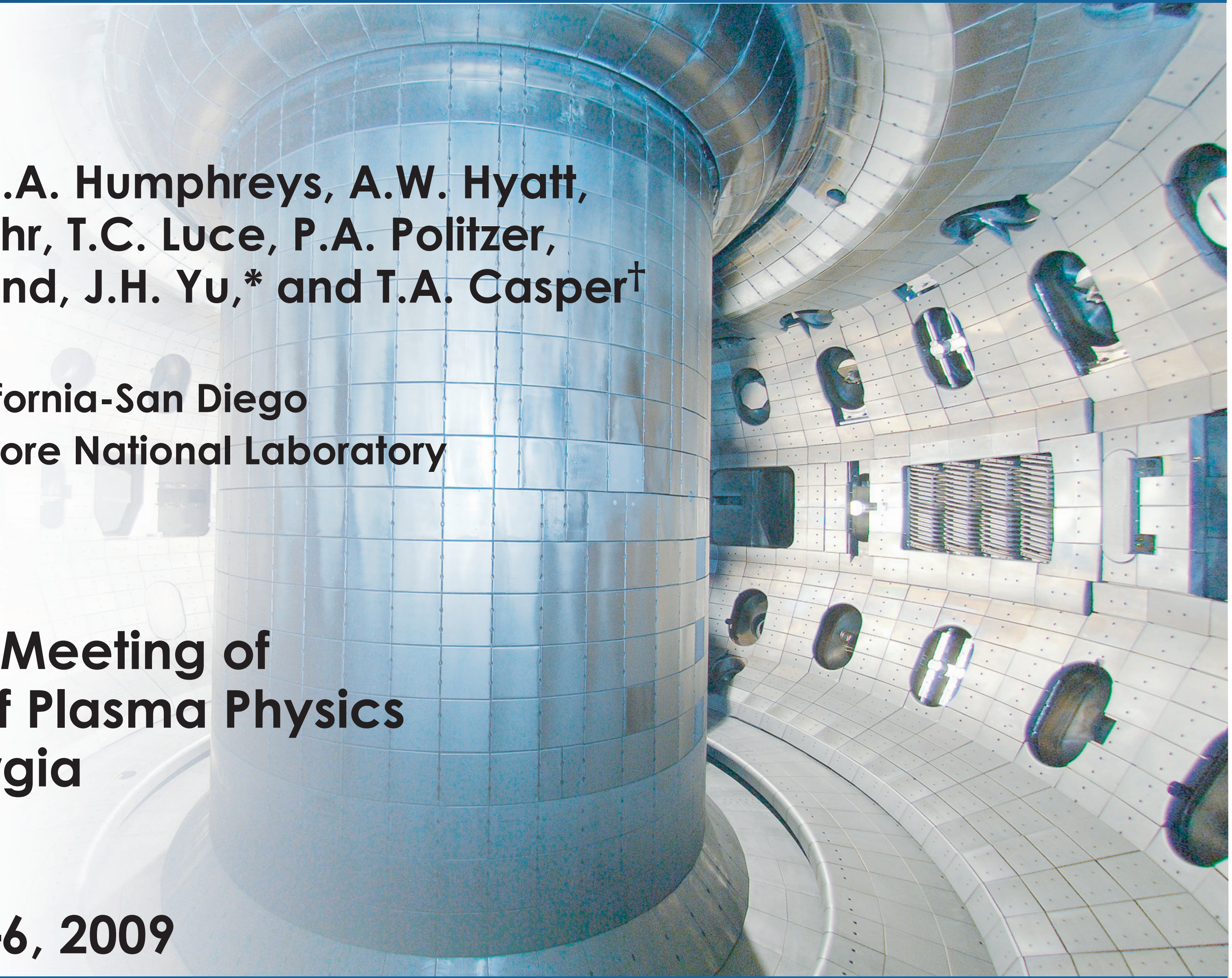
Understanding and Predicting the Dynamics of Tokamak Discharges During Startup and Rampdown



by

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Presented at

Fifty-First APS Meeting of
the Division of Plasma Physics
Atlanta, Georgia

November 2–6, 2009

DIII-D
NATIONAL FUSION FACILITY

GENERAL ATOMICS
133-09/GLJ/jy

Transient Phases (Startup and Rampdown) Place Unique Constraints on ITER, Requiring Improved Understanding

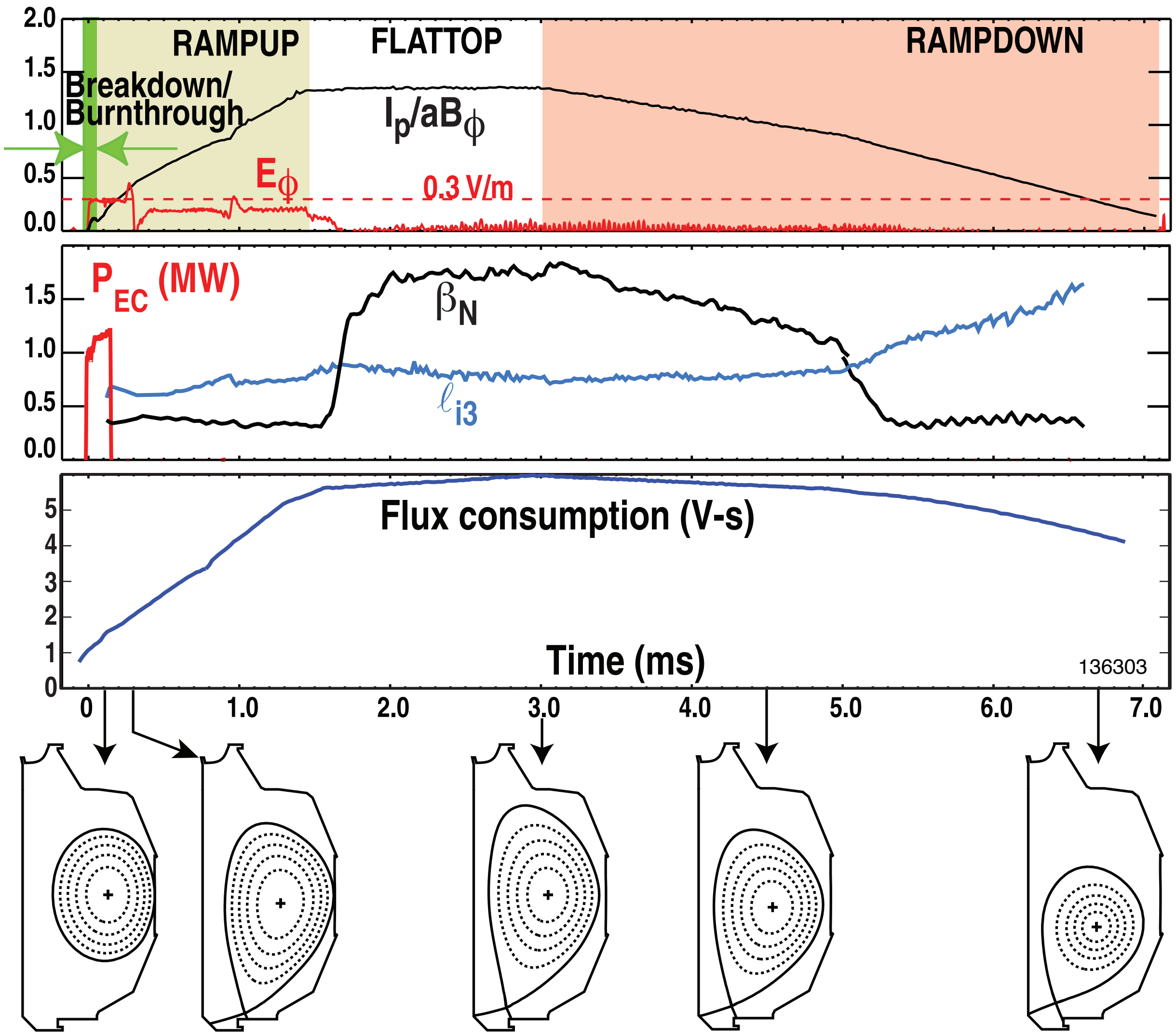
ITER CHALLENGE

- Low inductive electric field and large vessel currents for startup
- Limited Ohmic power for burnthrough phase
- Power supplies limit range of current density profiles
- Minimize flux consumption
- Control heat flux to sensitive areas
- Discharges must operate well within stability limits

