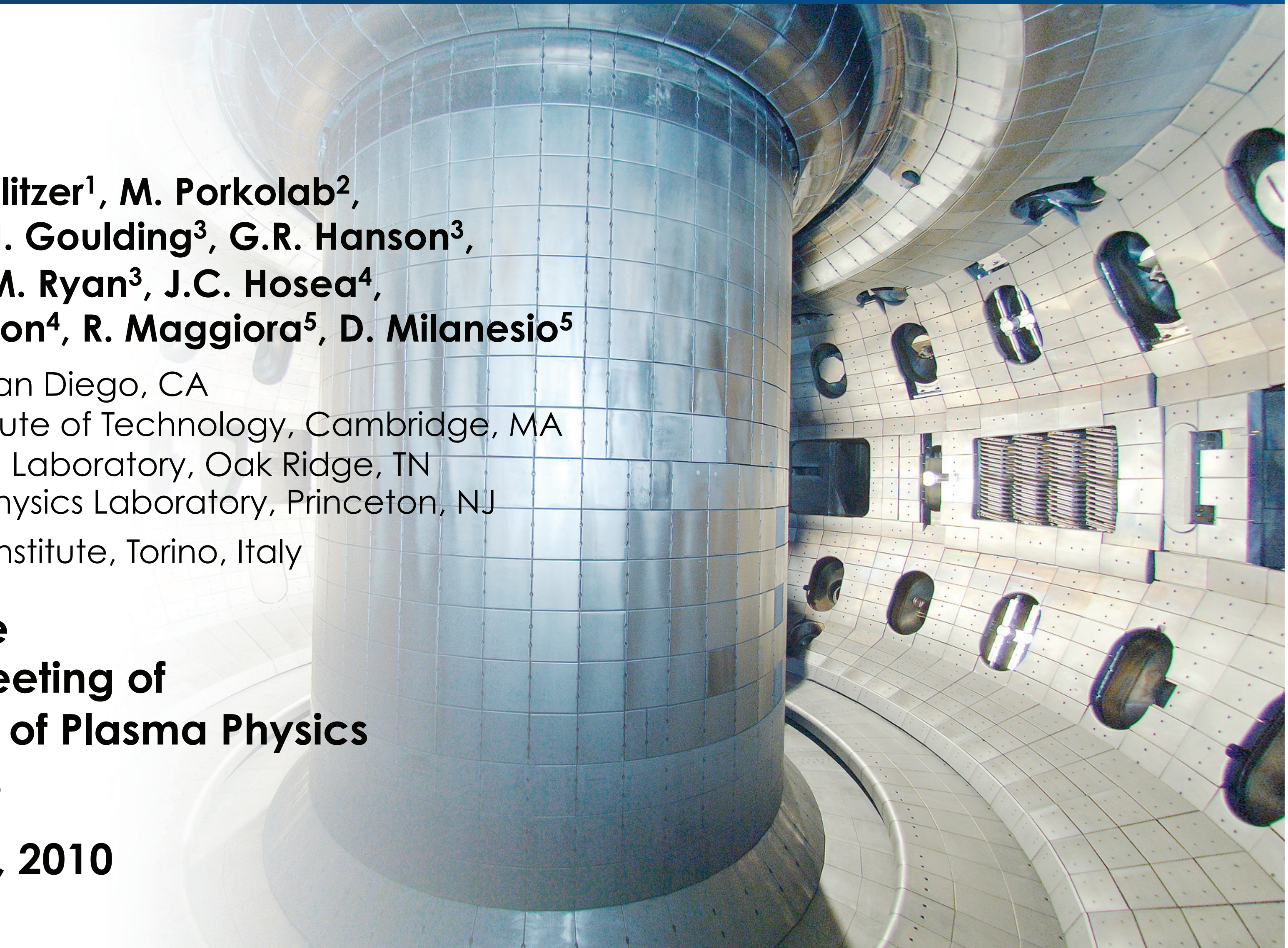
High-Power Fast Wave Coupling Experiments in Advanced Regimes in DIII-D



