STATUS OF ACCELERATOR DEVELOPMENT AT FERMILAB

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The Fermilab accelerator is comprised of four major systems: the high-energy beam-extraction and switching system, the main accelerator (main ring), the booster, and the linear accelerator. The Fermilab accelerator produces accelerated beam for a vigorous international high-energy physics program. The basic design features and operation for high-energy physics have been described a number of times in the past.[1,2] In this report, for the most part, only those features that are particularly significant in increasing the usefulness of the accelerator as a tool for high-energy physics will be discussed in any detail.

Briefly, the current status of the major systems is as follows: The extraction system[3] has been very successful in extracting high energy beam from the main ring with losses of about 1%. The extraction system poses a restriction on beam intensity ultimately because of residual radioactivity problems (primarily at beam splitting stations) even with the very high efficiency the system achieves. Routinely, the extraction losses can limit the beam intensity because of stability problems in the main ring which can arise from a large number of sources (not limited to the main ring). There are two basic extraction modes, a fast mode and a slow one. The fast mode can be used to extract the beam in one turn (20μs) or several turns. The slow mode can accomplish a uniform extraction of beam over a period of at least two seconds.

Usually, the beam is extracted using a combination of the two modes with the fractions determined by the high-energy physics program. It is likely that the minimum duration possible with the slow mode can be shortened to about one-half millisecond from the present one millisecond.

The main ring has accelerated protons to 500 GeV, although the usual operating energy is 400 GeV. Reaching 500 GeV required extensive development of the computer program that controls the operation of the magnet power supplies and of the reliability of the power supplies themselves. This reliability has been developed to the point where operation at 400 GeV is as reliable as operation at the original design energy of 200 GeV.

The main ring has reached intensities as high as 2.0×10^{13} protons/pulse and operates typically in the range of $1.5 - 2.0 \times 10^{13}$. The factor by which the accelerator has failed to achieve its design intensity is equal to the factor by which it has exceeded its design energy.

Losses in the main ring are usually of the order of 15-30% at high intensities and are associated with problems at injection, at the start of acceleration, and, most prominently at high intensity, at transition energy. Injection to the main ring is complicated by the fact that 13 booster pulses are required to fill the main ring. The booster beam is injected synchronously into stationary rf buckets in the main ring (84 buckets per booster pulse). The fact that small injection errors - either longitudinal or transverse - not only result in losses in the main ring but also can have striking effects on the efficiency of extraction and the structure of the extracted beam places unusually high demands on the stability required of the main ring and booster, and even the linac.

The main-ring losses at the start of acceleration are usually small and are continually being reduced by improvements being made to the main-ring magnet power-supply system and the rf program. The losses at transition are much more serious and much more difficult to deal with. These losses are now a principal subject of investigation in the main ring, early problems with nonlinear remanent fields having been ameliorated. The problems at 2×10^{13} protons/pulse are primarily those associated with the necessary manipulations of the main-ring rf under high beam-loading conditions. It is unknown at what intensity space-charge problems at transition will become dominant or even to what extent they would contribute at present intensities if there were no beam-loading problems.

The booster suffers from the unenviable position of having to take what the linac is able to deliver and to furnish beam to an extremely demanding main ring. In addition, the booster suffers from all the problems one would expect in a rapid-cycling synchrotron - vacuum problems, rf problems, and, not the least, measurement and diagnostic problems. Considerable progress has been made in dealing with the booster's difficulties. The vacuum and rf problems are largely under control. Substantial improvements have been in the 200-MeV injection and beam-transport line, including hardware and control improvements, as well as the addition of a debuncher and a change in the style of injection from a multiturn-injection mode to a much more efficient high-current single-turn mode.

The addition of a fast vertical beam damper sometime this Fall is expected to result in an immediate modest improvement in booster performance. It will ease the difficulties of studying the causes of very small horizontal acceptance, which appears to be the main reason for beam loss in the booster. The combined size effects of emittance, synchrotron motion, and average radial-position variations are not compatible with the observed horizontal acceptance during the early part of the acceleration cycle. The main thrust of the development effort on the booster has been to understand the causes of this small acceptance.

