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High Power Microwave Tubes: In the Laboratory and Online

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"HIGH–POWER MICROWAVE" TUBES: IN THE LABORATORY AND ON–LINE*

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ABSTRACT

The possibility of incapacitating the electronic circuits of hostile equipment with high-energy microwave pulses has created a demand for microwave tubes capable of very high peak pulsed powers. Experimentalists, primarily from the plasma physics community, have been working in this field, dubbed *High–Power Microwave* or *HPM*. Separately, research in high-energy physics requires electron–positron colliders with energies approaching 1 trillion electron-volts (1 terra-electron-volt, or TeV). Such accelerators must be powered by microwave sources that are very similar to some that are proposed for the HPM application. The paper points out that for these tubes to be used on-line in the manner intended, they must be designed and built to operate at a very high internal vacuum, which is not the case for many of the HPM laboratory projects. The development of a particular klystron at the Stanford Linear Accelerator Center is described in detail in order to illustrate the need for special facilities and strong Quality Control. Should the Defense requirements for HPM survive the end of the cold war, an effort should be made to coordinate the tube development activities serving these two widely disparate applications.

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* Work supported by Department of Energy contract DE–AC03–76SF00515.

I. BACKGROUND

The pursuit of a microwave source capable of producing 1–kJ pulses (or a single pulse) has caused a revival of sorts in the microwave tube art and has given birth to a new acronym—HPM for High–Power Microwave. The practitioners of the new art are universities, some government laboratories, and certain defense contractors. The quest for the kilojoule pulse is based on what the military believe is required of a microwave source to power systems that can inflict serious damage to the electronics of hostile aircraft or missiles. The 50-year-old tube industry, currently in deep recession, is not participating in this miniboom, and doesn't quite know what to make of it.

The emphasis appears to be on high peak power, rather than long pulses. One gigawatt at 1 μs is 1000 J, and that may be easier to approach than 100 MW at 10 μs, as we shall see. Since gigawatts generally require megavolts, HPM sources must be either relativistic or use very high currents. A new crop of acronyms has been generated: *RKOs* for Relativistic Klystron Oscillators, *CARMs* for Cyclotron Autoresonance Masers, *Vircators* for virtual cathode oscillators, and so on. This is reminiscent of the golden days of the development of microwave tubes, in the '50s and '60s, when most of the "trons" were invented. The difference is that, in those days, there was some serious government funding to produce working prototypes. At Stanford alone in the late '50s, a half-dozen or so dissertations were written each year, based on experimental microwave tube work, all sponsored by the Office of Naval Research. The DOD also supported the microwave tube industry (well into the '70s) in developing new high-power devices. Today, new HPM devices are not well funded and remain, for the most part, laboratory curiosities or research projects.

Single-pulse expendable devices are probably in a class by themselves. They only have to perform once, and then perhaps only for a few nanoseconds. This is not enough time for gas problems to develop, and consequently design strategies could be significantly different. An HPM tube that has to be operated repeatedly, however, must have a particularly hard vacuum, if it is to be part of an operating system. This paper is about microwave tubes that can be operated reliably for extended periods of time, and the realities associated with their manufacture.

II. THE STATE OF THE ART

Since the subject is high peak power and the objective is manufacturability and reliability, an appropriate paradigm are the klystrons being developed at SLAC for future linear colliders. I will explore the problems in designing, building, and testing these tubes, and comment on similar problems that the designers of kilojoule, short-pulse tubes can expect if their devices are to graduate from the laboratory to system use.* Stanford Linear Accelerator Center (SLAC) klystrons for the Next Linear Collider (NLC) operate at 11.4 GHz. The goal for power output is 100 MW with 1.5-ms pulses, i.e., *only* 150 J per pulse. On the other hand, this particular collider design requires 180 pps, so the average power is about 30 KW, a relatively high level for the operating frequency. Giving credence to the hoary old scaling law that average power scales as the square of the wavelength, the power density on the rf surfaces of such a tube makes it equivalent to a 0.5-MW-average power tube at the standard accelerator frequency of 2.856 GHz. If, on the other hand, the comparison is made on the basis of propensity toward rf breakdown, the S–band equivalent peak power is 400 MW, as will be shown later.

No such S–band klystrons exist, hence the 100 MW X–band klystron project breaks new ground. A tube that only approaches this performance is the workhorse of the Stanford Linear Collider (SLC), the 5045 klystron (Fig. 1), with an output of 65 MW at 3.5 μs and an average power of 40 KW. A total of 245 SLAC 5045 klystrons operate in the SLC. Approximately 600 such klystrons have been built at SLAC in the last ten years. At the time the initial complement

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* This paper is written in the first person in order to separate the author's occasionally opinionated views from any that might be held at SLAC or in the microwave tube industry.

was produced for the SLC, the production rate was 15 tubes per month, and the SLAC facilities were built to accommodate that rate. These klystrons are currently being produced (mostly rebuilt) at the rate of 4 tubes/month. In the last five years, the production yield (for new tubes) has averaged 88%. Mean Time Between Failures (MTBF) is higher than 50,000 hours for the same period (Fig. 2).

Several years of research and development for production were required to reach this level of performance. The starting point (in 1982) was the 30 MW klystrons that were developed for SLAC in the '60s and early '70s, by several microwave tube companies working independently.[◊] The 65 MW output is considered conservative and the proper operating level for a machine that must operate reliably for 6000 hours or more each year. The 5045 has been operated at an output power as high as 100 MW, albeit with shorter pulses than the normal 3.5 μs. Windows were the limiting components of the tube for a long time, but a decision to use two windows per tube and extensive work on coatings (and cleanliness) have eliminated windows as a major source of failures. The failure mechanisms limiting life today are mostly associated with the gun and the temperature of the cathode, which determines how much barium is deposited on the anode and contributes to arcing.

It should also be pointed out that the long MTBF of the 5045 klystrons is in part attributable to the controlled conditions under which these tubes are operated. Industrial klystrons of comparable average power may experience significantly lower MTBFs in some military systems, simply because the necessary expert care and maintenance may not be available in the field as it is in a scientific machine such as the SLC.

[◊] The four companies were RCA, Sperry, Litton, and Eimac. Only Litton Industries is in the microwave tube business today.

III. HIGH–POWER MICROWAVE TUBE MANUFACTURING PRACTICES

Because of its performance and the established processes on which it is based, the SLAC–5045 was the departure point for the 100–MW X–band design. Since the X–band project depends heavily on the same processes, as any project involving high-power/high-frequency microwave sources should, it is appropriate to describe them at this point.

The fundamental reason for establishing stringent manufacturing processes is to maintain a high vacuum in an operating tube. Without a good vacuum it is not possible to maintain an active dispenser cathode, develop the necessary high-voltage gradients at the electron gun, or rf gradients at the tube output cavity and window.

To obtain a high operating vacuum (order of 10^{-9} Torr), it is necessary to develop a manufacturing discipline (or QC system) that is religiously applied. This should begin with specifications and lot control for all raw materials used. A fully equipped inspection unit and facilities for metallography and chemical tests are necessary, to check for purity in metals. Obviously, only materials with low vapor pressures can be used in these tubes. Copper, which is the most commonly used material for rf parts, should be Oxygen–Free Electronic (OFE) grade. Alloys containing silver are not acceptable for brazing. Special stainless steels must be used for gun parts. Iron pole pieces, if internal to the vacuum, must be vacuum cast. Parts can only be machined with approved cooling fluids or lubricants, and must be chemically cleaned according to specific protocols before they are assembled. Dispenser cathodes are stored in vacuum containers until used.

The foregoing procedures would place an impossible stress on an ordinary research laboratory where the emphasis is on completing experiments as expeditiously as possible. Similar care is essential in industry but, even there, corners are often cut in the interests of the profit-and-loss statement. At SLAC, the yield of 5045 klystrons when they first went into production was unacceptable until strict quality control rules were established. Naturally, in addition to procedures, a fully equipped production facility had to be installed. This facility is operated separately from other SLAC engineering groups, more or less as a production organization. All high-power tubes at SLAC—the 5045s, as well as experimental klystrons—are constructed there, and the same philosophy applies to all.

Before returning to NLC klystrons, it is useful to discuss the difficulties associated with the development of such tubes, or of HPM devices in general. Simulation techniques have come a long way and, in many cases, are adequate to guide design and help avoid tiresome cold tests. However, they have not advanced enough to permit design and construction of a complete tube with predictable performance. To the extent that it is still necessary to build a model or prototype in order to evaluate a novel concept, the experimentalist faces a serious financial problem. A large sum of money must be committed to the experiment if the device is to be constructed well enough to permit evaluation at the high voltages and power levels required. If, in a new design, issues such as beam transmission, stability, efficiency, or high gradients must be resolved experimentally, then a Catch–22 situation exists: in the absence of previous experience with a similar device, a decision to fund must be based on blind faith or dire necessity. Operation in one or several of the following modalities, which avoid the above constraints, does not provide a realistic evaluation of a new HPM device if, eventually, it must become part of an operating system:

- Very short pulse lengths [ionization and breakdown that might occur at the required pulse length are avoided]
- Very low, or no Pulse Repetition Frequency (PRF) [if any significant average power is required, gas evolution and drift problems are not evaluated].
- Use of field emission cathodes [much higher current densities at the gun than can be obtained with conventional cathodes, but very short cathode life].
- No output window [an output window is required in operation and is one of the most critical components of the tube].

IV. THE NLC X–BAND KLYSTRON PROGRAM AT SLAC

The reasons for these caveats will become more obvious in the discussion of the design of the 100 MW X–band klystron at SLAC, which follows.

