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THERMAL LOADS ON THE IGNITOR LIMITER FOR ELONGATED PLASMAS

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We present an analysis of the energy flux to the axisymmetric limiter in Ignitor for plasmas with elongation κ from 1.0 to 1.32 and midplane scrape off distances λ from 0.5 cm to 3.0 cm. We find that the elongation for a given scrape-off distance is limited by the allowable limiter edge heat load. We also find that by varying the elongation as a function of scrape-off distance, we can limit the peak energy flux to approximately 300 W/cm^2 for 0.5 cm $\leq \lambda \leq$ 3.0 cm, assuming 4.5 MW total power incident on the limiter.

1. Introduction

The success of the ignition experiment, Ignitor [1], will depend to a considerable extend on minimizing the plasma impurity contamination. A key element in this is the careful design of the limiter system for thermal energy removal. Owing to the compact nature of the device and the concomitant smaller surface to volume ratio, the energy removal problem is particularly delicate. Furthermore, to maximize the space available for plasma operation, it is desirable that the limiter be restricted as much as possible in its radial extent. Consequently, it is imperative that the limiter thermal loads be minimized to whatever extent possible in order to facilitate a simpler and more compact design.

In this paper we provide calculations of the thermal loads on the Ignitor limiter. We consider an axisymmetric limiter [2] located on the small major radius side of the vacuum vessel, subtending a poloidal angle of $\pm 90°$ about the midplane. The poloidal cross section of the limiter is elliptical. The energy deposition on the limiter is calculated for elliptical plasmas with varying elongation. Due to uncertainties in edge plasma parameters [3], we consider a range of scrape-off distances from 0.5 cm to 3.0 cm. We find that the elongation modifies the energy deposition profiles dramatically with a strong scrape-off dependence. Owing to the power loading at the limiter edge, there is a limit to the elongation for a given scrape-off distance. We also find that that the elongation can be used to minimize the peak heat flux on the limiter for any scrape-off distance in the range considered. In this way it is possible to accommodate plasmas with a wide variation in edge parameters using a limiter of fixed cross section.

In section 2 we present the model used for the energy flux calculations. Our results are presented in section 3. Section 4 provides a summary and discussion.

2. Energy deposition model

The physical arrangement for the plasma and limiter which we assume for the present calculations is shown diagrammatically in fig. 1. The limiter is an axisymmetric structure with a major radius of 74 cm. Its cross section is elliptical, with a semi-major axis, b_L of 35 cm and a semi-minor axis, a_L of 25 cm. The limiter spans a poloidal angle of $\pm 90°$ on the small major radius side of the vacuum vessel. At $\pm 90°$, it is assumed that the limiter surface is vertical as shown. The detailed structure of the limiter is discussed elsewhere [4,5].

For the present calculations, we assume that the

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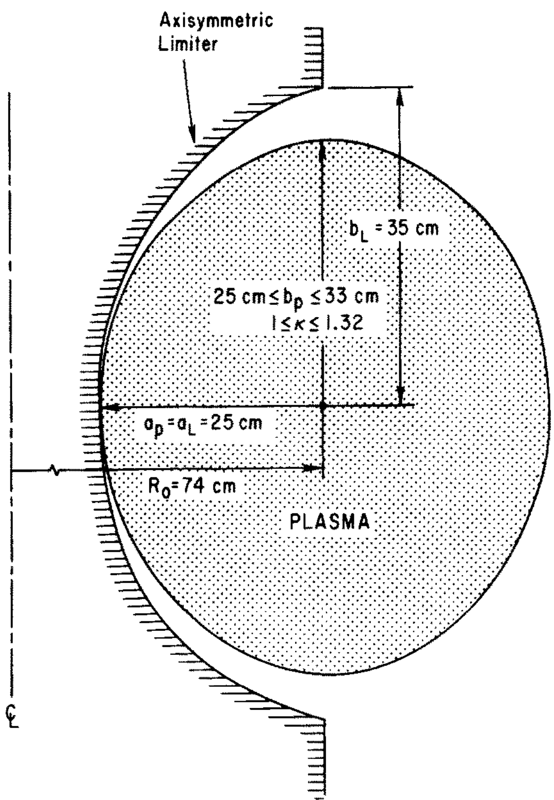

