TFTR Twenty Year Perspective

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Abstract

Deuterium-tritium plasmas (D-T) with core parameters almost identical to those expected in the core of ignited plasmas in ITER have served as a test bed to carry out the first detailed studies of D-T plasma physics including the first observations of alpha particle heating and alpha driven instabilities. TFTR operated above the original engineering design requirements and with high availability in D-T until experimental operation was terminated due to U.S. fusion budget cutbacks. A most valuable lesson learned was that D-T operation of a large experimental device is feasible as TFTR operation could have continued many more years while remaining within tritium and neutron activation limits. The flexibility and control of plasma parameters (e.g. plasma rotation) and the comprehensive diagnostic system enabled TFTR to make seminal contributions to tokamak plasma science such as first confirmation of the bootstrap current in a tokamak, detailed turbulence studies leading to a new paradigm for transport understanding, first observations of neoclassical tearing modes, and detailed measurements and modeling of plasma disruptions. Recent advances in understanding the fundamental processes controlling plasma transport provide new opportunities for improving tokamak plasma performance. Implementation of recent knowledge could lead to D-T operating regimes with strong alpha heating with modest extensions of the TFTR operating regimes.

I. INTRODUCTION

Twenty years ago energy supply was a national issue in the U. S., Europe, Japan and the Soviet Union. At this same time significant technical progress was being made in nuclear fusion experiments based on the tokamak concept. In mid 1974, a neutral beam driven tokamak to demonstrate fusion energy production was proposed in the U.S. and in 1976 the Tokamak Fusion Test Reactor (TFTR) was approved for construction. The general objective for TFTR and the other large tokamak projects, JET and JT-60, that were approved for construction at that time was to demonstrate the "scientific feasibility" of magnetic fusion. For TFTR this was expressed in terms of the official project objectives [1] given below:

Table I
TFTR Mission (1976)

1. Study plasma physics of large tokamaks
2. Gain experience with reactor scale engineering
3. Demonstrate D-T fusion energy production.
   1 to 10 MJ per pulse

The first objective was to study the plasma physics of large tokamaks at reactor plasma parameters to provide the design information for the next step in the development of tokamak fusion reactors. Equally important was the need to gain experience with reactor scale engineering. TFTR was given a specific objective of demonstrating the production of significant D-T fusion energy on a pulsed basis. The official milestone was to produce between 1 to 10 MJ of D-T fusion energy in a single pulse. Since the pulses were about 1 s long, this corresponded to 1 to 10 MW of fusion power and would result in fusion power densities of ~ 1 MWm^{-3} and power gains of order unity. These objectives were tremendously ambitious given the state of fusion research in the mid 1970s. The results from the 1974 IAEA meeting on Plasma Physics and Controlled Nuclear Fusion are summarized on Fig. 1 where the highest experimental achievements are indicated.

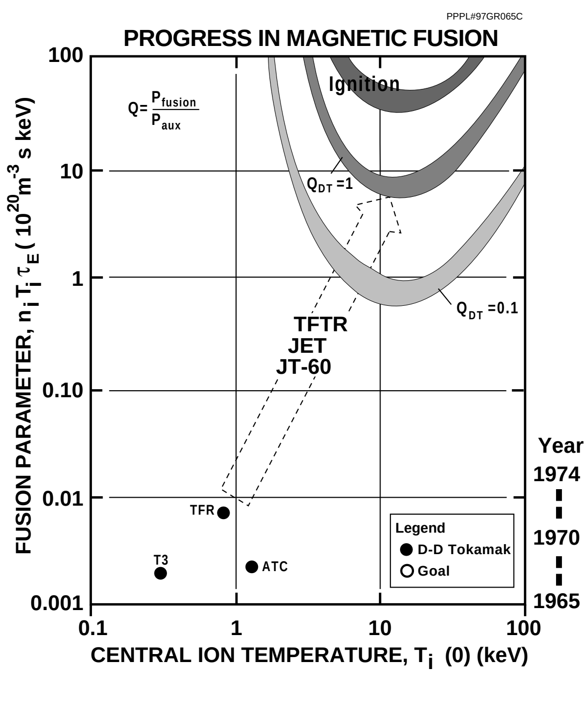

Fig. 1. Status of magnetic fusion in 1974 and goals of the Three Large Tokamaks.

The three large tokamaks (TFTR, JET and JT-60) were to increase T_i by at least a factor of 10 and $n_i T_i \tau_E$ by a factor of 1000 in order to produce plasmas that were sufficiently close to reactor conditions to yield relevant design data.

Table II
Extrapolation of Tokamak Parameters

	1974	TFTR	Increase
Plasma Current (MA)	0.3	3	~10
Toroidal Field (T)	2	5.2	~1
Magnetic Energy (GJ)	0.01	1.5	$\sim 10^2$
Auxiliary Heating (MW)	0.2	30	$\sim 10^2$
Fuel	D	D-T	< 2
T_i (keV)	1	10	~10
Pulse Length (s)	0.01	10	$\sim 10^3$
$nT\tau$ (10^{20} m^{-3}keVs)	0.01	10	$\sim 10^3$
Fusion Power (MW)	0.0000001	10	$\sim 10^8$
Fusion Power Gain	0.0000003	~1	$\sim 10^6$

This required a very large extrapolation beyond the experimental conditions available in 1974 as illustrated in Table II which compares the parameters of the Adiabatic Toroidal Compressor (ATC) as operated in 1974 and the requirements for TFTR. The major scientific issues that needed to be addressed to achieve these goals are given below:

- Confinement Scaling,
- MHD Stability,
- Impurity Control,
- Fusion Power Production, and
- Large scale engineering and operation of D-T devices.

These are the same issues of importance today for the design of the next step magnetic fusion device. Due to space limitations this paper will focus on confinement scaling, fusion power production and large scale engineering.

