Gyrotron Amplifiers for Driving Multi-TeV Colliders at Microwave Wavelengths $\leq$ 1 cm *

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ABSTRACT

There has been considerable interest in microwave amplifiers operating in the 30-100 GHz range for driving multi-TeV colliders. Gyroklystron amplifiers appear to be feasible candidates for these applications. Two designs of three-cavity, coaxial, 35 GHz gyroklystrons operating at the second and fourth harmonics are presented here. An energy recovery system using a single-stage depressed collector is proposed to increase the net efficiency of each design. The net efficiency estimates (including the energy recovery) for the second and fourth harmonic designs at 35 GHz are 51 % and 35 %, respectively. In addition, a preliminary design of 100 GHz system is also presented.

I. INTRODUCTION

Various high power microwave sources in the frequency range from 8 to 100 GHz are being developed for driving linear colliders. Research efforts are in progress to develop efficient microwave sources for this application with typically 50-100 MW power level and 1 μs pulse-length. Klystrons [1], [2], intense beam traveling-wave-tubes [3], magnicons [4], CARMs [5], ubitrons (FELs) [6], and gyroklystrons [7] are the main microwave sources being considered to fulfill these requirements. By choosing a relatively high microwave drive frequency, the accelerating gradient can be larger and the overall length of the collider can be minimized. There has been considerable interest both in Europe and in the U.S. in colliders operating in the 30-35 GHz range [8], [9]. The gyroklystron is a microwave amplifier type that is especially well configured to handle high power at wavelength of about 1 cm (f = 30 GHz) or less.

This paper presents initial design studies of gyroklystron amplifiers operating at 35 GHz and 100 GHz. In gyro-devices, the relativistic dependence of the electron cyclotron frequency on electron energy leads to cyclotron maser instability which causes bunching in gyro-phases. This bunching in gyroklystrons proceeds in a way similar to the electron ballistic bunching in conventional klystrons. However, the frequency selectivity of the cyclotron resonance interaction enables one to use large, overmoded cavities and drift regions in gyroklystrons. This has two advantages over conventional klystrons; first, the device is less susceptible to breakdown at high power levels and second, it can operate at higher frequencies. The high power levels required for the future accelerators can be reached by using relativistic electron beams in the device.

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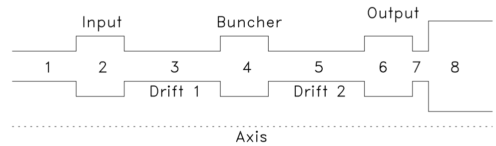

Figure 1: Schematic diagram of a three-cavity, coaxial gyroklystron system

The development of relativistic gyroklystrons for the accelerator applications is being carried out at the University of Maryland. The early investigations have demonstrated power levels up to 27-32 MW and efficiency of 28 % in 10 GHz and 20 GHz experiments at the fundamental and second cyclotron harmonics, respectively [10]-[12]. Ongoing experiments are based on 100-150 MW designs in 8.57 GHz and 17.14 GHz presented in Ref. [13]. Simulations predict over 40 % efficiency and over 45 dB gain for these experiments. This paper extends the design studies presented in Ref. 13 to develop sources at 35 GHz and 100 GHz.

Designs of two relativistic gyroklystron systems are presented here, both employing three-cavity, coaxial microwave circuits. A coaxial microwave circuit has been chosen to alleviate the problems associated with the highly overmoded waveguides, especially self-excitation in the drift regions. It also serves to reduce the potential depression due to the space charge in the beam. A schematic diagram of a coaxial, three-cavity gyroklystron system is shown in Fig. 1. For both systems, the input cavities are resonant at the input signal frequency of 17.5 GHz and the penultimate (buncher) and output cavities are resonant at 35 GHz. We refer to each system by the specific cyclotron harmonic in each cavity, e.g., 1-2-2 system is a three-cavity system with the input cavity at the fundamental frequency and the buncher and output cavities at the second harmonic of the cyclotron frequency. The first design is of 1-2-2 type system which requires approximately 10 kG magnetic field that could be supplied either by a water-cooled solenoidal electromagnets or by a superconducting magnet. The second design is of 2-4-4 system with the output at the fourth cyclotron harmonic. It requires only 5 kG magnetic field that could be supplied by permanent magnets which would be required to reduce power consumption and/or costs in a large collider. We have also investigated 1-2-4 scheme [14], but 2-4-4 scheme results in higher efficiencies.

