PPPL-3230 - Preprint: February 1997, UC-420, 421, 426

Deuterium-tritium plasmas in novel regimes in the Tokamak Fusion Test Reactor*

M.G. BELL, S. BATHA,[1] M. BEER, R.E. BELL, A. BELOV,[2] H. BERK,[3] S. BERNABEI, M. BITTER, B. BREIZMAN,[3] N.L. BRETZ, R. BUDNY, C.E. BUSH,[4] J. CALLEN,[5] S. CAUFFMAN, C.S. CHANG,[6] Z. CHANG, C.Z. CHENG, D.S. DARROW, R.O. DENDY,[7] W. DORLAND,[3] H. DUONG,[8] P.C. EFTHIMION, D. ERNST,[9] H. EVENSON,[5] N.J. FISCH, R. FISHER,[8] R.J. FONCK,[5] E.D. FREDRICKSON, G.Y. FU, H.P. FURTH, N.N. GORELENKOV,[2] V.YA. GOLOBOROD'KO,[10] B. GREK, L.R. GRISHAM, G.W. HAMMETT, R.J. HAWRYLUK, W. HEIDBRINK,[11] H.W. HERRMANN, M.C. HERRMANN,[4] K.W. HILL, J. HOGAN,[4] B. HOOPER,[12] J.C. HOSEA, W.A. HOULBERG,[4] M. HUGHES,[13] D.L. JASSBY, F.C. JOBES, D.W. JOHNSON, R. KAITA, S. KAYE, J. KESNER,[9] J.S. KIM,[5] M. KISSICK,[5] A.V. KRASILNIKOV,[2] H. KUGEL, A. KUMAR,[14] N.T. LAM,[5] P. LAMARCHE, B. LEBLANC, F.M. LEVINTON,[1] C. LUDESCHER, J. MACHUZAK,[9] R.P. MAJESKI, J. MANICKAM, D.K. MANSFIELD, M. MAUEL,[15] E. MAZZUCATO, J. MCCHESNEY,[8] D.C. MCCUNE, G. MCKEE,[8] K.M. MCGUIRE, D.M. MEADE, S.S. MEDLEY, D.R. MIKKELSEN, S.V. MIRNOV,[2] D. MUELLER, Y. NAGAYAMA,[16] G.A. NAVRATIL,[15] R. NAZIKIAN, M. OKABAYASHI, M. OSAKABE,[16] D.K. OWENS, H.K. PARK, W. PARK, S.F. PAUL, M.P. PETROV,[17] C.K. PHILLIPS, M. PHILLIPS,[13] P. PHILLIPS,[3] A.T. RAMSEY, B. RICE,[12] M.H. REDI, G. REWOLDT, S. REZNIK,[10] A.L. ROQUEMORE, J. ROGERS, E. RUSKOV, S.A. SABBAGH,[15] M. SASAO,[16] G. SCHILLING, G.L. SCHMIDT, S.D. SCOTT, I. SEMENOV,[2] T. SENKO, C.H. SKINNER, T. STEVENSON, E.J. STRAIT,[8] B.C. STRATTON, J.D. STRACHAN, W. STODIEK, E. SYNAKOWSKI, H. TAKAHASHI, W. TANG, G. TAYLOR, M.E. THOMPSON, S. VON GOELER, A. VON HALLE, R.T. WALTERS, S. WANG,[18] R. WHITE, R.M. WIELAND, M. WILLIAMS, J.R. WILSON, K.L. WONG, G.A. WURDEN,[19] M. YAMADA, V. YAVORSKI,[10] K.M. YOUNG, L. ZAKHAROV, M.C. ZARNSTORFF, S.J. ZWEBEN

---

* Invited paper presented at the Thirty-Eighth Annual Meeting of the Division of Plasma Physics, American Physical Society; Denver, Colorado, 11-15 November 1996

[1] Fusion Physics and Technology, Torrance, California
[2] Troitsk Institute of Innovative and Thermonuclear Research, Moscow, Russia
[3] University of Texas, Institute for Fusion Studies, Austin, Texas
[4] Oak Ridge National Laboratory, Oak Ridge, Tennessee
[5] University of Wisconsin, Madison, Wisconsin
[6] Courant Institute, New York University, New York, New York
[7] UKAEA Culham Laboratory, Abingdon, United Kingdom
[8] General Atomics, San Diego, California
[9] Massachusetts Institute of Technology, Cambridge, Massachusetts
[10] Ukrainian Institute of Nuclear Research, Kiev, Ukraine
[11] University of California, Irvine, California
[12] Lawrence Livermore National Laboratory, Livermore, California
[13] Northrop-Grumman Corporation, Princeton, New Jersey
[14] University of California, Los Angeles, California
[15] Columbia University, New York, New York
[16] National Institute for Fusion Science, Nagoya, Japan
[17] Ioffe Physical-Technical Institute, St. Petersburg, Russia
[18] Institute of Plasma Physics, Academy of Science, Hefei, China
[19] Los Alamos National Laboratory, Los Alamos, New Mexico

