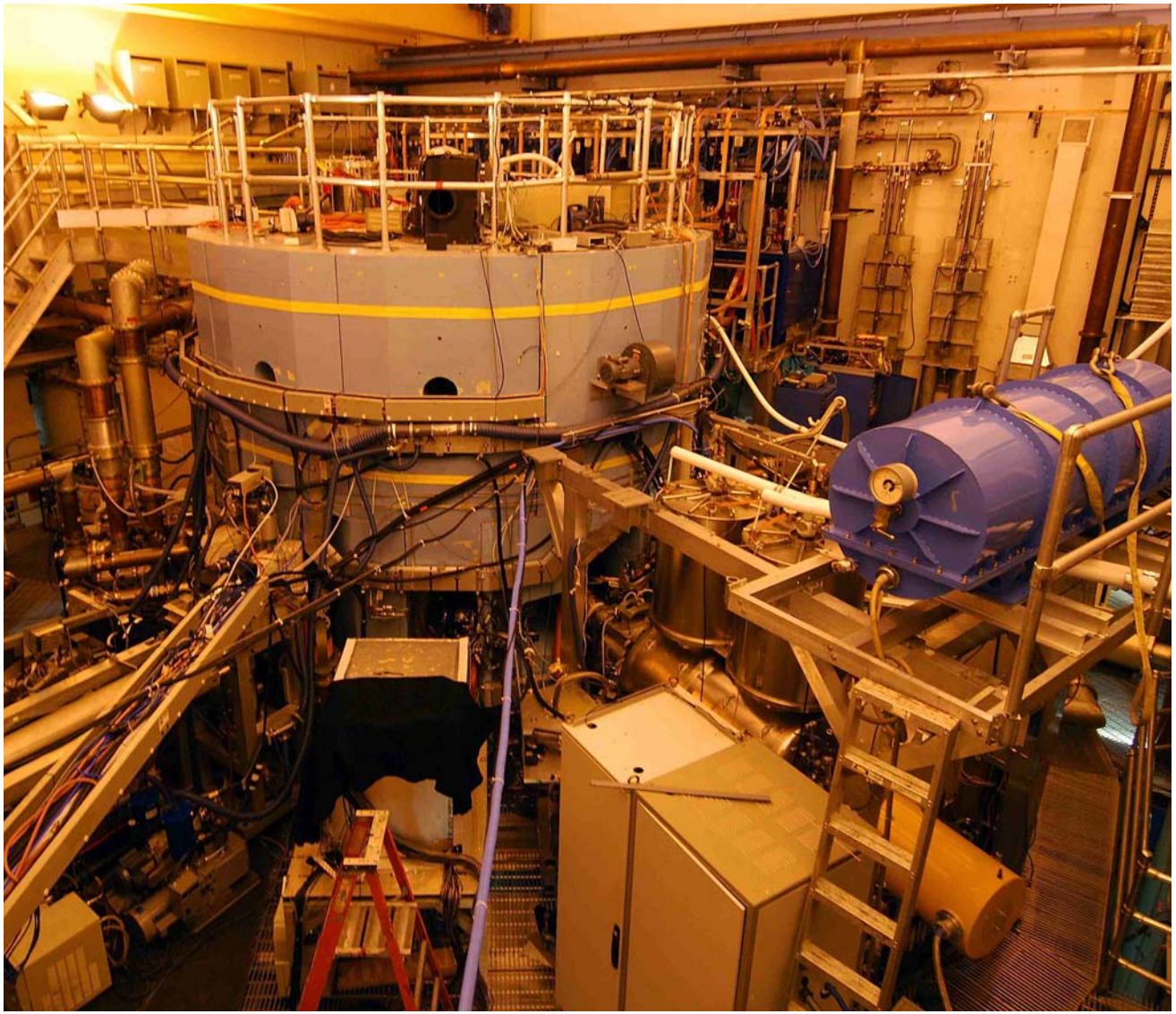
Alcator C-Mod
Research Highlights and Plans



PPPL Colloquium
May 14, 2008

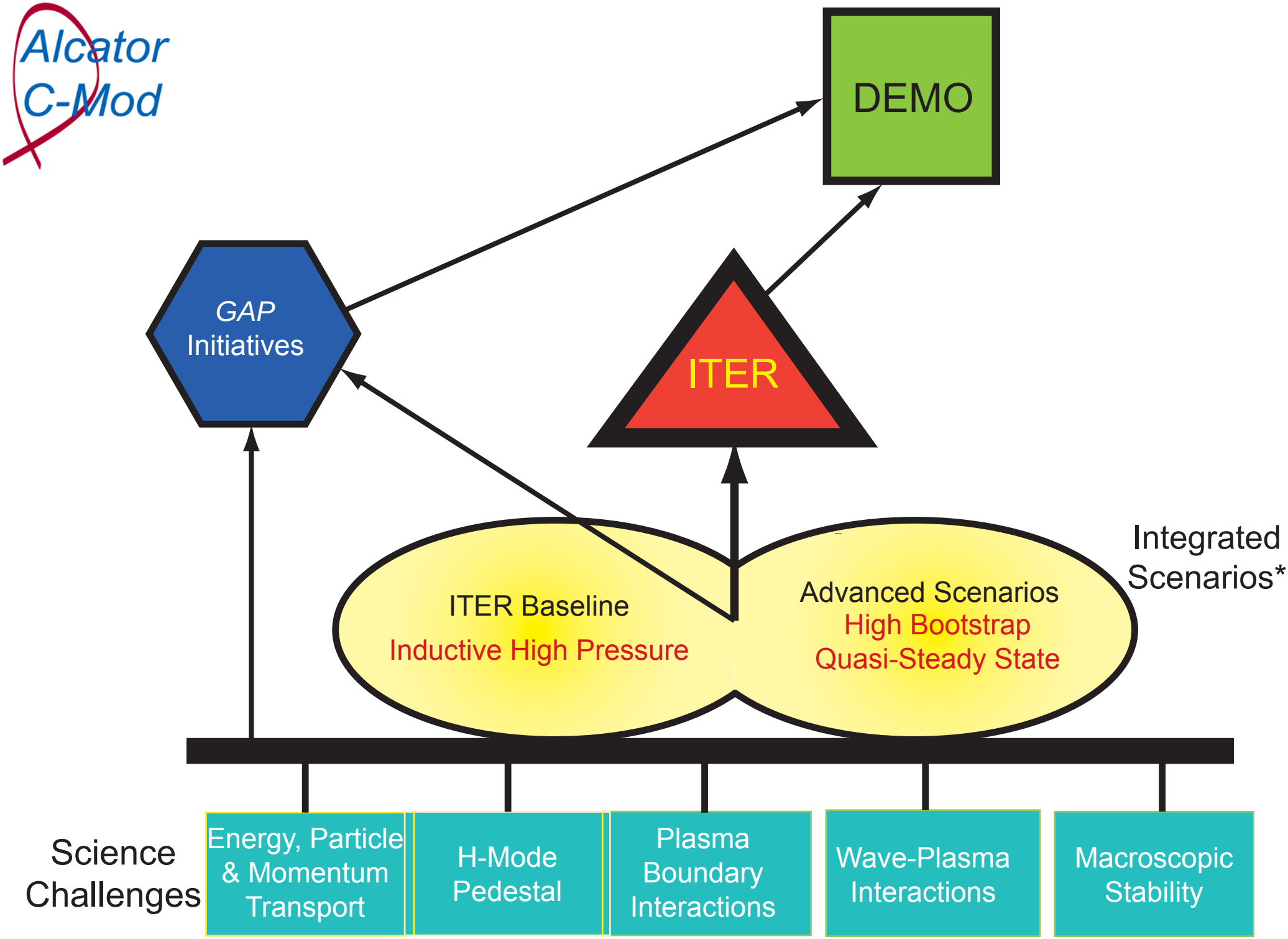
E. S. Marmar
for the Alcator Group

Developing the steady state, high-Z wall, high-field tokamak for ITER and beyond

Research on C-Mod is a Team Effort

Alcator C-Mod

- **C-Mod Team**
  - **More than 100 at MIT, including 27 PhD candidate graduate students**
  - **Major collaborations with Princeton Plasma Physics Laboratory, U. Texas Austin Fusion Research Center**
  - **Numerous smaller-scale collaborations from around the country and all over the world**



*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive

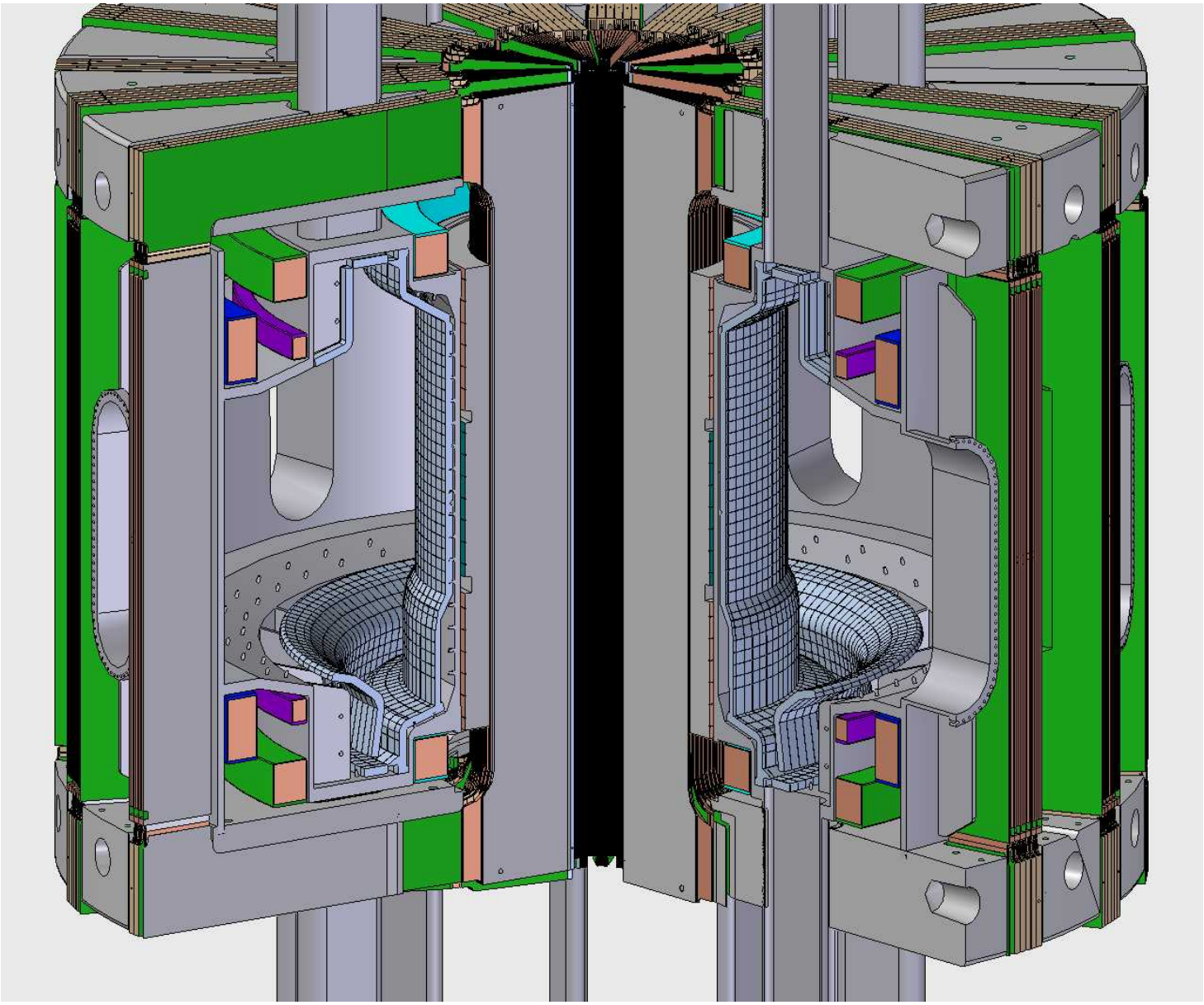
Outline

- Lower Hybrid Current Drive
- Spontaneous Rotation and Momentum Transport
- ICRF Impurity/Sheath Effects
- Hydrogenic Retention in All-Metal Plasma Facing Materials
- Improved L-Mode
- Plans (2009-2013)

C-Mod Is A Compact High-Field Tokamak

- C-Mod Parameters (Major Radius = 0.67m, Minor Radius = 0.22m)
  - B_T = 2 – 8 T
  - I_P = 0.2 – 2 MA
  - n_e = 0.2 – 15.0 x 10^{20} m^{-3}
  - T_e = 1 – 6 keV
- Tend to run at higher collisionality and lower β ($\propto P/B^2$), higher pressure than lower-field devices.
  - Equilibrated ions/electrons
    - as in reactor
  - Same field and pressure as ITER
- RF auxiliary heating & current drive
  - No core particle source
  - No direct momentum source
- Lower Hybrid Current Drive
  - Efficient off-axis drive
  - Initial results are very positive
- All metal first wall

C-Mod Magnets and Vacuum Vessel



1 meter

Goals of C-Mod LH program

Use as a current drive and profile control tool for advanced scenarios on C-Mod.

Challenge: learning to use LH as a tool in combination with ICRF, in various confinement regimes.

Simulate and document LH physics in conditions as similar as possible to ITER and to benchmark advanced scenario models.

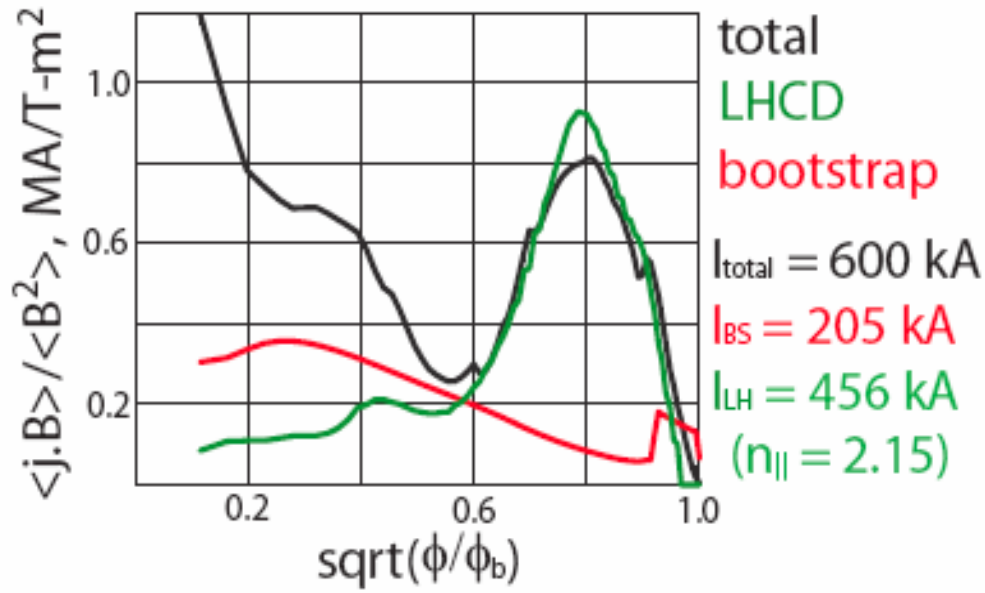
Main focus so far.

Standard C-Mod B_T=5.4 T.

Density range of LH experiments is n_{e0}~0.5-2.5x10^{20} m^{-3}, spanning ITER range.

f=4.6 GHz.

LH will contribute to further studies of underlying physics in tokamak plasmas



TSC simulation of scenario with $\langle n_e\rangle$ ~10^{20} m^{-3}, adding

3 MW LH at $N_{//}$=2.15.

3.5 MW ICRH

5.4 T, 600 kA.

T_{e0} 6.1 keV, T_{i0} 4.1 keV

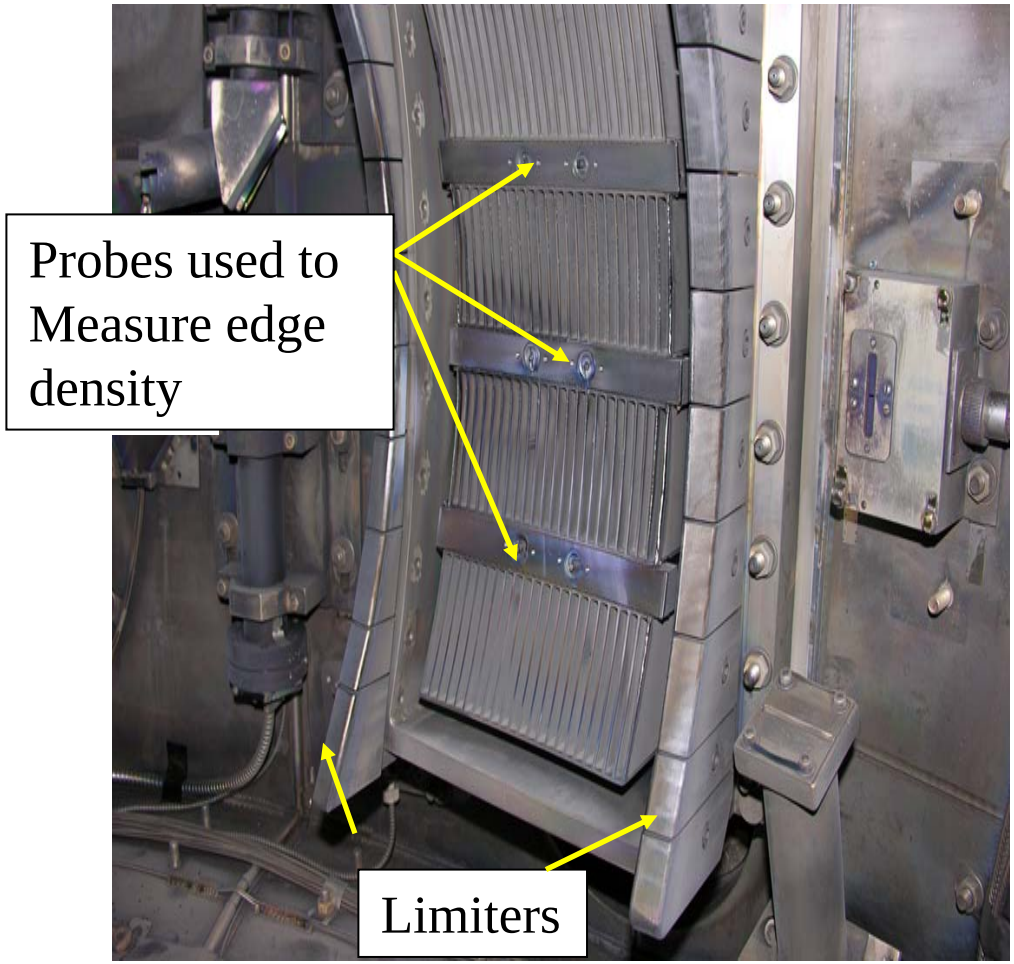
C. Kessel (PPPL)