The NLC is an e+e- machine with a center-of-mass energy of 500 GeV initially, expandable to 1 TeV and, eventually, to as much as 1.5 TeV. It is currently in the design stage at several research centers in Europe, the US, and Japan, with a variety of design approaches. The US/SLAC design is an X–band machine, with several bunches per pulse for increased luminosity. At the 0.5 TeV level, the relevant machine parameters are (approximately): 2000 klystrons, operating at 11.4 GHz with an output power of 100 MW and a pulse width of 1.5 μs, compressed to 200 ns for driving the accelerator sections. For the higher energy levels, the number of klystrons would have to increase by the square of the increase in energy, resulting in quantities of tubes never before contemplated for a single system. Alternatively, sources capable of much higher power would have to be developed. It is small wonder that the NLC source requirement is about to replace the 1-kJ electronic warfare goal as the Holy Grail pursued by HPM engineers and physicists.

At SLAC the development of the X–band NLC klystron went through several stages. The design began as a straightfoward klystron, with a conventional reentrant output cavity. The tube used a fairly high perveance§ (1.8×10^{-6}) beam, in order to make use of existing modulators, capable of operation at 440 kV, 510 A. The beam was produced by an electrostatic convergence gun and subsequent magnetic compression to a 7 mm diameter in a 9.5 mm beam tunnel. To produce the required 100 MW, the klystron would have to be more than 40% efficient, which 2.5D simulations predicted (SLAC's CONDOR code).

The results were disappointing. The maximum power attained (at 440 kV) was only 67 MW, but most importantly, that level could only be sustained in pulses of 50 ns or less. At a pulse length of 1 μs, the maximum power attainable without pulse "shortening" was 20 MW (Fig. 3). The tube was operated for several days (at 60 pps), while doing the usual things klystron engineers do to improve power output, adjusting the drive, expanding the beam magnetically, changing the frequency slightly, etc. It was observed that the optimum frequency of operation shifted higher with time, as it would if the output cavity resonant frequency were increasing. Eventually, one of the output windows failed and the tube was opened for a postmortem.

It should be noted here that high-power pulsed SLAC klystrons are operated with vacuum on both sides of the window. As indicated above, the vacuum on the tube side of the window is in the 10^{-9} Torr scale (SLAC klystrons are baked at 550°C in double-vacuum exhaust stations). On the load side, the wave guide is baked in place at 200°C and operated in the 10^{-8} scale, except that when it is initially rf-processed, the pressure is allowed to rise about one scale. The windows in this first klystron, designated XC1, were of the pillbox type, approximately 1-mm thick. They are sputter-coated with a thin layer of titanium nitride to discourage multipactor discharges.

The postmortem provided two important pieces of information:

- First, it showed that there had been heavy beam interception in the funnel-shaped part of the klystron where the magnetic beam compression took place.
- Second, the output gap appeared to be eroded by rf discharges, presumably when pulse breakup was observed on the scope.

The latter observation explained why the cavity frequency was drifting upward. The two effects were probably related—it is possible that beam interception triggered plasma discharges that otherwise might have required higher voltages to be initiated.

These findings made it quite clear that the desired power level of the klystron would require optics of the highest quality and that rf gradients at the output would have to be limited to well below 1 MV/cm, which was the calculated level for the gap in XC1 at full output power. It was

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§ "Perveance," defined as I/V3/2, is a common parameter in electron gun design. Generally, higher perveance, because of the higher space charge it implies, results in more difficult electron optics and lower efficiency in klystrons.

decided that a lower perveance (1.2×10^{-6}) was desirable to improve optics and efficiency, and that the output should be an extended interaction circuit of either the standing-wave or traveling-wave type. Since a new modulator had to be built to accommodate the required beam voltage of 550 kV at the new perveance, it was also decided that, in the interim, the work at microperveance 1.8 would continue. There was an urgent need for high-power sources to test accelerator components at 11.4 GHz, and it was felt that much could be learned about the design of output circuits even if the perveance was high and the efficiency on the low side.

A total of seven more klystrons (XC2 through XC8) were built in the series. The beam size and drift tube were not changed, but after XC3 a new gun was designed with an electrostatic convergence of 100, matched (confined flow) by a similarly convergent magnetic field. Despite the high convergence, the cathode loading was too high (about 25 A/cm^2 at the cathode edge) for a final product with good cathode life, but once again the XC tubes were considered experimental.

A number of output circuits were evaluated. The initial attempt was to use the same circuit used in an earlier (1985) SLAC developmental klystron [1] that produced 150 MW at S–band. This consisted of two reentrant cavities, coupled with an inductive iris, and operating in the 2π mode. (See Fig. 3 for the complete family of output circuits used). Three klystrons, XC2, XC3, and XC4, were built with this output, initially with thin windows (that turned out to be very fragile) and eventually with half-wave windows, that were better. These klystrons produced 30 MW at 1 μs, approximately. However, above the 30 MW level, the pulse broke up before the desired 1 μs could be attained. After a number of repairs for broken windows, XC2 and XC3 are still operating as sources for accelerator and resonant ring experiments.

Since window breakage also limited maximum power output, XC4 was built without windows, but with internal loads and directional couplers. This tube also incorporated the new optics, and hence there was hope that with improved beam transmission, pulse breakup would be less of a problem. These hopes were dashed as well when the tube was evaluated. Pulse breakup was just as severe and, despite determined attempts to age through it, it persisted, beginning approximately at the 30 MW level and above 500 ns, or so.

Now, the 2π circuit used in XC2–4 was not circularly symmetric because of the inductive iris and, as a consequence, we were never able to directly simulate the interaction process with the CONDOR program. We relied instead on an indirect method that made use of an impedance matrix for the circuit, determined through cold test, and introduced into CONDOR to calculate gap voltages. It was thought that the gap gradients would be much lower than in XC1, or about 700 kv/cm. The postmortem on XC4 established that the gaps were not the problem, and that the activity was all in the inductive iris between the cavities, which had melted. Clearly the gradient there was much higher than in the gap. It is not known what the value was because the 2π circuit was abandoned at that point. The azimuthal nonuniformity was considered not only an impediment to simulation, but also a potential cause for field asymmetries in the gap, and hence a trigger for potential dipole modes that might defocus the beam.

All subsequent klystrons except XC6 employed disc-loaded waveguide output circuits (Fig. 3, types C and D). These have circular symmetry, except of course for the output waveguides. The CONDOR program assumes that the output coupling is a radial transmission line and that certain tests have to be performed, sometimes with the help of a MAFIA simulation (without the beam) to ensure that the circuit actually used in the klystron is equivalent to that assumed by CONDOR. These computational refinements were not available early in the program. Nevertheless, the XC5 klystron (Fig. 5), which used a traveling-wave output (type C), demonstrated reasonable agreement with simulations, producing 52 MW with 1 μs pulses, at an efficiency of 30%. As can be seen from Fig. 6, these were well-formed pulses and there was no pulse breakup after some processing, up to that power level, which was at the voltage limit of the modulator. This klystron eventually failed due to an open cathode heater. It was also repaired once after a window failure.

This and many other window failures, both in tubes and experimental setups, led to a decision to abandon the TE_{11}–type windows, which require current to flow across the metallized and brazed joint between ceramic and metal, and to employ TE_{01} windows instead, particularly since in the proposed NLC all power transmission between the klystrons and the accelerator is by means of circular TE_{01} waveguide to minimize transmission losses.

It should be noted at this point that SLAC has long emphasized research on high-power windows. All windows used in both the production 5045 klystrons and in these experimental X–band tubes are sputter-coated with a layer of Titanium Nitride to prevent multipactor discharges. A parallel program on X–band windows is being pursued, using a traveling-wave resonant ring (Fig. 7). This ring has a power gain of ten and has been operated at 300 MW, with 800–ns pulses, using one of the early klystrons (XC3) as a driver.

In order to use a TE_{01} window in a klystron, it is necessary to provide a transition from rectangular WR90 waveguide, used to couple to the output circuit. Conventional transitions of the *Marié* type are much too long to conveniently include in the klystron vacuum envelope, so a new compact coupler was developed and tested in the ring up to the 150–MW level. It is known as the "flower-petal" coupler and is shown in Fig. 8. Ring tests of a "windowtron" consisting of TE_{01} 1.75–inch diameter, 4–mm alumina window, with flower-petal transitions on either side, have shown that this window is capable of transmitting at least 65 MW at 1 μs. The first test window failed (Fig. 9) at approximately 80 MW with a puncture at about 50% of the radius, where the highest electric field gradient is calculated to be. It should be noted that most of the TE_{11} windows that have failed in the ring, in tubes, or in high-power accelerator tests, did so due to a discharge at the joint between the window and its metal sleeve. New, higher purity ceramics (manufactured by an isostatic pressure process) will be investigated. They are less likely to contain microvoids, which are considered to lower the window's resistance to high fields. A TE_{01} window will be used in the first klystron of the XL series.

The XL series of klystrons will be the sources in the SLAC Next Linear Collider Test Accelerator (NLCTA), and will operate at 50 MW, at 440 kV and 350 A. The first klystron of this series is nearing test, and incorporates several new features worth describing here.

The new perveance 1.2×10^{-6} gun design was evaluated in a diode (Fig. 10) and the results compared to the EGUN calculations used to design the optics. Gun parameters are given in Table 1. Electron trajectories are shown in Fig. 11. These are calculated by EGUN in the presence of a magnetic field matching the electrostatic trajectories to produce "confined flow" with a field three times "Brillouin," which is necessary in view of the large convergence and the need for near-perfect beam transmission. There was no magnetic field in the diode, however. The EGUN prediction was that, without immersing the beam in a magnetic field, it would become defocused at the lower voltages. Because of relativistic effects, the electrostatic optics could only be optimized at the higher voltage of 440 kV. The beam tester results agreed very well with the EGUN predictions: the beam interception showed characteristic "rabbit ears" at the rise and fall intervals (Fig. 12), and transmission of 99.5% at the flat center of the pulse.

