SLAC-PUB-247
January 1967

A TWO-MILE-LONG ELECTRON BEAM*

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(Submitted to The Physics Teacher)

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

For several months now a stream of electrons has been leaving a cathode near the center of the San Francisco peninsula and speeding along a straight-line course at nearly the speed of light to a target two miles away. On the way, these electrons are accelerated to nearly 20 billion electron volts (GeV) of energy, the highest energy ever given electrons by man. Teams of physicists are busily studying the results of the interactions between these high energy electrons and the nuclei of the target material.

The facility which makes this possible is the Stanford Linear Accelerator Center (SLAC) (Fig. 1), built and operated at and by Stanford University, under contract with the U. S. Atomic Energy Commission. Under the direction of Professor W. K. H. Panofsky, this 480-acre national facility cost $114,000,000 to build. SLAC currently requires an 1100-man staff to operate the machine and to carry out and support the research activities of experimental physicists.

In order to study the nucleus of the atom, it is of course necessary to be able to get at it. The probes used to approach and study atomic nuclei are beams made up of high-speed subatomic particles. These beams interact with the nuclei at which they are aimed and the results of the interactions provide data leading to understanding nuclear structure.

When a moving particle is caused to speed closely by an atomic nucleus, the two will interact. The approaching particle will be caused to veer off and continue its motion at some angle off the axis of approach. At the same time, in order to conserve momentum, the interacting nucleus is caused to recoil a small amount. Such a phenomenon is known as "elastic scattering" of the bombarding particle. The bombarded nucleus remains unchanged, caused only to recoil.

Sometimes, however, the bombarded nucleus is intrinsically changed. In the scattering interaction, the bombarding particle can give up some of its energy to the approached nucleus. The nucleus becomes "excited," containing more internal energy than normal. The nucleus remains in this state only momentarily and then must release this excess energy. The release can take place in the form of x-rays (photons) or in the form of emitted subnuclear particles. This energy transfer means that less energy remains to form the momenta of the scattered bombarding particle and of the recoiling nucleus. This phenomenon is known as "inelastic scattering" of the bombarding particle.

Analysis of the angular patterns of elastic scattering, of the angular and energy loss patterns of inelastic scattering, and of the degree and kind of secondary subnuclear particle production associated with inelastic scattering, provides information about the target nucleus.

If the bombarding particle is a nuclear particle itself, it can be captured by the target nucleus. This changes the target nucleus, usually into an unstable form. This new unstable nucleus will then release another subnuclear particle in order to become stable again. If this released subparticle is different from the one captured, the target nucleus has been permanently changed from one kind to another; atomic transmutation has taken place.

The first man-controlled particle beam for bombarding material was created in 1911 by Lord Rutherford. He put radioactive radium in a container having a small opening. The alpha particles which emanate naturally from disintegrating radium passed out of the container through the opening, forming a beam. This beam was directed at a gold foil. Almost all the alpha particles in the beam passed straight through the foil, showing that matter is mostly a void. However, a statistically significant small number of bombarding alpha particles were deflected in their path by the foil, some of them even bouncing backwards. Because so few alpha particles did this, it was demonstrated that matter contains tiny, widely separated points of concentrated mass. This was the experimental discovery of the nucleus.

At first it was thought that the nucleus was made up entirely of matter, subparticles perhaps, having only positive charge, sufficient positive charge to balance the total charge of all the light negative electrons which had been found to be surrounding the nucleus. But then in 1932, Irene Curie and Frederick Joliot aimed a beam of alpha particles (from a radioactive polonium source in this case) at a foil of beryllium. Transmutation of the beryllium took place and neutral particles weighing about as much as a hydrogen nucleus were emitted from the foil. This was the experimental discovery of the neutron.

So far particle beams had been used to study the nucleus itself in the field of science known as "nuclear physics." The study of the nucleus led to glimpses of an internal structure to the nucleus and to the realization that there existed some "sub-nuclear" or apparently "elementary" particles. Thus was born the new field of science, "elementary particle physics."

Another source of particle beams is the natural, ever-present shower of cosmic rays raining on the earth. Cosmic rays are themselves subatomic particles traveling at great speeds. Cosmic ray particles have a disadvantage in that they are random things but have the advantage of possessing much more kinetic energy than either radiation from radioactive sources or man-made beams. It had been postulated that there should exist a positively charged electron in nature, rare but real and only with very high energy. With a cloud chamber in 1932, C. D. Anderson discovered the existence of this "positron" in cosmic rays.

Later experimental research eventually resulted in the discovery of several types of mesons in cosmic rays, particles which are in some way associated with nuclear structure and which have masses between those of electrons and nucleons. In order to be able to study mesons under controlled laboratory conditions rather than with random cosmic rays, science turned to the accelerator. Accelerators had been long in use for the generation of various kinds of particle beams for such purposes as producing x-rays, creating elemental transmutation, and for particle scattering. It was believed that if accelerators large enough to produce beams with very high energies were to be built, these beams could be used to in turn produce mesons and other particles by interacting with target nuclei inelastically.

Such proved to be the case. In 1948 at the synchrocyclotron at the University of California, a beam of 380-MeV alpha particles bombarded a target and resulted in detectable pi mesons being emitted. Pi mesons were also produced using a high energy electron beam for bombardment at Berkeley's electron synchrotron. Both pi and mu mesons were produced by the 1-GeV linear electron beam on a nuclear target at Stanford during the early 1950's. These and other successes led to the building of more and larger accelerators for higher and higher beam energies. When the Cosmotron at Brookhaven National Laboratory went into operation in 1953, its 3-GeV proton beam was capable of reproducing all the particles previously observed in cosmic ray research. It was calculated that to produce copiously the as yet unseen anti-proton it would be necessary to bombard a target with a proton beam having an energy of 6 GeV. To accomplish this, and to perform other advanced elementary particle physics research, the University of California built its Bevatron. In 1955, the proton beam from the Bevatron did indeed result in the production of anti-protons.

As technology advanced and more new and exciting results appeared, more and more accelerators were built. The aim has always been to produce higher energy beams of greater intensities. The higher the energy of a bombarding particle, the closer it can come to a target nucleus for scattering and the more different kinds of secondary particles can be produced from inelastic interactions. (Hence "elementary particle physics" is becoming known as "high energy physics.") The greater the intensity of the beam (more particles in the beam) the more likely it is for a good number of interesting interactions to take place in a short time; i.e., the greater the flux of secondary particles.

