Recent Results from Alcator C-Mod

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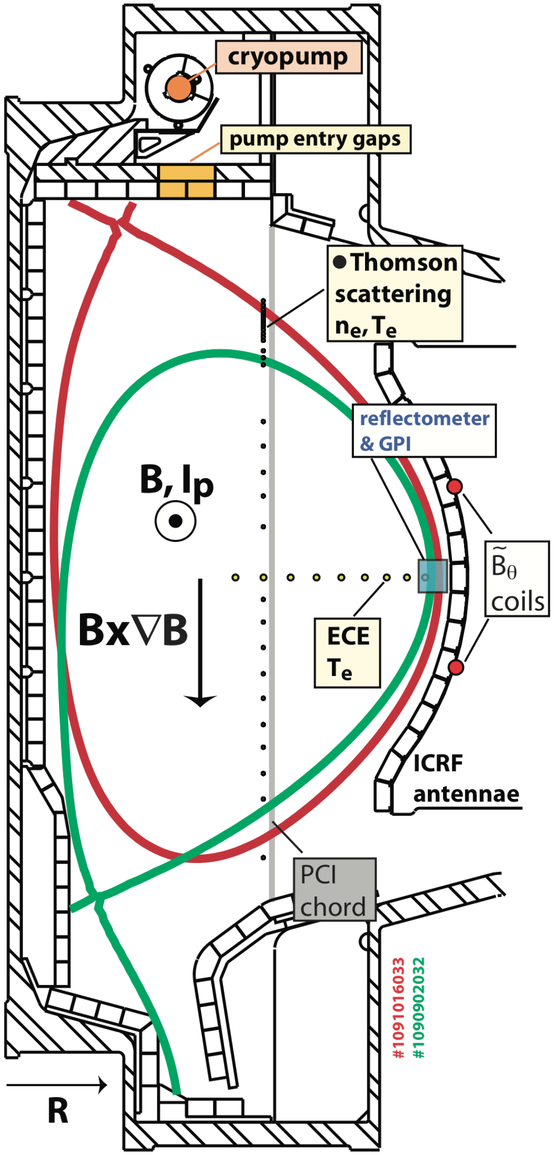
C-Mod research program focuses on areas of unique capability, ITER and reactor relevance

- Solid high-Z metal walls
- Reactor-like power density / divertor plasma
- High density and neutral opacity
- ICRF and LHCD at ITER/reactor B_T, density:
- Transport studies in electron dominated regimes



R=0.67 m

a =0.22 m

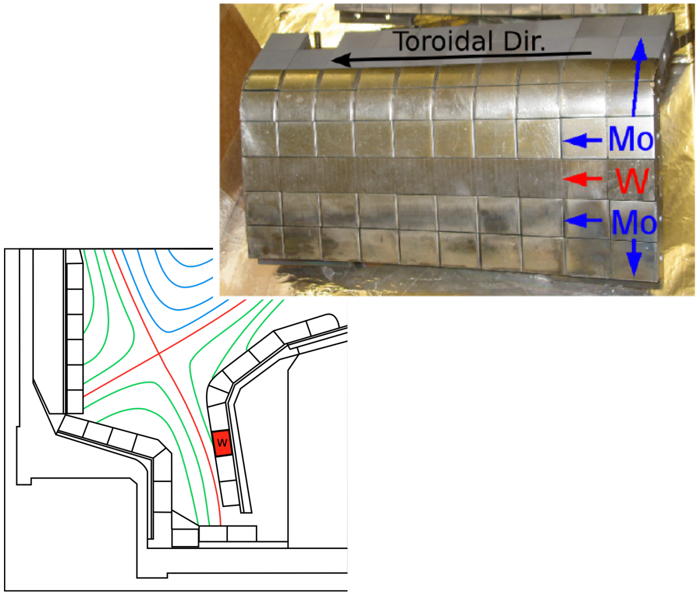
$B_T \leq 8$ T

$I_p \leq 1.3$ MA

$P_{ICRF} \leq 6$ MW

$P_{LHCD} \leq 2$ MW

Different tungsten (W) erosion scenarios lead to different W sources for plasma impurities



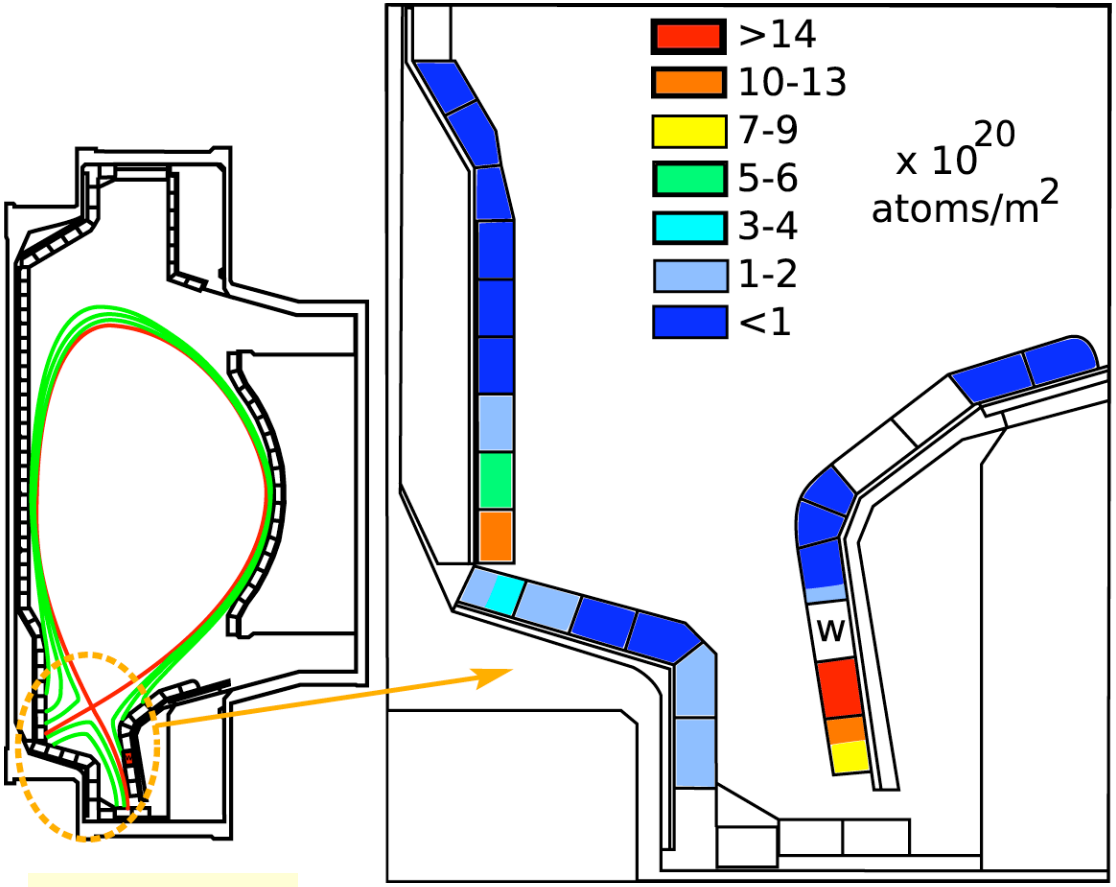
Sputtering Scenario:

- For two campaigns (2007-2008), W erosion is due to physical erosion of W tiles at outer strike point.
- Small, toroidally-symmetric W source
  - Small amounts of W in the core
  - SUCCESS: “acceptable” **net** W sputtering rate of ~0.05 nm/s =1.5 mm/year

Melting Scenario:

- Failed W tile leading to significant W melting in 2009-2010 Campaign
- Strong, local W source
  - Significant W detected in core.
  - Operation with strikpoint on W row impossible due to excessive W core contamination

Sputtering : W inventory in the divertor indicates reactor-acceptable net erosion rate & test of erosion models



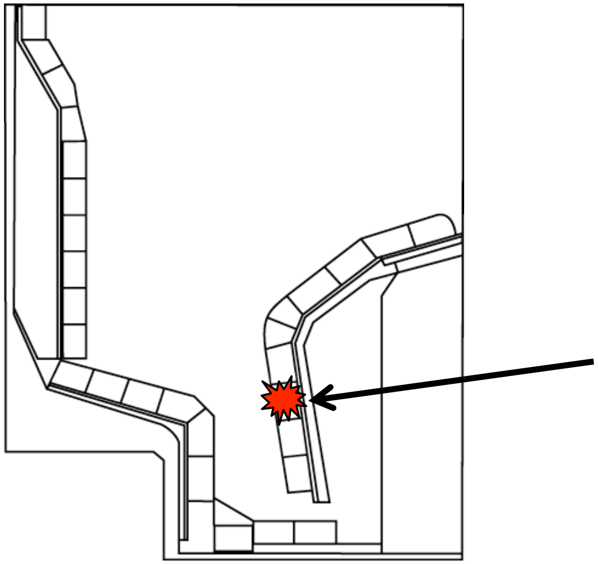
Barnard, PSI 2010

- A *net* effective thickness 4×10^{21} W atoms/m^2 (~ 60 nm) has been removed from W tile
  - ➢ ~0.05 nm/s
  - ➢ ~1.5 mm/exposure-year

➢ Modeling of erosion & transport starting.

