JANUARY 1976 MATT-1203

# ALUMINUM LIMITER EXPERIMENT IN ST TOKAMAK

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| *Pages | NTIS Selling Price |
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| 1-50 | $ 4.00 |
| 51-150 | 5.45 |
| 151-325 | 7.60 |
| 326-500 | 10.60 |
| 501-1000 | 13.60 |

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# ERRATA

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Therefore the observed differences in the plasma behavior are presumably caused by differences in the radial distribution of current density j(r) and the consequent differences in magnetic topography and of power input.

Because of the positive correlation between the local power input, temperature, conductivity, and current density, the radial distributions of these quantities are indeed sensitively affected by local inelastic collision rates. Thus, minor changes in the plasma composition can produce significant changes in j(r), especially because the effect of the collisions in forming the j(r) profile in a particular discharge is cumulative over several confinement times.

The experimental evidence then shows that the variations of j(r) need not be very dramatic to be significant, or, in other words, that the electron kinetic energy confinement must depend very sensitively on the current distribution.

## ACKNOWLEDGMENT

This work was supported by United States Energy Research and Development Administration Contract E(11-1)-3073.

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## ABSTRACT

In order to investigate the effects of a light-element limiter on plasma parameters, aluminum rail limiters interchangeable with Mo rails were installed top, bottom, and outside directions in the ST tokamak. The inside limiter remained a fixed Mo rail. Compared with discharges produced immediately before and after with the usual Mo limiters, the "aluminum" discharges showed an increase of $T_e$ (by factors of 1.4-2 near the center) and of energy confinement (by factors of 2 to 3 in el. energy/power input, depending on time of observation). $H_2$ and He discharges showed practically identical effects. In plasma composition, the Mo concentration dropped significantly, but Fe only slightly if at all; the Al concentration was about 3-5% (i.e., large compared to the heavier metals), whereas oxygen, about 4 to 8% to start with, dropped to insignificance, probably as a result of Al evaporation. The $Z_{eff}$ from resistivity increased 20-30% although the resistance dropped because of the higher $T_e$. The improved $T_e$ and energy confinement are thought to be the result of cumulative effects of more favorable radial current and power input distributions rather than direct energy losses by radiation.

## 1. INTRODUCTION

In the course of the ST Tokamak experimental program, it was noticed that the achievable plasma properties, such as electron temperature or energy confinement time, showed considerable variations for the same externally controllable parameters, such as toroidal field, ohmic heating current, and initial pressure of the working gas. Gradually such variations were correlated with changes of plasma composition, which could be caused either by previous history (opening the vacuum vessel, especially if accompanied by major additions or deletions of materials exposed to the plasma), or by deliberate additions of various elements (esp. inert gas) for some diagnostic purposes. Parts of this evidence have been published [1-3]; other parts are still in preparation.

The most important features of the problem may be summarized as follows. In all but very few exceptional cases the plasma resistivity is determined by the impurities rather than the working gas (hydrogen or helium)--and, of course, the electron temperature. The impurities may be classified as light (O, C, N, Ne), or heavy (wall or limiter materials, or Kr, Xe additions), depending on whether or not they become fully stripped over a substantial part of the discharge volume. Of naturally occurring impurities, oxygen on the one hand and the wall (Fe, Cr, Ni) and limiter (Mo) materials on the other exhibit a reciprocal behavior: discharges high in oxygen are low in metals. As oxygen becomes depleted in repeated discharges, metal concentrations increase. The process is reversible by discharges using $O_2$ or air as the working gas for a few hundred pulses [4]. Qualitatively similar results have been reported recently from other tokamak programs [5-7].

Discharges with relatively high concentration of light elements ($\gtrsim 10^{12}$ atoms/cm$^3$ with total electron density $\sim 3 \times 10^{13}$ el/cm$^3$) achieved relatively high temperature, hence low power input and long energy confinement time. Discharges with relatively high heavy element concentrations ($\sim 10^{11}$ cm$^{-3}$, i.e., in absolute quantities still low compared to oxygen) have considerably lower temperatures and energy confinement times. In either case total radiation is typically a small (< 30%) fraction of power input [1,2,8,9] and not obviously correlated with the achieved temperature.

The ultimate experiment in ST Tokamak was an attempt to eliminate the heavy elements (Mo and stainless steel) from the plasma without increasing the oxygen concentration. Both aluminum and graphite were intended to be used successively as construction materials for this purpose, but time ran out on ST before the graphite experiment could be realized. In this paper we give a brief summary of the results of the aluminum limiter experiment.

## 2. EXPERIMENT

In addition to the usual set of molybdenum limiters, a movable set of aluminum rail limiters was installed in the top, bottom, and outside positions in the ST in such a fashion that they could be interchanged with the molybdenum limiters. The inside limiter remained a fixed Mo rail at 13 cm from the vacuum vessel center because of limitation of available time for the experiment. Furthermore, 3 mm diameter aluminum wires, mounted on probe drives at five toroidal locations, were installed with the intent of coating the stainless-steel vacuum vessel with evaporated aluminum by feeding the wires gradually into the discharge.