II. TFTR ENGINEERING EXPERIENCE

TFTR began operation in December 1982 with hydrogen and by July 1983 was operating with deuterium. Tritium was introduced into the plasma in November 1993, and TFTR was operated routinely with tritium for over three years until April 1997. Over 1,090 D-T plasma discharges were produced among a total of 23,500 high power plasma discharges during the D-T phase. Just over 1.5 GJ of fusion energy was produced with peak fusion powers up to 10.7 MW. TFTR produced a maximum of 7.6 MJ per pulse thereby satisfying the original Project Goal for fusion energy production (Table I). The tokamak and neutral beam systems operated reliably above the original design specifications with the toroidal field operating up to 6T (5.2T design) and the maximum beam power up to 40 MW (33 MW design). High availability (>85%) was maintained throughout the D-T phase. During the D-T phase the neutron activation of TFTR came in to equilibrium at ~1.5 mSv/hr which allowed "hands on maintenance" of all systems outside the vacuum vessel. Prior to the last operating run, TFTR had a vacuum opening to replace RF antennas, install new diagnostics and perform maintenance. The radiation exposure to personnel during the D-T phase was comparable to exposure during the preceding deuterium phase. The radioactivity associated with neutron activation of the 304L stainless steel vacuum vessel was not a limit to continued operation of TFTR.

III. TRITIUM HANDLING EXPERIENCE ON TFTR

TFTR had a very flexible tritium injection system in which any of the 12 neutral beam ion sources could be operated with tritium or deuterium and this could be changed between pulses. This capability allowed systematic control of tritium to deuterium ratios and also sheared plasma flows(section VII). The TFTR tritium system was a closed cycle cryogenic distillation system with a throughput of ~0.5 gram of tritium per day. This system had a low tritium inventory of 1.5 g which enhanced the safety features of TFTR. The tritium system for TFTR was continuously improved during operation and operated with high reliability. About 99 g of tritium was processed through TFTR within the 5 g "in process" site limit.

During the three years of D-T operation, there were over 1,000 interventions into the tritium system with no personnel contamination. TFTR operated well below all site annual boundary dose limits(100 mSv) with annual site boundary doses from all sources (airborne, n, γ) < 4 mSv. The low inventory limit, while sometimes challenging operationally, turned out to be an important safety feature and was a key in establishing tritium credibility with the local community.

The 304L stainless steel (now carbon coated) vacuum vessel was baked to 150 °C. The graphite/carbon fiber composite bumper limiter was operated at ambient temperature, and heated to 250°C during discharge cleaning. The cumulative tritium retention was ~35% of the total tritium injected into the vacuum vessel, mainly in co-deposited layers. The administrative limit for releasable tritium inventory in the vessel was <2 g to minimize the effect of potential accidental release scenarios. A total of 4.4 g of tritium was injected into the vacuum vessel. Air purges, glow and pulse discharge cleaning using HeO or D were used to reduce the vacuum vessel tritium inventory. The HeO reduction rate was substantially less than test lab results. Controlled experiments were done to confirm that the releasable tritium inventory was well below the safety limit. The releasable tritium inventory in the TFTR vacuum vessel was controlled and was not a limit to continued TFTR operation.

The TFTR engineering experience demonstrated that large fusion experiments could be designed, built and operated to meet technical and budgetary requirements.

IV. D-T PLASMA OPERATION ON TFTR

The introduction of tritium into the TFTR plasmas allowed the study of fusion plasma dynamics. The evolution of fusion power versus time is shown in Fig 2a for maximum power and in Fig. 2b for cases used to study alpha particle physics under equilibrium conditions.

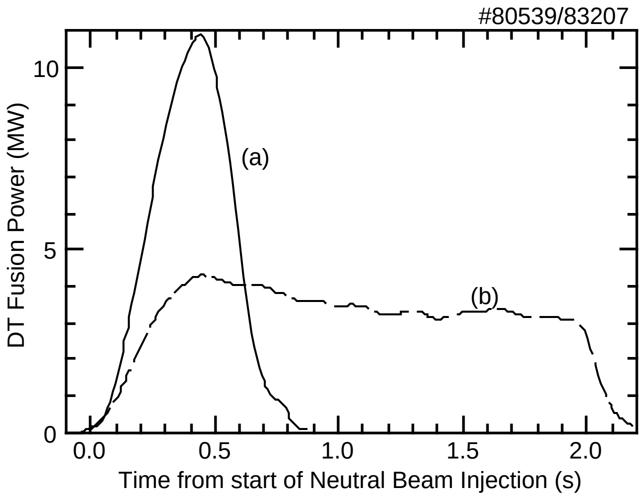

Fig. 2. Evolution of fusion power in TFTR for case a with injected neutral beam power of 40 MW and case b of 22 MW.

For the Three Large Tokamaks fusion power gain, Q = fusion power /plasma heating power, was established in the design phase as a measure of fusion plasma performance. In retrospect a more meaningful measure would be Q = fusion energy produced per pulse / plasma heating energy per pulse [2]. It should be emphasized that the fusion power density in the core of a D-T plasma in TFTR is actually higher than that predicted for ignited plasmas producing 1,500 MW in ITER, and much higher than the central power density in JET plasmas producing 13 MW.

