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# Experiments Simulating ITER Rampdown and Startup Scenarios in the DIII-D Tokamak

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Successful burning plasma operation in ITER requires reliable startup, a burning plasma flattop phase, and disruption-free rampdown. We report on recent experiments to simulate the ITER startup and rampdown phases in the DIII-D tokamak, where ITER discharges were scaled to DIII-D by the ratio of current resistive time (≈50) and either the low field side (LFS) radii (during the limited phase) or the major radius (during the diverted phase) while maintaining the ITER value of I/aB.

Previous experiments in DIII-D have simulated portions of the ITER startup scenario including low inductive voltage ($V_{loop}$) startup, as low as 2.2 V (0.21 V/m), with 2nd harmonic X-mode (X2) electron cyclotron (EC) assist [1]. The ITER baseline design is $E_\phi \leq$ 0.3 V/m. In addition, an improved "large-bore" startup was developed and $l_i$ feedback control was successfully demonstrated [1]. EC assisted breakdown and burnthrough, and optimization of the vertical magnetic field, $B_v$, is required for robust and reproducible startup at these reduced voltages.

With EC assist, the optimum breakdown magnetic field configuration is not that which produces the longest connection lengths along a field line between the ionizing region and the wall, but rather alignment of flux surfaces with the EC resonant location [2]. Images in $D_\alpha$ light during the pre-ionization phase of two discharges with different programmed vertical magnetic fields, $B_{v,pgm}$, are shown in Fig. 1. The highest pre-ionization $D_\alpha$ intensity, along with the most robust burnthrough and startup, occurs with a programmed vertical field of –45 G [Fig. 1(a)] which is an order of magnitude higher than the 0 G case, Fig. 1(b). The EC resonant radius, $R_{X2}$ is shown as a vertical line in Fig. 1(c) and the EC beam intersects the X2 resonance at $z$≈0.065 cm, near the midplane. The slight difference between the radius of peak $D_\alpha$ intensity and $R_{X2}$ in Fig. 1(c), ≈3–4 cm is currently under investigation. For *Ohmic* DIII-D startup, no additional vertical field is applied and an algorithm is used to optimize the field null and connection length, albeit at higher $V_{loop}$. However at the reduced $V_{loop}$ in these experiments, both pre-ionization $D_\alpha$ intensity and the initial plasma current [Fig. 1(d)] are significantly reduced without additional $B_v$. A vertical field scan is shown in Fig. 2 for both the peak line integrated electron density during the pre-ionization phase [Fig. 2(a)] and the initial plasma current at $t$=20 ms [Fig. 2(b)], after closed flux surfaces have formed. The peak pre-ionization density and maximum initial ramp rate occur at approximately –45 G ($\boldsymbol{I_\phi}$ **x** $\boldsymbol{B_v}$ force is inward). The ITER gyrotrons are limited to a minimum oblique launch angle of approximately 20°, so radial launch (black, 0°) is compared to oblique launch (red, 23.6°), which is more representative of the ITER scenario. Startup was successfully achieved over a broad range of $B_v$ in both cases. We note that in previous work, where $B_{v,pgm}$=0 and $D_2$ prefill was lower by a factor of 2.5, pre-ionization was effective only for radial launch [2].

