PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

Long-term Fusion Vision, Strategy, and Role

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Presented to the NAS Committee for a
Strategic Plan for US Burning Plasma Research
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Outline

Perspectives on:

1. Status of US research supporting burning plasma science
2. PPPL plans that might strengthen or accelerate US research in burning plasma science
3. Strategic elements supporting a long-term vision for US fusion energy research and promote leadership in the field

Building on the talk by R.J. Hawryluk in Austin, TX

Summary

- Strong participation in ITER is the best approach to develop burning plasma research, technology, and understanding
  - advance to fusion energy research

- Innovation is required to improve fusion energy prospects in US
  - reduce size, cost, and increase efficiency, reliability of burning plasma
  - examples: liquid metals, compact tokamaks (ST) and stellarators, HTS, advanced materials…
  - advance towards commercial fusion power

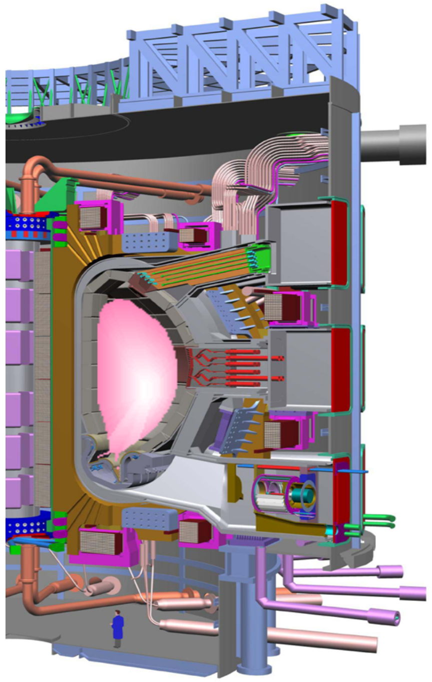
- Both provide opportunities for US leadership

US Burning Plasma Research is Centered on ITER

- ITER is the US facility for burning plasma research
  - Construction is well along
  - Benefits from world-wide effort and investment

- US participation in science and technology development
  - Training of US personnel in all aspects
  - Significant US leadership

- Thru ITER: joint ownership of results, IP rights, expertise



-- The science and technology from ITER will inform all magnetic-confinement approaches

Status of US Burning Plasma Research Activities

- ITER design is largely fixed, candidate Q=10 scenarios identified
  - Steady state Q=5 scenario is still being investigated

- PPPL leading US diagnostic design and development
  Critical for ITER's research capability
  Area of US leadership & responsibility, including port design

- Develop validated approaches for high-priority topics
  - Disruptions and runaway electron beams
  - Edge instability (ELM) suppression
  - Power-exhaust width

Disruption & Runaway Electron Mitigation

- SciDAC - Center for Tokamak Transient Simulations (PPPL led collab.)
  - 3D simulation of tokamak disruptions with conducting wall
  - Disruption dynamics, shattered pellet mitigation, connect to engr.

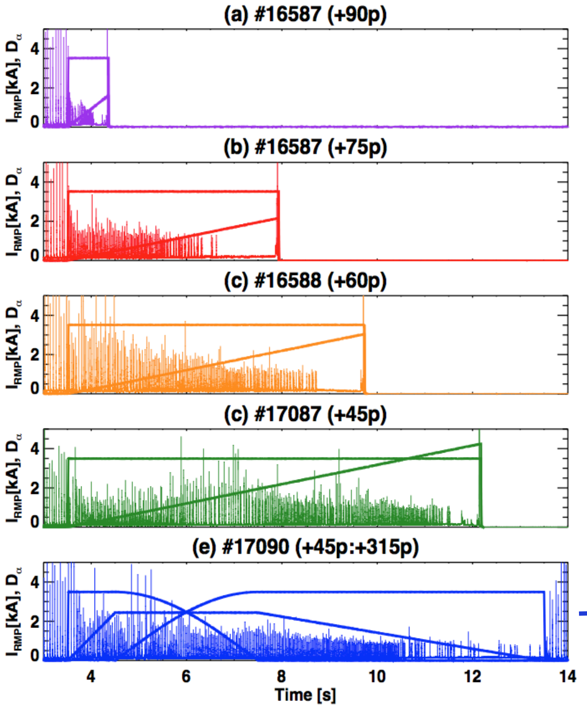
- SciDAC - SCREAM on runaway electron modeling (PPPL led collab.)
  - New results: generation & scattering by Whistler waves
  - Appears to explain puzzling experimental observations
  - ITER implications not yet evaluated

