SLAC-PUB-915
(ACC)
May 1971

FABRICATION OF A SUPERCONDUCTING LINEAR ACCELERATOR BY ELECTRON BEAM WELDING*

A. E. Johnston, R. R. Cochran, W. B. Herrmannsfeldt, and G. P. Fritzke
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The electron beam welding of columbium (niobium) is being studied as part of a program to convert the Stanford Linear Accelerator to a superconducting accelerator fabricated from niobium. This paper describes the construction and operation of a welder to provide test parts for this program.

The Stanford Linear Accelerator Center has as its principal instrument a two-mile long linear electron accelerator. This machine is capable of accelerating electrons to an energy above 2×10^{10} electron-volts. The maximum beam power is over 600 kW. The chief limitations of this instrument are the maximum energy and the low duty cycle of only about 1 part in 2000. The long term productivity of the laboratory would be greatly enhanced if both the energy and the duty cycle could be increased. Accordingly, a study program[1] is under way with the goal of converting the accelerator to a superconducting accelerator capable of achieving energies of about 10^{11} electron-volts while also achieving substantial improvement in the duty cycle.

High energy accelerator design and construction has throughout the world advanced to a point at which further significant gains in operating parameters must use "new technology" or be prohibitively expensive. Thus the two newest accelerators to be approved, the NAL 200-500 GeV proton synchrotron[2] and the CERN 300 GeV proton synchrotron,[3] both project further increases in energy as

---

*Work supported by the U. S. Atomic Energy Commission.

(Presented at the Eleventh Symposium on Electron, Ion, and Laser Beam Technology, University of Colorado, Boulder, Colorado, May 12-14, 1971)

coming from "new technology", namely the construction of superconducting magnets.

In the case of linear accelerator design, the "new technology" also involves the phenomenon of superconductivity, but in an entirely different way. A linear accelerator consists of an accelerating structure which is excited with radiofrequency power to create electric fields on which charged particles can be accelerated. In a conventional accelerator, this structure is generally fabricated from copper to get good efficiency, i.e., perhaps 10 percent of the rf power can be converted to beam power. Substantial improvements in efficiency depend on reducing the resistive losses in the structure itself. Unlike the case of dc resistivity which goes to zero at superconducting temperatures, the rf resistance remains finite although it does decrease somewhat as a function of temperature. Of the metals which exhibit superconducting properties only two, lead and niobium, have been found to have improvement factors large enough to be considered seriously for this application. The improvement factor, defined as the ratio of room temperature copper resistivity to the resistivity of the superconducting material, much be of the order of 10^6 to make it possible to reach significantly higher fields and still keep the losses low enough to make the refrigeration system economically feasible. The poor structural properties of lead and its tendency to be easily oxidized leave niobium as the best known material for a superconducting accelerator structure.

All the successful laboratory tests indicate that the accelerating structure surface must be very smooth and very clean to achieve the required improvement factors. At present, the process used to achieve these surface properties involves chemical etching and vacuum firing the parts at about 1900°C. Needless to say, the niobium itself must be very pure.

In addition to surface properties, the structure must be dimensionally accurate and stable. The welds must have the same properties as the rest of the surface and must be such that dimensional changes (if any) produced by the weld are consistent from weld to weld. Since the structure operates immersed in superfluid liquid helium, all joints must be absolutely tight.

In order to prevent contamination of the pure niobium by the welding process, it was decided that the welding chamber and vacuum system would be designed to operate at a pressure of about 10^{-6} Torr. In addition, cryopanels, which are copper shields, cooled by liquid nitrogen, would be used in the vicinity of critical joints to further reduce the possibility of contamination. These panels are designed for each critical set up. When used, they lower the pressure locally (and often in the whole chamber) by at least one order of magnitude.

Before describing the welding fixtures, procedures, and parameters, a brief description of the welder and weld chamber is in order.

The electron gun and optical assembly plus all the electronics are parts from a salvaged 25 kW Hamilton-Standard welder. The welder is shown in Fig. 1. The vacuum chamber, which was designed and fabricated at SLAC, is 60 inches wide, 64 inches high and 108 inches long. The full size doors at either end can be removed to add chamber sections if additional length is required. The chamber walls are bare carbon steel. Some concern had been expressed about wall contamination or rust. However, after seven months of operation, there is no sign of rust, and the vacuums achieved speak for themselves.

The chamber design generally follows that of an equivalent Hamilton-Standard chamber. The principal differences, aside from the vacuum system, are in the frame and some of the details. Square and rectangular tubing was used to reinforce the walls and simultaneously support the chamber and the diffusion pumps. Instead of laminating the leaded X-ray glass for the windows, a 3/4 inch thick piece of plate glass was used to take the vacuum load and to make the seal. The lead glass was then placed over the window out of the vacuum. This reduces the cost of the window and allows easy removal of X-ray glass for annealing out radiation browning.

The vacuum system consists of two CVC 20 inch diffusion pumps with refrigerated cold caps, backed up with two 50 cfm mechanical pumps. A 300 cfm Stokes Microvac mechanical pump is provided for roughing the chamber and for additional backing for the diffusion pumps. The pumps are isolated from the chamber by 20" vacuum valves. For most welds (without cryopanels), this system pumps the chamber down to 10^{-6} Torr in about 30 minutes. During one typical pump down, the chamber base pressure was 5×10^{-7} Torr and after cooling down the cryopanels, the pressure was 6×10^{-8} Torr. Cooling down and warming up the cryopanels usually takes longer than pumping down and letting up the chamber vacuum.

Parts are positioned by an X-Y table of 1200 lbs capacity. The table drive is mounted under the operator's platform and coupled to the vacuum feed-thru shafts by elastomeric couplings. These couplings have effectively isolated drive vibration from the welding chamber. The X-Y table can be run out on tracks to facilitate making setups outside the chamber. Entrance to the chamber is from a pressure and humidity controlled enclosure which helps keep gross contamination under control.

