DIII-D Experimental Simulation of ITER Scenario Access and Termination

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DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

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

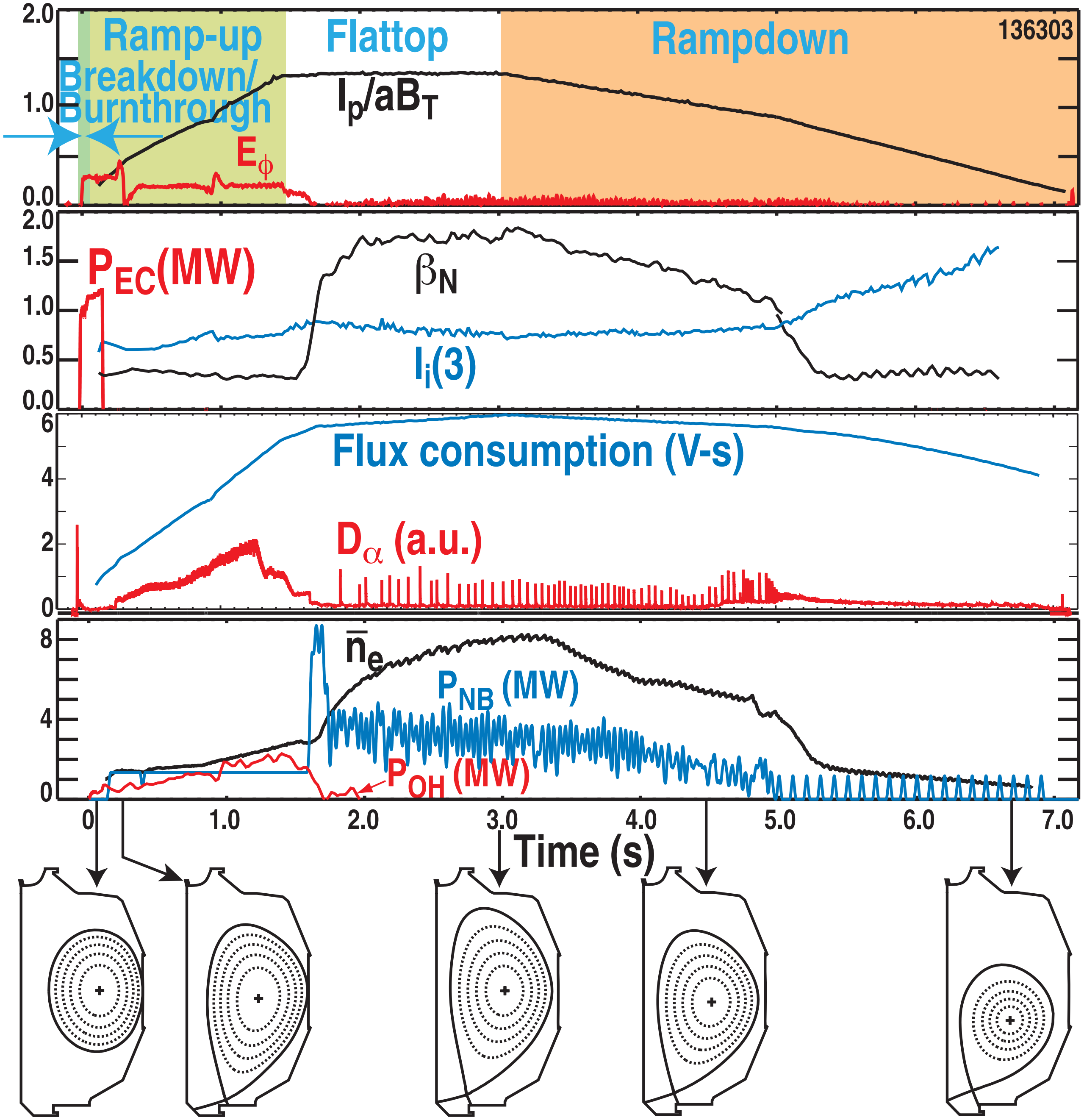
ITER CHALLENGE

- 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
- Rampdown to a “soft landing”

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

Initial EC-assisted Startup Experiments Have Led DIII-D to Simulate a Complete ITER Sequence, Including Rampdown



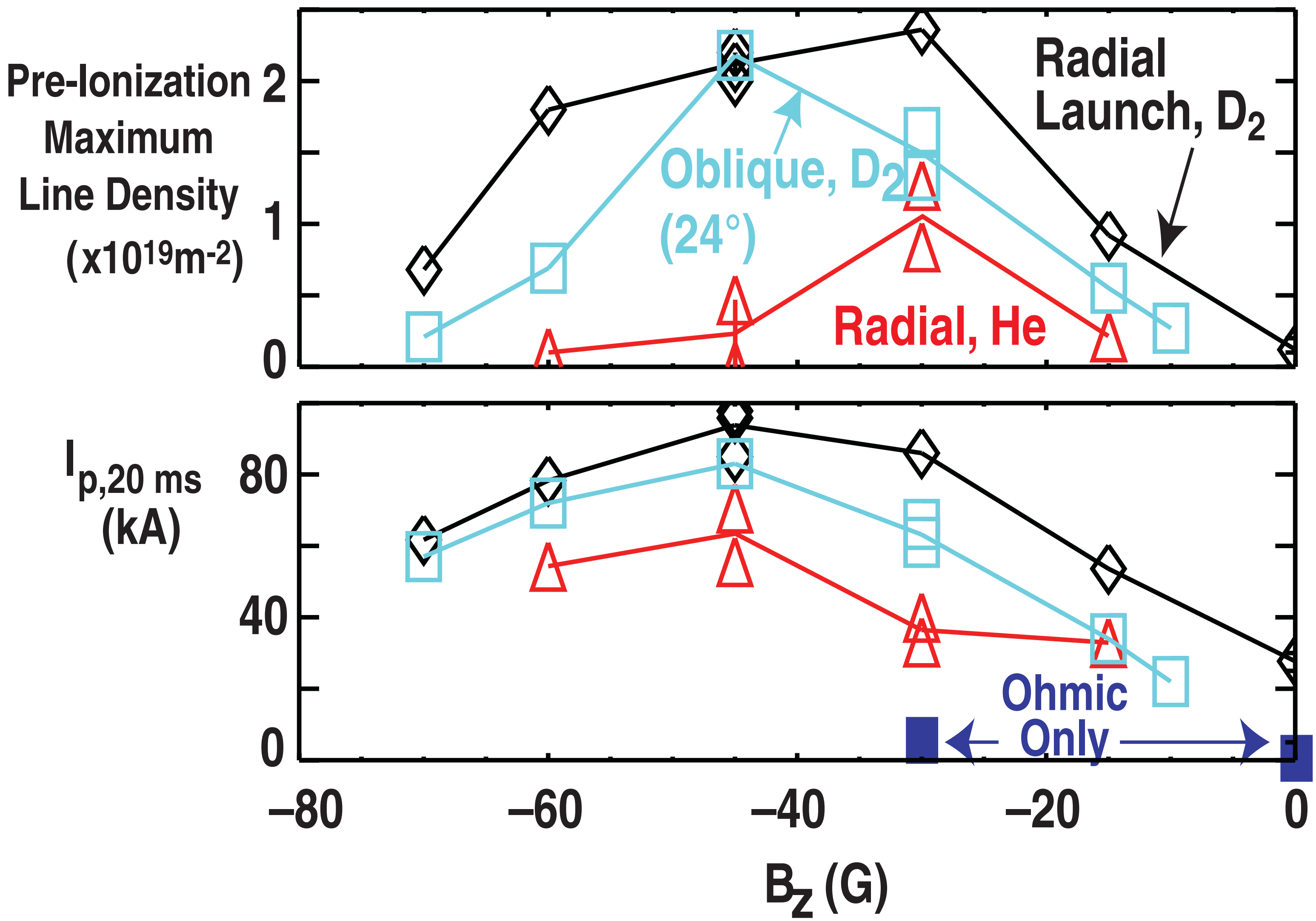
- EC assist allowed robust rampup for $E_\phi \geq 0.21$ V/m
- Improved "large-bore" startup developed for ITER
- "soft landing" achieved with ITER prescription
- ITER Baseline H-mode achieved
- No additional flux consumption during rampdown
- Strike points held fixed during aperture reduction

