Simulating the ITER Plasma Startup Scenario in the DIII-D Tokamak

by G.L. Jackson

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- **Abstract**

DIII-D experiments have investigated ITER startup scenarios, including an initial phase where the plasma was limited on low field side (LFS) poloidal bumpers. Both the original ITER "small-bore" (constant q_{95}) startup and a "large-bore" lower internal inductance (ℓ_i) startup have been simulated. In addition, ℓ_i feedback control has been tested with the goal of producing discharges at the ITER design value, $\ell_i = 0.85$. These discharges have been simulated using the Corsica free boundary equilibrium code. High performance hybrid scenario discharges ($\beta_N = 2.8$, $H_{98y2} = 1.4$) and ITER H-mode baseline discharges ($\beta_N > 1.6$, $H_{98y2} = 1–1.2$) have been obtained experimentally in an ITER-similar shape after the ITER-relevant startup

DIII-D Experiments and Modeling Have Evaluated ITER Startup Scenarios

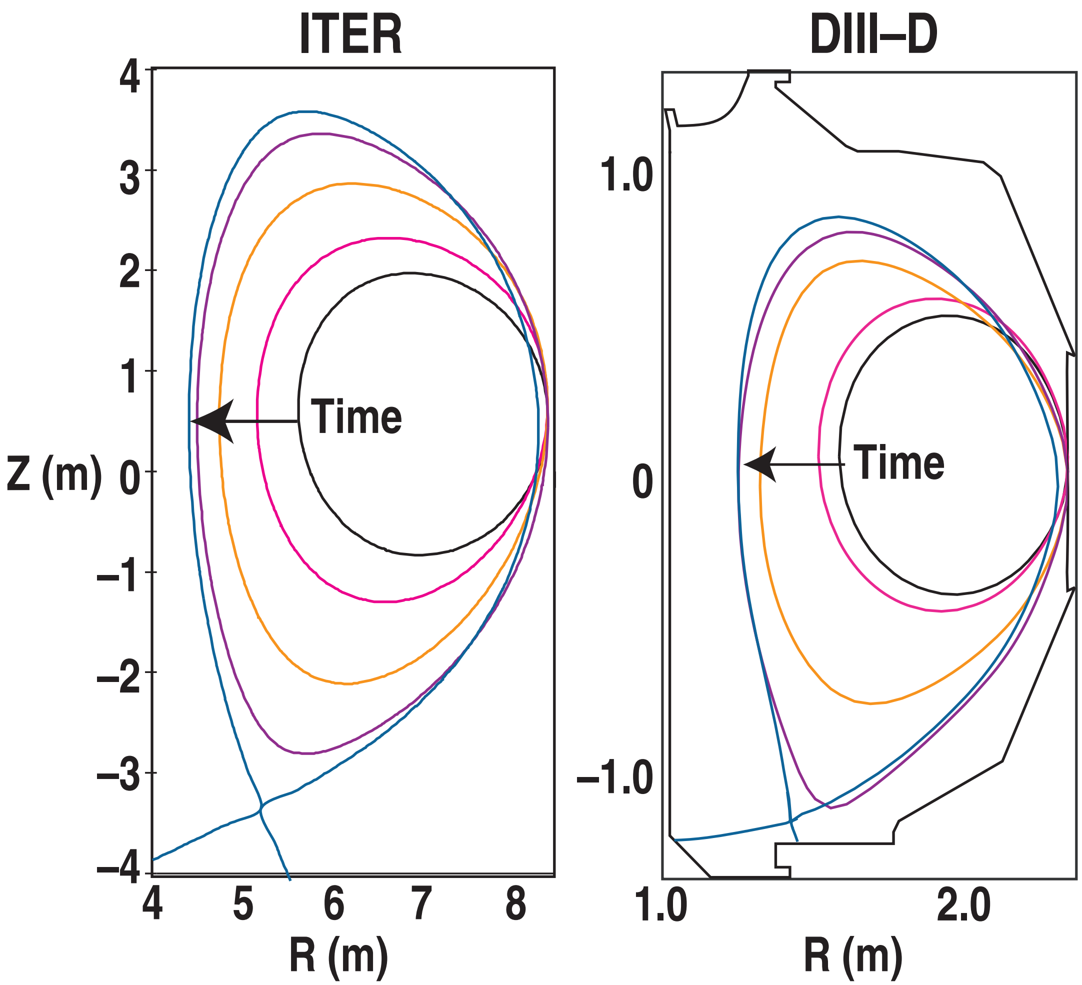
- Baseline startup ("small-bore", constant q_{95}, limited on the low field side)
- Improved larger volume ("large-bore") low field side startup
- High field side comparison (conventional tokamak startup)

Plasma Startup in ITER Must Address Several Issues

Challenge	Implications for ITER
• Plasma rampup while limiting on outer wall bumper limiters	Beryllium limiters close to engineering limits
• Operation near n=0 vertical stability limit (places constraints on maximum ℓ_i) D. A. Humphreys, IT/2-4Rb	Disruptions may occur
• Initiation at relatively low toroidal electric field (~0.3 V/m)	Burnthrough and reproducibility problems
• q_{min} > 1 for advanced inductive (AI) and advanced tokamak scenarios	Startup may be unfavorable for AI

The ITER "Small-Bore" Shape Has Been Evolved in DIII-D

SMALL-BORE ITER BASELINE SCENARIO



SCALING PARAMETERS

- I/aB is constant
- Time is scaled by the resistive time constant, L/R_{plasma} (≈50:1)
- Shape scaled by
  $R_{outer\ limiter}$ (limited phase) ≈3.5:1
  R_0 (diverted phase) ≈3.65:1

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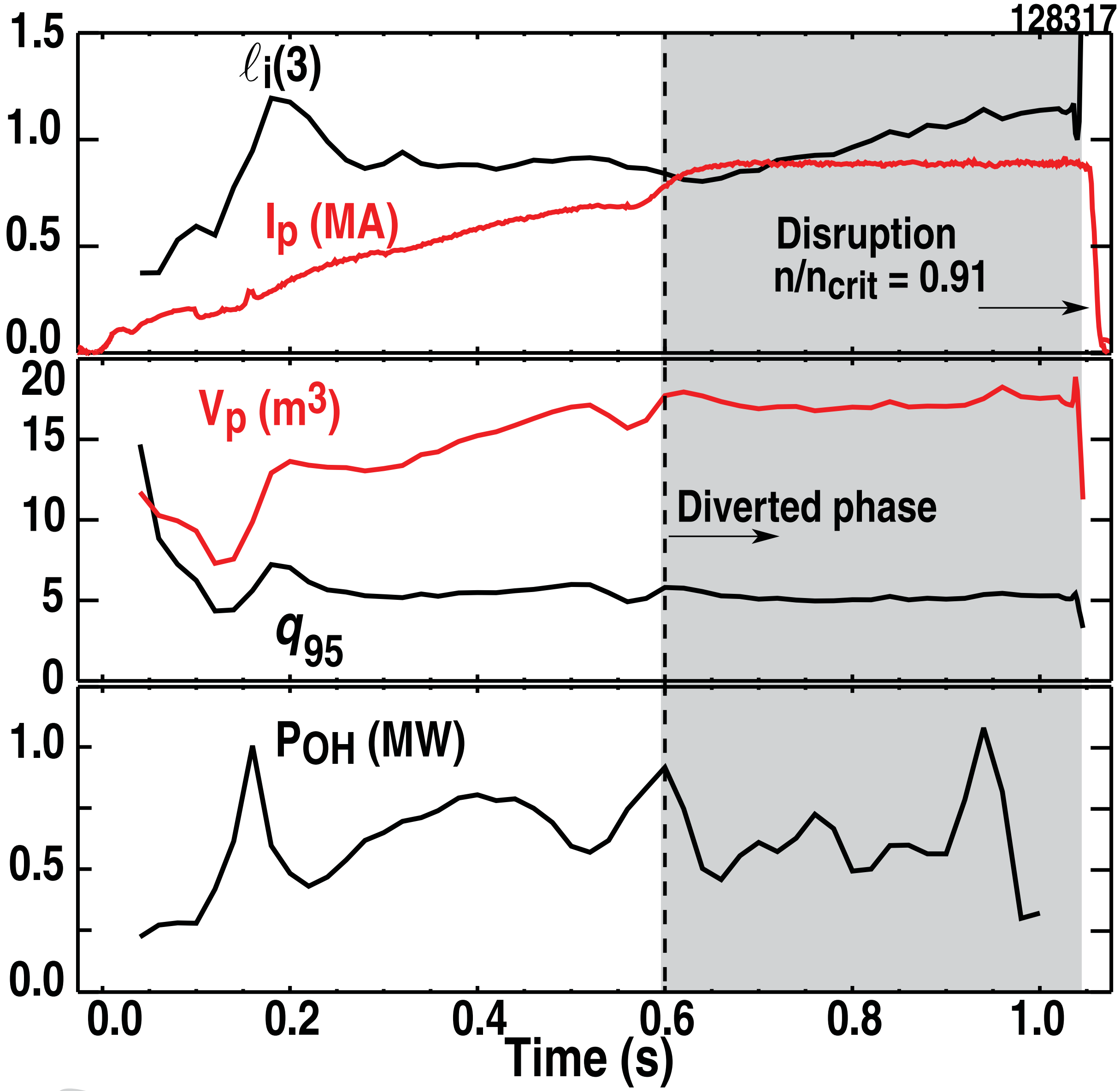
The ITER "Small-Bore" Temporal Evolution Has Maintained $q_{95} \approx$ Constant During the Limited Phase