The rf cavities of XL1 (Fig. 13) are contained in two subassemblies that are welded together when the tube is assembled prior to bake-out. The first section consists of three gain cavities of conventional design. The second section is more complex and incorporates three inductively tuned cavities designed to divide the voltage necessary for the final bunching of the beam. The output circuit is a three-section π-mode extended interaction cavity, with two symmetrical waveguide couplings that are brought together through a "T" to a single waveguide. Figure 14 shows the CONDOR simulation of the bunched beam entering the output and the subsequent energy extraction and debunching. Figure 15 shows the calculated rf current in relation to the various cavity positions. The predicted efficiency is 42% with the actual beam and magnetic field used in the simulation. A traveling-wave output section has also been simulated with a predicted efficiency of over 55%. The next klystron (XL2) will use this TW output, with everything else remaining the same. As indicated above, all klystrons of the XL series will use single TE_{01} windows.

V. REMAINING PROBLEMS AND FUTURE DIRECTIONS

When a half-dozen or so working XLs have been built for the NLCTA, development of 100–MW klystrons will continue, using the new 600–kV modulator for test. A new gun will have to be designed with even higher convergence (150:1, or more) and a larger overall diameter in order to withstand the higher gradients. It is expected that the approach to the output circuit will be the same, with perhaps longer circuits. Whether a single window can be used is an issue that will have to wait until more tests are conducted in the resonant ring.

The ultimate limit to the power that can be produced by a klystron of this general design depends, first, on a better understanding of the rf breakdown mechanism in the presence of a beam and, second, on the quality of beam optics that can be designed into the very high convergence beam that is necessary for conservative cathode loading. In separate experiments with resonant sections of the X–band accelerator, surface gradients as high as 500 MV/m have been attained after some "processing"; i.e., after several days of gradually increasing power, experiencing some arcing and increases in pressure, but eventually attaining stable operation at a good vacuum. (The Kilpatric criterion [2] would predict approximately a sixth of that value, so clearly a new theory is needed). The experience with the XC klystron series, however, would suggest that only about a tenth of this gradient is safe when a high-power beam is traversing the cavity. It is not clear whether the problem is beam "halo"; i.e., stray electrons forming a low-density sheath outside the actual beam diameter, or beam spreading due to increased space charge resulting from rf saturation, or other causes. This is a good research topic, and one that must be pursued seriously if much higher powers are to be reached. Earlier research by Loew and Wang [32] suggested an $f^{1/2}$ or $f^{1/3}$ dependence of the breakdown gradient on frequency and a strong, but undetermined, dependence on pulse duration. Their experiments were conducted in a narrow range of pulse lengths, 1.5 to 2.5 μs. More needs to be learned about mechanisms of breakdown in the presence of the beam, as well as about the treatment of surfaces for higher resistance to breakdown. It may well be that, at elevated gradients and very short pulses of the order of 50 ns or less, it is actually easier to add energy without breakdown in the pulse by increasing the peak power, rather than by increasing the pulse length.

For all the reasons above, experimental work in kilojoule-pulse microwave sources should be done at longer pulse lengths than a few nanoseconds, if these devices are ever to leave the laboratory. If, for instance, only 50–ns-long pulses were to be used, the peak power required for the goal of one kilojoule would be 20 GW. This is not a practical system solution because it would require an accelerator to provide the beam for the klystron.

It is not clear whether interest in defense uses of HPM will survive the end of the cold war, or whether the magic 1-kilojoule goal will continue to attract R&D funds for the development of short-pulse, high-power sources. It is likely that future e^+e^- colliders will provide a more credible future market for devices that are very similar. The microwave tubes that will be required, however, will have to operate *on-line*. They must have clean spectra (no spurious frequencies in the output), be reliable and long-lived (MTBFs greater than 20,000 hours), and above all, manufacturable and relatively inexpensive (less than $50,000 in large quantities). Otherwise, these future e^+e^- colliders, which someday may provide a major boost to an ailing microwave tube industry, will simply not happen.

VI. ACKNOWLEDGMENTS

The NLC klystron development described in this paper was initially conducted with Terry Lee as project engineer. Ed Wright is now project engineer, following Lee's retirement. Ken Eppley, Randy Fowkes, Bob Phillips, Sami Tantawi and Arnold Vlieks all contributed significantly to various aspects of the tube's electrical design. Karen Fant and Chris Pearson were responsible for mechanical design and fabrication. George Miram, a consultant to SLAC, worked on gun optics. Erling Lien, also a consultant, contributed to output circuit design.

Note: Since this paper was written (in October 1993), the first low perveance klystron, XL1 (Fig. 10) was built and tested.

The tube performed substantially as predicted by simulation, producing 52 MW at 415 kV. Pulse length was 1.5 μs and repetition rate was 60 Hz.

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BIOGRAPHY

George Caryotakis holds a BSEE degree from Syracuse University and a PhD in Electrical Engineering from Stanford University. He joined Varian Associates after graduation from Stanford, serving initially as an engineer in the Tube Research Department and eventually as President of the Varian Electron Device Group. The group consisted of ten divisions manufacturing microwave tubes and solid state devices, as well as power grid and x-ray tubes.

He retired from Varian after 30 years of service and is now at the Stanford Linear Accelerator Center (SLAC), heading its Klystron/ Microwave Department. This unit has responsibility for microwave engineering and rf maintenance of the Stanford Linear Collider (SLC). The Klystron/ Microwave Department also develops and manufactures high power microwave sources for the SLC and future colliders.

Dr. Caryotakis holds several patents on microwave tube design. He has served on DOD advisory committees and was instrumental in establishing AFTER, an Air Force sponsored university program for training graduate microwave tube engineers. AFTER was the predecessor to ATRI (Advanced Thermionic Research Initiative), recently awarded to a collaboration of universities and national laboratories, including SLAC, headed by the University of California at Davis.

TABLE I. XL Gun Parameters

Beam voltage	440	kV
Beam current	350	A
Perveance	1.2×10^{-6}	
Maximum cathode loading	12.8	A/cm^2
Beam area of convergence	127:1	
Beam diameter	6.4	mm
Tunnel diameter	9.525	mm

FIGURE CAPTIONS

1. The SLAC 5045 klystron.
2. On-line performance of the 5045 klystrons.
3. Maximum power output (before breakdown) versus pulse length in the XC1 klystron.
4. Output circuits used in various klystrons of the XC series, drawn to the same scale.
5. The XC5 klystron.
6. Test results for the XC5 klystron.
7. X–band traveling-wave resonant ring (power gain: 10 db). This ring has been operated at 300 MW, with 1 μs pulses.
8. "Flower-petal" transition. Mode purity: 99.5%. Voltage Standing–Wave Ratio at 11.424 GHz: 1.02.
9. A failed TE_{01} window (failure was at approximately 85 MW, 1 μs).
10. The XL1 beam tester diode.
11. EGUN calculation of XL1 trajectories, in a confining magnetic field.
12. Interception in beam-tester diode showing the effect of relativity on beam size. (No confining magnetic field).
13. XL1 klystron design.
14. CONDOR simulation of output cavity interaction.
15. CONDOR simulation of the rf current in the XL1 beam.