BREAKDOWN AND BURNTHROUGH

Plasma Initiation with EC Assist can Relax Constraints on ITER Startup and Produce Robust and Reproducible Discharges

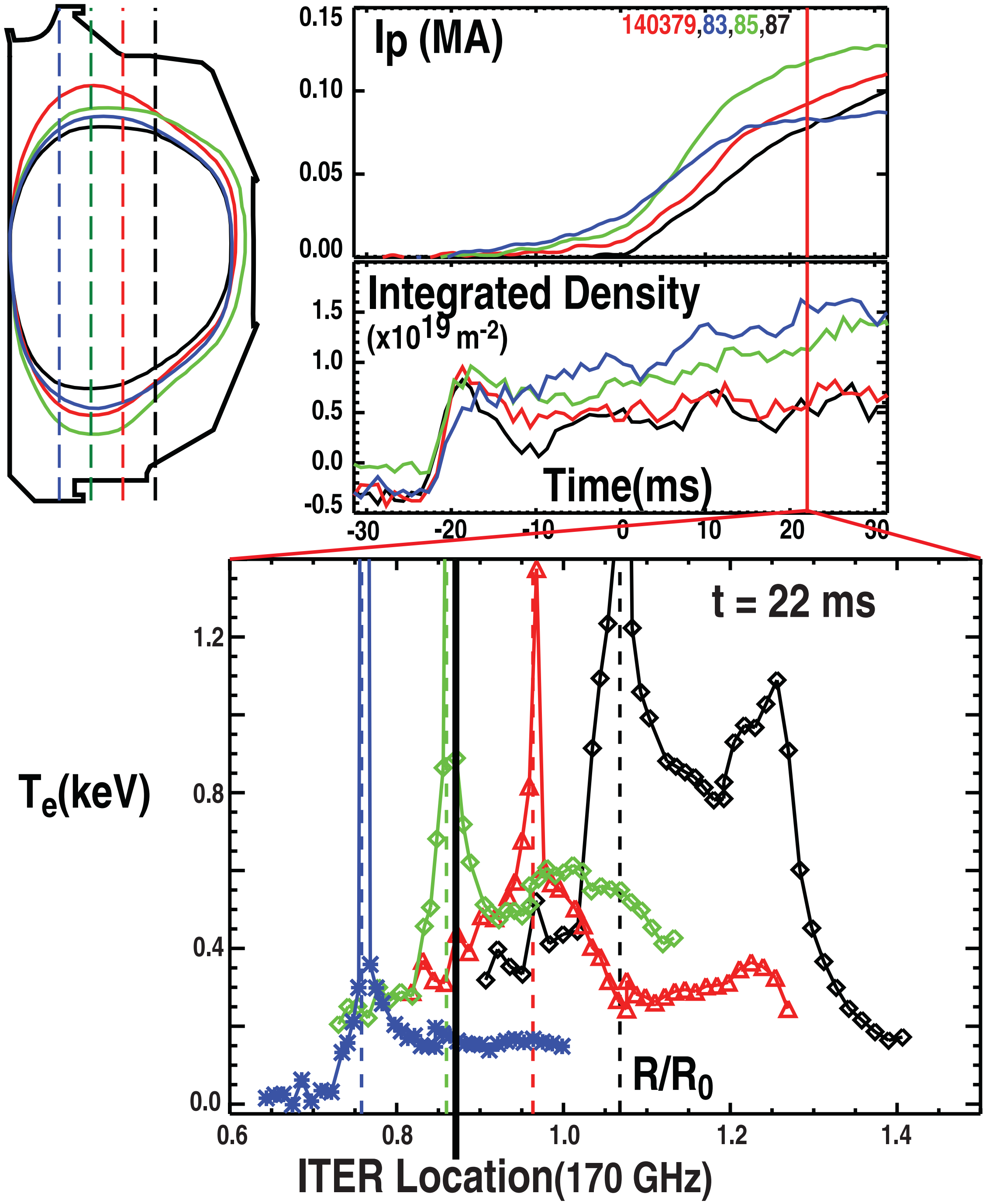
- **Breakdown for ITER simulated discharges are prompt with 1 MW of ECH**
  - 110 GHz, 2nd harmonic X-mode
  - Occurs near the EC resonance radius in all cases
  - Plasma expands outward due to **ExB** force
- **Programmed vertical field improves the EC breakdown**
- **Oblique EC launch provided reliable startup at E_ϕ=0.3 V/m**
- **ITER-like startup in helium was successful with EC assist**
- **Burnthrough of low Z impurities was faster with ECH**
- **Startup obtained with E_ϕ as low as 0.21 V/m**
  - Below the ITER requirement (0.3 V/m)

EC Assisted Startup at low E_ϕ (0.3 V/m) Achieved with Radial and Oblique Launch and in Helium Plasmas



- Oblique EC launch (required for ITER) is effective when vertical field and prefill are optimized
- Low E_ϕ startup in helium (0.3V/m) also achieved
- Best startup requires -45 < B_{VF} < -30 G

EC Resonance Scan (Varying B_T) Demonstrates Robust Breakdown and Reliable Initial I_p Ramp Under All Conditions



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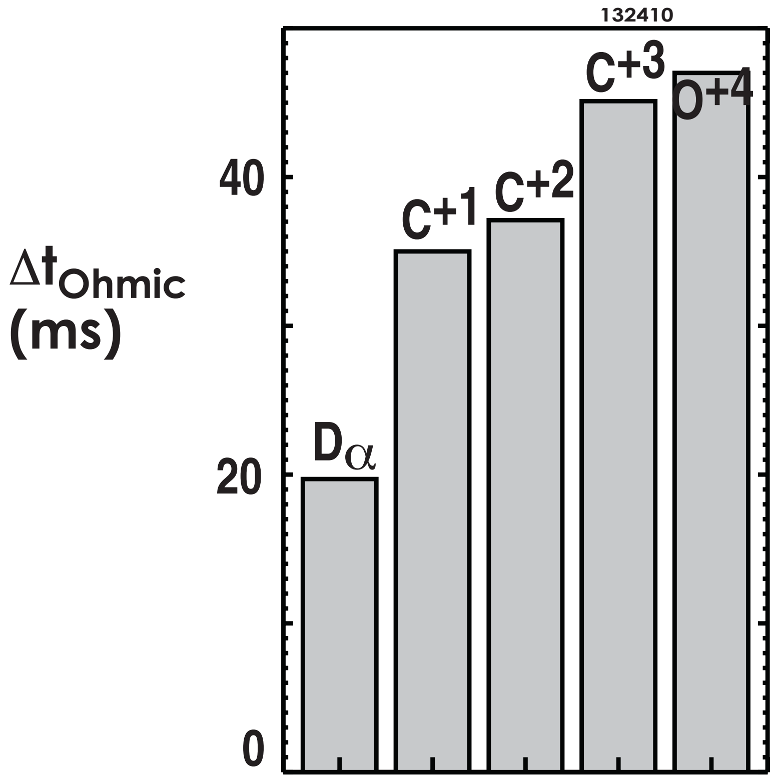
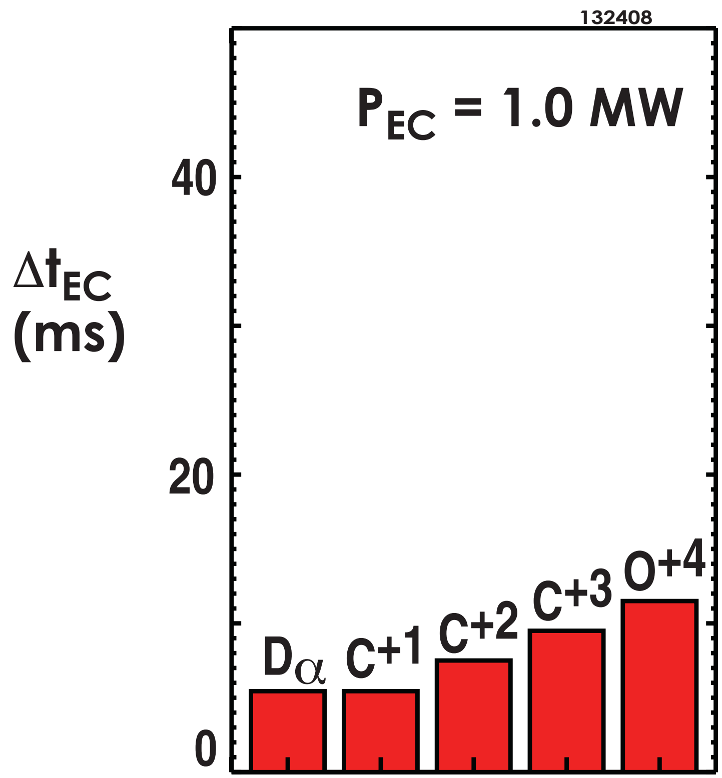
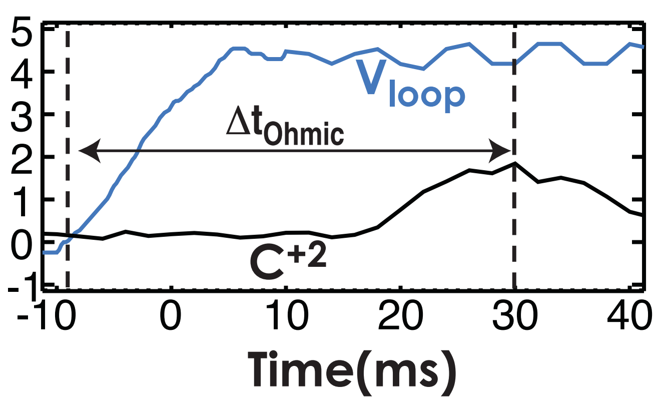
Burnthrough of Low Z Impurities is More Prompt and Reproducible with EC Assist (E_ϕ = 0.41 V/m, B_ϕ = 2.1 T)

