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PROGRESS IN THE NEUTRAL BEAM INJECTION HEATING EXPERIMENT ON THE TOKAMAK FUSION TEST REACTOR

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The principal heating system for the Tokamak Fusion Test Reactor (TFTR) consists of four beamlines to inject beams of neutral deuterium into the tokamak plasma. We have recently injected beams at total powers up to about 30 MW, and we have achieved ion temperatures in the plasma core of 30 keV and more.

1. Introduction

The Tokamak Fusion Test Reactor (TFTR) is the largest of the current generation of tokamaks in the US, and has as its ultimate goal the study of deuterium–tritium plasmas under conditions near energy breakeven (Q near 1). Q is defined as the ratio of the power released through nuclear fusion reactions divided by the total external heating power applied to the plasma. By far the majority of this heating power is supplied by neutral beam injectors which use large ion sources [1] (developed by Lawrence Berkeley Laboratory) to produce deuterium ions which are then electrostatically accelerated, neutralized, and allowed to enter the tokamak where they reionize, circulate along the magnetic field lines, and transfer their energy to the resident plasma through collisons. These injectors, which consist of four beam boxes, each fitted with a horizontal fan array of three sources, have been described prevously [2]. The beamlines are aimed such that they are nearly tangent to the major radius of the torus.

2. Beam performance

One major recent change to the beam system is that we have reoriented the beamlines so that two of them now inject approximately parallel to the plasma current, while the other two inject in the opposite direction, allowing us to balance the injected angular momentum (and minimize induced toroidal rotation) up to the full power capability of the beam system (the previous configuration featured three beamlines in one direction and one in the opposing direction, limiting the power range over which momentum balance could be maintained). The other major change is that we replaced the short pulse (0.5 s) LBL ion sources with LBL sources capable of long pulse operation (but limited to about 2 s by power handling contraints in the dumps for the residual unneutralized ions). These sources differ from the earlier short pulse sources in that they have water cooled accelerator rails, deeper plasma chambers, and

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most importantly, samarium–cobalt magnets arranged around the plasma chamber in a cusp confinement configuration. Doppler shift analysis of the beam light indicates that the plasma produced in the long pulse sources is composed of a larger fraction of atomic ions than was the case with the short pulse sources (for instance, at conditions appropriate to 90 kV beam extraction the long pulse sources are about 75% atomic, whereas the short pulse ones were about 57% atomic). The higher atomic fraction means that a larger portion of the neutral beam is at the full energy of the accelerator. Using Langmuir probes, we have found the plasma density in these long pulse sources to be extremely uniform (essentially flat over the extraction area). This is presumably due to the cusp magnetic field configuration in the plasma chamber, since the earlier short pulse sources, which lacked this field, exhibited nonuniformities of as much as ±20%. The uniformity of the source plasma allowed us to extract beam at the divergence-optimized perveance over the full area of the accelerator (12×43 cm^2), with the result that we were able to achieve low beam divergences (typically 0.3° in the direction parallel to the extraction rails and 0.7°–1.2° in the perpendicular direction).

These LBL long pulse sources have proven to be robust and predictable in operation; these characteristics, coupled with refinements in operating beam system practices and the gradual shakeout of weak components over time, have resulted in substantial improvements in beam reliability. During the present run period the beams have had an average shot performance factor of 92% (meaning that average beam operating voltage and pulse length supplied were 92% of what was requested). During this same period the overall system performance factor (defined as the actual operating capability compared to a nominal capability of twelve sources at 110 kV) has averaged 84%.

The reliability achieved is in its own right a salient result from the present TFTR experimental run since, in the past, the perceived unreliability of neutral beam systems has often been viewed as one of the impediments to eventually heating reactors with negative-ion based beams.

Although the sources operate well at 2 s pulse lengths, most of our beam injection has been limited to 1 s or less in order to minimize the activation of TFTR. We have injected up to roughly 30 MW of beam power for 1 s at an average accelerator voltage of 108.5 kV. This is the largest amount of heating power ever put into a tokamak plasma by any one means.

