X-3060 Klystron Design Improvement Program Status

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The X-3060 klystron, a 100 kW continuous wave amplifier klystron, was introduced in the DSN in 1965. Questions have arisen since its introduction regarding its field performance record but its operational performance has been difficult to assess. An early design defect was corrected in 1974 by rebuilding all tubes with an improved potted heater design and only one failure has been recorded since that time. However, due to early "start up" failures, age of the present units, and efforts to establish the most reliable performance possible, a study program was begun to evaluate the klystron design. This article describes the results of Phase I (Study Definition) and Phase II (Design Improvement) of a four-phase program. Phase I revealed certain weaknesses and design features that conflict with ultrareliable klystron performance. Phase II has produced a new paper design that overcomes the deficiencies and unreliable features shown by the Phase I effort.

I. Introduction

The study program was originally directed toward the eventual redesign of the X-3060 and X-3075 S-band klystrons. At the conclusion of Phase I (Study Definition), however, the decision was made at JPL to direct the remaining effort of the study program toward improvement of the X-3060 klystron only. The evaluation was completed in October, 1977. Results of the analysis were presented to JPL in a design review meeting on 27 October 1977. This critical examination of the X-3060 design revealed certain weaknesses and design features which conflicted with ultrareliable klystron performance. The findings and recommendations of the Phase I evaluation are summarized in Table 1.

The primary goal of the study program (Phase II) was to produce a new paper design for the X-3060 klystron which would overcome the deficiencies and undesirable features shown by the Phase I evaluation. A fundamental requirement of the new design is increased reliability. A secondary effort is directed toward increasing the efficiency of the X-3060, but only insofar as it does not compromise reliability. Although Phase II primarily concerns itself with computer designs and analysis, detailed layout and outline drawings have been generated to present a more complete comparison between the new and the old designs. The design improvements, discussed in the following paragraphs, are presented in two parts: electrical design improvements and mechanical design improvements.

II. Electrical Design Improvements

The electrical design improvements, as a result of Phase II of the study, deal with redesign of the electron gun and RF structure of the klystron.

A. Electron Gun

Redesign and analysis of the existing X-3060 klystron electron gun have shown that a considerable gain can be made in lowering the voltage gradients in the electron gun. This will certainly provide a marked improvement in tube performance with regard to gun arcing. Additionally, lengthening of the electron gun envelope insulator may be incorporated as an option in the new design if it is desired, to eliminate the oil-filled socket tank. Assuming that the changes are consistent with the requirements of field applications, removal of the modulating anode is highly recommended.

Because the preliminary findings (Phase I) indicated that substantial voltage gradient improvement could be made by removing the modulating anode, a new physical design has been generated to accomplish this improvement. Figure 1 is the physical layout of the existing X-3060 electron gun. Figure 2 shows, for comparison, the physical arrangement of the new design.

In addition to the modulating anode removal, lengthening of the ceramic insulator enclosing the electron gun should be considered. This lengthening was not considered or discussed during the Phase I investigation and is introduced here as a suggestion only. Such lengthening will not affect the electron optics or the internal voltage gradients of the gun, but will lower the external voltage gradients to permit reliable operation in air. In future systems installations, this could eliminate the very costly oil-filled socket tank now used.

Upon completion of the new physical layout, computer analysis was made for the voltage gradients and electron optics of the new design. Figure 3 shows comparative voltage gradients between the old and new designs. As predicted from the Phase I estimates, the highest gradients were substantially reduced, and the highest gradient calculated in the new design was 100 kV/cm (254 kV/in.).

B. RF Structure

Computer analysis shows that by lengthening the RF structure and rearranging the RF design parameters, significant improvement can be made to three important operational parameters (i.e., gain, bandwidth, and efficiency). Importantly, no far-out or "state of the art" techniques need be employed to obtain these results. Following present-day good design practice is all that is required. Actual predicted performance is summarized in Table 2 and the original design is compared to performance results obtained from an X-3060 built recently (May 1978).

