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LOW PLASMA EDGE TEMPERATURES FOR THE SELF-PUMPED LIMITER

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Abstract

Transport code calculations have been performed to study the operation of an INTOR-like tokamak plasma from which helium is removed by a self-pumped limiter, which traps helium, but not hydrogen, in its surface layers. To prevent saturation by helium, the surface is renewed by continuous injection of the surface material (vanadium in this study) into the scrape-off layer. The presence of the injected vanadium leads to plasma temperatures well below 50eV in the scrape-off layer, with supplementary rf heating. Operation in this edge temperature regime is essential for the use of medium- and high-Z limiter coatings.

I. Introduction

The self-pumped impurity control system proposed by Brooks and Mattas(1) is a concept for flushing helium fusion products from a D-T fusion plasma without using a bulky vacuum pumping system. The concept relies on the fact that some candidate limiter and divertor coating materials can trap helium atoms which impinge on their surfaces, while releasing hydrogenic atoms to be recycled (2). We expect vanadium to behave in this manner, because of the solubility behavior of helium and hydrogen in vanadium. This process can continue until the ratio of helium atoms to metal atoms reaches the range of roughly .2 to .5, at which time the metal becomes saturated with helium. To prevent saturation, one must continuously replenish the surface with a fresh layer of metal. Eventually, the coating would become too thick and the surface would have to be replaced; however, the replacement interval is expected to be at least six months, which is competitive with conventional limiter and divertor designs.

This study focuses on the self-pumped limiter, which is the more economical version of the self-pumped impurity control system. Two requirements on the interaction between the plasma and the limiter must be met before the self-pumped limiter can be feasible. The first requirement concerns edge temperature. Since all candidate coating materials for the self-pumped limiter have Z>20, and since such materials are subject to runaway self-sputtering when exposed to plasmas hotter than about 50eV, it is necessary to keep plasma temperatures adjacent to the limiter trapping regions below this level. The second requirement is that atoms of the coating material injected to replenish the limiter surface must not build up in the plasma in such quantities that they terminate the thermonuclear burn by radiative cooling.

These issues have been examined with a modified version of the transport code WHIST, which has been developed by Oak Ridge National Laboratory to simulate tokamaks and axisymmetric stellarators(3). We have applied the code to an INTOR-like tokamak configuration, using a vanadium impurity as a typical sputtered and injected limiter coating material. Such high-Z impurities as vanadium are to be avoided in ignition experiments, as they inhibit ignition by emitting relatively high radiated power. However, in ignited reactors, a means may have to be provided to remove excess fusion product heating, and such high-Z impurities as iodine have been proposed for this purpose (4, 5).

II. The Calculational Model and its Limitations

WHIST is a 1 1/2-dimensional transport code - that is, properties are assumed constant on flux surfaces, with a flux surface label serving as the single (radial) variable for transport, but with such quantities as flux surface area computed from a two-dimensional solution of the plasma equilibrium equation(6).

The transport mechanisms used for this work are 'Alcator transport' ($D\sim\chi_e\sim 1/n_e$, where D=particle diffusivity, χ_e=electron thermal diffusivity, and n_e=electron density), full neoclassical diffusivity tensors (tripled over the theoretical values for consistency with the INTOR model(7)), the Ware pinch, and ripple contributions to ion thermal conduction. Also, a model of sawtooth oscillations provides an intermittent radial transport. The radiative energy transport mechanisms are Bremsstrahlung, cyclotron radiation, and line and recombination radiation. Transport in the scrape-off layer (established by the limiter) includes neoclassical effects, plus a constant of 1 m^2/s added to the electron and ion thermal diffusivities and the diagonal particle diffusivities to simulate Bohm diffusion. Streaming of particles into the limiter, and recycling of neutrals, are also accounted for.

As discussed in more detail in Ref. 8, there is ambiguity in experimental studies of transport mechanisms for high-Z impurities in tokamak plasmas. Most of the evidence suggests that such impurities will not diffuse by neoclassical mechanisms. In this paper, the neoclassical contributions to the vanadium particle diffusivity are omitted, except for the contribution of the Ware pinch. In Ref. 8, transport of sputtered impurities by combined Alcator and neoclassical mechanisms was investigated. It was found that neoclassical fluxes cause a buildup of the impurity in a peak near the 'shoulder' in the fuel ion density profile, and that the amplitude of this peak is usually sufficient to cause a plasma quench by a 'cold-edge instability' driven by excessive line radiation. The absence of inward neoclassical impurity fluxes is probably important to any use of medium-to-high-Z coating materials on surfaces exposed to tokamak plasmas.

