REVIEW ARTICLES

Fusion plasma experiments on TFTR: A 20 year retrospective*

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The Tokamak Fusion Test Reactor (TFTR) (R. J. Hawryluk, to be published in Rev. Mod. Phys.) experiments on high-temperature plasmas, that culminated in the study of deuterium–tritium D–T plasmas containing significant populations of energetic alpha particles, spanned over two decades from conception to completion. During the design of TFTR, the key physics issues were magnetohydrodynamic (MHD) equilibrium and stability, plasma energy transport, impurity effects, and plasma reactivity. Energetic particle physics was given less attention during this phase because, in part, of the necessity to address the issues that would create the conditions for the study of energetic particles and also the lack of diagnostics to study the energetic particles in detail. The worldwide tokamak program including the contributions from TFTR made substantial progress during the past two decades in addressing the fundamental issues affecting the performance of high-temperature plasmas and the behavior of energetic particles. The progress has been the result of the construction of new facilities, which enabled the production of high-temperature well-confined plasmas, development of sophisticated diagnostic techniques to study both the background plasma and the resulting energetic fusion products, and computational techniques to both interpret the experimental results and to predict the outcome of experiments. © *1998 American Institute of Physics.* [S1070-664X(98)92905-6]

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I. INTRODUCTION

The design of the Tokamak Fusion Test Reactor (TFTR),[1] which began in 1974, was based on encouraging experimental results from relatively small devices and an evolving theoretical framework for the underlying physics. The conceptual design of TFTR,[2] papers in the Proceedings of the 5th and 6th Conferences on Plasma Physics and Controlled Fusion Research, and the publication of the report WASH-1295[3] provide insight into both the state-of-the-art and the underlying understanding at that time. In reviewing the experiments on TFTR, we observe a dynamic interplay between technology required to create and heat the plasma, including the sophisticated instrumentation to diagnose the plasma, and experiments to both expand the operating boundaries and to study the underlying physics and theory to predict the outcome of experiments. This interplay between technology, experiment, and theory has been critical in developing the understanding required to advance fusion science and technology. The original project objectives for TFTR in 1976 were the following: ''(1) to demonstrate fusion energy production from the burning, on a pulsed basis, of deuterium and tritium in a magnetically confined toroidal plasma system; (2) to study the plasma physics of large tokamaks; and (3) to gain experience in the solution of engineering problems associated with large fusion systems that approach the size of planned experimental power reactors.''

A unique aspect of the TFTR and Joint European Torus (JET)[4] experimental program has been the use of deuterium–tritium (D–T) fuel. The original motivation for the use of tritium was to demonstrate significant fusion energy production. Until the operation of the present generation of large tokamaks, the plasma parameters that determine the reaction rate and the concentration of fusion products were not adequate to warrant using tritium fuel, with its consequent increase in machine activation from the increased plasma reactivity. However, experiments on TFTR and JET[5] have produced conditions in which the fusion energy per pulse is significant, and the fusion power density and the resulting population of energetic alpha particles are comparable to a reactor. Thus, the study of D–T plasmas enables the study of critical physics issues associated not only with D–T fuel, but also with alpha-particle physics.

With the completion of experiments on TFTR in April 1997, a review of what was accomplished and, more importantly, how our understanding has evolved, is timely. However, in discussing the results from TFTR, it is important to note that this work was an integral part of the worldwide effort on tokamak research and both contributed to and benefited from this effort. In this short paper we will not attempt to review all of the important work that has been done on tokamaks and we will not even be able to review all of the contributions from TFTR. A review of results from the D–T experiment on TFTR during the period from December 1993 to December 1996 was recently performed by Hawryluk.[1] This paper will highlight the evolution of our understanding through the results from TFTR. The paper will begin with a brief description of the TFTR device, followed by a discussion of transport, MHD stability, fusion power production, and alpha-physics studies.

TABLE I. TFTR engineering parameters.

	TFTR
Plasma major radius, R	2.6 m
Plasma minor radius (horizontal), a	0.9 m
Plasma elongation ratio, κ	1.0
Toroidal magnetic field ($R=2.48$ m), B_t	6.0 T
Plasma current, I_p	3.0 MA
Neutral beam power, P_b	40 MW
ICRF power, P_{ICRF}	11 MW

II. TFTR DEVICE

During the design of TFTR, one of the outstanding issues was the choice of limiter material used to protect the vacuum vessel. Results from the Princeton Large Torus[6] (PLT) with a tungsten limiter had demonstrated substantial concentration of tungsten, resulting in radiative collapse of the core. Simulations of TFTR discharges indicated that the duration of the high confinement phase would be limited by the influx of metallic impurities. Subsequent experiments with graphite limiters on PLT showed acceptable power handling characteristics and impurity influxes, and graphite was incorporated in the TFTR design. The nearly circular TFTR plasma is limited by a limiter on the inboard (high-field) side composed of graphite and carbon–fiber composite (CFC) tiles mounted on a water-cooled inconel backing plate. Carbon–carbon composite tiles were used due to the preferential power handling. A set of poloidal ring limiters composed of carbon fiber composite tiles is used to protect RF launchers on the outboard side that are used to heat the plasma. The limiter can withstand heat outflow from the plasmas of ~30 MW for 1 s. With the configuration shown, metallic influxes from the walls did not contribute significantly to the power balance or the value of Z_{eff}. The influx of carbon in high-performance discharges was the dominant impurity and resulted in Z_{eff} values of ~2. The principal engineering parameters for TFTR are given in Table I.

Heating by both neutral beam injection (NBI) and by waves in the ion cyclotron range of frequencies (ICRF) were used on TFTR. The development of high-power neutral beams was a major technological undertaking. The maximum injected power into a tokamak in 1976 was a few hundreds of kW though 4.8 MW was injected into a mirror machine.[7] The TFTR neutral beam system eventually deployed was composed of four beamlines, each with three positive-ion sources. The ion sources operated either in deuterium or in tritium. The maximum operating voltage was 120 kV and a maximum injected power into a D–T discharge was 40 MW. In addition to heating the discharge, the neutral beams are an effective means of fueling the discharge. On TFTR, this fueling has been varied from all deuterium to all tritium.

The TFTR ICRF system used four antennas to launch magnetosonic waves. Hydrogen and ^{3}He minority, second harmonic tritium, and second harmonic deuterium heating were studied. In addition, fast wave conversion into Ion Bernstein waves was used to heat and drive currents in multiple ion species plasmas. During the final experiments on TFTR, a fast wave antenna was replaced with an antenna designed to launch an Ion Bernstein wave.[8]

The ability to operate reliably a large tokamak device in D–T was a major issue during the design of TFTR. TFTR met and in many cases (B_t, P_{NB}, I_p) exceeded the original design objectives. Despite the complications introduced by D–T operation, TFTR operated routinely and reliably from the start of D–T operations in November 1993 to the completion of experiments in April 1997. Over 23 000 high-power pulses were made during this period, including 1090 D–T shots. Tritium was used in both the neutral beam and gas injection valves to fuel the plasma. A low inventory tritium purification system was installed and operated in the final phases of the D–T campaign to decrease the shipments of tritium to the facility. More than 0.95 MCi of tritium was processed by the tritium system.

