DEVELOPMENT OF A LINEAR ELECTRON ACCELERATOR FOR MEDICAL AND RADIOGRAPHICAL PURPOSES

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CONTRACT Nonr 225(06)
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M.L. Report No. 518
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W. W. Hansen Laboratories of Physics
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SUMMARY

A sealed-off linear electron accelerator for medical use has been developed, and its operation for routine cancer therapy has proved very satisfactory. The construction of more compact accelerators operating at shorter wavelengths has been shown to be feasible. The major cost of such accelerators is in the rf power supply and the mechanical mounting, and it is in these components that further development is required if the overall cost is to be significantly reduced. This final report summarizes the individual aspects of the contract research, and also contains a list of the Technical Reports that have been issued. A reprint of a summary paper on "The Stanford Medical Linear Accelerator," not previously issued, is also included.

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FINAL REPORT
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I. INTRODUCTION

This is the Final Report on Contract Nonr 225(06), "Development of a linear electron accelerator for medical and radiographical purposes," which began on March 1, 1952 and ended on May 31, 1958. Much of the research under this contract has been reported in detail in the Technical Reports which have been issued and in two papers which have been published. These are listed in Section VI of this report. Appendix A of this report is a reprint of the paper by Ginzton, Kaplan and Mallory, "The Stanford Medical Linear Accelerator, I. Design and Development," which has not been previously issued as a Technical Report. This Final Report, then, summarizes the various aspects of the contract work, with particular attention to those subjects which have not been covered by Technical Reports. The senior scientific personnel who have been active in the research work under this contract are E. L. Ginzton, M. Chodorow, K. B. Mallory, E. L. Chu, and A. L. Eldridge,* of the Microwave Laboratory.

The purpose of the contract was to study problems essential to the development of the linear electron accelerator as an inexpensive and reliable source of penetrating X-rays for medical and radiographical uses. Specific problems to be studied were (1) sealing off the accelerator waveguide; (2) increasing the electron beam intensity; (3) efficient low-voltage electron injection systems; (4) compact design; (5) beam focusing; (6) radiation shielding. Major achievement was accomplished on items 1, 3, 4 and 5. At the present state of its development the linear accelerator is still not very inexpensive, but may be considered a reliable device.

The work can be conveniently divided into four parts: (a) development of fabrication techniques; (b) development of an electron gun; (c) investigation of the feasibility of scaling an accelerator design to a different operating wavelength; and (d) development of a practical accelerator for medical use.

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Fabrication techniques

A fabrication technique was developed which satisfies the very close dimensional tolerances required in a linear accelerator waveguide and which allows sealing off the accelerator so that no vacuum pumps are needed in any part of the accelerator system. The required disk-loaded structure is constructed by electroforming a copper cylinder on a mandrel consisting of a multi-layer "sandwich" of copper loading disks and aluminum spacers. After electroforming, the aluminum spacers are etched away, leaving a vacuum-tight envelope with the desired internal geometry. A vacuum-tight joint for connecting various parts of the accelerator using a gold-diffusion process was also developed.

Electron gun

An electron gun was developed which provides a well-focused electron beam at high intensity and at the proper voltage for injection to the accelerator. Provision is made for separate control of injection current and voltage. The gun is compact and allows replacement of the cathode; the cathode itself has a long life.

Choice of operating wavelength

A study was made of the effect of the choice of operating wavelength on the various performance characteristics of an accelerator. An accelerator waveguide operating at 3.2 cm wavelength was built and its performance compared with the performance of other accelerators operating at 10.5 cm. It appears that the fabrication problems for such a smaller pipe are easily solved and that its performance is in substantial agreement with theory.

Development of medical accelerator

In cooperation with the American Cancer Society and the United States Public Health Service, a 6 Mev accelerator was developed, constructed and installed at the Stanford Hospital in San Francisco. It has been in operation for two years with no significant interruptions of its treatment schedule. It is, therefore, a reliable machine. There are no other directly equivalent supervoltage X-ray machines;

it is difficult to make a comparison of its cost with that of other supervoltage machines.

II. FABRICATION TECHNIQUES FOR A SEALED-OFF LINEAR ACCELERATOR

Electroforming

A linear accelerator waveguide consists of a disk-loaded cylinder such as that shown in Fig. 1, which must be fabricated to very close dimensional tolerances. Typical dimensions are indicated in the figure. Although electroforming had already been used as a technique to allow complicated or precise machine-work on the inside of a part to be replaced by machine-work on the outside of a mandrel, standard commercial processes were not suitable for the production of a vacuum-tight envelope.