PLASMA PHYSICS LABORATORY, PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY, 08543, USA

Preprint: PPPL-3230, February 1997

Abstract

Experiments in the Tokamak Fusion Test Reactor (TFTR) [Phys. Plasmas **2**, 2176 (1995)] have explored several novel regimes of improved tokamak confinement in deuterium-tritium (D-T) plasmas, including plasmas with reduced or reversed magnetic shear in the core and high-current plasmas with increased shear in the outer region (high-l_i). New techniques have also been developed to enhance the confinement in these regimes by modifying the plasma-limiter interaction through *in-situ* deposition of lithium. In reversed-shear plasmas, transitions to enhanced confinement have been observed at plasma currents up to 2.2 MA ($q_a \approx 4.3$), accompanied by the formation of internal transport barriers, where large radial gradients develop in the temperature and density profiles. Experiments have been performed to elucidate the mechanism of the barrier formation and its relationship with the magnetic configuration and with the heating characteristics. The increased stability of high-current, high-l_i plasmas produced by rapid expansion of the minor cross-section, coupled with improvement in the confinement by lithium deposition has enabled the achievement of high fusion power, up to 8.7 MW, with D-T neutral beam heating. The physics of fusion alpha-particle confinement has been investigated in these regimes, including the interactions of the alphas with endogenous plasma instabilities and externally applied waves in the ion cyclotron range of frequencies. In D-T plasmas with $q_0 > 1$ and weak magnetic shear in the central region, a toroidal Alfvén eigenmode instability driven purely by the alpha particles has been observed for the first time. The interactions of energetic ions with ion Bernstein waves produced by mode-conversion from fast waves in mixed-species plasmas have been studied as a possible mechanism for transferring the energy of the alphas to fuel ions.

PACS Numbers: 28.52.Cx, 52.25.Fi, 52.55.Fa

I Introduction

Since the Tokamak Fusion Test Reactor (TFTR)[1] began its deuterium-tritium (D-T) phase of operation in December 1993, more than 1.2 GJ of D-T fusion energy has been produced. Over this period, 841 plasmas containing high concentrations of tritium have been made for a wide variety of experiments. About 90 g of tritium has been processed. TFTR has achieved high availability for experiments while maintaining a record of safe operation and compliance with the regulatory requirements of a nuclear facility. The tokamak, heating systems and power supplies have all been operated at, or beyond, their original design specifications.

During the first year of D-T operation, experiments concentrated on achieving the maximum fusion power in order to validate the extrapolability of experience in deuterium plasmas to D-T plasmas and to study alpha particle physics in the most reactor relevant conditions.[1] During that period, it became apparent that the fusion performance of TFTR was being limited by plasma stability and that the development of alternate modes of operation could extend its ability to explore reactor relevant phenomena in D-T plasmas. For the last eighteen months, therefore, considerable effort has been devoted to developing new operational regimes which offer the possibility of increased plasma stability while preserving the good confinement and extremely high fusion reactivity of existing TFTR regimes.

In February 1995, it was discovered that plasmas in TFTR with reversed magnetic shear ($\partial q/\partial r < 0$) in the central region could undergo a spontaneous transition during neutral beam heating to a state of enhanced confinement, the so-called Enhanced Reverse Shear (ERS) regime,[2] which appeared to be associated with the formation of a localized transport barrier in the interior of the plasma. A similar regime was also discovered in the DIII-D tokamak[3] at about the same time and has since been studied in several tokamaks, including JT-60U[4] and JET.[5] Although it is produced by a different heating method, namely neutral beam injection, the ERS regime has strong similarities to two other regimes of improved confinement involving modification of the q profile, namely the Pellet Enhanced Performance mode in JET[6] and that occurring in Tore-Supra with Lower-Hybrid Current Drive.[7] Since reversed magnetic shear also offers the prospect of improved stability to certain pressure-driven magnetohydrodynamic (MHD) modes, the ERS regime seemed particularly attractive for further exploration in TFTR. Experiments with this regime in the 1996 run are described in Sec. II.

A second line of investigation grew out of previous experiments to improve plasma stability by creating more highly peaked current profiles through current rampdown.[8] This technique, which increases the internal inductance parameter, l_i, of the plasma, and produces what is called the high-l_i regime, had already achieved high normalized-β and significant fusion power but was limited operationally in its extrapolability to higher performance. An innovative method has now been developed to produce high-l_i plasmas at much higher plasma current. Experiments utilizing this technique will be described in Section III.

Section IV discusses the D-T reactivity achieved in these different operational regimes and compares the achieved reactivity with that of extrapolations based on experience in deuterium plasmas. Section V presents recent results in alpha-particle physics while Section VI describes the experiments with heating by waves in the ion-cyclotron range of frequencies (ICRF) in various plasma and wave coupling regimes.

