High efficiency cavity design of a 170 GHz gyrotron for fusion applications

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The design of high power, continuous wave (cw), 170 GHz gyrotron cavities is considered. The anticipated degradation of efficiency with beam velocity spread places a premium on the optimization of efficiency. For parameters of interest achievement of high efficiency requires utilization of a high quality cavity. Two options are considered: a barrel cavity and a long simple tapered cavity operating at low voltage. The cavities are examined for their sensitivity to velocity spread, their mode competition, and their maximum Ohmic power dissipation. [S1070-664X(97)00401-1]

I. INTRODUCTION

High power (⩾1 MW) and high frequency (⩾100 GHz) gyrotrons are required for electron cyclotron resonance heating (ECRH) of a magnetically confined plasma.[1,2] For instance, the gyrotron system for ECRH on (the International Thermonuclear Experimental Reactor) ITER[3] will require a rf power greater than 50 MW at a frequency near 170 GHz operating continuously.[4] Many research groups have been working on the development of high power and high frequency gyrotrons around the world and great progress has been achieved.[1,2,4–7] In recent experiments and designs the electronic efficiency is around 35%. This is particularly the case in recent designs which take account of the expected velocity spread of the injected beam which can degrade the efficiency. Any enhancement of the electronic efficiency of the gyrotrons will be worthwhile since it will reduce the requirements on prime power and cooling systems of gyrotron and the numbers of gyrotrons in the ECRH system. In this paper a study will be performed to compare the conventional and the barrel (or iris) cavity in regards to efficiency, Ohmic heating, and the mode competition. These issues will be examined with the prime motivation being to optimize the gyrotron efficiency. Already, very promising experimental results have been achieved at 170 GHz using this type of cavity.[8]

The type of cavity considered is shown in Fig. 1. It is a four-section cavity with a downtaper cutoff section, a uniform mid-section where the interaction between the electromagnetic field and electron beam occurs, a region of constriction to increase the quality factor Q, and an uptaper section which joins the cavity to the output waveguide and the launcher of the quasi-optical coupler. The motivation for increasing the cavity quality factor is the fact that as the transverse cavity size is increased (to handle high power) the coupling efficiency of the beam and radiation decreases. Thus, to access the high efficiency operation point (at fixed voltage and current) it is necessary to raise the cavity quality factor. Increasing the quality factor by lengthening the cavity raises the dimensionless interaction length $\mu=(L_G k)\beta_\perp^2/\beta_z$, where L_G is the half width at the axial field profile, k is the vacuum wave number, and $\beta_\perp$ and β_z are the transverse and axial velocities of the injected electrons normalized to the speed of light. For values of μ in excess of 15 mode competition becomes a problem in that the operating mode will be unstable with respect to the excitation of higher frequency modes of the cavity. Thus, to raise the quality factor at a fixed axial length one is lead to consider barrel cavities.

Our studies will show that the high Q barrel cavity (at a given beam voltage and current) represents a significant improvement over a simple tapered cavity with regard to efficiency and insensitivity to velocity spread. Additionally the parameters of the barrel cavity can be adjusted to ensure single mode operation. Finally however, a not unexpected result of raising the cavity quality factor is an increase in the maximum power density dissipated in the cavity walls. Attainment of the maximum efficiency equilibrium results in a level of power dissipation density which is determined primarily by the beam voltage. The most straightforward way to reduce the power density is to reduce the voltage. This will be seen later in the paper where a simple tapered cavity operating at a lower voltage will be discussed.

The basic parameters of the barrel cavity are listed in the caption of Fig. 1. The operating mode is selected to be $TE_{28,8^-}$ at 170 GHz. The results of this cavity will be compared first with a simple tapered cavity in which $z_{b1}=z_{b2}=\theta_b=0$. The basic conventional cavity used in this work has the same dimensions as those used in the design of ITER gyrotrons which must work at 170 GHz, 1 MW.[4]

To determine the values of the parameters in the barrel section which will yield the optimum efficiency of the cavity, numerical simulations were performed using the self-consistent, time dependent, multimode, multifrequency code MAGY.[9] This numerical code integrates the electron equations of motion for an ensemble of electrons uniformly distributed in azimuthal angle, self-consistently with the solution Maxwell's equations, computing the energy exchange between the electron beam and the electromagnetic field of the cavity. Each of the modes has a time dependent axial profile which is determined self-consistently by the response of the electrons and which satisfies appropriate boundary conditions at both ends of the cavity. Also considered are voltage depression, electron beam energy and pitch ratio spread, and ac space charge. The pitch ratio is defined as the