- Deep-learning pre-disruption trigger for mitigation (Internal funding)
- Rail-gun launched pellet mitigation, for hot plasma edge (Internal funding, with U. Washington)

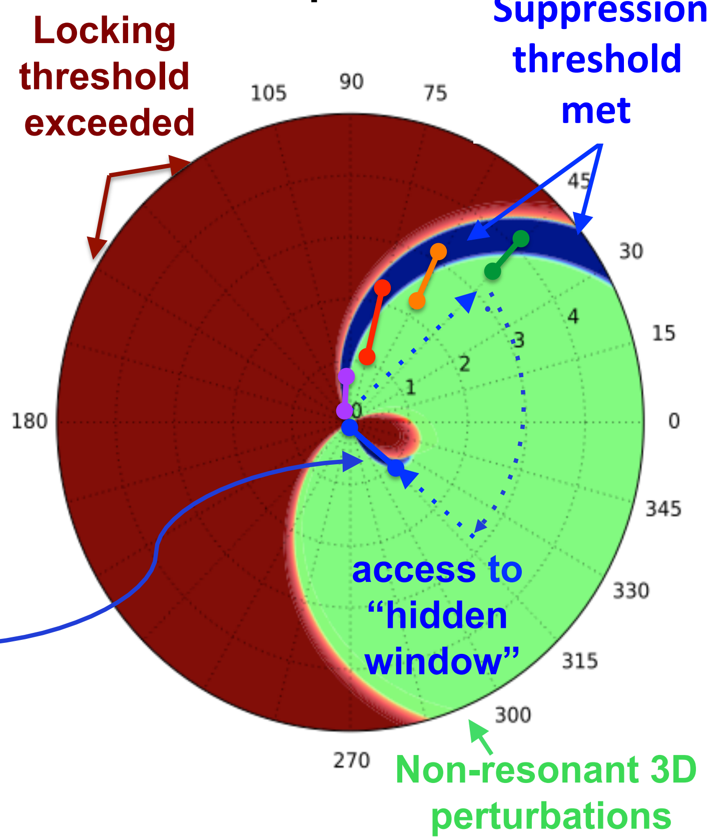
Edge Instability Control Window Understood

- Building on experiments at DIII-D and NSTX
- Control of KSTAR edge stability using 3-rows of perturbation coils at edge
- Vary amplitude and toroidal phase of middle rows of coils
- Quantitative validation of theoretical model for edge instabilities control