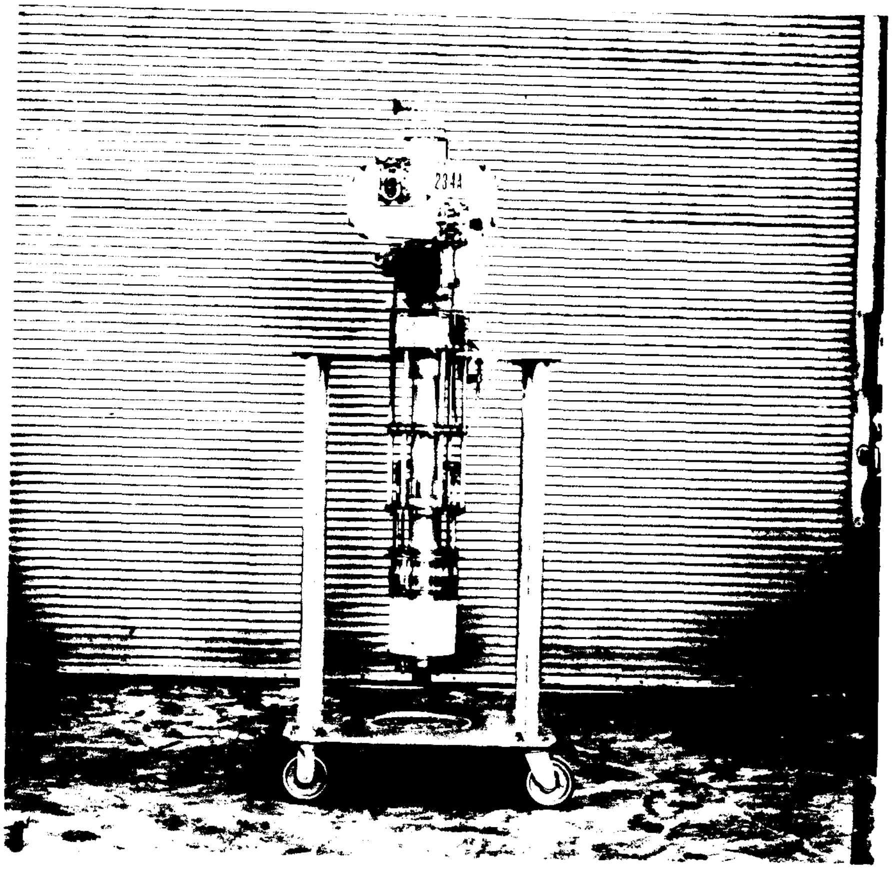


Fig. 1

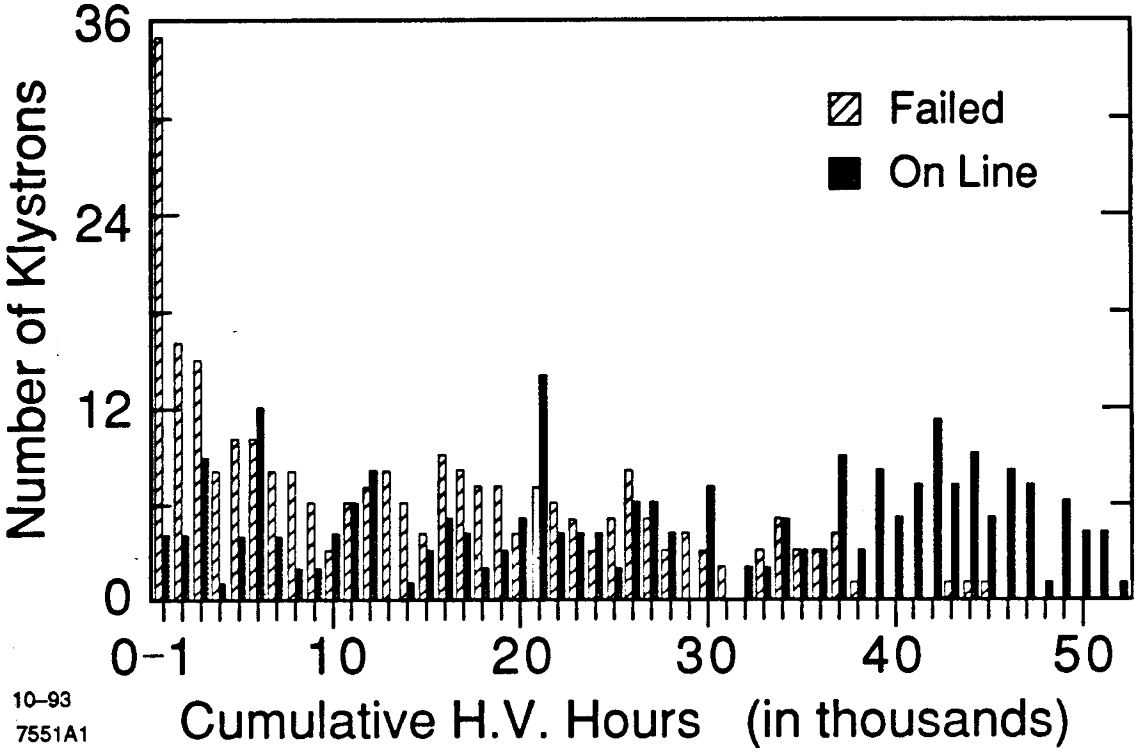
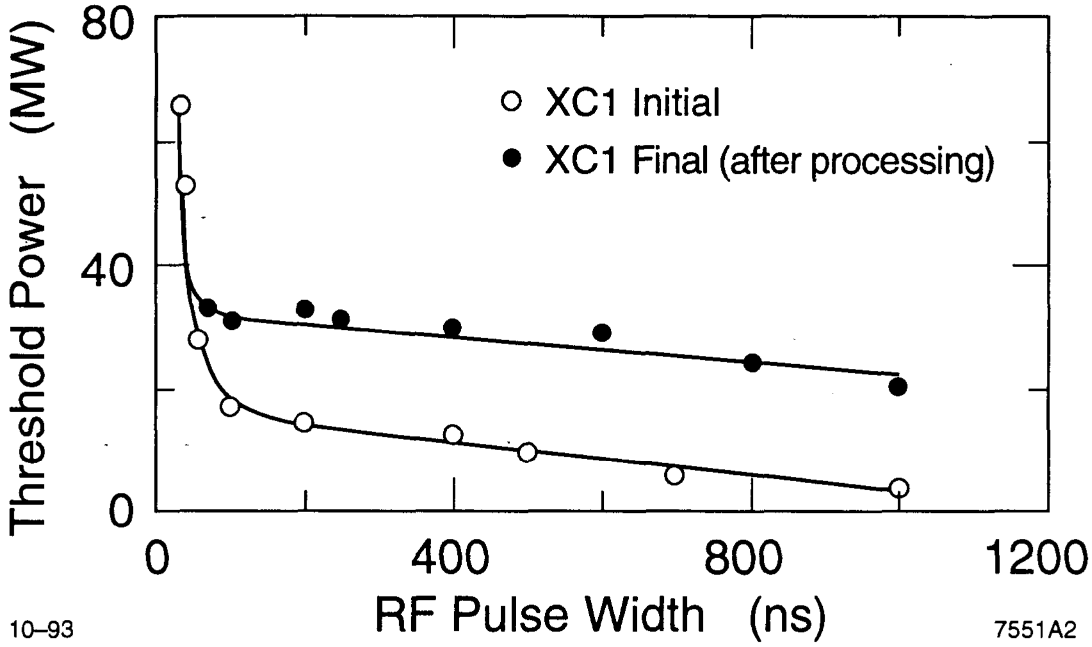
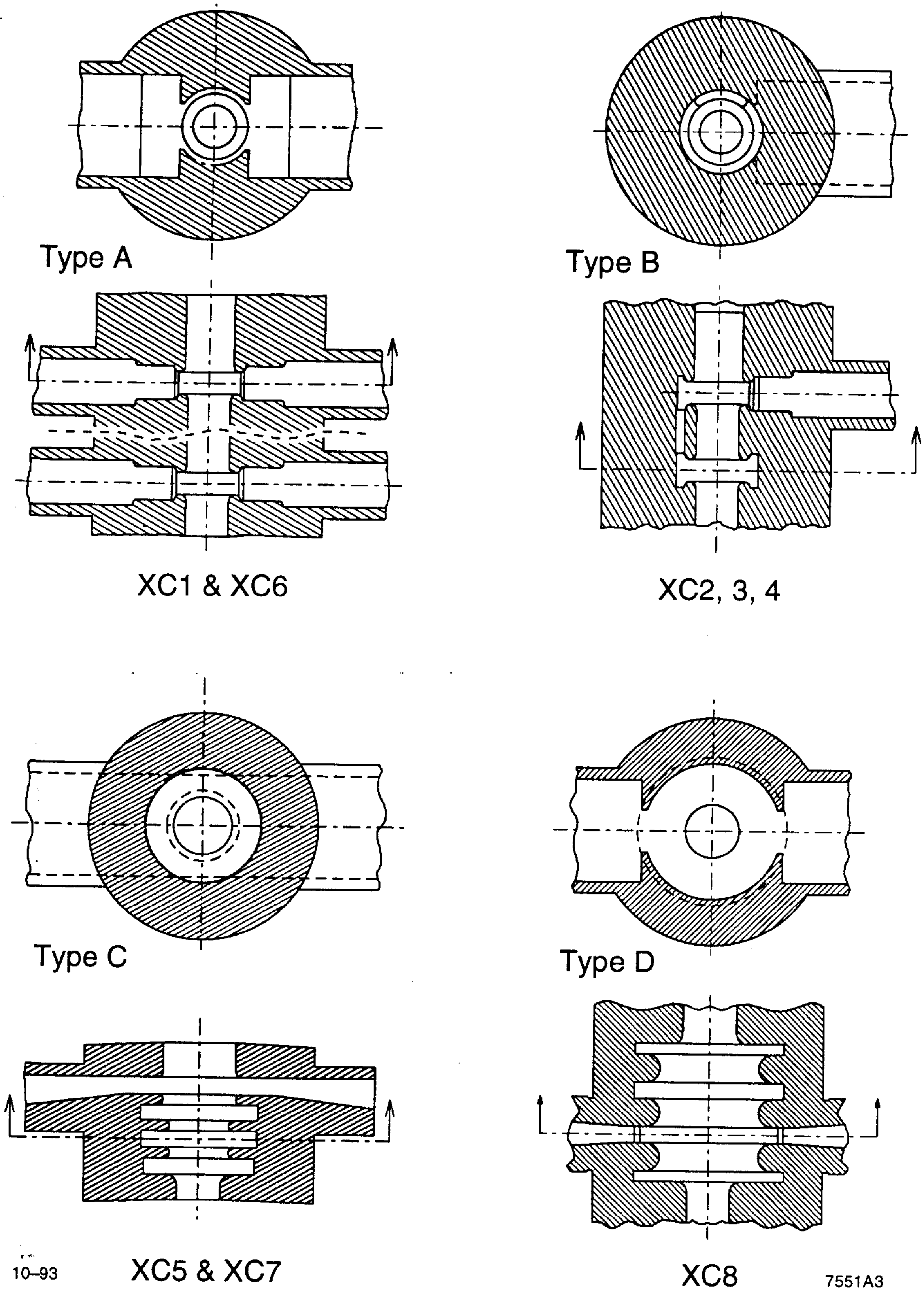

36
24
12
0
Number of Klystrons
▨ Failed
■ On Line
0–1
10
20
30
40
50
Cumulative H.V. Hours (in thousands)
10–93
7551A1

Fig. 2



Threshold Power (MW)
80
40
0
0
400
800
1200
RF Pulse Width (ns)
○ XC1 Initial
● XC1 Final (after processing)
10–93
7551A2

