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Throat and vented pump limiters particle collection experiments with auxiliary heating in Tore Supra

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Abstract

Particle collection experiments using one throat pump limiter and one vented pump limiter (hereafter Throat-PL and Vented-PL, respectively) are reported for discharges with additional power (D_2 fuelling, $I_p = 1 \div 1.3$ MA, $\langle n_e \rangle \approx 2 \div 5 \times 10^{19}$ m^{-3}, P_{tot} up to 6.6 MW). Since both limiters have the same area (0.16 m^2), a direct comparison of pressures and exhaust efficiencies is possible. It is shown that the neutral pressure (Π) in the plena of both the Vented and Throat-PLs increases with additional power and volume averaged density proportionally to $\langle n_e \rangle^2 P_{tot}^{1/3}$. The collection efficiencies (η_{coll}), which are also experimentally estimated, are constant in the range of power and density considered (with values $\approx$ 12% for the Throat-PL, and 4% for the Vented-PL). These experiments are interpreted with the help of a model of ions and neutrals recirculation in the SOL. The ratio of the calculated pumping efficiencies (ε_{pump}) of both devices remains roughly constant with increasing power and density. The flux amplification factor (f) and the particle exhaust efficiency are calculated to vary with the conducted power proportionally to $P_{cond}^{1/3}$ and the particle lifetime (τ_p) to decrease as $P_{cond}^{-1/5}$.

Keywords: Tore Supra; Limiter; Active pumping; Particle balance

1. Introduction

For limiter as well as for divertor tokamaks, there are only two methods to pump particles. The first method consists in pumping a part of the parallel ion flux, while the second relies on pumping a fraction of the neutral recycled flux. In limiter tokamaks [1], pump limiters with throats are used for particle pumping by ionic collection, and vented pump limiters for neutral collection (hereafter Throat-PL and Vented-PL, respectively). The principle of the Vented-PL is the following: since the cascade of reactions experienced by the recycled flux (dissociation, charge-exchange) yields to a nearly isotropic neutrals distribution, roughly half of the recycled flux comes back towards the limiter. If the limiter head is designed to be semi-transparent to neutrals (slots between tiles), a significant fraction of the backflowing flux can enter the limiter plenum and be extracted. The geometry of the Vented-PL of Tore Supra is shown in Fig. 1. The neutral collection is ensured by two sets of slots (1.2 cm × 9.5 cm, for a total molecular conductance $C = 3.5$ m^3/s), which are part of the limiter head and aligned along the toroidal direction. Previous experiments for ohmic plasmas comparing a Throat-PL to a Vented-PL have been reported in [1]. There was shown that the vented structure had a sufficient particle exhaust capability while allowing a moderate heat flux density on the whole limiter surface. Moreover, it was demonstrated that the plasma density and wall content could be actively controlled by both a Throat- and a Vented-PL. In this paper, we extend this comparison to ICR heated plasmas and give the dependence of the main parameters characterizing the plasma-limiter interaction on power and density.

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[1] In axisymmetric divertor tokamaks, the active particle pumping is based on the removal of a fraction of the recycled flux (neutral collection), but in their first design, the neutralizers of the ergodic divertor of Tore Supra were designed to scrape the direct ion flux (ionic collection).

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2. Experiments

One Vented-PL and one Throat-PL have been simultaneously tested on a series of discharges with different powers and volume averaged densities, the plasma laying on both devices. Since the areas of the limiters are identical ($\Sigma = 0.16$ m^2) and since the molecular conductance of the throats of the Throat-PL ($C = 4$ m^3/s) is close to that of the set of slots of the Vented-PL ($C = 3.5$ m^3/s), one can directly compare the pressures measured in the limiters plena and the corresponding collection efficiencies. The time history of a typical discharge is shown in Fig. 2. The working gas is deuterium and the pumping in the limiters plena is switched off. A three seconds long pulse of additional power (Fig. 2b) is carried out in the middle of the current plateau. During this time, the pressure in the limiters plena reaches a quasi steady-state (Fig. 2c). During the pulse, the density remains constant at a value slightly higher than during the ohmic phase (Fig. 2a); the ohmic power decreases and the radiated power increases (Fig. 2b). The increase of the radiated fraction, correlated to the raise of the effective charge of the plasma (Z_{eff}), remains moderate (from 30% to 50% for P_{tot} ranging from 1 MW to 6.6 MW and Z_{eff} from ≈ 1.1 to ≈ 1.6). The edge parameters (density n_e and temperature T_e, e-folding lengths in the SOL: λ_n and λ_T) are known from reflectometry and Langmuir probe measurements. Typical values are: $n_e(a) = 1.3 \div 2 \times 10^{19}$ m^{-3}, $T_e(a) = 50 \div 85$ eV, $\lambda_n = 3.3$ cm and $\lambda_T = 3.7$ cm.