Rotary welds are made on a powered spindle similar to that on a Hardinge lathe so that Hardinge collets and chucks may be used directly. The spindle housing is provided with tapped holes to facilitate adding a tail stock or other special fixture as required. The dc drive motor is sealed in a vacuum tight housing and drives the spindle or other fixture by roller chain and sprockets. The rotary fixture is shown on the X-Y Table in Fig. 2.

Figure 3 shows the design of a short test accelerator structure called Leapfrog. It is a traveling wave structure which means, from a practical point of view, that it has a return path for the rf power. This is in the form of rectangular waveguide. The latter provides a location for various tuning and monitoring devices as well as a place for a power input. The return loop is attached to the accelerating structure through special "coupler" cavities at each end. Each cavity must be welded at the inner and outer diameters. A typical cavity is shown in Fig. 5.

The cavities are cold formed in the shape of cups or, in special cases, by machining out of solid bar stock. Referring to Fig. 3, one can see that the accelerator structure is not circularly symmetrical. The structure is welded in a specially designed and fabricated rotary fixture which can be split apart down the center after the ends are welded on. Figure 2 also shows this fixture.

The rectangular waveguide, which has many joints, is welded in a fixture which can be rotated so that successive welds can be done around a joint without opening the chamber. See Fig. 4. Rotation is achieved by pushing a plunger against the chamber wall with the X-Y table. The plunger in turn pushes an arm which is connected to a shaft through a one-way roller clutch. Detents are provided every 90° and a pointer tells the operator when he is near a detent. This fixture saves at least 3 out of 4 possible pumpdowns. It is also possible to have both the rectangular waveguide and the cavity welds done during the same pumpdown, saving considerable time.

Welding Experience

Due to the requirements on surface quality outlined earlier, it was decided to weld all cavity joints both on the inside and outside. The inside weld is to be as smooth as possible, with no regard to strength. This is called a cosmetic weld. It also serves the purpose of preventing spatter on the inside of the cavity from an external weld. Outside welds are usually done at higher power to develop strength in the joints.

Typically, cosmetic welds are done at about 2 i.p.s., 120 kV and a beam current of 6 mA with about 15% defocus. The latter parameter is at present set by focusing to the smallest beam spot visually, then changing the focus controls by a predetermined amount. Eventually, it is planned to mount a flying wire scanner on a small elevator which will provide a more accurate and convenient way of measuring and setting beam focus. A circle generator is often used which sweeps the beam in a circle up to .060 inches in diameter or an ellipse as narrow as .010 inches by .125 inches. Strength welds are typically made at 120 kV, 8 mA, a defocus of 5% and about 2 i.p.s. Needless to say, these are not the only parameters that are used and some of the others are noted on Figs. 6 through 10.

Although there is a flood lamp in each upper corner of the chamber and lamps associated with the operator's telescope, one of the biggest problems is in seeing the workpiece. Most of the round parts are so shiny that light and images bounce any way except up the telescope. So the operator sees either a glare or two or three joints instead of the one that is actually there. A quartz-halogen lamp mounted at the lower end of the rotary fixture provides good viewing of internal welds. However, no arrangement of lamps has been satisfactory for external welds. Rectangular and flat parts do not usually present a problem.

We have now successfully made several welds in test cavities. However, the weld joining the small diameters of the cups has not been optimized. The cosmetic weld at the tip is very weak and the strength weld from the outside shrinks, tending to pull the joint open at the tip and distort the cavity shape. A more detailed description of weld requirements and results is in the following section.

Weld Analysis

Numerous samples have been examined to determine the degree to which the various welding goals have been achieved. For discussion purposes, these goals are:

1. Smoothness of cosmetic welds.
2. The depth of penetration of the strength welds.
3. The effects of subsequent processing (usually a high-temperature vacuum anneal) on the weld.

1. Cosmetic welds. Since no quantitative information is available to act as a guide for the smoothness of a cosmetic weld, qualitative comparisons were the only kinds of comparisons that could be made. "Strength" welds are made from the outside and cosmetic welds are required only on the inside surfaces, but some depth of fusion must take place with cosmetic welds or else there will be insufficient molten metal to bridge over the small gap between two components. As examples, Fig. 6 illustrates three typical electron-beam seam welds and shows all of the features we look for in various welds. Figure 6a shows a good cosmetic weld with relatively smooth surface, little weld ripple and no undercutting or weld spatter. Figure 6b shows a strength weld where, when it becomes necessary to achieve deep fusion, a pronounced weld ripple and some slight undercutting can be seen. Figure 6c illustrates a "typical" EB weld in niobium and it contains all

of the features undesirable in a cosmetic weld. Note the regions where the "fit up" has not been bridged over. Parameters have now been established for all of these types of welds which are reproducible.

2. Depth of penetration. Usually, strength welds will be made first and, if the parts are not tightly clamped, these deeply-fused welds will cause the inside surfaces to gap open and produce difficult-to-make cosmetic welds. Also, when weld penetration is excessive, several undesirable features can result. One is the formation of cold shuts, usually associated with a too-sharply focussed beam. Figures 7 and 8 illustrate the appearances of typical cold shuts in two different planes. These cold shuts can trap acid and other impurities if an intermediate cleaning operation becomes necessary between the strength and cosmetic welds and these voids will not close up in the high-temperature vacuum firing. Also, over-penetration produces some "micro dingle berries" which are not detrimental to most welds, but will cause microwave perturbations if not removed during the cosmetic pass. Since cosmetic welds are of such low-energy and cannot be expected to remove the dingle berries, excessive penetration is considered to be highly undesirable.

3. Effects of vacuum annealing on welds. Our vacuum annealing conditions are at such high temperatures and for such times that huge grains grow after recrystallization which obliterates all trace of the original wrought grains. Enough impurities are mixed into the weld bead, however, so there remain some traces of the original weld beam configuration. (See Fig. 9.) There is no outer surface change, except perhaps for a slight smoothing action of the high spots of the ripples in the weld bead by sublimation. Figure 10 illustrates the fact that the original surface morphology (for instance, a weld bead) seems to be completely oblivious to the subsequent growth of new grains.

