

## The Saturation of Beta in W7-AS

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Quasi-stationary, MHD-quiescent discharges with volume-averaged  $\beta$ -values,  $\langle\beta\rangle$ , up to 3.5% were sustained in the W7-AS for more than 100 energy confinement times [1, 2]. A stability limit was not observed. The achieved  $\langle\beta\rangle$  is much higher than the observed or calculated threshold for  $n = 1$  and 2 ideal-MHD instabilities. Experimentally, these instabilities typically saturate and do not impede access to higher  $\beta$  values. The achieved  $\langle\beta\rangle$  appears to be limited by confinement, but is sensitive to the magnetic configuration. W7-AS has a flexible coil set, with modular coils for the helical field, toroidal field coils for varying the rotational transform  $\iota \equiv 1/q$ , island-divertor control coils, and vertical field coils. All of these modify the magnetic configuration and affect the achieved  $\beta$ , with the strongest variations being due to  $\iota$  and the divertor control coil.

Previous analysis [2] using free-boundary equilibria calculated by PIES[4] with scaled pressure profiles found that the magnetic field near the plasma edge becomes increasingly stochastic as  $\beta$  increases. The variation of the achieved  $\langle\beta\rangle$ -value with divertor control coil perturbation was correlated with a calculated loss of the outer ~35% of the minor radius to islands and stochastic fields. The control coil is calculated to have no effect on  $\iota$  or the neoclassical ripple transport. The maximum  $\beta$  is achieved for central vacuum rotational transform  $\iota_{vac}(0) = 0.47$ , and decreases for  $\iota_{vac}$  above and below this value. For  $\iota_{vac} < 0.47$ , the calculated Shafranov shift of the magnetic axis approaches  $\langle a \rangle / 2$ , where  $\langle a \rangle$  is the average minor radius, and  $\langle\beta\rangle$  appears to be constrained by the classical equilibrium limit. As  $\iota_{vac}$  increases above 0.47, the Shafranov shift is reduced and the global energy confinement time should increase [3], yet the observed maximum  $\langle\beta\rangle$  decreases.

In this paper, we examine heating power scan experiments at two different values of  $\iota$  to clarify the processes limiting  $\langle\beta\rangle$ . Figure 1 shows the variation of the plasma  $\langle\beta\rangle$ , from diamagnetic loop measurements, with neutral beam injected power  $P_{\text{inj}}$  for two plasma conditions: (a)  $\iota_{\text{vac}}(0)=0.445$  and (b)  $\iota_{\text{vac}}(0)=0.575$ . These plasmas are in the high-density H-mode (HDH) confinement regime[5]. The average density  $\bar{n}_e$  was held constant in each scan using gas-puff feedback. The high density forces equilibration of the ion and electron temperatures and minimizes the fast-ion energy content.

At the highest  $P_{\text{inj}}$ , the  $\langle\beta\rangle$ -value

saturates at 3.1% and 2.1%, respectively. At low power, both scans show confinement incrementally varying as  $\tau_E \propto P_{\text{inj}}^{-0.5}$ , as expected from global scaling relations. At high  $P_{\text{inj}}$ , the confinement incrementally varies as  $\tau_E \propto P_{\text{inj}}^{-0.75}$  for  $\iota_{\text{vac}}(0)=0.445$ , and as  $P_{\text{inj}}^{-0.9}$  for  $\iota_{\text{vac}}(0)=0.575$ . Thus, the experimental confinement saturates as the maximum observed  $\langle\beta\rangle$  is approached, and  $\langle\beta\rangle$  becomes insensitive to the heating power. Low-level saturated MHD activity is observed on the Mirnov coils in these plasmas. The amplitude of this MHD activity is approximately an order of magnitude smaller than the level previously correlated with confinement degradation [2]. In many cases where the toroidal and poloidal mode numbers can be identified, the modes apparently are not resonant with the rational surfaces calculated to be in the plasma. In addition, at high  $P_{\text{inj}}$ , very small high frequency modes (100 – 400kHz) modes are observed. These may be Alfvénic modes, but they are not expected to influence confinement due to their low amplitude ( $\sim 1$  mG) and the low-level of fast ion pressure, due to the high  $\bar{n}_e$ .