Fig. 3



Type A

XC1 & XC6

Type B

XC2, 3, 4

Type C

XC5 & XC7

Type D

XC8

Fig. 4

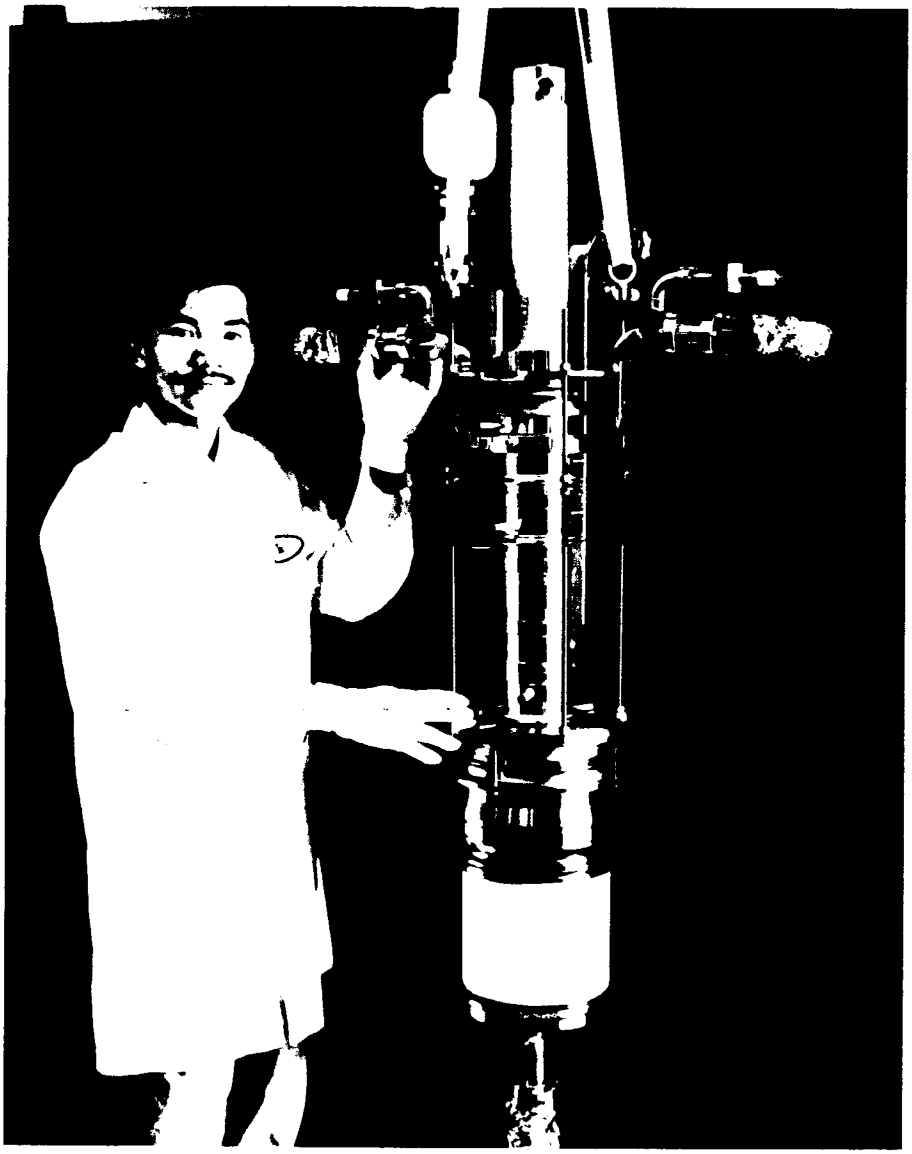


Fig. 5

Pulse rep. freq.: 60 Hz
Beam voltage: 447 kV
Beam current: 527 A
Total power output: 51.1 MW

