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Recent progress on the National Spherical Torus Experiment (NSTX)*

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Abstract

Recent upgrades to the NSTX facility have led to improved plasma performance. Using 5MW of neutral beam injection, plasmas with toroidal β_T (= $2\mu_0\langle p\rangle/B_T^2$ where B_T is the vacuum toroidal field at the plasma geometric center) > 30% have been achieved with normalized β_N (= $\beta_T aB_T/I_p$) ≈ 6 %·m·T/MA. The highest β discharge exceeded the calculated no-wall β limit for several wall times. The stored energy has reached 390kJ at higher toroidal field (0.55T) corresponding to $\beta_T \approx 20\%$ and $\beta_N = 5.4$. Long pulse (~1s) high β_p (~1.5) discharges have also been obtained at higher B_ϕ (0.5T) with up to 6MW NBI power. The highest energy confinement times, up to 120ms, were observed during H-mode operation which is now routine. Confinement times of ~ 1.5 times ITER98pby2 for several τ_E are observed during both H-Mode and non-H-Mode discharges. Calculations indicate that many NSTX discharges have very good ion confinement, approaching neoclassical levels. High Harmonic Fast Wave current drive has been demonstrated by comparing discharges with waves launched parallel and anti-parallel to the plasma current.

Machine improvements

Several improvements to the NSTX facility have improved plasma performance. In particular, 350°C bakeout capability, along with the addition of a gas fuelling port on the high field side of the plasma, has improved access to the H-mode. In addition, the realignment of one of the poloidal field coils has reduced the non-axisymmetric error fields in the plasma region and decreased the occurrence of locked modes that were observed in the first NSTX physics campaign [1]. These improvements have led to a large expansion of the operational regime on NSTX.

High β

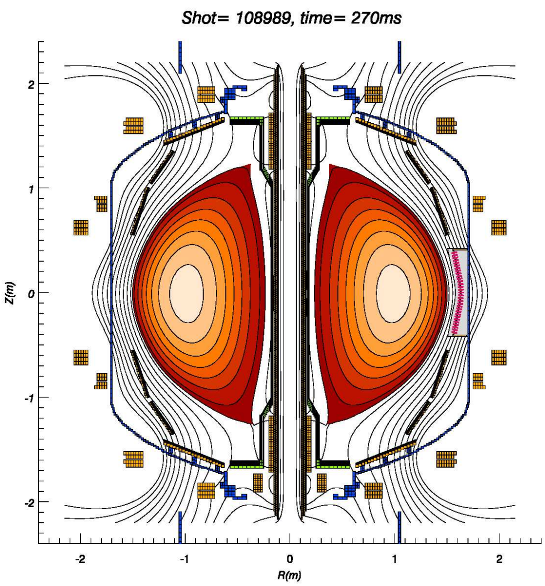

Figure 1 *Equilbrium flux plot for shot 108989* β_T *= 34%,* I_p*=1.2MA,* B_T *= 0.3Tesla*

NSTX has achieved very high values of toroidal β_T ~34%, similar to those achieved on the START device [2,3]. The highest β's were achieved in a high triangularity double null configuration with modest elongation κ ~ 1.8. A high β equilibrium reconstruction [4], from shot 108989, is shown in Figure 1. The stabilizing effect of high triangularity is amplified at low aspect ratio, due to the strong variation of the toroidal field. High triangularity double null discharges at higher toroidal field and plasma current have also led to the highest stored energies (0.4MJ) achieved to date on NSTX.

Figure 2 shows the measured kinetic profiles for shot 107227 close to the time of peak β. The ion temperature is measured using charge-exchange recombination spectroscopy, and the electron density and temperature are

