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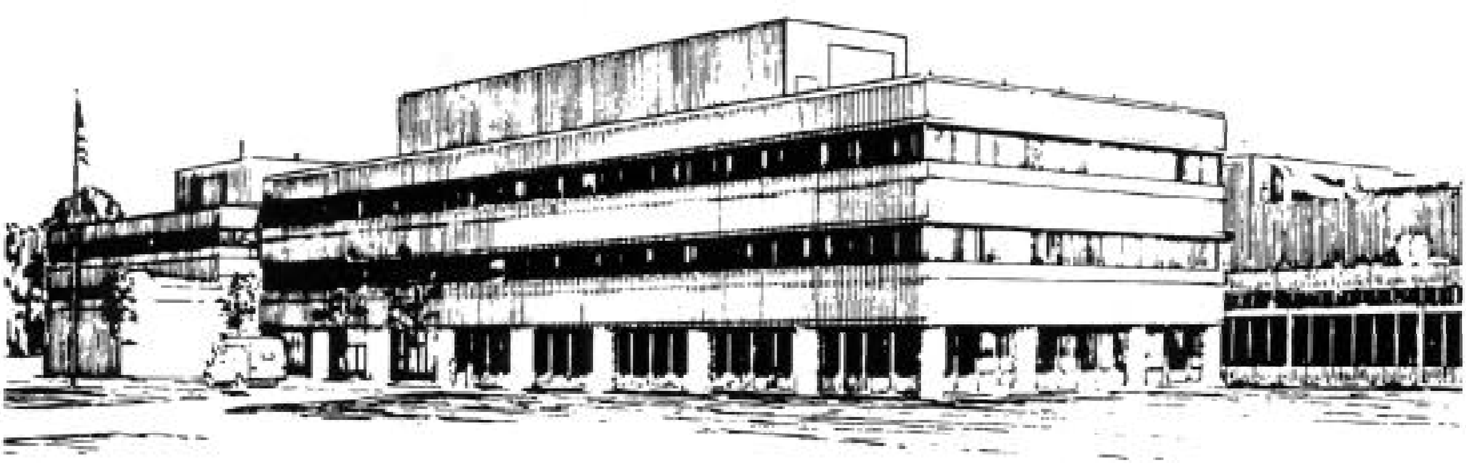

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Flux Consumption Optimization and the Achievement of 1MA Discharges on NSTX

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Abstract. The spherical tokamak (ST), because of its slender central column, has very limited volt-second capability relative to a standard aspect ratio tokamak of similar plasma cross-section. Recent experiments on the National Spherical Torus Experiment (NSTX) have begun to quantify and optimize the ohmic current drive efficiency in a MA-class ST device. Sustainable ramp-rates in excess of 5MA/sec during the current rise phase have been achieved on NSTX, while faster ramps generate significant MHD activity. Discharges with I_P exceeding 1MA have been achieved in NSTX with nominal parameters: aspect ratio A=1.3-1.4, elongation κ=2-2.2, triangularity δ=0.4, internal inductance l_i=0.6, and Ejima coefficient C_E=0.35. Flux consumption efficiency results, performance improvements associated with first boronization, and comparisons to neoclassical resistivity are described.

1. Introduction

Spherical tokamak (ST) plasmas [1] have received considerable attention due to encouraging experimental results [2, 3, 4] from the Small Tight Aspect Ratio Tokamak (START) [5] and promising theoretical predictions regarding stability and confinement . The long-term goal of ST research is the development of steady-state configurations with high plasma β and a high fraction of bootstrap current. Nevertheless, near-term research in the ST will rely 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) [6, 7] 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 < 68 cm, aspect ratio A=R_0/a > 1.26, elongation κ < 2.2, triangularity δ < 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 have been conducted to characterize the ohmic current drive efficiency, maximize the achievable plasma current, investigate MHD instabilities observed during NSTX operation, and allow a preliminary test of neoclassical resistivity theory. The results of these experiments are described in the following sections.