The three highest energy accelerators in operation in the world are the 28-GeV proton synchrotron at CERN in Switzerland, the 33-GeV proton synchrotron at Brookhaven in New York (both of these are circular) and the 20-GeV linear electron accelerator at Stanford, the subject of this article.

Circular types of accelerators have many distinct advantages. Most accelerators in the world are of a round configuration. But in the one case where it is desired in particular to produce a beam of electrons having a very high energy, it has been found to be more advantageous to build linear accelerators. This is because all charged particles confined to a non-linear path radiate away from themselves some of the energy they have been given. The higher the energy given the beam particle, the more it loses. So long as the beam particle is a proton (or other nucleus), this loss of energy is negligible. But electrons, being very light, exhibit this phenomenon to a much greater degree. After an electron has been accelerated to near 10 GeV of energy in a circular accelerator, it begins to lose more energy by radiation loss than can be economically replaced.

Another advantage of linear accelerators over circular kinds is the fact that in linear machines more particles per second can be accelerated, resulting in a higher current or intensity in the high energy beam.

Thus Stanford's two-mile accelerator's primary qualities are the acceleration of electrons to higher energies than ever before and the acceleration of more electrons per second than ever before.

To accomplish this, Stanford has constructed a 10,000-foot-long concrete tunnel, 25 feet underground. This tunnel, 10 feet by 11 feet in internal cross section, houses the accelerator proper, a copper cylinder four inches in diameter. Electrons are injected into the west end of this small cylinder and exit from it, after traveling its two-mile length, having been accelerated to as much as 20 billion electron volts of energy.

Parallel to this 10,000-foot tunnel and directly above it at ground level is another 10,000-foot-long structure, a 17-foot-high by 30-foot-wide sheet steel shed. This structure, called the "klystron gallery," contains all the components and devices for providing for the acceleration of the subterranean electron beam. Integration of the functions of these two structures is performed via vertical holes ("penetrations") in the separating earth fill. These penetrations, usually 20 feet apart along the entire length, permit interconnection between the equipment in the upper structure and the accelerator tube in the lower structure (Figs. 2 and 3).

The beam from the two-mile machine exits at the east end of the accelerator and enters a 1000-foot-long "beam switchyard" (Fig. 4). The beam switchyard is an extension of the underground accelerator housing and lies in the same horizontal plane as the end of the housing. In order to direct the accelerated beam to any of selected research areas, the beam switchyard gradually becomes wider toward its output end. In this beam switchyard, huge electromagnets process and direct the beam into experimental areas located in two target buildings.

Because processing of a curved electron beam results in more radiation than does the motion of a linear beam, the beam switchyard is covered with 40 feet of shielding earth and concrete.

Two target buildings were planned in order to be able (1) to be preparing one experiment in one target building while the beam is in use in the other, (2) to "share" the beam if desired by directing part of it to one target building and part of it to the other, and (3) to design and equip the two target buildings differently for the two major classes of experiments performed with this kind of machine (electron scattering and secondary particle production).

The larger of the two target buildings is equipped with three hugh magnetic spectrometers (Fig. 5) to measure scattering. One is over 150 feet long and weighs more than 1700 tons. These spectrometers can be swung around an axis and are set at various angles from the line of the bombarding beam in order to accept particles scattered at particular angles. Magnets in the spectrometer then separate out all particles except those having a particular energy and electric charge. By electronic means, particles of a particular energy are identified with respect to their mass. The result in each spectrometer then is a tally of the number of particles of a unique kind scattered at a unique angle.

The three spectrometers are of different sizes and thus cover different ranges of scattering energies. With each covering a wide arc and analyzing many scattering angles successively, a complete picture of the results of an interaction can be obtained. In the process of elastic scattering, the electrons of a given energy are scattered at a unique angle. This energy, which, of course, depends upon the energy given the electron by the accelerator, can be calculated. In inelastic scattering, because energy has gone into the creation of other kinds of particles, the scattered electrons can have different amounts of energy at a particular angle, but always less than the energy of an elastically-scattered electron.

Setting a spectrometer to receive only particles having the energy permitted with elastic scattering provides data for understanding of that kind of action. Setting a spectrometer to discriminate against particles having the energy of elastic scattering provides information about the inelastic scattering process. Not only can the scattered electrons be studied, but also the secondary particles produced.

In the smaller of the two target buildings, the accelerated electron beam is used to produce secondary particles from inelastic scattering for observation and study. When the high energy electrons bombard a target at the entrance to the target building, a shower of all kinds of radiation and secondary particles is produced. Magnet systems then direct selected portions of this shower into separation systems which stop all particles except the particular ones of interest at that time to the particular experimenter. The resultant beam of chosen secondary particles is next directed to a piece of research equipment. Typical equipment used to study these secondary particles includes bubble chambers and spark chambers.

At the entrance to the experimental chamber, the special beam of secondary particles is directed at another target. Again scattering occurs, this time of the secondary particles. Again further secondary particles are produced from inelastic collisions between the bombarding secondary particle beam and the target at the chamber. As scattered and produced particles pass through the chamber, they leave tracks of their passage. Measurement and analysis of these resultant tracks provide information regarding the nature of the secondary particles delivered to the chamber.

The two-mile-long accelerated electron beam, which is the primary instigator of the nuclear interactions to be studied, was first activated over its entire 10,000-foot-long course on May 21, 1966. From the very start, the machine has operated very successfully. At the time of this writing the beam has been accelerated to 19 GeV of energy. Use of the machine in physics research is now well underway. Physicists from all over the nation are preparing to perform experiments at SLAC.