The behavior of the pressure with total power is shown in Fig. 3 for a density $\langle n_e \rangle = 3.5 \times 10^{19}$ m^{-3}. When P_{tot} is increased from 1 to 6.6 MW, the pressure in the Throat-PL increases from 0.5 to 1.5 Pa when, in the Vented-PL, the pressure goes from 0.12 to 0.35 Pa. In both cases, the pressure increases roughly as the cubic root of the total power. The behavior of the pressure with volume averaged density is displayed in Fig. 4 for ohmic ($P_{tot} = 1.65$ MW) and ICR heated discharges ($P_{tot} = 3.8$ MW). For both limiters, the pressure increases approximately as the square of the density. The distance of two lines on the figure indicates the ratio $(3.8/1.65)^{1/3}$, following the scaling law of Π with P_{tot} given above. In all cases, the ratio

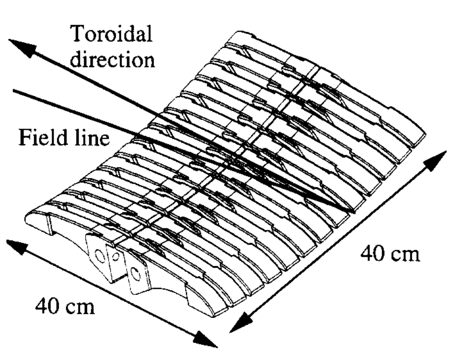

Fig. 1. The Tore Supra vented limiter.

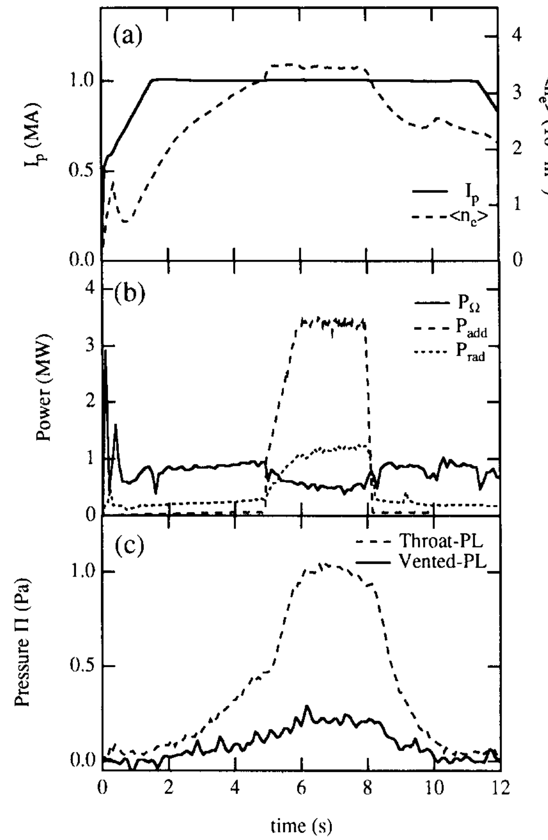

Fig. 2. Time history of a typical discharge: (a) plasma current and volume averaged density; (b) ohmic power, RF pulse and radiated power; (c) pressure in the plena of the Throat- and Vented-PLs.