3. Recent results with beam injection

During the early phases of the neutral beam heating experiment on TFTR, the plasma energy confinement time behaved according to the predictions of Goldston low mode scaling [3] which leads to relatively unfavorable confinement times with large amounts of auxiliary heating power. Subsequently, as reported at this conference in 1986 [4], we found a tokamak operation mode in which we started with a low density target plasma that was heated and fuelled by the beams to acquire a strongly peaked density profile with a broader electron temperature profile.

This beam fuelled mode was characterized by enhanced energy confinement (2–3 times Goldston low mode) and augmented plasma reactivity (as evidenced by the fusion neutron production). For lack of a better name, this came to be called the "supershot" mode.

Over the past two years we have continued to study these beam fuelled enhanced confinement plasmas, with the main thrust of our effort going into extending the range and reactivity of the supershot mode. We observed early on that in the supershot mode, the energy confinement and reactivity were most enhanced when the injected power was nearly balanced – i.e., when the power injected in a co-going direction (relative to the plasma current) was about equal to the counter injected power. During our 1986 and 1987 experimental runs the orientation of our beamlines (three aimed in one direction and one in the other) limited the power at which balance could be maintained to roughly 14 MW.

The beamline reorientation which took place prior to the 1988 experimental run has allowed us to maintain approximate balance at any power level. This has allowed us to exploit the supershot mode at higher tokamak plasma currents, achieving higher nuclear reactivities.

Fig. 1 shows Q_{DD} as a function of balance of the injected neutral beam power. Q_{DD} is the ratio of the power released through fusion reactions between deuterons to the beam heating power. For these plasmas the equivalent Q_{DT} (the Q that would be obtained if the plasma were an approximately equal mixture of

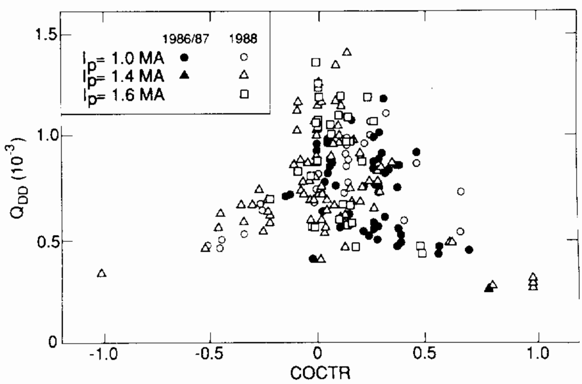

Fig. 1. Comparison of recent results from TFTR with data from 1986 and 1987, showing Q_{DD} vs the balance of the injected power.

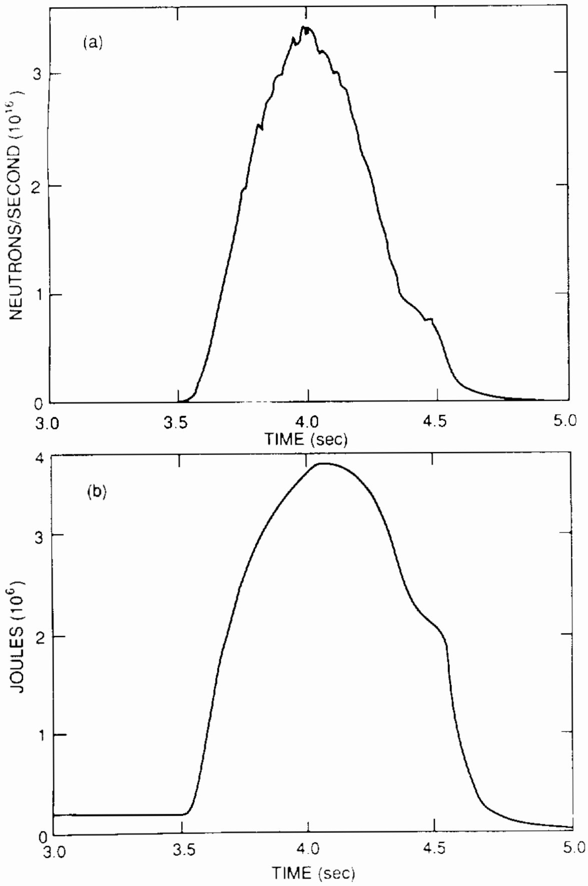

Fig. 2. Neutron source strength and plasma stored energy during a supershot.

deuterium and tritium) is roughly 200 times greater than Q_{DD}. During some of our best shots so far the equivalent Q_{DT} was about 0.29. At our highest heating powers the achieved reactivities have been such that, if the plasma had been equally mixed deuterium and tritium, the fusion reactions would have been releasing around 8 MW or more. The "coctr" parameter in fig. 1 is defined as coctr $= (P_{co} - P_{ctr})/(P_{co} + P_{ctr})$, where P_{co} and P_{ctr} are the co-injected and counter-injected powers. It is apparent that the best shots (highest Q_{DD}) achievable at varying values of the coctr parameter define an envelope peaking at near-balanced injection, but with the optimum appearing to occur perhaps where there is just a little more co-injected than counter-injected power.