It must not be inferred that massive increases in horizontal acceptance in the booster would solve all the problems in the accelerator because the horizontal acceptance of the main ring, appropriately scaled, is not a great deal larger than that of the booster, but it should be possible to increase the

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booster efficiency appreciably with only a small attendant effect in the main ring. At present, the booster can accelerate as much as 2.6×10^{13} protons/13 pulses with an efficiency of just under 50%. The efficiency increases steadily, but not dramatically, as the intensity is lowered.

In addition to programs designed to increase the acceptance of the booster and 200-MeV transport line, there is a major effort being made to improve the quality of the beam injected into the booster. The first step in that effort was the addition of a debuncher. Although the main reason for the installation of the debuncher was to decrease the momentum spread of the beam (which is adiabatically captured in the booster), thus reducing the very severe demands made on the booster rf system, that is by no means the only benefit of the debuncher. Most significantly, the debuncher automatically stabilizes the mean momentum of the beam injected to the booster and makes it possible to operate the linac at much higher intensities than would be possible otherwise and still deliver an acceptable beam to the booster. There is sufficient rf power available to accelerate 80 to 100 mA of protons in the Fermilab 200-MeV linac (depending on the state of health of the rf power amplifiers). Anything in excess of that current must necessarily be accelerated at the expense of stored energy in the linac accelerating cavities. Obviously, arbitrarily long beam pulses cannot be accelerated under such conditions, but, since the booster requires only a 3 μs beam pulse for single-turn injection, it has been possible to accelerate as much as 270 mA in the linac without experiencing increased losses in the linac, without more than a slow monotonic increase in transverse emittance, and with a variation in mean momentum during the entire pulse (almost 5 μs long because of slow electronics at the ion source) of less than ±0.1%. That momentum variation would be completely intolerable for the booster without the debuncher, but it vanishes to first order with the debuncher. Improvement in the ion-source electronics will result in a more nearly square beam pulse of minimum necessary width and a consequent improvement in mean momentum variation during the pulse.

It is necessary to use artificially produced error signals to control the rf power amplifiers during and shortly before the beam pulse in order to use the avilable rf power because conventional feedback systems would be too slow (the delays inherent in the entire rf system are too long). The pulse width, time, and amplitude of the artificial error signal necessary for minimum momentum variation during the pulse are easily determined empircially. (This is a flexibility enjoyed by multi-cavity linacs that compensates in part for some of the difficulties they suffer.) The principal disadvantages of this mode of operation are that the dynamic range is rather small - more than a small change in current necessitates a readjustment of the error signal - and that considerable care must be taken to ensure that the artificial error signal vanishes when the beam vanishes, for example when the Cockcroft-Walton injector sparks. With a computer-controlled system such as that for the Fermilab linac,[4] it is possible to preset different sets of parameters appropriate for different currents so manual readjustments of the error signal need not be done when the current is changed, although we have not yet taken advantage of that possibility.

In our present high-current mode of operation, the linac current is limited by the current available from the injector. Improvements are in progress.

Another approach to high booster current is also being pursued - that of negative-ion injection. By passing the negative ions through a thin-foil stripper on a temporarily perturbed orbit in such a way that the resulting proton has the correct position and angle to that orbit, it is possible to continue to inject negative ions, strip them, and add them to the circulating proton beam. At the end of the injected beam pulse, the orbit perturbation is removed and the circulating beam is moved away from the stripper foil into its normal orbit for acceleration. The stripper foil must be thick enough to strip the ions effectively and thin enough not to cause excessive multiple scattering and emittance growth. (The energy loss in any foil of interest is trivial.) In order to achieve injected charge equivalent to that now possible with one turn and 250 mA, assuming approximately the same emittance and momentum spread for the negative-ion beam and for a proton beam, it will be necessary to inject a 25-mA negative ion beam for ten turns or 10 mA for 25 turns. The negative-ion injection project is being done in such a way that it will serve as an alternative mode of injection rather than as a replacement for the existing one.