The accelerator itself consists of a precisely machined 4-inch-diameter copper cylinder in which 1/4-inch-thick copper disks are spaced about 1-1/4 inches apart over the entire two-mile length (Figs. 6 and 7). An aperture in each disk of about 1-inch diameter permits passage of the electron beam. At 10-foot intervals along the accelerator tube, microwave power at a frequency of 2856 million cycles per second is fed into the underground accelerator from high power klystron amplifier tubes located in the above-ground 2-mile-long gallery (Fig. 8). Altogether, there are 245 such klystrons each providing about 20 million watts of microwave power in short bursts lasting a little over two-millionths of a second and recurring at set rates up to 360 times per second. By dividing the power from each klystron into four equal parts, about 5 million watts are fed to the accelerator at each 10-foot interval (Fig. 9). Upon entering the accelerator, the microwave power propagates axially along the structure, passing through the apertures in the accelerator disks in the form of a "traveling wave" moving at the velocity of light. The electron beam injected into the accelerator by an electron "gun" is carried along by this wave and in the process the electrons attain a velocity nearly equal to that of light (186,000 miles per second). In the first 100 feet of travel, the electrons reach a speed equal to 99.9997 percent of the velocity of light. At the end of the accelerator the electrons' speed is 99.99999997 percent of the velocity of light. Since, in accordance with Einstein's Special Theory of Relativity, the electrons cannot exceed the velocity of light, their gain in kinetic energy is principally evidenced by a corresponding gain in mass. In fact, when it exits from the output end of the accelerator, each electron weighs some 40,000 times as much as it did when it was injected at the starting point. It is this large kinetic energy which enables the electron to penetrate closely into the heart of matter, revealing to the questing physicists the size, shape, structure and magnetic characteristics of atomic nuclei and their constituents.

LIST OF FIGURES

of the end stations to bubble chambers and spark chambers in the smaller buildings in the foreground.

5. Inside the larger of the two end stations are three huge electromagnetic spectrometers. Debris emanating from the point of interaction between the electron beam and a central target scatter in all directions. Each of the spectrometers can accept scattered particles of a particular energy range. Each of the spectrometers can be swung slowly in an arc about the point of interaction to study various angles of scattering, one at a time.

6. Each ten-foot-long section of the accelerator includes 86 one-inch-long cylinders separated by 86 quarter-inch-thick disks with small holes to permit beam passage. Furnace brazing fused all the parts of each ten-foot section into a solid copper structure.

7. Each finished ten-foot section of accelerator waveguide is surrounded by a complex network of small brazed water pipes. This network provides for temperature control of the section (to within a half degree) to maintain dimensional stability.

8. Two hundred forty 24-megawatt klystron power amplifier tubes, placed along the two-mile-long surface gallery, feed microwave power to the underground accelerator through holes in the floor.

9. With the technique of power splitting, each of the 240 klystrons is able to feed six megawatts of traveling microwave power to each of four 10-foot sections of accelerator underground. It would thus be possible in the future to increase the energy of the beam by installing more klystrons in the gallery, decoupling power splitters, and feeding each klystron power output to fewer sections.

