Continued Research on Alcator C-Mod at MIT is Critical to Make Fusion a Viable Energy Source

Miklos Porkolab
with input from Earl Marmar

MIT Plasma Science and Fusion Center

Presented at the Fusion Power Associates Meeting
Washington, D.C., December 5, 2012

Introduction

Alcator C-Mod

- **Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, e.g., how to optimize ITER operation**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- **Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta
- **Progress in theory and computational science has been impressive, but serious gaps remain to predict tokamak performance, e.g., electron transport, steady state and path to the burning plasma regime**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta
- Progress in theory and computational science has been impressive, but serious gaps remain to predict tokamak performance, e.g., electron transport, steady state and path to the burning plasma regime
- **Vigorous research in the next decade is necessary on existing tokamak facilities with upgrades in heating and current drive power as well as advanced plasma diagnostics and tungsten Plasma Facing Components (PFC)**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta
- Progress in theory and computational science has been impressive, but serious gaps remain to predict tokamak performance, e.g., electron transport, steady state and path to the burning plasma regime
- Vigorous research in the next decade is necessary on existing tokamak facilities with upgrades in heating and current drive power as well as advanced plasma diagnostics and tungsten Plasma Facing Components (PFC)
- **Need to study impact of high power density on PFC, including ELMS, disruptions, and impurity generation due to ICRF (RF sheath-wall interaction)**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta
- Progress in theory and computational science has been impressive, but serious gaps remain to predict tokamak performance, e.g., electron transport, steady state and path to the burning plasma regime
- Vigorous research in the next decade is necessary on existing tokamak facilities with upgrades in heating and current drive power as well as advanced plasma diagnostics and tungsten Plasma Facing Components (PFC)
- Need to study impact of high power density on PFC, including ELMS, disruptions, and impurity generation due to ICRF (RF sheath-wall interaction)
- **Superconducting facilities play a special role to study long pulse material erosion (walls) and heat load tolerance (divertor) – but well diagnosed copper coil facilities with a few L/R pulse lengths may be better suited to study much of the above plasma physics issues**

Introduction

- Progress in fusion research in the past decade has been impressive but key plasma physics issues remain, eg, how to optimize ITER operation
- Plasma physics issues for an attractive DEMO remain challenging and yet to be demonstrated, eg, MHD stable, steady state and high electron beta
- Progress in theory and computational science has been impressive, but serious gaps remain to predict tokamak performance, e.g., electron transport, steady state and path to the burning plasma regime
- Vigorous research in the next decade is necessary on existing tokamak facilities with upgrades in heating and current drive power as well as advanced plasma diagnostics and tungsten Plasma Facing Components (PFC)
- Need to study impact of high power density on PFC, including ELMS, disruptions, and impurity generation due to ICRF (RF sheath-wall interaction)
- Superconducting facilities play a special role to study long pulse material erosion (walls) and heat load tolerance (divertor) – but well diagnosed copper coil facilities with a few L/R pulse lengths may be better suited to study much of the above plasma physics issues
- **Graduate education must remain a central element of the program**

C-Mod has a World-Leading Program Critical to the Success of ITER and the Development of Fusion Energy

Alcator C-Mod

- Pioneered the vertical-plate divertor and high-Z plasma facing components
  - Both adopted for ITER: only viable solution for high power density, low retention
  - Now taking this to the next level with high temperature tungsten: best (only?) hope for FNSF/DEMO/Reactor
- New approaches to RF for heating, current drive, flow drive - plasma control
  - Making rapid progress on the challenge of ICRF-induced impurities: Solution(s) within view
  - Unique LHCD studies at fields, densities, frequency for ITER, FNSF, DEMO - leading way to solution for steady-state tokamak reactor
- Discovered and developing potential solution to the ELM problem:

  - I-mode - likely as credible as the RMP approach
- C-Mod operates with dominant electron heating with RF without external momentum input - prototypical of ITER and the reactor regime
- C-Mod is a major educator of the next generation of plasma physicists and fusion scientists

2012 FESAC report: Tungsten PMI Research at T > 500 ^{0}C with "Reactor-like Plasma and Temperature" Conditions is High Near-Term Priority

Alcator C-Mod

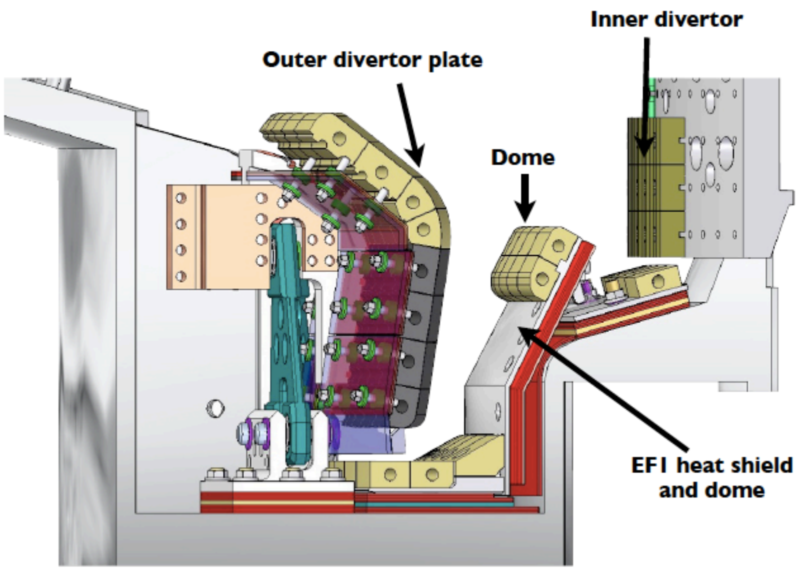
"The leading FNSF/DEMO candidate solid material to meet the variety of PFC material requirements is tungsten due to its projected erosion resistance, high melting temperature and high thermal conductivity."

