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THE GYROCON RADIO-FREQUENCY GENERATOR FOR FY-80 and FY-81

by

Paul J. Tallerico

ABSTRACT

The gyrocon is a high-power, high-efficiency amplifier that operates by deflection modulation of an electron beam. The spatial bunching can be better than the temporal bunching in a klystron, especially for high output powers and uhf frequencies. Soviet gyrocons have produced over 40 MW of pulsed power at 430 MHz and 250-kW cw at 181 MHz.

The progress on the construction and testing of a 450-MHz prototype gyrocon is discussed. The maximum pulsed output power that has been achieved in the reporting period is 1 kW. Although these powers are significantly below the design goal of 650 kW, there is a good chance that the experimental program in FY-82 will result in increased output power.

I. INTRODUCTION

The gyrocon rf generator is a deflection-modulated amplifier that has the capability of very high peak and average output power and high dc-to-rf conversion efficiency. The gyrocon has been studied at Los Alamos¹⁻³ and in the Soviet Union.^{4,5} The Soviets have built two gyrocons at 180 and 430 MHz, and the reported dc-to-rf conversion efficiency is between 75 and 80%. A prototype gyrocon to produce 500 kW at 450 MHz was designed and built in Los Alamos. In FY-80 the project's primary effort was focused on building a prototype rf amplifier to produce 500 kW of rf power at 450 MHz. A limited amount of work also was performed on extending the two major gyrocon analysis codes, GYRO1 and GYROS, to more realistically model the interaction process. The major

accomplishment during 1980 was the complete assembly of the prototype gyrocon and the commencement of testing. A summary of the prior experimental and theoretical work is presented in Ref. 6.

The program in FY-81 was to test this prototype, to modify it as required to meet the original specifications, and to start a preliminary design on a higher power device. The design of the higher power gyrocon was dropped because of funding limitations. Thus, the primary goal became obtaining full output power from the prototype.

The maximum output power that has been achieved to date is 1000 W, although brief periods with up to 50 kW of output power have been achieved as of this writing (April 1982). Two major problems are limiting this power: first, the full design beam current has not been realized; second, electron multipactor in the deflection and output cavities has severely restricted the field amplitudes in these cavities.

II. CONSTRUCTION OF THE PROTOTYPE GYROCON

A scale drawing of the prototype gyrocon is shown in Fig. 1. The diameter of the flange beneath the deflection cavity is 92 cm. The prototype comprises six major subassemblies: the electron gun and valve assembly, the deflection cavity, the output cavity, the collector, the conical bender solenoid, and the output couplers. In addition, there is a first-focus coil between the electron gun and the deflection cavity and a pair of output-focus coils immediately inside the output gap. The major design parameters of the prototype are summarized in Table I. At the start of FY-80, the electron gun and valve assembly and the collector were on hand at Los Alamos but not assembled.

The major construction problem involved completion of the output and deflection cavities, which were being built outside Los Alamos. Although the contractual delivery date for these large components was September 1979, the final mechanical and vacuum acceptance tests were performed early in 1980. By the end of March, all outside-manufactured components had been delivered to Los Alamos. A significant design change was made in the output cavity to allow adjustment of the output loops after the gyrocon is built. The output cavity was sent to the main shops at Los Alamos for modifications to accommodate this

Fig. 1.
Cross-sectional assembly drawing of the prototype gyrocon.

TABLE I

MAJOR DESIGN OF THE PROTOTYPE GYROCON

Beam voltage	86 kV
Beam current	9.0 A
Operating frequency	450 MHz
Deflection angle	13.4°
Deflection-cavity length	8.0 cm
Deflection-cavity field	2.0 MV/m
Total deflection power	31.4 kW
First-focus coil ampere turns	-1540
Conical bender ampere turns	14 000
Second-focus coil ampere turns	4000
Output cavity, i.r.	16.8 cm
Output cavity, o.r.	23.8 cm
Output-cavity field	1.80 MV/m
Electronic efficiency	93.0%
Radio-frequency gain ratio	22.0
Overall efficiency	86.1%
Output power	691.9 kW

design change. A rough check of the output-cavity frequency was done at the main shops; the frequency was compatible with that of the deflection cavity.

