6. WALL LOADING SENSITIVITY

Since blistering-injected plasma impurities may limit the reactor burn time, it is important to consider ways to reduce alpha bombardment of the first wall. Previous workers [4,6] have examined the sensitivity of alpha losses, but only over narrow parameter ranges for a few devices. Our present work studies a broad range of devices and a wide spectrum of parameters which are important for designing practical reactors.

6.1 Approach

Our approach is to consider variations in the key parameters: major and minor plasma radii, wall radius, and q-value. For this purpose, a detailed study of wall loading profiles for various tokamaks is not feasible due to the computation time required. Instead, the parameters required for first wall design are considered: peak and average fluxes. The peak flux, F_{pk}, is used as a key indicator because this determines the worst region for wall effects. Also, the ratio of peak-to-average fluxes, P/A, is insensitive to the parameter variations considered here, as demonstrated through the relation to the ratio, F_{pk}/F_{ℓ}, namely:

$$0.4 \leq (0.3\text{-}0.4) \times P/A \simeq (F_{pk}/F_{\ell})(2\pi r_w R_o/S) \leq 1.2 \qquad (6.1)$$

See Appendix C for details of this scaling argument. These limits follow because F_ℓ(c.f. Eq. 4.4) and F_{pk}(c.f. Eq. 4.5) have the same functional form. (The loss fraction is related to the average flux, $\overline{F}$, because $\overline{F}$ is equal to $F_\ell \times S/\Delta A$, where S is the total fusion source rate, c.f. the denominator of Eq. 4.4.) Since F_{pk} is closely related to both F_ℓ and $\overline{F}$ via Eq. (6.1), we concentrate on changes in F_{pk}. For reference, typical loss fractions are included in Table 5.1.

6.2 Results

Figure 6.1 shows F_{pk} for 3.5-MeV alphas versus the wall radius, r_w, for a sequence of typical tokamaks ranging from near-term experiment to large reactors (other parameters fixed, c.f. Table 5.1). Since the wall loadings are quite sensitive to the current density profile [4] (difficult to measure and not controllable at this stage of tokamak development), results are plotted for several different profiles, namely: $J/J_o = 1, 1 - (\frac{r}{a})^2$, and $1 - (\frac{r}{a})^{.01}$. A uniform current density yields the poorest fp confinement, while the centrally peaked current density produces the best(c.f.Sec.4.2.3). Increasing r_w(with constant minor plasma radius) allows more space between the plasma and wall for alphas to orbit back into the plasma, reducing the wall flux. Increasing r_w in small devices (r_w, $a \lesssim \rho_\theta$, where ρ_θ = poloidal gyroradius) causes F_{pk} to decrease slowly. However, for larger devices (r_w, $a > 2\rho_\theta$) like ORNL-EPR and UWMAK-I, there is up to a 10^4-fold decrease in F_{pk} for a 50% increase in r_w.