It appears from tests now being conducted on two negative-ion sources that negative-ion currents of 30 mA at 200 MeV will be realistically achievable. Although that is a modest current, several advantages accrue to handling modest currents, not the least of which is an enormous reduction of beam loading in the linac. Space-charge induced increases in momentum spread and emittance will also be reduced. The emittance to be expected is not known with any certainty. Measurements made at Novosibirsk and at Brookhaven National Laboratory on similar sources indicate very small emittances. We are assuming that the emittance at 200 MeV will be similar to that attainable with the same current of protons. If that assumption proves to be valid, or conservative, we easily should be able to match the present booster performance with much less severe demands on the linac. It is impossible to predict the increase in current in the booster, but it seems reasonable to expect that a fairly substantial increase is not unlikely.

Although not related to high-energy physics, there are two other applications of the linac system. One is an experiment in proton radiography, which will use a very low intensity 200-MeV proton beam scattered from a target inserted between the 40° spectrometer magnet and the beam dump in the 200-MeV diagnostic area. Aside from the minor inconveniences associated with the installation of the target and beam line, we anticipate no conflicts with the high-energy physics program, only an occasional, brief loss of the use of the momentum-analysis equipment while radiography is being carried out. The experiment should be operational in October.

The other use made of the linac beam is the production of neutrons for radiotherapy. For this application, a Cancer Therapy Facility has been built. Because during normal high-energy physics operation, the linac produces beam for only 13 pulses at a rate of 15 Hz and then is not again required to furnish beam for the booster until the start of the next main-ring cycle - from a few seconds to about 15 seconds depending on the main-ring energy and the length of time spent at the maximum field for slow extraction - it is possible to produce linac beam during that unused time for other purposes.

Because of the energy spectrum of the neutrons produced, 66-MeV protons on beryllium were chosen for the neutron source. The 66-MeV proton beam is extracted near the center of the linac after being accelerated through the first three cavities and drifted through the fourth. The beam strikes the target in a shielded enclosure in the basement of the linac building where patient treatment takes place. Patient irradiation time is approximately 4 minutes when the linac is operating near maximum peak intensity, because the neutron production efficiency is low although the neutron spectrum is throught to be a desirable one. At low linac peak intensities, it is possible to operate at higher average proton current and thus reduce irradiation time, but low peak-current operation is rarely compatible with high-energy physics operation. It would be extremely difficult to set up a situation in which one current and one pulse width would be used for high-energy physics and another set of conditions used for radiotherapy because massive retuning of a large number of devices, including some which are very slow, would be necessary twice per main-ring cycle. The retuning would have to be accomplished in a time of less than one second in order for there to be a profit in the exercise. Patient treatment started on September 7, 1976.

This paper has concentrated on a review of improvements to the present Fermilab accelerator. In addition, superconducting magnets are being constructed and tested for the Energy Saver/Doubler, which will be installed in the main ring beneath the present magnets and will accelerate beam to 1000 GeV. In the longer range, we are studying colliding-beam devices, accumulators, and antiproton cooling rings. At least some of these devices will be built to extend the range of physics studies possible at Fermilab.

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DISCUSSION

E.F. Parker, ANL: What is the $\Delta p/p$ of the radiography beam?

L.C. Teng, FNAL: We can collimate down the beam coming out of the analyzing magnet to get any desired $\Delta p/p$ on the diffraction scattering target. The momentum spread in the scattered beam will depend in addition on the diffraction scattering kinematics and further collimation in the beam downstream of the target.

G. Dome, CERN: What is the method used at FERMILAB to raise the rf voltage smoothly in the booster? Is it antiphasing of the rf cavities?

Teng: Yes, we found that with the antiphasing mode of rf voltage turn-on we get a slightly better capture efficiency than the staircase turn-on. But we are now antiphasing all the rf cavities in two groups. We are modifying the system to antiphase between pairs of cavities.