Fig. 1. Diagram of the physical arrangement used for the present calculations. The limiter is axisymmetric with an elliptical cross section of dimensions as shown. The major radius of the limiter and the plasma is 74 cm. The plasma elongation is varied from 1.0 to 1.32.

plasma parameters are those for the compressed configuration [1]. The major radius, R_0, is 74 cm. The cross section is elliptical, with a semi-major axis a_p of 25 cm and a semi-major axis b_p which varies from 25 cm to 33 cm. The corresponding variation in the elongation $\kappa = (a_p/b_p)$, is from 1.0 to 1.32. The plasma current is 4.5 MA and the toroidal magnetic field is 15 T. The total thermal power leaving the plasma is estimated to be 6.75 MW. It is assumed, conservatively, that 66% of this value, or 4.5 MW, is incident on the limiter. In order to see the related effects of changing elongation and scrape off, we do not introduce any elongation dependence for the total incident power; however, the effects of such dependence are noted in section 3.

We utilize a model for the plasma–limiter interaction [3] in which it is assumed that the thermal energy leaving the plasma flows along field lines. It is further assumed that the energy flux is constant on a magnetic surface and decreases exponentially from the plasma edge with a characteristic length given by the midplane scrape-off distance λ. The energy flux at any point on the limiter $\Gamma(\theta)$ is given by:

$$\Gamma(\theta) = \Gamma_0 \sin(\phi) \exp(-\delta/\lambda), \tag{1}$$

where θ is the poloidal angle measured from $R_0 = 74$ cm, δ is the distance at the midplane from a_p to the flux surface which intersects the limiter at angle θ, and ϕ is the angle between the poloidal direction of the field line and the plane tangent to the limiter surface at angle θ. Γ_0 is the normalization coefficient given by integrating the flux in eq. (1) over the limiter surface and equating the integral to the total incident power, P_T. The normalization is continued along the vertical surfaces at $\theta = \pm 90°$ for 5 scrape-off distances. This is done to avoid underestimating the loading at the limiter edge. For the actual design, the edge of the limiter will be contoured to ameliorate the loading problem. To illustrate more directly the effects considered here, we assume that the field lines are normal to the limiter edge.

3. Results

The calculations were performed numerically using a computer code which takes into account the elliptical cross sections of both the limiter and the plasma. Fig. 2 shows the energy flux distribution for a scrape-off distance of 0.5 cm and elongations of 1.0 to 1.32. For all cases, the energy flux is predicted to be zero at the midplane where ϕ is zero. For $\kappa = 1.0$, the peak heat flux is 860 W/cm^2, and occurs at $\theta = 12°$. The flux falls

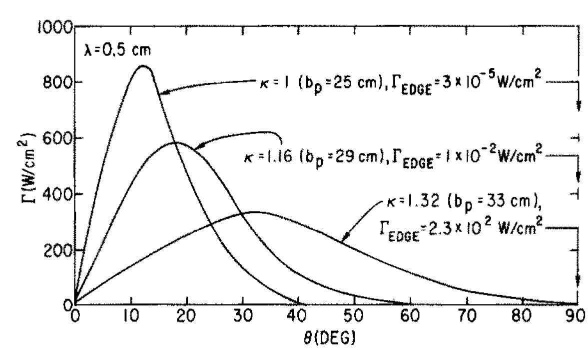

Fig. 2. Energy flux distribution on the limiter for $\lambda = 0.5$ cm and three values of elongation ($\kappa = 1.0$, 1.16, and 1.32). θ is the poloidal angle measured from the midplane assuming $R_0 = 74$ cm. The flux at the limiter edge ($\theta = \pm 90°$), where the field lines are normal is shown for each case.