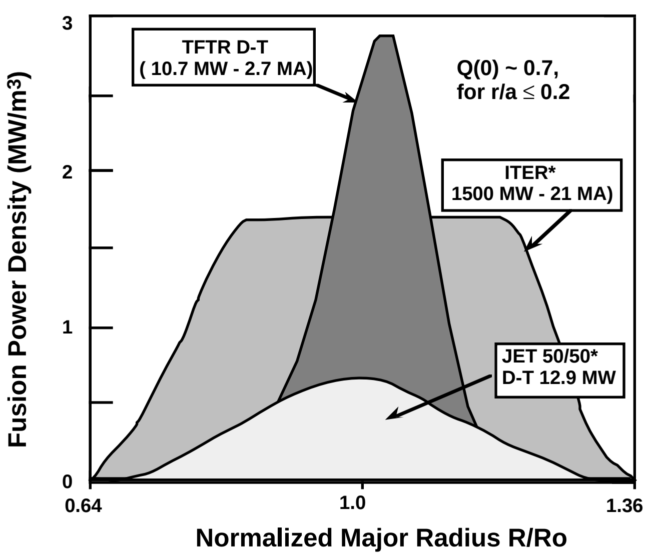

Fig. 3. Fusion Power Density on TFTR compared to JET extrapolated from 1.7 MW in the Preliminary Tritium Experiment and for an ignited ITER scenario.

A comparison of important plasma parameters is shown in Table IV, note that the TFTR and ITER parameters [3] are nearly identical with TFTR being somewhat more collisionless and ITER having about 1/3 the normalized gyro-radius of TFTR due to its larger size. Therefore one would expect the basic D-T plasma physics regimes in the core of ITER and TFTR to be similar.

Table IV
The Core Plasma Parameters Achieved in TFTR D-T Plasmas are ITER-like.

All simultaneous parameters	TFTR (#80539)	ITER (DDR nominal)
Electron density (10^{20} m^{-3})	1	1.3
T_i (keV)/T_e (keV)	32/13.5	20/20
D/T	1	1
B_t (T)	5.6	5.7
β(0), %	7.3	5
Collision frequency * (10^{-3})	1	2
ρ_i/a (10^{-3})	6	2
Fusion Power Density (MWm^{-3})	2.8	2

V. BURNING PLASMA PHYSICS

A major reason for studying D-T plasmas in TFTR was to carryout the first investigations of alpha particle physics. The key parameters for alpha particle physics are compared in Table V for TFTR and ITER, therefore TFTR was able to access regimes of importance to burning plasmas on ITER.

Table V
The Core Alpha Particle Parameters Achieved in TFTR D-T Plasmas are ITER-like.

All simultaneous parameters	TFTR (#76770)	ITER (nominal)
Fusion Power (MW)	7.5	1500
Alpha Heating Density (MWm^{-3})	0.6	0.4
$n_\alpha(0)/n_e(0)$, %	0.3	0.2
Toroidal Alfvén Eigenmode Parameters		
$R\nabla\beta_\alpha$	0.02	0.06
TAE Mode Number (most unstable theoretically)	4	20

The various alpha particle issues that are important for burning plasmas are given in Fig. 4 as a function of increasing fusion gain. A key parameter is the fraction of self-heating in the core of a burning plasma which is given by Q/(Q + 5).

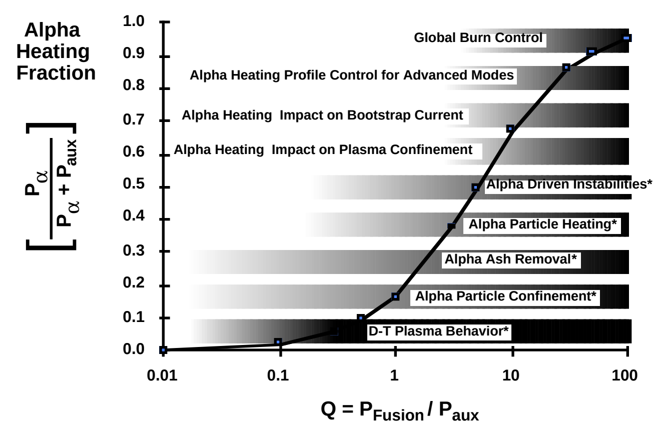

Fig. 4. Burning plasma issues of importance to magnetic fusion. The issues indicated with an asterisk* were first addressed on TFTR.

The self-heating fraction on TFTR ranged up to 0.12 in the core while ITER is expected to have self-heating fractions from 0.36 to 0.7. Notice that most burning plasma phenomena increase continuously as the self-heating is increased. The exception is alpha driven instabilities which have a threshold at a particular alpha pressure gradient.

TFTR had a comprehensive set of tokamak plasma diagnostics which enabled high resolution measurements of all relevant parameters in space and time. During the D-T experiments a diagnostic to measure the radial electric field was invented and implemented. A charge exchange recombination system to measure the poloidal plasma flows with high resolution was developed and utilized. A measurement of alpha particles was also required to study the burning plasma phenomena on TFTR. The birth rate and location of the alpha particles was measured with a 10 channel neutron collimator. This neutron detector and the total yield neutron detectors were calibrated absolutely by positioning a neutron source inside the vacuum vessel. Alpha particles escaping from the plasma at high energy were measured using a set of four energy/pitch angle resolving detectors placed inside the vacuum vessel at different poloidal locations. The energetic confined alpha particles (1.0 to 3.6 MeV) were measured by injecting a lithium pellet that caused a double charge exchange of the energetic alpha particle. Medium energy alpha particles (0.1 to 0.6 MeV) were measured by charge exchange of the energetic alpha particles with the neutrals injected by the neutral beams. All of these diagnostics were integrated into data analysis system that allowed rapid data analysis.

