TFTR: PRESENT RESULTS AND PROSPECTS FOR TRITIUM OPERATION

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ABSTRACT

Experiments in TFTR are making contributions to several critical problem areas of tokamak reactor design. The magnitude of tokamak plasma transport is found to be sensitive to the shape of the density profile: central peaking may be advantageous for high-temperature tokamak confinement. For moderate-Q reactor operation, the present TFTR data base suffices to solve the three main steady-state reactor-plasma-physics problems of current drive, refuelling, and impurity control. The achievement of high Q-values at high fusion power densities is being pursued in the economically promising direction of maximizing performance at moderate plasma current. In TFTR D-T plasmas, fusion reactions due to non-Maxwellian energetic-ion components will serve to generate alpha-particle populations of significant magnitude, permitting the near-term study of collective alpha-particle phenomena.

INTRODUCTION: TOKAMAK REACTOR OBJECTIVES

In 1969, the T-3 tokamak (Artsimovich et al., 1969) provided the first experimental data base supporting the existence of a magnetic fusion reactor embodiment of feasible size. Meanwhile, reactor studies have become more sophisticated, and the requirements for a practical power reactor are more specifically demanding, but there is also a vista of increasingly attractive design alternatives.

The present tokamak data base supports the expectation that high-Q operation should be achievable in a 30-MA tokamak reactor [even for L-mode confinement (Goldston, 1984)] -- but a 10-MA tokamak reactor would offer an easier development path and a more clearly economical end product. Transformer-driven tokamaks can be expected to yield reactor burn-pulses lasting many hours -- but true steady-state operation would lend itself to important engineering simplifications and cost reductions. Fusion power densities achieved at plasma beta values below the Troyon limit (Troyon, 1984) are adequate to reach the desired neutron wall-loading at high magnetic fields -- but entry into the second stability regime (Michailovskii and

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Shafranov, 1973a, 1973b; Coppi et al., 1979) would permit technically simpler and more economical tokamak operation. Finally, the burning and breeding of D-T fuel offers the most likely near-term reactor solution -- but advances in the capability to confine stable high-pressure tokamak plasmas may lend themselves to the use of D-³He fuel (Kulcinski et al., 1979).

Table I illustrates a family of "advanced" tokamak reactor concepts that follows the main guidelines of the ARIES study (Conn and Najmabadi, 1987): steady-state operation at moderately low plasma currents, compensated by moderately high aspect ratios ($R/a \sim 5-6$). The achievability of high-Q, high-power-density operation depends on substantial advances either in superconductor technology, so as to provide very strong magnetic fields at the plasma ($\sim 10T$), or in plasma-handling capability, so as to transcend the Troyon beta limit. If advances along both lines prove possible, the burning of advanced fuels could become economically attractive. On the other hand, if reactor design is restricted to the present state of the art, a steady-state, moderate-current (but also moderate-Q) tokamak reactor could be documented on the basis of the available experimental data (Budny et al., to be published).

The present paper reviews a number of areas of TFTR experimental research from the point of view of their potential contributions to the advancement of tokamak reactor prospects. Section 1 discusses the problem of enhancing tokamak confinement, with particular reference to the potential usefulness of peaked density profiles. Section 2 addresses several physics topics relating to steady-state operation -- current drive, fuelling, and impurity control. Section 3 deals with MHD stability and beta limits. Section 4 assesses the potential of TFTR for exploring the physics of burning plasmas.

TABLE I. A Family of Steady-State Tokamak Reactors
(Conn and Najmabadi, 1987)

(Characteristics: Moderate I_p , moderately high R/a)

	Low β	High β
Low β	1st Stability Moderate-Q D-T	2nd Stability High-Q D-T
High β	1st Stability High-Q D-T	2nd Stability High-Q D- ³ He

1. OPTIMIZATION OF CONFINEMENT

As illustrated in Fig. 1a, neutral-beam-heated TFTR plasmas can reach reactorlike conditions in regard to such characteristic parameters as the collisionality ν_* and the magnetic Reynolds number S . The hot central core of "supershot" plasmas (Hawryluk et al., 1987; Goldston et al., 1987; Strachan et al., 1987) is particularly well suited for reactor-relevant confinement studies, and almost the entire profile remains well within the collisionless regime (Fig. 1b).

Tokamak Transport

The general trend of confinement results on TFTR appears to support and extend a tokamak transport picture that emerged during the early 1980's from smaller experiments, and particularly from Alcator C (Greenwald et al., 1987). When the electron heat-flow channel predominates, as for low-density ohmic heating or electron-cyclotron heating, the confinement scaling is of the neo-Alcator or Mazurshkin-Mukhavatov (1981) type. With rising density or direct ion heating, the ion channel becomes important, and confinement scaling of the L-mode type (Goldston, 1984) begins to dominate.