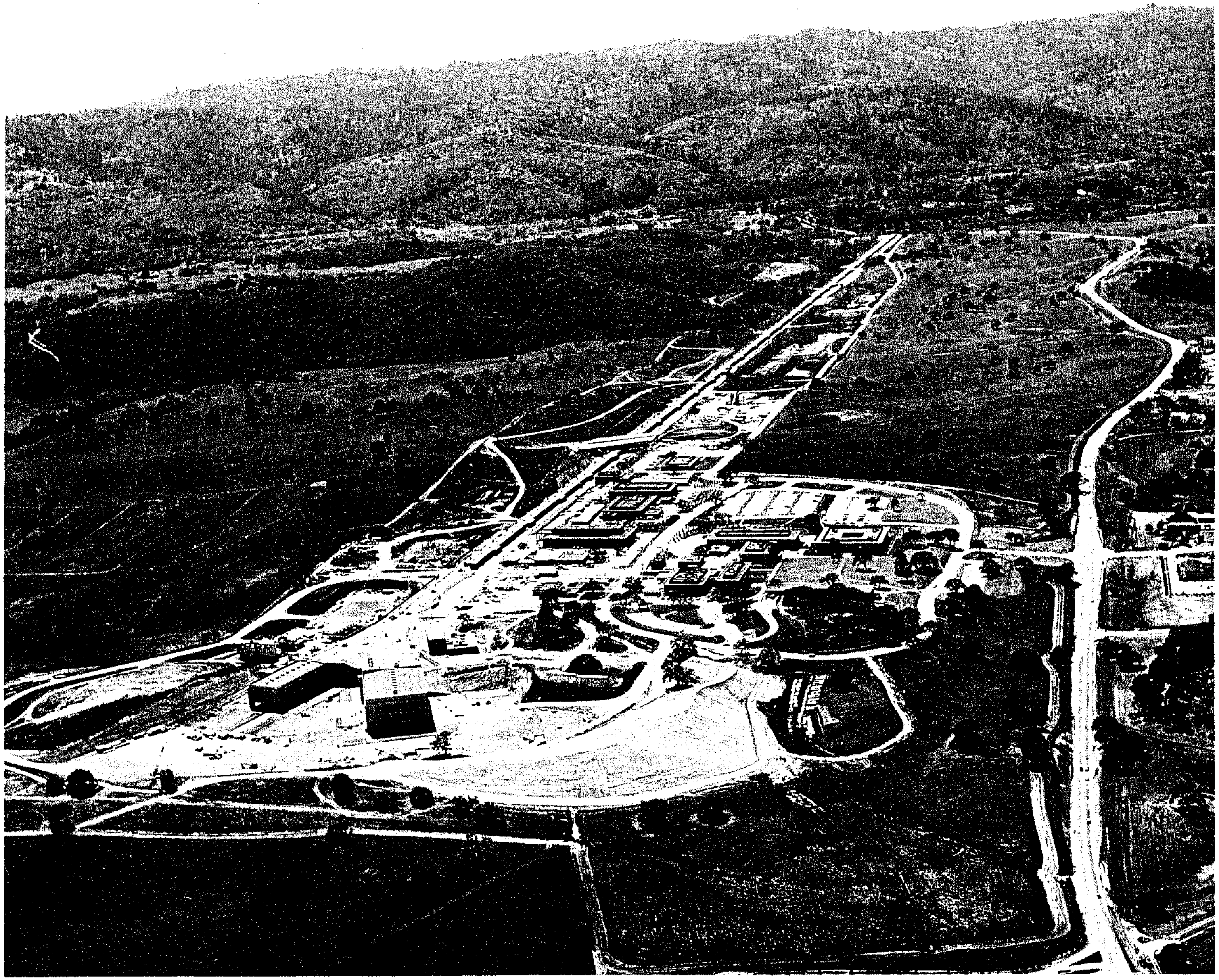


FIG. 1

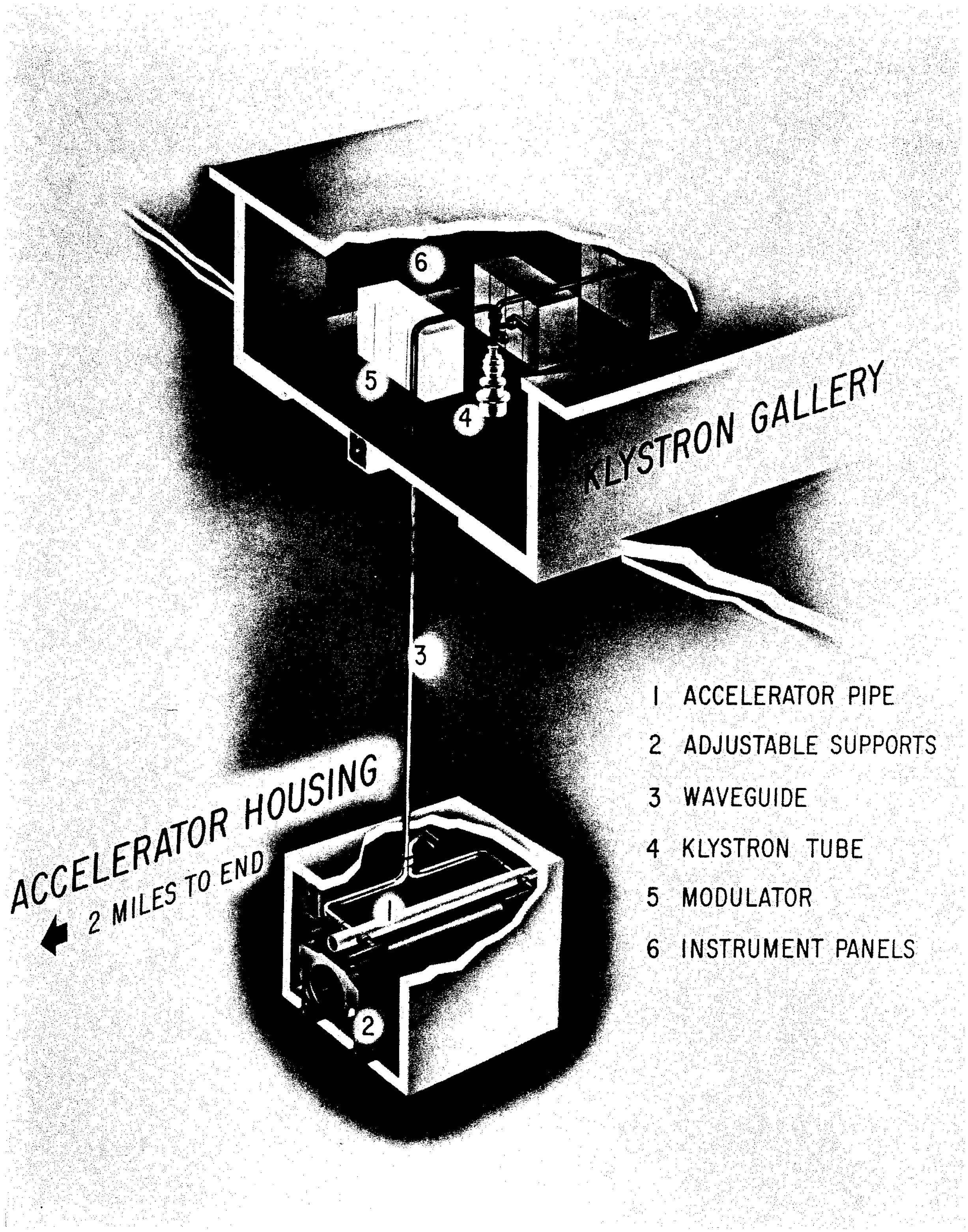

6
5
4
KLYSTRON GALLERY
3
ACCELERATOR HOUSING
2 MILES TO END
1
2
1 ACCELERATOR PIPE
2 ADJUSTABLE SUPPORTS
3 WAVEGUIDE
4 KLYSTRON TUBE
5 MODULATOR
6 INSTRUMENT PANELS

