JANUARY 1975 MATT-1098

MEASUREMENT OF THE ENERGY BALANCE IN ATC - TOKAMAK

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DISCLAIMER

(I) INTRODUCTION

There are three major energy loss mechanisms in a tokamak: radiation loss; energy loss associated with fast neutrals as a result of the charge-exchange process; and the energy loss associated with charged particle diffusion and thermal conduction. The first two mechanisms occur somewhat uniformly throughout the surface of the plasma, while the charged particle loss should occur mainly at the limiters. In our experiment on the ATC tokamak [1] the energy losses to the limiters and through the plasma surface were monitored. The temperature of the limiters was measured by thermocouple and thermistor, from which the total energy loss to the limiters could be calculated. However, there was no time resolution of the energy deposition because of the high noise level at the limiters. To measure the radiation and the charge exchange losses a bolometer was devised out of a thick film flake thermistor, which had a time resolution on the order of 1 millisecond. Several points were concluded from our measurements: (1) the total loss from the plasma surface (radiation and charge-exchange) in a normal discharge with or without disruption was always less than 40% of the total energy input; (2) for a normal discharge (40-45 msec duration) or a discharge with a short life (5-10 msec) the absolute level of the surface energy losses was relatively constant, i.e., within a factor of 2. On the other hand, the limiters detected either a major portion of the input energy for a normal discharge or a negligible portion of the input energy for a short-lived discharge

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ABSTRACT

Gross properties of the energy balance in the ATC tokamak have been investigated. During the quasi-steady state phase of a normal discharge, the major part of the energy loss was found to be to the limiters. Radiation and charge-exchange play minor roles during this quasi-steady state phase, but are nevertheless the dominant loss mechanisms at the termination of a discharge; and account for a substantial portion of the stored poloidal magnetic energy associated with the plasma current.

This work was supported by USAEC Contract AT(11-1)-3073.

(3) with the occurrence of a disruptive instability the rate of energy flow to the bolometer approximately doubled; (4) at the termination of a normal discharge without disruption there was an increment in the integrated flux to the bolometer which could not be accounted for by the plasma kinetic energy only and must have included a substantial part of the stored poloidal magnetic energy as well; (5) the addition of a small amount of neon caused a substantial increase in the radiation loss.

(II) INSTRUMENTATION FOR THE ENERGY MEASUREMENT

Under the uncompressed normal operating conditions of the ATC-tokamak the net energy transferred to the plasma and to the poloidal field of the plasma current is about 4-8 kJ per pulse. This amount of energy must escape to the wall from the plasma surface (area $\simeq 5 \times 10^4 \mathrm{cm}^2$) and/or be deposited on two rail-type limiters (mass ≈ 1kg). The limiters are made of molybdenum or stainless steel bars with dimensions as shown in Figure 1. These limiters are electrically insulated from the vacuum vessel and their thermal relaxation time constant is much longer than the time between discharge pulses. For normal operation the temperature of the limiters increases pulse by pulse until it reaches about 150°-200° C. Corrosion and ablation of the limiters are nevertheless negligible. Thus, the per-pulse temperature rise of the limiters is an accurate indicator of the energy deposition. Each of the limiters was instrumented with a thermocouple and a thermistor.

Also shown in Figure 1 is the design of the bolometric probe. The basic element of this probe was a VECO "thinistor," which is a thick film flake thermistor made of boron-doped, P-type silicon semiconductor of 40 microns thickness. The thinistor was surface-mounted in the center of a disc of anodized nickel foil 3 cm in diameter and 25 microns thick. The nickel disc was then sandwiched by two 2-cm-inner-diameter copper rings with good thermal contact to the nickel foil. There were also ten layers of electroformed mesh with different size concentric holes cut so as to fit the composite transparency to a Bessel function $J_0\ (\frac{r}{a}\chi_0)$, where a is the radius of the nickel foil (1 cm in our case) and χ_0 is the first zero of the Bessel function J_0. This mask was designed to cut down the higher modes in the temperature decay, so that its time behavior was derivable from the time constant of the fundamental mode alone. The sensitivity threshold of the probe could be as good as 1 erg/cm^2 in low noise conditions, the resolving time was less than 5 msec, and the temperature decay time for the lowest mode was about 2 seconds, so that the probe acted as an integrator of the impinging energy flux. Calibration with an Eppley thermopile (Model 16-J) indicated that the absorption coefficient of the bolometer was about 0.9 for a mercury source, and it was estimated that the absorptivity for UV and soft x-rays was close to unity. However, it is not yet clear how the charge-exchange fast neutrals can be separated from the radiation loss. Attempts at making an aluminum oxide thin film (~ 0.05 micron) filter to eliminate the fast neutrals did not give quantitative results, but qualitative indications were that the bolometer measured a substantial amount of fast neutrals also. That moving away from the plasma surface caused no significant change (< 10%) in the calibrated power input indicated that the plasma charged particles did not play any important role in the bolometric measurement. A bolometer placed close to the limiters and another about 180° in the toroidal plane away from the limiters measured within 15% of the same value, and gave no consistent indication of a higher energy loss rate near the limiter.

