Development in the DIII-D Tokamak of Hybrid Operations Scenarios for Burning Plasma Experiments

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General Atomics

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MOTIVATION

- Baseline scenarios for burning plasma designs such as ITER and FIRE are based largely on projections from multi-machine databases. It is important to verify the scenarios in present day devices in stationary discharges and probe the limits in these conditions

- ITER specifically has an additional reduced-performance scenario for increasing the neutron fluence (“hybrid” scerario). It is important to assess the physics capabilities of the design for this mission

- Extension of present regimes to the current relaxation time scale may uncover new phenomena; for example, slow relaxation oscillations in Tore Supra

BACKGROUND

- In the mid-1990's, enhanced discharges with q_{min} ~1 but limited by fishbones rather than sawteeth were found. These were not pursued because they could not be projected to fully non-inductive operation [B.W. Rice, et al., Nucl. Fusion 39, 1855 (1999)]

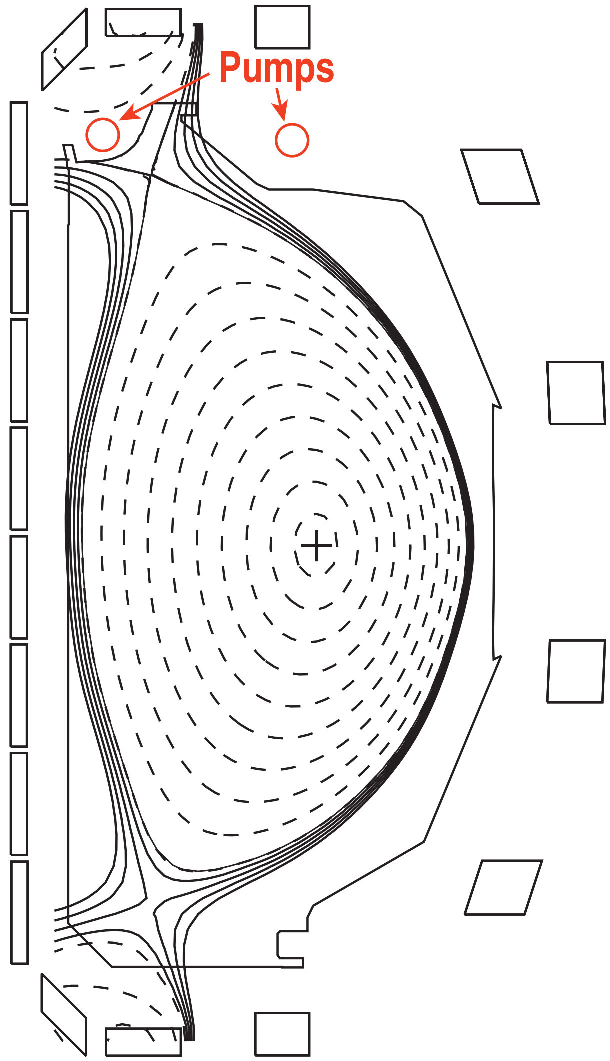
- In 2000, a stationary scenario was developed for testing ECCD in enhanced performance plasmas. By controlling β and density, it was found that $\beta_N = 2.7$, $q_{95} = 4.2$ discharges could be run for > 6s without sawteeth [T.C. Luce, et al., Nucl. Fusion 41, 1585 (2001), M.R. Wade, et al., Phys. Plasmas 8, 2208 (2001)]

- In 2001, it was found that these discharges could be pushed to $\beta_N > 3$ if the β is raised after the current profile is relaxed [T.C. Luce, et al., Nucl. Fusion, 43, 321 (2003)]

- In 2002, based on results from AUG, JT-60U, and DIII–D, the Steady State Operation topical group and the Transport topical group independently requested that DIII–D and other tokamaks map the performance as a function of q_{95} and density, and note the instability which limits the current peaking