The development of sophisticated diagnostics to measure the plasma profiles, fluctuations, and energetic particles was a critical element in the research program on TFTR. Most of the diagnostic techniques either did not exist or had to be substantially modified to operate in a high radiation environment with a limited number of D–T discharges. The extensive diagnostic development effort required to study new physics continued throughout the history of TFTR.

III. TRANSPORT

Prior to the design of TFTR, two important transport concepts were identified. First, classical transport due to Coulomb collisions had been generalized to a toroidal axisymmetric geometry (neoclassical transport).[9] Second, turbulent transport due to electrostatic or electromagnetic instabilities had been invoked to describe the observed experimental transport, which was much larger than predicted by neoclassical transport. Linear growth rates were calculated for many instabilities in the 1960s–1970s, and analytic estimates of turbulence levels were developed in the 1970s. The original predictions for TFTR performance were based on a multiregime model of electrostatic instabilities. These models were not well benchmarked at the time due to the limited diagnostic capability and lack of high-power heating, and were limited due to the treatment of the turbulence level and choice of instabilities analyzed. One of the main purposes of TFTR was to obtain the data to establish the confinement and transport coefficients of a reactor grade plasma. As a result of the limitations of the physics based models in use at that time empirical approaches to predicting performance were widely used. These scalings were based on results from existing smaller devices. The predictions of these models differed considerably. The model used in the design of INTOR[10] (Alcator scaling for the thermal electron diffusivity and ion neoclassical) was very optimistic, while the L mode scaling[11] (based on high-power heating results on smaller devices) was pessimistic for the performance of TFTR. The initial high-power heating experiments on TFTR appeared to confirm the validity and applicability of L-mode (low confinement mode) scaling, in which $\tau_E \propto P_{aux}^{-1/2}$ and increases with I_p (Ref. 12.)

In 1986, Strachan *et al.*[13] demonstrated that by extensively conditioning the limiters to decrease the influx of deuterium and carbon from the limiters, greatly enhanced confinement times could be obtained in limiter discharges. These enhanced confinement discharges were characterized by beam fueling of the plasma core, peaked density profiles, hot ions with $T_i(0)/T_e(0) \sim 2-4$, high edge ion temperature, and strong beam particle fueling. These discharges, commonly referred to as supershots, have been extensively studied on TFTR. Recently, more effective conditioning techniques involving lithium coating of the limiter have been used to further suppress the influx of deuterium and carbon and extend the range of operation.[14] Table II provides a summary of parameters from high-performance deuterium–tritium supershot discharges on TFTR, while a comparison of the profiles of an L mode and supershot is given in Fig. 1.

As shown in Fig. 1, $T_i(0) > T_e(0)$ in supershots due to a combination of intense ion heating by neutral beam injection and favorable transport. This is advantageous for a larger fraction of the stored energy is in the reacting ions, which enhances the plasma reactivity. Furthermore, the favorable transport characteristics of this hot-ion regime motivate the development of techniques that enhance the transfer of alpha heating power to the ions, such as alpha channeling, rather than preferentially to the electrons by classical Coulomb collisions.

In retrospect, the discovery of the supershot operating regime was important for two reasons. The first was that it provided a reliable approach to achieving reactor grade plasmas, which was an essential element in demonstrating fusion energy production. The second was that it demonstrated that the empirical scaling laws had limited applicability and could not be used alone to optimize performance of an existing facility. Thus, the need for exploration and development of an understanding of the underlying physics was even more important.

With the development of increasingly sophisticated and accurate diagnostics, the characterization and understanding of transport proceeded. One of the first studies was made possible by the supershot regime for the value of β_p became large enough that the bootstrap current predicted by neoclassical theory was significant. Zarnstorff *et al.*[15] had concluded that during Ohmic discharges the surface voltage was well described by neoclassical resistivity, although the bootstrap current in these discharges was very small. In the supershot experiments, the change in surface voltage could only be well described by including both the bootstrap current and the beam current, which accounted for most of the plasma current in some supershots.[16] The availability of co- and counterdirected NBI in TFTR was crucial to separating the bootstrap- and beam-driven currents. Neoclassical theory was found to adequately describe parallel transport along the magnetic field.

The problem of cross-field transport proved to be more challenging, however. In TFTR L-mode discharges, the cross-field transport has the following features.[17]

TABLE II. Summary of TFTR experimental parameters achieved in high–performance supershot discharges.

Parameters	Units	68522	76778	80539	83546
Plasma current (I_p)	MA	2.0	2.5	2.7	2.3
Toroidal field (B_t)	T	5.0	5.1	5.6	5.5
NB Power (P_b)	MW	30.8	33.7	39.6	17.4
Tritium NB power	MW	0	20.0	25.5	17.4
Central electron density $[n_e(0)]$	10^{19} m^{-3}	9.6	8.5	10.2	8.5
Central hydrogenic density $n_{\mathrm{HYD}}(0)=[n_{\mathrm{H}}(0)+n_{\mathrm{D}}(0)+n_{\mathrm{T}}(0)]$	10^{19} m^{-3}	6.8	6.3	6.7	6.6
Z_{eff}		2.6	2.2	2.4	2.0
$T_e(0)$	keV	11.7	11.5	13	12.0
$T_i(0)$	keV	29.0	44	36	43
Plasma energy (W_{TOT})	MJ	5.4	6.5	6.9	4.9
dW_{TOT}/dt	MW	2.1	7.5	0	3.0
$\tau_E=W_{\mathrm{TOT}}/(P_{\mathrm{TOT}}-dW/dt)$	s	0.19	0.24	0.18	0.34
$n_{\mathrm{HYD}}(0)T_i(0)\tau_E$	10^{20} m^{-3} keV s	3.9	7.1	4.3	9.6
$n_{\mathrm{HYD}}(0)T_i(0)\tau_E^*$	10^{20} m^{-3} keV s	3.6	5.5	4.2	8.0
Ratio of average T to (D+T) density		0	0.5	0.47	0.58
Maximum fusion power	MW	0.065	9.3	10.7	2.8
β_N		2.1	2.0	1.8	1.5
β_N^*		3.5	3.1	3.0	3.0

(a) The radial transport is governed by turbulent processes such that the electron and ion heat, particle, and momentum transport is much larger than predicted by collisional transport theories.

(b) The degradation of thermal confinement with power, $\tau_E^{\mathrm{th}}\sim P^{-0.7}$, is even stronger than given by the global scaling relationship.

(c) Local transport coefficients [electron heat diffusivity (χ_e), ion heat diffusivity (χ_i), and toroidal momentum diffusivity (χ_ϕ)] increase strongly with power or temperature.

(d) Here $\chi_i\sim\chi_\phi$, as expected from microturbulence theories.

(e) Degradation is not caused by anomalous loss of fast ions. For a comprehensive review of energetic particle losses, see Heidbrink and Sadler.[18]

(f) Perturbative measurements of the electron particle transport indicate an adverse temperature scaling.

