OPERATING RESULTS FROM NAL*

The NAL Staff
(Presented by D. E. Young)
National Accelerator Laboratory
Batavia, Illinois

Summary

The NAL accelerator achieved design energy of 200 GeV on March 1, 1972. Since that time, the main accelerator has operated as high as 400 GeV and regularly operates at 300 GeV. The highest intensity to date has been 1.8×10^{12} protons per pulse at 300 GeV. This beam has been extracted from the accelerator using a half-integral resonance system to give a slow spill over approximately 250 ms. The extracted beam is presently being split and sent into three different experimental areas. In addition, a target area in the main accelerator enclosure allows experiments to be done on the internal, circulating beam.

Introduction

This paper summarizes the results of the first year of operation of the NAL accelerator. It was just a little over a year ago, on March 1, 1972, that the accelerator achieved design energy of 200 GeV. Now, a year later, we have operated as high as 400 GeV and regularly operate at 300 GeV. Our best recorded intensity has been 1.86×10^{12} protons per pulse at 300 GeV. During a recent high-energy physics run, we accelerated 10^{17} protons in two weeks, an average of 5×10^{11} protons per pulse over all possible pulses in that period. Although we have not reached our design goal of 5×10^{13} protons per pulse, we have come some way toward it and are working hard to improve.

Description

The NAL accelerator has been described elsewhere.[1,2,3] and a brief review will suffice to recall its principal features. Figure 1 shows an aerial view of the entire accelerator. An artist's view picturing the separated beam lines to the three experimental areas is shown in Figure 2.

The injector consists of a 9-cavity, 200 MHz, 200-MeV linear accelerator (Figure 3), and a 8-GeV rapid-cycling alternating-gradient booster synchrotron (Figure 4). The booster contains 96 10-ft long magnets on a 75.5-m radius. The magnet lattice is divided into 24 periods, each containing four combined-function magnets and a 6-m long straight section. The 16 RF acceleration cavities are located in eight of the straight sections. The magnets are excited at a 15-Hz frequency. The beam from the linac is injected into the booster at a minimum magnetic field of approximately 500 G and is extracted near the maximum field of approximately 7000 G. The accelerating frequency of the cavities is varied from 30 MHz at injection to 53 MHz at extraction by biasing ferrite tuners.

The beam from the linac is bunched at 200 MHz, but the momentum spread is large enough that it debunches in less than two turns around the booster. The beam is then adiabatically rebunched and captured in the 30-MHz RF buckets by turning on the booster RF voltage in 16 steps over a period of 150 μs.

Figure 1. Aerial view of accelerator complex (August, 1972).

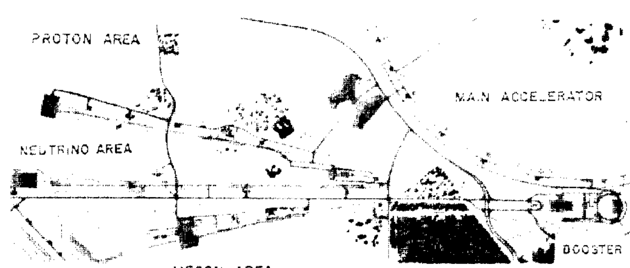

Figure 2. Artists view of beam lines and experimental area.

The main accelerator is a separated-function synchrotron of 1000-m radius consisting of 774 bending magnets, 192 standard cell quadrupoles, and 48 short quadrupoles (Figure 5). The synchrotron lattice is divided into six identical superperiods, each containing