There is growing experimental evidence that the detailed profile shapes of the tokamak temperature and density play important roles in defining the magnitude of electron and ion transport coefficients. The $T_e(r)$ -profile tends to be coupled to the $J(r)$ -profile via Ohm's Law, and the associated $q(r)$ -profile is constrained to a limited range of shapes for given values of $q(0)$ and $q(a)$, so as to preserve ideal and resistive MHD kink stability (Cheng et al., 1987). Within this gross constraint, additional "profile-consistency" effects (Coppi, 1980; Goldston et al., 1986; Fredrickson et al., 1986) appear to favor particular shapes of $T_e(r)/T_e(0)$; on the other hand, in MHD-stable plasmas there is virtually no sensitivity of the $T_e(r)$ -profile to the $n(r)$ profile (Bell et al., 1988; Zarnstorff et al., 1988b) -- contrary to the expectation that would apply if there were some critical pressure gradient. Recent results relating to the shape of the $T_i(r)$ -profile (Zarnstorff et al., 1988b; Zarnstorff et al., 1989) support the idea (Coppi et al., 1967) that ion heat flow is not controlled by prescribed magnitudes of χ_i , but that transport may instead adjust itself so as to keep the parameter $\eta_i = d \log T_i / d \log n$ below some prescribed limit $\eta_i \leq \eta_{crit}$ (cf. Fig. 2), which could turn out to be amenable to theoretical prediction (Tang et al., 1988; Biglari et al., 1988; Romanelli, 1989).

Central Density Peaking

In the context of this overall tokamak transport picture, there are obvious theoretical considerations favoring the use of centrally peaked plasma-density profiles as a means for enhancing energy confinement. (The associated MHD-stability considerations are discussed in Sec. 3.) Even if the heat transport coefficients χ were not directly improved by density-profile shaping, increases in $n(0)/n(\text{edge})$ would tend to give rise to increases in τ_E , simply by reducing the heat-outflow at the plasma edge (Furth, 1986). A plausible use of density peaking to obtain a direct beneficial effect on ion energy

transport is illustrated schematically in Fig. 3: In the presence of a fixed n_i -constraint and a given edge value of the ion temperature, lowering the plasma density at the plasma edge, as in 3a, permits maximum values of central ion-energy storage to be achieved.

A strong correlation of this kind has been observed experimentally (Bell et al., 1988; Zarnstorff et al., 1988b; Zarnstorff et al., 1989) when comparing TFTR supershot and L-mode plasmas of the same plasma current and heating power: The peaked-density supershot case reaches central ion temperatures $T_i(0) \sim 28$ keV, while the L-mode case, where the density profile is flattened by edge-recycling of helium gas, is limited to $T_i(0) \sim 5$ keV. Analysis of the accompanying transport coefficients shows order-of-magnitude improvements in the mid-region x_i for the supershot case, accompanied by somewhat smaller improvements in x_e . The favorable effect of density-peaking on the confinement of both the total plasma energy (including the beam-injected ions) and the energy in the thermalized plasma component is illustrated in Fig. 4.

Strongly peaked tokamak plasma-density profiles with favorable confinement properties were first achieved by means of pellet injection in Alcator C (Greenwald et al., 1987) and later in TFTR (Hawryluk et al., 1987; Goldston et al., 1987), ASDEX (Niedermeyer et al., 1987), and JET (Schmidt et al., 1988; Kaufmann et al., 1988; Milora et al., 1989). The supershot regime represents an extension of this approach to higher-temperature, quasi-steady-state plasma conditions, using neutral beams for central fuelling and using specially conditioned graphite-tile limiters for the suppression of recycling at the plasma edge. Figure 5 illustrates that the achievability of highly peaked profiles [$n_e(0)/\langle n_e \rangle \geq 2.3$] has been restricted to a limited range of plasma currents and neutral-beam heating powers. On the side of higher injected power P and lower I_p , the peaked-density range is bounded by the beta limit. On the side of low P and high I_p , the plasma is MHD-stable, but the effectiveness of the profile-peaking mechanisms tends to disappear. The strong τ_E -dependence on $n_e(0)/\langle n_e \rangle$ and the narrowness of the favorable high- $n_e(0)/\langle n_e \rangle$ range within the I_p - P diagram would seem to account for the observed insensitivity (Bell et al., 1988; Zarnstorff et al., 1988b) of supershot τ_E -values to variations of I_p and P -- which contrasts markedly with the familiar L-mode parameter-dependences of the form $\tau_E \propto I_p P^{-1/2}$. In the supershot case, any direct variations of τ_E as a function of I_p and P could be masked by accompanying changes in density profile shape (or by changes in mean density).

The existence of a finite zone of high- $n_e(0)/\langle n_e \rangle$ supershot plasmas, like that of Fig. 5, depends on the avoidance of density-profile broadening due to recycling at the limiter. Figure 6 illustrates that high $n_e(0)/\langle n_e \rangle$ is correlated with low initial target-plasma density prior to neutral-beam injection -- a measure of the condition of the vacuum-vessel wall and limiter. During the 1988 TFTR experimental run (Bell et al., 1988; Zarnstorff et al., 1988b) the evolution of carbon impurities from the graphite limiter tiles proved to be the ultimate impediment to lowering the density of the initial target plasma (and also served to shorten the effective beam-heating phase by generating spectacular "carbon blooms"). Meanwhile 35 seriously damaged tiles have been replaced, and the whole limiter assembly has been

aligned carefully, so as to reduce variations in major radius by almost an order of magnitude (to ± 0.05 cm). The objective of the limiter improvement effort is to enhance the density-peaking factors that will be achievable for given magnitudes of I_p and P , during the 1989 TFTR experimental run. The ability to investigate parameter dependences will be further enhanced by the use of pellet injection and ICRF heating to gain separate control over the two functions of particle and energy input, which at present have a common dependence on the magnitude of the injected neutral-beam power.