Two technical reports have been issued which describe the electroforming procedures developed at Stanford for fabrication of vacuum tube parts in general and accelerators in particular. One describes the first technique successfully used to electroform accelerator structures and discusses some of the physical properties of the deposited material.[1] The second describes later developments and current procedures.[2]

Basically, the procedure involves the deposition of a thick copper wall over a cylindrical mandrel. This mandrel, in turn, is a "sandwich" of alternating machined copper loading disks and aluminum spacers. The spacers are machined to the precise dimensions required for the cavity between adjacent disks. After electroforming, the aluminum spacers are etched away, leaving a structure such as is shown in Appendix A, Fig. 6.

The original procedure required plating a thin layer of silver on the Al-Cu sandwich, followed by the copper. Difficulty was experienced with blisters forming between the aluminum and the layer of silver and with poor adherence between the silver and the copper disks. The silver had been used to insure that any cracks between the disks and spacers would be filled. It was found that copper would also fill such cracks if a low enough current were used. But copper plated

[1]For references, see list of contract reports, Section VI below.

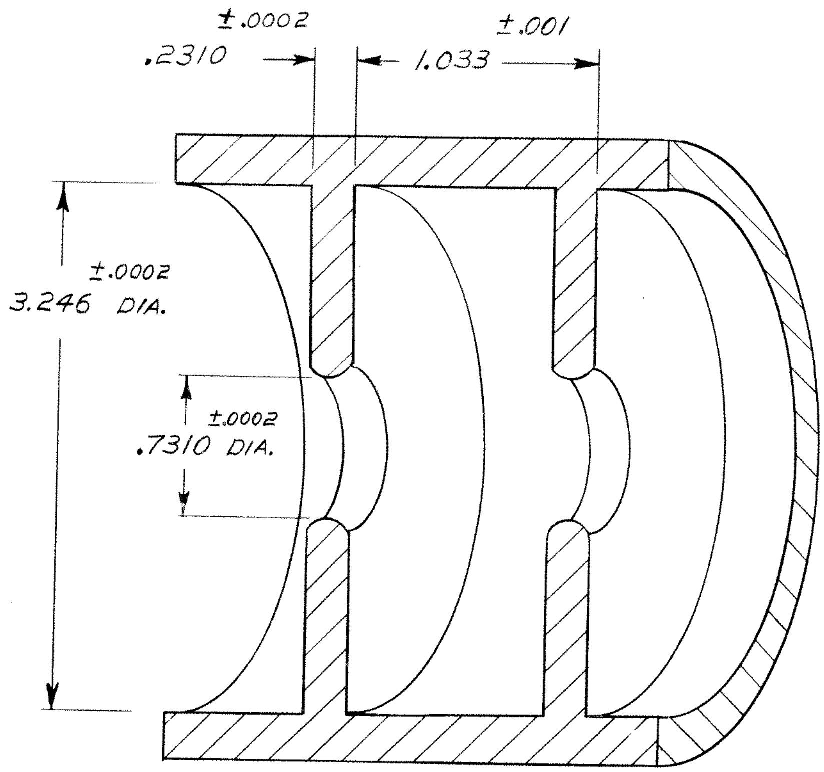

FIG. 1--Section through S-band linear accelerator structure.

out of an acid solution onto an assembly containing aluminum and copper parts would not adhere to the copper. The disks would therefore be loose inside the finished cylinder.

Reference 2 discusses two ways to solve the problem: (1) to pre-plate the outer rim of the spacers with a thin copper layer so that the mandrel assembly presents only a copper surface to the final electroforming bath, and (2) to start the electroforming procedure directly on the Al-Cu sandwich, but in an alkaline bath. Both methods have proved feasible. The latter procedure requires somewhat more investment in plating equipment but considerably less handling of the spacers, and is thus probably saving on total cost.

A test was run on the effect of plating speed on the smoothness of the final surface. Keeping other factors constant, it was found that below some rather definite current a reasonably smooth surface is formed. Above this current large single crystals start growing. The base of such a crystal is surrounded by many large voids, making a weak and porous structure. Using a standard bath and tank at Stanford, 5 to 10 amperes per square foot of anode produced a surface considered satisfactory; 15 amperes per square foot produced oversize single crystals. Increased agitation of the solution increases the allowable current slightly, but the best agitation available was of little use when the current was higher than 50 amps per square foot.