Figure 2 shows the variation of the electron temperature  $T_e$  profile with  $P_{\text{inj}}$  in both scans, as measured by the core and edge Thomson scattering systems. The Thomson scattering-measured electron density profiles do not change noticeably with  $P_{\text{inj}}$ , either in shape or magnitude, due to the gas-puff feedback control. Remarkably, in the both scans,  $T_e$  and  $\nabla T_e$  do not change appreciably in the outer region of the plasma, even though  $P_{\text{inj}}$  increases by a factor of 2.5 (for  $\iota_{\text{vac}}(0)=0.445$ ) or 2 (for  $\iota_{\text{vac}}(0)=0.575$ ). Thus, the thermal diffusivity must be degraded by approximately these factors of as  $P_{\text{inj}}$  increases. In both

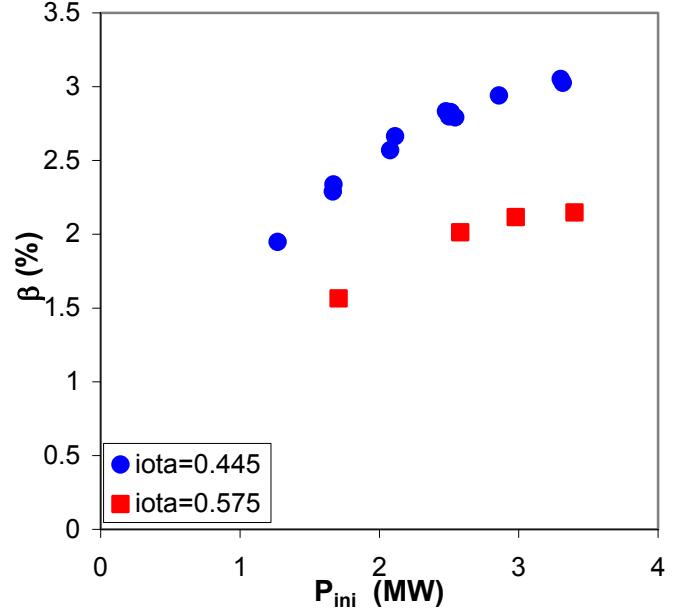


FIG. 1. Variation of  $\langle\beta\rangle$  versus injected beam power  $P_{\text{inj}}$  for (a)  $\iota_{\text{vac}}(0) = 0.445$ ,  $B=1.0T$ ,  $\bar{n}_e = 2.4 \times 10^{20} \text{ m}^{-3}$ ,  $I_{CC}/I_M = 0.15$  and (b)  $\iota_{\text{vac}}(0) = 0.575$ ,  $B=1.25T$ ,  $\bar{n}_e = 1.7 \times 10^{20} \text{ m}^{-3}$ ,  $I_{CC}/I_M = 0.14$ .

scans, only  $T_e$  in the core region is measured to increase with  $P_{inj}$ , and must be responsible for any increase in  $\langle\beta\rangle$ . In this way, the saturation of confinement is due to the degradation of edge transport and the steepening of the core  $T_e$  profile leading to larger transport losses. While  $T_e$  and  $\nabla T_e$  in the outer plasma do not vary within either power scan, they differ between the scans. The edge  $\nabla T_e$  is approximately a factor of two larger for the  $t_{vac}(0)=0.445$  plasmas than for  $t_{vac}(0)=0.575$ , indicating generally lower transport coefficients at lower  $t_{vac}$ . In addition, the  $t_{vac}(0)=0.445$  profiles appear to show structure near  $R=1.87$  m, perhaps indicating the presence of magnetic islands.

To assess the role of the magnetic flux topology on the saturation of  $\langle\beta\rangle$ , free-boundary three-dimensional equilibria have been numerically calculated by the PIES code for some of the plasmas in Fig. 1. The calculations impose the measured pressure profile from Thomson scattering, using the STELLOPT/VMEC[6] equilibrium reconstruction method discussed in Ref. [2]. PIES calculated equilibria are shown in Fig. 3 for the high and low power  $t_{vac}(0)=0.575$  cases, and the low power  $t_{vac}(0)=0.445$  case with  $\langle\beta\rangle = 1.9\%$ , which is close to the saturated value for the high- $t_{vac}$  scan. For  $t_{vac}(0)=0.575$ , the analysis indicates that increasing  $\langle\beta\rangle$  reduces the volume of good flux surfaces, as found previously. However, the outer region appears to be filled with large  $m=8$  islands and has a relatively short connection length to the limiting surfaces. This is in contrast to the  $t_{vac}(0)=0.445$  equilibrium, Fig. 3(C), where a long connection length stochastic region is due to interaction of smaller  $m=11$  islands. This is qualitatively similar to the equilibria in Ref. [2].