(g) Toroidal velocity profile measurements following off-axis neutral beam injection can be modeled without introducing an inward momentum pinch.

(h) Recently, it was observed that the energy confinement time is higher in highly rotating plasmas produced by either co- or counterdirected NBI than in equivalent plasmas with balanced NBI injection, indicating that rotation affects confinement.

Core transport in supershot discharges is substantially reduced compared with L-mode discharges. The global parametric confinement scalings that characterize L-mode discharges do not describe the trends in supershot discharges.[19] In supershots, the confinement time remains approximately constant with both neutral beam heating power and the plasma current, whereas in L- and H-mode discharges the confinement is observed to decrease with power and increase with current. Regressions on the supershot database, as well as dedicated experiments, reveal a strong adverse dependence of confinement upon the influx rates of carbon and deuterium measured spectroscopically.[20] One consequence of an increased influx of carbon and deuterium is to broaden the density profile and reduce the depth of penetration by the neutral beam. Park *et al.*[21] has shown that the energy confinement time is also correlated with central beam fueling.

Local transport studies of supershots indicate that most of the improvement in confinement is associated with the reduction of ion heat conduction[22] and ion particle transport.[23] Figure 2 shows the transport coefficients for a supershot. Though in L-mode discharges, the ion heat conduction is typically much larger than ion heat convection, in the core of supershots the upper bound for the ratio of $Q_i/\Gamma_i T_i$, where Q_i is the total ion heat transport and T_i is the ion particle flux, is only ~1.5 with balanced injection, indicating that conduction is relatively small. In the electron channel, the ratio of $Q_e/\Gamma_e T_e$ is 2. As noted by Zarnstorff *et al.*,[24] this implies that electron heat transport is not consistent with a strong stochastic particle loss and lends support for the contention that the transport is caused by electrostatic turbulence. The transport studies also indicate a very different scaling of χ_i and χ_ϕ with T_i. Meade *et al.*[25] observed that χ_i and χ_ϕ decreased with T_i in the core of supershot discharges.

Measurements of the underlying turbulence have been performed and show the following features: (a) Relatively broad spectrum with a peak at $k_\perp\rho_i\sim 0.2$; (b) $\tilde{T}_i/T_i > \tilde{n}_i/n_i$, indicating that ion dynamics are important.

The results from the transport studies along with the fluctuation measurements suggest a theoretical model for core transport involving electrostatic modes. Since ion dynamics are important, ion-temperature-gradient-driven modes are candidates. In addition, flow shear, which is believed to be important in the formation of a transport barrier at the edge, is predicted to suppress turbulence. Furthermore, the electrostatic turbulence calculation indicates that transport could be affected by the current profile. Each of these mechanisms has been explored and will be discussed below.

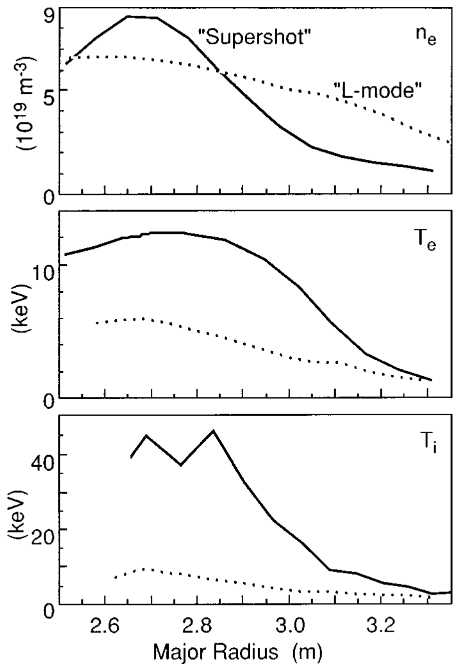

FIG. 1. Radial profiles of the electron density and electron and ion temperature for TFTR pulse number 83546, a high-performance supershot, is contrasted with a comparable L-mode discharge with similar plasma current and heating power.

Progress has been made in the understanding of the transport process in the core of L-mode discharges. Kotschenreuther *et al.*[26] utilizing gyrokinetic linear and gyrofluid nonlinear simulations of the plasma turbulence, reproduced the observed (L-mode) variation of the confinement time and the ion and electron temperature profile with plasma current and neutral beam power. The principal transport mechanism in these simulations is low-frequency electrostatic turbulence driven by ion temperature gradients. In the inner half-radius, the ion temperature profile is near marginal stability to the mode responsible for the turbulence.

When applied to supershots, the analysis of Kotschenreuther *et al.*[26] indicates that the reduction in thermal transport is associated with the suppression of ion-temperature-gradient-driven modes due to large values of T_i/T_e, high edge ion temperature, and peaked density profiles. Although quite successful for L-mode plasmas, the model used by Kotschenreuther *et al.*[26] has some important limitations, especially when applied to enhanced confinement regimes. First, the model is not applicable to the edge region (roughly $r/a > 0.85$), and experimental measurements are required to set the boundary conditions. Furthermore, particle transport (and hence the heat transport by convection) has not yet been incorporated into the model. This transport is known to be important in regimes of operation in which the ion-temperature-gradient-driven turbulence is suppressed. Radial electric field shear was neglected, although more recent versions of the model have taken the toroidal velocity component as an approximation to the radial electric field. Radial electric field shear is an especially important mechanism in turbulence suppression and the formation of transport barriers, as discussed below. Despite these caveats, this model

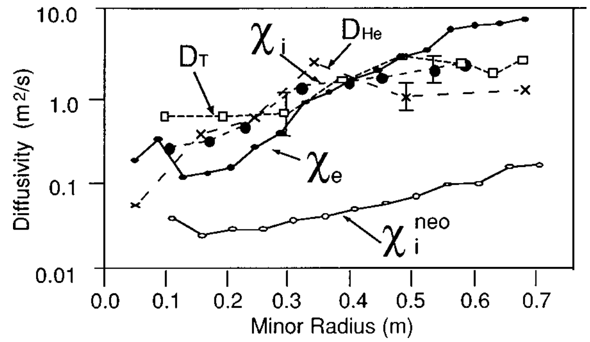

FIG. 2. The thermal (χ_e and χ_i) and particle diffusivity (D_e, D_{He}, and D_T) in a supershot are shown as a function of minor radius; the inferred values are substantially larger than the predicted neoclassical coefficients.

provides a satisfactory description of the performance of L-mode discharges within its domain of applicability, and provides insight into the performance of supershots.

Another approach has been pursued by Kinsey and Bateman[27] using a multimode model in which analytic expressions for the transport associated with various models are used to describe the dependence of plasma energy and particle transport in TFTR, JET, and DIII-D[28] discharges. In this approach, the numerical factor setting the transport level for each model is obtained by fitting the experimental data and evaluating the overall fit to the data. The edge conditions are not taken from experimental data; however, the influx of neutrals from the edge is adjusted to obtain agreement with the measured density. The transport is predicted to be governed by electrostatic drift-wave turbulence and ballooning modes. The agreement between theory and experiment is satisfactory for a broad range of conditions. Further tests of the model employing both a wider range of data, as well as the response to plasma perturbations, are required to evaluate the range of validity of the multimode model.