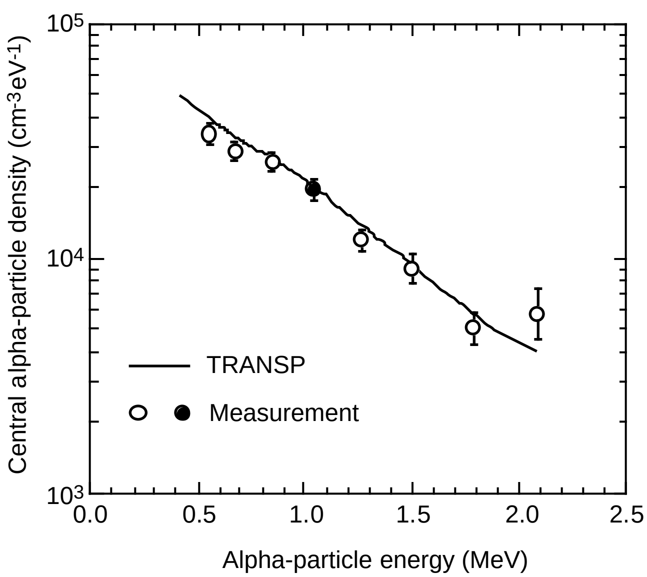

Fig. 5 Alpha-particle energy distribution at the center of a DT plasma 0.2s after the end of the NBI. The spectrum is determined by energy analysis of helium neutrals produced by double charge-exchange in the neutral cloud surrounding an ablating lithium pellet. The measurements are normalized to the TRANSP calculation at the solid point.

The transfer of alpha energy to the plasma is evident from Fig. 5 where energy is taken out of the energetic alpha distribution in accord with classical processes and the alpha energy then appears as a measured increase in the electron temperature as shown in Fig. 6.

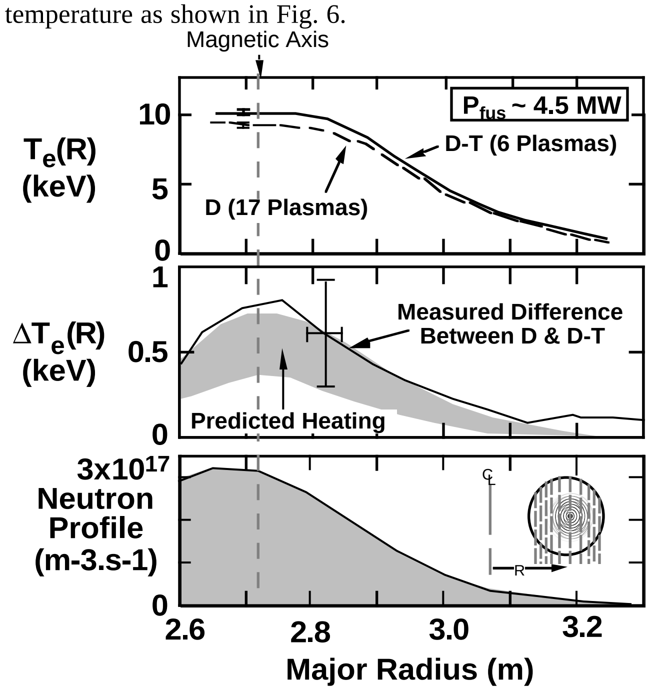

Fig. 6. Alpha heating of electrons was observed on TFTR (G. Taylor et al, Phys Rev Lett **76**,2722, 1997).

In the mid 1980s, theory predicted [4] that energetic alphas could drive toroidal Alfvén eigen modes (TAE) unstable thereby ejecting energetic alpha particles and reducing alpha heating. These modes were first simulated using energetic beam ions on TFTR [5]. In 1996 these modes driven by fusion alpha particles were observed for the first time in a configuration predicted to be unstable by theory (Fig. 7).

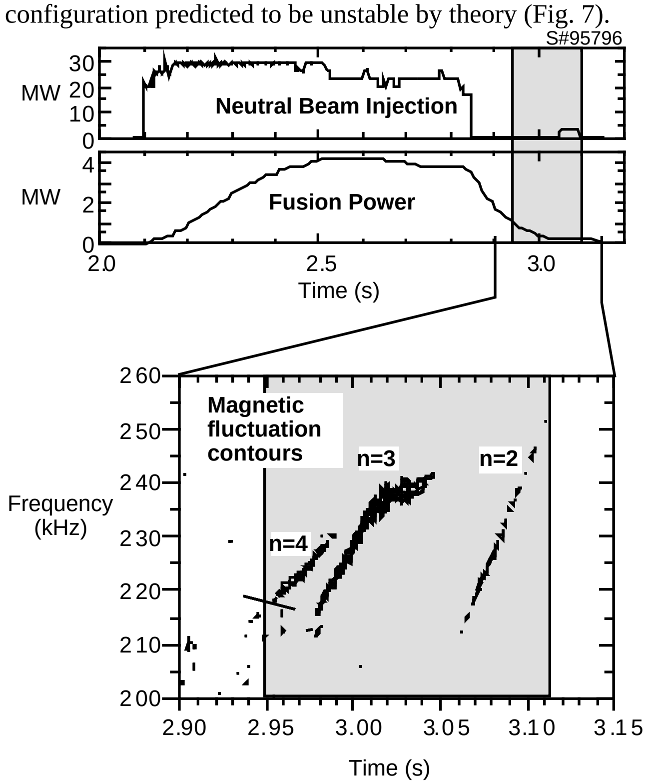

Fig. 7. Toroidal Alfvén eigen modes driven by alpha particles were first observed on TFTR [6].

The modes are present when the strong damping by beam ions is reduced in the afterglow and when the magnetic shear is reduced as in the center of some reversed shear discharges. The results of the actual alpha particle experiments on TFTR exceeded the expectations of the original proposal.