The time history of the experiment, which spanned two days and about 1400 discharges, is depicted in Fig. 1. At first a discharge was established in the usual fashion, with the aluminum limiters retracted to 14 cm each, and the Mo limiters at ± 12 cm vertically, ± 13 cm in the plane of the torus, and with helium as the working gas ($P_o \sim 0.2$ mtorr). The radial electron temperature and density profiles were determined near the time of the peak current (about 75 kA), and the intensities of certain resonance lines of the principal impurities, iron (λ285Å, Fe XV), molybdenum (λ341, Mo XIII), oxygen (λ1033 OVI), and aluminum (λ333, Al X) were measured. It turned out to be a fairly typical low-oxygen, high-metal discharge. The energy confinement parameter (total electron energy, $W_e$, divided by power input, $P_{in}$) and the plasma resistance, $R$ (in units of straight-current Spitzer resistance $R_1$ for a pure hydrogen plasma at the measured electron temperature) are shown in the central part of Fig. 1; the data shown near shot number 100 are typical for this initial condition. The top part of Fig. 1 shows relative intensities of the iron and molybdenum resonance lines.

Although a detailed analysis of the impurity content has not been done here, on the basis of previous experience it is estimated from the line intensities that at the start of the experiment the concentrations of Mo and Fe are about $0.5 - 1.0 \times 10^{11}$ $cm^{-3}$, of O, about $3\text{-}5 \times 10^{11}$ $cm^{-3}$, of He about $6\text{-}7 \times 10^{12}$ $cm^{-3}$, and of aluminum too small to be measured. (Thus, the percentage of oxygen is still fairly high, but it is called a low-oxygen discharge because the absolute concentration is low, and oxygen does not strongly dominate the plasma resistivity, as it does in high-oxygen discharges.) The intensities of the resonance lines shown in Fig. 1 (with wavelengths fairly close together, and in a region where the spectrometer sensitivity is almost constant) are to be taken only as an approximate qualitative indication of the impurity concentration. The actual relationship between the intensity and the concentration also includes electron densities, and the radial diffusion velocities and electron temperature profiles, all of which change slightly with discharge conditions.

At about shot number 170 the aluminum limiters were inserted to the same radii as the Mo limiters. During this time Al X lines became observable with intensities comparable to the Mo and Fe lines, but with no evident changes in the discharge behavior. Between shot numbers 203 and 430 the Mo limiters were retracted in steps, and the vertical B-field adjusted to keep the discharge slightly outside the center in order to minimize interaction with the remaining (inside) Mo rail. As a result, the Mo line intensity dropped by a factor 2-3, and the Al line grew to a level 2-3 times the initial Mo line intensity. The electron temperature and energy confinement time increased significantly, but there was no substantial change in the relative resistance (i.e., the drop in resistance is entirely accounted for by the increased electron temperature, if changes of toroidal curvature effects are neglected). The iron line intensity did not change appreciably, which, with a 20% increase in electron density, indicates at most a small drop of iron concentration.

Between shot numbers 430 and 1200 the various aluminum wires were successively fed into the discharge, a few millimeters at a time, in an effort to reduce the iron (or rather stainless steel) concentration in the plasma. The wires were fed in between discharges, and the first following discharge broke up, apparently as a result of a large density increase. The second discharge following showed somewhat increased Al radiation (perhaps up to twice the levels indicated in Fig. 1), and following discharges were generally well-behaved. There was a general increase--nearly doubling--of the aluminum light, a modest ($\sim$ 30%) increase of density, and a slight further improvement of energy confinement, but the iron concentration steadfastly refused to be reduced. However, the oxygen concentration dropped to a level where measurements became difficult. Undoubtedly the drop of the oxygen concentration compensated to a considerable extent for the increase in aluminum in determining plasma resistivity and electron density. The aluminum concentration at this time is probably near the figures quoted earlier for oxygen: $\sim 5 \times 10^{11}$ cm$^{-3}$.

At shot number $\sim$ 1220, the working gas was changed to hydrogen ($P_o \sim 0.3$ mtorr), with no particularly significant effect on the plasma characteristics. It is this condition that is described below in more detail under "Al limiter". At shot number 1375, the aluminum limiters were moved out and the molybdenum ones put back in the initial configuration. There was an immediate substantial drop of electron temperature and energy confinement. The Al light dropped by about 3 times and Mo light increased 2 to 3 times. The iron light dropped by nearly 2 times and the electron density by about 1.5 times. The relative plasma resistance probably dropped slightly.