Summary of LH Progress

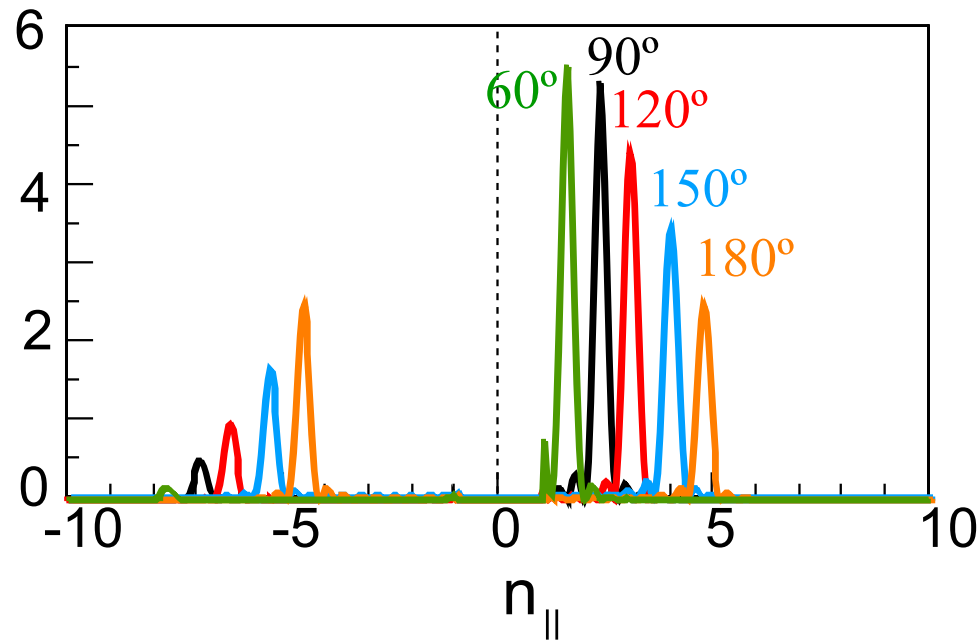
- LHCD is operating routinely on C-Mod at the 1 MW coupled power level (up to 1.2 MW).
- Results include:
  - Nearly full CD in 1 MA plasmas at n_{e0}~0.5-1.0x10 ^{20} m^{-3}, in line with model expectations.
  - Controlled variations in radial x-ray profile with $n_{//}$ and T_e
  - Successfully combined with ICRH, in current rise and flat top.
  - Suppression or delay of sawteeth.
  - Reduction in collisionality (lower n, higher T) in some H-mode experiments. (core and pedestal)
  - Clear counter-I_p change in core rotation in L and H-mode plasmas.

- Detailed comparisons with models, aimed at benchmarking in ITER-like parameter range are underway
  - Differences between traditional ray-tracing and full simulations seen, may indicate importance of diffraction at ITER like parameters
  - Major effort in conjunction with SciDAC

LH Launcher designed with wide range flexible spectrum

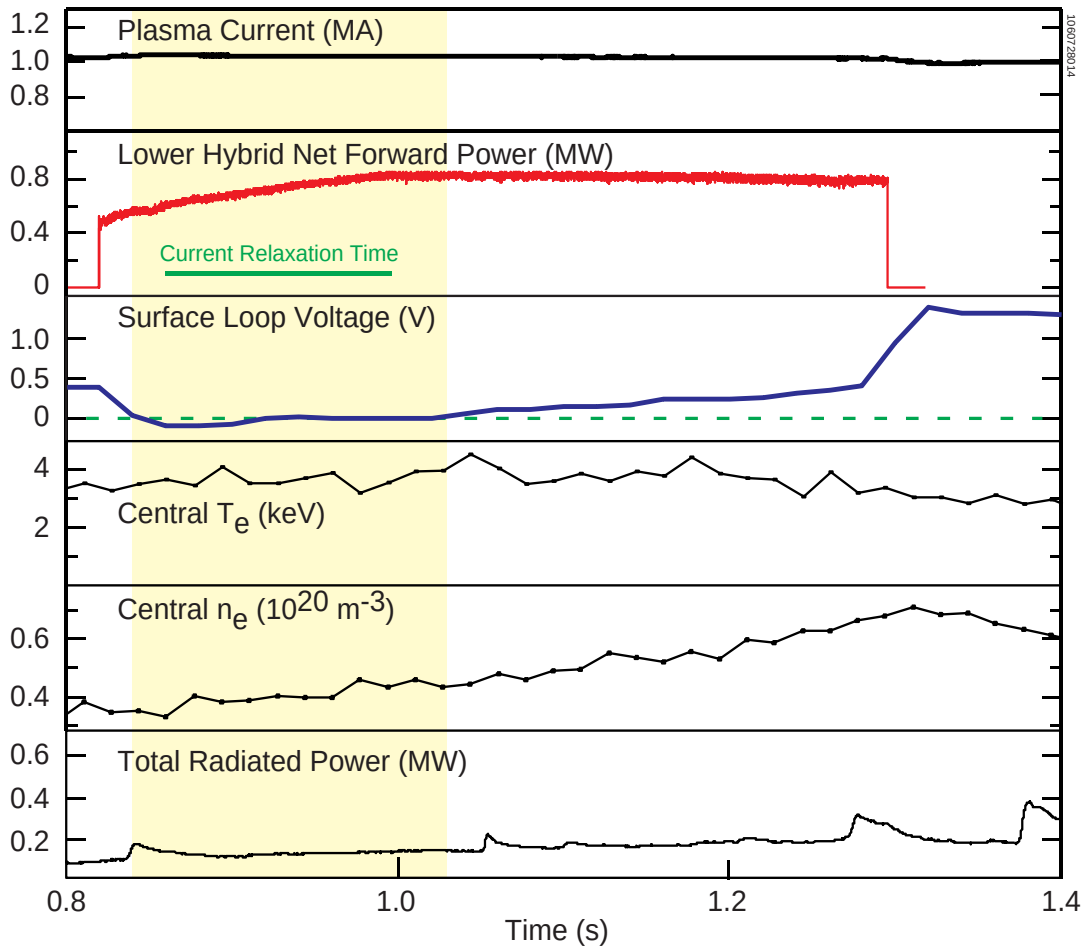


Radially movable with respect to fixed limiters



- Source frequency - **4.6 GHz**
- Variable $n_{//}$ range of 1.6 – 4.0.
- **Phase can be varied during discharge on a 1 msec. time scale** using electronic phase shifters.

Large fraction of plasma current has been driven by LHCD

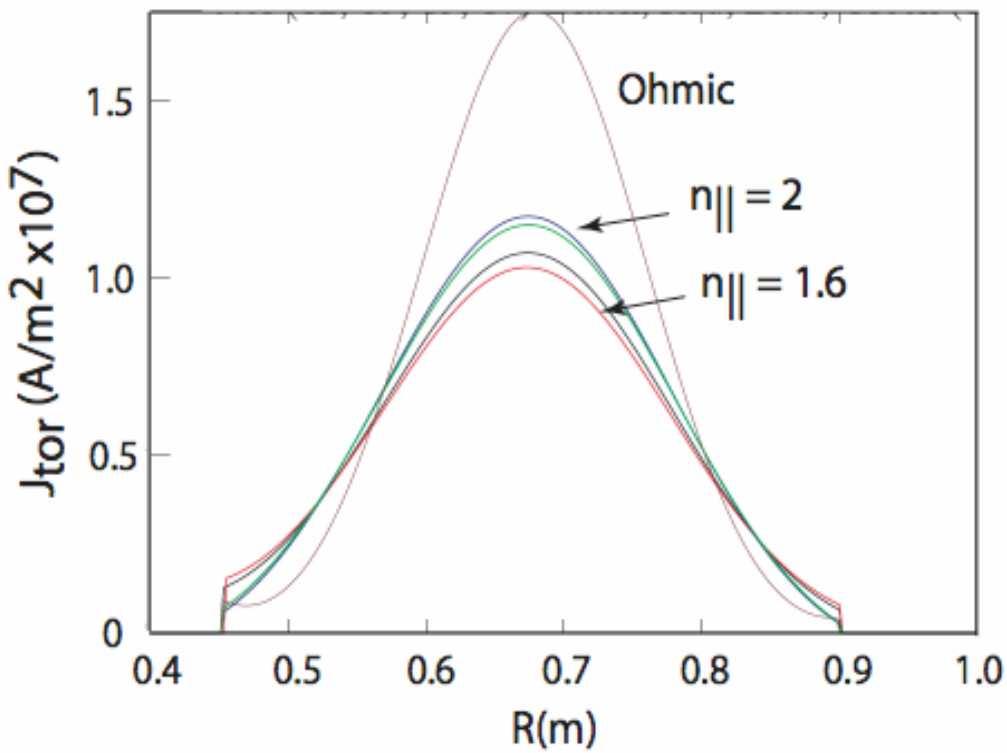


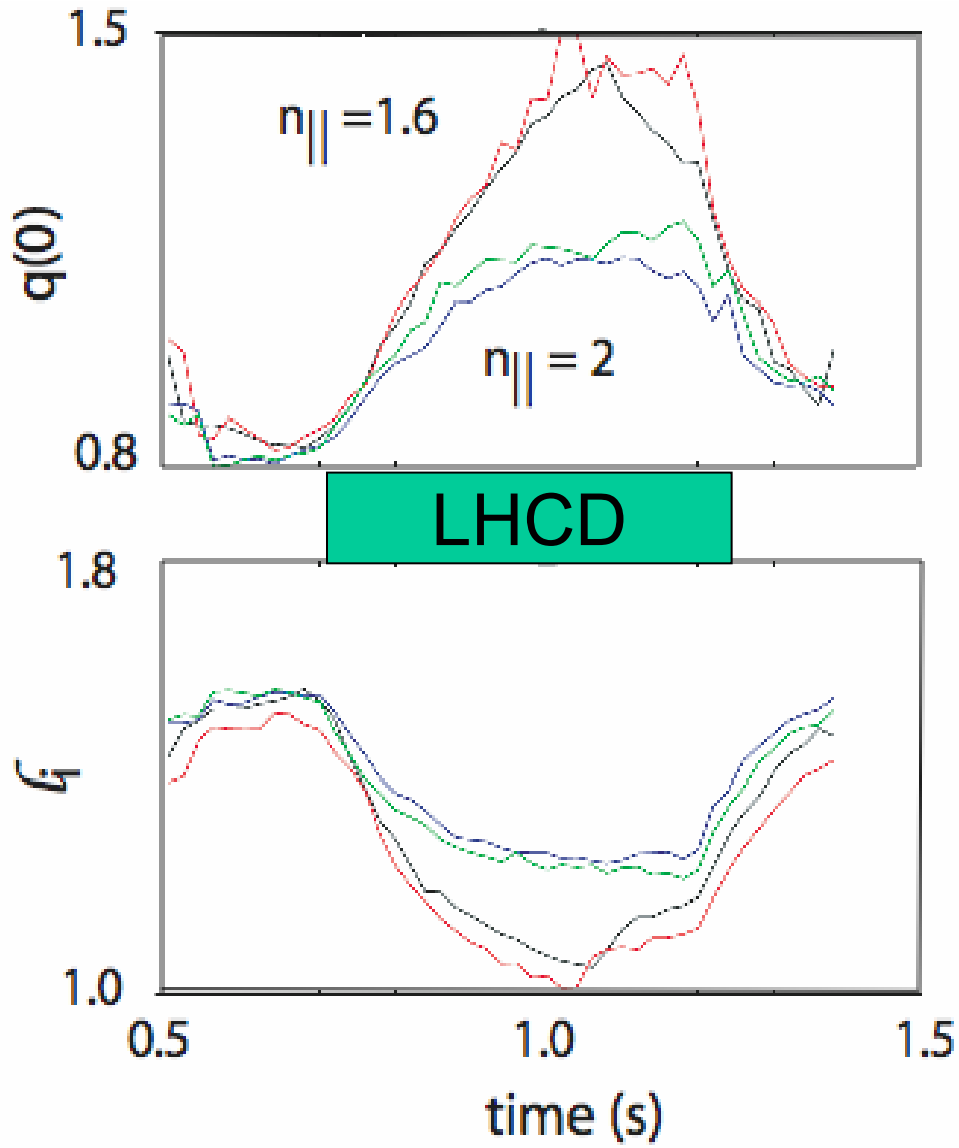
Nearly complete I_p supplied by LHCD at 1 MA in low density L-Mode

- Magnitude of CD in agreement with Fisch-Karney theory
- Current is driven off axis, q(0)>1
- Largest magnitude of current driven by fastest waves

Future work will concentrate on detailed comparison to theory and simulation including time evolution

MSE Constrained EFIT Now Available





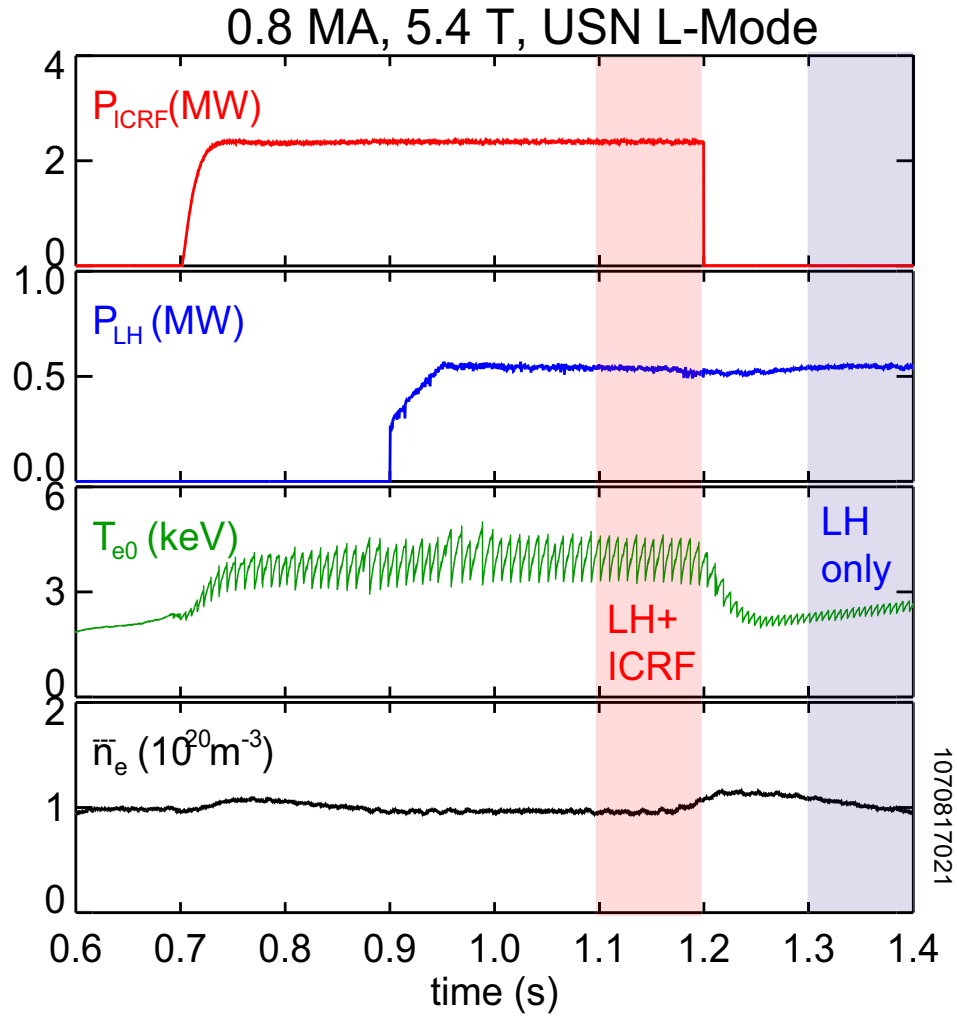
Further refinements in MSE system will improve ability to observe details in the current profile

I_p = 800 kA P_{LH} = 0.8-0.9 MW
$\overline{n_e}$ = 5-5.5 x10^{19} I_{LH} = ~550 kA

S. Scott, J. Ko, S. Shiraiwa

Successful Combination of ICRF and LH Required for Advanced Scenarios

- Simultaneous operation of LH and ICRF has been difficult on JET and TORE-SUPRA due to density reductions
- Similar effects observed on C-Mod when ICRF antenna is magnetically connected to the LH launcher
- Have combined LH with up to 3 MW ICRF

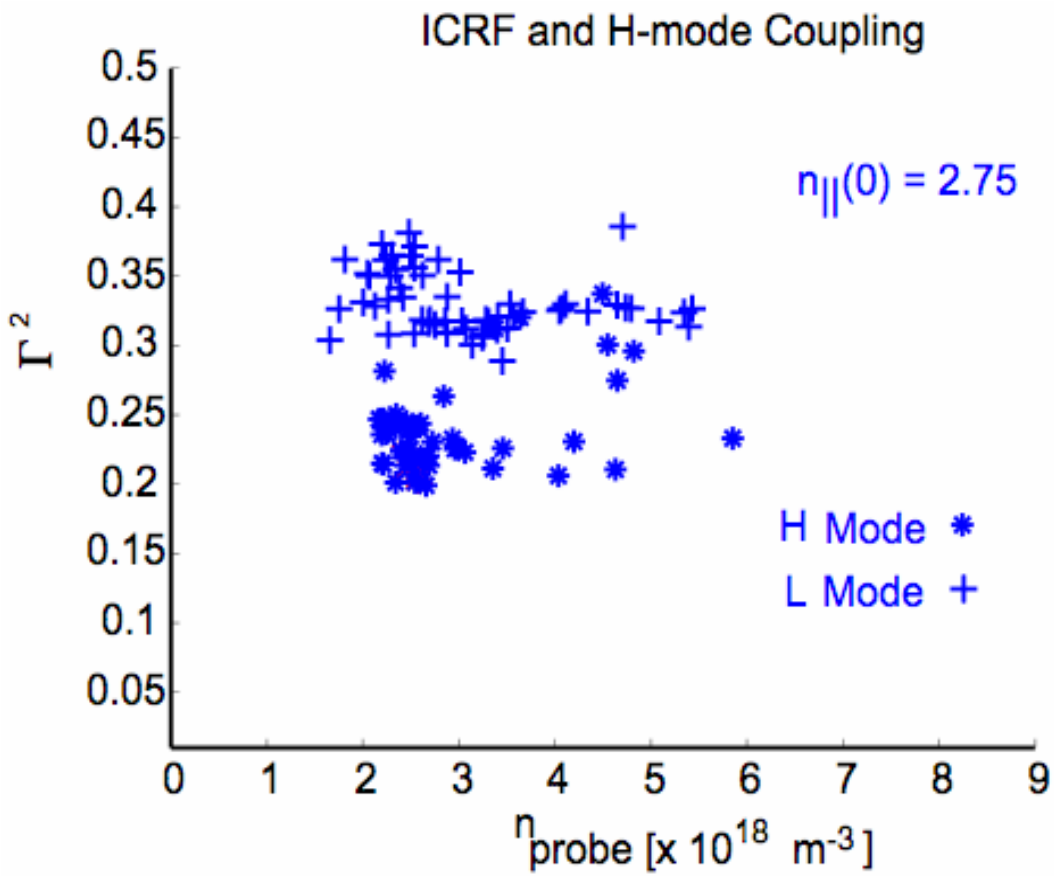


Relocating antennas for future campaigns will allow full 5-6 MW ICRF in advanced scenarios.

