Recent Results on Coupling Fast Waves to High Performance Plasmas in DIII-D

by

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with

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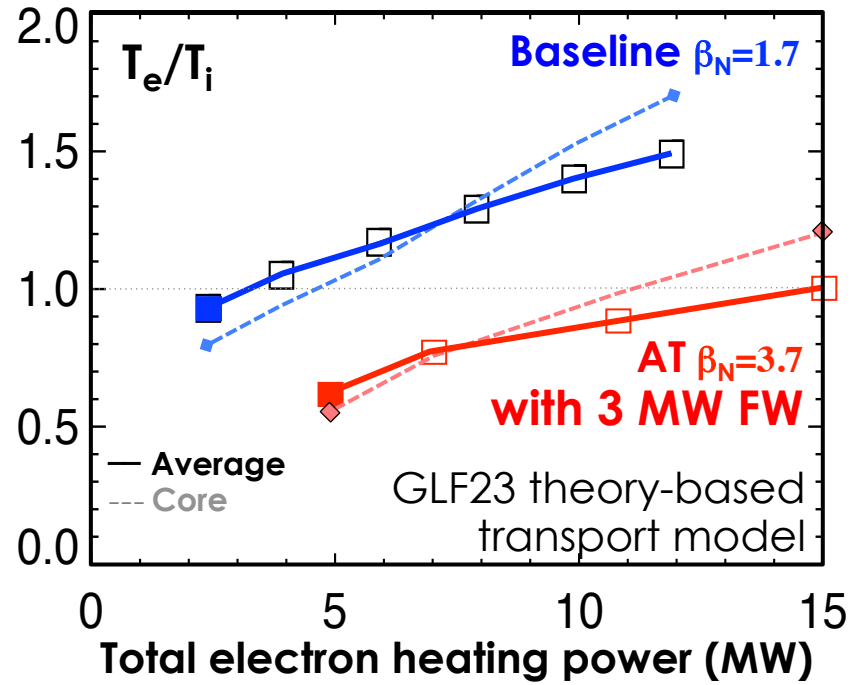
Introduction: applying Fast Wave power to Advanced Tokamak regimes

- **An important thrust in DIII-D program: Advanced Tokamak (AT) regimes with predominant electron heating (ITER, reactor relevant)**
- **Principal role of Fast Wave (FW) system going forward: complement EC system in synergistic way**



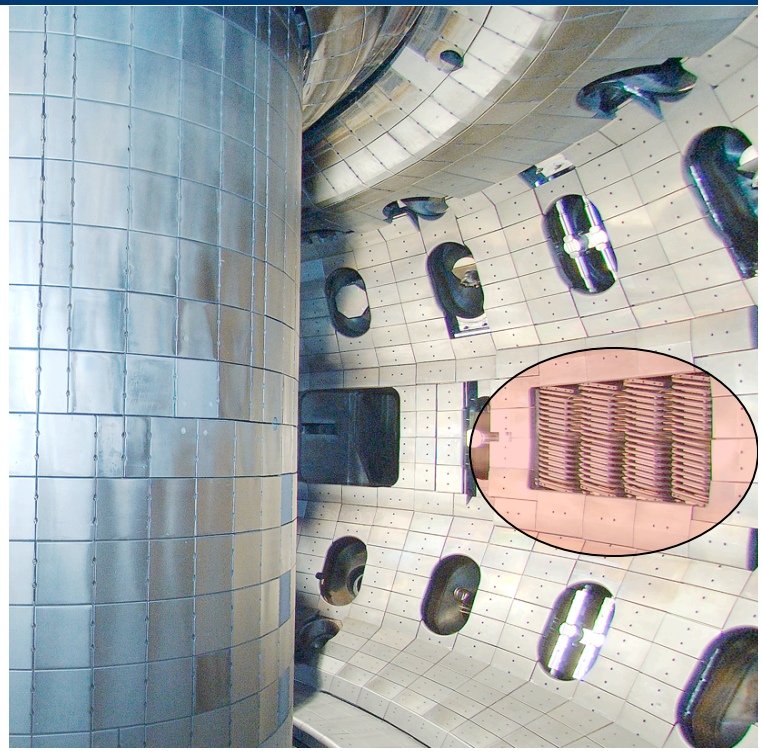
- **Key questions**
  - How much FW power can be coupled to these discharges with existing system?
  - What upgrades can be considered to increase coupled FW power?

Outline/summary

- Up to 1.5 MW of FW power successfully coupled to core of ELMing H-mode discharges with β_N ~ 2.5 with 7.5 MW of NBI + 1.5 MW of EC
- FW core electron heating efficiency similar to that of EC, as expected with very good first-pass FW absorption on core electrons (76%)
- Antenna loading in agreement with modeling using measured edge density profiles
- Local D_2 puffing is studied as a means of increasing the loading and hence the coupled power
- Gas puffing and other techniques to increase the antenna loading are evaluated: effect on core plasma performance
- Projection of the coupled FW power levels towards 3 MW goal

DIII-D Fast Wave hardware

- 3 antenna arrays of two designs, located in the 285/300 (60 MHz) and 0 deg and 180 deg (both 90 MHz in these experiments) midplane ports
- 285/300 ~ 1 m wide, 0.5 m high
- 0 deg, 180 deg ~ 0.8 m wide, 0.4 m high
- All three 4-element arrays operated in 90 degree toroidal phasing, using decoupler
- 0, 180 deg use conventional tuning network, while 285/300 uses tunerless arrangement; both load-resilient at 90 deg phasing



- All three antennas operate up to ~20-25 kV peak system voltage – this sets the limit of the total power that can be coupled for a given loading

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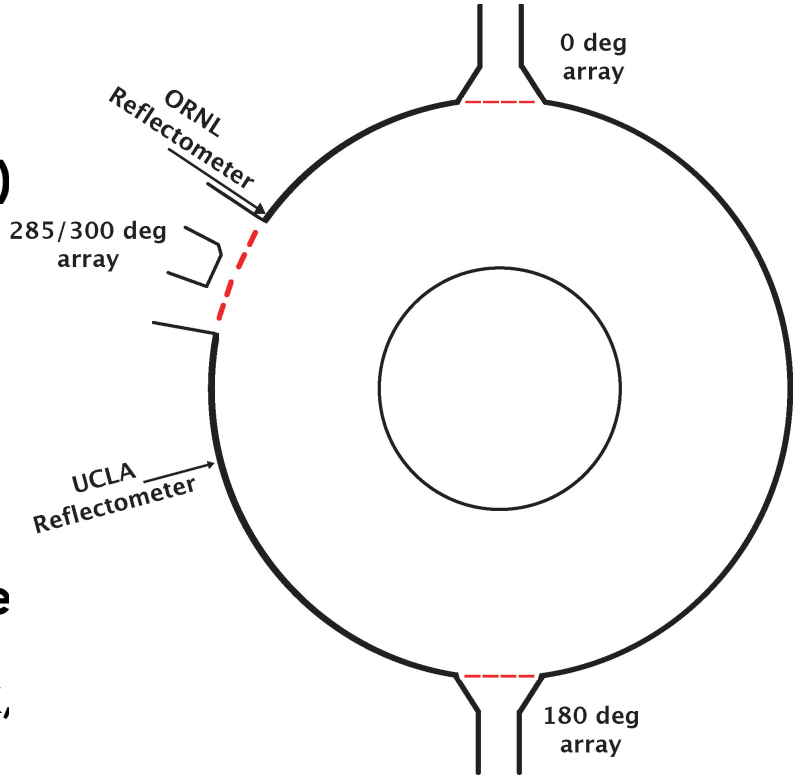


- All three antennas operate up to ~20-25 kV peak system voltage – this sets the limit of the total power that can be coupled for a given loading