DIII-D EXPERIMENTS HAVE INVESTIGATED ALL PHASES OF AN ITER DISCHARGE

- Time scaled by resistive diffusion time (≈50:1)
- Size scaled by machine dimensions of ITER & DIII-D (3.6:1)
- Normalized parameters (I_p/aB, ℓ_i, β_N, and shape) are similar

DIII-D Has Experimentally Simulated All Phases of the ITER Scenario in a Single Discharge



- EC assist allowed robust rampup for $E_\phi \geq 0.21$ V/m
- ITER Baseline H-mode (scenario 2) achieved after OH rampup

Doyle UO4-15, Th. pm

- ECH produced reliable breakdown and burnthrough of low Z impurities
- No additional flux consumption during rampdown
- Strike points held fixed during aperture reduction

Outline

- ITER Rampdown scenarios
- Startup studies and modeling
- Dynamics of breakdown and burnthrough
- Conclusions

RAMPDOWN

Controlled Termination (Rampdown) of Burning Plasmas in Necessary to Mitigate Heat Fluxes and Mechanical Forces

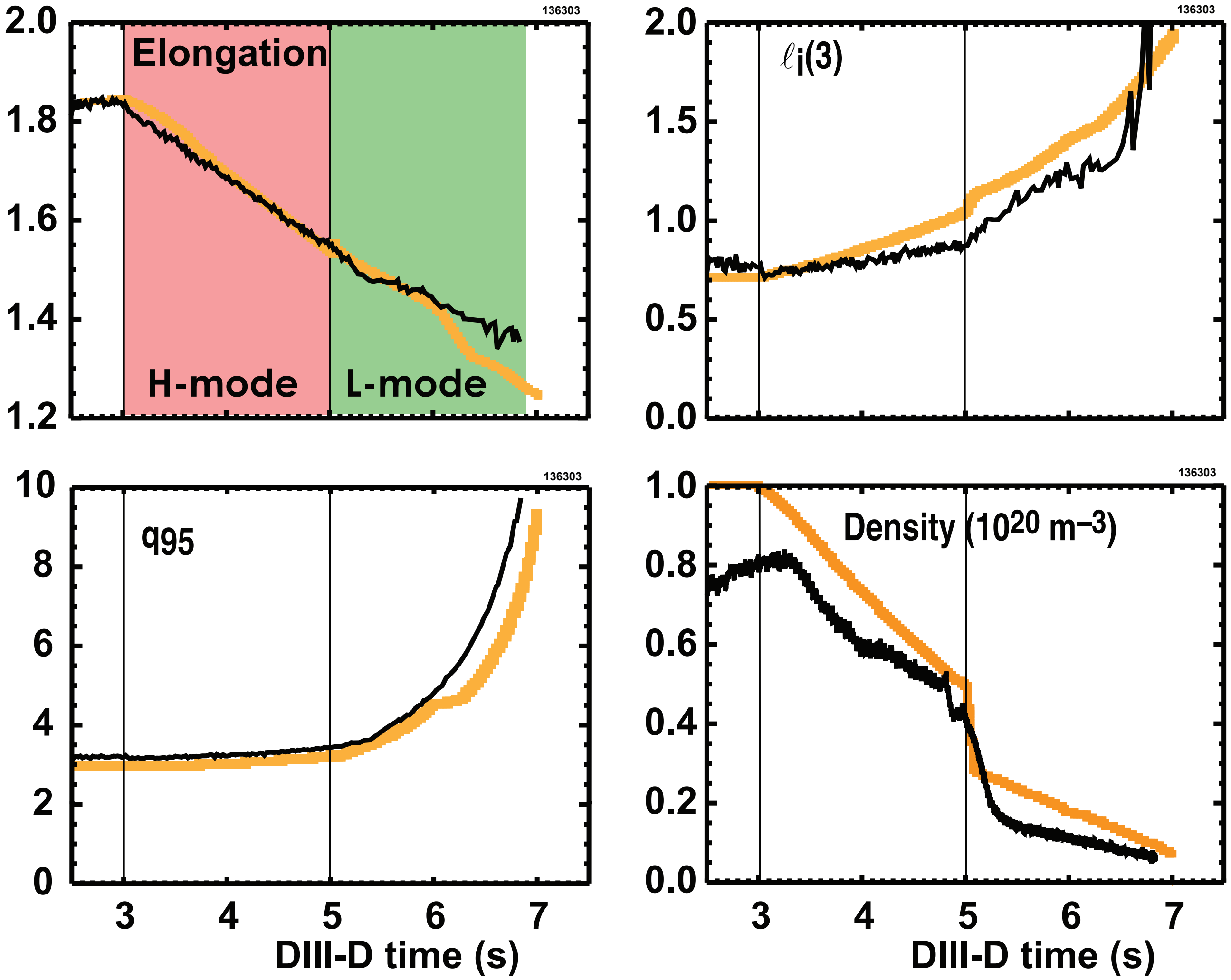
- **Safe and controlled discharge termination becomes increasingly important.**

  Up to 750 MJ is available in ITER (baseline scenario)

Rampdown challenge for ITER
Additional flux and solenoid current limit burn duration
Slow density decay may be near density limit
Strike points remain in divertor region with elongation ramp
Vertical instabilities

P. Politzer (Th. pm) U04-9

The ITER Rampdown Phase has been Experimentally Simulated in DIII-D with Similar κ, β_p, ℓ_i, and q_{95}



black: DIII-D

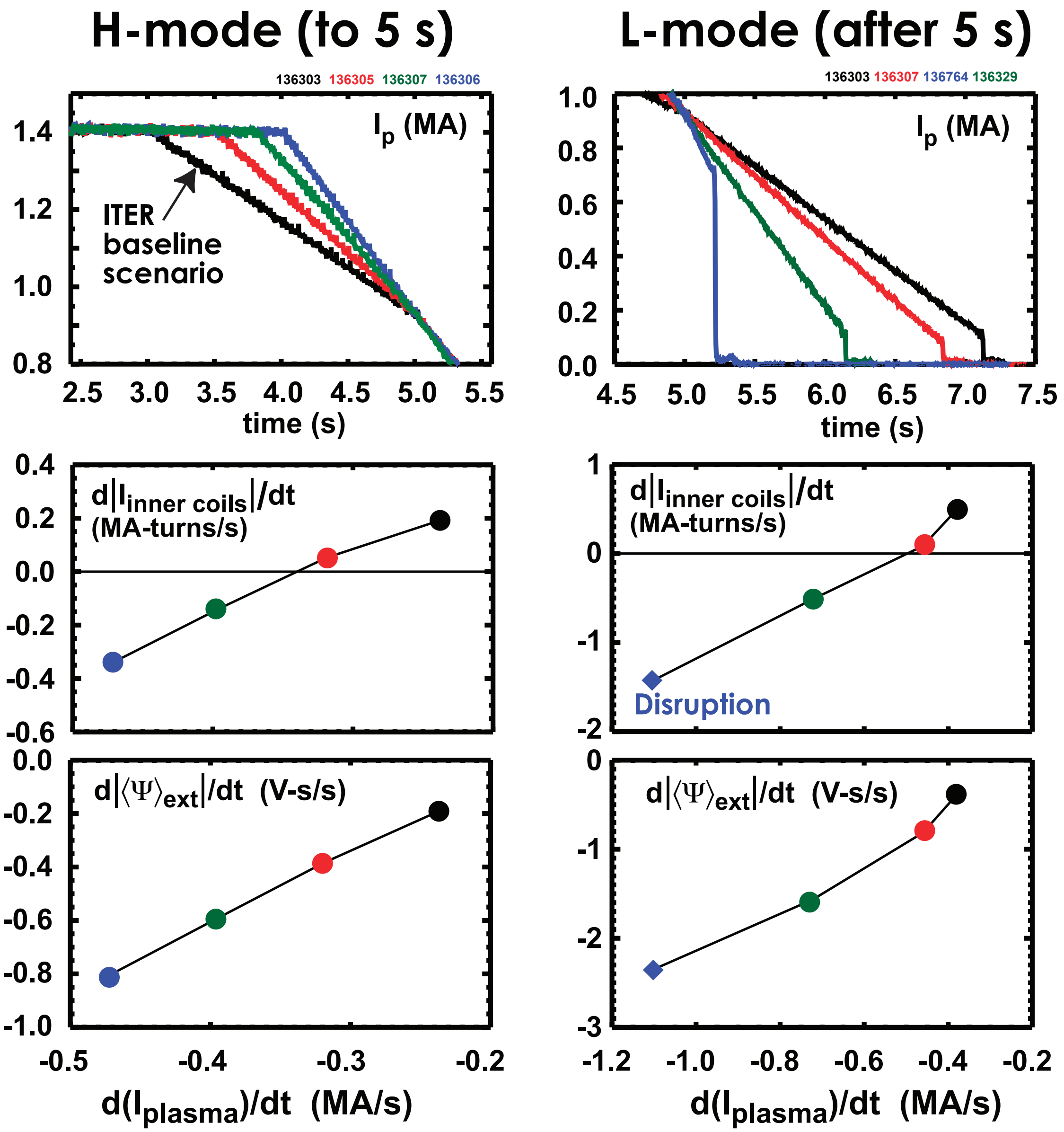
gold: ITER simulation using DINA code

ITER density trajectory is assumed

P. Politzer

Rampdown Rate Scan Indicates Need to Ramp Faster

- **Current ramp rate in both H-mode and L-mode phases must be faster than the scaled ITER reference case (black)**
  - To avoid further increase of the inner coil currents (limit to burn duration in ITER)
- **Too fast leads to disruption**
- **Flux consumption is not a problem**
  - $d|\langle\Psi\rangle|/dt$ always < 0



