A Submillimeter-Wave Gyroklystron: Theory and Design

G.S. Nusinovich, M. Walter, M. Kremer and M.E. Read
Physical Sciences Inc.

D. Boehme
Sandia National Laboratory


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A Submillimeter-Wave Gyroklystron: Theory and Design

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Abstract

New elements of the theory and a preliminary design for a pulse/CW 360 GHz gyroklystron are presented. Issues germane to very high frequency operation of gyroklystron amplifiers, including drive power and limits on cavity Q, are discussed. A specific two cavity design is described. That device had a gain of 33 dB and a beam extraction power of 1 kW with an electronic efficiency of 8% and a power output of 700 W after taking into account Ohmic losses. To produce fast rising pulses, the beam velocity ratio was varied via the modulating anode of a magnetron injection gun. A design for an electron gun through which reduction of the output signal by -50 dB was achieved by a 400 V modulation is given. The input coupler, cavities, electron gun, collector, output coupling optics and collector are described. In addition, issues concerning the fabrication of the high precision, ~2 mm diameter cavities are discussed.

Key Words

Microwave, millimeter wave, sub-millimeter wave, electron gun, gyrotron, gyroklystron
I. Introduction

For a long time mastering of the submillimeter wavelength region was a challenge for developers of gyro-devices/cyclotron resonance masers (CRMs). So far, these efforts were focused on the development of free running oscillators. In 1964, I. M. Bott reported about the generation of less than 1 milliwatt pulsed power at wavelengths $\lambda \geq 0.95 \text{ mm}$ at the second cyclotron harmonic [1]. Later, in 1974, second harmonic operation of gyrotrons delivering 1.5 kW CW power at 0.92 mm wavelengths was described in Ref. [2]. (Note that, although this breakthrough in the development of high-power submillimeter-wave sources was highly evaluated by the Western microwave community, see J.M. Osepchuk [3], this is still the highest CW power level realized in this frequency range.).

In the early 1980's submillimeter wave gyrotrons operating at the fundamental cyclotron resonance were developed at the Institute of Applied Physics, Nizhny Novgorod, Russia [4,5]. The magnetic field required for operation at the fundamental resonance at high frequencies was generated by pulse solenoids producing up to 27T magnetic fields in pulses about 5 ms long. (These pulses were long enough for providing the penetration of the variable magnetic field inside the metallic tube). The tube delivered more than 100 kW in 70 microsecond pulses at frequencies up to 500 GHz (wavelengths $\geq 0.6 \text{ mm}$) with the efficiency from 8.2% to 15%. At the shortest wavelength of 0.54mm the power reached 60 kW [5]. A few years later 40 kilowatts with 3.5% efficiency were generated in the same tube at the wavelength 0.46mm [6].

In the late 1980's there were experiments with a second harmonic, submillimeter wave gyrotron conducted at MIT [7]. In these experiments the gyrotron was placed in a Bitter magnet producing fields up to 10T, and a series of second harmonic modes at frequencies from 300 GHz to 503 GHz were generated. Output power to 22 kW and efficiencies to 6% (typical pulse length 1-2 microseconds) were achieved.

During the 1990's there was an active development of medium-power (~100 W) submillimeter-wave gyrotrons with stabilized parameters of output radiation for plasma scattering measurements and electron spin resonance experiments. These were done at Fukui University, Japan. A review of this work was published recently [8]. Experiments with a 250 GHz gyrotron oscillator for Electron Paramagnetic Resonance (EPR) spectroscopy is going on at MIT [9]. The theoretical consideration of some issues important for the development of step-tunable gyrotron oscillators operating a first two cyclotron harmonics at frequencies from 150 GHz to 600 GHz was described in Ref. [10].

To develop spectrometers for EPR experiments not only free running oscillators but phase controlled amplifiers are also of interest [11]. This is the motivation for our present paper, which is devoted to the theory and design of a submillimeter-wave gyroklystron. In contrast to free running gyrotron oscillators operating at very high-order modes, in order to provide stable operation, gyroamplifiers operate at low order modes, making the transverse dimensions of submillimeter wave gyroklystron circuits very small. This raised a number of issues not the least of which was the difficulty of manufacture.
This paper is organized as follows. In Section II, we discuss some theoretical issues important for the development of very high frequency gyroklystrons. In Section III, we present a design for a 1 kW, 360 GHz gyroklystron. In Section IV, we discuss the technological issues related to tolerances in fabrication of critical components. Section V contains the summary of our work.