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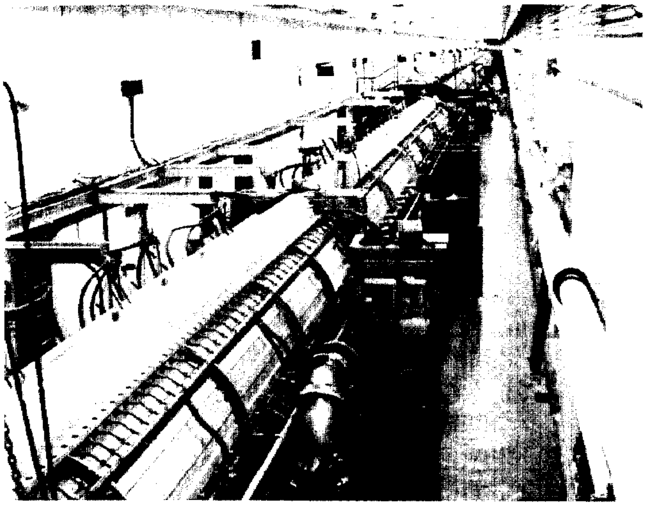

Figure 3. 200-MeV linear accelerator.

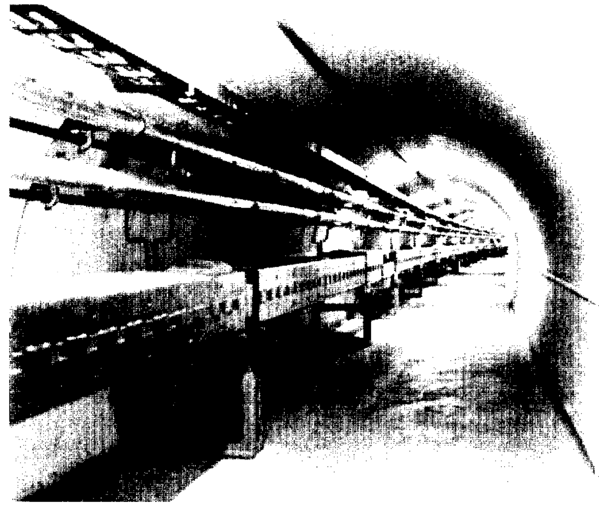

Figure 5. Installed main accelerator magnets.

sixteen cells and separated by a 51-m long straight section. The normal cell consists of a radially focusing quadrupole, four bending magnets, a defocusing quadrupole, and another four bending magnets. At 400 GeV, the peak field in the bending magnets is 18 kG, and the peak quadrupole gradient is 2.5 kG/cm over a width of ±2½ in. The long straight sections are used as follows: one for beam injection and extraction, one for the RF acceleration cavities, one for a beam-abort system, one for an internal-target area, and two presently unused. The magnets are driven from a power supply[4] according to a flexible cycle derived by a program in a controlling computer. A typical 300-GeV cycle is shown in Figure 6 where the injection takes place during the 0.8-s rest field, and the acceleration occurs while the field is increasing at a nominal rate of 125 GeV/s. Extraction of the beam takes place during the flattop at the peak field.

Acceleration in the main accelerator is accomplished by using up to 15 cavities operating at a frequency of from 52.812 MHz to 53.105 MHz. Typical accelerating voltages are approximately 2.8 mV per turn. The cavities are shown installed in Figure 7.

The 8-GeV beam is extracted from the booster with a fast kicker-magnet system that produces a beam pulse whose length is equal to the circumference of the booster. To fill the main ring with beam, the magnetic guide field in the main ring is held constant at the injection field strength for 0.8 s at the beginning of each main-ring cycle to allow up to 13 pulses of beam from successive cycles of the booster to be stacked end to end in the main ring. To reach the design intensity of 5×10^{13} protons per pulse in the main synchrotron, the booster must inject 13 pulses of 3.8×10^{12} protons each at the beginning of each cycle of the main ring. To achieve this intensity in the booster, multiturn injection from the linac into the booster has been planned. Four turns of 75 mA from the linac stacked radially in the booster should produce the desired current.

Slow extraction from the main accelerator

Figure 4. The booster synchrotron showing an installed girder module with a focusing and defocusing magnet.

