May 14-18, 1984
CONF-840520--24-Draft

DISCHARGE CLEANING AND PLASMA PURITY IN ISX-B*

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CONF-840520--24-Draft

DE85 001270

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

ABSTRACT

Two simply measured parameters are shown to be useful in characterizing the vacuum vessel and plasma cleanliness and in predicting plasma performance in the ISX-B tokamak. It is demonstrated that the parameter $P_{rad}/\overline{n}_e$, measured at the start of each tokamak discharge, is related to both the available operating space (I_p, $\overline{n}_e$) with Ohmic heating and the energy confinement times achieved with neutral beam injection. An assessment of $P_{rad}/\overline{n}_e$ on both a shot-to-shot and a day-to-day basis then determines the changing cleanliness of the plasma. It is further shown that $P_{rad}/\overline{n}_e$ can be predicted by the results of a residual gas analysis performed after discharge cleaning; specifically, it is directly proportional to the fractional concentration of water vapor.

CHOICE OF CHARACTERISTIC PARAMETER

A parameter indicative of plasma cleanliness is required to ensure optimum operating conditions. The value of $P_{rad}/\overline{n}_e$ at 60 ms has been recorded for each discharge obtained on ISX-B [1,2]. The total radiated power P_{rad} is measured with a bolometer viewing the plasma cross section away from any limiters. The line-averaged density, $\overline{n}_e = \int n_e \, dl/(\int dl)$, is measured with an interferometer. The time of the measurement, 60 ms, was chosen because the plasma is usually free of large MHD oscillations at this point, and it is before any additional heating is applied. Typical conditions at this time are $I_p \simeq 100$ kA, $B_\phi \simeq 1$ T, $\overline{n}_e \simeq 1.5 \times 10^{19}$ m^{-3}. The usual working gas is deuterium, although discharge cleaning is done with hydrogen. Other parameters have been considered (e.g., Z_{eff}) but are more difficult to evaluate.

Figure 1 shows the history of $P_{rad}/\overline{n}_e$ for a period of over one year. Each point represents the average value for the day's operation, typically consisting of ≈100 discharges. The error bars shown indicate experimental scatter about this average; as the average decreases, so does the scatter.

From previous analysis [1,2], the smallest expected values $P_{rad}/\overline{n}_e$ are known, and these are shown in the figure for both discharge-cleaned and gettered vacuum vessels. Using a typical plasma volume and density profile, the smallest value achieved is equivalent to $\lesssim 8 \times 10^{-16}$ W • electron^{-1}, or $\lesssim 5$ eV • ms^{-1} • electron^{-1}. Table I lists events relevant to the vacuum conditions and plasma purity.

OPERATING SPACE

A parameter often invoked to characterize tokamak operation is the region of operational space, I_p and $\overline{n}_e$, that is available. A normalized form $(1/q_\psi, \overline{n}_e R/B_\phi)$ has been used to show that, at least for circular cross sections with Ohmic heating, the density at which disruptions occur increases with decreasing Rq_ψ/B_ϕ and P_{rad} [3]. This suggests the use of a normalized density, $n_R = \overline{n}_e R q_\psi/(16 B_\phi)$, to characterize the approach to optimum conditions. The value 16 is chosen to make $n_R = 1$ for the optimum conditions with Ohmically heated, circular cross-section plasmas ($\overline{n}_e R/B_\phi = 8 \times 10^{-19}$ m^{-2} • T^{-1} at $q_\psi = 2$) [2].

Figure 2 shows the relationship between this normalized density and the normalized radiation $P_{rad}/\overline{n}_e$ for the time period of Fig. 1. Values represent the highest density achieved in an Ohmically heated plasma on each day. The results demonstrate that the maximum density achievable decreases with increasing radiation. A higher density is also possible if elongated plasma cross sections ($b/a = 1.5$) are used. The large number of points beneath the limiting lines is explained by the fact that on many days no attempt was made to optimize conditions for maximum density.

PLASMA CONFINEMENT

Figure 3 shows the global energy confinement time, normalized to a scaling law derived during operation in 1981 with beam heating and a well-gettered vacuum vessel, $\tau_E \propto I_p^{3/2} P_b^{-2/3}$ [4], where P_b is the beam power. The values shown were obtained with beam injection and are representative of the best confinement achieved on a given day. If the scaling law were always applicable, the ratio τ_E/τ_E^{ISX} should always equal 1.0, as it did in 1981. There was a tendency for energy confinement (with beam heating) to be larger on days when the radiation ($P_{rad}/\overline{n}_e$ at 60 ms, Fig. 1) was larger. This is especially noticeable over the period up to day 140. This unexplained trend, previously noted in comparing results with and without gettering [2], has led to the addition of extrinsic impurities, such as neon, to enhance confinement [5].