(III) RESULTS AND DISCUSSION

The input power due to the ohmic heating can be calculated from voltage and current measurements such as shown in Figure 2. In the ATC tokamak the voltage loop is at 34 cm minor radius and the plasma has a minor radius of about 17 cm, so that there is considerable leakage inductance in addition to the self-inductance of the plasma, both of which have to be corrected in order to get an accurate resistive voltage measurement. For convenience of comparison the energy "throughput" was calculated from the following formula:

$$W_{\text{thruput}} = \int_{t_1}^{t_2} VIdt - \frac{\mu_\circ R}{4} \left(2\ell n2 + \ell_i + \frac{3}{2} \beta_p\right) \left(I(t_2)^2 - I(t_1)^2\right) \qquad (1)$$

where R is the major radius, ℓ_i the internal inductance, β_p the poloidal beta. Thus we define the energy "throughput" as the total energy flow through the flux surface on which the voltage loop lies less the increase in the poloidal magnetic energy and the plasma kinetic energy (but neglecting changes in ℓ_i and β_p, which tend to remain rather constant). The energy "throughput" corresponds to the expected energy loss to the vacuum wall and the limiters except for the first 10 msec when the plasma is still cold and the potential energy of ionization is therefore a larger fraction of the kinetic energy. For the ATC plasma ℓ_i is estimated to be about unity or higher at the limiter radius and β_p is about 0.3 to 0.5, as determined from the force balance and the Thomson scattering measurements. The correction term in Equation (1) amounts to about 20% of the first term.

An example of a typical discharge is shown in Figure 2. The energy throughput between 10 msec and 20 msec was at a rate slightly less than 200 kW, and between 20 msec and 40 msec about 220 kW, for a total of about 6 kJ. During this high-current period of the plasma the bolometer measured a steady influx of energy of about 1.2 kJ total, which corresponded to only about 20% of the total energy throughput. The rate of energy flow was quite uniform until the termination of the discharge, when a large increase occurred. The uniformity of the energy flow to the bolometer during the discharge signified a constant level of radiation and charge-exchange power loss as estimated earlier for ST [2] and the measured level was in good agreement with the T-3 results [3]. However, the large increase of energy influx at the termination of the discharge required careful scrutiny.

As shown in Figure 2, the temperature rise at the termination of the discharge consisted of two parts: a fast rise in 5 msec after the current was sharply reduced and a slow rise afterward for about 50 msec. As we ascertained from various related observations, the total rise including the fast and the slow parts corresponded to the total surge of energy through the plasma surface at the termination of the discharge. This total amount (1.4 kJ) was definitely more than the plasma kinetic energy (about .5 kJ) and could be accounted for as a major portion (60-80%) of the stored kinetic energy plus the poloidal magnetic energy (~1.5 kJ). The above-mentioned observations relevant to this last surge in the bolometric measurement are as follows:

(1) The recombination light as detected in the visible region typically lasts for about 4.7 msec after the current decay. This time duration is about the same as the interval for the fast rise of the bolometer temperature.

(2) The slow rise after the sharp decay of the current is probably due to the fact that the incoming flux was not normally incident on the bolometric surface but at an angle, and therefore, the hottest spot was not at the center and the additional rise was a result of the temperature relaxation of an off-center hottest spot. The duration of the slow rise was quite variable (from 10-50 msec were observed) which implies a somewhat random variation in the location of the hottest spot. That interpretation is supported by streak pictures of the discharge, which show that for a few milliseconds at the end of the

discharge the visible light is much stronger at either the upper or the lower side of the plasma. Since the duration of the slow rise is only a few percent of the temperature relaxation time of the fundamental mode, the final tempertaure should not be significantly affected by the asymmetry of the radiation to the bolometer.