KEY ELEMENTS

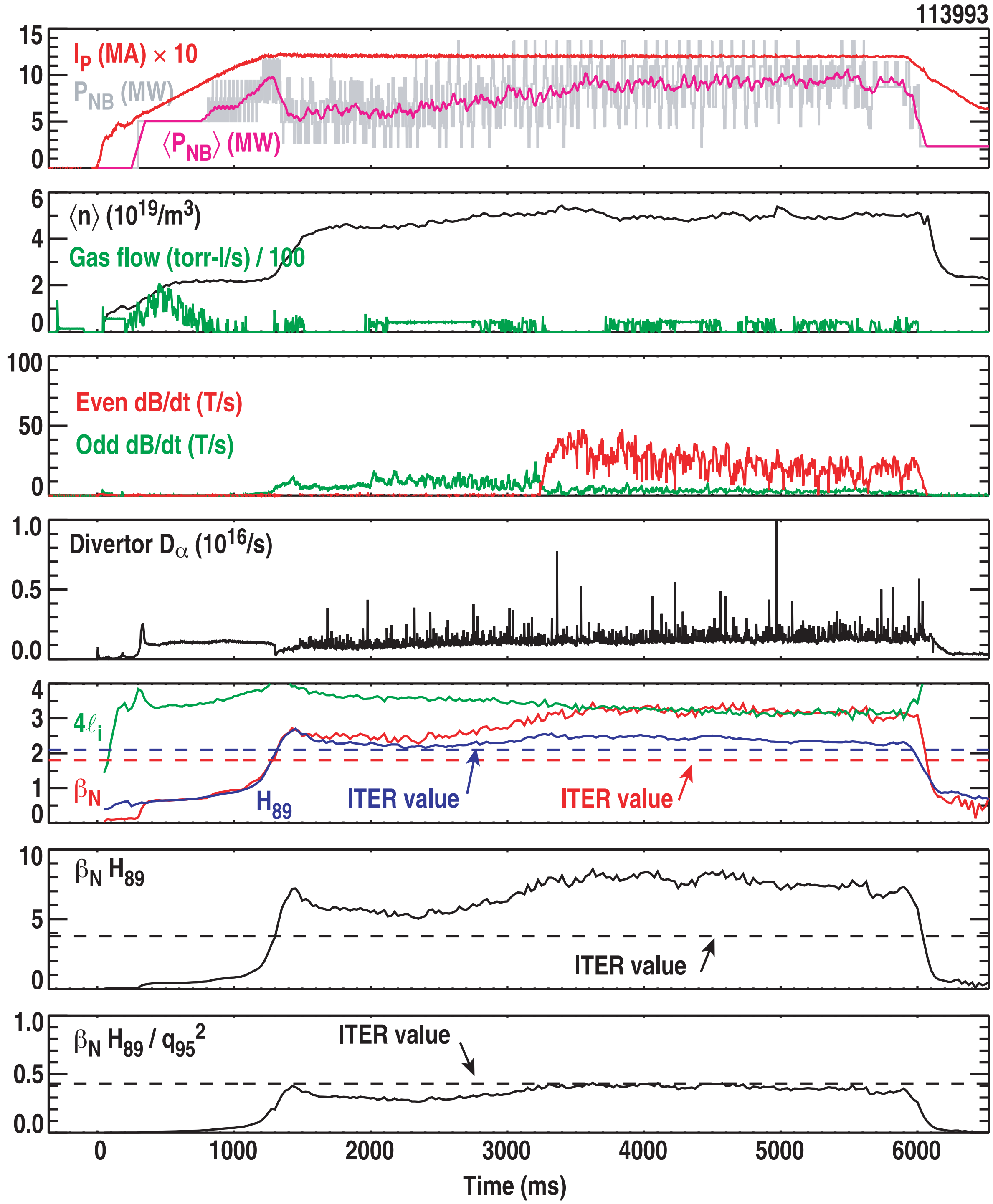
- Density control requires pumping and gas puffing to remove the wall from the particle balance. For DIII–D, this means controlling the shape to keep the pumps engaged and only the upper x point active



- β control requires real-time feedback on the neutral beam injection power. Feedback is PD with a target duty cycle. A model-based controller is needed to improve the robustness. To eliminate the errors from shot-to-shot jitter in the L-H transition timing, the feedback is triggered when the stored energy reaches a preset level

- The essential operational element appears to be reaching high enough β to trigger the m=3/n=2 tearing mode, then waiting for the current profile to relax before raising β further

