FINAL REPORT

Development of a 30 GHz Gyroklystron

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Michael Read, Principal Investigator

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Technical Abstract

DOE requires sources for testing of high gradient accelerator structures. A power of 50 MW is required at K and Ka band. The pulse length must be ~ 1 microsecond and the pulse repetition frequency at least 100 Hz. At least some applications may require phase stability not offered by a free running oscillator

How is this problem being addressed

CCR proposes to build a 50 MW 30 GHz gyroklystron amplifier. This approach will give the required phase stability. The frequency will be at the second harmonic of the cyclotron frequency and will use the TE₀₂ mode. This will make it possible to design a device without an inner conductor, and with a conventional (non-inverted) MIG. This minimizes cost and the risk due to mechanical alignment issues.

What was done in Phase I

Two designs were produced. One was at the fundamental of the cyclotron frequency. Simulations predicted an output power of 72 MW with an efficiency of 48%. The other was at the second harmonic, producing 37 MW with an efficiency of 37%.

Commercial Applications

Sources for testing are required by SLAC and CERN. The CERN application may require up to 8 gyrotrons. Other potential applications include very high power terrestrial and deep space radar.

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Introduction

Program Goals

The goal of the program was to develop a 50 MW 30 GHz gyrokystron for use in the testing of high gradient accelerator structures. In Phase I, the subject of this report, designs were realized for devices operating at the fundamental and second harmonic of the cyclotron frequency. The program was fully successful. Through detailed simulations, it was found that operation at the fundamental of the cyclotron resonance will yield over 70 MW, but because of space charge limits on beam formation, the power using the second harmonic will be about 37 MW.

Table 1. Design goals of the program.

Pulse power	50 MW
Gain	~ 50 dB
Pulse width	~ 1 microsecond
Frequency	30 GHz
Voltage	≤ 500 kV

While all of the design goals were met, the market for the proposed device essentially vanished when the results of work at several laboratories concluded that increasing the frequency of accelerator structures was not likely to lead to higher accelerating gradients. With these results, there was no longer significant interest in high frequency sources for accelerators. Since gyrotrons are of interest largely because of their ability to generate frequencies in the mm bands and above, accelerators ceased to be a useful market. No other markets of potential interest to DOE were identified for the gyrokystron, and thus CCR did not submit a Phase II proposal.

Summary

The program included the design of all of the critical elements, including the electron gun, RF structure, collector, input and output couplers and the output window.

Two designs were considered: one operating at the fundamental of the cyclotron frequency, the other running at the second harmonic. The cavities for the gyrokystron operating at the fundamental were coaxial. Parameters of the two devices are shown in Table 2.

Operation at the second harmonic was of particular interest because the structure does not include an inner conductor. However, because the average beam radius must be about 0.5 cm, the beam current, for voltages less than 500 kV, was limited by space charge to about 200 A. With an efficiency of 37%, the power was 37 MW, significantly less than the required 50 MW.

Operation at the fundamental with a coaxial inner conductor allowed the use of a much larger diameter beam. Beam currents to 300 A were possible even with very low velocity spread. With an efficiency of 48%, powers to 72 MW were predicted.

Table 2. Parameters of gyroklystrons at the fundamental and second harmonic

Parameter	Funda- mental	Second harmonic
Peak Efficiency (%)	48	37
Large signal gain (dB)	53.8	46.1
Output Power (MW)	72	37
Input Power (kW)	0.3	0.92
Drive frequency (kHz)	30.051	15.008
Beam guiding radius (cm)	1.0	0.5
Beam Voltage (kV)	500	500
Beam Current (A)	300	200
Average velocity ratio	1.5	1.5
Axial velocity spread (%)	6	5
Drive cavity f (GHz)	30.000	15.000
Tube length (cm)	12.56	16.58
Drift tube ID (cm)	.78	NA
Drift tube OD (cm)	1.22	0.97

Detailed Discussion of the Results

Operation at the fundamental of the cyclotron frequency

Electron gun

Based on experience in a previous program to develop a 30 MW gyrokylystron, [1] an inverted Magnetron Injection Gun (MIG) was originally proposed for the current program. The inverted gun for this gyrokylystron would be similar to one reported earlier, shown in Figure 1. That gun had a spread in parallel velocity of 3% with a velocity ratio, α , of 1.5. The current was 179 A at 350 kV. To produce the desired 50 MW output power, the voltage would have to be scaled to about 500 kV. This appeared feasible, but an inverted MIG is more difficult to fabricate than a conventional MIG, and it was decided to see if that approach could be used.

