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EXPERIMENTAL RESULTS FROM DETACHED PLASMAS IN TFTR

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Detached plasmas are formed in TFTR which have the principal property that the boundary to the high temperature plasma core is defined by a radiating layer. This paper documents the properties of TFTR ohmic detached plasmas with a range of plasma densities at two different plasma currents.

1. Introduction

On several tokamaks [1–5], it is possible to form a plasma where most (and probably all) of the input power is radiated from the plasma periphery. Often these plasmas have been called "detached" since the radiating periphery of the plasma can separate from the limiter. Most of the published literature has been concerned with the relation between these detached plasmas and the disruptive instability. Our experiments on TFTR have indicated that these plasmas have other, unique features including:

(a) low quantities of high Z impurities in the plasma [5],

(b) small heat deposition on the limiter and nearly uniform power loading on the entire wall of the vacuum vessel, by radiation,

(c) the simplification of the plasma transport analysis due to the poloidally and toroidally symmetric nature of the detached plasma, and

(d) the implication of an entirely new plasma boundary condition with its implicit hope that the global plasma transport can be influenced in the manner of the H-mode and Z-mode.

In a previous paper, we documented one technique used to form a TFTR detached plasma. In this paper, results from about 50 ohmically heated, detached plasmas are presented with the emphasis on the influence of the plasma current and density on the characteristics of the detached plasma. Further work is continuing on neutral beam injection into the detached plasma which will be reported elsewhere.

2. Experiment

On TFTR, the detached plasmas can be produced when the current is reduced while the density is maintained by gas puffing. During the current reduction, the plasma usually experiences a MARFE [6] and the plasma subsequently detaches [5]. So far, we have not experimented with alternative formation methods but have exploited the current rampdown technique since it is reproducible. In this paper, we examine the effect of different plasma currents and the plasma density levels on the steady-state detached plasma. The effect of the plasma current can be seen on the plasma shown in fig. 1 where the plasma current was increased after the detached state was formed. The increase in the plasma current resulted in an expansion of the plasma minor radius (fig. 1). During the initial stages of the current rise, the peak edge emissivity decreased while the plasma edge was expanding at its fastest rate. The radiating ring (detached state) was maintained even though the plasma current rose to the value (1.2 MA) at which the plasma was initially attached.

The minor radius of the plasma is defined as either the peak of the Abel inverted radiation profile or the edge of the electron temperature profile which are about equal (fig. 2). The electron temperature in the region between the radiating layer and the limiter is below the present TFTR Thomson Scattering system minimum detectable electron temperature of about 100 eV. These low temperatures mean that essentially all of the plasma current is carried inside the core plasma.

From the bolometer diagnostics, it appears that the plasma minor radius has begun to shrink considerably during the MARFE which precedes the detached state. For the series of plasmas like those in fig. 1, the plasma minor radius is about 10 cm from the limiter when the radiation has become symmetric. Although the limiter q value increases, the sawtooth inversion radius (fig. 1) is a sizeable fraction ($\approx 40\%$) of the minor radius.

The density in the boundary plasma as measured using the 9 channel infrared interferometer has been found to be about 5×10^{12} cm^{-3} (fig. 3) which is a result substantially in agreement with density measurements on DITE [3] for the density in the boundary plasma between the radiating layer and limiter.

We define a detached plasma as one in which the total radiated power essentially equals the input heating power so that detachment means that the limiter does not take the main power load. In fact for TFTR, we

