by
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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

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 (Ip/aB, li, βN, 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
- 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)

<table>
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<tr>
<th>Rampdown challenge for ITER</th>
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<td>Additional flux and solenoid current limit burn duration</td>
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P. Politzer (Th. pm) U04-9
The ITER Rampdown Phase has been Experimentally Simulated in DIII-D with Similar $\kappa$, $\beta_p$, $\ell_i$, and $q_{95}$.

- **Elongation**

- **H-mode**

- **L-mode**

- **$\ell_i(3)$**

- **Density ($10^{20}$ m$^{-3}$)**

- **ITER density trajectory is assumed**

- **Black**: DIII-D

- **Gold**: ITER simulation using DINA code

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P. Politzer

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

133-09/GLJ/jy
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
  - $\frac{d|\langle\Psi\rangle|}{dt}$ 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 $\kappa$ (black) rampdown
- Less frequent ELMs
- ELM-free H-mode at 4.5 s
  - Higher $\ell_i$, lower PNB
  - Density increases
  - $\beta_p$ 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 $z_{\text{cur}}$

- Vertically stable until $\Delta Z_{\text{max}}$ 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.

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<td>Develop algorithms for fixed strike points at low Ip and elongation</td>
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<td>Vertical instabilities</td>
<td>Quantify stability boundary and optimize vertical control</td>
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### ITER challenge

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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 $q_{\text{min}}$ (delayed saw-teeth) with large-bore scenario
- Energy to LFS limiters reduced with earlier divert time
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 $l_i(3)$ realtime (rtEFIT)
  - $l_i(3)$ 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

\[ \psi_{\text{inductive}} \] (V-S)

\[ \psi_R \] (V-S)

\[ \psi \] \( \text{inductive} \) (V-S)

\[ \psi \] \( \text{R} \) (V-S)

\[ C_{\text{Ejima}} \]

\[ \overline{P} \] (MW)

136295, 88, 87

OH

NB

EC

\[ P_{\text{OH}} \]

\[ P_{\text{NB}} \]

\[ P_{\text{EC}} \]
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 temperature is increased

T.C. Casper

G.L. Jackson/APS-DPP/Nov 2009
### DIII-D has Explored Rampup Scenarios to Address ITER Needs

<table>
<thead>
<tr>
<th>ITER Challenge</th>
<th>ITER Small bore scenario</th>
<th>DIII-D experimental approach</th>
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<tr>
<td>Heat flux on poloidal limiters</td>
<td>High heat flux near engineering limits</td>
<td>Divert earlier in rampup</td>
</tr>
<tr>
<td>Current profile during rampup</td>
<td>High $l_i$ near vertical control limits</td>
<td>Higher volume (large-bore) reduces $l_i$</td>
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<tr>
<td>Different current profiles for advanced scenarios</td>
<td>$l_i$ feedback using $I_p$ ramp rate</td>
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<td>Minimize flux</td>
<td>Auxiliary heating investigated</td>
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<td>Extrapolate DIII-D results to ITER</td>
<td>Corsica benchmarking of DIII-D experiments</td>
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BREAKDOWN AND BURNTHROUGH
Normal Ohmic Breakdown in DIII-D Occurs Near the High Field Side

- 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

RIW(midplane) = 1.02 m
RX2 = 1.64 m
ROW(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

J.H. Yu

G.L. Jackson/APS-DPP/Nov 2009
ECH Allows Breakdown to Initiate Near the Vessel Center and Initially Expand Outward

- Abel inversion shows plasma expansion at nearly constant velocity
- $v_{\text{expansion}} \approx 50 \text{ m/s} (P_{EC} = 1 \text{ MW})$
  Expansion is a function of heating power and $T_e$
  - 90 m/s for $P_{EC} = 2 \text{ MW}$
- 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 Voltage Startup (0.3 V/m) is Optimized with Vertical Field

- Oblique EC launch (required for ITER) is effective when vertical field and prefil are optimized
- Low $E_\phi$ startup in helium (0.3 V/m) also achieved
Burnthrough of Low Z Impurities is More Prompt and Reproducible with EC Assist

- $t-t_0,\text{inductive}$ (ms)
- $t-t_0,\text{EC}$ (ms)

<table>
<thead>
<tr>
<th>$D_\alpha$</th>
<th>C$^1$</th>
<th>C$^2$</th>
<th>C$^3$</th>
<th>O$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
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PEC = 1.0 MW

- $E_\phi = 0.41$ V/m,
- $B_\phi = 2.1$ 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, 2\textsuperscript{nd} harmonic X-mode
  - Occurs near the EC resonance radius
  - Plasma expands outward due to $\mathbf{E} \times \mathbf{B}$ force

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

- **Noninductive toroidal current ($\leq 5$ 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 $E_\phi$ 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_{ITER equiv.} < 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