LH successfully coupled to H-mode Plasma

Alcator C-Mod

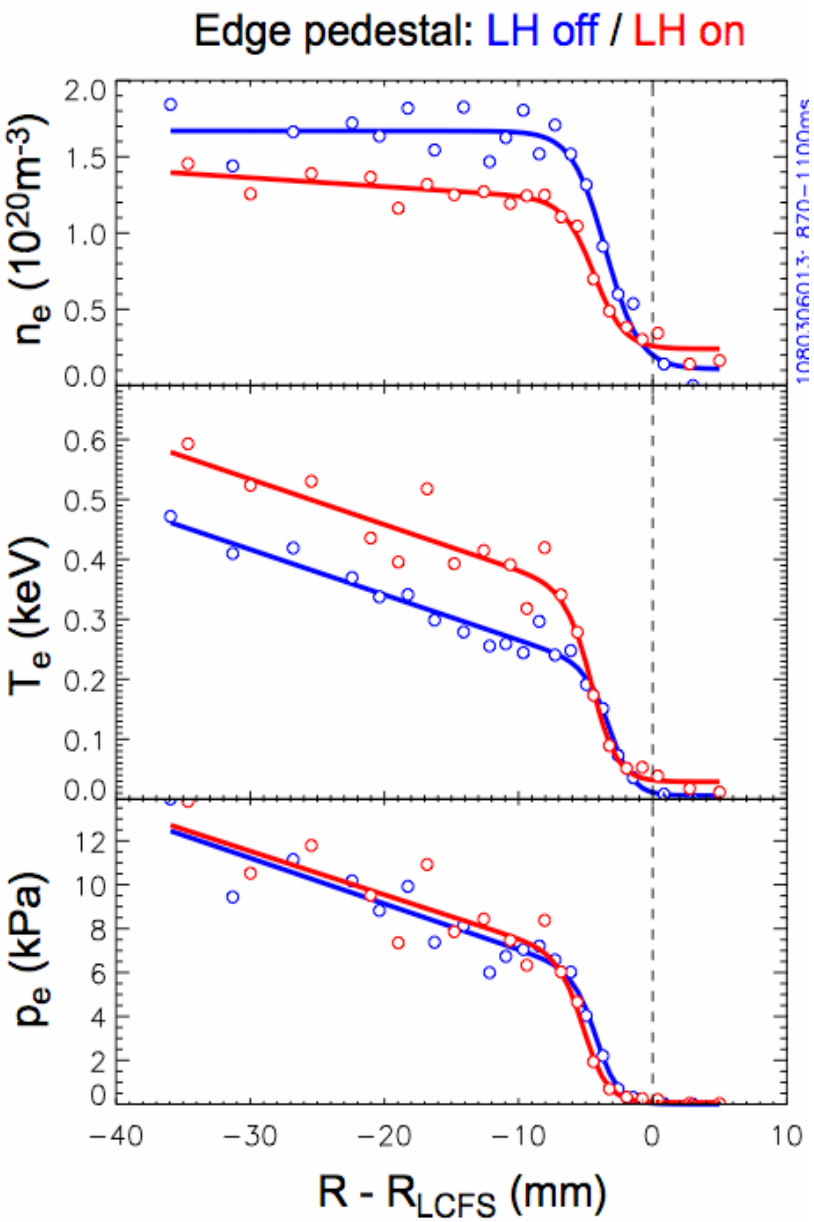
- H-modes are known to have much different density profiles in both SOL and pedestal region, a potential concern for LH wave coupling and propagation.
  - C-Mod a particularly stringent test since H-mode pedestal widths and SOL e-folding lengths are only a few mm.
- Reflection coefficients into ICRF H-modes are even lower than L-modes, though with higher fluctuations.
- In some discharges, the additional LH heating power has triggered H-mode.



G. Wallace

As power raised will study modification of scrape-off and ability to couple as gap is increased

Edge Pedestal Collisionality modified with LHCD



H-modes stay EDA, with similar QC modes, throughout LHCD phase.

No major change in edge rotation (central rotation reduced to near zero)

Major opportunity for further research:
What is the mechanism?
How does it scale with power, phase etc. ?
Can LH affect elms?

J. Hughes

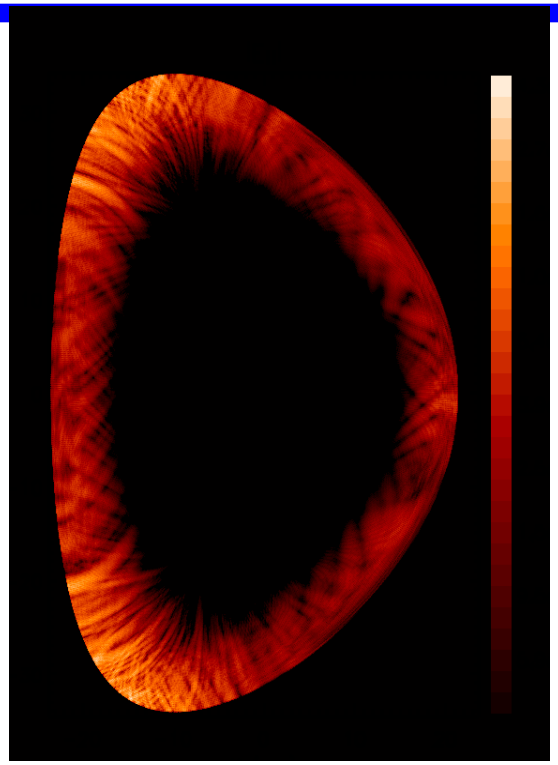
C-Mod profile measurements will be used to validate deposition codes

X-ray profiles are some-what broader than with synthetic diagnostic from GENRAY-CQL3D

- Exploring possibility of fast electron diffusion (preliminary experiments and modeling say no)
- Exploring possibility that diffraction playing large role on wave propagation
  - Expected to occur at higher densities
- Full wave code prediction may explain discrepancy

If true in C-Mod should be true in ITER

- Same wave/plasma parameters, unlike many earlier experiments



$|E_z|$

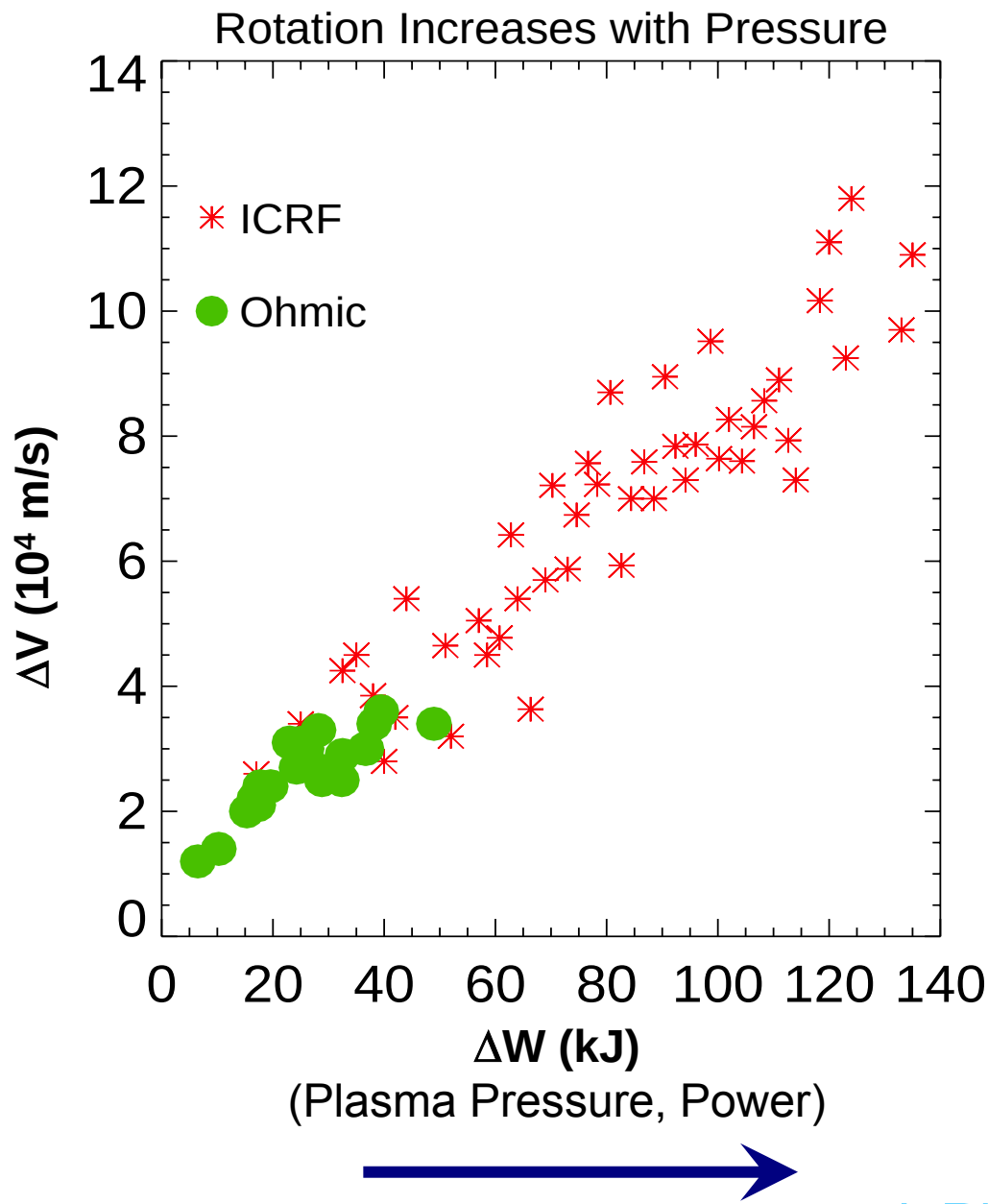
Full wave simulation SciDAC Collaboration J.Wright

On-going work
Need to couple to Fokker-Plank code

Ongoing work in this area will validate LHCD codes for ITER parameters

Momentum Input Difficult in a Reactor Important to Understand Spontaneous Rotation

- C-Mod has no external momentum drive
- Spontaneous core rotation in high pressure (gradient?) plasmas
  - Rotation responds to changes at plasma edge (L to H transition)
  - Profile evolution shows that momentum is transported in from the edge (diffusion + convection)
  - In at least some cases, scrape-off layer flows play a role
- Increase is in co-current direction
- Also seen on Tore-Supra, JET, DIII-D, TCV
  - Masked by torque from high power neutral beams in most experiments
- Cross-machine scalings indicate Mach number proportional to β_N



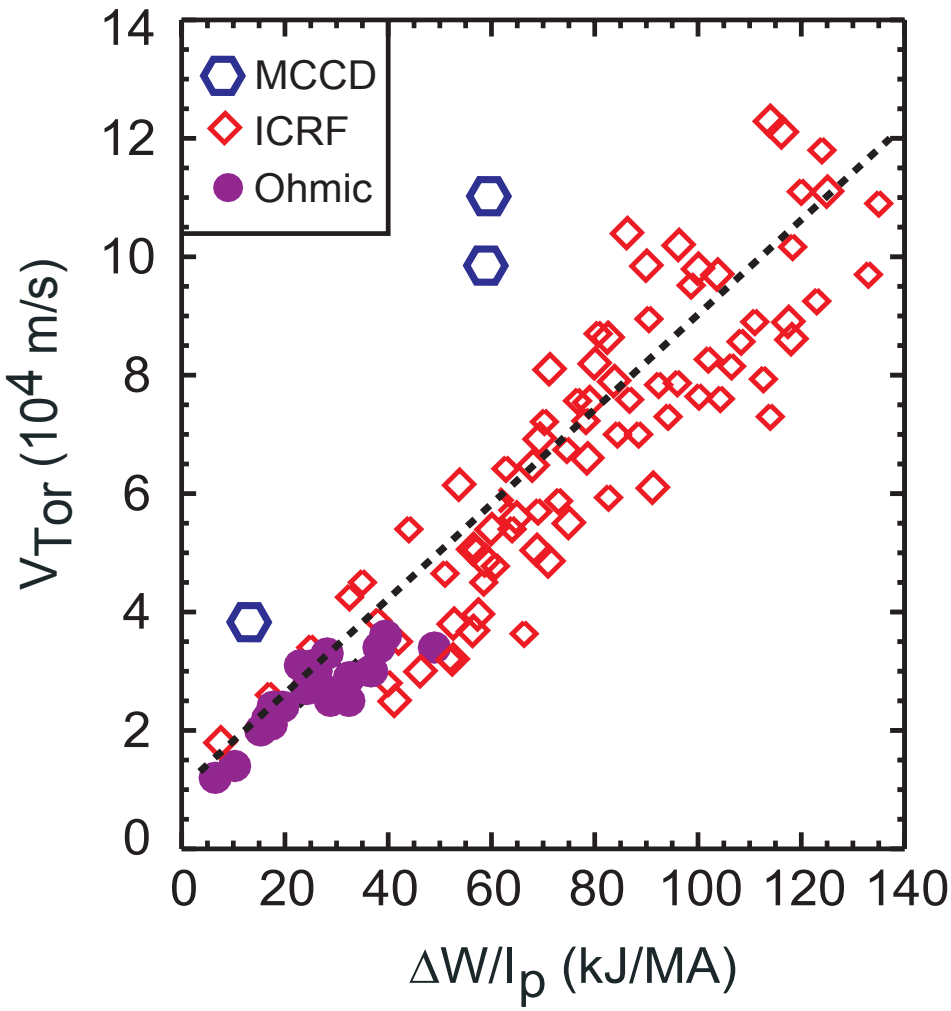
J. Rice

Recent Results Show Flow Drive in ICRF Mode-Conversion Current Drive Experiments

- MCCD can provide central seed current in Advanced Scenarios
- MCCD can be used for sawtooth control/pacing
- Tantalizing new results on driven rotation
  - At least a factor of 2 above the usual scaling seen with pressure/current
- Use multi-frequency capability (50% power at 80 MHz, proton minority, 50% at 50 MHz, ^{3}He mode conversion)
  - Both layers near the axis
- Speculate: near-axis conversion to ion cyclotron wave, which propagates to low field side, damps at ^{3}He cyclotron layer
  - Largest flow for wave V_{phase} in co-current direction
- More measurements and modeling to follow

Mode Conversion Flow Drive

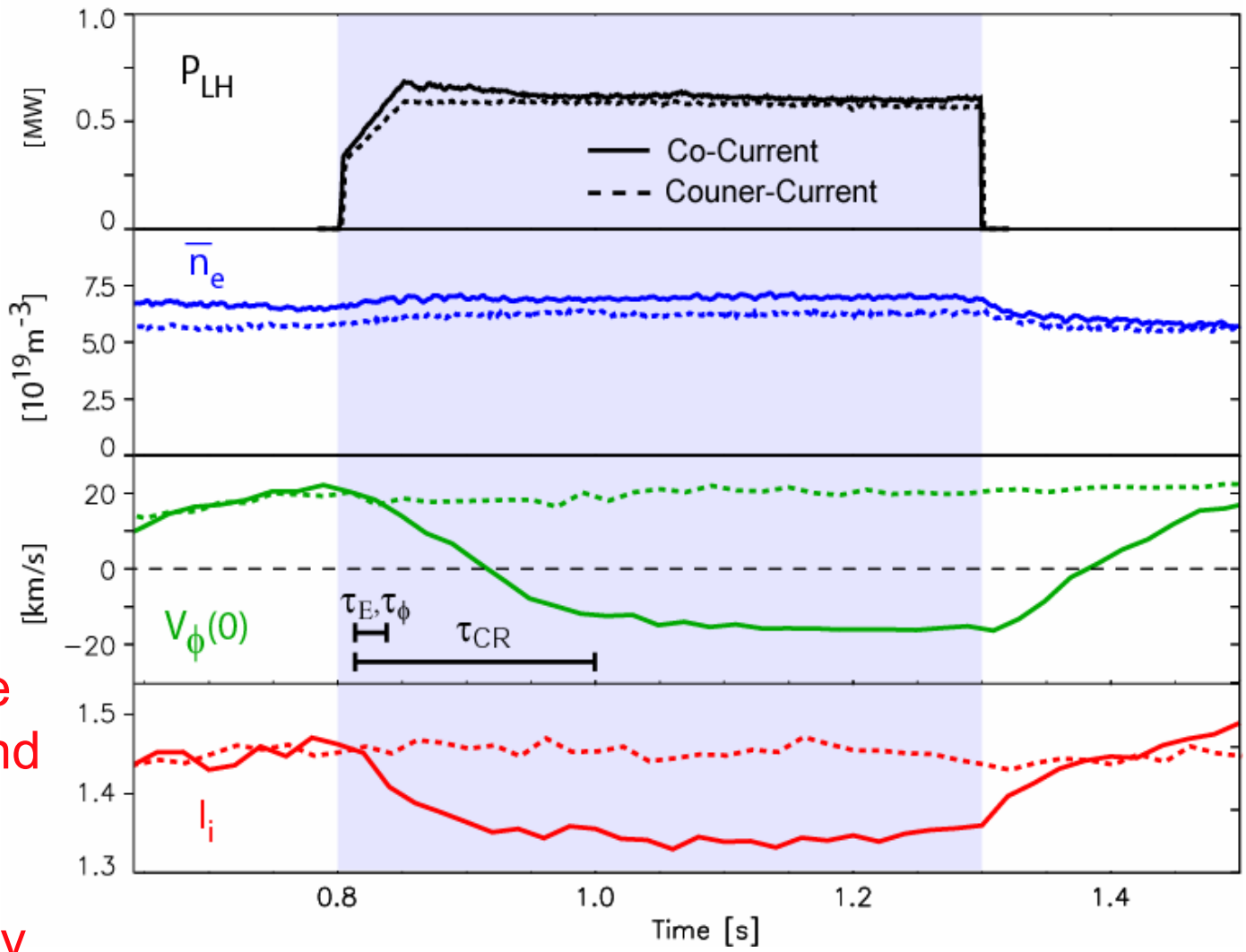
$B(R_0)$ = 5.1 Tesla; ^{3}He fraction ~ 20%



Yijun Lin

Strong counter-I_p shift in core rotation seen during LHCD

- V_{tor} profiles (He and H like Argon) measured by Imaging x-ray crystal spectrometer (PPPL-MIT coll.).
- V_{tor} evolves on current relaxation, not energy confinement, time scale.
- Only occurs with CD phasing, and magnitude scales with l_i change.