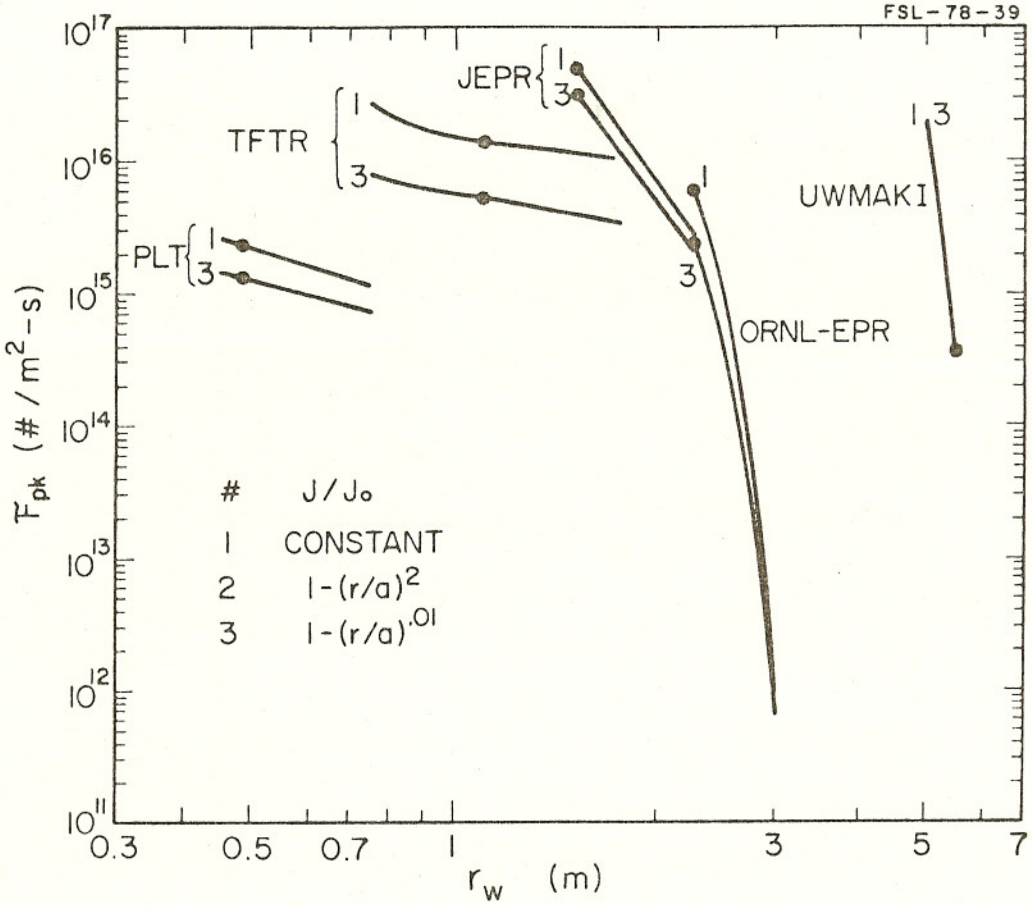

Figure 6.1 Variation in peak 3.5-MeV α-flux, F_{pk}, versus wall radius, r_w, for various tokamaks and current density profiles. Dots on the various curves indicate design points as given in Table 5.1.

Changes in $\mathcal{F}_{pk}$ versus q-values are shown in Fig. 6.2, where q is the "safety factor" $aB_o/R_oB_\theta(a)$. Strong changes ($\tilde{>} 10^3$ - fold increase) are obtained by increasing q from 1 to 5. This can be simply understood [4] by noting that $\cos\chi$ in Eqn. (3.1) is proportional to q $r_g/a \sim 1/I$, where r_g is the gyroradius. Thus the loss region will decrease as the plasma current increases. That is, by increasing q, the current decreases, which increases losses due to the larger banana width.

Figure 6.3 is a plot of $\mathcal{F}_{pk}$ as the minor radius, a, varies such that (r_w-a) is constant with q (a) also held fixed. Up to a 100-fold decrease occurs as the minor radius is increased by a factor of 4. This is a result of a growing zero-loss region in the plasma as the minor radius increases. Since $\cos\chi$ is proportional to q r_g/a, increasing the minor radius with q constant, decreases the losses.

Variations in peak flux with major radius, R_o, for q fixed, are shown in Fig. 6.4. Weak changes ($\leq$ 3-fold increase) are obtained for two-fold increases in R_o. This increase occurs because the zero-loss region decreases (i.e., more fp's can escape to the wall) as R_o increases due to the total current being proportional to R_o^{-1} for fixed q.

6.3 Application

These results have important implications for cost-effective first wall design. A modest increase in r_w produces drastic