II Reverse-Shear Plasmas

Plasmas with reversed magnetic shear in the central region are produced in TFTR by applying a period of low-power neutral beam injection (NBI) heating (typically $< 10\,\mathrm{MW}$), to large cross-section plasmas while the toroidal current is being ramped up to its final level.[2] This heating, referred to as the NBI "prelude", and the large plasma size combine to inhibit penetration of the induced current, thereby creating a hollow current profile and reversed magnetic shear. After the final current has been reached, a period of high-power NBI is applied to study the confinement and stability properties. The high-power phase may be followed by a second period of lower power NBI, known as the "postlude" phase, to sustain the period of ERS confinement. The q profile of a reversed-shear plasma may be characterized, at the most basic level, by the minimum q, q_{min}, and by the normalized minor-radius, ρ_{min} (= r/a) of the surface of minimum q. Experiments in 1995 had developed a reliable startup for reversed shear plasmas at a plasma current I_p = 1.6 MA (major radius $R_p = 2.60\,\mathrm{m}$; minor radius $a = 0.90\,\mathrm{m}$; toroidal magnetic field B_T, = 4.6 T, $q_a \approx 5.8$).[2] These plasmas generally had $2 \le q_{min} \le 3$ and $\rho_{min} = 0.3 - 0.4$ and in those plasmas that underwent ERS transitions, the region of improved confinement, appeared to coincide with the region of shear reversal, *i.e.* $\rho \le \rho_{min}$. The 1.6 MA ERS plasmas exhibited a limiting Troyon-normalized-β, β_N ($= 10^8 \beta_T a B_T / I_p$, where $\beta_T = 2\mu_0 \langle p \rangle / B_T^2$ and $\langle p \rangle$ is the volume-average plasma pressure), of about 2; this modest β-limit was attributed to the small volume of high pressure plasma within the transport barrier.

The 1996 reversed-shear experiments continued to use this reliable 1.6 MA plasma for studies of ERS transition physics and the formation of the transport barrier,[9] but a considerable effort was also devoted to exploring higher current scenarios with the goal of producing plasmas having $1 < q_{min} < 2$ and larger ρ_{min} which theoretical studies[10] had suggested would have a substantially improved β-limit. A plasma current of 2.2 MA, corresponding to $q_a \approx 4.3$ with the other major parameters held fixed, was chosen for this development because it was expected to be compatible with producing a D-T fusion power approaching 10 MW at β_N slightly greater than 2.

To produce reversed shear at lower q_a, it is necessary to avoid deleterious MHD instabilities, sometimes resulting in disruptions, during the current ramp phase, particularly when the edge q passes through integral values. In standard TFTR operation, the plasma is grown in minor cross-section during the current ramp to bring the q_a to its final value as early as possible and then to maintain it constant; this procedure results in rapid current penetration and usually inhibits MHD activity during the current ramp. In order to avoid the MHD activity during the reversed-shear startup, it was found necessary to program brief reductions in the current ramp rate the prelude NBI heating power as the troublesome integral q_a values were approached. Disruptions were particularly a problem if, in addition to passing through an integral q_a, the value of q_{min} was simultaneously close to a rational value. As shown in Fig. 1, shear reversal was produced over a larger radius at the higher current. However, the desired reduction in q_{min} could not be achieved simultaneously. Despite variations of the startup phase, including variations of the prelude NBI and the introduction of partial plasma growth to increase current penetration, within the accessible, reliable range of startup conditions at 2.2 MA, lower q_{min} could only be achieved at the expense of reduced ρ_{min}. This apparent relationship between q_{min} and ρ_{min} is illustrated in Fig. 2. Similar difficulty in achieving $q_{min} < 2$ has also been experienced by the JT-60U team developing reversed shear plasmas in that device.[4]

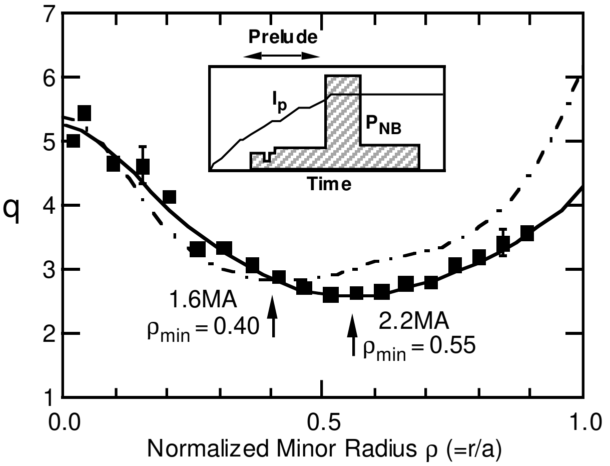

Fig. 1 q-profiles calculated for 2.2 MA (solid) and 1.6 MA (dashed) reversed shear plasmas at the end of the neutral beam prelude. The solid points are the motional Stark-effect (MSE) data for the 2.2 MA plasmas. Conditions: R_p = 2.60 m, a = 0.95 m, B_T = 4.6 T. Schematic waveforms of the plasma current and neutral beam power are shown in the inset.