The scaling of confinement time with isotopic mass is important, not only for projecting the performance of future devices operating in D–T, but also as a test of different transport models. It was immediately apparent in the initial TFTR D–T experiments that the global energy confinement in supershots is significantly better (20%) in D–T plasmas than in comparable D plasmas.[29,30] This favorable result was also evident in high-l_i plasmas, including those with H-mode transitions. Recent D–T experiments in L-mode plasmas[31] on TFTR have shown that the global and thermal plasma energy confinement scale, at least as favorably with an average ion mass as the $\tau_E \propto \langle A_{\mathrm{HYD}} \rangle^{0.5}$ dependence embodied in the ITER-89 L-mode scaling. Most transport theories involving small-scale turbulence scale as gyro-Bohm i.e. $\chi \propto \chi_B \rho^*$, where $\chi_B = cT/eB$, $\rho^* \equiv \rho/a$, and ρ is the ion Larmor radius, and would therefore predict an unfavorable scaling with ion mass, in disagreement with the TFTR observations and many other previous experiments conducted in hydrogen and deuterium.[32]

As in the case of H-mode transport barrier formation, another mechanism that can be important in both L-mode and supershot discharges is electric field shear stabilization of the turbulence.[33] Bush *et al.*[34] observed a correlation between lithium conditioning of the limiter and the development of steep ion temperatures and toroidal velocity gradients. Ernst[35] has shown that the favorable ion thermal confinement trends of supershot discharges can be reproduced by self-consistently including the effects of a neoclassical radial electric field, using the linear parts of the model of Kotschenreuther *et al.*[26] to describe the stability of ion-temperature-gradient-driven modes. A careful analysis of a large number of high-power supershot experiments indicates (Fig. 3) that by including flow shear stabilization in this way, it is possible to reproduce the dependence of χ_i on heating power, recycling, density peakedness, toroidal rotation, and isotopic mass. Fully nonlinear simulations for the same set of discharges are confirming. Furthermore, Scott *et al.*[31] have shown that the model of shear flow modification to the ion-temperature-gradient turbulence reproduces the observed isotopic effect in L-mode plasma. The experimental observation that optimal global confinement in supershots is obtained with slightly codominated injection is another hint that the radial electric field affects confinement. A more direct experiment has recently been performed, which indicates that in L-mode discharges there is a dependence of confinement time on the direction of beam injection. This is another indication that flow shear is important, and raises the question of the range of validity of empirical scaling relations that do not take into account the externally induced flow shear in the plasma.

Experimental work on a number of devices indicated the reduction of core transport that was possibly associated with the formation of regions of reversed shear. These initial experimental observations were further encouraged by the theoretical work of Kessel *et al.*,[36] who predicted that plasma transport could be reduced in discharges with reversed magnetic shear. The recent development of operational techniques to reliably create this magnetic configuration, coupled with new diagnostics to measure the pitch of the magnetic field on TFTR,[37] DIII-D,[38] and JT-60U,[39,40] have resulted in rapid progress and exciting new results.

To create a reverse magnetic shear configuration, the plasma is typically started at full size, and the current is ramped up rapidly. Since the current diffusion time is slower than the rise time of the total plasma current, the current density profile, $j(r)$, is hollow during and for some time after the ramp.

The confinement characteristics of reverse shear shots on TFTR in the main heating phase resemble supershots with the same machine parameters. In particular, the global confinement time is enhanced relative to L-mode scaling and convection is important in the core power balance. However, above a power threshold (which depends on machine conditioning and the q profile) the core transport changes abruptly at 0.2–0.3 s into the main heating phase within the region of reversed shear. In TFTR discharges, the effect is most clearly seen on the central density evolution that can rise by more than a factor of 2 in 0.3 s. Since the density outside the reversed shear region changes little, the density profile following the transition became very peaked, reaching values of $n_e(0)/\langle n_e\rangle \sim 5$. This state of improved confinement in the core of reverse shear plasmas is known as enhanced reverse shear (ERS) in TFTR.

At the transition, the inferred electron particle diffusivity in the region of the steepest gradient drops by a factor of 10–50 to near-neoclassical levels, while the ion thermal diffusivity falls to levels well below predictions from conventional neoclassical theory.[37] Similar improvements in the ion momentum diffusivity have also been observed. The region of steepest pressure gradients and where the transport coefficients drop is where a transport barrier is assumed to form. However, relatively small changes are observed in the electron heat conductivity on TFTR. Similar behavior of the transport coefficients in reverse shear plasmas is seen on DIII-D as well, but JT-60U,[40] Tore Supra,[41,42] and DIII-D in rf heated plasmas[43] have reported significant decreases in χ_e. Possible explanations for the apparent subneoclassical ion thermal diffusivity are the violation of the assumptions of standard neoclassical theory, the presence of anomalous electron–ion coupling, or a thermal pinch. Recent calculations by Lin *et al.*[44] indicate that a more comprehensive analysis of neoclassical transport, which considers orbit dimensions comparable with pressure scale lengths, is in better agreement with the data in the enhanced confinement regime. Inasmuch as neoclassical transport is usually thought to be the minimum transport possible, these results represent a dramatic improvement in confinement.

Theories developed to explain the edge transport barrier formation in H-mode discharges are being investigated to assess their relevance and applicability to the formation of the internal transport barrier in ERS discharges.[33,45,46] In TFTR, the inferred shear in the radial electric field increases in the region of the transport barrier after the transitions. This growth in the shear is driven by the increasing pressure gradient in TFTR discharges, though in experiments with unidirectional beam injection such as DIII-D, toroidal velocity gradients appear to be important. A model for enhanced core confinement is being investigated.[46] The model's central features are positive feedback between increased pressure gradients, the accompanying growth in electric field shear, and subsequent turbulence decorrelation and confinement improvement. In addition, the gradients in the shift of the center of the magnetic flux surfaces with a minor radius (Shafranov shift) of reverse shear plasmas lead to favorable drift precession of trapped electrons and subsequent reduction of turbulence-induced flows.[47] The ERS transition has been correlated with the suppression of turbulence by the $\mathbf{E}\times\mathbf{B}$ shear flow; that is when the shearing rate $\gamma_s \equiv |(RB_p/B)d/dr(E_r/RB_p)|$ exceeds the plasma turbulence decorrelation rate, which is estimated to be about the linear growth rate of the mode responsible for the turbulence. After the ERS transition, the fluctuation level in the core is dramatically suppressed according to reflectometer measurements.[48] Experiments on TFTR indicate that $\mathbf{E}\times\mathbf{B}$ shear is necessary to achieve an internal barrier and that the gradient in the Shafranov shift is not sufficient to maintain the barrier.[49] In the final series of experiments on TFTR, a recently developed poloidal rotation diagnostic was used. These experiments showed that in most discharges studied that undergo a transition prior to the formation of an internal

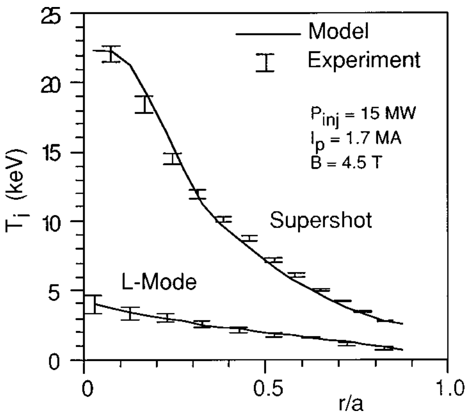

FIG. 3. A comparison of the observed and simulated ion temperatures for an L mode plasma, using the gyrofluid model proposed by Kotschenreuther *et al.*,[26] and a supershot plasma with similar machine parameters, using the extended model of Ernst[34] with self-consistent shear-flow stabilization.

transport barrier a highly localized and transient excursion in the poloidal flow velocity occurred. The induced flow is much larger than predicted by neoclassical theory. The role of this excursion in the dynamics of the barrier formation is under investigation.

