Princeton Plasma Physics Laboratory

PPPL-4216
PPPL-4216

Tearing Mode Stability of Model Plasmas in the National Compact Stellarator Experiment

E.D. Fredrickson, M.C. Zarnstorff, and E.A. Lazarus

Preprint
(February 2007)

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

Tearing mode stability of model plasmas in the National Compact Stellarator experiment.

E D Fredrickson,

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton New Jersey 08544

M C Zarnstorff

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton New Jersey 08544

E. A. Lazarus

Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee

E D Fredrickson,

P.O. Box 451,

Princeton, New Jersey, 08543

Telephone – (609) 243-2945, Fax – (609)243-2874

efredrickson@pppl.gov

21 pages,

6 Figures

Tearing mode stability of model plasmas in the National Compact Stellarator experiment.

E D Fredrickson,

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton New Jersey 08544

M C Zarnstorff

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton New Jersey 08544

E. A. Lazarus

Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee

Abstract Predictive simulations of target plasmas for the National Compact Stellarator Experiment (NCSX) were performed as part of the design effort. The resistive stability of these simulated target plasmas was studied using a quasi-cylindrical Δ' stability code as has been done with some success for W7-AS plasmas. The plasmas were found to be classically unstable to an m=2, n=1 tearing mode during the start-up, but the 2/1 saturated island size in the target equilibrium was small, < 2%. Inclusion of neoclassical effects resulted in negligible island sizes throughout.

KEYWORDS: NCSX, Neoclassical Tearing Modes, Stellarators

I. INTRODUCTION

The NCSX stellarator [1] will have a substantial amount of plasma current, ≈ 100 - 200 kA, driven inductively or by the bootstrap effect. The presence of plasma current provides a potential source of free energy, which can then drive MHD instabilities such as tearing modes, [2,3] degrading confinement and performance. Calculations of the non-linear evolution of tearing modes, including neoclassical effects [4] (bootstrap current) in the full 3-D geometry of NCSX is beyond the capability of present MHD codes. In the tokamak community, qualitative modeling of tearing modes has been successfully done using a simple, quasi-cylindrical, low beta model as described below [5-11]. The validity of the application of this model to stellarators is supported by experiments on W7-A [12] and W7-AS [13] where reasonable agreement between experiment and modeling was found. The calculations presented below suggest that the start-up, equilibrium, and high beta phases of the baseline NCSX plasma should be stable to internally driven tearing modes with the inclusion of neoclassical effects. The target equilibrium is predicted to be marginally stable, with less than 2% islands.

The TRANSP code [14] is a 1-D, time-dependent power balance analysis code. As such it has various RF power deposition and current drive packages, beam deposition packages and can simulate the evolution of an ohmically driven current. It usually takes as input the time-dependent electron density, electron temperature and ion temperature profiles, but can also simulate the evolution of these using a variety of transport models. It was developed for the analysis of axi-symmetric (tokamak) plasmas. The TRANSP simulations analysed in this paper are described in more detail in Lazarus, *et al.,* Ref. 15. To apply TRANSP to an NCSX plasma, the NCSX 3-D stellarator equilibrium was mapped to a 1 1/2-D axisymmetric equilibrium (the cross-sectional shaping is decomposed into moments). The externally imposed iota profile was simulated by using an imposed "lower hybrid driven" current profile. The inductive (ohmic) and bootstrap currents were calculated in the axisymmetric geometry. The bootstrap current calculation may be more valid for the NCSX stellarator, than for stellarators in general, as the NCSX is designed for a magnetic geometry which results in particle orbits with features similar to those in axisymmetric systems (*e.g.,* tokamaks).