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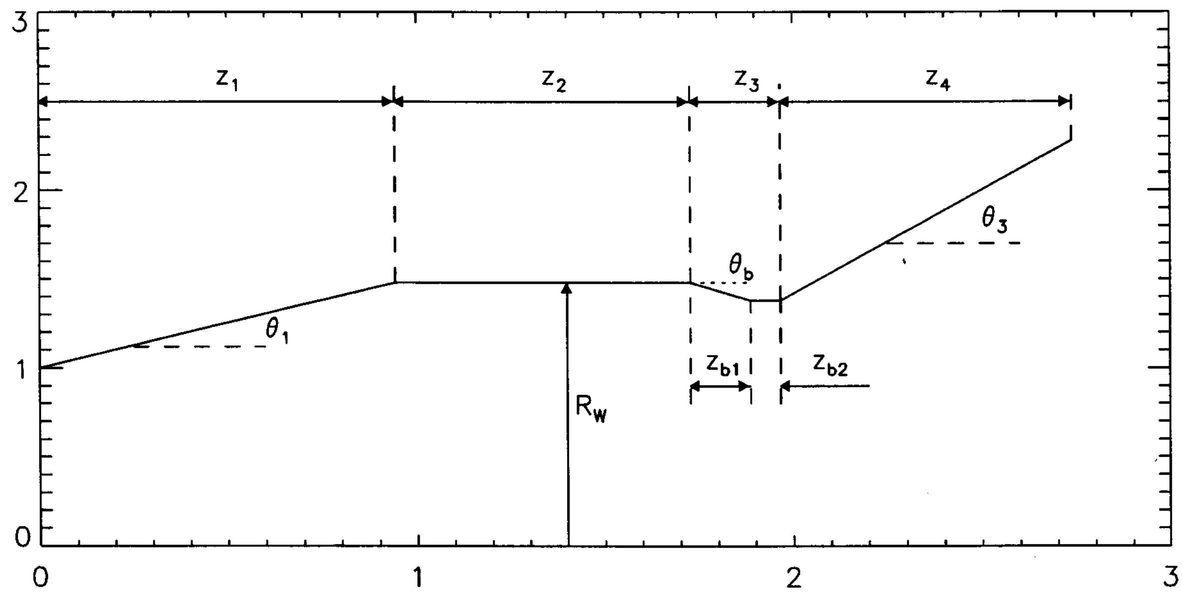

FIG. 1. Barrel cavity geometry. Basic parameters used are $\theta_1=3^0$; $\theta_2=7^0$; $R_w=1.689$ cm, $z_1=1.0$ cm, $z_2=0.785$ cm, $z_3=0.207$ cm, and $z_4=0.8$ cm.

velocity ratio $\alpha=v_{\perp 0}/v_{\parallel 0}$ at the entrance to the interaction region. In this work only spreads in velocity pitch ratio are considered. The shape of the distribution function for the injected pitch ratio is taken from experimental measurements.[10] The distribution function is then rescaled to allow for arbitrary rms spread in pitch ratios.

II. GENERAL CONSIDERATIONS

The gyrotron starting current[11] is inversely proportional to the coupling coefficient, given by

$$C_m^2=\frac{J_{m\pm 1}^2(2\pi R_b/\lambda)}{(\nu_{mp}^2-m^2)J_m^2(\nu_{mp})}, \tag{1}$$

where R_b is electron beam radius, λ is the wavelength of the radiation, and ν_{mp} is the eigenvalue of the operating mode $TE_{m,p,1}$, i.e. the pth root of the boundary equation $J_m'(\nu_{mp})=0$. J_m is the Bessel function of order m. Figure 2 shows the coupling coefficient as function of the electron beam radius for the operating mode ($TE_{28,8^-}$) as well as for some competing modes. Since starting current for the operating mode should be the smallest in relation to the starting current of the competitors, the electron beam position should be in the maximum of the operating mode coupling coefficient. From Fig. 2 we can observe that the maximum coupling between the beam and the operating mode $TE_{28,8^-}$ is obtained by placing the beam at a radius of $0.49R_w$, where R_w is the cavity radius. For the cavity in Fig. 1 this implies an electron beam radius of 0.828 cm. The minus sign $(-)$ in the mode designation means that the field and the electrons rotate in the same sense, inversely the plus signal $(+)$ means that the field and the electrons rotate in the opposite senses.