Another interesting factor for which we had great hopes was investigated with negative results. We had hoped that the unfused weld joint, from an underpenetrated strength weld, would diffuse together under the combined annealing conditions and shrinkage stresses in the weld. Stress relief in pure niobium probably takes place fast enough to prevent this factor from being operative at high temperatures for diffusion to take place. We have tried to vacuum anneal specimens immediately after welding to minimize surface contamination, but with no good results. Chemical cleaning is, of course, another approach, but we felt the high probability of surface contamination by the cleaning chemicals and the difficulty of removing chemicals from the capillary joint would prevent a good diffusion bond.

References

1. P. B. Wilson, R. B. Neal, G. A. Loew, H. A. Hogg, W. B. Herrmannsfeldt, R. H. Helm and M. A. Allen, "Superconducting accelerator research and development at SLAC," Particle Accelerators 1, 223 (1970).
2. Design Report, National Accelerator Laboratory, University Research Association (1968).
3. Edoardo Amaldi, "The 300 GeV accelerator in the European programme for high energy physics," Proceedings of the Sixth International Conference on High Energy Accelerators, CEAL-2000 (1967).

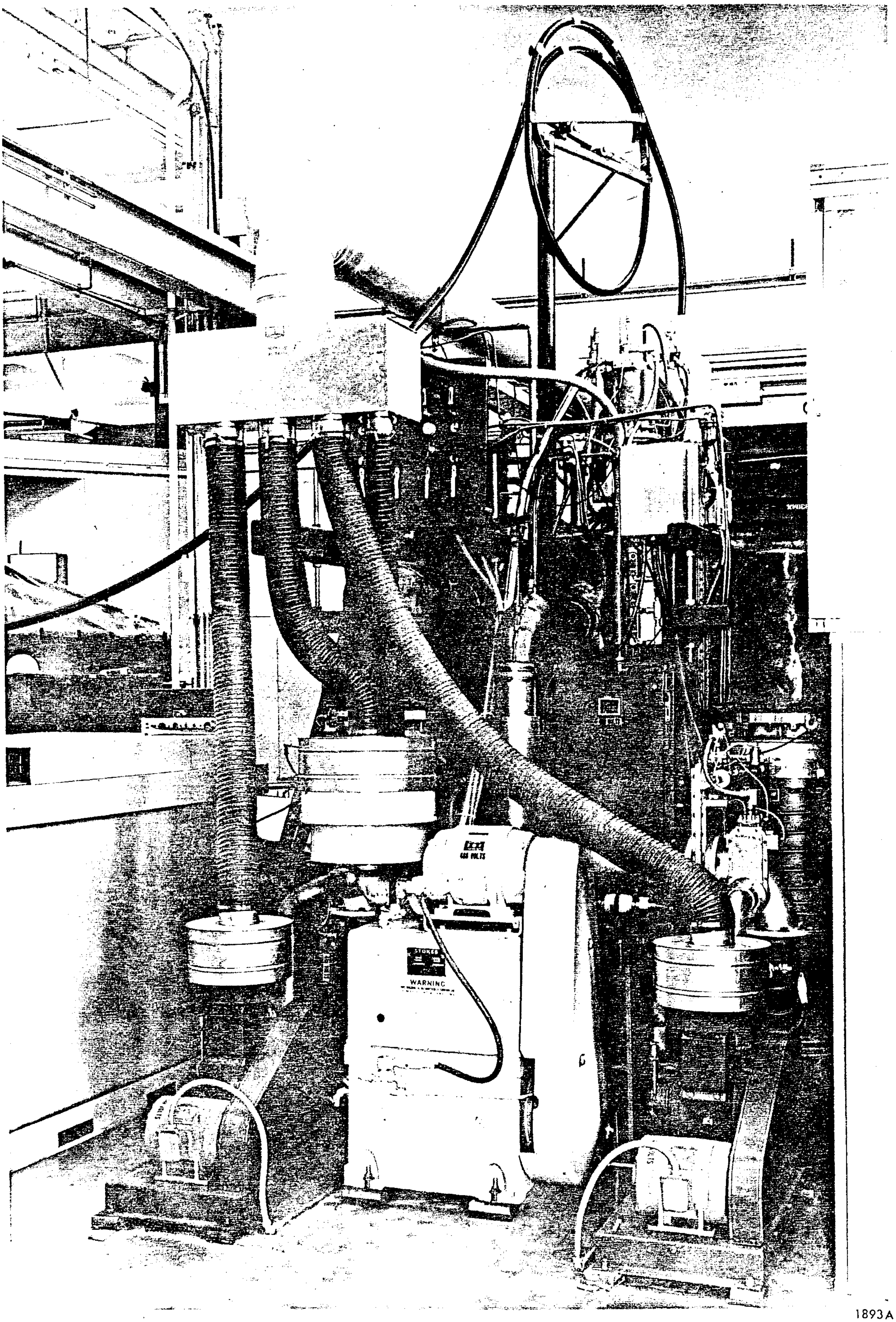


FIG. 1--Exterior of welder showing vacuum pumps and humidity controlled enclosure.