DISCHARGE WITH q95 = 4.4 RUNS STABLY NEAR THE NO-WALL β LIMIT FOR >2s



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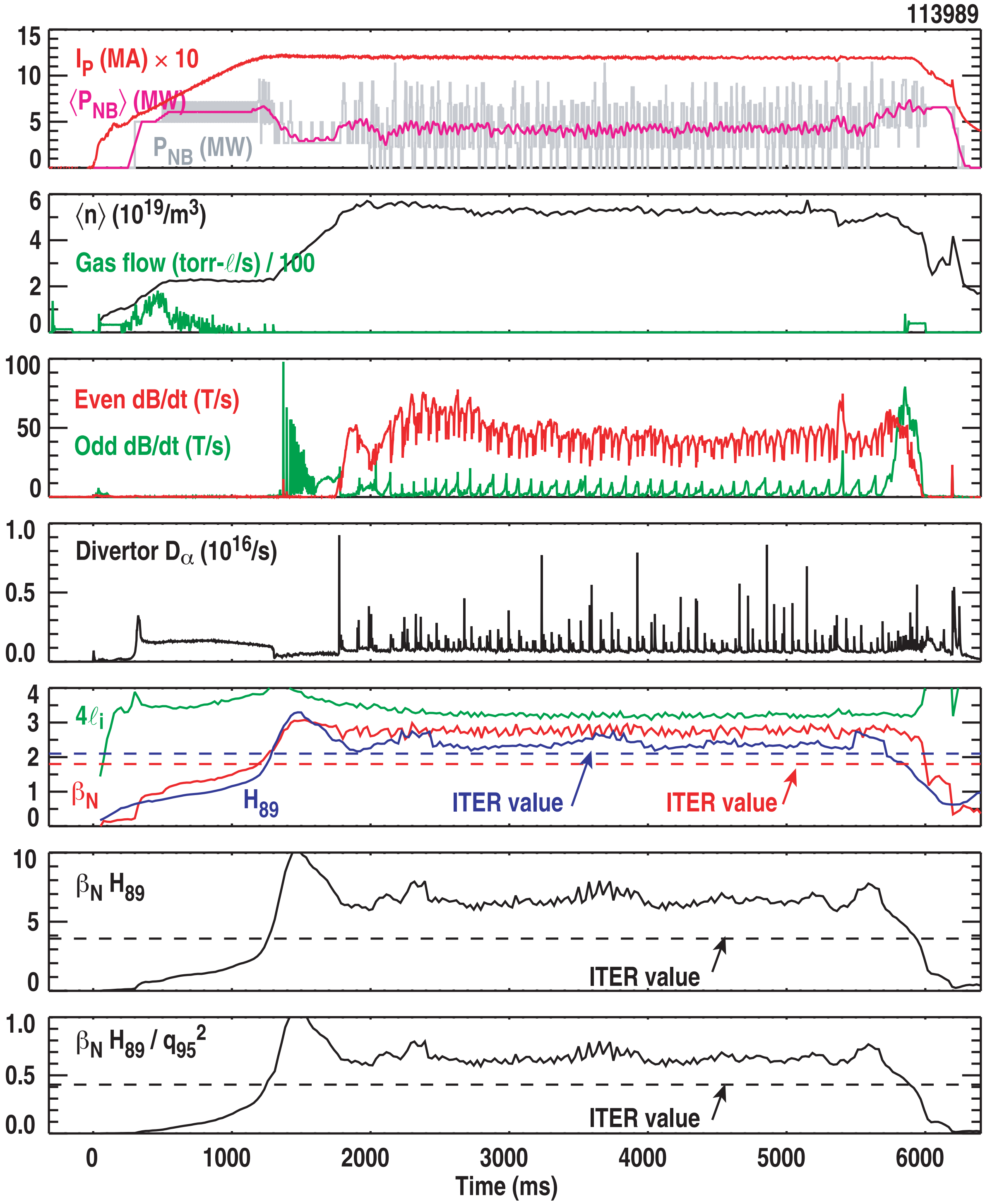
DISCHARGE WITH q_{95} = 3.2 RUNS WELL ABOVE ITER BASELINE VALUES FOR > 3s



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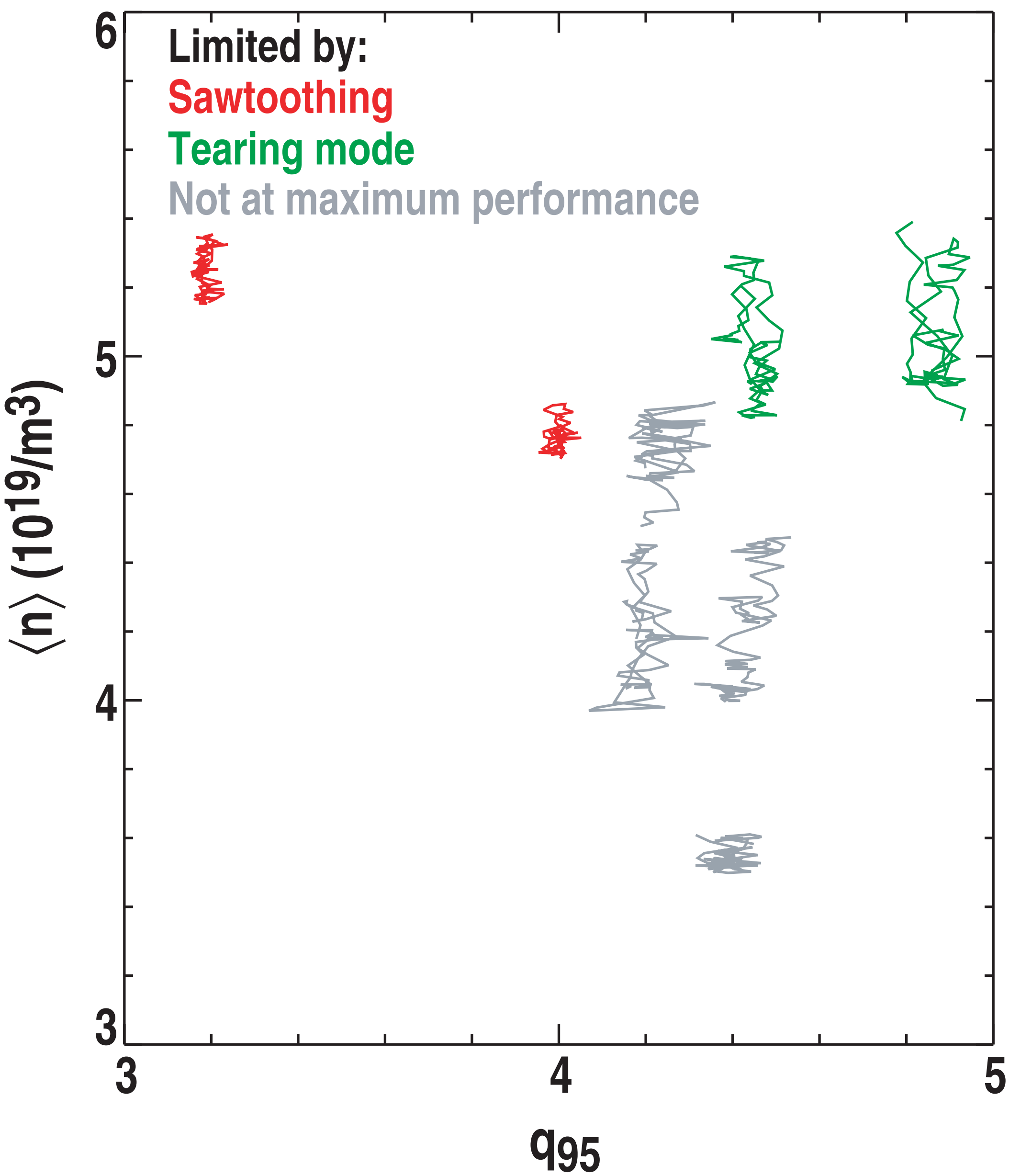
CURRENT PEAKING IS LIMITED BY SAWTEETH FOR $q_{95} \leq 4$ AND TEARING MODES FOR $q_{95} > 4$