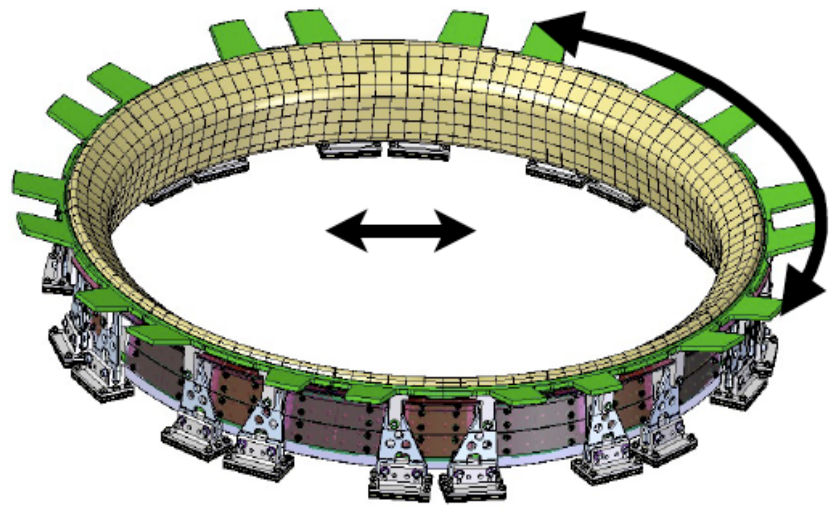
"Initiatives with the following objectives are required… characterize tungsten-based materials in appropriate plasma, thermal and radiation damage environments"

"Important considerations are the impact on the core plasma via impurities, their response to plasma particle bombardment, … their thermal performance under high heat flux and operating temperatures above 500°C."

2012 FESAC Report: Tungsten PMI Research at T>500 ^{0}C with "Reactor-like Plasma and Temperature" Conditions is High Near-Term Priority

- The new hot-divertor on Alcator will provide first of a kind studies of tungsten PMI in the reactor-relevant plasma + thermal environment
- Divertor will be operating with the power and particle loading, plasma density, magnetic field, divertor geometry, materials and temperatures prototypical of a reactor.





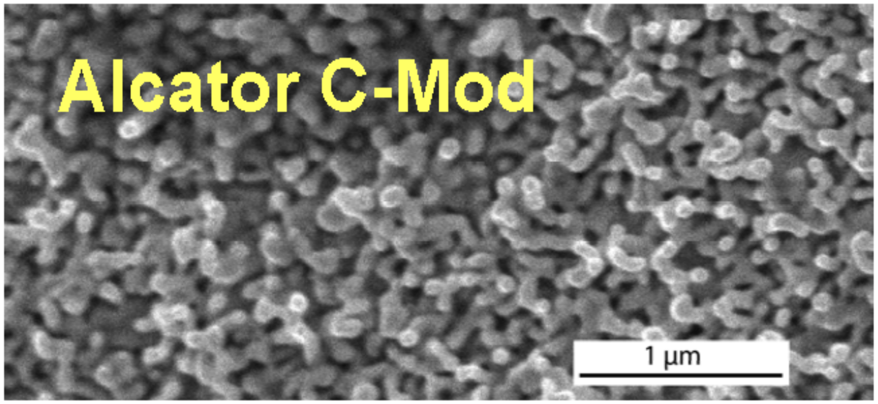
Install FY14, Operate FY15

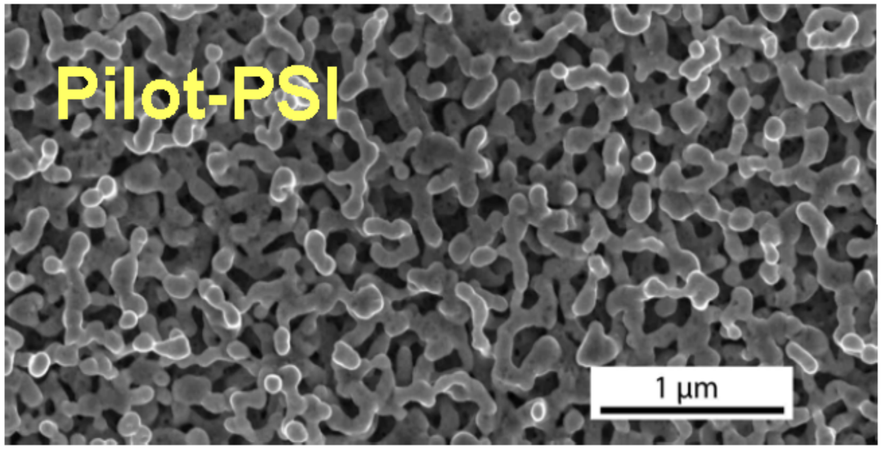
Tungsten Nanostructures Observed In C-Mod: First Time Ever in a Tokamak

-Temperature Matters!