Plasma Rotation and Fluctuation Studies

Neutral-beam heating in TFTR is based on balanced tangential injectors, which are normally adjusted for little or no net toroidal rotation, but can be used to impart toroidal velocities in the 10^5 - 10^6 m/sec range (cf. Fig. 7). Strong and controllably variable toroidal rotation has been clearly an interesting tool for testing various anomalous-confinement models: For example, there should be a vigorous interaction of the toroidal shear-flow with the radial magnetic-field component of magnetic surfaces that are assumed to be ergodic. The experimental indications are that τ_E is only moderately affected by vigorous rotation in either the co- or counter direction (Hawryluk et al., 1987; Goldston et al., 1987; Bell et al., 1988; Zarnstorff et al., 1988b). The transport coefficient $\chi_\perp$ for toroidal momentum is found to be remarkably similar to χ_i (cf. Fig. 7b), and bears no resemblance to the neoclassical rotation damping that is expected to arise from toroidal-field ripple.

In connection with plasma-density fluctuation studies using microwave scattering (Bretz et al., 1988), controlled toroidal plasma rotation offers a useful tool for verifying the radial location of the microwave-scattering fluctuations. During unbalanced neutral-beam injection into TFTR, part of the observed fluctuation spectrum is seen to Doppler-shift continuously (into the 0.3-0.5 MHz range), as would be expected for fluctuations that are located within the region of finite V_{tor} and B_p . The time-dependences and wavelength characteristics of these fluctuations are therefore known to relate to internal-plasma phenomena. Another part of the observed fluctuation spectrum, which exhibits substantial bandwidth (~ 0.05 MHz) but no toroidal Doppler shift, is presumably due to single-pass or multi-pass scattering of the incident 60-GHz microwave beam from non-rotating edge-plasma fluctuations. The somewhat smaller density-fluctuation level that is seen prior to beam injection could turn out to be associated with either bulk or edge-plasma phenomena.

Another promising approach to the study of density fluctuations is to photograph them, using H α light from ionizing neutrals. At the plasma edge, where limiter recycling provides a strong source of H α illumination, a distinct pattern of moving striations has been observed in TFTR (Zweben and Medley, 1989), with characteristic parameters $\bar{n}/n - 1$, $k_\perp \rho_s \sim 0.02$, $\lambda_\perp = 3$ -5 cm and with magnitudes of $\lambda_\perp$ that appear to be as short as 10^2 cm -- a result that would create yet another element of surprise relative to theoretical expectation.

Global Confinement

Noting the strong profile-dependence of tokamak energy confinement within the plasma core, one can think of the global energy-confinement time as being governed by two different types of anomalous behavior: (1) The magnitudes of ion and electron temperature close to the plasma edge are determined by transport phenomena that are still poorly understood and that may well be sensitive to such "extraneous" factors as atomic effects and irregular plasma boundary conditions; and (2) the rise of $T_i(r)/T(\text{edge})$ and $T_e(r)/T(\text{edge})$ from the plasma edge towards the plasma center is controlled by profile effects that are at least partly intelligible in terms of a priori theory. The collaboration of these two types of phenomena determines the plasma energy content for a given power throughput, thus defining τ_E .

2. STEADY-STATE TOKAMAK OPERATION

If a tokamak reactor is to operate in true steady state, some key problems will be: (1) driving the plasma current by noninductive means; (2) refuelling the plasma -- particularly if a peaked density profile is to be maintained; (3) preventing the accumulation of impurity ions within the plasma core; (4) pumping the plasma particle outflow with minimal recycling, while withstanding the plasma heat outflow.

The TFTR supershot regime can be seen to provide a significant calibration of progress towards solving the first three of these problems. Analyzing the actual TFTR experimental data in terms of the TRANSP code, one can, for example, extrapolate directly to a steady-state tokamak regime (Budny et al., to be published). Machine parameters only slightly greater than those of TFTR ($R = 3.9$ m, $a = 0.95$ m, $\kappa = 1.6$, $I_p = 5.5$ MA, $B = 7.2$ T, and a total of 150 MW of 250-keV D^0 and 350-keV T^0 neutral-beam power), are found to satisfy the basic plasma-related requirements for a $Q \geq 2$ steady-state D-T reactor of the type envisaged in Table I. The extension of these steady-state plasma capabilities to a high- Q tokamak reactor regime will, however, call for significant further progress in all three areas of plasma-physics concern.

The challenging plasma-engineering issues associated with the fourth key problem area, the removal of plasma particles and heat, are yet to be addressed by high-powered, long-pulse tokamak divertor experiments, such as ASDEX-U and JT-60-U. The initial divertor studies on ASDEX, PDX, D-III, JET, and other tokamak experiments have established the basic effectiveness of the poloidal-field divertor design for channeling the plasma outflow, and have discovered a plasma-confinement regime [the H-mode (Wagner et al., '982)], which relies on a form of profile-optimization that differs from the central-density-peaking approach described in Sec. 1. A common feature of the H-mode and the supershot is that the enhancement of confinement depends on the suppression of recycling at the plasma edge. A basic divergence of the H-mode from the profile-shaping approach outlined in Fig. 3b is that a sharp rise in both $T_i(r)$ and $n(r)$ takes place just inside the divertor separatrix, with $n(r)$ typically assuming a rather flat profile $n_a(a)/\langle n_a \rangle \leq 1.5$ within the plasma interior. The feasibility of combining the best features of the supershot and the tokamak divertor regime is made somewhat plausible by initial experimental

results (Niedermeyer et al., 1987; Schmidt et al., 1988; Kaufmann et al., 1988; Milora et al., 1989). Under special conditions, TFTR supershots have been found to exhibit specifically H-mode-like edge-plasma transitions, but without a clear-cut improvement in global energy confinement relative to the supershot regime. The most natural combination of peaked density profiles and divertors may be exemplified by the "improved L-mode" (IL) of the JFT-2M experiment (Mori et al., 1988), where confinement is sufficiently good so that transition back to the H-mode is accompanied by a small decrease in τ_E . As regards the effect of density-profile peaking on heat outflow from the plasma edge, one notes that reducing $n(\text{edge})$ for a given $x(\text{edge})$ and $T(\text{edge})$ should not aggravate the engineering problems associated with heat removal.