Experimental Validation of Model



IPEC Prediction of stability Space



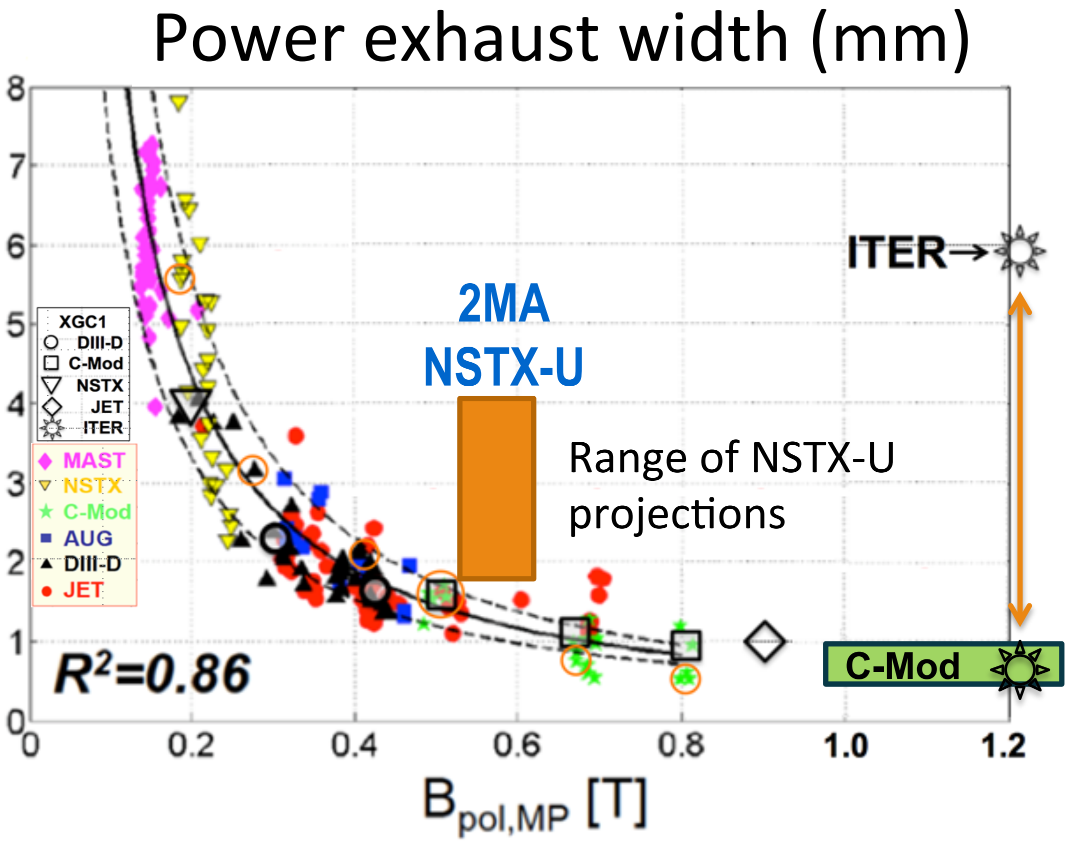
Locking threshold exceeded

Suppression threshold met

access to “hidden window”

Non-resonant 3D perturbations

Divertor Heat-Flux

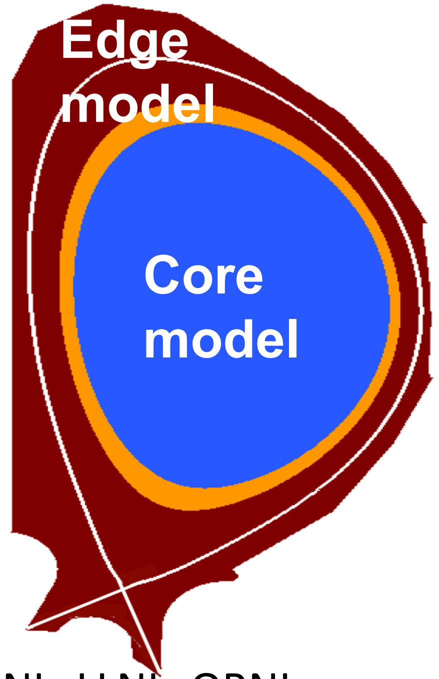


- Initially understood thru heuristic drift-model (PPPL)
- Prediction for ITER: < 1mm heat flux width => very high heat flux
- XGC1 (PPPL) reproduces data variation, but predicts turbulence broadens ITER. Is this correct?
- NSTX-U will test broadening & mitigation by flux expansion

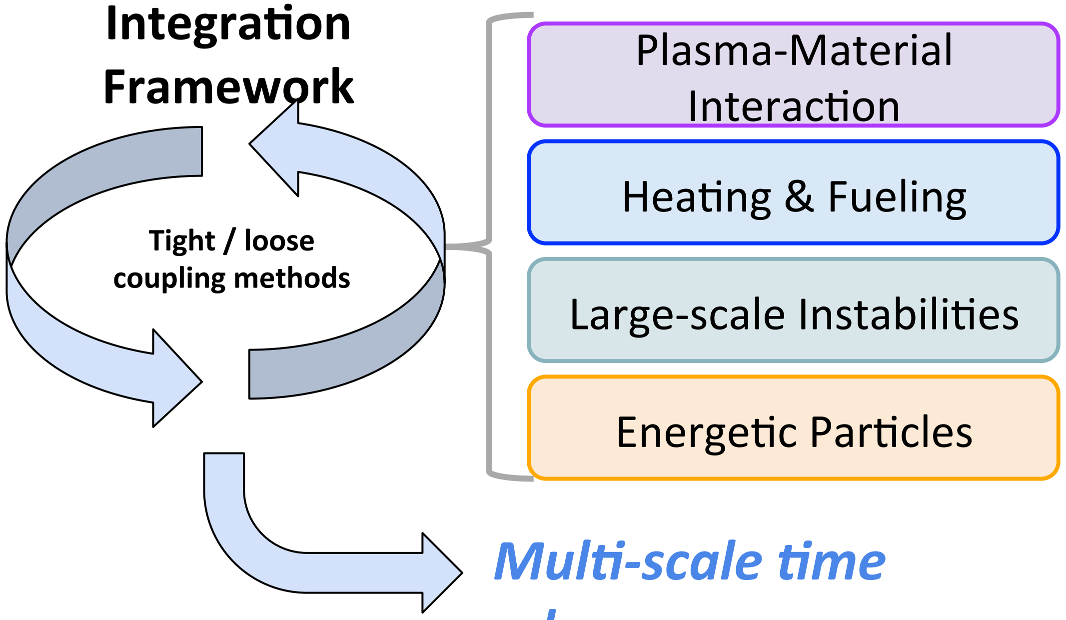
2. Accelerate Preparations for Burning Plasma Science: Integrated Modeling