Alcator C-Mod

- Growth of W nano-structures has been observed in PWI test-stands
  - Hypothesis: Small filaments "extruded" by helium bubbles captured in metal substrate
  - Could be major source of erosion and dust production in future reactor – if process occurs in that environment
- Open question: Could these processes occur, undisturbed in operating tokamak environment?
- On C-Mod, careful experiments were performed to raise sample to correct temperature range (~2000˚K)

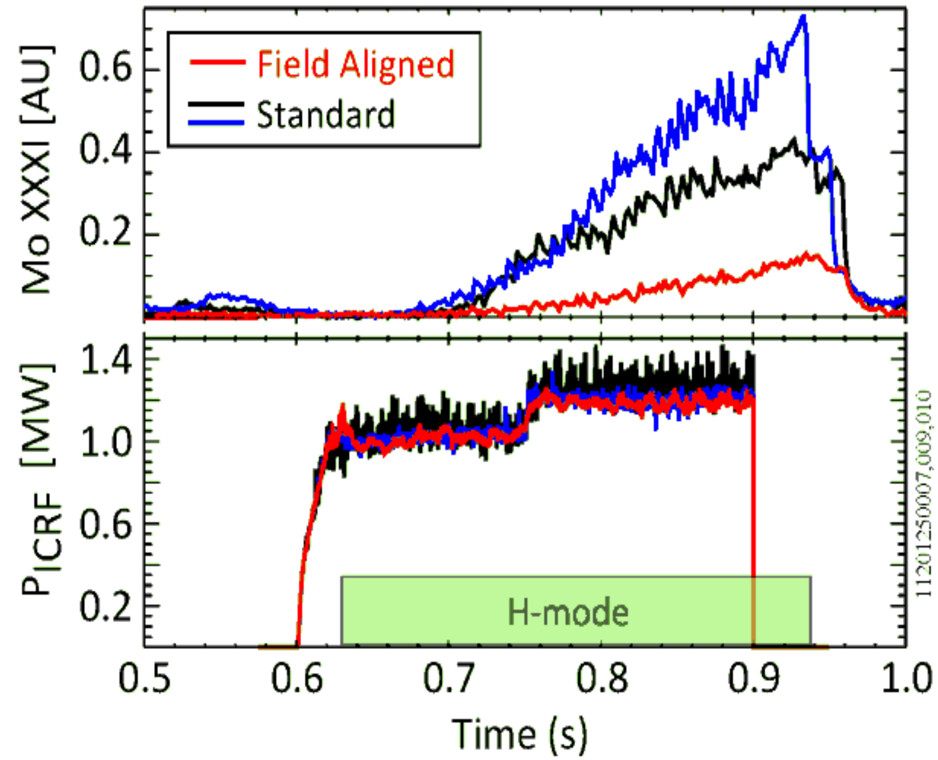


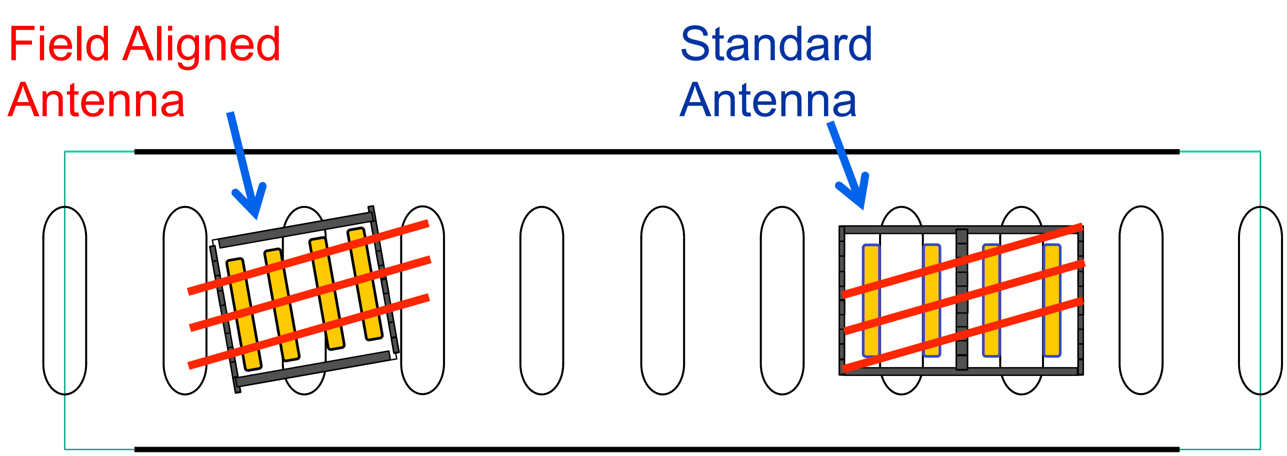


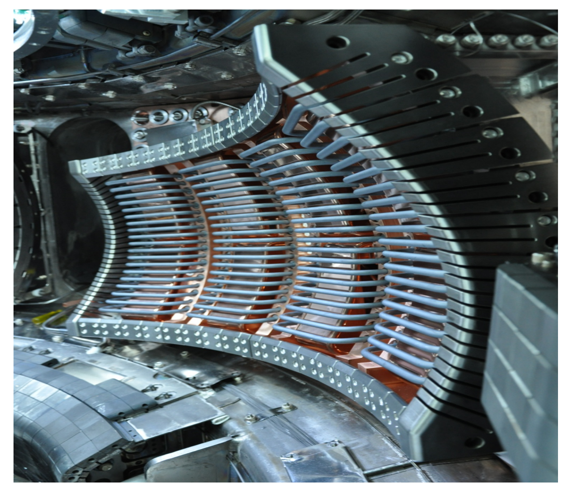
- Morphology (tendrils ~100nm) and growth rates (~600nm in 13 sec) match
- Provides confidence that key growth parameters, from linear devices, can be used for prediction in future devices.