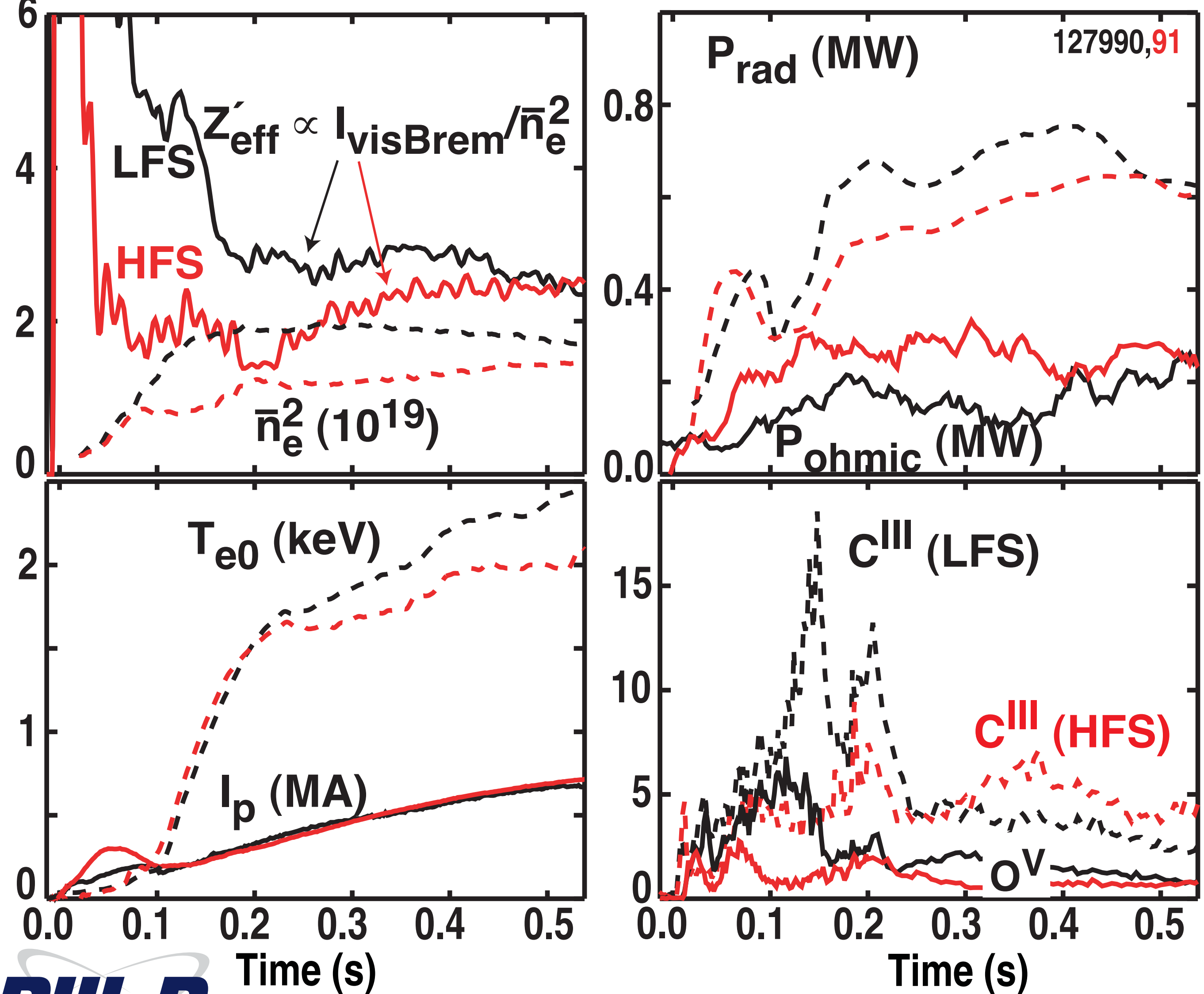


- $\ell_i(3)$ exceeds the ITER design range (0.7–1.0) sometimes leading to a disruption

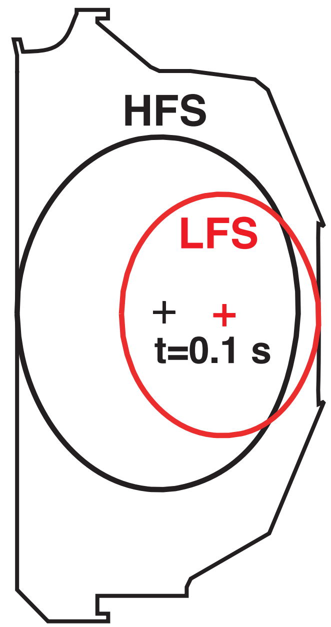
$$\ell_i(3) \equiv 2V\langle B_p^2\rangle/[(\mu_o I_p)^2 R]$$

Small-Bore LFS ITER Startup Scenario Has Been Compared to More Conventional High Field Side (HFS) Startup

HIGH FIELD SIDE COMPARISON

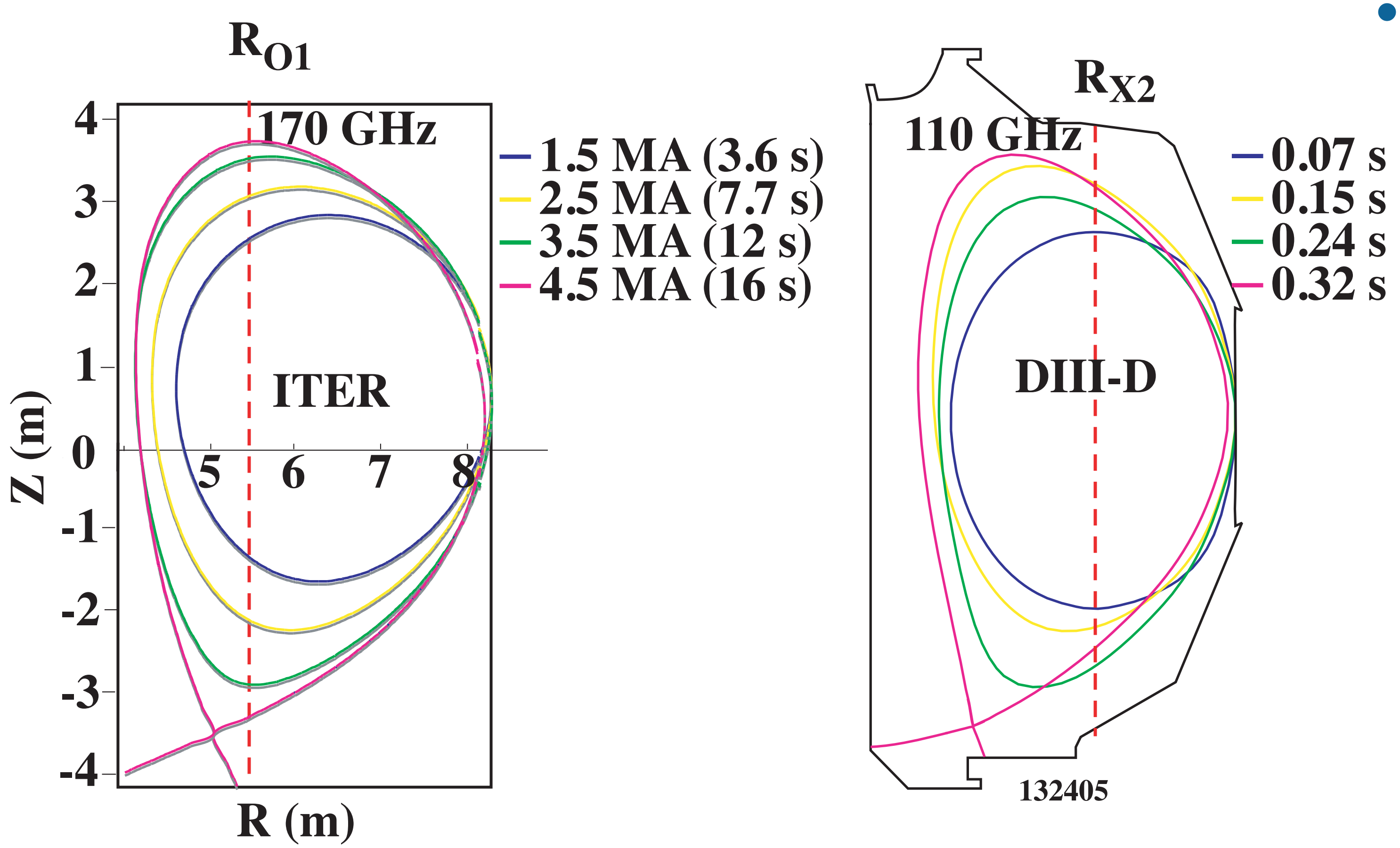


- Z_{eff} is initially higher for the small-bore low field side (LFS) startup, but approaches HFS levels later in time
- Both C^{III} (dashed) and O^{V} (solid) are initially higher for the small bore startup



A New, Larger Volume, Startup Scenario Was Developed, Diverting Earlier in Time to Minimize Limiter Heating