Current Drive

The basic suitability of the TFTR supershot regime for steady-state current drive is illustrated in Fig. 8. The combination of beam current-drive and bootstrap current suffices to produce a negative transient of the transformer loop voltage (Hawryluk et al., 1987; Zarnstorff et al., 1988a; Scott et al., 1988), consistent with neoclassical prediction. Extrapolation to the steady-state regime (Budny et al., to be published) points towards the existence of a practical equilibrium solution, but the detailed requirements for maintenance of an appropriately shaped Δ' -stable $J(r)$ profile (Goldston, 1984) remain to be verified. (The "dynamo mechanism" of the tokamak may also take care of the $J(r)$ -shaping task (Boozer, 1986) -- hopefully, without excessive impairment of the quality of tokamak plasma confinement.) To extend steady-state current drive to a high-Q tokamak reactor plasma would call for penetrating neutral beams plus a major bootstrap-current contribution. The associated reactor economics clearly favor low- I_p , high- R/a solutions of the type envisaged by the ARIES study (Conn and Najmabadi, 1987).

Plasma Fuelling

In the problem area of steady-state plasma fuelling, the supershot regime is inherently well suited to maintain a peaked plasma-density profile -- and even to provide precise control of the D-T fuel mixture. For the case of a high-Q power reactor, beam-fuelling is more problematical, because high beam energy is needed to insure penetration, and the associated energy investment per fuel ion imposes an upper limit on the Q-value. There is clearly a useful role for initial density peaking by means of pellets or beams, to facilitate entry into the equilibrium-burn regime, but the maintenance of steady-state peaking may depend on the success of more speculative approaches, such as the development of means for highly penetrating "compact torus injection" (Hartman et al., 1988) or the combination of edge-fuelling with an appropriate form of the tokamak "self-pinching" phenomenon.

To improve our present understanding of the tokamak pinch effect, a program of time-dependent analyses has been developed, which is able to provide a fairly clear differentiation between convective and diffusive particle transport. This program was applied (Efthimion et al., 1988) to the study of density transients produced by injecting small gas puffs into the TFTR edge plasma.

Meanwhile the study has been extended to gas puffs of sufficient magnitude so as to alter the initial density profile, resulting in the documentation of "nonlinear" changes in the diffusion constant D and pinch velocity V . Recently, the analysis was also applied to the high- n_{Te} pellet-injected regimes reported by Hawryluk (1987), Goldston (1987), and Schmiz (1987). The remarkably slow relaxation of the pellet-generated peaked-density profiles (on a time scale of about one second) is found to arise from a rather low diffusion constant $D \leq 10^3 \text{ cm}^2 \text{ sec}^{-1}$ within the central plasma region, together with an anomalously large inward pinch velocity, in the range $V = 10\text{-}30 \text{ cm/sec}$. The pursuit of an extensive and accurate data base concerning the anomalous pinch effect will clearly be of central importance, both in achieving a fuller understanding of the physics of tokamak transport and in devising optimal confinement strategies for steady-state operation.

Impurity Control

When a centrally peaked plasma-density profile is maintained, neo-classical theory predicts the preferential accumulation of high- Z impurities. By contrast, simple physical intuition suggests that, at least in the centrally-fuelled case, there should actually be an "outflow" of impurity ions: Anomalous particle transport is likely to take the form of turbulent $\vec{E} \times \vec{B}$ motions that carry out the old fuel along with its impurity content as new fuel arrives to occupy the central plasma region. The existence of such a cleansing process in the supershot regime, which is indicated by the observation of moderately low values of Z_{eff} (typically 2-3), can be illustrated dramatically by impurity-injection studies, such as the germanium laser-blowoff experiment (Scott et al., 1988) of Fig. 9. For the case of balanced neutral beams, one finds that the germanium is "flushed out" on a time scale of about 100 ms, less than one global energy confinement time. The germanium decay times for the cases of both co- and counter-rotating plasmas drop down to the 50-ms range -- a result that seems to contrast with the observed accumulation of impurities in ASDEX plasmas where the density profile has been peaked by counter-injection (Soldner et al., 1988).

Even more strikingly anomalous (and encouraging) results have been reported for lithium-pellet injection into ohmically heated Alcator C plasmas (Marmar et al., 1988). The lithium ions manage to escape from the peaked-density region on a time scale that is several times faster than the relaxation of the profile-peaking phenomenon itself. As a result, there is a remarkable five-fold increase in the $D\text{-}D$ neutron rate -- resulting from lithium injection. Since lithium pellets are several times more penetrating than frozen deuterium pellets, there is a strong motivation for applying this plasma-peaking technique to TFTR supershots. Preparations have been made in collaboration with Marmar et al. (1988) for an experiment of the lithium-pellet type during the 1989 TFTR run period.