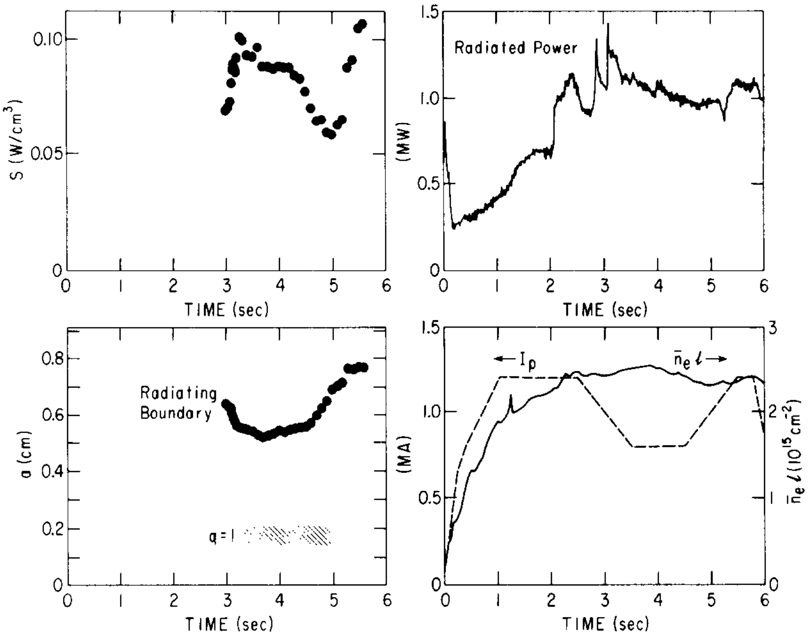


Fig. 1. Evolution of a detached plasma with an increase in plasma current in the detached state. Parameters include the peak radiation emissivity (S) at the radiating boundary, the radius of the radiating boundary, the sawtooth inversion radius, the plasma current, the total radiated power, and the electron density.

presently have a slight excess of output power over input power by about 200 kW (fig. 4). By this definition, it is unclear whether the plasma becomes detached during or after the MARFE. The transient nature of the MARFE makes it difficult to determine the input power.

3. Results

Increasing the plasma current once the plasma is already in the detached state results in an expansion of the plasma minor radius (figs. 1 at 4.5 to 5 s). Interestingly, the peak power in the radiating boundary at first decreases during the expansion and then increases (fig. 1). The result of an increase in the electron density due to gas puffing (fig. 5) is a decrease in the minor radius with a transient increase in the edge (peak) radiated power.

A best fit (fig. 6) to all the steady-state ohmic plasmas indicated a scaling of the plasma minor radius

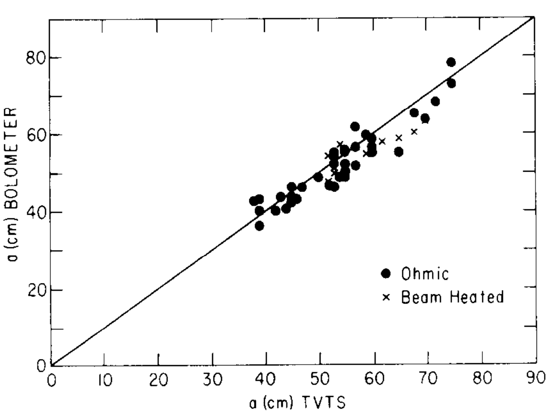


Fig. 2. Comparison of plasma minor radius as defined by the peak of the radiation in the boundary and by the edge of the electron temperature profile. All ohmic and beam heated cases are shown although beam heated detached plasmas are not further discussed in this paper.

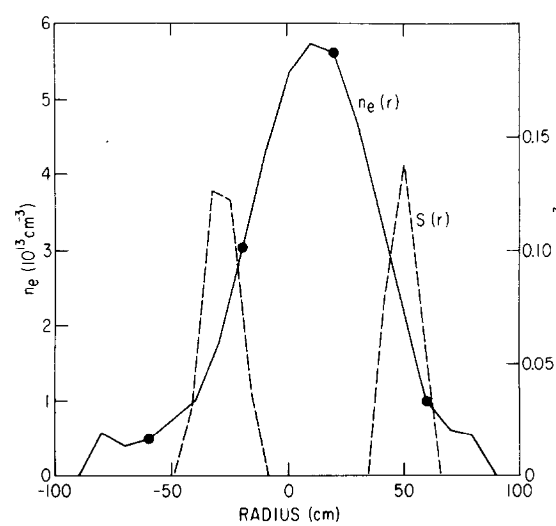


Fig. 3. Radiated power profile and electron density profile for a detached plasma.