II. Elements of the Theory

The theory of the very high frequency gyroklystron is, certainly, based on the same equations which are widely used for studying and designing the lower frequency gyroklystrons, e.g., Refs. [12–14]. Specific features of the theory considered here are determined by the fact that these devices are to operate at submillimeter wavelengths. This is the wavelength region where, first, it is a problem to find a driver with a high enough power, and second, the ohmic losses of microwave power in cavity walls are comparable with the diffractive losses that determine the outgoing microwave radiation. In addition, for EPR spectroscopy it is important to be able to produce short pulses. Let us discuss the consequences from these factors successively.

A. Drive Power

When we consider an ideal electron beam without velocity spread there is no limitation on the minimum power required for driving a gyroklystron amplifier. Even the field of a very small amplitude excited by a low power driver in the input cavity causes modulation in electron energies which, in long enough drift sections, may lead to significant orbital bunching which is similar to ballistic bunching used in klystrons. However, real electron beams always have a spread in electron velocities. This sets a certain limit on the minimum drive power. Let us estimate this power by using very simple equations.

From the equation for electron energy, $\varepsilon$

$$\frac{d\varepsilon}{dt} = -e\left(\vec{v} \cdot \vec{E}\right)$$  \hspace{1cm} (1)

it follows that the energy of an electron moving through a cavity of a length, $L$, with the axial velocity, $v_z$, will be modulated by the field of an amplitude, $A$, as:

$$|\Delta \varepsilon| \sim e v_{\perp} A \frac{L}{v_z}$$  \hspace{1cm} (2)

Here $v_z$ is electron orbital velocity. Since at low operating voltages (below 100 kV) the electron interaction with TE-waves changes mostly the orbital momentum, one can rewrite Eq. (1) assuming
\[\Delta e \approx \Delta e_\perp \quad \text{where} \quad e_\perp = \frac{m v_\perp^2}{2} \quad \text{is the kinetic energy of electron orbital motion as} \]

\[
\left| \frac{\Delta v_\perp}{v_\perp} \right| \approx \frac{eA L}{mc^2} \frac{1}{\beta_z \beta_\perp}
\]

(3)

Here, \(\beta_z\) and \(\beta_\perp\) are the electron velocity components normalized to the speed of light.

For electrons to be trapped by the field of such a wave, the velocity modulation given by Eq. (3) must exceed an initial spread in electron orbital velocities, \(\Delta v_\perp / v_\perp\). Correspondingly, the intensity of the field in the input cavity must obey the following relation:

\[A^2 > \left( \frac{mc^2}{eL} \right)^2 \left| \frac{\Delta v_\perp}{v_\perp} \right|_{\text{init}}^2 \beta_z^2 \beta_\perp^2\]

(4)

To determine the relation between \(A^2\) and the input drive power, \(P_{dr}\), let us recall the balance equation for the input cavity:

\[P_{dr} + \eta_{el} P_b = \frac{\omega}{Q} W\]

(5)

Here, the left hand side represents the power introduced into the cavity, consisting of the input power provided by a driver plus the power withdrawn from the beam, while the right hand side represents the microwave losses in the cavity with a certain Q-factor and stored energy, \(W\). \(\eta_{el}\) is the interaction efficiency and \(P_b = V_b I_b\) is the beam power.

