Strategic Plan for Burning Plasma Research

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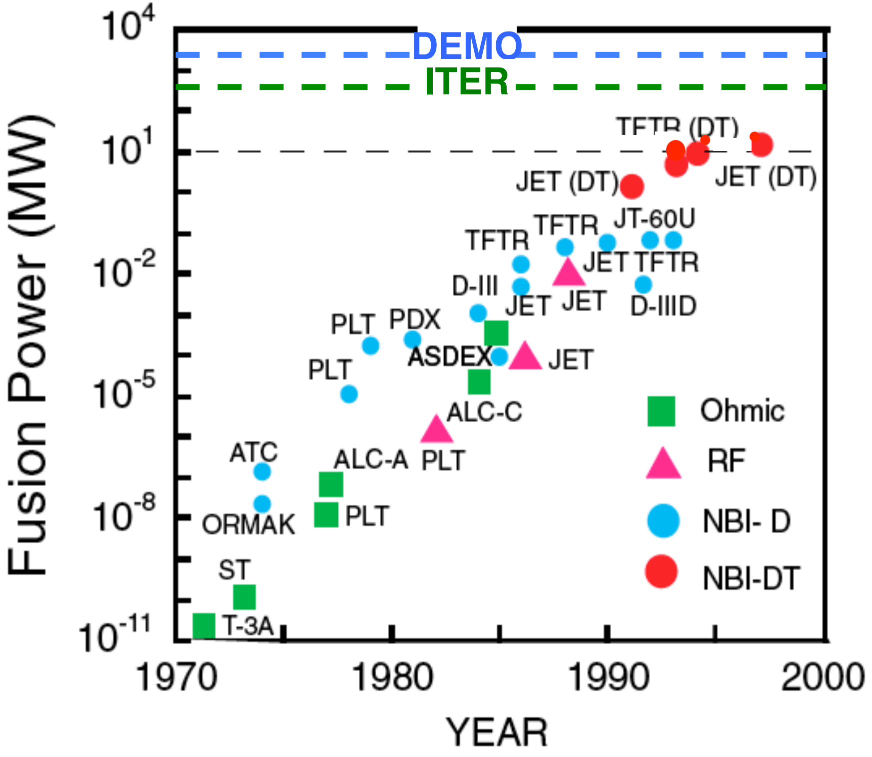
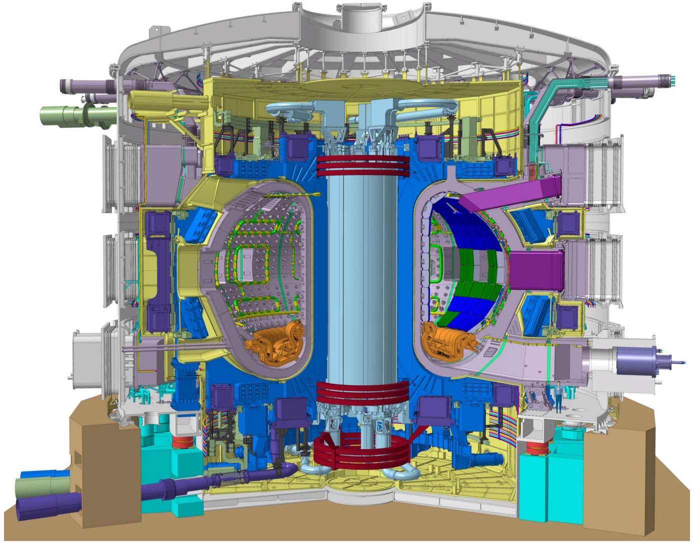
Fusion Performance Has Increased Substantially Until 1997

- Existing experiments have achieved Gain = Q_{DT} ~ 0.6
- JET and TFTR have produced DT fusion powers >10MW for ~1s
- ITER is designed to a scale which should yield $Q_{DT} \geq 10$ at a fusion power of 400 – 500 MW for 300 – 500 s
  - Progress has been determined by:
    - Scientific advances
    - Larger more powerful facilities
- **Need the next generation of facilities to make progress to burning plasmas**



ITER Will Enable the Understanding of Burning Plasmas

- Understanding of:
  - Sustaining hot burning plasma by alpha-particles
  - Confinement of reactor-scale plasma
  - Stability from micro to macro in burning plasmas
  - Plasma wall interactions at high heat flux
  - High gain dynamics