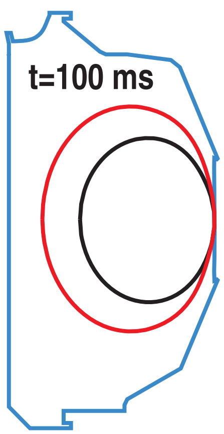
LARGE-BORE ITER STARTUP SCENARIO

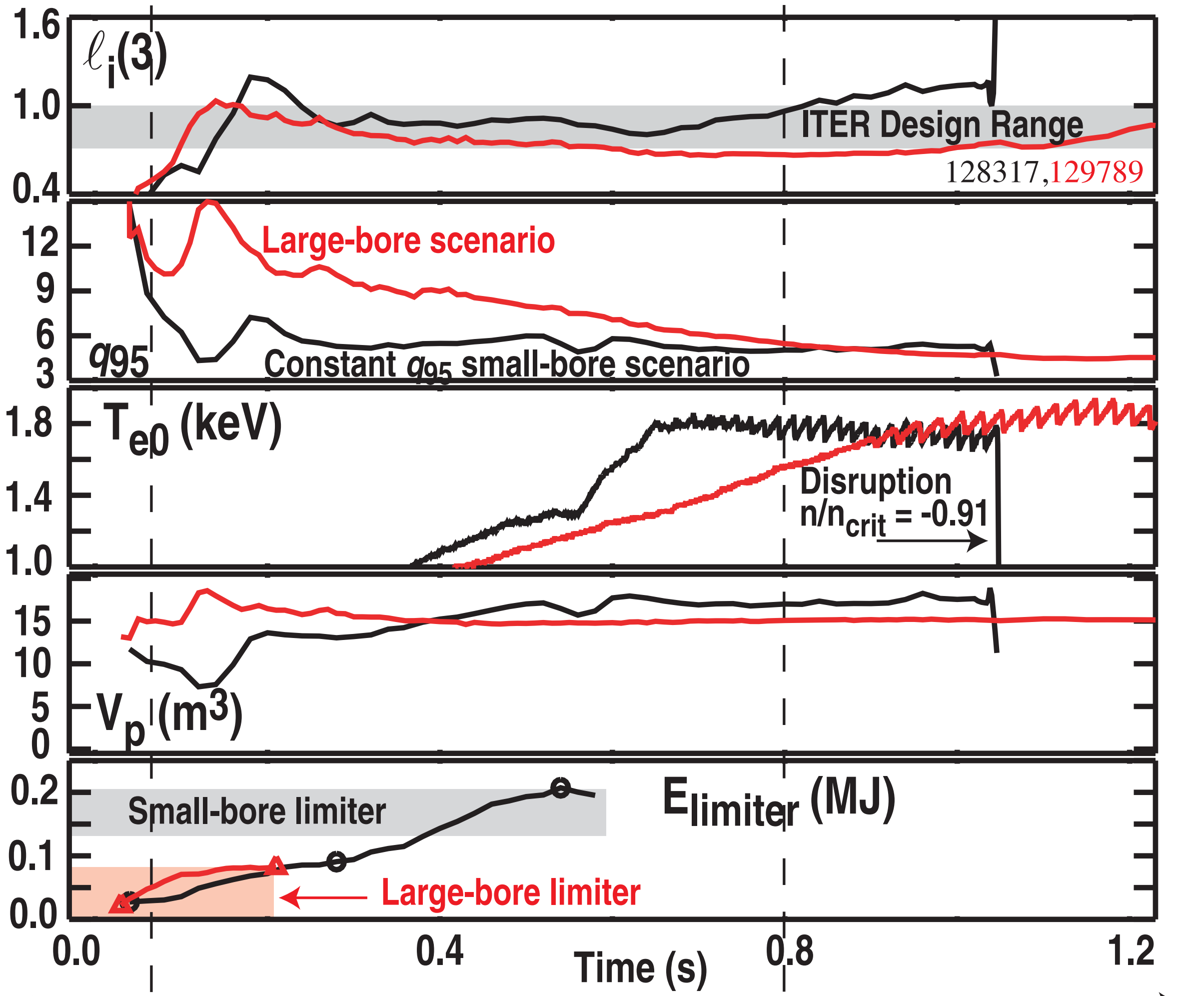


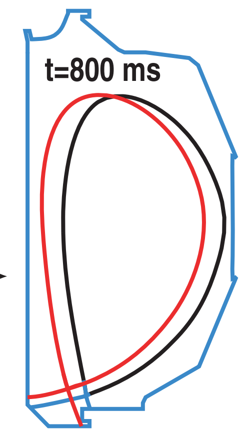
- **The EC resonance location is inside the plasma volume for effective power deposition during burnthrough in both devices**
  - Fundamental O-mode in ITER
  - 2nd harmonic X-mode in DIII-D

- **Temporal evolution of the large-bore ITER startup scenario**

DIII-D Has Evaluated the ITER Baseline Startup Scenario and Helped Develop an Improved ITER Startup







- ℓ_i(3) (large-bore, **red**) is near or below ITER design limit
- Higher q_{min} (delayed sawteeth) with large bore scenario
- Energy to LFS limiters is reduced with earlier divert time

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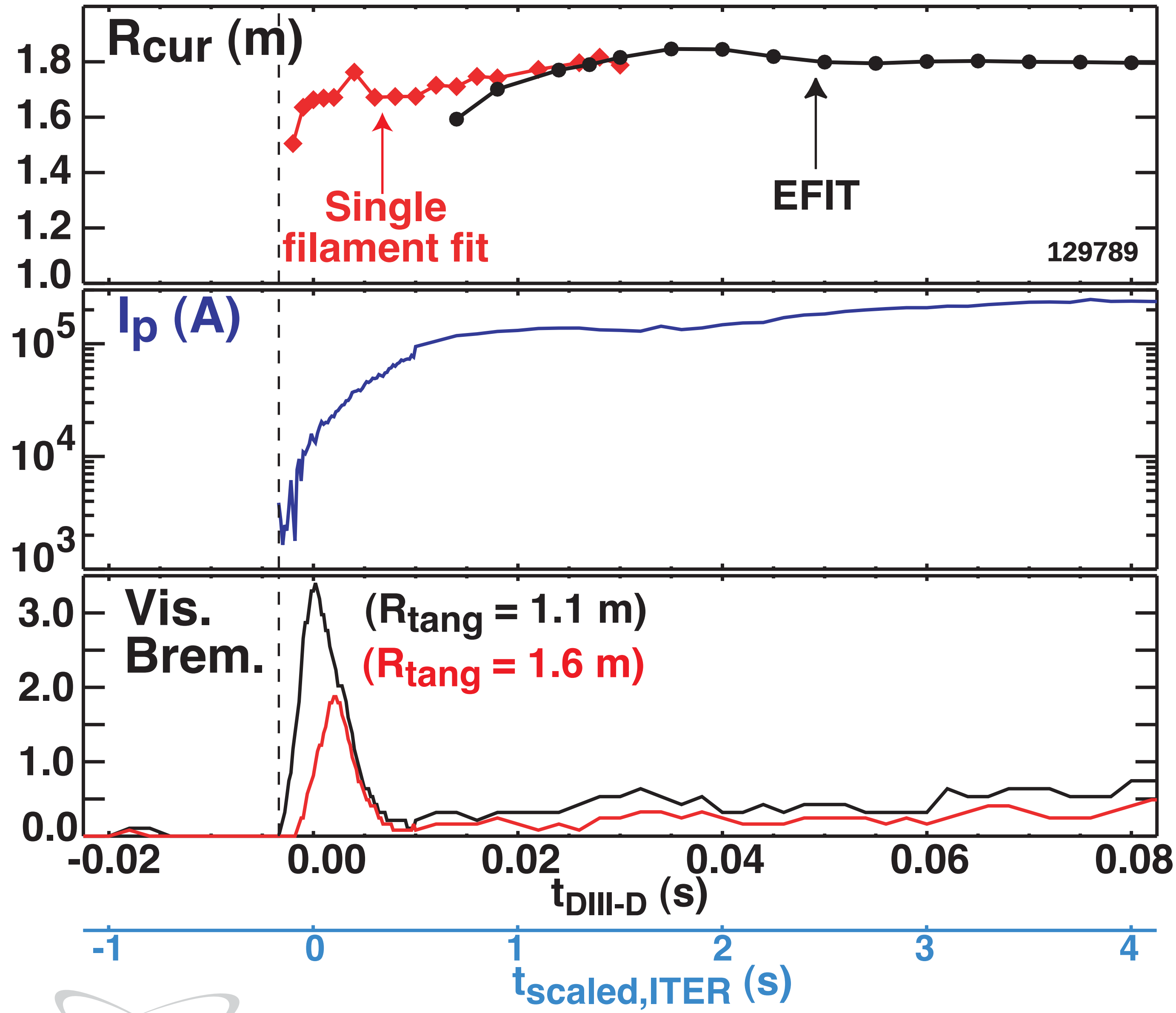
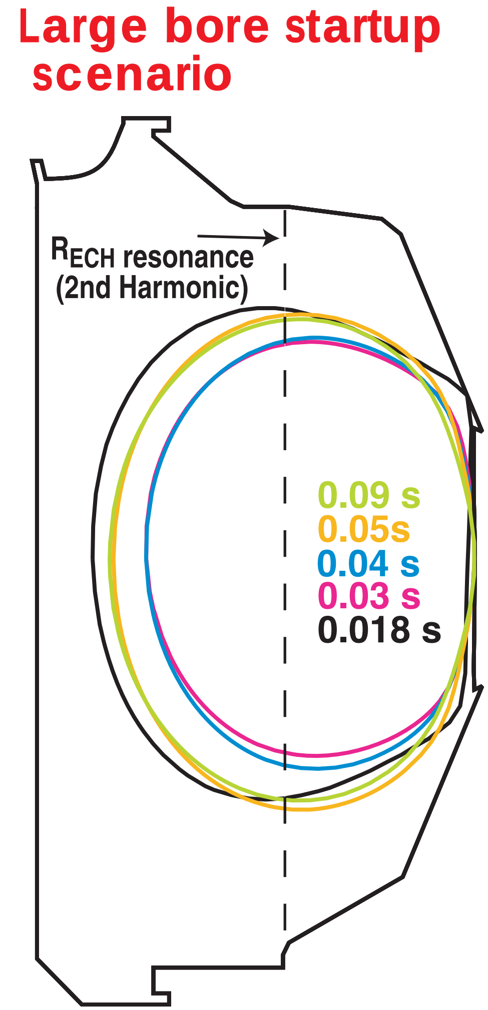
Plasma Formation in DIII-D is on the HFS (R < 1.7 m), But Rapidly Limits on the Outer Wall (<1 s on ITER Time Scale)