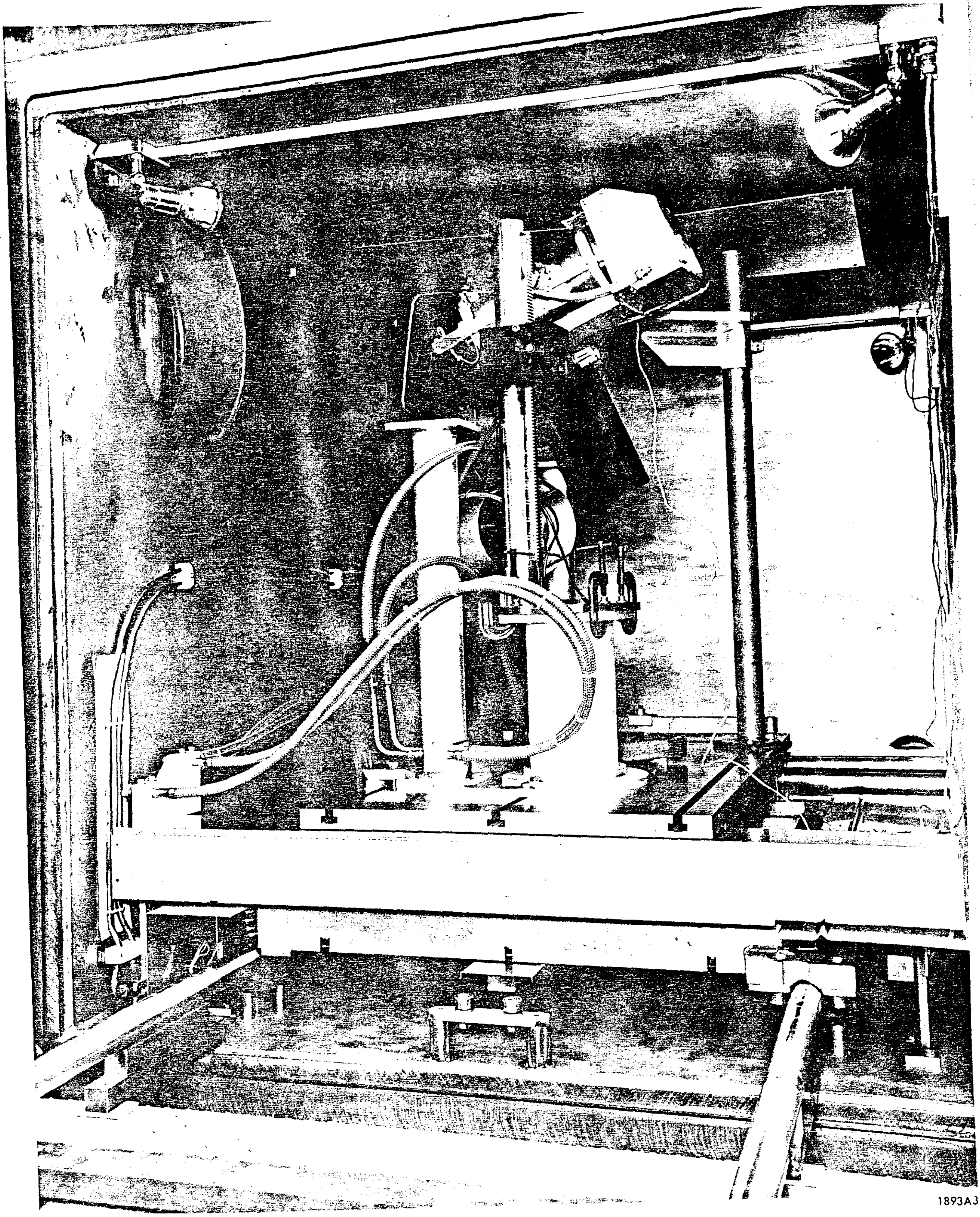


FIG. 2--Interior of weld chamber. Rotary fixture with cryopanel for welding accelerating structure mounted on X-Y table.