2. Ohmic Flux Consumption

Since the ohmic solenoid flux in the ST configuration is so limited, it is desirable to quantify the relationship between the available solenoid flux, the flux at the plasma surface, and the maximum plasma current and flat-top duration achievable with these fluxes.

2.1 The Poynting Method

The most commonly used method of flux consumption analysis was first applied to the Doublet III device by Ejima [8]. This method is derived from a global electromagnetic power balance using the poloidal field (PF) portion of Poynting's theorem. It can be shown that the total poloidal flux change at the plasma surface $\Delta\Phi_S(t)$ can be expressed approximately as:

$$-\Delta\Phi_S(t) = \int_0^t V_S dt' \approx \Delta\Phi_I(t) + \Delta\Phi_R(t) \tag{1}$$

where

$$\Delta\Phi_I(t) = \int_0^t \frac{dt'}{I_P} \int \frac{\partial}{\partial t}\left(\frac{B_P^2}{2\mu_0}\right) dV \tag{2}$$

and

$$\Delta\Phi_R(t) = \int_0^t \frac{dt'}{I_P} \int J_\phi E_\phi dV. \tag{3}$$

In devices such as NSTX which have a small gap between the ohmic heating solenoid and the inner-most portion of the plasma boundary, the total flux-swing capability of the OH solenoid ($\Delta\Phi_{OH}$) is nearly equal to $\Delta\Phi_S$. Therefore, the relationship between $\Delta\Phi_S$ and I_P determines the ultimate toroidal current carrying capability of the device. By convention, the resistive flux consumption is parameterized with the Ejima coefficient $C_E \equiv \Delta\Phi_R/\mu_0 R_0 I_P$, and the total surface flux consumption is parameterized here using the Ejima-Wesley coefficient $C_{E-W} \equiv (\Delta\Phi_I + \Delta\Phi_R)/\mu_0 R_0 I_P$ [9]. For all the analysis that follows, EFIT [10, 11] equilibrium solutions were used to compute the volume and time integrals in Equations 2 and 3 explicitly.

3. Experimental Results

3.1 Initial High Current Discharges

The highest plasma current achieved during the initial phase of NSTX operation was 1MA. 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=0.4, and C_{E-W}=0.55. One of the more interesting aspects of the 1MA shots is the reproducible plasma current "hesitation" observable on the experimental I_P traces shown in Figure 1 near t=60msec. Operationally it was found that 1MA could only be achieved by

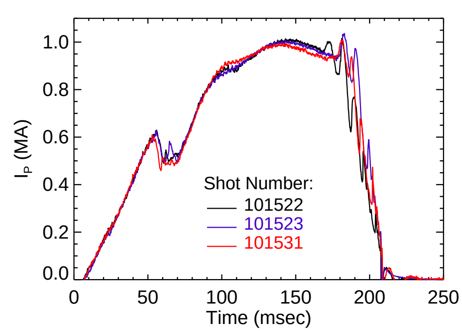

Figure 1: Plasma current traces for 1MA discharges from initial experiments in NSTX.

forcing this MHD event to occur early by ramping faster than 5MA/sec. This allowed the plasma to recover in such a way that no subsequent MHD was excited until the late reconnection events which occur after t=170msec. Plasma current ramp-rates both faster and slower than 7MA/sec again led to ramp-terminating MHD activity. The hesitation event in Figure 1 consumed a significant fraction (20%) of the OH flux and clearly reduced the achievable I_P flat-top duration. An important finding evident from analysis of the shots in Figure 1 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.

3.2 Tearing Activity

Many NSTX discharges exhibited coherent m=2 Mirnov fluctuations with decreasing mode frequency early in the plasma current rise-phase. This behavior may be indicative of the formation of locked (possibly double) tearing modes, and such modes may have dissipated OH flux during the ramp-up in many NSTX discharges. Figure 2 shows the frequency spectrum of a Mirnov sensor on the outboard mid-plane during the early phase of a discharge (shot 100856) with and average I_P ramp-rate of 8MA/sec. The mode frequency clearly decreases from 6kHz shortly after break-down and approaches zero within 40msec, apparently locks, and then grows rapidly near t=65msec. Not every discharge exhibits such strong locking behavior, although many show at least indications of such activity.