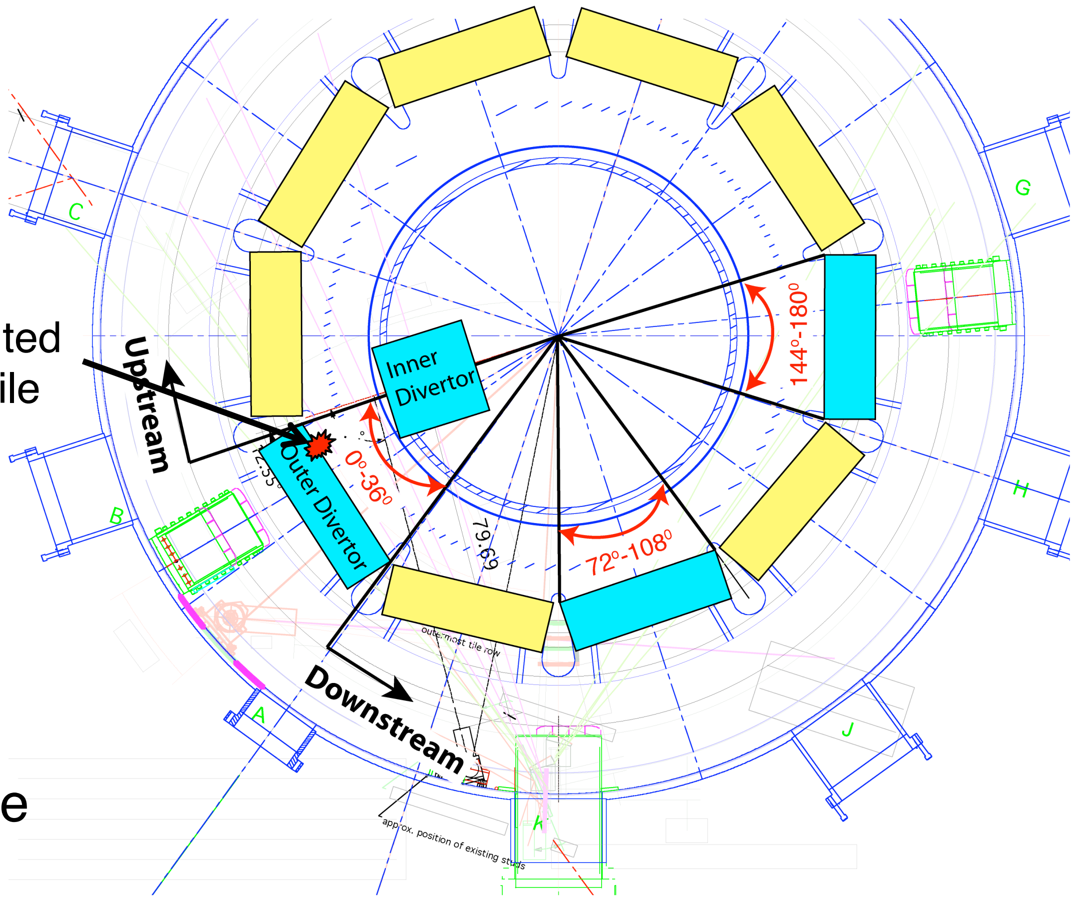
However, significant W melting led to high W core contamination during operation

Poloidal view



Melted W tile

Toroidal view



Melted tile at 0^o toroidal

- Strike-point could not be operated on the W row after the melting event due to W in the core and disruptions.

Wright, APS 2010

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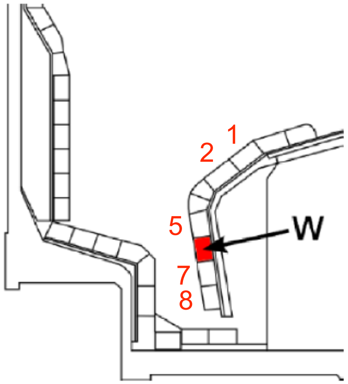
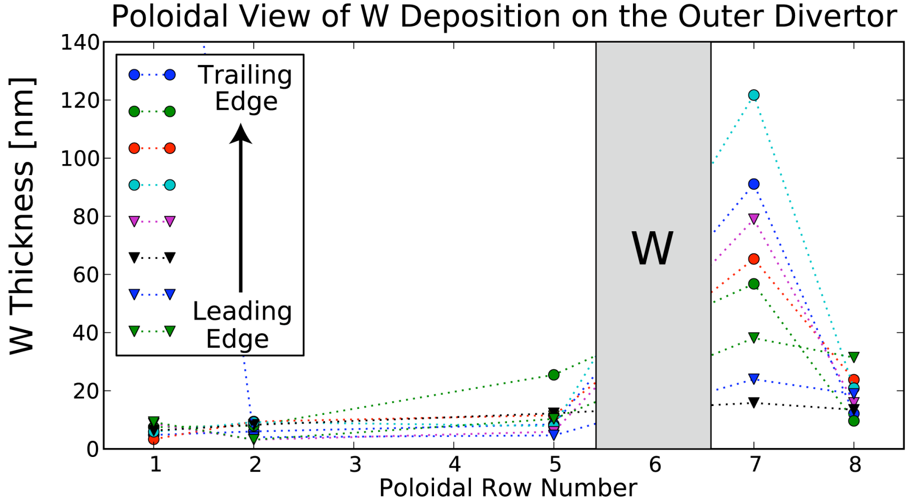
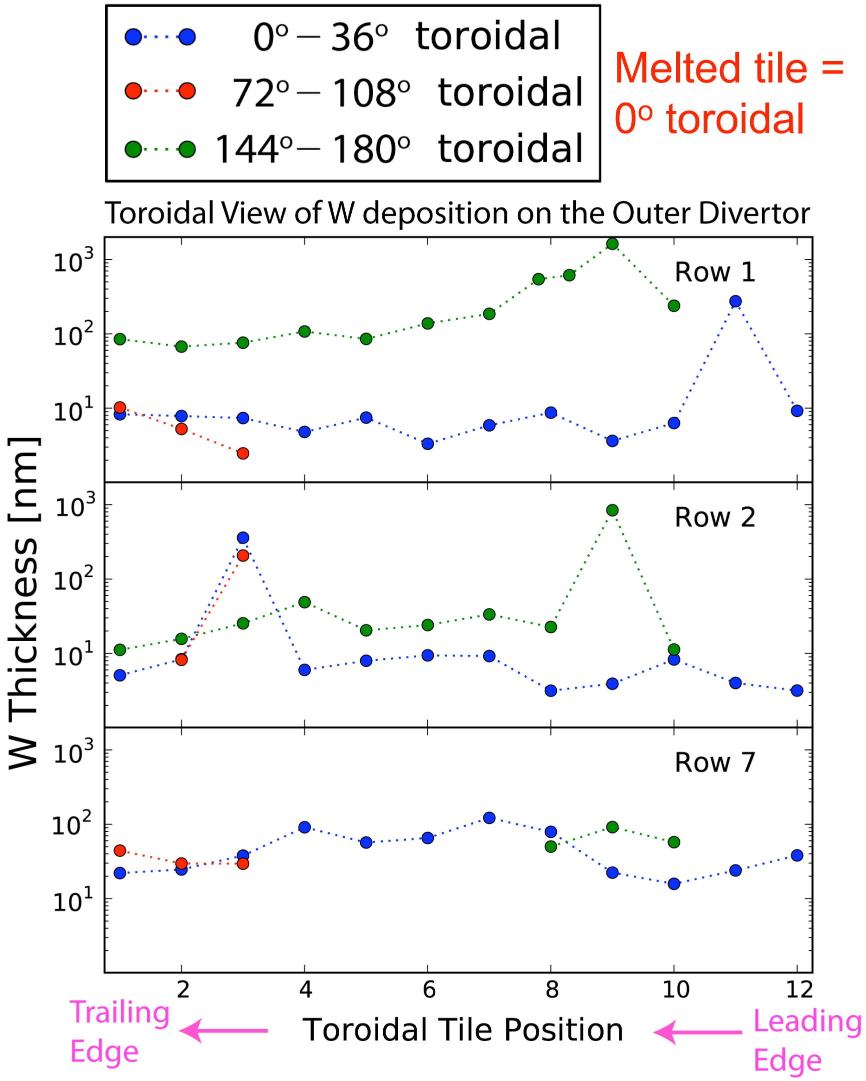
Melting scenario: W movement is non-uniform toroidally and highest far from melted tile. *Controlling mechanism uncertain*

- Much higher deposition than in sputtering scenario.
- Orders of magnitude difference in W deposition on neighboring tiles.



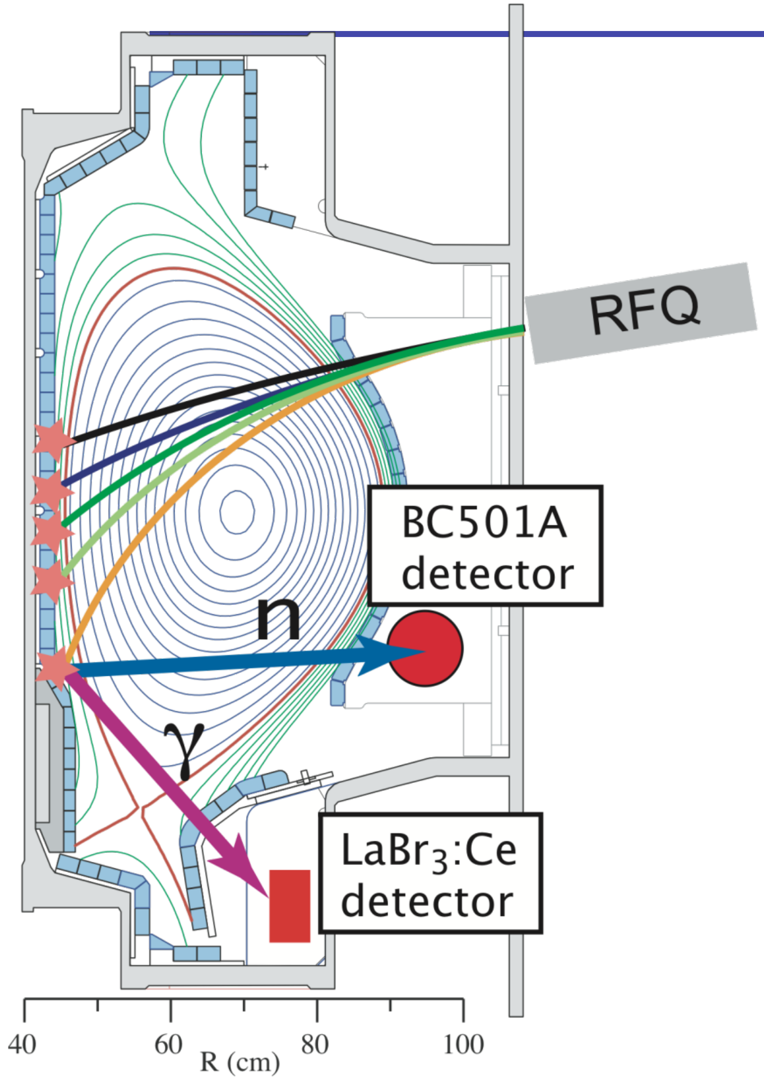
0°-36° toroidal (cassette w/ melted tile)





