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Flux Consumption Optimization and the Achievement of 1 MA Discharges on NSTX

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1. Introduction

The compact geometry of the spherical tokamak [1] (ST) greatly limits the inductive heating and current drive capability of its ohmic heating (OH) solenoid. Consequently, the development of non-inductive current drive is crucial to the ST concept. However, near-term research in the ST will rely heavily on OH current drive to generate target plasmas suitable for strong auxiliary heating to test the stability and confinement characteristics of the ST configuration. Recent experiments on the National Spherical Torus Experiment (NSTX) [2, 3] in the United States have begun to achieve high plasma current ohmically in a MA-class ST device. Typical parameters for present NSTX plasmas are: major radius R_0 = 85 cm, minor radius a = 67 cm, aspect ratio $A = R_0/a > 1.26$, elongation $\kappa < 2.2$, triangularity $\delta < 0.5$, vacuum toroidal field B_T = 0.3 Tesla at R_0, plasma current I_P <1 MA, and plasma pulse length up to 0.5 seconds. Systematic scans of plasma current ramp-rate and several diagnostics have been utilized to characterize the ohmic current drive efficiency, maximize the achievable plasma current, and to investigate the MHD instabilities observed during NSTX operation. The results of these experiments are described below.

2. Experimental Results

2.1. Plasma current ramp-rate scans

Flux consumption optimization is effectively equivalent to balancing the plasma current ramp-rate against the resistive relaxation of the current profile to obtain the broadest current profile which is stable to ramp-terminating MHD activity. Thus, the ability to modify the ramp-rate and control the plasma shape and volume during the ramp is essential, especially at high plasma current. Without the recently implemented digital plasma control system (PCS) [4], the achievement of the fast ramps discussed below would have been significantly more difficult.

Figure 1 shows the plasma current waveforms obtained during an early I_P ramp-rate scan on NSTX. For each discharge shown in the figure, the OH, PF, and TF coil currents are pre-programmed during the first 20 msec of the discharge. At t=20 msec, as long as the plasma current has reached a threshold value of 100 kA, coil power supply control is turned over to the plasma control system for subsequent I_P, radial position, and vertical position feedback control.

The requested I_P after t=20 msec was systematically increased to achieve increasingly faster ramps, and the PF shaping coil current ratios were adjusted to compensate for the higher natural elongation caused by the lower internal inductance of the faster ramps.

As seen in Figure 1, signatures of several different types of MHD events are apparent in the I_P traces. All ramp-rates scanned exhibited at least one late upward spike in the plasma current. This Internal Reconnection Event (IRE) [5, 6, 7] is a nearly ubiquitous feature of ST plasmas and was often associated with low loop voltage near the end of the discharge. For the fastest ramp-rates in the scan (6, 8, and 10 requested MA/sec), early large (likely m=2) MHD events terminated the ramp and the plasma current seldom exceeded its pre-event value. Slower ramp-rate discharges generally terminated either due to insufficient loop voltage and/or OH flux. The optimal ramp-rate of 5 MA/sec was just slow enough to avoid early MHD activity that terminated the current ramp.