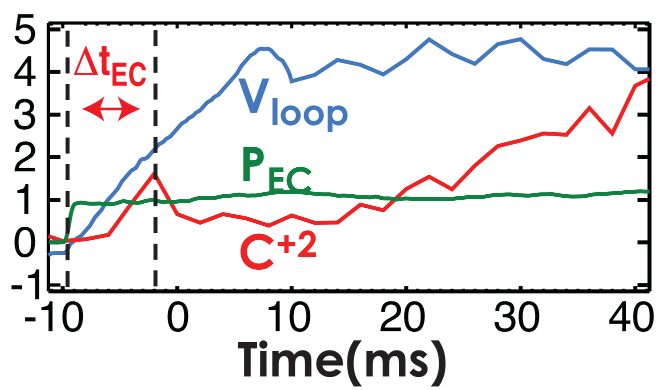


Burnthrough with OH



Burnthrough with EC Assist





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

($C^{III}_{ionization}$ = 48 eV, $C^{III}_{burnthrough} \approx$ 16-24 eV)

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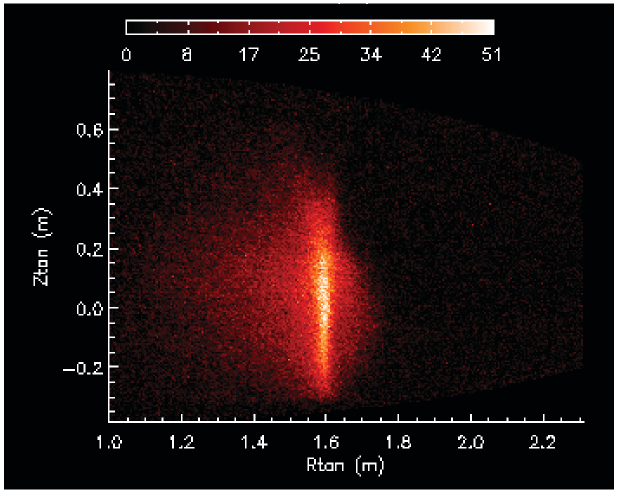
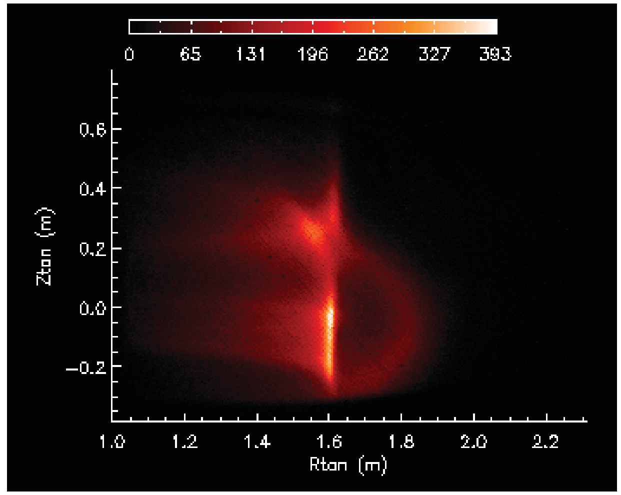
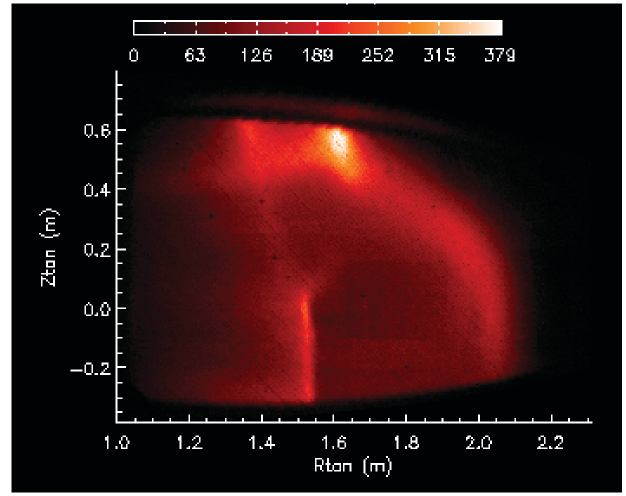


t= -12.7 ms, Ip =1.8 kA, V_L= 0V

Breakdown at R_{X2}

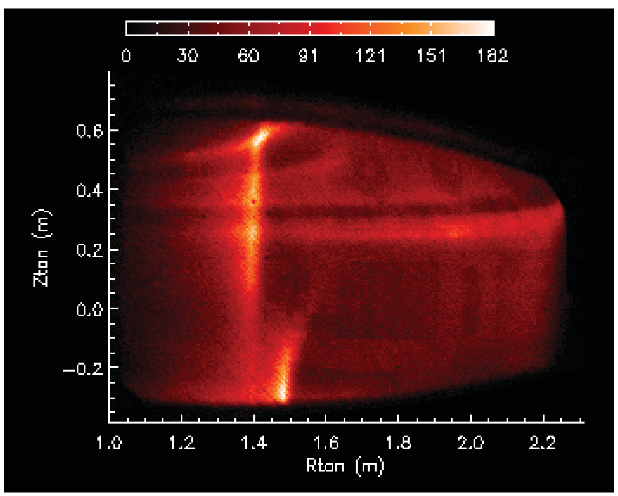


-9,3 ms, 1.9 kA, 0V



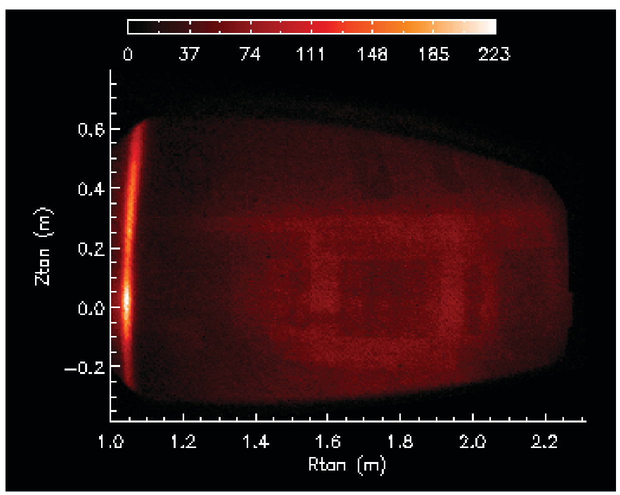
-4.3 ms, 5.6 kA, 0.6V

← Plamsa Expansion due to j x B →



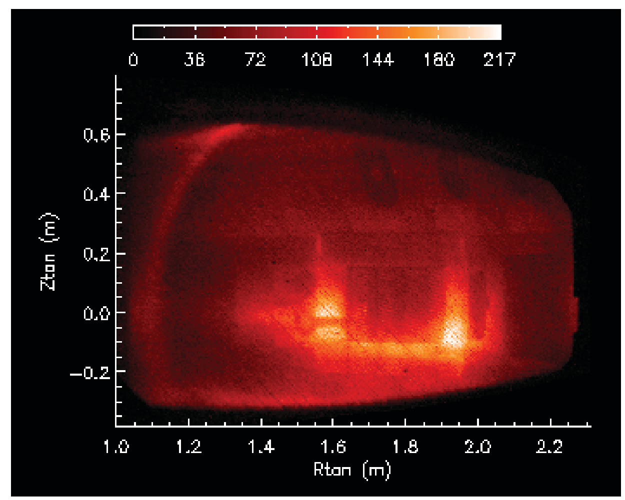
+4.0ms, 25kA, 2.6V

Closed flux surfaces form



t= +12 ms, Ip 61kA, V_L= 3.0V

Discharge established on HFS



+39 ms, 98kA, 3.0V

Radial position control (Limited on LFS)