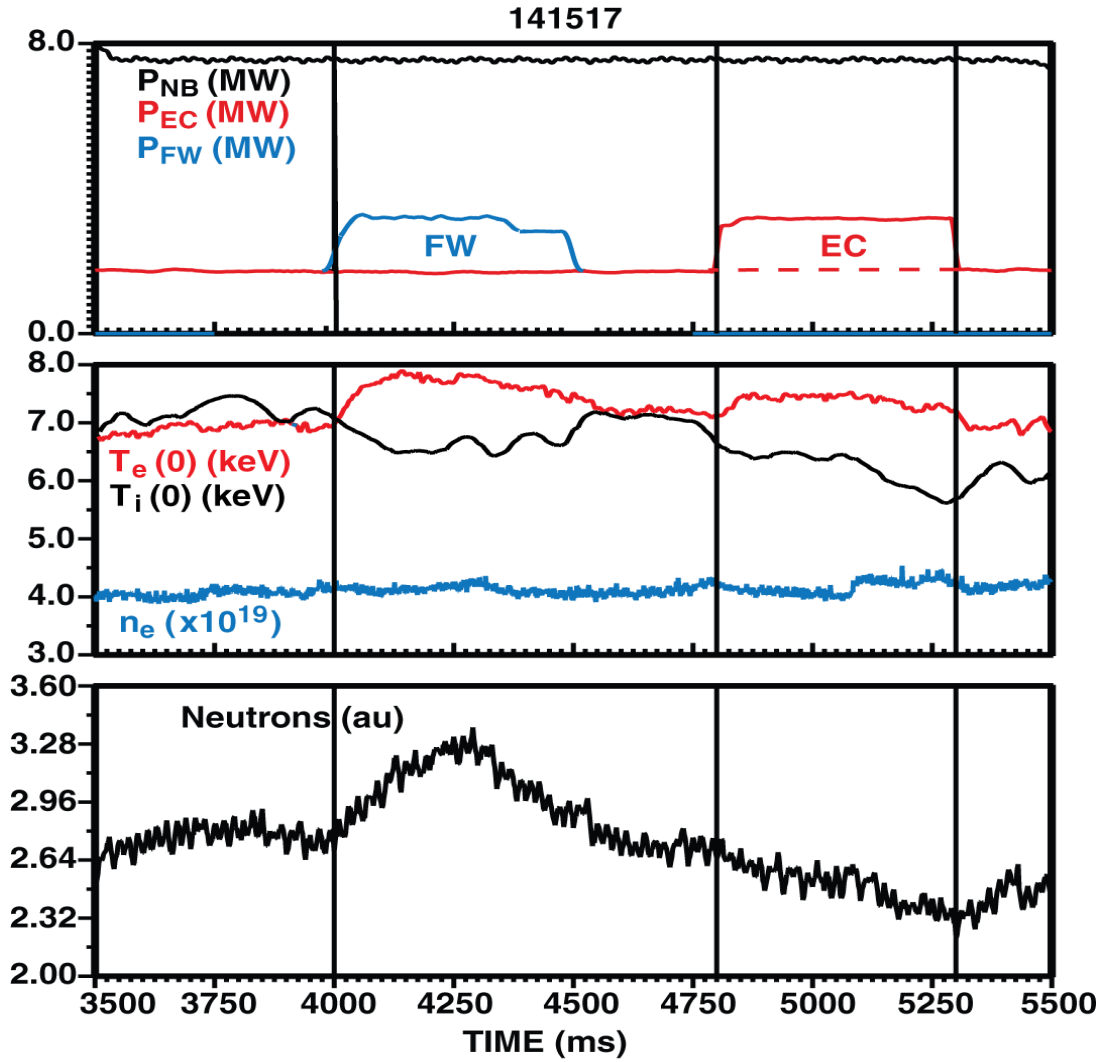
FW core absorption efficiency similar to EC at 1.5 MW level in Advanced Inductive discharge: η_{abs}~100%

Comparison is on top of 7.5 MW beams, 1.5 MW EC – predicted increment in total stored energy <6% - within noise (ELMing, etc.)

- **Either form of electron heating comparably raises $T_e(0)/T_i(0)$, FW more**
  - EC is at ρ = 0.25
  - FW deposition is more central

FW increases beam-target neutron rate through damping on beam ions

β_N~2.6



Why multi-pass absorption η_{abs} ~100%: 76% first-pass absorption in core, so multi-bounce edge losses should be small

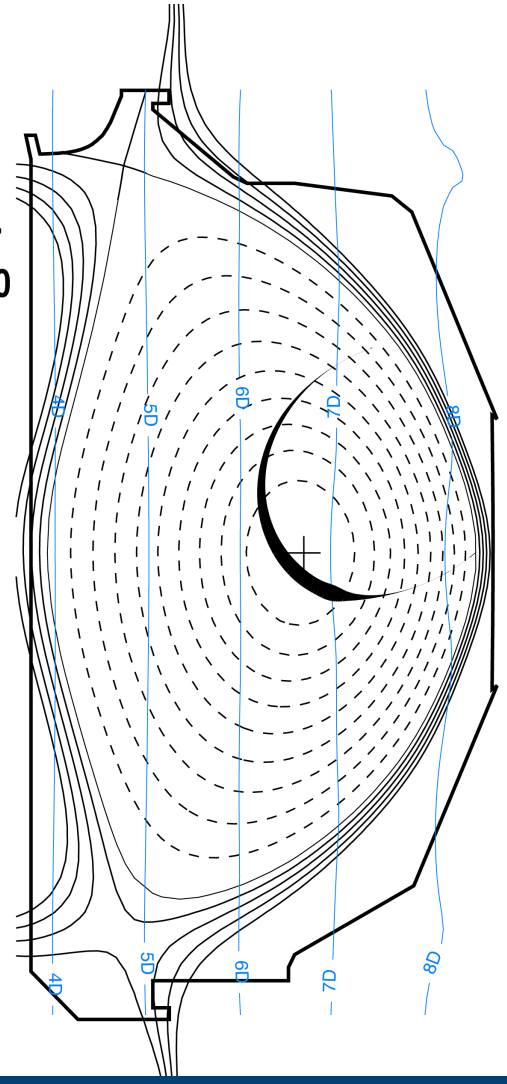
- $$\eta_{abs} = \frac{\left\langle \eta_{core}^{one-pass} \right\rangle}{\left\langle \eta_{core}^{one-pass} \right\rangle + \left\langle \eta_{edge}^{one-bounce} \right\rangle}$$

- In AI discharges, FW approaches the 'promised land' of high first-pass absorption

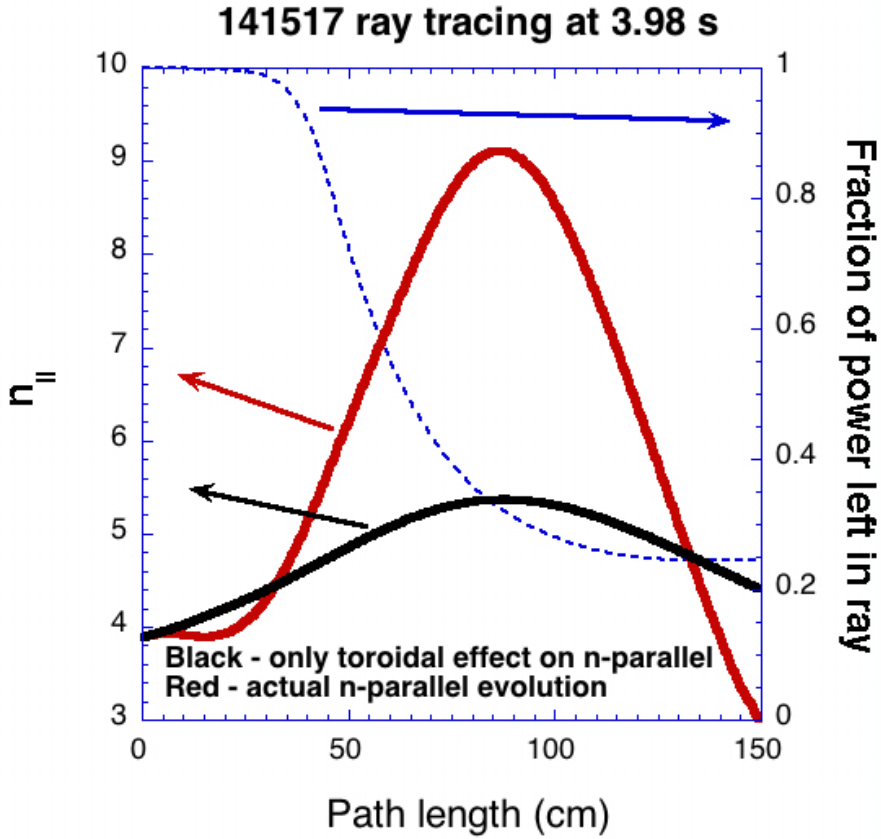
- Only 'prompt' edge losses should be important in this regime; cf. NSTX HHFW case