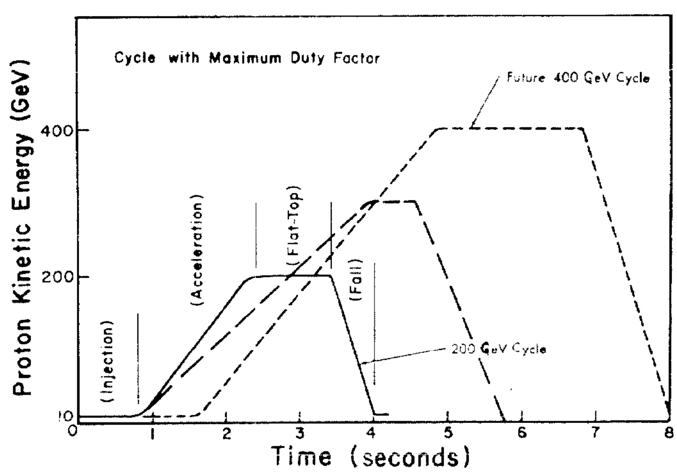

Figure 6. Acceleration cycles. The 300-GeV cycle shows a reduced rate of rise.

is accomplished by a half-integral resonance system.[5] The betatron oscillation frequency is moved to a value close to the half-integral resonance $\nu_x = 20.5$ after the beam has been moved radially close to the extraction channel. A quadrupole perturbation causes the beam to move into the resonance, resulting in an exponential growth in amplitude of the betatron motion to allow the beam to be slowly extracted from the accelerator. The extracted beam from the accelerator is then sent to the three experimental areas. Splitting stations have been installed in the transport lines to the experimental areas so that beam pulses can be shared with variable intensities between the different experimental areas.

Any beam which is not extracted from the accelerator is deposited in a beam dump consisting of a set of movable scrapers followed by radiation absorbers.[6] The beam is driven into the scrapers by exciting bump magnets at the end of the main-accelerator cycle. This beam-abort system has kept the radiation level low in most of the other accelerator components.

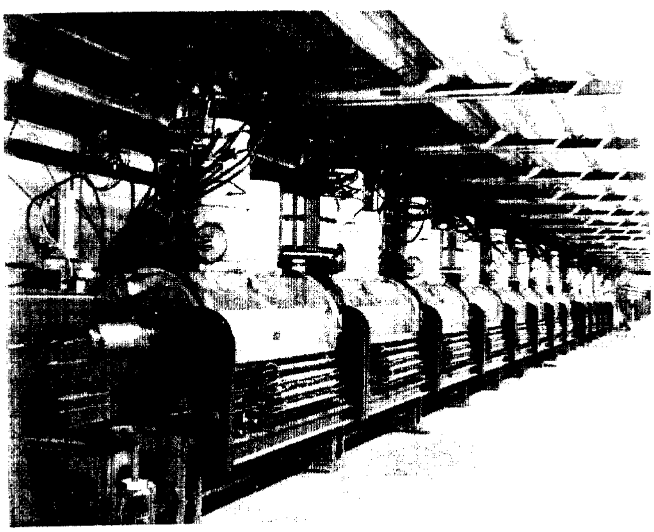

Figure 7. Installed main accelerator RF Cavities.

Accelerator Performance

Linac

The 200-MeV linac regularly produces a peak current of 80 to 90 mA, compared with the design current of 75 mA. The measured transverse emittances at this beam current are approximately 20% larger than the design value (10π mm-mrad). The total momentum spread (for 95% of the beam and no debuncher) is about 0.3%, very close to the design value.

The linac has operated almost continuously during the past year with a reliability of 90% or better.[7] The final-stage power-amplifier tubes used for exciting the cavities have caused the greatest operational concern because of their short lifetime and expense. Their present average lifetime is about 9000 hours, but it is hoped that this can be extended by improving manufacturing techniques. Efforts are underway to improve the beam intensity and quality by improving the ion source and the frequency response of the feedback loop that compensates for beam loading in the cavities.