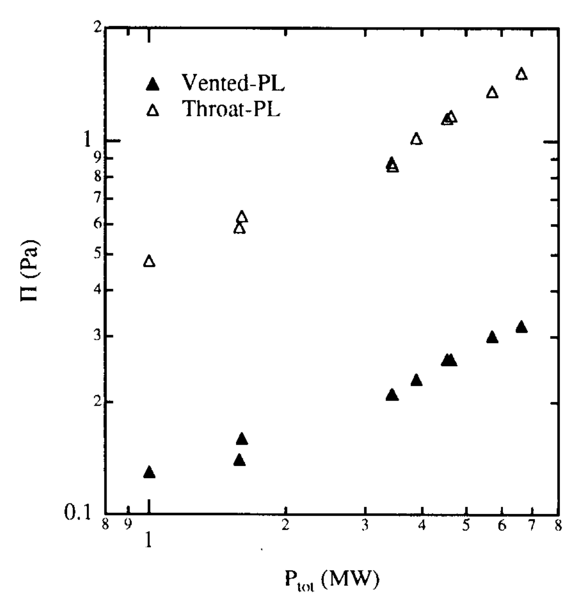

Fig. 3. Pressure in the limiters plena versus total power.

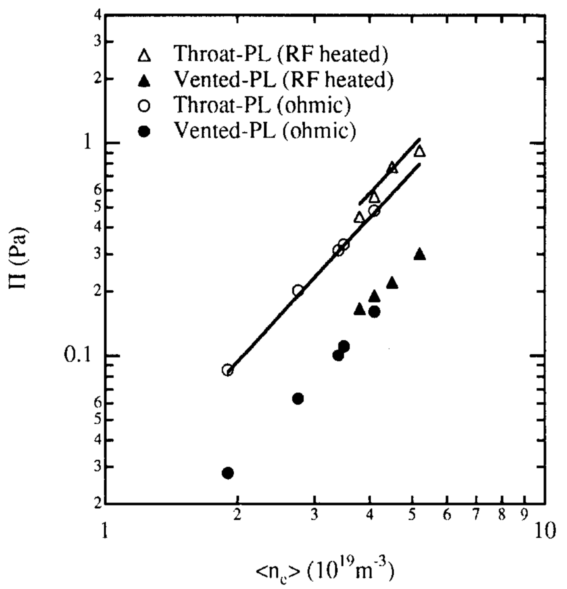

Fig. 4. Pressure in the limiters plena versus volume averaged density. The two lines are in the ratio $(3.8/1.65)^{1/3}$.

between the pressure in the Throat-PL and that in the Vented-PL is ≈ 4. This value, which characterizes the present devices, can be significantly reduced. Indeed, the design of the Throat-PL is optimized for both heat and particle control, in contrast to the case of the Vented-PL. In fact, as reported in Ref. [2], a proper shaping of the slots could increase the exhaust capability of the Vented-PL by ≈ 2, yielding $\Pi_{(\mathrm{Throat})}/\Pi_{(\mathrm{Vented})} \approx 2$.

The collection efficiency (η_{coll}) is defined as the ratio

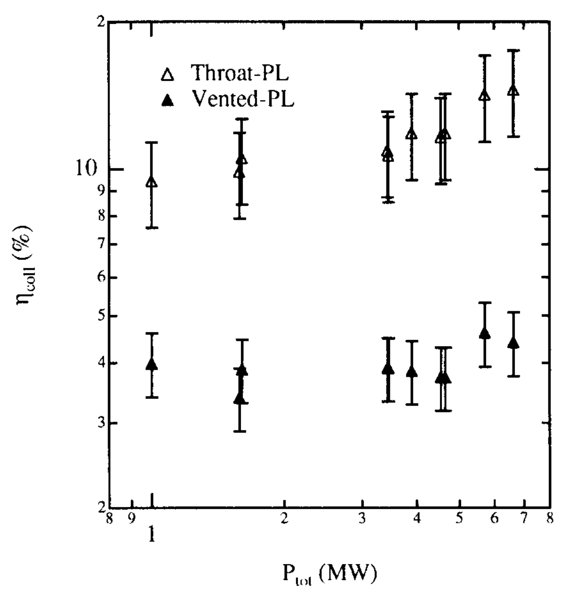

Fig. 5. Collection efficiency of the Throat- and Vented-PLs versus total power.

between the flux entering the limiter apertures and the total flux on the head. Since there is no active pumping for the experiments reported in this paper, the flux entering the limiter is equal to the backflowing flux from the plenum to the plasma, which is equal to ΠC. One has therefore:

$$\eta_{\mathrm{coll}} = \frac{\Pi C}{\int_{\Sigma} \frac{1}{2} n_e \cdot \vec{c}_s(T_e) \cdot \mathrm{d}\vec{\sigma}}$$

where $\vec{c}_s(T_e)$ is the ion sound speed at local temperature and where the sum is calculated over the whole limiter head. The corresponding values of η_{coll} are plotted versus the total power in Fig. 5, for both the Throat-PL and the Vented-PL. Due to the error bars on the edge measurements, it is unclear if the slight increase of η_{coll} with P_{tot} for the Throat-PL is significant or not. The average η_{coll} value is $\approx 12\%$ for the Throat-PL and $\approx 4\%$ for the Vented-PL.