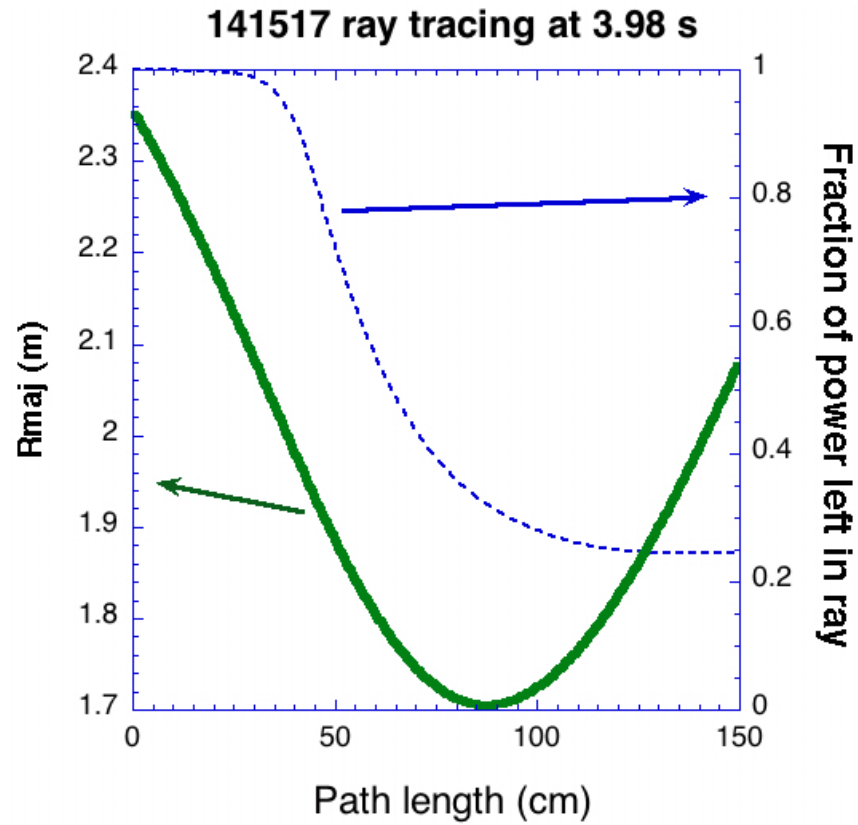
Shot 141517
time 3980.00

First-pass absorption on electrons:
76%



How can first-pass absorption be so high? Answer: significant $n_{||}$ upshift of the whistler-like wave





- **Angle between group velocity and static magnetic field is ~20 degrees (classic whistler characteristic)**
- **Ray path somewhat like resonance cone trajectory of slow wave in LH regime**

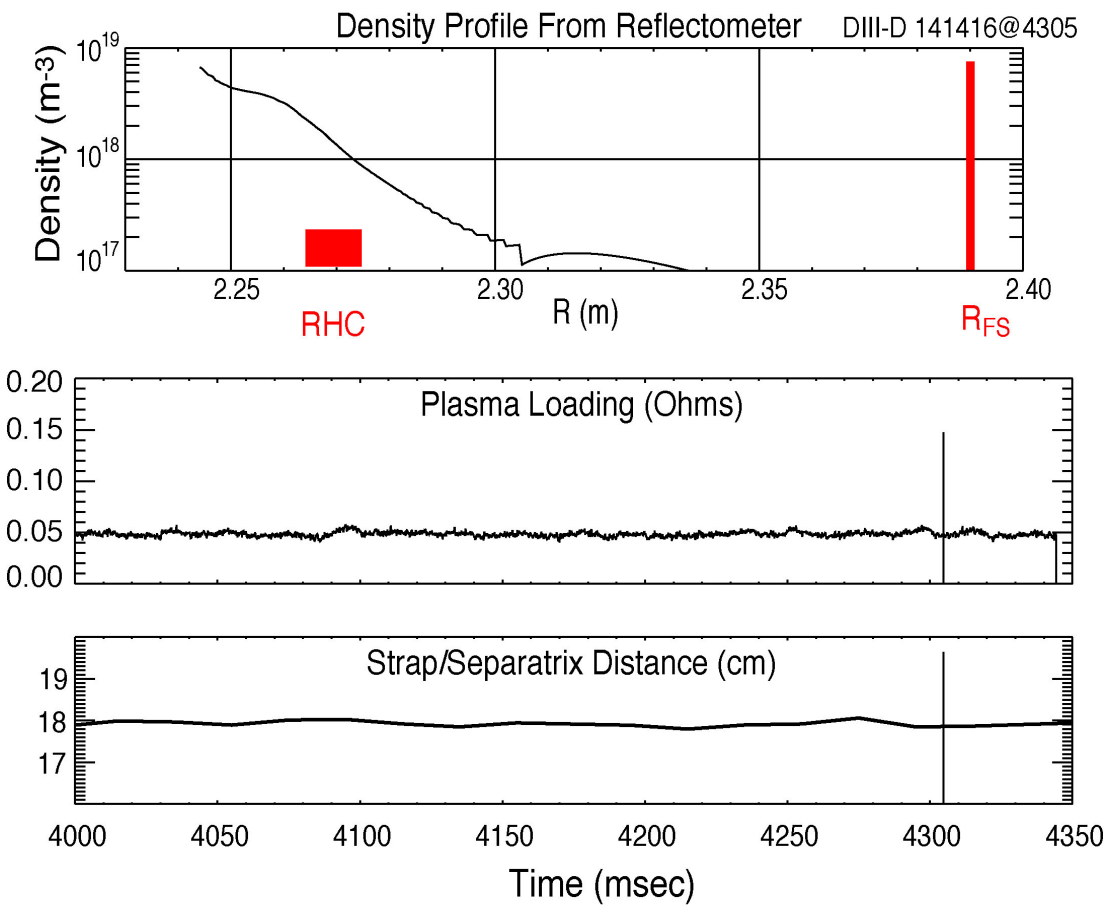
To increase coupled FW power, antenna loading in AI regime must be increased

$$P_{coupled} \propto \left(\frac{V_{\max}}{Z_0} \right)^2 R_L$$

- **Coupled FW power at fixed antenna voltage scales directly as loading resistance R_L**
- **R_L determined by density profile adjacent to the antenna surface and other edge parameters**
- **In AT regimes, confinement is also sensitive to edge parameters**
  - If edge is changed to increase loading but confinement significantly degraded by the change, no net gain
- **Goal: find techniques to enhance antenna loading with acceptable effect on confinement**

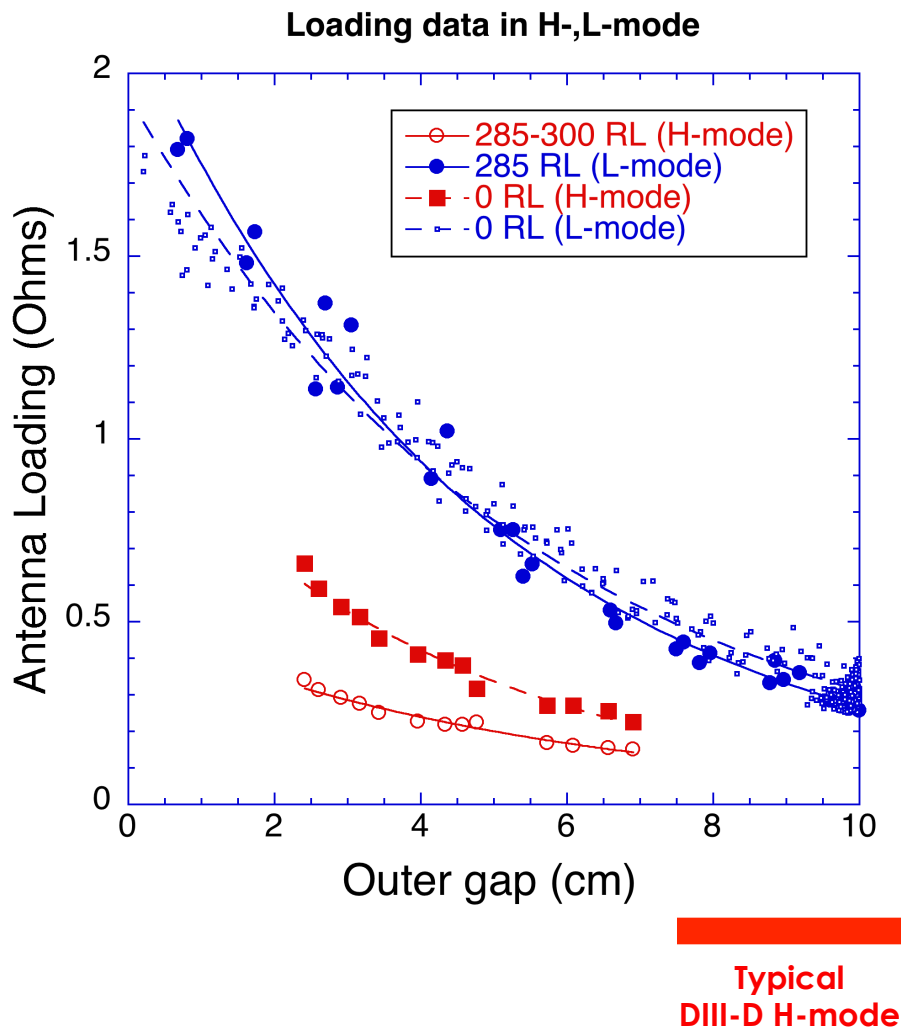
"Natural" R_L can be very small in high-confinement regimes, as in Quiescent H-mode case from DIII-D