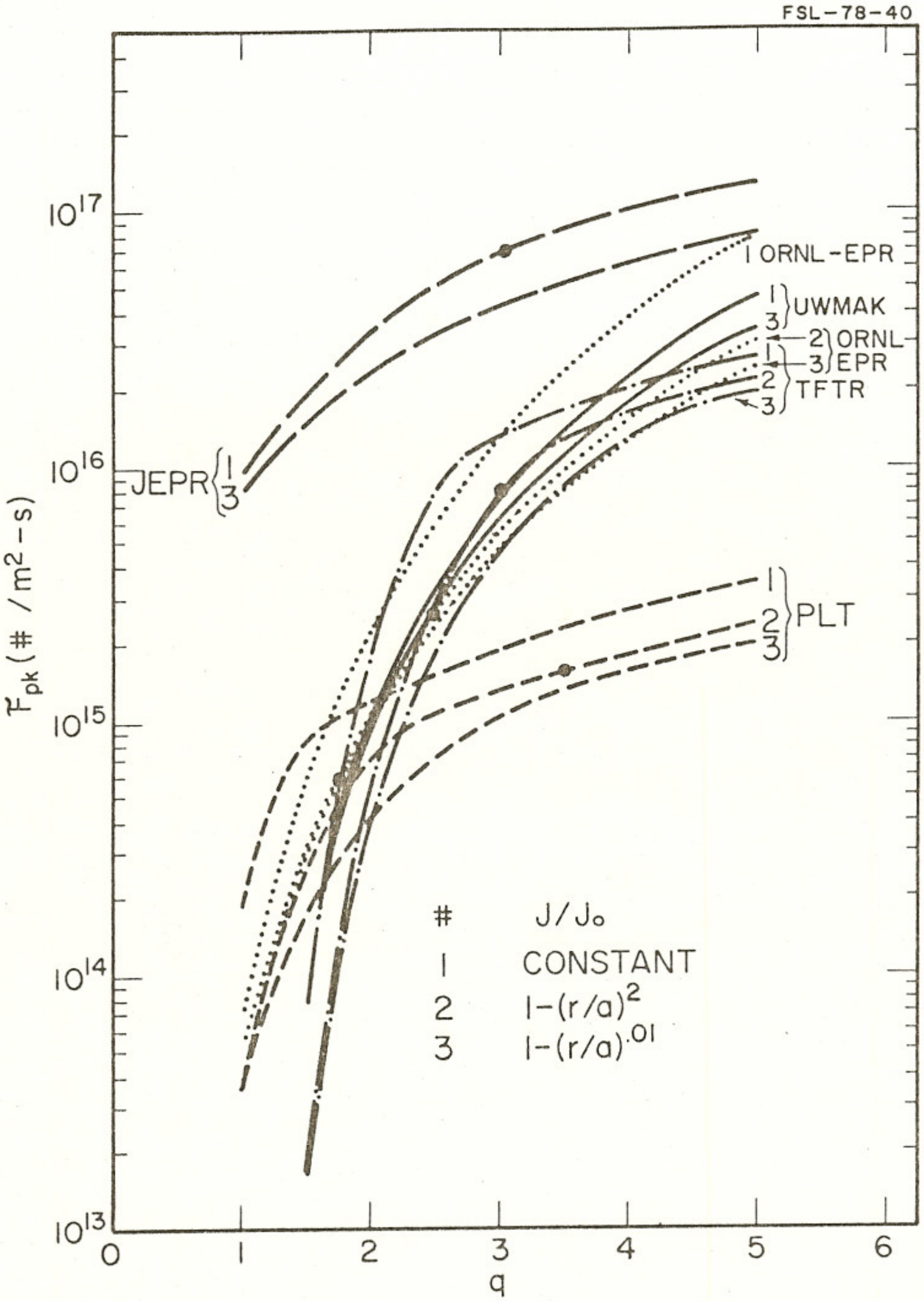

Figure 6.2 Variation in peak 3.5-MeV α-flux, $\mathcal{F}_{pk}$, versus q(a) for various tokamaks and current density profiles. Dots on the various curves indicate design points as given in Table 5.1.