In May 1980 there were over a hundred major gyrocon components to be assembled and leak checked. Some components, such as the coaxial-line-to-waveguide subassembly (Fig. 2), had many parts. Many of these parts had to be copper plated. Dozens of heliarc welds were made, and some copper plating had to be done after completion of the welding operations.

Some interference was found between the valve on the gun section and the deflection cavity and between the output and deflection cavities. A 1.3-cm spacer assembly was designed and built to fit between the vacuum valve and the deflection cavity. This spacer, and some remachining of the valve body, eliminated the interference in the valve region. The interference between the

Fig. 2.
One of the coaxial-line-to-waveguide transducers, before final assembly.

deflection and output cavities was eliminated by a 1-cm spacer at that location. Thus, the gyrocon became 2.3 cm longer by the two spacers that were required for assembly of the major subassemblies. The most serious problem encountered was the mismatch of resonant frequencies in the deflection and output cavities. The resonant frequency of the output cavity had been measured before the cavity was copper plated, and it was very close to that of the deflection cavity. After the output cavity was copper plated, the measurement was repeated and the problem was discovered. The tuners on the deflection cavity can only lower its frequency, whereas those on the output cavity can only

raise its frequency. The output frequency was slightly above the deflection-cavity frequency, so that they could not be tuned together. The output gap was remachined, and four rings were added to lower the frequency. (The rings increase the capacitance at the gap.) This process included several iterations of cutting the rings, measuring the new frequency, and repeating the process. In late September 1980 the gyrocon was assembled, and all water and vacuum joints were leak tight. A view of the assembled gyrocon is shown in Fig. 3.

The electron gun is the type used on LAMPF klystrons. The cathode was coated, and the cathode assembly was welded into the gun housing before final assembly of the gyrocon. When the gun housing was leak checked, a leak on the filament feedthrough was found that could not be permanently repaired, but a temporary repair was made with Vac-Seal. Then the gun housing was welded to the valve body, forming the electron gun and valve assembly. This assembly was baked to 150°C in the LAMPF klystron-repair oven, and the cathode was converted while in the bake station. The assembly was pinched off, and its vacuum maintained by a small 8 ℓ /s vacuum pump on the gun side of the valve.

III. EXPERIMENTAL MEASUREMENTS

The 500 ℓ /s ion pump and its manifold made the gyrocon too large to be baked in the LAMPF klystron oven; therefore, it was baked to $\sim$ 80°C with heater tapes. At the start of the FY-81 program, we found that the vacuum pressure in the gyrocon would rise toward 10^{-5} torr when both the cathode and the drive power were on, but that after 10 days of pumping with the two ion pumps (a small one near the electron gun and the larger main pump near the collector), the rf drive and the beam could be operated at the same time. Severe electron multipactoring was noted in the deflection cavity with only 100 W of drive power. The monitor loops in this cavity showed that the deflection fields increase until 100 W; then the fields remain constant as the drive power is increased. This behavior is typical of multipactor discharges--the added energy simply goes into heat at the multipactor location.⁷ The beam current was varied between 0.5 and 8.0 A for 100- μ s pulses at a 0.2- to 1-Hz repetition rate. Seven magnet power supplies were used to energize the various coils. For most conditions of magnet and beam currents, 30 to 60% of the cathode current arrived at the collector, and 20 to 100 W of output power was

Fig. 3.
The assembled gyrocon and its modulator.

produced at each rf output loop. The collector was mounted on ceramic stand-offs, and bias voltages of ± 300 V could be applied to the collector. The indicated collector current varied by $\pm 30\%$ with collector bias, indicating that the electrons that traveled to the collector were at least partially secondaries that were probably scattered off the bender cone. A quadrupole bender magnet, located between the electron gun and the vacuum valve, was designed and built to test the concentricity of the gyrocon's magnetic and mechanical axes. Maximum beam transmission to the collector occurred when the beam was deliberately moved off the mechanical axis and made to strike the bender cone. The electrical axis was found to be in good agreement with the mechanical axis by this experiment.