- Nonlinear interaction of turbulence, wall-interaction, external sources, fusion reactivity, macroscopic instabilities.
- Strong coupling between the plasma and "external" systems especially plasma-wall interactions

ITER is Developing Reactor Relevant Technology That Relies on Large Integration Effort

- First wall materials
- Superconducting magnets
- Remote handling
- Tests of breeding blankets (at modest neutron fluence)

Superconducting model Central Solenoid Coil

- Progress in burning plasma research and fusion development relies on integration of cutting edge physics and technology.
- ITER provides a unique opportunity to study burning plasmas
- ***Integration issues are complex and will never be captured in the published literature***

International Community Is Shifting Focus to After ITER

- ITER, while a very important step in developing fusion, is not the final step toward a power plant
- Important scientific and technological questions remain
  - In addition, cost issues for both future burning plasma experiments and the production of electricity have to be addressed
- Major design and R&D studies are underway in most of the ITER partners for the steps beyond ITER

Outstanding Scientific and Technical Challenges Beyond ITER

Scientific Challenges

- Improve plasma confinement
- Improve shaping, control
  - Simplifying, reducing size
- Increase plasma stability and sustainability
- The plasma-material interface:
  - effect of plasma on materials
  - effect of materials on plasma

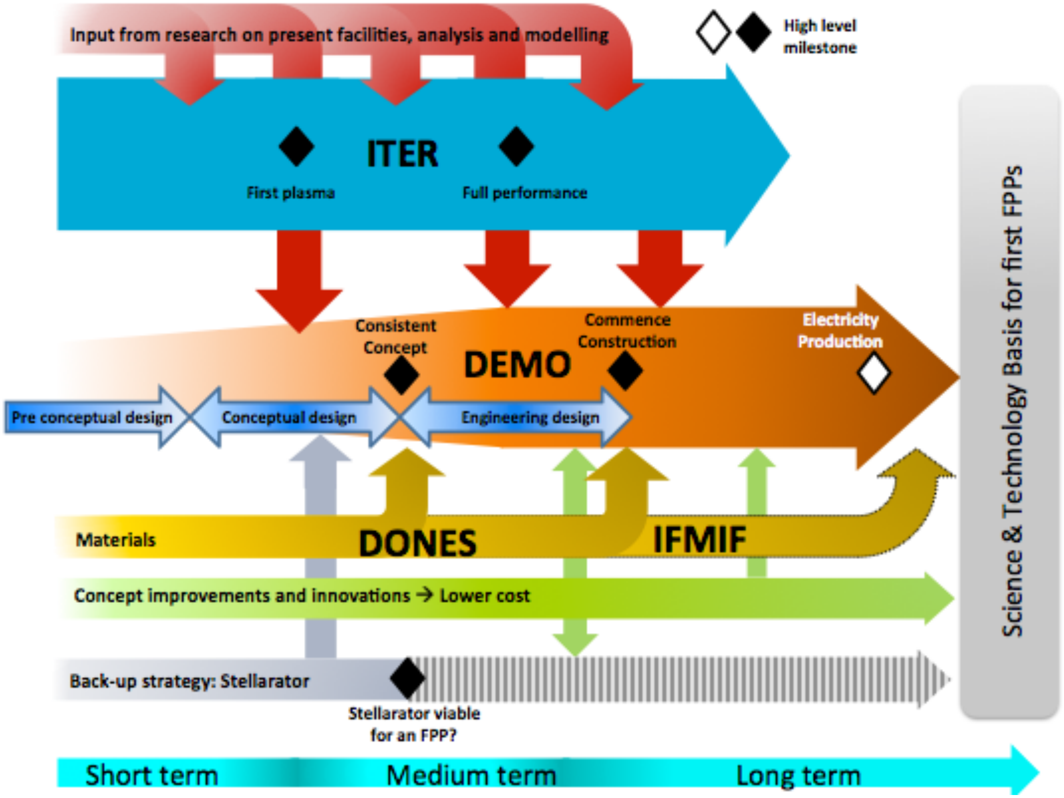
Technical Challenges

- Harnessing fusion power
  - durable materials in fusion neutron flux,
  - power extraction
- Tritium Breeding Ratio >1
- Increase magnetic field and current density
- Improve economic performance

European Fusion Roadmap: Put Electricity on the Grid Mid-Century

- Vision of a demonstration plant is defined largely by ITER
  - Initially pulsed operation
  - Substantial technological R&D program

