Recent Results from the PEGASUS Toroidal Experiment

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Abstract

The PEGASUS Toroidal Experiment is an extremely low aspect ratio university-scale spherical torus with a major radius of 0.25 - 0.45 m. β_t values of 25% (β_N~5) have been obtained to date in PEGASUS with no evidence of a beta limit. Densities range up to the Greenwald limit. The toroidal field utilization factor, I_p/I_{TF}, has reached 1.2. Normalized currents (I_N=I_p/aB) greater than 5 have been achieved. Stored energies are consistent with values expected from the ITER98PBy1 confinement scaling. The evolution of the plasma current is often limited by an MHD instability, which results in a rapid decrease in dI_p/dt. An m=2 mode is observed to rotate in the electron diamagnetic direction; the appearance of this mode is consistent with the existence of a q=2 surface in the plasma. Recent experimental campaigns have focused on accessing high β_t plasmas with ohmic heating, characterizing the equilibrium and stability of these plasmas. A complete set of magnetics diagnostics and new plasma-facing components, including core armor and divertor plates were recently installed. A HHFW antenna was also installed. Initial loading tests with relatively large plasmas (A~1.15) show an impedance on the order of 1 Ohm with the two straps anti-parallel.

Introduction

The Pegasus Toroidal Experiment is an extremely low aspect ratio university-scale spherical torus experiment. Plasmas with $A < 1.2$ are routinely produced. Major device parameters are $R = 0.25 – 0.45$ m, $A=1.15 – 1.3$, $\kappa = 1 - 3$, $I_p \sim 0.15$ MA, $B_t < 0.07$ T, and pulse length ≤ 0.03 s. The role of Pegasus in the ST research portfolio is twofold. The first is to contribute to the development of ST physics at the limit of very low A. This includes exploring stability limits (for example in β, I_N, q_ψ, etc.) as A approaches 1, accessing high toroidal beta at high normalized current without a close-fitting wall, studying global confinement at A<1.3, and studying new startup and sustainment schemes such as plasma guns and EBW heating. The second role of Pegasus is to explore the physics of $A\approx1$ plasmas as an alternate confinement concept. This involves studies of the effect of high toroidicity on plasma behavior, operation at high I_p/I_{TF}, stability as beta approaches unity (very low TF), and the exploration of relaxation at the tokamak/spheromak boundary.

Facility Status

Major upgrades were installed in early 2001. A new set of plasma facing components, including core armor, divertor plates, and an outer limiter, were installed. An extensive set of internal magnetics was mounted, including 26 flux loops, two arrays of poloidal Mirnov coils (22 coils for complete poloidal coverage and 21 coils on the centerstack), two arrays of toroidal Mirnov coils (7 coils on the HFS and 6 on the LFS), 2 continuous plasma Rogowski coils, 2 diamagnetic loops (plus an external compensation loop), and 6 external flux loops for determining wall currents. The 2-strap high-harmonic fast wave antenna was installed, and is currently undergoing testing at moderate power (about 100 kW.) Initial loading tests with the straps in parallel look quite good, with impedances on the order of 1 Ohm. The antenna should eventually deliver 1-2 MW of heating. In addition, a 200 kW steerable EBW antenna was installed.

Results of Ohmic Operation

Pegasus routinely produces plasmas at low toroidal field (0.04-0.08 Tesla) in the presence of toroidally continuous conducting walls. Startup scenarios are guided by modeling wall currents as discrete filaments in a time-varying inductive coupling code. Pegasus plasmas are produced and sustained by ohmic induction. This induction is provided by a novel high-stress solenoid magnet capable of routine operation at 10-14 Tesla. The solenoid has a radius of 5 cm and can deliver up to 0.12 V-s in a full double swing. (60 mV-s is a typical flux swing presently available, limited by power supplies.) At present, Pegasus has achieved values of β_t as high as 25%, and routinely produces plasmas with β_t of 15%-20%. Values of β_N up to 5 have been achieved, as have normalized currents (I_p/aB) up to 8. Line-averaged electron densities up to and slightly beyond the Greenwald limit have been obtained. ST-like MHD activity has been observed, including large magnetic islands, internal reconnection events, and double tearing modes. Values of I_p up to 140 kA are accessible with the present OH power supply at full field, and pulses up to 30 ms long are possible. Density control has been established with fast gas puffing and titanium wall gettering.