At shot number 1415, the working gas was again changed to helium. Aside from a slight increase of density and drop of temperature, there were again no significant changes in the plasma characteristics that could be attributed to the changes in working gas.

During the experiment, the top aluminum rail (which had to be installed by means of a holder with much lower thermal conduction than the other rails) suffered extensive damage by melting and evaporation. As molten drops formed on its lower surface, it was gradually pulled farther out, so as to maintain the current aperture and to put more of the heat load on the lower rail. The more efficiently cooled lower rail escaped practically undamaged, and the outside rail, which is subject to strong runaway electron bombardment during abnormal discharges, showed only moderate damage. In view of the considerable amounts of poorly controllable aluminum vapor sprayed into the plasma, the reproducibility of the discharges was quite remarkable.

## 3. RESULTS

Since the only substantial changes in the plasma parameters resulted directly from the change of the limiter materials, we shall now consider in more detail two discharges just before and just after the change from Al to Mo limiters (shot numbers 1340-70 and 1375-1405 respectively, in Fig. 1).

The time behavior of the ohmic heating current and the toroidal loop voltage (on the ceramic gap in the vacuum vessel) are shown in Fig. 2 for the two discharges, together with the linear average electron density $\bar{n}_e$ (from microwave measurements) and the Al X resonance line intensity. The corresponding Mo XIII line shows a similar time-shape, and an increase by a factor of about 2 (although at lower absolute values, as indicated in Fig. 1). The electron densities are very similar initially, when they are largely due to the hydrogen filling gas, but become noticeably lower in the Mo discharge at later times. Although the reduction of aluminum as a direct source of plasma electrons is undoubtedly a significant part of this density change, the change cannot be used to measure the aluminum loss quantitatively, since other effects (changes in electron confinement properties and perhaps changes in other impurities) may be of comparable importance.

Except during the first 10 milliseconds, the radial distribution of electron densities appears in all cases to be approximately parabolic within the accuracy of measurement; thus the peak densities are 1.5 times the averages given. Figure 3 shows the radial profiles of the electron temperatures, measured by Thomson scattering of laser light, at 70 msec, i.e., close to the peak current in each discharge. Also shown are the inverse rotational transforms q(r), calculated on the assumption of steady-state current distributed according to Spitzer conductivity and with no radial variation of the ion charge and no toroidal curvature effects. The symmetrized $T_e(r)$ curves in Fig. 3 are used for this calculation and for other radial distributions mentioned below.

In the Mo-limiter case the temperature is definitely less and the power input somewhat greater, thus leading to an energy confinement time less by a factor of 2.5. It appears that this difference in energy confinement is to be ascribed primarily to the rather modest variations of the magnetic field configuration, q(r), and of the corresponding current density and power input distributions, as discussed below.

The power transferred to the ions must be comparable in the two cases, or perhaps slightly larger in the case of the "aluminum" discharge (because of the higher density and higher $\overline{Z}$) and it is in any case a small fraction of power input. Radiation losses, although not very accurately known, must likewise be larger in the "aluminum" case. The iron (stainless steel) concentration is about the same in both cases, and, although molybdenum and oxygen concentrations dropped, this would be more than made up for by the increase in aluminum, which is a more efficient radiator than oxygen (11 strongly radiating states of ionization vs 6 in oxygen), and is present in much larger quantities than the lost molybdenum. In view of the lower power input, the fraction of the power radiated is probably significantly larger in the case of the aluminum limiter.

The radial distribution of the radiation is of course expected to be different in the two cases (we speak of "radiation" for simplicity, to mean inelastic electron-ion collisions: local lowering of the electron temperature results not only from radiation but also from ionization which requires kinetic energy to overcome the potential energy of ionization and produces extra cold electrons as well). Aluminum radiates primarily on the periphery, roughly $8 < r < 12$ cm. Farther in it is in heliumlike and hydrogenlike states with considerably reduced radiation efficiency, and near the center it is about 90% completely stripped, emitting only relatively trivial amounts of continuum radiation. Molybdenum and stainless steel ions on the other hand remain practically uniform in radiation efficiency under the present conditions. Therefore it is expected that the "aluminum" case, with stronger peripheral radiation, will force the current density more toward the center of the discharge--in qualitative agreement with the q(r) behavior in Fig. 3.

The unanswered question is why such a modest change in current distribution should cause such considerable changes in the loss of electron kinetic energy. To put the problem into a better perspective, we compare the present discharges with an earlier experiment, where the oxygen concentration was high ($\sim 2 \times 10^{12}$ $cm^{-3}$) and other impurities negligibly small. Thus this case should have a ratio of the peripheral to central inelastic collision rates even greater than in the aluminum discharge.