3. Modelling

The model developed to interpret these experiments is described in Ref. [2]. Steady-state conditions and isothermal magnetic surfaces are assumed (this last hypothesis reduces the validity domain to regions of temperature ≥ 10 eV). Schematically, three different physical processes can be distinguished, each of them corresponding to one module of the computer code:

(1) *Ionic (ballistic) collection*: This is the main collection process for the Throat-PL: the particles recycled on the neutralizer plates have a probability ≈ 0.70 to enter the plenum. For the Vented-PL, due to the angle between the slots and the field lines, a fraction of $\approx 15\%$ of the parallel ion flux enters the slots where it recycles on the lateral faces. Once neutralized, these particles have a significant probability (≈ 0.20) to directly enter the plenum.

(2) *Neutral collection*: The remaining flux (i.e. the part which is not ballistically collected) recycles towards the plasma as atoms or molecules (whose relative ratio and energy distribution are taken from [3]). It experiences several atomic reactions the most important of which are [4]: D_2 dissociation, D ionization and charge-exchange with D^+. For known plasma characteristics, the SOL ion source, the D and D_2 distributions in front of the limiter head, the flux entering the plenum and the corresponding pressure are determined from multi-1D calculations. Due to the geometry of the limiter head, this collection process is negligible for the Throat-PL.

(3) *SOL density modification*: Due to the ion source, an electrostatic potential develops in the SOL. This potential induces a reduction of the plasma density, associated with a macroscopic parallel flow for reasons of particle and momentum conservation. This density modification changes the reaction rates experienced by the recycled flux and influences the results of the calculations of module (2). The potential and density distributions are determined by a

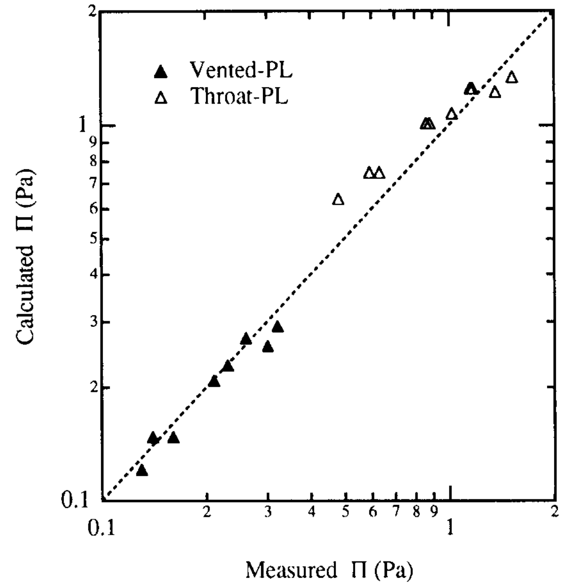

Fig. 6. Comparison between the calculated and measured pressures.

2D calculation, assuming a sonic flow at the limiter surface and neglecting the contribution of the neutral species (i.e. D and D_2) to the ion pressure.

Coupling these three modules allows to calculate the neutral species distributions, the flux entering the limiters, the pressure in the plena, the pumping efficiencies and the flux amplifications in the SOL and in the throats of the Throat-PL. The input parameters of the model are: n_e and T_e profiles in the SOL and up to 10 cm inside the last closed flux surface, the impurity concentration in the SOL (assumed to be CIII) and the limiter geometry.