II. SIMULATION STUDIES

The design analysis is carried out using a set of numerical codes developed at the University of Maryland for the relativistic gyroklystron systems. This set includes a scattering matrix code for cold-cavity fields [15], [16], a linear start-oscillation code for stability, and a nonlinear gyroklystron code [17] for optimizing parameters to get maximum efficiency and gain.

It is important to note that in a relativistic gyroklystron system, the distance traveled by an electron in one cyclotron period is on the order of the cavity length. For such short cavities the equations of particle motion cannot be simplified by averaging over the cyclotron period. Also the cyclotron resonance is broad such that more than one cyclotron harmonic can interact at a given frequency of operation. A detailed formulation of this problem is presented in Ref. 17.

The short cavities also imply that the inner and outer radii vary rapidly as compared to the wavelength, producing linear mode conversion. We model each cavity as a series of straight, uniform sections with abrupt radial discontinuities. The electromagnetic fields in each coaxial region are expanded in terms of its eigenmodes and matched at the boundary using a scattering matrix formulation. The cold cavity resonant frequencies and quality factors, Q's, are determined for each cavity. We assume that the Q is sufficiently high as compared to its difraction limit so that the field pattern is not altered significantly by introducing the electron beam.

Optimizing a design is an iterative procedure and involves modifying the cavity shapes, magnetic field profile, and operating parameters to achieve maximum efficiency and gain. The cavities are designed to have high mode purity, good intercavity isolation, strong beam coupling and desired value of Q. Simulations are carried out for a 500 kV beam with a current up to 700-800 A and a pitch-angle (velocity ratio $v_\perp/v_z$) of 1.5. Specific details of each design are given below.

A. Design of 1-2-2 System Operating at 35 GHz

The input cavity is designed to operate in TE_{01} mode at the input signal frequency (17.5 GHz) and at the fundamental cyclotron resonance. The buncher and the output cavities operate in the TE_{02} mode at 35 GHz at the second harmonic resonance. The drift sections are cutoff to the respective operating cavity modes at these frequencies. The dimensions of each section are tabulated in Table 1. The beam radius is 1.8 cm and the magnetic field is 10 kG.

The input and buncher cavities have infinitely large diffractive quality factors due to the cutoff drift sections on either side. The Q-value is brought down by loading the cavity with lossy dielectric materials to make it stable to self-excitation. The dielectric-loaded quality factor is adjusted experimentally to the desired value to ensure stability and efficient operation. The output cavity is formed with non-adiabatic radial wall transitions. A small lip at the end of the output cavity is used to confine the field energy and get the Q-value to the desired level (Q = 435). In circular cavities, mode conversion from TE_{02} to TE_{01} mode would occur at these transitions. Since the TE_{01} mode is above cut-off at the operating frequency (35 GHz), this converted power would flow back into the drift tube and could potentially cause cross-talk, instability, and heating problems. In a coaxial cavity, however, it is possible to choose inner and outer radial dimensions to suppress this mode conversion. Our output cavity has been designed with these considerations in mind. The scattering matrix code estimates the purity of the TE_{02} operation in the output cavity to be 97 % and a left-to-right power ratio (ratio of the power flowing backward to the power flowing forward) of -24 dB.

Using the nonlinear simulation code the efficiency of this design is estimated to be 42 % for an ideal beam. For a beam with 6 % RMS spread in axial velocity the efficiency is estimated to be 38 %. The total device efficiency can be boosted futher by employing energy recovery from the spent electron beam which will be discussed in a later section of this paper.