Fig. 2 shows the time dependence of the neutron emission and the plasma stored energy during one of the more reactive shots. Beam injection begins at $t = 3.5$ s and ends at about $t = 4.5$ s. The rollover in reactivity and stored energy which begins a half second after the start of injection is correlated with an influx of carbon at that time leading to radiative cooling of the plasma.

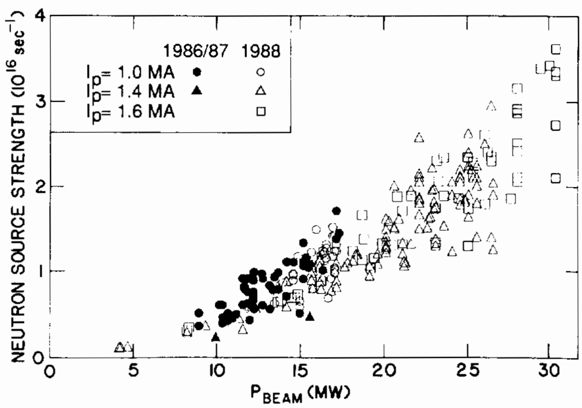

Fig. 3. Comparison of recent results from TFTR with data from 1986 and 1987, showing the neutron source strength vs the injected beam power.

During the present experimental run, this carbon influx has been a common problem due to a damaged graphite tile on the inner wall limiter. On shots where we avoid the large carbon influx the rollover is delayed by as much as another 200 ms, at which point the decline is usually associated with an increase in magnetohydrodynamic activity in the plasma. At more modest beam powers (20 MW) the stored energy and reactivity reach a steady state after about 0.5 s, and remain approximately constant until the end of the beam pulse.

Fig. 3 shows the neutron production rate as a function of the beam power. These shots correspond to varying values of the coctr parameter and of the plasma current. The best shots at each beam power (P_b) define a curve which is increasing as $P_b^{1.8}$. Our present expectation is that the maximum power at which we will be able to achieve reliable operation will be around 32 MW.

These supershots have also been characterized by very high ion temperatures. Fig. 4 shows an ion temperature radial profile, peaking at about 30 keV (1 keV =

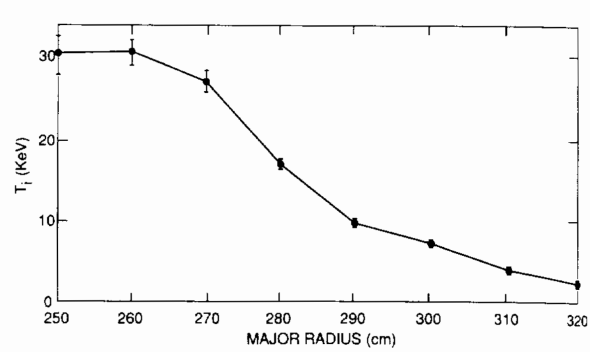

Fig. 4. Ion temperature radial profile for a typical good supershot as measured by charge exchange recombination spectroscopy.

11 600 000 ° C). Shots of this sort (including others in excess of 30 keV) yield the highest temperatures yet produced in a tokamak.

4. Conclusion and future plans

We have extended the supershot regime to higher beam powers and plasma currents, achieving in the process higher plasma reactivities, ion temperatures, and stored energy.

While we are continuing with the present studies in deuterium plasmas, we are now making preparations to produce tritium neutral beams in two of the beamlines during the final deuterium–tritium phase of TFTR (presently scheduled for 1991). The use of tritium in half the beamlines (and deuterium in the others) appears to be necessary to ensure that the reacting core of the plasma will have the proper isotopic mixture in this beam fuelled mode.

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