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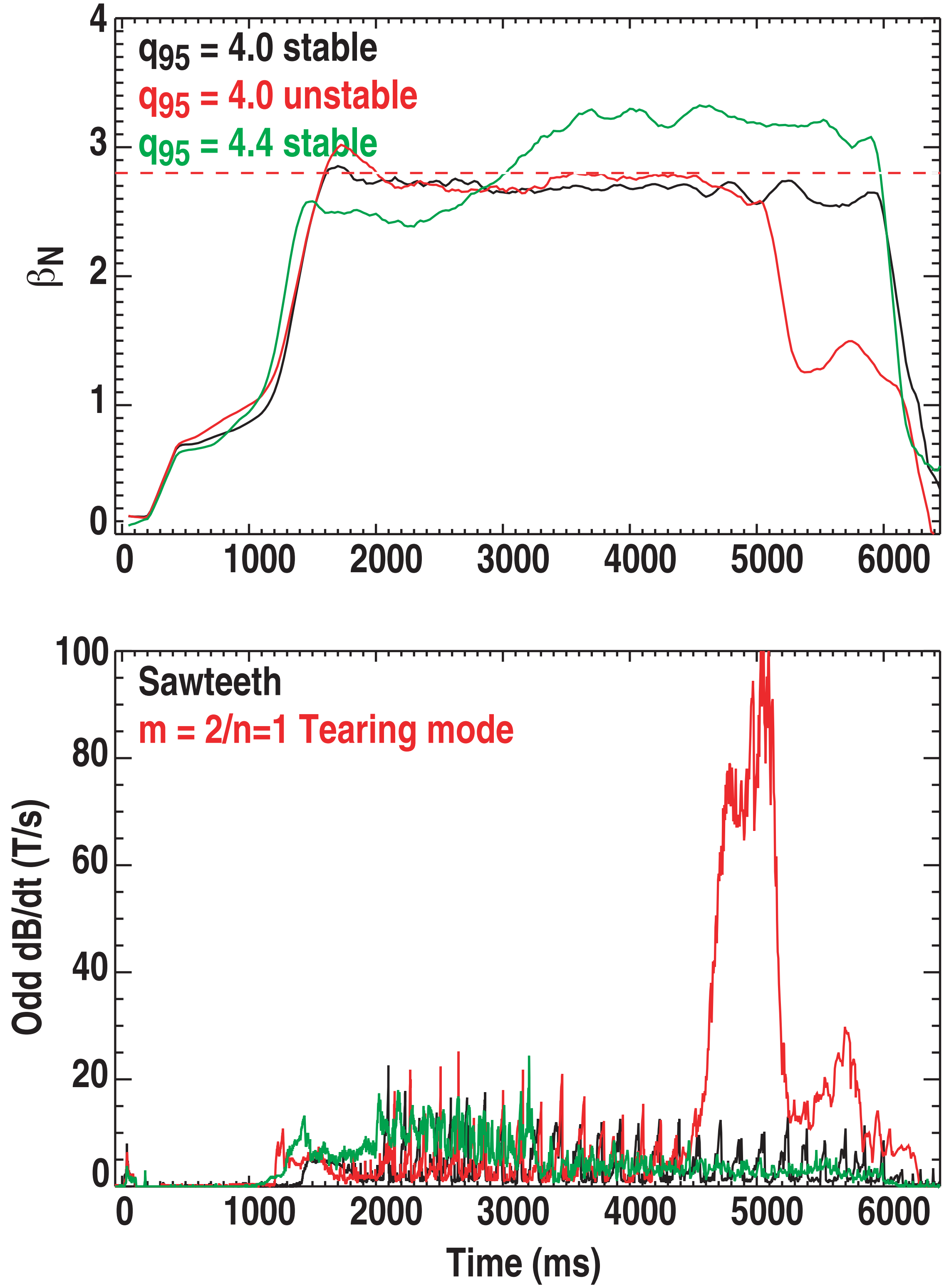
SAWTOOTHING DISCHARGES HAVE A LOWER β_N LIMIT