Innovative ICRF Antenna Developed To Address The Issue Of Metallic Impurity Generation

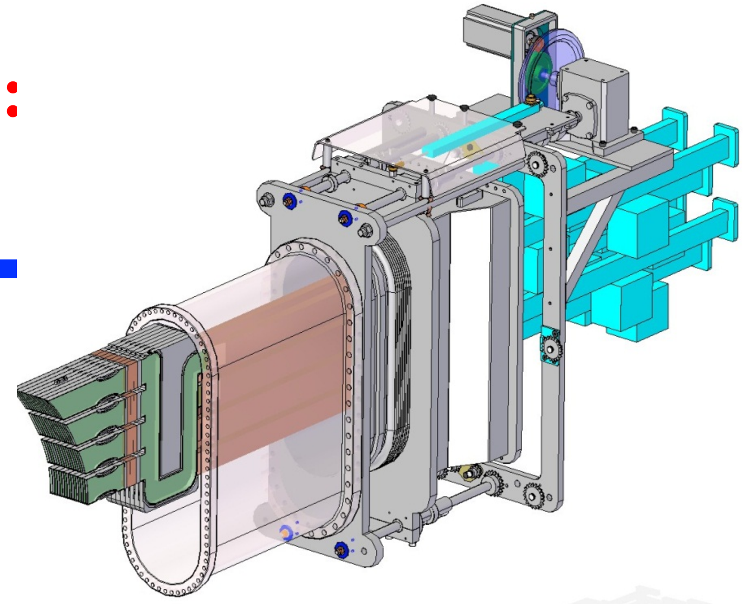
- **Critical issue for metal machines like ITER**
- **Hypothesis: RF sheath rectification and acceleration of ions into wall**
  - **Large RF potentials measured far from antenna**
- **Antenna designed to minimize $E_{||}$**
- **Results:**
  - **Improved RF power handling**
  - **Reduced Mo radiation**
  - **Discrepancies with models remain**
- **More experiments and modeling required**







LHCD at Reactor Relevant Density : Need High Single Pass Absorption



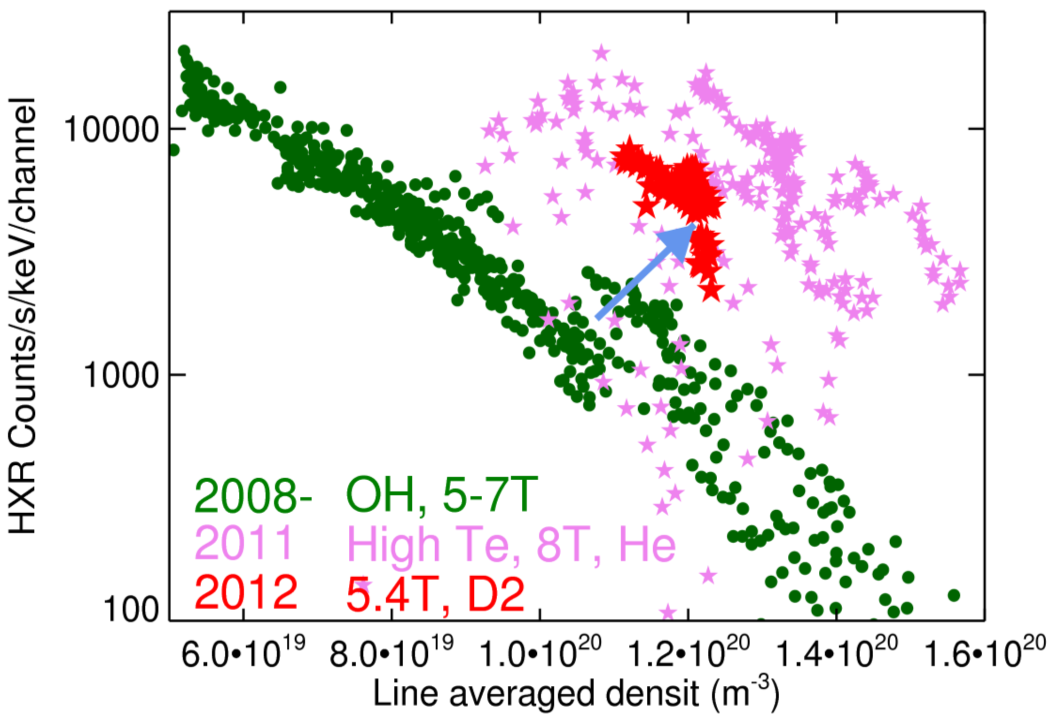
Extending LHCD toward high density is crucial for reactors.