II. DESCRIPTION OF RESISTIVE MODEL USED FOR STABILITY ANALYSIS

The Δ' formalism used in the following analysis is derived in a zero beta, straight circular cylindrical geometry. Somewhat more refined formalisms (*e.g.,* PEST III [16]) allow for finite beta and shaping. However they are still constrained to axisymmetric equilibria and do not easily allow decoupling of ι (= 1/q) and J (important for modeling stellarators with externally applied transform), nor do they calculate $\Delta'(w)$ (necessary for modeling the growth and saturation of tearing modes). Codes such as PIES [17] or M3D [18] can in principle do a much more complete analysis because they are 3-D codes, but they are prohibitively expensive in terms of time to run. The principle affect of finite beta and shaping (away from ideal limits) is the coupling of poloidal harmonics. Empirically, this coupling appears to play a minor role in tearing mode evolution and the Δ' formalism has been useful in the analysis of even shaped, moderate beta tokamak plasmas. However, tearing mode stability results found by application of the Δ' formalism to shaped, finite beta and/or toroidally asymmetric plasmas *must* be viewed with some skepticism.

The Δ' code used in the following calculations separates the $\iota(r)$ and J(r) profiles, necessary even in circular tokamaks such as TFTR, and particularly so in stellarators where a substantial fraction of the transform is not from the plasma current. The $\iota(r)$ and J(r) profiles are used in the standard differential equation governing the perturbed helical flux function [2]

$$[\partial^2/\partial r^2 + 1/r\ \partial/\partial r - m^2/r^2 - (\partial J_0/\partial r)/(\partial \psi_0/\partial r)]\ \psi_{m,n} = 0 \qquad (1)$$

where ψ_0 is defined from $\iota(r)$ by

$$\psi_0(r) = B_0/R_0 \int_0^r (\iota(r) - n/m)\, r\, dr\,. \qquad (2)$$

The J(r) includes the bootstrap, beam driven and inductively driven currents but does *not* include the "lower hybrid" current used to model the external transform. To map the TRANSP 2-D equilibrium to 1-D, cylindrical geometry the TRANSP radial coordinate, $[\psi_{tor}/\psi_{tor}(a)]^{1/2}$ becomes the cylindrical radial coordinate. This normalized coordinate, when necessary, is scaled by a parameter by which the cross-sectional area is preserved, *e.g.,* the effective plasma minor radius becomes $a_p = [(\text{cross sectional area})/\pi]^{1/2}$.

Equation 1 has a pole at the mode rational surface where $\iota(r) = n/m$. In the boundary layer region near this surface a full fourth order differential equation must be used; however it has been shown that the mode stability is determined by matching the external solution across the boundary layer using the "constant – ψ" approximation. The matching condition yields a discontinuity in the first derivative, which is quantified in Δ'. A positive value for Δ' represents an unstable tearing mode, a negative value; stability.

For islands smaller than the tearing layer width, the growth of the island is exponential in time. For islands with small enough growth rate, the growth slows to linear in time after this (the Rutherford regime [3]). The condition for the change to linear growth is that the growth rate be slower than the inverse of the current diffusion timescale across the tearing layer. This constraint is evaluated for NCSX parameters using the definitions from Rutherford[3]. The definition for the poloidal Alfvén time is $\tau_H \equiv (4\pi\rho)^{1/2} qR/(sB_0)$, the resistive diffusion time $\tau_s \equiv 4\pi a^2/\eta$ and the magnetic Reynolds number $S \equiv \tau_s/\tau_H$. The linear growth rate of the tearing mode $\gamma_{mode} \approx 0.5\, (\Delta' a)^{4/5}\, (ma/r_s)^{2/5}\, \tau_s^{-3/5}\, \tau_H^{-2/5}$. The tearing layer width, normalized to minor radius, is $x_T \approx (\gamma_{mode}\tau_H/m^2S)^{1/4}$ and the resistive diffusion time across this width is $\tau_\Delta \equiv \tau_s x_T^2$. For the NCSX simulation discussed here, the effective major and minor radii are 1.42 and 0.33 m, respectively, the electron temperature at the q = 2 surface is $T_e \approx 1.9$ keV, the toroidal field strength is 1.4 T, the density is 5 x $10^{19}/m^3$, the rational surface $r_s \approx 0.7$ a, and the shear at the q = 2 surface is $s = r_s\, q'/q \approx 0.3$. We find for the 2/1 island $\tau_s = 3.0$ s, $\tau_H = 3.2 \times 10^{-6}$ s, $S \approx 9 \times 10^5$, $x_T = 4.3 \times 10^{-3}$, $\tau_\Delta = 5.5 \times 10^{-5}$ s, and $\gamma_{mode} = 3.9 \times 10^2\ s^{-1}$. The constraint is then satisfied as $\gamma_{mode}\, \tau_\Delta \approx 2.2 \times 10^{-2} \ll 1$. For the estimated island growth rate above, $a\Delta' \approx 10$ was used, and $a\Delta' \approx 250$ gives $\gamma_{mode}\, \tau_\Delta \approx 1$.