New Opportunity to explore momentum confinement and plasma rotation
Since rotation direction opposite to ICRF effect may allow tailoring of rotation shear

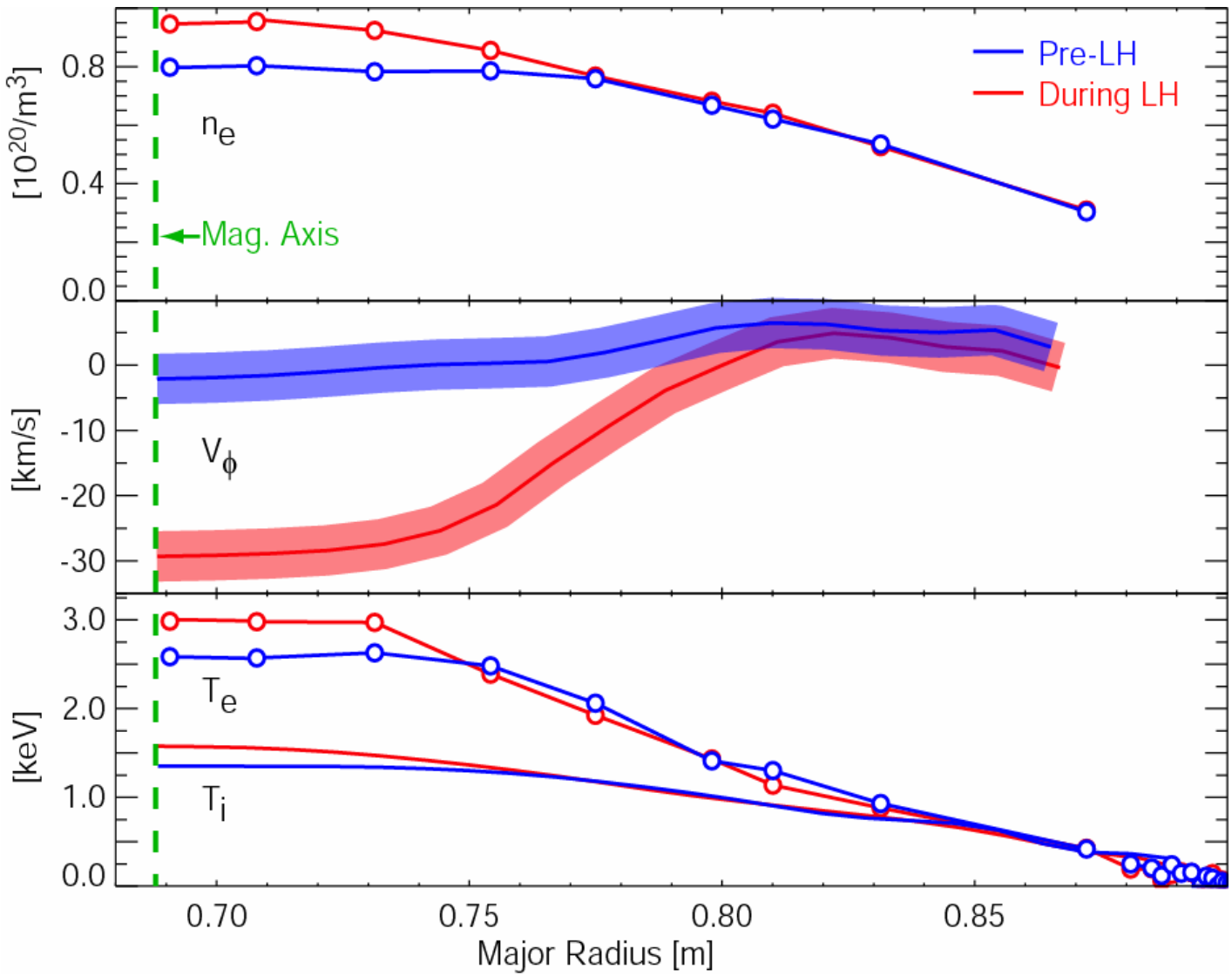
Alex Ince-Cushman

LHCD induced rotation change is strongest in core

- V_{tor} change is most pronounced at r/a < 0.4.
- Inflection point near where current is driven
- Mechanism?

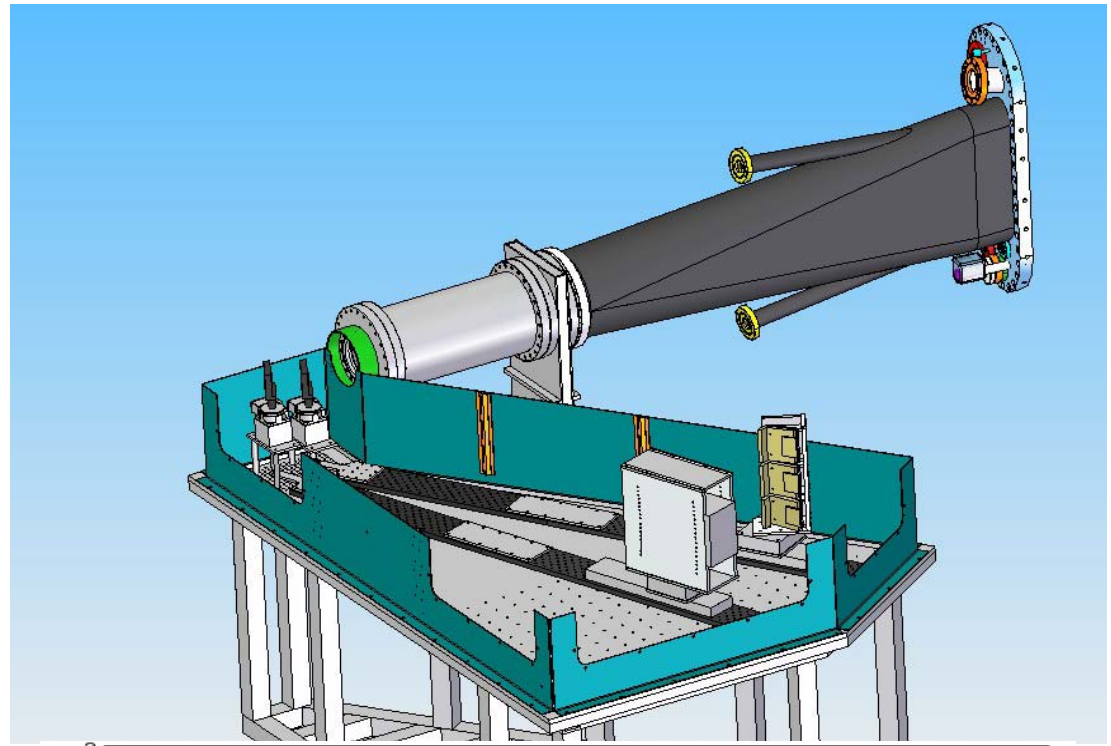
Plan:

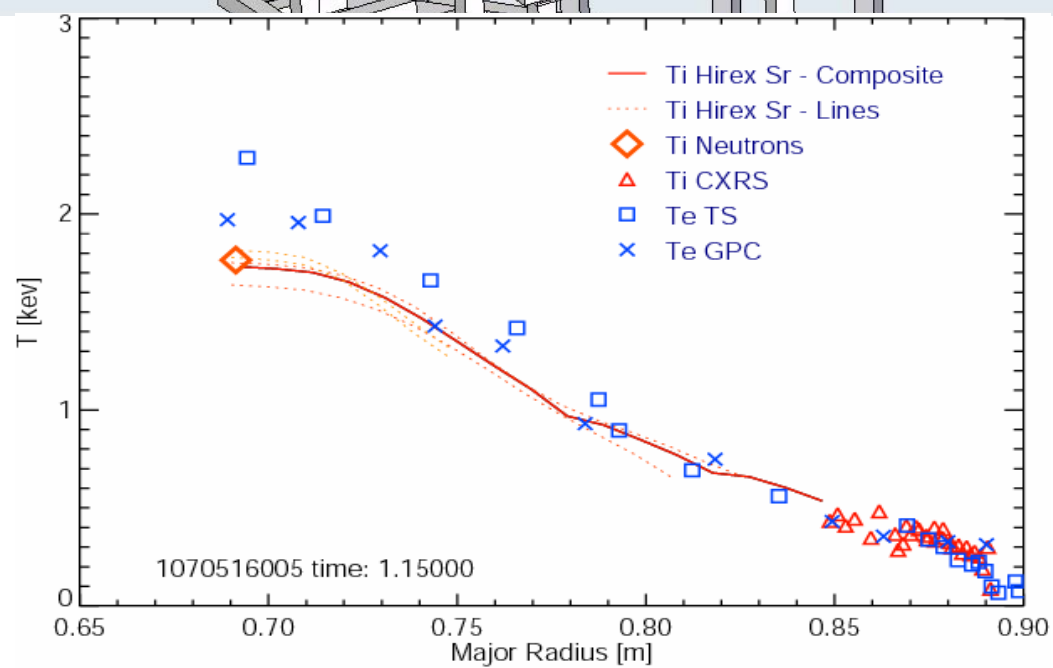
Use fluctuation measurements (PCI, reflectometry) for comparisons with advanced simulations



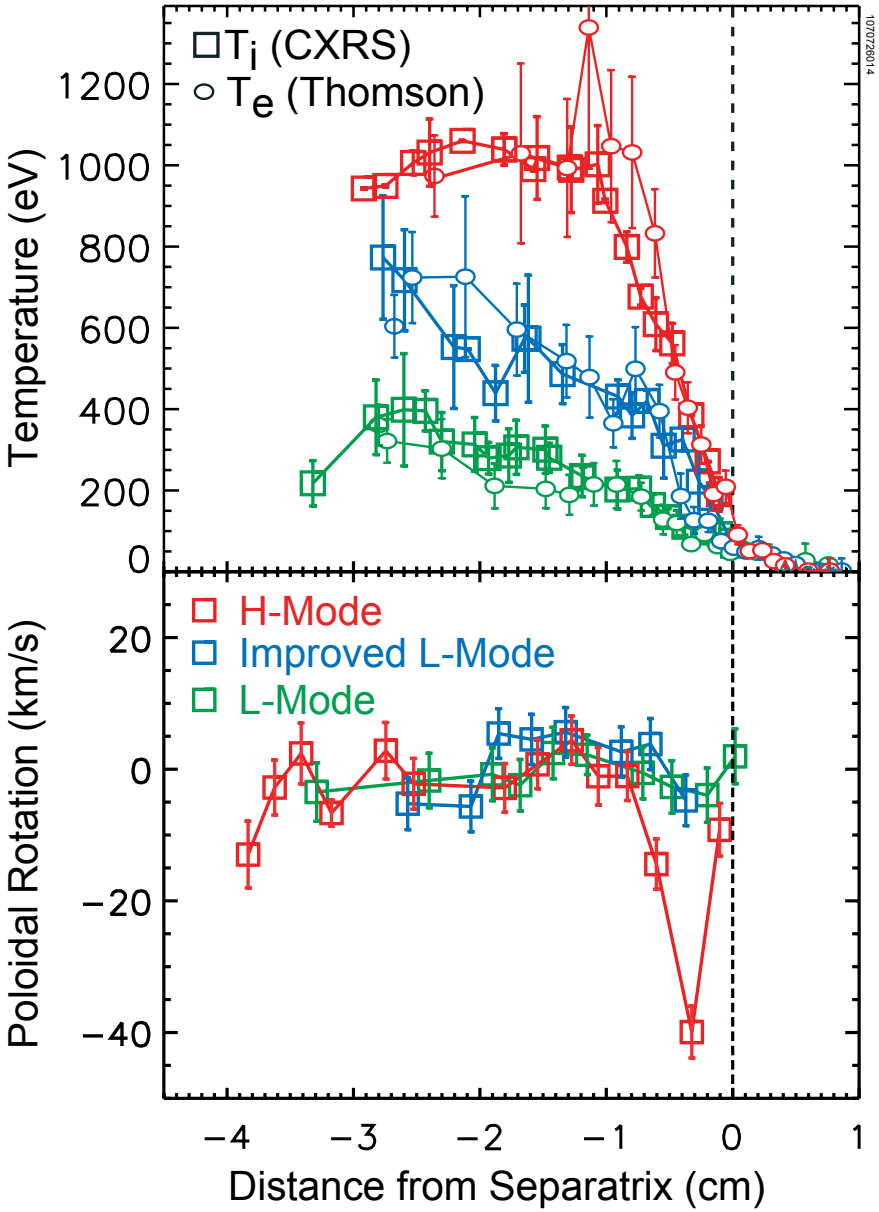
Many new results on rotation benefit from diagnostic enhancements

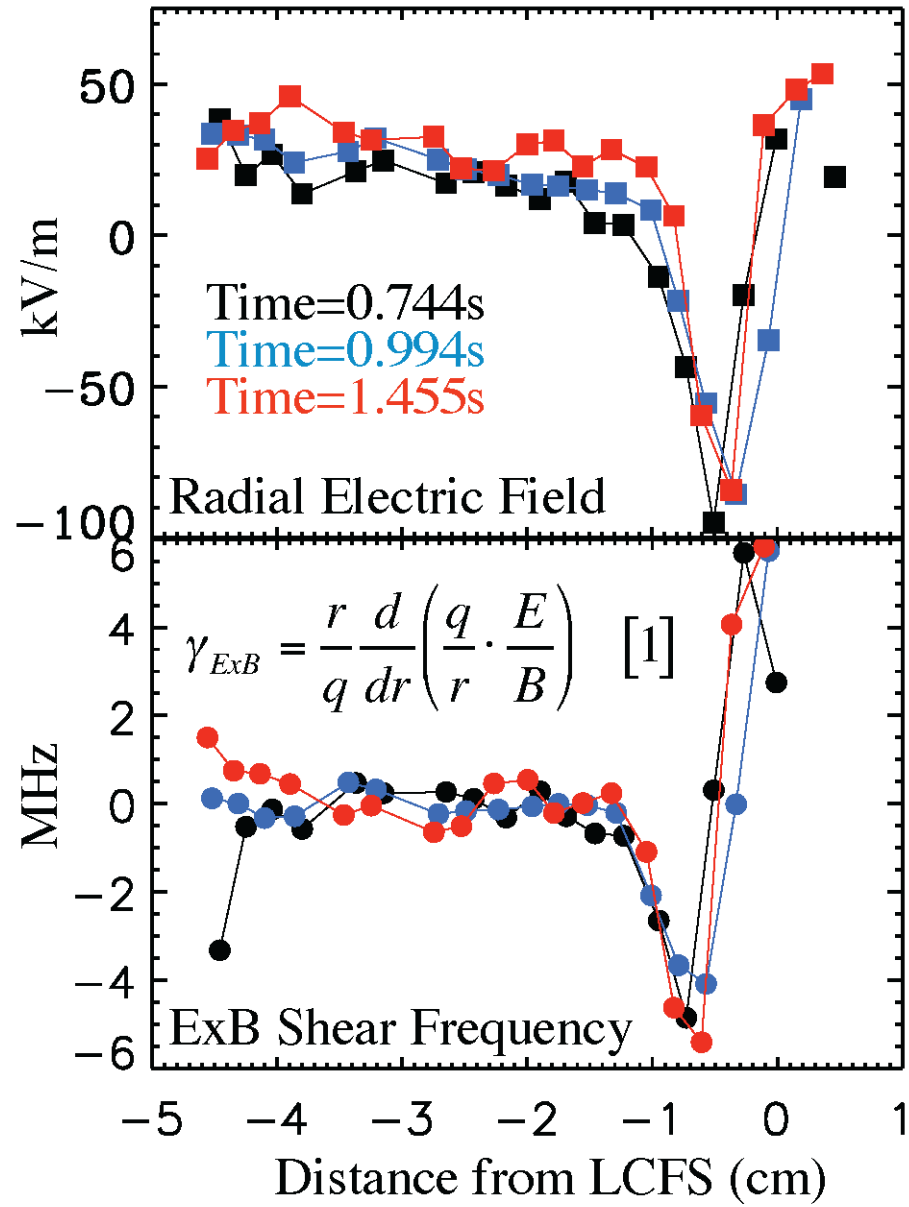
- High spatial and spectral resolution X-ray spectrometers
  - Development led by PPPL (Bitter, Hill), in close collaboration with MIT (Rice, Ince-Cushman)
  - Coverage from center of the plasma out to the top of the H-mode pedestal
- CXRS (with DNB)
  - Overlapping coverage with X-ray
  - ~3 mm spatial resolution across the pedestal and into the near scrape-off-layer





Detailed pedestal ion temperature and radial electric field profile measurements also routinely available