The essential parameters of the three discharges are compared in Table 1, and the radial distributions of electron energy density, and relative current distributions in Fig. 4. The current and toroidal field are slightly lower in the "high-oxygen" discharge, but this does not affect the comparison appreciably (an 85 kAmp discharge on the same day gave $W_e = 2.1$ kJ, $P_{in} = 200$ kW, $T_e(0) = 2.5$ keV). The electron energies in Fig. 4 are direct measurements by laser scattering except for symmetrizing and slight smoothing of the data. The sharp shoulder of the distribution is due to $T_e(r)$ ($n_e(r)$ is still parabolic), and nearly coincides with the calculated q = 1 surface. The lower curves in Fig. 4 are those of $rT_e^{3/2}(r)$, normalized to the same area, i.e., they represent the current or power input per cm radial shell in a steady-state straight Spitzer-conductivity plasma with constant composition and measured $T_e(r)$. Toroidal trapped particle effects would tend to contract the profiles--as indicated by dots in the case of the high-oxygen discharge, where the effect would be the most pronounced because of the high central temperatures. On the other hand, relative concentration of higher-Z ions toward the center (for which we have no experimental evidence [10]), would counteract this trend, and flatten the profiles. Thus, possibly the actual current profiles might show slightly greater variation in the three cases, but undoubtedly there will remain the general picture of not large differences.

Whether the flattening of the $T_e(r)$ curve and the corresponding bump in the current distribution in Fig. 4, pronounced in the lowest-temperature case, are real, and whether or not they may be connected with MHD fluctuations associated with the $q = 2$ surface are tantalizing questions that have not yet been studied in sufficient detail to warrant discussion here. The central flattening of the $T_e(r)$ profile, evident in the "high [0]" case and beginning to be observable in the "Al-limiter" case in Fig. 4, is certainly real and almost certainly caused by enhanced radial transport due to MHD activity [8,11-13].

The strong dependence of plasma parameters on details of composition is undoubtedly a major cause for the profusion of empirical scaling laws for tokamak discharges. The data in Table 1 and the Figures also show: that the $\beta_p$ can vary considerably even at a fixed current; that the energy confinement is not necessarily correlated with $Z_{eff}$ or resistive "anomaly"; and that the appearance of a flat-topped $q \leq 1$ region, at least one of moderate size, is not necessarily detrimental to energy confinement, nor is its absence indicative of good confinement.

In general, the conclusion from the aluminum limiter experiment is in accord with that of our earlier experiments adding oxygen or neon to the discharge, namely, that the addition of a light element which is totally stripped near the center of the plasma improves the confinement by raising the electron temperature. The principal mechanism appears to be an increase of the central current density by cooling the periphery, although (especially in the case of oxygen additions) a reduction of the heavier impurities may also be significant. The improvement of confinement wrought by the higher temperature easily overbalances any detrimental effects due to the development of a $q \leq 1$ region in the center, at least as long as the latter remains a minor fraction of the total plasma volume.

## 4. CONCLUSIONS

The plasma characteristics expressed in such important parameters as plasma energy, power input, and confinement time, are strongly influenced by relatively minor changes in plasma composition. While radiation, or more generally energy loss due to inelastic electron-ion collisions, is presumably the ultimate cause of the differences, it is not the direct cause. In fact, among the three cases considered, the ratio of radiated power to power input at the time of observation is smallest in the lowest-energy "Mo-limiter" discharge; and even the absolute radiation is probably also smallest in this case.

It would therefore appear that relatively small changes in the current distribution cause large changes in the electron energy confinement which are not a direct result of changes in the radiated energy. This presumably results from a bootstrapping effect between local power input, temperature, conductivity, and current density. It must accordingly be concluded that the electron kinetic energy confinement depends sensitively on the current distribution, since the latter is not dramatically different in the three cases considered above, whereas the electron kinetic energy confinement varies by nearly an order of magnitude.

## ACKNOWLEDGMENT

This work was supported by United States Energy Research and Development Administration Contract E(11-1)-3073.

## REFERENCES

[1] MESERVEY, E. B., BRETZ, N., DIMOCK, D. L., and HINNOV, E., Bull. Am. Phys. Soc. 18 (1973) 1254; also Princeton Plasma Physics Laboratory MATT-1175 (1975).

[2] BRETZ, N., DIMOCK, D. L., HINNOV, E., and MESERVEY, E. B., Nucl. Fusion 15 (1975) 313.

[3] HINNOV, E., J. Nucl. Materials 53 (1974) 9.

[4] BRETZ, N., DIMOCK, D. L., HINNOV, E., and MESERVEY, E. B., Bull. Am. Phys. Soc. 18 (1973) 1253; also Princeton Plasma Physics Laboratory MATT-1175 (1975).

[5] CLAUSING, R. E., EMERSON, L. C., HEATHERLY, L., COLCHIN, R. J., and TWICHELL, J. C., Paper at 22nd Meeting of National Vacuum Society, October 1975 (to be published in J. of Vacuum Science and Technology).