The equation describing the island width evolution in the Rutherford regime is,

$$dw/dt = 1.22\, \eta / \mu\, [\, \Delta'(w,t)]. \tag{3}$$

and in this paper the time dependent island width evolution is calculated by numerically integrating this equation. Here η is the resistivity and μ is the magnetic permeability. The $\Delta'(w)$ is calculated numerically at each TRANSP time step using the constant-ψ approximation [2].

The density and temperature gradient driven current in neoclassical theory, the bootstrap current, is affected by the presence of the magnetic island. The island flattens the temperature and density profile, locally reducing the bootstrap current and generating a helical current perturbation. The effect of this perturbed current on the island is modeled with an additional term in the Rutherford equation [4-11]

$$dw/dt = 1.22\, \eta / \mu\, [\, \Delta'(w) + \Delta_{nc}\,]. \tag{4}$$

In the model used below, Δ_{nc} is evaluated by using parameters calculated by TRANSP in the equation [8,9]

$$\Delta_{nc} = (16\,\pi / 5)\ k_1\, R_0\, J_{bs} / (s\, \iota\, B_0\, w\,). \qquad (5)$$

Here J_{bs} is the local bootstrap current density, s is the local shear and w is the island width. The constant k_1 accounts for approximations made in deriving the effective perturbation in the bootstrap current due to the island. For the simulations shown here, the same $k_1 \approx 1$ was used as had been used to fit TFTR experimental data.

Equation 5 would predict that all tearing modes would be unstable, as Δ_{nc} becomes very large for small islands. Physically, however, for small islands, the parallel transport will not be sufficient to keep temperatures and densities constant on flux surfaces. This effect is modeled by replacing the 1/w by $w/(w^2 + w_{crit}^2)$ [19]. The critical island width, w_{crit}, is a function of the ratio of the perpendicular to the parallel transport.

III. PREVIOUS COMPARISONS OF EXTENDED RUTHERFORD MODEL WITH EXPERIMENTS.

This approach has been well studied and used extensively to analyze experimental tearing mode data in tokamak experiments. It provides both a basis for translating the measured external magnetic fluctuation levels into a measure of the island size as well as predictions of saturated island widths, growth rate and mode stability. The inclusion of neoclassical effects, *i.e.*, the modeling of the effect of the island on the bootstrap current density and the concomitant effect of the perturbed bootstrap current on the island, has very successfully reproduced some of the observed characteristics of tearing modes in normal shear, high beta, low collisionality plasmas. This extensive experimental database [*e.g.,* 5-11] gives some credence to the neoclassical tearing mode model. However, neoclassical theory (applied to tearing modes) in the context of reversed shear plasmas has not been extensively tested.

In the circular cross-section TFTR tokamak this model found very good agreement between island widths predicted from edge magnetic fluctuation levels and island widths measured with the electron cyclotron emission temperature profile diagnostic [5,6]. The code used here to model tearing mode behavior in the simulated NCSX plasmas was extensively benchmarked on these TFTR data [7,8].

A study of double tearing modes in reversed shear plasmas in the TFTR tokamak found no evidence for neoclassical modifications to the tearing mode stability in the negative shear regions [7]. However, in this case the analysis of double tearing modes was sufficiently unique that it is quite possible that the physics of the coupling in the double tearing modes was not adequately represented, leading to uncertainty in the conclusions. Further, single tearing modes were not observed in the reversed shear region of TFTR plasmas, consistent with the prediction of the neoclassical model that the bootstrap term is stabilizing in reversed shear.