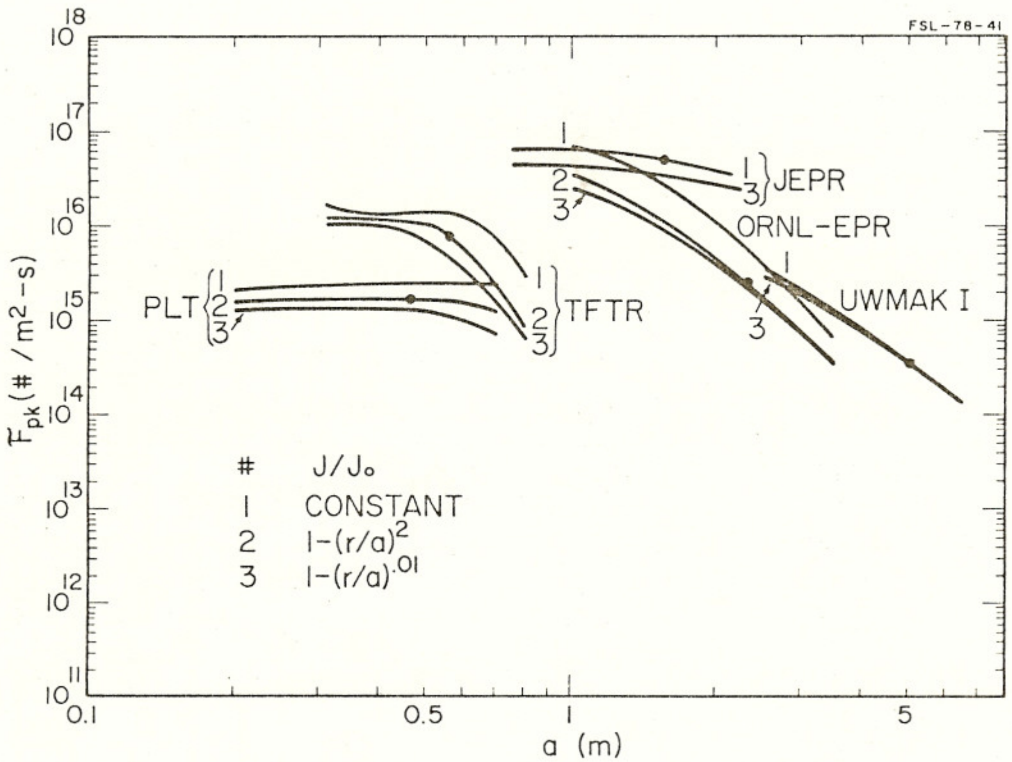

Figure 6.3 Variation in peak 3.5-MeV α-flux, $\mathcal{F}_{pk}$, versus minor plasma radius, a, for q(a) and (r_w-a) held constant for various tokamak and current density profiles. Dots on the various curves indicate design points as given in Table 5.1.