3. MHD STABILITY AND THE BETA LIMIT

MHD Kink Modes

The characteristically narrow $n(r)$ -profile and broadened $T_e(r)$ -profile of the supershot regime, together with the appearance of appreciable bootstrap current, suggests that the usual tokamak tendency toward central $J(r)$ -peaking may be reduced. This hypothesis is supported by the visible signs of MHD activity: In a high-grade supershot regime (i.e., typically for balanced beams or slight co-injection), the $m = 1, n = 1$ sawtooth activity disappears; instead, one finds that a prominent role is sometimes played not only by the $m = 2, n = 1$ mode, but also by the $m = 3, n = 2$ mode -- seldom seen in normal tokamak plasmas (Fredrickson et al., 1988). The growth of these modes is often accompanied by collapse of the stored tokamak energy content. To account for the observed $m = 3, n = 2$ activity in terms of Δ' -stability conditions (Cheng et al., 1987; McGuire et al., 1987, 1988), it is logical to suppose that $q(0)$ might be rising well above unity (i.e., towards 1.5) in supershot plasmas. A moderate rise of this kind is indicated by the TRANSP analysis. Some direct measurements of $q(0)$ have been performed in TFTR, but present error margins are still too large to allow an independent verification of the supershot $q(0)$ pattern.

Beta Limit

The limiting beta values of the supershot regime are on the low side of the conventional Troyon limit (Fig. 10a) -- possibly reflecting the theoretical non-optimality of strongly peaked pressure profiles for maximizing the space-average beta-value $\beta = 8\pi \langle nT \rangle / B^2$ within the first stability regime. For purposes of measuring reactor performance (in the 10-20 keV temperature range), the most relevant form of beta is actually the r.m.s. value $\beta^* = 8\pi \langle (nT)^2 \rangle^{1/2} / B^2$, since the fusion power density is proportional to $(\beta^*)^2$. Figure 10b shows that the best TFTR supershot β^* -values exceed the corresponding values of β by about 50% and compare favorably with the β^* -version of the theoretical Troyon limit (Manickam, to be published). The desire to use density-peaking as a tool for enhancing confinement provides a strong motivation to continue to push β^* beyond the conventionally accepted MHD stability limits.

A detailed comparison of TFTR data with ballooning-mode theory has been carried out, using the PEST code (Manickam et al., 1988). A simplified analysis has also been done in cylindrical geometry (Fig. 11), plotting the local shear and pressure gradient of supershots relative to theoretical "S- α curves" that define the first and second stability regions (McGuire et al., 1987, 1988). The bulk of the data points fall within the first-stability S- α region, consistent with the theoretical boundary curve. Towards the center of the plasma, there is an apparent "leakage" of data points into the second-stability region, as well as into the intervening strip of theoretically unstable S- α parameters. Operation near the boundary of the second stability regime has also been reported for intensely beam-heated plasmas with elevated $q(0)$ -values in DIII-D (Simonen et al., 1988).

Ballooning-mode-stable operation in the second stability regime becomes theoretically possible for standard (unshaped) tokamak plasmas, provided that $q(a)$ is raised to ~ 2.5 . Plausible equilibria of this kind have been calculated for TFTR supershots [for example, with $I_p = 1.74$ MA, $B = 5$ T, $q(a) = 7.5$, and $\beta = 2.4\%$, substantially exceeding the Troyon limit (Chance and McGuire, 1989)]. Experimental entry into such a regime would call for close control of $q(a)$ and skillful avoidance of kink-instability problems -- possibly aided by energetic-ion populations and wall-stabilization effects. The basic predisposition of the supershot plasma to give large β_p -values along with very high values of the magnetic Reynolds number (cf. Fig. 1) offers special hope that progress could be made in this direction.

Figure 12a illustrates that the central flux surfaces of supershot plasmas have quite substantial Shafranov shifts -- the characteristic geometric feature of progress towards second stability. An incidental advantage of the high- q approach is that at low plasma currents the TFTR poloidal-field-shaping system becomes more effective for modifying the circular outer plasma surface in the direction of moderate triangularity. Figure 12b illustrates the basic compatibility of the TFTR geometry with the type of optimal tokamak plasma geometry that is being envisaged in the ARIES study (Conn and Najmabadi, 1987). Useful guidelines concerning the existence, accessibility, and confinement properties of the second stability regime may be provided by the PBX-M experiment (Okabayashi et al., 1988), which is designed to use a plasma shape with very strong triangularity to make a stable transition directly from the first to the second stability regime.

4. THE PHYSICS OF BURNING PLASMAS

If fusion reactions did not produce any energetic charged secondaries, such as alpha particles, the reactor-plasma confinement problem could be addressed entirely by "hydrogen-plasma experiments"; the need for burning D-T plasmas would arise only in the context of reactor-engineering development. Real D-T plasmas have the merit that the 3.5-MeV alpha particles can take over the plasma-heating function when P_{fusion} approaches five times P_{loss} , but have the drawback that the alpha particles may also introduce new physics phenomena, so that the optimization of D-T reactor-plasma confinement cannot be performed definitively without using real D-T plasmas.

The "physics of burning plasmas" separates into three distinct categories: (1) single-alpha-particle phenomena, such as orbital excursions, classical slowing-down, and transport by bulk-plasma fluctuations; (2) alpha-particle-driven instabilities, such as fishbones, Alfvén waves, MHD-modes, and trapped-particle modes, along with alpha-particle-related MHD-stabilizing effects; (3) fusion-heat-driven temperature excursions, such as sawteeth or thermal run-away. The TFTR experiments seek to address all three of these categories: Single-energetic-particle phenomena are being studied already, using the charged products of D-D reactions. For the D-T-burning phase of TFTR (which was recently postponed from 1990-91 to 1993-94), projections from present data are favorable to achieving reactorlike alpha-particle populations, so that significant studies of collective alpha-physics phenomena

can be carried out. Finally, TFTR D-T plasmas in the $Q = 1$ range should provide useful initial information concerning fusion-heat-driven plasma phenomena, which will contribute to the data base for projected high- Q tokamak experiments of the next generation, such as CIT and ITER.