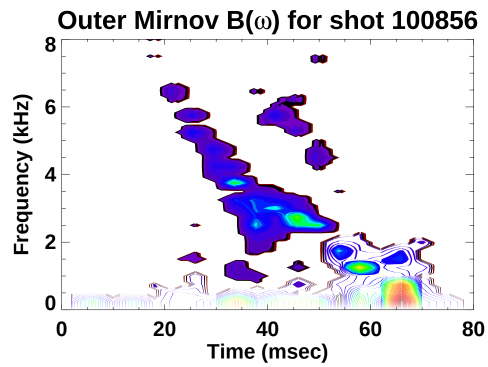

Figure 2: Outboard Mirnov frequency spectrum during the ramp-up phase of shot 100856.

3.3 Flux Consumption Post-boronization

In the interest of reducing impurity in-fluxes in NSTX, several device and operational improvements were made following the experiments described in Sections 3.1-3.2. First, all plasma facing metal surfaces were covered with graphite tiles. Second, the central column and passive plate graphite tiles were baked to 350 and 150°C, respectively. Finally, a 5% trimethyl-boron, 95% helium glow was performed to boronize the machine. Following boronization, visible Oxygen II light emission was reduced by a factor of ten and Carbon III light by a factor of two in subsequent discharges.

Such changes in the plasma impurity levels should have an immediate impact on resistive flux consumption, and Figure 3 shows the Ejima coefficients and internal inductance versus I_P

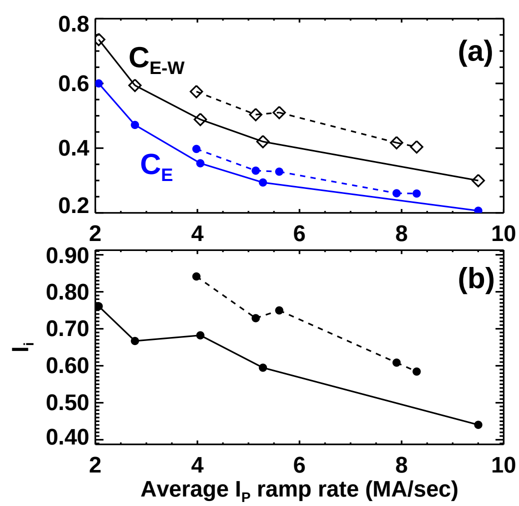

Figure 3: (a) Ejima coefficients versus ramp-rate in D plasmas before (dashed) and after (solid) boronization. (b) Internal inductance before and after boronization.

ramp-rate for inner-wall limited deuterium plasmas before and after boronization. For both scans, the line-average density at peak I_P was approximately $1-3\times10^{13}cm^{-3}$ and κ varied from 1.8 to 2.1. As seen in Figure 3a, the total surface flux consumption parameter C_{E-W} was reduced by 15-20%, and a similar fractional drop in the internal inductance is shown in Figure 3b. The resistive surface flux consumption parameter C_E dropped by roughly half this amount.

3.4 Comparison to Neoclassical Theory

By fitting recently obtained multi-pulse Thomson scattering data to poloidal flux functions, using recent formulas for the neoclassical conductivity in general geometry and collisionality regime [12], and using smoothed electric fields computed from the EFIT reconstructions, it is possible to compute the expected neoclassical toroidal current density. The time history of the estimated Z_{ave} (assuming a flat impurity density profile) can then be inferred from forcing the neoclassical Ejima coefficient to match the measured value in time during the ramp. Using the discharges from Figure 3 where Thomson data was available, Figure 4a shows that the ramp-average Z_{ave} (using $\int J_\phi^{neo} E_\phi dV$ as a weighting function) is above and near unity for all ramp-rates and impurity conditions tested in deuterium. Ignoring the presumably small bootstrap current, this implies that the measured resistive flux consumption is consistent with neoclassical resistivity. Further, the ratio of the two curves in Figure 4a is computed in Figure 4b and indicates that the ramp-average Z_{ave} was reduced by 10-30% after boronization. This drop apparently explains the flux consumption reduction evident in Figure 3.