Melted tile = 0° toroidal

Developing novel in-situ Materials/PSI diagnostics

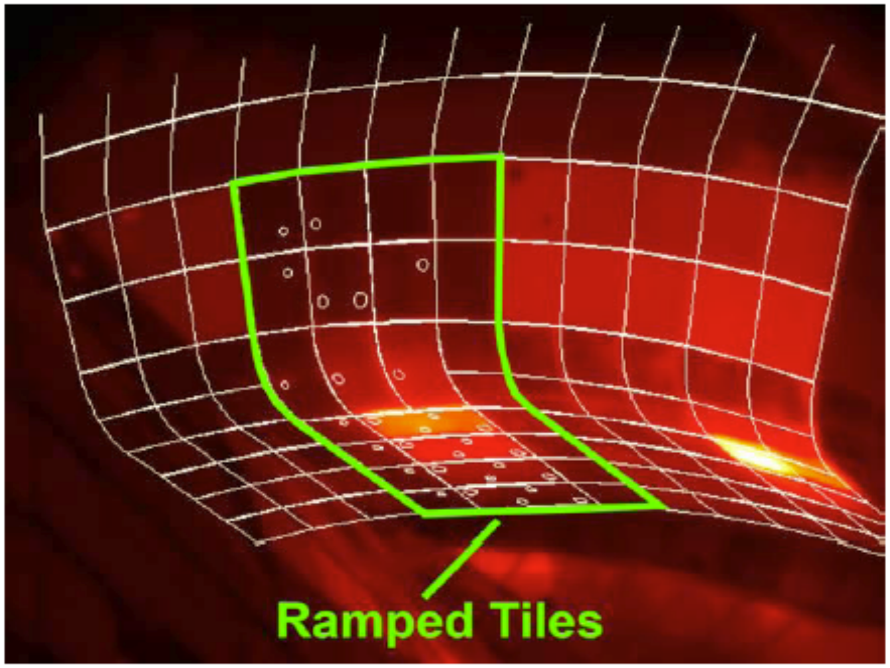


Hartwig, RSI 2010

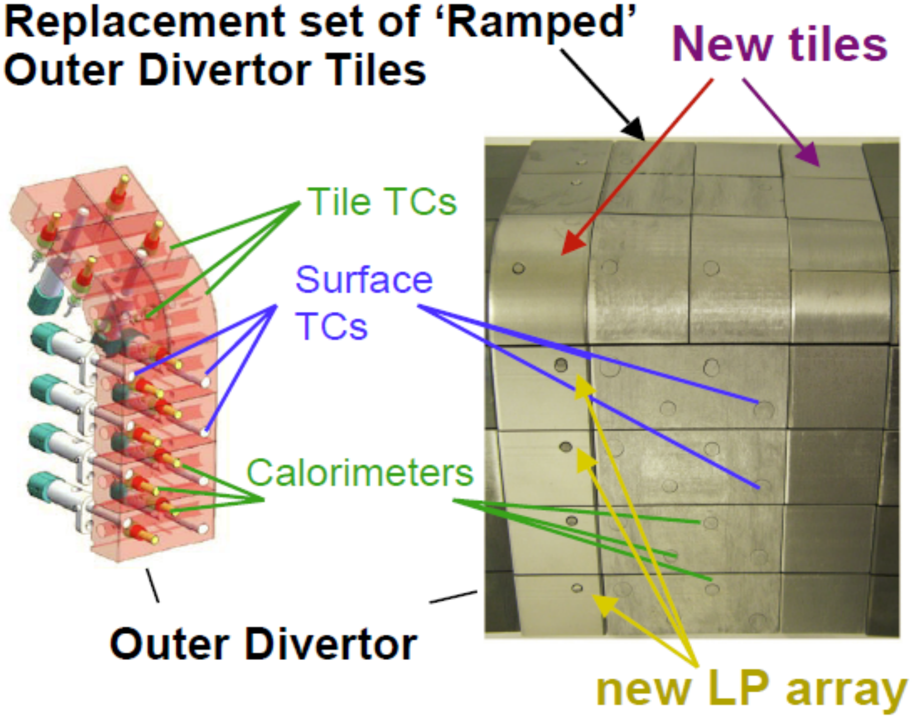
- RFQ accelerator and diagnostics
  - ➢ **In situ measurements of retention, erosion rates, boronization layer thickness, etc.**
- Strong collaboration with PSI Science center
  - ➢ **Three way comparisons with codes, lab test-stands, confinement devices.**

Significant upgrades to heat flux measurement capabilities in the divertor

IR Camera View of Ramped tiles



Replacement set of 'Ramped' Outer Divertor Tiles



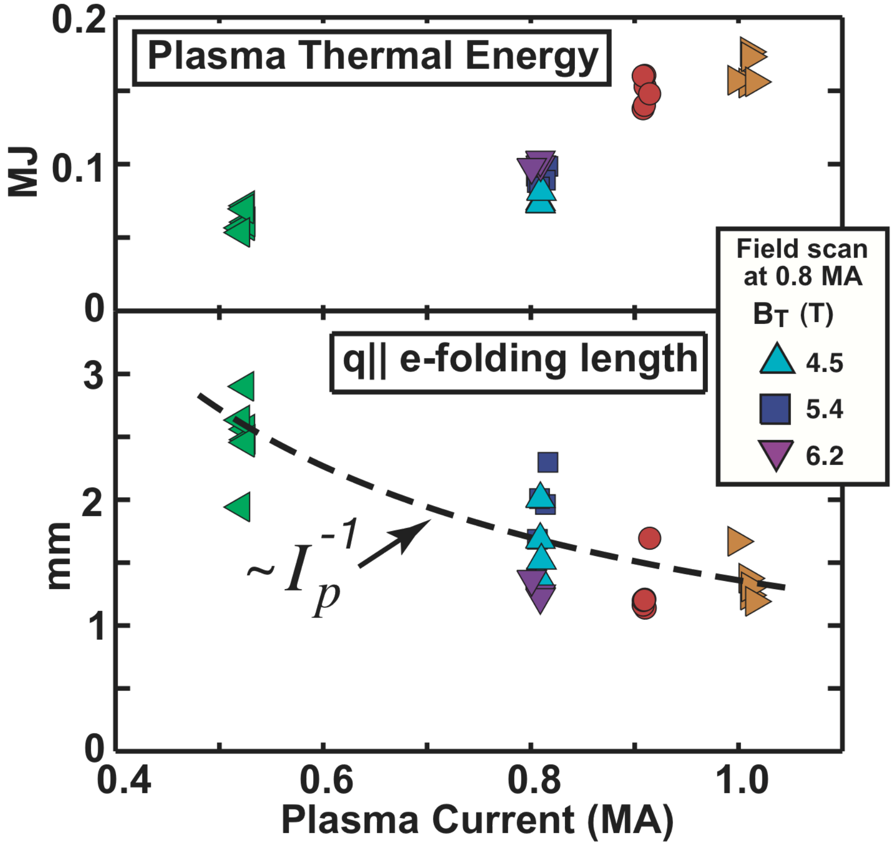
C-Mod "reactor-like" divertor

q_{target}>20 MW/m^2 n_e~10^{21} m^{-3} B~6T

Divertor heat flux width scales inversely with plasma current & connected to upstream pressure profile

Goal: Connect boundary layer transport to underlying physics

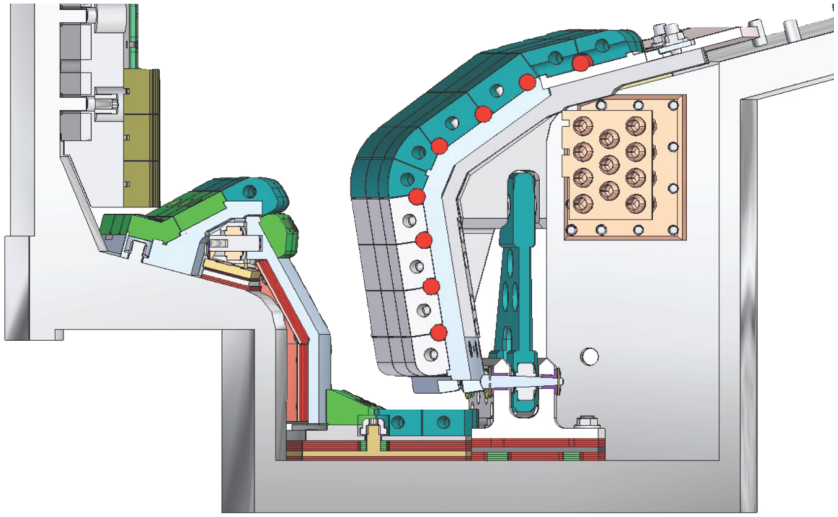
- $q_{\|}$ e-folding width <u>in near SOL</u> exhibits 1/Ip dependence in H-mode (JRT 2010)
  - No dependence on P_{DIV}, B_{TOR}
  - Similar dependencies found at DIII-D, NSTX - a key commonality
  - Similar scaling in L-mode
  - **We find a connection to β_{pol} gradient at/ inside the separatrix**

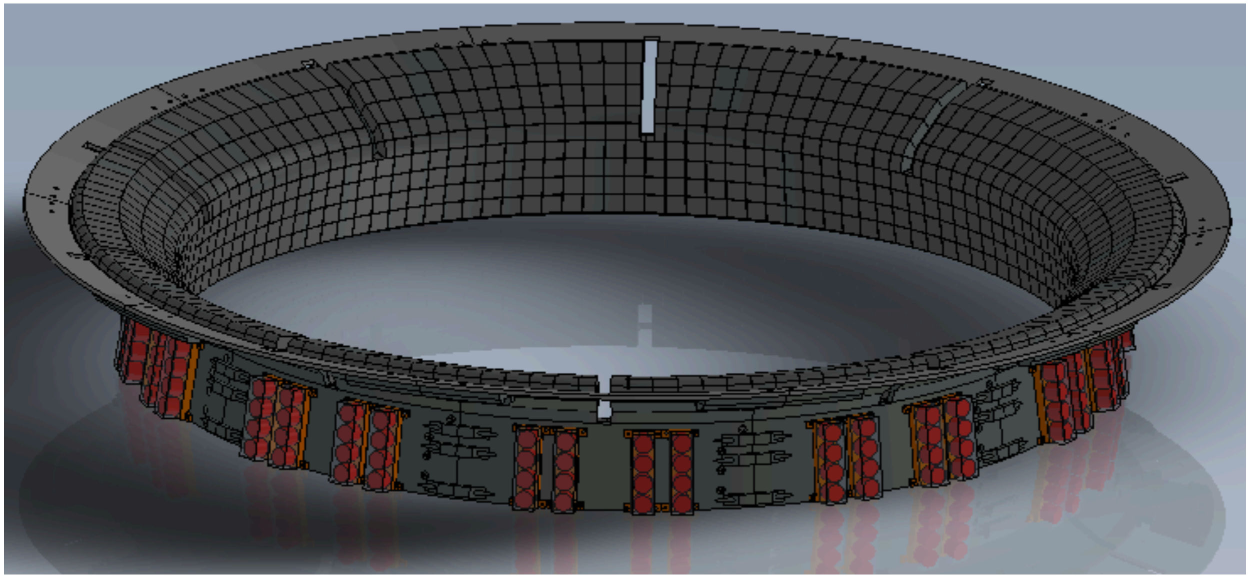


LaBombard, PoP 2011

High temperature tungsten divertor will begin to explore integrated PSI/materials response in DEMO-like divertor