by

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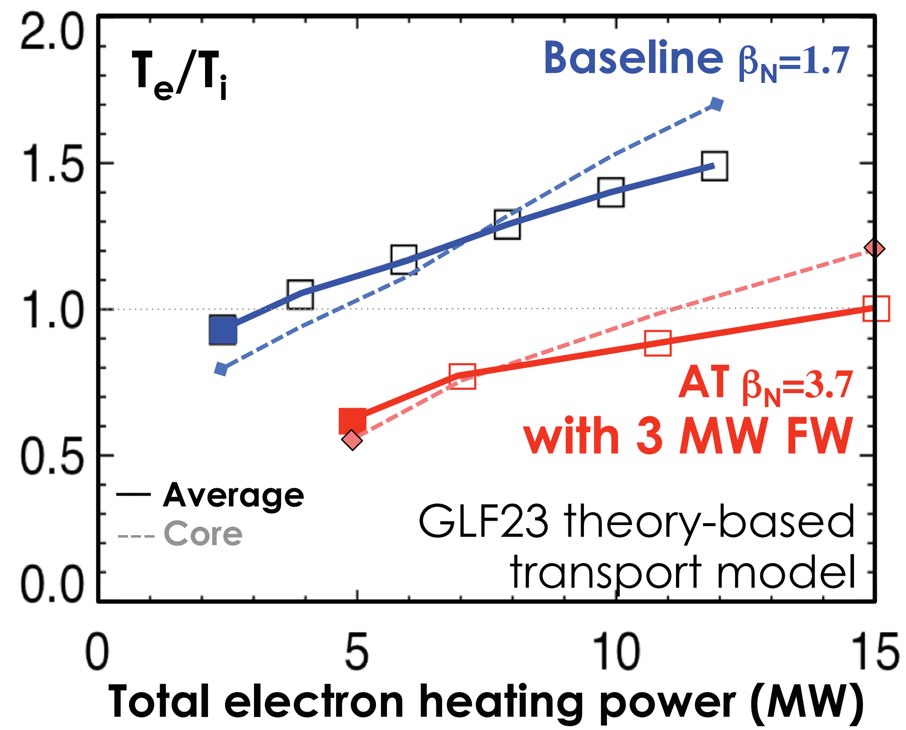
Introduction: Applying Fast Wave Power to Advanced Tokamak Regimes

- **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 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 3.5 MW goal

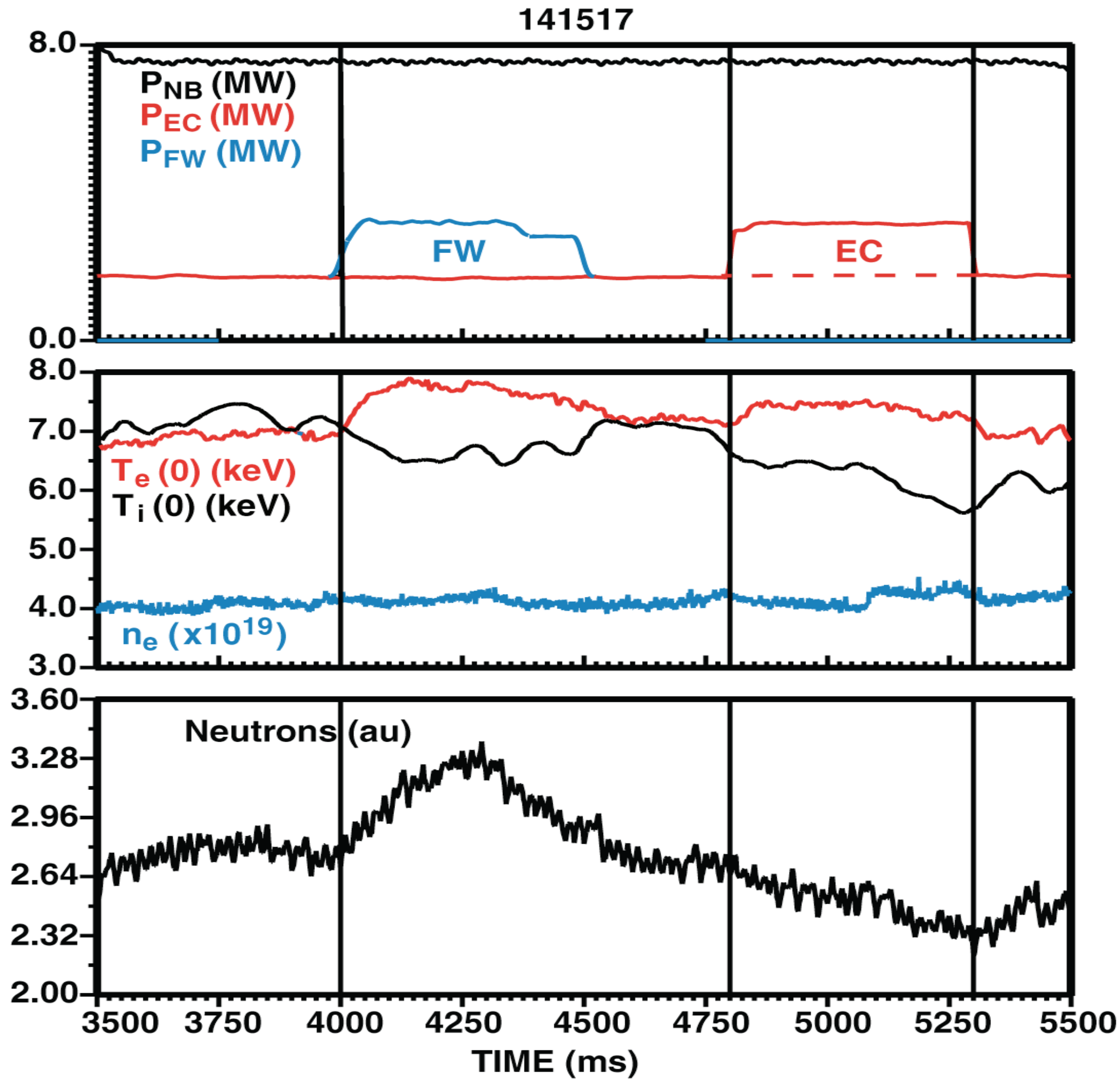
FW Core Absorption Efficiency Similar to EC at 1.5 MW Level in Advanced Inductive Discharge: η_{abs}~100%