Single-Particle Phenomena

The behavior of single energetic ions in TFTR is illustrated in Fig. 13 for the case of the 1.0-MeV tritons of the D-D reaction (Zweibel et al., 1989). The time-variation of the flux of escaping tritons is measured directly and is compared with the time-variation of the triton source term, as inferred from the D-D neutron flux. The substantial similarity in the shape of these two curves, as illustrated in Fig. 13a for an MHD-stable case, implies that the observed triton flux consists primarily of reaction products emitted on direct escape orbits, and sets a low upper limit of $D_{\perp} < 10^2$ cm²/sec for the maximum possible triton diffusion rate across magnetic surfaces -- a result that is consistent with theoretical expectation (White et al., 1988). The number of tritons escaping during the D-D-reactive phase of the pulse amounts to only a small part of the bulk triton population (probably less than 10%) and becomes entirely negligible after the triton source is turned off, while the stored tritons take much longer to slow down.

The presence of MHD activity (sawteeth or external resistive kink modes) tends to enhance the escaping triton flux, as illustrated in Fig. 13b, but the cumulative triton loss is still only a moderate part of the triton population. The apparent shortfall of the triton burn-up fraction that was reported by Strachan et al. (1988) cannot be accounted for in terms of directly observed triton losses, and is considered more likely to reflect uncertainties in the assumed bulk-plasma parameters, particularly during the latter part of the triton slowing-down process, when the neutral-beam-heating phase is over.

Collective Alpha-Particle Phenomena

The excitation of collective alpha-particle phenomena depends primarily on the alpha population fraction n_{α}/n_e and the alpha beta value β_{α} . As illustrated in Fig. 14, in the case of a Maxwellian plasma, these quantities are functions only of local plasma parameters (i.e., they do not depend on global parameters such as the plasma Q -value). Figure 14 indicates a threshold temperature around 15 keV for production of significant alpha-population fractions ($n_{\alpha}/n_e \geq 0.5\%$) in a clean Maxwellian D-T plasma. Present TFTR electron temperatures fall short of this goal, and the presence of Z_{eff} -values above unity has a further adverse effect, but the reactivity of the ions is sufficiently enhanced by the beam-injected energetic-ion tail, so that present-day TFTR data already project to levels of n_{α}/n_e approaching those expected for CIT and ITER (cf. Table II). In the context of creating relevant conditions for the study of collective alpha-particle phenomena, the TFTR D-T plasma-parameter projections are actually somewhat more advanced than those for a marginally ignited tokamak plasma, where the alpha-particle population thermalizes too quickly to reach appreciable values of β_{α} and n_{α}/n_e . A

special problem area for energetic-ion-generated alpha-populations is the potential interference of the energetic-ion-driven and alpha-particle-driven collective effects, but present indications are that the two should be easily separable in terms of their characteristic frequencies, as well as by experimental control of timing and fuel mix.

Table II. Alpha-Particle Plasma Physics

Parameter	TFTR DT projected	TFTR Objective	Low-T Ignition	CIT High-T	ITER
$n_\alpha(o)/n_e(o)$	0.16 - 0.5%	1%	0.1%	0.9%	0.7%
$\beta_\alpha(o)$	0.16 - 0.5%	1%	0.2%	2.5%	2.3%
$V_\alpha/V_{\text{Alfvén}}$	1.5 - 2.0	1.7	2.5	2.6	2.8

Fusion-Heat-Driven Phenomena

The effective study of fusion-heat-driven phenomena calls primarily for elevated Q-values -- corresponding loosely to sufficiently high values of the "confinement parameter" $T_i n_e \tau_E$. Peaked-density plasma regimes in TFTR have reached substantial levels of $T_i(o) n_e(o) \tau_E$, namely, $2 \cdot 10^{20}$ keV m⁻³ sec in the case of pellet fuelling experiments (Hawryluk et al., 1987) and $4 \cdot 10^{20}$ keV m⁻³ sec for beam-fuelling (Bell et al., 1988). Figure 15 makes a comparison between experimentally achieved $T_i n_e \tau_E$ -values and the projections for L-mode scaling originally proposed by Goldston (1984) assuming a fixed profile shape $n_0 T_0 / \langle nT \rangle$. For the TFTR supershot regime, $T_i n_e \tau_E$ is seen to rise far above the Goldston L-mode prediction, thus pointing towards the desired achievement of good reactor confinement properties at relatively low currents (Conn and Najmabadi (1987)). The strong central peaking of n and T_i is helpful in this regard, since, according to Goldston scaling, the quantity corresponding to $T_i(o) n(o) \tau_E$ is proportional to $(\beta/\beta^*)^2 I^2$.