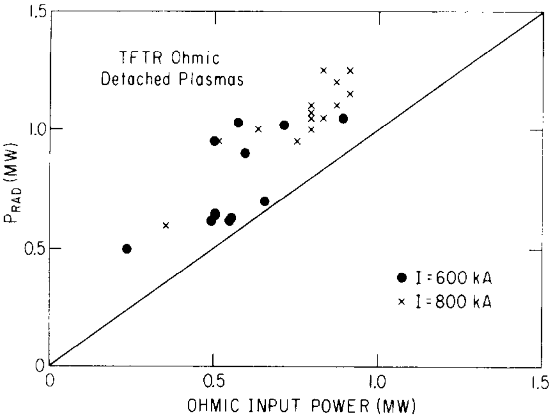


Fig. 4. Total radiated power compared to the ohmic input power. We interpret the over accountability of power as a calibration uncertainty.

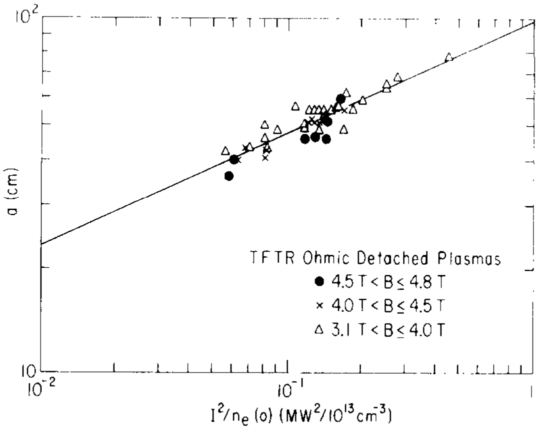
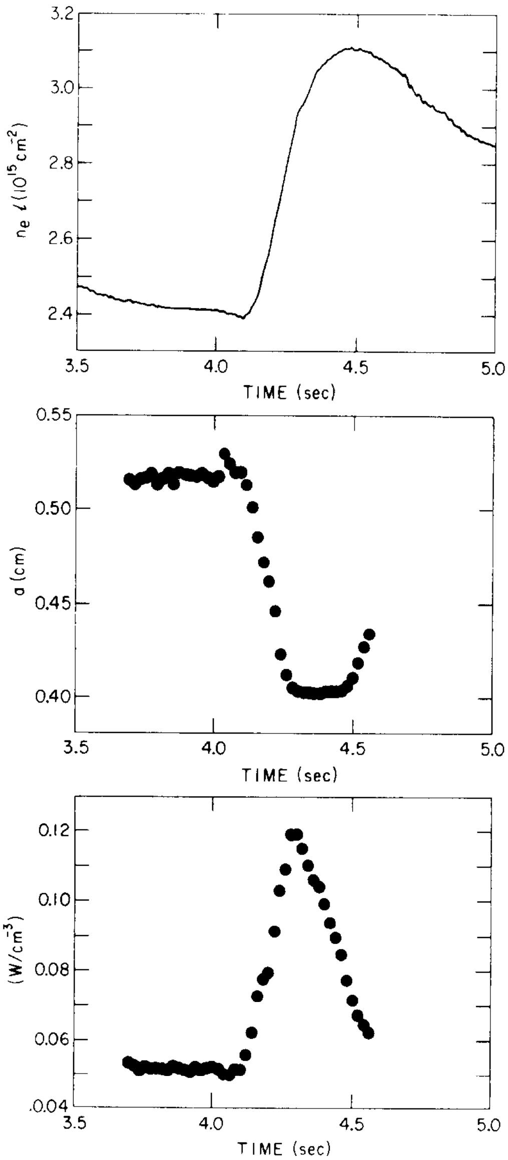