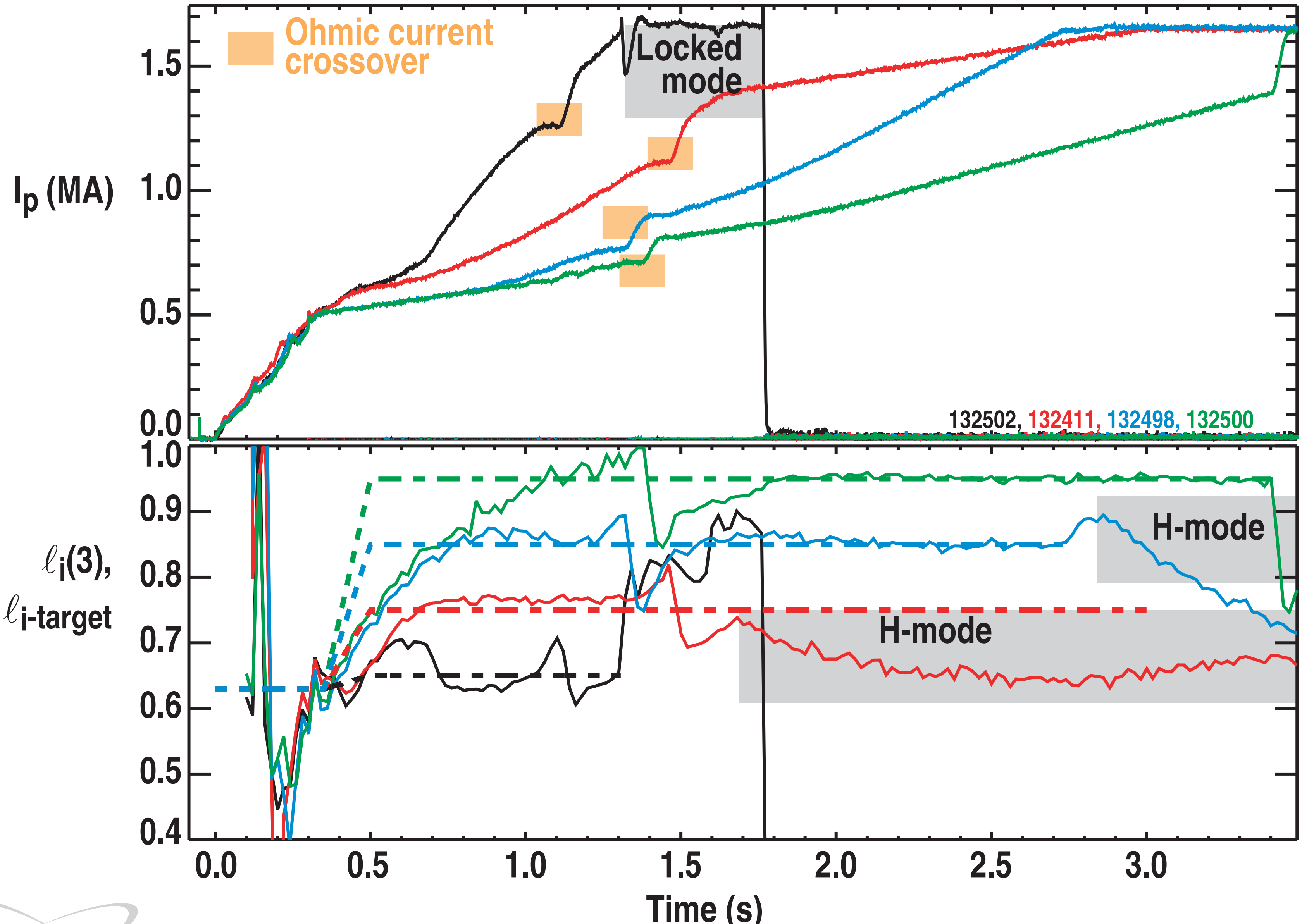


- DIII-D scaled to ITER using resistive current time (1:50)

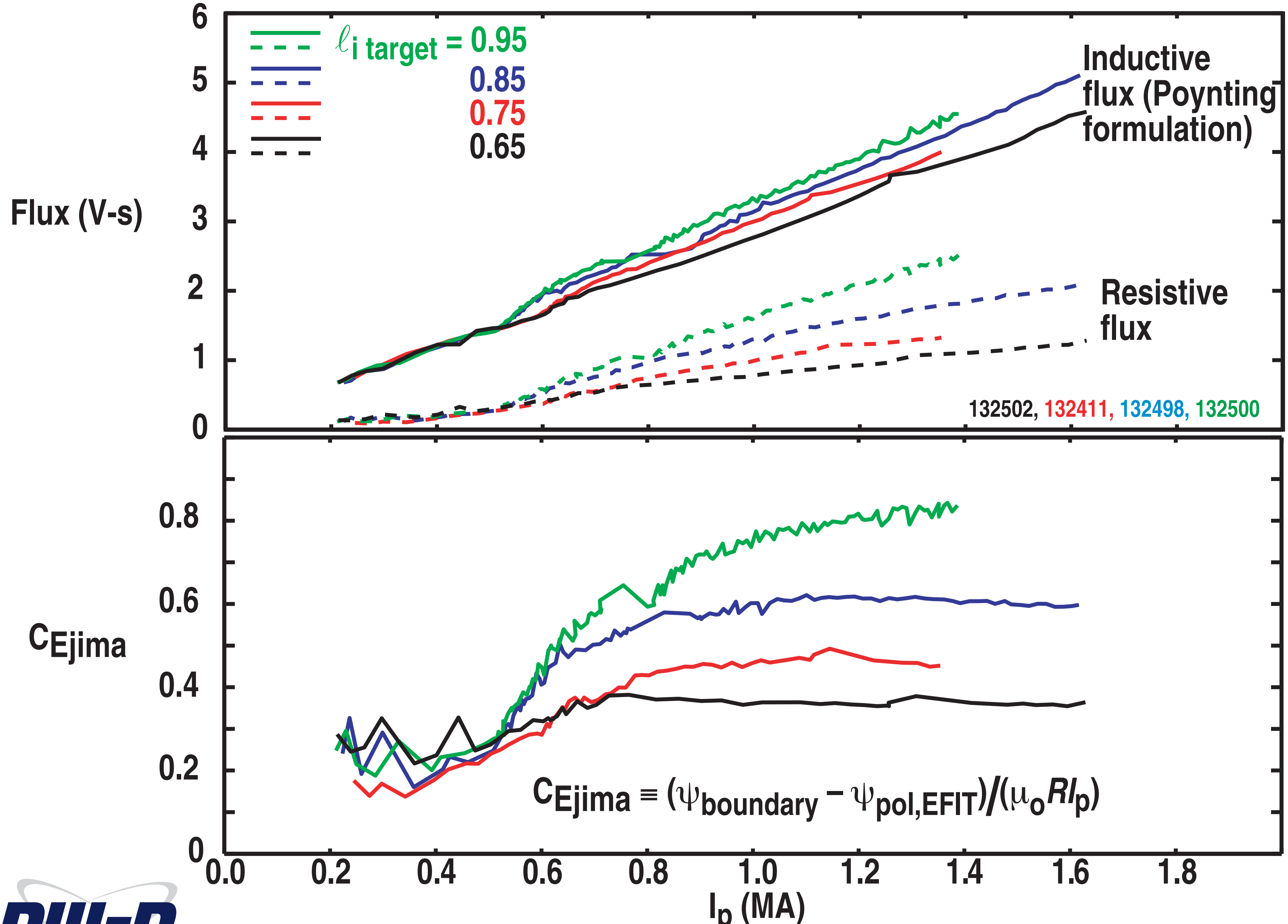
To Remain Within the ITER Design Range, ℓ_i Can Be Controlled During Rampup With a Variety of Techniques

