Demonstration in the DIII–D Tokamak of an Alternate Baseline Scenario for ITER and Other Burning Plasma Experiments

by
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GENERAL ATOMICS

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OUTLINE

- Motivation/summary of results
- Stationary current profiles
- Stability limits
- Particle/energy confinement
- Projection to burning plasma experiments

MOTIVATION

- Present burning plasma design rules balance the benefits of increased plasma current
  - $\beta \propto \mathbf{I}$ at fixed β_N
  - $\tau \propto \mathbf{I}$

  against the increasing potential for component damage at higher stored energy
  - Disruption forces $\propto \mathbf{I}^{1\text{-}2}$
  - ELM energy $\propto \mathbf{I}$

- Conventional wisdom chooses $q_{95} \sim 3$ as the balance point in the risk-benefit assessment

- Discharges in DIII–D have demonstrated the possibility of high fusion gain at reduced current (q_{95} = 4.0–4.5)

SUMMARY OF RESULTS

- Discharges with $\beta_N H_{89} \sim 7$ have been demonstrated with
  - Stationary current profiles ($t_{dur} > 2\ \tau_R$)
  - Stationary pressure profiles ($t_{dur} > 35\ \tau_E$, $H_{89} = 2.5$)
  - No wall pumping
  - No impurity accumulation ($Z_{eff} = 1.6$)
  - At $q_{95} = 4.0\text{-}4.5$, $\beta_N H_{89}/\ q_{95}^2 = 0.38\text{–}0.40$, (ITER-FEAT design value 0.42)
- Discharges with $\beta_N H_{89} \sim 9$ have been demonstrated at
  - $t_{dur} > 6\tau_E$, $H_{89} = 2.8$
  - $t_{dur} \sim 0.5\ \tau_R$
  - $\beta_N\ H_{89}/q_{95}^2 = 0.44$
- About 90 long-pulse high performance discharges have been made over 3 run campaigns (2000-2002)

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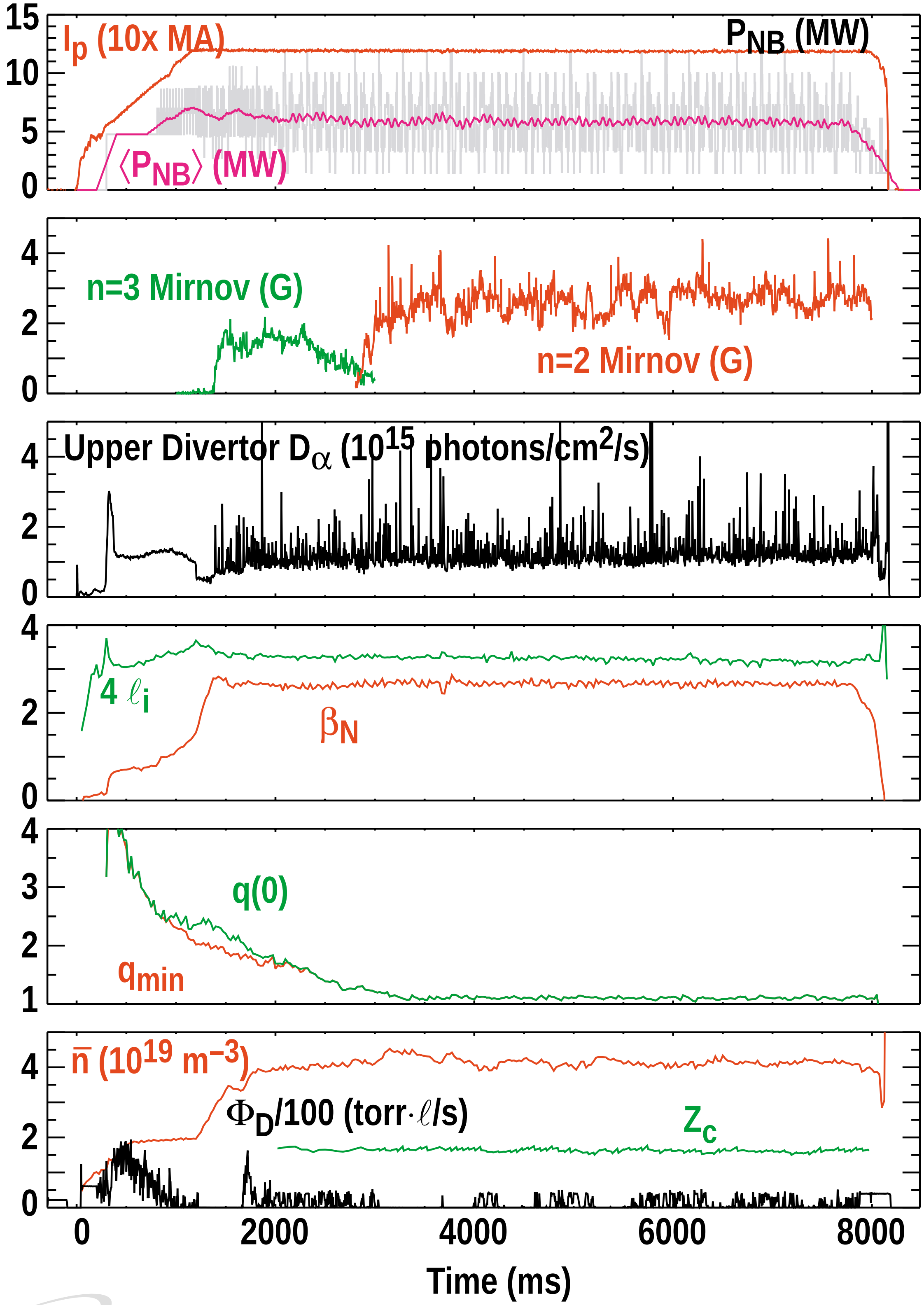
TYPICAL LONG-PULSE HIGH-PERFORMANCE DISCHARGE



