BEVATRON IMPROVEMENTS*

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(Presented by G. R. LAMBERTSON)

1. INTRODUCTION

The Bevatron was completed early in 1954 and the experimental program began in October of that year. The beam was about 10^{10} protons per pulse. The research program was pursued very intensively, with machine development limited to that which could be done without serious interruption to the program. This development resulted in a steady increase of beam to working levels of 1.5 to 2×10^{11} protons per pulse by 1960, with occasional maxima to 3×10^{11}. Many improvements in experimental facilities were made to provide for the increasingly complex experiments. It was clear, however, that there were limits to the development which could be done on this basis, and that the trend in high energy physics was such that even greater demands would be placed on the accelerator. It was also clear that a new and advanced accelerator would be needed to provide the logical continuity to the work in particle physics and accelerators which had been carried on at the Radiation Laboratory for thirty years. But a new large accelerator would take many years to design and build. Accordingly, a program of major improvements to the Bevatron to meet the immediate future needs was planned while at the same time longer-range plans for a new accelerator were under discussion. It was decided that the objectives would be higher intensity, greater reliability, and improved experimental facilities. The possibility of increasing energy by reducing the magnet gap was rejected because the gain would be too small to justify the effort. The main elements of the program that were evolved to meet these objectives were:

1) a new injection system working at higher energy and intensity,
2) complete shielding of the accelerator consistent with the expected higher intensity,
3) changes to the radio-frequency and control systems to improve reliability and flexibility,
4) additions and improvements to experimental facilities,
5) provision of an external proton beam.

Each of these topics will be discussed except the last, which is the subject of a separate paper by William A. Wenzel.

In addition there were some additions and changes to the building and a complete overhaul of the generators. The generator flywheels and flywheel shafts were replaced because we were not satisfied with the type of steel in them with respect to safety against brittle fracture. To accomplish this program, operation of the Bevatron was suspended for five and one-half weeks in the fall of 1961, three weeks in the spring of 1962, and 33 weeks starting in June, 1962. A small portion of the program remains to be completed but will require no further interruption. A program of this magnitude is obviously the work of many people — physicists, engineers, and technicians — who made exceptional efforts to minimize the interruption to the experimental program. The following persons had major responsibilities:

W. W. Chupp	H. G. Hereward**	R. B. Meuser.
B. Cork	R. M. Johnson	W. W. Salsig
R. Force	L. T. Kerth	L. Smith
J. Gunn*	G. T. Kuntz	H. A. Vogel
C. C. Harris	G. R. Lambertson	W. A. Wenzel
E. C. Hartwig	K. H. Lou	T. F. Zipf***

2. INJECTION SYSTEM

The new injector has an energy of 19.3 MeV and was designed for an intensity sufficiently high to exceed the space-charge limit of the Bevatron, which was estimated to be about 10^{13} protons per pulse at that injection energy. The ion gun is a 480-keV Cockcroft—Walton

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* Now at Stanford Linear Accelerator Center.
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generator with a modified Von Ardenne source. It can produce a 100-mA proton beam with an emittance of 100 mm·mrad. Solenoidal focusing magnets are used to match this beam to the magnetic quadrupole focusing of the 19.3-MeV linear accelerator. The proton linear accelerator is a single 200 Gs cavity 13 m long. The repeat length is $\beta\lambda$ with 73 drift tubes and two half drift tubes. The ratio of gap to repeat length changes from 0.225 at the entrance to 0.253 at the exit. The bore diameter of the entrance drift tube is 1.3 cm, the exit tube 3.1 cm.

The energy gain of the protons is 1.4 MeV/m. The cavity is preexcited by an Eimac 4W20,000 tetrode oscillator, tuned to the main cavity frequency. Energy is transmitted to the main cavity by ten driving oscillators, Eimac 3W10,000 triodes, each coupled direct to the main cavity. The power rating of the system is about 2.5 MW. Without beam loading, approximately 1 MW peak power is required to obtain the optimum gradient. The unloaded Q of the cavity, with drift tubes, is 75,000. Focusing is provided by quadrupoles located in each drift tube, and operated in the NSSN mode. At the entrance end the gradient of the magnetic focusing quadrupoles is 4300 Gs/cm, at the exit end 470 Gs/cm. These magnets are water-cooled and dc-excited at a power of about 400 W each.