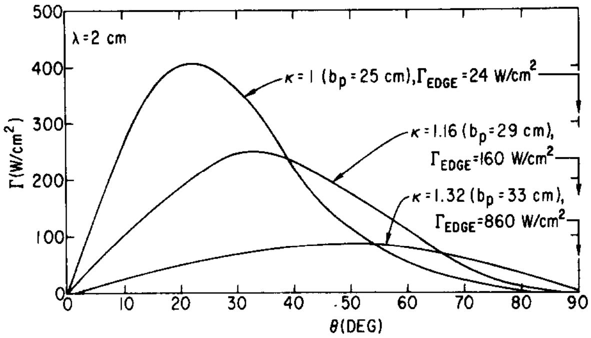

Fig. 3. Energy flux distribution on the limiter for $\lambda = 2.0$ cm and three values of elongation ($\kappa = 1.0$, 1.16, and 1.32). θ is the poloidal angle measured from the midplane assuming $R_0 = 74$ cm. The flux at the limiter edge ($\theta = \pm 90°$), where the field lines are normal, is shown for each case.

off rapidly with increasing ϕ and is insignificant on the limiter edge $\theta = 90°$. With increasing κ, we find that the peak heat flux decreases, with a corresponding increase in the edge loading. In particular, for $\kappa = 1.32$, the peak flux is 330 W/cm^2 and Γ_{edge} is 230 W/cm^2. By increasing the elongation, the plasma is made to conform more closely to the elliptical limiter surface. The effect of this is to spread out the heat deposition with a corresponding decrease in the peak flux and increase in the edge loading.

The case for $\lambda = 2.0$ cm is shown in fig. 3. Here the peak flux at $\kappa = 1.0$ is reduced from the $\lambda = 0.5$ cm case to 410 W/cm^2. At $\kappa = 1.32$, the peak is only 90 W/cm^2; however, the edge loading has increased to 860 W/cm^2. In this case it is clear that the larger values of the elongation produce intolerably large edge loadings.

If we invoke the design criterion that the edge heat load to be limited to 100 W/cm^2 in order to provide a tractable design, then we can plot the maximum allowable elongation κ_{max} as a function of scrape-off distance λ as shown in fig. 4. It should be noted that this criterion can be refined and will be influenced by the

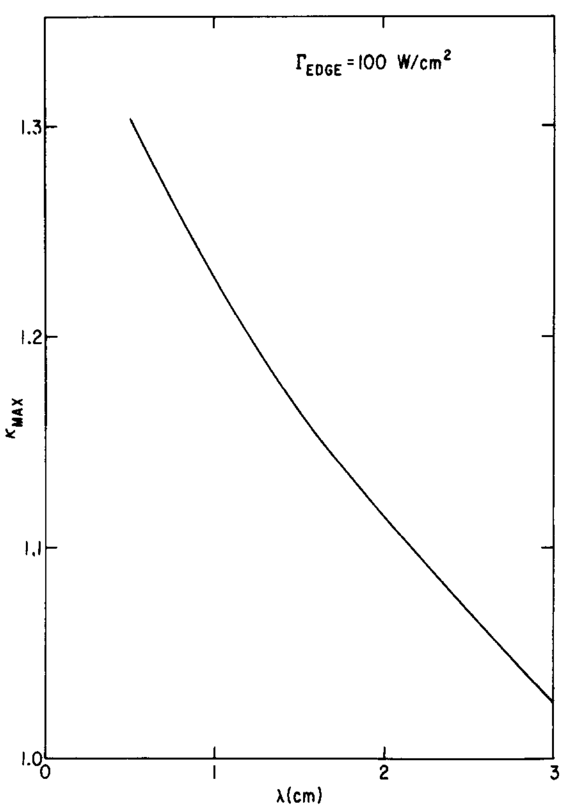

Fig. 4. Value of κ (κ_{max}) which results in a limiter edge load of 100 W/cm^2 as a function of λ.