[6] TFR Group (presented by C. DeMichelis) Proc. 7th European Conf. on Controlled Fusion and Plasma Physics, Lausanne, 1975, Vol. II (to be published by Ecole Polytechnique Federale de Lausanne, Switzerland).

[7] SESNIC, S., private communication on Pulsator Tokamak at Garching, Germany.

[8] DIMOCK, D. L., EUBANK, H. P., HINNOV, E., JOHNSON, L. C., and MESERVEY, E. B., Nucl. Fusion 13 (1973) 271.

[9] DIMOCK, D. L., et al., Plasma Physics and Controlled Nuclear Fusion (International Atomic Energy Agency, Vienna, 1971), Vol. 1, p. 451.

[10] VON GOELER, S., et al., Nucl. Fusion 15 (1975) 301.

[11] VON GOELER, S., STODIEK, W., and SAUTHOFF, N., Phys. Rev. Lett. 33 (1974) 1201.

[12] TFR Group (presented by D. Launois) Proc. 7th European Conf. on Controlled Fusion and Plasma Physics, Lausanne, 1975, Vol. II (to be published by Ecole Polytechnique Federale de Lausanne, Switzerland).

[13] DUNLAP, J. L., JAHNS, G. L., and HARRIS, J. H., Bull. Am. Phys. Soc. 20 (1975) 1255.

### TABLE 1

Discharge parameters at the time of current maxima for the two cases in Fig. 2, and an earlier discharge with [0] ≈ $2 \times 10^{12}$ cm$^{-3}$ and negligible other impurities.

| | Mo lim | Al lim | "High [0]" |
|---|---|---|---|
| $B_T$(kG) | 43 | 43 | 37 |
| $I_{OH}$(kA) | 74 | 77 | 65 |
| $q_{lim}$ | 3.9 | 3.7 | 3.8 |
| $V_m$(volt) | 4.6 | 3.7 | 2.5 |
| $P_{in}$(kW) | 345 | 290 | 160 |
| $W_e$(kJ) | 0.49 | 1.0 | 1.5 |
| $W_e/P_{in}$(msec) | 1.4 | 3.5 | 9.5 |
| $\bar{T}_e$(keV) | 0.58 | 0.89 | 0.95 |
| $T_e(0)$(keV) | 1.1 | 1.8 | 2.2 |
| $\bar{n}_e(10^{13}$ cm$^{-3})$ | 1.5 | 1.9 | 2.5 |
| $n_e(0)(10^{13}$ cm$^{-3})$ | 2.2 | 2.9 | 3.7 |
| $\beta_p$(el. only) | 0.17 | 0.33 | 0.69 |
| $R/R_1$ | 3.1 - 4.7 | 4.5 - 7.2 | 4.2 - 6.5 |
| $\bar{Z}$ | 4.3 - 6.9 | 6.6 - 11 | 5.8 - 9.9 |