Tearing modes have also been observed in stellarators such as the W7-AS and W7–A when net current is present. Simulations of the linear stability and non-linear evolution of the islands has been done, primarily with simple cylindrical Δ' models such as the one used here. In W7–A the analysis was able to predict reasonably well the observed magnetic fluctuation level, *i.e.*, the saturated island width [12]. In the W7-AS experiment, these predictions were within an order of magnitude for the external magnetic fluctuation level and in reasonable agreement with the tomographically determined island size [13] without the inclusion of neoclassical effects. Whether the neoclassical terms would have qualitatively changed the results is not clear. The conclusion of the authors was that, "…, *so far no direct evidence of neoclassical effects on the stability has been found*." This statement could be interpreted as meaning there is no evidence in the W7-AS data either for or against the validity of the neoclassical theory of tearing modes.

Evidence for healing of (vacuum) magnetic islands by low collisionality, moderate β plasmas with negative shear (in the tokamak sense) has been seen on the Large Helical Device [20]. In these experiments, the presence of magnetic islands was inferred from Thomson Scattering measurements of the electron temperature and density profiles. It was found that the vacuum islands were present in colder, collisional plasmas, but healed in hotter, higher β plasmas. The results were felt to be consistent with neoclassical theoretical predictions, however more detailed analysis was not presented.

IV. Δ′ ANALYSIS

Simulations of the start-up phase of the target NCSX plasma with the TRANSP code are described in detail in Ref. 15. These simulations predict the evolution of the ohmic, beam driven and bootstrap current profiles through the start-up phase to the target equilibrium as shown in Fig. 1. These time-dependent profiles have been analyzed for resistive stability to the lowest order tearing modes, the (2/1), (7/3) and (7/4) modes. The startup scenario has reversed shear (in the tokamak sense) and begins with $\iota(a) < 0.5$ [$q(a) > 2$]. As the plasma evolves the $\iota(a)$ rises until an m = 2, n = 1 rational surface enters the plasma from the edge at about 0.05 s.

In the time period between about 0.08 and 0.19 s, during the current ramp up, there is a flattish region in the iota profile around $\iota \approx 0.5$ or r/a of about 0.6 to 0.9 (*c.f.,* Fig. 2). During this time period, the flat spot results in unphysical tearing mode eigenfunctions. In simpler cylindrical or toroidal geometry, this would be indicative of approaching an ideal stability limit. (However, as shown in Ref. 21, the ideal stability calculation in the full 3-D stellarator geometry indicates that these plasmas are stable.) However, the analysis of the 2/1 stability with the Δ’ code is not meaningful until after ≈ 0.2s.

In Fig. 3 are shown the q profile and profiles of the bootstrap, beam driven and ohmic currents at 0.22s. In this example, the ohmic current, in magnitude and profile, largely cancels the beam driven currents. The bootstrap current dominates, and it is to be expected that the neoclassical tearing mode theory predicts a strong stabilizing effect from the bootstrap current. In Fig. 4a are shown the classical $\Delta_{2/1}'(w)$ at 0.22 s and at 0.4 s. The m=2, n=1 tearing mode is initially unstable (neglecting neoclassical effects), but by 0.4 s the plasma is only marginally unstable to the 2/1. In Fig. 4b is shown the neoclassical term, which is stabilizing due to the negative shear. As can be seen, the magnitude of the neoclassical term is much larger than that of $\Delta_{2/1}'(w)$, meaning that the predicted island sizes will be quite small.

The results of a tearing mode stability analysis for the 2/1 mode from 0.2 s to 0.4 s are shown in Figure 5. The $\Delta_{2/1}$'(w) is relatively large from 0.2 to 0.23 s and the first points after 0.2 s come close to violating the Rutherford linear growth criteria; $\gamma_{mode}\ \tau_{\Delta} \approx\ 0.3$. In Figure 5b the island width evolution in time is shown (solid curve), starting with a nearly zero width island at 0.2s. The predicted width of the 2/1 island becomes inconsequential (of order 2% of the plasma minor radius) after ≈ 0.3s, *i.e.*, in the "steady state" phase of the simulation. Also shown is the evolution of the "saturated" island width, calculated by artificially increasing the growth rate of the island by a large factor. For these simulations the $\Delta_{2/1}$'(w) is calculated at each TRANSP time step (approximately every 1 or 2 ms) and the Rutherford equation is integrated between each TRANSP time step using the $\Delta_{2/1}$'(w) and Δ_{nc}(w).