Example values of β_t obtained during the last campaign are shown in Figure 1. These results are shown superimposed over START data from Sykes et al [1]. This diagram gives the range of toroidal beta (25%) and normalized current (3-8) achieved in Pegasus. The scaling of increasing beta with increasing normalized current, similar to that in START, is as expected for an ohmically heated device. Values of β_t are consistent with those predicted by the ITER98PBy1 global confinement scaling [2] within error bars. Confinement characterization will be pursued more as estimates of the input power are refined.

Plasma equilibria are reconstructed from the array of magnetic diagnostics, especially the poloidal flux loops and the diamagnetic loop. The equilibrium solver code uses a nonlinear Levenberg-Marquardt algorithm to allow ready inclusion of new measurements. The results are often sensitive to the time-varying currents in the vacuum vessel wall, especially for the early plasma rampup phase of the discharge. These wall currents are sufficiently constrained by the array of flux loops placed on the outside wall of the vessel.

Typical equilibria feature low λ_i (0.3-0.6) and an extended region of low magnetic shear over a large portion of the plasma center (as expected at high toroidicity.) Estimated values of q_0 typically range between 1-2 for fully formed plasmas. The plasma elongation for long-pulse discharges ranged from 1.4 to 1.8 or so, and is reduced from the expected natural elongation by the temporary application of additional field curvature in the poloidal coil set. The DCON code has been coupled to the output of the equilibrium runs to examine these results for ideal stability.

The plasma density is controlled by Ti-gettering of the vacuum vessel walls every 10-20 full power shots. The discharges are often operated at relatively high density to obtain best confinement. In general, however, the observed densities have ranged from low ($\sim 10^{19}$ m^{-3}) up to and slightly above the Greenwald limit of $I_p/\pi a^2$.

All of the discharges to date have been run at constant, and low, toroidal field. Under such conditions, the critical figure of merit for the toroidal field utilization, I_p/I_{TF}, approaches and sometimes slightly exceeds unity. Limitations of I_p and I_p/I_{TF} appear to arise from a combination of strong MHD activity and limits in the available volt-seconds.

A variety of MHD activity has been observed in Pegasus plasmas. Perhaps most significant is a rotating m=2/n=1 mode observed in all high-power discharges. This mode rotates in the electron diamagnetic direction at a frequency from 4-10 kHz, which is on the order of the diamagnetic drift speed. This mode is highly poloidally asymmetric. The perturbed vertical field is on the order of 5-10 Gauss on the inboard (R=5 cm) and 3-5 Gauss on the outboard (R=90 cm). The mode's phase structure is strongly skewed toward the center column, as shown in Figure 2. Approximately 1.5 out of 2 wavelengths are observed along the centerstack Mirnov coils. This mode does not appear until after $q_0 < 2$, in agreement with the measured mode helicity, as shown in Figure 3.

Other tearing instabilities are observed besides the 2/1 mode. At large values of dI_p/dt (> 30 MA/s or so) a small, but abrupt drop in the current is observed; this is associated with a reduction in the ramp rate and a change in plasma shape. Evidence to date points to this phenomenon as the manifestation of a low-q double tearing mode. Additionally, a low-frequency mode (0.5-1 kHz) is sometimes observed during the current ramp; its appearance roughly correlates with a rollover in the plasma current. This mode has not been identified, although it appears to have n=1. Finally, as in other STs, internal reconnection events are observed on Pegasus, typically during the current decay phase. In many cases, a rapid growth in the amplitude of the 2/1 mode is observed roughly 1 ms before the IRE.

Future Directions

A variety of tools are under development to provide better plasma control and potential reduction of MHD activity. An upgrade to the OH power supply will improve total volt-seconds by roughly 50%, and will apply those volt-seconds in a more appropriate waveform than they now are (i.e. more flux for increased current, at the expense of pulse length). This increase, plus improved plasma position control via more flexible equilibrium field evolution, should provide access to higher electron temperatures and reduced resistivity and MHD.