- **Low R_L is due to large distance from antenna to right-hand cutoff (critical density for FWs): ~ 0.2 m**
- **Low R_L means that to couple 1 MW in this case would require V_{max}~ 80 kV**
  - Almost double maximum allowed for ITER
  - ~ 3 times higher than the existing DIII-D antenna can sustain

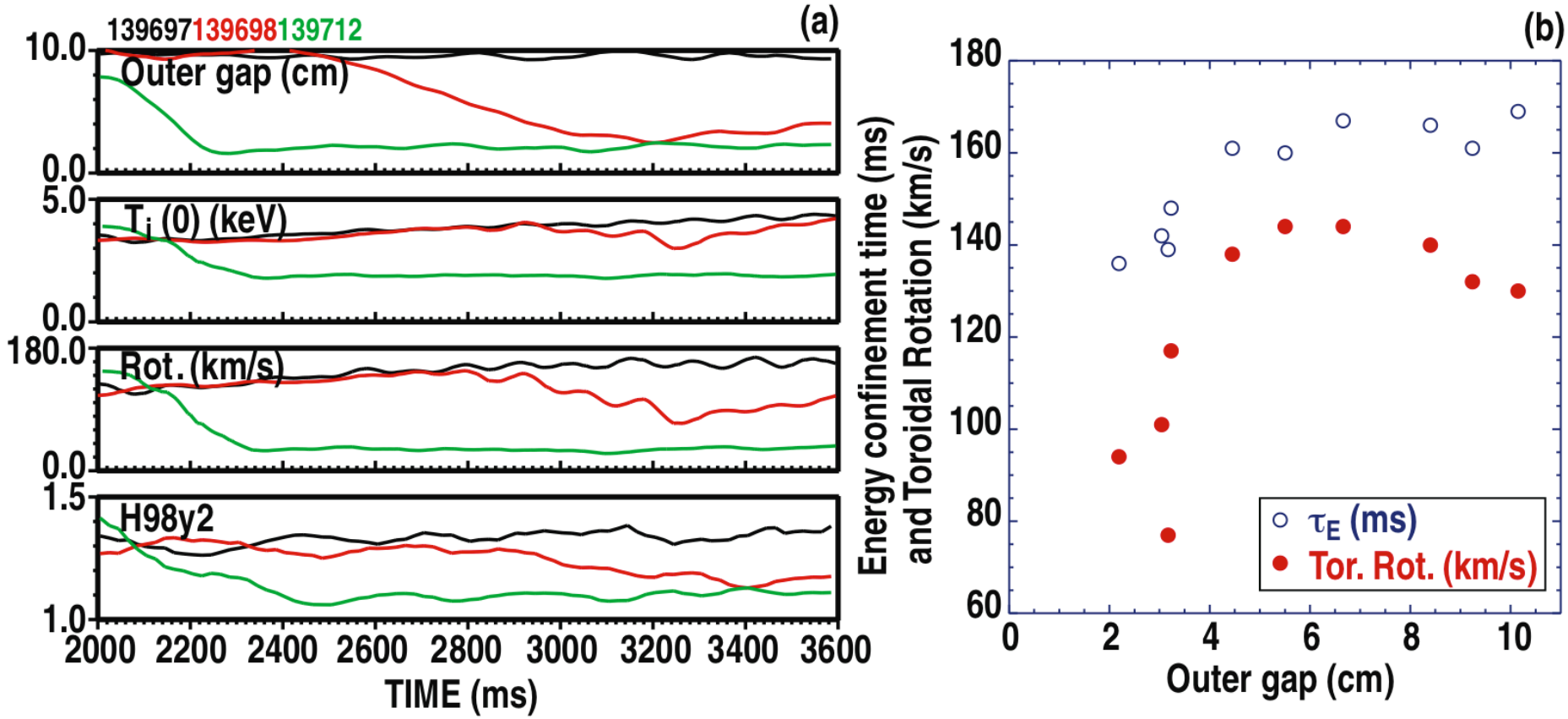


Loading increases exponentially as plasma/antenna gap is reduced; upgraded limiters enable smaller gap, higher R_L

- Surest way to raise R_L: reduce outer gap
- DIII-D could not run gaps < 6 cm with high power NBI up to mid-2009 (overheating)
- Replaced graphite limiter tiles with CFC (8/09)
- Now run 4 cm outer gap or smaller at ~8 MW of NBI successfully

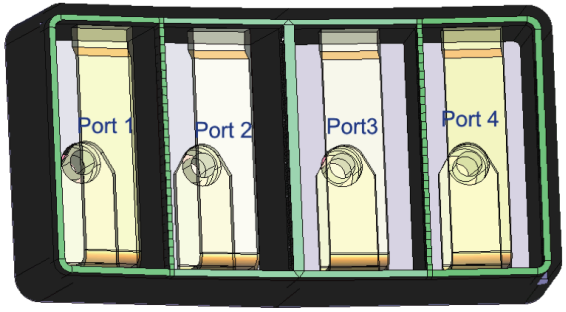


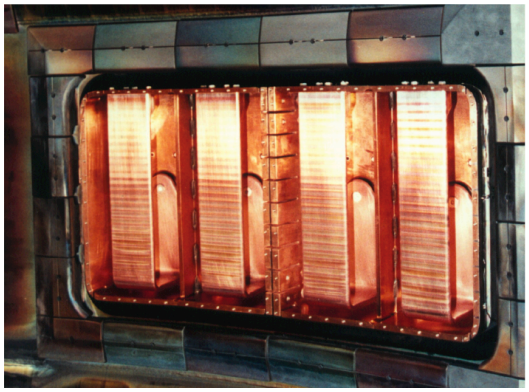
Price of too small outer gap in AI – precipitous drop in rotation, confinement (ion channel?) at gap < 4 cm