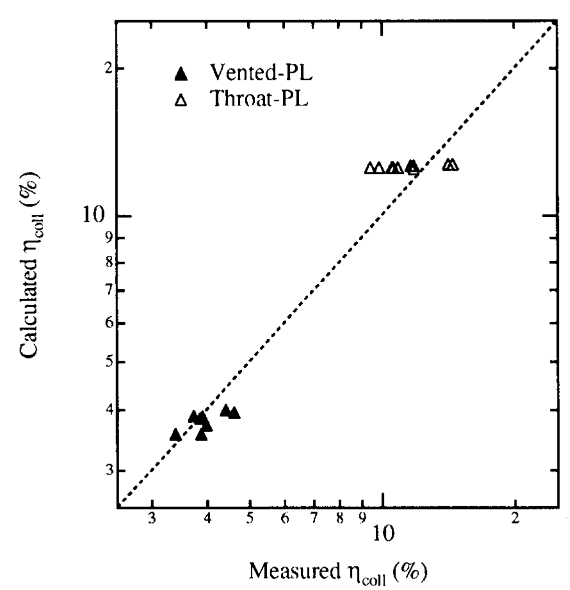

Fig. 7. Comparison between the calculated and measured collection efficiencies.

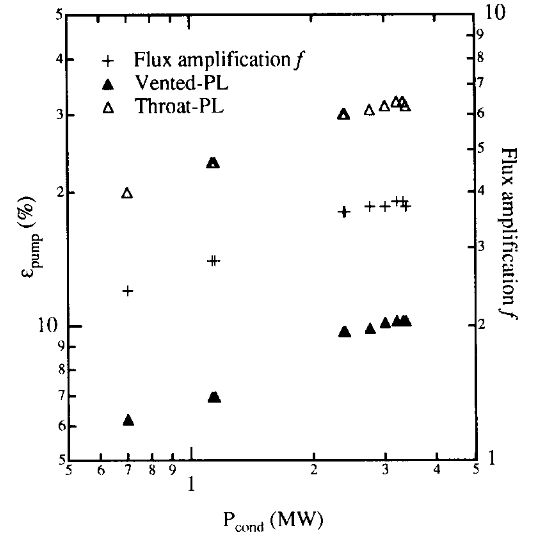

Fig. 8. Flux amplification and pumping efficiency of the Throat- and Vented-PLs versus conducted power.

The comparison between the calculated and measured pressures and collection efficiencies is shown in Figs. 6 and 7. For both Π and η_{coll}, the simulations compare well with the experiments and the ratio of the values corresponding to the Throat-PL to those corresponding to the Vented-PL are correctly reproduced by the model. This good agreement allows us to estimate, for similar plasma conditions, the performances of the Throat- and Vented-PLs with active pumping and to compare their efficiencies in terms of density control. The two quantities characterizing the plasma-limiter interaction are then the pumping efficiency (ε_{pump}) and the particle confinement time (τ_p). To estimate them requires the knowledge of the flux amplification f, defined as the ratio between the flux in the SOL and the net outflux of the plasma, which is calculated in the global SOL modelling. The pumping efficiency is defined as the ratio between the extracted flux and the net outflux of the plasma. It is linked to the limiter collection efficiency η_{coll}, to the flux amplification f and to the pumping speed S by the relation:

$$\varepsilon_{pump} = \eta_{coll} f \frac{S}{S + C}$$

where $S = 10\ m^3/s$ for the present Tore Supra pumping system. The particle confinement time (τ_p), which gives the magnitude of the extracted flux, is defined as the ratio between the total plasma content and the net outflux of the plasma:

$$\tau_p = \frac{f}{N_{lim}\Theta_{lim}} \frac{\langle n_e \rangle \cdot V_{plasma}}{\int_{SOL+L_\perp} n_e \cdot c_s(T_e) \cdot dx}$$

where N_{lim} is the number of limiters and Θ_{lim} the poloidal extension of one limiter; V_{plasma} is the plasma volume and

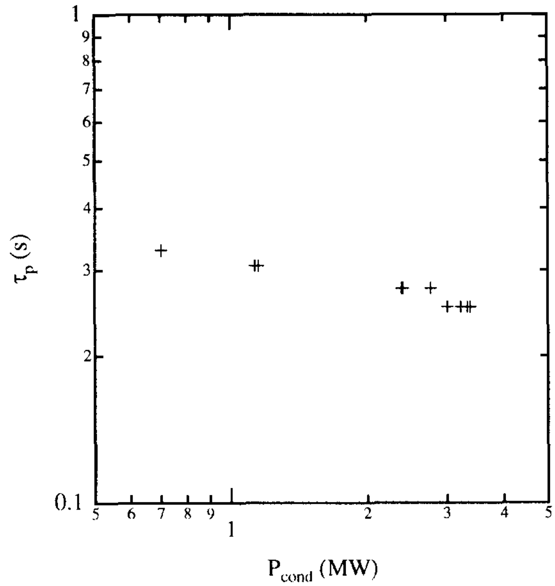

Fig. 9. Particle confinement time versus conducted power.