(3) Measurement of $\int VIdt$ at the termination of the discharge showed the total "backflow" of energy to be relatively small (0.5 ~ 0.8 kJ), but to be of the right order to account for that part of the stored energy which was not detected by the bolometer.

Another way that the discharge current can decrease to zero is through a series of disruptive instabilities. For such a case, as shown in Figure 3, the bolometer measured a steady influx of about 1 kJ in the first 30 msec and a sudden surge of almost 2 kJ in the following 10 msec during which the disruptive instabilities occurred. It was found in general that disruptive instabilities were unmistakably related to a higher level of bolometrically measured energy flux. However, there is no way as yet to guarantee the reproducibility of a disruptive instability and in general, it might not be as clear as shown in Figure 3. In this extreme case, a major portion of the total stored plasma kinetic and poloidal magnetic energy was seen to be radiated away from the plasma surface in the last

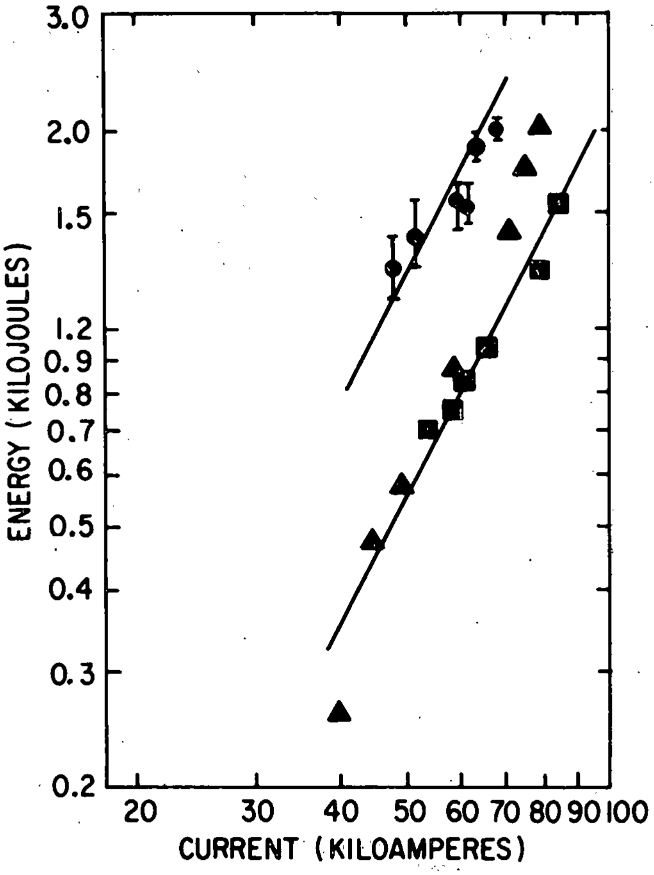

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Fig. 4. Bolometric energy versus the peak discharge current is shown by squares ☐ for a normal discharge and by circles O for a discharge with about 10% neon added to the hydrogen working gas. The triangle Δ shows the total bolometric energy at the termination of a normal discharge versus the current just before the final rapid decay.

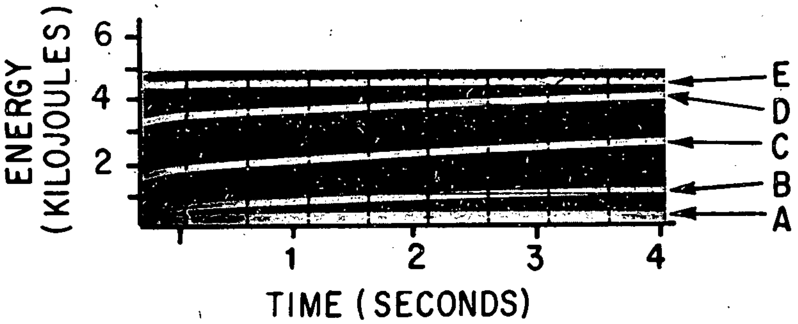

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Fig. 5. Temperature rise of one of the limiter bars is shown versus time after the discharge begins. The temperature rise is calibrated in terms of the energy deposition to the limiter. A and E are for 10 ms discharge pulses, B and D for 25 ms pulses and C is for a 45 ms pulse.