FIG. 2

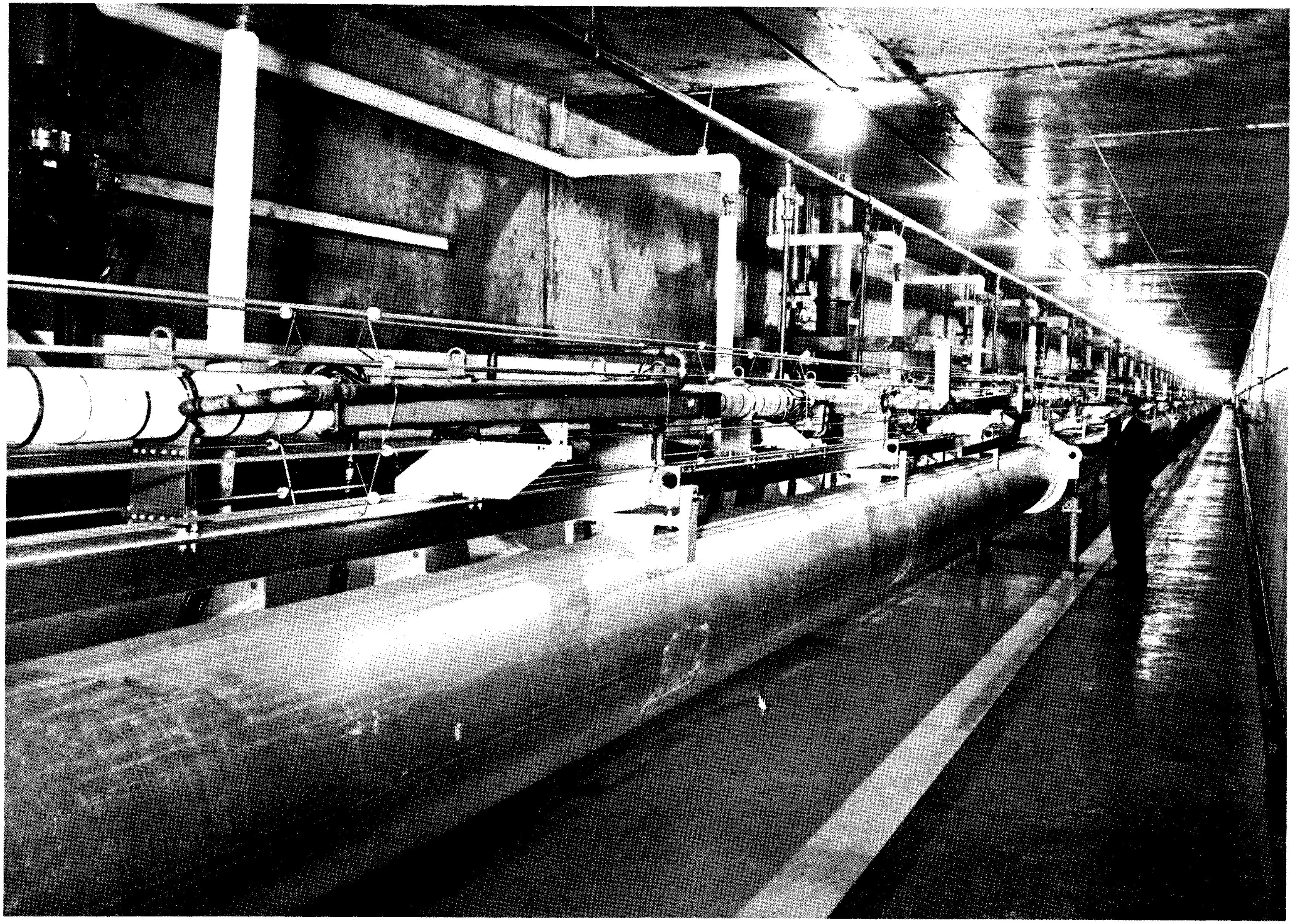


FIG. 3

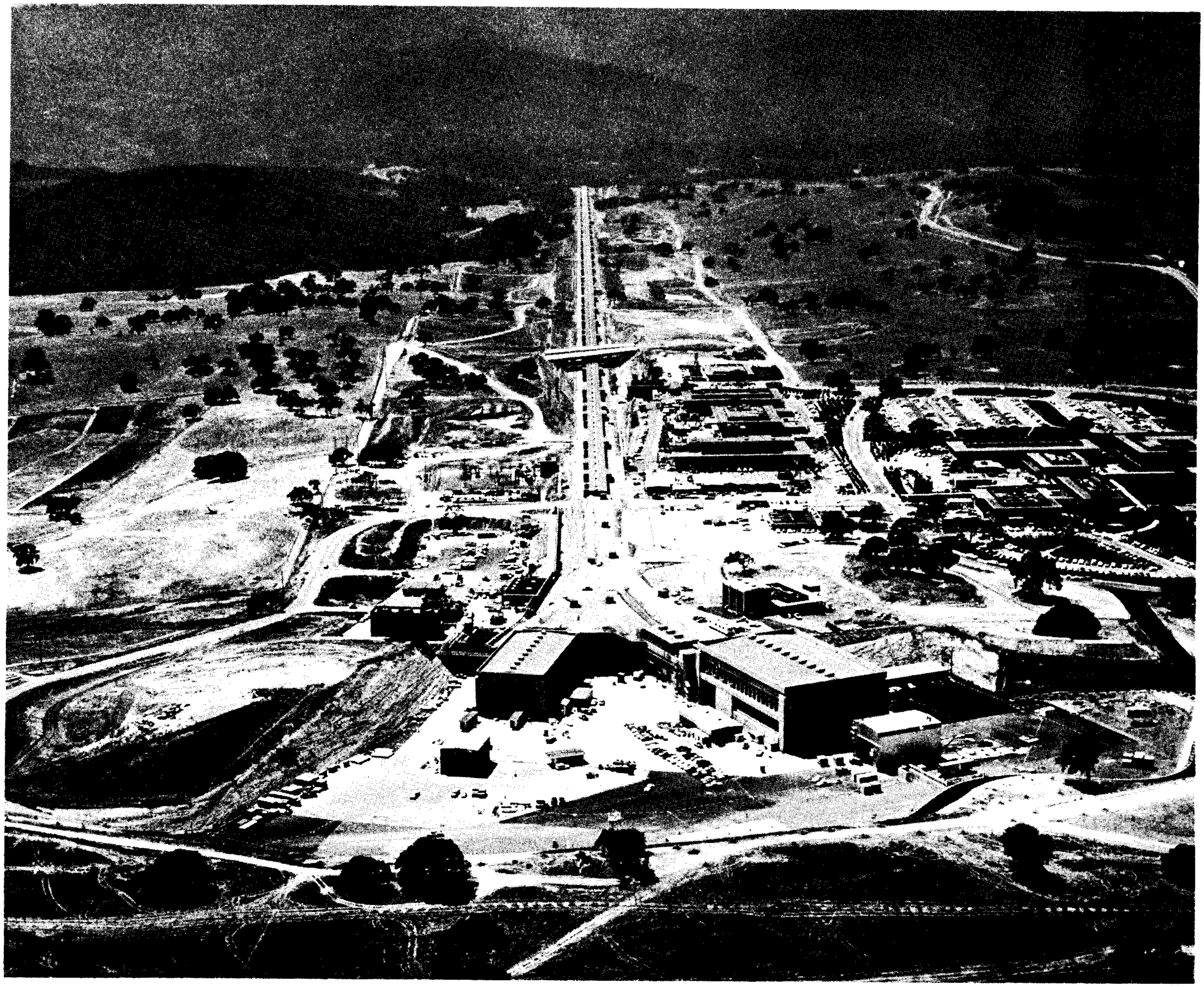


FIG. 4