The multiplication factor $M = P_{\text{fusion}} \tau_E / W_{\text{Tot}} = (Q^{-1} + 0.1)^{-1}$ which is the ratio of fusion energy generation to plasma heat loss, is also proportional to $(\beta/\beta^*)^2 I^2$, according to Goldston scaling. When using the quantity $T_i(o) n_e(o) \tau_E$ as a measure of the thermonuclear part of M, one should note, incidentally, that the correct identification is $M_{\text{Th}} \propto T_i n_e \tau_E [\langle \sigma v \rangle / T_i^2]$, where the multiplier in brackets is reasonably constant only within the range 7 keV < T_i < 30 keV. (The same cautionary remark applies to the use of $(\beta^*)^2$ as a measure of thermonuclear power density.) Figure 16 illustrates that the average ion temperature for the beam-fuelled TFTR case is such that $T_i n \tau_E$ is a meaningful figure of merit, while the temperature for the pellet-fuelled TFTR case falls well outside the relevant range.

The actual Q-value for TFTR D-D plasmas is several times larger than the thermonuclear part Q_{Th} , thanks to the presence of the energetic-ion tail, which reacts both with itself and with the thermal plasma. Total D-D-reaction rates up to $8 \cdot 10^{16} \text{ sec}^{-1}$ have been reached in TFTR supershots, with the beam-thermal reactions contributing about half the total. Since the publications by Bell (1988) and Strachan (1988), the calibration of the TFTR neutron diagnostics has been substantially improved by carrying out measurements on neutron sources moving within the vacuum vessel. The uncertainty in the neutron yield has been reduced to $\pm 12\%$, and the magnitude of measured yields has been adjusted upward by typically 20%, bringing them into good agreement with code predictions based on measured plasma parameters. The corresponding value of Q_{DD} is shown in Fig. 17.

To extrapolate from the deuterium-plasma results to a TFTR regime with a 50:50 D-T plasma mixture, one takes into account, first of all, the differences arising from the fusion cross sections and fusion-energy yields. For this purpose we use the measured values of $n_e(r)$, $T_e(r)$, $T_i(r)$ and Z_{eff} , and find, for the best cases, an "equivalent" Q_{DT} -value of 0.33 (about 190 times greater than Q_{DD}). To make a more realistic projection, one also needs to take into account the most obvious plasma effects that are entailed by the use of D-T fuel: the presence of alpha-particle heating and the favorable effects of the ion-mass increase on the quality of confinement and on the magnitude of the neutral-beam power. Neglecting additional contributions such as those associated with raising the beam energies to their full 120-keV value or with possible reductions in impurity content, one obtains a Q^*_{DT} -value of about 0.5, corresponding to $Q^*_{DT} \sim 300 Q_{DD}$.

In making D-T projections, one normally assumes that the neutral beams inject half deuterium and half tritium ions, so that the plasma composition does not vary as a result of beam-fuelling. The projected Q_{DT} -value turns out to be fairly insensitive to variations in the fuel-mix that apply a consistent D-T ratio to the beams and to the thermal plasma. On the other hand, the use of transients can produce some enhancement of alpha-heating effects (Zweber et al., 1988). In particular, the longer slowing-down time of the alpha particles, relative to the beam-injected particles, causes them to become more dominant in central-plasma heating during the period immediately following the beam-heating pulse.

The present TFTR schedule calls for the intensification of plasma-confinement and diagnostic studies during the next several years. According to current projections, break-even-level plasma regimes should be achievable in deuterium plasmas, and intensive D-T preparations will resume during 1991-93. The final D-T-burning phase of the TFTR experimental program is scheduled for 1993-94.

CONCLUSION: CONTRIBUTIONS OF TFTR TO TOKAMAK REACTOR PROSPECTS

In the context of the tokamak reactor objectives that were outlined in the Introduction, the TFTR experiments seem likely to make helpful contributions to four main areas, corresponding to the topics of the preceding four sections of this paper:

1. The part of confinement-physics research for which the TFTR experiments are particularly well suited is the study of transport and MHD stability in reactorlike plasma cores with low collisionalities and high magnetic Reynolds numbers. In regard to the enhancement of tokamak confinement, TFTR is pursuing the optimization of the main "freely variable" profile among the tokamak plasma parameters, namely, the plasma density profile. Central-density peaking seems to offer a number of fundamental advantages -- though giving rise to special problems of implementation.

2. The present TFTR data base for neutral-beam-driven supershot plasmas provides solutions to the three key plasma-physics problems of steady-state tokamak reactor operation: current-drive, refuelling, and impurity control -- but the present TFTR data base is only directly prototypical for a moderate-Q tokamak reactor. The experimental program aims at contributing to the development of tokamak reactor strategies that are suited to higher-Q steady-state operation.

3. Since the optimization of tokamak power-reactor economics seems likely to favor high fusion power output at relatively low total plasma current, the basic TFTR machine geometry is potentially well suited to the pursuit of relevant MHD-stability experiments. Central peaking of the plasma-pressure profile looks like a promising strategy for pushing beyond the first-stability constraint. Entry into the second stability regime is still speculative -- but potentially very rewarding.

4. The achievement of high T_{intE} -values and Q-values with relatively modest TFTR plasma currents has favorable economic implications, both for the continuing development of the tokamak reactor approach, and for the design of attractive power-reactor models. The presence of a significant energetic-ion tail within the beam-heated TFTR plasma enhances the total Q-value and -- more importantly -- serves to raise the alpha-particle population to an appropriate threshold level for the study of collective alpha-particle phenomena.