During the investigation of the present X-3060 RF design, a number of deficiencies were noted. These deficiencies are a natural result of designing a klystron with a wide tuning range (i.e., 2114 to 2388 MHz). In particular, drift tube gap spacing and gap-to-gap drift tube distances are often compromised to satisfy operation at both ends of the frequency tuning range. In fact, the output cavity drift tube gap in the present X-3060 design is far too long to provide optimum efficiency at either 2114 MHz or 2388 MHz, but it is designed this way to provide low gap capacitance, a requirement of wide tuning range cavities. It is also worth repeating that wide range tuning mechanisms (cavity tuners) in high power klystrons have traditionally compromised high reliability. Typical disadvantages are:

(1) The tuner is normally subjected to high RF fields, the consequence of which is high RF loss and subsequent thermal stress.

(2) Because of size limitations at high frequencies, coolant passages within the tuner are necessarily small and subject to blockage.

(3) The tuner can easily be subjected to mishandling and mistuning accidents caused by inexperienced personnel.

(4) Because of the inherent fragility and complexity, the tuner presents a problem with regard to its vacuum integrity during both initial construction and subsequent rebuilding operations.

Naturally, if system requirements dictate wide-range operation, nothing can be done to avoid the design compromises, and unfortunately, state of the art wide range tuner designs offer no improvement over what already exists in the X-3060. Present JPL requirements are unique, however, in that operation is confined to a few discrete frequencies at the extremities of the 2114 to 2388 MHz frequency range. It was suggested in the Phase I final report that the wide tuning range requirement be eliminated and that two tubes be developed, each electrically optimized for its particular frequency, one at 2114 MHz and the other at 2388 MHz. These tubes would have narrow range trim tuners only, to permit initial factory tune-up. This is the design philosophy used throughout the Phase II effort. The two tubes are mechanically interchangeable, using a common focusing magnet.

Two completely new designs have been developed. The first will operate at 2388 MHz and is referred to in the remainder of this article as the X-3060A. The second tube will operate at 2114 MHz and is referred to as the X-3060B. Both designs will be electrically similar to the 5K70SG klystron. The 5K70SG was used as the basic model because it has demonstrated a highly efficient performance, with reliability in numerous field applications for a period exceeding ten years.

Computer programs (Klystron Design Calculation Program) were used to translate the 5K70SG design criteria to the operational conditions of the X-3060A and X-3060B. Computer analysis showed that the X-3060B (2114 MHz) would have to be 10.16 cm (4 in.) longer than the existing X-3060 to satisfy the 5K70SG design criteria, and the X-3060A would have to be approximately 5.08 cm (2 in.) longer. Although this added length is not particularly desirable, its introduction into the next series of calculations (Gain-Bandwidth Computer Program) produced a larger than expected increase in the small-signal gain. This additional gain is not a requirement of the improvement program, but the gain can be traded off for additional bandwidth. Greater bandwidth will greatly improve the operational stability, particularly at the band edges (2384 MHz and 2392 MHz in the X-3060A, 2110 MHz and 2118 MHz in the X-3060B). Because of this worthwhile stability improvement, a new target bandwidth of 12 MHz was established (present requirements are 8 MHz), and the Gain-Bandwidth Programs were used to accomplish this new goal. The computer predicted performance exceeds even the new 12 MHz goal by a comfortable safety margin.

The calculations discussed above have established the preliminary operational parameters to be analyzed by the Varian LSCEX2 large-signal computer program. The large-signal program takes into account the space-charge debunching forces in the electron beam from the lowest level of RF drive power to the highest RF drive level required to obtain saturation (maximum) power output. During this final analysis phase, the preliminary design parameters may be readjusted slightly to obtain the ultimate goal which in this case is maximum efficiency consistent with electron beam stability.

Because the basic design parameters are essentially scaled from a klystron that performs well (5K70SG), no adjustment of drift tube diameters, gap spacings, or drift distances was required. Tens of iterations were used, however, to determine two parameters in particular: the output cavity Q_L (primarily the external coupling factor) and the frequency placement of the penultimate cavity. The interdependence of these two parameters was very thoroughly analyzed because of the many combinations that can be used to obtain a highly efficient performance and the markedly different effect each combination has on the action of electrons in or near the output cavity gap.