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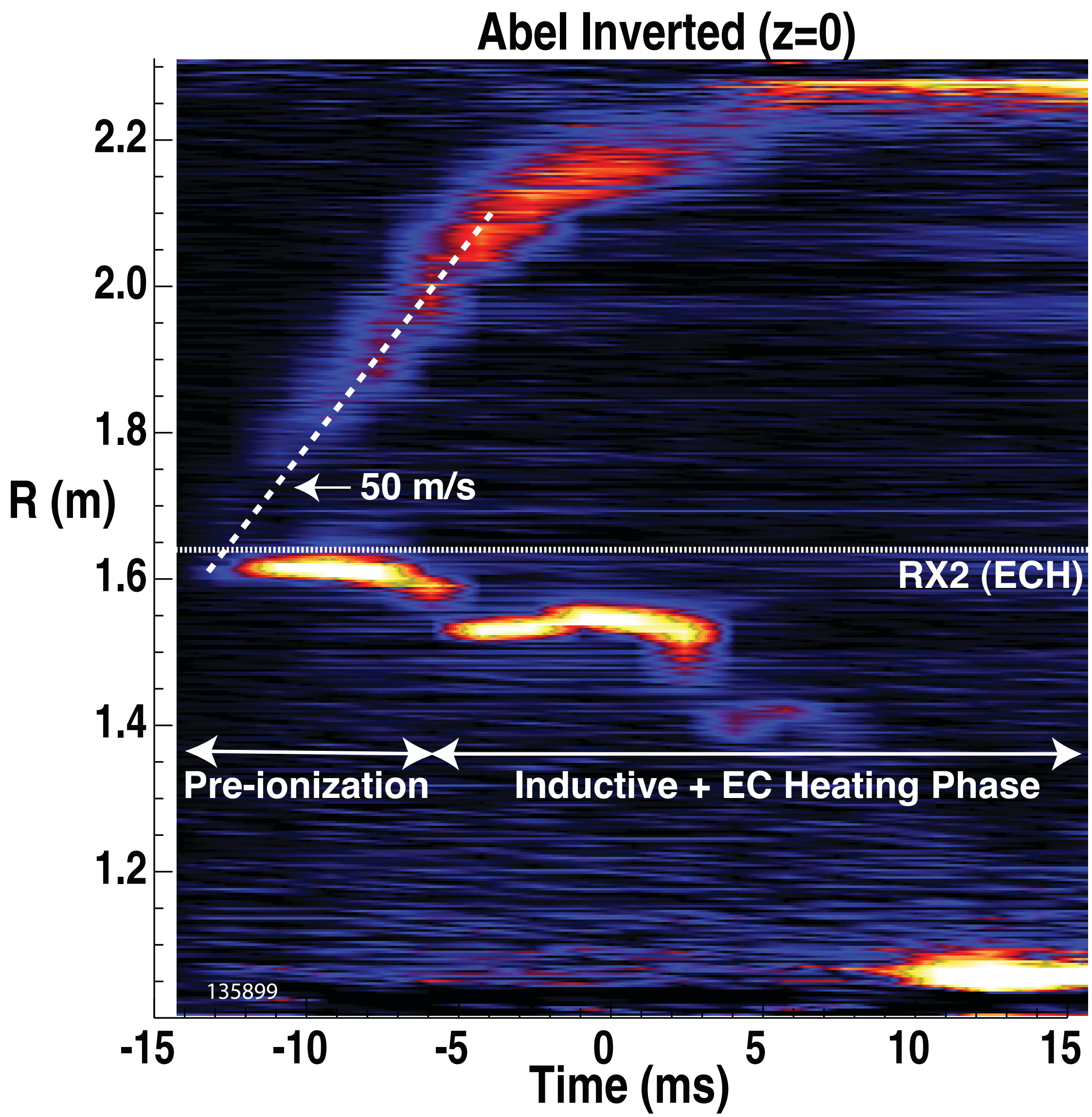
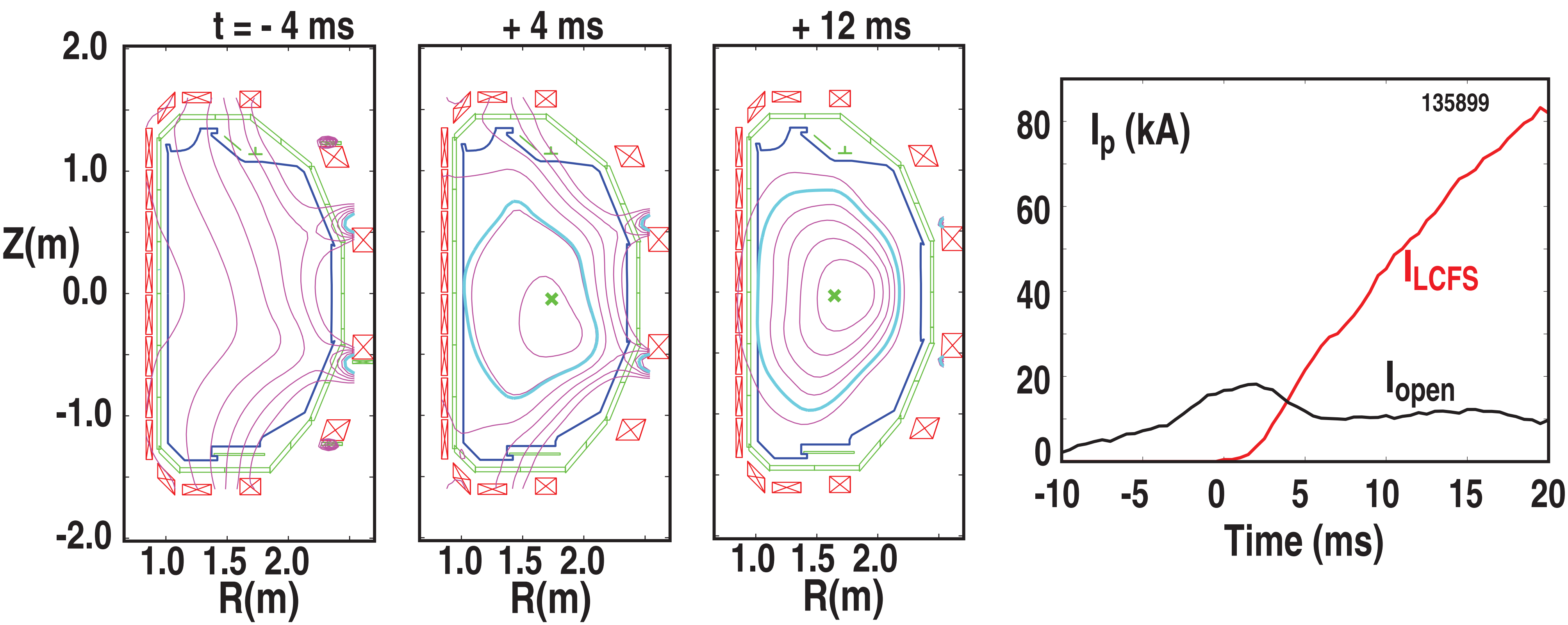
Abel Inversion Shows Initial Plasma Expansion at Nearly Constant Velocity (due to *ExB*)