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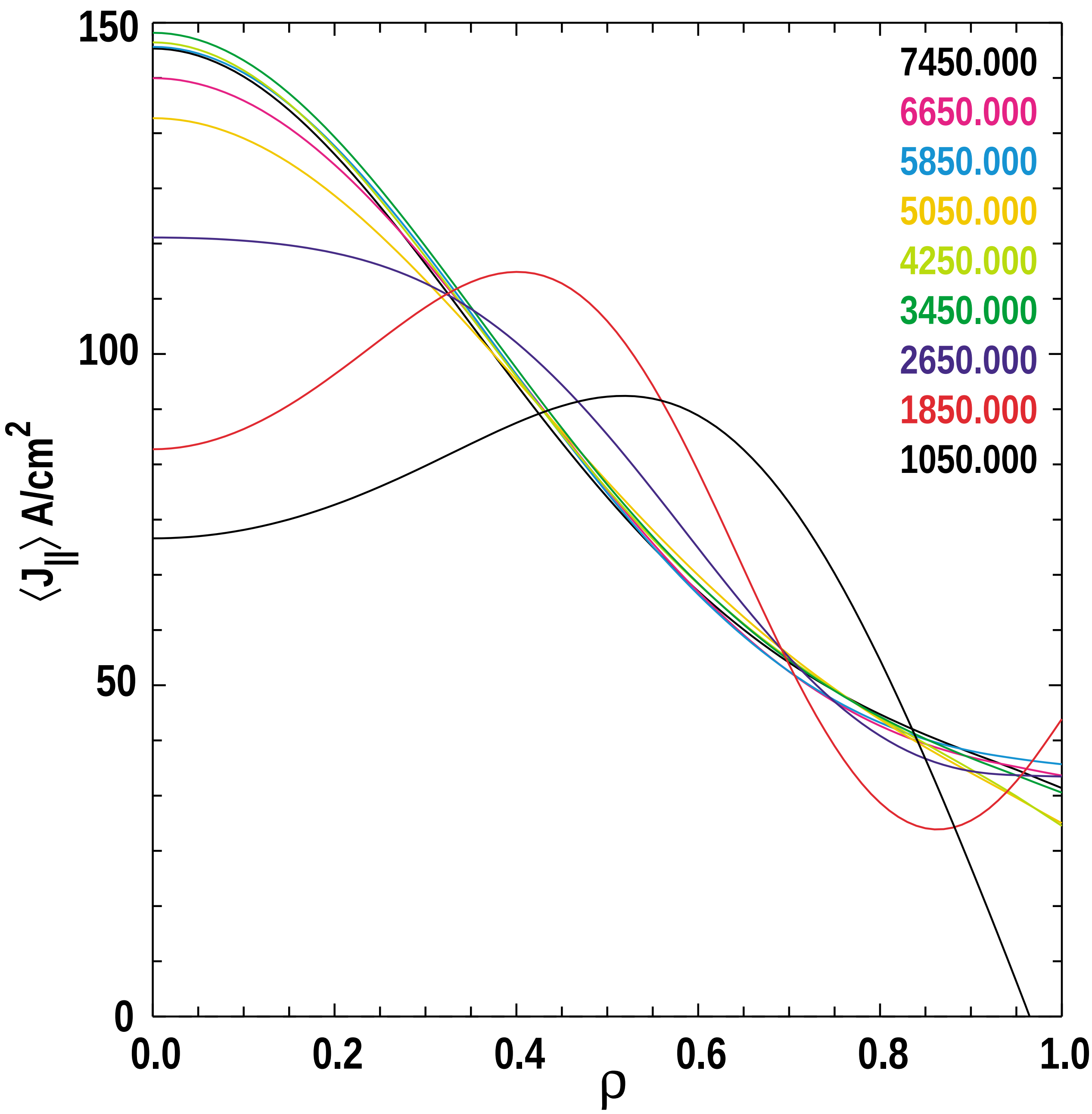
OPERATIONAL ELEMENTS FOR DEVELOPING STATIONARY LONG-PULSE DISCHARGES

- Density and neutral beam power waveforms in the current ramp are fixed empirically to give broad q profiles with slight reversal
- L mode during the current ramp is essential to maintain high ℓ_i and therefore high stability limits
- Pumping during the current ramp is essential to control the density rise at the L–H transition
- H mode transition is induced after the current flattop by power increase and geometry change
- Density and neutral beam power are feedback controlled during the stationary phase
- High β is reached well before $q_{min} = 1$
- No sawteeth or fishbones observed

CURRENT PROFILE EVOLUTION IS CONSISTENT WITH PREDICTED TIME SCALE



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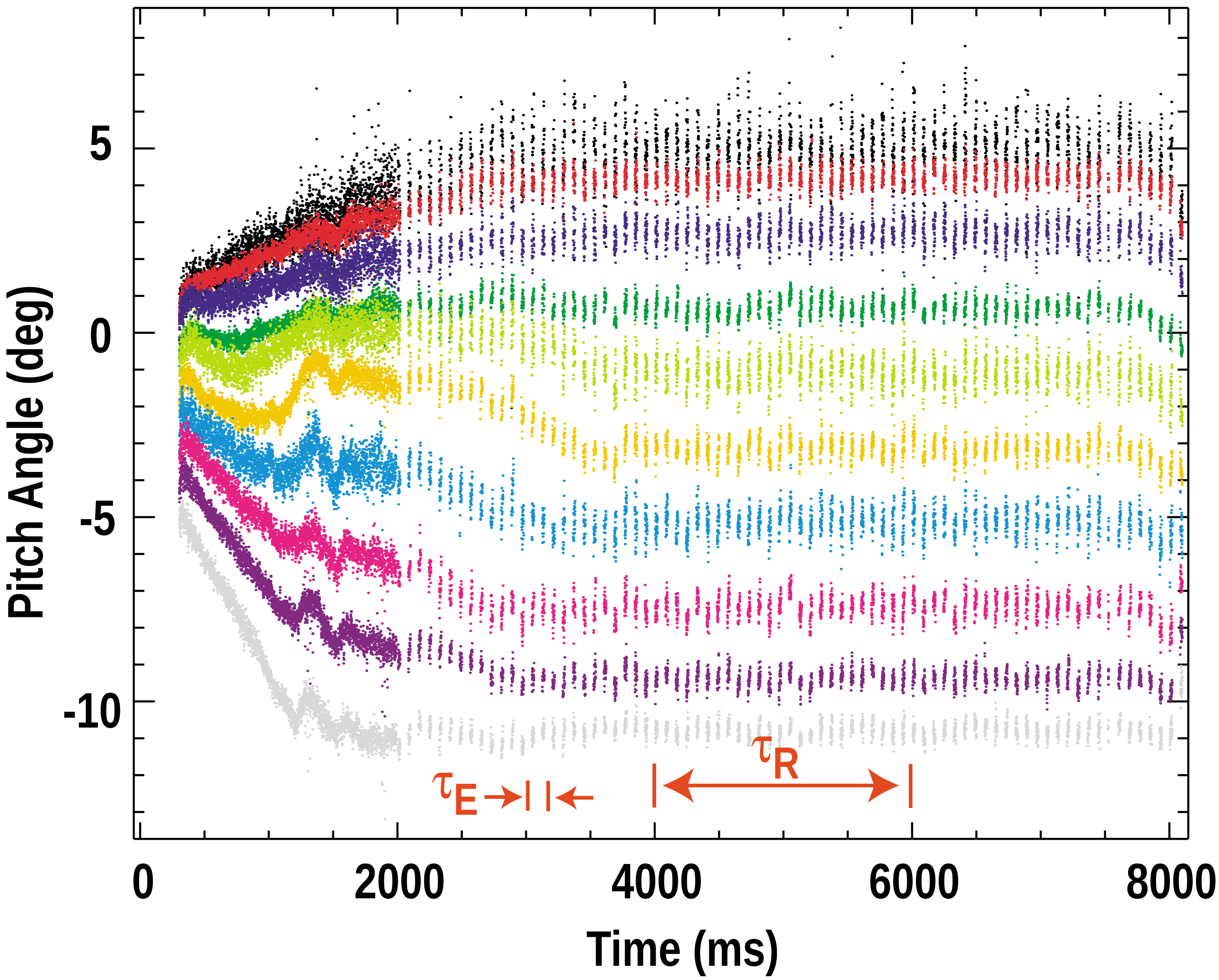
- Cylindrical, constant conductivity models for the current profile relaxation time at constant current give τ_R = 2 s for these plasmas