We considered a toroidal limiter coated with the vanadium trapping material over its entire surface. The limiter has no leading edges or pumping ducts. Deuterium and tritium ions striking the limiter are completely recycled, but helium ions striking the limiter are removed with a rather conservative effective pumping efficiency of 5%, to represent the partial trapping of helium by the self-pumped limiter. Fuel consumed by fusion is replaced by pellet injection. (We have previously found (8) that fuel ion density profiles are broader when these ions are fully recycled than when they are pumped, primarily because the fuel pellet injection rate into the interior plasma is reduced. As a result of this broadening, the edge temperatures are significantly lower, even compared with the case of 5% D-T pumping.) Sputtered vanadium is introduced as an ion source adjacent to the limiter tip, at a rate consistent with the predictions of the code REDEP(9), which models the impurity transport physics (including self-sputtering) of the scrape-off layer in detail. An additional source of vanadium ions is provided either by central injection for plasma temperature control or by injection into the scrape-off layer for the purpose of replenishing the limiter coating surface.

Three shortcomings of the code should be noted which affect the accuracy of the temperatures calculated for the scrape-off layer. First, the temperatures obtained by the code are flux-surface averages, so the temperatures near the limiter surface will tend to be lower than the values given by the code. Second, the power density emitted by vanadium line radiation when $T_e<20$eV is found by linear interpolation between 20eV and zero. Thus, the power radiated from portions of the plasma below 20eV is not modeled as well as it is at higher temperatures. Finally, because temperature fluctuations of the order of an eV are large fractions of the temperature when the temperature is only a few eV, the code is forced to take extremely small timesteps (in the range of 10^{-4}s) to prevent excessive temperature changes in any timestep. Despite our efforts to improve it, our density control algorithm gave slightly erratic results when the code took many successive very small timesteps, usually allowing the density to creep slowly upwards. (Because of different recycling physics, our version of WHIST uses a somewhat different density control algorithm from that in the ORNL version.) This quirk of the code had the effects of artificially cooling the plasma, especially near the edge, and of limiting the duration of the time interval over which we could obtain meaningful simulations.

Since the first of these shortcomings is conservative (i.e., it causes overprediction of plasma temperatures adjacent to the limiter), and the other two only appear when temperatures in the scrape-off layer are well below the 50eV level required (for finite self-sputtering/ for the use of such coatings as vanadium, we feel that our qualitative conclusions on the edge temperature regime attainable with the self-pumped limiter are valid. Refinement of these results is planned for future work, but entails a long-term project.

III. Results

A. Fully Ignited Operation

The first step in our study was to obtain a quasi-steady plasma configuration similar in dimensions and plasma parameters to the INTOR plasma(7), but with feedback temperature control by injected vanadium. Central vanadium injection (which we regard as an idealization of impurity pellet injection) was required to produce steep vanadium density profiles. Steep vanadium density profiles were required, in turn, to produce a large enough diffusive vanadium flux to reduce the central vanadium concentration rapidly. Finally, a rapid reduction in vanadium content was required to avoid overcooling the plasma during downward plasma temperature fluctuations. At this stage, no vanadium was sputtered into the plasma or injected into the scrape-off layer. The temperature and density profiles in this configuration are shown in Fig. 1.