- *E* from charge separation due to grad(B) and curvature drifts
- $v_{expansion} \approx 50$ m/s (P_{EC}=1 MW) Expansion is a function of heating power and T_e
- During the Ohmic heating phase, plasma expands inwards in discrete steps

Specialized Code (JFIT with Current Filaments) Required to Characterize Flux Evolution during Plasma Formation

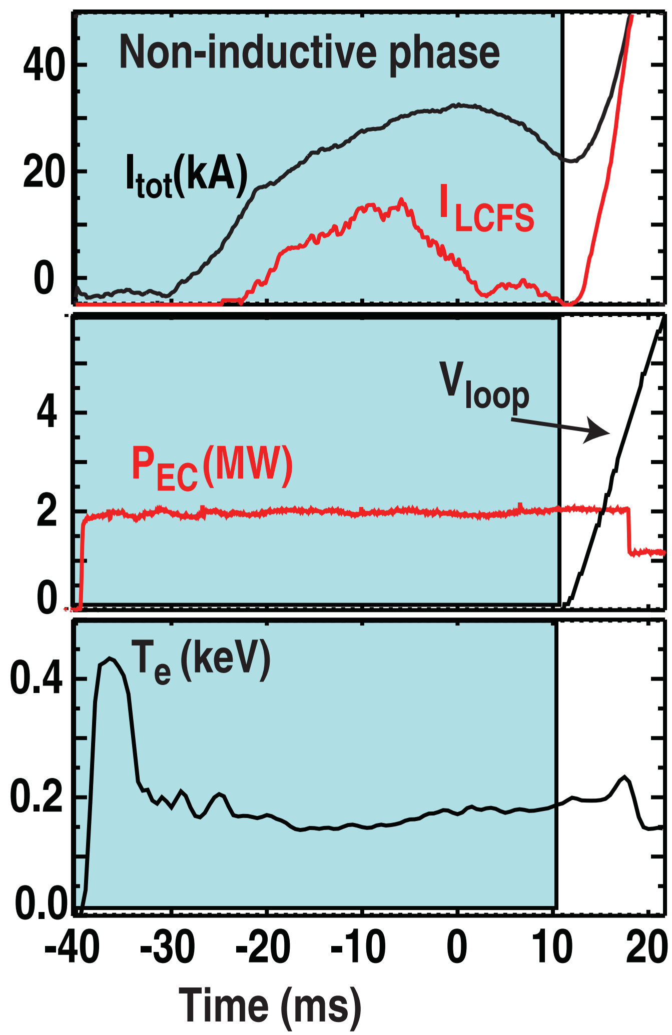


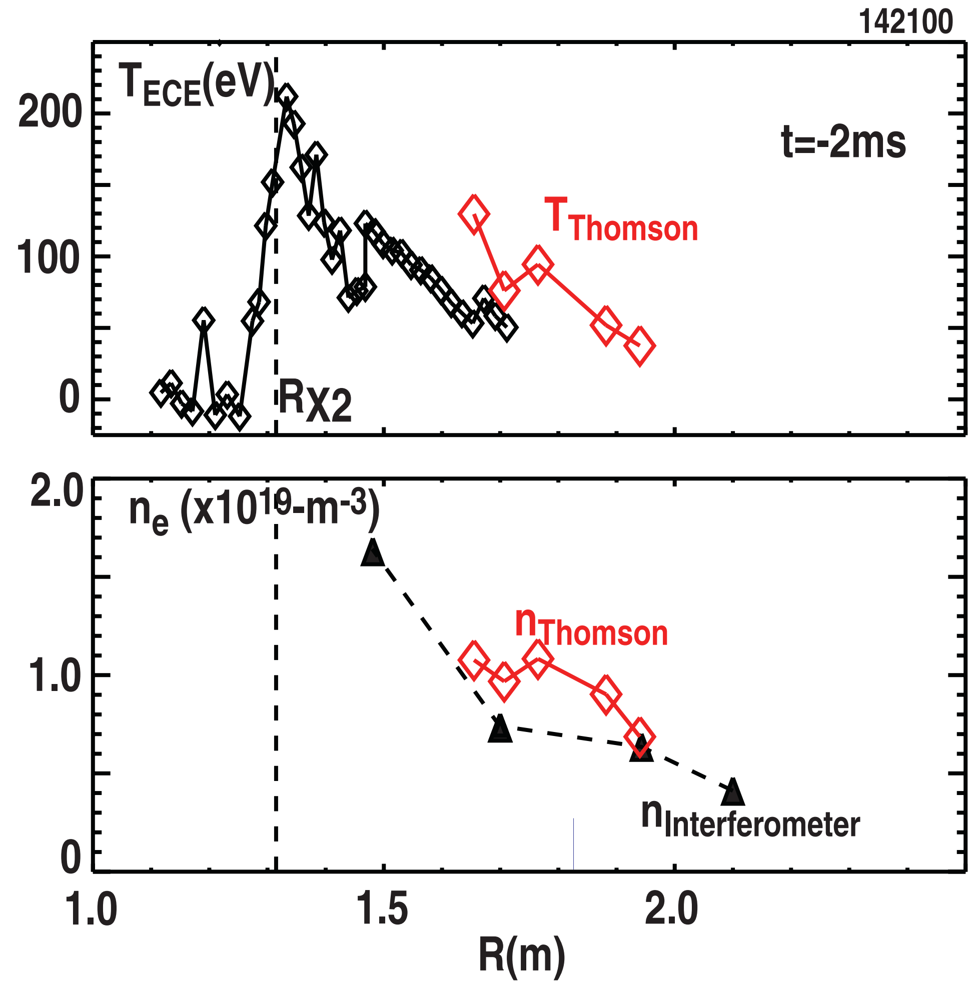
- Flux reconstruction shows I_p initially forming on open field lines (I_{open})
- With applied B_{VF} =-30G, discharge is initially limited on the HFS.
- Discharge is well established by t = +12ms and most current is inside the LCFS (I_{LCFS})

NON-INDUCTIVE I_p INITIATION

Non-inductive Plasma Current as High as 33 kA has been Observed with ECH During the Pre-ionization Phase

- May provide a suitable target for complete non-inductive startup with NB or EC current drive in Stellerators or Burning Plasma Devices
- Could provide a useful low I_p target for ITER in the comissioning phase
- NI currents are both Pfirsch-Schlüter and Bootstrap (Ejiri, et al., Nuc. Fus., 2006)





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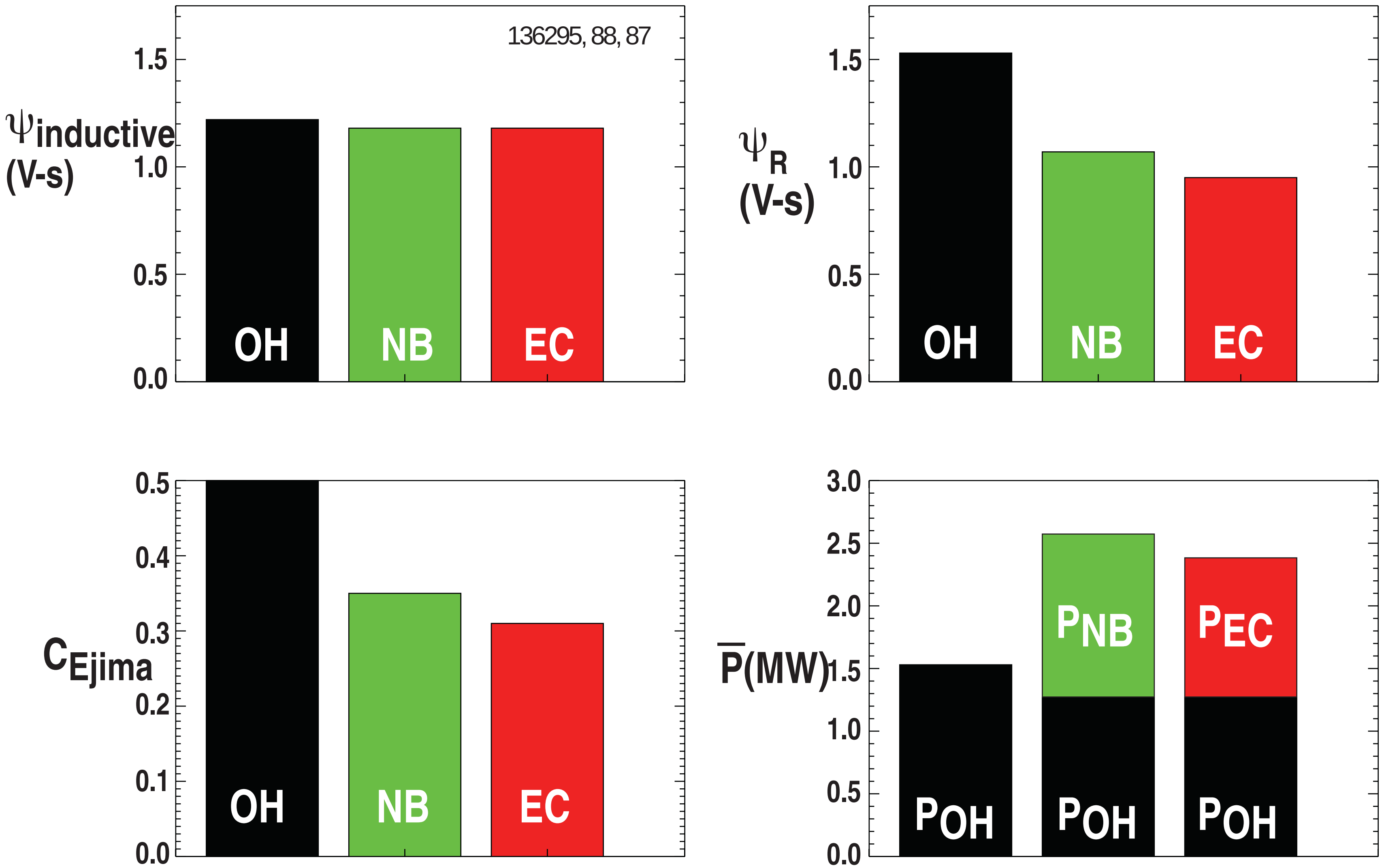
RAMPUP

