DESIGN AND PURPOSE OF THE NATIONAL ACCELERATOR LABORATORY

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December 1971

The sole purpose of the National Accelerator Laboratory is research on high-energy particles. The energy of a particle is measured in terms of a fictitious dc voltage which, if used to accelerate a charge equal in magnitude to that of an electron, would give the same kinetic energy. Thus the primary beam of protons at this Laboratory will be 200 to 400 billion electron bolts--BeV. The term GeV, from the prefix giga, is synonymous with BeV. We also use keV and MeV for thousands and millions of electron volts.

Most experiments will use beams of secondary particles, such as π mesons. These beams are made by steering the external proton beam onto a well-shielded target, then focusing and selecting some of the secondaries with magnets. Overall, this arrangement is very long because the primary and secondary beams bend so slightly in normal magnets. Some experiments will be two miles from the accelerator.

Most experiments use only a particular few of the numerous interactions in the experiment target. These events are usually identified and measured by the simultaneous triggering of several

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*Operated by Universities Research Association for the United States Atomic Energy Commission.

detectors. There is always a short time interval (0.01 μsec) when two or more other events in the target can trigger the detectors and give a false coincidence. The chance increases rapidly with the instantaneous beam current on the target, and many experiments have a strict limit to the instantaneous current. The time to perform such experiments will depend on the accelerator's duty factor, the fraction of time beam is actually present on the external targets.

We expect with proper development of the accelerator to produce a steady beam of 200 BeV or more for one out of every four seconds. This involves a sophisticated process of slow extraction from the accelerator. Without this process, the duty factor would be about 100 times worse and many of our planned experiments would be impractical. The provision of an adequate duty factor is an essential feature of the design of our accelerator.

Acceleration is a form of radio-frequency transformer. The magnetic field is confined inside a copper cavity that is tuned to the radio frequency. Accompanying the changing magnetic field is an emf, just as in a transformer, which appears in these cavities as an axial rf electric field. A particle passing through the transformer at the correct phase will be accelerated. Particles at other phases will receive no energy or will be slowed down. The basic problem with these devices is impedance match. A group of 16 rf transformers, such as we use in the main accelerator, can provide about 2 MeV energy gain per particle on each transit of the particle through the transformers and for a 0.25-A beam will deliver about one-half of the rf power to the beam, the rest being lost in the cavity walls. Our accelerator need only have an average current output of 2.5 μA (1.5 × 10^{13} protons/sec) but 100,000 times the energy!

Two methods are used to overcome this mismatch. The method used in linear accelerators is to pulse the rf supplies for a few microseconds at a low repetition rate while accelerating a pulse of particles. Thus one obtains a reasonable beam loading with a small average current. This method becomes impractical for high-energy accelerators and has a very bad duty factor.

The other method simply bends the particles in a circle by means of magnets and directs the same particles through the rf transformers again and again. For our accelerator, we need about 4 miles of bending and focusing magnets to return the high-energy protons to the rf transformers, which themselves occupy only 100 ft! The radio frequency must be precisely a multiple of the circulation frequency for the protons so that the protons return at the correct phase for acceleration. Properly speaking, there is very little acceleration in the main accelerator, particularly at higher energies, because the protons are almost at the speed of light. The radio frequency is close to 53 MHz, which is 1113 times the orbital frequency. Therefore, there are 1113 "buckets" moving around the main ring in which protons can get the proper energy gain per turn.

The circulating beam current is the charge (number of protons) in the ring times the orbital frequency. For our design values the current is 0.5 A. The extracted proton beam current is the charge divided by the extraction time or 10 μA for 1 sec.

The energy gain is quite slow. Protons start at a low energy and low magnetic fields are needed for the proper orbit. Over a period of 1.6 sec, the protons gain energy and the magnetic fields are increased, then for 1 sec the high-energy beam is extracted at constant magnetic field and no rf. A period of 0.6 sec is needed to return the magnets to the injection field and the remaining 0.8 sec of the 4-sec total period is used to refill the buckets. This is the nominal cycle. For experiments that use lower energy protons or that do not need a good duty factor, the total period may be reduced.

The main-accelerator ring required an injection energy beyond that reasonably available from a linac. The magnets (2×5 in. aperture) would have to be larger and more expensive to contain the greater divergence of a lower-energy beam. In addition, we would have a quite intractable orbit because of the arbitrary nature of the remanent fields of the magnets at very low fields and would also have space-charge problems. The injection energy of 8 BeV is more than enough to overcome these problems. With this choice, the orbital frequency changes only about 1/2% in the main ring. This allows simpler, more efficient rf transformers. Note that although the main accelerator provides most of the energy, the injector must provide almost all the actual acceleration.