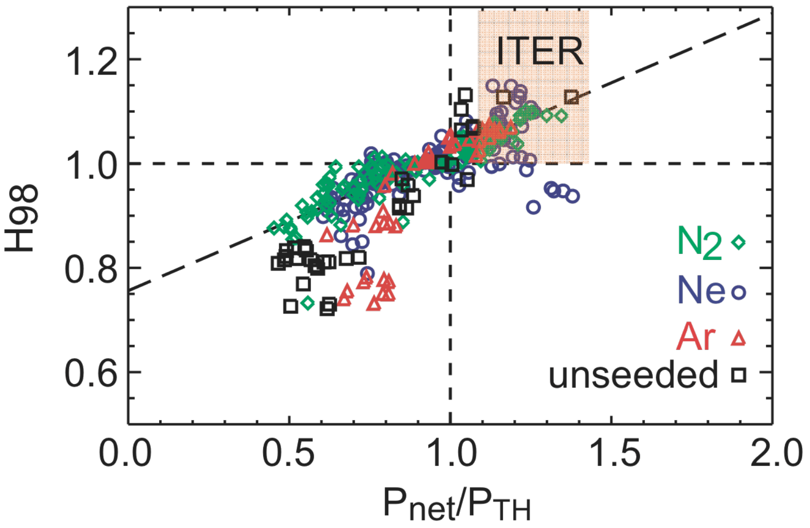
- Continuous vertical plate
  - No leading edges (higher power/ energy)
- Solid tungsten lamella plate tiles in high heat-flux region
- High temperature (~ 600 ^{0}C) for:
  - Long pulse, high power ops
  - Hydrogen isotope retention studies

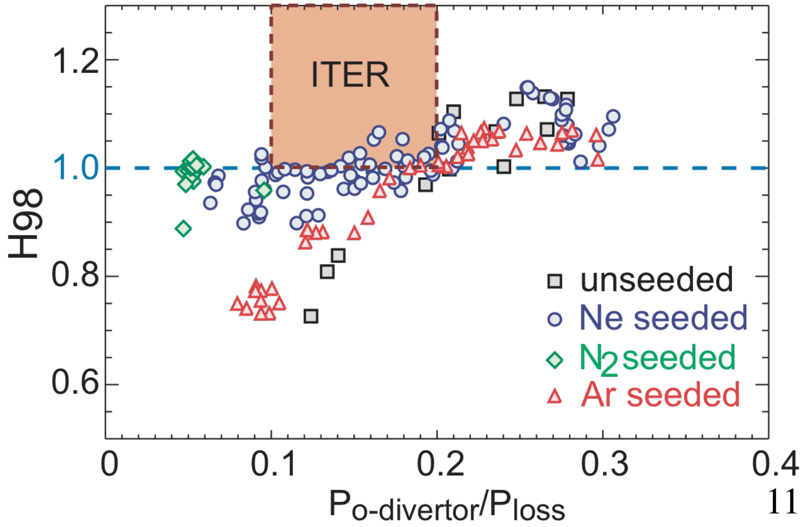




High performance impurity-seeded discharges maintained by controlling P_{NET} + very high dissipation of divertor power as required for ITER

- Evaluated power requirements for high performance H-mode access ($H_{98} \sim 1$) w/ seeding
- Seeding and ICRF power used to vary P_{NET}
    - $P_{NET} = P_{LOSS} - P_{RAD,core}$
    - $P_{LOSS} = P_{OH} + P_{RF} - dW/dt$
- Ne, N_2 cases are higher performance than un-seeded. Also reduces Mo injections and ICRF trips
- H_{98}, P_{NET}/P_{TH}, P_{div}/P_{loss} in ITER target range.



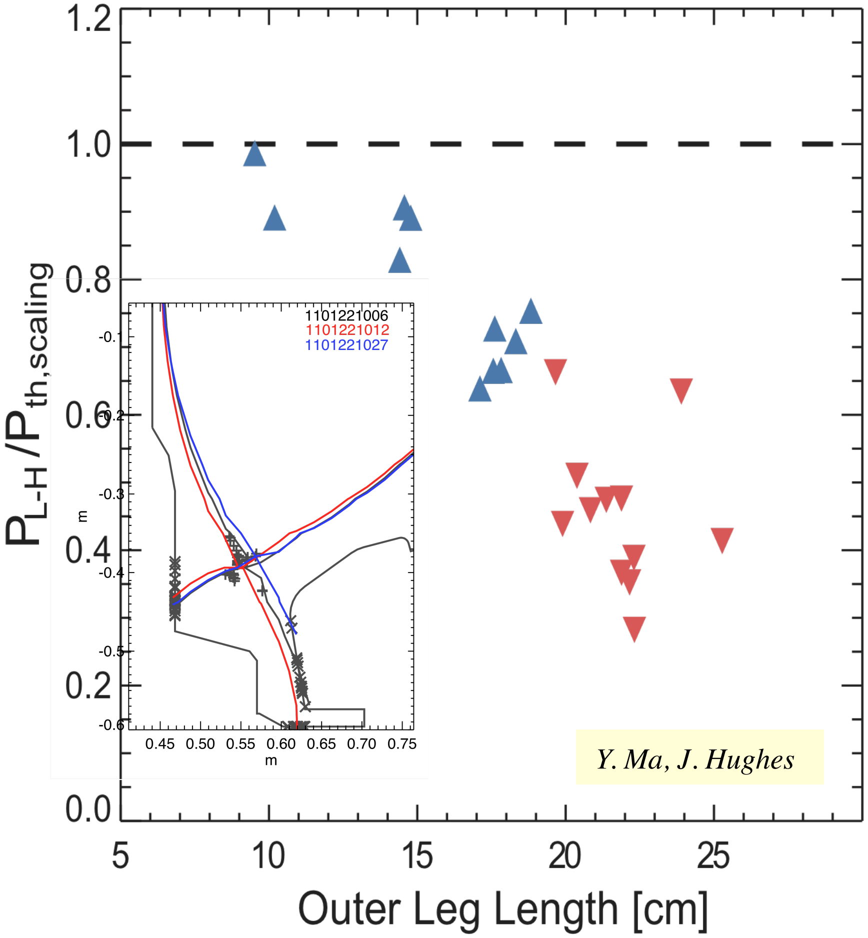


Loarte, APS 2010

Exploring the 'hidden variables' affecting the H-mode power threshold. Long-leg vertical target lowers threshold

Goal: Characterize physical mechanisms which determine transitions between confinement regimes (*i.e.* L⇔H, L⇔I⇔H)

- Experiments aimed at identifying departures from simple power threshold scaling law
  - Neutral pressure and fueling location – little effect
  - Magnetic topology – slight reduction in PTH near DN
  - X-point location – large reduction in P_{TH} as divertor leg length is increased (PEP-28)
  - ICRF deposition location – insensitive