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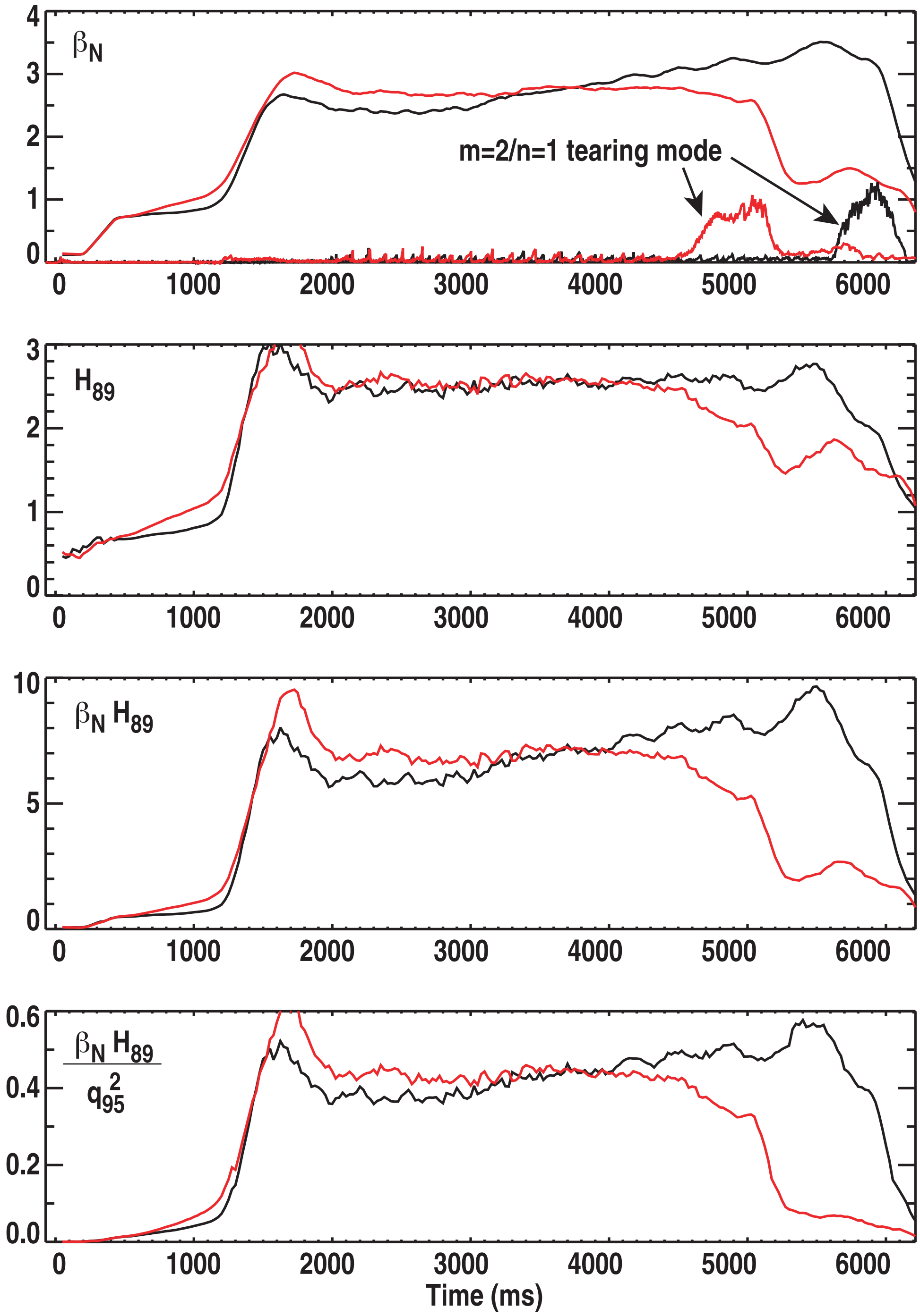
LONG-PULSE OPERATION IS IMPORTANT BECAUSE HIGHER β_N CAN BE OBTAINED UNDER NON-STATIONARY CONDITIONS