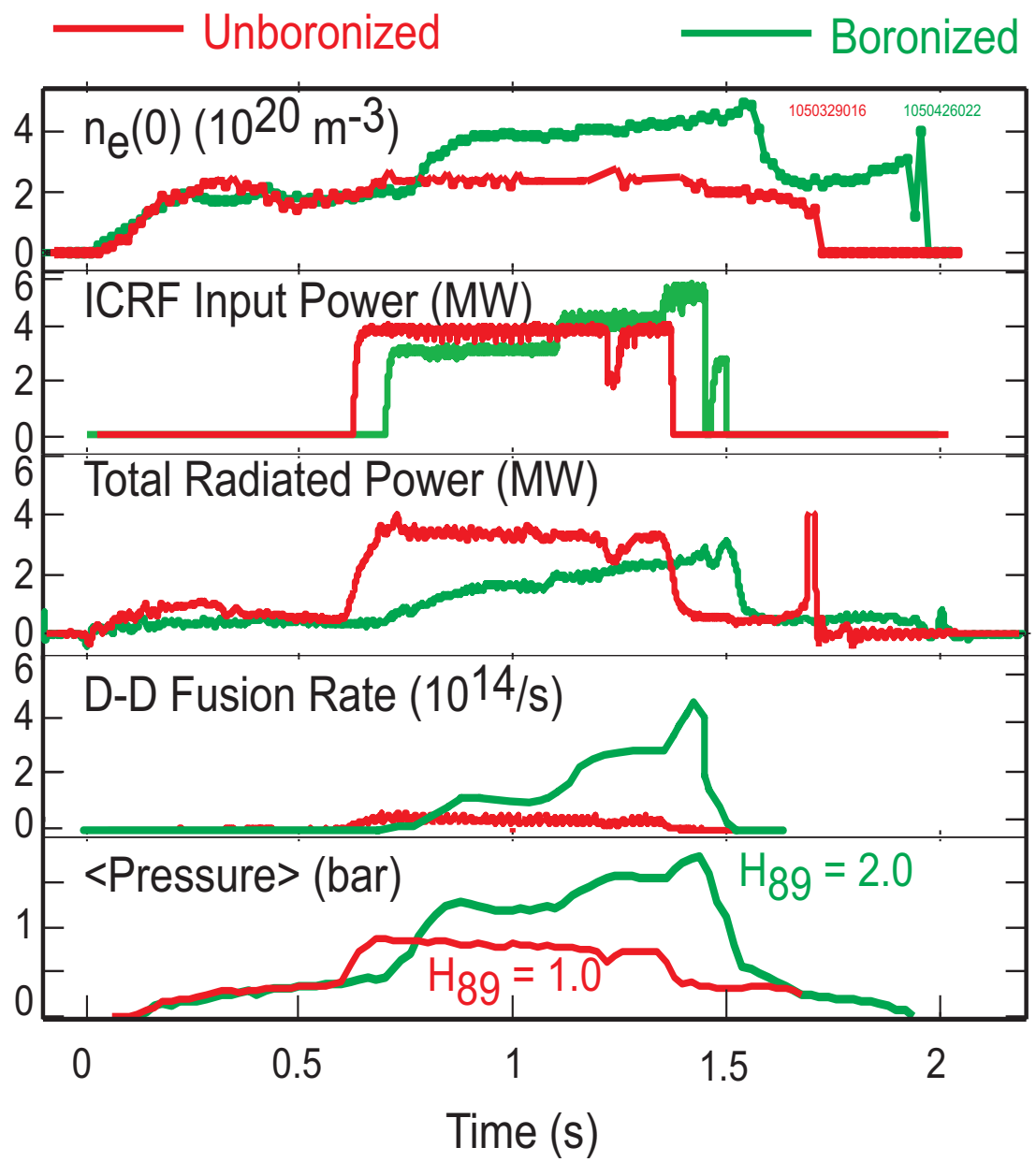


[1] Waltz, et al, Phys. of Plasmas Vol. 4, 2482 (1997)

Rachael McDermott

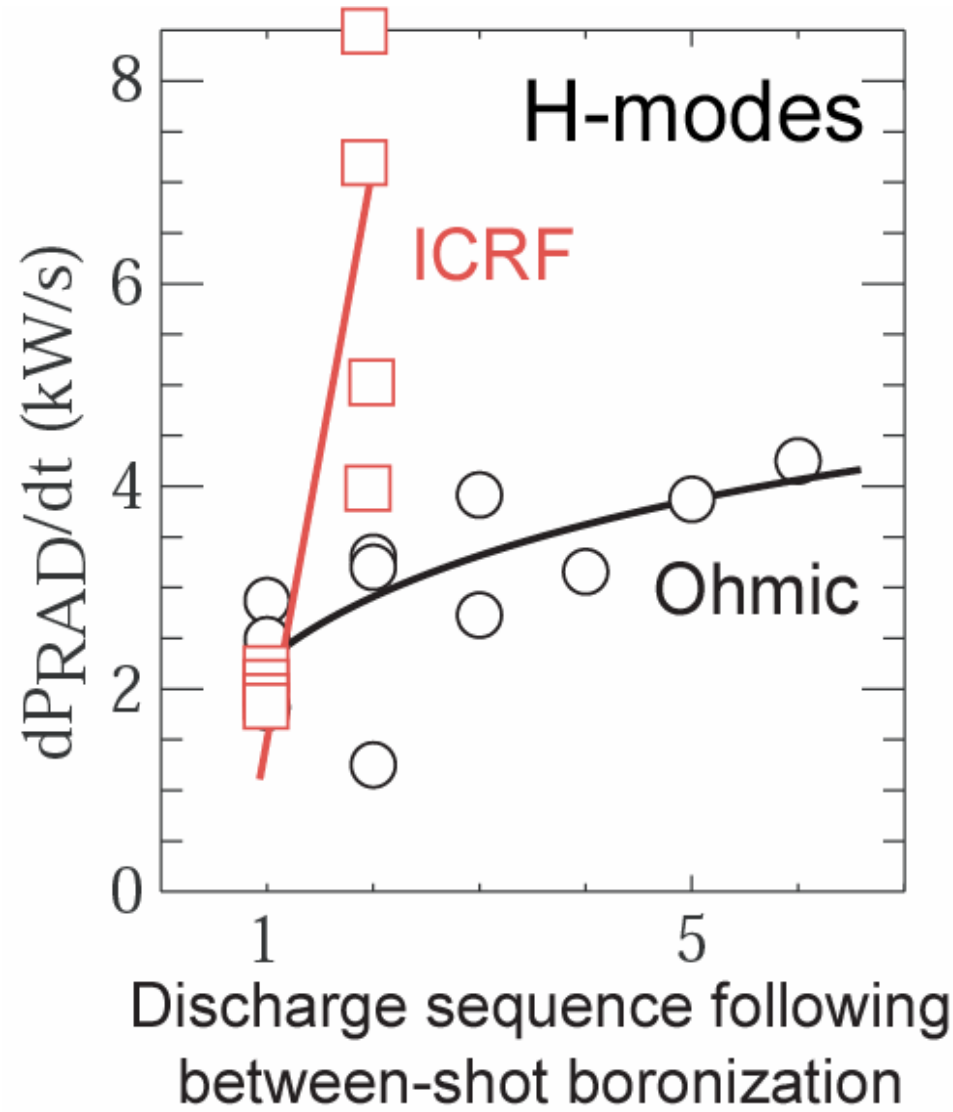
Excellent ICRF heating and plasma confinement Requires Boronization

- Testing compatibility of metal PFC's with high power density ICRF
- In unboronized H-mode, impurity buildup causes rediative degradation of H-mode confinement
- With thin (0.1 – 1 μm) boron coating, radiated power stays under control (<50%)
- Coatings wear off
  - Implications for ITER, Demo?



Boron Erosion And Mo Influx Clearly Enhanced by ICRF

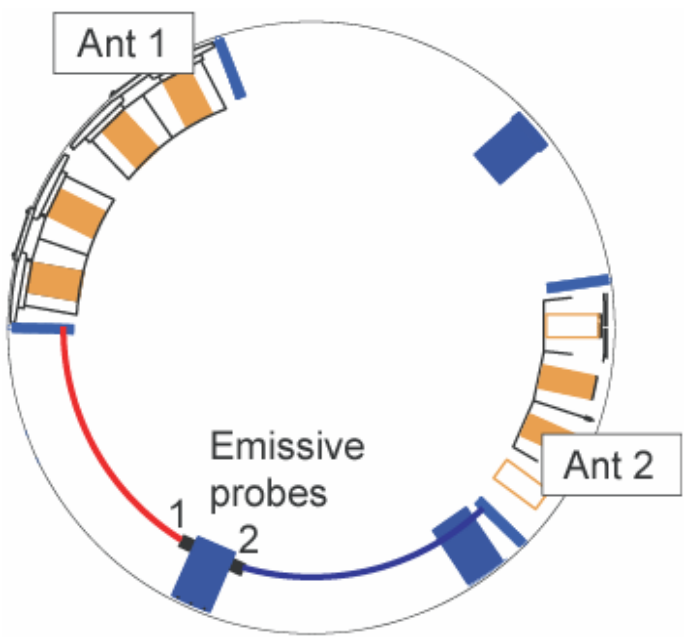
- Typical overnight boronization lasts for about 1 run day (10 to 30 seconds of high power discharges)
- Very thin boronization (between shot) lasts about 1 discharge
- Very clear enhancement of erosion with ICRF vs. ohmic (same total input energy)

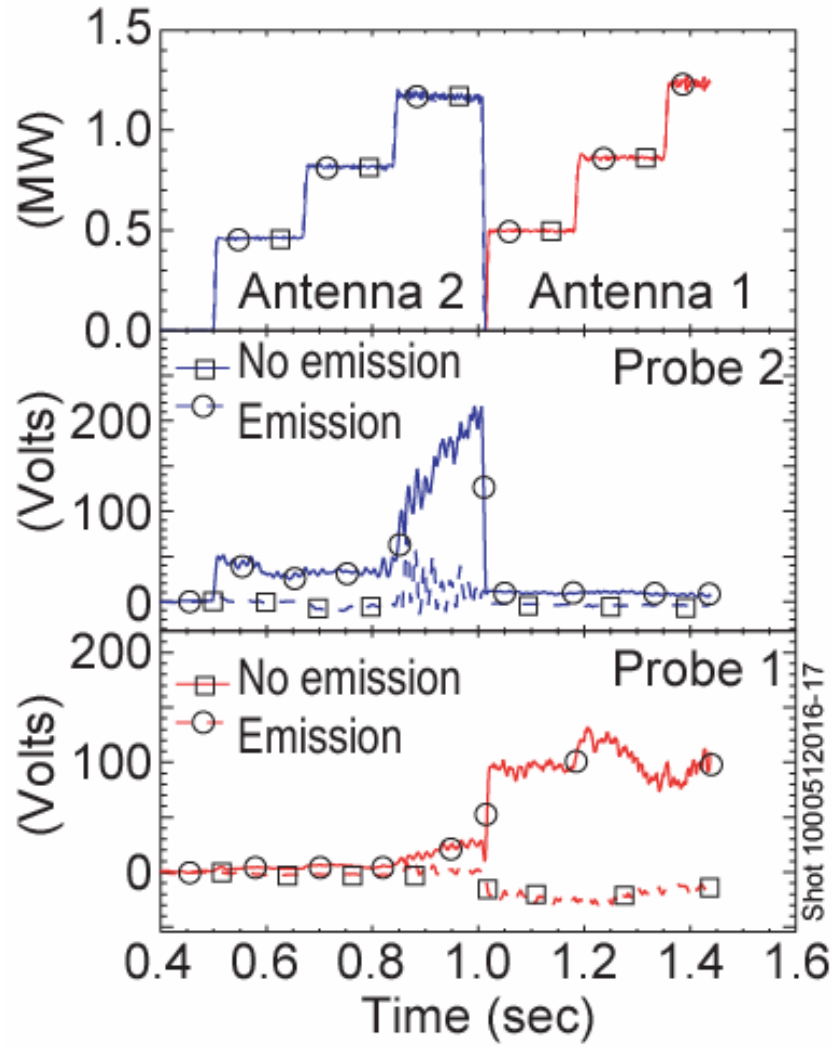


B. Lipschultz, D. Whyte, S. Wukitch, Y. Lin

ICRF Sheath Enhancement Responsible for both Mo sputtering and Boron Erosion

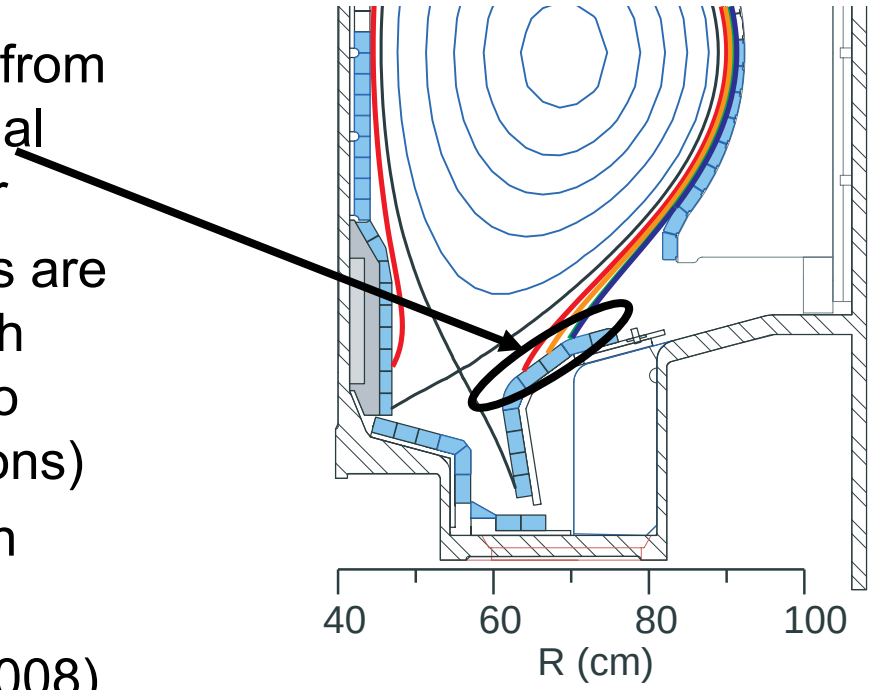
- Emissive probes show that sheath enhancement is ~100V for 1 MW ICRF power
- Increases D^+ energy above sputtering threshold
  - Even more dramatic effect on multiply ionized boron (principal low Z impurity)
- Enhancement appears on field lines that connect to the active antenna

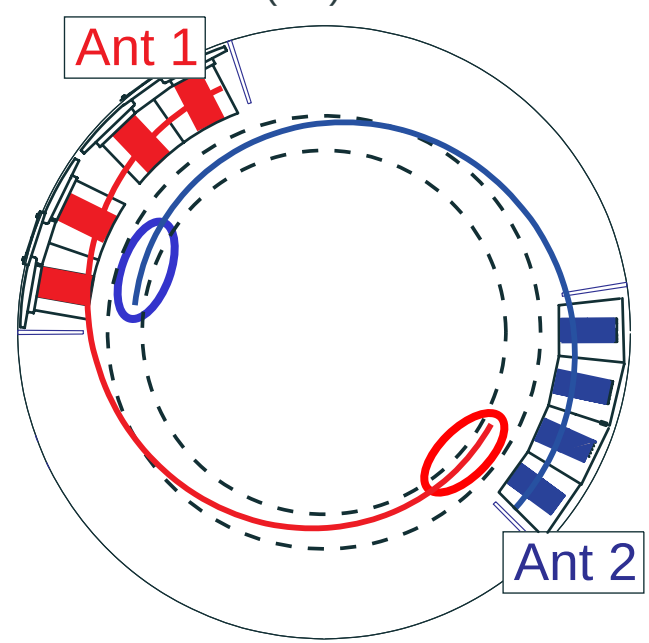




Varying Boronization Deposition points to regions outboard of the divertor and primary impurity source

- For the equilibrium studied, field lines map from the ICRF antennas, across outboard poloidal limiters to top shelf above the outer divertor
  - Secondary limiters next to the antennas are not the dominant sources (replaced with Boron-Nitride for several campaigns; no reduction of Mo in unboronized conditions)
- Plan to employ very thick boron coatings on shelf and limiter tiles (2009)
  - Prototypes performed well in C-Mod (2008)
  - Erosion on prototypes will be measured after the current campaign is finished
- Keep high heat flux regions uncoated Mo
  - Going to all tungsten for the outer divertor (2011)





C-Mod is an excellent test-bed for the study of hydrogenic retention

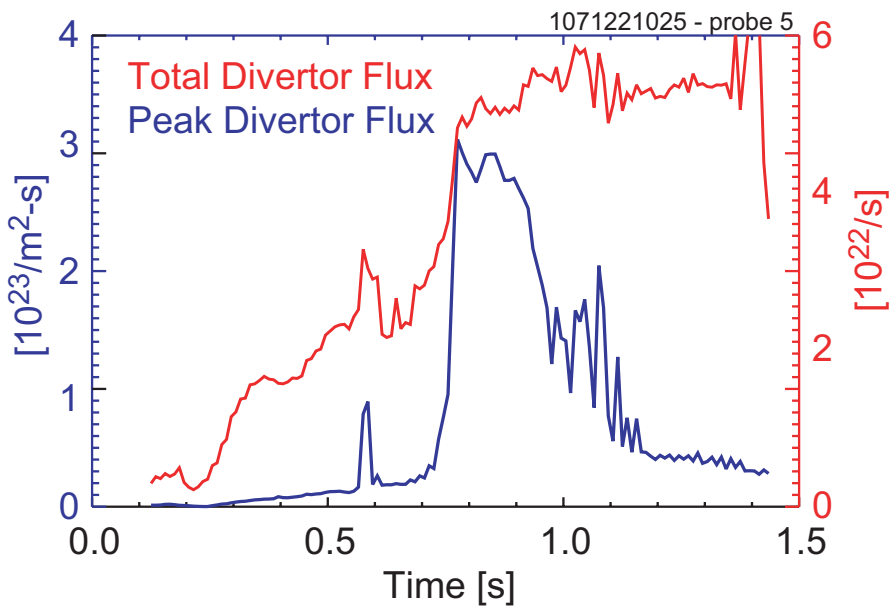
Serious concern about tritium retention in ITER (with or without carbon); Tungsten proposed

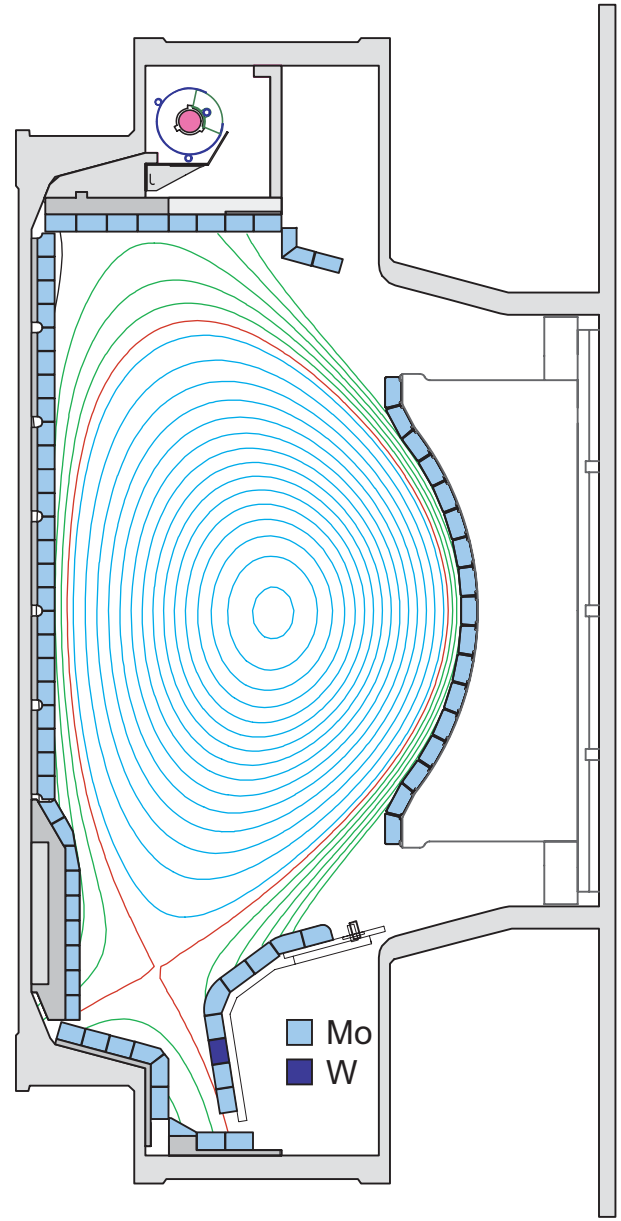
C-Mod Plasma Facing Components

- ~ 7000 tiles of solid molybdenum (essentially the same as tungsten for hydrogenic retention)
- One toroidal 'row' of solid tungsten lamella tiles in the strike point region of lower outer divertor

