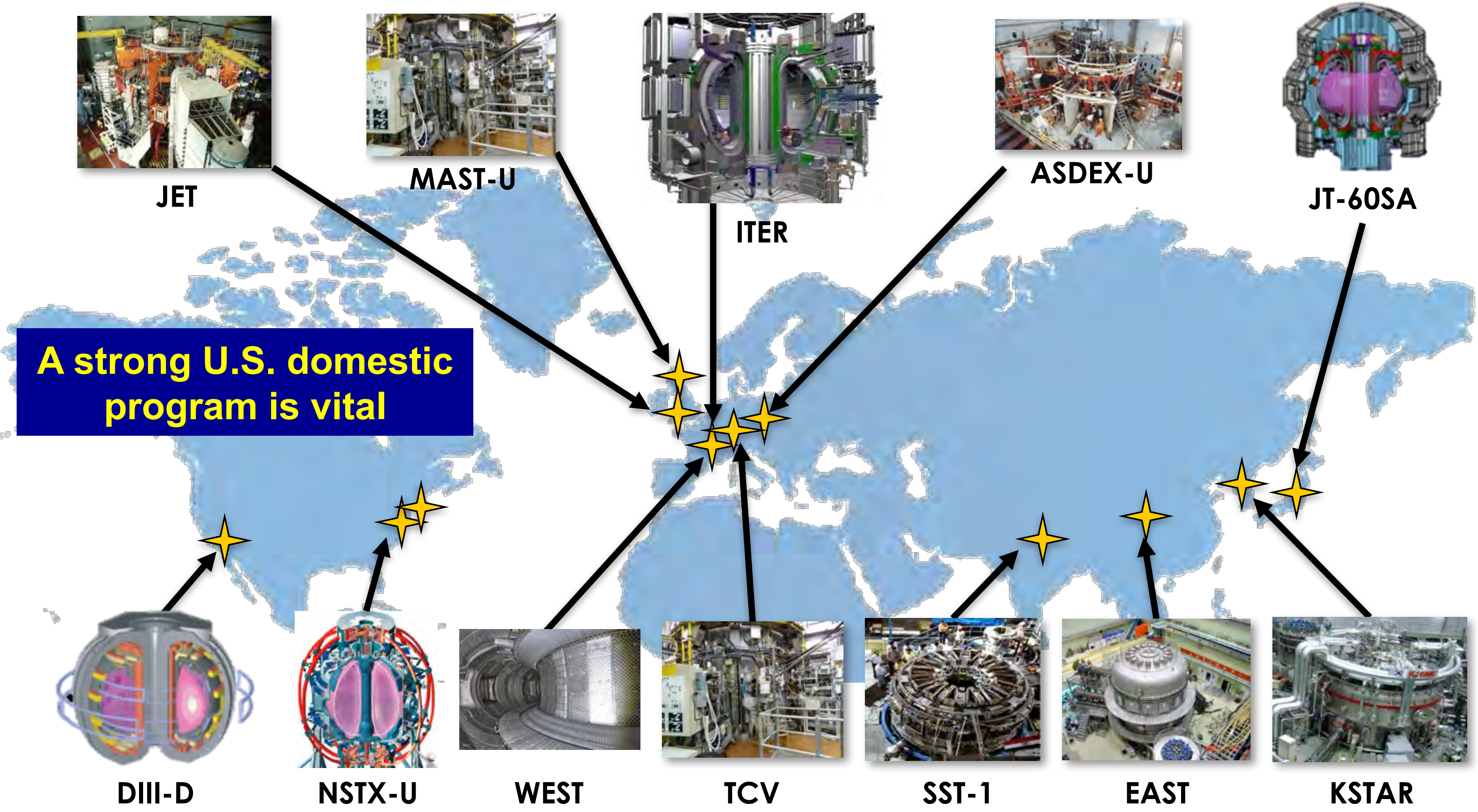
# Energetic Particles

- **Status**
  - Longstanding mysteries of transport of energetic particles (EPs) by Alfvén eigenmodes (AEs) are being solved through innovative experiments, diagnostics, and modeling
    - Impacts beam ions in present and future devices, alpha particles in burning plasmas
  - Innovative measurements providing opportunities for model validation
- **To do**
  - Heating physics of alphas, including alpha channeling
  - NBI heating and current drive physics in ITER
  - Linear and nonlinear understanding of AEs
  - EP interaction with non-AE MHD instabilities
  - Safe termination of high-Q burning plasma discharges
- **A burning plasma experiment is essential for understanding alpha transport since NBI is unable to recreate the isotropic alpha distribution**

# Transport and confinement

- **Status**
  - – Strong modeling program combined with unique set of turbulence models has led to
    - Understanding and improved predictive modeling of heat transport
    - Understanding of the L- to H-mode mechanism
    - Impurity transport through neoclassical simulations and experiments
    - Advances in understanding moment transport
- **To do:**
  - – The focus needs to shift to addressing transport in plasma regimes that are relevant for burning plasmas, with no ELMs, strong radiative divertor, current drive,…
  - – Build confidence that we can achieve high confinement, including core-edge integration
  - – Need capability to predict within a reasonable time and with reasonable accuracy how plasmas will behave in future experiments and future devices
    - Will be instrumental to the operation of ITER (or any burning plasma device)