Since the input cavity operates in a small-signal regime, the electronic efficiency, \(\eta_{el}\), can be represented [13] as

\[\eta_{el} = A^2 \chi_{Lin}''\]

(6)

where \(\chi_{Lin}''\) is the imaginary part of the linearized susceptibility [12,15] of the beam with respect to the cavity field. (In the small-signal regime \(\chi_{Lin}''\) does not depend on \(A\).) Also, the microwave energy \(W\) relates to \(A^2\) as

\[W = A^2 N\]

(7)
where $N$ is the norm of the mode which depends on the spatial structure of the operating mode and on the resonator volume. (For the electric field of the mode $\tilde{E} = \text{Re}\{A E_r(\tilde{r}) e^{i \alpha r}\}$, $N = \frac{1}{\pi \omega} \int_V |E_r| dV$, where $V$ is the resonator volume. Using Eqs. (6) and (7) one can rewrite Eq. (5) as

$$A^2 = \frac{P_{dr}}{\omega N - \chi_{Lin}^* P_b} \quad (8)$$

The balance between the power withdrawn for the beam and the power of microwave losses, $\frac{\omega}{Q} N = \chi_{Lin}^* P_b$, determines the start oscillation conditions. Typically, for stable operation the beam power should be about 0.8-0.9 of $P_{b,\text{start}}$, which, in accordance with Eq. (8) yields

$$A^2 = (5 - 10) \frac{Q P_{dr}}{\omega N} \quad (9)$$

Substituting Eq. (9) into Eq. (4) yields the following estimate for the required $P_{dr}$:

$$P_{dr} (kW) = (5 - 10) \times 10^6 \frac{N}{L^2 \lambda} \frac{1}{Q} \beta_r^2 \beta_z^2 \left(\frac{\Delta v_\perp}{v_\perp}\right)^2 \quad (10)$$

In getting Eq. (10) we used the relation $\frac{m^2 e^5}{\varepsilon^2} = 8.7 \times 10^6 \text{ kW}$. Let us show what follows from Eq. (10) in a concrete example. Consider the device driven by a 180 GHz signal in which the first cavity operates at the fundamental cyclotron resonance (the operating mode is $\text{TE}_{011}$) while all other cavities operate at the second harmonic. The output frequency is thus 360 GHz. Assume also that the input cavity is critically coupled, i.e., its coupling Q-factor, $Q_c$, is equal to the ohmic Q-factor, $Q_{\text{ohm}}$, which for the $\text{TE}_{011}$-mode at 180 GHz is close to $3.2 \times 10^3$. (In this estimate we assumed that the skin-depth due to the roughness of a cavity surface is two times larger that its value for an ideal copper.) Correspondingly, the total Q-factor is about $1.6 \times 10^3$. Let us also assume that the beam voltage is 40 kV and the electron orbital to axial velocity ratio, $v_\perp / v_z = 1$, which yields $\beta_z^2 = 0.07$. Finally, let us take the cavity length equal to 7 mm, corresponding to $L \approx 4 \lambda$. For a cylindrical cavity operating at the $\text{TE}_{011}$ - mode
where \( \nu_{01} \equiv 3.83 \) is the TE\(_{01}\) mode eigennumber. Using this and all parameters specified above we can readily get from Eq. (10)

\[
P_{dr} (kW) > (0.03 - 0.06) \left( \frac{\Delta v_\perp}{v_\perp} \right)^2
\]

(12)

This means that, for a beam with a 3% spread in orbital velocities, the driver power should exceed 30 - 60 mW. When the power of an available driver is lower than this value, one would have to operate closer to the region of self-excitation. This kind of operation is, however, prone to self-excitation due to some fluctuations in technical parameters (beam and mod-anode voltages, beam current, etc.).

**B. Ohmic Losses**

The role of ohmic losses is quite different between the cases of pulsed or a continuous wave (CW) operation. (The latter case, in a sense, is analogous to the pulse operation with a high duty-cycle.) In the case of high average power the restricting factor is the density of ohmic losses whose average value can be estimated from

\[
P_{ohm} = \frac{Q_D}{Q_{ohm}} \frac{P_{out}}{2 \pi R L} \approx \frac{Q_D}{Q_{ohm}} \frac{P_{out}}{v \lambda L}
\]

(13)

Here \( R \) is the cavity radius and in the case of operation near cutoff, \( v \approx 2 \pi R / \lambda \). \( Q_D \) is the diffractive \( Q \)-factor. So, for instance, the maximum power that can be achieved in a 360 GHz output cavity in the TE\(_{02}\) - mode, when the cavity length is \( L=6\lambda \), \( Q_D = Q_{ohm} \), and ohmic losses are limited to 1 kW/cm\(^2\), is 0.3 kW.