Divertor conditions

- ~ITER densities, temperatures, particle and power fluxes

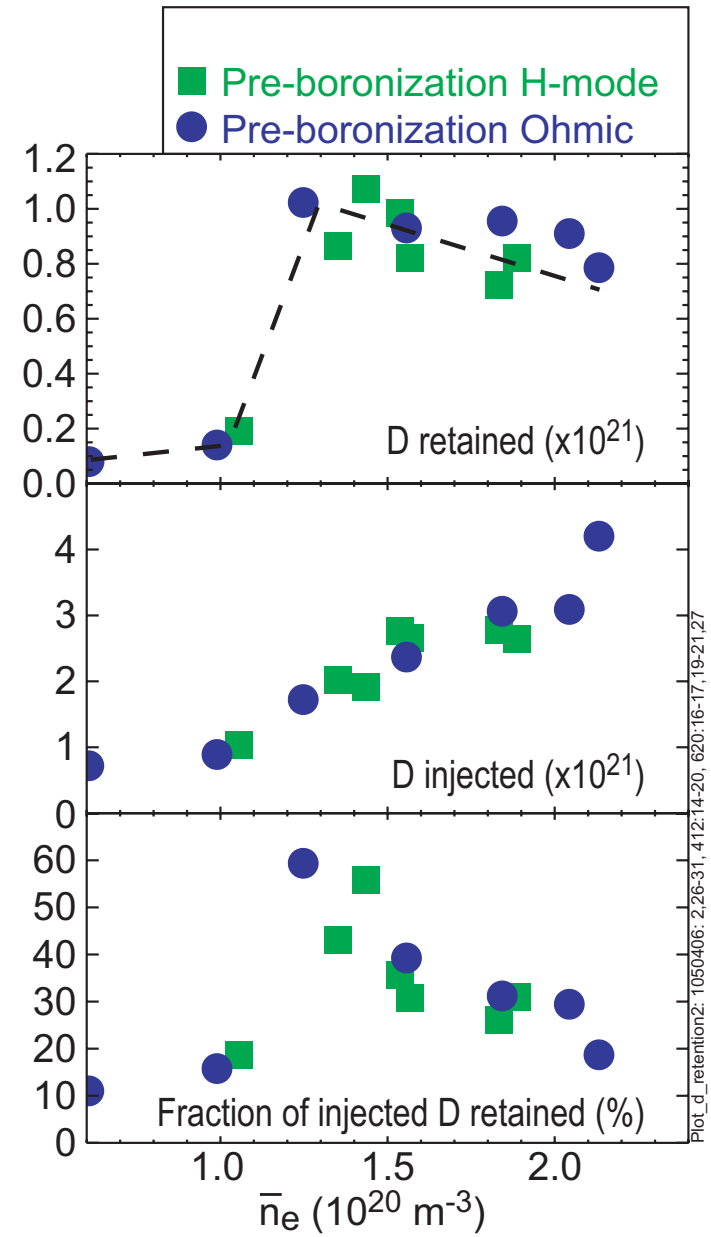




B. Lipschultz, D. Whyte

Retention can be a significant fraction of gas injected when surfaces cleaned of boron

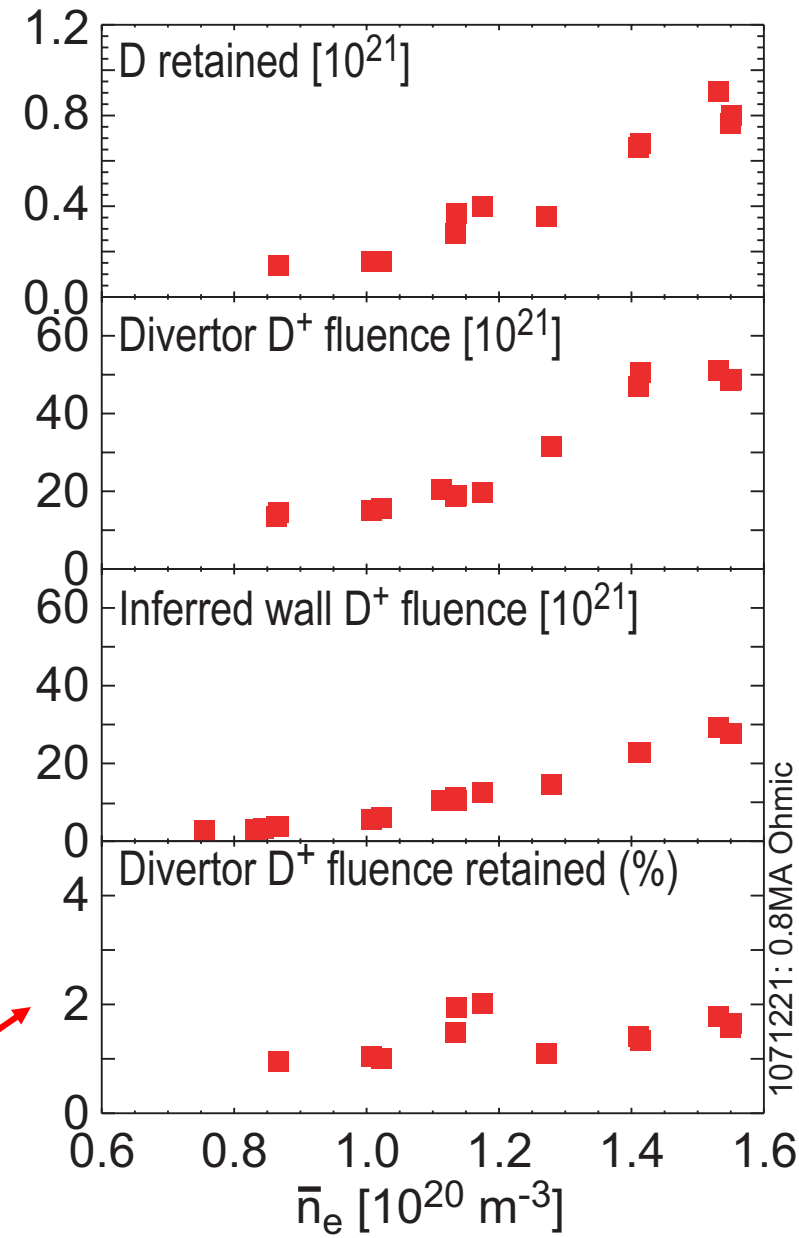
- All Plasma Facing Components (PFCs) are cleaned of B during the vacuum break between run periods
  - Surfaces are molybdenum with surface contaminants, primarily boron, but also C, O.
- Retention increases with increasing density, then becoming ~ constant
- Independent of heating or confinement mode
- Retention can be a large fraction of the injected gas!
  - surprisingly similar to carbon PFC tokamaks



A new equilibrium must be reached for each change in plasma density

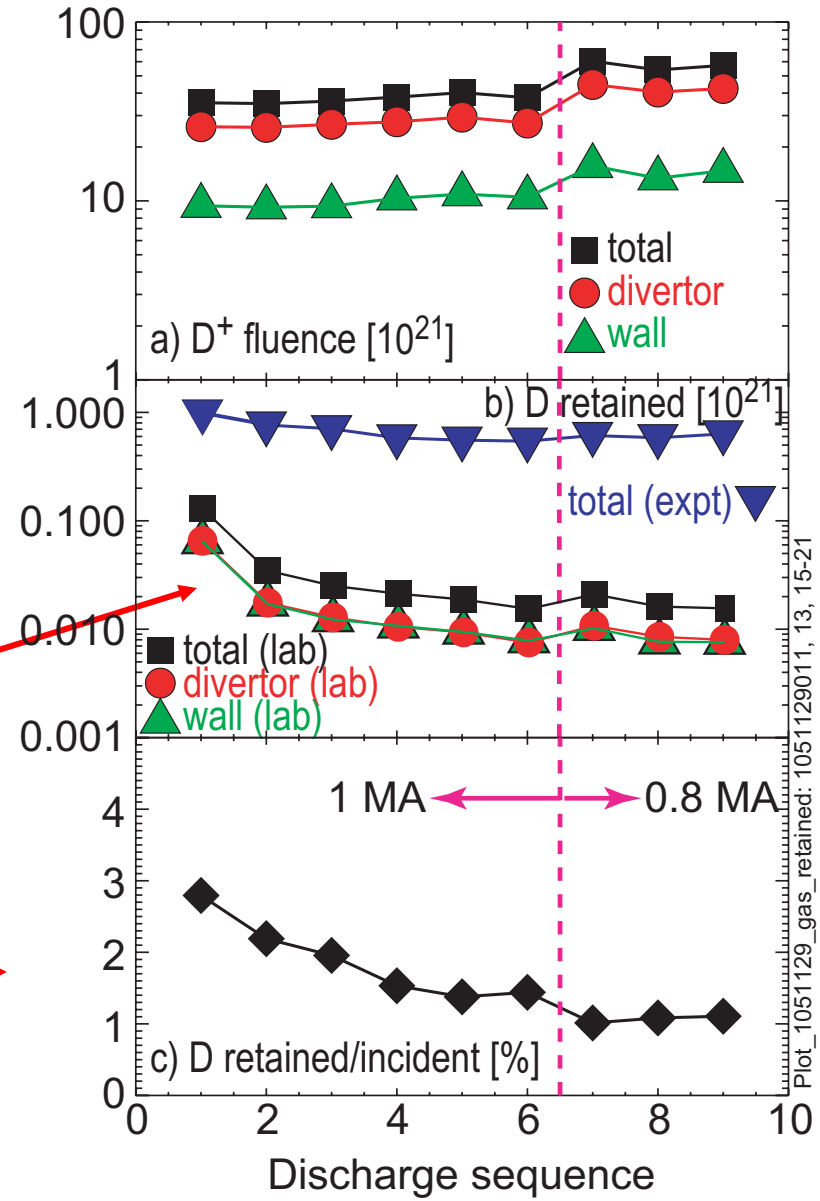
Density scan to examine how retention/fluence/re-emission equilibrium is reached at each density

- For each increase (and decrease) in n_e the neutrals in the surface must reach a new equilibrium with the incoming ion flux
- More discharges needed to reach equilibrium at lower n_e => equilibrium driven by fluence
- Reached an equilibrium when the retention normalized to divertor ion fluence reaches 1-2%



Retention does not saturate as expected

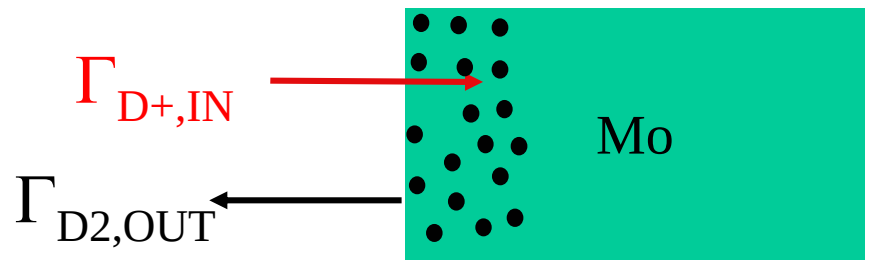
- A sequence of constant parameter discharges
  - Retention/discharge dropped slightly but thereafter essentially constant => no saturation of retention
    - $D_{retain} \sim \Gamma_{incident}^{1}$
- Laboratory experiments[1] at T=300°K showed that the retained D should saturate with increasing fluence
  - D_{retain} (#/m^2) = $1.66 \times 10^{12} \times \Gamma_{incident}^{0.345}$
- Application to C-Mod fluences (assuming no previous fluence) leads to lower retention which rapidly drops
- Retained fraction of divertor fluence, even after many seconds of high flux, is still in the range of ~ 1%
  - Local fluence in the mid 10^{23}/m^2/discharge (~ 1s)



[1]Haasz et al, J. Nucl. Mater. 241-243 (1997) 1076.

Lab studies support a newly postulated process: Incident ion fluence creates D 'traps' within the surface

- Ions are deposited in the surface (range ~ 2-3 nm) pick up an electron - D^0 atoms
- Atoms diffuse to the surface where they must combine with other atoms into a molecule to leave the surface
  - The rate of D_2 leaving the surface is determined by the local density, n_D, and the recombination coeff, R
- High n_D builds up stresses in the Mo lattice because of the low hydrogenic solubility of Mo (same expected in W)
- **Stresses are relieved through deformation of the lattice and the creation of vacancies, interstitials or voids** → 'traps' [1,2,3,4].

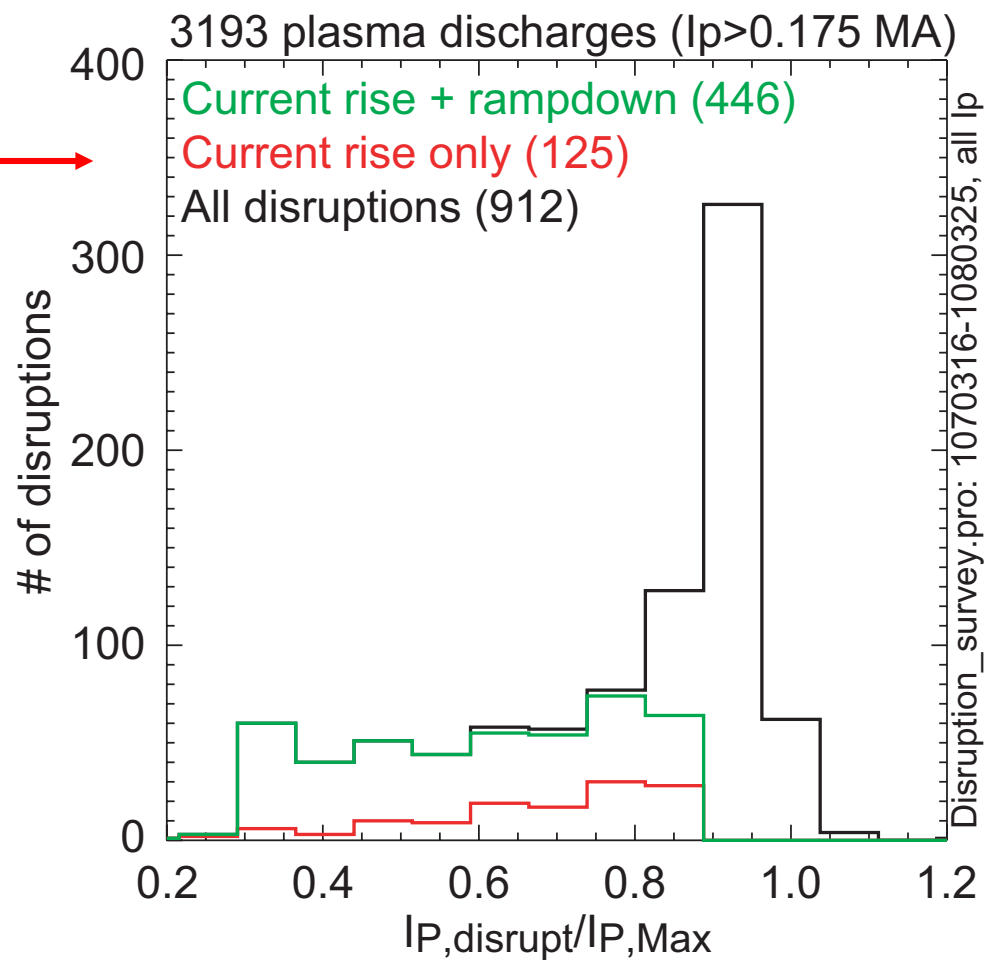


$$\Gamma_{D+,IN} \sim \frac{1}{2}\Gamma_{D2,OUT} = \frac{1}{2} n_D^2 \cdot R$$

[1] O. Ogorodnikova et al., **313-316** (2003) 469
[2] G. Wright, PhD thesis, U. Wisc. 2006
[3] M. Poon et al., J. Nucl. Mater. **307-311** (2002) 723
[4] V. Alimov, J. Roth, Phys. Scripta **T128** (2007) 6.