Y. Ma, J. Hughes

*ITPA L-H threshold working group
PEP-26

Developing efficient current drive with Lower Hybrid for ITER and beyond

Reversed shear current profiles

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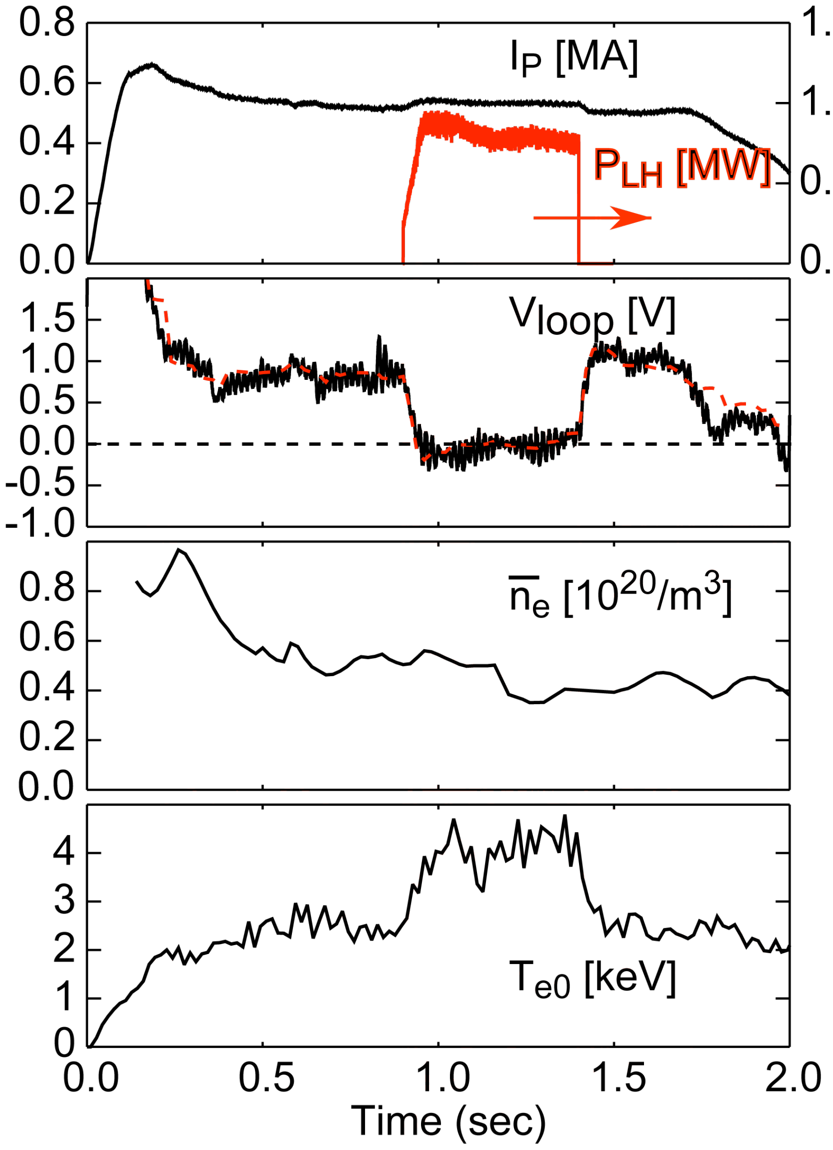
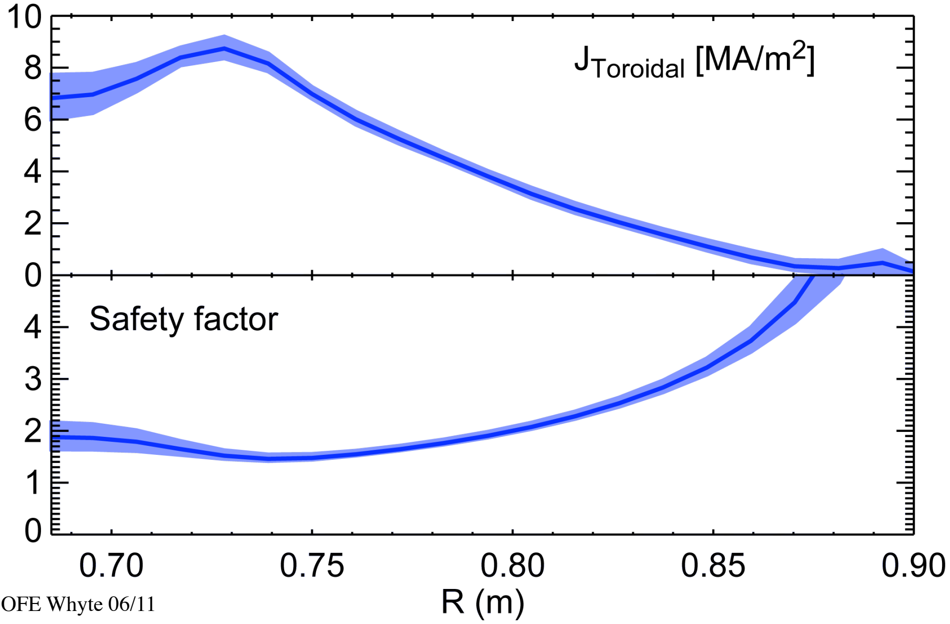
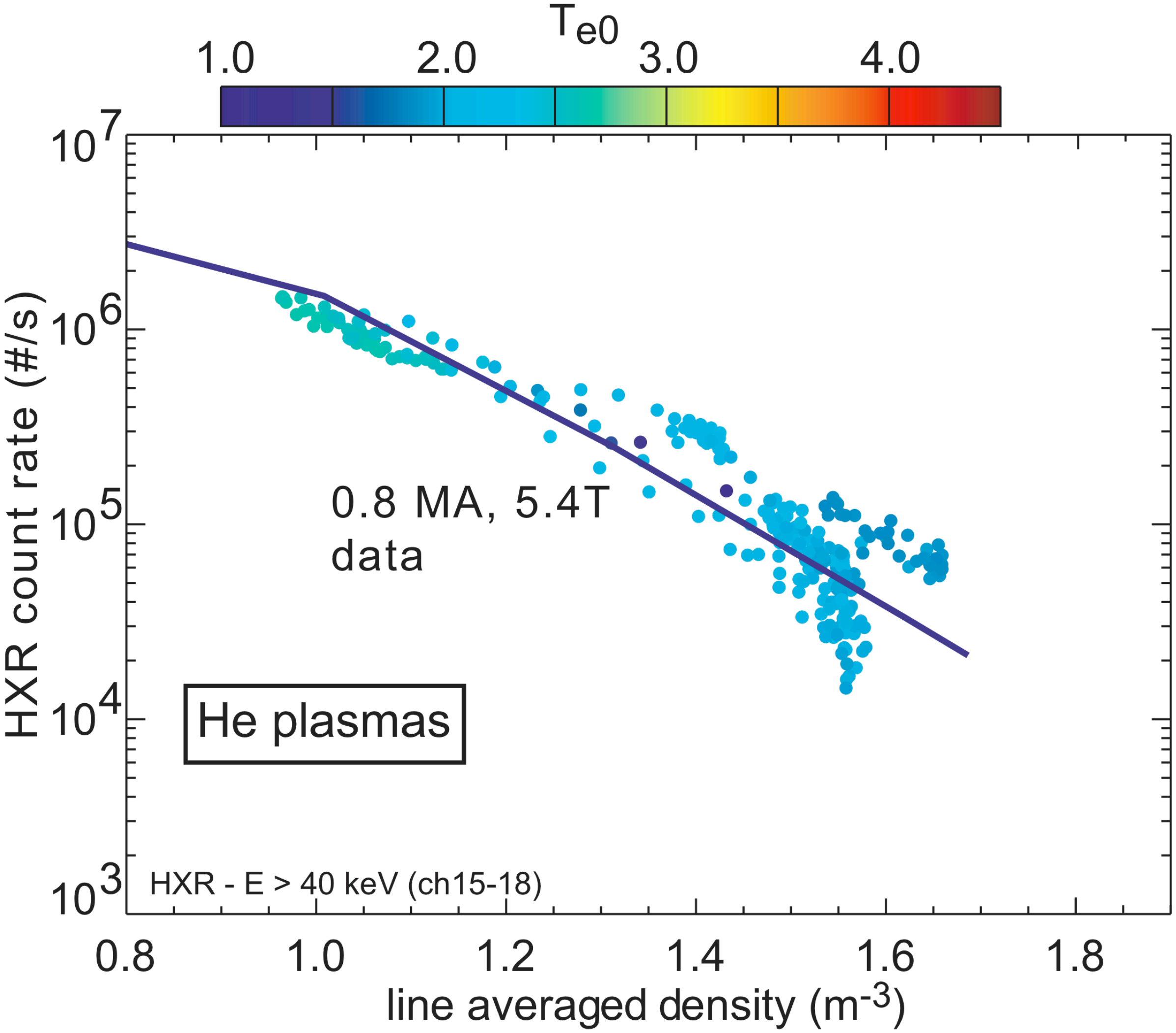
- Fully non-inductive scenario produced at near ITER densities (~ $5\text{x}10^{19}/\text{m}^3$)
- CD efficiency – $nI_PR/P \sim 2.5\text{x}10^{19}$ A/W/m^2, the efficiency assumed for ITER
- Driven current off axis, $q_0 \sim 2$, reversed shear





CD Efficiency dropoff at higher densities being investigated

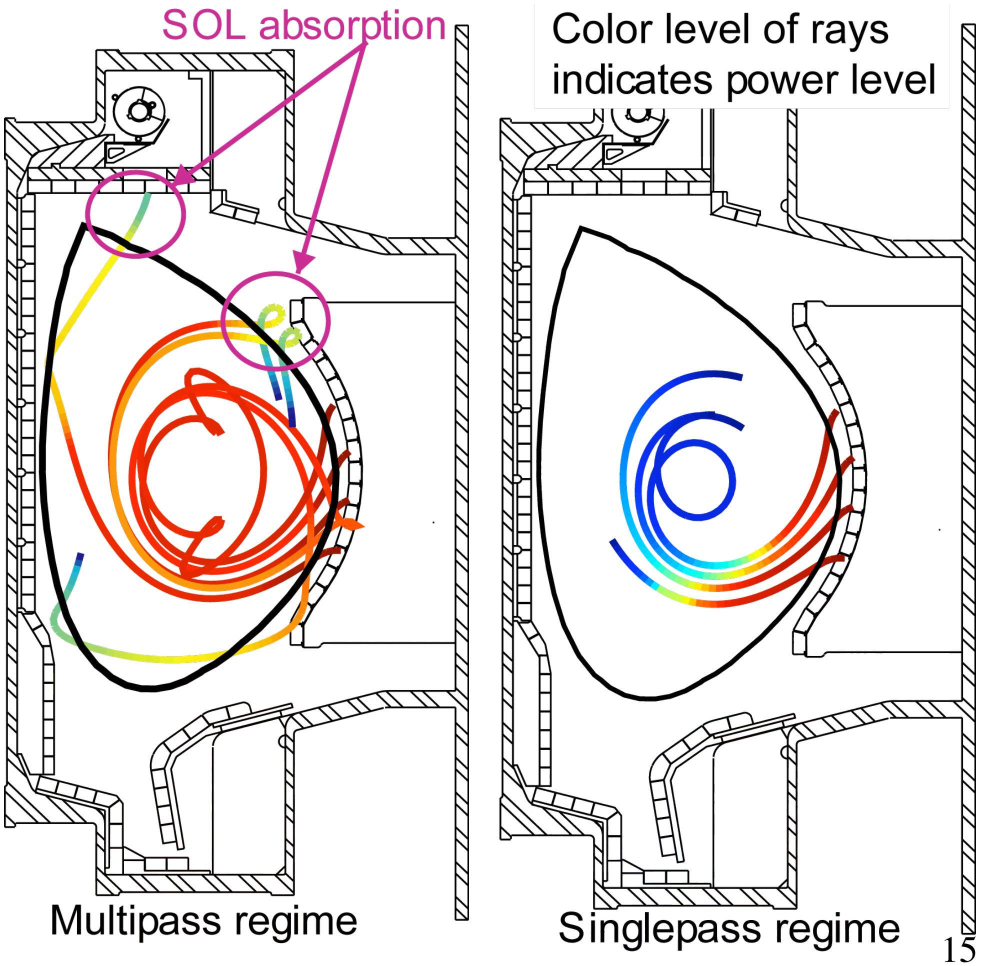
- Initial results showed a faster dropoff in CD efficiency than expected (HXR spectrum)
- A series of studies of the dependence of efficiency on topology, current, $n_{\|}$, and SOL parameters has been undertaken



Wallace, Shiraiwa, Meneghini

LHCD Efficiency dropoff at higher densities appears to be due to SOL absorption

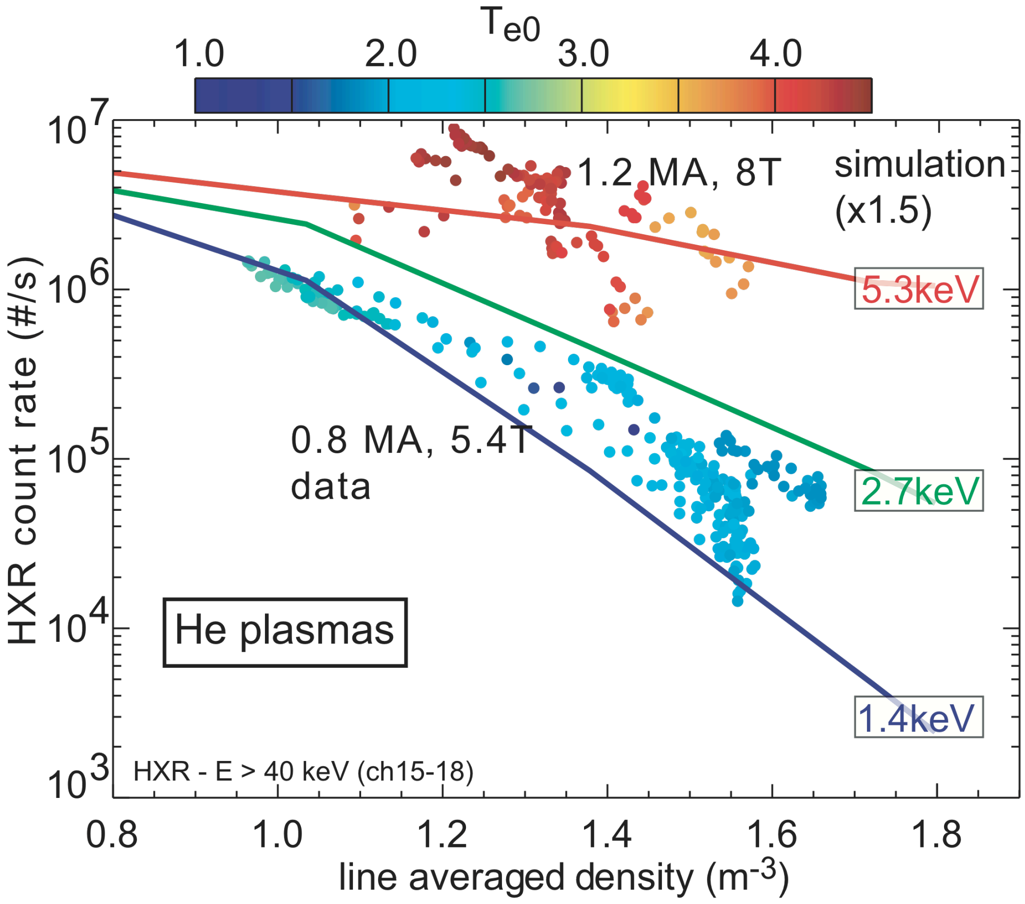
- Efficiency drop likely due to the many passes through the SOL and absorption there – supported by
    - Ray-tracing simulations
    - Changes in SOL profiles of n_e, T_e , potential and ionization light
- Proposed solution – enhance the single-pass absorption in core plasma