- Construction schedule is set by ITER results

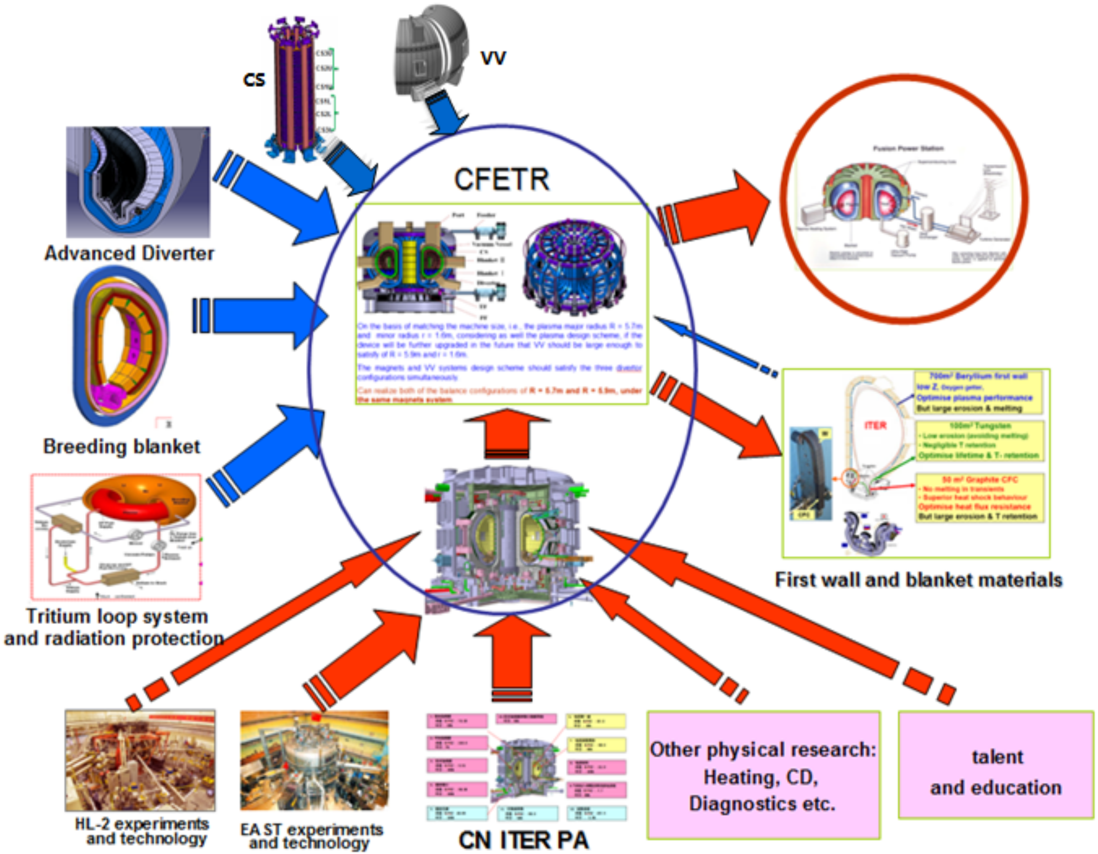


A.Donné presented in Beijing, Nov. 2017, to be issued in the spring 2018

China is Embarking on a More Aggressive Path

- China's Ministry (MOST) is funding the next step of China Fusion Engineering Test Reactor (CFETR)
- Relies heavily on ITER technology but goes beyond ITER
  - Exploring higher field and possibly high temperature superconductors
  - Steady state operation (200 MWe to 500MWe)
  - Tritium breeding
- Timeline is not tied directly into ITER's
- PPPL participates in both CFETR and South Korean DEMO studies

CFETR Design Takes Advantage of Work Done on ITER and Strong R&D Program to Address Specific Issues