The current 60-turn TF center-rod assembly will be replaced with a higher-current 12-turn rod assembly, and the DC power supply will be replaced with a capacitor-driven system. These changes will increase the toroidal field by a factor of 2-3, and will allow a rapid ramp-down of the toroidal field during the shot. Importantly, it will provide a means of keeping the safety factor high during plasma formation, and thus reducing the MHD activity growth.

New diagnostics will be installed to improve the understanding of plasma behavior. Diagnostics slated to be installed soon include: a tangential 2D soft X-ray camera for q-profile; a 2-color X-ray array and Ross filters for T_e; a visible bremsstrahlung array for density profile; a soft X-ray wave array for internal MHD structure; and a bolometer array for radiated power.

These additions, plus the availability of HHFW heating (up to 1 MW), should allow operation at higher current, transiently higher B_T, and decreased resistivity. This in turn may provide sufficient means of reducing the observed MHD and allowing access to operation at lower edge-q and higher β_T.

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References

[1] A. Sykes, Oral Presentation, 28th European Physical Society Conference on Controlled Fusion and Plasma Physics, Madeira, Portugal, June 18, 2001

[2] ITER Physics Expert Group, Nucl. Fusion **39** (1999) 2175.

Figures

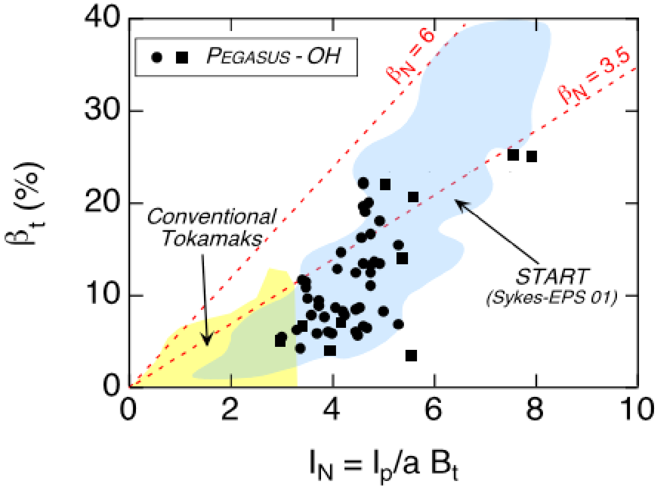

Figure 1. Scaling of Pegasus ohmic β_t values with normalized current.

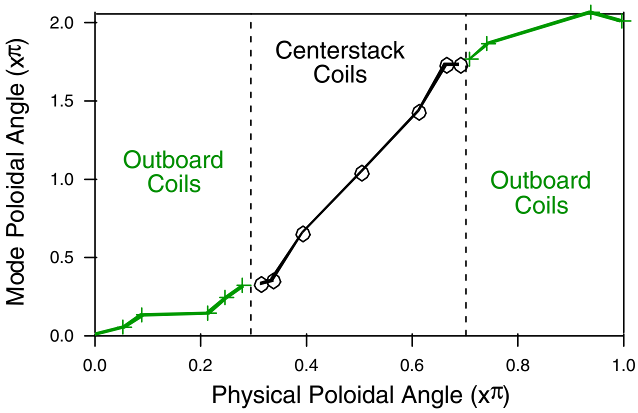

Figure 2. Poloidal structure of 2/1 mode.

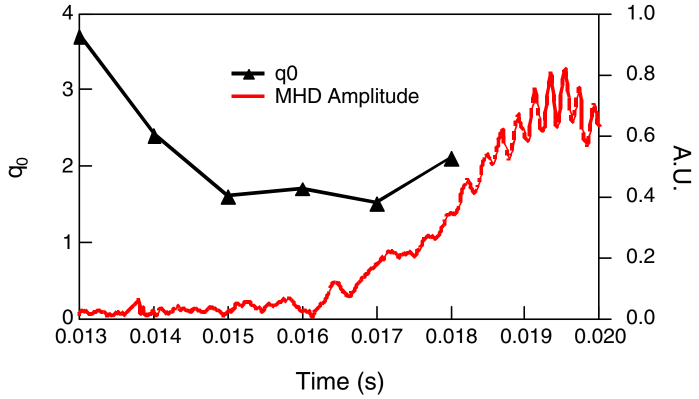

Figure 3. Evolution of MHD amplitude showing growth of 2/1 mode after $q_0 < 2$.