# THE FERMILAB ACCELERATOR:
# STATUS AND DEVELOPMENT PLANS

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## I. Introduction

The Fermilab accelerator has been in operation since 1972. The first operation was at 200 GeV, although the energy was soon raised to a nominal value of 300 GeV.[1] Since July 1975, 400 GeV has been the normal energy. The machine was operated at 500 GeV in May 1976.[2]

The accelerator system is composed of a 750-kV Cockcroft-Walton, a 200-MeV linac, an 8-GeV - 15-Hertz booster, and a 500-GeV main ring.[3] The linac injects one pulse into the booster and the booster injects the 8-GeV pulse into the main ring, each using single-turn injection. This process is repeated 13 times to fill the main ring circumference before acceleration begins. A switchyard system splits the extracted beam to 6 different external targets. There is one internal target area with 3 possible targets. The linac can also deliver a 66-MeV beam to a neutron cancer therapy facility[4] and a 200-MeV proton beam to a radiography experiment.[5]

A project is being initiated to study electron cooling of 200-MeV protons (discussed in another paper at this conference).[6] The scheme is similar to that developed at Novosibirsk.[7] Upon successful cooling of protons, studies will begin on the cooling and accumulation of antiprotons.[8] The antiprotons would be injected into the main ring and simultaneously accelerated with protons to produce antiproton-proton colliding beams.

Work is in progress at Fermilab on the construction of a 1000-GeV superconducting Energy Doubler/Saver[9] to be installed in the present main-ring tunnel. The status of the Energy Doubler/Saver is presented in another paper at this conference.[10] With both the main ring and energy doubler in the same tunnel, it is obvious proton-proton colliding beams will be possible.

The complete system of 1000-GeV fixed-target physics, 250 GeV (main ring) x 1000 GeV (doubler) proton-proton physics and 1000 GeV x 1000 GeV proton-antiproton physics in the doubler has been named the Tevatron.[11]

*Operated by Universities Research Association, Inc., under contract with the U. S. Energy Research and Development Administration.

## II. Present Operation

Recent improvements have given higher intensity and increased the reliability of the accelerator. These improvements include a new large aperture focussing 750-kV column, short pulse-high current linac injection into the booster,[12] ramping sextupoles in the booster, horizontal and vertical superdampers (30-50 megahertz) in the booster,[13] changing phase at high energy of 1 of the 18 booster rf cavities (1 cavity on 83rd harmonic, 17 cavities on 84th harmonic) to reduce coherent instabilities,[14] better alignment of main-ring magnets, modification of main-ring power supplies including additional filters, addition of electrical feeder cables to the main ring, insertion of a large series capacitor (17 mF) for enhancing the power factor between the main ring and the incoming line, alignment of extraction septa to .001 inches in 10 feet, and addition of shadow targets for the septa wires.

The intensity records achieved are:

| | |
|---|---|
| Linac 2.7-microsecond pulse, 300 mA | $6.6 \times 10^{13}$ protons/main ring cycle |
| Booster $2.3 \times 10^{12}$/pulse | $3.0 \times 10^{13}$ protons/main ring cycle |
| Main Ring | $2.5 \times 10^{13}$ protons/pulse |

Normal operation at present is $2 \times 10^{13}$ protons/pulse at 400 GeV with a 1.25-second flattop and a 10-second cycle time. Average extraction efficiency is greater than 98.5% and the slow-spill duty factor is greater than 70%. Figure 1 illustrates a typical mode of operation. The ramp, extraction and beam-splitting system is very flexible and many other modes of operation are possible such as a lower-energy front porch or a 2-second flattop. The cycle time is limited by the power budget.

The accelerator normally operates 43 weeks per year with 7 weeks of shutdown, 1 week of failure and 1 week of holidays. For the 43 weeks of high-energy physics operation, the accelerator delivers beam to at least one experiment an average of 110 hours per week. There is an average of 18 hours per week of accelerator beam studies. The other 40 hours per week are maintenance, development, tuneup, and failure. It is our goal to achieve 120 hours per week of high-energy physics and 20 hours per week of accelerator studies. Simultaneously, 60 hours per week of linac beam is delivered to the Cancer Therapy Facility and Radiography. The number of protons delivered per quarter year is shown in Fig. 2. The low number during the 3rd quarter of 1976 was due to budgetary limitations.