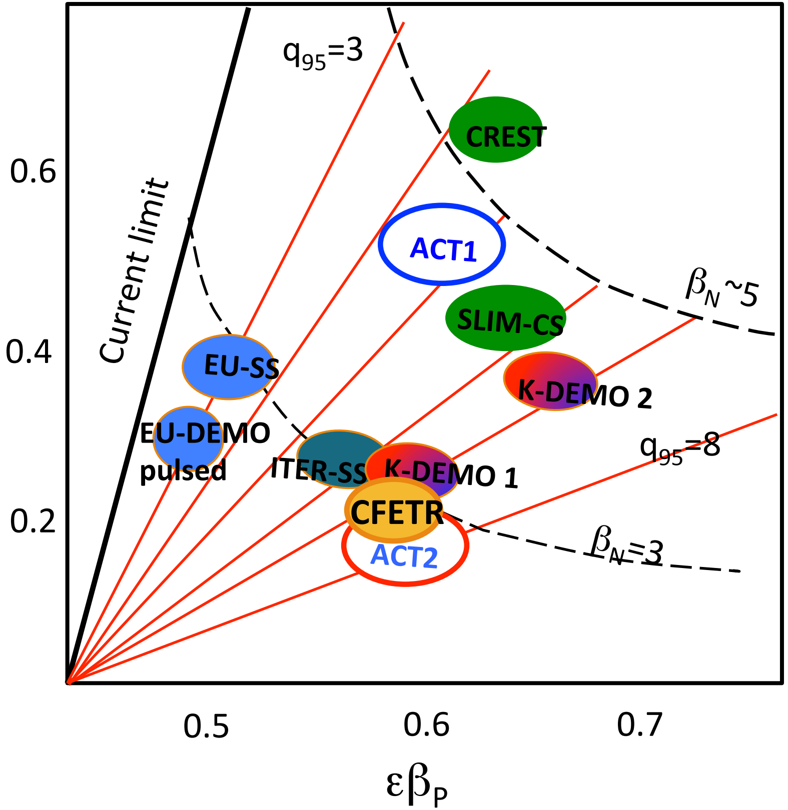


- EAST results and ITER procurement arrangements support both ITER and CFETR
- CFETR R&D includes work on:
  - Vacuum vessel
  - High Tc (?) central solenoid
  - Advanced divertor
  - Breeding blanket
  - Tritium system
- Goal is demonstrate TBR>1 and produce electricity

Different Perspectives Exist on the Future Direction of Tokamak Research

- US research has pioneered the operational boundaries
  - Options under discussion include pulsed/steady state, high β_T/ high βp (q_{95})
- Differences in perspective reflect integration assumptions:
  - Current drive efficiency
  - Magnitude of field
  - Power flux assumptions
- US studies have emphasized cost (high performance) and steady-state

$$\varepsilon \frac{\beta_T}{(1+k^2)/2}$$



What are the US' roles in burning plasma research and fusion energy development?

- The road to fusion energy is a long one with other countries stepping forward to take the lead
  - Unless there is a radical redirection in US funding, work on burning plasma and fusion energy development will have to done internationally
- To make an impact, US needs to be driving innovation based on strong scientific understanding
  - Identify key scientific and technical solutions to the challenges for ITER and beyond to:
    - Establish the scientific and technical viability and
    - Reduce the cost for fusion development and fusion energy
- **PPPL aims to extend this understanding to burning plasmas and use it for innovation**

On-going examples how PPPL Contributes to Understanding and Innovation

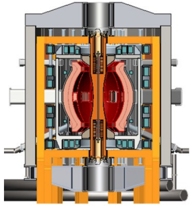
- NSTX-U: high-β compact configuration
- Develop predictive understanding of burning plasma
- Robust power and particle exhaust solution

NSTX-U Pursues Transformative Ideas to Accelerate Fusion Development

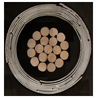
Fusion Technology and Performance

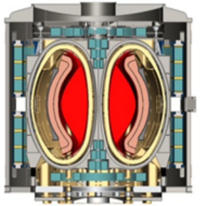
ST = Spherical Torus.
A magnetic confinement configuration that can lead to a smaller and more cost-competitive fusion energy reactor.

ST-based fusion neutron source
Provide steady-state fusion neutron environment for nuclear material and component R&D

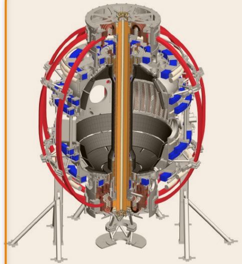


ST Pilot Plant for net electricity
Liquid metal blankets for high thermal efficiency and high−temperature superconducting coils