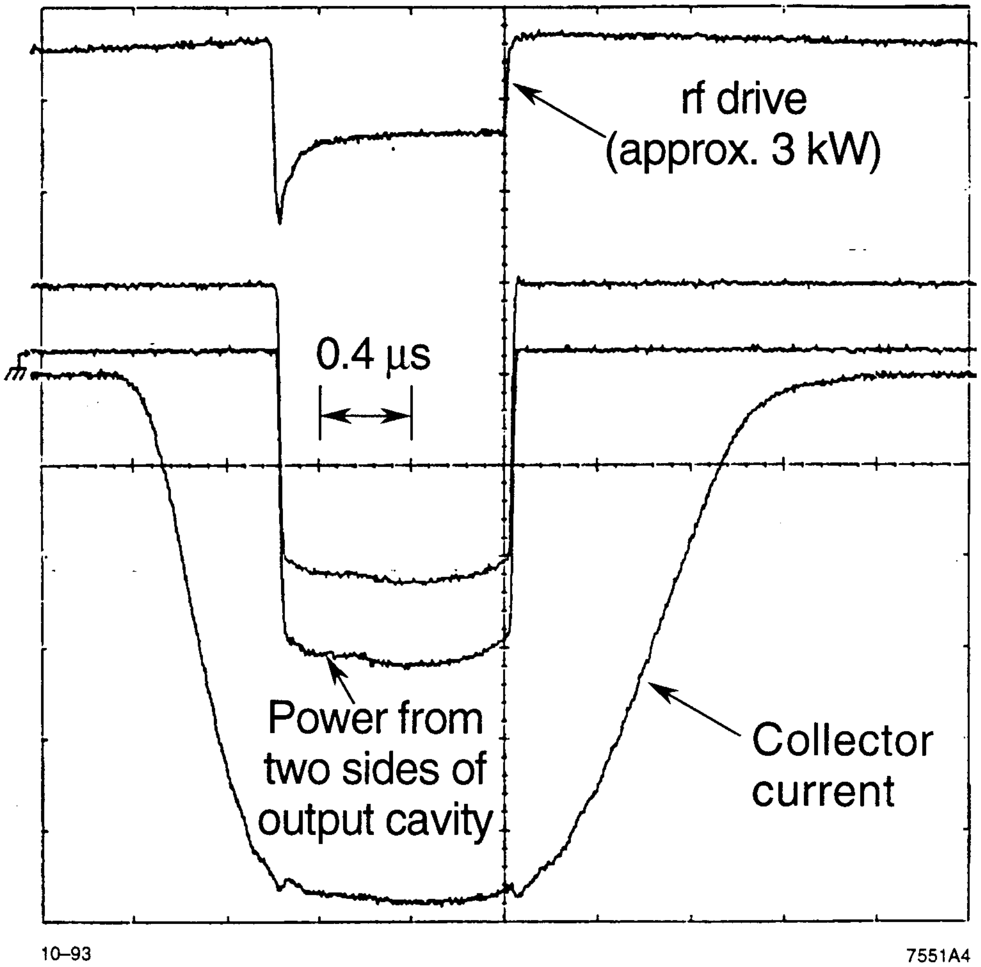


Fig. 6

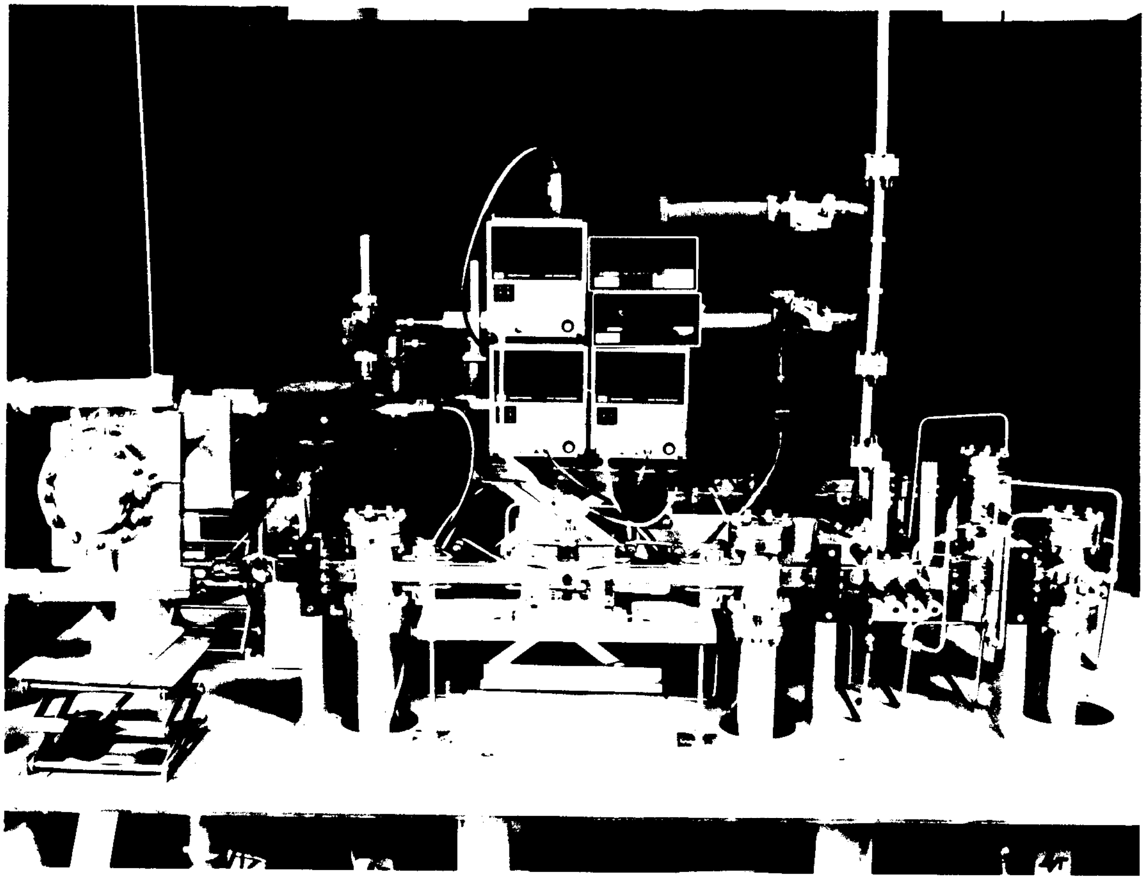


Fig. 7

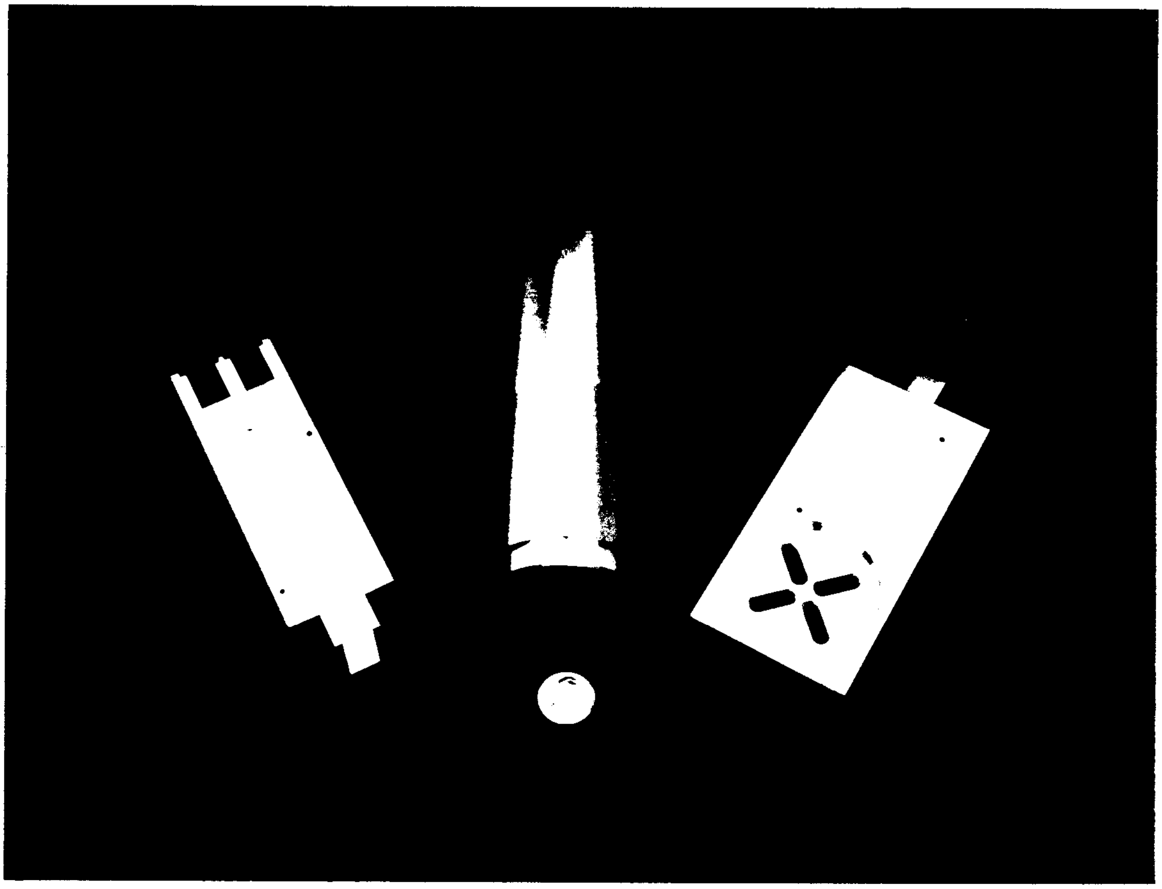


Fig. 8a

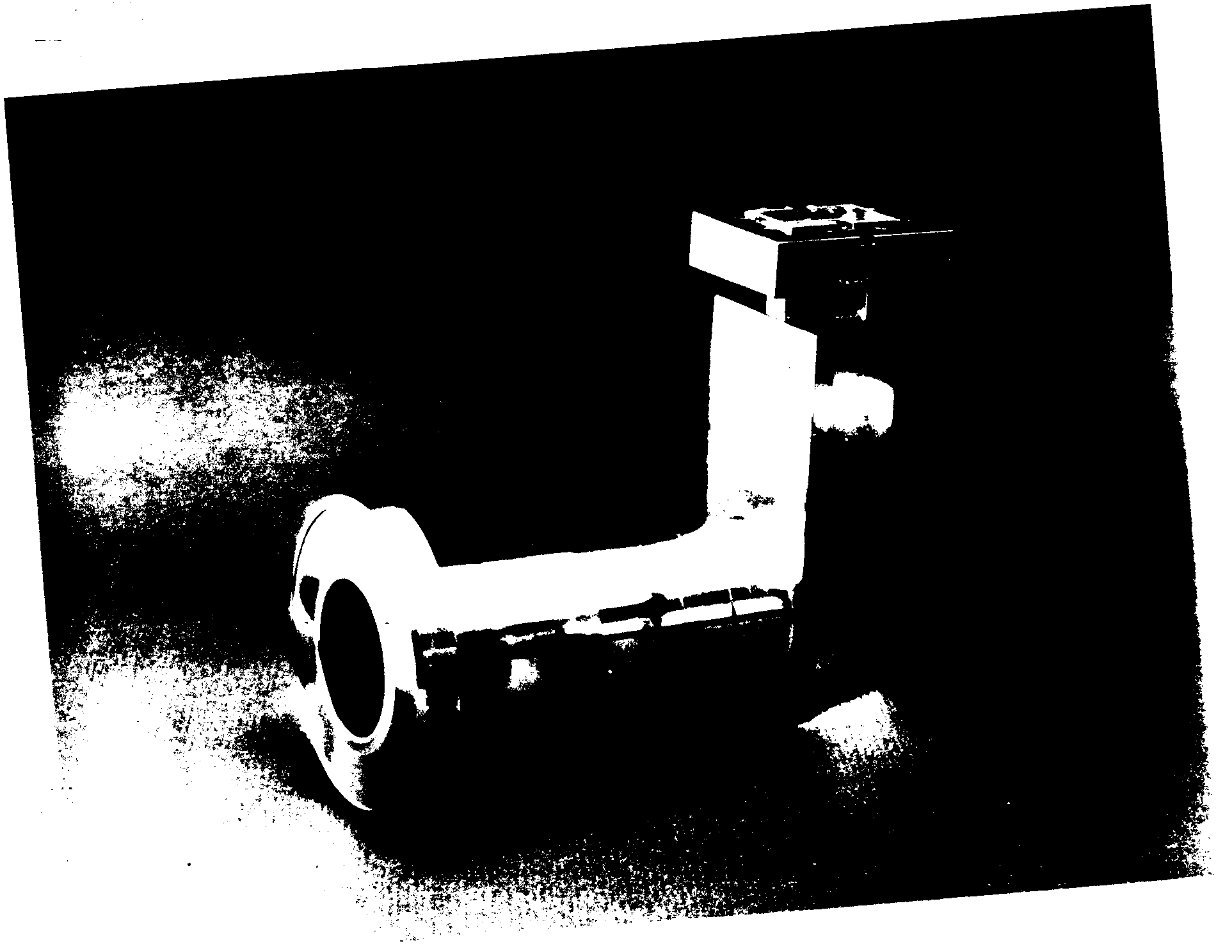


Fig. 8b

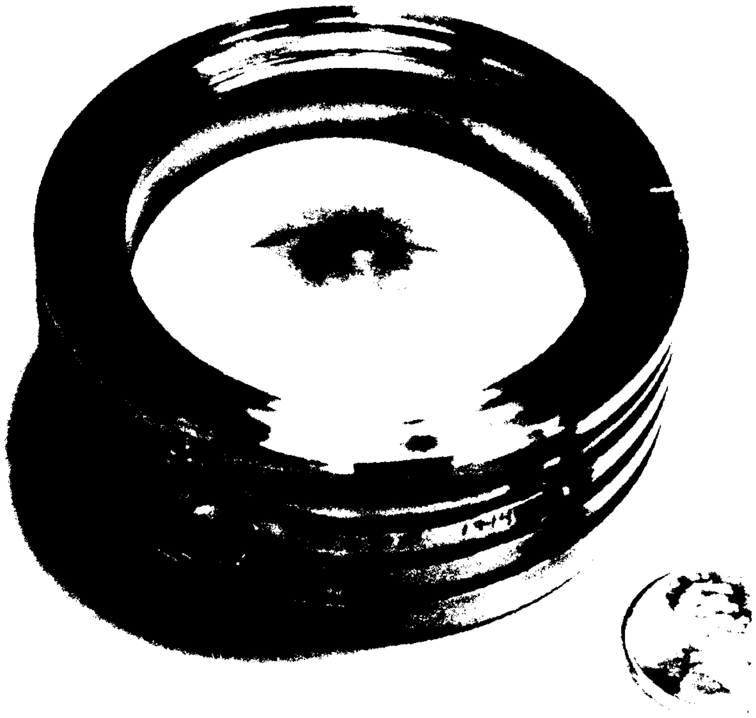


Fig. 9

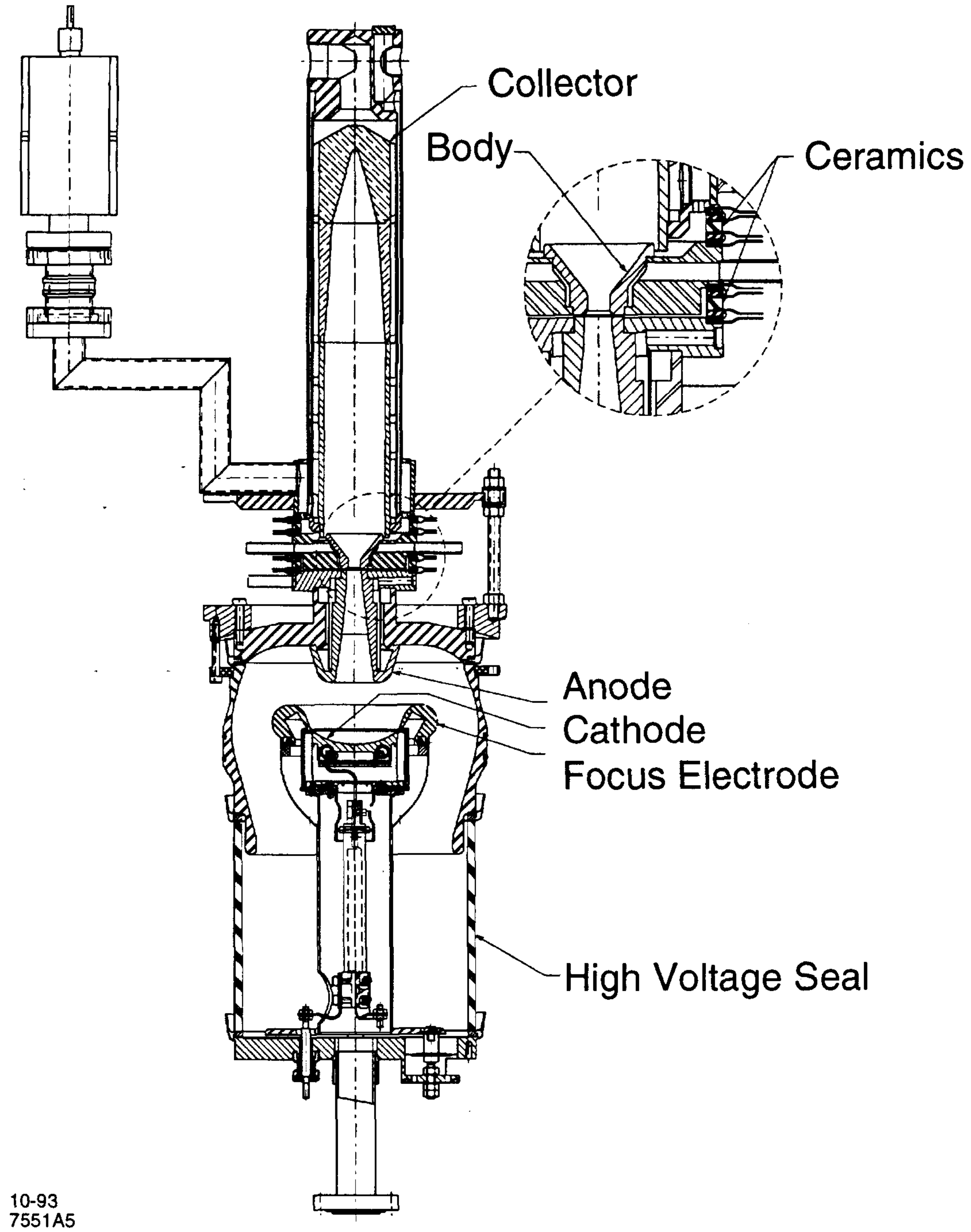