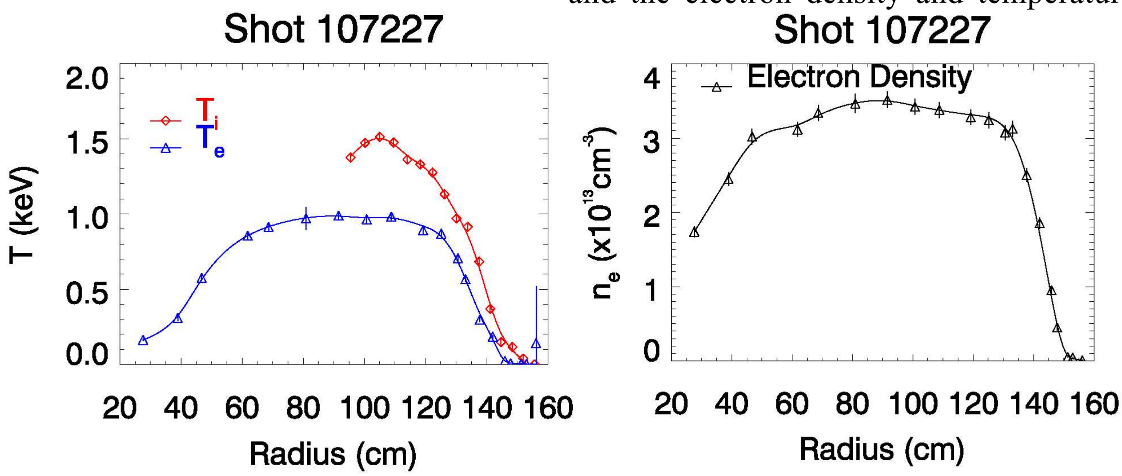

Figure 2 *Kinetic profiles for shot 107227,* β *= 32% ,* I_p*=1.2MA,* B_T *= 0.3Tesla*

measured using Thomson scattering. In general on NSTX, total stored energy calculated using the TRANSP code agrees well with the value obtained from magnetic reconstructions.

β limiting instabilities

Figure 3 shows the time evolution of the MHD stability parameter δW calculated by the DCON ideal stability code [5]. These results indicate that β exceeded the no-wall β-limit for approximately 10 wall penetration times. This indicates that either the plasma rotation speed is sufficiently high to cause the conducting structure to stabilize the calculated instability, or alternatively that the mode is being stabilized directly by rotational shear.

In plasmas that are closely coupled to the conducting structure in NSTX, non-rotating modes, identified as resistive wall modes [6], can limit β. The onset of these modes is preceded by the characteristic slowdown in plasma rotation.

For plasmas with q(0) ~ 1, neoclassical tearing modes are observed to limit β. These modes are slowly growing and, in many shots, are identified to be 3/2 islands. The mode growth is consistent with that predicted by the modified Rutherford equation. These modes are most easily avoided by operating plasmas with elevated q(0).

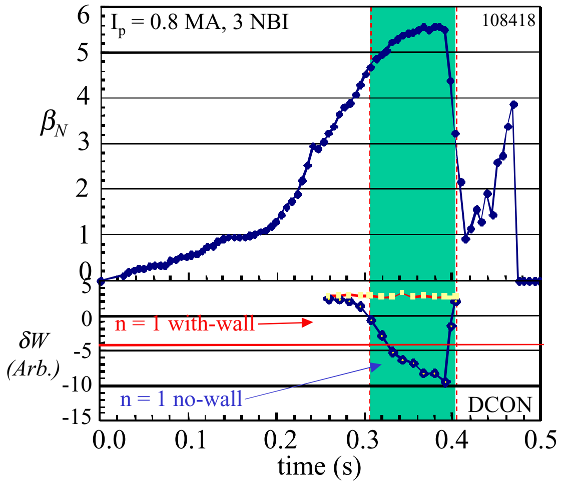

Figure 3 *The MHD stability parameter δW vs. time as calculated by the DCON ideal stability code*

Long pulse high β_p

Long pulse plasmas with very low loop voltage have been created on NSTX. These discharges typically operate at lower values of normalized current I_N *(= I/aB) ~ 3MA/m•T* to avoid ideal MHD instabilities, while raising β_p. The combined bootstrap and beam-driven current for these discharges is calculated by TRANSP to be up to ~50%. This is an important achievement, since ST reactor concepts rely heavily on non-inductive current drive to overcome the difficulties of installing a transformer in the slender center column of such devices.

These plasmas are exclusively operated in the H-mode, which is crucial for obtaining the broad pressure profiles that are required to operate at elevated values of β_N. Typically these plasmas are formed as lower single null divertors, due to the improved access to the H-mode. Pressure peaking factors (p(0)/<p>) as low as 1.9 have been measured during extended ELM-free H-modes on NSTX. Figure 4 shows a typical discharge evolution for such a discharge.