One effective way to determine which modes are the main competitors with the $TE_{28,8^-}$ mode is to find the starting current of those modes whose frequency lies in the amplification band of an electron beam and have coupling coefficients comparable to the coupling coefficient of the $TE_{28,8^-}$ mode. The amplification band is defined as

$$\Delta\omega_{am}\approx\frac{\pi}{T}, \tag{2}$$

where T is the transit time of electrons through the resonator. For the assumed electron beam voltage of 83 kV and mean pitch ratio $\alpha=1.65$, the amplification band is approximately 3.2 GHz. Starting currents as a function of magnetic field were generated for those modes that satisfy the conditions above and they are shown in Fig. 3. We have used the cold cavity-field profile to determine the starting current curves. From this figure we can observe that the main competitors of the $TE_{28,8^-}$ are the modes with the same radial index as the main mode ($TE_{30,8^-}$, $TE_{29,8^-}$, $TE_{27,8^-}$, $TE_{26,8^-}$), and the modes with the radial index 9 ($TE_{27,9^+}$, $TE_{26,9^+}$, $TE_{25,9^+}$). As we will find the most severe competition comes from the $TE_{25,9^+}$ mode.

Choosing the conventional cavity as a base, we changed the barrel parameters (z_{b1}, z_{b2}, and θ_b in Fig. 1) to find a configuration that resulted in maximum efficiency. We tried to keep the straight section plus the barrel section length in the barrel cavity roughly constant so as to keep $\mu\leqslant 15$. The barrel parameters that resulted in the best efficiency were $\theta_b=3^0$, $z_{b1}=0.157$ cm, and $z_{b2}=0.05$ cm. The highest perpendicular efficiency found was of 74.1%. In this case we used an electron beam with no spread. The corresponding electronic efficiency is 46.8% including the effect of the dc space charge depression. The maximum Ohmic heating power dissipated in the cavity wall is 3.6 kW/cm^2. For the conventional cavity, with resonant section length of 0.97 cm and remaining parameters equal to those of the barrel cavity, we found that the electronic efficiency of approximately 36% and maximum power density dissipated of 1.5 kW/cm^2.