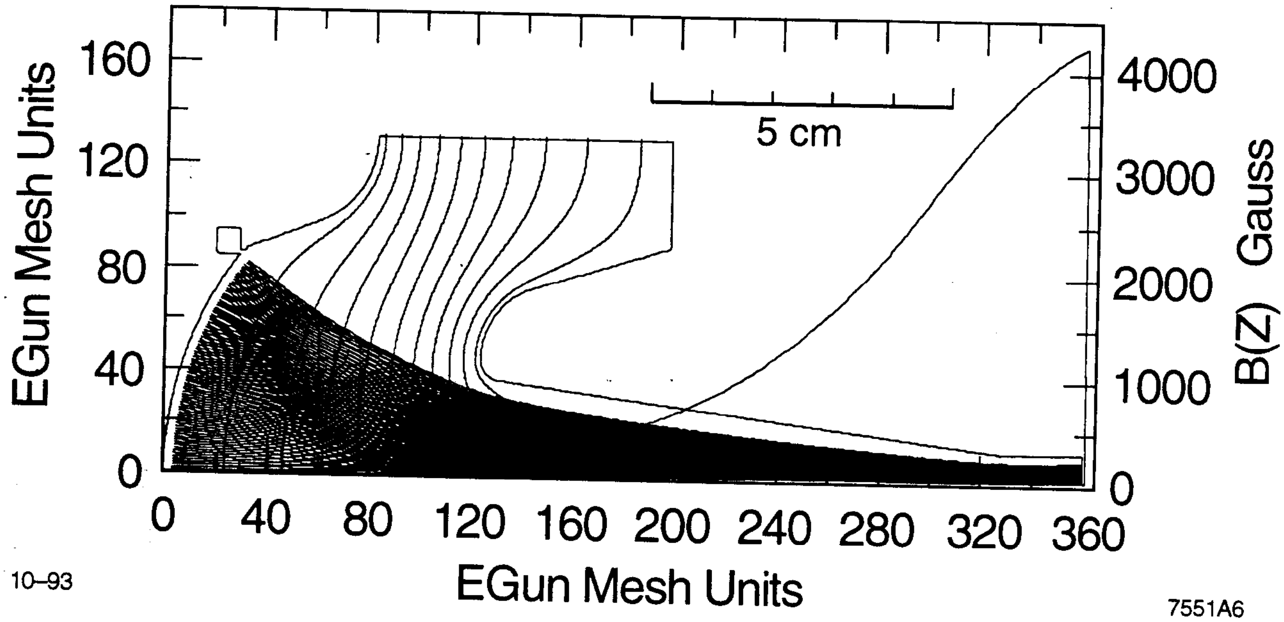
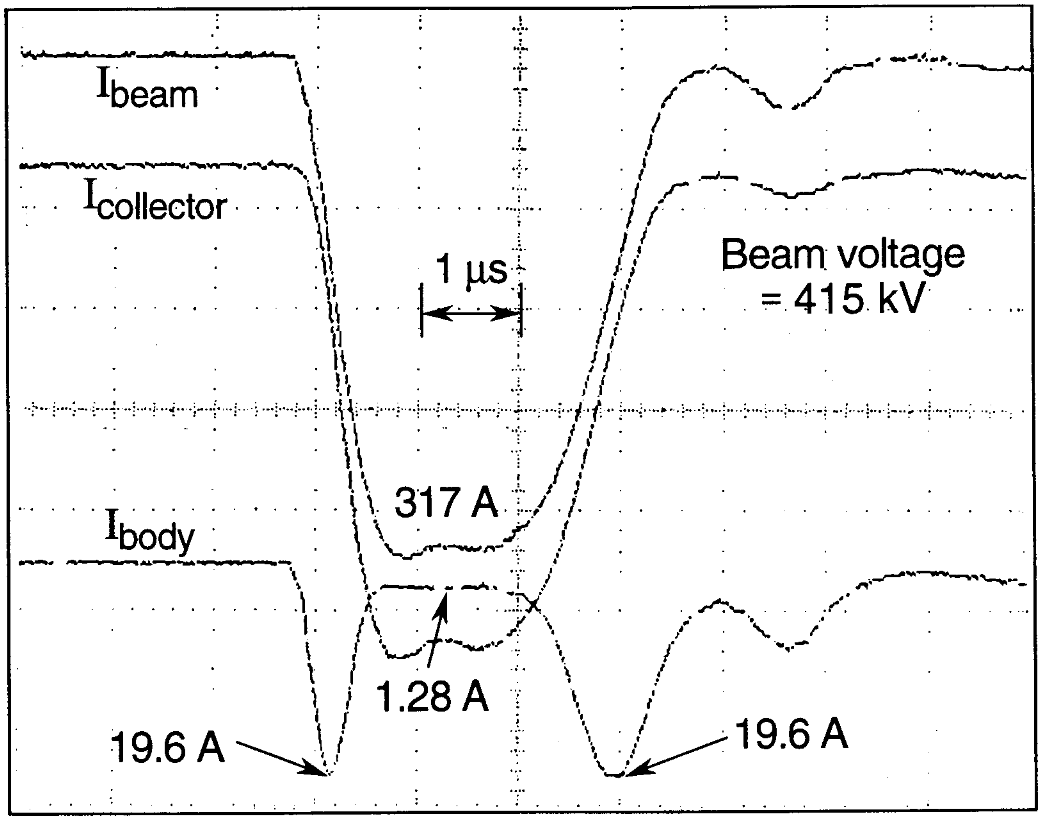

Collector
Body
Ceramics
Anode
Cathode
Focus Electrode
High Voltage Seal
10-93
7551A5

Fig. 10



160
120
80
40
0
EGun Mesh Units
0
40
80
120
160
200
240
280
320
360
EGun Mesh Units
4000
3000
2000
1000
0
B(Z) Gauss
5 cm
10–93
7551A6