Next, sputtered vanadium was introduced at a variety of rates in the range $10^{-4} \leq S_{eff} \leq 10^{-3}$, where S_{eff} = net vanadium source rate/rate of D-T flow into the limiter. For $S_{eff}=10^{-4}$, the vanadium edge density was insufficient to reduce the edge temperature significantly. For $S_{eff}=5x10^{-4}$, sputtering substantially increased the vanadium density near the edge, and thus flattened the vanadium density profile, as shown in Fig. 2. Consequently, when the temperature fluctuated below the level at which power inputs and outputs balanced for the existing vanadium content, the diffusive flux could no longer reduce the vanadium content fast enough to prevent further cooling, and the plasma was quenched. Hence, sputtered vanadium indirectly quenched the thermonuclear burn. Even during the quench, however, the temperatures at the limiter tip remained above 100eV. We conclude that operation with sputtered and centrally injected vanadium is thermally unstable; however, such materials as tungsten, which have very low S_{eff} (perhaps 10^{-6}) may give different results. Also, thermally stable operation may be an inherent quality of ignited tokomaks through the effects of a β-limit reached when temperature becomes high enough, so that no centrally injected impurity would be necessary. Such a β-limit could arise from

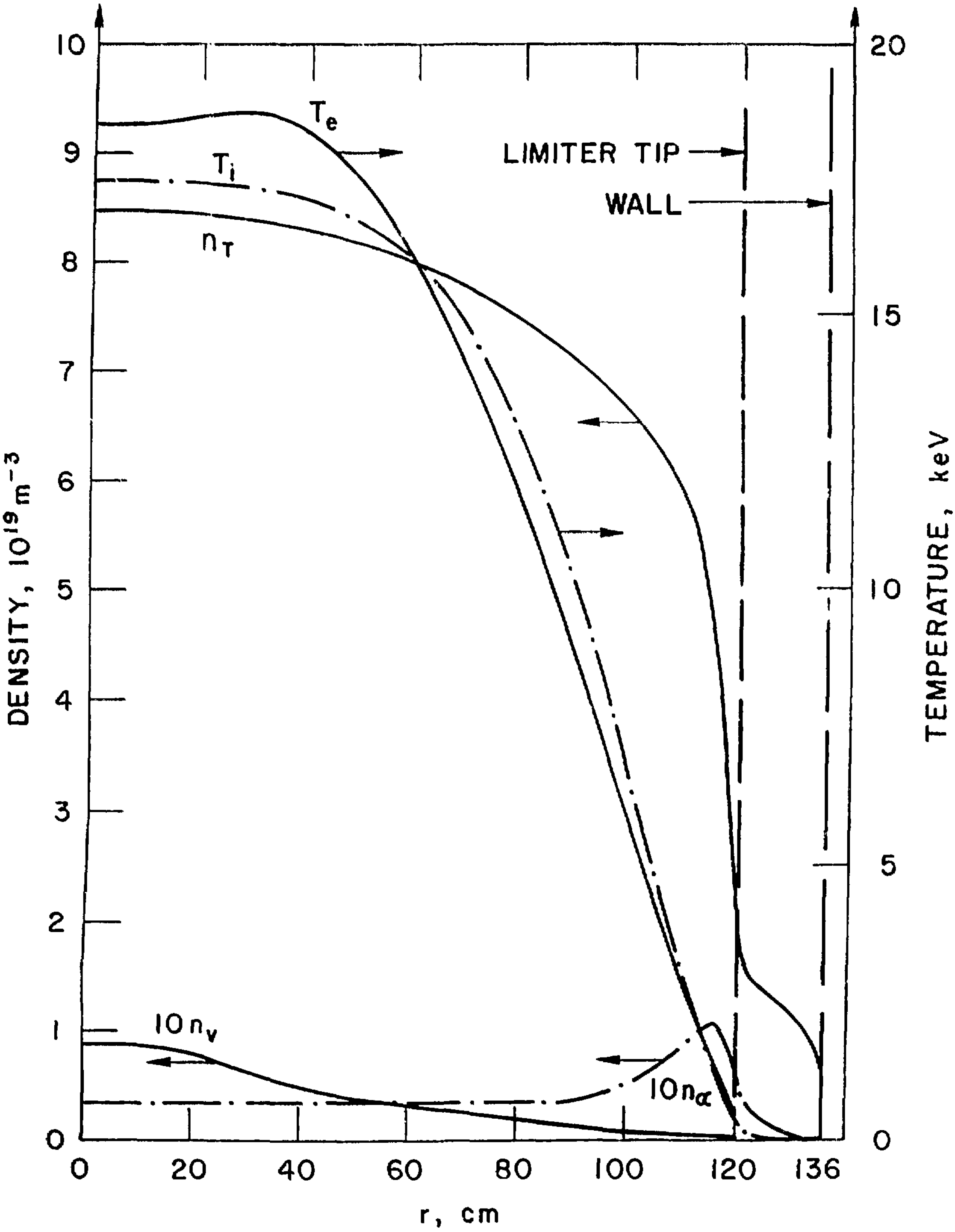

Fig. 1. Quasi-steady density and temperature profiles for INTOR-like plasma with feedback temperature control by centrally injected vanadium.