- The transients following end of the current ramp die out by 3450 ms, consistent with the above estimate of the relaxation time

- The non-inductive current is measured to be <50% and relatively constant during the relaxation phase due to the feedback on the NB power. Therefore, the evolution is dominated by the Ohmic relaxation

Note: The reconstructions are done with insufficient freedom to accurately model the edge current density profile. The value should be taken as indicative of the average current density in the outer 10% of the plasma

MEASURED MAGNETIC PITCH ANGLE SIGNALS FROM MSE ARE CONSTANT DURING THE STATIONARY PHASE



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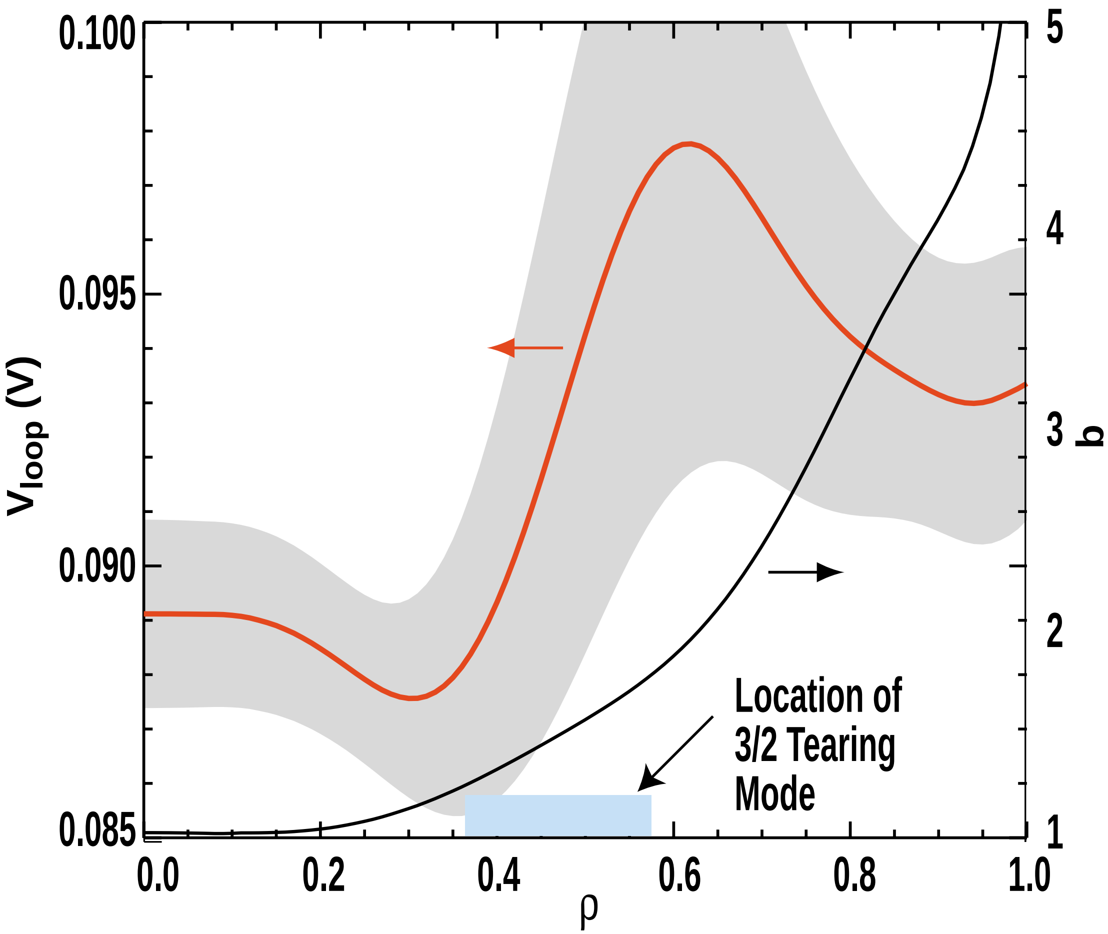
- From Ampére's law, the spacing between channels gives the incremental enclosed current

- From Faraday's law, the time derivative of the signal gives the change in electric field. Zero slope implies the value of the field is set by the boundary condition

- After 4 s, only fluctuations with zero average are observed. The fluctuations are correlated across all channels; therefore, they are likely due to plasma motion

VOLTAGE SOURCE AT THE LOCATION OF THE TEARING MODE APPEARS TO BE THE KEY ELEMENT TO MAINTAIN $q_{min} > 1$



- A voltage drop of ~5% is observed at the radial location of the 3/2 tearing mode
- This is conceptually consistent with the mode converting poloidal flux to toroidal flux or thermal energy by reconnection
- No means of making a quantitative, theory-based estimate of the voltage associated with a tearing mode has been found