It is concluded that the parameter $P_{rad}/\overline{n}_e$ is useful in characterizing plasma purity and its influence on both the operating space and the energy confinement times.

CLEANING TECHNIQUES AND RESIDUAL GAS ANALYSIS

Either overnight discharge cleaning in hydrogen [6] or gettering [1,2] is employed to condition the vacuum vessel before tokamak operation. Before the start of tokamak operation, a residual gas analysis is performed.

For a period of about 2 h after terminating the cleaning, while the torus base pressure fell from ~1 x 10^{-4} Torr to ~1 x 10^{-6} Torr, the ratio of atoms with mass 2 (n_2, hydrogen) to those with mass 18 (n_{18}, dominantly water vapour) remained constant within about ±10%. We are guided by the results of Ref. [6], in which the low-Z residual impurity concentration was shown to be proportional to the value of Z_{eff} obtained in plasmas produced later in the day. Figure 4 shows the relationship between $P_{rad}/\overline{n}_e$ obtained during tokamak operation (Fig. 1) and the ratio n_{18}/n_2 before tokamak operation. As long as discharge cleaning was employed the water vapour content was a good predictor of what could be expected from the day's operation. The insertion of various objects into the discharge (limiters or probes) always degraded the plasma purity from the value predicted by the residual gas analysis. Results from such occasions are distinguished.

No correlation between plasma purity and residual gas concentrations was found if more than 2 h elapsed between discharge cleaning and the residual gas analysis (for example, when gettering was to be employed and therefore no discharge cleaning was undertaken). These results suggest that the residual gases present for up to 2 h after cleaning are representative of the discharge cleaning plasma itself and that the discharge cleaning plasma is also representative of any consequent tokamak discharges. After 2 h, the residual gases are no longer representative of the cleaning discharge.

It was hoped that monitoring the discharge cleaning plasma itself would allow a prediction of the results of the residual gas analysis, and thus predict the ensuing tokamak performance. However, no correlation was found between simply measurable parameters of the discharge cleaning plasma (e.g., resistivity, oxygen line emissivities) and resulting tokamak purity.

We can now use the two parameters $P_{rad}/\overline{n}_e$ and the ratio n_{18}/n_2 to characterize the cleaning process used. After a major opening of the vacuum vessel (say, more than one week to air) it takes between 10 and 15 days of overnight cleaning and daytime tokamak operation to establish clean conditions. Following a short opening (e.g., 2 h to dry nitrogen), from one to three days are required to establish clean conditions.

CONCLUSIONS

Even though the parameter $P_{rad}/\overline{n}_e$ is dependent on many plasma characteristics, such as the radiation and density profiles themselves, it is well correlated with both the available operating space of Ohmically heated plasmas and the confinement time of beam-heated plasmas. As such, it is a readily available and useful monitor of plasma purity and its consequences. Variations of this parameter on both a discharge-to-discharge and a day-to-day timescale have formed the basis for halting operations and initiating either discharge cleaning or gettering.

If discharge cleaning is employed, it is possible to predict the plasma purity by monitoring the fractional concentration of water vapor, n_{18}/n_2. This allows an assessment of when the vessel is clean enough to allow good tokamak operation. Three regimes are distinguished, namely a) low concentration, ($n_{18}/n_2 < 4\%$ for ISX-B) after which high density tokamak operation can be expected, b) intermediate concentration ($4\% \lesssim n_{18}/n_2 \lesssim 6\%$ for ISX-B) after which reduced density operation, but high confinement times, can be expected, and c) high concentration (>6% for ISX-B) after which tokamak operation is severely restricted by x-ray production and gross MHD activity.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the members of the ISX-B operations and support staff for their invaluable contributions, in particular T. F. Rayburn and J. L. Yarber. Also, C. E. Bush, C. H. Ma, J. Simpkins, and J. Wilgen are thanked for making available their diagnostic data.

This research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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FIGURE CAPTIONS

FIG. 1. The history of the normalized radiation, $P_{rad}/\sqrt{n_e}$, obtained at 60 ms. Relevent occurrences are listed in Table I.

FIG. 2. The normalized density, $\bar{n}_e R q_\psi/(16B_\phi)$, as a function of the normalized radiation for both circular and elongated plasma cross sections (Ohmic heating).

FIG. 3. The history of the normalized energy confinement time, for the same timescale as in FIG. 1 (neutral beam heating).