A combination is chosen that satisfies requirements of gain and efficiency. But more importantly, a parameter combination must be chosen that does not permit electrons to stop, reverse their direction in the output gap, and return toward the input cavity. This is accomplished by selecting a sufficiently high minimum velocity for the slowest electrons found in the output gap.

III. Mechanical Design Improvements

The following paragraphs deal entirely with the mechanical redesign as applied to the new RF designs. The approach used to describe the mechanical changes is a comparative one, using the existing X-3060 as a model so that the merit of the new design can be seen relative to the old design.

A. Diaphragm Trim Tuner

For the purpose of this discussion, it is assumed that the present wide range tuning requirement can be eliminated and that a two-tube approach can be used to cover the present opérational frequencies. This assumption permits the introduction of a simple and reliable diaphragm tuner, many versions of which have been used in very high power applications.

The proposed trim tuner to be used in the X-3060A or X-3060B, and the wide-range tuner presently used in the X-3060, are shown in Fig. 4. Casual observation will show the complexity of the old tuner design as compared to the new trim tuner. Not so obvious in the old design are the six vacuum-to-water and three vacuum-to-air brazing joints used in the present X-3060 tuner. In addition to the large number, many of the brazing joints are blind; that is, they can neither be inspected nor repaired after the final braze pass. This type of assembly severely compromises reliability and rebuildability. Compared to this, the trim tuner design has only two vacuum-to-air brazing joints and no vacuum-to-water joints. Neither of the vacuum-to-air joints is blind, and both are easily repairable.

In addition to these mechanical advantages, the trim-tuner diaphragm is relatively far removed from the high RF fields at the drift tube gap center and will therefore be subjected to far less RF heating than the present X-3060 capacitive paddle. The diaphragm is thermally coupled by large cross-sectional areas of copper to the massive water cooled copper cavity walls. In Fig. 4A, a water cooled post is shown joined to the diaphragm face. This is a contingent plan only, and it is expected that this cooling can be eliminated.

In the authors' opinion, replacement of the complex wide range tuner with the simpler trim tuner is one of the most important steps that can be taken in redesign of the X-3060. If this recommendation cannot be followed, and wide frequency range operation is an absolute requirement, the present

X-3060 tuner must be completely redesigned mechanically, as recent experience has shown it to be almost unbuildable. At best, however, the wide range tuner will never compare in reliability to the proposed diaphragm trim tuner.

B. Extended Tailpipe Elimination

As described in the Phase I final report, the most significant deficiency of the present X-3060 klystron is the extended tailpipe design. The tailpipe is that region of the klystron just beyond the output cavity drift tube gap.

The extended tailpipe configuration shown in Fig. 5 was first introduced in the X-3060 klystron in 1965. Its purpose was to minimize the asymmetry normally caused by the exit path of the output waveguide through the focusing magnet, and to reduce to an absolute minimum body current interception caused by the magnetic asymmetry. Mechanical considerations, however, created an extended tailpipe section that is exposed to a rapidly expanding electron beam just beyond the output gap. This extended section has created both indirectly and directly related failures in the X-3060 klystron. The problem is caused by the fact that the electron beam expands in that region faster than was predicted at the time of the design introduction, and additionally, secondary electrons return from the collector to impinge on the tailpipe surfaces.

For the above reasons, and because the tailpipe is electrically part of the klystron body, the body current readings for the X-3060 have been recorded as high as 10% of the total beam current. This tailpipe current (reading as body current) completely masks body current interception in any other part of the RF structure and is unacceptable because it requires that body current protective circuit trip levels be set too high (1.0 amp). This removes the protection required in the remainder of the RF structure which may suffer damage from relatively low quantity (0.050 amp) but high velocity electrons. Under these circumstances, protection cannot be provided for the following common field conditions:

(1) Low or incorrectly adjusted magnetic field.

(2) Incorrect tuning.

(3) Overdrive.

(4) Stray magnetic fields (gun region).

(5) Disturbance of the main magnetic field by accidental introduction of ferrous materials (screwdrivers, wrenches, etc.).