DIII-D has Explored Rampup Scenarios to Address ITER Needs

ITER Challenge	*DIII-D experimental approach*
Heat flux on poloidal limiters	Divert earlier in rampup
Current profile during rampup	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 in rampup investigated
Extrapolate DIII-D results to ITER	Corsica, MMM95, Gyro/Gyro Bohm, TGLF, GLF23, and TRANSP transport codes benchmarked with DIII-D experiments

Total Flux Consumption in Rampup is Reduced ≈ 20% with Modest Addition of Auxiliary Heating



C_{Ejima} (Normalized Resistive flux) = $(\psi_{boundary} - \psi_{pol,EFIT})/(\mu_o R I_p)$

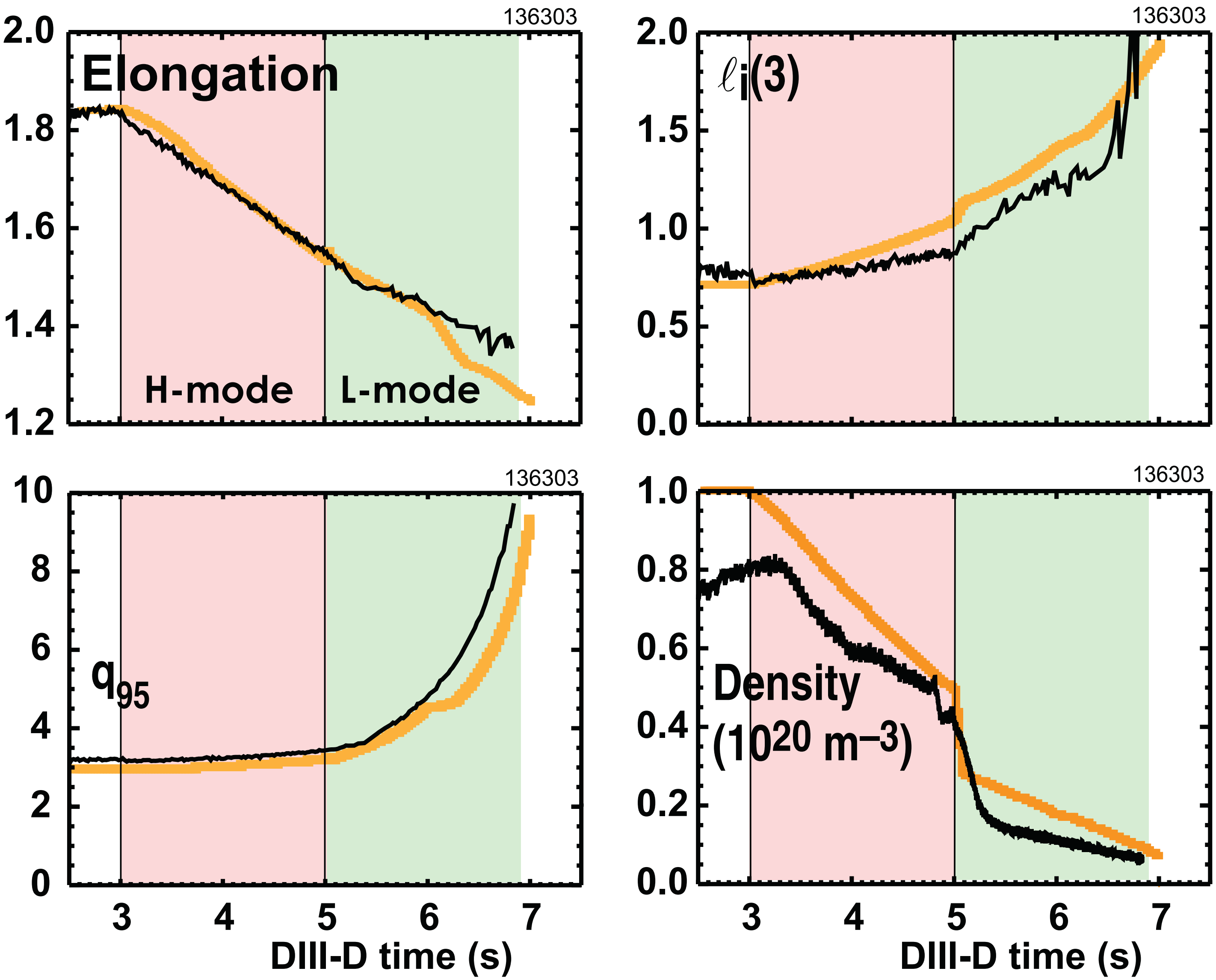
RAMPDOWN

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

- **Safe and controlled discharge termination becomes increasingly important.**
  - ≈ 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 Ip and elongation
Vertical instabilities	Quantify stablility boundary and optimize vertical control