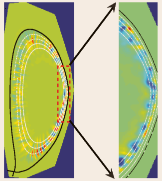




NSTX Upgrade Facility and Research Program

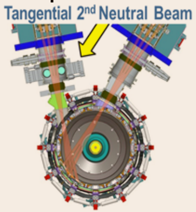


Extend ST confinement understanding to fusion-relevant temperatures

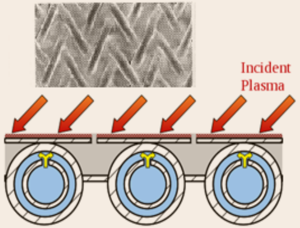


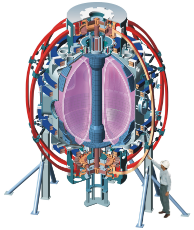
Advanced diagnostics + computation provide fundamental understanding and basis for next-step ST devices

Demonstrate sustainment for future steady-state operation



High-power NSTX-U tests of liquid metals as transformative wall solution

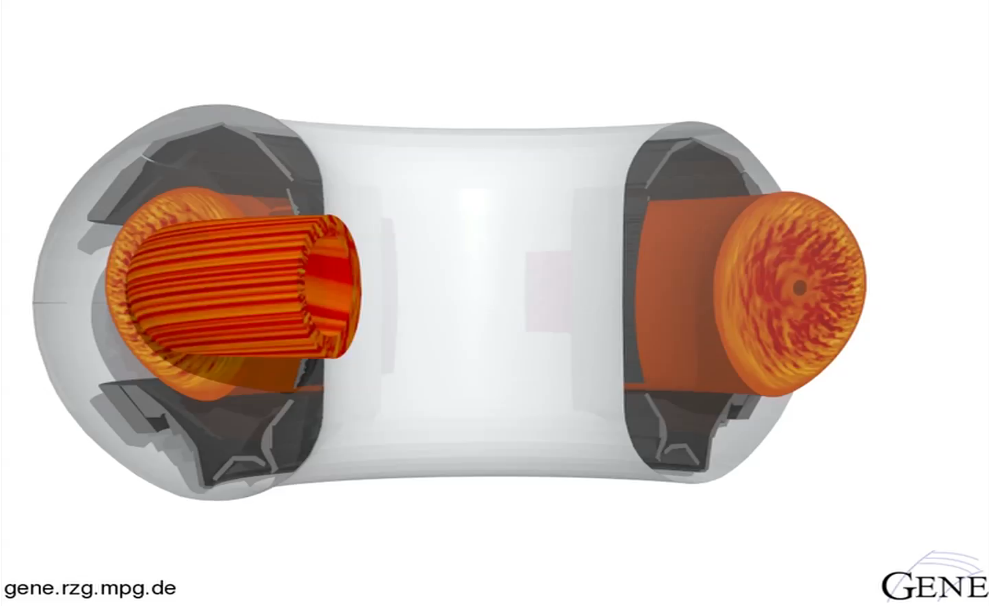


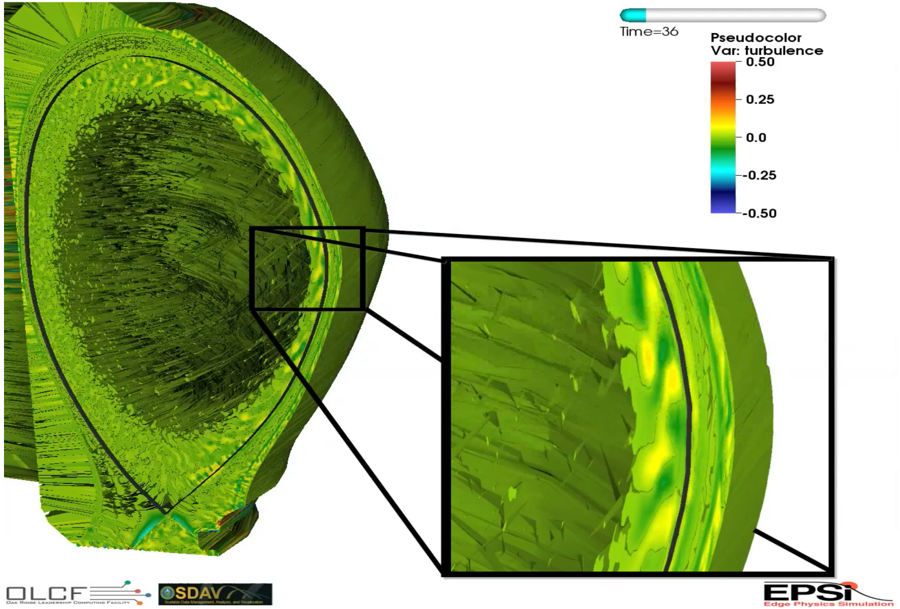


NSTX Explored ST stability and confinement

Fundamental Plasma and Materials Science

Exascale Project Offers Path to High Fidelity Whole Device Model





- First step is to integrate core with edge
- Design of new facilities and planning on burning plasma experiments will require whole device models