- **Feedback control of the current ramp**
  - Ohmic power supply is the actuator
  - Plasma control system (PCS) calculates $\ell_i(3)$ realtime (rtEFIT)
  - PCS computes an error signal and varies dI_p/dt by controlling power supply voltage
- **Neutral beam heating can affect internal inductance**
  - Heating modifies current profile
  - DIII-D experiments to date have examined NB heating at constant ℓ_i in the large-bore scenario
- **Changes in density can modify internal inductance**
  - Density changes indirectly change temperature and current profile
  - Small-bore DIII-D discharges have shown changes in internal inductance when varying gas puffing and wall conditions

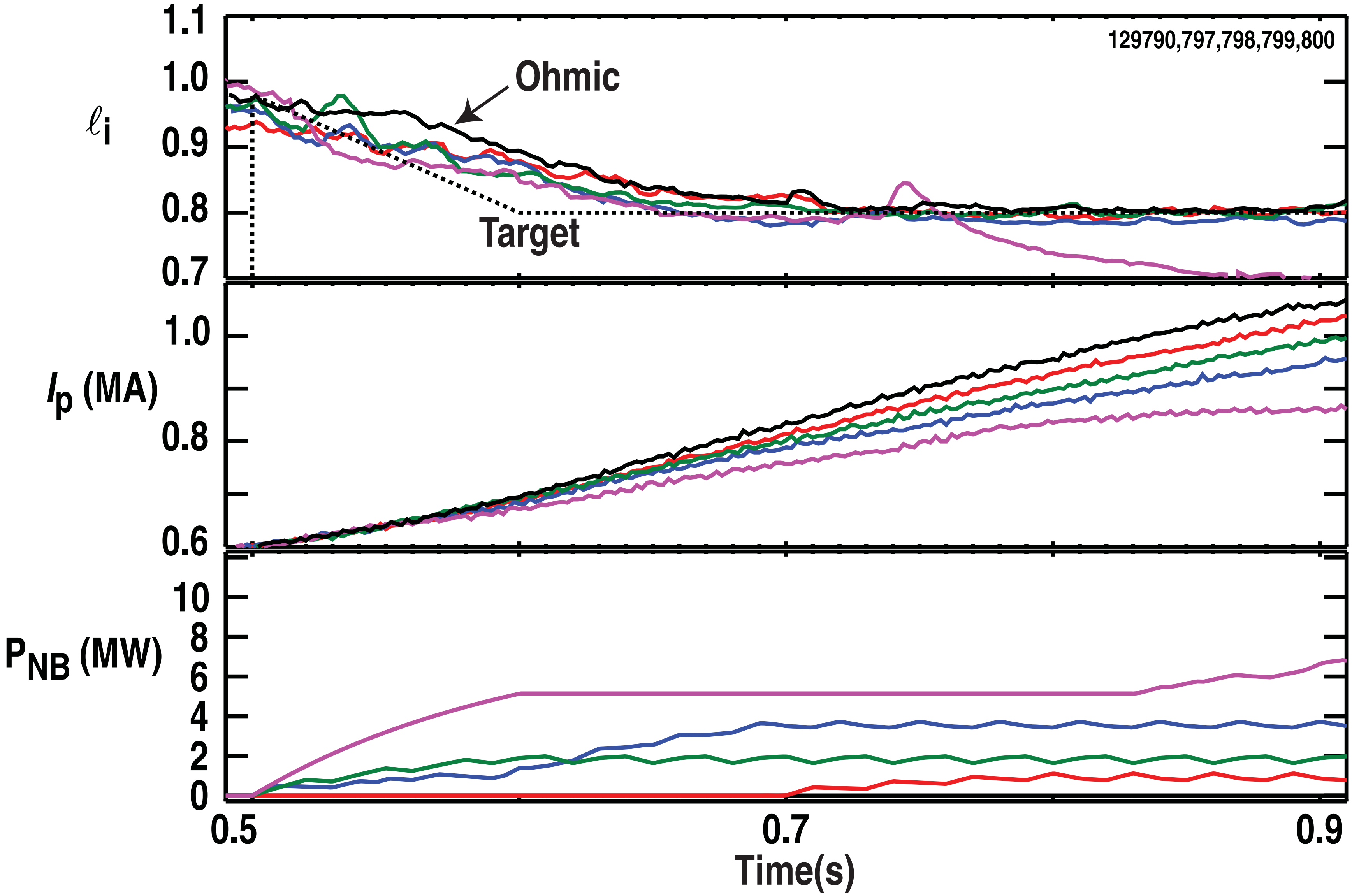
ℓ_i Feedback, Using the $\ell_i(3)$ Calculation in rtEFIT, Has Been Demonstrated in DIII-D



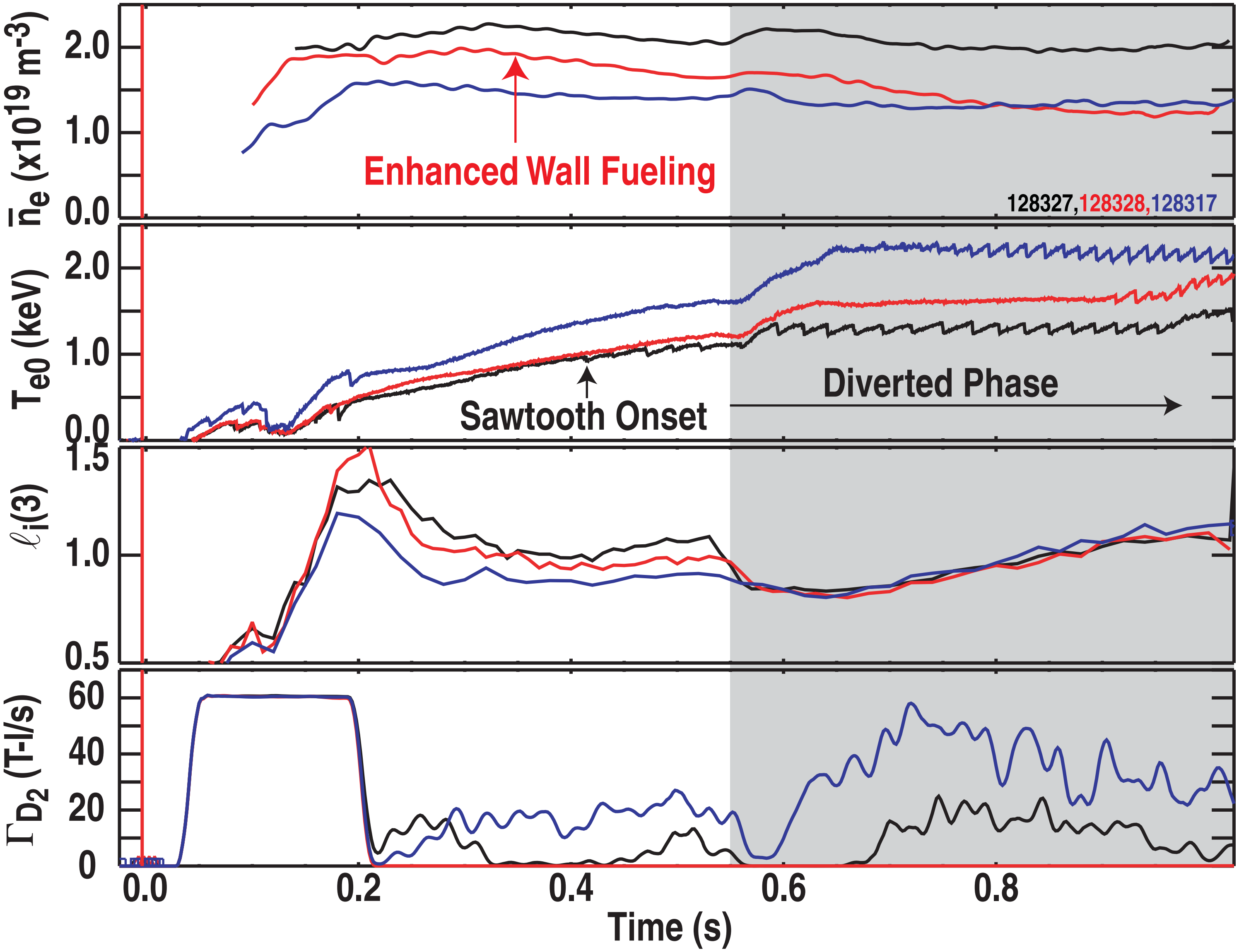
Both Flux Consumption and the Ejima Coefficient Are Reduced at Lower ℓ_i (and Higher dI_p/dt)



Neutral Beam Heating Reduces the I_p Ramp Rate Required for Constant ℓ_i



Internal Inductance is Lower in the Limited Phase as Density is Reduced (and T_e Increases)



- Density can be changed by gas puffing or wall conditioning
- Highest density has earliest sawteeth. Delayed onset with highest wall fueling
- ℓ_i is changed only during the limited phase
- Small-bore density scan is shown