In the case of operation in a pulsed, low duty-cycle regime the critical issue is the efficiency. The total efficiency, \( \eta \), related to the electronic or interaction, efficiency, \( \eta_{el} \), is

\[
\eta = \left( 1 - \frac{Q}{Q_{ohm}} \right) \eta_{el}
\]

(14)

where the total \( Q \)-factor is determined by ohmic and diffractive losses as
To avoid significant losses of microwave power in the cavity walls one should operate in cavities with low diffractive $Q$’s, i.e. where $Q_D \ll Q_{ohm}$. At the same time, the interaction efficiency increases with the normalized beam current parameter $I_0$, \cite{?} which is proportional to the product of the beam current, $Q$-factor and the intensity of cyclotron radiation at harmonics. The last factor is given approximately by $-\beta_{\perp}^2$ (where $s$ is the harmonic number). Therefore, in the case of operation at low currents, low voltages and high harmonics, to increase the electronic efficiency one should increase the total $Q$. However, this conclusion is contradicted by the above mentioned condition, $Q_D \ll Q_{ohm}$ for the low values of $Q_{ohm}$ encountered at high frequencies. The trade-off between these two contradicting tendencies, viz. to lower $Q_{dif}$ for decreasing microwave ohmic losses and increased $Q_{dif}$ for increasing electronic efficiency, was analyzed in Reference \cite{15}. Without going into details of the work done in Ref. \cite{?}, let us briefly describe two methods of optimization considered there. These methods are based on the fact that the diffractive $Q$-factor of open cavities used in gyro-devices can be determined as \cite{16}

$$
\frac{1}{Q} = \frac{1}{Q_D} + \frac{1}{Q_{ohm}}
$$

(15)

where $Q_D \approx 30(L/\lambda)^2$ is the minimum diffractive $Q$-factor of a cavity of a length $L$ open at the collector end. It is assumed that, as usual, there is a cutoff neck from the cathode side. $|R|$ is the absolute value of the reflection coefficient of the wave at the collector end. $R$ can be varied by changing the profile of the neck to achieve a design value for $Q$ when the current is high enough. We (1) choose the cavity length to be optimum for the electronic efficiency and then, (2) optimized the value of $Q_D$ by changing the reflection coefficient $|R|$. Then, as the current gets lower and the wavelength shortens, at a certain $Q_{ohm}$, a corresponding optimum value of $Q_D$ becomes equal to $Q_D^{min}$. Below this point $|R| \approx 0$, and hence the only way to increase the efficiency is to increase the cavity length $L$. In this situation the electrons interact with field of a small amplitude. However, the increase in the interaction length gives an opportunity of electron inertial bunching in gyro-phases and deceleration even in such a weak field.

Unfortunately, as will be shown below, in the case of a 360 GHz gyrokystron operating at the second harmonic, the method of optimization implies relatively low interaction efficiency and significant ohmic losses. Certainly, this efficiency increases when we approach the self-excitation region.
C. Effect of voltage modulation on the output power.

For such applications as pulse EPR it is important to rapidly modulate the output. As the name implies, this can be done by using the modulating anode of a triode type MIG. The voltage modulation required for such switching was estimated for gyrotron oscillators in Ref. [10], and experimentally studied in Ref. [8]. Below we show how to estimate the required modulation in the mod-anode voltage for frequency-doubling gyrokystrons (GKLs).