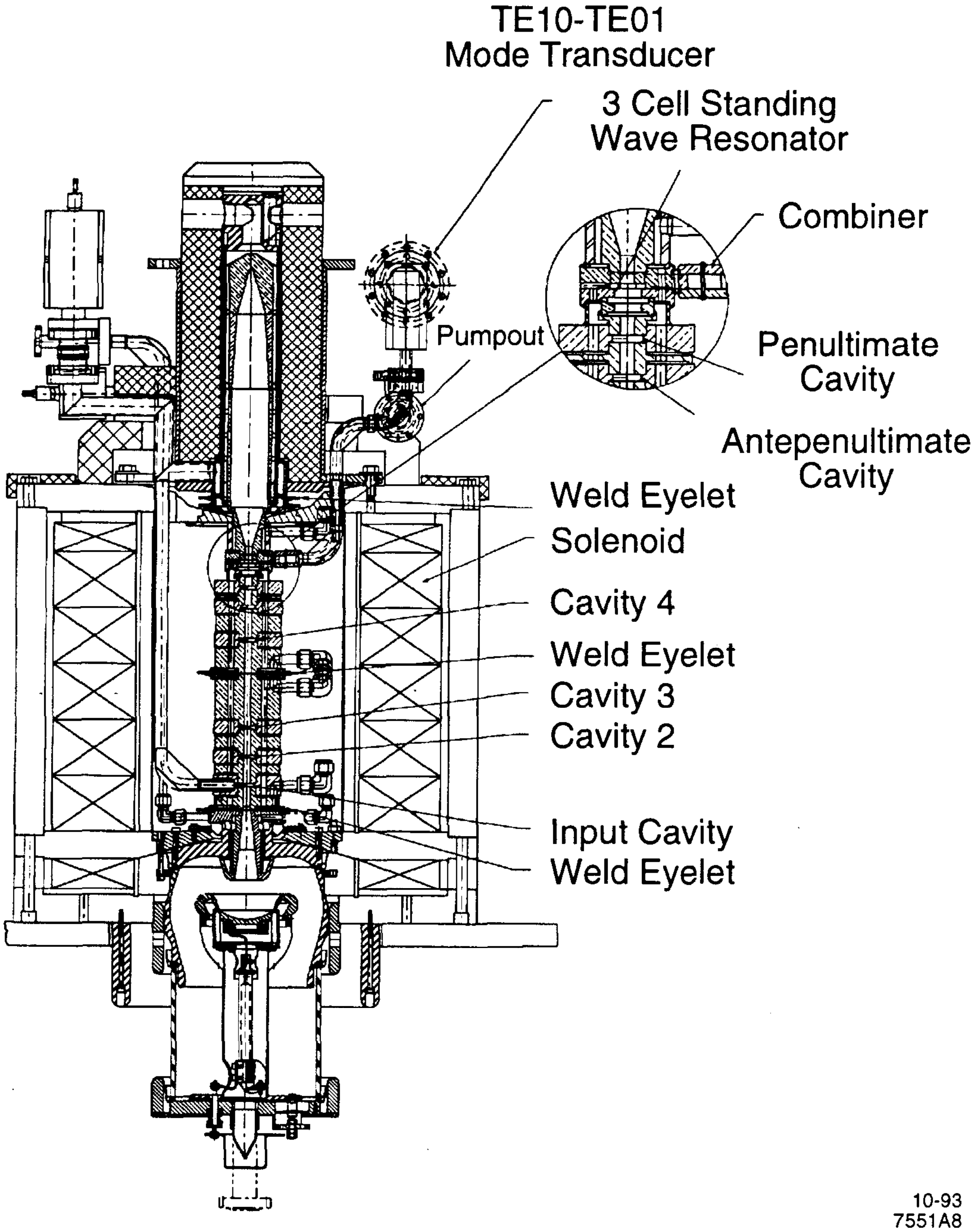
Fig. 11



I_{beam}
$I_{collector}$
1 μs
Beam voltage
= 415 kV
317 A
I_{body}
1.28 A
19.6 A
19.6 A

10–93
7551A7

Fig. 12



10-93
7551A8

Fig. 13

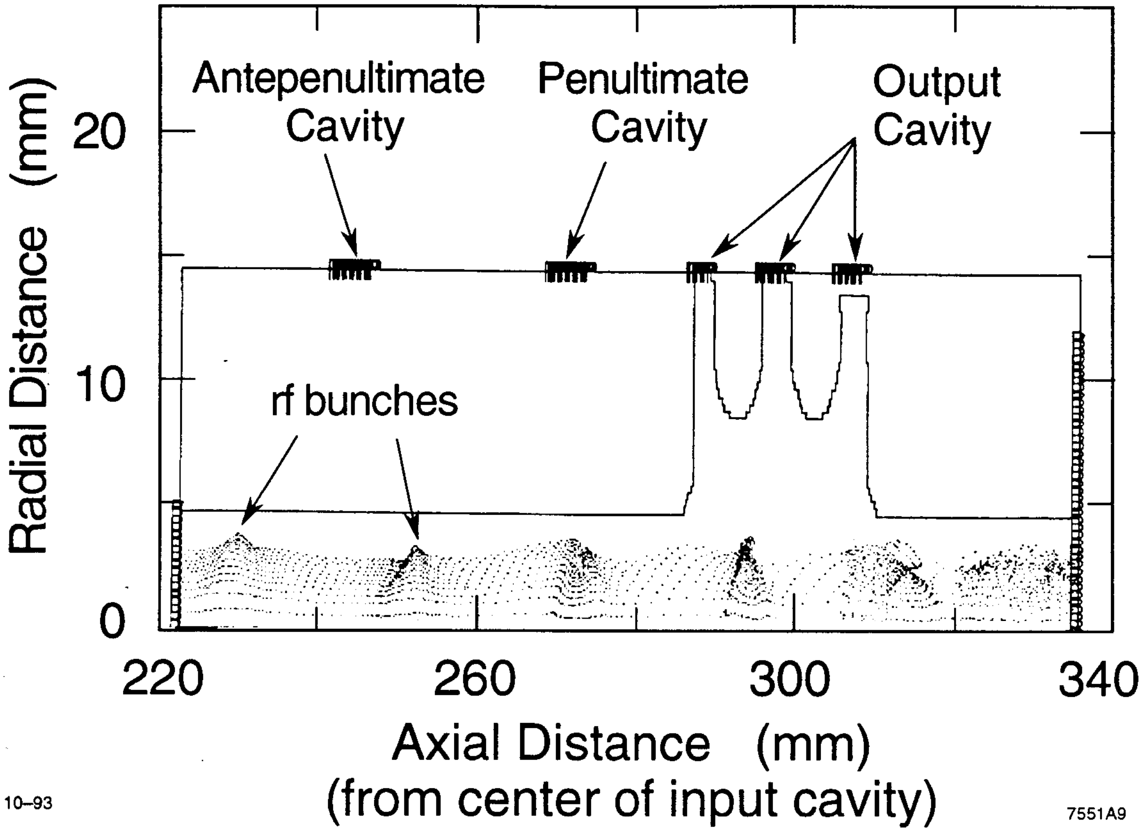
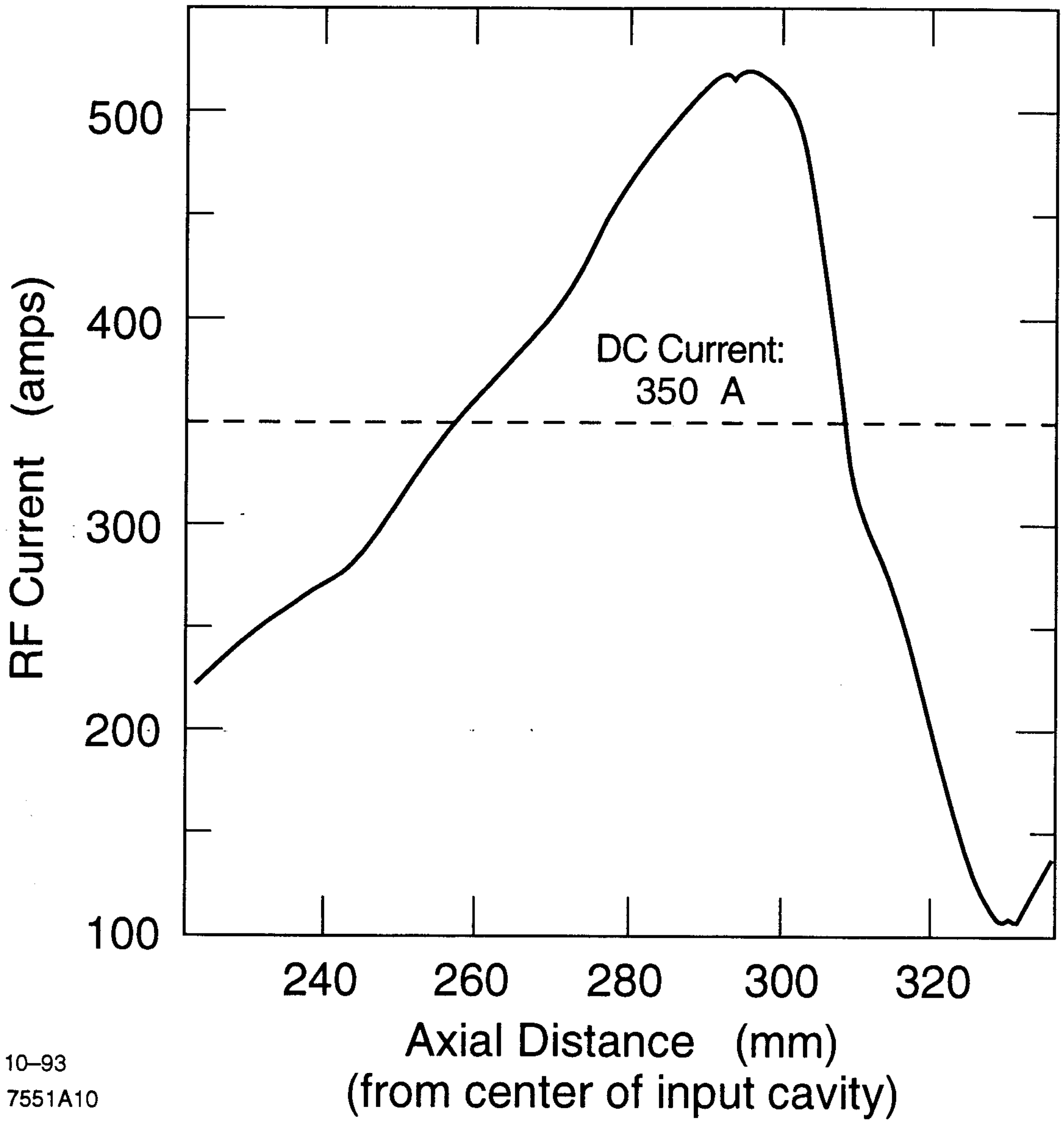

Antepenultimate Cavity
Penultimate Cavity
Output Cavity
rf bunches
Radial Distance (mm)
0
10
20
220
260
300
340
Axial Distance (mm)
(from center of input cavity)
10–93
7551A9

Fig. 14



RF Current (amps)
500
400
300
200
100
DC Current:
350 A
240
260
280
300
320
Axial Distance (mm)
(from center of input cavity)
10–93
7551A10

Fig. 15