The 8-GeV protons for the main ring are extracted in a single turn from a smaller circular accelerator called the booster. In principle, the booster operates the same way as the main accelerator. The major differences, in addition to the smaller size, are a much faster cycle and a large change in the proton velocity.

The booster is 500 ft in diameter or 1/13 the size of the main ring. Each shot from the booster fills 1/13 of the main-ring orbit. By careful timing one can inject 12 shots into the main ring, thereby almost filling its orbit, and allowing the good duty factor that we need. By running the booster at a rate of 15 Hz, only 0.8 seconds is needed to fill the main ring. For the rest of the 4-sec main-ring cycle, the booster idles. The magnets continue to pulse but the rf transformers and other equipment do not operate.

The smaller size of the booster allows stronger focusing and therefore lower injection energy with the same magnet aperture as the main ring. Our choice of 200 MeV is higher than the magnets require in order to relieve the strain on the booster rf accelerating system.

At 200 MeV, the proton velocity is 0.57 of the speed of light. By the end of the cycle this fraction, as we have noted, is 0.995. The booster rf transformers must be tuned over the range 30 to 53 MHz (84 times the orbit frequency) and provide 8-BeV energy gain all in

1/30 second. One can easily understand why the booster rf is one of the most expensive and technically difficult of the systems in our accelerator.

The change of velocity also affects the circulating current in the booster. At 8 BeV the current must be the same as the main ring, 0.5 A maximum, but at injection, because of the lower velocity, this current is 300 mA. We will build up this current by injecting 75 mA for four booster turns, about 12 μsec.

The injection beam for the booster comes from a linear accelerator. A linac is simply a line of rf transformers, 500 ft long in this case, through which the particles go once. The length is split into 9 rf cavities, called tanks, all operating at the same frequency of 200 MHz. The change of proton velocity is accommodated by varying the number and spacing of the accelerating gaps within each tank. It is necessary to start the protons with some velocity so the gap spacing in the first tank is not too small. The preaccelerator is a 750-kV dc high-voltage set. The ion source for the accelerators is housed in its high-voltage terminal.

A linac achieves a reasonable efficiency by pulsing. The rf is turned on, a short but intense pulse of protons is accelerated and the rf is turned off. In our case, the process repeats 15 times per second, each proton pulse being about 15 μsec long. In this short time neither the tanks nor the rf power supplies heat up excessively, even at high fields, and the pulsed current of 75 mA (measured at 200 MeV) absorbs a noticeable part of the rf power. After 12 pulses to the booster, the rf timing is shifted so that protons are not accelerated until needed again. Neither the ion source nor rf is turned off. A small change in the control computer program is all that is needed to accelerate protons 15 times in every second.

The accelerating power of the linac not used by the booster is substantial. Expressed as a dc average current, the output for radiation purposes is in excess of 10 μA at 200 MeV or 2 kW of beam power. The exact output will vary with the requirements of the high-energy research program. Some adjustment of the linac between pulses for the booster and for radiation is possible. The beam energy is readily adjusted by changing the phase of the rf. More difficult is adjustment of the ion-source pulse length and current. It will be necessary for the high-energy experimenter to believe that such adjustments do not degrade his beam.

The potential conflict can probably be avoided. The linac beam has too high an energy and much too high a current. In addition, the beam is too good for radiation work, its energy spread is less than 1% and its emittance (size times divergence) is such that it can readily be focused to a few mm^2 but not readily blown up to cover a square ft uniformly. Using a system of absorbers, slits, bending and focusing magnets one should be able to make a new beam of much lower current which can be adjusted in energy, energy spread and emittance.

In any case, the "free" protons of the linac are an excellent beam for proton radiation therapy.

One must be aware that there have been other proposals to use "free" protons, particularly to develop the booster for high-intensity 8-GeV physics research. Such proposals have been resisted on the basis that the overall effort will subtract something from our high-energy program. Of course, there exists extensive facilities for this type research a few miles away at Argonne National Laboratory. The situation is quite different for proton-therapy research, but it is still necessary for some organization within the medical profession to convince the Universities Research Association to expand its commitments in this direction. I hope that we can establish such a project, but big enough and with an organization that can insure continuous effort so that the entire Laboratory will be proud of our success.