$L_\perp \approx 5$ mm accounts for the region of increased perpendicular transport in front of the limiters [5]. The flux amplification f and the pumping efficiencies ε_{pump} for both the Throat- and the Vented-PL are plotted versus the conducted power P_{cond} in Fig. 8. When P_{cond} increases from 0.7 to 4 MW, f increases from 2.5 to 4, proportionally to $P_{cond}^{1/3}$ (correspondingly, the flux amplification in the throats of the Throat-PL increases from ≈ 1.5 to ≈ 2). Since S, C and η_{coll} are almost constant, the pumping efficiencies for both limiters have the same dependence on P_{cond}. They increase from 20% to 35% for the Throat-PL, and from 6% to 10% for the Vented-PL. The lower values, which correspond to ohmic plasmas, compare well with previous determinations of ε_{pump} obtained in similar conditions [6] [2]. The ratio between the pumping efficiencies of the Throat- and Vented-PLs is ≈ 3.5 but, as already mentioned in Section 2, a proper shaping of the slots could increase the exhaust capability of the Vented-PL by ≈ 2. The behavior of the particle confinement time τ_p with P_{cond} is shown in Fig. 9. For ohmic discharges of density $\langle n_e \rangle \approx 3 \div 4 \times 10^{19}$ m^{-3}, one has $\tau_p \approx 0.35$ s and the degradation of the particle confinement time with additional power is calculated to be proportional to $P_{cond}^{-1/5}$.

[2] when comparing ε_{pump} with the values reported in [1,6], caution must be paid to the value of the particle confinement time: $\tau_p \approx \tau_E \approx 200$ ms in [1]; $\tau_p = 500$ ms from particle transport modelling in [6] and $\tau_p \approx 300$ ms from self-consistent SOL modelling in the present study. Since ε_{pump} is proportional to τ_p, the obtained values for ε_{pump} reflect the differences in the choice of τ_p For the same choice of τ_p, the different determinations of ε_{pump} agree within 30%.

4. Summary

One Vented pump limiter and one Throat pump limiter have been simultaneously tested on a series of discharges with different powers and volume averaged densities (D_2 fuelling, $I_p = 1 \div 1.3$ MA, $\langle n_e \rangle \approx 2 \div 5 \times 10^{19}$ m^{-3}, P_{tot} up to 6.6 MW).

The experiments show that:

- the neutral pressure (Π) in the plena of both limiters increases proportionally to $\langle n_e \rangle^2 P_{tot}^{1/3}$, with values up to 1.5 Pa for the Throat limiter, and 0.35 Pa for the Vented limiter;
- the collection efficiencies (η_{coll}), i.e. the ratio between the flux entering the limiter apertures and the total flux on the head, are constant with values $\approx 12\%$ and $\approx 4\%$ for the Throat and the Vented limiter, respectively.

From modelling, it is shown that:

- the flux amplification factor ($f \approx 2.5 \div 4$) and the particle exhaust efficiency, i.e. the ratio between the extracted flux and the net outflux of the plasma ($\varepsilon_{pump} \approx 20 \div 35\%$ for the Throat pump limiter; $\approx 6 \div 10\%$ for the Vented pump limiter), vary with the conducted power proportionally to $P_{cond}^{1/3}$;
- the particle lifetime ($\tau_p \approx 0.35$ s in ohmic plasmas) decreases as $P_{cond}^{-1/5}$;
- the ratio $\varepsilon_{pump(Throat)}/\varepsilon_{pump(Vented)}$ remains roughly constant at a value of ≈ 3.5 for the investigated range of power and density, but the exhaust capability of the Vented pump limiter could be increased by ≈ 2 by optimizing the shape of the slots.

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