The 19-MeV proton beam is transported to the Bevatron through an achromatic inflector system, shown in Fig. 1. This consists of a +29-deg magnetic deflection, followed by a −35-deg magnetic deflection, then by a +31-deg magnetic deflection, and finally by a +4-deg electrostatic deflection into the aperture of the Bevatron. To increase the acceptance of the linear accelerator, a single-cavity buncher is used, with a drift distance of 1 m. A debuncher with a drift distance of 11 m has also been provided to decrease the energy spread of the linear accelerator.

Various devices have been used to improve the control and measurements of the proton beam. These include beam transformers, adjustable collimators to measure the emittance at the entrance and exit of the linac, a beam chopper to provide microsecond bursts of beam to be transmitted to the Bevatron, and a magnetic analyzer to measure the energy and energy spread at the exit of the linac. Typical performance obtained with a 50-mA, 1-ms pulsed proton beam into the linear accelerator is 25 mA of 19.3-MeV protons with an energy spread of less than $\pm$ 0.5%. The efficiency of the transport system and the inflector is 90%.

The horizontal and vertical emittances were measured at the exit of the linac and also at the exit of the first quadrant of the Bevatron and observed to be nearly equal. They were 14 mm·mrad for a 14-mA beam and 16.5 mm·mrad for a 24-mA peak intensity. Operation with the debuncher to give a more monochromatic beam, with less than $\pm$ 0.2% energy spread, does not increase the capture efficiency of the Bevatron, and therefore it is not used. The maximum full-energy beam obtained from the Bevatron is 3.2×10^{12} protons per pulse, and it requires a 10-mA injected beam. The intensity limit is discussed in a separate paper by Glen R. Lambertson.

3. SHIELDING

The original shielding of the Bevatron consisted only of an outer wall about 1.5 m thick and some partial covering of the straight section tanks. Even at the previous intensities, about 2×10^{11} protons per pulse, radiation levels were sufficiently high that access to certain areas in the building had to be limited, and it was necessary to provide local temporary shielded areas for persons who had to work in the experimental area. With the prospect of beams more than an order of magnitude greater, it was necessary to provide complete shielding. The new shielding was designed to be adequate for beams up to the space charge limit, 10^{13} protons per pulse, according to the usual standard that the maximum dose to persons working around the machine is not to exceed 5 rem per year. The most difficult problem connected with the shield was that adequate foundations to carry the added weight did not exist and construction of the foundation would be a major disruption. It was desired to keep that disruption to a minimum. The design that was adopted to meet these conditions is shown in Fig. 2. Basically, the wall is 3 m of concrete with a density of 3.6 g/cm^3, and the roof 2.1 m with a density of 2.4 g/cm^3. It should be noted that an important component of the total shield is the magnet itself which provides shielding of 75 to 130 cm of steel most of the way around. The inner foundation was made by tunneling under the Bevatron while it was in operation. The roof and outer walls are blocks which are moved with overhead cranes when beam channels are changed. The inner wall is strongly