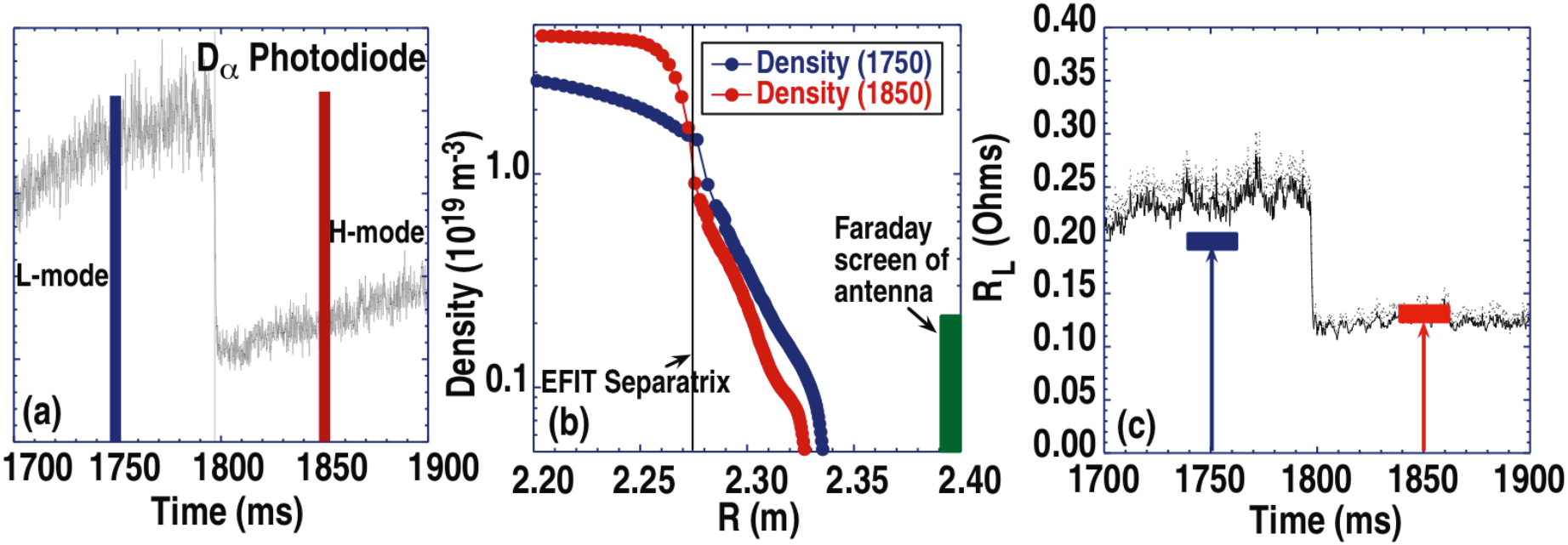


- **Subsequent experiments maintained at least 4 cm outer gap**

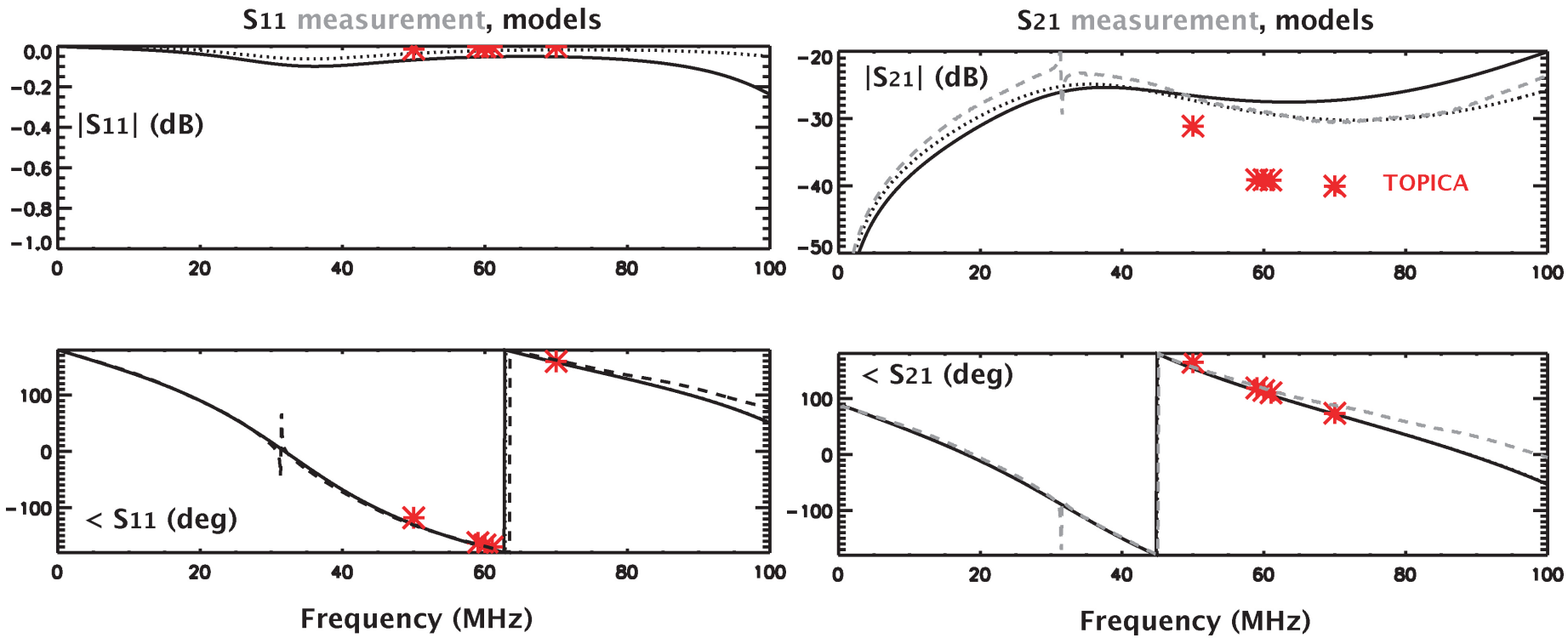
R_L agrees with TOPICA code using measured edge density profiles from reflectometers in L- and H-mode







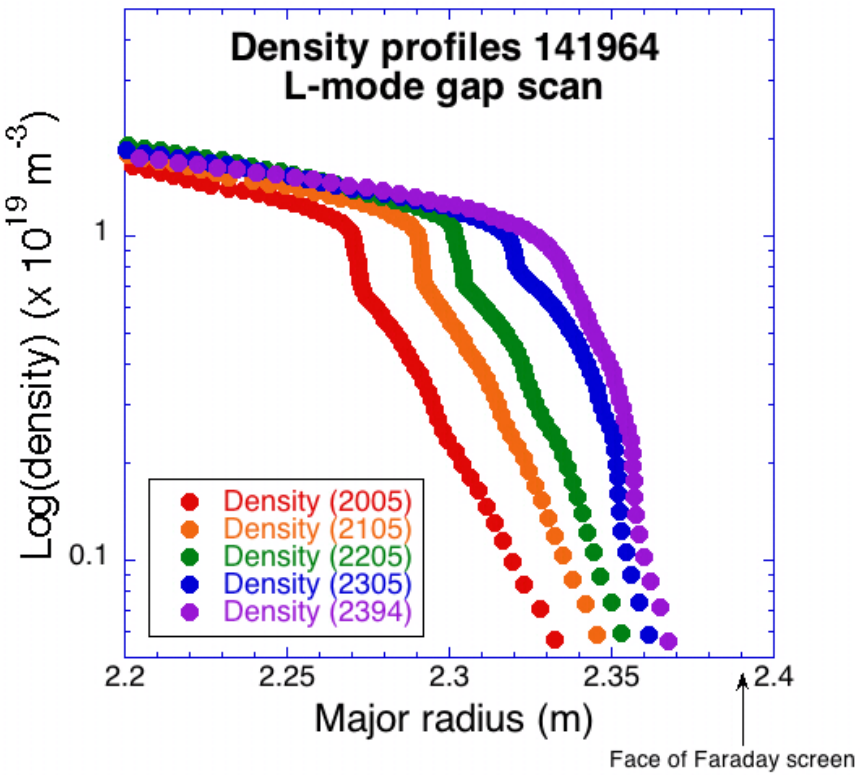
For detailed comparisons between TOPICA and experimental data, full model of feed system, diagnostics was implemented



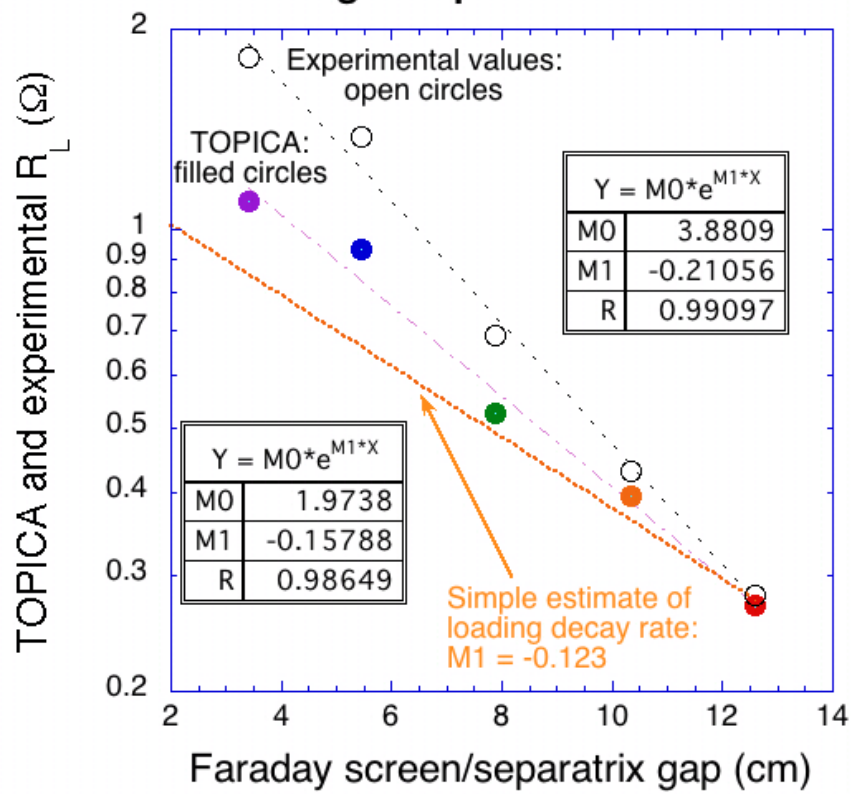
- **Example comparing measurements on the unloaded 285/300 antenna and TOPICA:**
  - TOPICA gets the electrical properties of the strap right, underestimates strap/strap coupling – but this appears to be due to an error in CAD model of antenna, which is being corrected (6/11)