Comparison is on top of 8 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 $\rho = 0.25$
  - 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 Edge Losses Should be Small

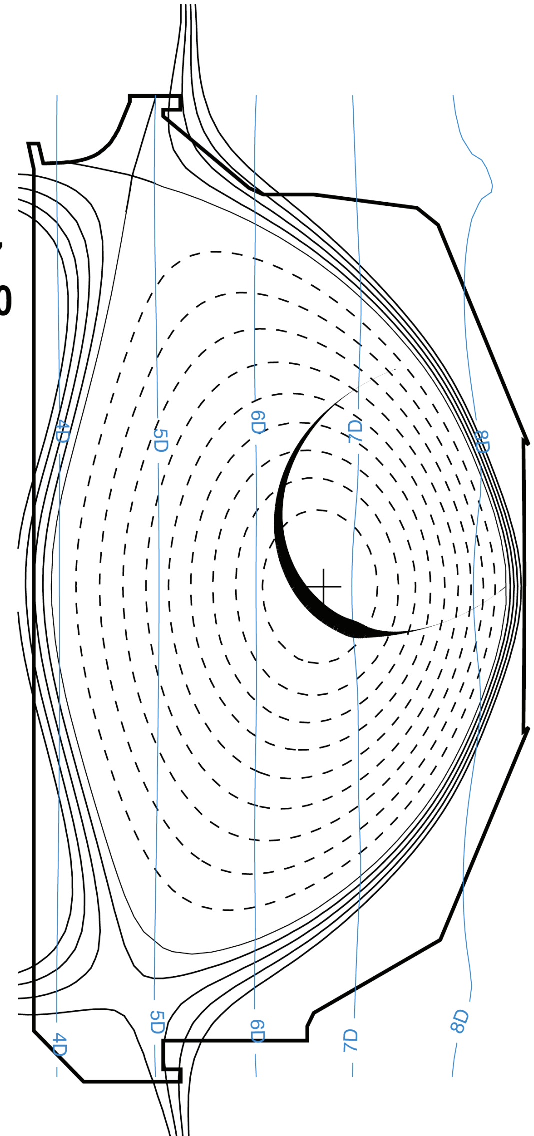
- $$\eta_{abs} = \frac{\langle \eta_{core}^{one-pass} \rangle}{\langle \eta_{core}^{one-pass} \rangle + \langle \eta_{edge}^{one-bounce} \rangle}$$