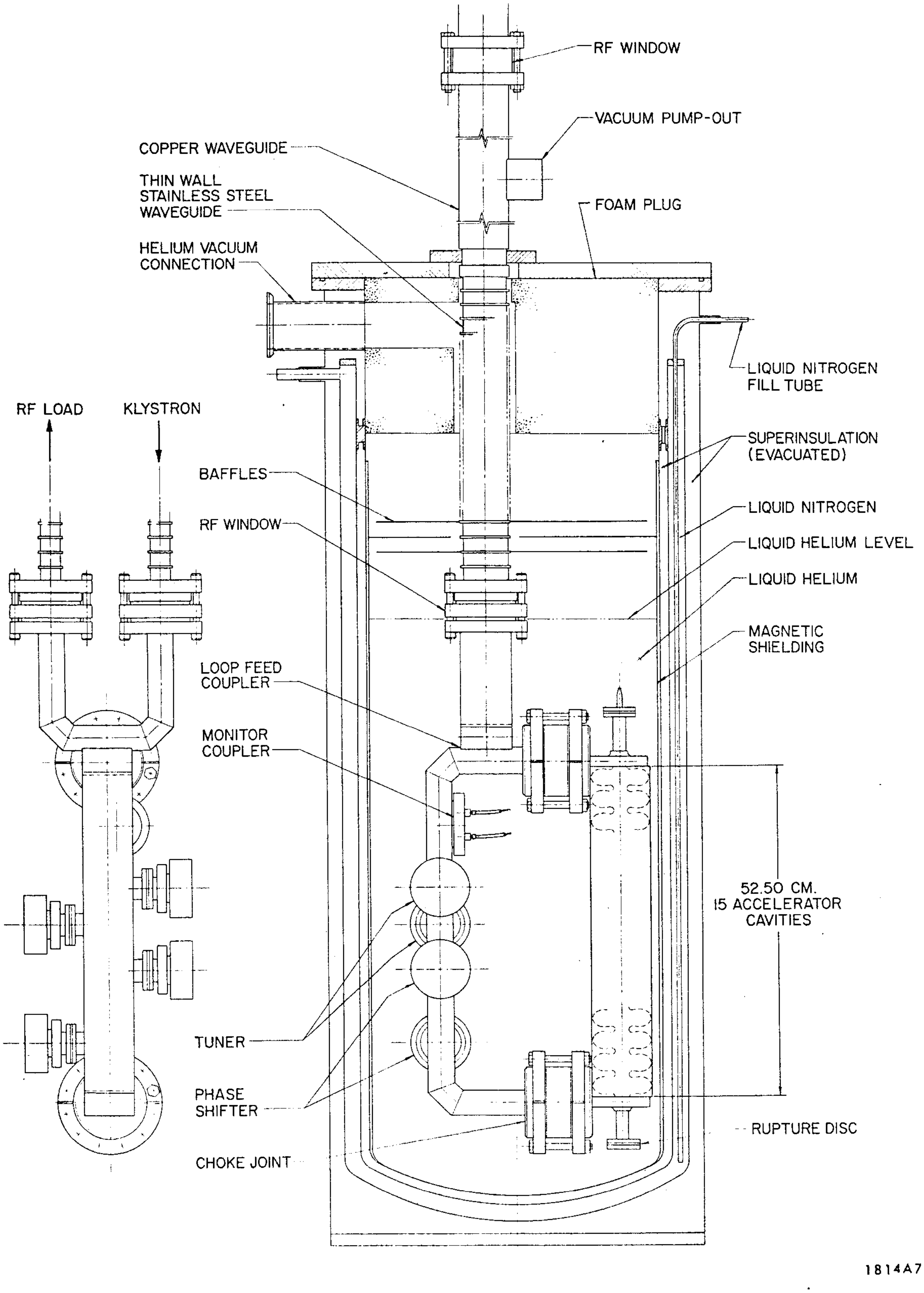
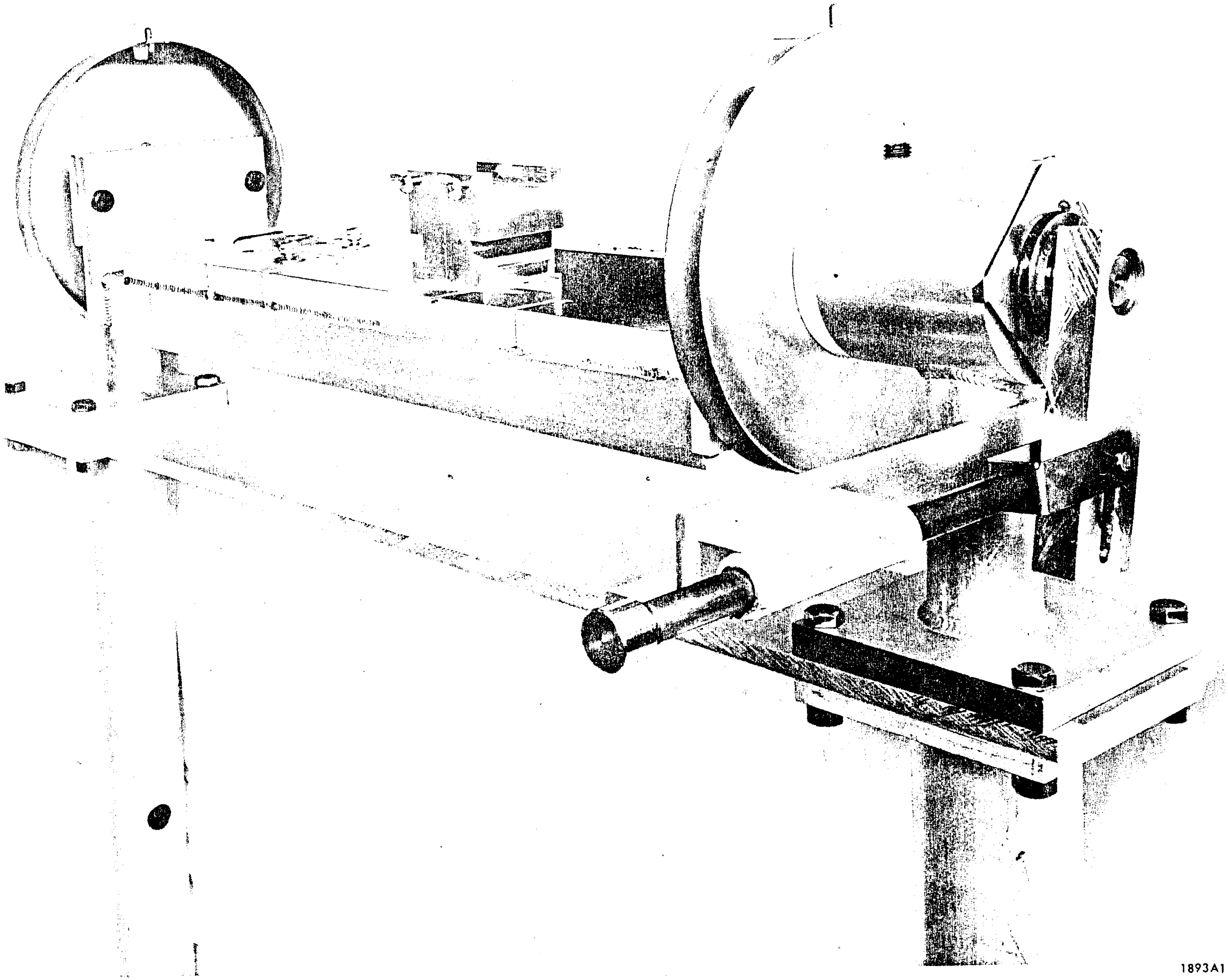


FIG. 3--"Leapfrog" superconducting accelerator test showing liquid He dewar and accelerator structure.