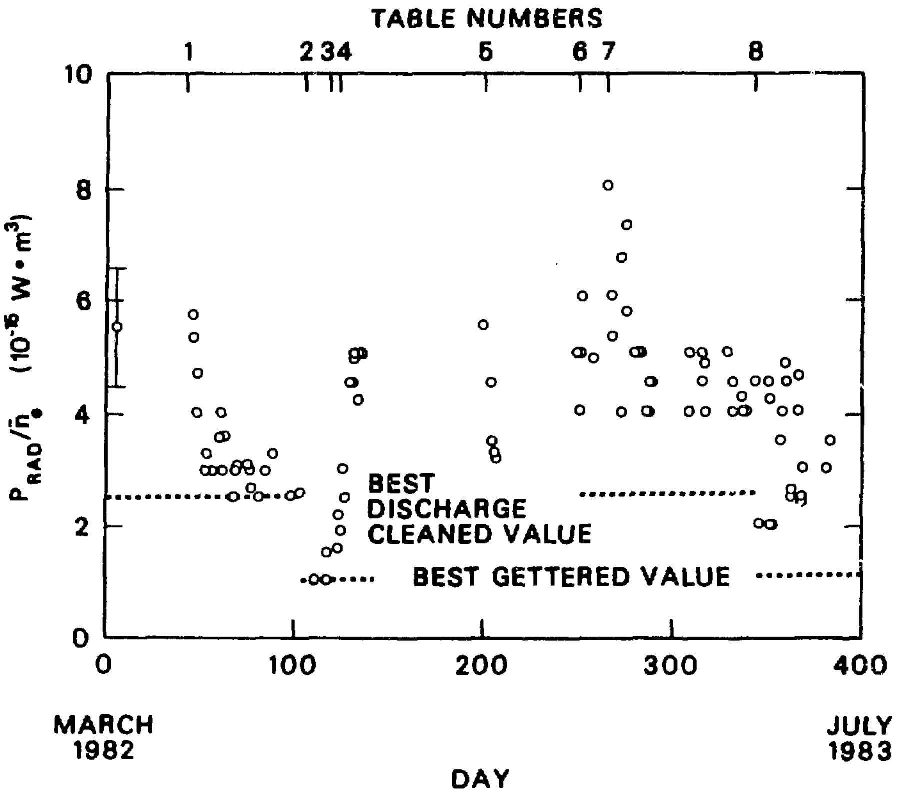
FIG. 4. The dependence of the normalized radiation levels $P_{rad}/\sqrt{n_e}$ at 60 ms on the fractional water vapour concentration n_{18}/n_2 obtained before the start of tokamak operation. Discharge cleaning and gettering are distinguished.

TABLE I. ISX-B OPERATIONS

	Date	Day	Operation
1.	May 1982	0	Initiate operations. Overnight discharge cleaning.
2.	7 July 1982	111	Initiate gettering. Start with 2 titanium balls; continue gettering to day 136, except days 132 and 133.
3.	16 July 1982	120	H_2O into beam line.
4.	22 July 1982	126	Reduce gettering (1 titanium ball); continue at reduced level to day 136.
5.	9 December 1982	200	Restart operations (after installation of new power supply). Use either discharge cleaning or Zr-Al getters
6.	2 February 1983	250	Restart operations. New limiters tested; discharge cleaning overnight.
7.	1 March 1983	267	Operate with small plasma radius and new limiters.
8.	17 May 1983	344	Initiate gettering (2 titanium balls).