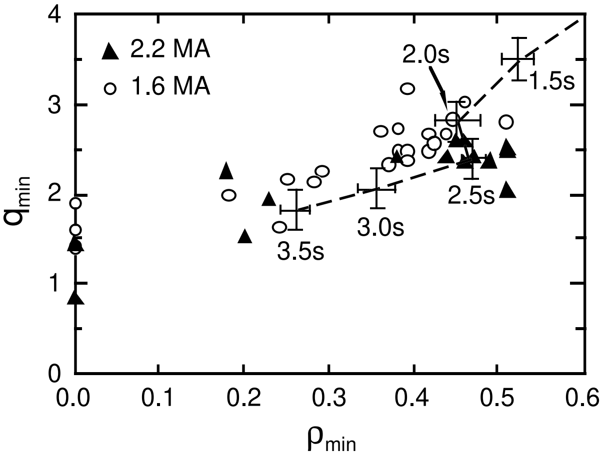

Fig. 2 Values of ρ_{min} and q_{min} at the start of the high-power NBI phase for 1.6 MA (open circles) and 2.2 MA (solid triangles) plasmas with varying startup conditions. Plasmas with $\rho_{min} > 0$ have reversed shear. Also shown is the trajectory in time followed by one 2.2 MA plasma. The radial error bars indicate the variability of ρ_{min} within a 0.1 s window about each time point.

Once a reliable startup had been developed, it was found that ERS transitions resulting in an improvement in global confinement, such as those observed at 1.6 MA, did not occur spontaneously under similar conditions at high current, possibly because the threshold power for the transition had increased beyond the available NBI power. (The peak deuterium NBI power available for ERS studies has been limited to about 29 MW because a longer total NBI heating duration is required in this mode of operation to span the prelude and postlude phases.) However, the transient formation of regions of increased gradient in the temperature profiles, particularly of the electron temperature, as opposed to the density profile was observed in some 2.2 MA reversed shear plasmas. These events were found to be associated with q_{min} crossing rational values, particularly $q_{min} = 5/2$ and 3; at higher rational values the temperature perturbation became progressively weaker. This phenomenon, while not producing profound changes in overall confinement, may shed light on the underlying mechanisms of confinement in these complex plasmas.

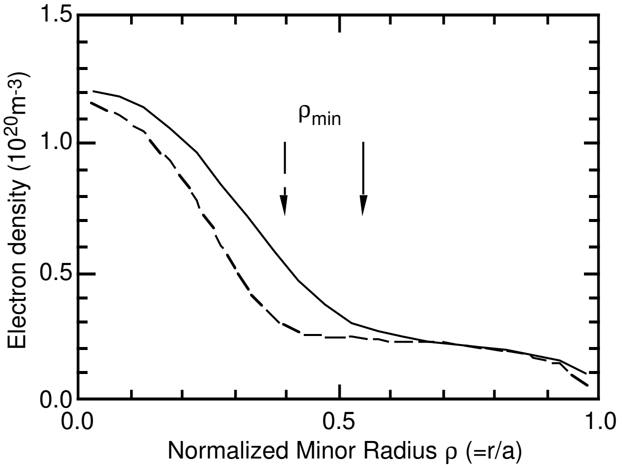

Fig. 3 Profiles of the electron density for 2.2 MA (solid) and 1.6 MA (dashed) ERS plasmas at the time of maximum plasma energy. The radii of minimum q at the start of the high-power NBI phase are indicated. The ERS transport barrier, indicated by the abrupt change in the density gradient, moves out with ρ_{min}.

Experience at lower current had suggested a role for edge conditions in determining the threshold power for the ERS transition. In particular, the use of lithium pellet injection before the start of the high-power NBI phase (by 0.1 – 0.5 s) had been found to reduce the threshold power. Lithium pellet injection was also found to stimulate ERS transitions at 2.2 MA, but only when the pellet injection essentially coincided with the start of the high power phase: a delay of as little as 0.15 s between the pellet and the start of the high power phase would inhibit the effect. Since the effect of lithium injection on wall influxes is known[11] to persist for periods of the order of 1 s, the mechanism for stimulation of the ERS transition by the pellet must involve other effects on the plasma, perhaps on the heating and temperature profiles. Once stimulated by the pellet injection the high-current ERS phase resembled that at lower current: the plasma developed a very well confined core inside a region of very steep gradients, particularly in the density, as illustrated in Fig. 3. Comparing the 1.6 and 2.2 MA data in this figure, it can be seen that the location of the transport barrier has indeed expanded with the increase in ρ_{min}, as observed in similar regimes in other devices.[4,12] Analysis of the transport in the high-current ERS plasmas shows that, as at lower current, the ion thermal and the particle diffusivities are reduced but that the electron thermal diffusivity is only slightly affected. The suppression of the transport in the ERS regime is correlated with a reduction inside the transport barrier in the level of turbulent density fluctuations measured by a multi-channel microwave reflectometer.[13] The fluctuations become suppressed at the time of the ERS transition and reappear when the plasma reverts to L-mode confinement towards the end of the NBI pulse.