Disruptions are a common occurrence affecting the long-term retention

- ~15% of all discharges have disruptions at full plasma current
  - Largest removal of D from surfaces
- Another 15% occur during during current rise or rampdown
  - Smaller amounts of D removed but significant

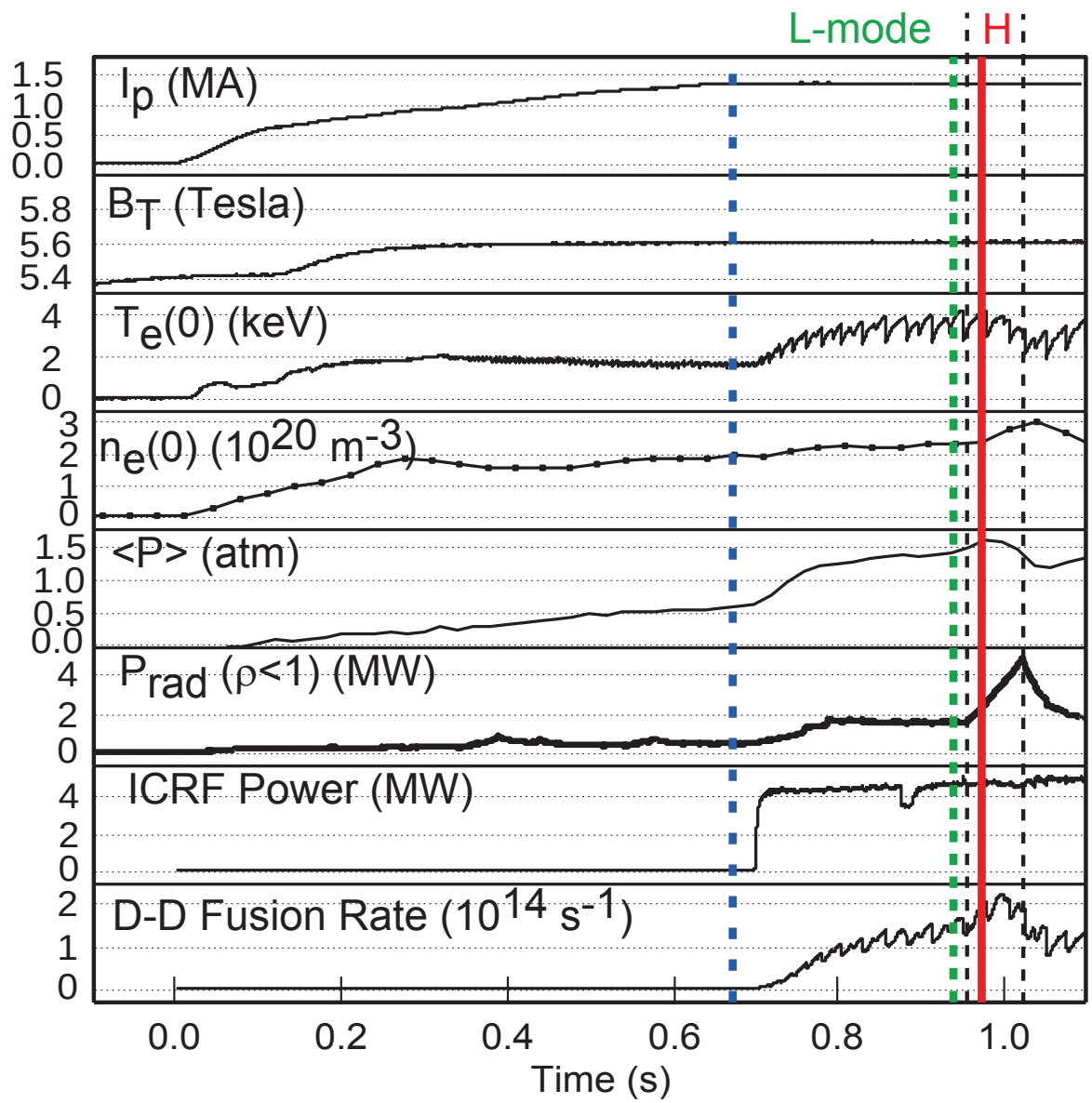


- Net effect on long-term gas retention is certainly opposite of single-discharge retention
  - Difficult to accurately predict the net long-term retention
    - Boronizations, conditioning, bakes…
- **On C-Mod, net long term retention is close to 0**

Improved L-mode: H-mode confinement with L-mode particle transport

- Unfavorable ∇B drift direction; increased δ, I_p
  - Very high H-mode threshold (at least x3)
- H-mode confinement
  - ($H_{ITER\text{-}98y2}$ = 1)
- T_e barrier, little or no additional n_e barrier
  - No ELMs, no impurity accumulation

I_p=1.35MA, q_{95}=2.9, δ_u=0.6, P_{ICRF}=4.7MW, $\langle P\rangle_L$=1.4 atm, $\langle P\rangle_H$=1.6 atm

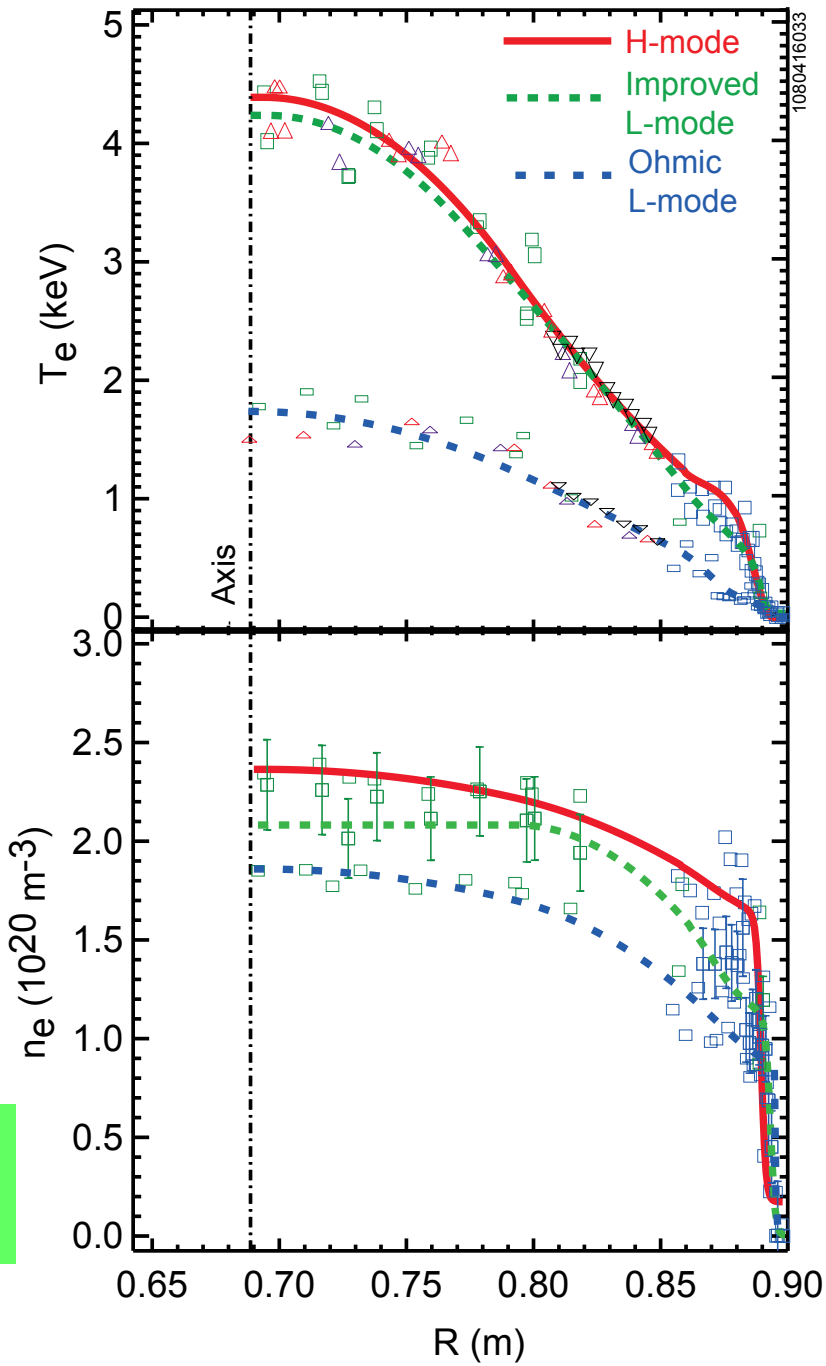


A. Hubbard, B. Lipschultz, D. Whyte

Improved L-mode: H-mode confinement with L-mode particle transport

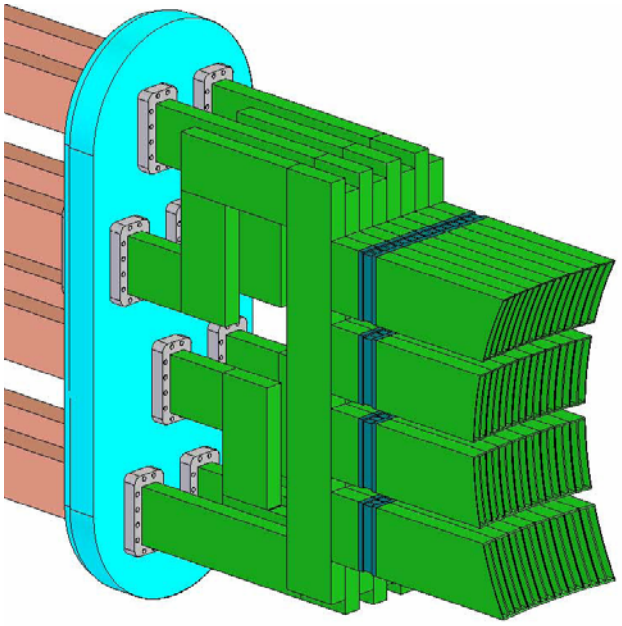
- Unfavorable ∇B drift direction; increased δ, I_p
  - Very high H-mode threshold (at least x3)
- H-mode confinement
  - (H-ITER-98y2 ~ 1)
- T_e barrier, little or no additional n_e barrier
  - No ELMs, no impurity accumulation
- Interesting potential as LHCD target for Advanced Scenarios

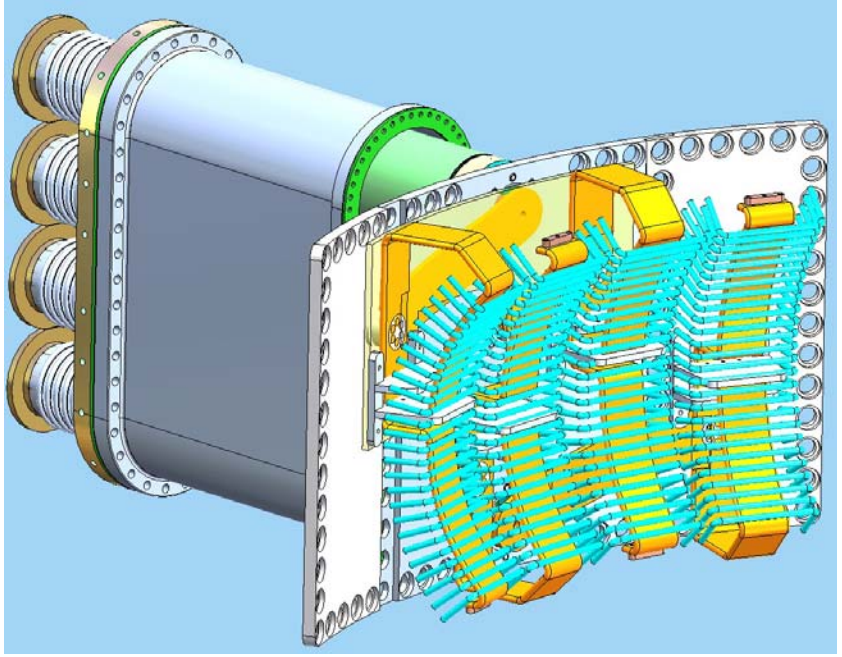
I_p=1.35MA, q_{95}=2.9, δ_u=0.6, P_{ICRF}=4.7MW, $\langle P \rangle_L$=1.4 atm, $\langle P \rangle_H$=1.6 atm



Facility Plans and Major Enhancements (2009-2013)

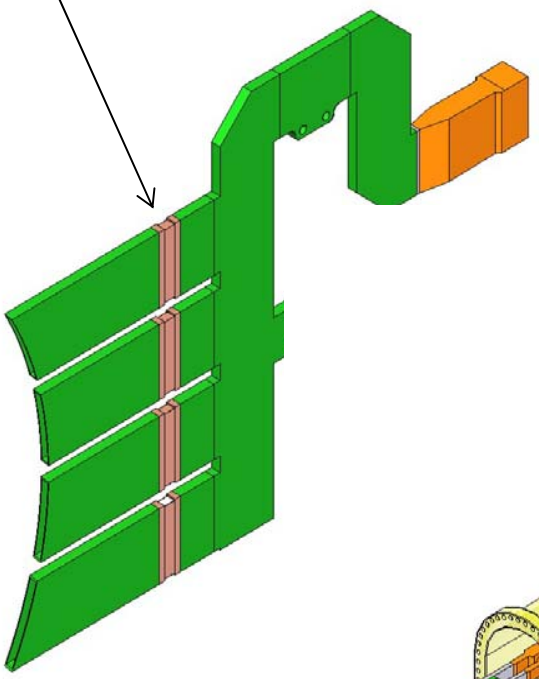
- Inspections: tokamak core and alternator/flywheel
  - insure facility reliability for at least the next 5 years
- Lower Hybrid upgrades
  - Add 1 MW source (to reach 4 MW)
  - add second launcher/coupler
  - new + spare klystrons
- ICRF upgrades
  - New 4-strap antennas (x2)
  - Fast-Ferrite Tuners for all 4 transmitters (real time adaptive tuning)
  - Power supply/control upgrades (improved reliability)
  - Tuneability (40 – 80 MHz) for 3rd and 4th transmitters



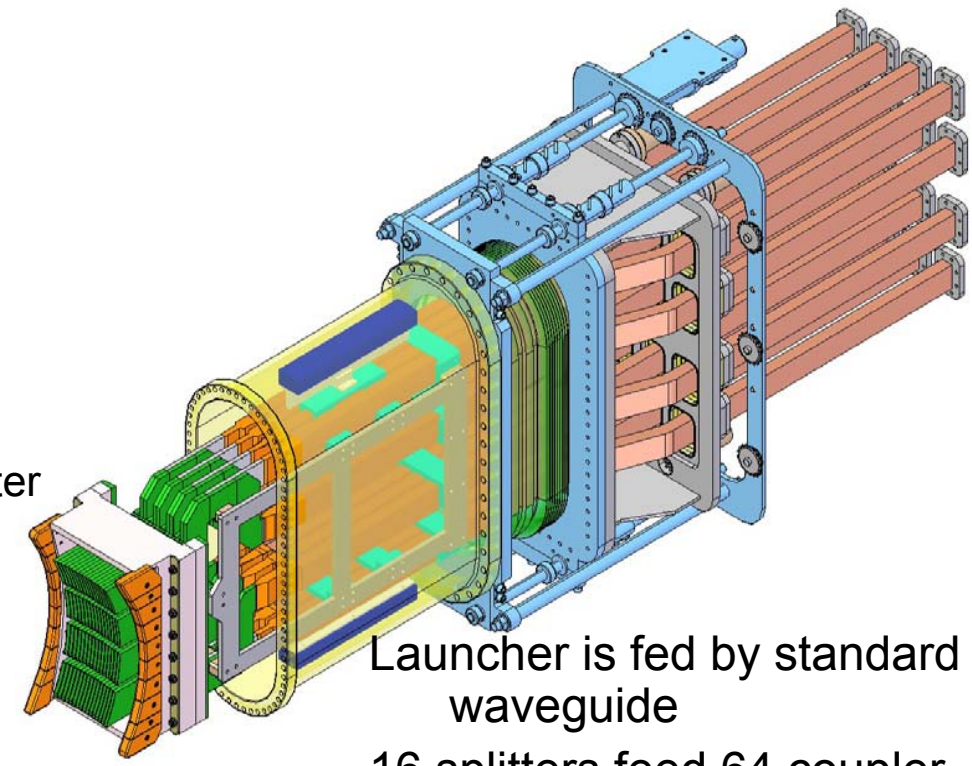


New Launcher minimizes length of narrow waveguide to reduce losses

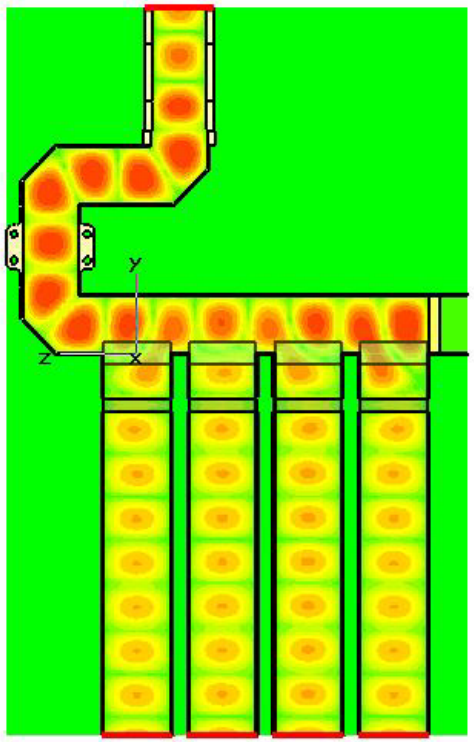
Individual vacuum windows



Compact 4-Way splitter



Simplified Splitter



Electric Field Distribution
In 4-Way Splitter

Launcher is fed by standard waveguide

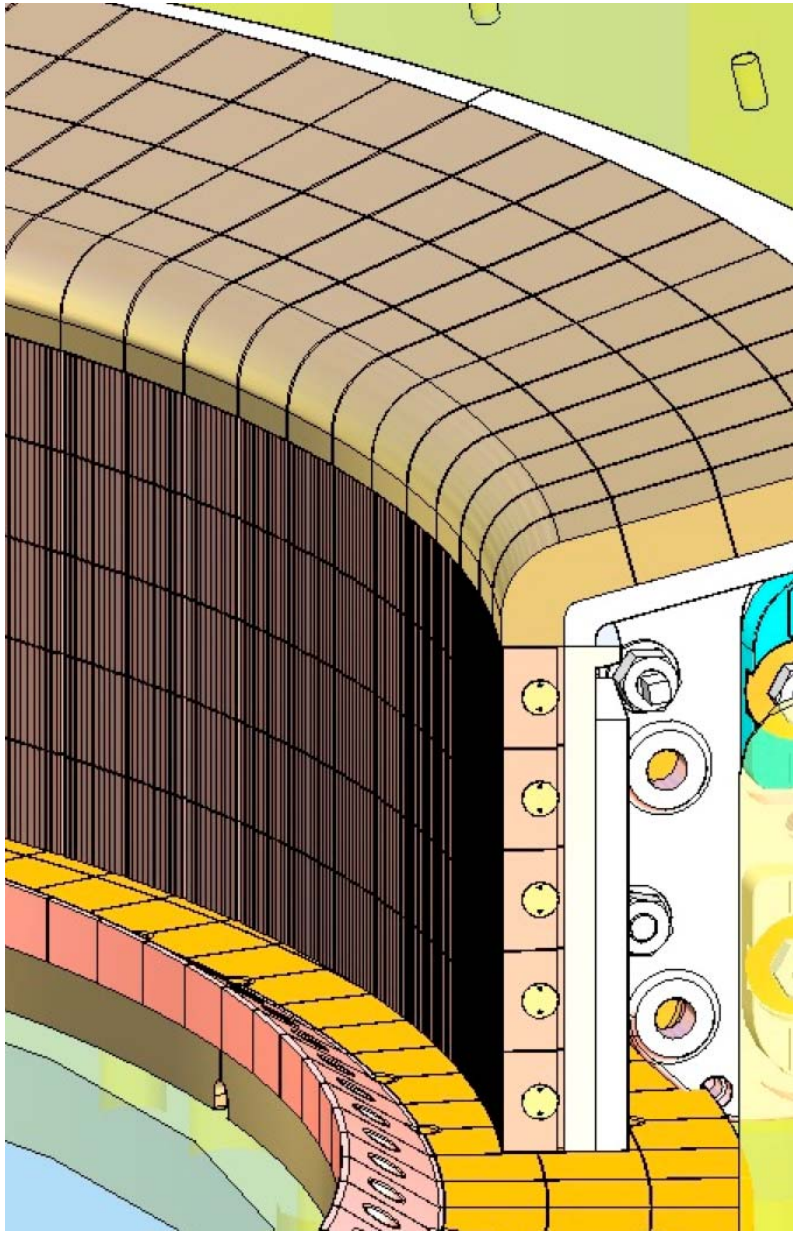
16 splitters feed 64 coupler waveguides

Window brazing greatly simplified (1 at a time, instead of 24 at once)