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

- **Only 'prompt' edge losses should be important in this regime**

Shot 141517
time 3980.00

First-pass absorption on electrons: 76%



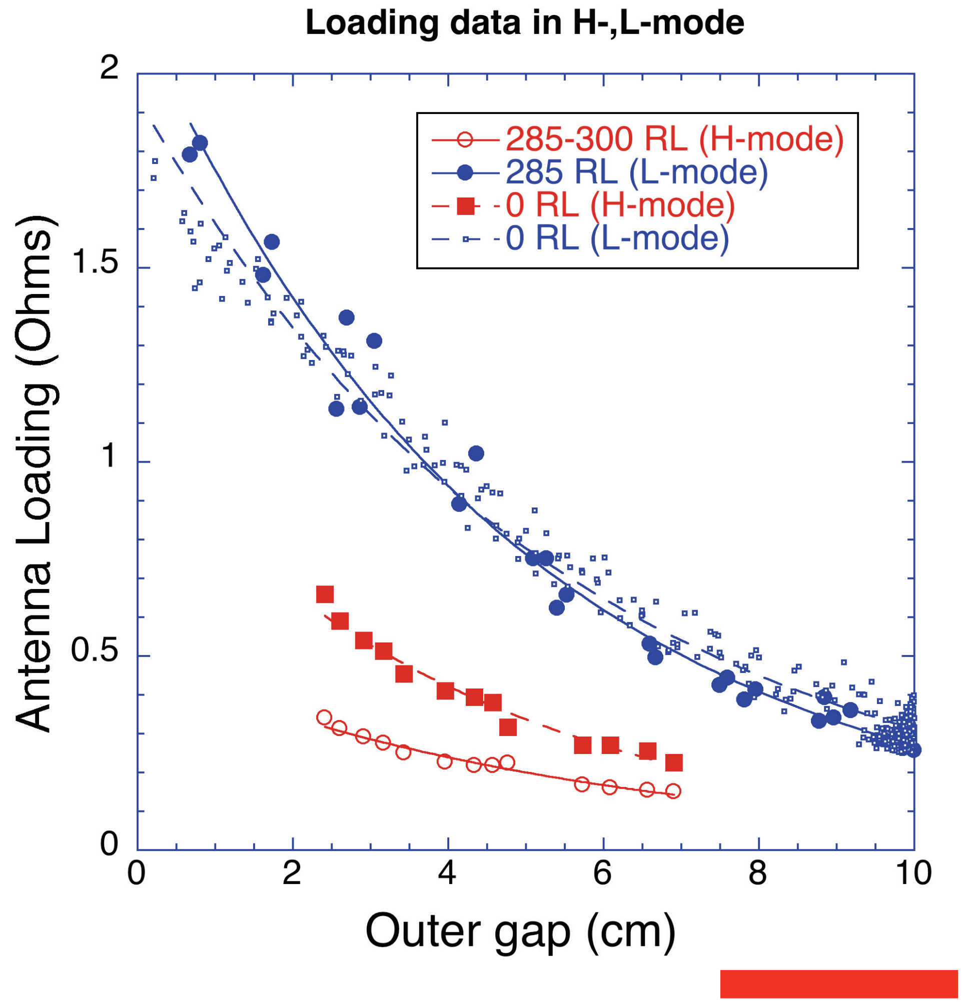
To Increase Coupled FW Power, Antenna Loading in AT regime Must be Increased