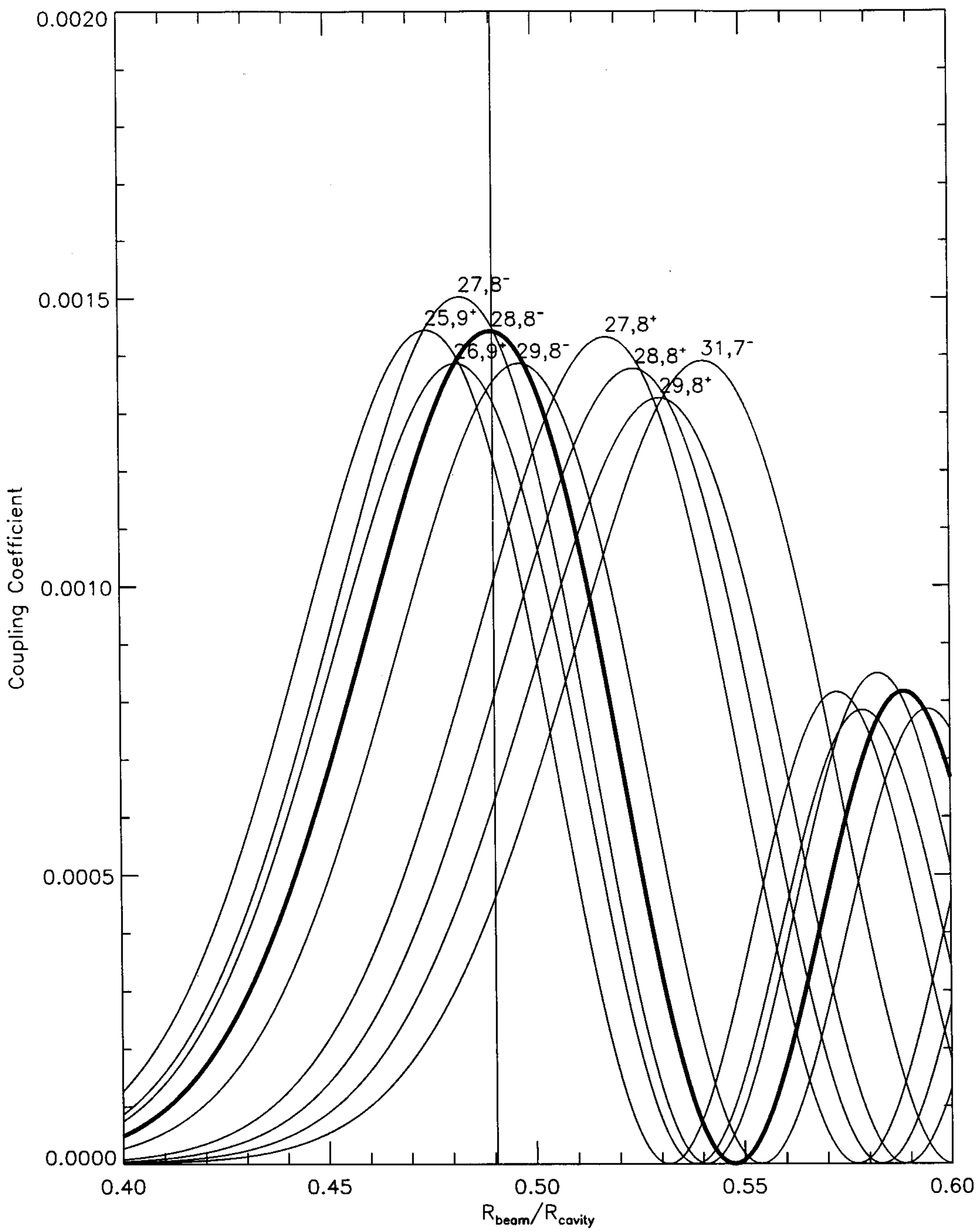

FIG. 2. Coupling coefficient versus the beam radius normalized by the cavity radius.

In Fig. 4 we plot the optimized efficiency at a current of 38 A against rms velocity spread for both the conventional and barrel cavities. We studied two conventional cavities that we named long ($z_2 = 1.106$ cm) and short ($z_2 = 0.97$ cm) cavities. In the following we examine the performance of the barrel and the short cavity. We can observe from this figure that the barrel cavity has higher efficiency for all values of spread. It is expected that the velocity spread will be as high as 8% for such a beam current.[10] In this case the efficiency of the barrel cavity is 40.5% compared with 32.1% for a conventional short cavity. This is the main advantage of operating near the maximum efficiency point.

III. MODE COMPETITION STUDIES

Additional single mode, cold beam simulations were performed to calculate the total efficiency as a function of the magnetic field for the main mode and its main competitors, Fig. 5. In this figure the soft and hard excitation regions are also indicated; soft and hard excitation equilibria with solid and dashed lines, respectively. In our simulation, hard excitation equilibria are obtained by using the output of a run in the soft excitation region as the initial condition for the evolution to the hard excitation equilibria. As is known the region of highest efficiency is located in the hard excitation