Shiraiwa, Meneghini

Recent experimental and modeling studies of higher Te target plasmas support growing understanding of the need for strong single-pass absorption

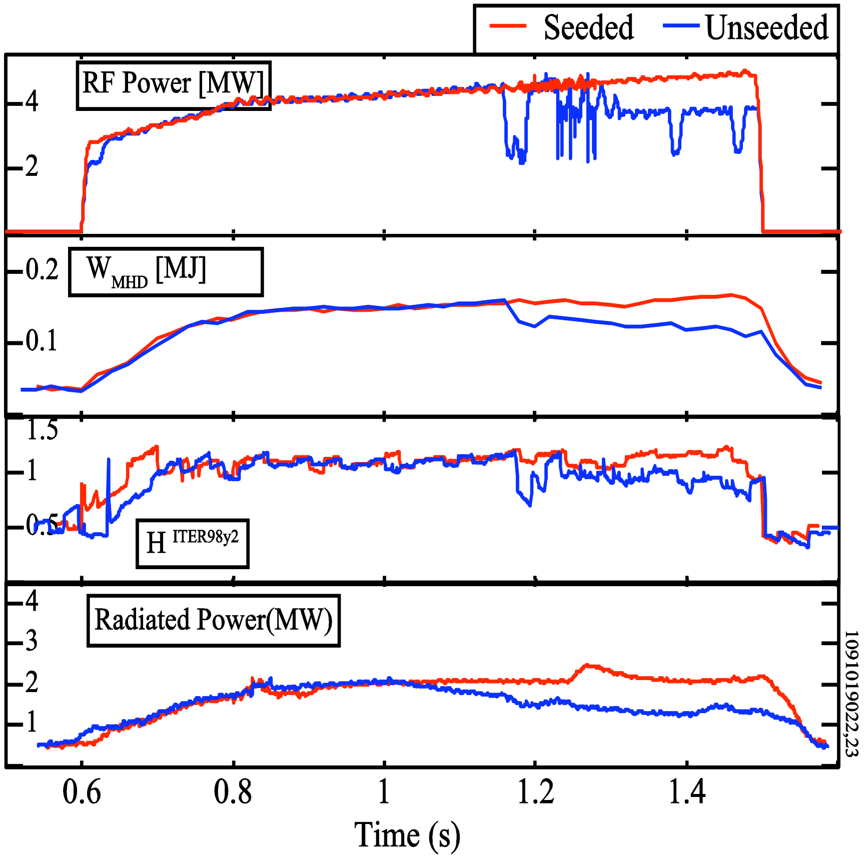
- New experimental and modeling results with high T_{e0}
- Positive result for application of LHCD in ITER and reactors.
- However exact SOL physics underlying absorption is still not understood.



C-Mod is pursuing a number of avenues for making ICRF more compatible with the high plasma performance

Goal: Fault-free, high-power ICRF operation with minimal impurity enhancement

- **Ne- and N_2-seeded discharges** lead to much better coupling of ICRF to the core plasma
- High-Z injections are eliminated
  - Antenna faulting greatly reduced
  - No change in SOL n_e, T_e profiles



Reinke, Wukitch

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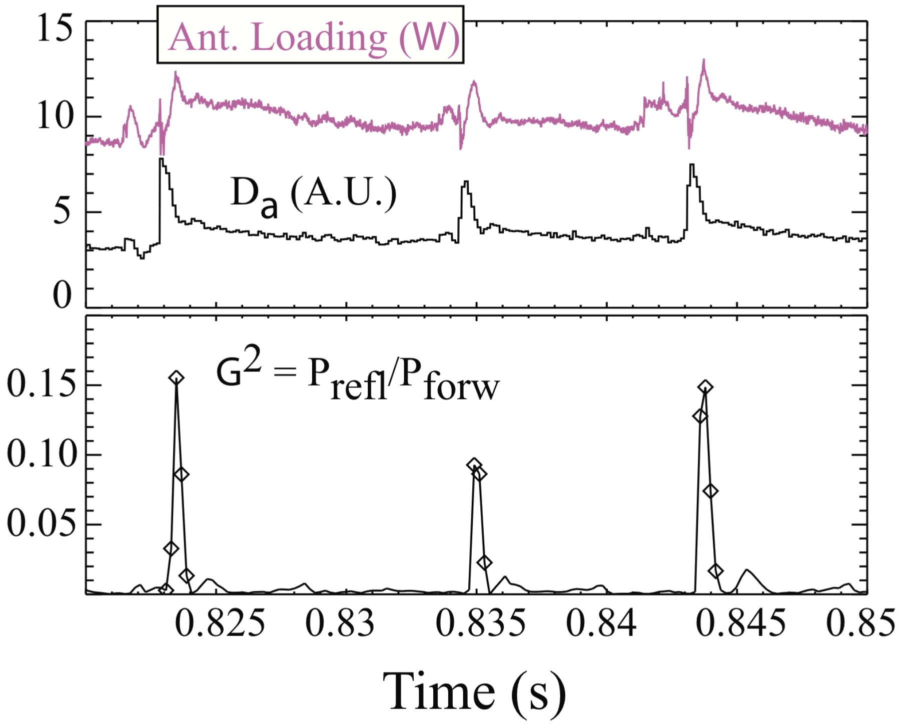
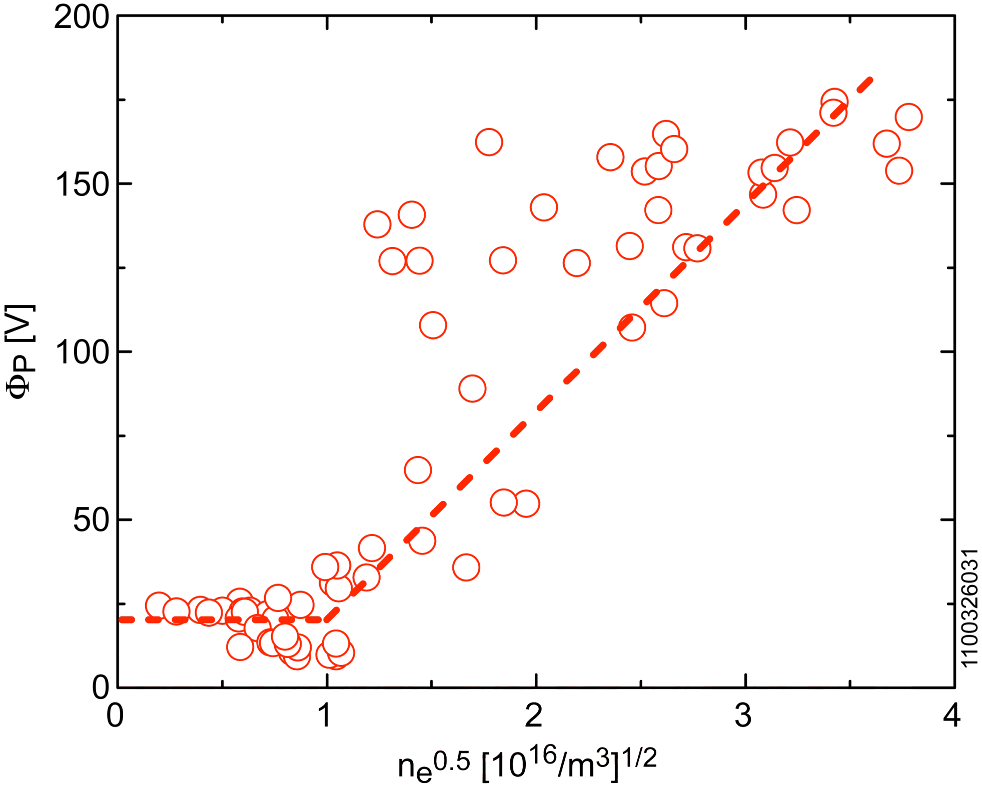
  - **Real-time matching** (fast ferrite tuners) greatly enhances power consistency
  - FFT follows load transitions associated with discharge evolution (e.g. L-H transition)
  - Power reflection during ELMs rises to 10-15% for < 400 µs – could be shorter with improved computational response time



Newly developed diagnostics show that the effect of ICRF on the SOL is more complicated than anticipated

- Measured plasma potential profiles suggests radial electric field
  - Used ‘Ion-sensitive’ and ‘emissive’ probes
  - Both near and far field effect
  - Comparison w/model* ongoing
    - Effect maps to antenna along B – ✓
    - Threshold in density – ✓
    - Slow wave not present – X