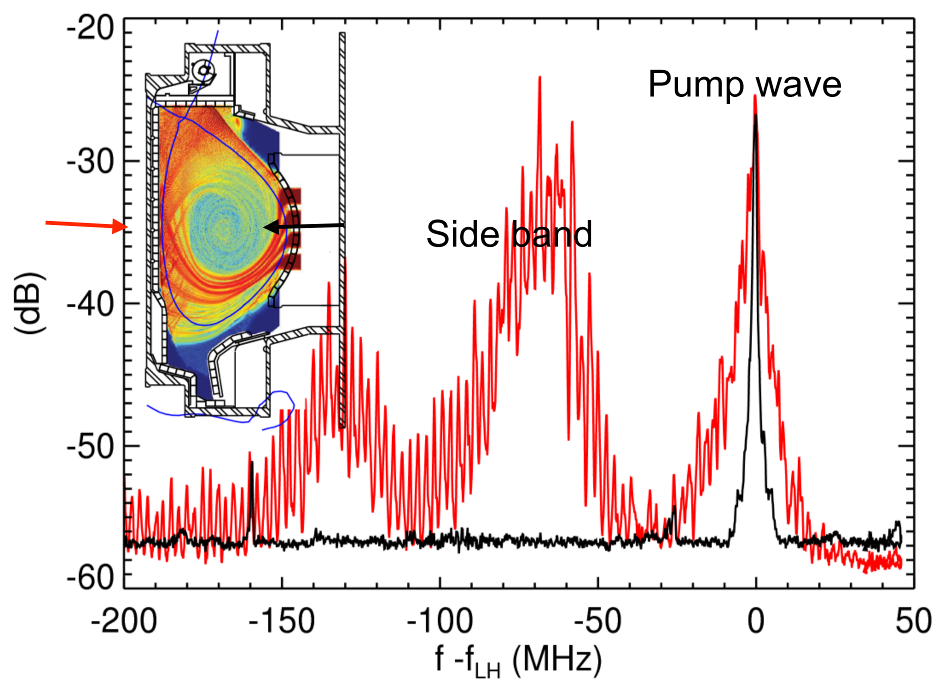
Key C-Mod LHCD results:

- Full non-inductive sustainment at n_e~$0.55 \times 10^{20} m^{-3}$ (ITER AT Case)
- Reversed Shear plasmas
- Efficient LHCD up to $1.4 \times 10^{20} m^{-3}$

High density :

- Strong non-linear(PDI) interactions in edge plasmas in multipass regimes
- PDI often happens only high field side