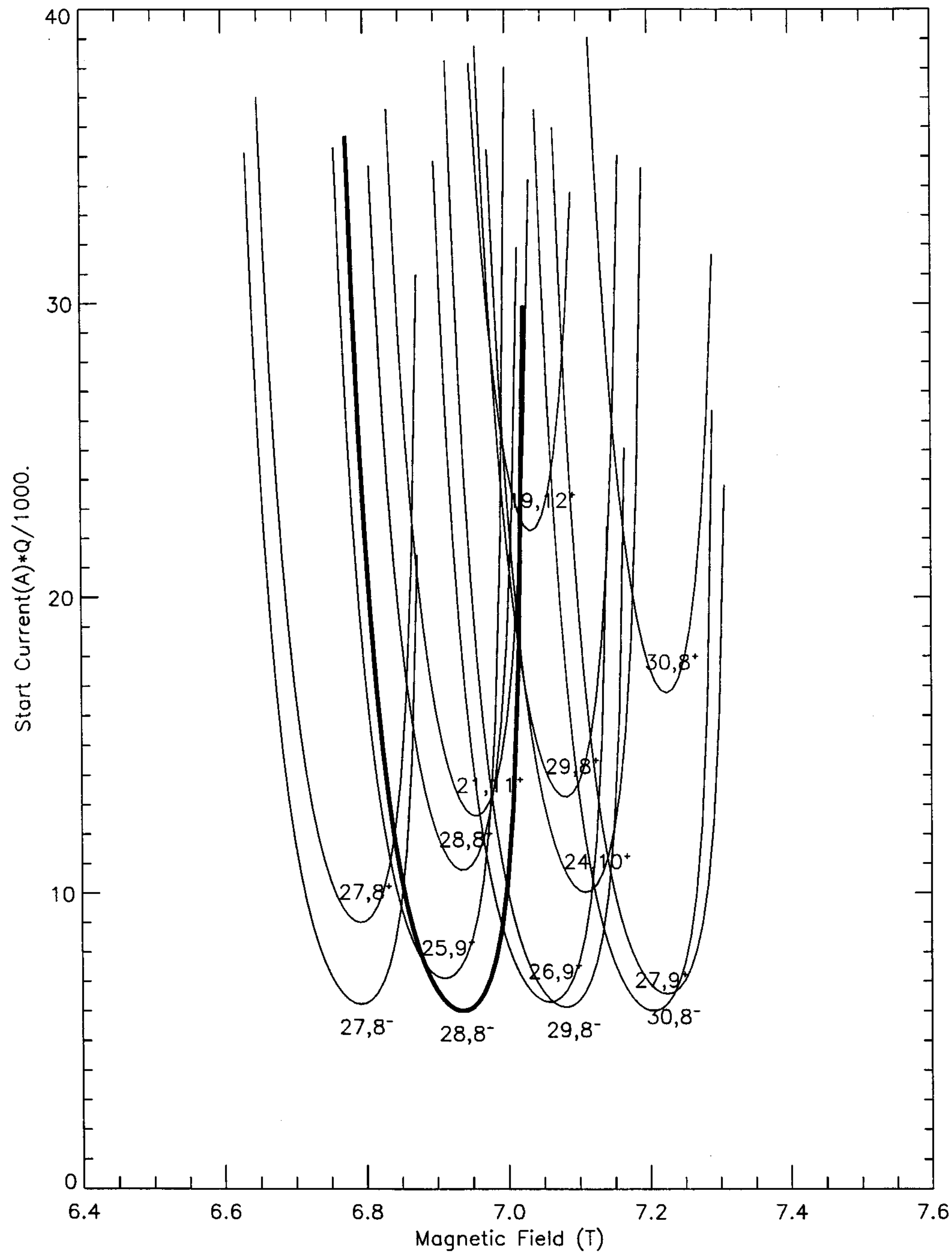

FIG. 3. Starting currents versus magnetic field for the barrel cavity.

region. For beam pitch ratio $\alpha = 1.65$, beam current 38 A, and voltage acceleration 83 kV, the maximum efficiency is approximately of 47% for the main mode. From this figure we can conclude that the optimum operating point corresponds to a magnetic field of 6.65 T and $I_b = 38$ A. At the operating point, in Fig. 3, the starting current of $TE_{28,8^-}$ is higher than the beam current, meaning that the operating point lies in the hard-excitation region of $TE_{28,8^-}$. From this figure it appears that mode competition may be an issue. It is not clear that the operating mode will dominate all other modes, resulting in stable oscillation during startup and at the operating point. To determine which mode or modes will survive at the operating point we will use the code MAGY to study mode competition between the $TE_{28,8^-}$ and its main competitors for a specific startup scenario. In our simulations we used the ''instant turn-on'' scenario, in which the voltage and current rise to their final values in a time smaller than the cavity decay time Q/ω. This corresponds roughly to the situation in which the beam current or pitch ratio rises while the total voltage is fixed.

Multifrequency simulations were carried out by including three waveguide modes that are nearly equally spaced in frequency. We used two groups of modes. The first group is composed of the modes $TE_{29,8^-}$, $TE_{28,8^-}$, and $TE_{27,8^-}$, and the second group is composed of the modes $TE_{30,8^-}$, $TE_{28,8^-}$, and $TE_{26,8^-}$. Each of the modes is allowed to interact with the electron beam self-consistently.[9] Competition between two modes was also considered, and in this case we