VI. CONFINEMENT OF A FUSION PLASMA

The single most important plasma physics issue to be studied and understood in the three large tokamaks is the confinement of a fusion plasma. TFTR had the advantage of outstanding diagnostics to measure basic plasma parameters, had the most quantitative measurements of plasma turbulence and had the greatest flexibility in controlling plasma flow shear, a key parameter in determining turbulence. Over the past three decades, the models and predictions of plasma confinement oscillated widely. In the early to mid 1960s, Bohm diffusion was prevalent with a strong decrease in confinement as temperature increased. In the late 1960s, tokamak energy confinement was described by Pseudoclassical(Artsimovitch) scaling which had a weak improvement with temperature. During the initial proposal phase of TFTR in the mid 1970s, a first principles drift wave turbulence model involving six regimes was used to estimate TFTR performance. This model incorporated a trapped ion mode which had a very strong negative dependence with increasing ion temperature. The Hot Ion results from PLT in 1978 led to the development of the Hot-Ion model for TFTR and results from Alcator A and low power beam heating experiments on ORMAK were consistent with a confinement model of neoclassical ion confinement and Alcator scaling for the electron energy confinement. These features led to a description of the Hot Ion mode for ignition with reduced confinement and beta requirements. In the early 1980s, higher power neutral beam injection experiments demonstrated a degradation of confinement with heating power the so called Low-Mode scaling which is reminiscent of Bohm scaling. In 1982, the High-Mode was discovered with a confinement scaling similar to Low mode but with an improvement factor, H, that was typically ~2. These results were systematized by Goldston [7] who formulated an empirical relationship between the confinement time and global plasma parameters based on a regression analysis of data from several experiments. The initial neutral beam heating experiments on TFTR, JET and JT-60 followed the prescription of L-mode scaling which projected low D-T fusion power levels < 1 MW with negligible alpha particle effects.

VII. CONFINEMENT BREAKTHROUGH

In 1985, experiments in TFTR with low plasma density and modest injection powers of 6 MW produced hot ion plasmas with temperatures approaching 10 keV. In early 1986, pellet injection produced peaked density profiles with confinement times approaching 0.6 s and a record $n\tau_E \sim 1.4 \times 10^{20}\ m^{-3}s$ which was within 30% of the minimum $n\tau_E$ required for ignition of a D-T plasma [8]. This plasma had a temperature of 1.4 keV with 25% of the central energy lost by free-free hydrogenic bremsstrahlung. In May/June 1986, a sequence of experiments led by Strachan [9] reduced the edge recycling by extensive discharge cleaning of the plasma limiter. This technique resulted in a dramatic increase in the central ion temperature, a peaking of the density profile and a significant increase in the electron temperature. For the same external parameters, I_p, B_t and P_{nb}, the fusion performance $n\tau_E T_i$ increased by a factor of 28, which contradicts the empirical scaling formula (Fig. 8).

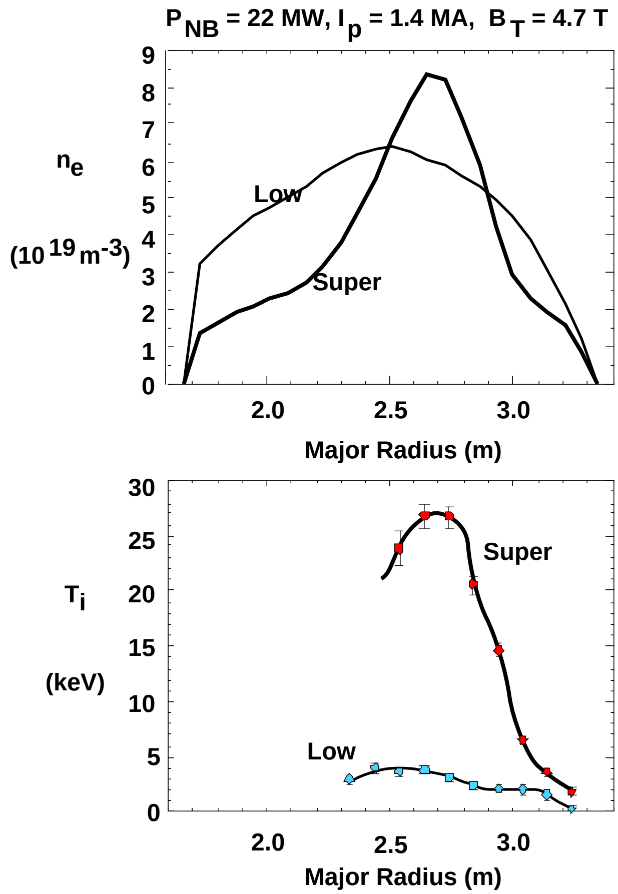

Fig. 8. Comparison of Super/Lmode for the same external conditions while edge plasma recycling is changed.

Due to the superior performance of this mode, it was named the supershot mode. Subsequent systematic scaling studies found that the confinement time of the supershot mode did not scale with Ip or Pnb as prescribed by the empirical scaling formula. In the early 1990s detailed measurements of turbulence in TFTR using Beam Emission Spectroscopy revealed small amplitude turbulence in TFTR with characteristics similar to that produced in simulations of ion temperature gradient(ITG) turbulence using nonlinear gyrokinetic models. A new distinguishing feature was that the eddies were elongated in the radial direction relative to the poloidal direction (i.e. $k_r < k_p$) and the wavelengths were larger than the ion gyroradius ($k\rho << 1$). Subsequent measurements of this turbulence has shown that $\delta T_i/T_i \sim$ (2-3) $\delta n/n$ which is expected for ITG instabilities. The main features of the gyro kinetic model were captured by a gyro-fluid model which allowed much more rapid simulations of ITG turbulence[10]. The gyro-fluid model formed the basis of the IFS/PPPL model for ITG turbulence which explains most of the anomalous features of the TFTR supershot results. A key part of the IFS/PPPL model is that the turbulence is so strong that the profiles are held near marginal stability profile and the transport is due to deviations from the marginal stability criterion. This basic concept is similar to the stability criteria for temperature gradient driven turbulence in the convection zone of the sun. In its simplest form the stability criterion is given by

$$\eta = (\mathrm{dln}T/\mathrm{d}r)/(\mathrm{dln}n/\mathrm{d}r) > \Gamma - 1 \quad (1)$$

where $\Gamma = 5/3$ for the sun and $\Gamma = 2$ for regions of interest in the tokamak. If the density profile is prescribed, then the central T is determined uniquely by the edge T. A key test of this model is shown in Fig. 9 where the edge T_i of TFTR is varied systematically by adjusting the edge recycling of neutral gas.