- High fidelity integrated model of burning plasma thru DOE Exascale Proj.
- Initial focus: core-edge tight integration, building on SciDAC models

tokamaks
&
stellarators



PPPL (lead), ANL, LLNL, ORNL,
Rutgers, U.Texas, UC-Boulder



Integration Framework

Tight / loose coupling methods

Plasma-Material Interaction

Heating & Fueling

Large-scale Instabilities

Energetic Particles

Multi-scale time advance

See talk by A. Bhattacharjee

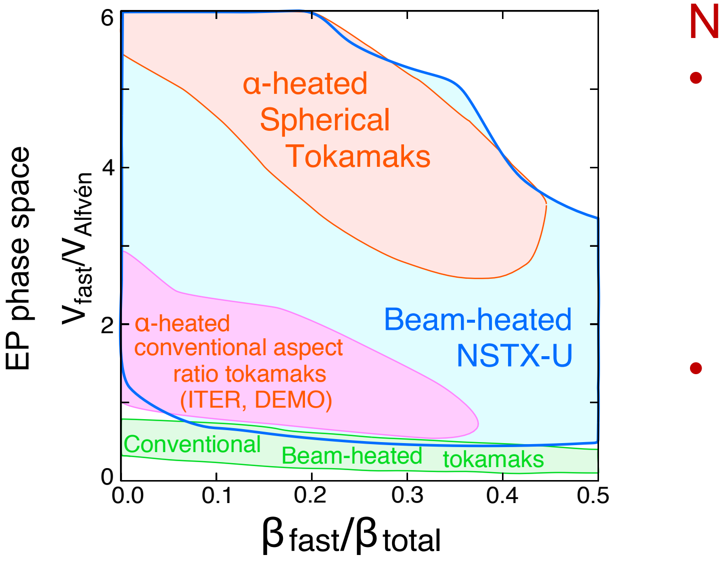
Preparing Production Whole-Device Models

- Reduced fidelity, faster, integrated models under development
  - For predictive modeling of proposed experiments
  - For routine analysis of data
  - Verified with high-fidelity models
  - Validated on current experiments, including DIII-D and NSTX-U

- Especially important for high pressure (β) and bootstrap-current for long-pulse experiments, due to non-linear evolution of equilibrium

- Similar efforts starting for stellarators

Example: NSTX-U is studying α-particle instabilities applicable to ITER

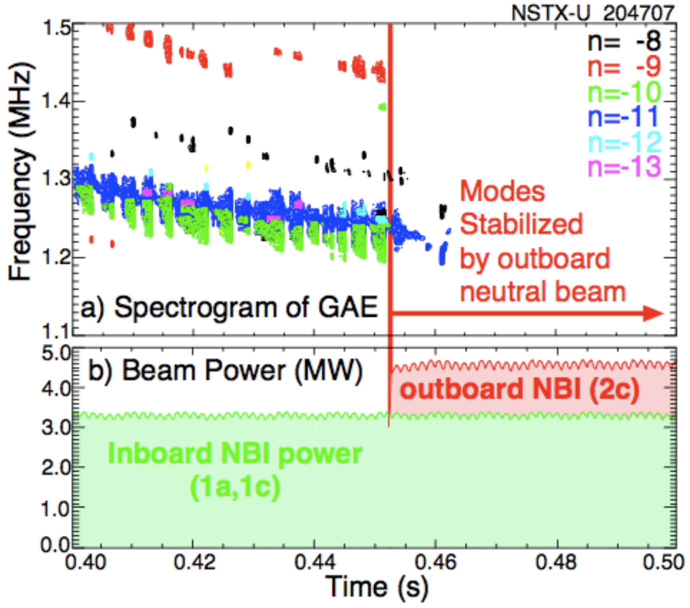


~ (EP-instability drive)/(EP-instability damping)

NSTX-U: Fast-ion dynamic range spanning ST and conventional A burning plasma regime

NSTX-U will:

- assess confinement of fast-ions in high-performance ST regimes
- extend predictive capabilities for energetic particle dynamics in burning plasma regime



Vary beam pitch angle, pressure profile → Assess mode stability as a function of ion phase space

3. Long-term Vision toward Fusion Energy

- ITER is a physics and technology experiment
  Will provide knowledge & experience
  for fusion energy research

- As in the 2004 NRC Burning Plasma Report, ITER is not a prototype for a commercial power reactor in the US
  - Need higher performance for size and cost

- Next steps based on ITER are larger and likely more expensive, e.g. EU DEMO

	EU DEMO **pulsed-ind.**
R_0 (m)	9.0
a (m)	2.5
B_T (T)	6.5
I_P (MA)	16.8
f_{Boot}	36%
β	2.6%
$H_{98,y2}$	1.0
$P_{thermal}$	2.2 GW
Net $P_{electic}$	500 MW

US Route to Commercial Fusion

- In some countries, fusion will be developed by their government

- US: development of commercial fusion will be led by industry
  - Role of government is to enable by developing underlying science
  - Enable via public-private partnerships

- Interest by start-up companies very important
  Sign of success in developing scientific and technical basis for fusion
  - Assessment that gaps probably can be closed
  - Builds on world-wide experiments (all kinds) and ITER

- Focus on prioritizing and resolving risks
  - At minimum scale (cost) and on a rapid timescale

Industry Requests

- Safety
- Long-term economically competitive
- Rapid construction and moderate capital cost per unit
- Licensing simplicity
- Reliability, availability, maintainability, inspectability (RAMI)
- Steady state, with load-following (quick shutdown/restart)
- Public acceptance
  - No need for wide-area evacuation

After EPRI, LIFE Adv. Committee

Not the same approach as some of our international partners

Implications: Innovation is Needed

- Robust, reliable operation – eliminate disruptions and “off normal events”
  - Thin first wall for T-breeding
- More efficient production of energy and use of plant
  - Higher fusion power density => higher β and/or B
  - Less recirculating power
- Smaller unit size than 1 GWe, especially during development
- Robust power handling with reduced maintenance
- Simplify, probably by elimination of some sub-systems
- Need long-lived materials, to reduce maintenance (esp. divertor)

Innovation Opportunities

- Liquid-metal boundaries (see M. Jaworski)
  - High power-flux, eliminate erosion, allows low-Z wall and higher confinement (NSTX-U, EAST?)
- Spherical tokamak (see S. Gerhardt)
  - More compact, high β, higher magnetic field utilization, lower capital cost (NSTX-U & MAST-U)
- Higher efficiency current drive
  - Helicon-wave and inside launch lower-hybrid current-drive (DIII-D & KSTAR)
- Compact stellarators / 3D-Tokamaks (committee's teleconference)
  - Eliminate disruptions, eliminate current-drive; high β, high density, high gain (US led, but ?)

Innovation Opportunities II

- HTS magnets (see M.Greenwald, S.Prestemon)
  - Higher B, higher current density, enables compact configurations
  - May allow simpler coil design

- Advanced materials
  - Longer life, higher strength at high temperature
  - Reduce maintenance, increase availability, increase thermal conv. efficiency

- Use validated simulation to guide extrapolation (See A.Bhattacharjee)
  - Reduce risks

- Aim at a "pilot plant" (see J. Menard)
  - Address integration risks at modest scale
  - Then mature technology and operating experience together
  - If innovations achieve high Q, net-power production is easier than life-time testing

PPPL is exploring many of these potential innovations with the community.

Strategy with ITER: Innovate in Parallel

- During ITER construction and burning plasma operation:
  - Explore and mature innovations
  - Attempt multi-innovation integration, increasing TRL
  - Validate models for simulation

- Assess combined results from ITER and innovations in modeled projections

- Go forward when projected systems are compelling, and address commercial needs
  - Pilot Plant as small as credible, to reduce risks, build confidence

Strategy without ITER: Innovate

- US out of ITER: loss of technical expertise, experience, momentum
  - Missed iteration will delay US advance to burning plasma research
  - Recover by exploring and maturing innovations; integrating

- Assess results from innovations combined with world's experiments in modeled projections, but will not have full ITER knowledge

- Go forward when projected systems are compelling, motivate funds
  - Recover burning plasma expertise and experience
  - May use innovations to partner with other programs post-ITER
  - Pilot Plant as small as credible, to reduce risks, build confidence

Summary

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