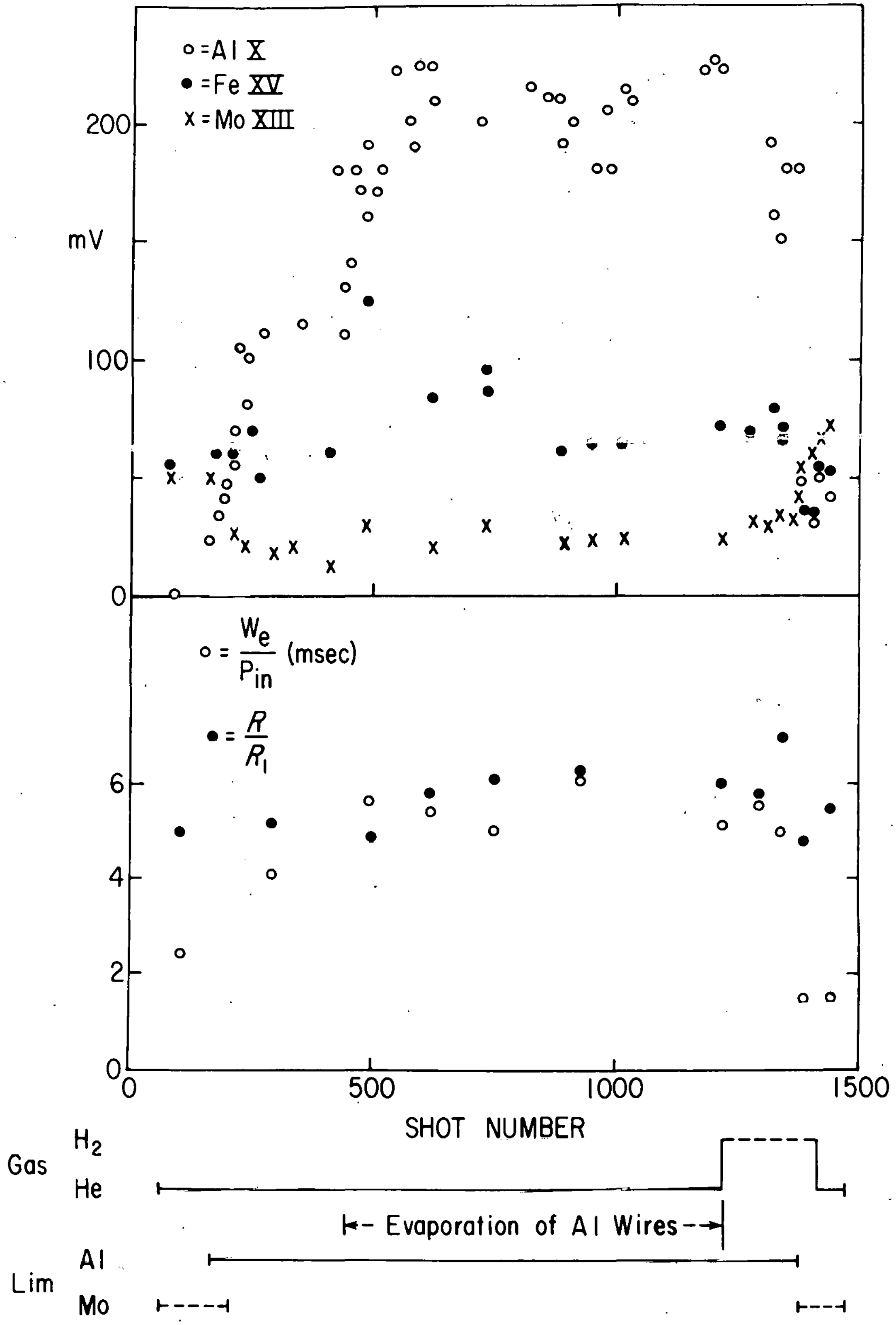

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Fig. 1. Time history of the experiment: bottom, limiter material, working gas, and period of wire evaporation vs shot number; center, energy confinement and relative plasma resistance ($R_1$ = resistance calculated from measured temperature distribution and Spitzer resistivity for Z = 1 plasma); top, relative intensity of various impurity ion resonance lines at the time of current maximum.