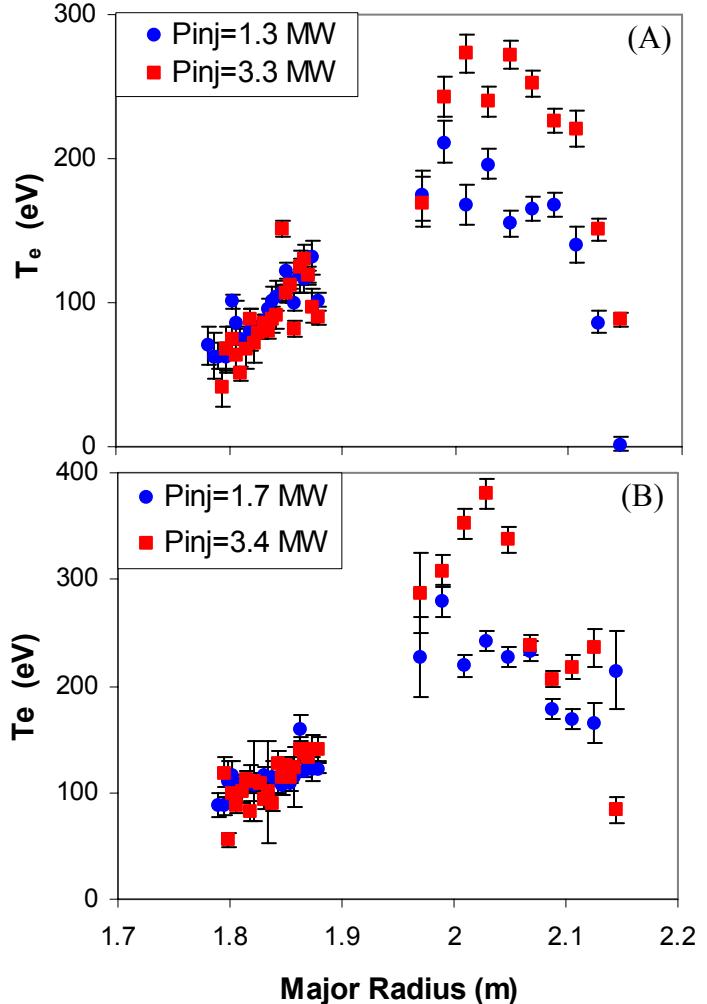
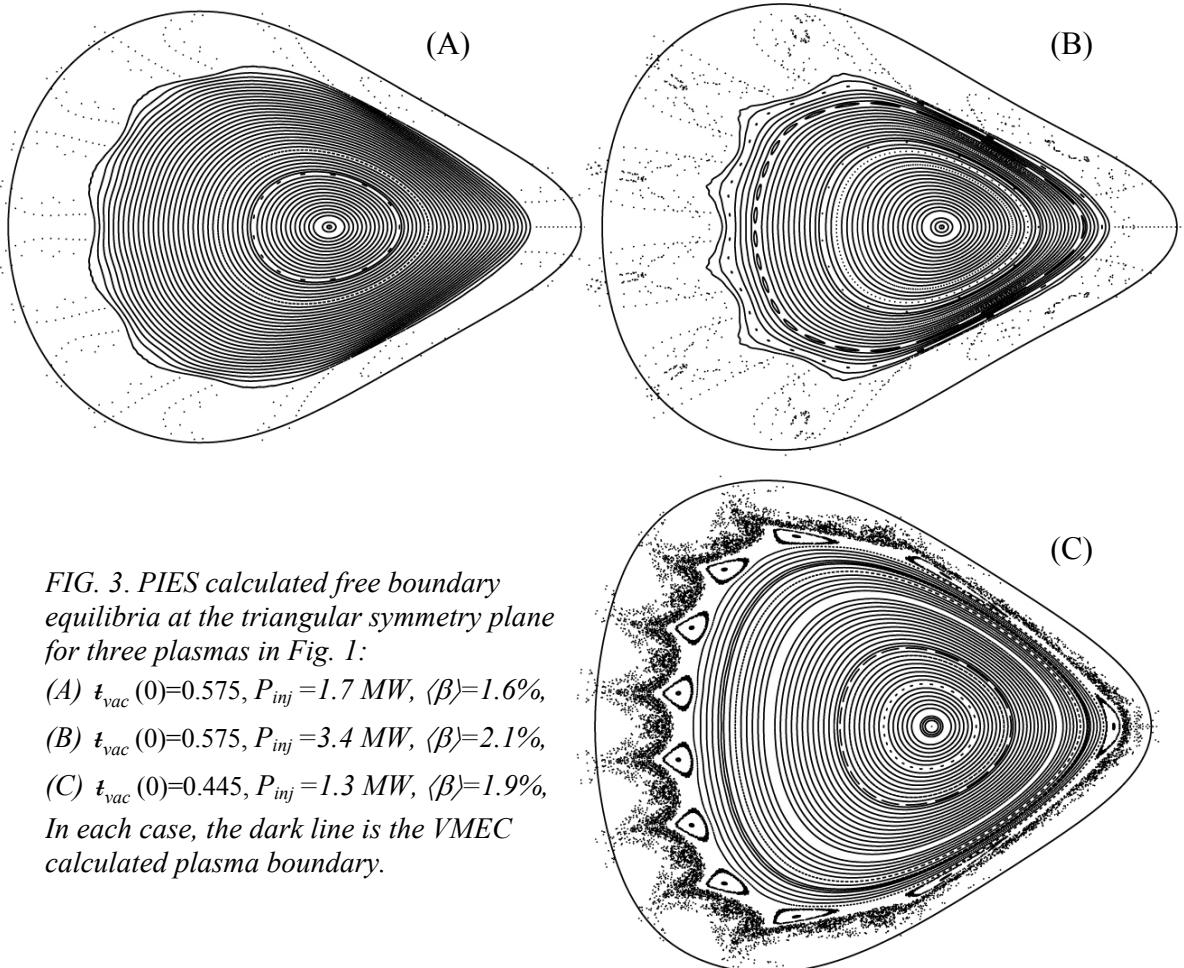