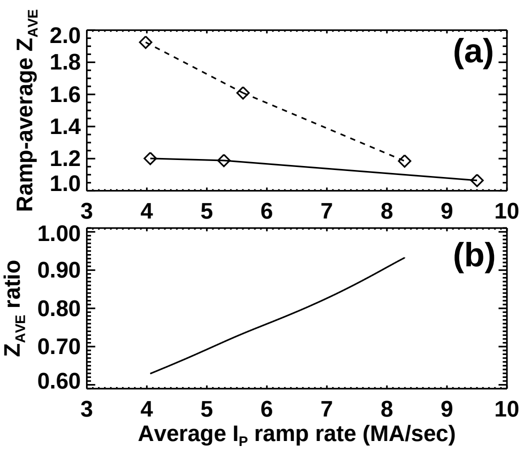

Figure 4: (a) Estimated Z_{ave} *vs. ramp-rate in D before (dashed) and after (solid) boronization. (b) Estimated ratio of post to pre-boronization* Z_{ave} *from data in (a).*

3.5 Performance Improvements

Finally, the reduction in total flux consumption made possible by improvements in machine conditioning and the plasma control system has allowed the achievement of NSTX plasma currents exceeding 1MA without MHD events during the current-rise phase and 800kA discharges with 100msec flat-top durations. Figure 5 shows the I_P waveforms for two such discharges. Both discharges ramp to peak current at just under 6MA/sec and have already been used as targets capable of absorbing significant neutral beam injection power. Future boronization and machine conditioning will hopefully aid in obtaining flat-tops at even higher plasma current values.

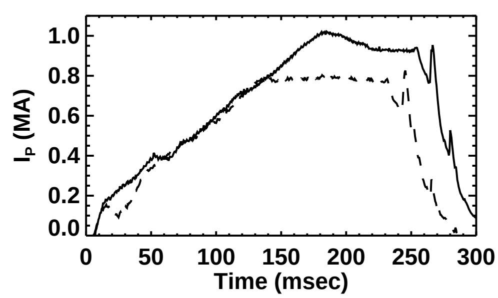

Figure 5: 1MA and 800kA flat-top discharges obtained after boronization.

4. Summary

Stable plasma current ramp-rates in the range of 5-6MA/sec appear to be optimal under present operating conditions. The Poynting method originally developed by Ejima has been utilized to quantify poloidal flux consumption in NSTX. With improved machine conditioning and boronization, total flux consumption parameterized by the Ejima-Wesley coefficient C_{E-W} has dropped from 0.55 to 0.45 for ramp-rates of 5MA/sec, and resistive flux consumption parameterized by the Ejima coefficient C_E has dropped from 0.4 to 0.3. High current discharges with I_P=1MA have been achieved in NSTX with nominal parameters: A=1.3-1.4, κ=2-2.2, δ=0.4, l_i=0.6, and Ejima coefficient C_E=0.35. Finally, Thomson scattering data has recently become available and has allowed a direct comparison of measured Ejima coefficients to those expected from neoclassical theory. Analysis indicates that neoclassical resistivity can explain the observed resistive flux consumption and that the average ion charge dropped by 10-30% following first boronization – consistent with the flux consumption studies. This analysis therefore also indicates that while early locked tearing activity may be present in NSTX discharges, such activity is apparently not strongly increasing the dissipation. Future work will concentrate on more accurate calculations of neoclassical resistivity to include multiple ion species effects.

Acknowledgments

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