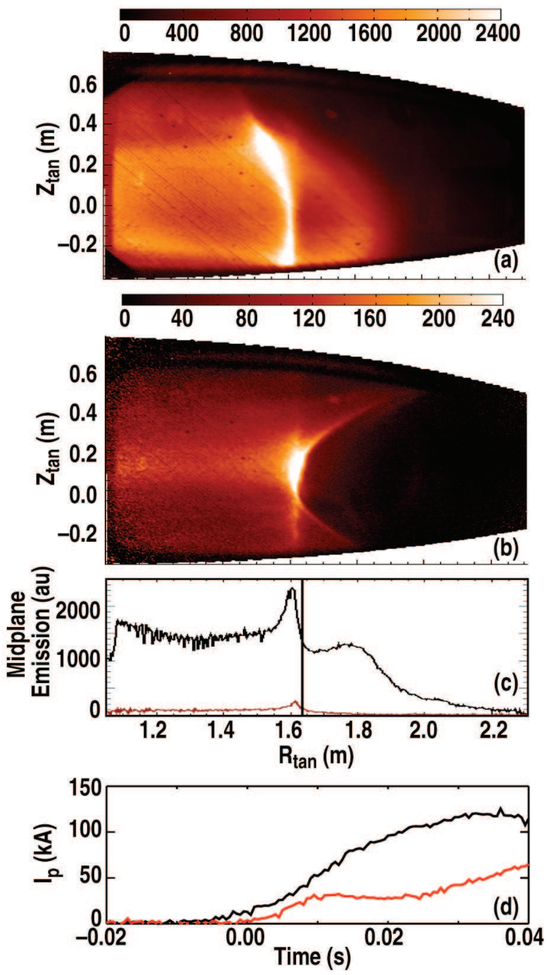


Fig. 1. $D_\alpha$ images from the tangential viewing DIII-D fast framing camera during EC pre-ionization at $t$=–10 ms. $P_{EC}$ = 1.2 MW, initiating at –15 ms ($V_{loop}$ initiates at –8 ms for discharges with applied vertical magnetic fields of –45 G (a), and 0 G (b). Intensity as a function of tangency radius (at $z$=0) is shown in (c) for $B_{v,pgm}$ = –45 G (black) and $B_{v,pgm}$ = 0 G (red). $R_{X2}$ is shown as a vertical line. The EC beam intersects $R_{X2}$ at $z \approx 0.065$ m. $V_{loop}$ = 3 V and $B_T$ = 1.9 T. $I_p$ is plotted in (d).

Minimum EC power for successful low voltage startup has also been determined, shown in Fig. 3. A minimum power threshold of ≈0.5 MW was required to successfully achieve burnthrough and reach current flattop. As the EC power is reduced, the initial current ramp rate, represented by the current at $t$=20 ms in Fig. 3(b), becomes lower. For the discharge with $P_{EC}$ = 0.46 MW (solid symbols), the discharge did not reach current flattop and there was a radiative collapse beginning at $t$=50 ms. Even

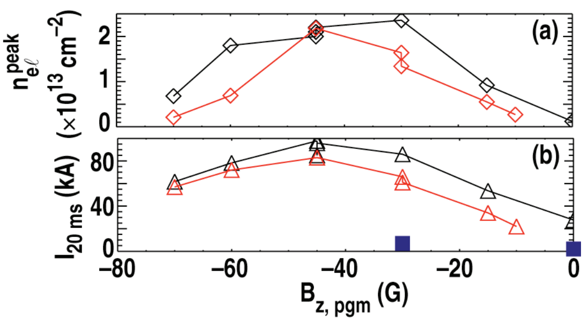


Fig. 2. Maximum pre-ionization line integrated density, (a), and plasma current at 20 ms (b), as a function of applied vertical field. $P_{EC}$ = 1.0–1.2 MW, $V_{loop}$ = 3 V, $P_{D2}$ = 0.15 mT, and $B_T$ = 1.9 T. EC radial launch (0°) is shown in black and oblique launch (23°) in red. Ohmic discharges, with no burnthrough, are shown as blue squares (b).

though burnthrough of $C^{III}$ was observed [Fig. 3(c), cross], burnthrough of all impurity states of carbon and oxygen was not achieved. An interesting feature of EC assist is that a small toroidal current is observed [Fig. 3(a)] before the application of $V_{loop}$. This current increases with increasing EC power, both for radial and oblique launch, hence it is not likely that the current is due to direct ECCD. Other possibilities, such as diamagnetic drift of the hot electrons, are under investigation.

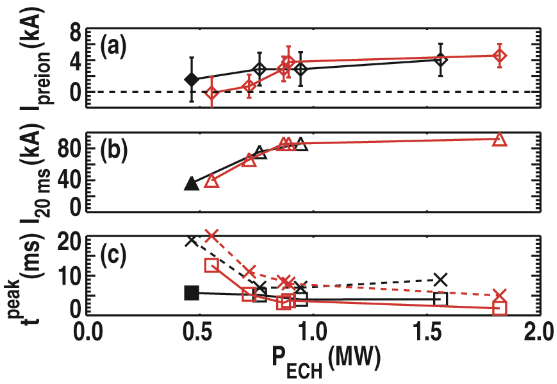


Fig. 3. EC power scan showing (a), initial toroidal plasma current at $t = -8$ ms, before the application of inductive loop voltage (b) plasma current at $t = 20$ ms when closed flux surfaces have formed, and (c) time from initiation of the EC pulse to peak $D_\alpha$ (squares) and $C^{III}$ (crosses) emission. Discharge with solid symbols exhibited a radiative collapse. Both EC radial launch (black, $B_{v,pgm} = -30$ G) and 23.6° oblique launch (red, $B_{v,pgm} = -45$ G) are plotted. $V_{loop} = 3$ V and $B_T = 1.9$ T.