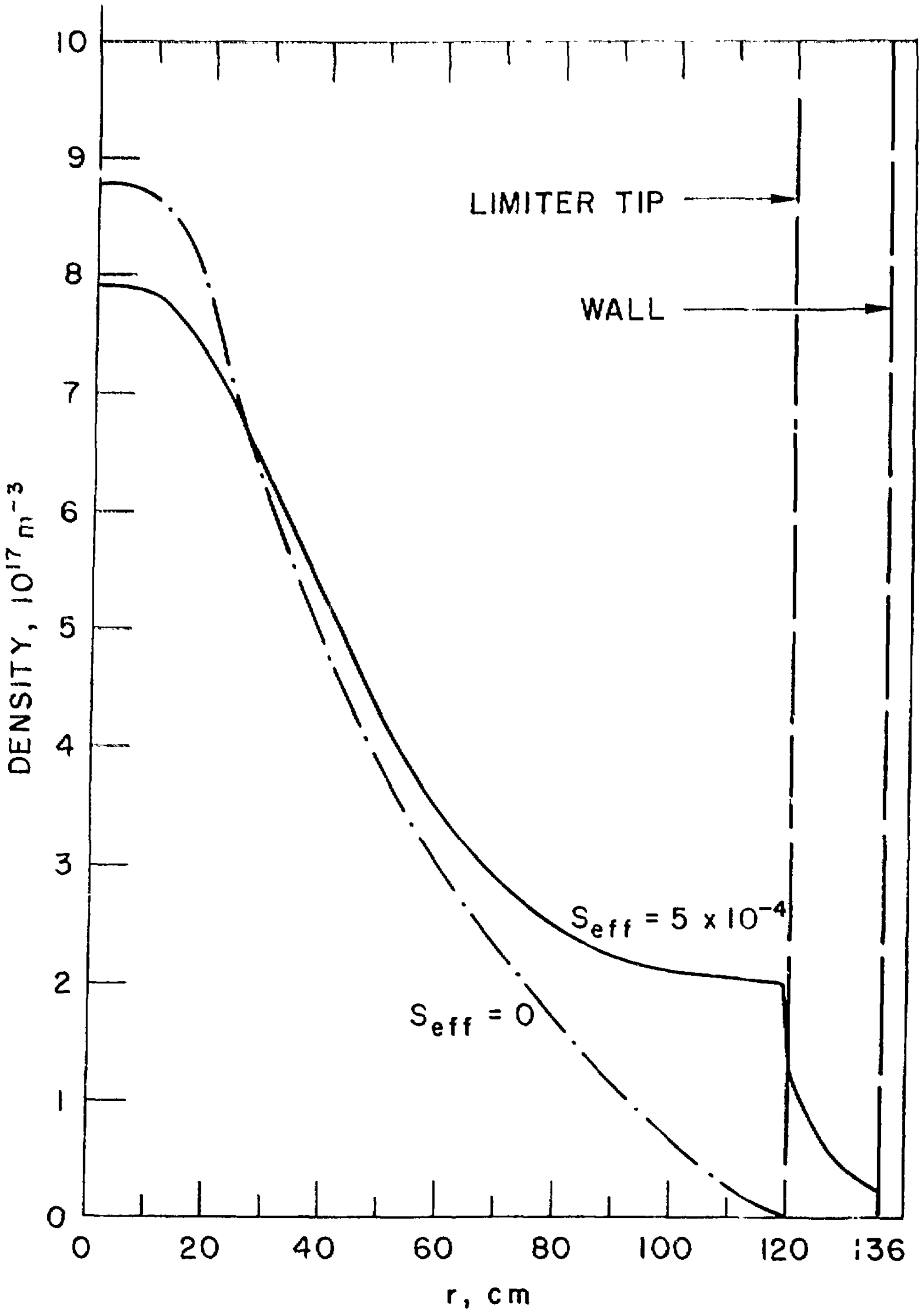

Fig. 2. Effect of sputtering on vanadium profile (Dashed line: no-sputtering case taken from Fig. 1; Solid line: $S_{eff} = 5 \times 10^{-4}$).

decreasing energy confinement quality with increasing β, as suggested by ISX-B results (10), for example.