Solutions with additives were not considered, since the final product must be suitable for use in high-vacuum systems and for hydrogen furnace brazing operations.

Gold-diffusion joint

An adaptation of the gold-diffusion joint (used, for example, for sealing magnetron cavities) was developed to join the accelerator waveguide to the rf input coupler and to the X-ray target. The method of making the joint between the rf input coupler and the accelerator waveguide is illustrated in Fig. 2. During the baking operation, which is a normal part of vacuum processing of the tube, gold from a foil placed between two mating parts diffuses into the adjacent copper surfaces, effecting a permanent bond. It was found that the

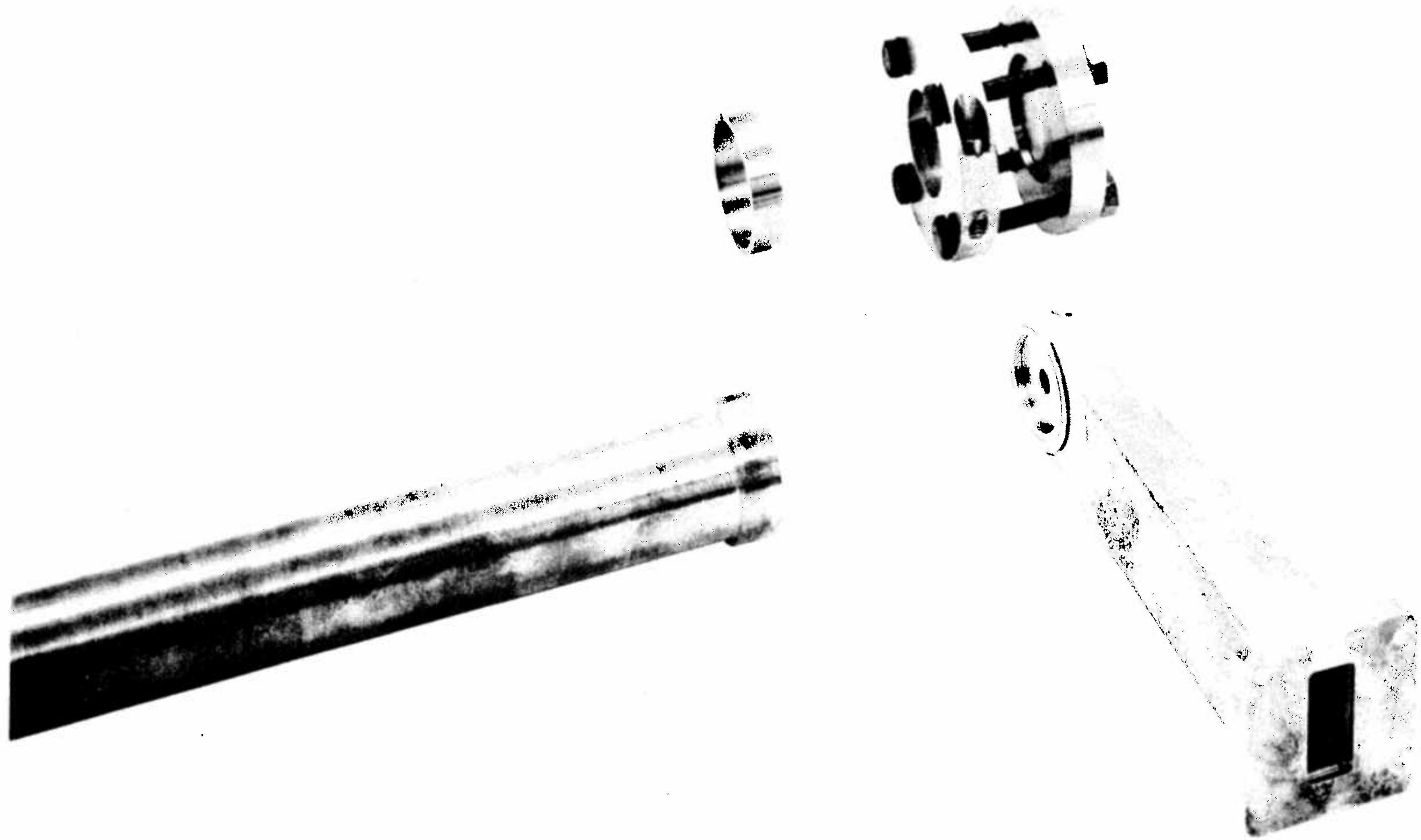

FIG. 2--Input coupler, accelerator, gold ring and clamps for gold-diffusion joint.