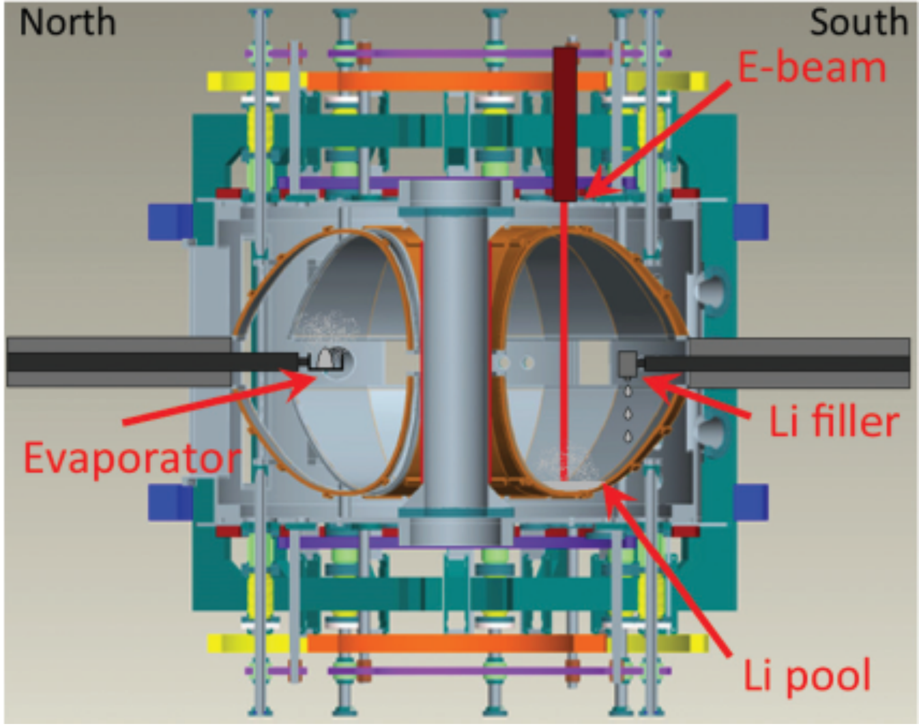
Develop Robust Power and Particle Exhaust Solution Compatible with High Performance

Liquid metal boundary is a potential solution to two challenges:

- Self-healing and may be a robust first wall of a burning plasma
- Increased plasma confinement and pressure

Current activities:

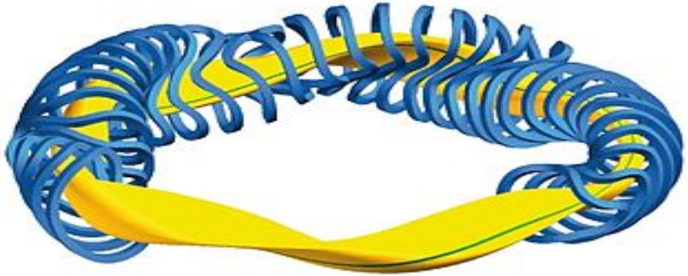
- PPPL's LTX-β
- EAST (China)
- Long term plan for full liquid boundary in NSTX-U
- Vapor metal concepts



PPPL LTX-β

3D Magnetic Shaping for Minimal Recirculating Power and Enhanced Stability

- Offer methods to **<u>transform the approach to fusion energy</u>**
  - Elimination of large-scale instabilities and termination events
  - Increased plasma sustainment efficiency
  - Improved pressure limits
  - Reduced turbulence
- Wendelstein 7-X (W7-X) goal is sustained 5% beta and validate stellarator optimization
  - Already demonstrated Te = 10keV
- Optimization of stellarator performance has a great deal of potential