Elimination of the extended tailpipe design is not only recommended, it is a mandatory condition for reliability. Figure 6 shows the new design to be employed in the X-3060A/B klystrons. As shown, the new design provides adequate clearance for the expanding beam and transfers tailpipe interception current to the collector where it is properly metered as collector current. With this configuration, body current readings will return to normal values in the order of 0.050 amp to 0.075 amp, and the RF structure can be properly protected with body current protective trips set at 0.100 amp.

One additional design change has been made. A reentrant output polepiece has been introduced to create a peak in the magnetic field near the output gap. Recent designs have shown that this peaked magnetic field is very beneficial in terms of reducing beam interception in the output region of the klystron. This reentrant design is shown in Fig. 6.

C. Cavity/Body Construction

It was found, during the investigation of the X-3060, that the rigidity of the RF structure was somewhat lacking and structural stiffeners were promised for proposed new designs. That will be the case, but in addition, recent tests of an X-3060 (May 1978) showed thermal drift attributable to cavity detuning, indicating a need for additional cavity cooling.

The proposed new design for the X-3060A/B will incorporate relatively massive copper cavities which have a wall thickness in the order of three times the wall thickness of the present X-3060. Not only will this create a rugged RF structure, it will permit the passage of water through the cavity walls to insure greater thermal stability. Comparative views of the present cavity structures and the proposed design are shown in Figs. 7 and 8. In addition to increased cavity wall thickness and cooling, cavity end walls and drift tubes will have increased thermal cross section to provide the best possible thermal stability.

In short, the RF structure will have construction closely paralleling a 450 kW klystron (X-3070) known to be operationally stable at the highest frequency of concern (i.e., 2388 MHz).

IV. Summary

The end product of the Phase II segment of the present study contract is the presentation of a new paper design which eliminates the deficiencies of the present X-3060 klystron. Below is a list of the major modifications involved in creating the new design:

(1) Gun ceramic lengthened to permit operation in air.

(2) Modulating anode removed to reduce voltage gradients.

(3) Increased drift tube and cavity wall cross section for improved thermal stability.

(4) Incorporation of cavity wall cooling for thermal stability.

(5) Modified gap and drift tube spacings for greater efficiency.

(6) Elimination of complex wide range tuner and replacement with simple trim tuner.

(7) Elimination of complex extended tailpipe design and replacement with conventional waveguide output circuit.

(8) Replacement of long taper waveguide with Tchebycheff step transition to maintain waveguide flange interface plane.

(9) Modification of collector to incorporate conventional flytrap design (replaces extended tailpipe).

(10) Modification of magnet to interface new tube design.

Table 1. X-3060 design evaluation summary

Parameter	Rating/ comments	Recommen- dations
A. Electron gun		
1. Cathode filament	Good	Maintain
2. Cathode loading	Excellent	Maintain
3. Voltage gradients	Fair	Redesign
4. Modulating anode	Unnecessary	Eliminate
B. Klystron body		
1. Tailpipe	Unacceptable	Redesign
2. Tube/Magnet alignment	Marginal	Redesign (accomplished)
3. Tuners	Disadvan- tageous	Redesign
4. Higher efficiency	Practical	Redesign
5. RF design parameters	Fair	Redesign
6. Mechanical rigidity	Marginal	Redesign
C. Magnet		
1. Tube/magnet alignment	Marginal	Redesign (accomplished)
2. Individual coil control		Recommended
3. Magnet assembly	Not compatible (new tailpipe design)	Redesign

Table 2. Predicted performance (X-3060A and X-3060B) versus performance of existing X-3060

Parameter	Units	Existing	X-3060	X-3060A	X-3060B
Frequency	MHz	2388	2114	2388	2114
Beam voltage	(kV)	36.0	36.0	36.0	36.0
Beam current	(A)	7.7	7.7	6.96	6.96
Power output	(kW)	115	112	125	132
Efficiency	%	41.4	40.4	50	52.7
Saturation gain	dB	56.6	54.7	59	59.3
Saturation BW	MHz	10.58	10.4	16.7	16.7
Small signal gain	dB	59.63	58.0	61	61
Small signal BW	MHz	6.1	6.4	14	13.8