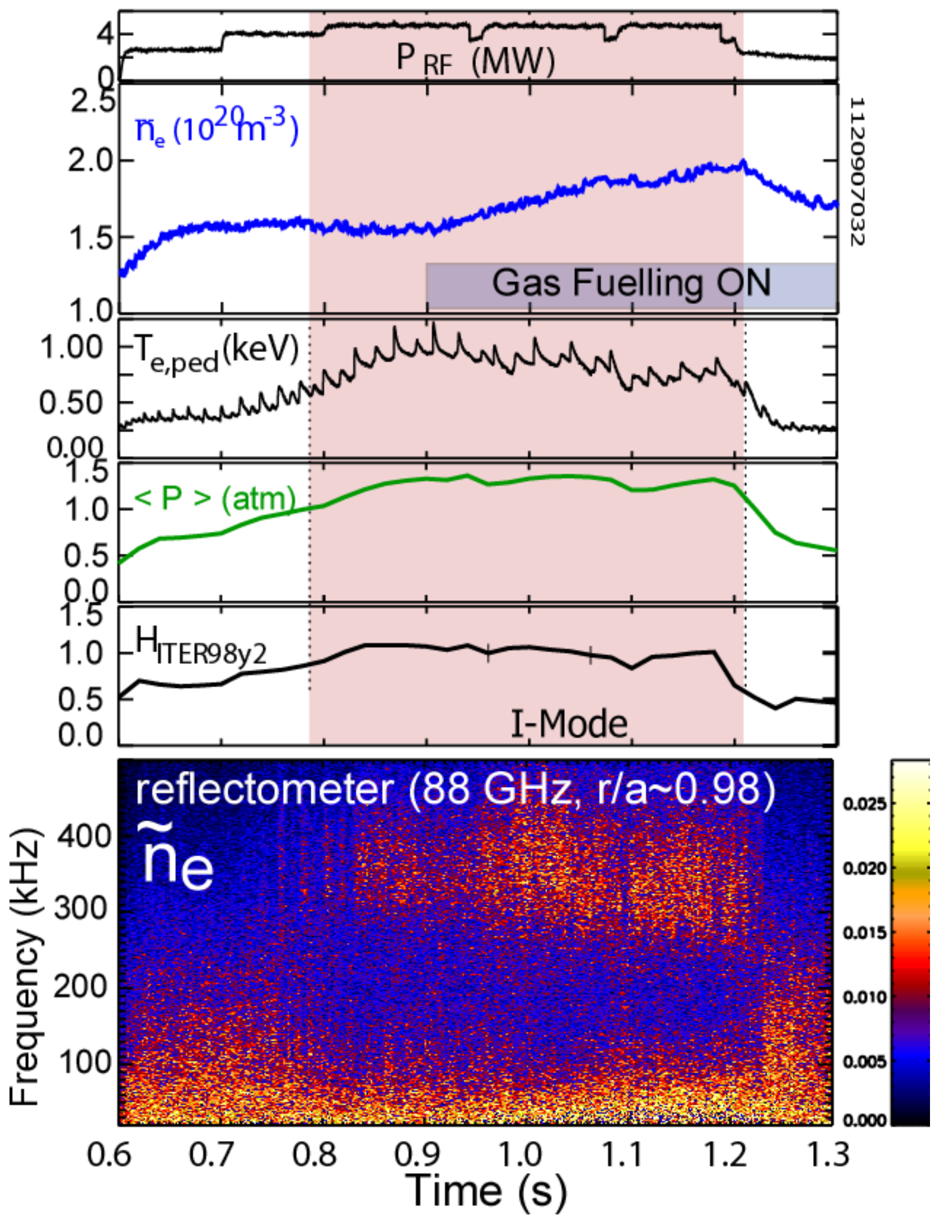




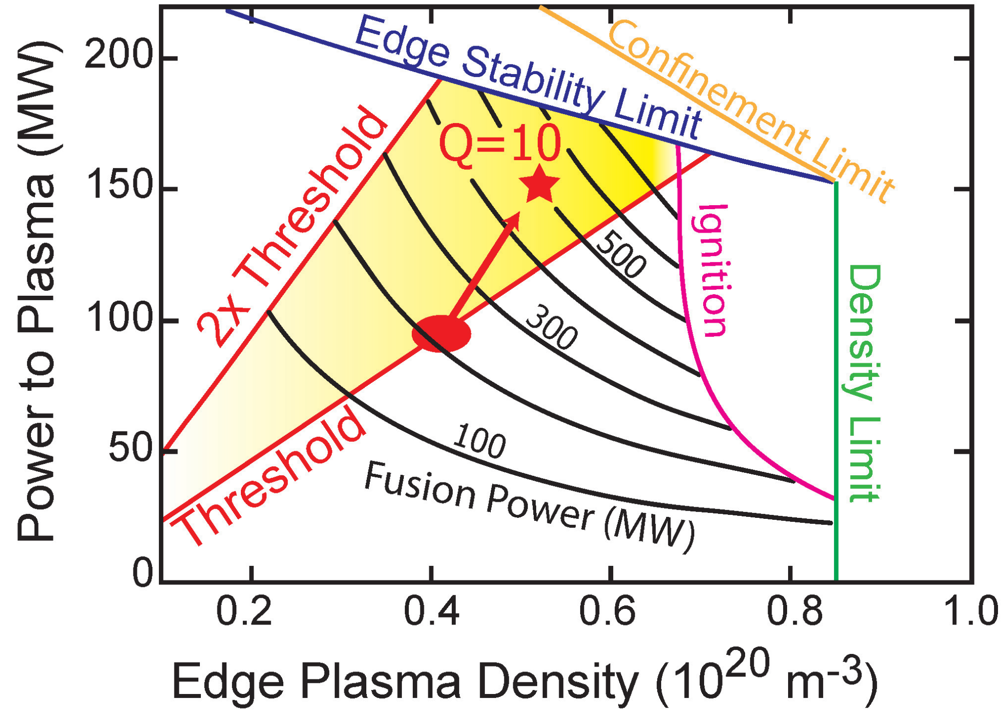
I-mode: Extrapolation to ITER Q=10 Requires Densification: Now Demonstrated on C-Mod