bond can loosen if the joint is baked again under stress. The joint must therefore be clamped to hold it tight during the baking operation each time the tube is reprocessed. In order to insure that the joint is vacuum tight, a steel ridge presses the gold foil into each copper surface. The steel may be one of the mating parts itself under an electroplated layer of copper, or it may be an auxilliary clamp, if one of the parts is thin.

III. THE ELECTRON GUN[3]

The major objective of the gun development program has been to develop a structure of medium-current capabilities ($\sim$ 200 ma peak) which would have a more or less indefinite life on both continuously pumped and sealed-off structures.

Description of gun

The present structure is a mechanical and electrical redesign of a gun employing a bombarded tantalum cathode, which was initially begun by a commercial subcontractor for the Stanford Hospital 6-Mev Medical Accelerator. As a result of the redesign the usable current has been doubled (over 200 ma peak current can now be obtained), and the rate of mechanical failures has been reduced by a factor of 5. A schematic diagram of this structure, approximately to scale, is shown in Appendix A, Fig. 9. A photograph of the completed structure and of a separate cathode assembly is shown in Appendix A, Fig. 10.

Because of previous unfortunate experience in the use of oxide cathodes for accelerators at Stanford (typical lifetimes for oxide-coated cathodes were anywhere from a few days to about two weeks), it was agreed at the outset of the program that the first cathodes developed should be of pure metal. One of the best metals for this purpose is tantalum. However, it must be heated to temperatures of the order of 2200°K in order to obtain a sufficiently large emission current (200 ma/cm^2). Inasmuch as indirect heating is not sufficient to reach such high temperatures, the tantalum cathode must be bombarded with energetic electrons. Unfortunately, this fact increases the complexity of both the gun and its modulator.

The design of the focusing and accelerating electrodes which follow the tantalum button depends upon the specific requirements of the linear accelerator to which the gun is to be attached. In particular, a very closely parallel beam of small cross-sectional area may be desired. This has been the case with most of the linear accelerators constructed to date, although there are obvious applications where a beam which fills the entire aperture of the accelerator is satisfactory and perhaps even desired. A parallel beam of electrons of small cross-sectional area appeared to be of more general value for the existing and proposed accelerators. The basic scheme is as follows. There are three essentially separate structures: (1) the bombarder, consisting of the spiral tungsten filament and the back surface of the tantalum button; (2) a "Pierce" gun structure consisting of the tantalum button, the focusing electrodes surrounding the button, and the first anode, which has an aperture of 0.186-in. diameter through which the beam passes to (3) the acceleration region which increases the energy of the beam to the desired injection voltage of the accelerator (a maximum voltage of 100 kv is allowed for the present structure). The beam then passes into the linear accelerator through a 1/4-in. aperture in the second anode.

The question may arise as to the utility of the first anode; that is, why not accelerate directly to the desired injection voltage? The principal disadvantages to single-stage guns are their inability to maintain a constant-diameter beam independent of beam current, and the difficulty of obtaining a parallel or nearly parallel beam at the moment of injection into the accelerator. They also may demand that the pulse shape of the injection voltage have short rise and decay times in addition to being relatively flat on top. In a "two-stage" structure, of the type shown in Fig. 9 of Appendix A, the parallelness of the beam is almost independent of beam current, as is the beam diameter; and the shape of the current pulse is determined almost entirely by the pulse applied to the first anode, which is of the order of a few kilovolts and hence easier to control. The voltage pulse applied to the second anode must still have a flat top in order to maintain a constant injection voltage, but the rise and decay times as well as the pulse length are now no longer important. This fact greatly simplifies the requirements imposed upon the 100-kv modulator system. Thus, it is apparent that a two-stage gun can provide a beam of electrons which is parallel and of constant cross-section and in addition is well defined in time.