Though the agreement between theory and experiment is promising, the present models do not adequately describe the dependence of the power threshold on the toroidal field and neutral beam-induced rotation. Also, it is unclear whether the higher-power threshold for ERS discharges in T vs D can be readily reconciled with simple $\mathbf{E}\times\mathbf{B}$ mechanisms.[31] Another topic requiring further investigation is the apparent decoupling of the electron and ion heat diffusivity, perhaps suggesting that more than one mechanism is important in core transport. Despite the need for additional experimental and theoretical work, the emerging physics models of electrostatic turbulence and its stabilization by flow shear are providing a valuable tool to describe the underlying physics and motivate new experiments to suppress turbulence.

One approach investigated during the final experiments on TFTR was to induce flow shear by the application of ion Bernstein waves. This technique had been used on Princeton Beta Experiment-Modified[50] (PBX-M) by Ono[51] to generate an internal transport barrier. However, in those experiments measurements of the induced flow velocities were not available. On TFTR, the poloidal flow measurements demonstrated that ion Bernstein waves can induce poloidal flow; however, with the limited available time insufficient power was coupled to the core to evaluate whether suppression of transport can be achieved.

IV. MHD STABILITY

During the design of TFTR, the present sophisticated tools for magnetohydrodynamic (MHD) equilibrium and stability analysis were under development. The approximate pressure limit for a tokamak was believed to be given by $\beta_p \sim R/a$, which corresponds approximately to when the inboard separatrix entered the vacuum vessel. The experimental and theoretical work at this time focused on sawteeth and resistive tearing modes. Prior to the operation of TFTR, the initial results from smaller devices demonstrated the existence of plasma pressure limits significantly below $\beta_p \sim R/a$ (Ref. 52). In parallel, two-dimensional MHD codes were developed and used to predict for the ''optimized'' pressure and current profile, the ideal MHD stability limits. Troyon *et al.*[53] and Sykes *et al.*[54] characterized their results in terms of the parameter $\beta_N \equiv \beta_T/(I_p/aB_T)$. Troyon *et al.*[53] showed that the pressure limit associated with low-n kink modes corresponds to $\beta_N < 2.8$, whereas Sykes [54] showed that for ballooning modes $\beta_N < 4.4$. The predictions of ideal MHD have important ramifications, for they imply that for a given facility with sufficient auxiliary heating and plasma confinement, the maximum fusion power is limited by the available plasma current and toroidal field (motivating efforts to ensure operation at and above design levels). An implicit consequence for present auxiliary heated experiments is that, since the total pressure governs stability and only the ion pressure contributes to fusion reactivity, operation in regimes in which $\beta_i > \beta_e$ increases fusion power performance. This motivates operation in the hot ion regime.

In high-performance supershot discharges, the sawtooth instability is typically stabilized, even when the central safety factor, $q(0)$, is less than unity. Levinton *et al.*[55] showed that when the pressure and density profiles are sufficiently peaked compared with the shear in the q profile, stabilization occurs, as predicted by a two-fluid MHD model. The stabilization of sawteeth has both practical as well as theoretical implications. Since the competing effects of the redistribution of particles and energy by the sawteeth are not present in high-performance discharges, this has facilitated transport studies and the identification of alpha heating. Theoretically, the observation of $q(0) < 1$ has significant consequences for the predicted pressure limits, as will be discussed below.

Experimentally, there are significant limitations to the range of pressure and current profile that can be produced while achieving good confinement and the control of the evolution of these profiles. Ideal MHD theory predicts that β_N depends on the peaking of the plasma and current profile for discharges with monatomic q profiles and $q(0) \geqslant 1$. As noted earlier, the supershot regime is characterized by peaked density and pressure profiles. The discharge with the highest confinement (~0.3 s) was achieved by means of extensive wall conditioning and Li deposition to control the influx of deuterium and carbon into the discharge. This discharge disrupted at a relatively low value of $\beta_N = 1.5$, whereas the highest fusion power discharge with broader pressure profiles achieved $\beta_N = 1.8$. Ideal MHD theory predicts that the maximum value of β_N would decrease with pressure profile peakedness as qualitatively observed and shown in Fig. 4. However, the parameter $\beta_N^* = [\langle\langle p\rangle\rangle/(I_p/aB_t)$, where $\langle\langle p\rangle\rangle = (\int p^2 dV/\int dV)^{0.5}]$, which is more relevant for fusion power production, is predicted to be a weaker function of the pressure profile peaking for circular cross-section tokamaks such as TFTR. The ideal MHD theory predicts that the stability limit should increase with the peaking of the current profile, or alternatively, the internal inductance. This has been successfully demonstrated by ramping the current down or by modifying the plasma initiation to peak the current profile. By means of current rampdown, $\epsilon\beta_p<1.6$ has been achieved with a separatrix inside the vessel and $\beta_N<4.7$ has been achieved.[56] These results demonstrate that ideal MHD calculations provide insight into approaches to optimize the performance of the machine. Quantitatively, there is one outstanding issue. In many TFTR discharges, $q(0)<1$. For such profiles the codes predict a vigorous internal $n=1$, $m=1$ mode that is not observed. Instead, this mode is stable or saturated at a low level. To obtain agreement with experiment, the codes assume $q(0)\geqslant1$; however, a comprehensive treatment of this mode is still needed.

The above considerations give an overview of the important considerations regarding the pressure limits on TFTR. However, detailed measurements and a comparison with theoretical work provide greater insight into the underlying dynamics. Two different mechanisms appear to be responsible for the β limit in supershot discharges on TFTR: neoclassical tearing modes and intermediate-n ballooning instabilities coupled to a lower-n kink mode. The MHD resistive tearing mode theory was extended to the long mean-free-path regime by the inclusion of neoclassical effects. The onset of tearing modes[57] was found to degrade the confinement, the plasma stored energy, and the neutron emission in the discharges, but did not typically result in an abrupt termination of the discharge. These modes appear spontaneously, have low frequencies (<50 kHz), and low poloidal and toroidal wave numbers $m/n=3/2$, 4/3, and 5/4. In contrast with the results on smaller devices, the 2/1 mode is rarely observed, but if it occurs it is particularly detrimental to confinement. The nonlinear evolution of these modes agrees well with the predictions of neoclassical pressure-gradient-driven tearing mode theory. The predicted evolution of the island width is found to be in reasonable agreement with measurements. Though the present theory predicts several important trends in the data, it does not predict a threshold island width, and therefore, which modes should grow and when.