Alcator C-Mod

ELM-free, High Performance



Extrapolation of I-mode from C-Mod to ITER

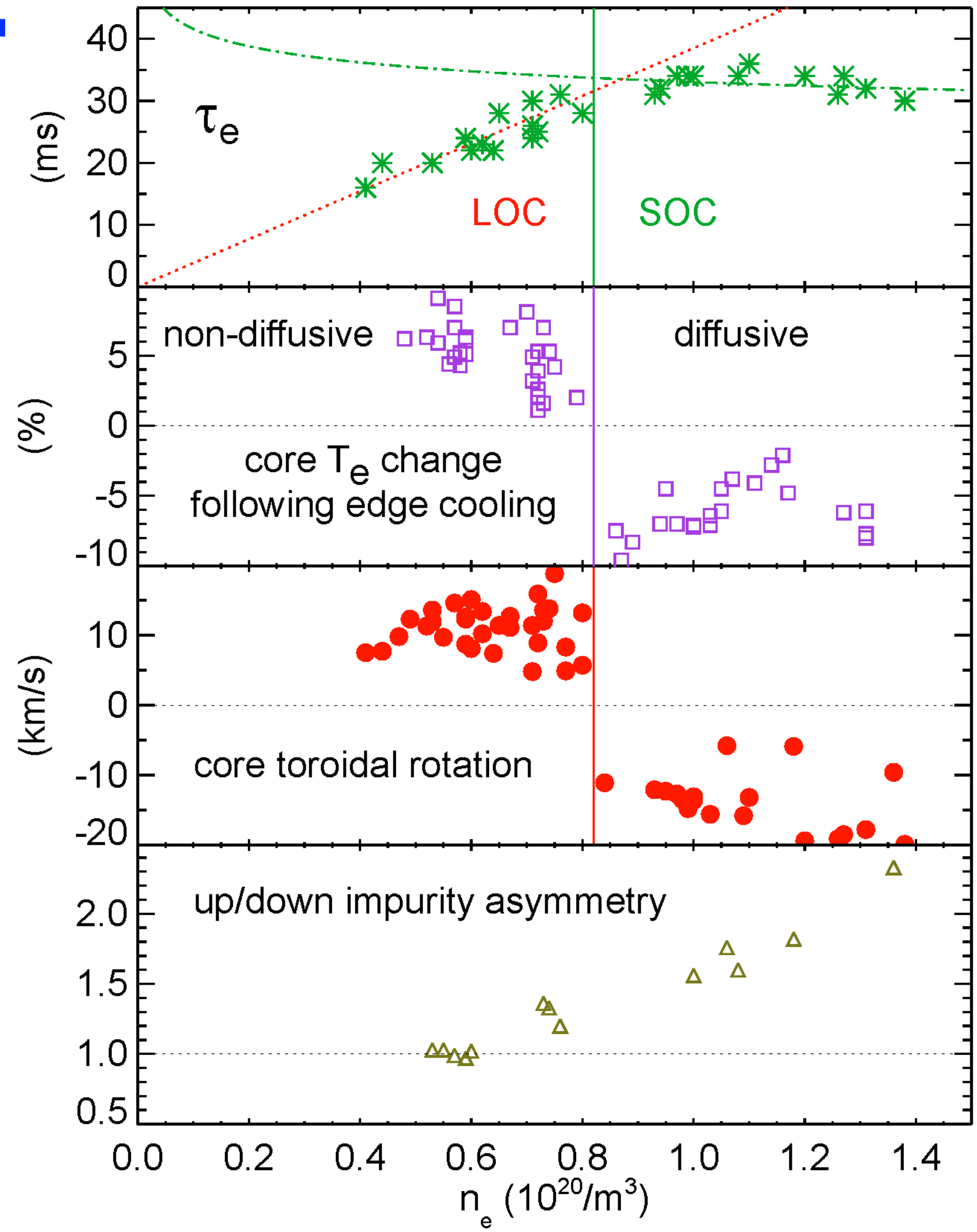


- Enter I-mode at low density (reduced P_{thresh})
- Stay in I-mode while increasing density
  - Fusion power increases as auxiliary power is decreased
- More experiments urgently needed, both on C-Mod and larger, lower field experiments (size scaling)

Intrinsic Rotation: Reversals Tie Together Seemingly Disparate Behaviors

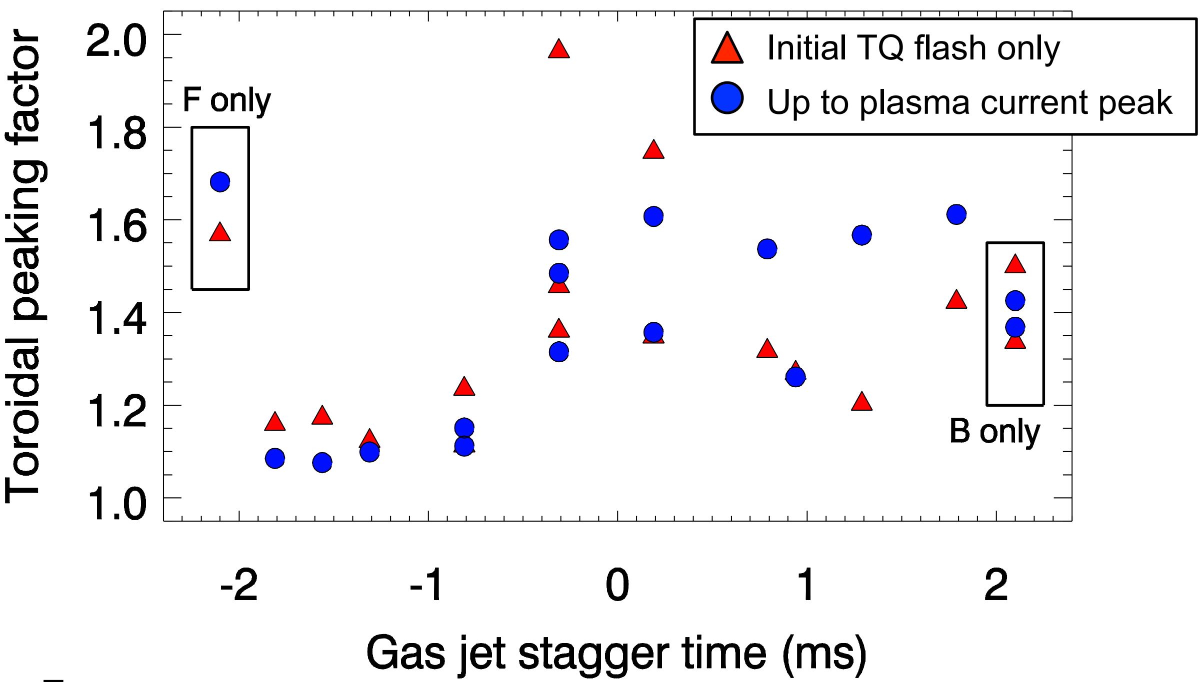
Alcator C-Mod

- Intrinsic rotation reversals reveal commonality of physics for multiple long-standing tokamak puzzles
  - Linear to Saturated confinement at critical density (LOC to SOC)
  - Non-diffusive heat transport
  - Up/down impurity asymmetries
- Rotation reversal is the most sensitive indicator
  - Clear changes in core and edge turbulence correlate with the reversal