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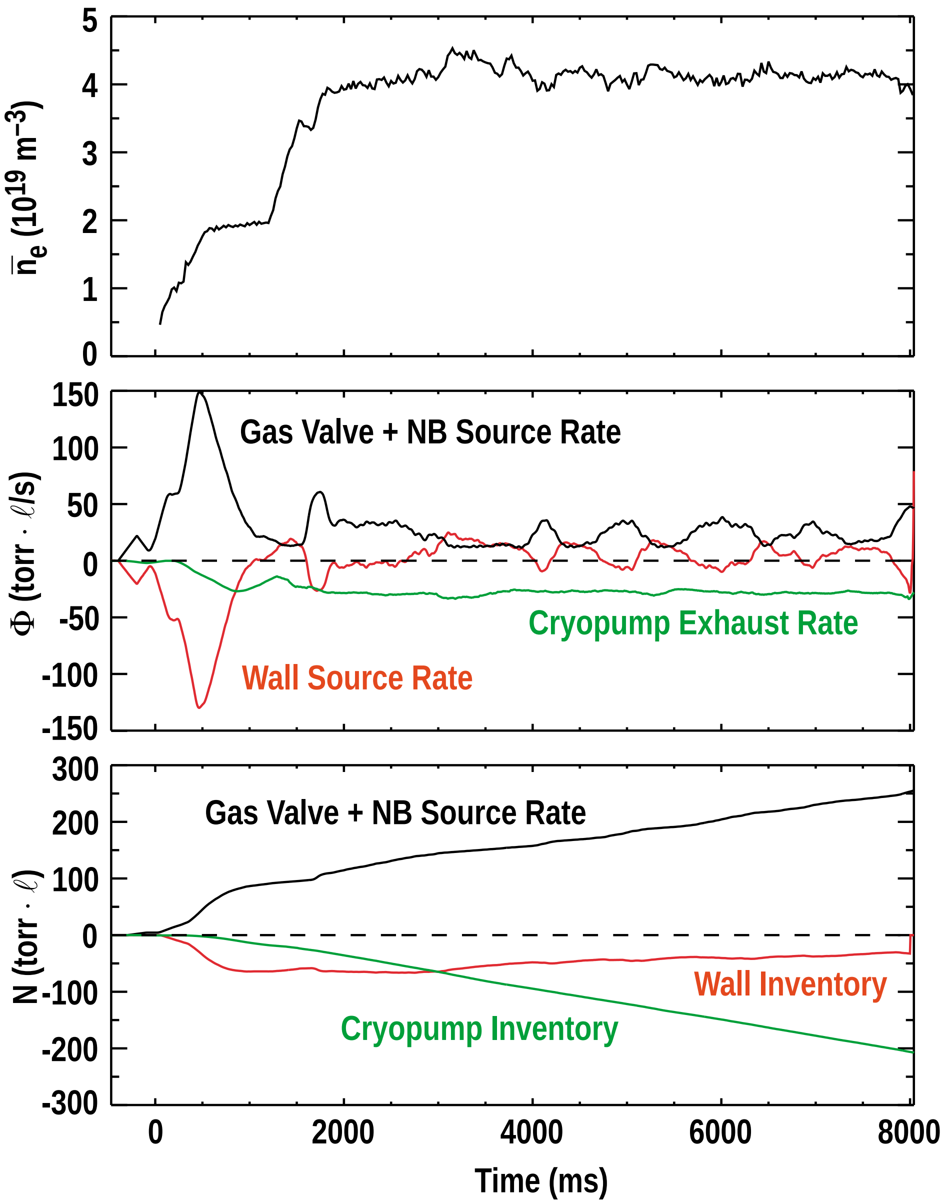
WALL PLAYS A SMALL ROLE IN THE STATIONARY PHASE PARTICLE BALANCE



- After the L–H transition, the wall slowly releases particles throughout the discharge. Other discharges have no wall flux for the entire stationary phase
- The dominant balance is between the gas valve + NB input and the pump exhaust which allows control of the plasma particle inventory by feedback
- Particle inventory in the wall is determined from the difference in the measured input and exhaust rates
- No special wall conditioning is required. Helium glow cleaning is performed between shots, but the dominant effect is regeneration of the cryopumps

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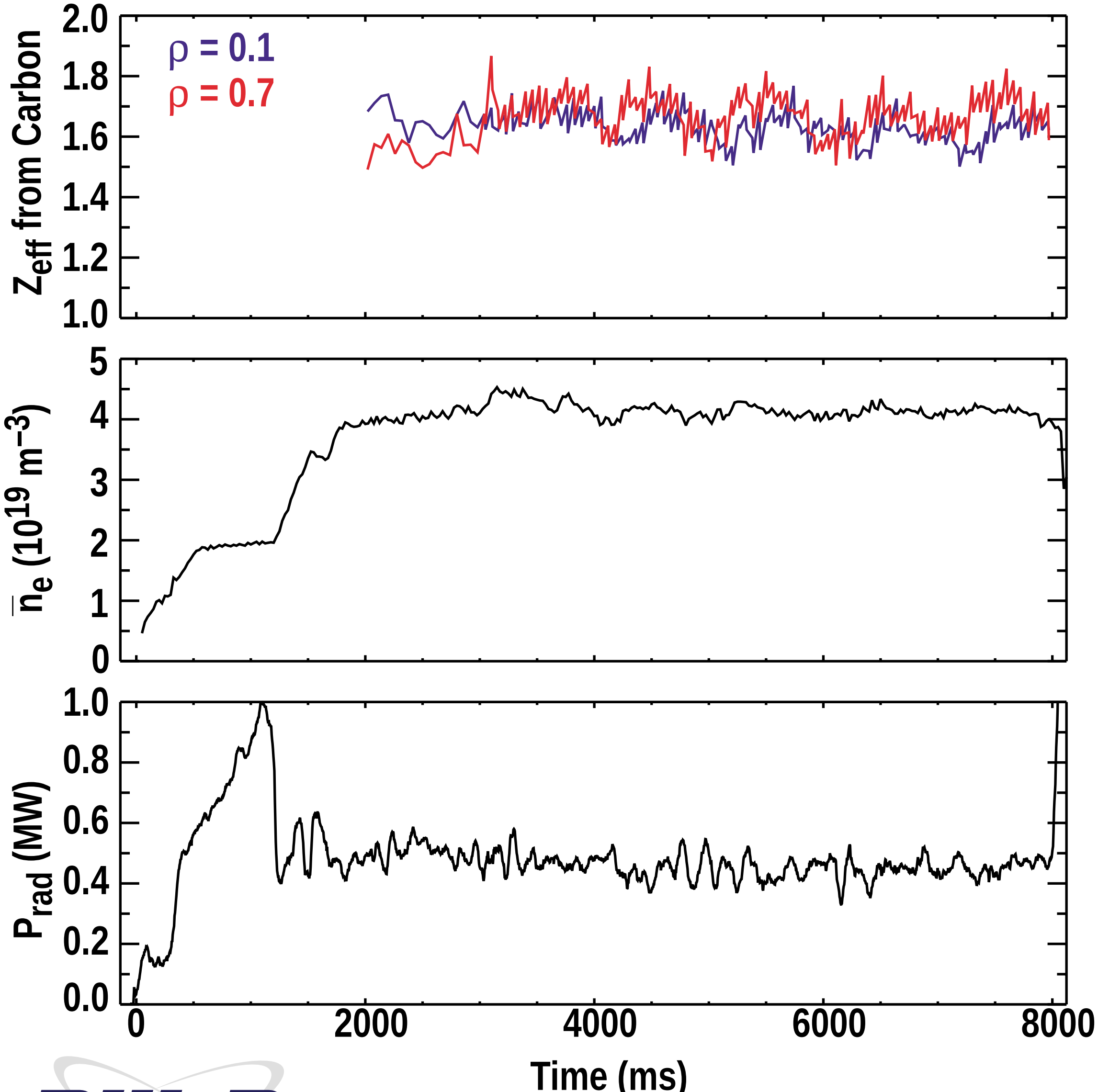
IMPURITY CONTENT OF THE PLASMA IS LOW AND STATIONARY