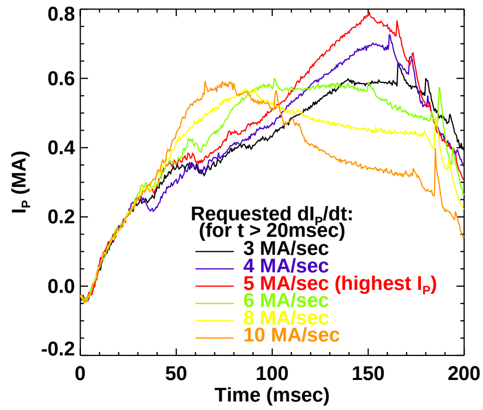

Figure 1. *Plasma current traces from a systematic scan of current ramp-rate.*

EFIT [8, 9] analysis of these discharges has been used to track the plasma shape, normalized internal inductance l_i, and flux consumption during the ramp-up. In the present treatment, the resistive flux consumption is parameterized with the Ejima [10] coefficient $C_E \equiv \Delta\Phi_R/\mu_0 R_0 I_P$, and the total surface flux consumption is parameterized using the Ejima-Wesley coefficient $C_{E\text{-}W} \equiv (\Delta\Phi_I + \Delta\Phi_R)/\mu_0 R_0 I_P$ [11]. The inductive and resistive fluxes Φ_I and $\Delta\Phi_R$ are derivable from Poynting's Theorem and have the following definitions: $\Delta\Phi_I(t) = \int_0^t \frac{dt'}{I_P} \int \frac{\partial}{\partial t}\frac{B_P^2}{2\mu_0} dV$ and $\Delta\Phi_R(t) = \int_0^t \frac{dt'}{I_P} \int J_\phi E_\phi dV$ where $\int dV$ refers to integration over the plasma volume.

For all of the shots shown in Figure 1, the PCS was used to keep the plasma shape throughout the ramp roughly fixed at A ≈1.3, κ≈1.8-2.2, and δ≈0.4. The internal inductance typically increases during these discharges from l_i=0.2-0.3 initially to 0.6-1.0 at the time of maximum current. Figure 2 shows that the internal inductance at peak current drops (as expected) by roughly 40% as the average ramp-rate doubles from 4 to 8 MA/sec. In addition, Figure 2 shows that lower normalized resistive and total flux consumption was achieved with faster ramps. A noteworthy feature of Figure 2 is that even though the internal inductance drops significantly, most of the drop in total flux consumption with increasing ramp-rate comes from a drop in the resistive component. This is because the inductive portion of the total flux is only a small fraction (30%) of the total at the end of the current ramp.

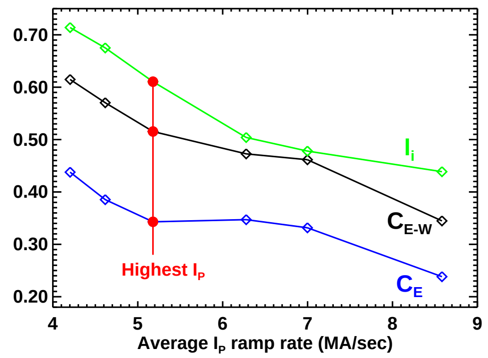

Figure 2. *Internal inductance and Ejima coefficients at peak I_P as a function of I_P ramp-rate for the discharges of Figure 1.*

This implies that either the resistive consumption is considerably higher or that the inductive consumption is lower at low aspect ratio. The most relevant C_E value is that obtained at the highest I_p, and for NSTX experiments thus far, shots optimized for minimal flux consumption have C_E = 0.35-0.4 and $C_{E\text{-}W}$ = 0.5-0.55. For comparison, for low loop voltage ramp-up to I_p=1 MA in the DIII-D tokamak [12], dI_p/dt = 1-1.5 MA/sec, C_E= 0.5, and $C_{E\text{-}W}$=0.9.

2.2. High current discharges

The highest plasma current achieved thus far on NSTX is 1 MA. Implementation of the full OH capability of NSTX and partial vacuum vessel bake-out were crucial in reaching this physics goal. Plasma parameters at peak I_p from EFIT reconstructions were: A=1.28, κ=1.9, δ=0.4, l_i=0.7, C_E=0.35, and $C_{E\text{-}W}$=0.5. One of the more interesting aspects of the 1 MA shots is the reproducible plasma current "hesitation" event observable on the experimental I_p traces shown in Figure 3 near t=60 msec. Operationally it was found that 1 MA could only be achieved by forcing this MHD event to occur early by ramping faster than 5 MA/sec. This allowed the plasma to recover in such a way that no subsequent MHD was excited until the late IREs which occur after t=170 msec. Plasma current ramp-rates both faster and slower than 7 MA/sec again led to ramp terminating MHD activity. The event in Figure 3 consumed a significant fraction (20%) of the OH flux and clearly reduced the achievable I_p flat-top duration. An important finding evident from Figure 2 and from analysis of the shots in Figure 3 is that Ejima coefficients in the expected range of 0.4 were only obtained with relatively fast I_p ramps even after (partial) vessel bake-out. Several possible dissipation mechanisms responsible for this are discussed below.