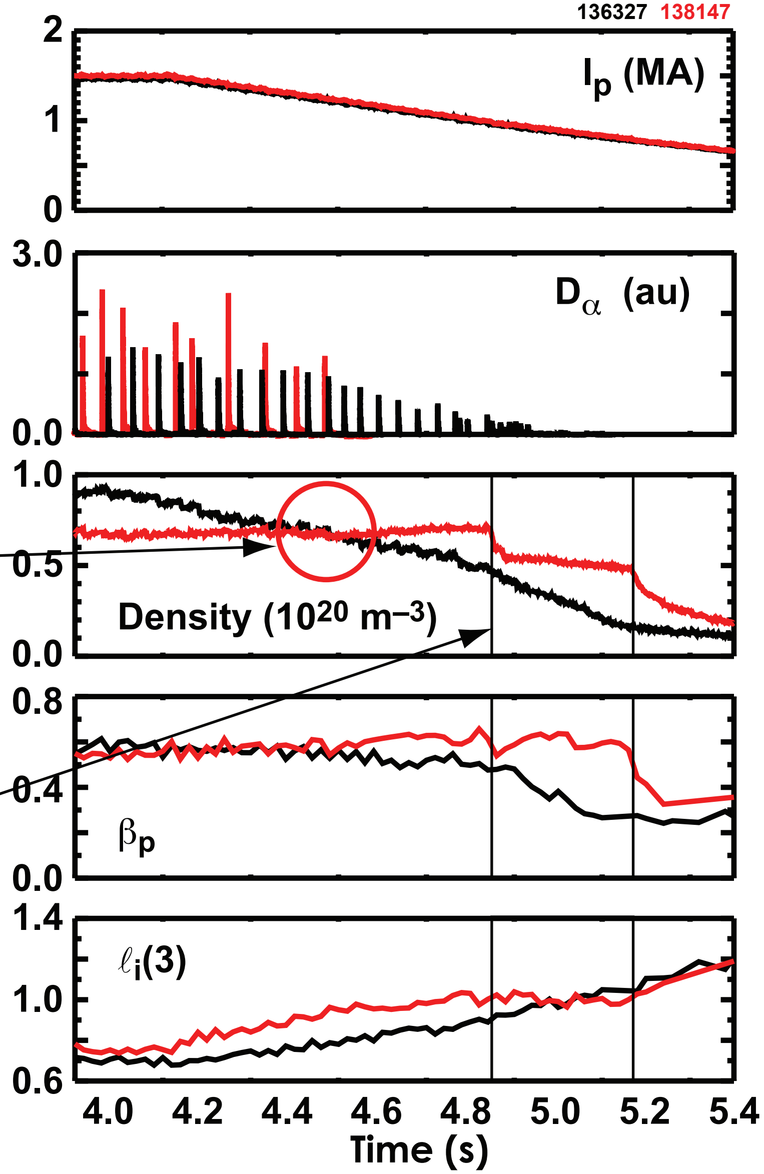
P. Politzer

Full-bore Rampdown Evaluated; Encountered Stability and Density Control Problems

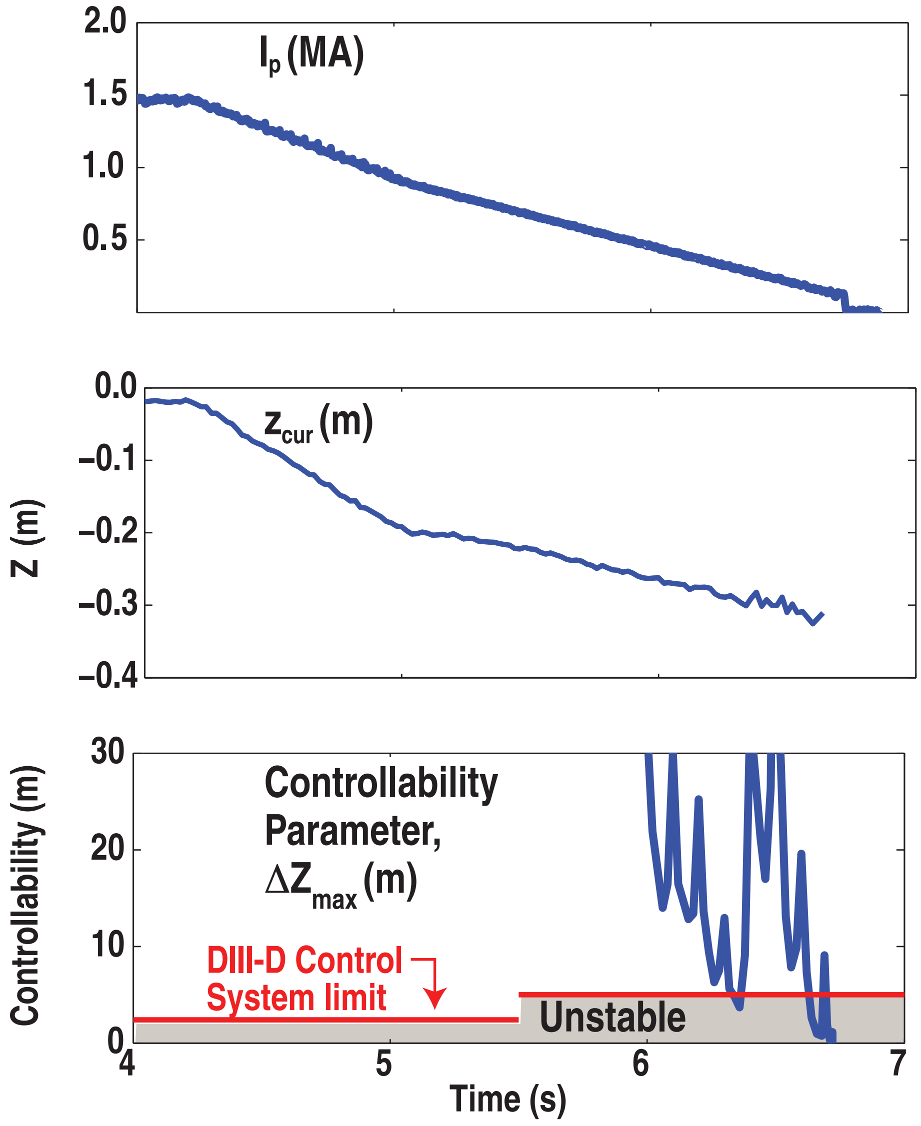
Full-bore:
maintain constant, full-size shape as current ramped down

- **Compare full-bore (red) with ramped κ (black) rampdown**
- **Less frequent ELMs**
- **ELM-free H-mode at 4.5 s**
  - Higher ℓ_i, lower P_{NB}
  - Density increases
  - β_p increases
  - n=1 mode appears and locks

> *Risks density limit and vertical instability during rampdown*



Rampdown without Vertical Instabilities Requires Temporal Changes in the Control Algorithm



- Successful rampdown to I_p < 0.14 MA (<1.4 MA ITER specified value)
- Plasma Control System (PCS) algorithm changed at 5.5 s for low elongation and z_{cur}
- Vertically stable until ΔZ_{max} decreases below DIII-D control limit (set by system noise)

Controlled Termination (Rampdown) of Burning Plasmas in Necessary to Mitigate Heat Fluxes and Mechanical Forces