Booster

The booster operated for some months at 7 GeV (instead of 8) and at 1 pulse/s because of RF problems. Blocking capacitors installed in the RF cavities reduced the gap voltage and overheated when the cavities were run at the 15-Hz rate. There was an unsuccessful interim attempt to water-cool them, but by the end of 1972 all had been replaced by new ceramic blocking capacitors. We now operate at 8 GeV and at the rate of 12 successive pulses at a 15-Hz frequency. No booster magnet has ever required replacement. The rapid-cycling power supply operates reliably. It required considerable work to regulate the peak field accurately enough for multiple-pulse injection into the main ring, but that problem is now solved. A program for simulating measured closed-orbit displacements on a computer and realigning magnets to reduce them has been carried out with good success. Closed-orbit errors are now one-fourth as large as they were originally.

The greatest difficulty in the booster has been in achieving higher intensity. We are currently operating at an intensity of about 5×10^{11} ppp for single-turn injection, which is about a factor of 8 below the design value. Multiturn injection efforts have not, as yet, resulted in an increase over this value, due partially to the fact that the measured radial and vertical acceptances seem to be approximately half the design values. This dimunition can be seen in all long straight sections around the booster. There is also evidence of both a coherent vertical oscillation and betatron-synchrotron-oscillation coupling. These effects are not understood at this time. We have made detailed measurements of tune as a function of radius and have installed sextupole lenses to correct the tune across the radius.

Earlier, there was a loss of beam at transition energy caused by the head-tail effect. It was cured by introducing some sextupole components with correction lenses.

There is also a decay of the beam in the first few milliseconds, which is less severe with dc field excitation and the RF off. It may be caused by betatron-synchrotron-oscillation coupling, but we are still investigating.

Main-Accelerator Magnets

A year ago we were having considerable difficulty with shorts occurring in the main accelerator magnets. Characteristically, these were shorts to ground, usually occurring approximately a foot in from one end. The most probable cause seemed to be cracks or voids in the insulation that made a path for water. The problem was aggravated by the extreme humidity in the tunnel in the early days. The situation has improved so that currently the failure rate amounts to a few per month. The most frequent mode of failure now occurs when a manifold insulator breaks and a magnet end is wetted. The failures are almost always very old magnets from early in the production. It requires about four hours to replace a magnet.

There have actually been four generations of bending magnets. The first generation utilized nonvacuum impregnated epoxy with plaster of paris to fill empty spaces. Of these, approximately 200 (practically all) have failed and been replaced. The second generation did not utilize plaster of paris, but the epoxy was still not vacuum impregnated. Of these, approximately 100 (about half) have failed and been replaced. The third generation utilizes vacuum-impregnated epoxy; a few of these have failed. The fourth (present) generation utilizes a partially cured epoxy assembly of the vacuum chamber and coils integrally impregnated into the core. Each new magnet is immersed in water, then tested to four times the maximum operating voltage. Only one of these has shorted.

The failed magnets are not a total loss. They are rebuilt as new, fourth-generation magnets for about one-third their original cost. The core and coils are completely salvagable. Only the insulation and assembly are redone.

There have been some difficulties with vacuum-chamber obstacles, now largely solved, that arise because cuttings from chamber flanges dropped into the chamber itself during the many changes. Considerable debris was removed by passing an umbrella-shaped device through the entire chamber. The stainless-steel cuttings become magnetic from cold-working. Two large (almost 1-in long) cuttings have been found that stood up when weak test fields were put on the magnets they were in. These cuttings were quite radioactive, so they must have intercepted some beam. We now follow a rigid procedure of cleaning and inspecting the chamber when we change a magnet.