DIII-D Experimental Discharges Match DINA Modeling of the ITER Rampdown Phase



black: DIII-D
gold: ITER simulation using DINA code

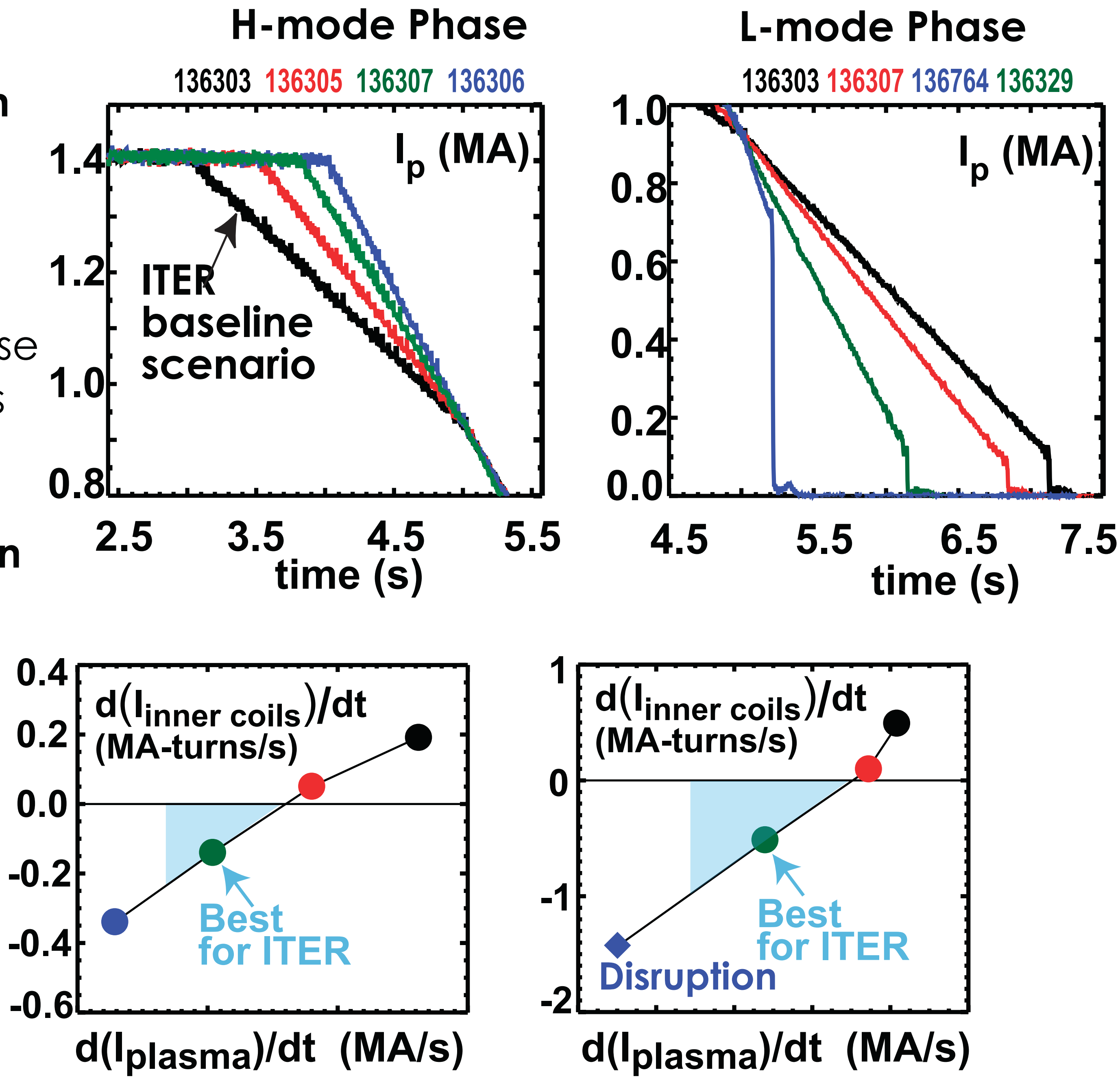
DIII-D normalized parameters κ, q_{95}, β_N, and $l_i(3)$ matched to ITER

ITER density trajectory is assumed

P. Politzer, Nuc. Fus. 2010

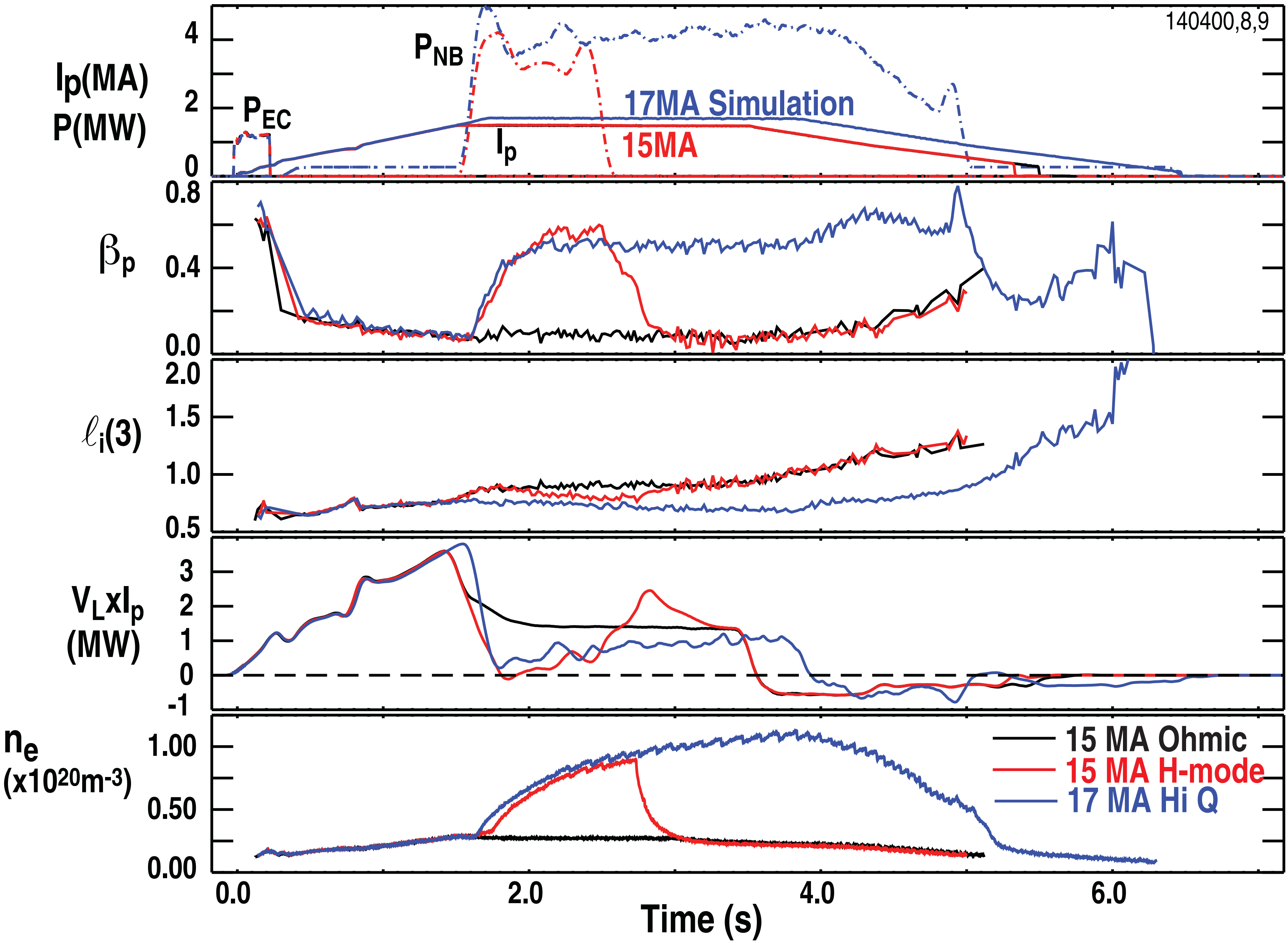
Rampdown Rate Scan Indicates Need to Ramp Faster

- **Current ramp rate in both H-mode and L-mode 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|⟨Ψ⟩|/dt always < 0



P. Politzer (APS09)

Rampdown to a "soft landing" has been Demonstrated for ITER 15 MA (H-mode & Ohmic) and 17 MA (High Q) scenarios