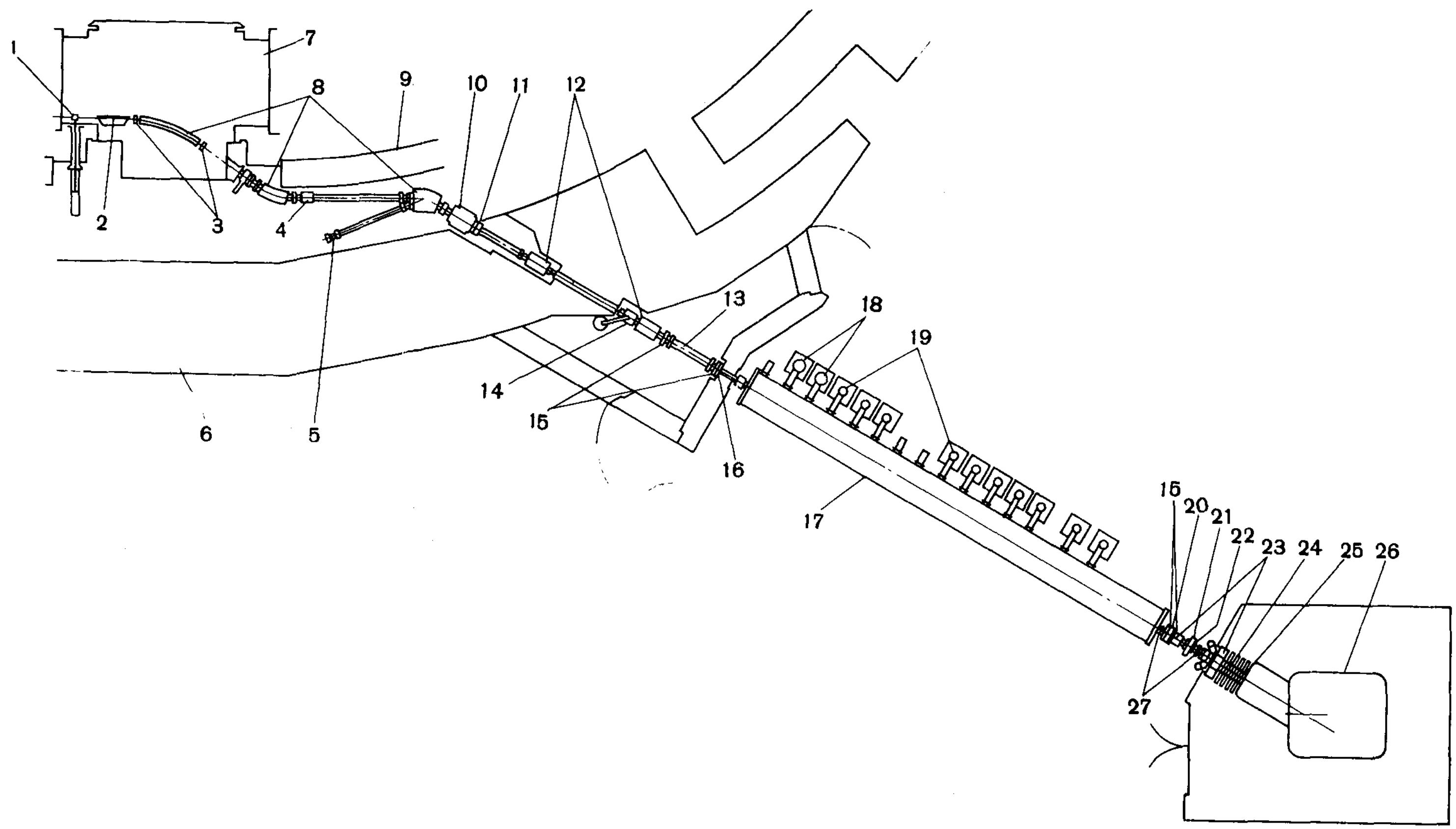

Fig. 1. Bevatron injection system:

1 — plunging Faraday cup and scanning slits; *2* — electrostatic inflector; *3* — beam transformer; *4* — chopped beam stop; *5* — 50° spectrometer Faraday cup; *6* — shielding wall; *7* — tangent tank; *8* — inflector magnets; *9* — bevatron magnet; *10* — debuncher; *11* — aperture; *12* — duadrupole magnets; *13* — steering coils; *14* — beam chopper; *15* — 4-jaw apertures; *16* — chopper defining aperture; *17* — linac tank; *18* — pre-exciters; *19* — oscillators; *20* — viewing box; *21* — buncher; *22* — carbon aperture; *23* — solenoid magnets; *24* — accelerating column; *25* — ion source; *26* — Generator Cockroft — Walton; *27* — steering magnets.