- **Safe and controlled discharge termination becomes increasingly important.**

  Up to 750 MJ is available in ITER (baseline scenario)

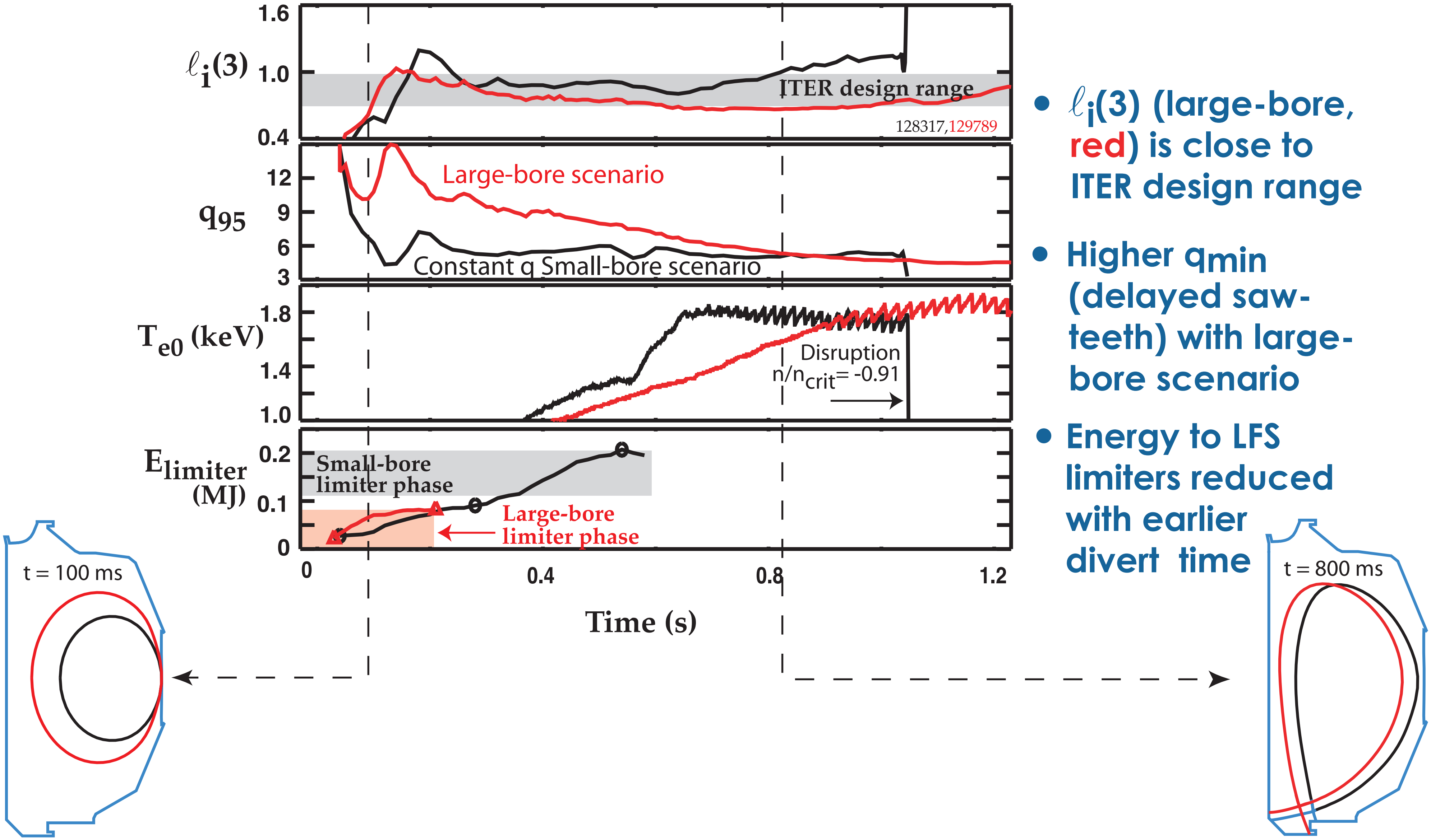
Rampdown challenge for ITER	*DIII-D experimental approach*
Additional flux and solenoid current limit burn duration	**Vary rampdown rate**
Slow density decay may be near density limit	**Vary elongation ramp**
Strike points remain in divertor region with elongation ramp	**Develop algorithms for fixed strike points at low I_p and elongation**
Vertical instabilities	**Quantify stablility boundary and optimize vertical control**

RAMPUP

DIII-D has Explored Rampup Scenarios to Address ITER Challenges

ITER challenge
Heat flux on poloidal limiters
Current profile during rampup
Different current profiles for advanced scenarios
Minimize flux
Extrapolate DIII-D results to ITER

DIII-D has Evaluated the ITER Baseline Startup Scenario and Developed an Improved “Large-bore” Startup

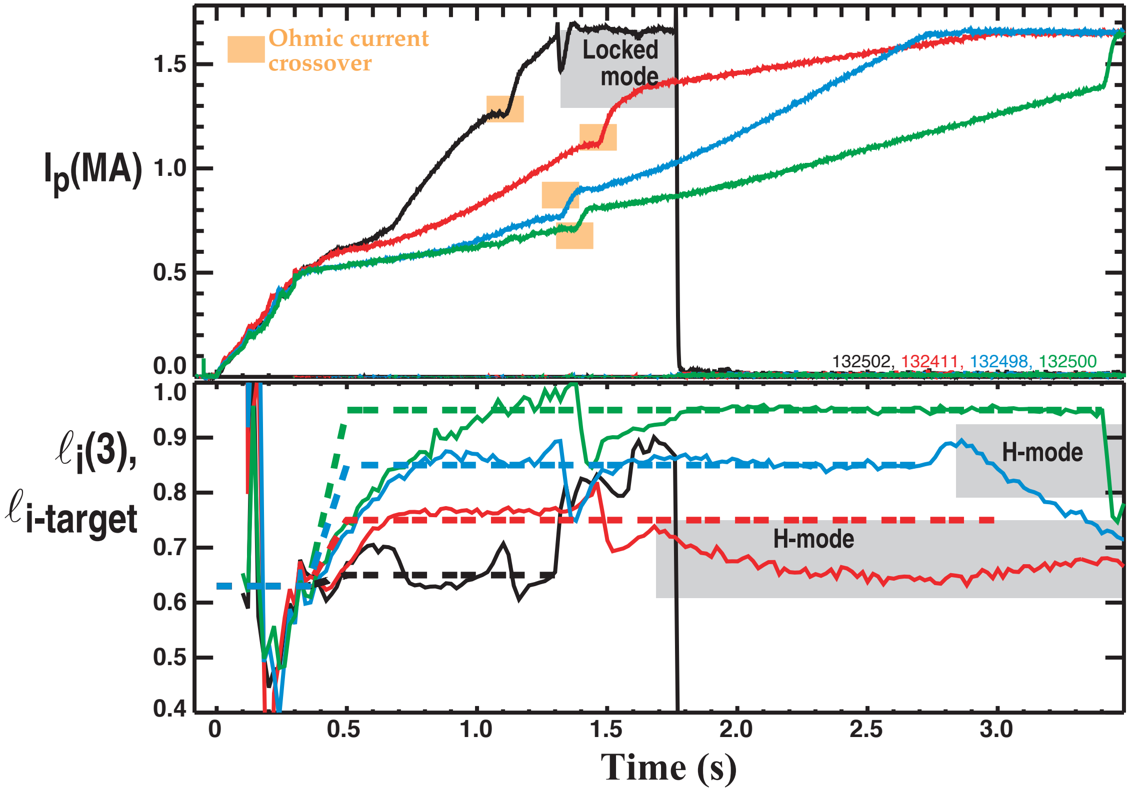


- $\ell_i(3)$ (large-bore, **red**) is close to ITER design range
- Higher q_{min} (delayed saw-teeth) with large-bore scenario
- Energy to LFS limiters reduced with earlier divert time