Inclusion of the neoclassical term, which is stabilizing, reduces the island size even further as shown in Fig. 6. In Fig. 6 are shown two curves for the time period beginning at 0.2 s and extending until the end of the shot. The first, solid, curve shows the evolution of the width of an island starting at 0.2 s. The actual island evolution would of course depend on the assumed initial island width at 0.2s. The second curve shows the saturated island width including the (stabilizing) bootstrap current term. In this case the predicted island widths are less than 0.1%; inclusion of either Glasser-Greene-Johnson or the polarization-drift terms would completely stabilize the islands. The island widths are shown here on a semi-logarithmic scale.

The next lowest order modes are the 7/3, and 7/4 modes. The 7/3 mode was calculated to be robustly stable, apart from a short period during which the core iota fell below 3/7. The stability calculation for the 7/4 mode was problematic. For this mode, located near the plasma boundary, the relatively large local edge current density introduces strong curvature in the radial eigenmode structure. The appearance of the eigenfunction shape suggests that this formalism is not applicable.

The failure could either result from the mapping of non-axisymmetric, finite beta and shaped equilibria to a circular cross-section, quasi-cylindrical, zero beta model or might indicate that the plasma was nearing the ideal stability marginal point (known to result in similar problems even in the simpler tokamak axisymmetric geometry).

V. SUMMARY

The simulation of the NCSX start-up described in Ref. 15 has been analyzed for stability to tearing modes driven by ohmic, beam and bootstrap driven currents. The analysis has been done with a simple quasi-cylindrical Δ' code of the type used successfully in the analysis of tokamak plasmas. The plasmas are found to be stable, in this model, to the low order tearing instabilities (7/3 mode) and somewhat unstable to the 2/1 mode in the growth phase. The inclusion of neoclassical effects is generally believed to be stabilizing for plasmas with negative shear ($d\iota/dr > 0$, or $dq/dr < 0$), and the calculations suggest that the neoclassical terms result in a robustly stable 2/1 mode. The simple quasi-cylindrical stability calculations for the 7/4 mode located between $r/a \approx 0.85$ and the plasma edge did not give reasonable results, possibly indicating problems with the Δ' formulation or with the high local current density near the plasma edge. Likewise, the calculation for the 2/1 mode stability between 0.08 and 0.19 s had a similar problem.

The Δ' formalism should be viewed as only a guide or qualitative estimate of mode stability. While the model has some success in predicting the evolution of saturated mode widths in many tokamaks, the fitting to data typically involves the use of arbitrarily adjustable factors. The analysis discussed above indicates that there is no reason to be particularly concerned with the stability of the target plasma. However, the flat spot in the q profile during the current ramp is potentially a cause for concern and it would be best to develop start-up scenarios which avoid this flat spot. It is a positive result that while the simple Δ' analysis in the "cylindrical" geometry had difficulty with this flat region, stability calculations done in the true geometry still found stability here.

Figure Captions

Figure 1a Evolution of bootstrap, beam driven and ohmic currents, as calculated with the TRANSP code.

Figure 1b Evolution of edge q during a simulated NCSX Shot.

Figure 1c. Central electron density.

Figure 1d. Central electron temperature.

Figure 2. Profile of q at 0.1 s showing flat region near q=2 between r/a ≈ 0.75 – 0.9.

Figure 3a Profiles of the bootstrap, beam driven and ohmic currents at 0.22 s as calculated by TRANSP.

Figure 3b. Profile of the safety factor, q.

Figure 4a The “classical” Δ’ vs. island width at 0.22 s where the saturated island width is predicted to be about 14% of the minor radius. The dashed curve shows the Δ’(w) at 0.4 s where the plasma is marginally unstable with an island width of <0.2% a.

Figure 4b. The neoclassical term at 0.22 s.

Figure 5a. Evolution of $r_s\Delta'(0)$ from 0.2s to 0.4 s

Figure 5b. Evolution of the island width calculated by solving the time-dependent Rutherford equation without neoclassical effects. “Saturated width” of the island found by artificially enhancing the growth rate.

Figure 6 Evolution of the island width as found by integrating the Rutherford equation in time, beginning with an island at the saturated size. The curve labeled “with bootstrap term” is the same calculation including neoclassical effects in the Rutherford equation.