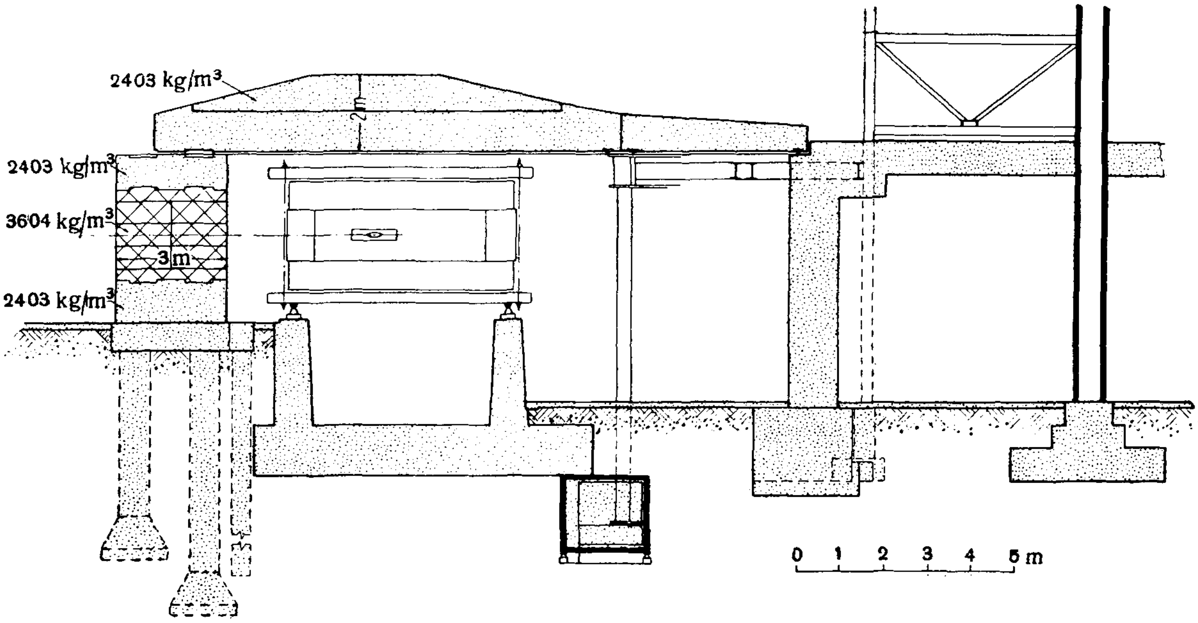

Fig. 2. Radiation shielding cross section.

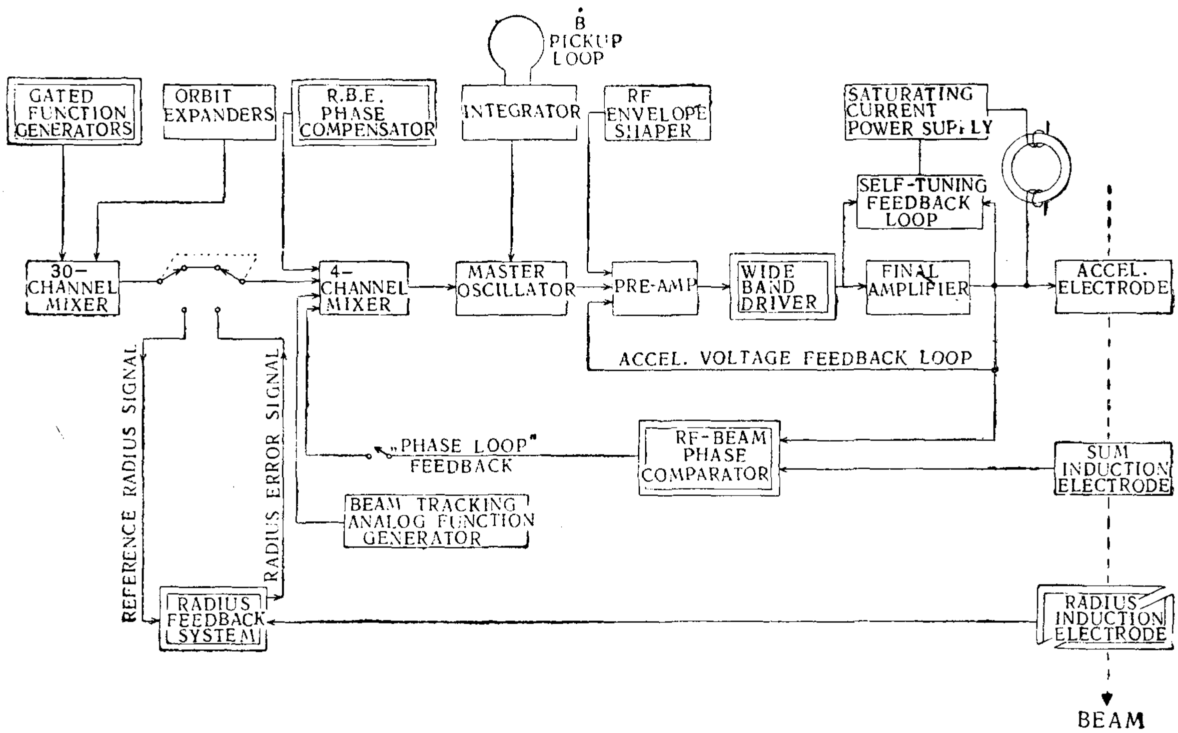

Fig. 3. Bevatron radio-frequency acceleration system. (New components are indicated in bold outline.)

