DIII-D Experimental Simulation of ITER Scenario Access and Termination

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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 ($I_p/aB$, $I_i$, $\beta_N$, 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
• 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 $\mathbf{E} \times \mathbf{B}$ force

• Programmed vertical field improves the EC breakdown

• Oblique EC launch provided reliable startup at $E_\phi = 0.3$ V/m

• ITER-like startup in helium was successful with EC assist

• Burnthrough of low Z impurities was faster with ECH

• Startup obtained with $E_\phi$ as low as 0.21 V/m
  – Below the ITER requirement (0.3 V/m)
EC Assisted Startup at low $E_\phi$ (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 $E_\phi$ startup in helium (0.3V/m) also achieved
- Best startup requires $-45 < B_{VF} < -30$ G

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![Graph showing pre-ionization, maximum line density, and Ip,20 ms for different Bz values with Radial, He and Oblique, D2 launches.](image-url)
EC Resonance Scan (Varying Bτ) Demonstrates Robust Breakdown and Reliable Initial Ip Ramp Under All Conditions
Burnthrough of Low Z Impurities is More Prompt and Reproducible with EC Assist ($E_\phi = 0.41 \text{ V/m, } B_\phi = 2.1 \text{ T}$)

- **Burnthrough with OH**
  - $\Delta t_{\text{Ohmic}}$ (ms)
  - $\Delta t_{\text{EC}}$ (ms)

- **Burnthrough with EC Assist**
  - $P_{\text{EC}} = 1.0 \text{ MW}$

![Graphs showing burnthrough times and energy levels](image-url)
Plasma Formation and Evolution is Observed by a Fast Camera, Viewing C\text{III} Emission

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

- \(-12.7 \text{ ms, } I_p = 1.8 \text{ kA, } V_L = 0 \text{V}\)
  - Breakdown at \(R_{X2}\)
- \(-9.3 \text{ ms, } 1.9 \text{ kA, } 0 \text{V}\)
- \(-4.3 \text{ ms, } 5.6 \text{ kA, } 0.6 \text{V}\)
- \(+4.0 \text{ ms, } 25 \text{kA, } 2.6 \text{V}\)
  - Closed flux surfaces form
- \(+12 \text{ ms, } I_p 61 \text{kA, } V_L = 3.0 \text{V}\)
  - Discharge established on HFS
- \(+39 \text{ ms, } 98 \text{kA, } 3.0 \text{V}\)
  - Radial position control (Limited on LFS)

Plasma Expansion due to \(j \times B\)
Abel Inversion Shows Initial Plasma Expansion at Nearly Constant Velocity (due to ExB)

- $E$ from charge separation due to $\text{grad}(B)$ and curvature drifts
- $v_{\text{expansion}} \approx 50 \text{ m/s} \ (P_{\text{EC}} = 1 \text{ MW})$
- 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 $t = +12$ms 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 Stellarators or Burning Plasma Devices
- Could provide a useful low $I_p$ target for ITER in the commissioning phase
- NI currents are both Pfirsch-Schlüter and Bootstrap (Ejiri, et al., Nuc. Fus., 2006)
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<td>Divert earlier in rampup</td>
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Total Flux Consumption in Rampup is Reduced $\approx 20\%$ with Modest Addition of Auxiliary Heating

$$CE_{jima} (\text{Normalized Resistive flux}) = \frac{\psi_{\text{boundary}} - \psi_{\text{pol,EIT}}}{\mu_0 R_{Ip}}$$
RAMPDOWN
Controlled Termination (Rampdown) of Burning Plasmas is Necessary to Mitigate Heat Fluxes and Mechanical Forces

- Safe and controlled discharge termination becomes increasingly important.

\[ \approx 750 \text{ MJ} \] is available in ITER (baseline scenario)

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<th>Rampdown challenge for ITER</th>
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<td>Additional flux and solenoid current limit burn duration</td>
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<td>Slow density decay may be near density limit</td>
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<td>Strike points remain in divertor region with elongation ramp</td>
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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 $\kappa$, $q_{95}$, $\beta_N$, 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
  - $d|\langle \Psi \rangle|/dt$ 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.
Rampdown without Vertical Instabilities Requires Temporal Changes in the Control Algorithm

- Successful rampdown to $I_{p, DIII-D} < 0.14$ 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 $\Delta Z_{max}$ 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 $I_i$ 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

\[ \ell_i(3) \]

\[ T_e(\rho=0.8) \text{ (keV)} \]

DIII-D #132411

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
  - $\ell_i$ 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 ($I_{\text{ITER equiv.}} < 1$ 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.