In discharges on TFTR with a high toroidal field and plasma current, the neoclassical tearing modes were not the most important limitation. In these discharges, the maximum stored plasma energy was limited by the onset of a rapidly growing intermediate-n ballooning instability ($n=10$–20) coupled to a low-n ideal kink mode.[58,59] The distortions to the plasma caused by the large low-n ideal mode appear to push the plasma over the ballooning mode stability boundary. The ballooning-mode precursor to the disruption was discovered using two grating polychromators separated toroidally by 126° to measure the electron temperature. From these measurements, it is possible to deduce that the ballooning mode is both toroidally and poloidally localized on the outboard midplane. Park *et al.*,[60] using a three-dimensional nonlinear MHD code, successfully modeled the observed electron temperature fluctuations. In this simulation, a saturated low-n mode is assumed to be present. These simulations indicate that the high-n mode becomes even more localized, producing a strong pressure bulge that destroys the flux surfaces, resulting in a thermal quench. This instability limits the maximum fusion power achieved in supershots on TFTR, and can result in a plasma disruption.

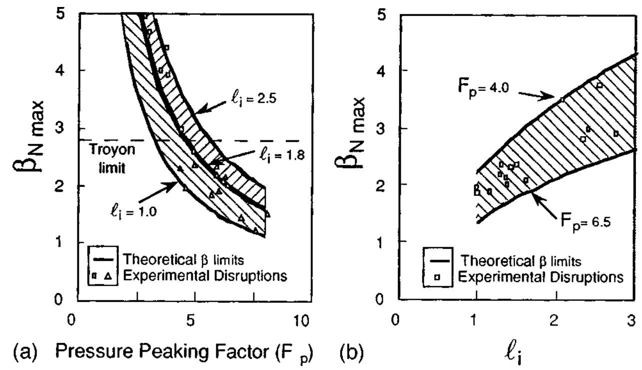

FIG. 4. (a) The value of β_n for disruptive discharges versus pressure profile peakedness $[F_p=p(0)/\langle p\rangle]$ is shown constrained by the value of l_i. The theoretical curves are based on ideal MHD calculations. (b) The value of β_n vs l_i, including the theoretical curves. The value of the pressure profile peakedness is constrained for the data shown.

The stability of reverse shear discharge provides both a valuable test bed for checking our understanding of MHD stability, as well as having the potential for increased performance.[36] In the region of reversed shear, MHD activity is absent in ERS discharges, as measured by the four-channel reflectometer, suggesting that, as predicted by theory, reversed shear plasmas may indeed have greater local MHD stability. The local pressure gradient in flux coordinates in enhanced reversed shear discharges on TFTR is larger, by a factor of 3–5, than in typical supershots with monotonic q profiles, which very often have low-n MHD modes in the core. However, as the transport barrier moves into the weak or positive shear region, and as the radius of the minimum value of q ($r_{\min}$) moves to the core region, a rapidly growing MHD instability is observed. The maximum pressure appears to be limited in this region by the ideal infernal mode. A comparison of the structure of the observed and calculated mode is in good agreement, and the threshold is in reasonable agreement.[61]

The MHD stability is governed by the evolution of the current profile and the development of an internal transport barrier with sharp pressure gradients. The implications of the TFTR experiments are that, to take advantage of the promise of the reverse shear regime, the development of efficient techniques to control the current and pressure profile are required. In a reactor in which self-heating and local transport coefficients will determine the pressure profile, it may be necessary to develop techniques to control transport or transport barrier formation to obtain good MHD stability.

V. FUSION POWER PRODUCTION

The achievement of good confinement and high pressure were prerequisites for proceeding with deuterium–tritium experiments to study alpha-particle physics and demonstrate fusion power production.[29,62] The discharge with the highest fusion power on TFTR is shown in Fig. 5. The decrease in fusion power is triggered by MHD instabilities (a minor disruption) followed by a carbon bloom (a sudden influx of carbon into the plasma from the limiter). The total fusion yield from a single plasma pulse on TFTR has reached 7.6

MJ. The achievement of 7.6 MJ satisfied the original TFTR objective of producing 1–10 MJ of fusion energy. During the design of TFTR, projections of performance indicated that fusion power densities of ~ 1 MW m^{-3} could be achieved in the center of TFTR with values of $P_{\text{fusion}}/P_{\text{aux}} \sim 1$. Fusion power densities of up to 2.8 MW m^{-3} achieved at the center of high-performance TFTR supershots are comparable to or greater than those expected in the International Thermonuclear Experimental Reactor (ITER), and exceed the original expectations.[63] The value of $P_{\text{fus}}/P_{\text{aux}}$ reached 0.27 in TFTR, which was less than some of the more optimistic projections performed during the design phase.

Dawson, Furth, and Tenney[64] showed that it would be possible to increase the plasma reactivity by neutral beam injection due to beam–thermal and beam–beam reactions. This concept was explicitly taken into account during the design of TFTR. Simulations of the neutron production on TFTR have been performed using the TRANSP data analysis code.[65] This code uses the measured electron density and temperature profiles, ion temperature profile, and visible bremsstrahlung measurements, in conjunction with other diagnostic and engineering data, such as the beam heating power and source divergence, to calculate the neutron source rate from thermal, beam–thermal, and beam–beam reactions. Monte Carlo techniques are used to compute the deposition of the neutral beams, and the distribution of the beam ions and fusion ions, such as alpha particles. The beam ions and fusion products are assumed to slow down classically. The ratio of thermal reactions to those from beam–thermal and beam–beam reactions depends upon the density, electron temperature, and beam parameters. The overall agreement for both the time dependence of the D–T neutron emission and the neutron emissivity profile is well described by the TRANSP code for TFTR supershot discharges. Bell *et al.*[66] noted, however, that, despite the reasonable agreement in D–T discharges, there appears to be a small but consistent difference in the TFTR results for similar D-only plasmas. The TRANSP code predicts the neutron emission in deuterium discharges to be lower than the measured values by approximately 20%. The cause for this relatively small discrepancy is not understood. Though the agreement is good in supershot discharges, detailed comparisons of the predicted neutron emission with experiment remain to be performed for the reverse shear discharges. Initial results indicate a discrepancy between the TRANSP prediction and actual measurements that may be due, in part, to stochastic ripple diffusion, though other mechanisms cannot be excluded at this time.

VI. ALPHA-PARTICLE PHYSICS

The behavior of alpha particles from D–T reactions is a fundamental consideration for the performance of a future D–T reactor. If a significant fraction of the alpha particles is not confined, then the $nT\tau$ requirements for ignition will increase; however, the confinement of the resultant alpha ash must be sufficiently short to avoid quenching the reaction. Also, if a small unanticipated fraction (a few percent) of the alpha particles is lost in a reactor such as ITER and the resulting heat flux is localized, damage to first-wall components could result. In addition, the study of energetic particle physics in a tokamak is scientifically interesting in itself.