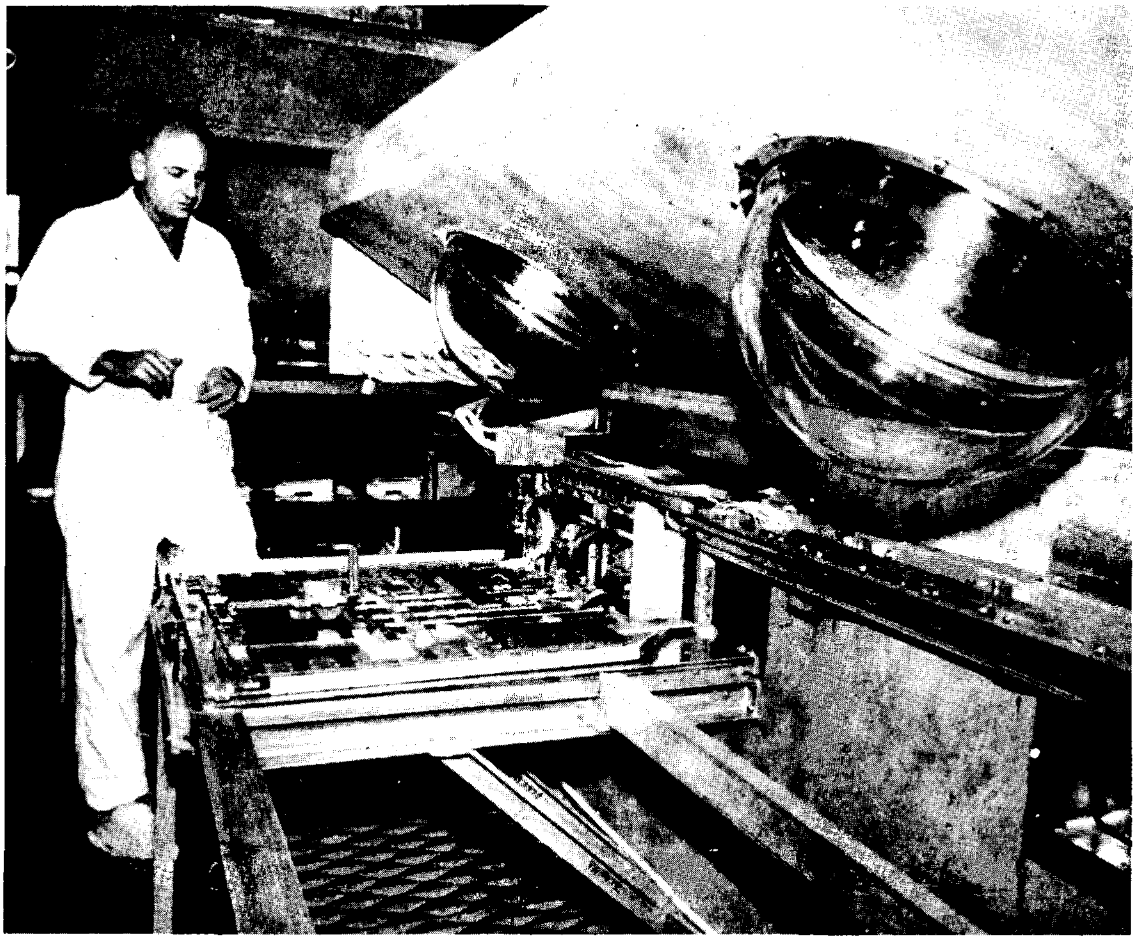

Fig. 4. Traveling target mechanism pictured at the air lock in the west straight section.

reinforced monolithic concrete and provides lateral stability to the entire structure by a system of keys which lock the roof blocks in place.

The performance of the shielding has not yet been analyzed in detail, but preliminary measurements show that radiation is reduced by a factor of 200 per unit beam compared to the previous partial shielding. This is adequate for our present operational levels, about 2×10^{12} protons per pulse. Radiation levels are about 12 $n/cm^2 \cdot s$ in the experimental area and one-tenth of that in the control room. There are a few known weak areas in the shield which can be improved rather easily if we operate at significantly higher beams.

4. RADIO-FREQUENCY SYSTEM

The radio-frequency acceleration system of the Bevatron is basically the same as that used previously. However, many of the components were rebuilt to improve operating characteristics and reliability. New features that have been incorporated are mainly in the frequency control system.