Performance data of the medium-current gun

Although all of the gun structures have been tested in a beam tester which measures the transmission properties of the gun and the parallelness of the beam, the ultimate test of the gun is its behavior on an actual accelerator. Various versions of the present structure have now been used on all of the Stanford machines. Typical data obtained from the first medical accelerator, which had a buncher designed to capture one-half of the injected electrons, were as follows: With an injected current of approximately 60 μa (140 ma peak) at 480 pps, over 16 μa (37 ma peak) of current has reached the end of the accelerator, producing around 70 to 100 roentgens/min. of high-energy X-rays. The gun optics have recently been further improved, so that up to 50-percent better transmission has been observed on the beam tester; the same 16 μa output current can now be obtained from the medical accelerator with 50 μa injected current. Significant measurements were also made on the Mark IV accelerator, which is a continuously pumped machine and hence is more flexible for making experiments. This machine did not have a buncher section. Even so, before the recent improvement in optics, up to 2 μa (one-fifth of the injected current) had been captured and accelerated to the full energy of the machine. With 1 μsec and 60 pps, this corresponds to a peak injection current of ~175 ma and a captured and accelerated peak current of greater than 35 ma. This result is a factor of 10 better than is presently achieved by a tungsten spiral single-stage gun on the Mark II (40 Mev) machine.

To obtain an idea of the focusing properties of this gun, the current transmitted through the first 12 ft of the Mark IV accelerator with and without a 1/8-in. diameter collimator after acceleration has been observed. The ratio of currents was approximately 6:1, indicating that the effective diameter of the beam at the end of 12 ft of acceleration is ~0.31 in.

IV. MEDICAL ACCELERATOR

The 6-Mev Stanford Medical Accelerator at the Stanford Hospital is described in Appendix A. That accelerator is a direct result of the research under this contract. A further result of this work is in a similar installation using the same accelerator waveguide at the General Electric X-ray Division in Milwaukee, and in an accelerator now being constructed at Pacific Union College in Angwin, California. A short prototype section, consisting of the buncher alone, is now in England for use by Dr. H. Motz in submillimeter-wave research, a continuation of work he started at Stanford with the same prototype.

V. SCALING

Design study

Up to the present time almost all linear electron accelerators built in this country and abroad have been operated at a wavelength of approximately 10 cm. This seemed to be a natural choice because of various practical matters such as available rf power tubes, working tolerances, physical size, etc. However, with other large power tubes and better construction techniques becoming available it became important to make a careful study of the choice of operating wavelength.[4] Only one type of accelerator structure, the disk-loaded waveguide, was considered, but the principles derived are applicable to other structures as well.

It was shown that the optimum design of a linear electron accelerator varies with the type of radiation required for its application (the electron beam or X-rays, or both) and depends on many factors such as the amount of available power, type of rf feed, the desired electron energy, the limiting size and weight of the accelerator, etc. The method of scaling the physical dimensions of the accelerator waveguide according to wavelength depends upon these factors. Shorter wavelengths are desirable for low- and medium-energy accelerators because of the greater shunt impedance, smaller physical size and better economy. Longer wavelengths are preferable for high-energy accelerators because the amount of available power per feed increases with wavelength by a factor F where $\lambda < F < \lambda^2$.

X-band accelerator

Although an accelerator with short operating wavelength is attractive from the viewpoint of size and economy, there remains the question of approximately how far the wavelength can be reduced. The availability of a source of rf power is one of the major considerations. Since a one-megawatt X-band klystron had been developed at Stanford, an X-band accelerator was constructed for the following purposes: (1) to demonstrate the feasibility of building and operating an accelerator with an operating wavelength of about 3 cm, (2) to verify the predictions of theory for the performance of accelerators at wavelengths other than 10 cm and (3) to provide a compact accelerator for physics research in the Microwave Laboratory. The auxiliary equipment for this accelerator was built under another contract, DA 36-039 SC-72785, which required such an accelerator as a tool for generation of submillimeter waves.

Description of accelerator

The accelerator waveguide is a scaled-down model of a section of the Stanford Mark III accelerator, with a modified buncher. With a view to simplifying the construction of the buncher, it was designed to use disks with a constant central hole size. This greatly restricts the choice of the remaining parameters of the buncher; nevertheless it is possible to design a buncher which should accept one-third of the total injected current and compress it to bunches 1/12 wavelength long. The buncher and accelerator were fabricated in one piece by an electroforming technique similar to that used for the sealed-off 6-Mev S-band accelerator. The coupler was joined to the accelerator by a gold-diffusion joint; the same gun is used for the X-band accelerator as for the S-band accelerators.