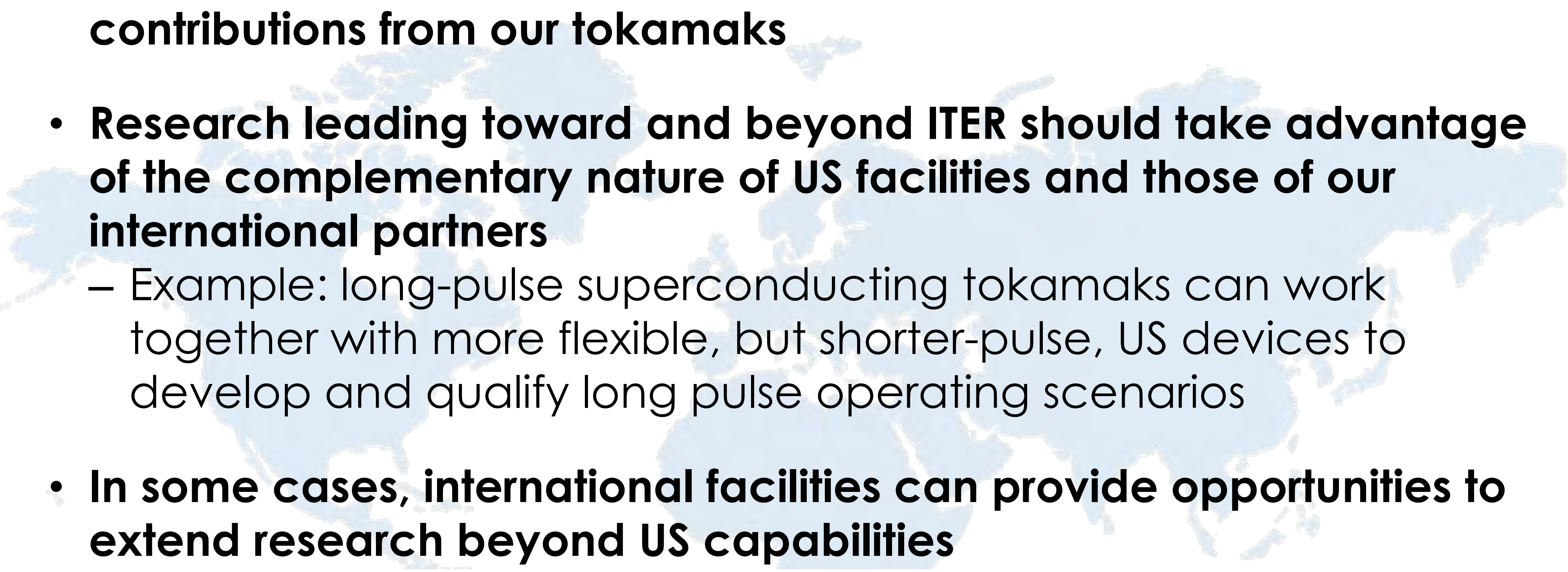
# International collaboration will accelerate fusion energy development and scientific understanding



**A strong U.S. domestic program is vital**

**Not a one-way progression from US to foreign devices – collaborations can and must go in both directions!**

# International collaboration will accelerate fusion energy development and scientific understanding



- **US is a major participant in ITPA due in large part to technical contributions from our tokamaks**
- **Research leading toward and beyond ITER should take advantage of the complementary nature of US facilities and those of our international partners**
  - Example: long-pulse superconducting tokamaks can work together with more flexible, but shorter-pulse, US devices to develop and qualify long pulse operating scenarios
- **In some cases, international facilities can provide opportunities to extend research beyond US capabilities**
  - Example: DT experiments in JET

**Not a one-way progression from US to foreign devices – collaborations can and must go in both directions!**

# Have any advancements or developments altered the importance of burning plasma research to the US fusion research program?

NO

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# NO

*"The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research… ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology"*

2002 Snowmass meeting press release; later endorsed by FESAC

- **Nothing has happened to make this statement *less* true**
- **The importance is the same**
- **Our readiness has advanced**

# The ITER project is moving ahead and making progress toward the burning plasma laboratory we envisioned in 2002

- **The ITER construction project will produce a scientific instrument that can achieve its specific technical goals**
  - Q=10 for hundreds of seconds
  - Q=5 in steady-state-capable scenarios for thousands of seconds
  - Provide a unique laboratory to study the physics and technology of burning plasmas and provide a significant part of the basis to proceed to a DEMO
- **The results will inform US efforts toward a fusion energy DEMO**
- **There is still work to be done**
  - The US FES program has the assets in place to prepare for a successful ITER program – we are world-leading in many areas

# Burning plasma is still the next frontier – as it has been since Snowmass

- **Advancements and developments since 2004 have only increased our readiness to take the burning plasma step**
- **International collaboration (present-day and an international burning plasma experiment such as ITER) can leverage our research, but a strong domestic program is needed**
- **ITER construction is on track – I believe that the best path to provide a burning plasma laboratory for the US and the world is to complete ITER and carry out its research program**
  - There have always been viable alternatives to ITER, but it seems unlikely that a US-only burning plasma experiment with similar mission could be available sooner or at a lower cost to the US
  - ITER is a science experiment and should not be taken as a prototype power plant; other fusion devices will be needed and we also need to prepare for them