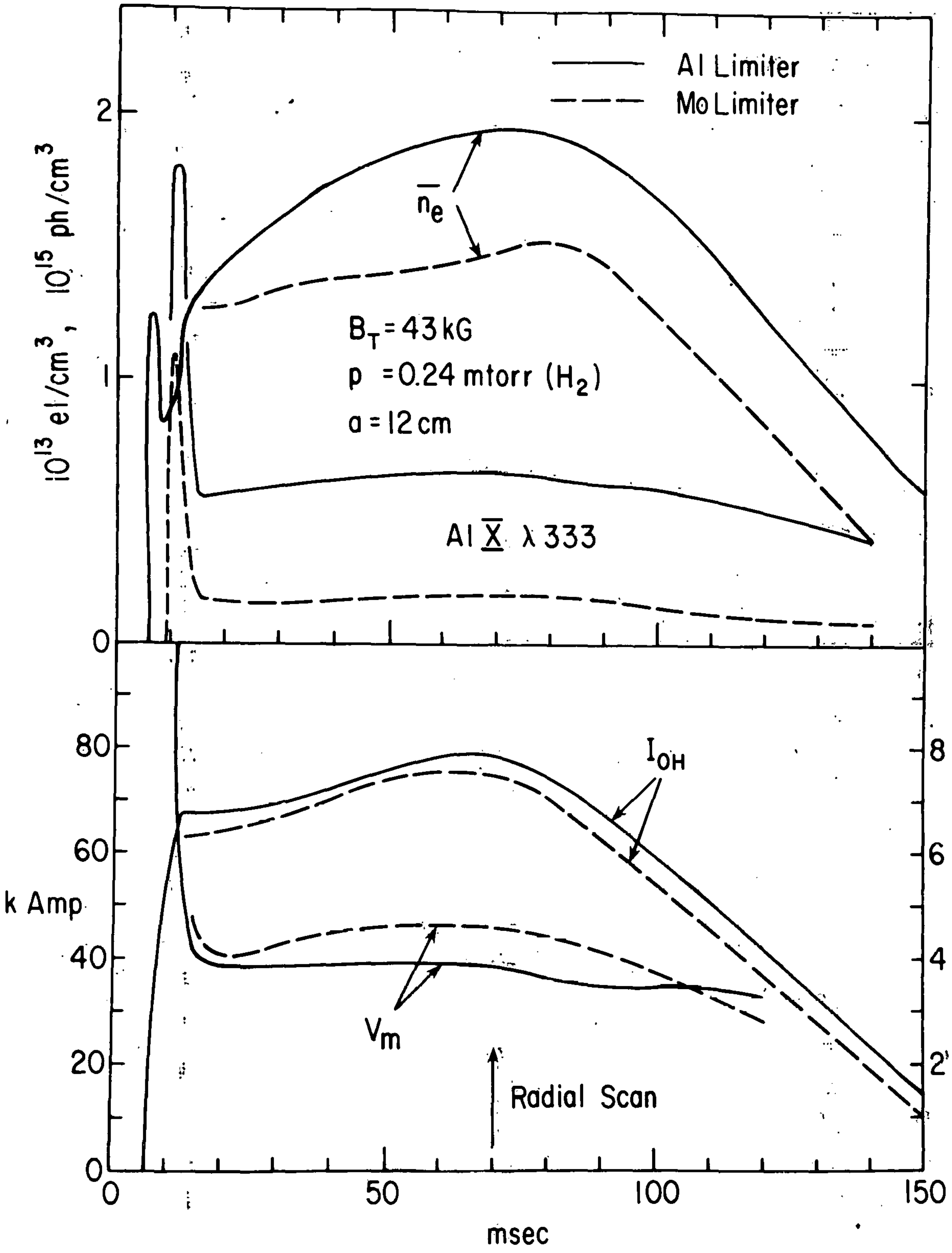

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Fig. 2. Time behavior of ohmic heating current, $I_{OH}$, measured toroidal voltage, $V_m$, average electron density, $\overline{n}_e$, and the Al X resonance line intensity just before and just after changing limiters from Al to Mo, in a hydrogen discharge.