The rf power is supplied by an X-band klystron amplifier which, in turn, is driven by a magnetron oscillator. Although the klystron is capable of operating at a high duty cycle, a low-average-power modulator was considered entirely adequate for operational tests. A photograph of the X-band accelerator with water jacket, the input coupler, and electron gun is shown in Fig. 3. Figure 4 shows a comparison of the S-band accelerator section and the smaller X-band Section.

FIG. 3--X-band accelerator in water jacket, with input coupler and electron gun.

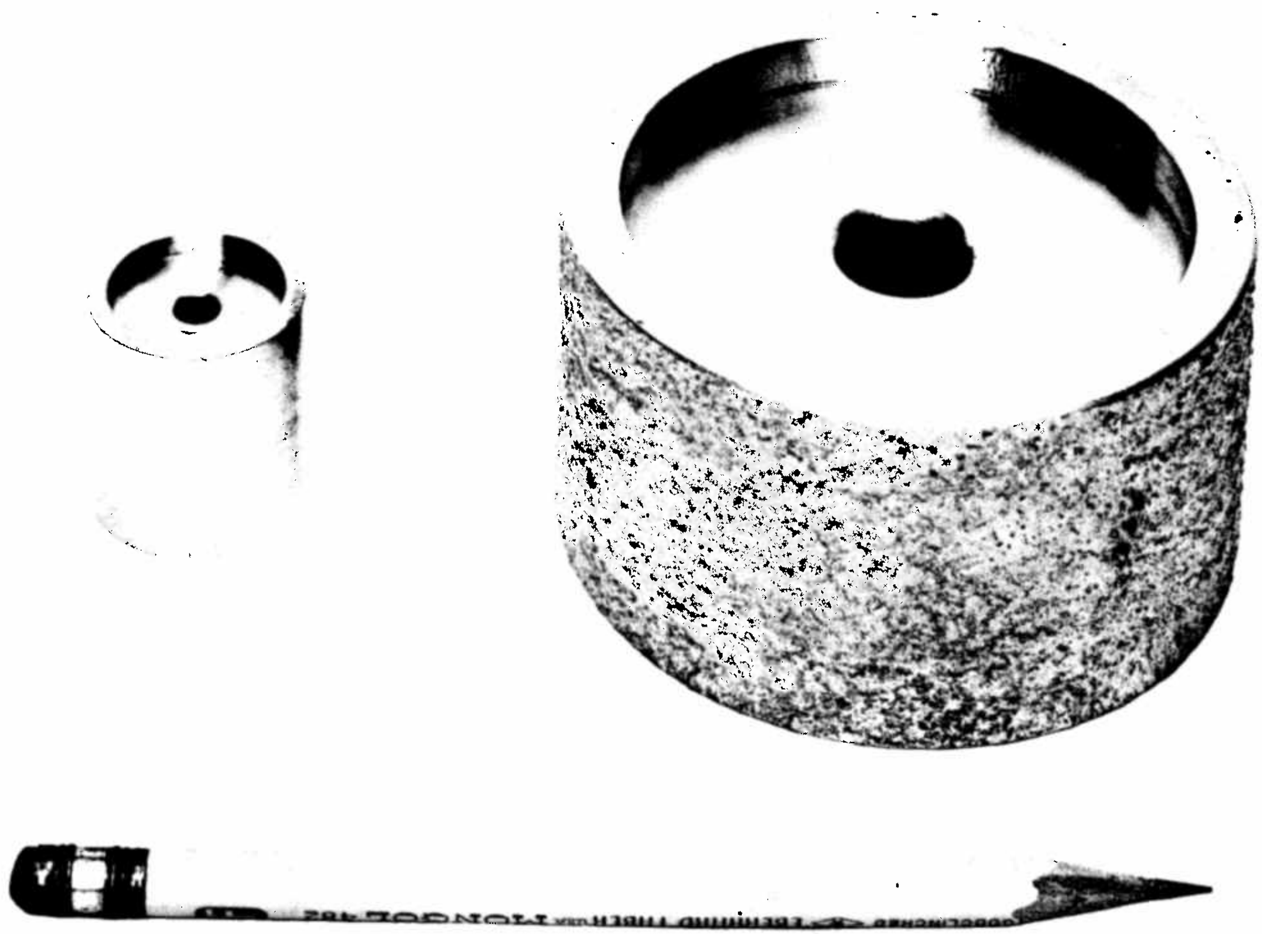

FIG. 4—Sections of the electroformed S-band accelerator waveguide and the smaller X-band waveguide.