G.L. Jackson/APS-DPP/Nov 2009

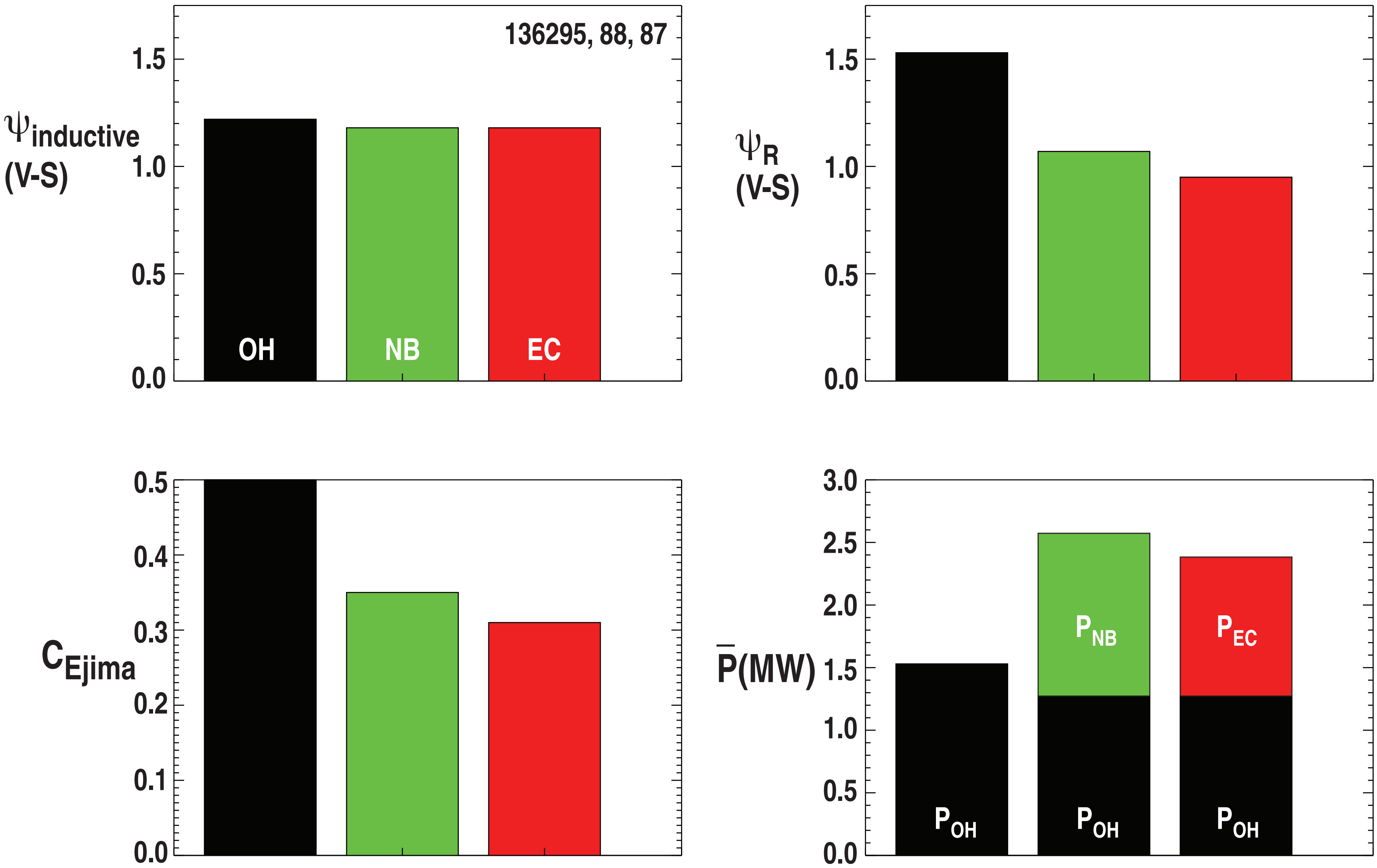
To Remain within the ITER Design Range, ℓ_i can be Controlled by varying the I_p Ramp Rate

- ITER Poloidal Field (PF) Coil constraints place limitations on ℓ_i
  - Specific ℓ_i may be required (within PF constraints) for advanced inductive scenarios
- Feedback control of I_p can produce desired ℓ_i target
  - Plasma Control System (PCS) calculates $\ell_i(3)$ realtime (rtEFIT)
  - $\ell_i(3)$ compared to target and PCS computes an error signal
  - I_p controlled with Ohmic power supply as the actuator



- Feedback control achieved over ITER design range

Flux Consumption is Reduced ≈20% with Modest Addition of Auxiliary Heating in Large-bore Startup

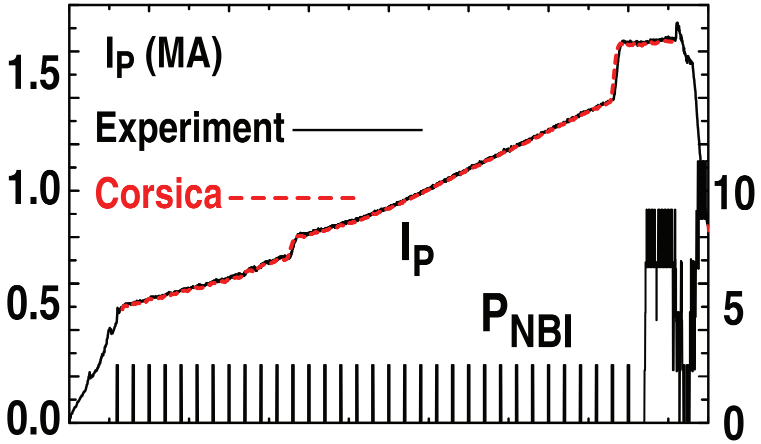


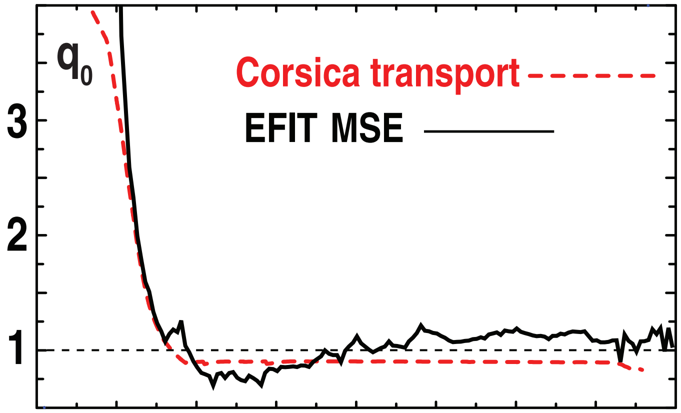
Benchmarking of DIII-D Experimental Results with Transport Models is Important to Predict ITER Performance

- Corsica equilibrium and transport code calculates $j(\psi)$ in 2 ways
  1. Constrained P . Pressure profiles derived from n_e and T_e at each time step
     - Used to verify code is working properly
  2. Transport. Evolved using ITER transport coefficients
     - Initial conditions determined from experimental data
- Coppi-Tang transport model
  - Same coefficients as in ITER modeling (transport mode)
  - Plasma current and T_e agree with data
  - Internal inductance is higher
- TRANSP modeling also benchmarks DIII-D results

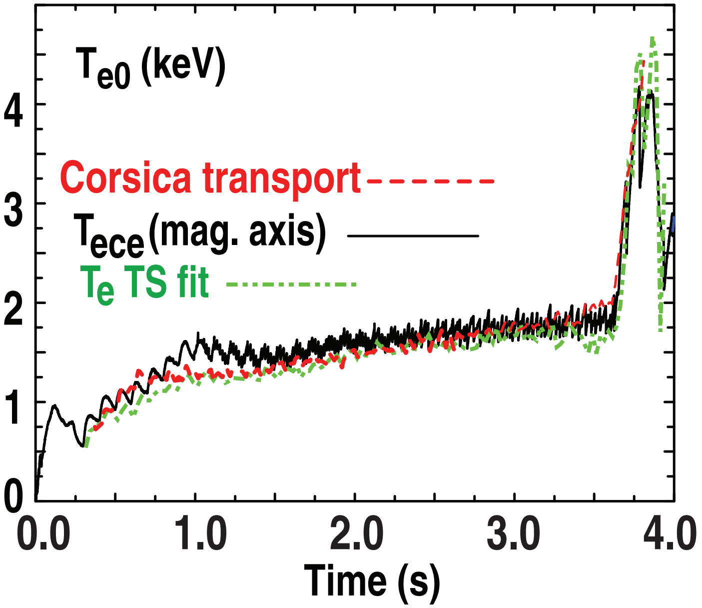
  (Budny, JP8.00102)