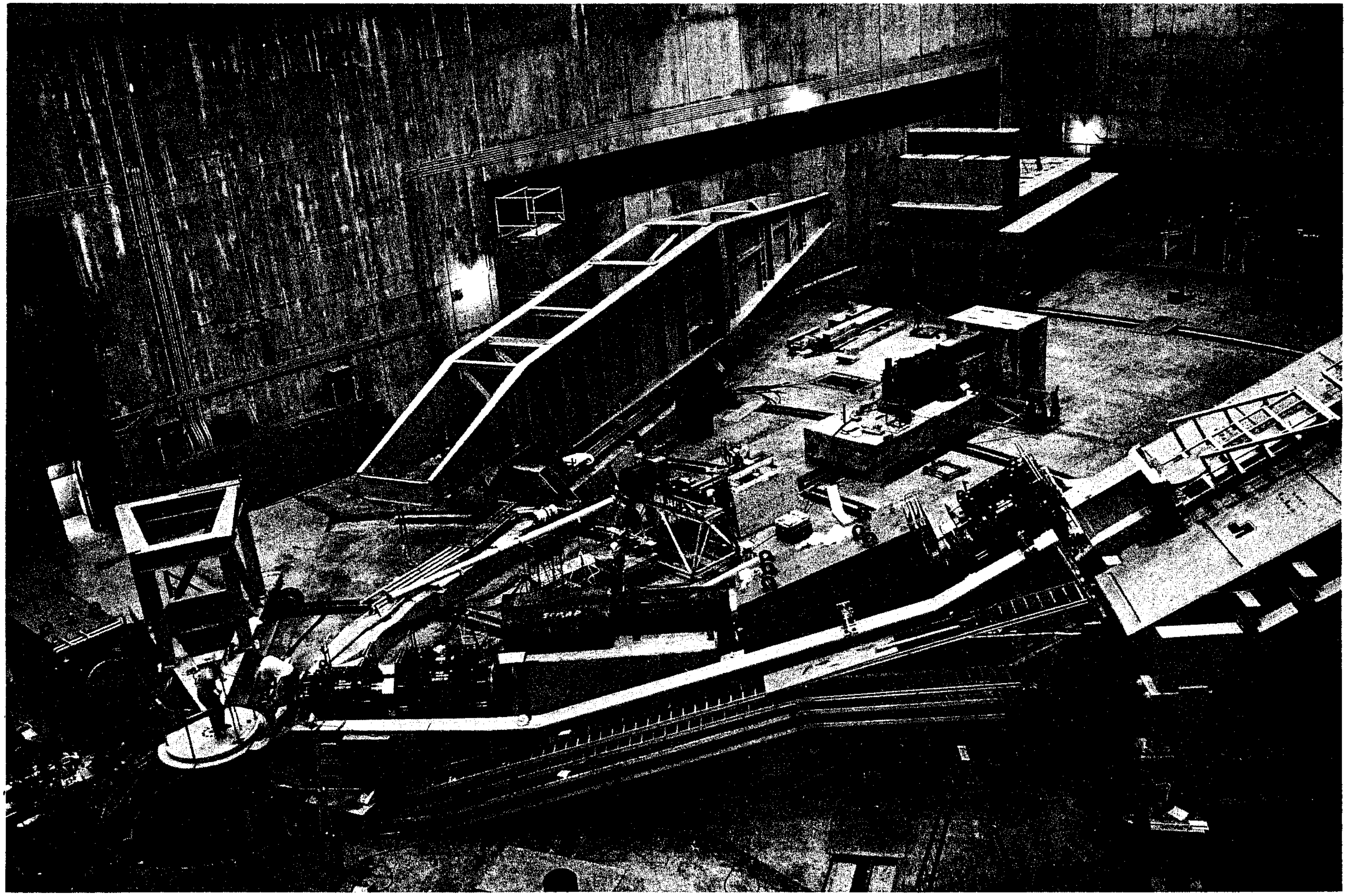


FIG. 5

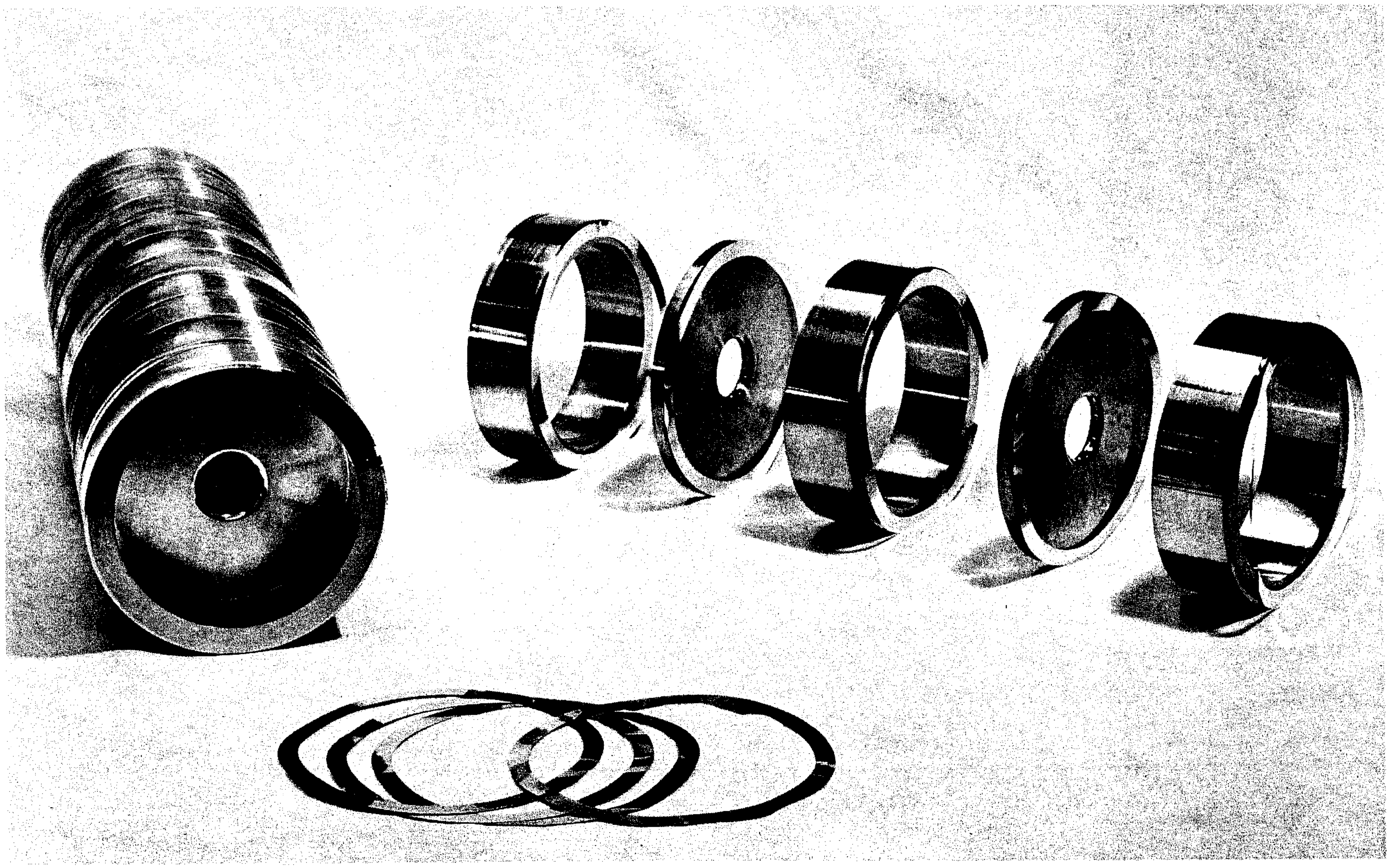


FIG. 6