Edge density profiles measured with reflectometers used in TOPICA modeling of loading in gap scans in L- and H-mode

UCLA Reflectometer plus Thomson



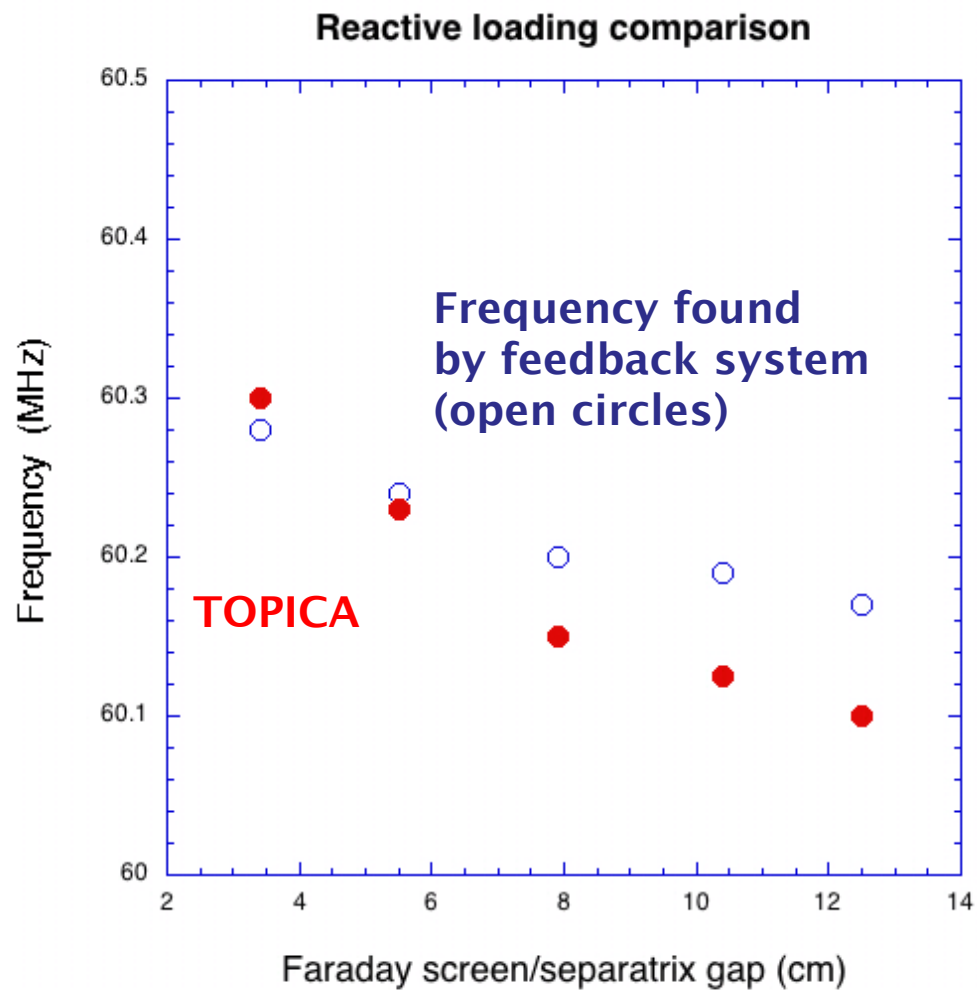
Loading comparison in L-mode



- **TOPICA in good agreement with data at large gap**
- **Rate of decay with gap is faster than simple expectation**

TOPICA predicts not only resistive loading, but also plasma-induced changes in self- and mutual reactances of antennas

- Changes in self-reactance as gap is scanned in L-mode predicted by TOPICA are compared with measured changes in resonant frequencies of transmission line loops (feedback system)
- Good agreement observed at small gaps

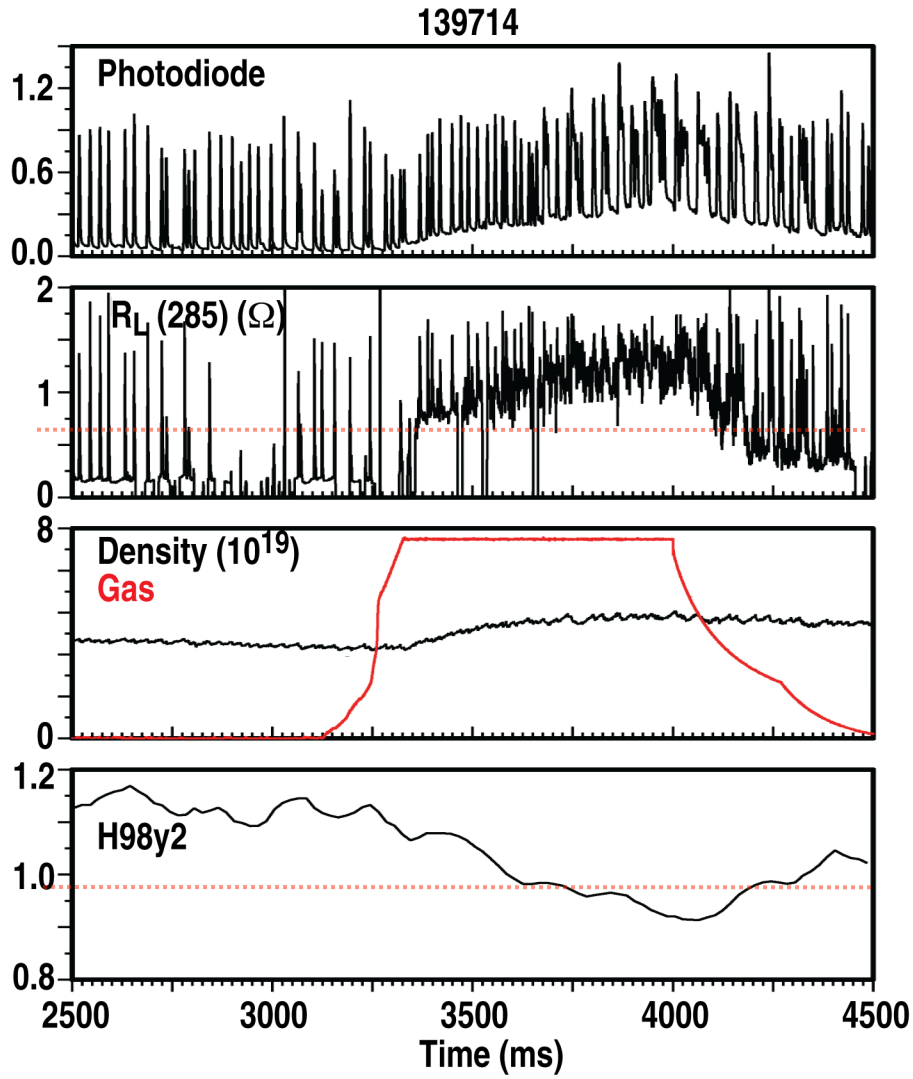


Key coupling physics: what part of low loading in H-mode is due to "index mismatching" effect vs. evanescence?