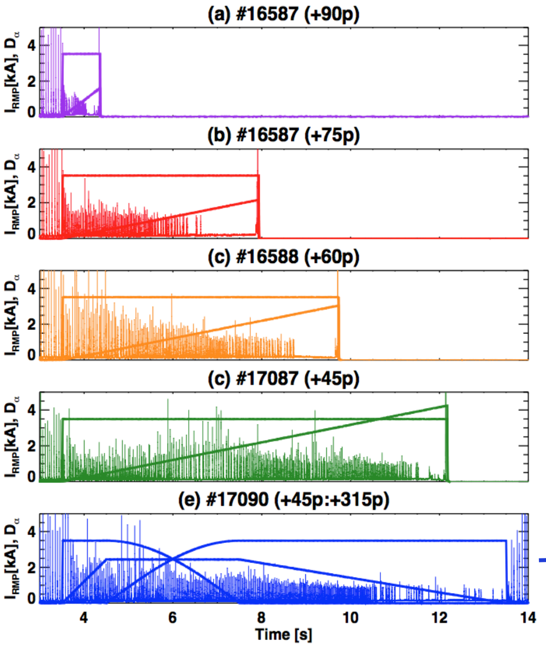


W 7-X

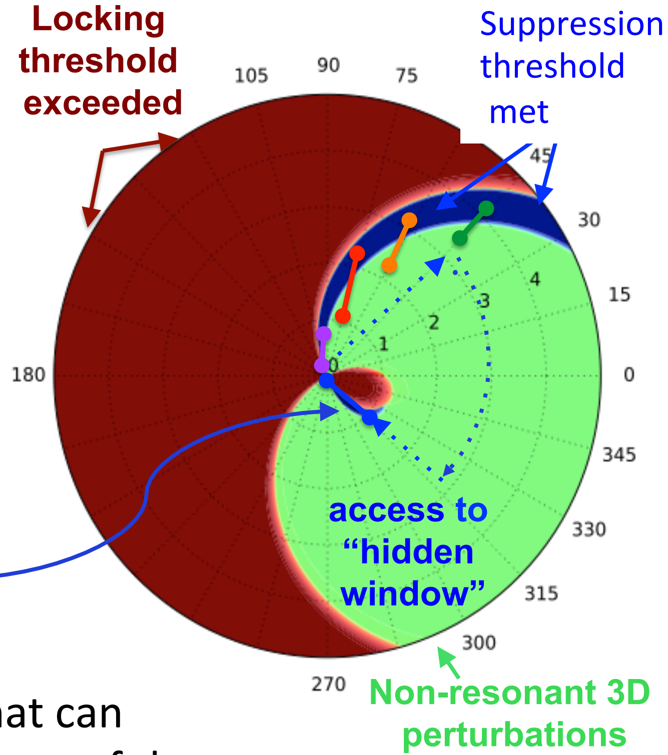
Even Small 3-D Magnetic Fields Have Big Effects!

- Control of plasma stability using small 3-D magnetic fields at edge
- Quantitative validation of theoretical model for edge instabilities
- Disruption threshold also validated

Experimental Validation of Model



IPEC Prediction of stability Space



Are there magnetic configurations with small 3-D fields that can improve the performance of tokamaks and decrease the cost of the stellarator coils?

Strategic Approach to Burning Plasma Research

- US decided in 1996 to pursue burning plasma internationally
  - US has an advantageous opportunity to participate in ITER to address key issues
  - Involvement in ITER needs to include universities, industry and national labs
  - For US to be effectively involved in ITER, need a strong domestic program
- If US were **to withdraw** from ITER, US program needs to increase focus on innovations
  - Withdrawal from ITER will undermine international collaboration
  - A decision for the US to do everything in fusion R&D supporting DT burning plasmas would require a major financial commitment
  - Need to determine if innovations can substantially reduce the costs and overcome the impact of going it alone to study burning plasmas in the US

Breakthrough Innovations and Detailed Understanding Positions US Strategically

- If US participates in ITER:
  - Enables us to exploit ITER effectively and transfer the knowledge to US
  - Breakthrough innovations position the US industry to follow up on ITER's success in the next step of fusion energy development
- If US does not participate in ITER:
  - Breakthrough innovations **may** open a pathway to a burning plasma that is consistent with constrained budgets. Examples include:
    - Practical high temperature superconducting magnets
    - High confinement at high β & low collisionality in NSTX-U
    - Sustained β=5% in W7X without disruptions
    - Enhanced sustained pedestal confinement
    - Liquid-PFC/divertor enabling higher heat-flux systems

US Fusion Strategy Needs to be Robust

- Needs to make major breakout contributions at all budget levels
- The US community needs to make the case that we can successfully address the scientific and technical challenges to deliver on an energy program
- Need to position ourselves to take advantage of a commitment to develop fusion energy
    - Nationally or internationally