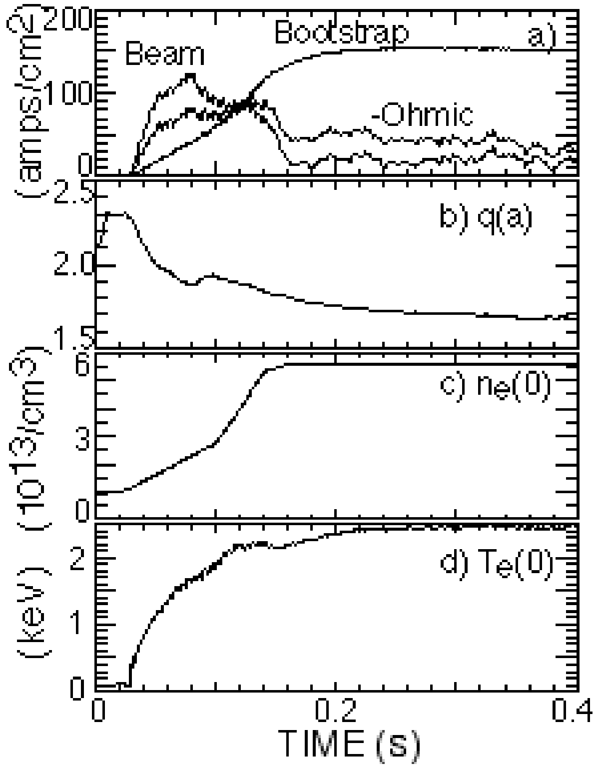

Figure 1a Evolution of bootstrap, beam driven and ohmic currents, as calculated with the TRANSP code.

Figure 1b Evolution of edge q during a simulated NCSX Shot.

Figure 1c. Central electron density.

Figure 1d. Central electron temperature.

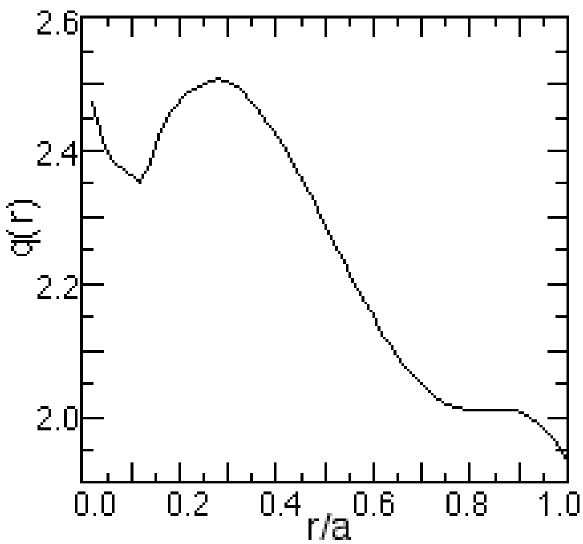

Figure 2. Profile of q at 0.1 s showing flat region near q=2 between r/a ≈ 0.75 – 0.9.

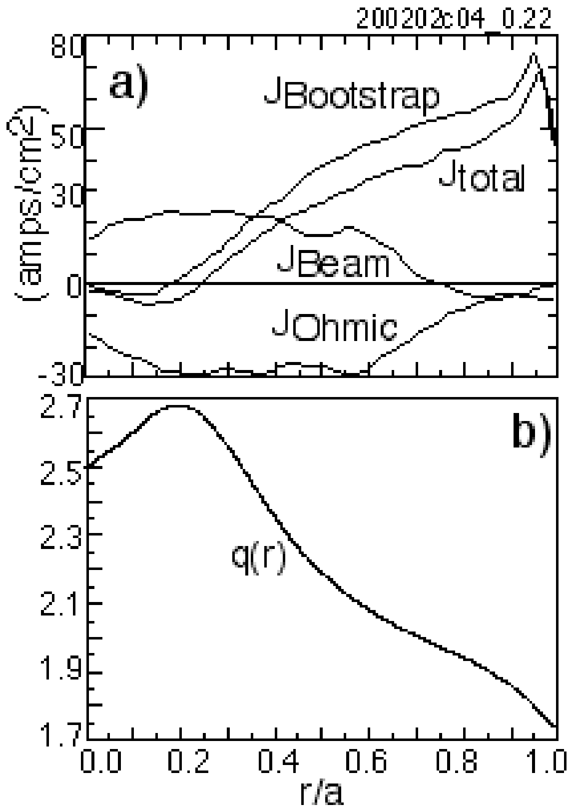

Figure 3a Profiles of the bootstrap, beam driven and ohmic currents at 0.22 s as calculated by TRANSP.