- The relative concentration of carbon is constant across the plasma
- The core radiated power is only ~10% of the input power
- Metallic impurities are low and not increasing

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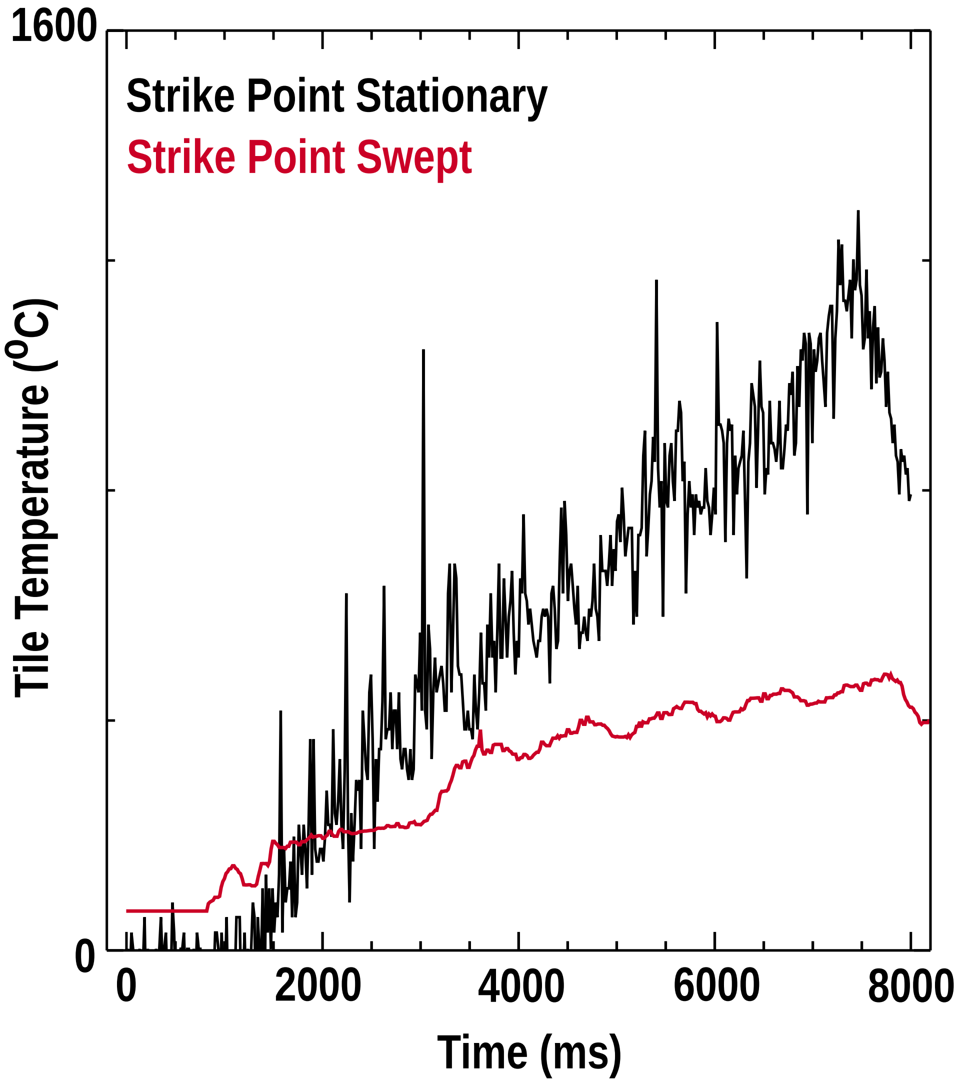
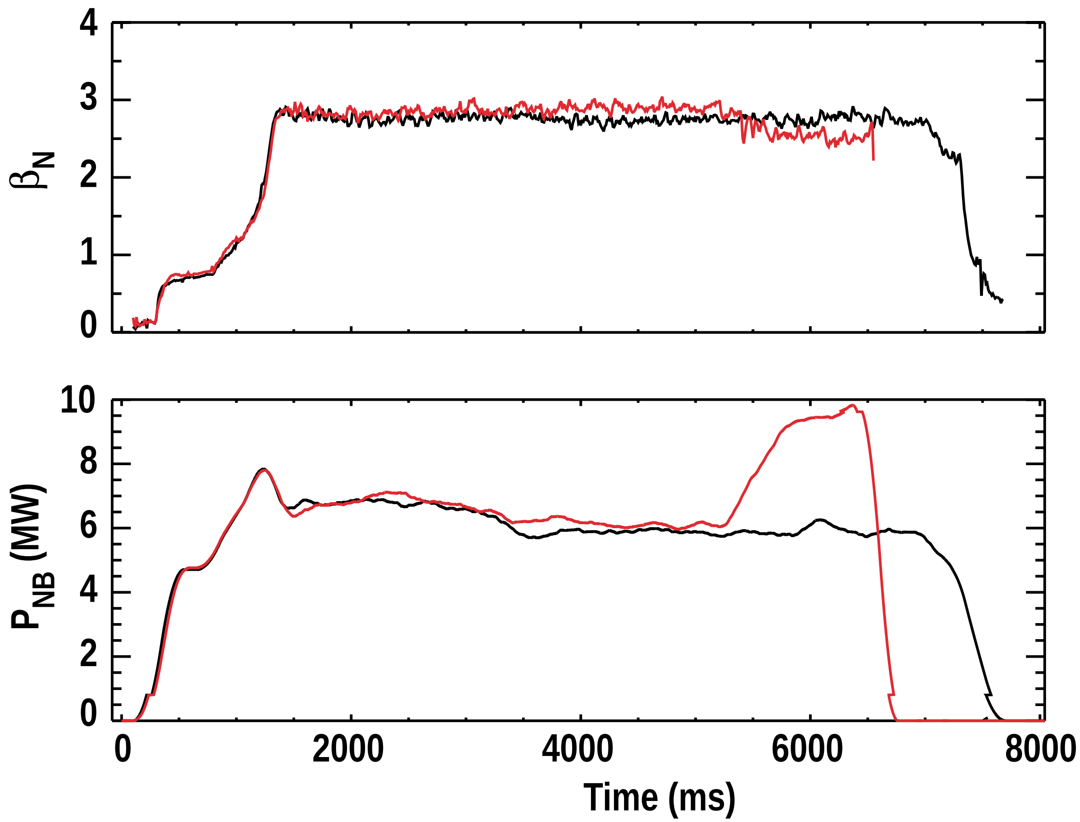
TILE HEATING COULD EVENTUALLY LIMIT DIII–D OPERATION