1893A1

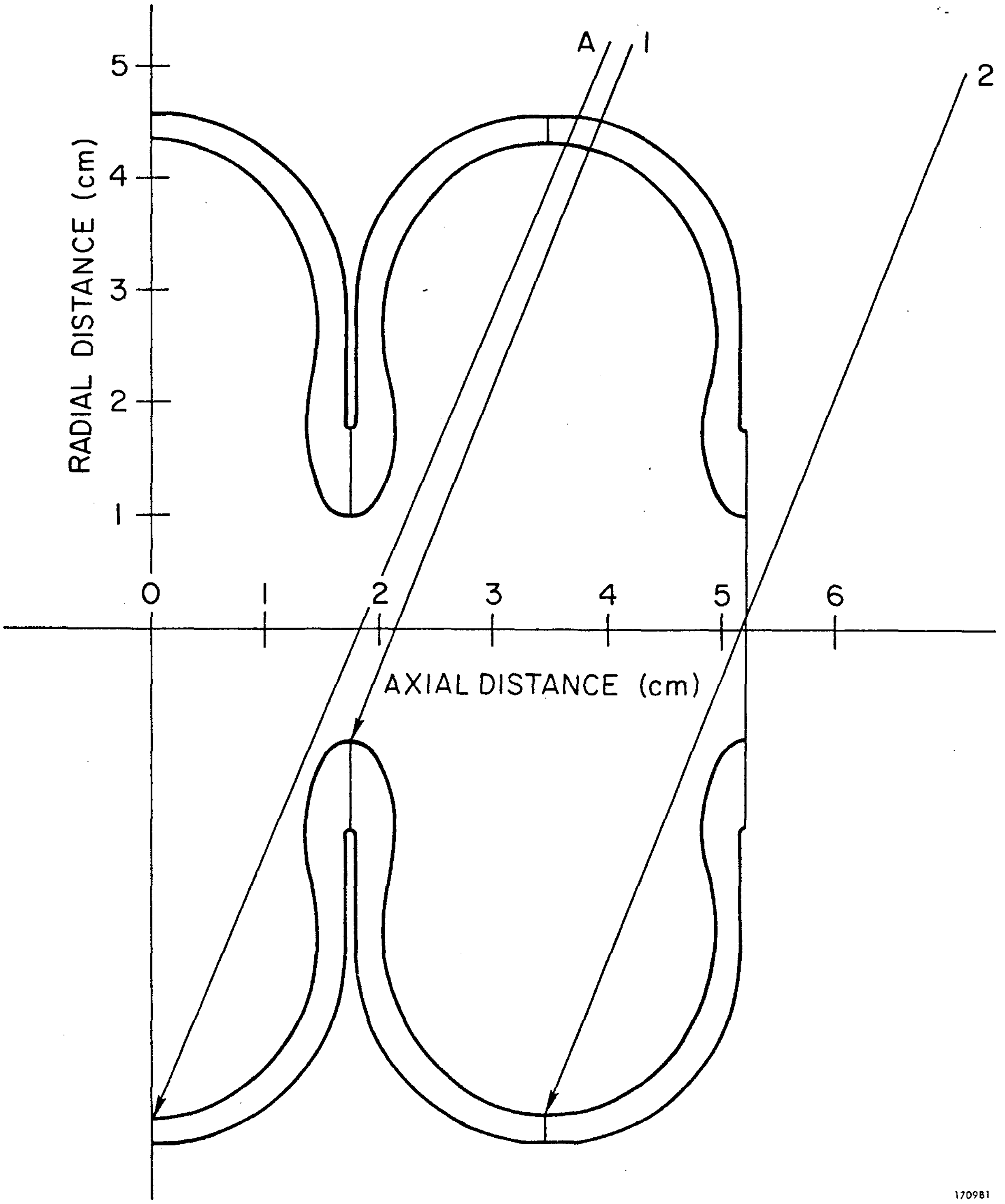


FIG. 5--Section of assembled structure. Lines 1 and 2 are successive beam paths to weld the structure from half-cavity shells. Line A is the path required if the structure is to be assembled from full-cavity sections.