Figure 1. Inverted MIG, simulated using TRAK.

A feasible design for a conventional MIG was obtained, and is shown in Figure 2. The current is 300 A at a voltage of 500 kV. The spread in parallel velocity, due to gun optics, was 2% with an α of 1.4. This spread would not affect the efficiency of the gyrokylystron.

Figure 2. Conventional MIG designed for use with the 50 MW gyrokystron operating at the fundamental of the cyclotron frequency. MIGDiode15.

Figure 3. Beam quality for the conventional MIG gun. The parallel velocity spread was 2% with an alpha of 1.4.

The electric fields in the gun are shown in Figure 4. The maximum field is 153 kV/cm, at the nose of the cathode. From Latham [2], the maximum safe electric field is given by

$$E_{\text{max}} = \frac{V}{\tau}$$

where τ is the pulse length and V is the voltage. For a voltage of 500 kV and a pulse length of 1 microsecond, the maximum field is 219 kV/cm.

Figure 4. Electric fields in the gun. The maximum field is 153 kV/cm, at the nose of the cathode.

The cathode loading was 6.8 A/cm^2 . This is acceptable for a MIG where the cathode is operated temperature-limited.

RF Structure

The RF structure for this device is shown in Figure 5. Details of the cavities are given in Table 3. Four coaxial cavities gave a large signal gain of 54 dB and an efficiency of 48%. These good performance characteristics were balanced by the need to support and cool the inner conductor. Fortunately, CCR dealt with this issue in a previous design[1], using an inverted Magnetron Injection Gun to support the inner conductor through the gun as well as in the collector. This issue is being reexamined, weighing the mechanical complexity of the gun against the problem of aligning and cooling the inner conductor.

Figure 5. RF structure and magnetic field for operation at the fundamental.

Table 3. Cavity parameters for the fundamental gyrokystron.

Drive cavity f (GHz)	30.000
Drive cavity Q	100
Second cavity f (GHz)	30.020
Second cavity Q	100
Third cavity f (GHz)	29.941
Third cavity Q	105
Output cavity f (GHz)	30.003
Output cavity Q	165
Tube length (cm)	12.56
Drift tube ID (cm)	.78
Drift tube OD (cm)	1.22

Figure 6. Gain curve for the fundamental gyrotron.

Input Coupler

The input cavity incorporates a wrap-around converter. This configuration is widely used for coupling from rectangular waveguide into TE_{01} cavities in gyroklstrons [3]. Again, 10 slots were chosen to avoid excitation of high order azimuthal modes. The converter, as modeled in HFSS is shown in Figure 7. The Q of the cavity due to the output guide is 400, which when combined with loading due to lossy rings will give the required total Q of 200. The field in the cavity has no visible variation around the azimuth, as is expected for a pure TE_{01} mode.

Figure 7. HFSS modeling of the wrap around input cavity.

Output Coupler

With the fundamental gyrokystron, the power can be extracted either radially outward or via the inner conductor. The latter approach was used in the design of a 25 MW gyrokystron, [1] and is of interest here because of the convenience of the output guide.

Figure 8. Output coupler.

A solid model of this configuration is shown in Figure 8. It consists of a break in the inner conductor that couples the TE_{01} mode of the cavity to the same mode inside the inner conductor. Ten pins are used to mechanically connect the two sections of the inner conductor. The number of pins was chosen to exceed the azimuthal eigenumber of the highest order coaxial mode that can exist in the cavity. Placement of the pins turned out to be quite critical, particularly in minimizing the magnitude of the RF fields in the gap. Also important was a rod on center, making the inner waveguide coaxial. That rod will be tapered to a stop downstream of the coupling region. HFSS simulations are shown in Figure 9 and Figure 10. Good uniformity of the fields in the azimuthal plane indicates high mode purity.