Whereas some 1.6 MA ERS plasmas had reached $\beta_N \approx 2.0$ without disruption, the 2.2 MA ERS plasmas suffered frequent disruptions, not only during the high-power NBI phase when β_N was rising but also, as shown in Fig. 4, during the postlude phase when β_N was *decreasing* in time. The highest normalized-β achieved at 2.2 MA was 1.45. The cause of this low β-limit has been investigated experimentally and theoretically.[14] The disruption is believed to arise from the growth of an ideal infernal/kink mode with toroidal mode number n = 1 that is driven primarily by the pressure gradient in the region of low magnetic shear around the surface of minimum q. During the ERS phase, extreme pressure gradients develop in this weak shear region and persist even when the NBI power is reduced in the postlude due to the low transport. The progressive reduction of the β-limit with time occurs because, as the q-profile evolves on a resistive timescale, q_{min} approaches 2. Parametric studies of reversed-shear stability have shown that the β-limit decreases when q_{min} is close to low-order rational values.[10] This emphasizes the importance of developing techniques for controlling both the current and pressure profiles if we are to take advantage of advanced operating modes, such as ERS, in the future. While the β-limit at 1.6 MA in TFTR, $\beta_N \approx 2.0$, appears low compared to the highest value reported for this regime in DIII-D,[12] it is actually very similar to the highest values reached in high-performance reversed-shear modes in JT-60U[4] and in JET[5] at comparable magnetic field.

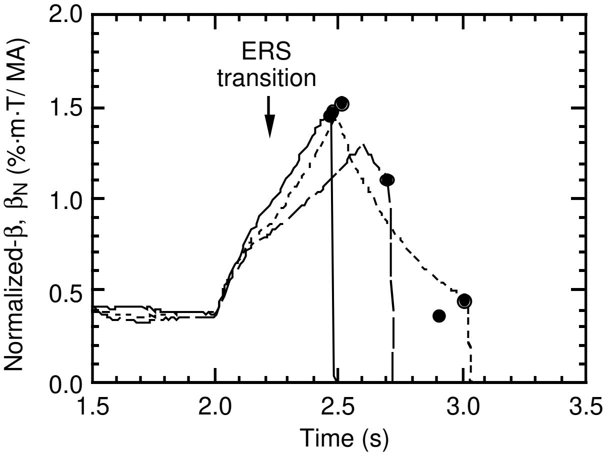

Fig. 4 Evolution of the normalized β, β_N, for three 2.2 MA ERS plasmas which disrupted at decreasing values of β_N as time progressed indicating an evolution of the pressure and q profiles towards reduced stability. The times and β_N values at the disruption for other such shots are indicated by the solid points. The high-power NBI phase starts at 2.0 s in each case and lasts 0.5 – 0.6 s. The approximate time of the ERS transitions is indicated.

While considerable time during the last run was devoted to developing the ERS regime and studying the physics of the associated transport barrier, only a few such plasmas were attempted in D-T, all of these at 1.6 MA. The long overall NBI pulses required for the reversed shear startup provides a practical constraint on the number of D-T shots that can be taken in this mode of operation in any one experiment. When D-T NBI was applied to 1.6 MA reversed shear plasmas, it was found that the threshold power for the ERS transition was considerably higher than for D-only NBI. Whereas with a well conditioned limiter, about 16 MW of D-NBI (6 NBI sources) was sufficient to induce an ERS transition, 27 MW was required in D-T (7 T-NBI and 3 D-NBI sources), at which power level the plasma would rapidly approach the β-limit following the ERS transition. The variation of the threshold power with isotopic mixture and also with magnetic field[9] provide clear tests for theories of ERS confinement. As a result of the difficulty of producing a suitable fuel mixture in the ERS plasmas, the maximum D-T fusion power produced by an ERS plasma has only reached 3.1 MW, although higher D-T power has been reached in both non-ERS reversed-shear plasmas and plasmas with weak positive shear having $q_0 > 1$. The 2.2 MA reversed-shear plasmas suffered from an additional impediment to D-T operation: the lithium pellets injected at the start of the high-power NBI to produce ERS transitions compromised the fusion reactivity of these plasmas. The internal transport barrier of the ERS plasmas caused the injected lithium to be retained in the plasma core, significantly diluting the reacting species. The lithium density profile measured by charge-exchange recombination spectroscopy was also found to have a very steep gradient at the transport barrier during the ERS phase, similar to the electron density profile. In 2.2 MA deuterium ERS plasmas, the peak DD reactivity was between 40 and 80% of that expected on the basis of the plasma total stored energy, scaling from both ERS plasmas at 1.6 MA and supershots in similar conditions of plasma size, current and magnetic field. This suggests that accumulation of helium ash may pose a problem for achieving sustained ignition in the ERS regime without active helium removal techniques.