The basic radio-frequency system consists of a B-dot integrator, a master oscillator, a wide-band driver, and a final amplifier which excites a tuned circuit consisting of the accelerating electrode and a saturable reactor. The frequency-time relationship for synchronous proton acceleration is derived to within 2%

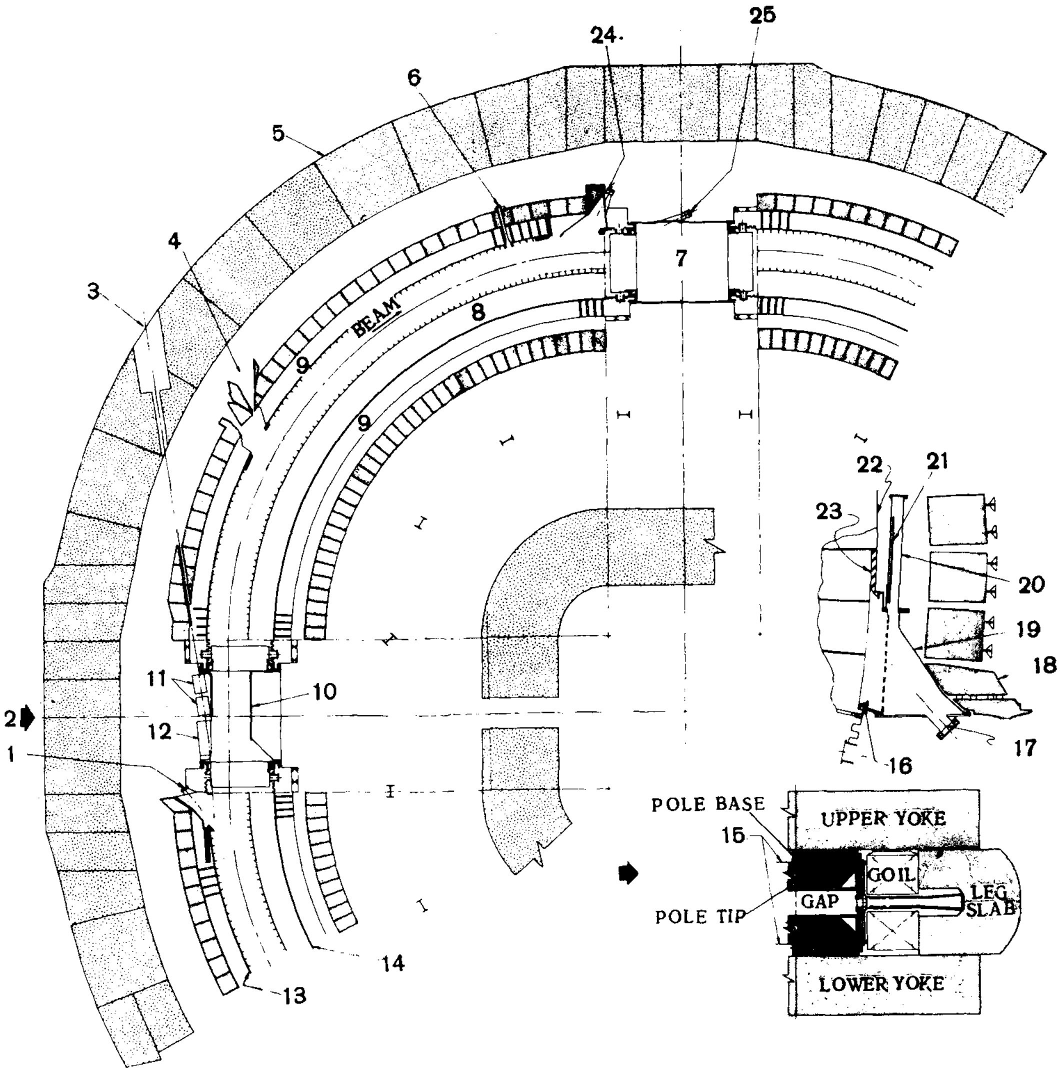

Fig. 5. Bevatron target areas. (The figure at right shows details of quad. 11—89° experimental area):