B. Driven Operation

Since the quench discussed above arose from the use of centrally injected vanadium for temperature control in conjunction with a substantial sputtered vanadium influx, we decided to attempt quasi-steady operation with sputtered vanadium by using a different form of temperature control. Although ignited operation might be possible by modulation of some externally controllable transport mechanism such as ripple heat flux, we took the more straightforward approach of reducing the plasma temperature below the level required for plasma ignition with a chosen vanadium content, and driving the plasma with rf heating. We did not attempt to model a specific rf heating mode; instead, rf heating in the main plasma was divided evenly between electrons and ions, and was distributed in a preselected intensity pattern (usually Gaussian although the results were not substantially changed when the intensity pattern was flat across most of the central plasma). Since the plasma was never ignited, the rf input power could be continuously modulated to maintain a desired average temperature.

Obviously, sputtered vanadium returning to the limiter can give no average net buildup. Therefore, an injected vanadium source in the scrape-off layer must be provided for replenishment of the trapping surface. (Such a source would also have been required had ignited operation worked, since the central vanadium injection rate was much less than the rate required to build up the limiter surface fast enough to prevent helium saturation.) We modeled this extra injection as an ion source uniformly distributed over the flux surfaces in the scrape-off layer, at a constant total rate of 10^{21}/s, which is approximately five times the rate of helium production by fusion.

As mentioned in Section II, our past experience(8) shows that large quantities of impurities near the plasma edge cause excessive radiative energy loss that triggers a 'cold-edge instability,' in which a cold layer of plasma broadens into the plasma interior. In order to prevent such edge quenches, we added heat to the scrape-off layer alone by an rf heating source separate from that used to drive the main plasma. The edge-heating rf source was uniformly supplied in the scrape-off layer to the electrons only, and was turned on only when the electron temperature anywhere in the scrape-off layer fell below 2eV.

Figure 3 shows temperature and density profiles for a typical case with $S_{eff}=10^{-3}$. After reaching the illustrated configuration, the edge temperature profile remained essentially unchanged for the 60ms duration of the run, which is longer than the time required for development of the cold-edge instabilities observed in previous work(8). Figure 3b shows slightly higher temperatures closer to the wall because the rf heating of the scrape-off layer was uniform while the plasma density decreased towards the wall. Also, very little of the vanadium injected into the scrape-off layer managed to enter the main plasma; the vanadium inventory was only about 10% higher than that obtained from a calculation without edge injection, and with an equal value of S_{eff}.