III High-l_i Regime Experiments

Plasmas in the high-l_i regime, with the current profile modified by ramping down the total current before or during the NBI heating pulse, have previously been shown to have improved stability, as measured by increases in the normalized-β sustainable without disruption.[8] However, in terms of the absolute-β, β_T, such plasmas did not exceed the level that could have been achieved at the maximum plasma current before the current rampdown. A new technique has been developed in TFTR to produce current profiles similar to those generated by rampdown but at higher plasma current.[15,16] The technique, which is illustrated in Fig. 5, involves producing a high-current ohmically heated plasma with reduced minor cross-section, and therefore, very low edge q, typically 2.3. This low-q plasma is then expanded in cross-section immediately before NBI heating to produce a plasma with a low current density in the outer region and, consequently, increased internal inductance. The major task in developing this regime was to produce the low-q plasma in a way that was compatible with achieving good limiter conditioning, *i.e.* low edge influxes of both hydrogen isotopes and carbon, during the NBI phase. This was accomplished by starting the plasma on the outboard limiter, with an aspect ratio of 7 initially, using gas puffing to control MHD activity while q_a was reduced to 2.3, and then, after the current had been raised at constant q_a, making a transition to the main inboard limiter where lithium pellet conditioning could be applied to control the edge influxes. Once optimized, the low-q_a phase of these discharges was remarkably reproducible and devoid of MHD activity although, following the final expansion, locked modes occasionally developed. These modes, which increased the edge influxes during the NBI and degraded confinement, were controlled by a brief period of co-tangential NBI which induced rapid plasma rotation before the main NBI pulse.

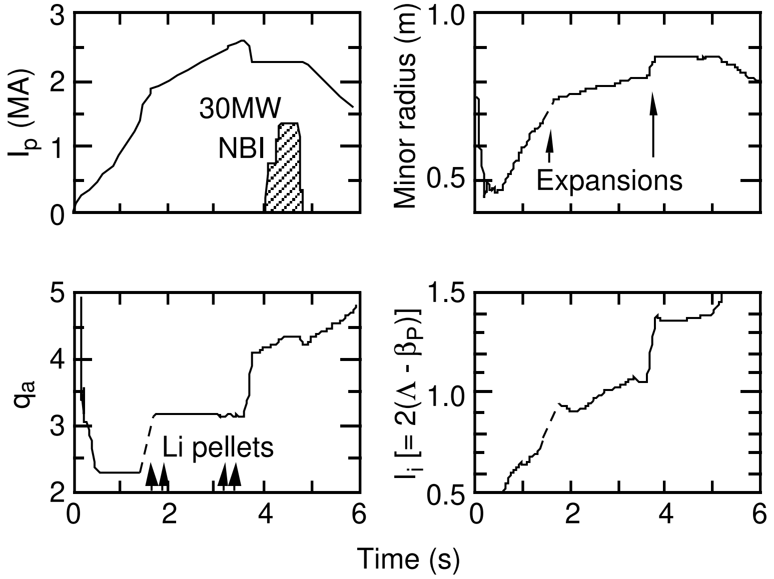

Fig. 5 Technique for producing high-l_i by cross-section expansion. This plasma is initiated on the outer limiter. The edge q is rapidly reduced to 2.4 and maintained there until 1.4 s when the plasma is moved onto the inner limiter, raising q_a to 3.2 to allow the injection of 4 lithium pellets for limiter conditioning. At 3.7 s, the boundary is expanded again before NBI starts at 4.0 s. The plasma current is slightly reduced during the final expansion to conserve poloidal flux.

This new high-l_i startup was developed for plasma currents up to $I_p = 2.3$ MA ($R = 2.52$ m, $a = 0.87$ m, $B_T = 5.5$ T). The product $I_p \cdot I_t \cdot l_i$, where I_t is the threading current of the toroidal field coil, which is a measure of the expected maximum plasma energy content, reached 208 MA^2 in these plasmas, exceeding the maximum produced with normal supershot startup techniques at higher plasma current. Compared to standard plasmas with the same global parameters, the sawtooth inversion radius was expanded as a result of the increased current density in the inner region of the plasma. The central q was measured to be in the range 0.75 – 0.80 (± 0.04).

These plasmas were extensively studied using both D-only and D-T NBI. With extensive lithium conditioning applied to the limiter, the high-l_i plasmas exhibited confinement properties very similar to supershots. The lithium conditioning was performed by the standard TFTR technique of pellet injection[11] and, once, by a new technique of evaporative coating *in situ*. This utilized a small oven inserted on a probe into the vacuum chamber between shots which deposited the equivalent of about 50 standard lithium pellets. This technique was successful in enhancing the confinement on the subsequent five or six shots with high-power NBI. Ultimately, however, the major limitation on D-T fusion performance of the high-l_i plasmas during the last run period was the power handling capability of the limiter. At high NBI power in D-T, the influx of hydrogen isotopes and lithium from the edge increased dramatically during the pulse, degrading confinement to the point where it was not possible to reach the β-limit at the highest plasma current. Preliminary experiments were conducted at the end of the last run investigating the use of a radiating boundary, induced by puffing into the plasma small amounts of either argon or krypton, to reduce the peak power flux to the limiter. While the initial results were encouraging, *i.e.* the radiated power fraction could be increased significantly without affecting global confinement adversely, there was not time to develop this technique for use specifically with the high-l_i D-T plasmas.

