Operational Limits in the National Spherical Torus Experiment

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I) Introduction

The National Spherical Torus Experiment (NSTX) is a proof-of-principle scale device whose mission is to establish the physics basis of low aspect configurations most notably in the areas of plasma stability, transport and non-inductive current drive [1,2]. The first series of physics experiments was conducted during the period from Sept. 1999 through Jan. 2000 [3-7]. Among the first experiments was a study to map out and characterize the operational density and q-limits. Density limits have typically been associated with enhanced radiated power due to overfuelling or impurity influx [8], although ion neoclassical transport may impose a density limit at very high densities in ohmic, gas-fueled plasmas [9]. q-limits have typically been manifestations of destabilization of m=2/n=1 kink or tearing modes that lead to a sudden discharge termination [8].

II) Experimental Procedure

The density and q-limit experiments in NSTX were performed in gas-fuelled ohmic plasmas with currents in the range from 0.3 to 0.6 MA, although discharges at the highest obtained current, 1 MA, were included since these discharges reached low-q (q_{95}~4). Typical discharge parameters for the density limit experiments were B_T=0.3 T, R/a=0.85/0.68 m ~ 1.25, κ=1.8, δ~0.4, D_2 gas fuelling. The ohmic heating power varied from 1 to 2.5 MW. The discharges were limited by the inner wall. The line-integral density was measured by a two-pass, 2 mm microwave interferometer, radiated power by a tangential bolometer array, and MHD activity was monitored by poloidal and toroidal arrays of Mirnov coils and by three Soft X-ray arrays for internal fluctuations. q-limit experiments were performed in similar plasmas with I_p=600 kA.

III) Density Limits

The density limit experiments were performed in ohmic discharges with flattop currents at the 0.3, 0.4 and 0.6 MA level. These shaped plasmas provide a good test of whether it is the Hugill or Greenwald limits that characterize the density limit, as the Greenwald limit ($\leq I_p/\pi a^2$) is almost a factor of two greater than the Hugill limit ($\leq 2B_T/Rq_{cyl}$, where $q_{cyl}=2.5a^2B_t(1+\kappa^2)/RI_p$) for the operating parameters. Gas puffing was employed during the current flattop period to raise the density. Figure 1 shows a 600 kA discharge in which the line-integral density rises to a value of approximately 3 x 10^{15} cm^{-2} (2.2 x 10^{13} cm^{-3} line-average). At the time of maximum density, a burst of MHD is seen to grow on an outside Mirnov coil, and the density ceases to increase. The MHD slows, locks, and shortly thereafter, at approximately t=0.23 sec, leads to a Global Reconnection Event that is responsible for loss of plasma current, stored energy, and ultimately leads to the discharge termination. There is no increase in the radiated power leading up to this density limit; as can be seen from the figure, estimates of the radiated power show levels of about 0.5 MW remaining steady through this period, which is approximately 30 to 50% of the ohmic

heating power. In general, the density limit so far observed in NSTX cannot be unambiguously tied to enhanced global radiation, as typically $P_{rad}/P_{oh} \leq 50\%$ at the limit.

A decrease in the radiated power occurs at t=0.13 sec. This represents an internal redistribution of the radiated power (and probably density) profile, and it may be associated with double tearing modes associated with core impurity accumulation and a resulting double-valued q-profile. A burst of m=2 activity is observed at on the Soft X-ray array this time.

Fig. 2 shows the Soft X-ray emission during the time of the MHD burst near t=0.22 sec plotted as a function of spatial channel (ordinate) and time (abscissa). The SXR signals, which are sensitive to emission with photon energies from 0.2 to 1.5 keV, show a clear m=1 snake associated with the MHD burst. The toroidal Mirnov coil array on the center stack reveals this burst to be n=1. All density limits encountered so far, except for the ones associated with the early profile redistribution, are characterized by growing and locking bursts of m=1 activity. Snakes are often associated with high-Z impurity radiation; other spectroscopy qualitatively shows non-negligible levels of metallic impurities (i.e. Cu from some non-graphite covered passive plates [10] and Fe) in the plasma. Thus it is probable that the present density limit is affected by the presence of metallic impurities.

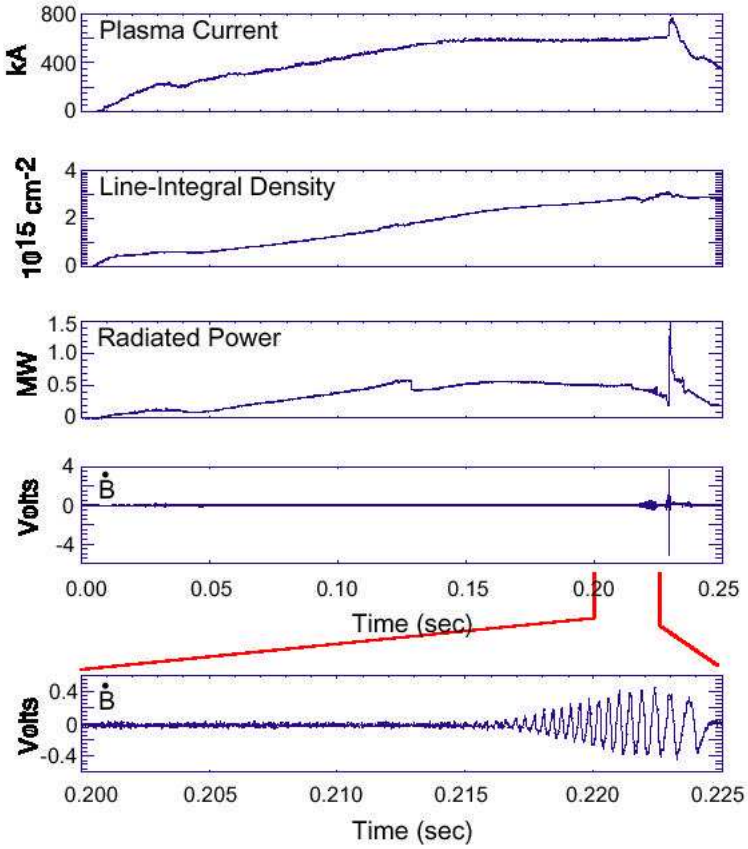

Fig. 1: Time evolution of discharge #101861 leading to density limit termination.

IV) q-Limits

Low-q was produced by either operating at high plasma current (1 MA) or by ramping the toroidal field down to approximately half the initial level during the current flattop period. One figure of merit for these discharges is the equivalent cylindrical q-values, q_{cyl}, values as low as 1.3 obtained with these methods. Fig. 3 shows the evolution of a discharge where the TF is ramped down from 0.3 to ~0.15 T at a rate of 1.4 T/sec. MHD, as seen on the Mirnov coil, begins at approximately the same time as when q_{cyl} passes through 2. The MHD leads to a severe distortion of the plasma surface at t=0.168 sec, as shown on the fast camera image, which leads to the discharge termination. The MHD fluctuations prior to the disruption are identified as m=2 from the SXR array, and their onset is associated with the q=2 surface expanding out to within 10 cm of the plasma edge.

V) Summary

Density and q-limits in NSTX have been explored in ohmic discharges during the device's initial period of operation. The limits are summarized in the Hugill diagram in Fig. 4, in which each line represents the trajectory in time of each individual discharge in the study. Density limits, which are associated with the growth of m=1 oscillations, are well described by the Hugill limit with $n_e R/B_T \leq 2/q_{cyl}$, which is about 60% of the Greenwald limit for the operating parameters of the experiment. Here, the use of the line-averaged, rather than volume-averaged density, in the absence of density profile information, gives a

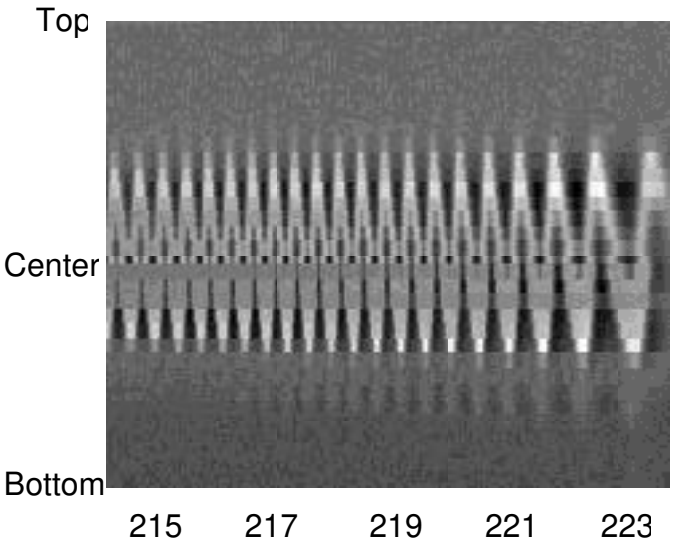

Fig. 2: Soft X-ray emissivity from horizontal arrays. Top, center and bottom are with respect to the plasma.

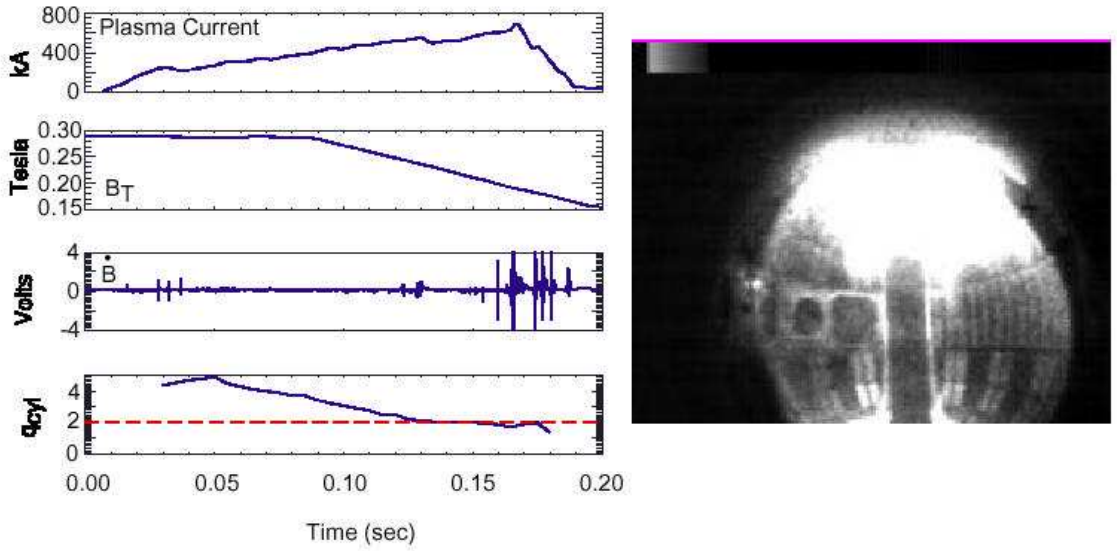

Fig. 3: Evolution of q-limit discharge (left), fast camera image of plasma at t=0.168 sec (right).

conservative view of the limit. As the plasma becomes cleaner (e.g., increased graphite tile coverage and boronization) and with introduction of auxiliary heating power, the observed density limit may well extend beyond the present limit. The q-limit was manifest as growing and locking 2/1 perturbations leading to severe kinking of the plasma surface and subsequent discharge termination as q_{cyl} decreased below 2, associated with the position of the q=2 surface expanding outward to within 10 cm of the plasma edge. Equivalent cylindrical q-values down to 1.3 (q_{95} down to 2.5) have been achieved.

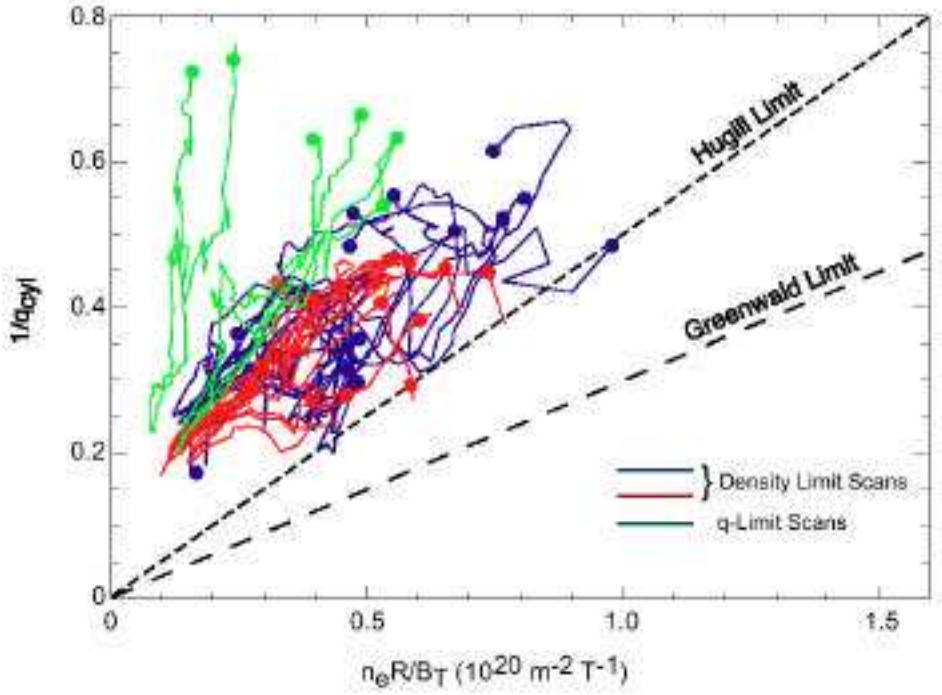

Fig. 4: Hugill diagram for density and q-limit study. Each line represents the time trajectory of each individual discharge. The dots on each trajectory indicate the last time point plotted for that discharge.

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