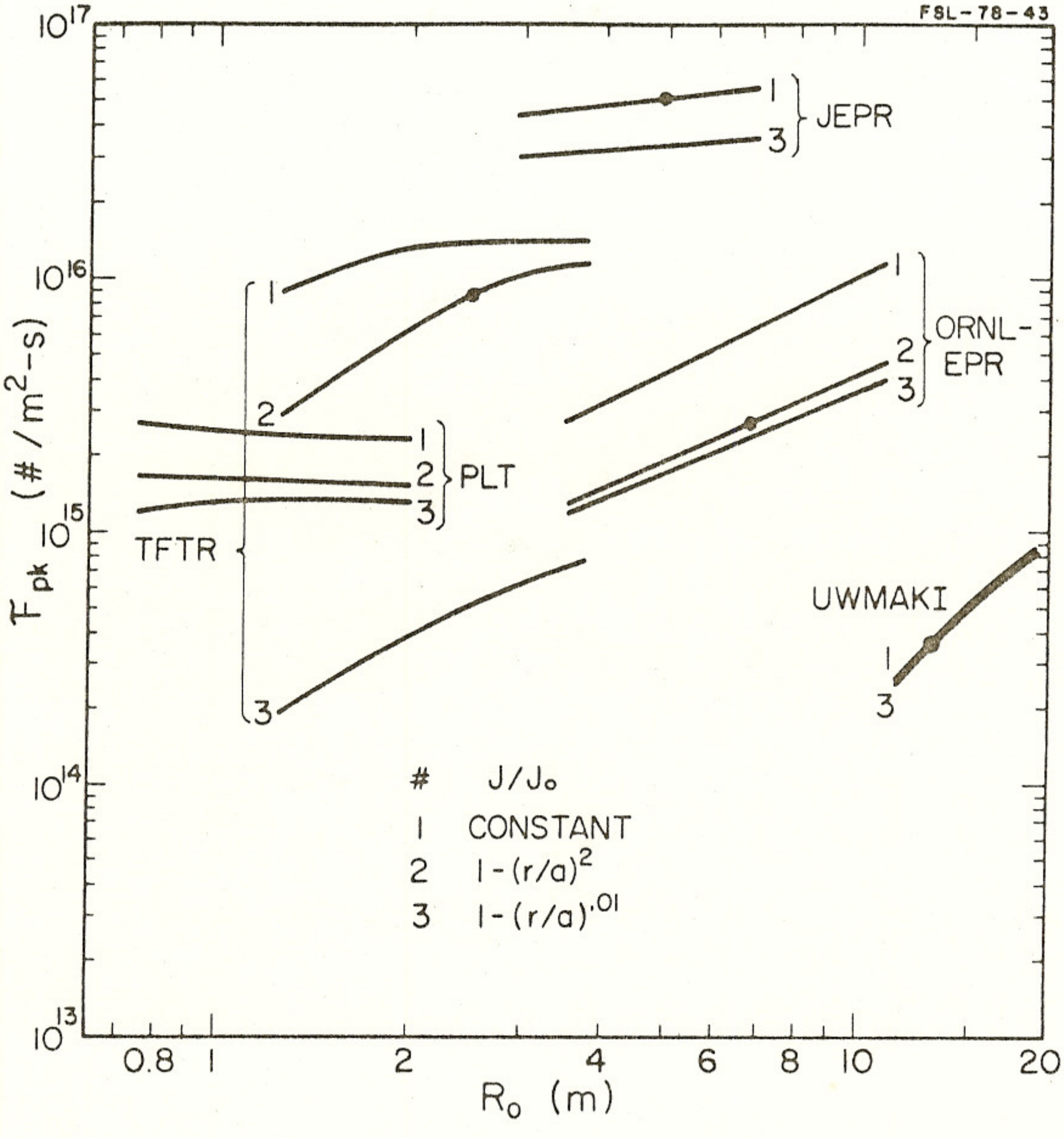

Figure 6.4 Variation of peak 3.5-MeV α-flux, F_{pk}, versus major plasma radius for q(a) fixed, for various tokamak and J-profiles. Dots on the various curves indicate design points as given in Table 5.1.

reductions in the first-bounce fp losses to the wall and consequent plasma contamination. However, increasing r_w must be balanced against the increased cost of the larger blanket and magnet size required. Increasing the plasma current is also helpful, but less effective. Changes in the major and minor radii have the least effect.

To demonstrate an application of these studies, the effect of varying the plasma-wall separation and the plasma current without impurity removal is studied. The fractional increase in the design value of r_w, required to obtain τ_L equal to a multiple of the burn time (e.g., $\tau_L = 10\tau_b$), is:

$$\Delta_w(\tau_L) = \Delta r_w / r_w. \tag{6.2}$$

Similarly, the fractional increase in the plasma current, required to achieve this goal is designated as:

$$\Delta_I(\tau_L) = \Delta I / I. \tag{6.3}$$

Corresponding values of Δ_w and Δ_I are shown in Table 5.2. For the ORNL-EPR design, a 20% increase in r_w yields a 20-fold decrease in the α flux with a corresponding reduction in blistering. Increasing the plasma current is less effective.

Increasing the plasma-wall separation appears "acceptable" from a cost point of view. For example in a recent TNS reactor design ($a = 1.2$m, $R_o = 5$m, $B_T = 5.3$T, $P_{fus} = 1140$ MW_T), a Δ_w - value of 20% raises the capital cost by 9% [42]. On the other hand, to accept a shorter burn time for this sample case requires increasing the plasma-wall separation by 40% to maintain fixed values of thermal wall loading and shut-down time. Consequently, the added capital cost to control α-generated impurities appears to be a good investment compared to the increased expense of a shorter burn time. A more sophisticated means of control is to take advantage of the α-flux peak at the outboard edge of the wall. This is done by leaving the plasma-wall separation unchanged at the inboard edge (i.e., $r_w - X_o - a$ = constant), while increasing it at the outboard edge (i.e., $r_w + X_o - a$ increasing). This avoids conflicts with space constraints at the tokamak centerline (e.g., the larger poloidal radius of magnet coils, shielding and blanket) that would be encountered in the first method. However, present economic models cannot assess this approach [42].