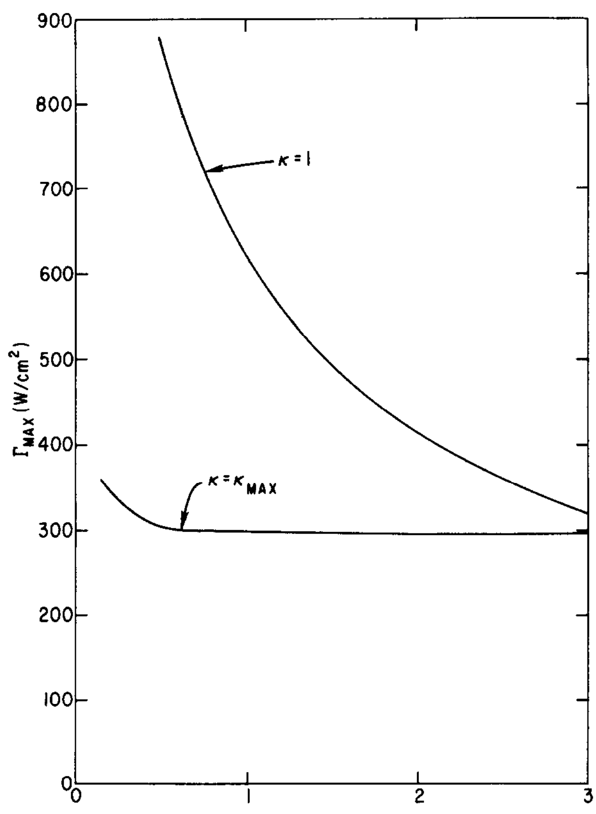

Fig. 5. Maximum energy flux on the limiter surface ($0° \leq \theta \pm 90°$) for elongations of $\kappa = 1.0$ and $\kappa = \kappa_{max}$ from fig. 4.

precise edge configuration. It would be possible to modify the design to provide for larger elongations; however, we make this particular assumption for simplicity. Using the values for κ from fig. 4, we plot in fig. 5 the maximum energy flux Γ_{max} on the limiter surface. For scrape-off distances of 0.5 cm to 3.0 cm, Γ_{max} is almost constant at approximately 300 W/cm^2. Also plotted in fig. 5 is the maximum energy flux for $\kappa = 1.0$. It is clear that substantial reductions in peak flux can be realized at the shorter scrape-off distances by utilizing the elongation of the plasma to extend the area of deposition, while ensuring that the edge loading is kept manageably small.

If the plasma thermal power density, energy confinement time, and fraction of power to the limiter are all independent of κ, then the total power to the limiter would depend linearly on κ. Including this effect would modify the results in figs. 4 and 5 somewhat in that there would be an approximately 30% reduction in peak energy flux for $\kappa = 1.0$ compared to $\kappa = 1.32$, although the results would be qualitatively similar.

4. Summary and discussion

We have calculated the energy flux to an axisymmetric limiter in Ignitor for scrape-off distances from 0.5 cm to 3.0 cm and elongations from 1.0 to 1.32. We find that for a given scrape-off distance, increasing the elongation results in a lower peak energy flux with an increase in the edge loading. To keep the edge loads to a tolerable level it may be necessary to limit the elongation depending on the scrape-off distance. Conversely, the elongation is a useful parameter for spreading out the heat load over the fixed limiter surface. Using the elongation in this manner allows a wide range of scrape-off distances to be accommodated with an essentially fixed maximum energy flux. In the actual limiter design, the precise nature of the criterion used the chose the maximum edge loading will depend on the details of the edge configuration. The general principle described here of utilizing the elongation to accommodate varying plasma conditions will remain a useful feature.

Acknowledgements

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