In order to test the β-limit in the high-l_i regime, it was necessary to reduce both the plasma current and the toroidal field. In a plasma with $I_p = 2.0$ MA, $B_T = 4.74$ T, which achieved a transient confinement time of 0.24 s, a fusion power of 8.7 MW was reached before the plasma disrupted at a normalized-β of 2.35. The evolution of this shot during NBI is compared with that of a high-current supershot producing a similar fusion power in Fig. 6. This shot at reduced current and field was the only high-l_i plasma which reached the β-limit and the only one which disrupted during the NB heating phase.[16] If the power handling capability of the TFTR limiter can be improved through the use of a radiating boundary, or other means, the high-current versions of the high-l_i plasmas already developed should be capable of producing D-T fusion power considerably above 10 MW.

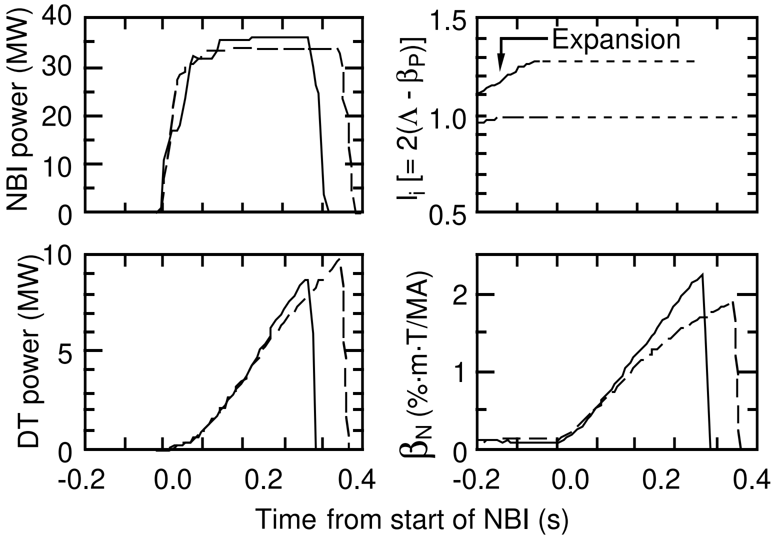

Fig. 6 Comparison of the evolution of high-l_i (2.0 MA, 4.75 T, shown solid) and supershot (2.5 MA, 5.1 T, dashed) D-T plasmas producing similar fusion power. Both plasmas have $R_p = 2.52$ m, $a = 0.87$ m during NBI. The internal inductance calculated from magnetic diagnostic data is extrapolated through the NBI pulse when the plasma pressure becomes anisotropic. The increase in the normalized β-limit is proportional to the increase in l_i.

IV Scaling of DT reactivity and modeling from D plasmas

An important issue for the design of future fusion experiments is the extrapolability of data obtained from experiments with deuterium plasmas to eventual operation with D-T plasmas. There are two types of effects to consider here: effects due to changes in the energy dependence of the reaction cross-sections and effects on the plasma itself resulting from the change in plasma composition, the so-called isotopic effects. While the first type might seem straightforward to calculate, the result can be changed significantly in practice by a combination of subtle changes of the second type, particularly because a plasma is usually subject to multiple constraints simultaneously. For example, in TFTR, a change from D to T NBI is accompanied by a change in beam acceleration voltage, total beam power, beam species mix, power and particle deposition profiles, ripple loss, beam thermalization time, ion and electron heating fractions, and also a change in the underlying confinement of the thermalized plasma.[17] The expected fusion reactivity enhancement in D-T plasmas over otherwise identical deuterium counterparts can be estimated from the ratio of the velocity-weighted fusion cross-sections for DT and DD reactions. For fixed fuel density and temperatures the fusion power ratio, $P_{D\text{-}T}/P_{D\text{-}D}$, of purely thermal reactions reaches an idealized maximum of ~225 for T_i ~ 12 keV but the ratio falls to 150 at $T_i = 30$ keV. In plasmas with a significant population of non-thermal fuel ions from neutral beam injection, the beam-target reactivity enhancement also drops for T_i above 15 keV. Furthermore, in D-T plasmas, the ion temperature is generally higher than in comparable D plasmas, which is a manifestation of the favorable isotopic effect but which actually penalizes the D-T reactivity. As a result, the measured ratio of fusion power in TFTR supershots is ~115 if plasmas with the *same stored energy* are compared. This ratio would be appropriate if the D plasma were at the β-limit, for example. When comparing plasmas with the same *heating power*, the isotope effect on confinement raises the DT fusion power and the fusion power ratio is then ~140. Furthermore, higher neutral beam power can be achieved with D-T operation due to the higher neutralization efficiency of tritium. As a result of this increase in power, the highest DT fusion power is actually 165 times the highest DD fusion power achieved in TFTR. However, it must be noted that to achieve this power ratio, the plasma energy increased from 5.6 MJ in the D plasma to 7.0 MJ in the D-T plasma. This complex behavior is illustrated in Fig. 7. This figure makes use of the fact that in TFTR supershots, in which the plasma energy is dominated by the ion component, a very constrained relationship is observed between the plasma energy and the fusion power output in both D and D-T plasmas.[18] The data in Fig. 7 emphasizes the importance of improving stability limits to achieving high fusion performance and demonstrates that the extrapolation of the highest performance D-only results, which are often limited by stability or power handling, to D-T plasmas is not a simple matter of idealized species substitution.