The abrupt corners in the temperature profiles at r = 118cm are due

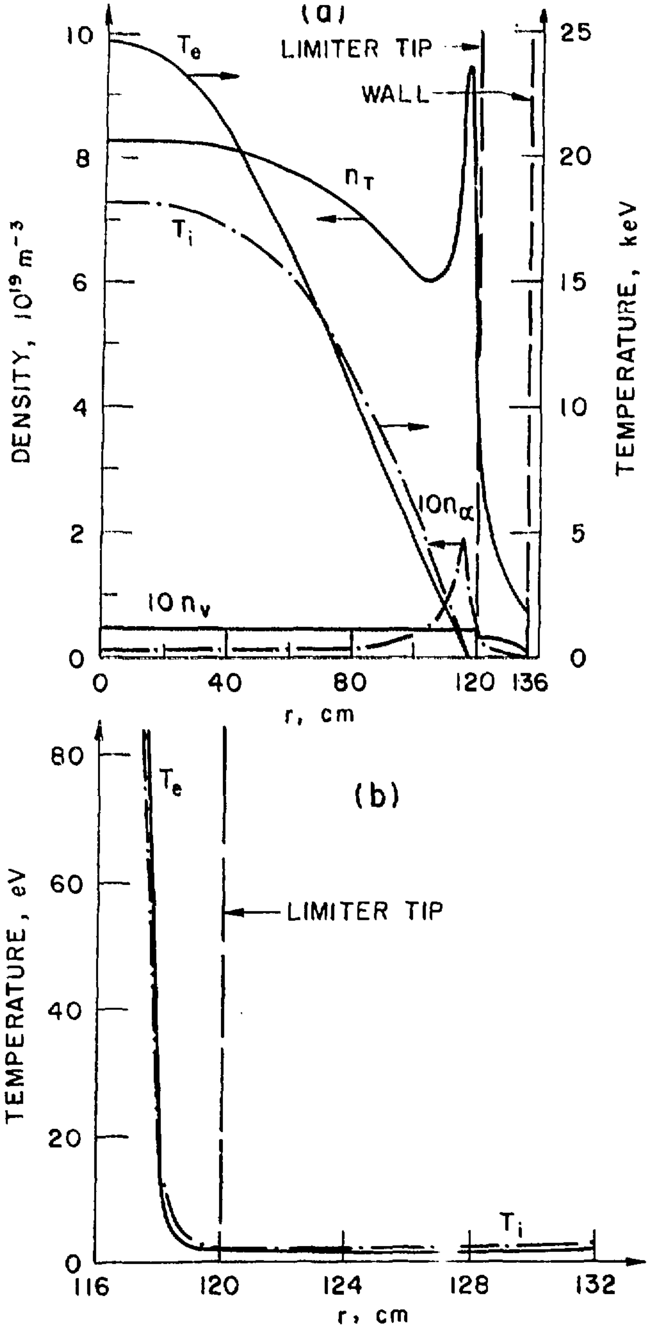

Fig. 3. Quasi-steady density and temperature profile for INTOR-like plasma operated in driven mode, with feedback temperature control by rf heating and with vanadium injected into the scrapeoff layer and sputtered with $S_{eff} = 10^{-3}$. (a) Profiles for entire plasma. (b) Temperatures near edge.

basically to the character of the dependency of vanadium radiative power density on temperature. This quantity increases by an order of magnitude from T_e=200eV to T_e=20eV, and then rapidly decreases (cf. Ref. 11, which is the source of impurity radiation data for WHIST). Regions of plasma in the 20-30eV range radiate strongly, requiring correspondingly large heat inputs to maintain steady temperatures. The local vanadium radiative power density at r=118cm is 12.6W/cm^3, which is much greater than even the maximum rf input power density anywhere in the plasma (1.44W/cm^3). The radiative power loss in the 20eV region is balanced almost entirely by thermal conduction, which requires a large temperature gradient between the 200eV region and the 20eV region as seen in Fig. 3a. (The plasma density spike is required for pressure balance in the region of sharply decreasing temperature.) Because rf heating is a relatively minor effect in this crucial location, the edge temperature regime is rather insensitive to variations in the central rf heating profile. Figure 4 shows the distribution of vanadium line radiative power density and rf power density in the plasma.

Table I summarizes the power balance for the configuration of Fig. 3. The total rf input is about 90MW, while the fusion power is about 600MW. However, we did not fully optimize the operating condition. In particular, if we refined our feedback algorithm for temperature control by rf heating, we could operate much closer to ignition without actually igniting, thereby substantially reducing the rf input requirement. Also, if the toroidal plasma current were driven by rf waves, the same rf system might be usable for heating and current drive.