The alpha-particle confinement experiments on TFTR have been reviewed by Zweben *et al.*[67] and by Hawryluk,[1] and will be briefly summarized in this section. These results will be discussed in terms of the conventional description of alpha particles typically used in calculating the performance of new devices. In the conventional approach, the confinement of alpha particles is described in terms of three mechanisms: neoclassical processes (single-particle orbit effects); the transfer of power by Coulomb collisions; and the enhanced transport of the alpha ash from the core by a turbulent processer. Since the transport of the background plasma is typically more rapid than predicted by neoclassical theory, it is appropriate to reexamine the recent results with respect to our conventional understanding.

Measurements of the confined alpha particles, using the charge exchange recombination measurements as shown in Fig. 6, as well as the loss measurements, indicate that in MHD quiescent discharges the radial diffusion coefficient for alpha particles is indeed very small, and up to ten times smaller than that of the thermal ions.[68] A possible explanation is that ''orbit averaging'' effects, which occur when the ion banana width is large compared to the turbulence correlation length, reduce the effect of the underlying background turbulence.[69] The size of the reduction in alpha transport in larger devices may depend on the scaling of the size of the turbulence correlation length with machine size. The good confinement of beam ions in present machines[18] with smaller orbits than those of fusion products supports the hypothesis that the alpha particles should be well confined in larger devices.

As predicted by Monte Carlo calculations, first orbit losses are indeed quite small ($\approx$3%) at high current in TFTR, and should not be important in larger devices. However, the implications of the observation of partially thermalized alpha-particle loss reported by Herrmann *et al.*[70] is not well understood. Measurements of the confined alpha particles, as well as loss measurements, indicate the presence of stochastic ripple diffusion, which is predicted to be larger than first orbit losses. Difficulties in the interpretation of the loss measurements have not, as yet, made possible a quantitative comparison between theory and experiment and highlight the need for further computational improvements to calculate the loss in realistic geometries.

The good agreement between the measured alpha-particle energy spectrum and theory indicates that the transfer of power is well described by Coulomb collisions and orbit effects.[68,71] These results are also consistent with the observations of beam-ion thermalization on TFTR in D and D–T plasmas, as well as many other devices.[18] It should be noted that such measurements only sample a small fraction of the alpha distribution function. As will be discussed below, alpha-particle heating is small in TFTR plasmas, and cannot be used to obtain an accurate assessment of the power transferred from the alpha particles.

Another confirmation of the conventional model is the He ash experiment. The modeled helium ash time evolution indicates that the alpha-particle slowing-down calculations

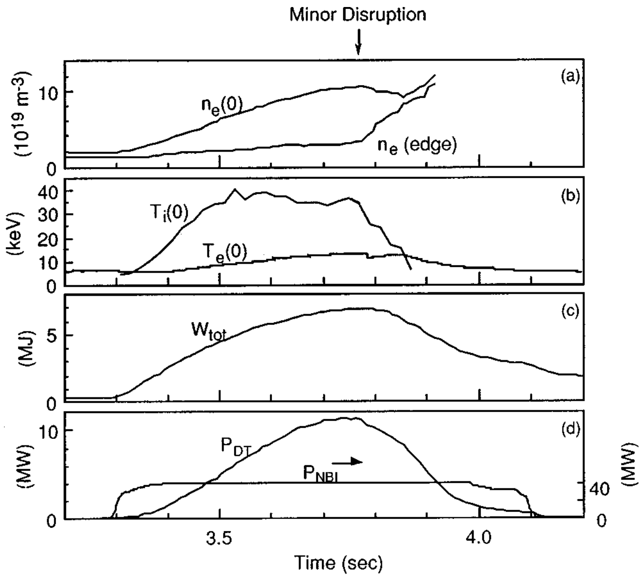

FIG. 5. Evolution of the central electron density, ion temperature, electron temperature, stored energy, and fusion power for TFTR Shot No. 80539.

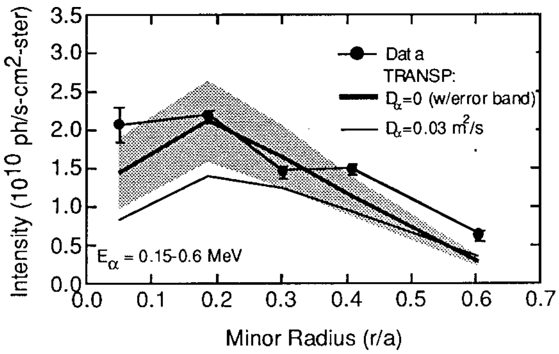

FIG. 6. Absolute intensity measurement of the charge exchange recombination signal for low-energy alpha particle $E_\alpha = 0.15-0.6$ MeV as a function of the minor radius are in good agreement with TRANSP calculations indicating good radial confinement.

and transport assumptions in supershot discharges for the ash are consistent with measurements. The best agreement between the modeling and measurements is obtained using the measured radial particle transport and wall recycling coefficients for the thermal He. When the slowing-down rate is varied by a factor of 2, the data falls within the predicted evolution of the ash density. The time behavior is inconsistent with large anomalous energetic alpha particle loss.[72] The data do not exclude the possibility of modest (20%–30%) losses, due, for example, to unobserved MHD.

In the highest-performance D–T discharges produced on TFTR, the alpha-particle heating is a relatively small fraction of the total power heating the plasma, making its detection difficult. Nevertheless, the electron temperature rise in TFTR D–T shots during beam injection is greater than in D-only or T-only shots.[29,73,74] Recent analysis indicates that the change in electron temperature requires including both alpha heating and isotope effects.[74] When the database is constrained to take into account the change in electron temperature associated with confinement, the residual change has been determined to be in reasonable agreement with the predicted alpha heating. Further experiments with a higher ratio of alpha heating to beam heating power will be required to evaluate the efficiency of alpha heating.

MHD activity is found to affect the confinement of alpha particles. For example, sawteeth can radially redistribute the alpha particle. Substantial loss (up to 20%) to the walls occurs during disruptions. Enhanced loss has been observed during the occurrence of neoclassical tearing modes and kinetic ballooning modes. Most of the MHD- and rf-induced alpha-particle loss on TFTR occurs at the passing–trapped particle boundary, at which point alpha particles in the core of TFTR can go onto loss orbits. This effect should be smaller in future larger devices such as ITER, with a smaller first-orbit loss region; however, the analogous ripple loss region could be sensitive to the wave-induced internal diffusion of alpha particles.[67]

Energetic particles such as alphas can also destabilize (or in some cases stabilize) MHD modes. A comprehensive review of this work in H and D discharges has been given by Heidbrink and Sadler.[18] This is a potentially important topic because of the coupling between alpha heating and MHD stability in a reactor, as well as the loss of alpha particles to first wall components caused by the induced collective instabilities. In this paper, the effect of alpha particles on the stability of toroidal Alfvén eigenmodes (TAE) will be discussed.