The main-accelerator magnet power supply[4] has proved to be flexible and easy to use. There have been problems with burning cut thyristors, but the cooling and protection circuitry have now been developed to the point where thyristor-module failure is a less severe problem. A problem that has been growing in magnitude recently involves failures in the flexible water hoses used to supply cooling water to the heat sinks for the thyristors. When a failure occurs, the power supply is wetted and must be removed from the circuit. These hoses are being replaced. The power-supply control system is, we believe, a real advance. It is quite a sight to see the magnet cycle learn to regulate itself on successive pulses. After just a few minutes of a completely new cycle, the regulation is good enough to accelerate particles.

Main-Accelerator Orbits

In the first days of acceleration, well over 90% of the injected beam was lost during the injection front porch and the beginning of acceleration. The loss may have been gas scattering in a very restricted aperture, with considerable coupling of radial and vertical motion to enhance the effect. The injection loss has been gradually reduced as we have improved the vacuum, straightened out the closed orbit and realigned the magnets. We now lose perhaps 30% of the injected beam when the accelerator is well tuned (Figure 8). Part of the loss now appears to be caused by third-integral nonlinear resonances, which we see in both the radial and vertical motion. That is, there is a sharp beam loss when either ν_x or ν_y is close to 20.33.

The main ring has large numbers of radial and vertical correction dipoles for use at injection. They can be used individually, can be ganged together by the control computer to give local orbit bumps, or used as a whole to produce any desired harmonic. They are important to getting a good circulating beam, principally because of remanent fields in the bending magnets. The orbit-straightening program discussed below has reduced the dipole correction needed.

There are also correction sextupoles. We cannot get good circulating beam without them, because there is a considerable remanent sextupole field in the bending magnets. Even though our ramp starts with a 200-ms parabola to minimize eddy currents, we must pulse the sextupoles off as the ramp starts up or we lose beam. There are also trim quadrupoles and skew quadrupoles in the ring. The skew quadrupoles improve the beam significantly by reducing radial-vertical coupling.

An orbit-straightening program[8] similar to that in the booster has been carried out. The major difference is that the main-ring computer simulation can search for a minimal number of magnet moves, which is important because the main ring is so large. The high-field closed-orbit distortion has been reduced by about a factor of two in both planes from the values measured in the earliest 200-GeV operation. Occasional readjustment has been

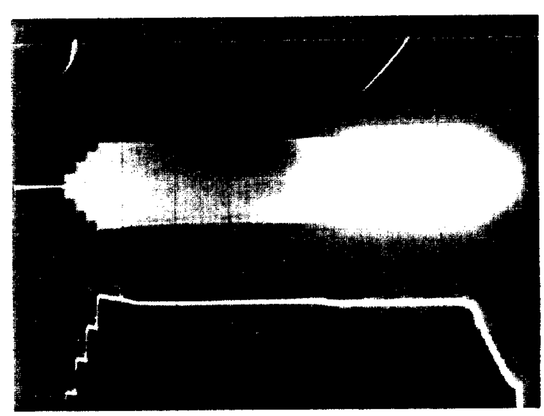

Figure 8. Injection, acceleration to 200 GeV, and slow extraction of 4 booster pulses, measured on two different detectors. Time scale is 0.5s per division and the total accelerated charge is 4×10^{11} protons.

required to hold this level due to magnet replacements, etc. The current maxima are 2 cm radial and 0.6 cm vertical. We have also reduced the coupling by leveling all bending magnets (bending-magnet position is not important; only the twist affects orbits) and rolling selected quadrupoles about the beam axis.

We have measured ν_x and ν_y throughout the acceleration cycle by inducing an oscillation with an air-core kicker and counting waves on a position detector. The tunes can be kept quite constant throughout acceleration by adjusting the ratio of the bend and quadrupole currents, except near injection and at the top when we purposely vary them for extraction.

We still have considerable work to do to increase the available aperture in the main ring in order to reduce beam loss and to prepare for higher booster intensity. We have as yet observed no space-charge effects in the main ring.