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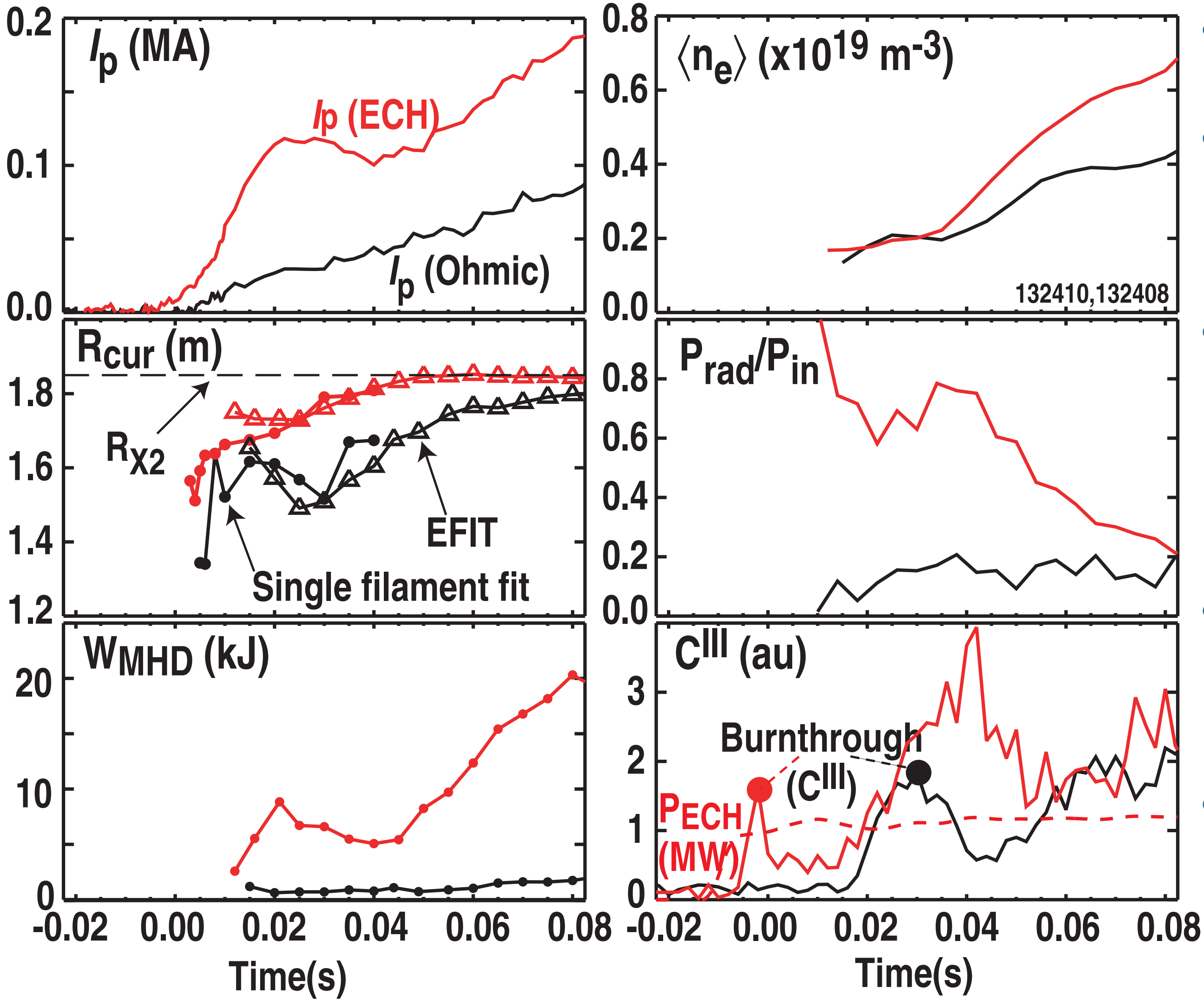
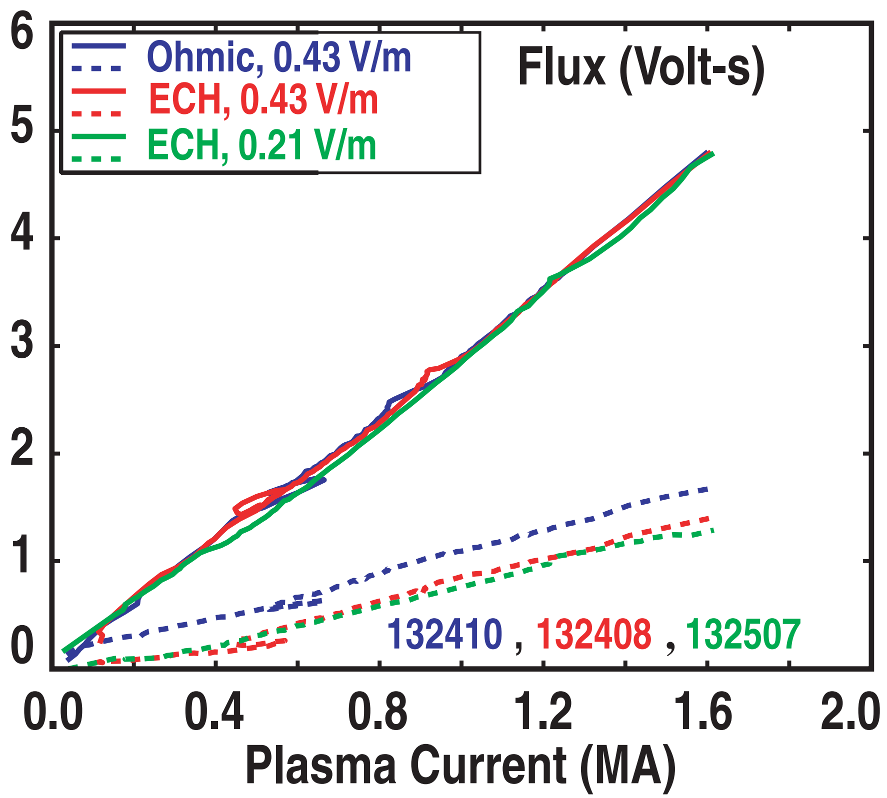
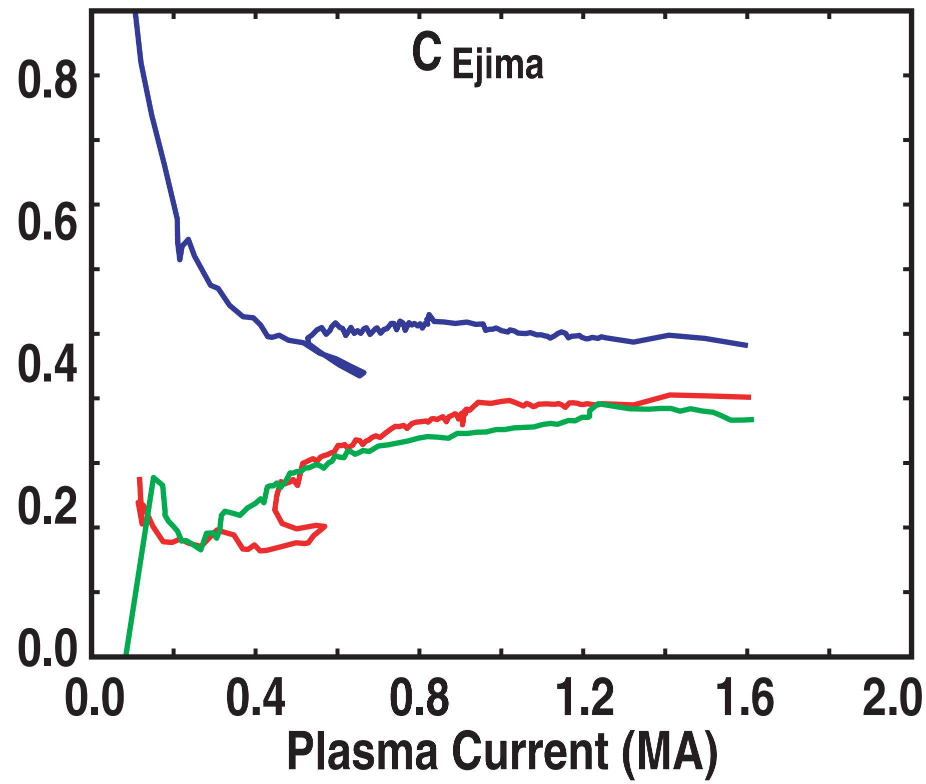
Ohmic and ECH Large-Bore Discharges Have Been Compared at 4.5 V, 0.43 V/m (ITER Design = 0.3 V/m)