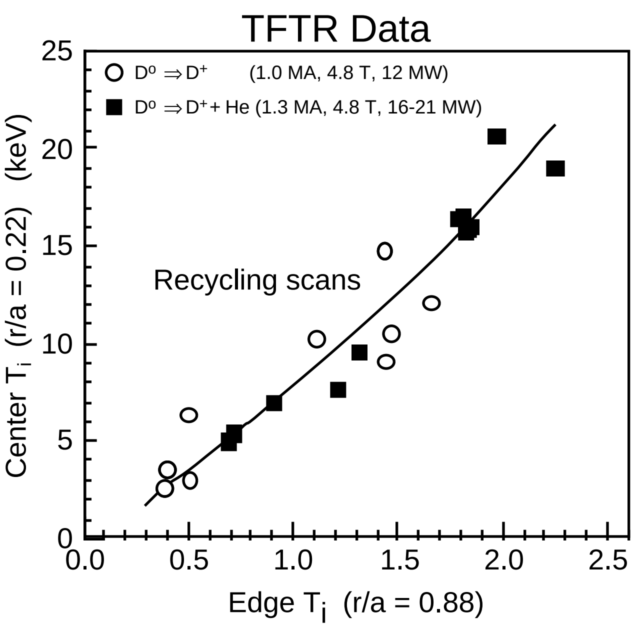

Fig. 9. Relationship of Ti(o) vs Ti(edge) as the edge plasma recycling is changed for fixed external tokamak parameters.

As the edge temperature is increased the central temperature also increases as predicted by the IFS/PPPL model. This model also explains the paradox of the TFTR supershot results in Fig. 8 and why empirical scaling is not valid. However, there are several cases where the initial version of the IFS/PPPL model deviates from the experimental results. A survey of the experimental data shows that sheared plasma flow, a variable previously ignored in the empirical scaling and the initial IFS/PPPL model, is very important in stabilizing ITG turbulence. TFTR has the unique ability to control sheared flow by controlling the injecting of toroidal momentum using various combinations of neutral beam ion sources. An example is shown in Fig. 10 where the measured ion energy transport and the associated turbulence are reduced by sheared flow. This sheared plasma flow feature has now been incorporated into the marginal stability model for ITG turbulence and is able to reproduce a unique features of supershots that are not explainable with the empirical model of plasma transport [11].

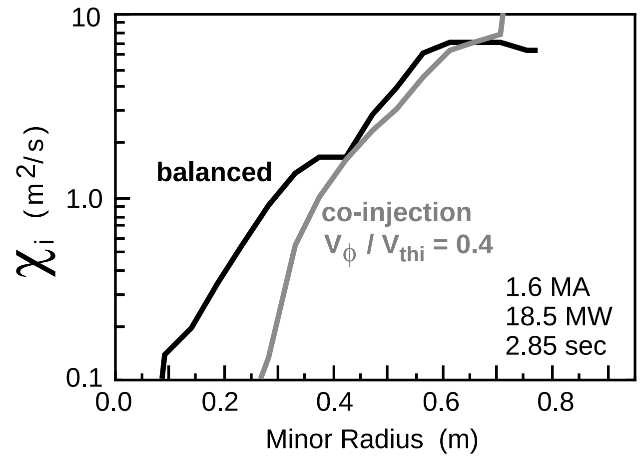

Fig. 10. Ion thermal conductivity for balanced injection with low sheared flow is reduced during co-injection with larger sheared flow produced during co-injection.

For example, in 1990 the ion thermal conductivity was observed to increase with T_i in L-mode and H-mode while it decreased with increasing T_i in the high temperature range of the supershot mode (Fig. 11).

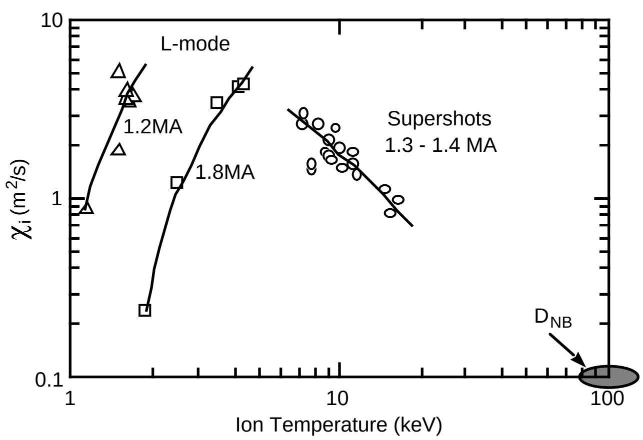

Fig. 11. Ion thermal conductivity increases with T_i for the L-mode and decreases with T_i for the supershot mode.

Note, the confinement of energetic fast ions (100 keV deuterons) from neutral beam injection and the MeV energy ions from fusion reactions are also very well confined in TFTR plasmas. The ion thermal conductivity in both the L-mode and supershot can be explained using the IFS/PPPL model with sheared flow due to the calculated neoclassical electric fields [11].

VIII. ENHANCED REVERSED SHEAR

In early 1995, TFTR discovered a new confinement regime [12] where the ion thermal conductivity was measured to be less than 10% of the calculated minimum neoclassical values calculated using the standard Chang-Hinton model. The operational signature of this regime is shown in Fig. 12 where two plasma discharges with identical magnetic field parameters are compared. The lower curve has reversed magnetic shear in the core produced by a transient skin effect and has confinement properties similar to a standard supershot plasma.