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

- **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**

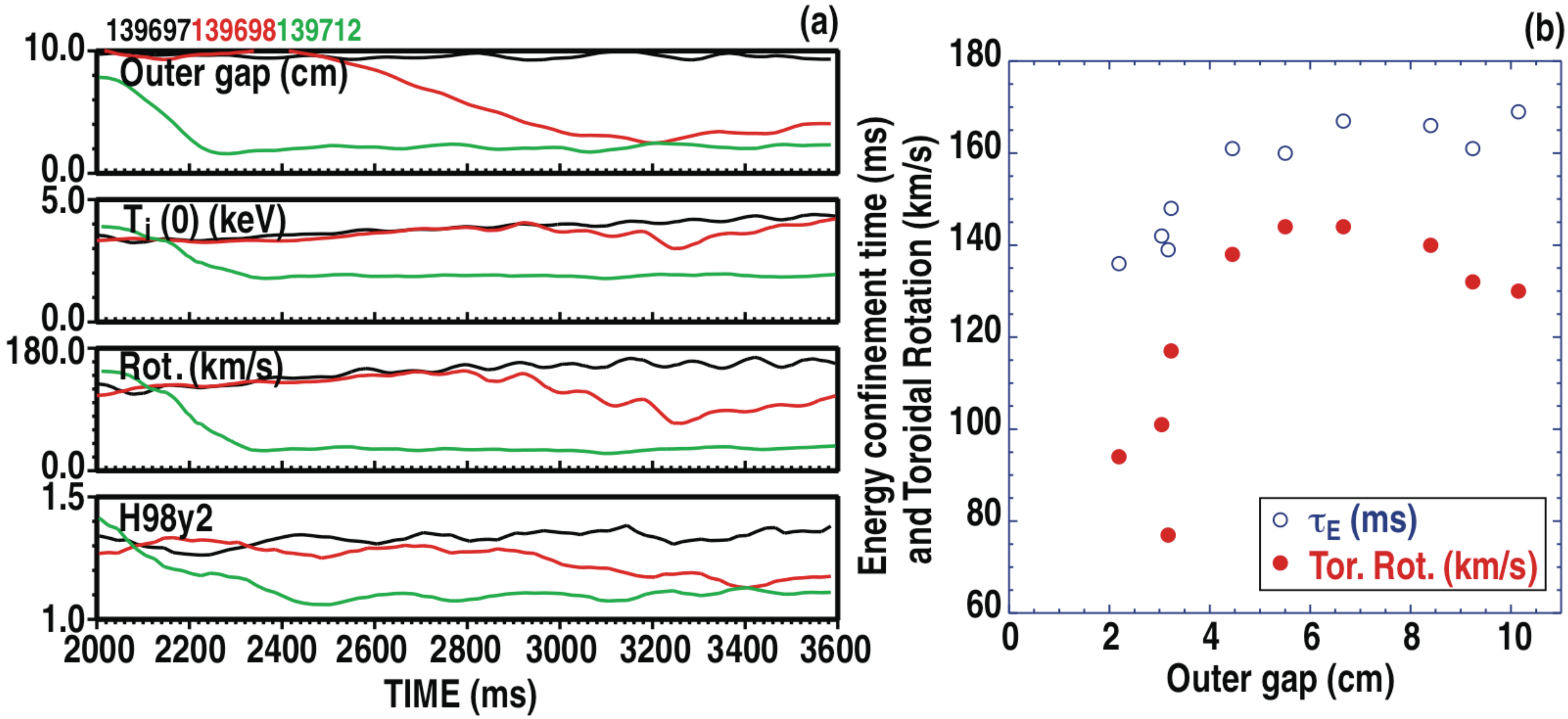
Loading Increases Exponentially as Plasma/Antenna Gap is Reduced; Upgraded Limiters Enable Smaller Gap, Higher R_L

- 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



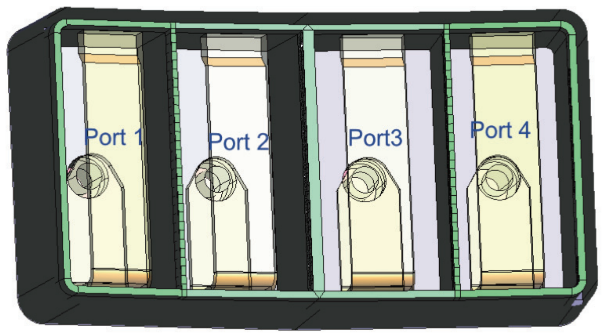
Typical DIII-D H-mode

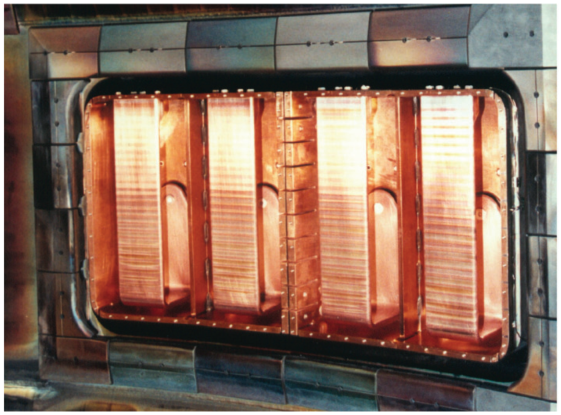
Price of Too Small Outer Gap in AT – Precipitous Drop in Rotation, Confinement (Ion Channel?) at Gap < 4 cm