- Tile edges are measured to be 200°–300°C higher
- Effects of toroidal symmetry are unknown
- Divertor strike point sweeping is effective at keeping the average temperature rise lower
- Impurity seeding radiative divertor experiments are planned
- Despite large erosion and redeposition observed upon entry to the vessel, no evidence of impurity accumulation is seen in the plasma

PREVIOUS EXPERIMENTS INDICATED A β LIMIT AT β_N = 2.9



- Limit was set by m=2/n=1 tearing modes
- Limit was normally non-disruptive. Confinement was insufficient to maintain the requested β_N at full power
- β was requested to be higher from the onset of the feedback control phase

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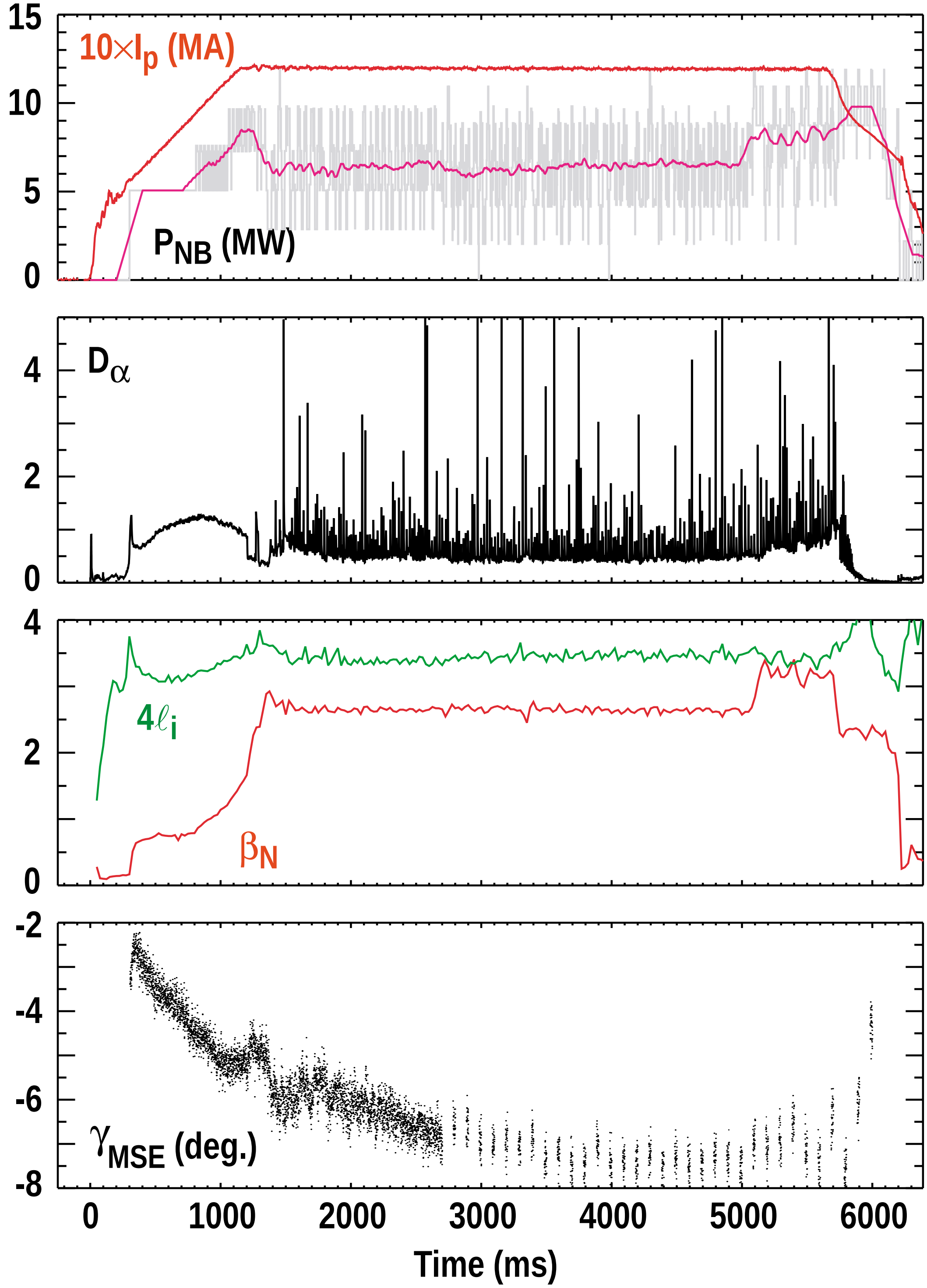
β WAS RAISED TO NEAR THE NO-WALL IDEAL MHD LIMIT LATE IN THE DISCHARGE