Successful rampdown of ITER plasmas is an important consideration because the ITER design allows for only a small number of disruptions. The internal inductance can increase during rampdown, approaching either a density limit or the control limit for vertical stability. By simultaneously decreasing the elongation and plasma current, ITER-like discharges (baseline H-mode-scenario 2) have successfully achieved a 'soft landing' in DIII-D without loss of vertical stability. The ITER rampdown scenario maintains H-mode while decreasing κ and ramping $I_p^{ITER}$ from 15 MA to 10 MA. After an H-L back transition, both κ and $I_p$ continue decreasing while the strikepoints are maintained on the ITER divertor target plates. For $I_p^{ITER} \leq$ 1.4 MA ($I_p^{DIII-D} =$ 0.14 MA) the ITER discharge can terminate abruptly without any deleterious effects. Using the scaling described above, this scenario has been successfully demonstrated in DIII-D. Vertical position control was maintained using only the outer DIII-D poloidal field (PF) coils, similar to the ITER design (normally both inner and outer PF coils are used in DIII-D for vertical position control). An important consideration for ITER is that no additional flux be consumed during current rampdown. Figure 4 shows a scan of the $I_p$ ramp rate and Ohmic transformer current

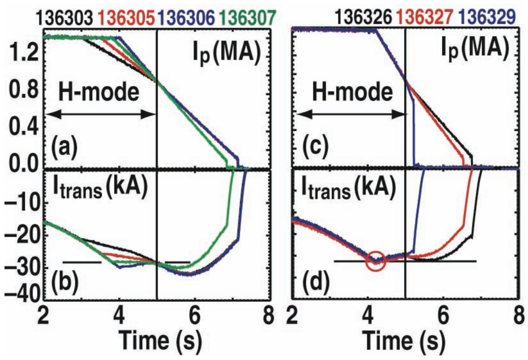


Fig. 4. Scan of $I_p$ rampdown rates. Discharge remains in H-mode until 1.0 MA (10 MA ITER). $I_p$ ramp rate is varied during the H-mode phase (a) and in the L-mode phase (c). The corresponding Ohmic transformer current is shown in (b) and (d) respectively. Horizontal lines indicate the initial values of transformer current before rampdown.

which is a direct measure of flux consumption. Figure 4(a,b) initially demonstrated that ramp rates faster than the ITER design during H-mode could be successfully achieved. When this was coupled with a slower ramp rate during the L-mode phase, successful rampdown was achieved within the ITER limits [Fig. 4(c,d)] without additional flux consumption. However a faster L-mode rampdown rate [Fig. 4(c), blue] produced a loss of vertical control and early plasma termination. Further work will explore the limits over which rampdown is possible without additional flux consumption. During the rampdown phase, the density decreased montonically (although not linearly) as $I_p$ decreased and no density limit disruptions were observed, even at the highest rampdown rates.

In conclusion, both the ITER reference startup and rampdown phases have been successfully simulated in the DIII-D tokamak. A series of scans during startup has demonstrated that low inductive field startup, ≤0.3 V/m, can be achieved with EC assist. To date Ohmic startup under the same conditions has not been successfully achieved. An EC power threshold of ≈0.5 MW has been observed for successful low voltage startup. However to obtain robust startup, optimization of both the vertical field and neutral density pressure is important. We find that with EC assist, optimizing the vertical field is more important than obtaining a large poloidal magnetic field null (and a long connection length to the wall) for good breakdown and early current evolution. Simulation of the ITER reference rampdown has demonstrated successful discharge termination. The ITER specified shape and $\beta_p$ were maintained during the entire rampdown while strikepoints were held within the specified geometry of the ITER dirvertor target plates, required for heat flux removal. By increasing the rampdown rate above the ITER reference value, the additional flux consumption during rampdown was eliminated while maintaining vertical stability and achieving a "soft landing".

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**References**

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