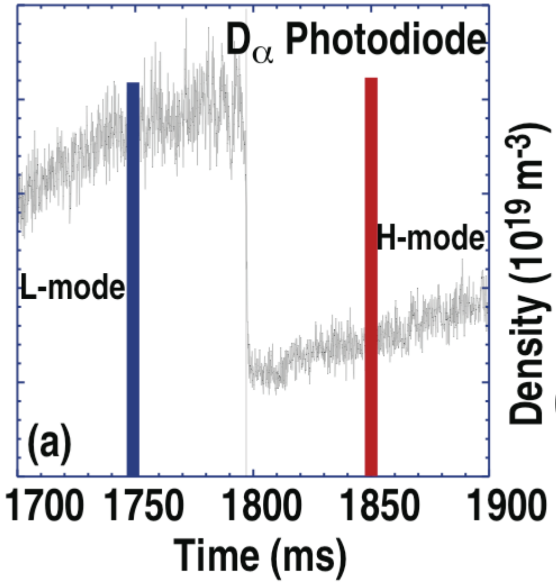


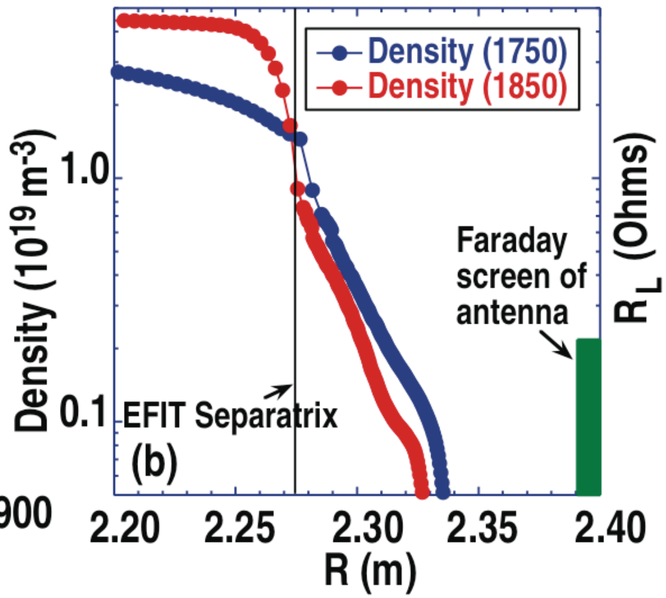
- **Subsequent experiments maintained at least 4 cm outer gap**

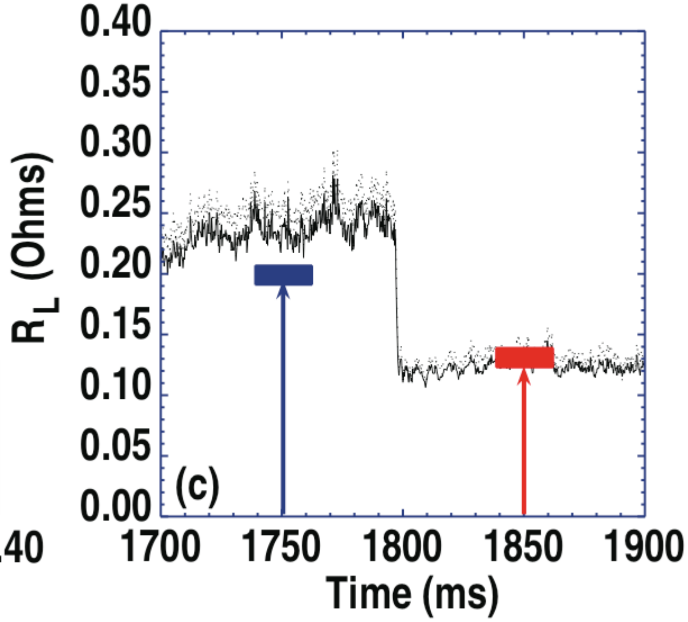
R_L Agrees with TOPICA Code Using Measured Edge Density Profiles from Reflectometers in L- and H-mode