Let us start from the expression for the small signal gain in two-cavity frequency-doubling GKLs given in Ref. [17]

\[
G = 20 \log \left\{ q_0 \frac{2|\mu_1|u_2|I_{02}\mu_{dr}}{|I_{01}\chi''_1(0)|^2 - |I_{02}\chi''_2(0)|^2} \right\}
\]  

(17)

Since the frequency multiplication is a nonlinear effect, as the bunching parameter \( q_0 = 2A_1|u_1|\mu_{dr} \) decreases, the gain becomes vanishingly small. Here \( A_1 \) is the normalized field amplitude of the first cavity field excited by a driver, see for example Eq. (8) and Ref [14]. The quantity \( \mu_{dr} = \left( \beta_{\perp 0}^2 / 2\beta_{z 0} \right) \left( \Omega_0 L_{dr} / c \right) \) is the normalized drift section length and \( \Omega_0 \) is the initial electron cyclotron frequency. Also,

\[
I_{os} = \frac{eI_b}{m c^3 \gamma_0} Q_s \left( \frac{n_s}{(n_s - 1)!} \right)^2 \beta_{\perp 0}^{2(n_s - 3)} 4^{(2-n_s)} G_s
\]

(18)

is the normalized current parameter for the s-th cavity. \( I_{os} \) is proportional to the Q-factor and the coupling impedance \( G_s \) of an electron beam to a given mode. The functions

\[
u_s = \int_{0}^{\mu_i} f_s(\zeta)e^{in_s\Delta_s\zeta}d\zeta
\]

(19)

describe the transit effects in corresponding cavities. Here, \( f_s(\zeta) \) describes the axial structure of the s-th cavity field, \( \zeta = \left( \beta_{\perp 0}^2 / 2\beta_{z 0} \right) \left( \Omega_0 z / c \right) \) is the normalized axial coordinate, \( n_s \) is the cyclotron resonance harmonic number for the s-th cavity and \( \Delta_s = \left( 2 / \beta_{\perp 0}^2 \right) \left[ (\omega - n_s\Omega_0) / \omega \right] \) is the normalized cyclotron resonance mismatch. In the first cavity \( \omega \) is the signal frequency, \( \omega_{sg} \), while
in the second cavity $\omega = 2\omega_{\text{sig}}$. The imaginary part of the linearized susceptibility which was present in Eq. (17) was used in Eqs (6) and (8). This susceptibility which was described in Refs. 17, 18, and 19 determines the start current for oscillations in the cavity, $I_{s,tt}$. Thus the product, $I_{os} \tilde{X}_s(0)$, can be rewritten as $I_b / I_{s,tt}$. This ratio, as well as the function $u_S$ given by Eq. (19), depends on the normalized length of each $\mu_S$ and on the transit angle $\theta_S = \Delta, \mu_s$. (For some specific axial distributions of the cavity fields the ratio $I_b / I_{s,tt}$ can be found elsewhere [18-20]). These normalized parameters $\theta_S$ and $\mu_S$, in their turn, depend on the orbital-to-axial velocity ratio, $\alpha = \nu_\perp \theta_0 / \nu_\perp 0$. In the frame of the adiabatic theory of magnetron injection guns [21], $\nu_\perp$ is proportional to the mod-anode voltage, $V_m$. In addition, the changes in $\nu_\perp$ affect the axial velocity when the beam voltage, $V_b$, is fixed. We only emphasize that when the cavities operate close to the region of self-excitation, even small changes in $\alpha$ may cause significant changes in the $I_b / I_{s,tt}$ ratio, and correspondingly the gain.
III. Design

A two-cavity design is presented here. While this approach has limitations, as discussed below, it has the advantage of simplicity. This is of particular importance when considering the difficulties of fabrication.

The goals of the design were:
- Output frequency: 360 GHz
- Input frequency: 180 GHz
- Peak power: 1 kW
- Average power, in pulse mode: 100 W
- Pulse width from 10 ns to 1 ms via mod-anode modulation

The design of the electron gun, input cavity, interaction section and the collector are described briefly below.

A. Electron Gun

Optics

The design of the electron gun using EGUN [22] was straightforward, and the results are summarized in Table 1 and Figures 1 through 3. The principal goals were a velocity ratio, \( \alpha \), of 1.5, a low velocity spread, and a low cathode mod-anode voltage to facilitate modulation. These goals were achieved.