Expected performance

The expected performance of the accelerator was discussed in some detail in the Status Report for the contract covering the first two quarters of 1957. It was found that the attenuation in the accelerator waveguide is 0.17 db/cm. In the Mark III accelerator, the attenuation is 0.024 db/cm. Since the one is a scaled-down model of the other, and since attenuation scales as $\lambda^{3/2}$, the predicted attenuation is 0.14 db/cm. The discrepancy is largely explained by a consideration of the relatively loose tolerances (0.0005 in.) allowed in building the X-band accelerator. A tolerance requirement of 0.0002 in. would have made the predicted and measured attenuation agree better. The energy loss caused by this additional attenuation is 8 per cent. The rf input coupler has a bad solder joint which is very loose. Approximately 30 per cent of the rf input power is lost in this cavity and is not available for accelerating electrons.

By simple scaling, the energy output of an accelerator of "optimum design" is given by the formula $V = (rP_0L)^{1/2} = A\,P_0^{1/2}\,L^{1/2}\,\lambda^{-1/4}$, where A is a constant depending on the type of waveguide (disk-loaded, dielectric-loaded) and on its materials. For the Stanford Mark III accelerator, V = 30 million volts for 10 Mw power input, 10 ft length, and 10.5 cm wavelength. For the X-band accelerator, then, with a nominal 1 Mw power input, 2 ft length and 3.2 cm wavelength, the expected energy would be 5.7 Mev.

But in the buncher (the first five inches of the accelerator) the electrons are not riding on the crest of the rf input wave, nor, indeed, is the field strength so high in the buncher as is assumed in the above computation. The prediction of 5.7 Mev output assumes that the electrons gain 1.6 Mev in the first five inches. It has been computed that the electrons actually would gain only 700 kv in the buncher. The output should therefore be about 4.8 Mev with one Mw of the rf power input. The anomalous attenuation described above and the loss in the rf coupler further reduce the predicted energy to 3.7 Mev for 1 Mw.

Operational results

The accelerator operates very dependably for moderate power inputs. At higher power (over 500 kw peak), the pressurized waveguide between the klystron and the accelerator breaks down and the vacuum windows are threatened. Since the output energy varies as the square root of the input power, the predicted energy is $3.7 \times \sqrt{340/1000} = 2.2$ Mev, in agreement with the observed results. The probable error in this comparison is about 10 per cent. The energy spread is about 4 per cent, which suggests that the bunches are about 35° wide, in reasonable agreement with predictions.

The beam transmission is about 10 per cent. This is accompanied by a large amount of soft X-radiation from the walls of the accelerator, indicating that the beam is not well focused and a significant fraction is being lost to the walls. No check of the acceptance angle of the buncher has been possible.

VI. REPORTS AND PAPERS

The following is a list of Technical Reports and journal papers prepared under Contract Nonr 225(06). Superscript references throughout the text refer to this list.

1. "Electroforming of copper for high-vacuum applications," by L. H. LaForge, Jr., Microwave Laboratory Report No. 255, February, 1955.

2. "Electroforming of linear accelerator structures," by J. A. Pope, Microwave Laboratory Report No. 398, June, 1957. Also, Plating, 44:1291, December, 1957.

3. The description of the electron gun is an abridgment of an Internal Memorandum, "Report on the development of an electron gun for linear accelerators," by K. L. Brown, Microwave Laboratory Report No. 300, March, 1956.

4. "Choice of wavelength and characteristic parameters in the design of linear electron accelerators," by E. L. Chu and E. L. Ginzton, Microwave Laboratory Report No. 274, September, 1955.

VII. STUDENT PARTICIPATION

During the course of this contract seven graduate students, in Physics or Electrical Engineering, have participated in the work. One of these, Roderic E. Steele, has been awarded the Ph.D. in Electrical Engineering as a result of work directly associated with the contract. His Ph.D. dissertation was on "4 Mevp X-ray dosimetry."

APPENDIX A

A reprint of the paper, "The Stanford medical linear accelerator, I. Design and development," by Edward L. Ginzton, Kenneth B. Mallory and Henry S. Kaplan, Stanford Medical Bulletin, 15:123-140, August, 1957, follows.