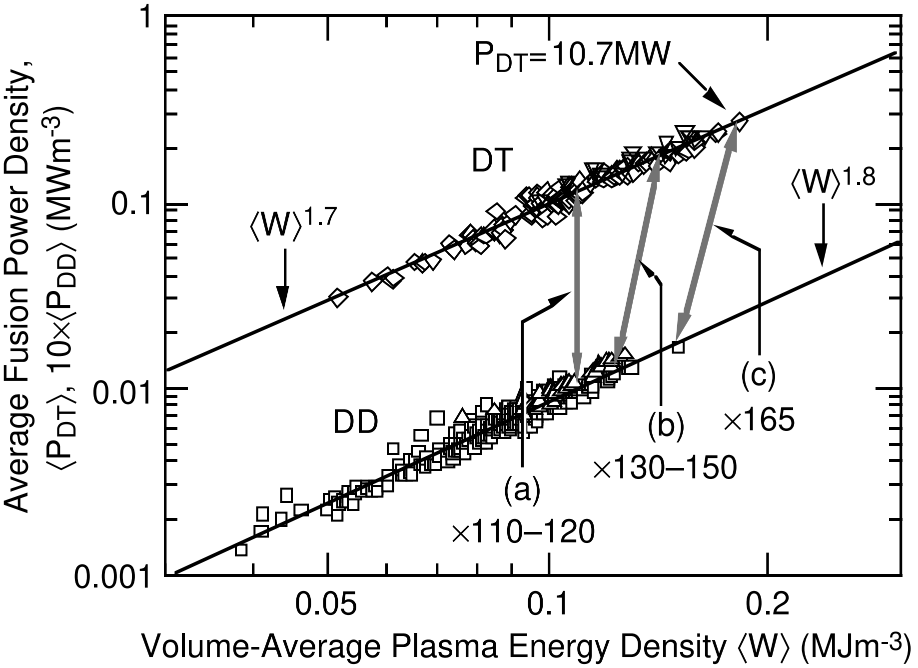

Fig. 7 In NBI-heated supershots and high-l_i plasmas, there is a close relationship between the volume-average plasma energy density ($\langle W\rangle \propto \beta B^2$) and the volume-average fusion power density for both DD ($\propto \langle W\rangle^{1.8}$) and DT ($\propto \langle W\rangle^{1.7}$) reactions. The data is for plasmas with $I_p \geq 2$ MA and volumes 31 – 46 m^3. The D-T plasmas are restricted to those with nearly optimal D-T mixture. The arrowed lines indicate the reactivity ratio achievable under various constraints: (a) for constant β; (b) for constant NBI power, taking advantage of the isotope effect on global confinement; (c) at maximum supershot performance, taking advantage of the higher NBI power available with tritium NBI.

V Alpha-Particle Physics

Alpha-particle physics continues to be a major focus of the TFTR D-T program. Recent experiments in this area include the study of toroidal Alfvén eigenmodes (TAEs) driven by the alpha particles in plasmas with reduced magnetic shear in the central region, and measurements of the effects of sawteeth on the spatial and energy distributions of confined alpha particles.

Despite careful scrutiny, the early D-T plasmas in TFTR, which were predominantly in the supershot regime, showed no signs of any TAE instability attributable to the presence of the energetic fusion alpha particles, despite reaching central β_α up to about 0.3%. Recently, the more comprehensive TAE theory, which was developing in parallel with and driven by these experiments, suggested that by modifying the q profile in the core of the plasma, it might be possible to destabilize the TAE in TFTR.[19,20] This would occur if the gap structure in the Alfvén continuum were more closely aligned to the region of the highest spatial gradient in the alpha-particle pressure. Thus, a search for TAE instability was recently undertaken in plasmas with increased central q, $q_0 = 1.1 - 2.5$ and reduced magnetic shear in the central region. As predicted by the theory, transient modes in the Alfvén frequency range, 150 – 250 kHz, with toroidal mode number n = 2, 3, 4, were observed in D-T plasmas 0.1 – 0.3 s following the end of the NBI heating pulse.[21,22] Over this timescale following NBI, the alpha-particle population remains sufficiently energetic to drive the TAE but the NB-injected ions, which damp the instability, have become thermalized. The TAE has been observed both on signals from Mirnov coils and on a microwave reflectometer signal from the region r/a = 0.3 – 0.4 which coincides with the maximum $\nabla\beta_\alpha$. Typical results for a plasma with q_0 = 1.1 – 1.3 are shown in Fig. 8. The mode rises in frequency as the density at the mode location decays following the NBI pulse. For these plasmas, the TAE was observed when the peak fusion power exceeded 2.5 MW, corresponding to $\beta_\alpha(0) > 0.03\%$ at the onset of the mode. These alpha-driven TAEs have not yet been sufficiently strong to cause detectable losses of the alpha particles.