Figure 3b. Profile of the safety factor, q.

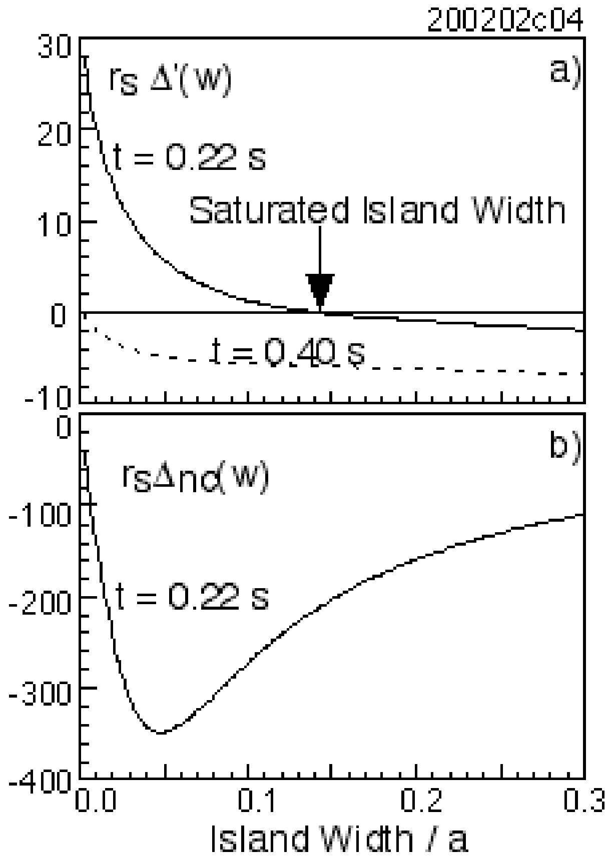

Figure 4a The "classical" Δ' vs. island width at 0.22 s where the saturated island width is predicted to be about 14% of the minor radius. The dashed curve shows the Δ'(w) at 0.4 s where the plasma is marginally unstable with an island width of <0.2% a.

Figure 4b. The neoclassical term at 0.22 s.

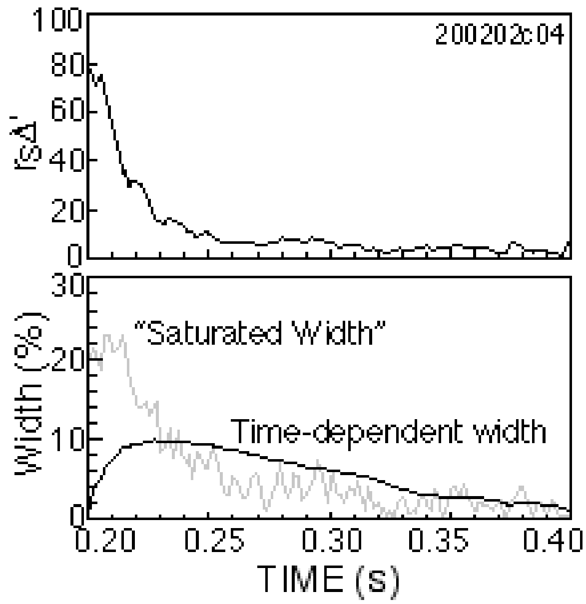

Figure 5a. Evolution of $r_s\Delta'(0)$ from 0.2s to 0.4 s

Figure 5b. Evolution of the island width calculated by solving the time-dependent Rutherford equation without neoclassical effects. "Saturated width" of the island found by artificially enhancing the growth rate.