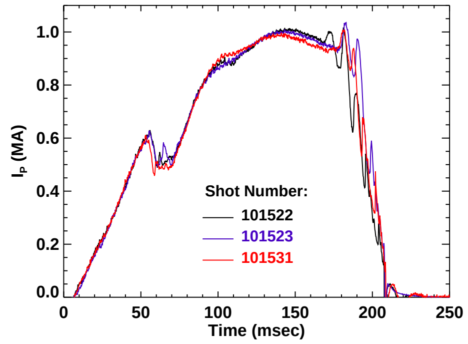

Figure 3. *Plasma current traces for reproducible 1 MA discharges in NSTX.*

Many NSTX discharges exhibited coherent outboard Mirnov fluctuations with decreasing mode frequency early in the plasma current rise-phase. This behavior may be indicative of the formation of locked tearing modes, and such modes may have dissipated OH flux during the ramp-up in many NSTX discharges. The observed mode frequency typically decreases from 8kHz shortly after break-down and approaches zero within 40 msec, apparently locks, and then grows rapidly near t=60 msec. Not every discharge exhibits such strong locking behavior, but many show at least indications of such activity.

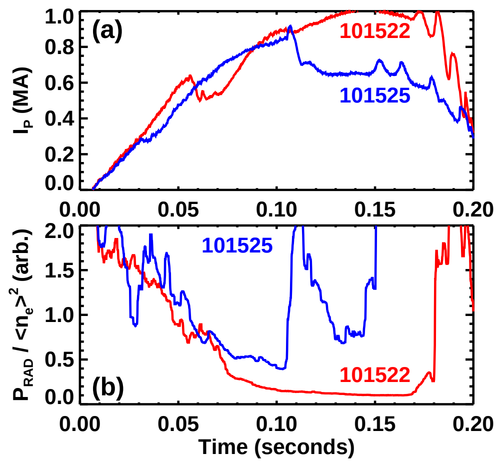

Figure 4. *(a) Plasma currents for a 1 MA shot and a failed 1 MA attempt (b) Density-normalized radiated power traces.*

The most obvious dissipation mechanism is of course plasma resistivity, and aside from the predicted neoclassical enhancement of the parallel resistivity due to increased particle trapping, soft x-ray and bolometer signals often showed an emission profile highly peaked on axis in the energy band dominated by metallic impurities. Figure 4 compares plasma current and density-normalized radiated power traces for a successful 1 MA discharge and a 1 MA attempt which failed due to a delayed early MHD event. The only difference between these two shots is the early time history of the requested I_p which modified the applied loop voltage after t=30 msec. The 850 kA peak plasma current trace (shot 101525) in Figure 4a indicates a reconnection event at t=103 msec, and Figure 4b shows that a potentially important difference between these shots is the significant decrease in the density-normalized radiated power of shot 101522 after its first MHD event. This is in contrast to the rapid rise in radiated power after the first event of shot 101525. EFITs (using only external magnetics) suggest q(0) is near 2 just after the events in both discharges in Figure 4, and it is possible that these events are caused by m=2 (possibly double) tearing modes. A plausible interpretation of Figure 4 is that forcing the reconnection event to occur early allowed some fraction of the core impurities to be expelled without destroying the subsequent confinement.

3. Summary

Average plasma current ramp-rates of 5-7 MA/sec are found to maximize ohmic flux consumption efficiency during initial experiments on NSTX. The highest plasma current achieved thus far on NSTX is 1 MA with plasma parameters at peak I_p of: A=1.28, κ=1.9, δ=0.4, l_i=0.7, C_E=0.35, and $C_{E\text{-}W}$=0.5. The dissipation mechanisms most likely responsible for the fast ramps required to achieve C_E=0.35 are enhanced neoclassical resistivity, early locked tearing modes, and metallic impurity accumulation in the plasma core.

Acknowledgments

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