Main Accelerator RF

Beam from the booster is injected into existing main-ring buckets, that is, with RF on.[9] The first booster batch gives frequency and phase signals to the main-ring RF, which phase-locks to this beam. Subsequent booster batches are phase-locked to the main ring.

We found that there were large phase oscillations in later-injected batches. At 8 GeV, the booster is above transition energy and the main ring is below. Consequently, the effect of the RF radial feedback signal in the main ring when the momentum of the first batch did not closely match the guide field was to require the booster to extract the next batch at an even worse momentum, which gave large phase oscillations. This problem has been cured by regulating the main-ring guide field during injection from the RF radial-position signal (with RF radial-position feedback turned off). The resulting gain in stability of injection has been very gratifying. We can now capture all 12 batches that we can inject (Figure 9).

The major causes of downtime in the RF system have been two cracked gap insulators. The second such failure resulted in an excessive amount of downtime due to difficulties in reestablishing good vacuum, mainly as a result of deterioration of the ion pumps.

Extraction

The early physics program at NAL was started using fast extraction (single turn) of the single booster pulse accelerated in the main accelerator. The 1.6-μs pulse can be extracted with nearly 100% efficiency and this is a useful beam for tuning up beam lines and checking calibrations of beam detectors. Slow extraction is accomplished by tuning close to the half-integral stopband and pulsing an extraction quadrupole to move the beam into the stopband. Beam spills during flattop of 250 ms have been achieved with an efficiency of 95% (with an uncertainty of +3% and -5%). Our best measure of the extraction efficiency is the induced

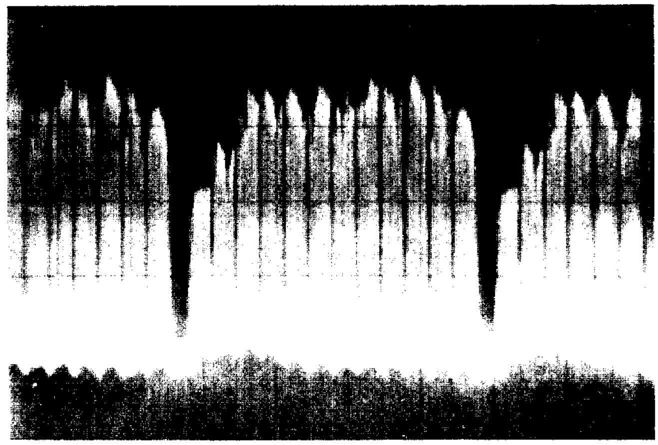

Figure 9. Twelve booster pulses early after injection in the main accelerator.

radioactivity in the extraction components after an extended period of running. This slow-resonant extraction can be followed by a "pinged" fast beam that allows a small amount of the slow-spill beam to be extracted in a single-short pulse. This small amount of fast-extracted beam is usually sent down a bypass for bubble-chamber experiments. Shorter extraction time can be achieved by bringing the tune close to the stopband and "pinging" a coherent betatron oscillation to bring it into the unstable region. The beam can then be extracted with good efficiency in 5 to 10 turns (100 to 200 μs).[10]

One noteworthy success has been the smoothing out of the extracted beam by using a feedback signal from it to drive an air-core quadrupole in the ring. The major effect is to damp out effects of 720-Hz ripple in the magnetic field.

Accelerator Controls

In the last year, the accelerator controls[11] have been unified so as to develop a versatile control system capable of providing real-time status and monitoring information. The control system, though sometimes frustrating when it malfunctions, has been of great aid in understanding and improving the operation of the accelerator. The great flexibility and versatility of the system has allowed a number of accelerator variations and experiments to be quickly implemented. The system is still undergoing extensive development.