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Figure Captions

- Fig. 1. (a) Present and proposed tokamak experiments are compared in regard to collisionlessness $\nu_{*}^{-1} = \nu_b/\nu_c$, (where ν_b is the bounce frequency of a trapped particle and ν_c is the collision frequency) and magnetic Reynolds number $S = \tau_R/\tau_A$ (where τ_R is the resistive diffusion time and τ_A is the Alfvén transit time, based on the poloidal field strength). (b) The TFTR supershot plasma is in the collisionless regime over virtually the whole range of minor radii. By comparison, high-density ohmic plasmas in TFTR tend to remain in the collisional regime.
- Fig. 2. The measured TFTR values for $L_{Ti} = (d \log T_i/dr)^{-1}$ and $L_{ne} = (d \log n_e/dr)^{-1}$, including both supershot and L-mode cases (Zarnstorff et al., 1989), tend to cluster around $\eta_i \equiv L_{ne}/L_{Ti} \sim 2$.
- Fig. 3. If the density and temperature profiles are related by the condition $\eta(r) = 2$, a moderate amount of density peaking (a) gives rise to a great improvement in T/T_{edge} , relative to the flat-density case (b). (Illustration provided by R.J. Goldston.)
- Fig. 4. Confinement-enhancement factors in TFTR, relative to the Goldston L-mode prediction, as a function of density peaking.
- Fig. 5. TFTR operating space within which strongly peaked density profiles are achieved.
- Fig. 6. Density-peaking factor for TFTR supershots as a function of the line-averaged density of the initial ohmic-heated target plasma.
- Fig. 7. (a) Minor-radius profiles of the toroidal plasma velocity and ion temperature in strongly rotating TFTR supershots with unbalanced co-injection (Scott et al., 1988). (b) Comparison of the toroidal-momentum transport coefficient χ_{ϕ} with the ion thermal conductivity χ_i .
- Fig. 8. Comparison of theoretically expected and measured surface voltages in TFTR, for co-only and balanced injection. When the theoretical model includes beam-driven and bootstrap currents, the correspondence to experiment is good. When the bootstrap current term is omitted, there is a marked disagreement with the results of balanced-injection experiments. (Analysis carried out by M.C. Zarnstorff.)

- Fig. 9. Impurity retention in 1.1-MA TFTR supershots is explored by means of laser-blowoff-injected germanium ions (Scott et al., 1988). The time of residence within the hot-plasma core is monitored by means of the $123\text{\AA}$ line of GeXXX. Case (a) has 14 MW of balanced beam power, with $\bar{n}_e = 2.6 \cdot 10^{13} \text{ cm}^{-3}$ and $\tau_E = 125 \text{ msec}$. Case (b) has 12 MW of counter-injected power, with $\bar{n}_e = 2.4 \cdot 10^{13} \text{ cm}^{-3}$ and $\tau_E = 80 \text{ msec}$.
- Fig. 10. Comparison of measured plasma beta values (McGuire et al., 1987, 1988) in TFTR with the respective Troyon limits for $\beta = 8\pi \langle nT \rangle / B^2$ and $\beta^* = 8\pi \langle n^2 T^2 \rangle^{1/2} / B^2$, as a function of the MHD q-value at the limiter.
- Fig. 11. Distribution of TFTR supershot data points (McGuire et al., 1987, 1988) within the S- α diagram. The low-S, low- α section of Figure (a), which corresponds to the central plasma region, is shown enlarged in (b).
- Fig. 12. (a) The measured plasma cross-section for a TFTR supershot with $I_p = 0.9 \text{ MA}$, $B = 5.2 \text{ T}$ and $s_D = 2$. (b) An illustrative high-R/a plasma cross-section calculated by S.C. Jardin for the ARIES study (scaled down to TFTR size).
- Fig. 13. The time-dependence of the flux of escaping tritons is measured at the plasma edge and compared with the time-dependence of the triton source, as indicated by the (normalized) magnitude of the D-D neutron flux (Zweibel et al., 1989).
- Fig. 14. For thermalized D-T plasmas, the fractional alpha-particle population n_α/n_e and the fractional alpha β -value β_α/β_{th} are functions only of temperature. The effect of impurities is indicated by the case where a carbon-ion admixture raises Z_{eff} to 2. (Calculations are by Y. Sun and G. Bateman.)
- Fig. 15. Typical experimental values of $n_e(0)$, τ_E , $T_i(0)$ are compared (somewhat schematically) with the Goldston L-mode prediction $n_e(0) \tau_E T_i(0) \approx I^2 (R/a)^{2.5} a^{-0.24} (A_i/1.5)$.
- Fig. 16. The quantity $\langle \sigma v \rangle / T^2$, which measures the ratio $M_{Th} = P_{Fusion} \tau_E / W_{Tot}$ to the parameter $T_i n_\tau$ for a thermonuclear ion distribution, is given as a function of ion temperature. Arrows indicate the average ion temperatures within the reacting regions of pellet-fuelled and beam-fuelled TFTR plasmas. (Illustration provided by D. L. Jassby.)

Fig. 17. The measured ratio of D-D fusion-energy release relative to heating-power input is plotted as a function of heating power. The JET H-mode and L-mode points are from Bickerton et al. (1988) and Gibson (1988). Improvements in TFTR neutron-source calibration have raised the supershot point relative to the value reported by Bell et al. (1988), and have narrowed the range of uncertainty. For TFTR the projected Q-value in D-T operation, Q_{D-T} , is about 300 times larger than Q_{D-D} . (For JET, the proposed multiplier is about 400.)

Fig. 1

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Fig. 3

Fig. 4

Fig. 6

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Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

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Fig. 12

Fig. 13

Fig. 14

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Fig. 15

Fig. 17

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