Table 1. Design parameters of the electron gun.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode-Anode Voltage</td>
<td>40 kV</td>
</tr>
<tr>
<td>Cathode-Mod Anode Voltage</td>
<td>3.8 kV</td>
</tr>
<tr>
<td>Current</td>
<td>( \leq 0.35 ) A</td>
</tr>
<tr>
<td>Velocity ratio, ( \frac{v_{\text{perp}}}{v_{\text{parallel}}} = \alpha )</td>
<td>1.5</td>
</tr>
<tr>
<td>Spread in ( v_{\text{perp}} )</td>
<td>2.2%</td>
</tr>
<tr>
<td>Max Electric Field (at cathode)</td>
<td>65 kV/cm</td>
</tr>
<tr>
<td>Emitter current density</td>
<td>5 A/cm(^2)</td>
</tr>
<tr>
<td>Magnetic compression ratio</td>
<td>35:1</td>
</tr>
<tr>
<td>Cathode radius</td>
<td>1.73 mm</td>
</tr>
</tbody>
</table>

Figure 1. Output from EGUN for the gun region alone.
The design was done using 3 sections for the gun-to-cavity region to insure adequate resolution while keeping the number of mesh units low enough to avoid difficulties with convergence of the Poisson solver. The region from the cavities to the collector was simulated using another four sections.

The output from EGUN for the gun region is shown in Figure 1. The entire simulation to the collector region is shown in Figure 9. As has been found in previous simulations, the parameter most critical in determining the velocity spread was how close the beam came to the cathode surface after one cycle. This was controlled by the shape of the cathode (principally the length of the nose), and the gradient of the magnetic field. The sensitivities of $\alpha$ and the velocity spread to the nose length are shown in Figure 2. This shows that a tolerance on the nose length of at least $\pm$ 25 microns will be required. This is within normal (careful) machining tolerances. As shown in Figure 3, the sensitivity of the spread to current changes is acceptable, requiring a current stability of about $\pm$ 10%.

**Modulation**

One of the primary goals was to be able generate short (< 10 ns) pulses. Although this could be accomplished by modulating the input driver, it appeared easiest to switch the modulating anode of the magnetron injection gun. Because of the small size, the capacitance of the structure formed by the cathode and modulating anode was only about 3 pF. The beam could be completely switched off by applying +200 V to the mod-anode, and thus the total modulation needed is 4 kV. The energy associated with this modulation

![Figure 2](image2.png)  **Figure 2.** Alpha and spread in $v_{\text{perp}}$ as a function of changes in the length of the nose of the cathode.

![Figure 3](image3.png)  **Figure 3.** Dependence of the velocity spread and alpha (measured at the output of the gun region) on beam current.

![Figure 4](image4.png)  **Figure 4.** Relative output power as a function of the ratio of the beam velocity ratio, $\alpha$, normalized to $\alpha = 1.5$. 

...
is only 24 microJoules. This is not a difficult switching problem. However, the problem of switching the RF is even easier, as follows from the results shown in Figure 4. Figure 4 was produced using Eq. (17) for the parameters of the electron beam given above and those of the interaction circuit given below in Table 2. In terms of normalized parameters this means for the first cavity $\mu_1 = 6.15$ and $\Theta_1 \approx 0.8$, yielding $I_b \approx 0.88 I_{1,st}$ for the nominal modulating anode voltage. Correspondingly, for the second cavity, $\mu_2 \approx 14$ and $\Theta_2 \approx 2.15$ and $I_b \approx 0.843 I_{2,st}$. Using Eq. (17) with these parameters gives Figure 4, from which it follows that only about 400 V is required to reduce the RF output by -50 dB. This can be achieved with at least one commercially available modulator. For example, the model GRX-1.5KE made by Directed Energy Inc. [23] will produce a 1.5 kV pulse with a 2-3 ns rise time into a 50 pF load at a PRF of the required 1 kHz.

B. RF Driver

As indicated in Section IIA, the driver must have a minimum power. For our beam parameters, this was about 60 mW. Low noise solid state sources such as Gunn oscillators at 180 GHz are limited to about 25 mW. The selection was then limited to a tube source, of which only one, an extended interaction klystron oscillator, appeared suitable. A tube from Communications and Power Industries Inc. produces about 2 W, CW at the required frequency.