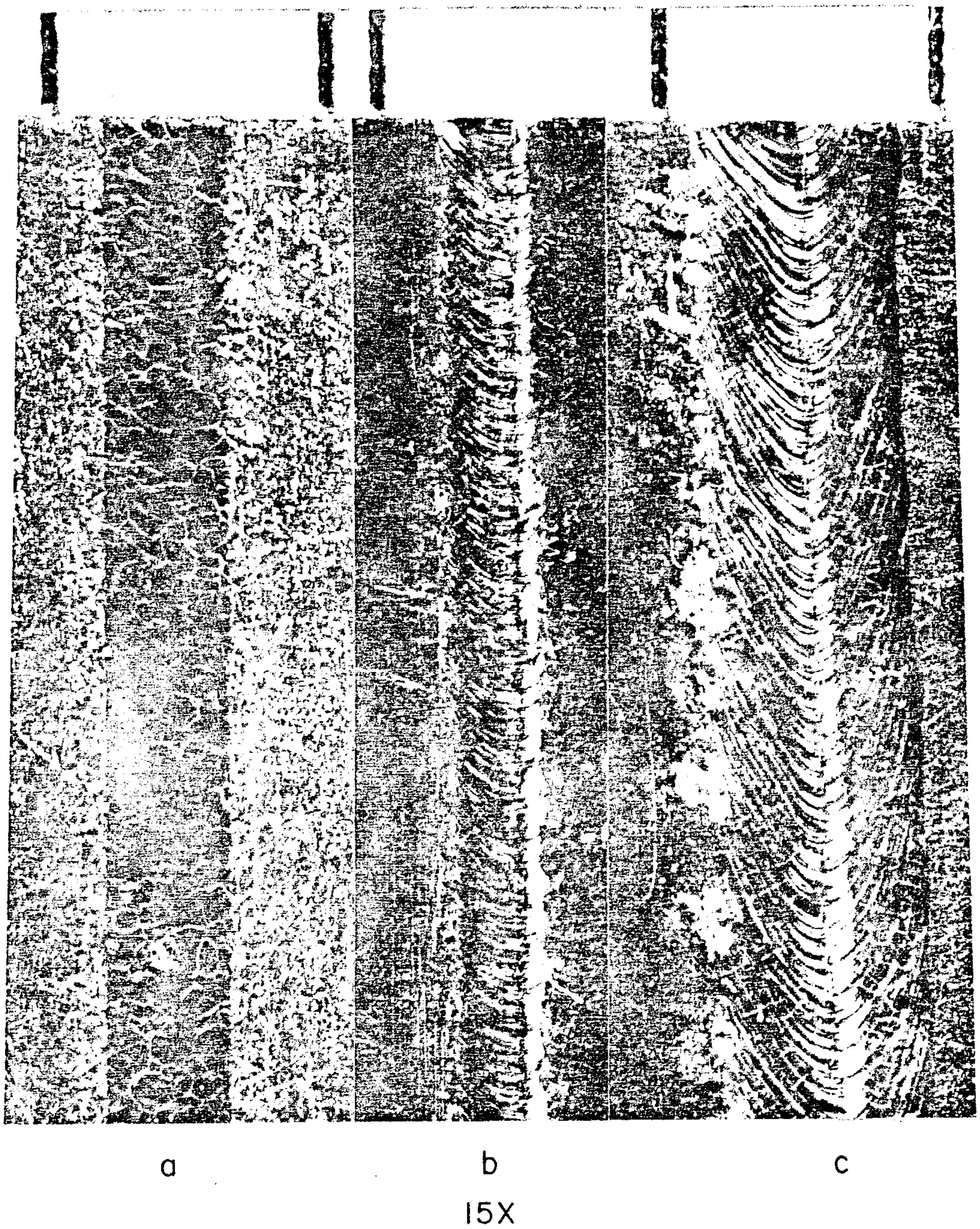


FIG. 6--Cosmetic (a), strength (b), and "typical" (c) electron beam welds in niobium.

FIG. 7--Cold shuts in electron-beam welded niobium. Weld is at top and parent metal at bottom.