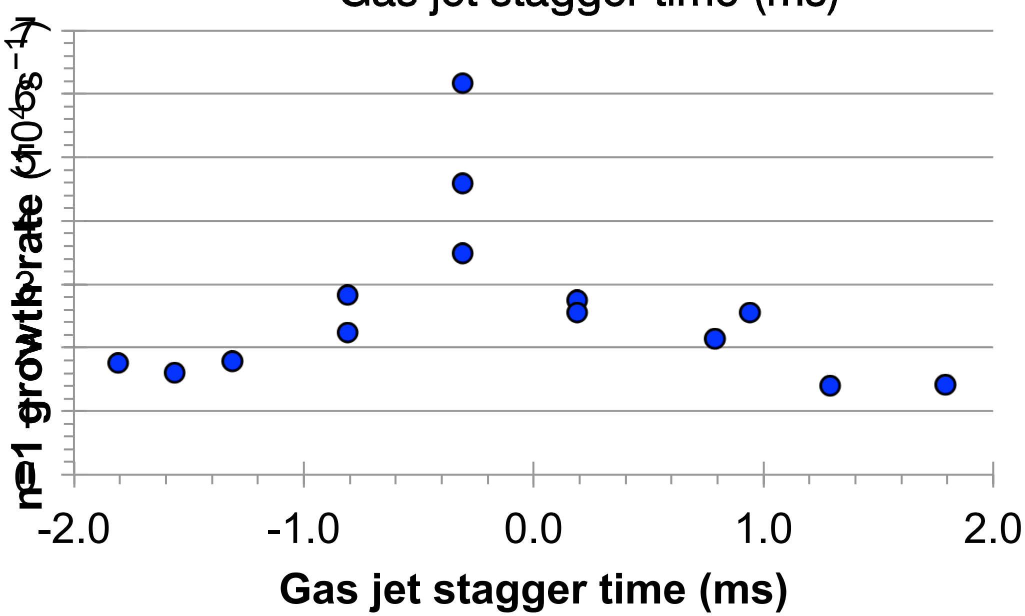


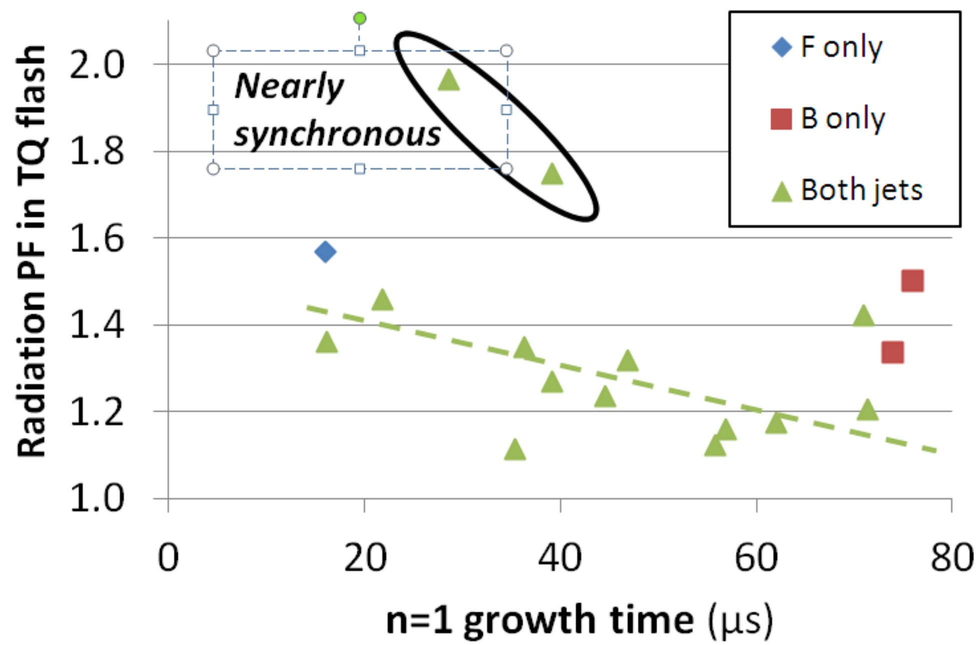
Radiation Peaking During Mitigated Disruptions Critical for ITER: First Results with Multiple Gas Jets

Alcator C-Mod



- Rapid shutdowns of 1 MW ICRF-heated L-mode plasmas (LSN diverted) using 15% Ar / 85% He
- Toroidally separated gas injectors (144° toroidal separation)
- Most symmetric thermal quench when jets not synchronous
- Toroidal peaking is controlled by *n*=1 MHD





C-Mod Central and Critical to OFES' "10 year vision"

OFES *Vision*	Critical C-Mod Contributions
ITER	1) Maximize ITER's chance of success (tungsten divertor, disruptions, ELM-free scenarios, RF heating and current drive, transport and turbulence studies in electron heated regimes); 2) Workforce development.
Fusion materials science	1) Erosion, tritium retention, formation of nano-structures, in reactor temperature tungsten divertor; 2) World-leading diagnostics; 3) Close collaboration with MIT Surface Science Center
Extend the reach of plasma control science and plasma-wall interactions	1) ITER and reactor-relevant RF control tools (heating, current-drive, flow-drive); 2) Plasma-wall interactions at reactor-relevant particle- and power-densities, with solid high-z materials; 3) Unique DEMO-like actively heated tungsten divertor
Validated predictive capability	1) Extremely well-diagnosed experiments; 2) Tight coupling to world-leading theorists and modelers (in-house and through collaborations); 3) State of the art computational models and codes.

Summary

Alcator C-Mod

- Much physics remains to be explored on existing tokamaks in order to optimize ITER operation (transport and stability in electron heated regimes (alpha heating), ELM mitigation, disruption control
- For DEMO and for a fusion power plant we must expand plasma parameters beyond ITER (density by a factor of 3, magnetic field by 1.5, surface power density by 3, with significant impact on actuators such as heating and current drive, as well as divertor geometry and wall materials
- Advanced Tokamak (AT) physics (pressure and CD profile control

  - both driven and bootstrap) must be demonstrated at reactor

  relevant fields (B =6-9 T) and densities (n_e= 2.8×10^{20} m^{-3})
- C-Mod is well suited to explore many aspects of this physics
- Graduate education in plasma and fusion physics must be continued at all levels, including top rated universities to attract the best talent