Cavity or Section	No.	Inner Radius (cm)	Outer Radius (cm)	Length (cm)
Inlet	1	1.420	2.180	4.000
Input	2	1.320	2.280	1.270
Drift 1	3	1.420	2.180	4.000
Buncher	4	1.350	2.250	1.060
Drift 2	5	1.420	2.180	8.000
Output	6	1.350	2.250	1.050
Output Lip	7	1.415	2.185	0.300
Outlet	8	1.300	2.300	2.000

Table I: Dimensions of the 1-2-2 system design

Cavity or Section	No.	Inner Radius (cm)	Outer Radius (cm)	Length (cm)
Inlet	1	1.825	3.325	4.000
Input	2	1.620	3.530	1.410
Drift 1	3	1.825	3.325	2.000
Buncher	4	1.680	3.470	1.245
Drift 2	5	1.825	3.325	3.000
Output	6	1.685	3.465	1.268
Output Lip	7	1.790	3.360	0.300
Outlet	8	1.600	3.550	3.000

Table II: Dimensions of the 2-4-4 system design

Parameters	Design 1-2-2	Design 2-4-4
Voltage	500 kV	500 kV
Current	700 A	700 A
Pitch-Angle	1.50	1.50
Magnetic Field	10 kG	5 kG
Beam Radius	1.80 cm	2.57 cm
Q-Output Cavity	435	1100
Gain	48 dB	43 dB
Efficiency (ideal)	42 %	22 %
Efficiency (w/spread)	38 %	16 %
Output Power	133 MW	56 MW

Table III: Comparision of operating parameters for the 35 GHz gyroklystron designs (for the 1-2-2 and 2-4-4 systems)

B. Design of 2-4-4 System Operating at 35 GHz

In this design the input cavity is resonant at the second cyclotron harmonic in the TE_{02} mode. The buncher and output cavities are resonant at the fourth harmonic in the TE_{04} mode. The output cavity is designed to have a Q value of 1100. The dimensions of this system are tabulated in Table 2. The beam radius is 2.6 cm and the magnetic field is 5 kG. The efficiency of this system is estimated to be 22 % for an ideal beam. The operation at the fourth harmonic is more susceptible to the spread in axial velocity. The efficiency value drops to 16 % for 6 % RMS spread in the beam. Energy recovery can of course be more effective in raising overall efficiency when intrinsic efficiency is smaller. The main advantage of this 2-4-4 operating scheme is that the magnetic field strength is only 5 kG. The operating parameters for these two schemes are tabulated in Table 3.

C. Design of 1-1 System Operating at 100 GHz

Some preliminary studies of 100 GHz gyroklystron design are also carried out. The initial design is a two-cavity 1-1 system with both the input and the output cavities operating at the fundamental cyclotron frequency in the TE_{23} mode. The geometry of the output cavity has equal radial steps in inner and outer radii. This symmetry tends to suppress mode conversion from mode with radial index $l = 3$ to mode with $l = 2$. This leads to higher Q values and greater stability. The azimuthal mode index of $p = 2$ is chosen so that the competition from modes with $p = 0, 1$, or 3 can be eliminated by using four axial slots in the wall (which are dielectric loaded and symmetrically positioned at $\pi/2$ radians from each other) in the output cavity. The magnetic field strength for this design is 5.7 T which can be supplied by the superconducting magnets.

The efficiency for this preliminary 1-1 design is estimated to be 18 % for the ideal beam. For a beam current of 710 A and a voltage of 500 kV this design can produce 64 MW power output. The efficiency is expected to improve significantly when a three-cavity 1-1-1 configuration is used. In addition, energy recovery can further boost the overall efficiency. The designs of three-cavity systems operating at the cyclotron harmonics should also be considerred.

III. ENHANCEMENT OF DEVICE EFFICIENCY WITH ENERGY RECOVERY

A significant portion of the initial electron energy is still left in the spent electron beam after it exits the interaction region. Depressed collectors can be used to recover this energy from the spent beam by decelerating it by an external electric field. Such energy recovery is commonly used in traveling-wave tubes, klystrons, and other microwave amplifiers [18], [19]. In gyro-devices a large component of the beam energy is in transverse motion. This orbital component of the energy should be converted into the longitudinal component before the energy recovery [20], [21].

Multi-stage depressed collectors are being used for energy recovery in low to medium power (up to 100's of kW), CW microwave sources. However, the present gyroklystron amplifiers are very high power, pulsed devices. It is very challenging to couple the recovered energy back to the power supply of such devices. In order to minimize the difficulties in implementing the recovery scheme we consider only a single electrode depressed collector system here. The spent beam can be extracted either radially through a gap in the wall or axially. In our case, the Larmor radius of the beam is very large (1/4 times guiding center radius) and hence the gap required for radial extraction is very large (about 4 cm); the electromagnetic power loss through this gap is unacceptable. Therefore we have chosen a simple geometry in which the cylindrical beam-dump is at a depressed potential.