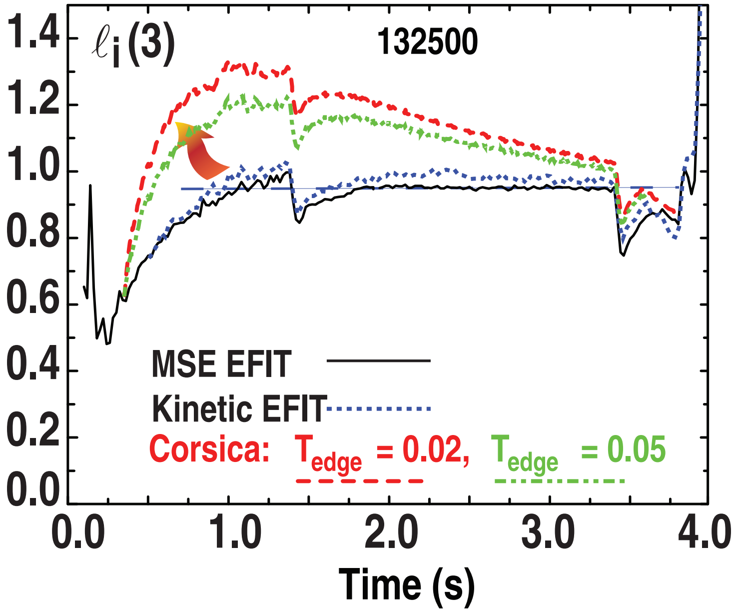
Corsica Transport Modeling During Rampup Properly Evolves $T_e(0)$ and q_0, but Current Profile Evolution Does Not Agree





- **ITER transport coefficients are used for DIII-D modeling**





- **Closer agreement with experiment if edge temperarture is increased**

T.C. Casper

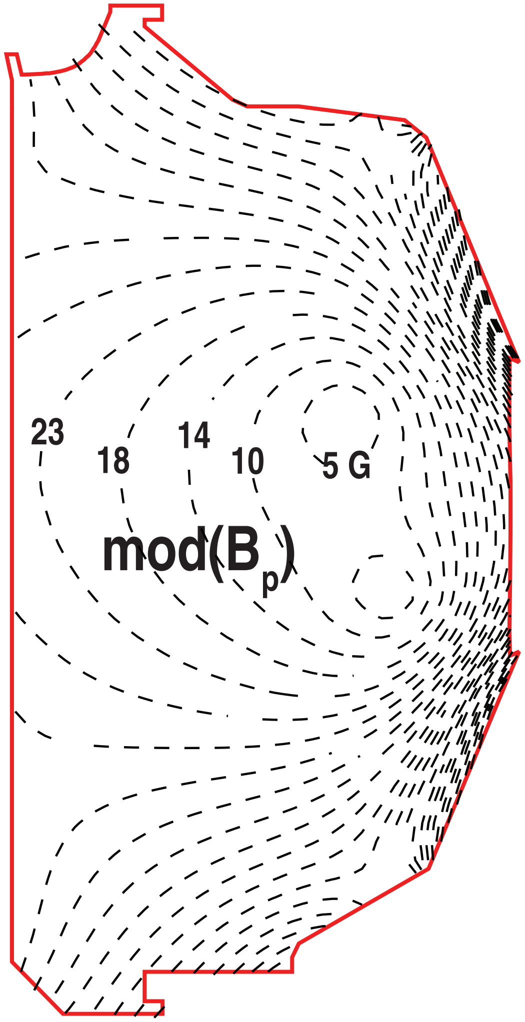
DIII-D has Explored Rampup Scenarios to Address ITER Needs

ITER Challenge	*ITER Small bore scenario*	*DIII-D experimental approach*
Heat flux on poloidal limiters	High heat flux near engineering limits	Divert earlier in rampup
Current profile during rampup	High ℓ_i near vertical control limits	Higher volume (large-bore) reduces ℓ_i
Different current profiles for advanced scenarios		ℓ_i feedback using I_p ramp rate
Minimize flux		Auxiliary heating investigated
Extrapolate DIII-D results to ITER		Corsica benchmarking of DIII-D experiments

BREAKDOWN AND BURNTHROUGH

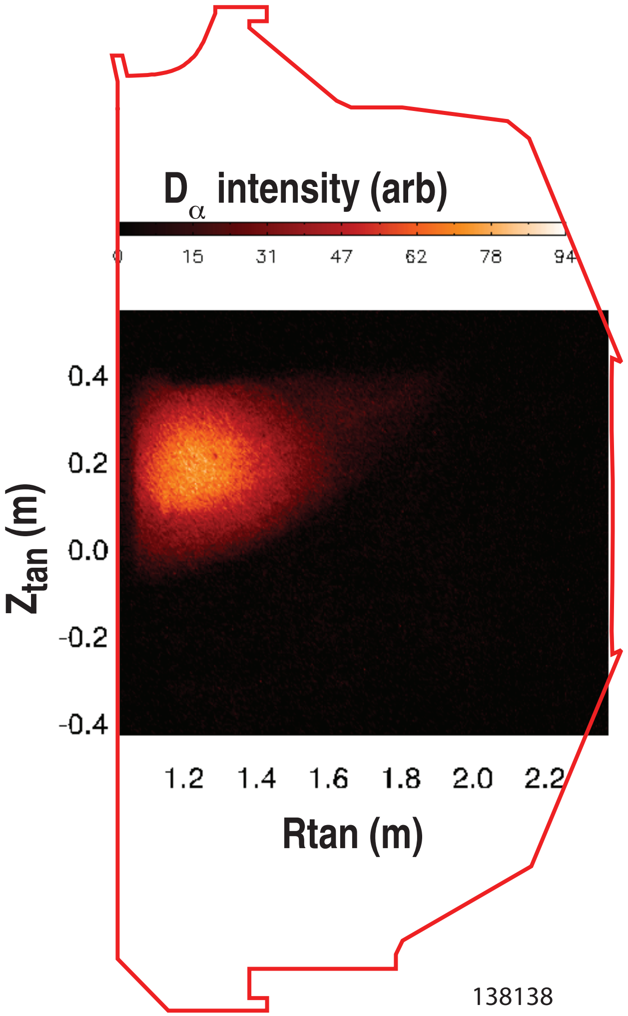
Normal Ohmic Breakdown in DIII-D Occurs Near the High Field Side

Vacuum B_p contours



t = -6 ms

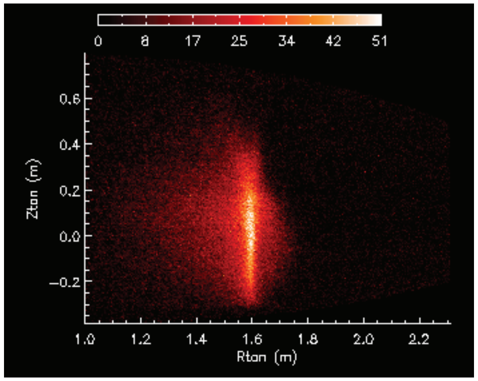
Fast visible camera



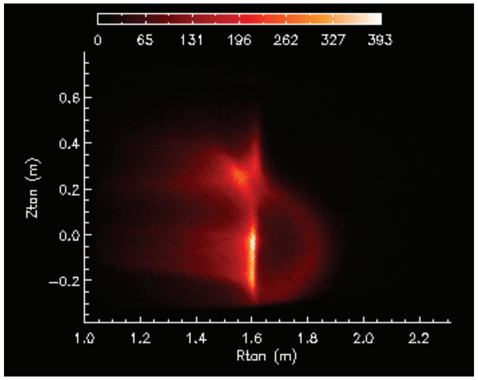
t = +9.3 ms

- **Ohmic breakdown at 0.42 V/m**
  - ITER requires 0.3 V/m
- **Breakdown is near inner wall even when field nulls are on HFS**

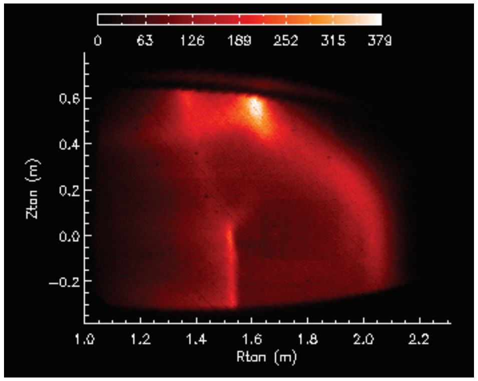
Plasma Formation and Evolution is Observed by Fast Camera, Viewing C^{III} Emission