C. Input Coupler and Interaction Circuit

The 360 GHz circuit was designed initially as a two cavity system using a set of codes developed by personnel at the University of Maryland - Institute for Plasma Research and Naval Research Laboratory. These codes included Cascade for calculating cavity fields [24], QPb for calculating starting currents [25], MAGYKL [26] and MAGY II[27] for calculating interaction efficiency. The beam was assumed to have been launched with a voltage of 40 kV, and a current equal to 0.35 A. The perpendicular to parallel velocity ratio, $\alpha$ equaled 1.5 with a guiding center radius of 0.3 mm.

Interaction within the input cavity was primarily between the beam fundamental harmonic and the TE$_{011}$ cavity mode which was fed by an input coupler operating in the TE$_{011}$ coaxial mode. The beam then traveled through a long drift section to the output cavity. The output cavity was designed to operate in the TE$_{021}$ cavity mode near the second harmonic, $s=2$, of the beam cyclotron frequency.

<table>
<thead>
<tr>
<th></th>
<th>Length [cm]</th>
<th>Radius [cm]</th>
<th>Q factor</th>
<th>Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input cavity</td>
<td>0.70</td>
<td>0.1034</td>
<td>2100</td>
<td>178.110</td>
</tr>
<tr>
<td>Output cavity</td>
<td>0.80</td>
<td>0.09409</td>
<td>2000</td>
<td>356.220</td>
</tr>
<tr>
<td>Drift tube</td>
<td>0.60</td>
<td>0.038</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input coupler</td>
<td>0.109</td>
<td>$r_{inner} = 0.1200$</td>
<td>$r_{outer} = 0.2554$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Microwave cavity parameters
A nonlinear uptapered section was then added to bring the radius to a final value of 0.15 cm while minimizing mode conversion. The beam was confined by a constant axial magnetic field of 6.57 Tesla through the input cavity and increasing at 0.23 T/cm from the drift region through the output taper. The circuit schematic is presented in Figure 5. The primary design consideration for the initial phase of this design was to achieve 1.0 kilowatt of output power. The parameters of the microwave circuit realized toward this goal are listed in Table 2.

The input coupler was essentially a piece of WR-4 waveguide wrapped around the midplane of the input cavity. Dimensions for the input coupler are also listed in Table 2. The outer ring of the input coupler was connected to the input cavity by means of four radial coupling slots. In the initial design each slot opened a 10 degree arc of the input cavity outer circumference. The slot dimensions may be adjusted in the final design to change the coupling coefficient of the input cavity and optimize both bandwidth and mode purity of the TE_{011} mode within the input cavity. HFSS[28,29] predicted field shapes as shown in Figure 6 using these dimensions and a drive frequency of 178.110 GHz.

Performance of this design is characterized in Figure 7. The
maximum output power extracted from the beam was 1.0 kW, corresponding to an electronic
efficiency of 8.4% and gain of over 33 dB. However, the ohmic and diffraction Q’s of the output
cavity were 7800 and 2700, resulting in about 26% of the power being lost to ohmic heating. Figure
7 is for a beam with no velocity spread. With a spread in the perpendicular velocity of 2.5%, the
peak power was reduced only slightly to 950 Watts. The net maximum output power, with both
ohmic losses and velocity spread included, was 706 W.

The bandwidth of this system is extremely narrow, approximately 6 MHz.

Improvements to this design have already begun. Of concern are the ohmic losses, which while not
presenting a cooling problem because of the modest average power, do reduce the output power. To
reduce the required diffraction Q of the output cavity, the gain required in that element will be
reduced by adding a buncher (and, if necessary, a fourth) cavity. The resonant frequency of this
cavity will be slightly offset from that of the output cavity to increase the bandwidth.