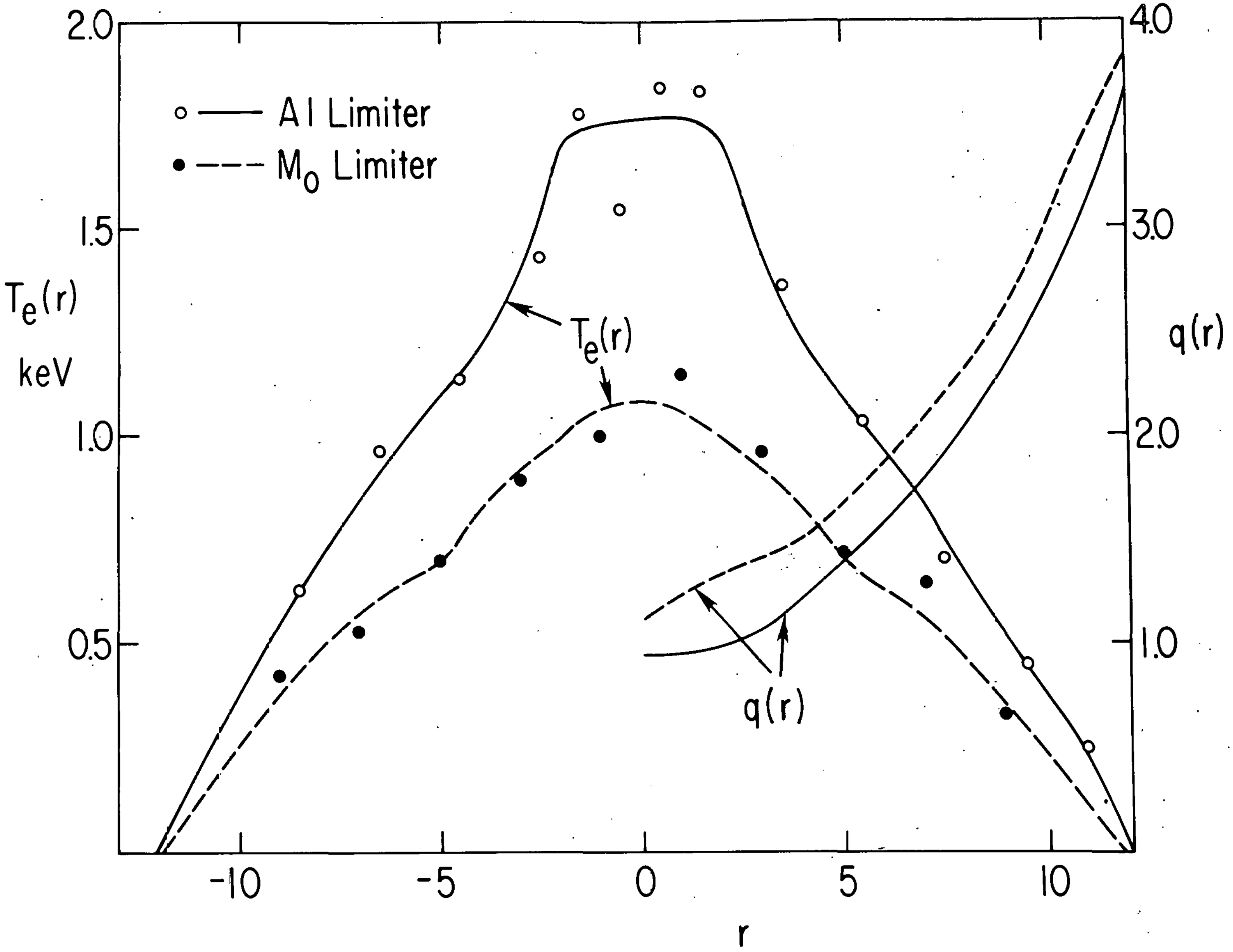

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Fig. 3. Measured electron temperature radial profiles (in the plane of the torus) from Thomson scattering of laser light at the time indicated in Fig. 2 for the two discharges, and inverse rotational transforms, q(r), calculated from the symmetrized $T_e(r)$ profiles shown in the figure.

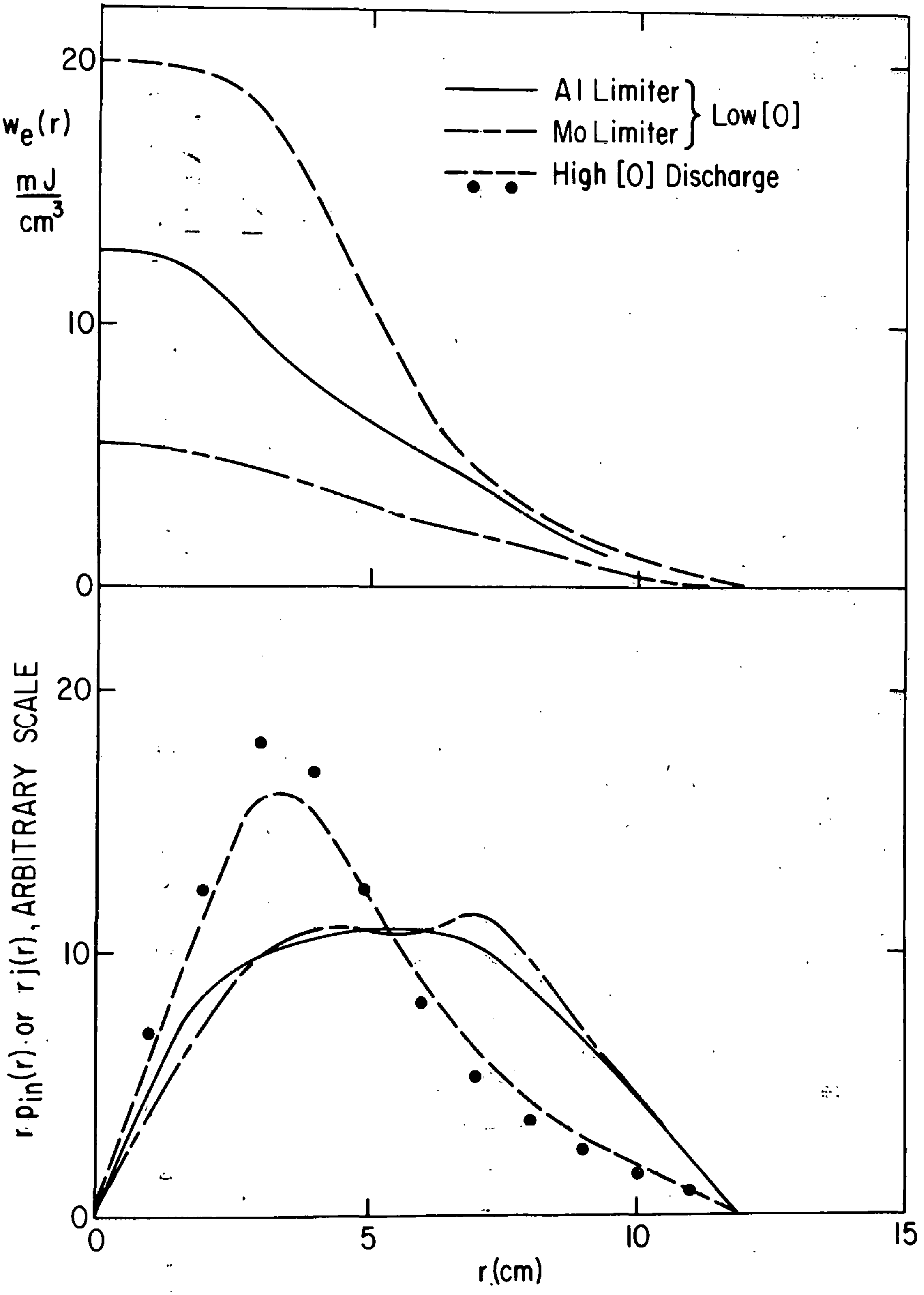

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Fig. 4. Local electron energy densities from Thomson scattering measurements, and relative current or power input per unit cylindrical shell for the discharges in Fig. 2, and for a discharge with high oxygen concentration measured previously.