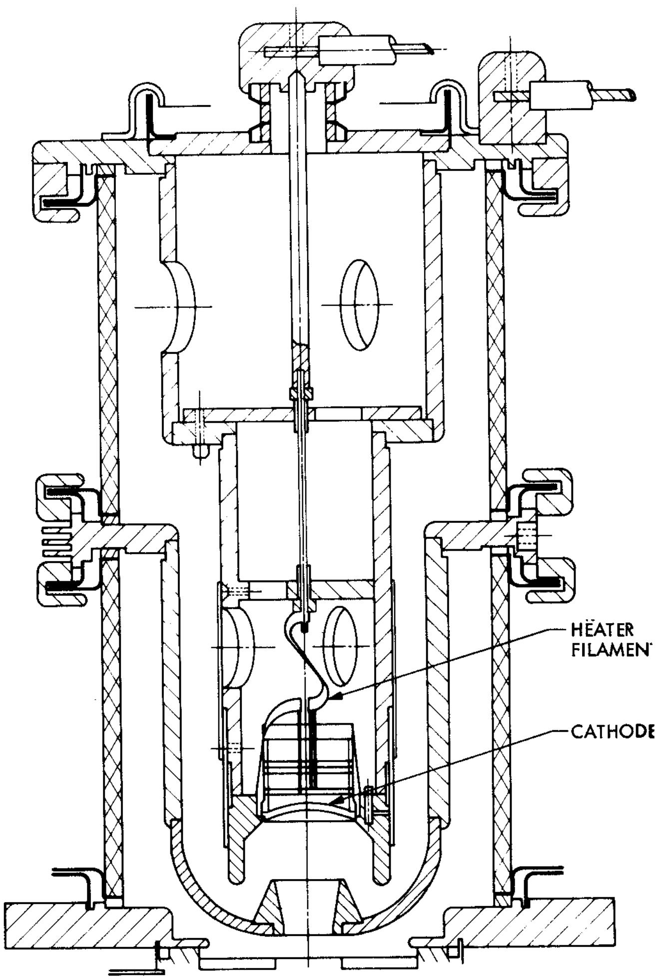

Fig. 1. Existing X-3060 electron gun layout

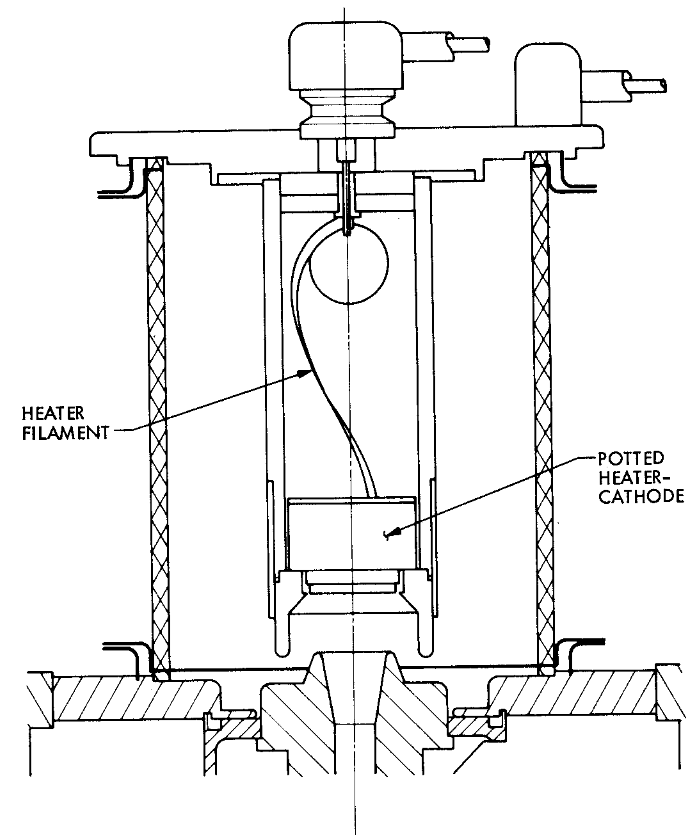

Fig. 2. New design X-3060 electron gun layout