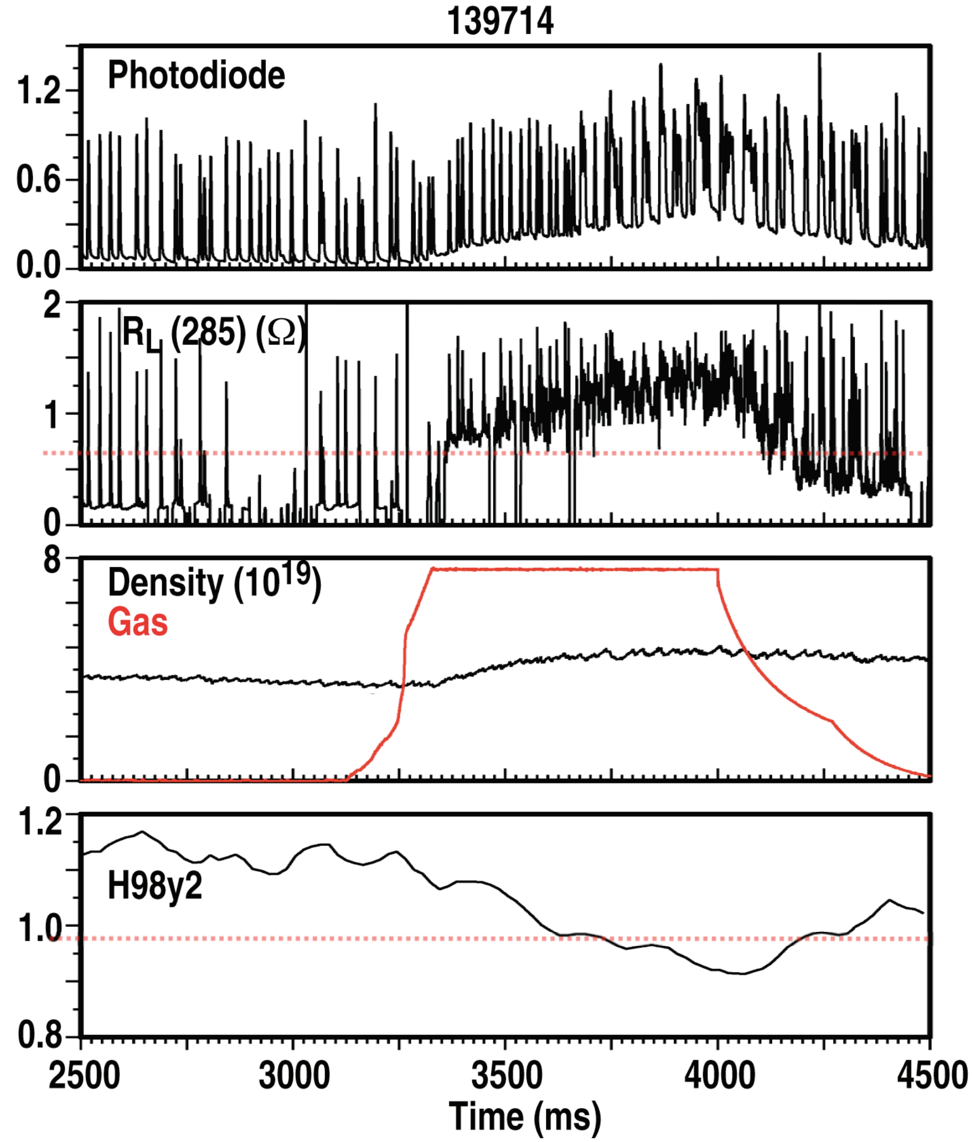






Gas Puffing Increased Loading by Up to a Factor of Six in Some H-mode Regimes

- 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



Projection to 2011 Experiments — Higher FW Power will be Coupled to AI/AT Discharges

- **Optimization of existing discharge already should yield core coupled FW power ~2.5 MW at acceptable voltage**
- **All three antennas being moved to 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 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%)
- Antenna loading in agreement with modeling using measured edge density profiles
- 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 3.5 MW goal in 2011

Backup Slide Follows

Enhanced Loading Also Obtained by Changes in Pumping and ELMs without Puffing

- **Downwards bias (drsep = -2 cm) yields higher SOL density and antenna loading *without* gas puffing**
- **Density marginally acceptable for near-central EC at X2**
- **Even without EC, Te(0)~4 keV at this density yields ~65-70% first-pass core FW absorption**
- **Acceptable confinement, β_N~ 2.6, loading should permit optimized FW power of ~2.5 MW at acceptable antenna voltage**