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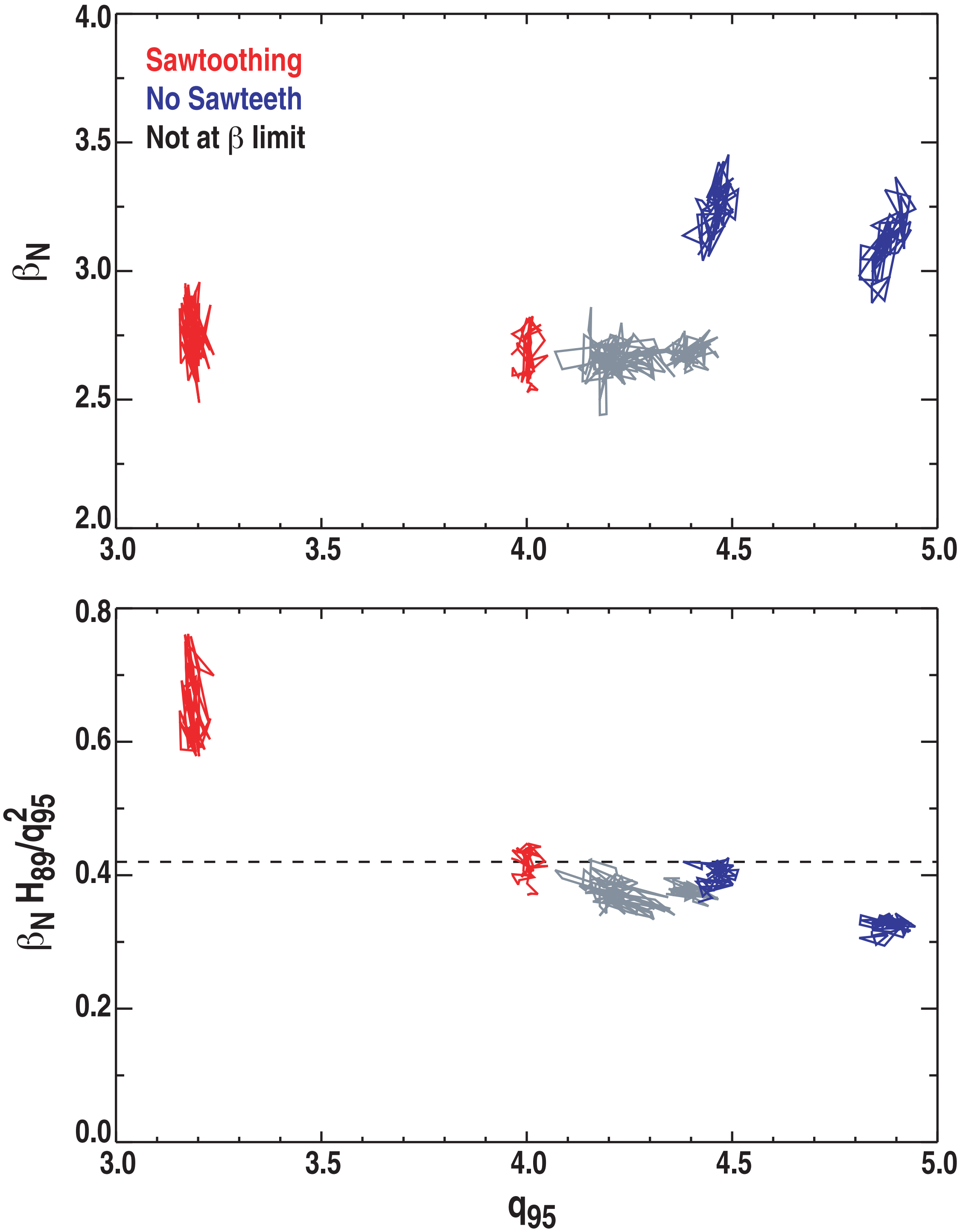
β_N LIMIT IS NEARLY INDEPENDENT OF q_{95} IN EACH REGIME, BUT FUSION PERFORMANCE MAXIMIZES AT THE LOWEST q_{95}