1 — quad. II — 89° experimental area; 2 — quad. II — 90° experimental area; *3* — external proton beam outlet; *4* — quad. III — 29° experimental area; *5* — 10 ft. concrete shielding wall; *6* — quad. III — 76° beam port; *7* — north tangent tank; *8* — crawl space; 9 — coil; *10* — west tangent tank; *11* — focus; *12* — bending; *13* — outer vacuum tank wall; *14* — inner vacuum tank wall; *15* — vacuum tank wall; *16* — flexible joint gasket; *17* — thin window; *18* — modified leg slab; *19* — vacuum nozzle wall; *20* — vacuum tank extension; *21* — gate valve door; *22* — curve tank wall; *23* — *3* sector stanchion; *24* — quad. III — 89° experimental area; *25* — quad. III—90° experimental area.

by integrating the voltage generated in a one-turn loop in the Bevatron magnetic field. This signal is used to modulate the frequency of the master oscillator which sweeps from 0.5 to 2.5 MHz during the acceleration cycle. The necessary 0.1% tracking accuracy is accomplished by introducing several correction signals into the master oscillator. These are shown in the block diagram, Fig. 3.

An analog-function generator produces a time-varying correction signal which has been empirically determined and can be adjusted by the operators. A phase-comparator circuit senses and corrects phase errors that develop during the acceleration cycle between the phase of the radio-frequency electrode voltage and the beam bunch. A radius feedback system provides a servo feedback of the radial position of the proton beam. It compares the beam radial position with an adjustable radius reference signal and generates a suitable correction signal. Additional gated function generators are provided to allow beam-steering flexibility, particularly to control beam spill and to divide the beam between several targets.

The wide-band diriver was redesigned to give greater reliability and control, and to provide the increase power capability — 10 to 20 kW— necessitated by additional beam loading. The final amplifier was essentially unchanged, although it had to be relocated to allow radiation shielding of the north straight section. The accelerating electrode was redesigned to eliminate beam-excited modes which had previously resulted in the beam loss at beam intensities above 10^{11} protons per pulse.

5. EXPERIMENTAL FACILITIES

Provision has been made for a flat-top magnet pulse to give the advantage of a long uniform spill, as is necessary for counter and spark-chamber experiments. The magnet power supply consists of two motor-generator sets and 48 rectifier-inverters to control the energy exchange between the magnet and the ac generators. Flat-topping is done by control of the firing angle of these rectifier-inverters, one machine being switched to the inversion mode while the other remains in rectification. Losses are compensated and any arbitrary rate of rise of the magnetic field may be achieved during the flat-top period by suitable adjustment of the rectifier-inverter firing angles. On alternate pulses, the roles of the generators are reversed to equalize the time average load on the generators.

The scheme in use provides a flat-top period of 350 ms at full energy, with a variation in start time of less than $\pm$ 5 ms. The pulse repetition rate is 9.3 pulses/min, compared to the normal 11. Longer flat-top periods, up to 1 s, and faster repetition rates are possible at lower beam energies. A small rate of rise of field during the flat-top, about 450 Gs/s is usually desirable to facilitate beam spill. This mode of operation increases the ripple on the power supply which must be compensated so that the modulation of the average B-dot is less than 100 Gs/s. The ripple is compensated separately in each quadrant by currents in the pole-face windings. These currents are modulated by transistorized amplifiers which are controlled by B-dot loops.

The flip targets used in the magnet gaps have been developed to a high degree of reliability, and have operated one and one-half million pulses without failure. They had the limitation, however, that they could be moved or replaced only by going down to air. We have now mounted these target mechanisms on trucks and have provided a set of tracks on which these trucks can move to any azimuthal position extending over 119-deg in the second and third quadrants of the Bevatron. An air lock has been provided in one of the straight sections so that the trucks can be removed to replace the target or to change its radial position without going down to air. We have four trucks each with two target mechanisms. The position of the targets can be read on a meter to an accuracy of 0.02-deg. The mechanism is shown in Fig. 4.

Facilities for extracting secondary particle beams have been substantially improved. At present, secondary-beam-transport systems may be vacuum-coupled to the Bevatron at four places — at the exit end of Quadrants II and III, at the north straight section, and at 29-deg in Quadrant III. Fig. 5 shows an overall layout of the Bevatron target areas. The curved thin aluminum window (0.5 mm) at the west straight section is used for extraction of both the deflected proton beam and secondary particle beams. Finally we have approximately doubled our beam transport equipment and now have 58 quadrupole elements, 25 bending magnets, and 11 MW of dc power.