FIG. 2.  $T_e$  profile versus major radius, measured by Thomson scattering, for (A)  $t_{vac}(0)=0.445$  and (B)  $t_{vac}(0)=0.575$ .



*FIG. 3. PIES calculated free boundary equilibria at the triangular symmetry plane for three plasmas in Fig. 1:*  
 (A)  $t_{vac}(0)=0.575$ ,  $P_{inj}=1.7$  MW,  $\langle\beta\rangle=1.6\%$ ,  
 (B)  $t_{vac}(0)=0.575$ ,  $P_{inj}=3.4$  MW,  $\langle\beta\rangle=2.1\%$ ,  
 (C)  $t_{vac}(0)=0.445$ ,  $P_{inj}=1.3$  MW,  $\langle\beta\rangle=1.9\%$ ,  
 In each case, the dark line is the VMEC calculated plasma boundary.

The short connection length calculated by PIES for  $t_{vac}(0)=0.575$  is qualitatively consistent with the measured reduction of  $\nabla T_e$ . The short connection length should allow rapid radial transport by parallel conduction, even for these collisional plasmas. Note that the short connection length and reduced  $\nabla T_e$  are already present at  $\langle\beta\rangle = 1.6\%$ ,  $P_{inj}=1.7$  MW, the lowest  $P_{inj}$  studied for this  $t_{vac}$ . This plausibly explains the reduction in the accessible  $\langle\beta\rangle$  to 2.1% for  $t_{vac}(0)= 0.575$ . At this maximum  $\langle\beta\rangle$  value, PIES calculates that the outer 28% of the flux surfaces have been lost, similar to earlier calculations for lower  $t_{vac}$ . In addition, the  $T_e$  structures measured near  $R=1.87$ m for  $t_{vac}(0)= 0.445$  in Fig. 2(A) for  $t_{vac}(0)= 0.445$  may be related to the small edge island structures calculated in Fig. 3(C).

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