The electron gun used in the first experiments had a leak in the heater feedthrough. The cathode was partially poisoned by this leak; it could produce the design current only for several minutes, and then the current would decrease with time. The prototype is designed to be demountable: the gun can be isolated with its valve and the output cavity taken apart. The electron gun uses an oxide cathode; therefore, it always must be kept under vacuum after the cathode is activated.

In January 1981 the bender solenoid was removed, and a titanium evaporator was designed, built, and used to evaporate a thin film of titanium onto the inside of the deflection cavity.⁸ The bender-cone apex (Fig. 4) was slightly damaged by the electron beam, indicating that the beam had been well focused (at least part of the time) and not deflected. In addition, a phosphor-screen and aperture-plate system was designed and built. A transparent viewing port was used to seal the opening where the bender magnet had been.

By March 1981 the gyrocon was reassembled with the phosphor view screen. The screen indicated that the dc electron optics was poor and that there was a continued decline in the electron beam current. The multipactor in the deflection cavity was reduced, but it was still quite troublesome.

More rf fields than before (detected signals of 1.0 V at the monitor loops and with 10 kW of rf drive) were achieved, and small deflections of the beam were observed (Fig. 5) when the deflection cavity was driven. The beam is underdeflected, and the original photograph shows that the outside beam edge is partially intercepted by a limiting aperture between the deflection cavity and the output cavity assembly. When the rf drive to the deflection cavity is removed, a uniform grid of dots is seen on the phosphor screen (Fig. 6). Thus,

Fig. 4.

Tip of the bender cone, showing several areas that were melted on the surface by the electron beam.

there is good evidence that the deflection cavity has operated according to theory. The major problem is that the beam, both with and without deflection, is too large. The original trajectory calculations for the dc beam were repeated, both for the design case of space-charge-limited cathode current and for the experimentally observed case of temperature-limited emission. The beam was found to make a crossover before the deflection cavity (Fig. 7a) when the beam current was too low. At higher currents, the space-charge forces prevented the crossover, and a small beam diameter could be reached at the screen (Fig. 7b). Unfortunately, the gun could not produce large enough beam currents, and the results corresponding to those in Fig. 7b were never seen. Some improvement in beam size with first-focus current was observed, but this coil, which is air-cooled, shorted out. The bender coil was reinstalled, and

Fig. 5.
Phosphor-screen results showing the large-diameter beam being deflected in small circles.

Fig. 6.
Phosphor-screen image of undeflected electron beam through the aperture plate.

(7a)

(7b)

Fig. 7.
Equipotentials and trajectories in the prototype electron gun with no magnetic fields.

~20 W of output power was measured. A factor of 2.5 error in the focus-coil strength was found; therefore, a new gun-focus coil with three times the number of turns was designed and built.

A major rebuild of the gyrocon was done, and a new gun and a new gun-focus coil were installed. The gyrocon was reassembled in May 1981 with the phosphor screen once again in place. The new gun-focus coil could focus the beam to a 1-cm-diam spot on the screen. After conditioning the deflection cavity to suppress the multipactor, the beam could be deflected into an annular pattern on the screen (Fig. 8). Amplitude and phase controllers were added to the rf drive system. The beam current with the new gun is still low, and it varies between 1 and 2.5 A, depending on the heater voltage. Evidently there is enough gas evolution from the unbaked surfaces to poison the oxide cathode. The new gun is lasting much longer than the first one, and the vacuum generally is better. The phosphor screen was removed and the bender installed. At 86-kV beam voltage and 0.5-A beam current, peak output powers of 200 to 500 W per output loop were measured. However, the output power and the field levels inside the output cavity remained constant as the beam current was increased to 2.5 A. The field strength and output power are also independent of beam voltage when the beam voltage is varied from 60 to 120 kV. The data indicate that the output cavity is now multipactoring. The output power is independent of the output-cavity tuning because the electron multipactor loads the cavity so heavily. The coupling of the loops to the output resonator was varied to try to break through the multipactor, but the situation remains unchanged.

