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. The upgrades include the reduction of error fields by realignment of some poloidal field coils, 350°C bakeout capability, and improved fuelling and shape control. Using 5MW of neutral beam injection at 80keV, 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 (= $\beta_T aB_I/I_p$) ≈ 6 for I_p > 1.0MA and B_T = 0.3T. Calculations indicate that the highest β discharge exceeded the no-wall β limit for several wall times. Plasmas with stored energies up to 390kJ have been created at higher toroidal field (0.55T) corresponding to β_T ≈ 20% and β_N = 5.4. Neo-classical tearing modes occur and limit performance during long pulse high-beta discharges. Long pulse (~900ms) high β_p (~1.5) discharges have been obtained at higher B_ϕ (5kGauss) with up to 6MW NBI power. The highest energy confinement times, up to 120ms, were observed during H-mode operation. H-Mode plasmas are now routinely produced. Confinement times of ~ 1.5 times ITER98pby2 are routinely observed during both H-Mode and non-H-mode discharges. Calculations indicate that many NSTX discharges have very good ion confinement, approaching or exceeding neoclassical levels. High Harmonic Fast Wave heating has heated the electrons to central temperatures above 3keV on NSTX; the profiles in these discharges suggest the

formation of internal electron transport barriers. HHFW current drive has been demonstrated by comparing co and counter current drive phasings.

Machine Improvements

Several improvements to the NSTX facility have led to 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 vastly improved access to the H-mode. In addition, the realignment of one of the poloidal field coils has reduced 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

NSTX has achieved very high values of toroidal β_T ~32%, similar to those achieved on the pioneering START device [2,3]. The highest β's were achieved in a high triangularity double null configuration with modest κ ~ 1.8. A typical high β equilibrium, from shot 107227, 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.

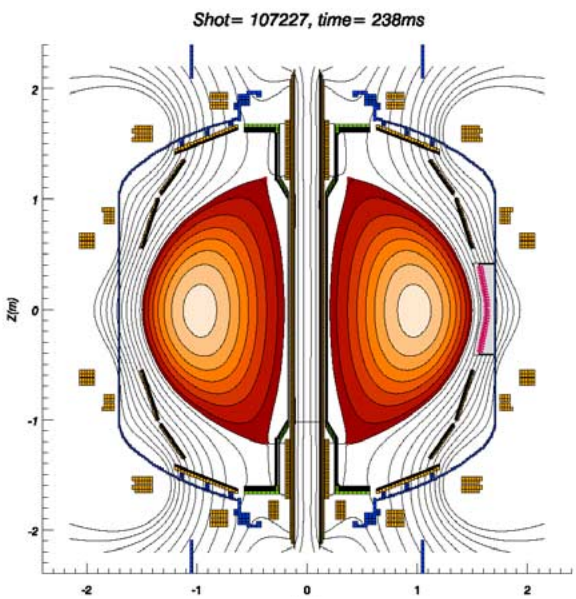

Figure 1 *Equilbrium flux plot for shot 107227* β_T *= 32%,* I_p*=1.2MA,* B_T *= 0.3Tesla*

Figure 2 shows the measured kinetic profiles for shot 107227. The ion temperature is measured using charge-exchange recombination spectroscopy, and the electron density and temperature are measured using Thomson scattering. In general on NSTX, total stored energy as calculated using the TRANSP code agrees well with that predicted from magnetic reconstructions.

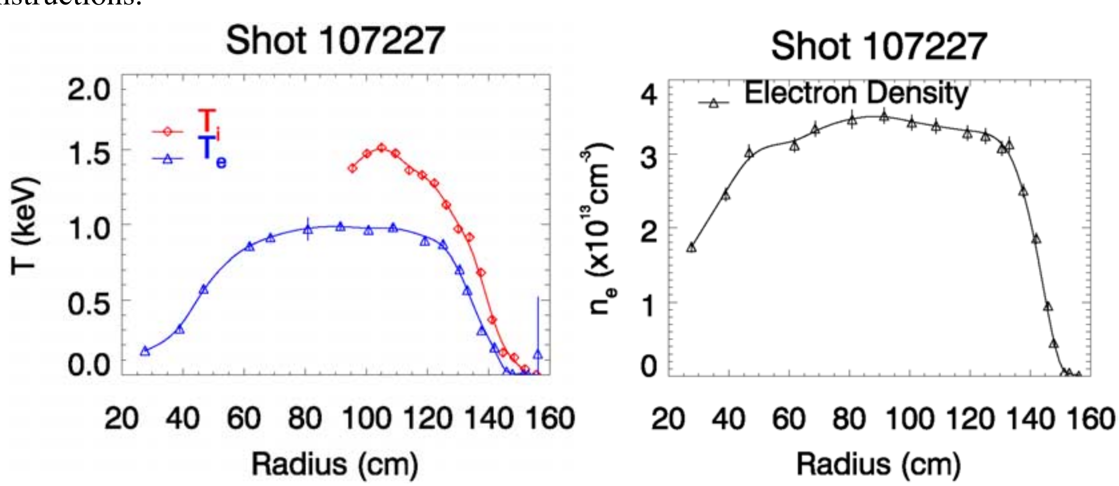

Figure 2 *Kinetic profiles for shot 107227*

β limiting instabilities

Figure 3 shows the MHD stability parameter δW, first shown in [4] as calculated by the DCON ideal stability code[5]. These results indicate that the β exceeds the no-wall β -limit for an extended period of time ($\sim 27\tau_{wall}$). This indicates either that the high plasma rotation speed is sufficiently high to cause the conducting structure to stabilize the calculated instability, or alternatively for the mode to be stabilized directly by rotational effects.

In plasmas that are closely coupled to the conducting structure in NSTX, non-rotating modes are observed to limit β. These modes have been tentatively identified as resistive wall modes [4]. These onset of these modes is preceded by a slowdown in plasma rotation, characteristic of resistive wall modes.

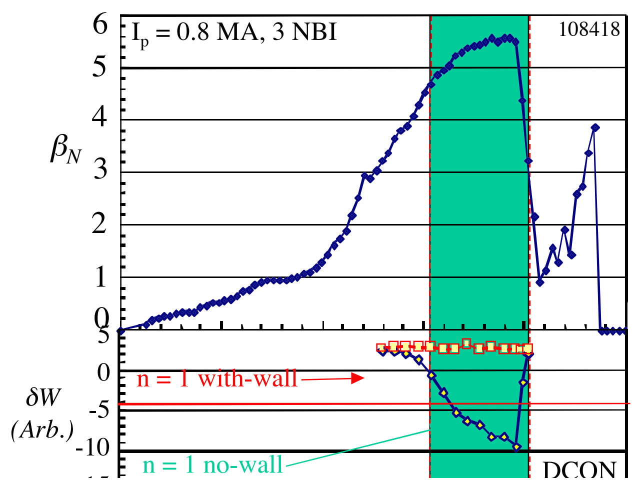

Figure 3 *The MHD stability parameter δW vs. time as calculated by the DCON ideal stability code*

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 the modified Rutherford equation. These modes are most easily avoided by operating plasmas with elevated q(0).

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 $I_N \sim 3$ ($I_N = I/aB(MA/m \bullet T)$) to avoid ideal MHD instabilities, while raising β_p. The calculated non-inductive current for these discharges is ~50%. This is an extremely important achievement for the ST concept, 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.

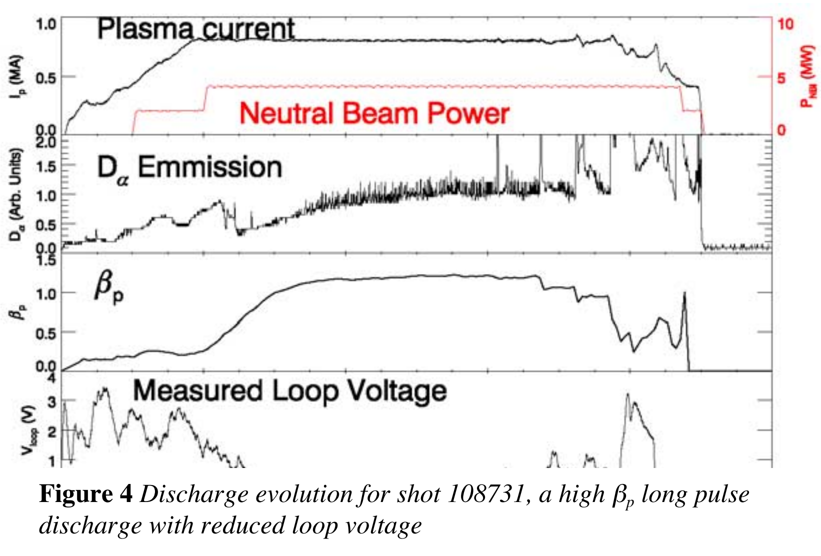

Figure 4 *Discharge evolution for shot 108731, a high β_p long pulse discharge with reduced loop voltage*

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 as low as 1.9 have been measured during extended ELM-free H-modes on NSTX. Fiigure 4 shows a typical discharge evolution for such a discharge.

High confinement and H-Mode

Confinement in NSTX beam heated discharges is usually above those predicted by tokamak scaling laws. Global confinement time H factors, compared to ITER98pby2, are typically H ~1.5. 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 calculated ion thermal conductivity is very low, in many cases it is even negative. The cause of this mystery is still under investigation. One intriguing possibility is anomalous heating of thermal ions by beam ions [6]. Heating of ions by ETG streamers and neoclassical heat pinches have been suggested as other potential explanations.

Particle diffusivity has been inferred from soft x-ray emission during neon impurity puffing. The core neon diffusivity is on the order of that predicted from neoclassical theory as predicted by the NCLASS [7] code. The diffusivity was modeled using the MIST [8] atomic physics code.

Radio Frequency heating and current drive

High Harmonic Fast Wave (HHFW) heating and current drive have been demonstrated on NSTX. Heating has been demonstrated previously [9]. However, recent experiments have now demonstrated substantial current drive. Figure shows the measured loop voltage for two plasma discharges for which the phasing of the 12 strap antenna system was varied form co-current drive phasing to counter. 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 2 cases. These results were achieved with only ??? MW of RF power. The apparent loss of current drive in associated with the onset of MHD activity.

Summary

NSTX has pushed the ST concept into previously unattained parameter regimes while achieving the high β and good confinement. In particular, stored energy has reached 0.4MJ with 7MW of injected neutral beam power at a plasma current of 1.5MA. The ideal no-wall b limit has been exceeded for many wall times, but has not exceeded the calculated ideal wall case. Toroidal β has reached as high 32%, and β_p ~1.5 has been reached. The high β_p discharges had very low loop voltage (>0.2V for > 0.4s), indicative of a high bootstrap and beam driven current fraction. The confinement on NSTX often substantially exceeds the predictions of tokamak scaling laws with H_{89p} ~ 2.5-3 and H_{98pby2} ~ 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 are very exciting results as the indicate that many of the predicted advantages of low aspect ratio are have been realized.

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