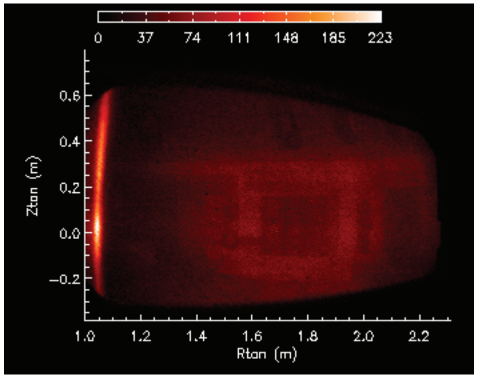
t = -12.7 ms, Ip =1.8 kA, V_L= 0 V



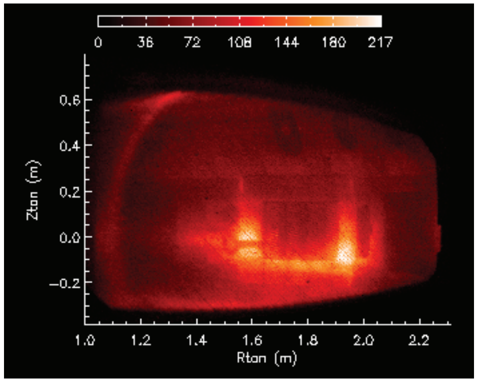
-9.3 ms, 1.9 kA, 0 V



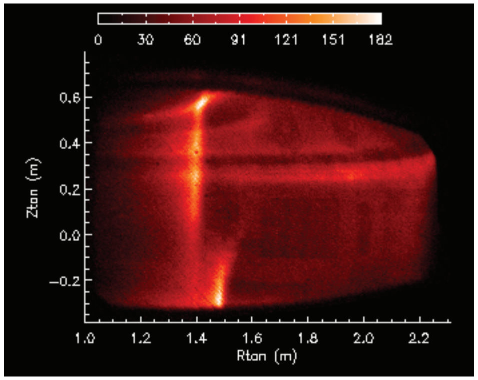
-4.3 ms, 5.6 kA, 0.6 V



t = 12 ms, I_p 61 kA, V_L= 3.0 V



+39 ms, 98 kA, 3.0 V

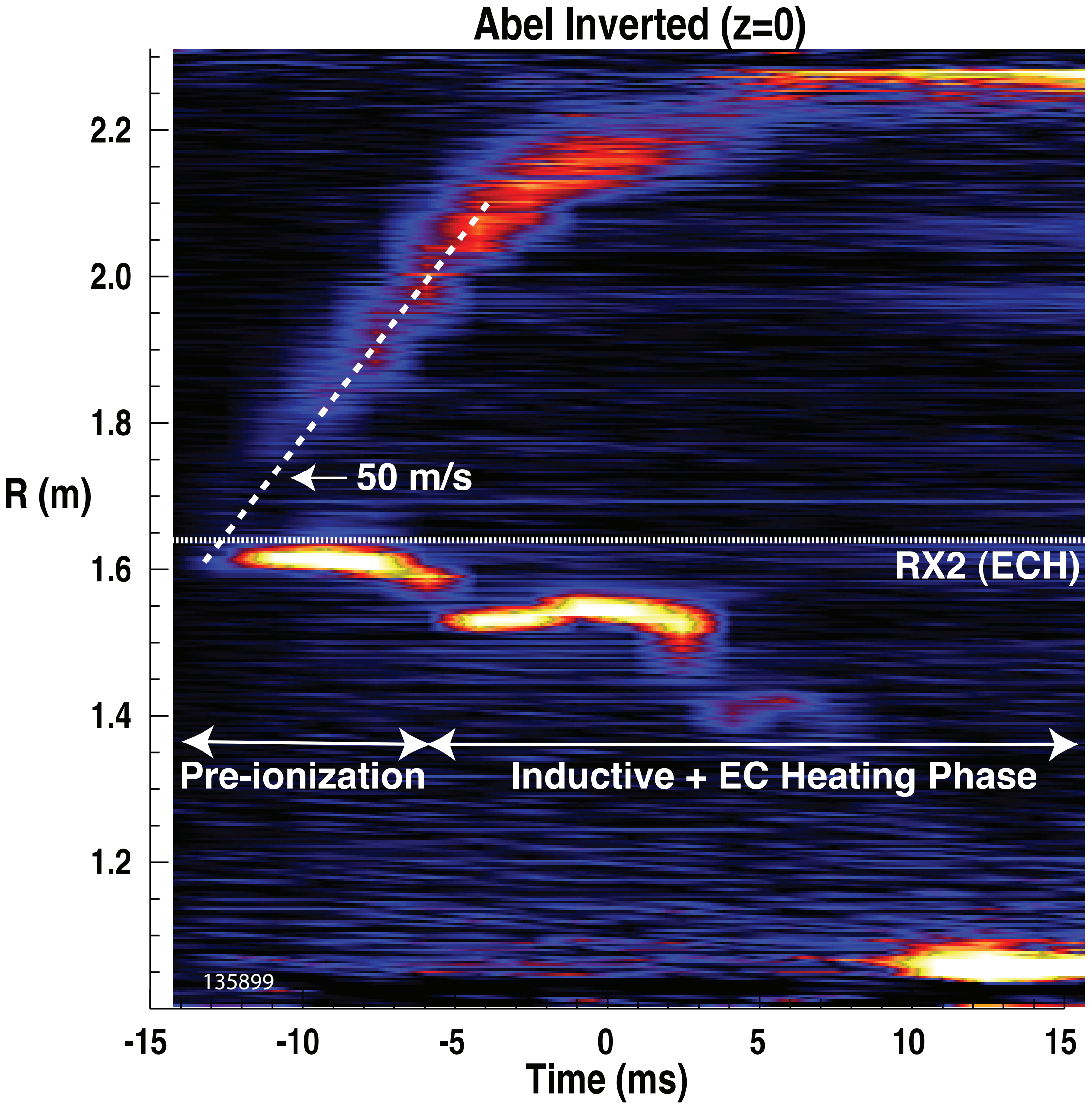


+4.0 ms, 25 kA, 2.6 V

R_{IW}(midplane) = 1.02 m
R_{X2} = 1.64 m
R_{OW}(midplane) = 2.36 m
B_ϕ = 1.9 T, V_L = 3V, $B_{V,pgm}$ = -30 G
$C^{III}_{ionization}$ = 48 eV
$C^{III}_{burnthrough}$ ≈ 16-24 eV
135899

J.H .Yu

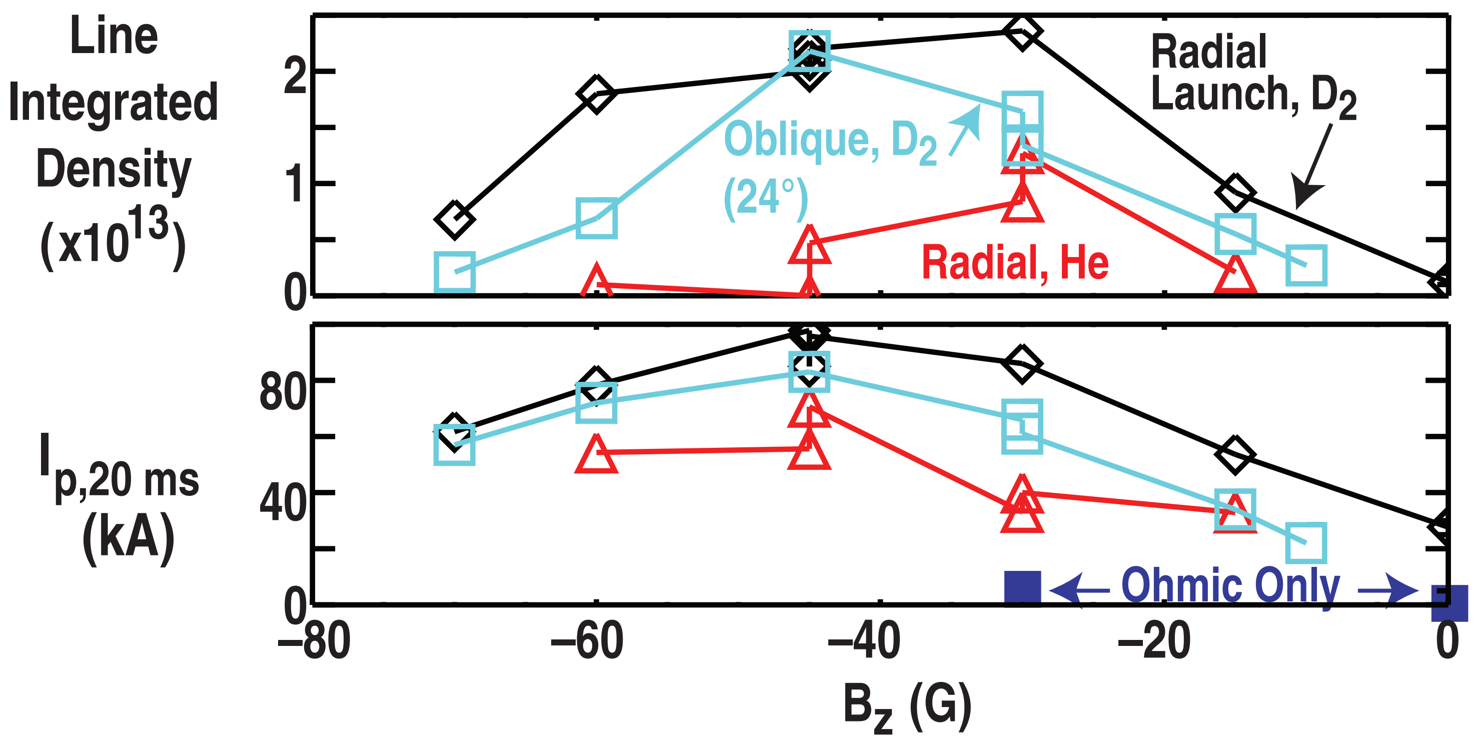
ECH Allows Breakdown to Initiate Near the Vessel Center and Initially Expand Outward