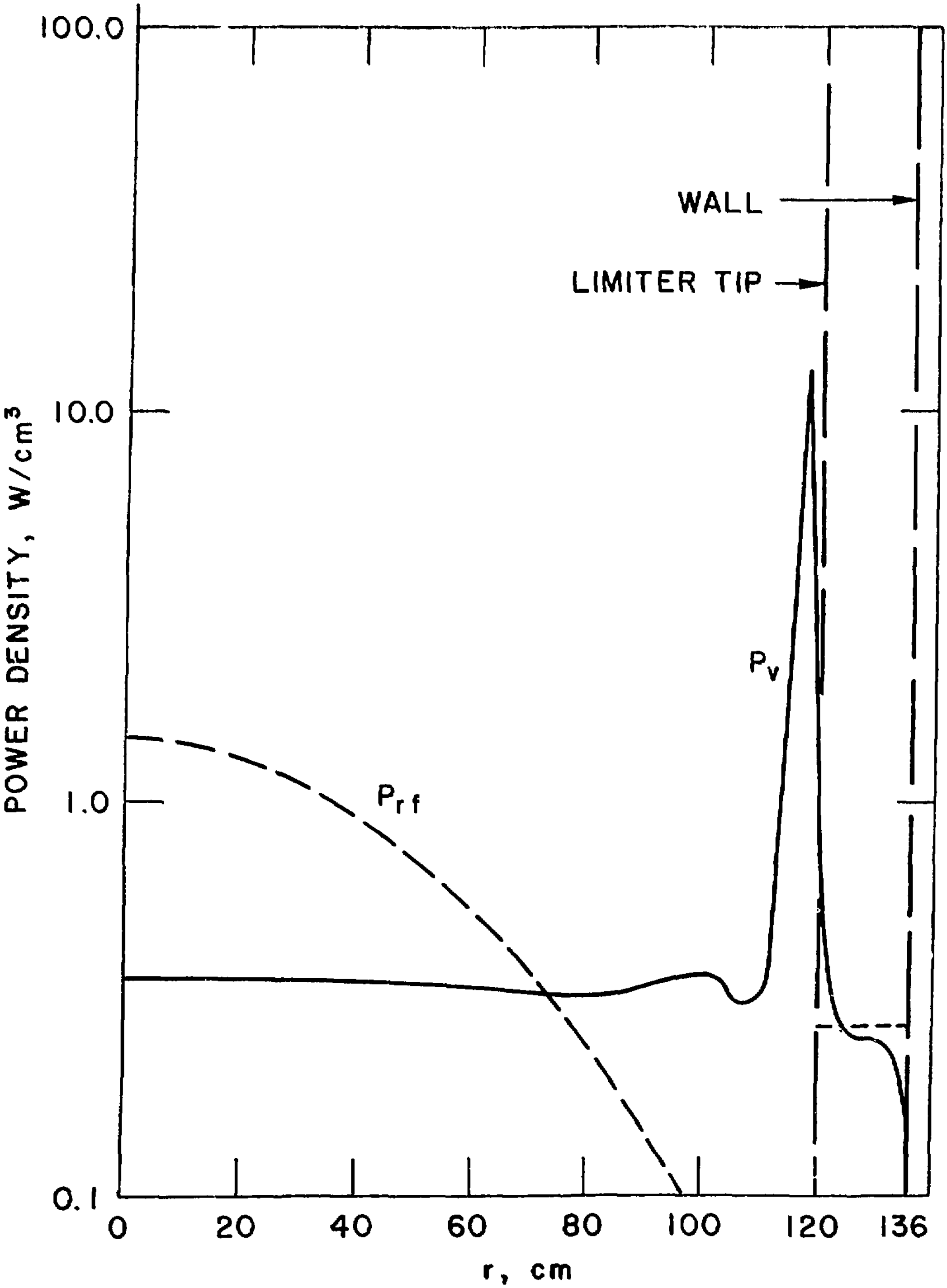

Fig. 4. Power density profiles of vanadium line radiation and rf heating for plasma of Fig. 3.

Table I.

Power Balance Components for Plasma of Fig. 3.

Alpha-particle heating of plasma	122 MW
Total fusion power	610 MW
Line radiation power	180 MW
Bremsstrahlung & cyclotron radiation power	22 MW
rf power to main plasma	85 MW
rf power to scrape-off layer	10 MW

IV. Conclusions

We have displayed a quasi-steady operating regime for an rf-driven tokamak plasma in which very low, stable plasma edge temperatures are achieved in the region adjacent to a self-pumped limiter. These low temperatures result because of a large infusion of vanadium into the scrape-off layer, as required for the proper function of this limiter design. Although we do not consider the exact numerical values predicted for the scrape-off layer by the code to be accurate, these values are far below the 50eV maximum for the use of vanadium and other high-Z materials as self-pumping limiter coatings. Also, it should be noted that the amount of rf input into the scrape-off layer can be adjusted to influence the actual edge temperature achieved. Thus, our calculations strongly support the qualitative conclusion that plasma temperatures well under 50eV can be achieved adjacent to a vanadium-coated self-pumped limiter in a tokamak.

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