R. Parker, P. Koert, R. Vieira, R. Wilson

Facility Plans and Major Enhancements (cont'd)

- Outer divertor upgrade – DEMO-like divertor
  - Continuous vertical plate (higher power/energy handling)
  - Tungsten lamella plate design
  - Controlled temperature (≤ 600 ^{0}C)
    - Hydrogen isotope retention studies
- ECDC/Boronization upgrades [higher frequency, plasma density, better localization]
- Non-axisymmetric coil upgrade (increased toroidal mode number flexibility, resonant magnetic perturbation)
- Massively parallel computing cluster upgrade
- Magnet power supply upgrades (poloidal field)
  - Improved control at high current, high elongation, long pulse

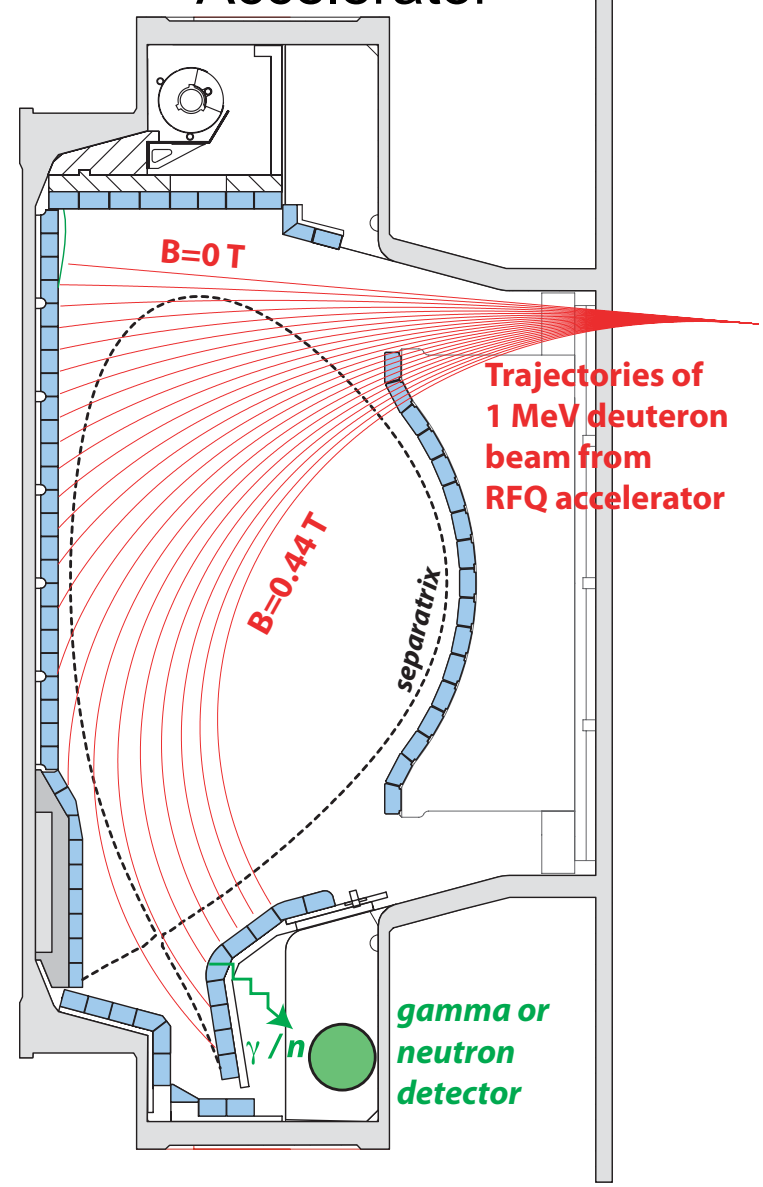


B. Labombard, B. Lipschultz., D. Whyte

Major Diagnostic Enhancements/Upgrades 2009-2013

- Polarimetry [j(r), n_e(r), magnetic fluctuations]
- DNB aperture [improved spatial resolution for beam-based diagnostics]
- MSE upgrade [more radial channels]
- Doppler reflectometry [fluctuations, flows]
- Heterodyne ECE upgrade [improved views]
- SOL Thomson scattering
- Compact Neutral Particle Analyzer [multiple chords]
- ICRF antenna reflectometer
- In-situ accelerator [first wall analysis]
- SPRED survey spectrometer
- Fast-ion loss detector
- IR camera upgrade [divertor heat loading]
- Gas puff imaging upgrades [edge fluctuations]
- Vertical viewing high harmonic ECE [LH-driven fast electrons]
- Synchrotron imaging [runaway electrons]
- CO_2 scattering [fluctuations, waves]

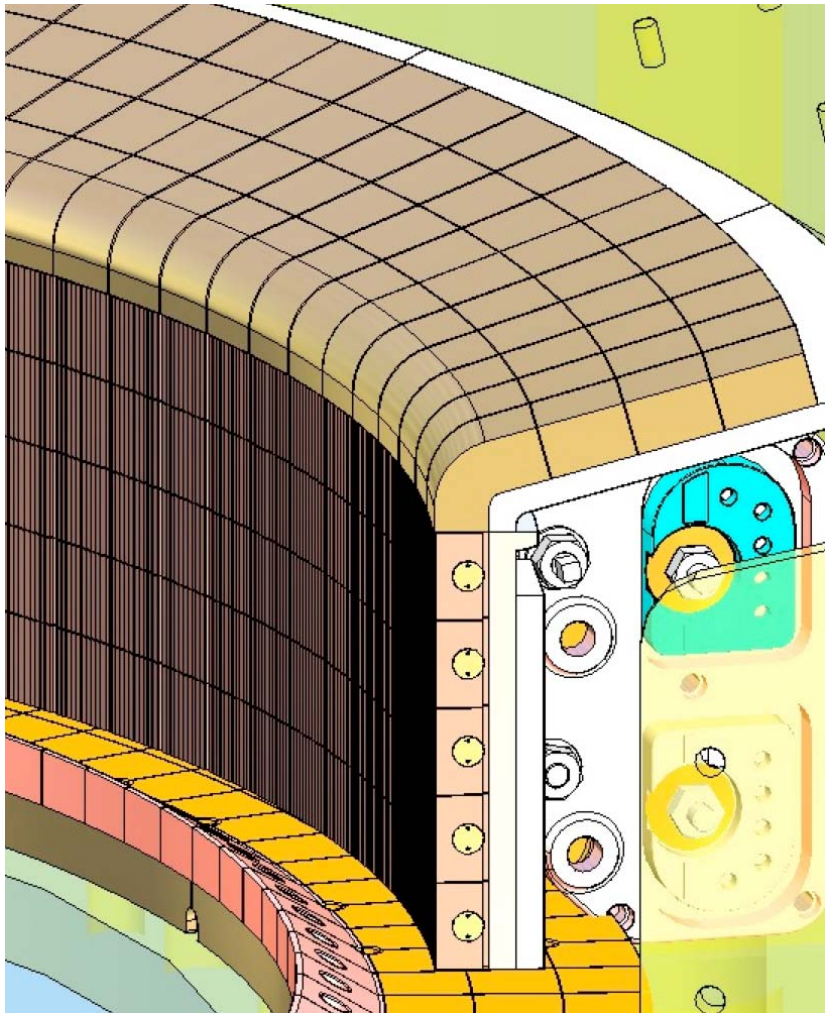
In-Situ Surface Analysis Accelerator

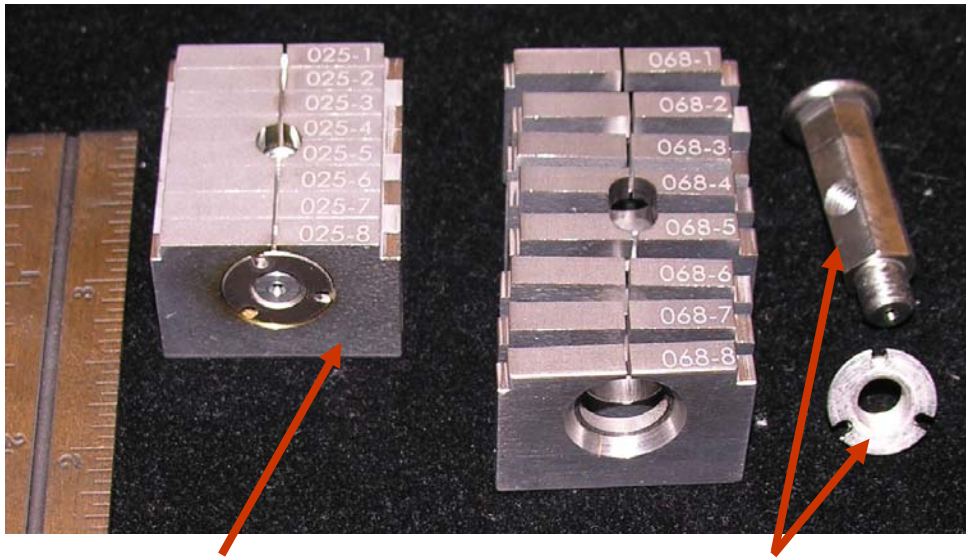


D. Whyte

DEMO-like divertor can directly address significant aspects of Gap G-9

- DEMO-Like Tungsten Divertor (600 ^{0}C) can actually address a significant part of Gap G-9: *Sufficient understanding of all plasma-wall interactions necessary to predict the environment for, and behavior of, plasma facing and other internal components for DEMO conditions*.
  - First investigations in a tokamak with actively heated high temperature metal plasma facing
  - Critical tests of plasma-wall interactions, hydrogenic retention
- Design, construction, installation (FY08-FY10)
- First operation, FY11



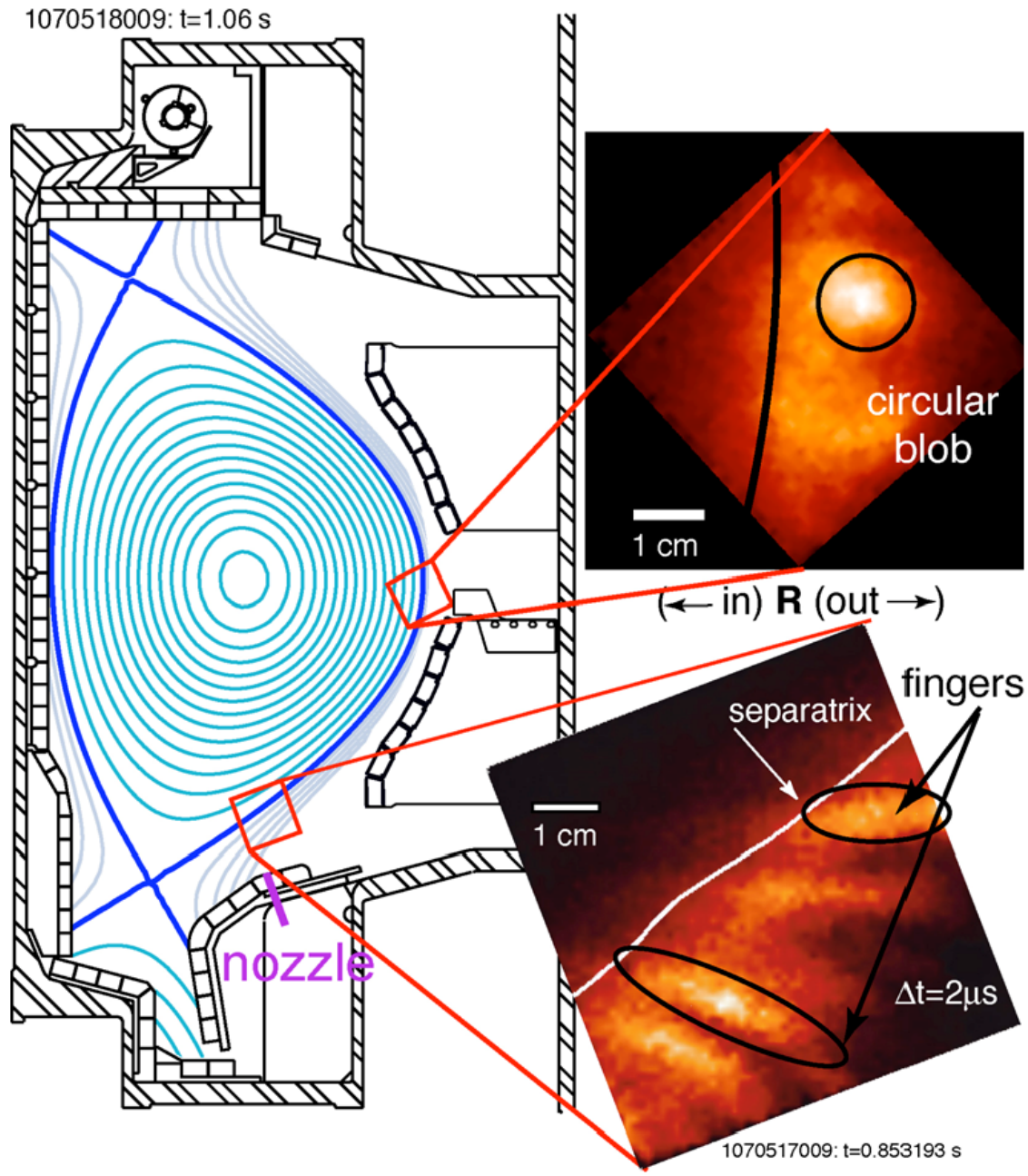


Assembled tungsten lamella tile as installed in C-Mod

Bolt and nut secure tiles and anchor to support plate

PPPL Collaboration: Major Themes

- Heating and Current Drive
  - Lower Hybrid Current Drive
  - ICRF heating and current drive
- Advanced plasma scenario development
- Edge turbulence
- Core turbulence
- Turbulence/Transport modeling, analysis
- Engineering support for LHCD, ICRF and diagnostic systems
- Diagnostic development:

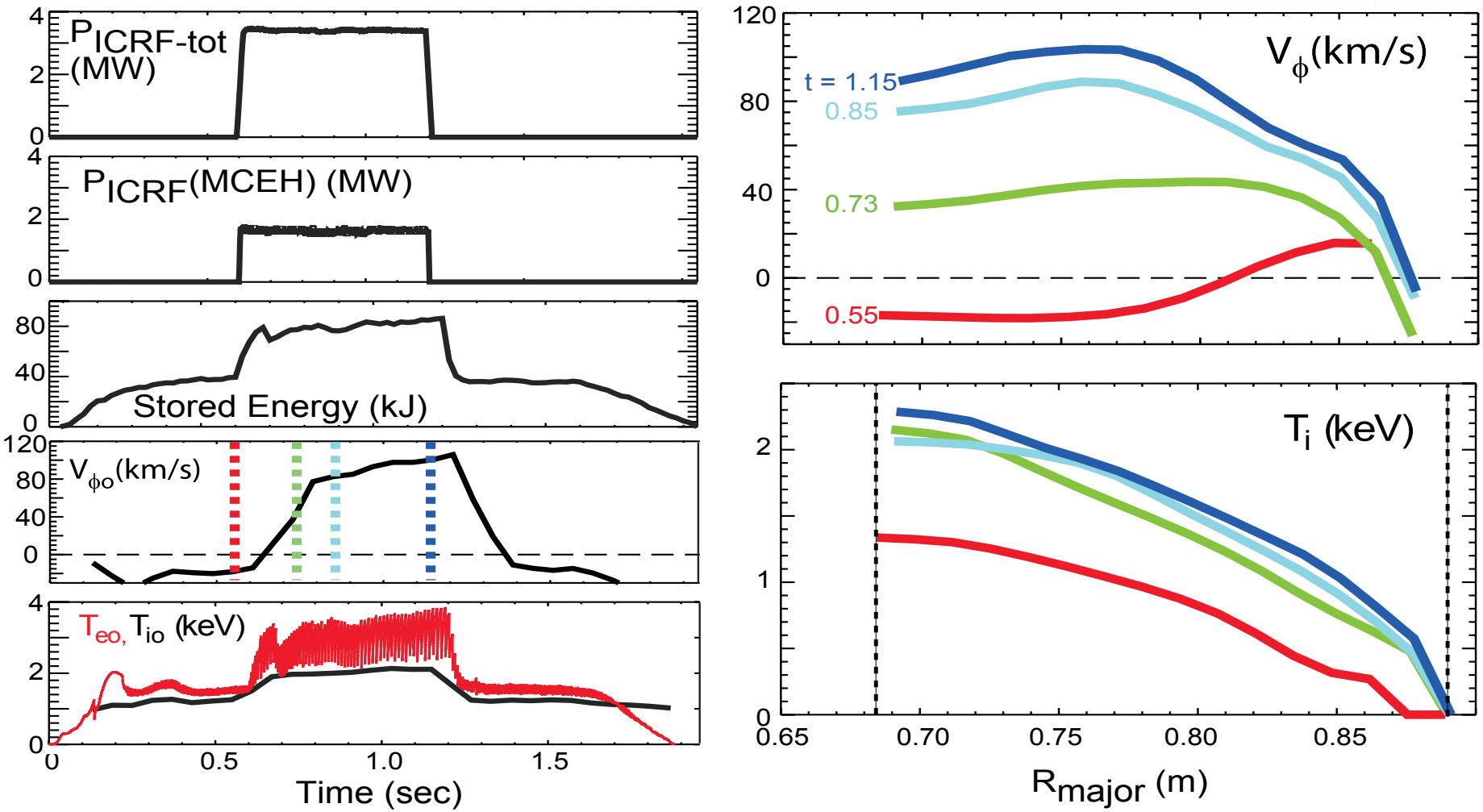


S. Zweben, J. Terry

PPPL Collaboration: Diagnostic Development

- High spectral resolution imaging X-ray spectrometer ($T_i(r)$, $V_\phi(r)$)
- Ultra high speed gas puff imaging (edge turbulence)
- MSE (current density profile)
- Swept-frequency reflectometry (fluctuation correlation)

Detailed Profile Evolution: Mode-Conversion Electron Heating



Summary

- Many exciting results from recent C-Mod investigations – and many more that I didn't have time to discuss:
  - Disruption mitigation
  - SOL transport, flows, turbulence
  - Pedestal stability, regulation, scaling, ELM regimes
  - H-mode threshold at low density
  - Error fields/locked modes, braking
  - Fast-particle-driven Alfven Eigenmode physics
  - Core energy and particle transport
  - Internal inductance control during ramp-up/ramp-down
- Significant upgrades planned in the coming few years
  - Both facility and diagnostics
- Increasing emphasis on integrated scenarios
  - ITER H-Mode baseline
  - Advanced scenarios looking toward fully non-inductive, steady-state