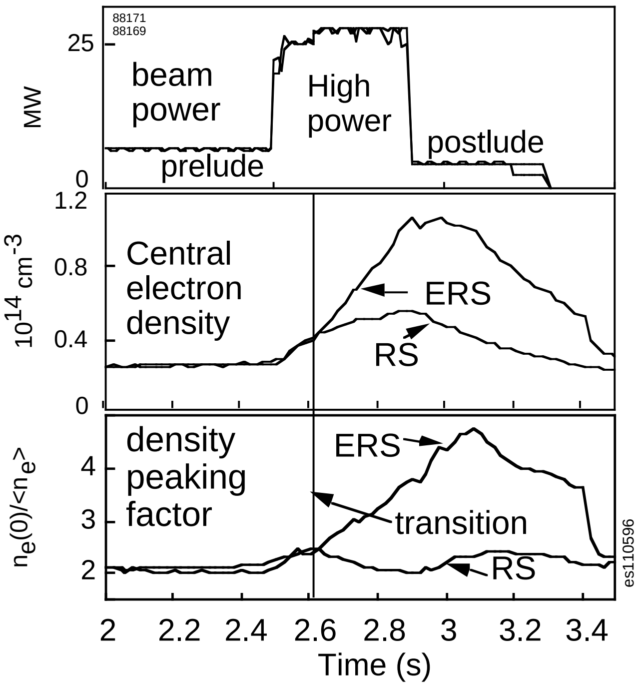

Fig. 12. Plasma waveforms for two discharges with identical external parameters including plasma current profile at the time of transition.

The upper curve, which has the same reversed magnetic shear but slightly higher neutral beam power, undergoes a transition at 2.7s, at which time the particle confinement becomes very good and the center of the plasma simply integrates the incoming particle flux from the neutral beams. A detailed analysis of the transport coefficients (Fig. 13) shows that the ion thermal conductivity is reduced to < 1% of its value prior to the transition and is significantly less than the standard calculation of neoclassical transport to particle collisions.

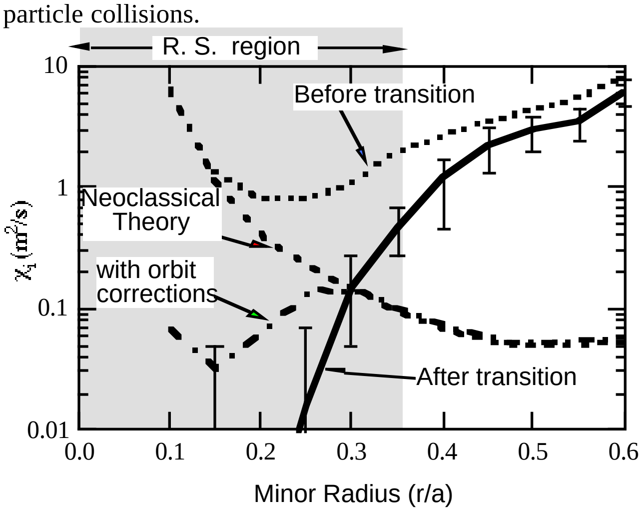

Fig. 13. The ion thermal conductivity determined from power balance analysis. The electron particle diffusivity shows a similar large reduction while the electron thermal diffusivity was reduced less than a factor of two.

The detailed physics of the transition to enhanced reversed shear has now been understood as due to the stabilizing effects of sheared plasma flow as shown in Fig. 14 where the poloidal plasma flows have been measured directly using a new high resolution diagnostic invented on TFTR.

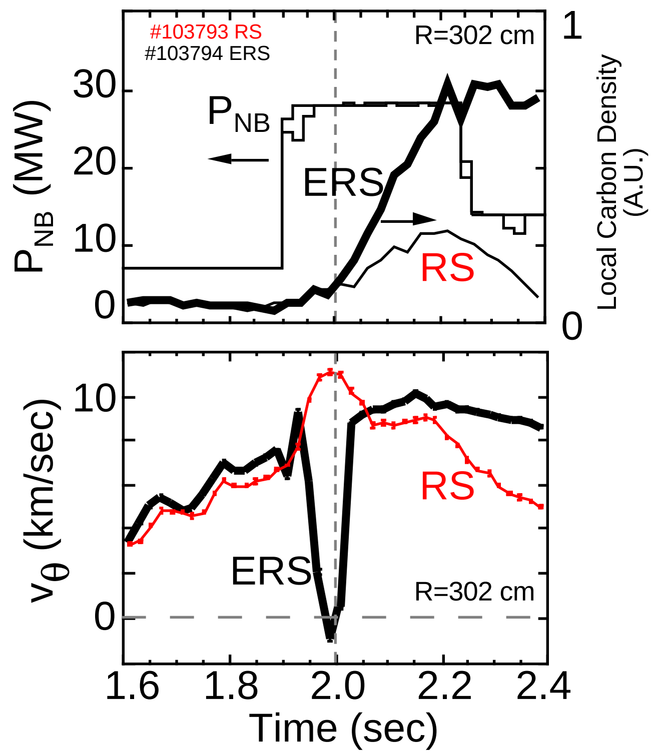

Fig. 14. Measurement of the poloidal velocity at the time of transition to enhanced reversed shear.

During the last days of TFTR experiments, a detailed series of experiments confirmed many of the predictions of this new model of plasma transport. In Fig. 15, the small amplitude linear growth rate, γ_{lin}, of the ITG instability is calculated from measured plasma profiles and is compared with the stabilizing term due to sheared plasma flows, γ_{ExB}.