Fig. 6. Best fit to the plasma minor radius as a function of plasma current and electron density with toroidal magnetic field used to define the different symbols.



with plasma current and central electron density as

$$a \propto I^{0.64 \pm 0.05} n_e(0)^{-0.3 \pm 0.04}. \tag{1}$$

The symbols in fig. 6 represent different toroidal fields and the toroidal field dependence is smaller than the scatter in the data. Many of the TFTR ohmic detached plasmas have been obtained at plasma currents of 0.6 or 0.8 MA with central densities in the range of 1.5 to 6.5×10^{13} cm^{-3}. In figs. 7 and 8, the characteristics of these plasmas have been plotted as a function of the central electron density with the different symbols indicating the two plasma currents (0.6 or 0.8 MA). From these data, the minor radius was smaller for larger electron density or smaller plasma current (fig. 7). The total radiated power increased when either the density or the plasma current was increased (fig. 7). However, the peak of the radiated power emissivity at the plasma boundary dependent only on the electron density and not on the plasma current (fig. 7). We interpret the increase in the minor radius with plasma current at constant density as the volumetric response of the plasma to increase the radiated power under the constraint of constant radiating emissivity at the plasma periphery.

The q values at the limiter clearly depend trivially on the plasma current while the q values at the plasma edge are surprisingly independent of current and decrease with increased density down to cylindrical values approaching two (fig. 8). It is likely then, that MHD constraints are also important in defining the minor

Fig. 5. Evolution of plasma density, plasma minor radius and peak radiation emissivity for a detached plasma with a constant current and a short gas puff. The deuterium plasma had a toroidal magnetic field of 4 T, current of 0.8 MA, and major radius of 2.65 m.

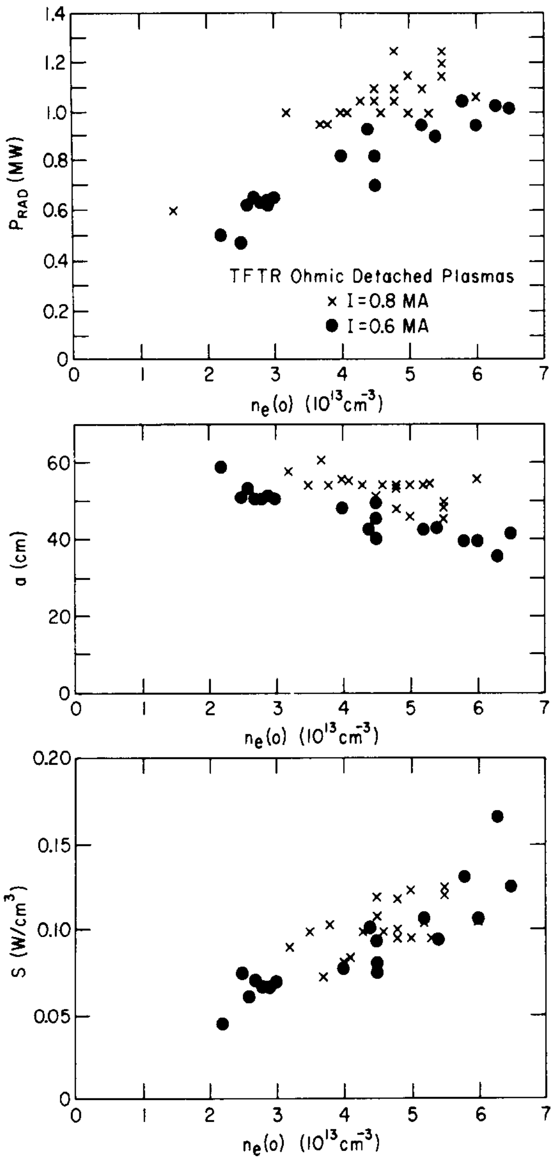


Fig. 7. Total radiated power, plasma minor radius, and peak radiation emissivity, S, as a function of the central electron density for detached ohmic plasmas at 0.6 MA (O) and 0.8 MA (×).