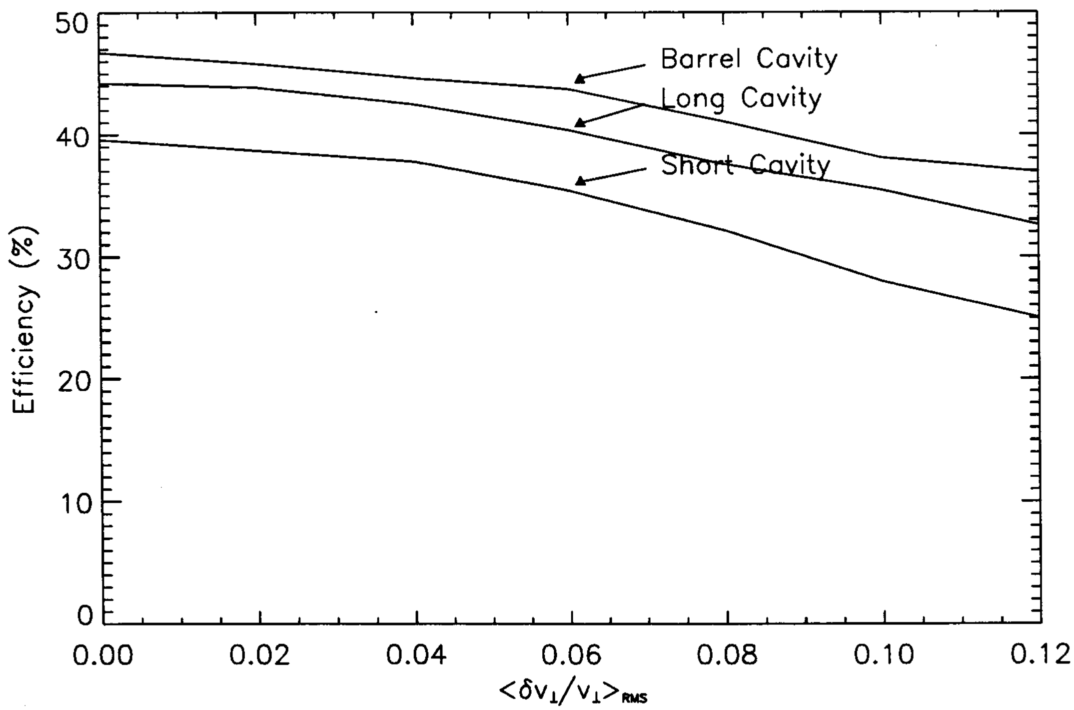

FIG. 4. Efficiency versus velocity spread for conventional and barrel cavities, with $I=38$ A, $\alpha=1.65$, and the $TE_{28,8^-}$ mode.

ran the program with the main mode $TE_{28,8^-}$ and one of the following modes $TE_{25,9^+}$, $TE_{26,9^+}$, or $TE_{27,9^+}$. In all these cases, except one to be discussed, we obtained stable, single mode ($TE_{28,8^-}$) oscillation in state, steady, with the competing modes oscillating at the noise level. In the case where competition between the $TE_{28,8^-}$ and the $TE_{25,9^+}$ modes was considered, the $TE_{25,9^+}$ mode was the surviving mode. To avoid excitation of this mode we increased the electron beam radius slightly, thus decreasing slightly the coupling coefficient of the $TE_{28,8^-}$ mode, but significantly decreasing the coupling coefficient of $TE_{25,9^+}$ mode. The electron beam radius was increased from 0.828 to 0.8445 cm. With the electron beam in this new position we observe, in our multimodes simulations, stable, single mode oscillation in steady state and the only surviving mode is the $TE_{28,8^-}$. In this case, however, the total efficiency decreased from 46.8% to 45.6% and the the maximum power dissipation remained in 3.6 kW/cm^2.

Two other possible ways to avoid excitation of the $TE_{25,9^+}$ in the barrel cavity without increasing the beam radius are to use a coaxial cavity, or to use a different startup scenario. With a coaxial cavity it is possible to increase the starting current of modes with radial indices different from that of the operating mode, so that unwanted modes would not be excited. The starting current of the operating mode will remain almost unchanged.[12] The second approach would be to use a more convenient start up scenario, in which the operating mode would be the first and the only mode to be excited.[13–15]

To decrease the power dissipation in the cavity wall we have altered the cavity profile. Table I shows some cavity configurations and their respective total efficiency and maximum Ohmic heating power dissipated in the cavity wall.

We can observe from this table that the Ohmic heating is reduced from 3.6 to 2.7 kW/cm^2 with a small decrease in efficiency from 45.6% to 44.2%. The later version of the cavity, which has less Ohmic heating, seems to be the optimum cavity design for the given beam parameters of 83 kV and 38 A.

IV. LOW VOLTAGE ALTERNATIVE

In the previous section we discussed the design of a barrel cavity, and attempted to minimize wall losses while maintaining high efficiency. Optimization was performed utilizing a fixed beam voltage. In this section we will consider the advantages of reducing beam voltage.