* *Myra et al PRL*
Ochoukov RSI 2010

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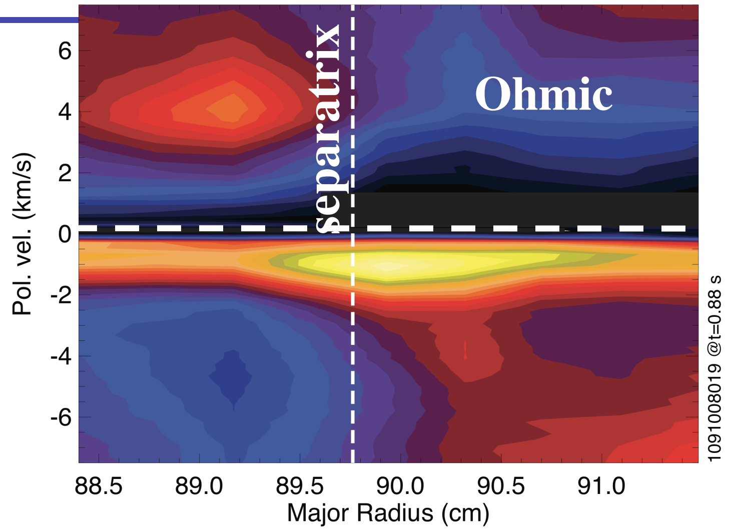
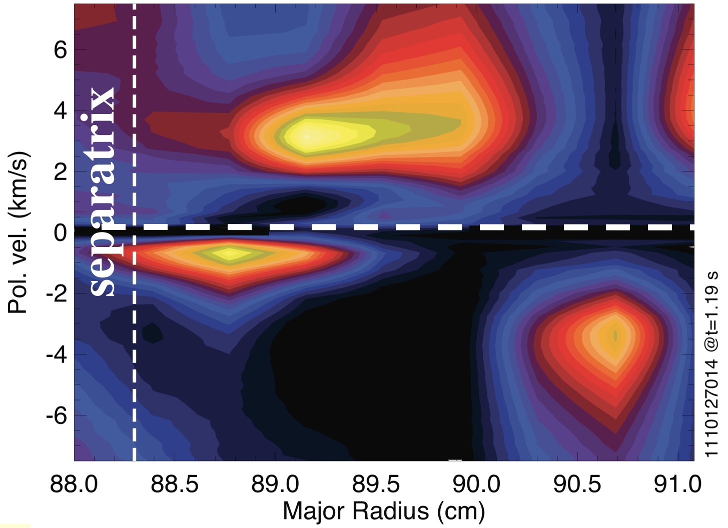
  - Observed fine structure in poloidal flows
    - Turbulence flows reverse at different radii
    - Could be evidence of convective cells which, if they exist, could enhance impurity transport into core
  - Density decreased near antenna (near field)
    - May be indicative of convective transport



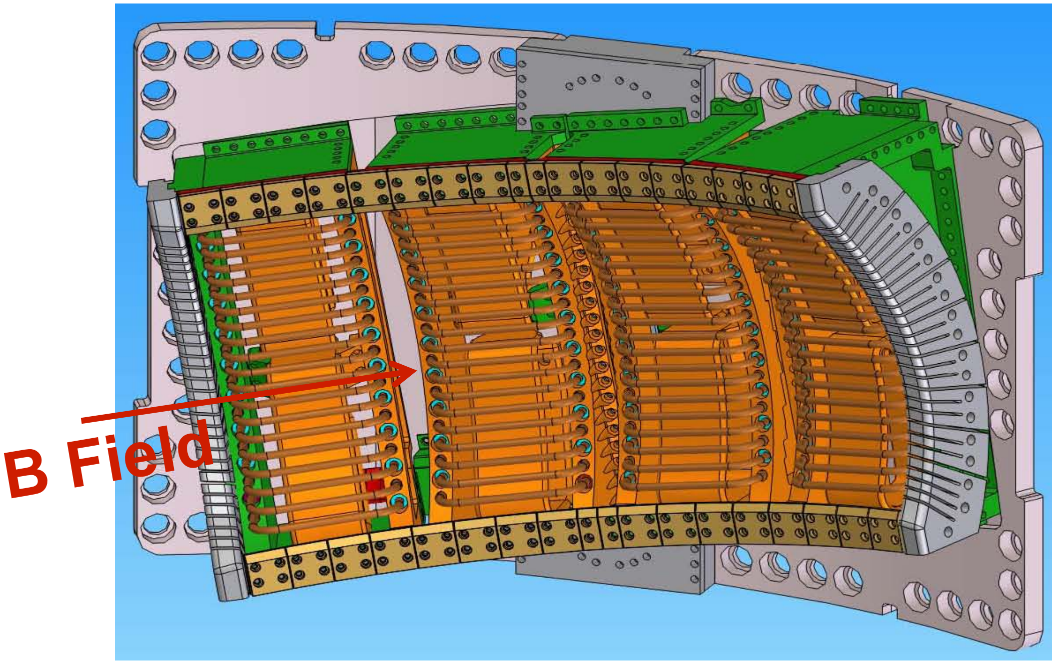
L-mode with $P_{ICRF} > 0.6$ MW



Cziegler PhD 2011

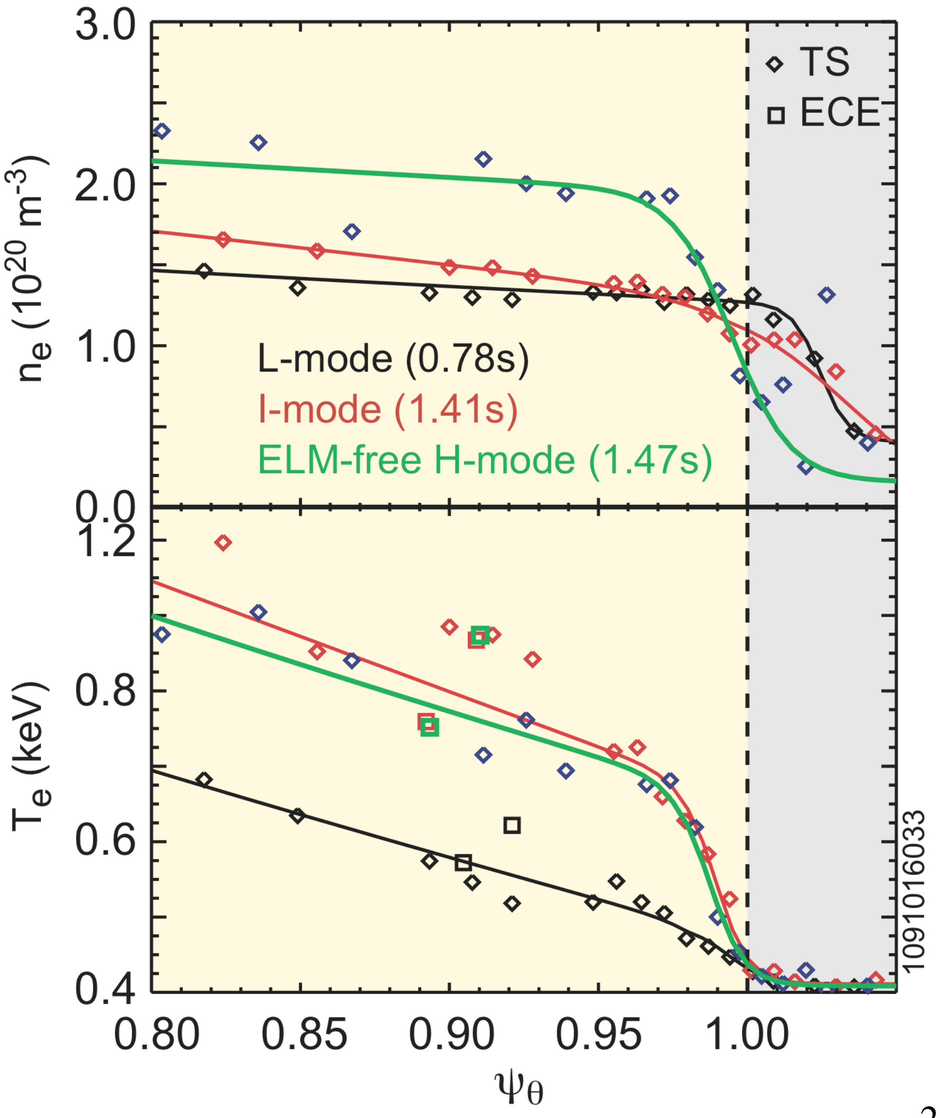
Ongoing Concern About Impurities With High-Power ICRF Interacting With Metal Walls → New Field Aligned Antenna

- Long standing issue on C-Mod, importance accentuated by
  - ASDEX results with W films
  - ITER needs
- Underlying cause of impurity generation sheath rectification
  - Although complicated.
- New ICRF antennae is rotated to zero/minimized parallel electric field to B
  - Modeling suggests strong reductions in sheath



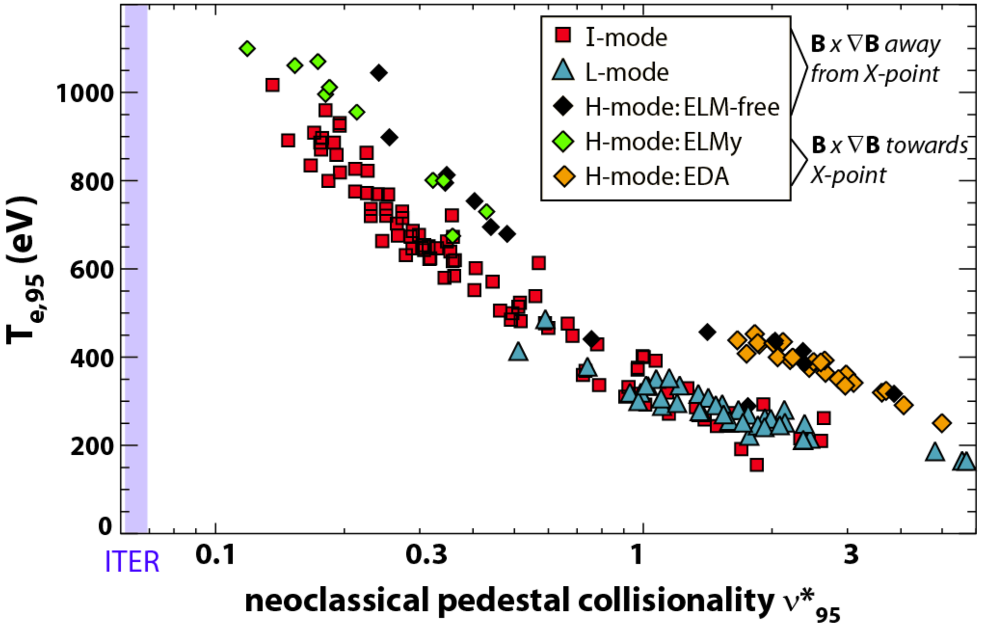
I-mode confinement regime is of growing interest for its operational advantages and its clear separation of energy and particle transport