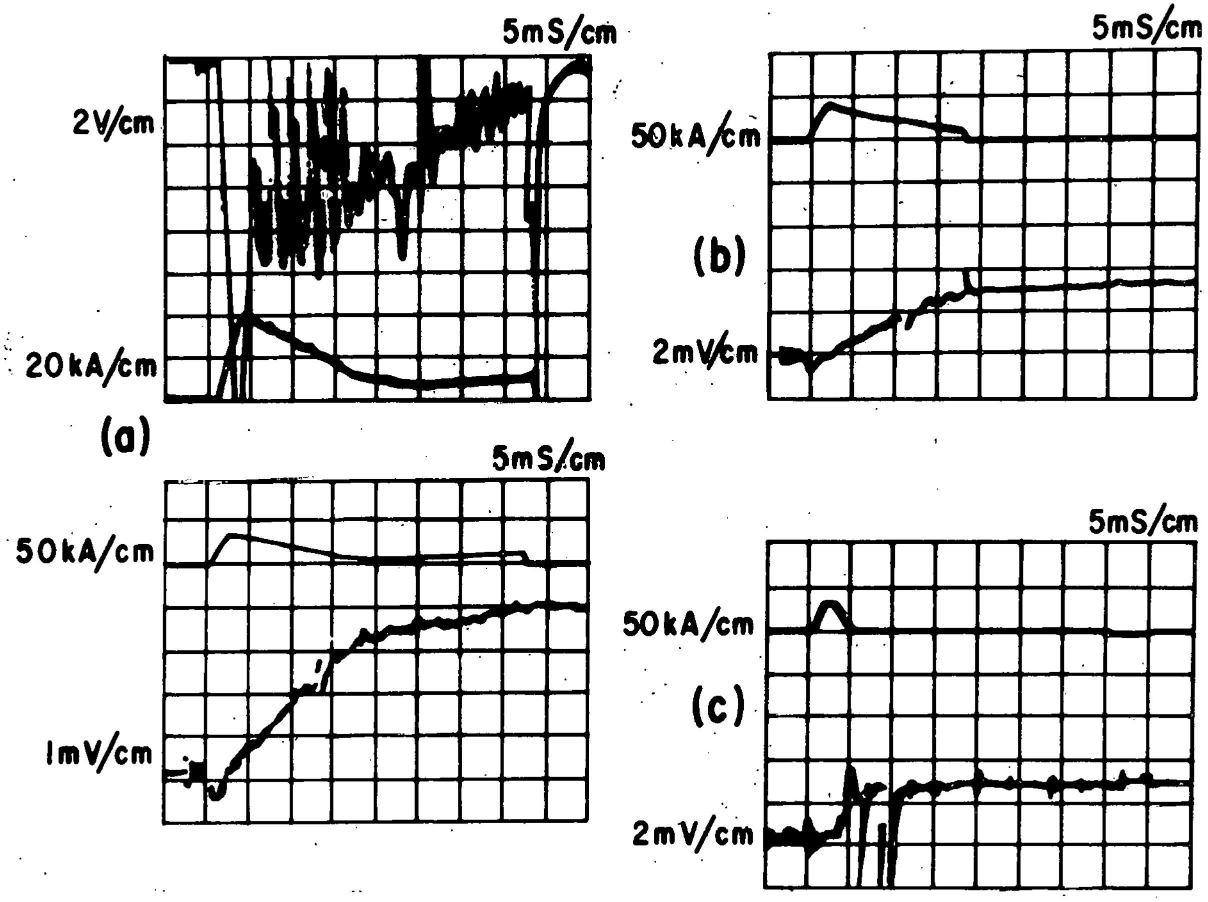

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Fig. 6. The effect of large (20%) neon contamination in the hydrogen working gas: (a) the voltage, current and bolometric traces for the virtually same operating condition but a slight difference in stabilizing vertical field. 1 mV stands for 0.47 kilojoules in bolometric energy. However, in (b) the energy loss is at a somewhat constant level, while in (c) the energy loss occurs in a surge as the current decays.