We have taken the spent beam from the 1-2-2 design operating at the maximum efficiency to design the energy recovery system. The distribution function of the spent beam is studied as a function of the total energy of each particle. The lowest energy of the particles is about 140 keV. The pitch angle corresponding to these lowest energy electrons is only 0.7, indicating that only about one third of their energy is in the orbital component. Further, the beam enters a tapered region in which the axial magnetic field is gradually reduced. For strictly adiabatic variation, a factor of 7 reduction in axial magnetic field would lead to a factor of $\sqrt{7}$ in radial expansion of the beam and a factor of 7 reduction in orbital energy. Thus, most of the orbital energy would be converted into the axial component.

The axial distance required for adiabatic reduction of orbital energy is very large. Therefore we have chosen magnetic field pattern which is non-adiabatic to get the best energy recovery possible in a limited distance. We have introduced an additional coil and iron shield to get the required magnetic field pattern in the depressed collector region. Using the EGUN code we have traced the particle trajectories through this magnetic field from the end of the RF structure. For 100 % collection of the beam at the depressed collector, the maximum allowable potential difference between the anode and the collector is 125 kV. The power supply requirements can therefore be lowered from 500 kV to 375 kV. Thus the device efficiency can be improved from 42 % to 56 % for an ideal beam. For a more realistic beam with 6 % spread in the initial axial velocity the device efficiency improves from 38 % to 51 %. There will be some additional power loss through the gap between the taper and the collector (1.6 cm in length). It can be minimized by designing a resonant choke flange.

Similar analysis can be performed for the 2-4-4 system. Since the elctronic efficiency is only 22 % (or 16 % with spread), the spent beam carries a relatively large portion of the initial energy. The minimum energy of the electron distribution is above 300 kV. In this case a depressed collector at 275 kV can collect the entire beam. Thus, the total efficiency of the 2-4-4 system can be improved to 48 % (or 35 % with 6 % spread).

In order to implement the energy recovery scheme the system would require two power supplies. A high current power supply connected between the cathode and the depressed collector would provide the entire beam current. A low current biasing supply would provide voltage between the anode and the depressed collector. This also implies that the potential for the depressed collector is likely to be fixed beforehand and cannot be changed based on the operating conditions. In the case of the 1-2-2 system, the high current supply would require only 375 kV voltage. This reduces the power supply requirements by a factor of 4/3. In the case of 2-4-4 system the voltage required is reduced to 225 kV, which means reduction by a factor of about 2.2.

Either the cavities and the anode or the depressed collector should be at a ground potential. If the collector is grounded then the body and gun housing etc. would float. That means the solenoid magnets must have larger bore size to ensure enough separation from the body; the problem is alleviated if permanent magnets replace the solenoids. On the other hand, the floating collector would require additional gap between collector and output window and waveguides. It also implies that the power supply handling the total current would not be grounded. We prefer the first option of grounding the collector. It is also important to minimize the time delay introduced by the long cable between the collector and the gun. This delay leads to waste of energy due to slow rise and fall of the beam voltage. Improved results could be obtained with a gridded-MIG gun which has a fast rise time due to triode type of geometry.

IV. SUMMARY

Gyroklystron amplifiers appear to be feasible candidates for driving linear colliders in the frequency range of 30-100 GHz. Two designs of three-cavity, coaxial, 35 GHz gyroklystrons operating at the second and fourth harmonics are presented here. The second harmonic system (1-2-2) is estimated to give 38 % efficiency which can be futher improved to 51 % using a single-stage depressed collector, while the fourth harmonic system (2-4-4) has lower efficiency of 16 % which can be improved to 35 % with a single-stage depressed collector. For the fourth harmonic system, the external magnetic field requirement is 5 kG which could be supplied by permanent magnets. Operation at the second harmonic would require a superconducting solenoid which would have acceptably low power consumption; however, capital costs would need to be carefully evaluated.

The design of the 100 GHz gyroklystron amplifier is in the preliminary stages. The initial two-cavity 1-1 system is estimated to give 18 % efficiency. This can be further improved by using three-cavity design and adding energy recovery system.

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