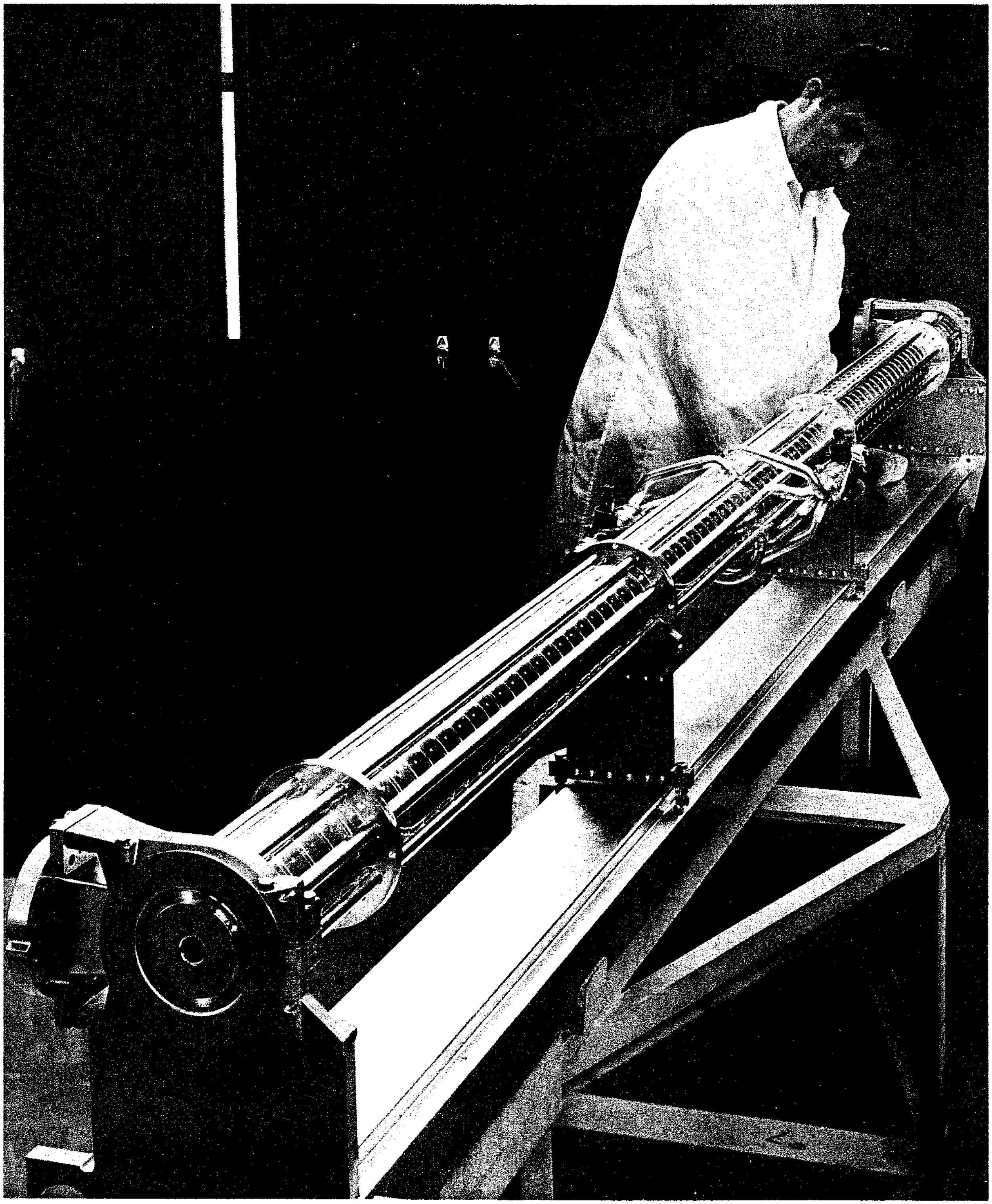


FIG. 7

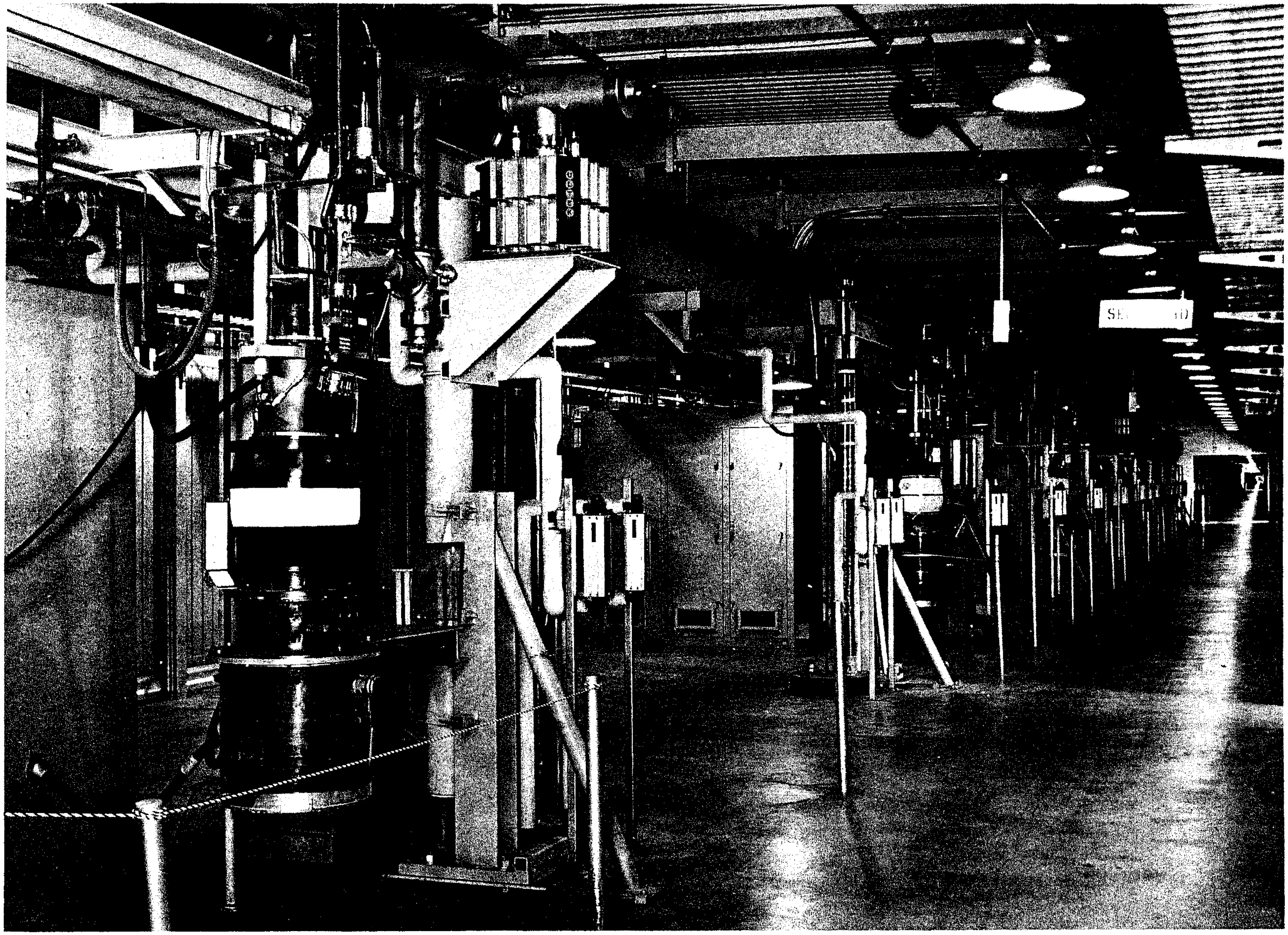
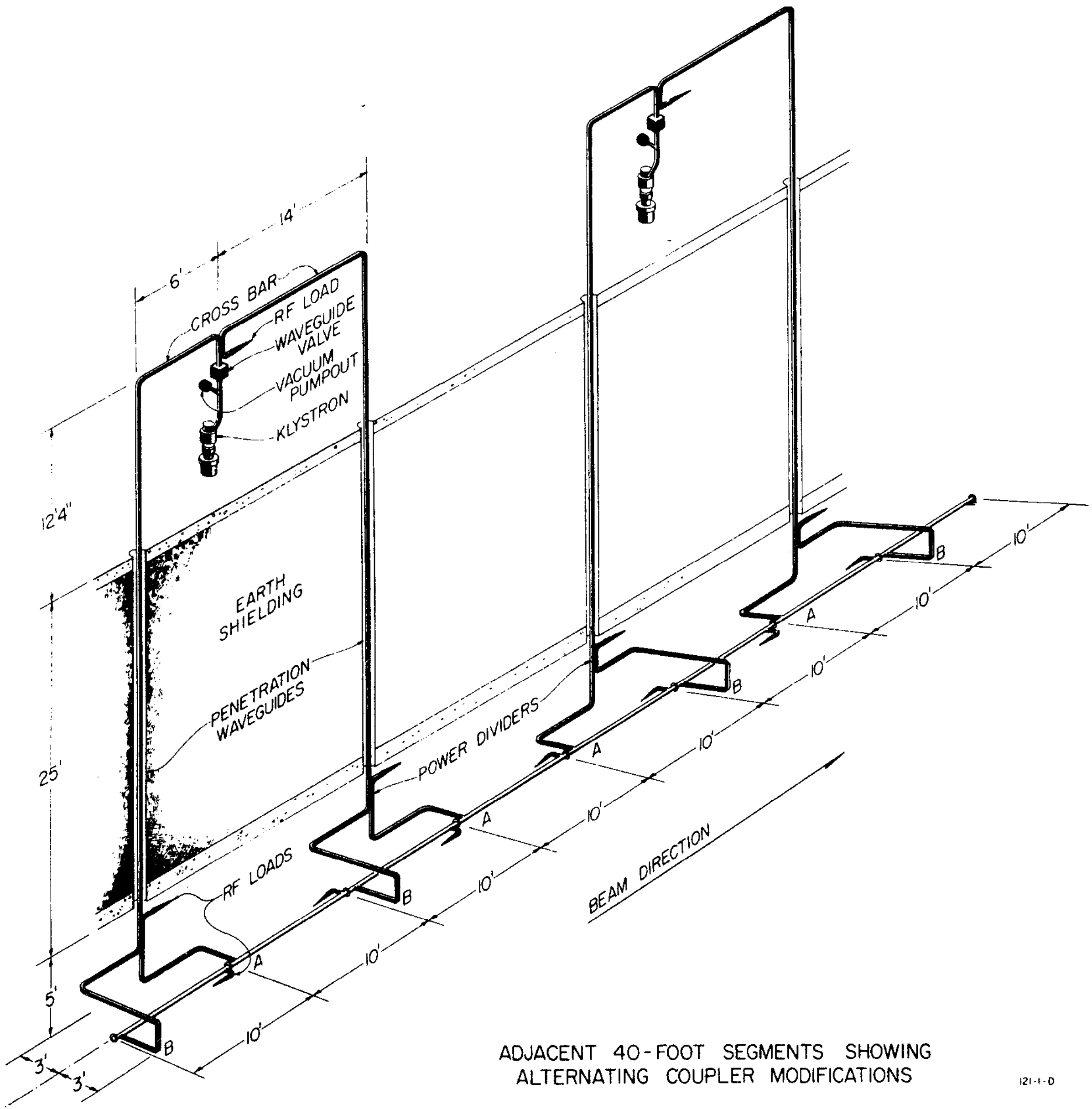


FIG. 8



ADJACENT 40-FOOT SEGMENTS SHOWING
ALTERNATING COUPLER MODIFICATIONS

121-1-D

FIG. 9