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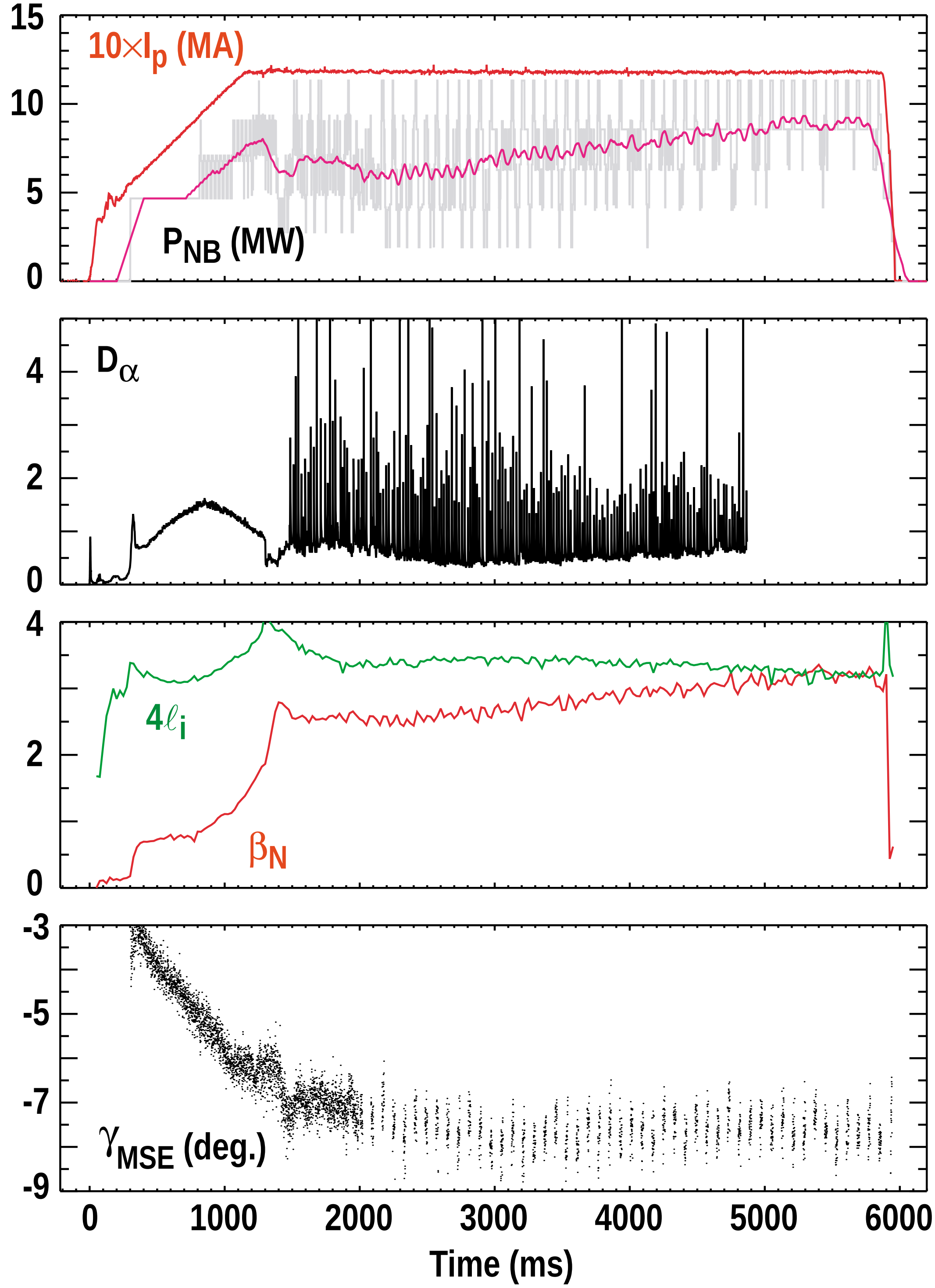
- The β request was a step change at 5000 ms

- The stationary current profile was well-established by this time

- The high β phase was terminated by a vertical field coil power supply fault, not by a plasma instability

- Larger steps in β resulted in an m=2/n=1 tearing mode

β WAS GRADUALLY RAISED TO NEAR THE NO-WALL LIMIT



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- The key to raising β above $\beta_N = 2.7$ is to wait until the current profile is established

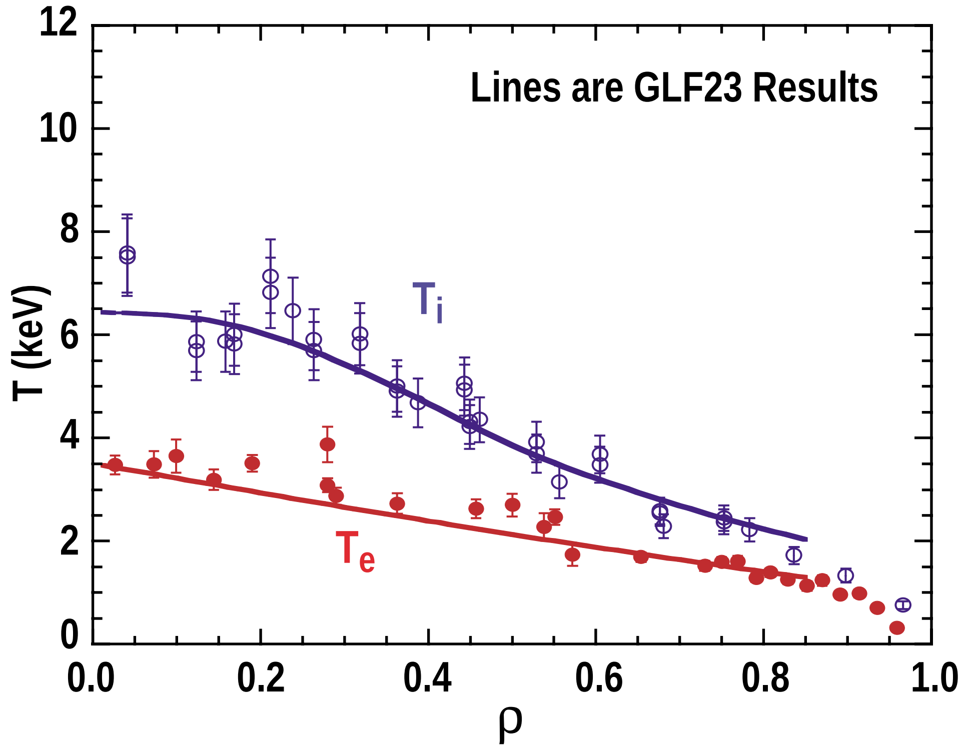
- β request was ramped starting after the current profile was nearly stationary (2400 ms)

- β value and discharge duration were limited by power available on this day not by instability

- No evidence of resistive wall modes is seen. The plasma is rotating sufficiently fast for the wall to provide stabilization

- The current profile is little changed by the increase in β, consistent with the non-inductive component being <50%