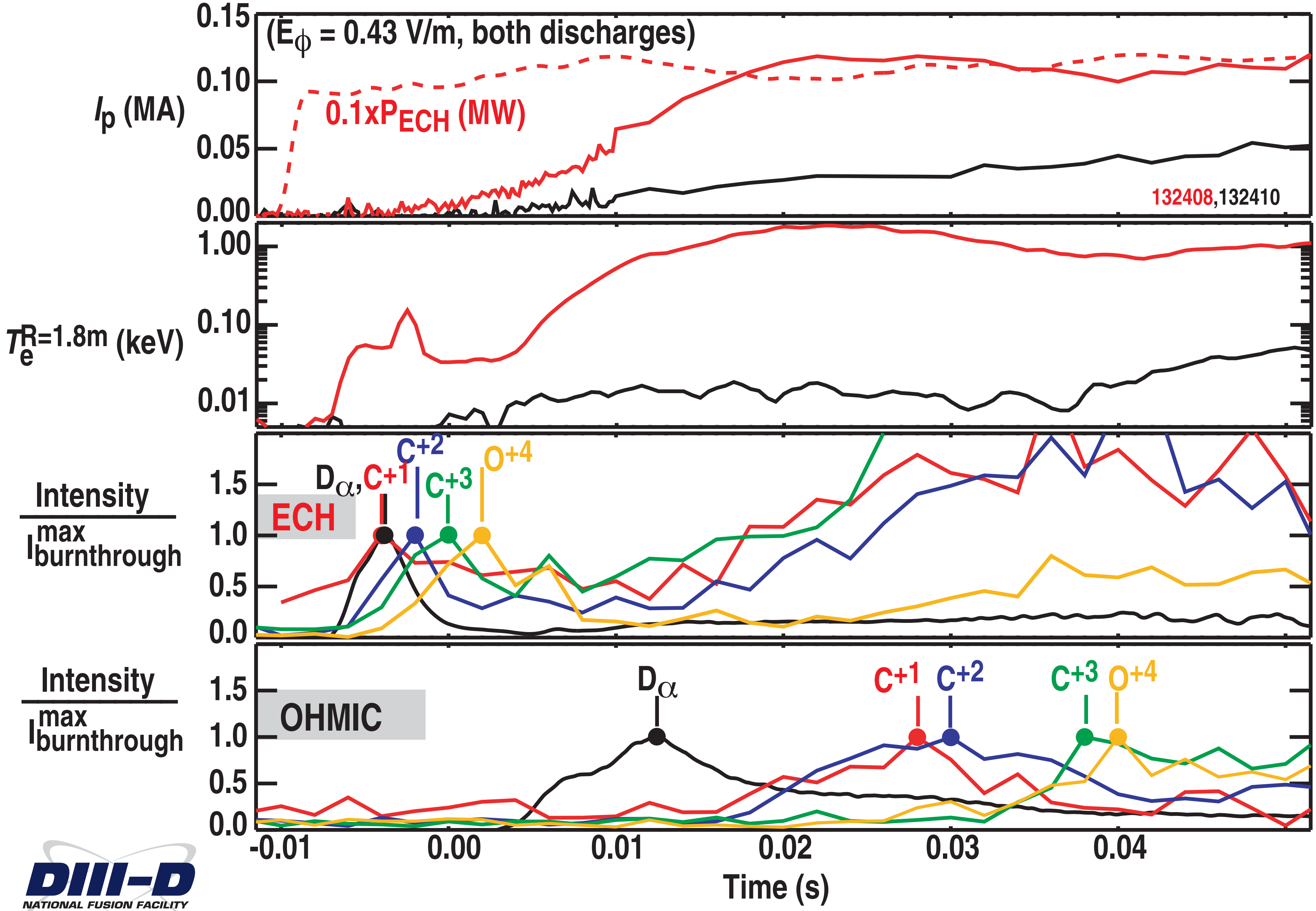
- I_p initiates faster with 2nd harmonic ECH
- Current channel is more outboard and burnthrough more prompt with ECH
- Prompt current initiation and higher W_{MHD} indicate effective ECH power deposition (110 GHz, X2, radial launch)
- Fraction of radiated power is comparable with Ohmic & EC assist as discharge evolves
- EC-assisted startup as low as 2.2 V (0.21 V/m) achieved
  - Ohmic LFS startup at 0.3 V/m still needs to be developed

Resistive Flux Consumption is Reduced With ECH Applied During the Limited Phase





Breakdown and Burnthrough are More Prompt and More Reproducible With EC Assist (Large-Bore)



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GL Jackson/IAEA/Oct2008

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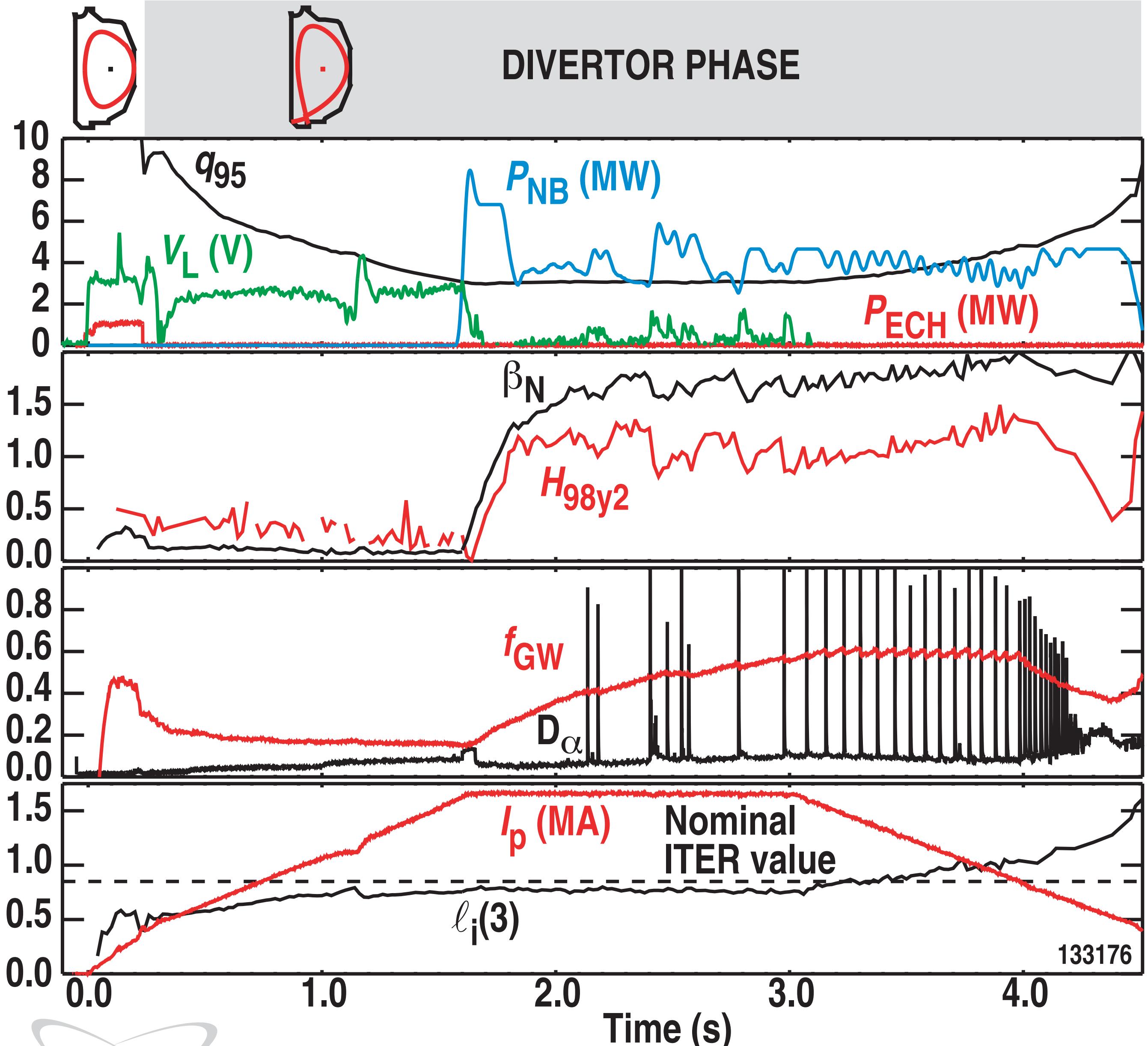
Large-Bore Startup Has Been Successfully Coupled With ITER Burning Plasma Scenarios During I_p Flattop

- **ITER H-mode (baseline scenario 2) achieved**
  - I/aB = 1.4, $\beta_N \geq 1.6$, $q_{95} = 3.0$
- **ITER hybrid mode (scenario 3) has been obtained (Doyle, EX/1-3)**
  - I/aB = 1.1, $\beta_N \geq 2.6$, $q_{95} = 4.1$
- **ELM modification in ITER baseline scenario H-mode with applied Resonant Magnetic Perturbations (*n*=3 I-coils)**
- **Rampdown of H-mode discharge demonstrated**
  - Auxiliary heating during rampdown maintained H-mode and reduced ℓ_i

Large-Bore Startup Followed by ITER H-mode Burning Plasma Scenario Was Evaluated on DIII-D



- **ECH allowed robust initiation**
  - E_ϕ as low as 0.21 V/m
  - ITER design is ≤0.3 V/m
- **Large-bore startup**
  - Limited on LFS
  - Earlier divert time reduced heat flux to LFS limiters
  - Original small-bore scenario had higher ℓ_i
- **Ohmic rampup without instabilities**
  - 15 MA Q=10 baseline is shown
  - 12 MA hybrid scenario also achieved
- **Rampdown experiments initiated**
  - Discharge remained in H-mode to reduce ℓ_i
  - HFS limited when I/aB = 0.24, q_{95} = 14