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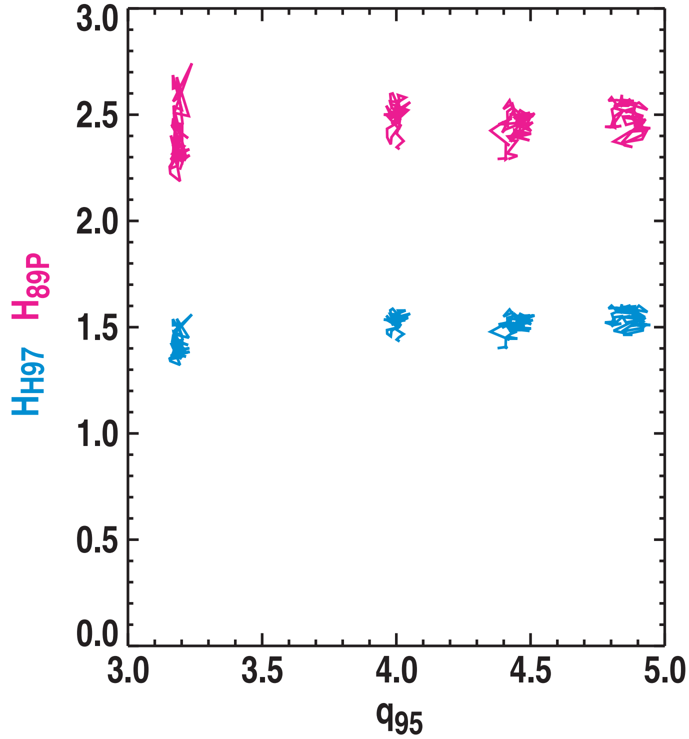
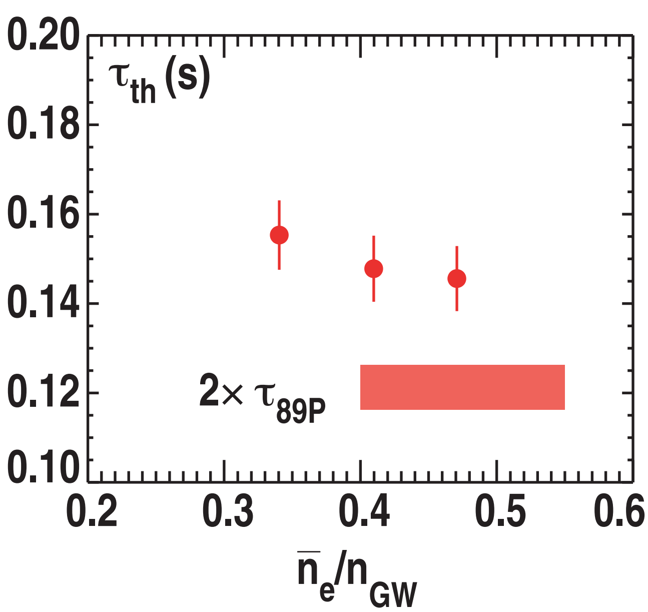
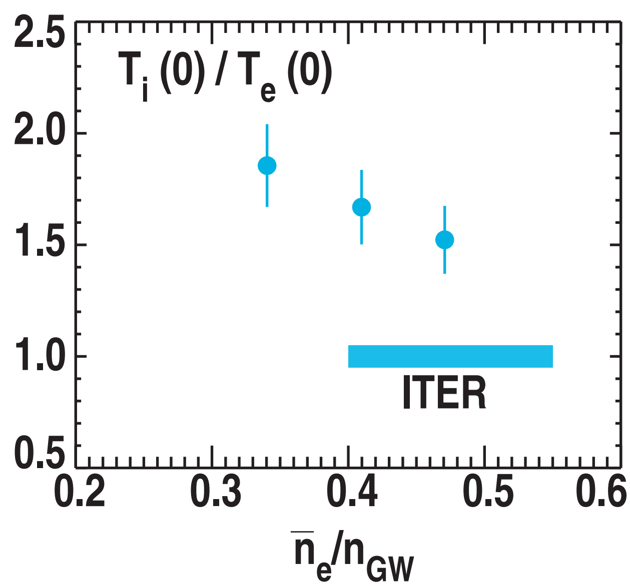
CONFINEMENT ENHANCEMENT IS ROUGHLY INDEPENDENT OF q_{95} AND WEAKLY DEPENDENT ON T_e/T_i







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METHODOLOGY FOR PROJECTION TO ITER/FIRE

- Fixed poloidal cross section
- Fixed q_{95}
- Fixed β_N
- Fixed confinement multiplier H (but 3 scalings)
- Choose n/n_G (fixed ν_* would be $n/n_G > 2$)
- Use machine's Z_{eff} prescription:
  - ITER: 2% Be 1.2% Carbon
  - FIRE: $Z_{eff} = 1.4$ (maybe 3% Be — need to check)
- He ash self-consistently used
- Choose 50/50 D-T, mix
- Use thermal heating scheme (no beam-target fusion reactions)
- Use DIII–D n_e, T_e profiles
- Fix $T_e = T_i$

PROJECTION OF 113993 TO ITER

$q_{95} = 4.4$	$\beta_N = 3.2$	$n/n_G = 1$	min $\nu_{*,i} = 0.026$
$B = 5.3$ T	$I = 10.3$ MA	$\alpha_n = 1.38$	$\alpha_T = 1.93$
Flattop time	= 4500s	= 1.25h	

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.2	670	165	4.1
IPB98y2	1.58	650	64	10.2
Pure gB	1.45 (1.61)	630	0	∞