Motivation for decreasing voltage is as follows. The peak power density dissipated in the walls may be expressed as[16]

$$P_d=\frac{\delta k^2}{2(2\pi L_G)^{1/2}}\frac{QP_{out}}{(\nu_{mp}^2-m^2)}, \tag{3}$$

where δ is the skin depth, P_{out} is the output power, and we have assumed that the axial profile of the field is approximately Gaussian with a half width L_G. To operate at the maximum efficiency point one must have a sufficiently large value of the dimensionless current,

$$I_G=\left(\frac{2}{\pi}\right)^{1/2}\frac{IQ}{I_0}\frac{kL_G}{\beta_z}C_m^2, \tag{4}$$

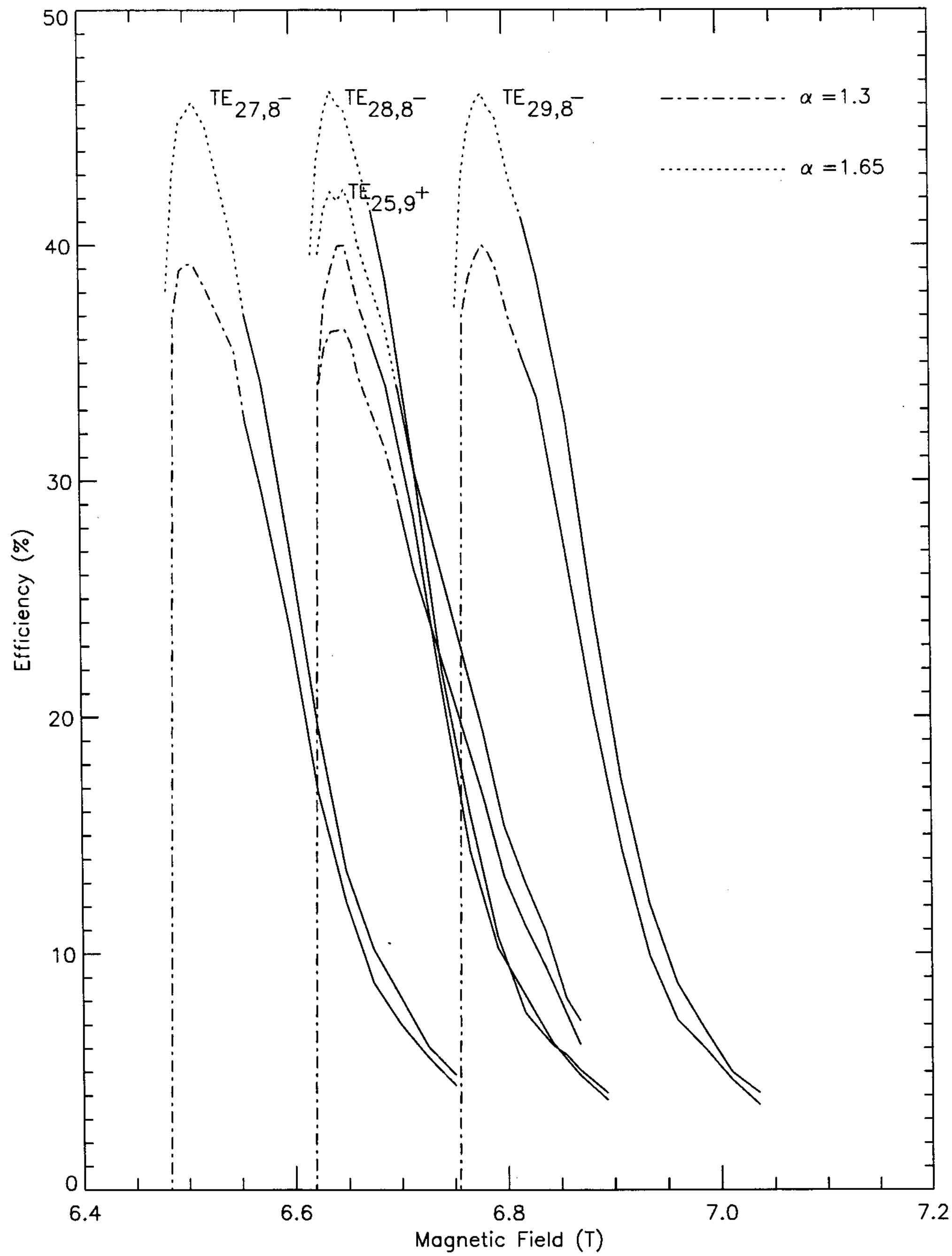

FIG. 5. Total efficiency versus magnetic field curves obtained from single frequency simulations and the cold beam. The dotted line on each curve denotes the hard excitation region.