Output Coupler and Collector

![Figure 8](image)

**Figure 8.** Arrangement for separating the microwave output from the
collector.

Because a Gaussian output mode will be most useful for the application, and the small diameter of
the waveguide, the microwave output will be via the side of the tube. This has been done in a
number of lower frequency, but much higher power gyrotrons. The arrangement is shown in Figure
8. It consists of a Vlasov coupler [30] that converts the TE02 mode into a quasi-Gaussian mode,
followed by a steering/shaping mirror. Based on similar couplers designed for other gyrotrons, a
conversion efficiency of over 90% should be achievable with this approach [31-33]. The electron
optics, as calculated using EGUN, for a collector suitable for the side-coupled RF output are shown
in Figure 9. To spread the beam out, a room temperature coil 30 cm long with its left edge at 40 cm
has been added to shape the field. The average power density, for the full 12 kW beam with RF off
is 480 W/cm², and at 10% duty cycle, 48 W/cm². A small AC field can be superimposed to sweep
the beam over a few cm to avoid hot spots, and make water cooling very straightforward.

It is noted that the magnetic field drops off fairly slowly downstream of the cavity. This could be
a source of instabilities in the output waveguide. This is issue will be studied further, and steps taken
Figure 9. Approximate output coupler/collector arrangement where the radiation is extracted via the side of the tube. Note that the vertical scale is strongly magnified relative to the horizontal scale.

to alter the magnetic field and/or the cavity profiles.

Output Window

At 10% duty cycle, the average power will be 100 Watts. This does not make for a difficult window problem. A number of materials should be satisfactory. For example, sapphire has a loss of 0.1 nepers/cm [34], and a 1.06 mm thick window would accordingly absorb 1.5 W from a 100 W beam. This can be easily face cooled with air. This window would be 4 wavelengths thick, and thus have a narrow bandwidth. However, this is consistent with the very low tunability of the source.

Issues associated with Fabrication

A rough layout of the tube is shown in Figure 10. This shows the approximate sizes of most of the major components and the arrangement for the input waveguide, pumping manifold, etc. One of the most difficult aspects of the development of the gyroklystron will be the fabrication of the cavities and input coupler. The cavity Q’s are about 2000, and thus their bandwidths are approximately 0.05%. (It is important to distinguish this “bandwidth,” which determines how closely the cavities must be machined, from that of the gyroklystron, which, as can be seen from Figure 7, is about $10^{-5}$.) The cavity diameters are on the order of 2 mm. Thus, the tolerance on the diameter must be better than ± 1 micrometers (microns). Conventional machining methods (including EDM) are limited to about ± 0.1 mil, or ± 2.5 microns. However, a relatively new method for fabrication, called LIGA appears to be appropriate. LIGA (an acronym from German words for lithography, electroplating, and molding) is a micro machining technology originated in the early 1980’s at the Karlsruhe Nuclear Research Center. In this process, precision parts are made through electroplating PMMA molds made through an x-ray lithographic process. Resolutions of at least 1 micron have been achieved. The parts that can be made using this process are essentially planar, with the geometry most relevant to the present problem being a disk. But the disks can be up to 6 mm thick, and thus the cavity structure can be formed by joining a number of disks.
A critical step in this assembly is the alignment of the individual cavity sections. Because it is doubtful that any mechanical alignment aide (a dowel pin, slotted wedge, etc.) can align and maintain the plus or minus one micron tolerance required, an alignment V-block or double V-block, is suggested as the means for positioning the sections together prior to diffusion bonding or brazing. The alignment will register the outside diameter of the individual sections since they will all have identical outer dimensions based on the original x-ray mask lay-out (Figure 11). Temperatures for diffusion bonding of the OFHC copper can be in the range of 450 – 600°C. Based on that temperature regime, a V-block alignment holder can be fabricated using quartz (temperature capability to 950°C) which will provide an inert clamping environment with no reaction with the electroplated copper. This process should result in a vacuum-tight cavity with the appropriate tolerances.

The cathode, although small, appears to be within the state-of-the-art [35] and does not require any new methods for its fabrication.

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Figure 11. Schematic of alignment procedure in single or double V-block assembly (top view). Sections are registered to the outer diameter. Side view shows position of sections in V-block fixture and between proposed pressure platens or pressure fixture before diffusion bonding process. Prior to positioning, section will have been PVD coated with Ni and Au on the bonding surface.
References


35. Based on a design from SpectraMat, Watsonville, CA, personal communication (1999).