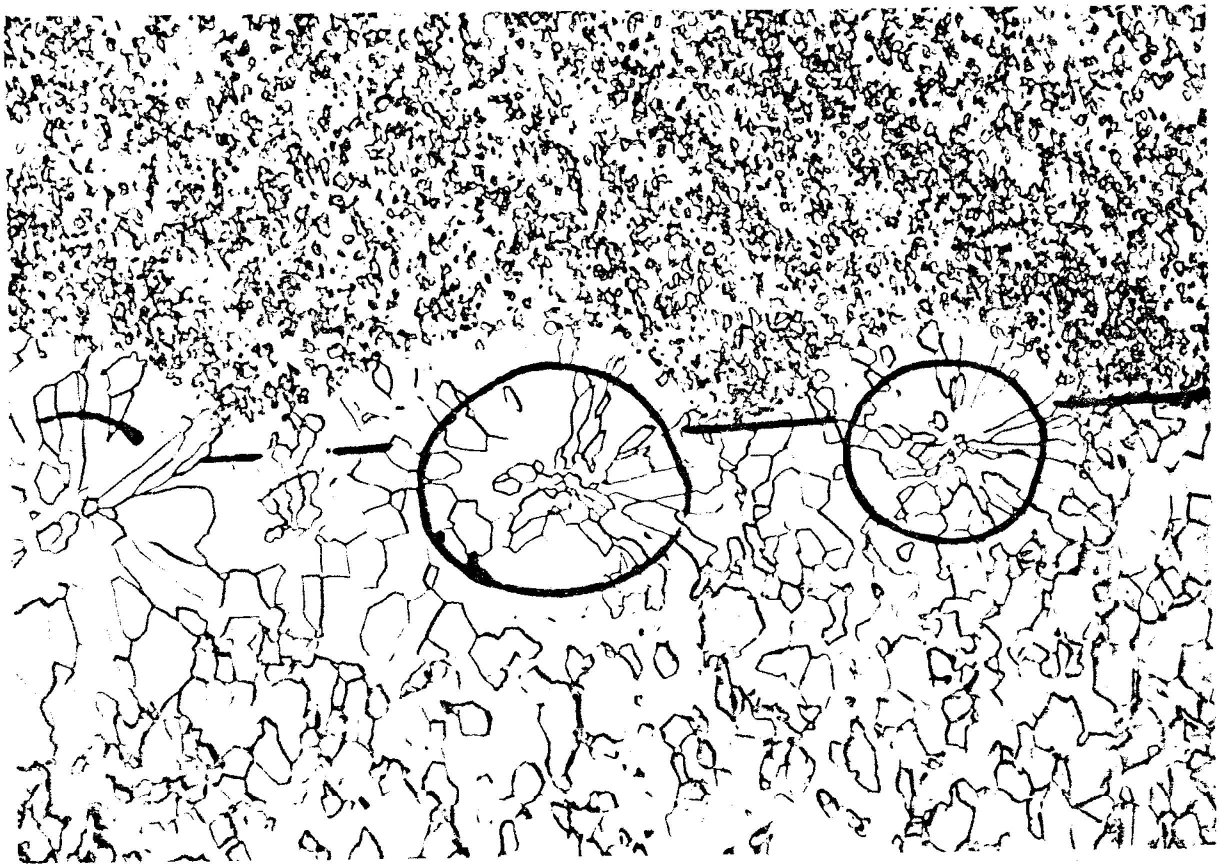
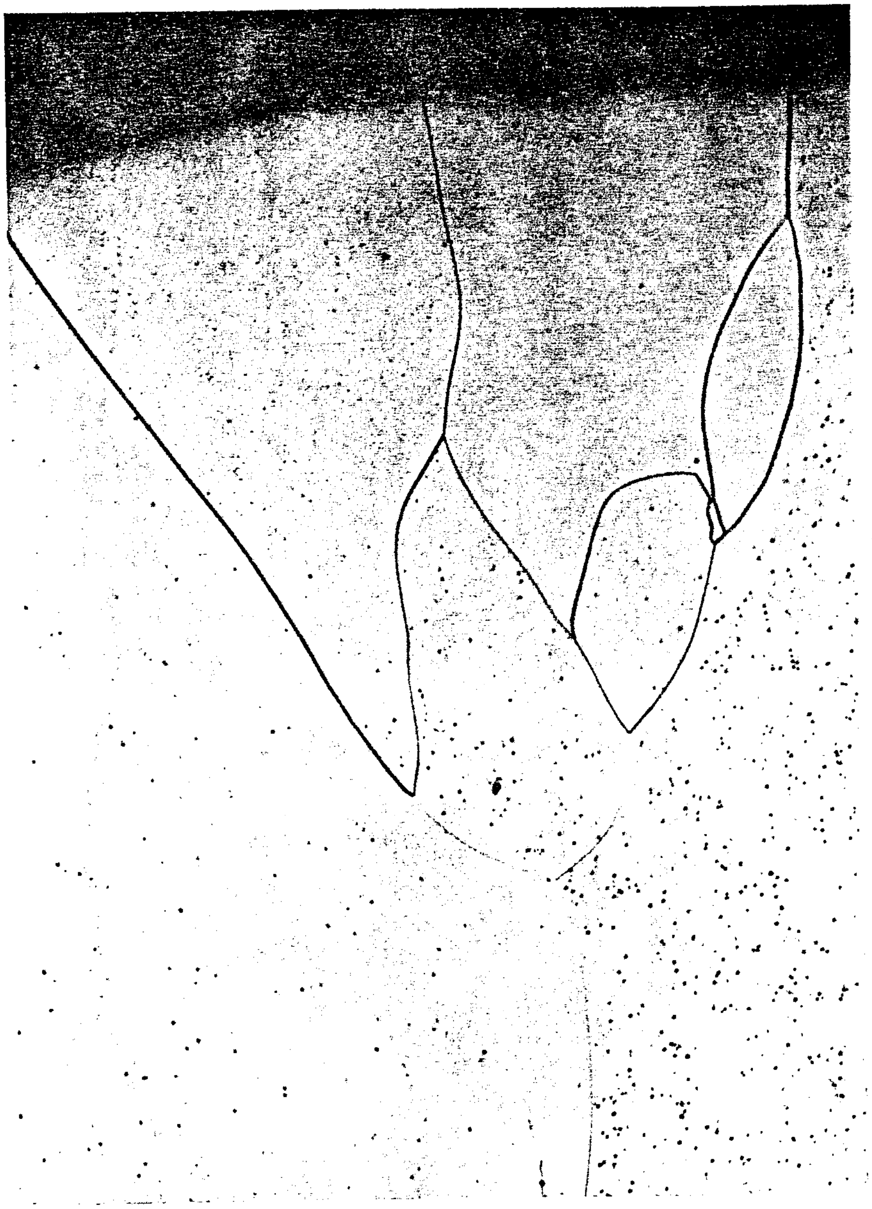
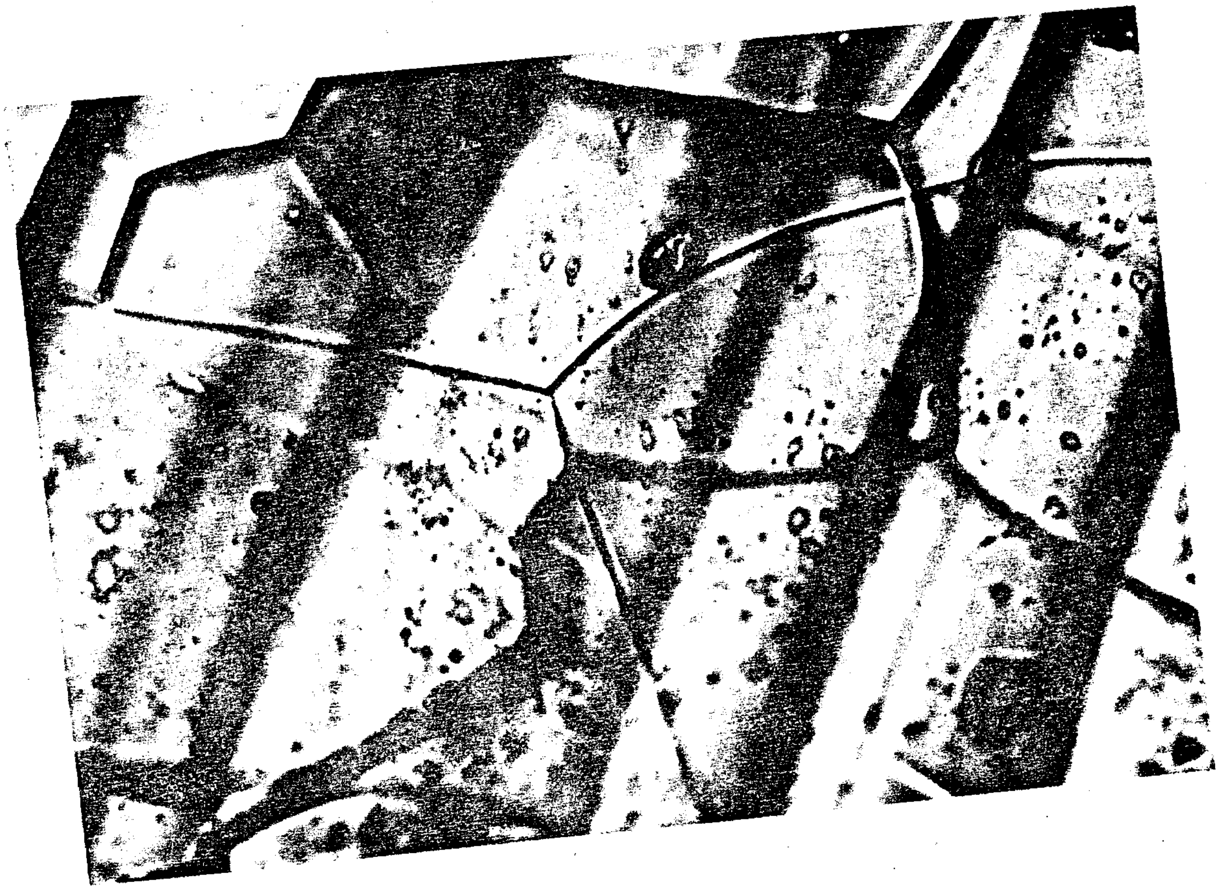


FIG. 8--Cold shuts in electron-beam welded niobium. Looking vertically into weld seam.



68X

FIG. 9--Electron-beam weld in niobium after vacuum annealing at 2000°C for 20 hours.



150X

FIG. 10--Recrystallized grain boundary (triple point) among weld-bead ripples.