The experimental program was halted in August 1981 because of funding limitations. The two major problems are the electron multipactor in the rf cavities and the fairly short life of the electron gun. The multipactor in the deflection cavity limits the phase and amplitudes of the deflection field. The multipactor in the output cavity limits the output power to about 1 kW total. We are confident that the output power can be raised during the next fiscal year, using several schemes to reduce the multipactor.

Although the main program objective of 500-kW output power was not achieved, several important milestones were reached. These include the measurement of the proper beam deflection and the design, construction, and testing of the phase and amplitude control system. The advantages of the demountable construction were demonstrated, and the gyrocon can be taken apart and put back together in just a few days. The titanium treatment of the deflection cavity

Fig. 8.
Phosphor-screen image of deflected electron beam.

has reduced, but not eliminated, the tendency to multipactor. Similar treatment of the output cavity should also be efficacious.

A poster paper on the plasma heating applications of the gyrocon was presented at the 1981 Plasma Science Conference,⁹ and an interim status report on the project was presented at the 1981 Particle Accelerator Conference.¹⁰

IV. GYROCON CODE-DEVELOPMENT WORK

The computer code for analyzing the spherical gyrocon was completed, and a summary of the calculations for S-band spherical gyrocons was presented.³ A self-consistent output-cavity field calculation was added to GYROS, the spherical-gyrocon code. An induced-current integral is calculated, so that the efficiency can be calculated from the circuit energy, as well as from the change in kinetic energy of the electron beam. Self-consistency is achieved when the circuit-energy and kinetic-energy losses are equal, and the code automatically finds these conditions. Tests of this new calculation method with the S-band results indicate a 2 or 3% reduction in overall efficiency compared to the original solution method.³ Because of the small size of this effect, the self-consistent field calculation was not added to the radial-gyrocon analysis code.

Work has started on a fringe-field calculation method for the radial-gyrocon analysis code GYRO1. We use the electrostatic approximation to calculate the fringe fields because of the slots in the output waveguide. The input and output slots are only a slot-width apart on the experimental gyrocon; the calculated fields, which are based on a single slot far from any other discontinuities, do not match the fields calculated by SUPERFISH. The fringe fields in the output and deflection cavities are expected to have a significant effect on gyrocon performance, but efforts in this area have been proceeding at a slow pace because of the greater importance of the experimental program.

V. CONCLUSION

The understanding of the prototype gyrocon's operational characteristics was greatly increased during the reporting period. The output power increased

from a barely discernable signal to 1 kW during this learning experience. The drive system has two amplifier chains that are excited by a common source. Initially there was no phase or amplitude control system to maintain the stability of the drive power. Several control systems were built and tested during the project's history; each time a significant improvement was made in the control system, the gyrocon responded by producing more output power.

From January to April 1982, the output power was increased from 1 to over 100 kW by improvement in the control system and by rf conditioning the output cavity. The electron gun has been performing well and is able to deliver 4- to 5-A pulses for several hours of testing each day. The major problems are now multipactor discharge in the output cavity, fringe fields outside the output cavity, and the experimental difficulty of keeping the two modes in the two resonators on frequency. Surface treatment of the output cavity will be employed to reduce the multipactor, and a screen arrangement is being designed to reduce the fringe fields near the output cavity. A temperature control loop will be added to the cavity water system to keep the cavities on frequency.

Because of the rapid experimental improvement in the prototype gyrocon in FY 82, the author remains convinced that the gyrocon can be employed to generate large amounts of rf power at very high dc-to-rf conversion efficiencies. Although the highest efficiency measured to date is 23% on the prototype gyrocon, the author's calculations and the Soviet claims of 70 to 80% conversion efficiency seem achievable.

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