ITER89P: P.N. Yushmanov et al., Nucl. Fusion 30, 1999 (1990)
IPB98y2: ITER Physics Basis Editors, et al., Nucl. Fusion 39, 2137 (1999)

Pure gB: C.C. Petty, et al., Fusion Sci. Tech. 43, 1 (2003)

Numbers in parenthesis are the values for the DIII–D case. The confinement multiplier must be reduced in the ignition cases to obtain energy balance

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PROJECTION OF 113989 TO ITER

q_{95} = 3.2	β_N = 2.8	n/n_G = 1	min $\nu_{*,i}$ = 0.047
B = 5.3 T	I = 13.9 MA	α_n = 1.25	α_T = 1.92
Flattop time	= 1900s	> 30 min	

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	950	31	31
IPB98y2	1.34 (1.47)	940	0	∞
Pure gB	0.99 (1.63)	940	0	∞

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PROJECTION OF 113989 TO FIRE

$q_{95} = 3.2$ $\beta_N = 2.8$ $n/n_G = 0.7$ $\min \nu_{*,i} = 0.062$

$B = 10$ T $I = 6.3$ MA $\alpha_n = 1.25$ $\alpha_T = 1.92$

20s flattop needs 30 Volt-seconds

	H	P_{fus} (MW)	P_{aux} (MW)	Q_{fus}
ITER89P	2.4	280	48	5.8
IPB98y2	1.47	280	35	8.0
Pure gB	1.55 (1.63)	270	0	820

A potential advantage of the high field approach is high Q_{fus} with $n/n_G < 1$

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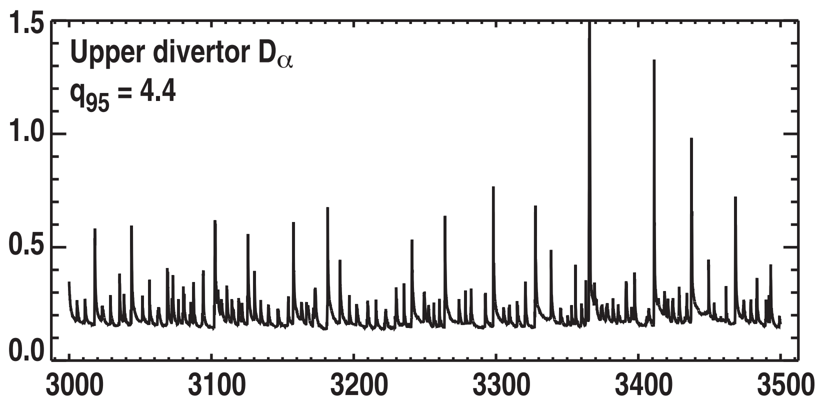
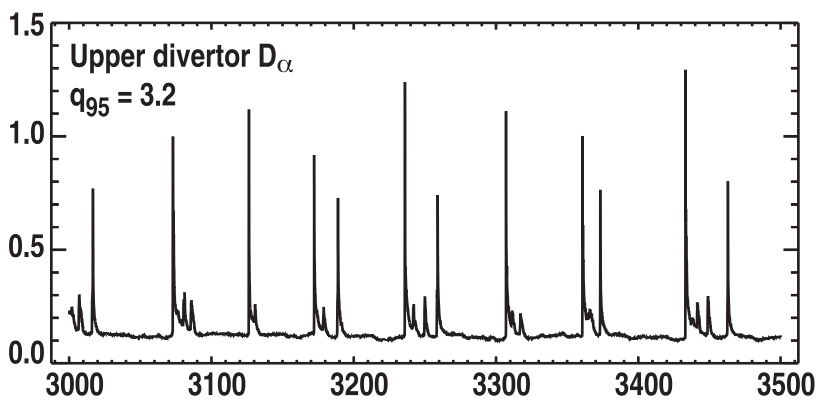
REMAINING PHYSICS ISSUES FOR PROJECTION

- Confinement dependence on T_e/T_i
  - Need density scans at fixed q_{95} however, H seems independent of this parameter in present range of density, so dependence may be weak
- Physics of current profile evolution at high q_{95}
  - Need good stationary data at low density to get ECE data. The main questions are whether there is dynamo-like action in the tearing mode and does it require a fluctuating amplitude?
- Divertor issues
  - Lower current means lower absolute density which may place greater strain on the divertor. Perhaps the ELM behavior is better at higher q_{95}





CONCLUSIONS

- Stationary high-performance discharges in DIII–D provide confidence that ITER and FIRE can meet and exceed their baseline performance

- Based on the DIII–D dischanges at higher q_{95}, ITER could match baseline performance with an inductive capability of > 4000s operation for its nuclear testing mission

- The variance in the confinement projections points to the need for data from JET and JT-60U to reduce the uncertainties

- Physics studies involving multiple machines are necessary to validate any conclusions on the remaining physics issues