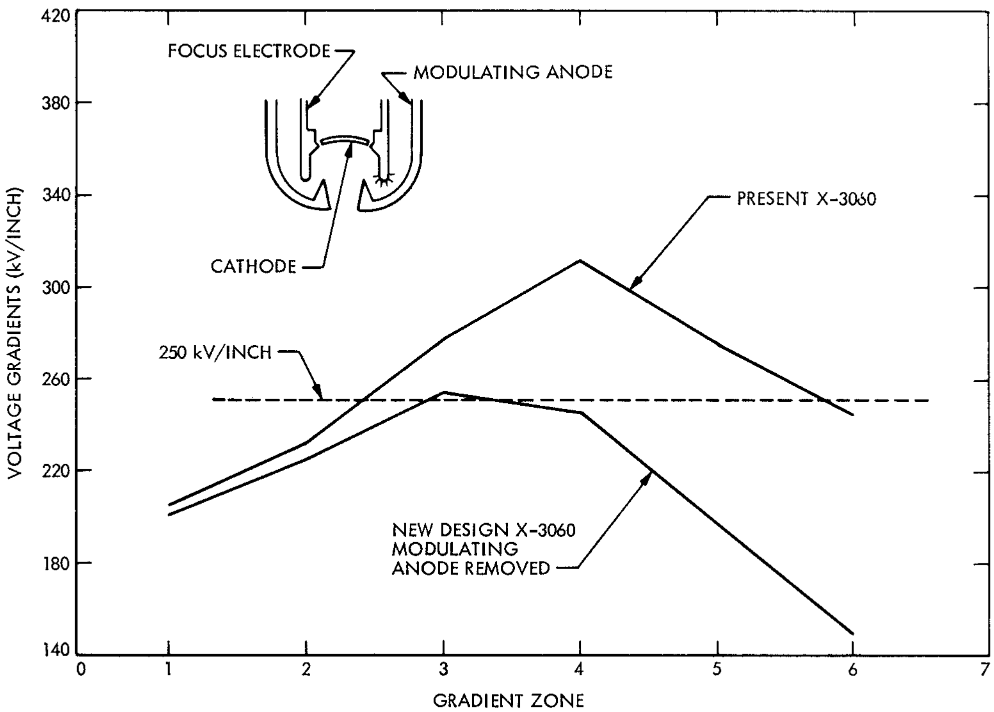

Fig. 3. Gradient comparison: new vs. old design

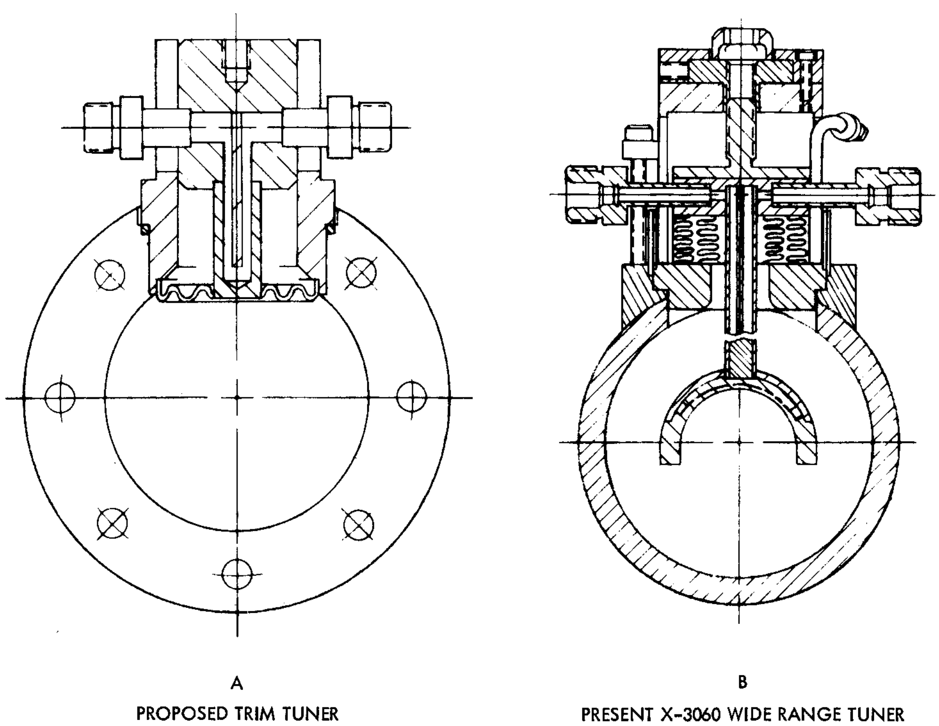

Fig. 4. Tuner designs