Figure 9. HSFF modeling of the output coupler, showing the fields in the azimuthal plane in an 18 degree wedge.

Figure 10. Fields in the RZ plane.

The RF electric field normal to the pin surface was examined carefully. The plane on which it was highest is shown in Figure 11. The maximum field is approximately 34 MV/m, just below the 40 MV/m that is considered the limit for fields normal to conductors for microsecond pulses.

Figure 11. RF electric field normal to a connecting pin. The maximum field at 72 MW is about 34 MV/m.

Collector

A simulation of the collector is shown in Figure 12. The maximum power density of 480 kW/cm² is too high, but this level is due to the collector ending too soon. Otherwise, the power density peaks close to 300 kW/cm². With a 1 microsecond pulse, this will produce a temperature rise of about 100°C. This is acceptable.

Figure 12. Collector for the fundamental mode klystron.

Figure 13. Collector power density with the full beam power.

Figure 14. With 37% efficiency simulated by lowering the beam voltage to 315 kV.

Operating at the Second Harmonic of the Cyclotron Frequency

Operation at the second harmonic allowed the use of a driver at half the frequency, and the design that was realized did not require a coaxial structure. This design was significantly simpler than at the fundamental, but the use of hollow cavities required a smaller diameter beam.

Initially, the maximum current that could be generated in this smaller beam was found to be 200 A, and the cavity design was based on this. This, coupled with the somewhat lower efficiency, resulted in the power being one-half of that of the fundamental, but still 74% of the required 50 MW. Near the end of the program, alternate gun designs operating near the space charge limit were explored, and currents to 270 A with low velocity spreads were obtained. Due to resource limitations, the cavity design was not revised. If the 37% efficiency achieved with 200 A could be maintained at 270 A, the output power would be 50 MW.

Electron gun

The beam guiding center radius for operation at the second harmonic without a center conductor, i.e., with conventional cavities, is 0.5 cm. This smaller beam diameter made the gun design more difficult because of higher space charge effects. However, by allowing operation at nearly the space charge current limit, a current of 270 A was achieved. This design is shown in Figure 15. As shown in Figure 16, the rms parallel velocity spread was 6.3% with an alpha of 1.4.

Figure 15. 270a @ 500 kV, nearly-space charge limited (MIG30).

Figure 16. Particle distribution for the MIG shown in Figure 15. The RMS parallel velocity spread is 6.3% with an alpha of 1.4.

Cavity

The design included four cavities, two at the fundamental, and two at the second harmonic. The structure is shown in Figure 17, and the cavity parameters are given in Table 4. The current for this design was 200 A.

Figure 17. Second harmonic cavity.

Table 4. Cavity parameters of the second harmonic gyrotron.

Drive cavity f (GHz)	15.000
Drive cavity Q	75
Second cavity f (GHz)	15.020
Second cavity Q	75
Third cavity f (GHz)	29.867
Third cavity Q	115
Output cavity f (GHz)	29.989
Output cavity Q	225
Tube length (cm)	16.58
Drift tube ID (cm)	0.00
Drift tube OD (cm)	0.97

The drive curve is given in Figure 18.

Figure 18. Drive curve for the second harmonic.

Collector

The collector is shown in Figure 19. The peak power density is 300 kW/cm^2 . With a $1 \text{ }\mu\text{s}$ pulse, this will produce a temperature rise of $100 \text{ }^\circ\text{C}$. The collector is larger than the output guide, and the transition shown in Figure 19 will produce an unacceptable level of mode conversion. The actual output guide and collector with up and down tapers are shown in Figure 20. With 100 TE_{01} input, the output will be $99.9\% \text{ TE}_{01}$. The calculation, made using CASCADE, included a single disk output window.

Figure 19. Collector for the second harmonic tube. Top: geometry and trajectories, lower left: power density; lower right, results of 1D heating calculation showing temperature rise vs heat flux for a $1 \text{ }\mu\text{s}$ pulse.

Figure 20. Output guide, tapers, collector and single disk window.

References

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