- Abel inversion shows plasma expansion at nearly constant velocity
- $v_{expansion} \approx 50$ m/s (P_{EC} = 1 MW) Expansion is a function of heating power and T_e
  - 90 m/s for P_{EC} = 2 MW
- Breakdown initiates near the 2nd harmonic resonance (R_{X2})
- During the Ohmic heating phase, plasma expands inwards in discrete steps

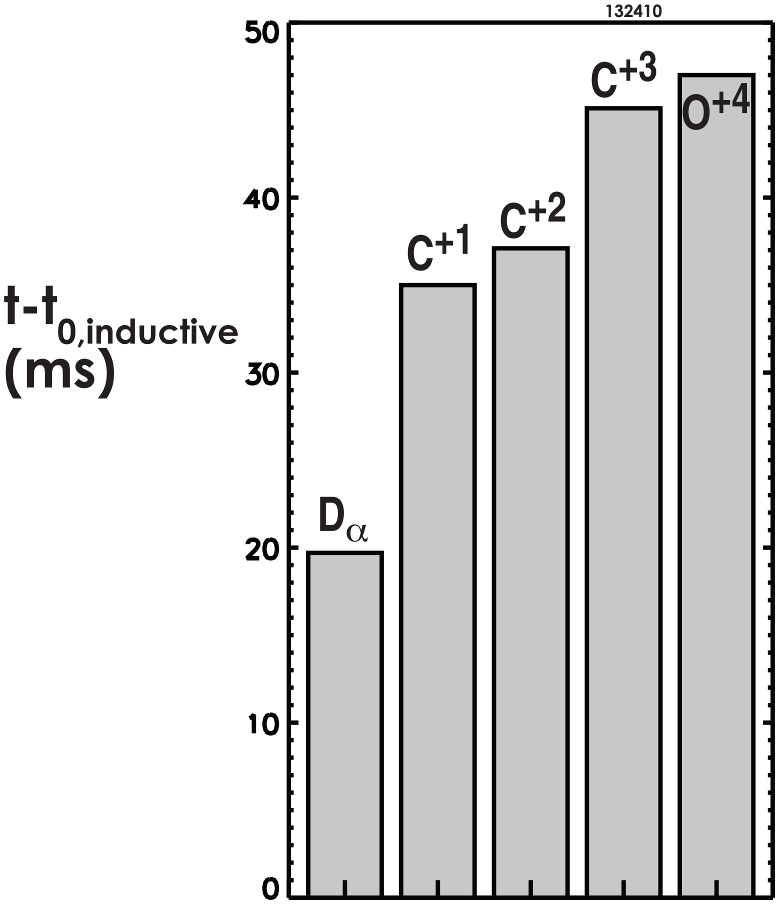
M. Van Zeeland

Low Inductive Volage Startup (0.3 V/m) is Optimized with Vertical Field

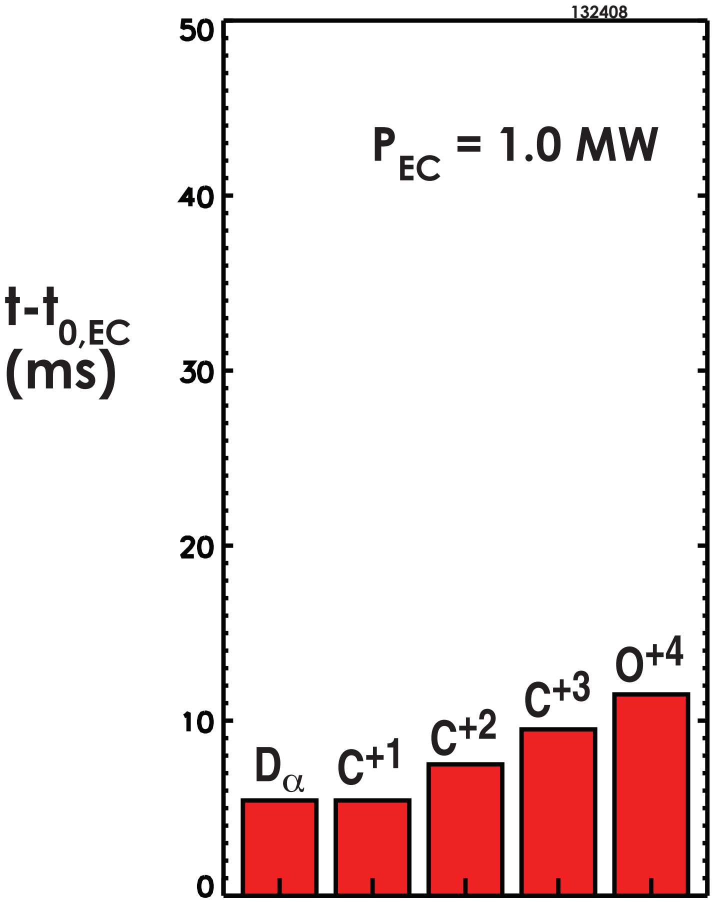


- Oblique EC launch (required for ITER) is effective when vertical field and prefill are optimized
- Low E_ϕ startup in helium (0.3 V/m) also achieved

Burnthrough of Low Z Impurities is More Prompt and Reproducible with EC Assist



Burnthrough with OH



Burnthrough with EC Assist

- E_ϕ = 0.41 V/m,
- B_ϕ = 2.1 T

Plasma Initiation with EC Assist is Robust and Reproducible, but the Dynamics are More Complex than for Ohmic Alone

- **Breakdown is prompt with 1 MW of ECH**
  - 110 GHz, 2nd harmonic X-mode
  - Occurs near the EC resonance radius
  - Plasma expands outward due to **ExB** force

- **Additional vertical field improves the EC breakdown**
  - Even though field line connection length, $L_{R_{X2}\text{-wall}}$ is reduced

- **Noninductive toroidal current (≤ 5 kA) can provide a target for the inductive phase**
  - may reduce flux consumption in ITER

- **Burnthrough of low Z impurities is faster with ECH**

- **Startup obtained with E_ϕ as low as 0.21 V/m**
  - Below the ITER requirement (0.3 V/m)

Conclusions

- **All phases of an ITER discharge have been experimentally simulated in DIII-D**
- **Rampdown within the ITER scenario has been demonstrated to <0.1 MA without disruptions ($I_{\text{ITER eqiv.}}$ < 1 MA)**
  - ITER rampdown scenario tested, and improved rampdown developed
- **Rampup (ITER 15 MA scenario, I/aB = 1.42) successfully achieved**
  - Improved "large-bore" startup reduced heat flux to poloidal limiters
  - ℓ_i feedback demonstrated
  - Flux consumption reduced by 20% with auxiliary heating
  - Corsica modeling has benchmarked DIII-D rampup phase
- **Two types of low inductive voltage startup investigated**
  - Ohmic startup initiates on the HFS with $E_\phi \geq 0.42$ V/m
  - EC assisted startup achieved, $E_\phi \geq 0.21$ V/m
- **EC assisted startup represents a different startup scenario**
  - Breakdown and burnthrough robust and reproducible
  - May reduce flux consumption in ITER