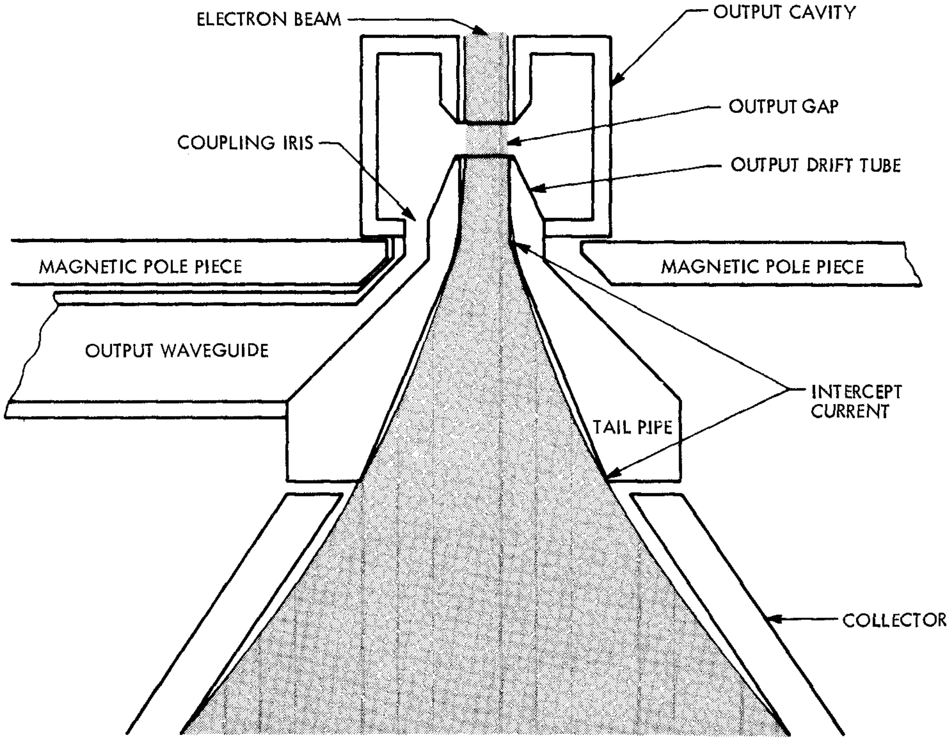

Fig. 5. X-3060 output circuit showing extended tailpipe

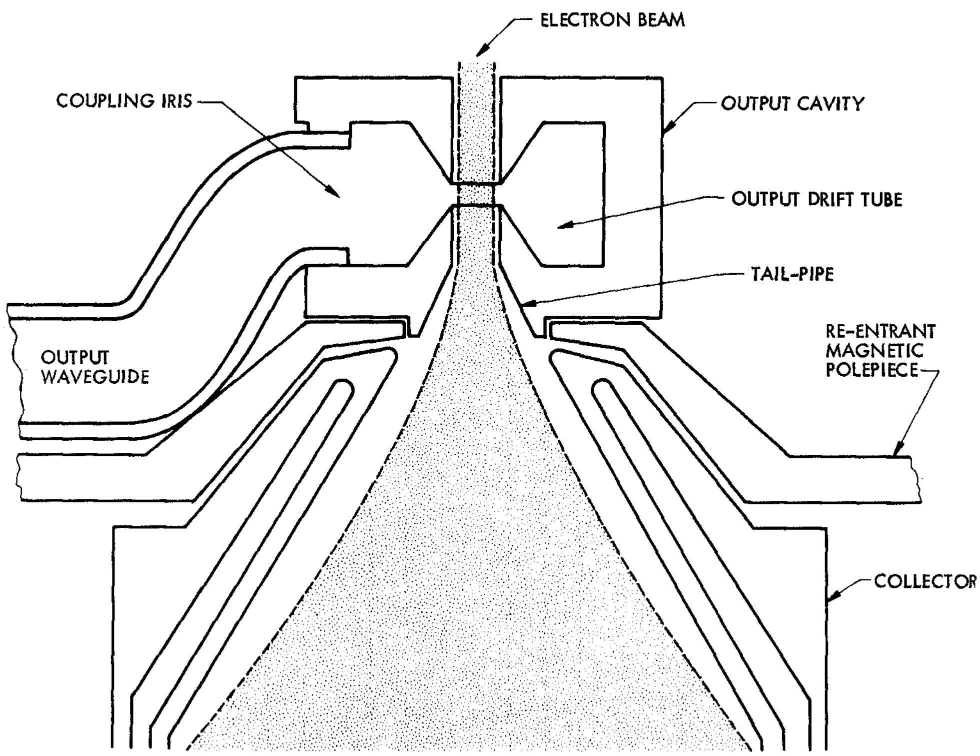

Fig. 6. New design X-3060A/B output circuit