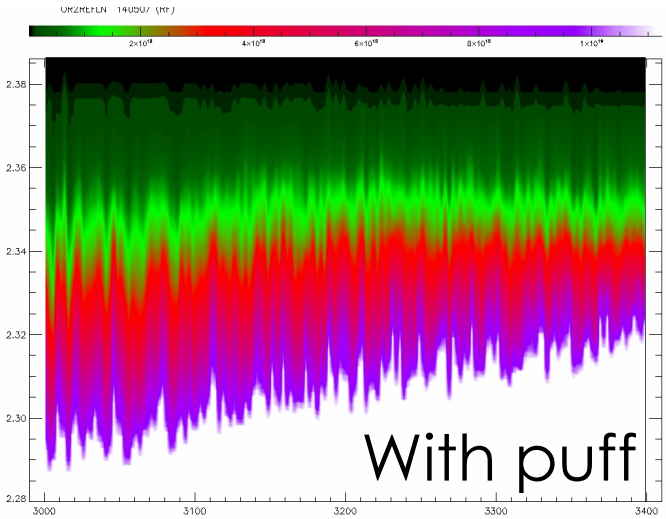
- Bilato, et al. showed that decay rate of R_L as distance of RHC to antenna should be slower than simplest estimate based on vacuum evanescence
- Experiment seems to show significantly more rapid decay rate with gap than even conservative simple estimate
- TOPICA decay rate is intermediate – not as rapid as experiment, but more rapid than simple estimate
- Role of 'index mismatching' (or impedance matching) effect is being evaluated

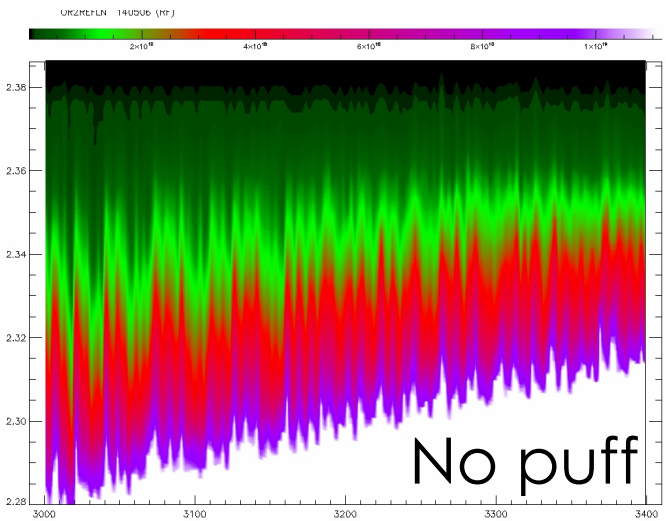
Gas puffing increased loading by up to a factor of six in some H-mode regimes

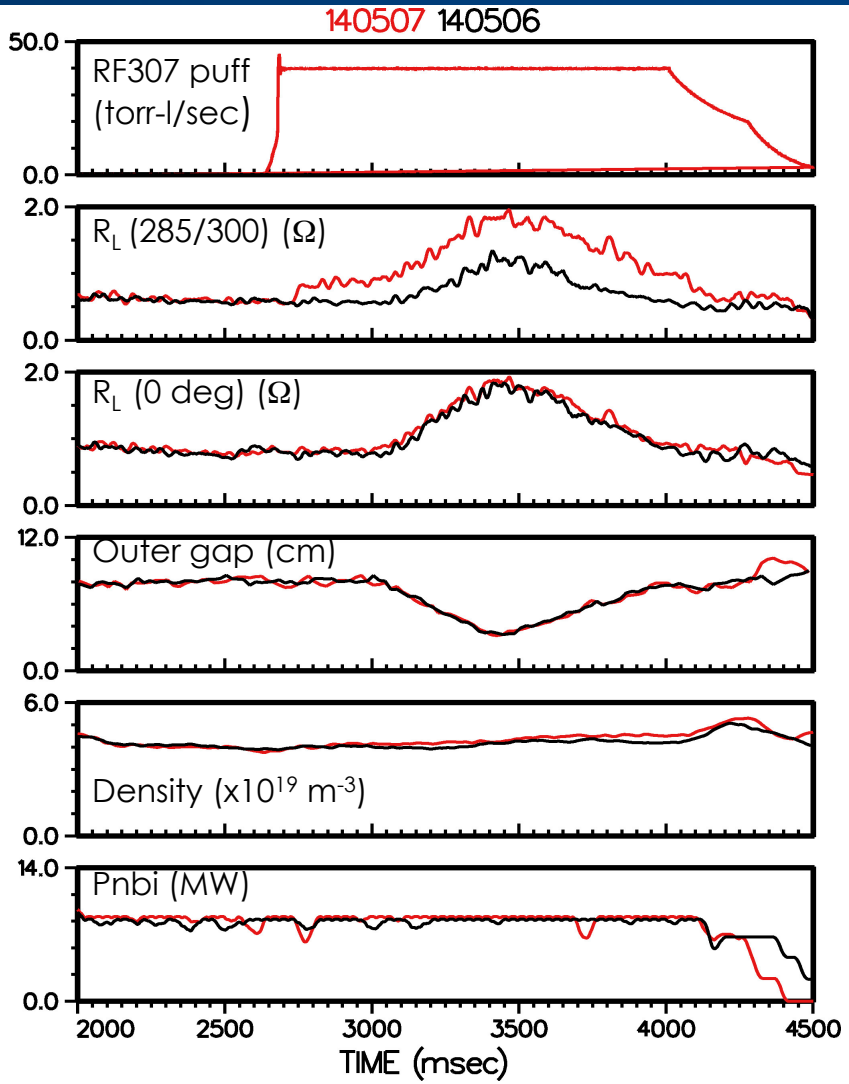
- Gas puffing installed near 285/300 antenna; used in AI experiments to raise loading
- Increase of a factor of 6 in loading between ELMs, from 0.17 Ω to ~1 Ω
- Costs: increased density, decrease in confinement (H98 from 1.1 to 0.9)
- Far SOL density also can be increased without puffing by adjusting shape (balance of pumping, ELMs)
- Acceptable performance obtained at loading that will allow ~2.5 MW of FW power with 65-70% first-pass absorption on electrons



ORNL reflectometer used to study effect of local vs. global puffing on edge density profile in ELMing H-mode