Toroidal Alfvén eigenmodes have been shown to exist with discrete frequencies located inside the shear Alfvén continuum gaps created due to toroidal coupling of different poloidal harmonics. These modes were predicted to be driven unstable by energetic particles through wave–particle resonances by tapping the free energy associated with the energetic alpha pressure gradient.[75] Since this initial theoretical work, a large theoretical literature has developed that includes additional important effects, both in the analysis of the instability criteria, as well as in the nonlinear saturation mechanisms. Experiments on TFTR and DIII-D have shown that the toroidal Alfvén eigenmode could be destabilized by the energetic ion populations created either by neutral beam injection or ICRF heating.[18] These instabilities can be sufficiently strong to eject a large fraction of the fast particles[76] and damage the first wall.

The initial D–T experiments on TFTR in supershot and L-mode discharges, however, showed no signs of alpha-driven instability in the TAE frequency range, and the alpha-particle loss rate remained a constant fraction of the alpha production rate as the alpha pressure increased, suggesting that deleterious collective alpha instabilities were not being excited. Theory has since shown that, although TFTR achieves levels of the alpha-particle driving terms nearly comparable to those of a reactor, the damping of the mode in TFTR is generally stronger than the alpha-particle drive. Recent theoretical calculations have shown that the predicted alpha-driven TAE threshold is sensitive to the q profile.[77] This is potentially important in advanced tokamak configurations in which the current profile is modified to achieve higher stability. In experiments with weak magnetic shear on TFTR, TAE driven by energetic alpha particles have been

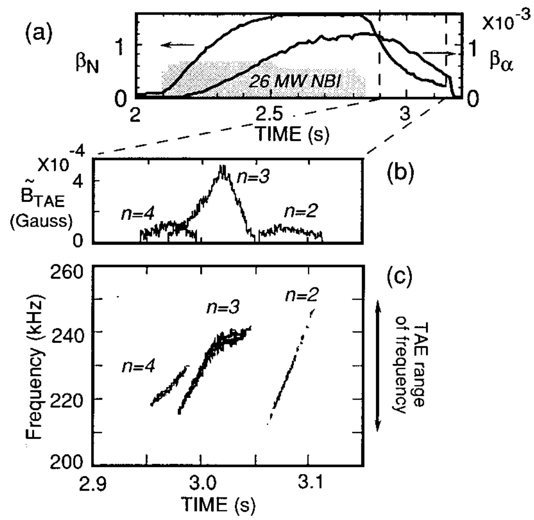

FIG. 7. The alpha-driven TAE mode in TFTR occurring ≈0.1 s after neutral beam injection in a D–T discharge with weak central magnetic shear. (a) The evolution of β_N and β_α. (b) The occurrence of magnetic fluctuations with different toroidal mode numbers is observed. (c) The evolution of the frequency of the magnetic fluctuations is consistent with the density-dependent TAE frequency, and mode timing is in reasonable agreement with the theoretical prediction.[77]

observed in D–T plasmas.[78,79] These modes are observed only after the end of the high-power heating phase, when the beam ion density and plasma pressure are decaying more rapidly than the alpha pressure, as shown in Fig. 7. The fusion power threshold is ~1.0 MW with $\beta_\alpha(0) \sim 10^{-4}$ for $q(0) \simeq 2.4$. This threshold is much lower than the value of $\beta_\alpha(0)$ obtained in high-powered supershot discharges with $q(0) \leqslant 1$ and monotonically increasing q profile, which were observed to be stable. The onset of mode activity is generally consistent with NOVA-K linear stability calculations, though the poloidal mode structure remains to be clarified.[80] The mode amplitude increases with increasing fusion power.

So far, the amplitude of this mode is very small and no loss of alpha particles has been detected. This is consistent with the general arguments presented by White,[80] which indicate that little radial transport would occur due to a weak single mode. Pellet charge exchange measurements do, however, indicate a radial redistribution of the energetic deeply trapped alpha particles. Analysis of these results is in progress. In larger machines, higher values of the mode number can be excited, and overlapping modes may result in stochastic diffusion and perhaps increased transport. These recent experimental results have clarified the threshold criteria for alpha-driven TAE instability; however, further experimental work is required, with larger-amplitude modes and perhaps with overlapping modes, to test the nonlinear saturation mechanisms and alpha transport physics due to these instabilities.

VII. SUMMARY

During the past 20 years, substantial progress has been made in fusion technology, plasma diagnostics, experiments, and theory, which has increased our understanding of the underlying physics, and enabled the study of the physics under conditions similar to that in the core of a reactor. Progress has been made by an increasingly productive dialogue between theory and experiment, both of which have been confronted with and challenged by increasingly sophisticated and accurate measurements.

In the area of transport, the limited applicability of empirical scaling relationships has been demonstrated. Enhanced confinement regimes with and without transport barriers at the edge indicate opportunities for further improvement in performance and have been a critical element in the achievement of reactor-grade plasma on TFTR. Several of the underlying mechanisms associated with transport suppression and transport barrier formation are emerging both theoretically and experimentally. Theoretical predictions are increasingly being used to motivate experiments to improve performance. The resulting experiments benchmark the theory and associated codes. However, further work is needed to establish a quantitative predictive capability. MHD instabilities due to pressure-driven modes were a major consideration in the experimental program. MHD theory was increasingly used to guide experimental design and operation. The observation of a strong interplay between the $n=1$ kink and ballooning modes demonstrates the need for three-dimensional MHD codes to clarify the disruption mechanism. The observation of neoclassical tearing modes has shown the importance of the inclusion of kinetic effects appropriate to the long-mean-free-path regime associated with the core of a tokamak. The development of three-dimensional codes with additional kinetic effects may enable a more detailed study of sawtooth stabilization and the stability of the $m=1$ internal modes, where $q(0)<1$.

For the first time, a comprehensive study of alpha-particle physics was performed. The development of new diagnostics enabled the study of the confined alpha particles in addition to the lost particles. In MHD quiescent discharges, the alpha-particle behavior is consistent with the conventional model of neoclassical target and transfer of energy by Coulomb collisions. The first indications of alpha heating have been made. However, MHD instabilities can and do affect the radial redistribution and loss of alpha particles. Alpha particles have also destabilized the Toroidal Alfvén Eigenomodes in weak shear discharges, which was an important test of energetic particle interaction with MHD waves.

In reviewing the developments on TFTR during the past 20 years, it is clear major progress that has been achieved not only in higher values of $nT\tau$ and fusion power but also in the fundamental understanding of the underlying physics. Nonetheless, many questions remain, as is always the case in an area of active research. Many of these will be answered in existing devices; however, some will only be answered on a burning plasma device operating near ignition.

ACKNOWLEDGMENTS

The work on TFTR is the product of a great team effort by scientists, engineers, and technical staff from PPPL, other national and international Laboratories, Universities, and industries. The work highlighted here is but a short summary of a large body of work, some of it yet to be published. We wish to express our appreciation to all of the men and women who have contributed to TFTR and to R. Davidson, H. Furth, R. Goldston, M. Gottlieb, and D. Grove for their steadfast support and encouragement.

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