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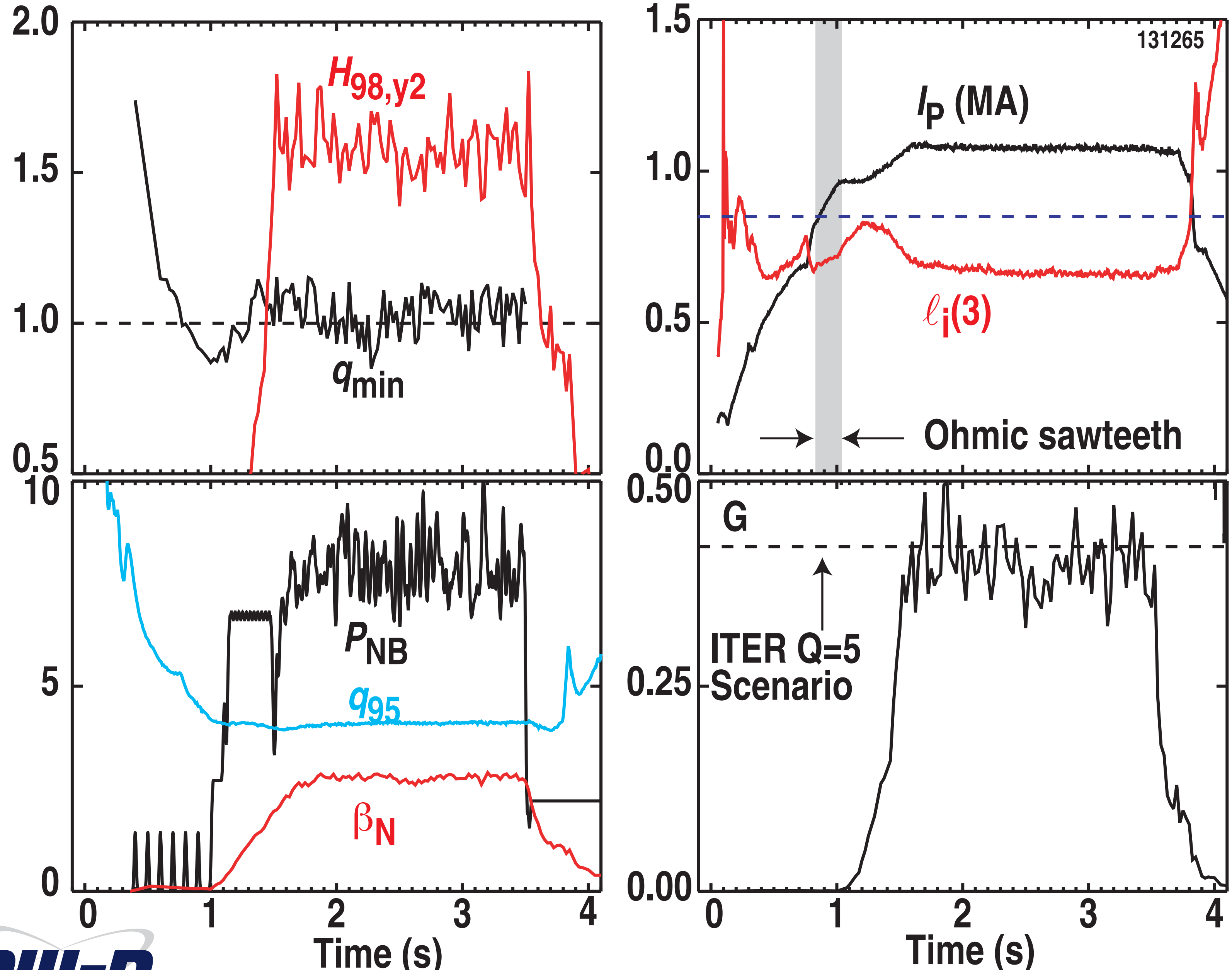
Hybrid Discharges Have Been Obtained Using the Large-Bore ITER Startup Scenario



With hybrid, q_{95} = 4.1 β_N = 2.8

Fusion gain, G = $\beta_N H_{89}/q_{95}^2$

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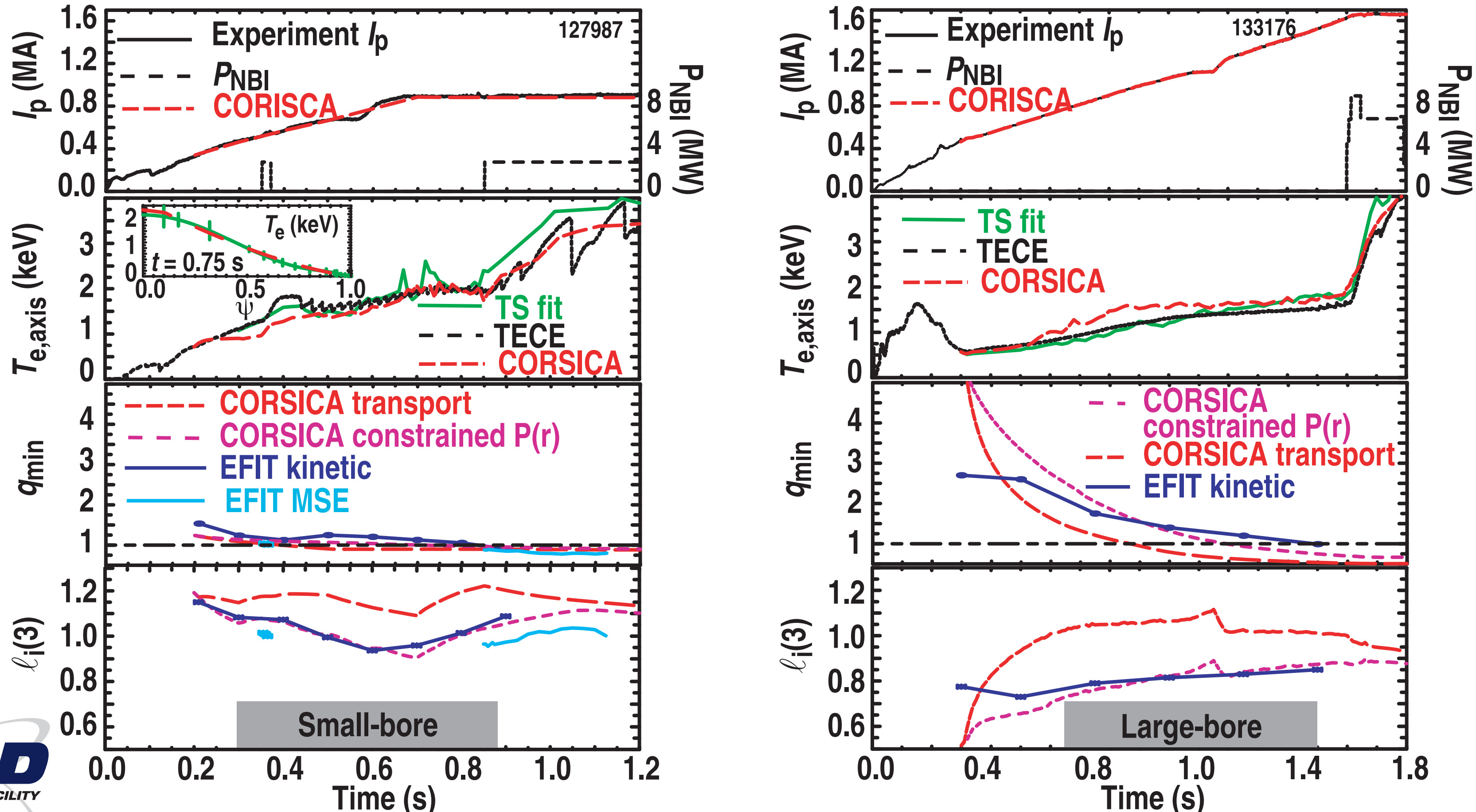
The CORSICA Code Has Been Used to Benchmark DIII-D Experimental Data

- **CORSICA calculates the current profile in two ways**
  - **Transport**. Evolved in time using ITER transport coefficients (initial conditions determined from experimental data)
  - **Constrained P**. Experimental pressure profiles derived from T_e (using Thomson scattering data) as discharge evolves
- **Both small-bore and large-bore startup have been simulated**

(T.C. Casper, PO3.14, 2008 APS-DPP Meeting, Nov. 17–21, Dallas, TX)



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Summary of Results

- **Three ITER startup scenarios have been evaluated**
  - Small-bore LFS (ℓ_i was higher than ITER design range)
  - Large-bore LFS (ℓ_i was within acceptable range. Early diverted time reduced limiter heating)
  - HFS comparison (to compare impurity influx with LFS startup)

- **Feedback (using I_p ramp rate) controlled ℓ_i during startup**
  - ℓ_i was also varied by neutral beam heating and density changes

- **EC assist improved breakdown and burnthrough**
  - EC startup was robust down to 0.21 V/m (below ITER design of 0.3 V/m)
  - Ohmic startup ≥0.43 V/m obtained (further work required to reach 0.3 V/m)

- **Large-bore ITER startup was merged with ITER burning plasma scenarios**
  - Baseline H-mode (scenario 2, Q=10, I/aB = 1.4) was evaluated, including rampdown
  - Hybrid mode achieved (Scenario 3, Q=5, fusion gain = 0.4)

- **Startup modeling (CORSICA code) is being benchmarked with DIII-D data**

Implications of DIII-D Startup Experiments for ITER

- **Large-bore startup is compatible with the ITER scenarios investigated**
  - Early divert time reduces heat flux to LFS limiters
  - ℓ_i is reduced compared to the small-bore scenario (approximately within ITER design limits)
  - ITER H-mode and hybrid burning plasma scenarios achieved with large-bore startup
- **EC assist allows for robust burnthrough and reproducible breakdown even down to 0.21 V/m**
  - Ohmic operating range is more limited
- **ℓ_i feedback is a useful tool to control ℓ_i**
  - Density feedback can also be used, but control may be more difficult
  - ℓ_i can also be controlled by auxiliary heating during I_p ramp, if available for ITER
- **Auxiliary heating during I_p rampup reduces resistive flux consumption**
  - Ejima coefficient is reduced, but overall flux reduction is modest
- **Preliminary modeling results (CORSICA code) indicate somewhat lower edge current evolution than experimentally observed when using transport model parameters from ITER studies**