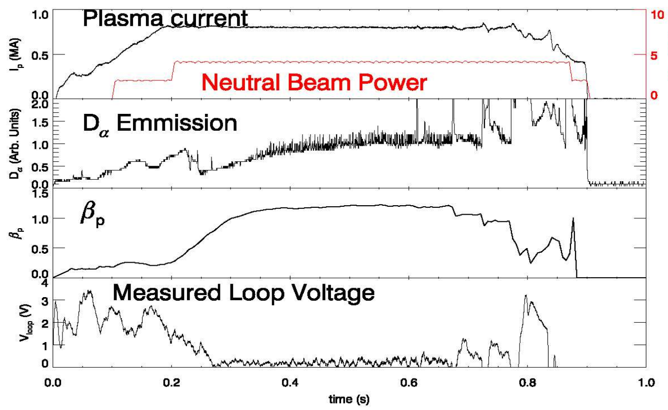

Figure 4 *Discharge evolution for shot 108731, a high β_p long pulse discharge with reduced loop voltage*

Transport

Confinement in NSTX beam heated discharges is usually above that predicted by tokamak scaling laws. Global confinement time H factors, compared to ITER98pby2, are typically H ~1.5, lasting for several τ_E. Interestingly, this improved confinement seems independent of whether the plasmas are operated with H-mode or L-mode edges.

The usual situation in NSTX beam heated discharges is that the ion thermal conductivity calculated by TRANSP with standard assumptions for beam thermalization and power balance is very low or even negative. The cause of this mystery is still under investigation. One intriguing possibility is anomalous heating of thermal ions by beam ions [7]. Heating of ions by turbulence associated with the electron temperature gradient instability or by neoclassical heat pinches have been suggested as other potential explanations.

Particle diffusivity has been inferred from the evolution of the soft x-ray emission profile following neon impurity puffing[8]. The core neon diffusivity is on the order of that predicted from neoclassical theory. The diffusivity was modeled using the MIST [9] atomic physics code.

Radio frequency heating and current drive

High Harmonic Fast Wave (HHFW) heating by RF waves at 30MHz ($10 - 30 \times f_{ci}$) has been demonstrated previously on NSTX [10]. Recent experiments have also demonstrated substantial HHFW current drive 11. Figure 5 shows the measured loop voltage for two plasma discharges for which the phasing of the 12-strap antenna system was varied to launch waves with phase velocity either parallel (co-) or anti-parallel (counter-) to the plasma current. The co-current phasing shows a substantially reduced loop voltage relative to the counter-current drive case. The electron temperature and density are well matched between the two cases. The apparent loss of current drive is caused by an increase in the temperature of the counter current drive case over time.

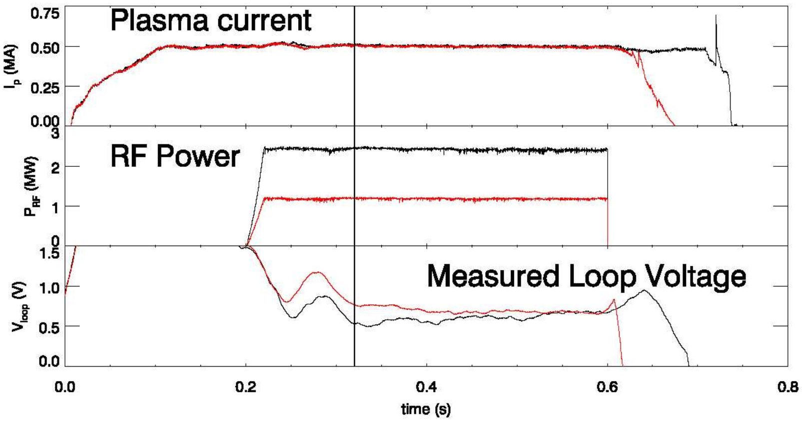

Figure 5 *Co-counter current drive comparison using High Harmonic Fast waves(Co = black, Counter = red)*

Summary

NSTX has led the ST concept into new parameter regimes by achieving both high β and good confinement. The stored energy has reached 0.4MJ with 7MW of injected neutral beam power at a plasma current of 1.5MA. The ideal no-wall β limit has been exceeded for many wall times, but has not exceeded the calculated ideal wall limit. Toroidal β_T has reached 34%, and poloidal $\beta_p \approx 1.5$ has been produced. The high β_p discharges had a high bootstrap and beam driven current fraction. The confinement on NSTX often substantially exceeds the predictions of tokamak scaling laws with $H_{89p} \sim 2.5$-3 and $H_{98pby2} \sim 1.5$. The ion confinement is particularly good on NSTX, and in many cases the ion temperature exceeds the predictions of classical beam heating. These results indicate that many of the predicted advantages of low aspect ratio are have been realized.

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