Experimental Program

High-energy physics experiments started in the Internal Target Area almost with the first 200-GeV protons accelerated. By May an extracted beam had been transported to the first target station in the Neutrino Beam Area. This fast extracted beam was used for 200-GeV bubble chamber pictures in June. By July a muon experiment had started and more bubble chamber pictures were taken at 100 and 300 GeV. In September, beam had been sent briefly into the other two experimental areas, the Meson Area and the Proton Area. The

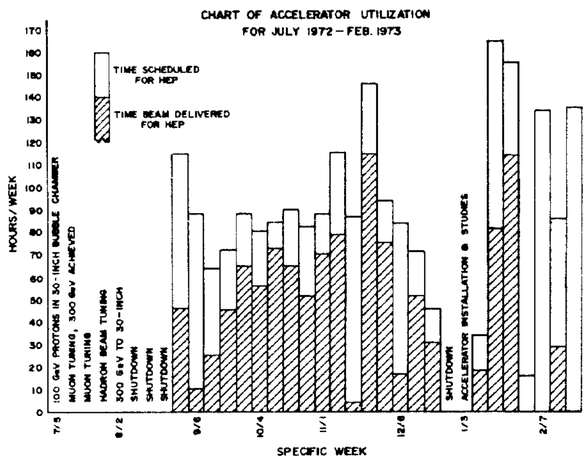

Figure 10. Accelerator utilization for high-energy physics experiments.

increase in accelerator intensity by filling more of the main accelerator circumference with additional pulses from the booster and the improvement in the slow-extracted beam have enhanced the data collection in the Neutrino Area and numerous neutrino events have been collected. At the present time, beam-splitting stations[12] have been installed so that several experimental areas can be operating simultaneously, with beam pulses split to divide the intensity in varying proportions. A notable milestone was achieved in December when nearly half a million proton elastic-scattering events were observed during several hours of accelerator operation at 400 GeV.

The current status of the experimental program can be summarized as follows:

Experiments with published results	6
Experiments with completed exposures	10
Experiments in progress	13
Experiments in test stage	6
Experiments being installed	9

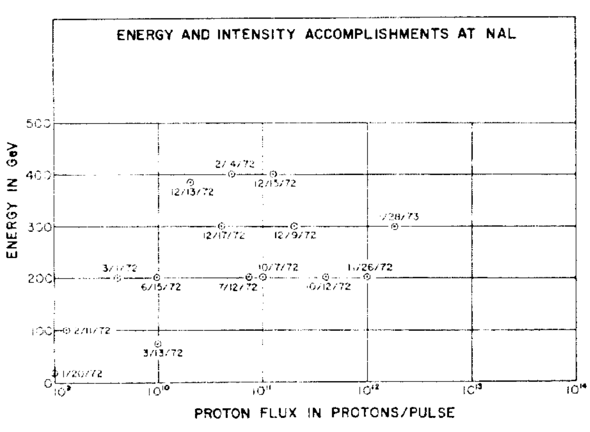

Figure 11. Accelerator improvements in energy and intensity.

At present, considerable time is still being devoted to accelerator and beam-line development, but more protons are continually being delivered on target for longer periods of time. The accelerator utilization is shown in Figure 10, where the time scheduled per week is compared to the actual time that beam was delivered during the scheduled period. Figure 11 shows, with dates, the improvement in the accelerator in energy and intensity. It is clear, we believe, that the accelerator is a useful physics instrument.

Conclusion

Many of the problems of the NAL accelerator have been solved and it operates with some reliability, but, of course, we still have a few problems to work on. We believe we have shown that the fundamental design concepts of the accelerator are sound. At the end of the first year of operation, we are working to improve our reliability and to increase our intensity up to the design goal of 5 x 10^{13} protons per pulse. We have come a long way toward this goal from our initial operation. We hope we will be able to report success at the next conference.

Acknowledgements

The construction, operation, development, and utilization of the accelerator is the entire laboratory effort. Any achievements or credits should be shared by the entire laboratory staff, but special credit is due to those people who have, by their dedicated work, helped to accomplish the work reported here.

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