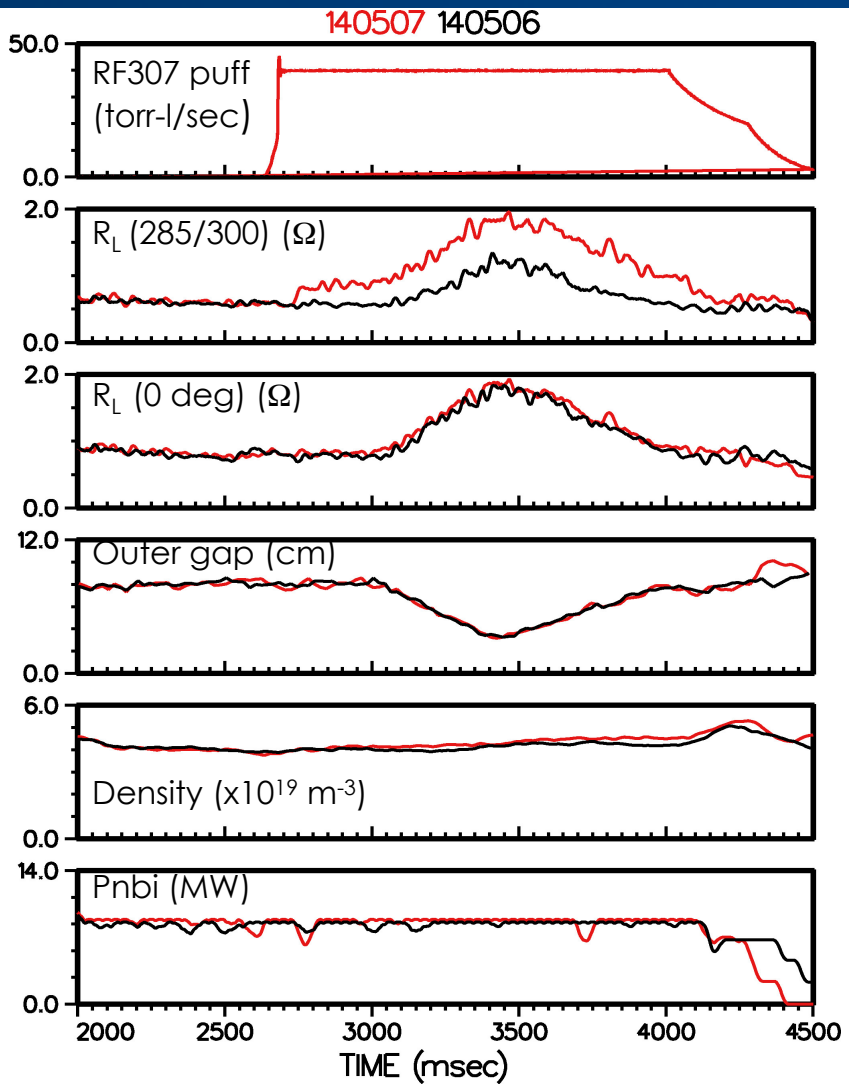






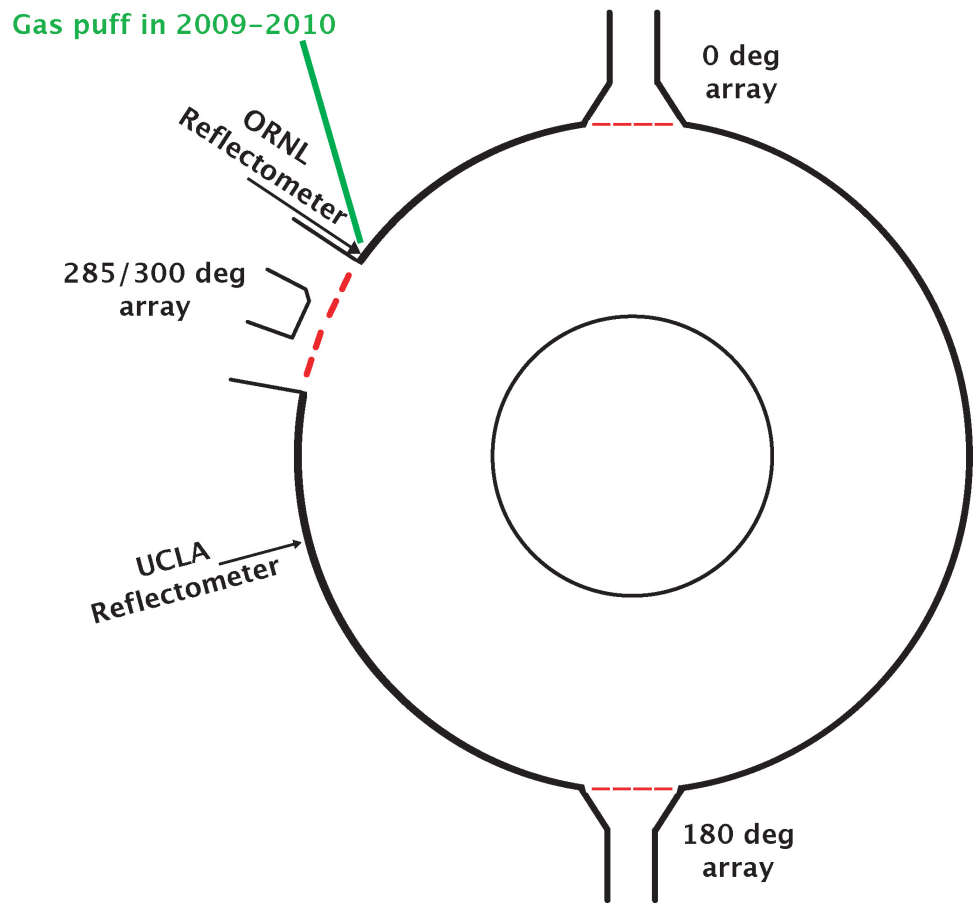
ORNL reflectometer used to study effect of local vs. global puffing on edge density profile in ELMing H-mode

- **Antenna with local puffing shows strong increase in loading, measured at very low power (0.1 kW), while distant array shows no effect of puffing (at 50 kW)**
- **Need to check FW power dependence of effect in this case**



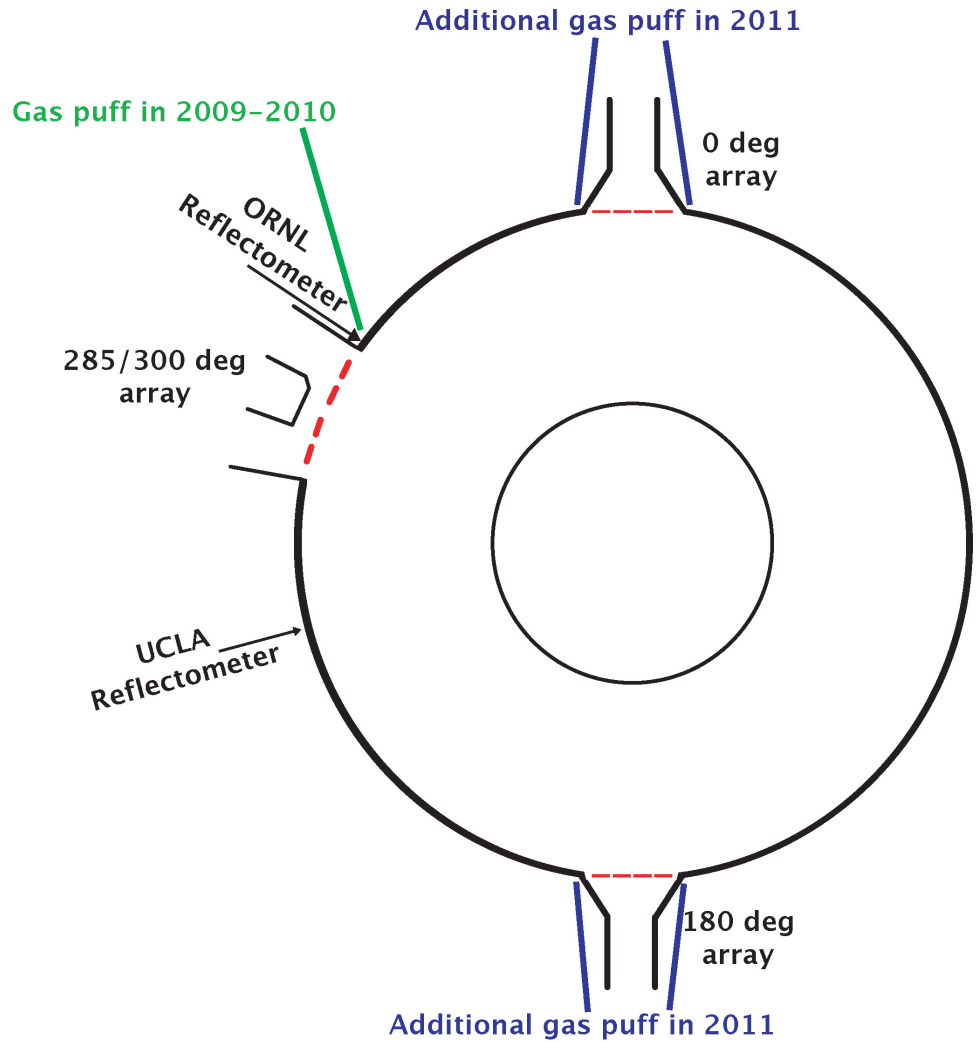
Extension of gas puffing experiments in 2011

- A key question for gas puffing experiments to control antenna loading: what part of the effect is local vs. global?
- To address this point, compare gas puffing near antenna with remote puffing



Extension of gas puffing experiments in 2011

- A key question for gas puffing experiments to control antenna loading: what part of the effect is local vs. global?
- To address this point, compare gas puffing near antenna with remote puffing
- Add local puffing orifices at either side of both 0 deg and 180 deg arrays
- Experiment this summer



Projection to 2011 experiments — higher FW power will be coupled to AI/AT discharges

- **Optimization of existing discharges already should yield core coupled FW power ~2.5 MW at acceptable voltage**
- **All three antennas have been moved to ~1 cm smaller R**
  - At fixed outer gap, loading and power should increase by at least 20% from this change alone
- **Technical improvements in arc detection/ELM discrimination should allow further increase of power in this regime**
- **Goal is demonstration of >3 MW of FW power coupled to core of AT discharge in 2011**

Summary and conclusions

- Up to 1.5 MW of FW power successfully coupled to core of ELMing H-mode discharges with β_N ~ 2.5 with 7.5 MW NBI + 1.5 MW of EC
- FW core electron heating efficiency similar to that of EC, as expected with very good first-pass FW absorption on core electrons (76%), resulting from high β_e and $n_{||}$ upshift
- Antenna loading in agreement with modeling using measured edge density profiles – detailed studies ongoing
- Local D_2 puffing can increase coupled power, but with significant effects on performance
- Advanced regimes consistent with good performance found that will allow ~2.5 MW of coupled FW power
- Incremental improvements should allow achievement of the 3 MW goal in 2011