where $I_0 = 1.7 \times 10^4$ A and the coupling coefficient C_m is defined in Eq. (1). Optimum efficiency occurs for $I_G \simeq 0.3$ and physically corresponds to having a sufficiently large product of current, quality factor, interaction length, and coupling coefficient. Since a cavity quality factor appears in both expressions (3) and (4), they can be combined to yield

$$P_d = \left(\frac{\delta k^3}{4} \right) \left(\frac{I_0 V \beta_\perp^4}{\beta_z} \right) \left(\frac{\eta I_G}{\mu^2} \right) \left(\frac{J_m^2(\nu_{mp})}{J_{m+1}^2(\nu_{mp} R_b / R_w)} \right), \quad (5)$$

where we have introduced the normalized length $\mu = k L_G \beta_\perp^2 / \beta_z$. Expression (5) is useful in that it describes

TABLE I. Performance of several barrel cavities. Dimensions refer to Fig. 1.

L (cm)	zb_1 (cm)	zb_2 (cm)	θ_b (deg)	η_T (%)	P_Ω (kW/cm^2)
0.785	0.15	0.05	−3.0	45.23	3.4
0.785	0.16	0.05	−3.0	46.57	3.6
0.785	0.17	0.05	−3.0	46.78	4.0
0.785	0.17	0.05	−2.0	44.99	3.0
0.790	0.17	0.05	−2.0	45.22	3.0
0.790	0.17	0.05	−2.5	45.64	3.5
0.800	0.15	0.05	−2.0	44.24	2.7

the level of wall dissipation in terms of various parameters while maintaining optimum efficiency. The first factor depends only on frequency and the conductivity of the wall. The second factor depends only on beam voltage and pitch ratio. The third factor depends on the operating point. The maximum safe value of the normalized length is $\mu=15$. Efficiency will be about 50% for $\alpha=1.6$. Thus, this factor is fixed at 6.7×10^{-4}. The last factor depends on the selected mode. Actually, it varies little with mode indices if the beam is placed on the maximum of the relevant coupling coefficient, $J_m^2(\nu_{mp})/J_{m+1}^2(\nu_{mp}R_b/R_w)\simeq R_b/2R_w$. Physically, this quantity relates the magnetic field of the mode at the wall to the electric field at the beam. This quantity can be made small by increasing the diameter of the interaction region. However, at some point the space charge depression of the beam energy becomes significant and a center conductor is needed.

Of the above factors the most adjustable is the one involving voltage and it has a $V^{5/2}$ dependence. Thus, small decreases in voltage give rise to large reductions in power dissipation. In Ref. 16 arguments are given for not raising voltage above the 60–80 kV range. Formula (5) shows that small changes in voltage within this range can substantially lower wall dissipation. The strong dependence on voltage is a consequence of the following. At a lower voltage it takes a smaller electric field to decelerate a beam electron. Further, the deceleration can occur over a proportionately longer distance of fixed μ. The required electric field is thus reduced at a lower voltage. To test these scalings we have designed a long simple tapered cavity to operate at 64 kV (Long Cavity). This voltage is chosen since it allows for an interaction length for which the diffractive Q of the cavity is sufficient to reach maximum efficiency.

Plots of efficiency versus beam thermal spread for this cavity are shown in Fig. 4. Its efficiency is nearly identical to that of the barrel cavity with the same beam radius. The maximum output power and wall dissipation are lower for this cavity than for the barrel cavity. For a cold beam the predicted output power is 1.1 MW and the peak power density 1.6 kW/cm^2 whereas for the barrel cavity with an 83 kV beam the corresponding numbers are 1.4 MW and 2.7 kW/cm^2, respectively. Output power at low voltage could be increased by increasing the radius of the cavity and the beam current. Eventually however, space charge voltage depression will become significant requiring consideration of coaxial cavities.[17]

V. CONCLUSION

We have designed a barrel cavity that has high total efficiency (44%) and low power dissipation in the cavity wall (2.7 kW/cm^2), and operates with an 83 kV beam. Whereas for the conventional cavity at this voltage the best efficiency is of 36% with a power dissipation of 1.5 kW/cm^2. Calculation of total efficiency as a function of electron beam transverse velocity spread was performed for conventional and barrel cavities. These calculations have shown that for a realistic value of the velocity spread the barrel cavity efficiency was 40.5% while in a conventional cavity it was only 32.1%. Multimode simulations have shown that we have stable, single mode oscillation in a steady state with $TE_{28,8^-}$ being the resulting mode. Additionally we have examined a low voltage alternative where high efficiency and significantly reduced wall losses were realized.

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