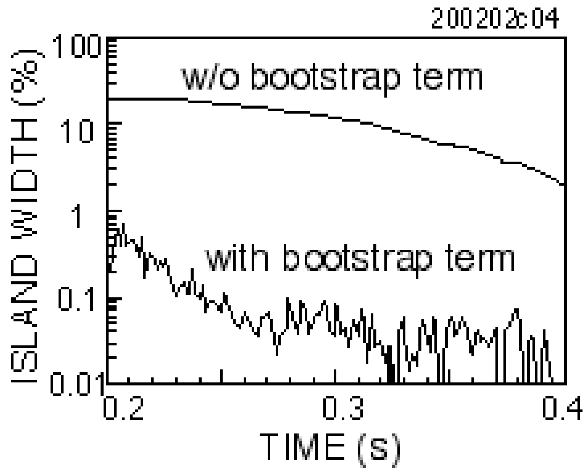

Figure 6 Evolution of the island width as found by integrating the Rutherford equation in time, beginning with an island at the saturated size. The curve labeled "with bootstrap term" is the same calculation including neoclassical effects in the Rutherford equation.

References

[1] NEILSON, G.H., ZARNSTORFF, M.C., LYON, J.F., and the NCSX Team, Journal of Plasma and Fusion Research **78** (2002) 214-219.

[2] H.P. FURTH, J. KILLEEN, AND M.N. ROSENBLUTH, Phys. Fluids **6**, (1963) 459.

[3] P. H. RUTHERFORD, Phys. Fluids **16**, (1973) 1903.

[4] J.D. CALLEN, W.X. XU, K.D. SIEBERT, B.A. CARRERAS, K.C. SHAING, AND D. A. SPONG, in *Plasma Physics and Controlled Nuclear Fusion Research* 1986, Kyoto (International Atomic Energy Agency, Viena, 1987), Vol. 2, p. 157.

[5] Z. CHANG, J.D. CALLEN, E.D. FREDRICKSON, et al, Phys. Rev. Lett. **74**, (1995) 4663.

[6] Z. CHANG, E. D. FREDRICKSON, S. H. BATHA, M. G. BELL, R. V. BUDNY, F. M. LEVINTON, K.M. MCGUIRE, G. TAYLOR, M. C. ZARNSTORFF and the TFTR Group, Physics of Plasmas **5**, (1998) 1076.

[7] E. FREDRICKSON, M. BELL, R.V. BUDNY, AND E. SYNAKOWSKI, Phys. of Plasmas **7**, (2000) 4112.

[8] E. D. FREDRICKSON, Phys. of Plasmas **9**, (2002) 548.

[9] D.A. GATES, B. LLOYD, A.W. MORRIS, et al., Nucl. Fusion **37** (1997) 1593.

[10] R.J. LAHAYE, L.L. LAO, E.J. STRAIT, T.S. TAYLOR, Nucl. Fusion **37** (1997) 397.

[11] Q. YU, S. GÜNTER, Phys. of Plasmas **5** (1998) 3924.

[12] W VII-A TEAM, Nucl. Fusion **20**, (1980) 1093.

[13] E. SALLANDER, A. WELLER, W7-AS Team, Nucl. Fusion **40**, (2000) 1499.

[14] R V BUDNY, Nucl. Fusion **34** (1994) 1247.

[15] E. A. LAZARUS, M. C. ZARNSTORFF, S. R. HUDSON, L-P KU, D. C. MCCUNE, D. R. MIKKELSEN, D. A. MONTICELLO, N. POMPHREY, A. H. REIMAN, Fusion Science and Tech. **46** (2004) 209.

[16] PLETZER, A, BONDESON A AND DEWAR R L, J. Comput. Phys. 115, 530 (1994).

[17] A H REIMAN AND N POMPHREY, J. Comput. Phys. **94**, 225 (1991).

[18] W PARK, E V BELOVA, G Y FU, X Z TANG, H R STRAUSS, L E SUGIYAMA, Phys. of Plasmas **6** (1999) 1796.

[19] R. FITZPATRICK, Phys. Plasmas **2**, 825 (1995)

[20] K. NARIHARA, K. Y. WATANABE, I. YAMADA, et al., Phys. Rev. Lett. **87**, (2001) 135002-1.

[21] G. FU, *et al.*, Fusion Sci. Technol., this issue

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov