# Performance and Stability of Near-Unity Aspect-Ratio Plasmas in the Pegasus Toroidal Experiment

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The Pegasus Toroidal Experiment [1] is a mid-sized, extremely low aspect ratio spherical torus. Access to near-unity aspect ratio is achieved through use of a novel high-stress reinforced solenoid magnet assembly. It has the dual roles of exploring the limits of spherical torus plasma behavior as the aspect ratio, A, approaches 1 and examining alternate confinement concepts in the tokamak-spheromak overlap regime. Unique MHD properties arise with possibilities of strong mode coupling at very high toroidicity. Operation with ohmic heating has started to demonstrate the high-$\beta$ stability capabilities of operation at near-unity aspect ratio. Major parameters are R = 0.25 - 0.45 m, A = 1.1 – 1.4, $\kappa$ = 1 - 3.5, $I_p \sim 0.15$ MA, $B_t < 0.07$ T, and $P_{aux}$(HHFW)=1 MW.

Global magnetic parameters are obtained through equilibrium reconstruction using a wide array of magnetics diagnostics. The vacuum vessel is continuous and has a skin time on the order of the plasma formation time. Induced currents in the wall are generally greater than the plasma current, and are estimated with a coupled current-filament model. These results are used as “coil” inputs to the equilibrium code and are constrained in reconstruction by wall-mounted flux loops and B-dot coils. Equilibria are reconstructed by a locally produced code, which uses a two-step iterative procedure to solve the Grad-Shafranov equation. The Gauss-Seidel multigrid relaxation technique is used to solve this equation each iteration, and the Levenberg-Marquardt method is used between iterations to minimize $\chi^2$. Benchmarking is done against Tokamac (Columbia) and EFIT (GA). A sample equilibrium is given in Figure 1.

High-beta plasmas are obtained by operation at very low toroidal field, and cover a regime of $\beta_t$ vs $I_N$ space similar to neutral-beam heated high-$\beta_t$ plasmas in START and other ST experiments (Figure 2) [2]. As indicated, $\beta_t$ values up to 20% and $\beta_N \sim 5$ have been obtained with no evidence of a limit to date. Densities range up to the Greenwald limit ($\sim I_p/\pi a^2$). Stored energies are consistent with values expected from the ITER98pby1 confinement scaling. Plasma startup is characterized by high current ramp rates (15-45 MA/s), low internal inductance ($\ell_i \sim 0.3$), and high elongation.

The toroidal field utilization factor, $I_p/I_{TF}$, is a useful parameter for characterizing access to the operational regime between tokamak ($I_p/I_{TF} << 1$) and spheromak ($I_p/I_{TF} >> 1$)

regimes. To date, $I_p/I_{TF}$ reaches values as high as (and slightly exceeding) unity, as shown in Figure 3, but appears to approach an operational boundary at that level. Two factors appear to contribute to this soft limit. The first is the difficulty inherent in plasma startup at increasingly lower toroidal field. This is due both to the effect of field errors at very low $B_t$ and poorer coupling of the 5.5 GHz preionization source to the breakdown region. Plasma formation occurs later in time as the toroidal field is reduced, reflecting the fact that the loop voltage is increasing in time during the startup phase. The result of this delayed startup is a reduction in flux available for current drive. Flux consumption analyses indicate, however, that toroidal field effects alone do not explain the $I_p/I_{TF} \approx 1$ limit.

The second factor limiting access to high-$I_p$ plasmas at low $B_t$ is the presence of significant resistive MHD activity. In all high power discharges, an m=2/n=1 mode appears during the current ramp and can persist for most of the shot duration. This mode rotates in the electron diamagnetic direction with frequencies on the order of a few kHz. The mode is highly non-cylindrical, with $3\pi$ of $4\pi$ of the poloidal phase shift observed along the center column. The onset of this 2/1 activity coincides with the development of a large region of low shear near the q = 2 surface (Figure 4), and soft X-ray measurements indicate these modes extend over a large fraction of the plasma interior. Improved plasma control has produced plasmas where the 2/1 mode is suppressed, but a 3/2 mode arises following a quiescent period. As the 3/2 mode grows, a weaker 2/1 mode appears to be destabilized, presumably due to profile modification and/or increased toroidal mode coupling. The 2/1 mode is frequently accompanied by harmonic n = 2 and 3 components indicating a high degree of toroidicity. The broad extent of this mode and indications of mode coupling may suggest that these discharges have characteristics combining elements from both the standard tokamak and the more self-organized spheromak regime.

This internal activity has a strong impact on plasma performance. At large amplitude, both the internal inductance and stored energy remain low, and the Ejima flux consumption coefficient ($C_E$) increases to > 0.8. In contrast, reduction of this internal activity leads to higher $\ell_i$, an increase of stored energy, and a reduction of $C_E$ to ~ 0.4, indicating significantly decreased dissipation and better confinement of input energy. [3]

A critical issue for operation at A~1 and low-$B_t$ is the behavior of the external kink stability boundary, and Pegasus experiments are beginning to access this boundary region. The highest-current discharges (150 kA) frequently are observed to terminate in abrupt disruptions, in contrast to lower-current plasmas which experience a more gradual decay of plasma current accompanied by one or more internal reconnection events (IREs).

Magnetic fluctuations with n=1 are observed on the center column immediately prior (~ 100 μs) to disruption as $q_{95}$ approaches 5 (Figure 5). Stability calculations using the VACUUM and DCON codes indicate that the calculated free-boundary energy decreases to zero as these oscillations begin, indicating instability to the external kink. The unstable mode grows on a time scale between the Alfvén time and $q(dq/dt)^{-1}$, roughly as expected for a plasma slowly crossing an instability boundary [4], although more work needs to be done in this area. This onset of an ideal kink at relatively high $q_{95}$ is consistent with general expectations that the ideal kink is more virulent at higher edge q as the aspect ratio approaches unity [5] and with the generally low values of $\ell_i$ observed in these plasmas.

Plasmas with $\beta_t \sim 1$ as A approaches unity in the tokamak-spheromak overlap region appear accessible with the addition of planned new capabilities aimed at lowering the plasma resistivity and manipulating the evolution of the q-profile to suppress limiting MHD activity. These capabilities include significantly improved control of the plasma position, current, and edge using new switches [6], as well as HHFW heating. Control over the ohmic waveform will allow better control over the current profile evolution and provide increased volt-seconds, while radial position control will allow better coupling to the HHFW antenna and control of plasma size. The toroidal field will be increased significantly during startup to avoid low order rationals during the early stages of plasma formation, and reduced later to obtain high $\beta_t$. TSC modeling of fast TF rampdown scenarios indicate accessible paths to regimes of higher current and increased stored energy. Operation with the two-strap high-power Higher Harmonic Fast Wave heating system has begun. Initial loading tests show an impedance of roughly 1 ohm, and power up to 200 KW has been injected into plasma to date.

**References**


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**Figures**

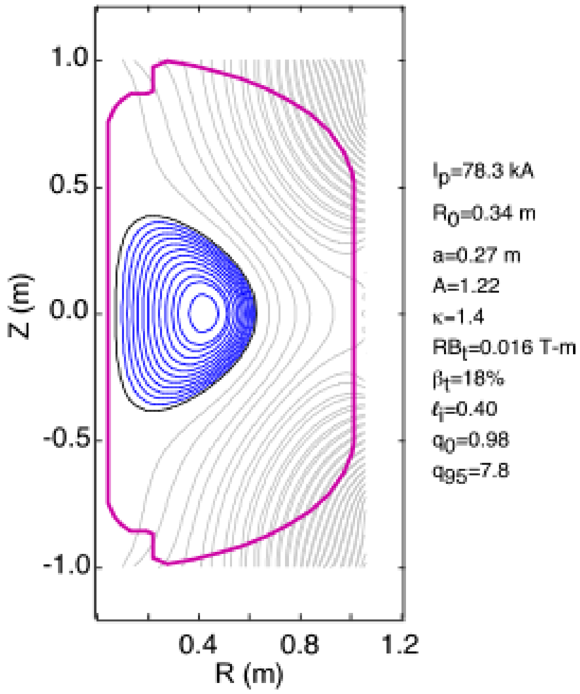


Figure 1. Sample reconstructed equilibrium.

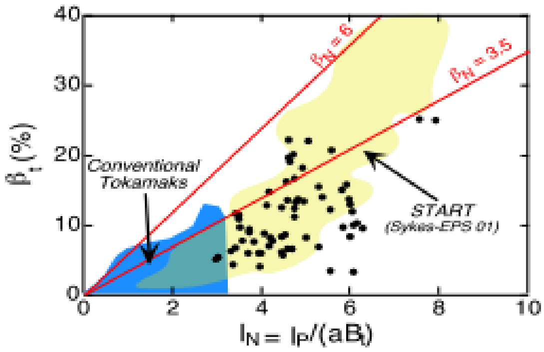


Figure 2. $\beta_t$ vs $I_N$ for Pegasus and START [2].

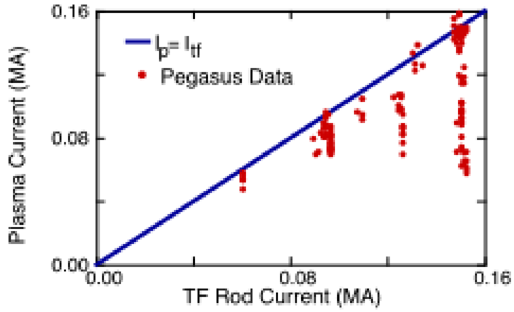


Figure 3. Plasma current vs toroidal field rod current.

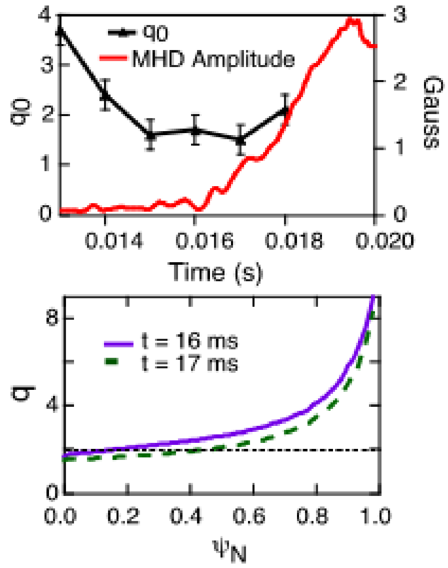


Figure 4. Signatures of internal 2/1 mode: calculated $q_0$ and mode amplitude vs time, and q(r) from equilibrium reconstruction.

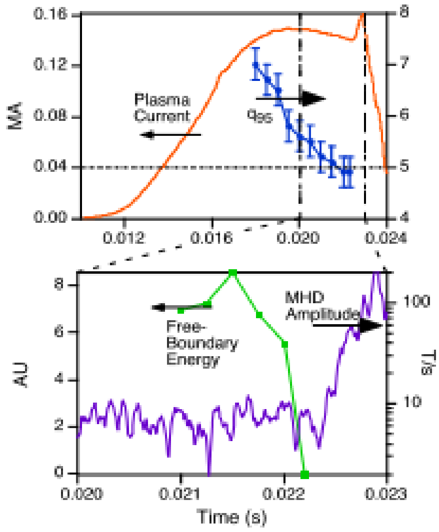


Figure 5. Characteristics of external kink mode at $q_{95}$=5: plasma current and q95 evolution through the shot, and details of mode amplitude and calculated free boundary energy prior to disruption.