OBSERVED HIGH CONFINEMENT IS CONSISTENT WITH DRIFT-WAVE TURBULENCE MODELS



- Lines are GLF23 calculations using experimental density, rotation, impurity, radiation, and neutral beam source profiles. The boundary conditions are taken to be the experimental temperatures at $\rho = 0.85$
- The GLF23 model includes ITG, TEM, and ETG modes and a linear, no-threshold model for the effects of $E\times B$ shear
- $E\times B$ shear stabilization is significant in the model calculations, but the calculated flux is still larger than neoclassical

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CURRENT PROFILE ISSUES FOR PROJECTION TO BURNING PLASMA EXPERIMENTS

- For a burning plasma, there will be a trade-off between fusion gain and ease of obtaining $q_{min} > 1$ with q_{95}
- If the dynamo associated with the m=3/n=2 tearing mode is the key factor which leads to a stationary profile, it is not obvious how this scales to any other plasma
- Active control with counter-fast wave current drive is probably the best solution. The profile of the driven currrent is broad and the heating is central. Any residual tearing modes should have a minor impact on confinement
- Off-axis co-electron cyclotron current drive may also be possible. If the radius where it is needed is too large, the confinement quality may suffer
- Any reduction of neutral beam for FW or EC power will be beneficial in DIII–D for reducing the co-neutral beam current drive and increasing the bootstrap current by lowering T_i/T_e

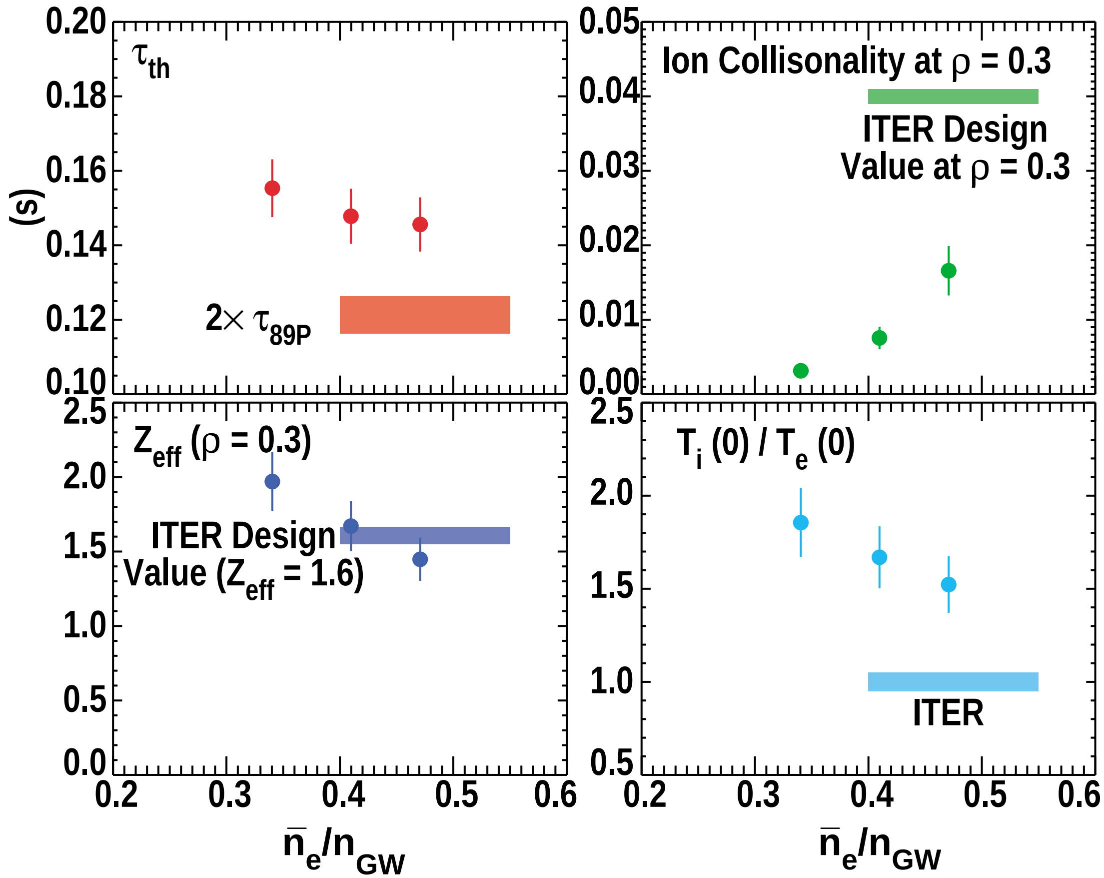
STABILITY ISSUES FOR PROJECTION TO BURNING PLASMA EXPERIMENTS

- The key stability issue is avoidance of sawteeth and fishbones which allows β up to the no-wall ideal limit without tearing modes

- Operation between the no-wall limit and the ideal wall limit may be possible in DIII–D due to plasma rotation. A burning plasma experiment would likely need active mode control. However, conditions projected to Q = 10 in ITER-FEAT have been demonstrated in DIII–D below the no-wall limit

- Stability of the m=2/n=1 tearing mode sets the present β limit. Active stabilization with ECCD has been achieved at low β in DIII–D, but no attempt to raise β following stabilization has been made

TRANSPORT ISSUES FOR PROJECTION TO BURNING PLASMA EXPERIMENTS



- T_i/T_e effect appears to be weak over present range of density
- E×B shear stabilization is significant, but the under-lying transport should still have gyroBohm scaling
- Because of the inconsistency in the β scaling in experiments and the scaling relations, it is difficult to project to a burning plasma

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LIMITS TO DURATION IN HIGH PERFORMANCE STATIONARY DISCHARGES IN DIII–D

- All stationary discharges to date have been limited by conservative hardware protection circuits, not by fundamental physics or hardware limits
- The true limitation at present is the maximum energy which can be extracted from the neutral beam injection system (60–65 MJ)
- At parameters run under stationary conditions (β_N = 2.7, B = 1.7 T), a 10 s high performance phase appears to be the limit
- For operation near the no-wall β limit, discharges lasting 5 s at high performance may be possible
- At maximum field (maximum fusion power), the high performance phase would be relatively short due to limits on the toroidal field coils
- Upgrades of the toroidal field cooling and neutral beam energy handling are under investigation

CONCLUSIONS

- High performance plasmas consistent with high fusion gain (Q = 10) in burning plasma experiments have been operated under stationary conditions in DIII–D ($t_{dur} > 35\ \tau_E$, $2\ \tau_R$) with $q_{95} = 4.0–4.5$

- The key elements are no β limit due to tearing modes up to the no-wall β limit and much better confinement at high β than predicted by scaling relations

- The high fusion gain at high q_{95} reduces the potential for damage of the tokamak hardware by disruptions at high current