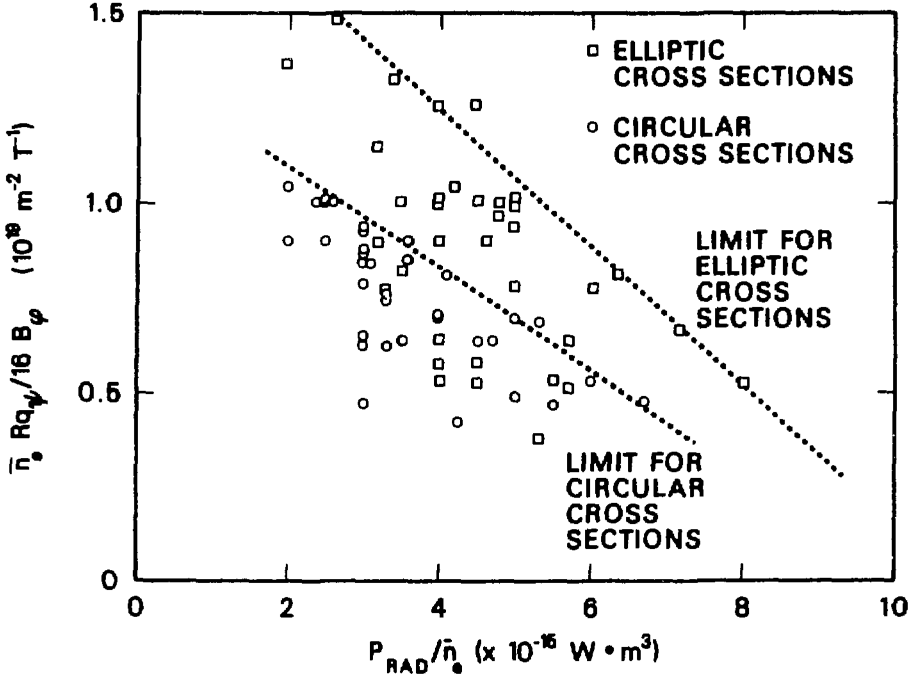
NORMALIZED RADIATION HISTORY

ORNL-DWG 84C-2429 FED

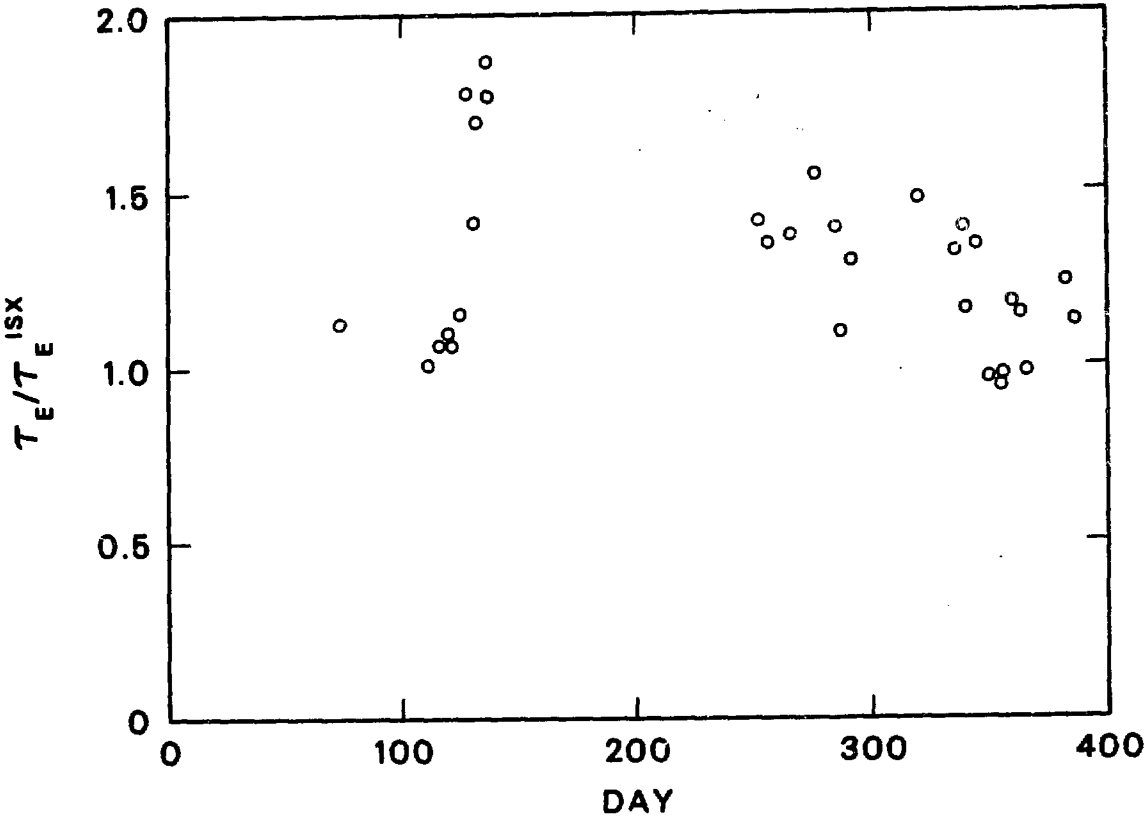


NORMALIZED PEAK DENSITY AGAINST NORMALIZED RADIATION

ORNL-DWG 84C-2433 FED



ORNL-DWG 84C-2434 FED



RELATION BETWEEN RADIATION
AND WATER VAPOR LEVELS

ORNL-DWG 84C-2436 FED