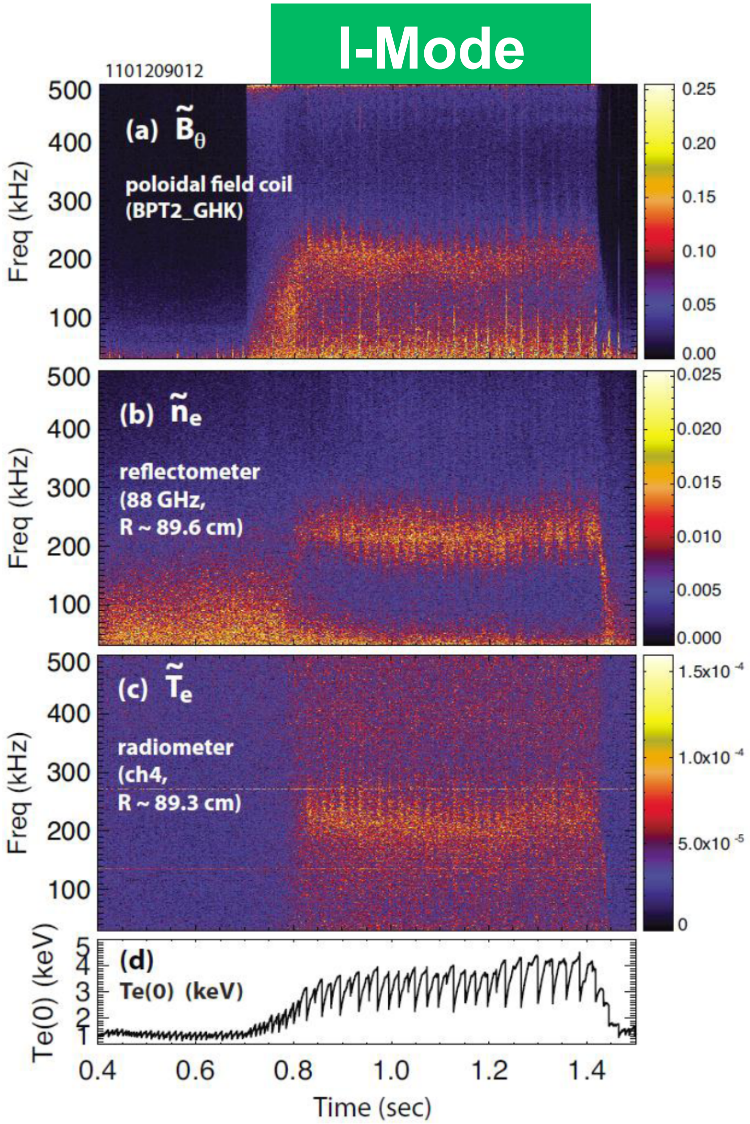
- I-mode is clearly distinct from L- and H-mode
  - H-mode energy confinement ($H_{98} \geq 1$) with L-mode impurity confinement
  - Clear T pedestal w/o density pedestal
- I-mode operational advantages
  - Best performance at low q_{95} and high PNET
  - Stationary pedestal with no impurity buildup (does not require ELMs)
  - Compatible with high-Z first-wall
  - Steady-state and large P_{in} range



Whyte et al Nucl Fusion 2010
Hubbard et al PoP 2011

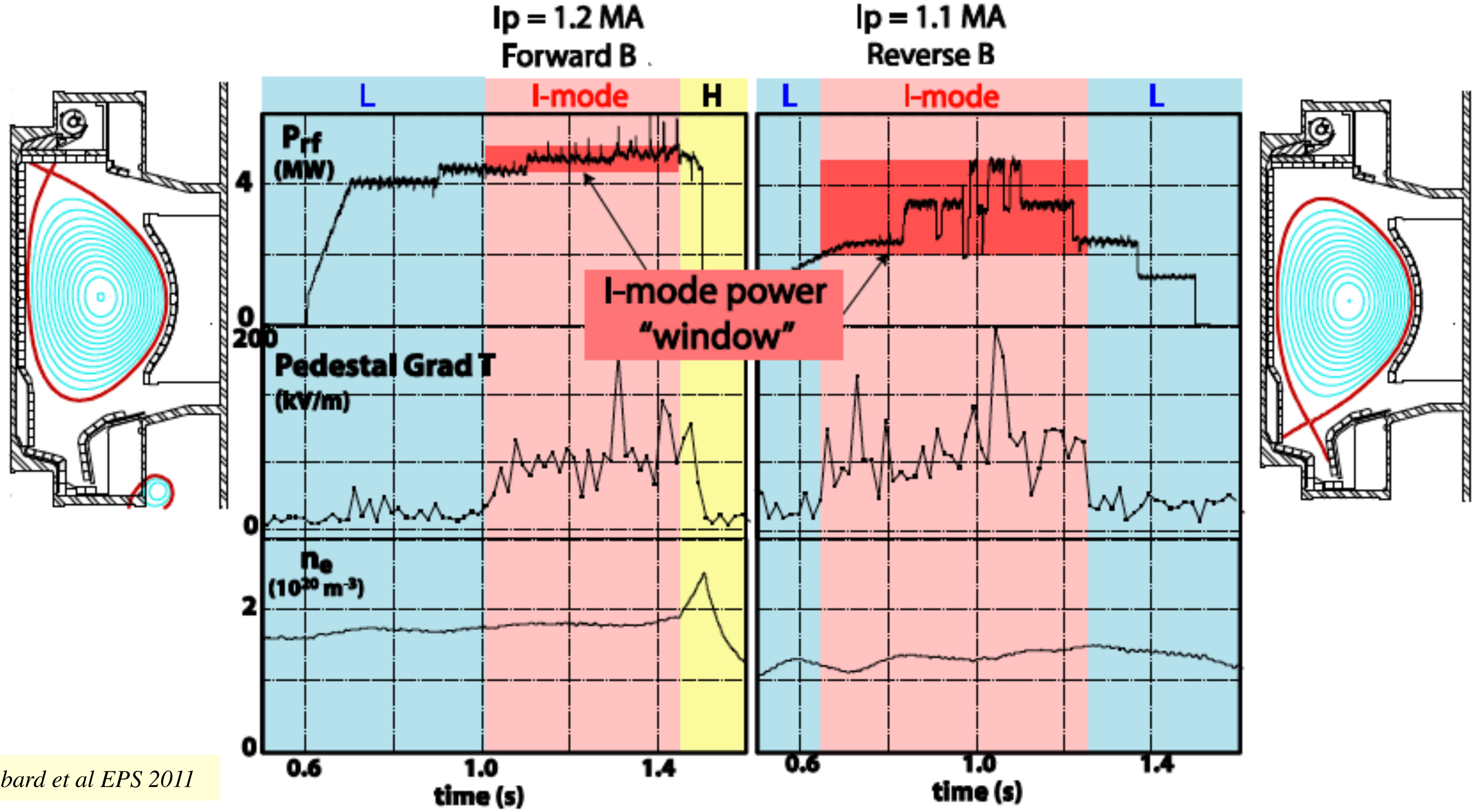
I-mode: High-Performance, Low Collisionality, ELM-free Regime is linked to changed fluctuations in pedestal region





Whyte et al Nucl Fusion 2010
White submitted Nucl Fusion 2011

Recent experiments: I-mode operational window is significantly enlarged using shaping and vertical target divertor geometry



Hubbard et al EPS 2011

Simple extrapolation indicates ITER could achieve I-mode with reverse B topology

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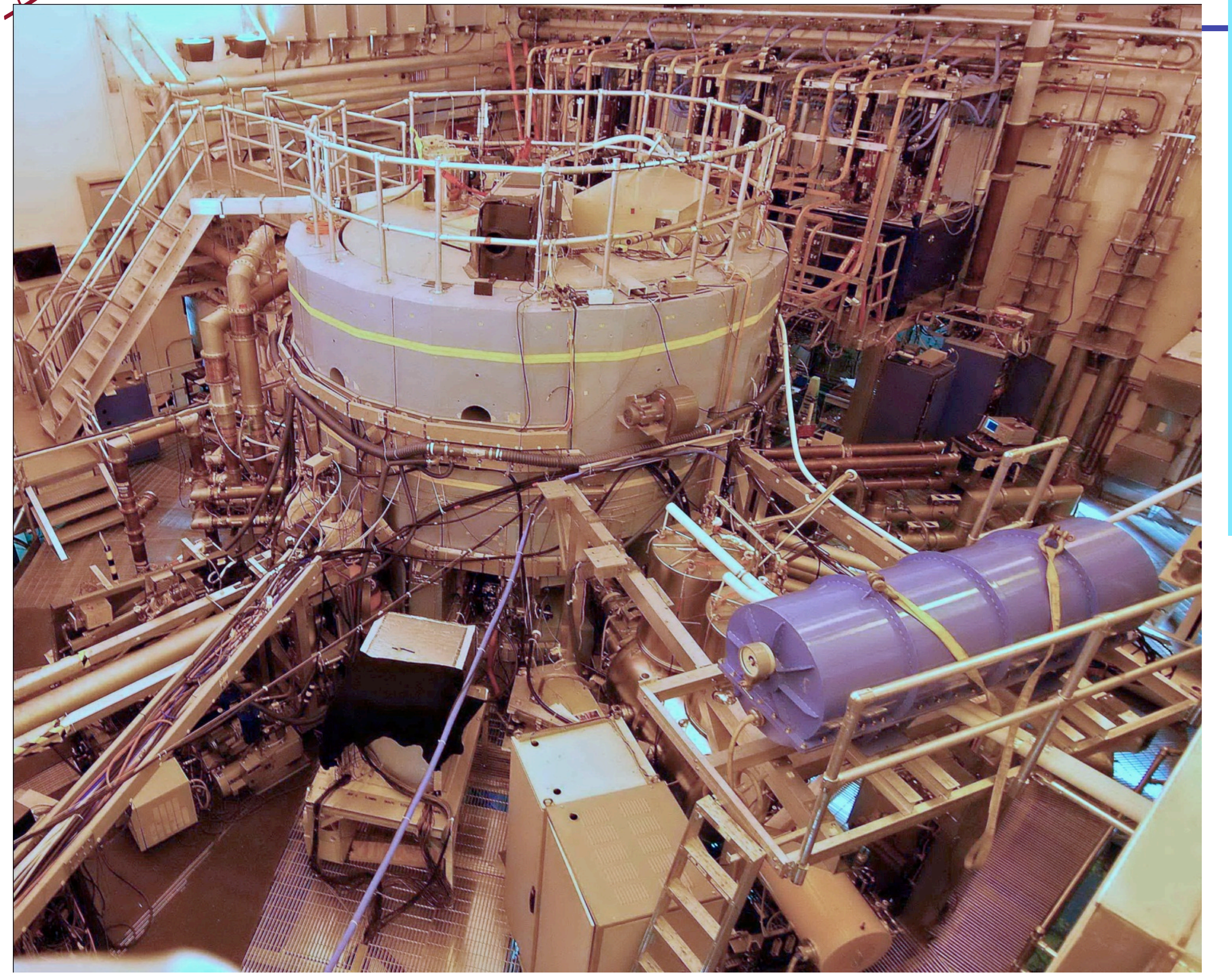

Compact high-performance divertor tokamak research to establish the plasma physics and engineering necessary for a burning plasma tokamak experiment and for attractive fusion reactors.

Research supported by U.S. Department of Energy, Fusion Energy Sciences

Thank you for your attention!