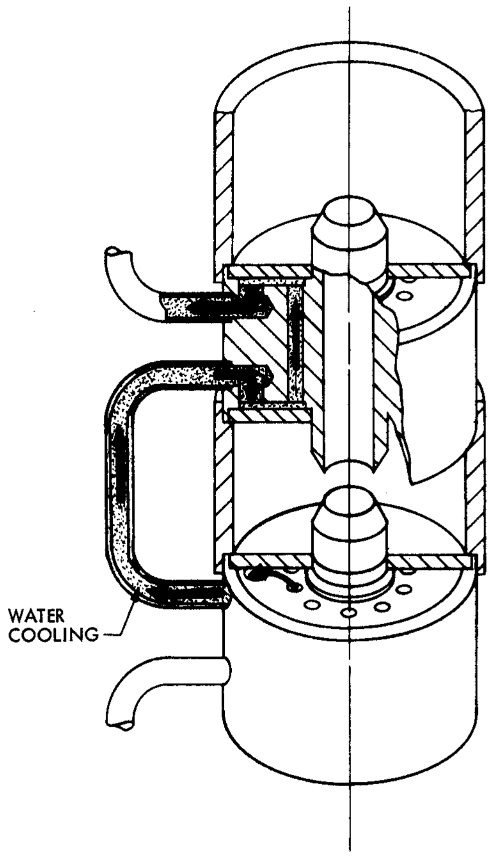

Fig. 7. Present cavity structure, X-3060

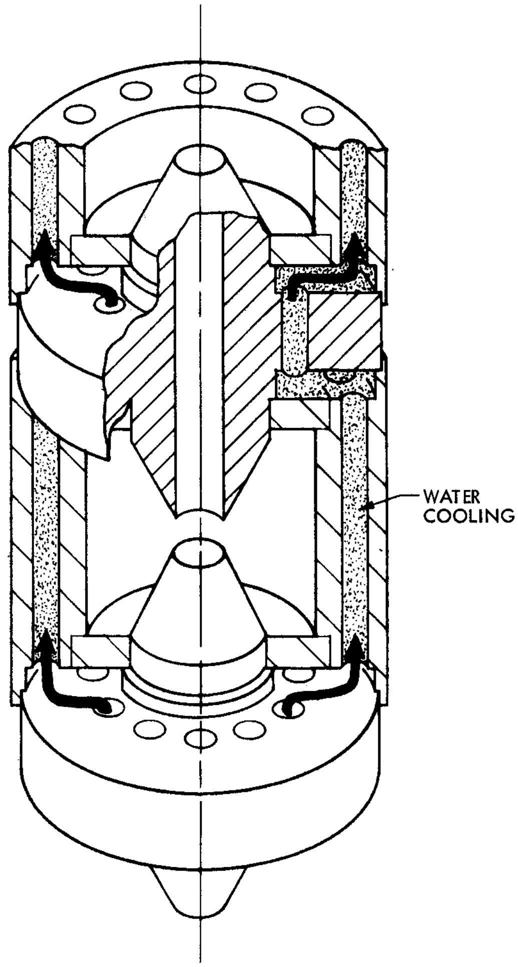

Fig. 8. Proposed cavity structure, X-3060A/B