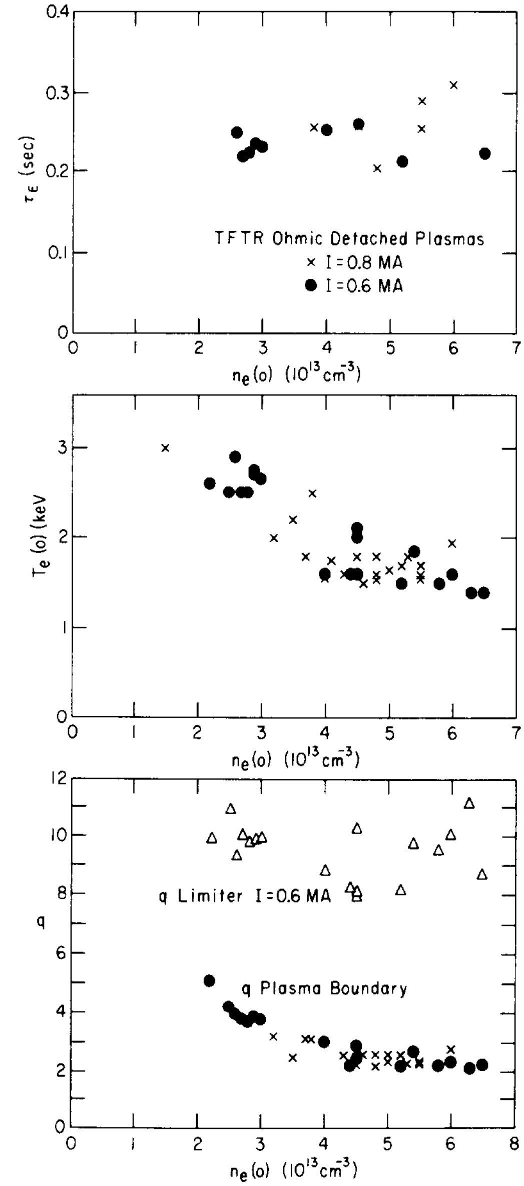


Fig. 8. Gross energy confinement time, central electron temperature, and q values as a function of the central electron density for detached ohmic plasmas at 0.6 MA (O) and 0.8 MA (×). The q values are defined at the plasma boundary except for the Δ points which are the 0.6 MA points defined at the limiter. The scatter in the limiter q values at constant plasma current is due to the variation in the toroidal magnetic field.

radius of the detached plasmas (at least at high densities). Experimentally, attempts to further increase the density by gas puffing can cause disruptions. The central electron temperature seems only to depend on electron density and not on plasma current (fig. 8). The confinement times (fig. 8) are in the range of 200–300 ms. We feel that we have not yet established an independent confinement scaling for detached plasmas but do note two important results:

(1) The magnitude of neoclassical ion conduction losses is about 10% of the total power input and thus the detached plasmas are in the regime where ion losses from the core are just beginning to be important. The neutron emission tends to agree with the 1 × neoclassical ion energy balance, however with a scatter of about a factor of two.

(2) The magnitude of the confinement time about equals TFTR ohmic scaling laws ($\tau_E \propto \bar{n}_e q R^2 a$) when q is defined by the radiating boundary of the plasma (fig. 7).

In summary, we have established the influence of the plasma current and plasma density on the minor radius of ohmic detached TFTR plasmas. Attempts to increase the plasma density will need to appreciate the very low q values at the plasma edge. Careful programming of major radius contraction, or plasma expansion through an increase in the plasma current, may allow higher densities to be achieved.

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