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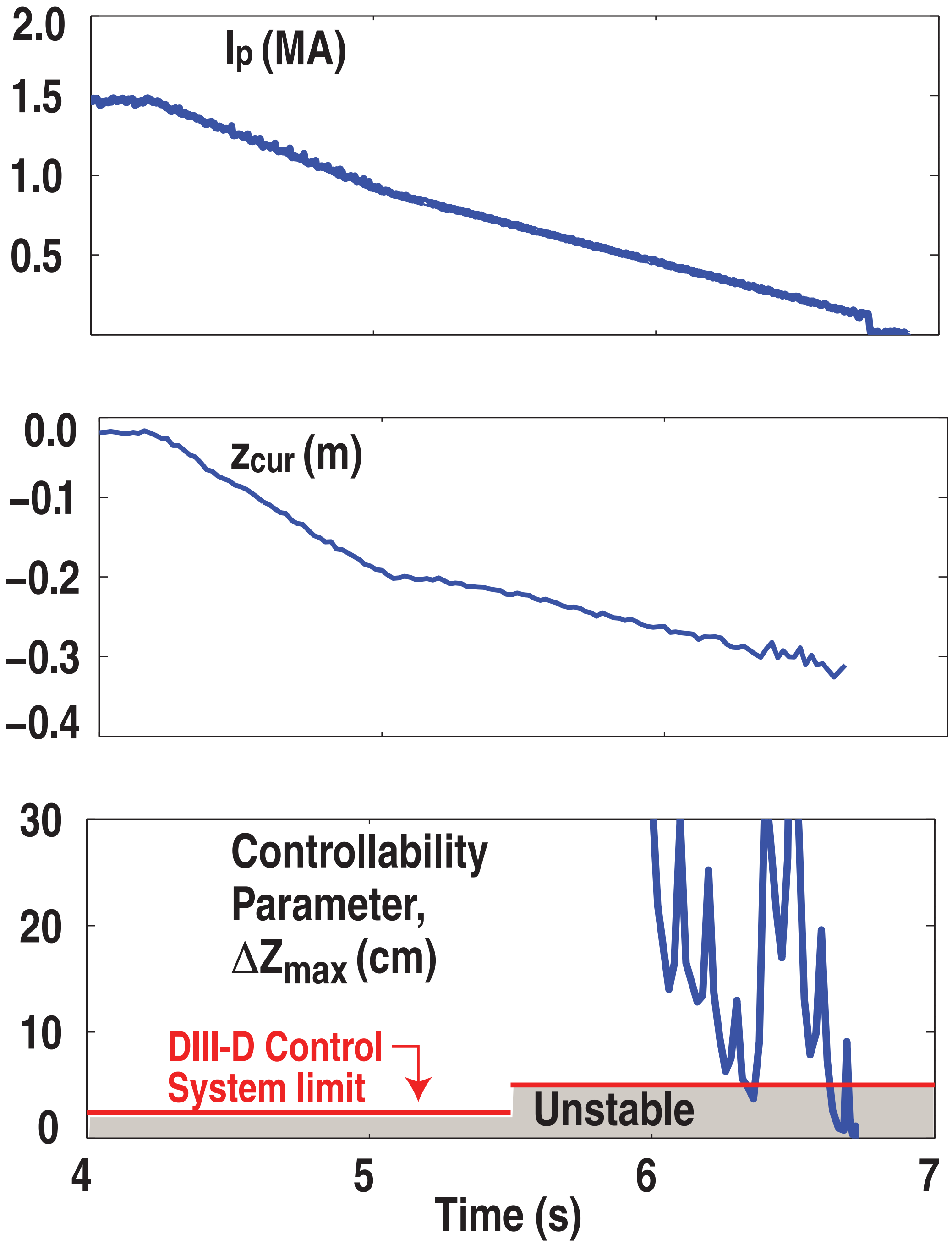
Rampdown without Vertical Instabilities Requires Temporal Changes in the Control Algorithm



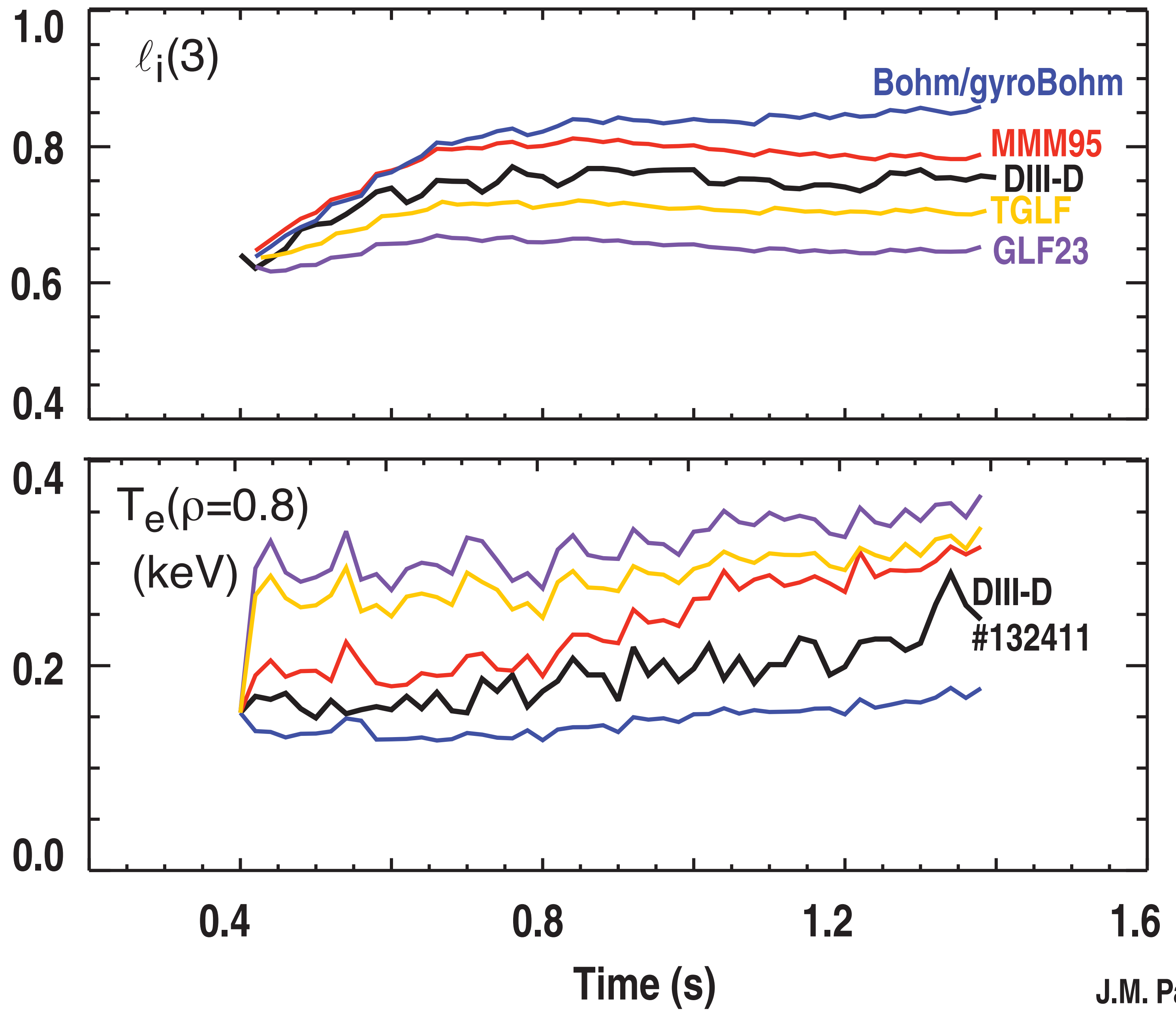
- Successful rampdown to $I_{p,DIII\text{-}D}$ < 0.14 MA (corresponds to <1.4 MA ITER specified value for a “soft landing”)
- Plasma Control System (PCS) algorithm changed at 5.5 s for low elongation and z_{cur} well below the midplane
- Vertically stable until ΔZ_{max} decreases below DIII-D control limit (set by system noise)

BENCHMARKING DIII-D EXPERIMENTS

The Next Step in Extrapolating to ITER is to Benchmark Transport Codes Using DIII-D Results

- Corsica equilibrium and transport code calculates $j(\psi)$ in 2 ways (using Coppi-Tang transport model)
  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
     - Same coefficients as in ITER modeling
     - Predicts sawtooth onset time and T_e evolution, but l_i not as well matched
- MMM95, Bohm/gyroBohm, GLF23, and TGLF transport models have been directly compared using experimental DIII-D data
  - Temporal evolution varies between models and appears to be sensitive to edge temperature profiles
- TRANSP modeling in progress to benchmark DIII-D results

Improvements in Transport Models are Required to Better Match DIII-D Experimental Results



J.M. Park

SUMMARY

- **All phases of an ITER discharge have been experimentally simulated in DIII-D**
  - Both ITER baseline H-mode and Hybrid flattop phases achieved after ITER-like startup
- **Ramp-up to ITER 15 MA and 17 MA scenarios demonstrated**
  - Improved "large-bore" startup reduced heat flux to poloidal limiters
  - ℓ_i feedback kept internal inductance within acceptable range for ITER
  - Flux consumption reduced by 20% with auxiliary heating
  - Models have been tested with DIII-D discharges in the ramp-up phase
  - EC assisted startup successful within a wide parameter range
- **Rampdown to a "soft landing" has been demonstrated, I_p < 0.1 MA ($I_{ITER\ eqiv.}$ < 1 MA)**
  - ITER rampdown scenario tested, and an improved rampdown developed
- **Non-inductive plasma formation up to 33 kA obtained with ECH**
  - May provide a target for NB and EC current drive allowing a complete non-inductive current ramp-up
- **Access to ITER flattop scenarios, and successful termination, should be possible under a variety of conditions in ITER.**