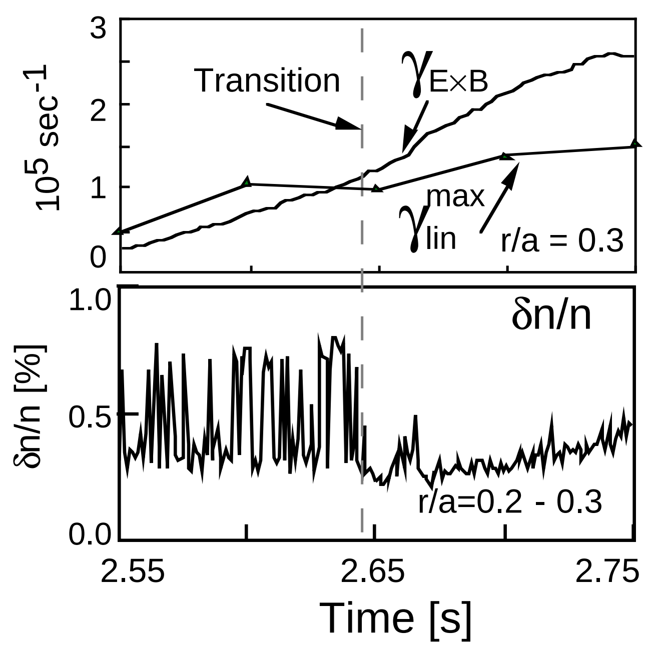

Fig. 15. Stabilization of turbulence and confinement improves when flow shear rate > linear growth rate.

In the simplest version of this effect the plasma is stabilized when $\gamma_{ExB} > \gamma_{lin}$ which is in remarkable agreement with the controlled experiments shown. This accumulating evidence provides detailed support for the IFS/PPPL model with shear flow stabilization and provides additional examples of the failure of empirical scaling to explain the experimental results.

IX. ENHANCED BURNING PLASMA EXPERIMENTS

The minimum plasma current of a D-T ignition experiment in a tokamak with a toroidal aspect ratio of 3 is about 3 MA, the plasma current required to confine the energetic alpha particle. The large plasma currents of 21 MA in the ITER design are required to overcome deficiencies in plasma confinement. This recent detailed understanding of plasma transport opens up new opportunities for burning plasma experiments on TFTR and offers the possibility of producing ignition in a plasma not much larger than TFTR/JET plasmas. A number of scenarios of enhanced TFTR performance were simulated and published [13]. For a modest extension of TFTR capability to increase the reversed shear region from r/a = 0.35 to 0.45 using Lower Hybrid current drive, the fusion gain could be tripled from the present value to ~1 as is shown in Fig 16.

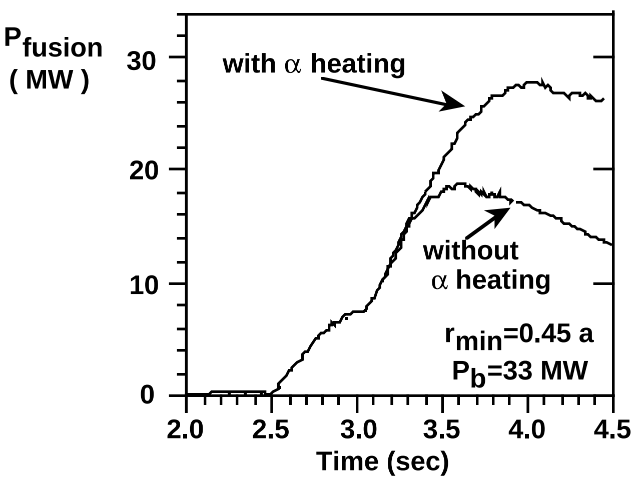

Fig. 16. Fusion power estimated for extension of ERS regime on TFTR with better control of current profiles to increase reverse shear radius from r/a = 0.35 to 0.45.

This would have allowed alpha particle physics to be studied up to burning plasma parameters of 0.3 where the alpha particles would begin to react back on the plasma pressure. A key burning plasma issue is local burn control (Fig. 5) which is required to control the plasma pressure produced by alpha heating within the MHD stable regime. Techniques are needed that will control the transport of a strongly self heated plasma if the potential of these enhanced operating modes is to be realized. One such technique is to use RF waves to produce sheared plasma flows thereby creating a transport barrier at the desired position. Experiments carried out during the last days of the TFTR D-T experiments verified in detail that the sheared flow could be produced in a fusion plasma. Unfortunately, the TFTR experiments were terminated before the coupling of the RF waves could be optimized to increase the sheared flow above the linear growth rate.

VII. UNFINISHED BUSINESS

While one could argue that TFTR exceeded the original objectives in nearly all areas, one must also note that the premature termination of TFTR due to budget shortages has left a large number of unresolved issues on the table that TFTR was uniquely able to resolve. The advances in transport understanding should have been extended to D-T plasmas where the potential exists to use the improved performance to carry out affordable burning plasma experiments. The Hot Ion mode, which is used for all high performance regimes on all tokamaks today, should have been exploited for near term burning plasmas possibly using alpha channeling mechanisms. The high density pellet results on TFTR with $n\tau_E = 1.4\text{x}10^{20}$ $m^{-3}s$ (70% of $n\tau_E$ required for ignition), a possible route to low cost burning plasma experiments, were never exploited with high power ICRF in D-T due to lack of funding and experimental time.

VII. SUMMARY OF TFTR D-T EXPERIMENTS

Fusion plasmas have been produced and studied in detail for the first time in the laboratory. Good experience with D-T operation and tritium handling has been gained over a three year period. Diagnostic development and controlled D-T plasma conditions have allowed detailed exploration of a wide range of alpha particle effects. Recent advances in understanding the fundamental processes controlling plasma transport have provided new opportunities for improving plasma performance. Implementation of recent knowledge could lead to D-T regimes with strong alpha heating with modest extensions of TFTR operating regimes.

ACKNOWLEDGMENTS

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