Typical Operation

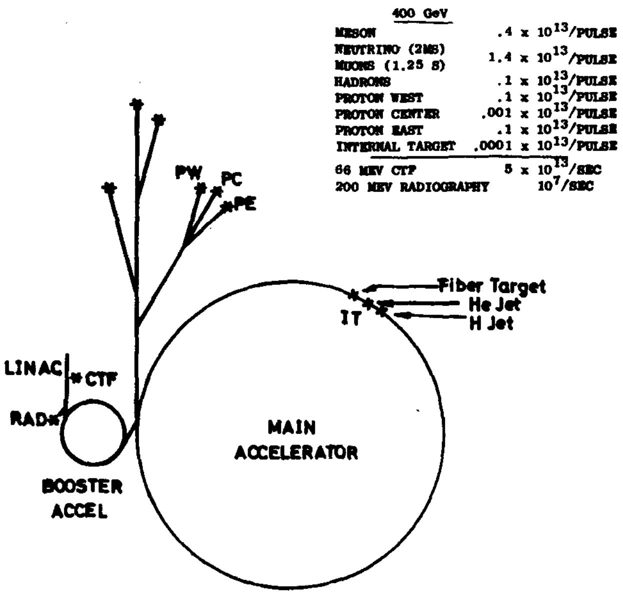


Fig. 1. Typical operation of the Fermilab accelerator illustrating division of the beam.

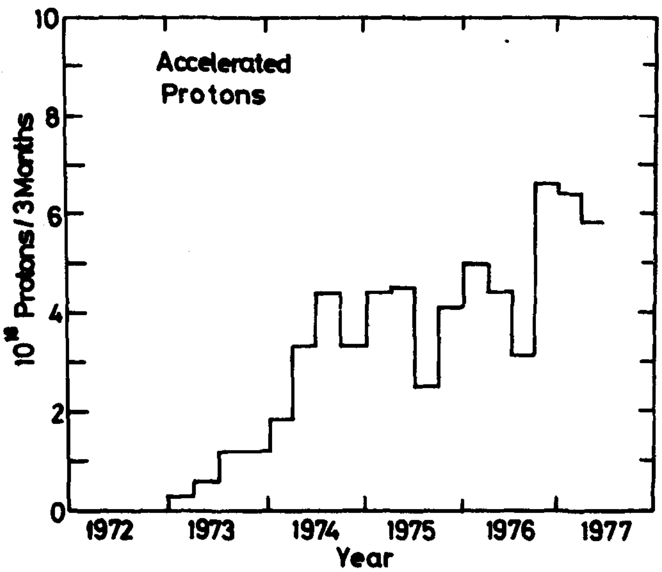


Fig. 2. Number of protons accelerated per 3 month interval.

## III. Intensity Improvements

The design intensity for the accelerator is $5 \times 10^{13}$ protons per pulse. There are many projects in progress to achieve this goal. Most of these projects will come to fruition by the end of next year. The present limit on intensity is the booster. Therefore, booster projects have been emphasized.

### Preacc-Linac-Booster

This fall, we will install a negative-ion injection system for the booster. More reliable operation with increased intensity is expected. A new cesium-loaded magnetron ion source has been developed and will be installed in a spare Cockcroft-Walton beside the present one. This will permit fast changeover from protons to negative ions for injection into the linac. A carbon-stripping foil has been developed for stripping the electrons from the $H^-$. We plan to inject up to 20 turns of 30-milliamp linac beam into the booster ($\geq 10^{14}$ protons/main-ring cycle).

### Booster

We have found that it is possible to increase the rf voltage on the booster cavities by reducing the voltage at the onset of a spark. A deviation on the rf voltage envelope is used as a trigger. Using this method, the cavities can be voltage-conditioned from a normal 22 kV up to 30 kV. This will not only give more redundancy, but will provide a larger rf bucket and the required voltage for future 10-GeV operation.

Modifications are being made to the booster power supply to permit operation at 10 GeV. The smaller 10 GeV beam should make transfer of beam from the booster to the main ring more efficient and thus increase the main ring intensity.

A quadrupole system is being designed for the booster to provide a tune "jump" across transition. This should reduce losses associated with transition.

A new larger aperture extraction system is being designed for the booster. This septum will have equal but opposite field on either side of the septum. The present septum has zero field on the circulating-beam side. The new septum magnet will be coupled to 2 bump magnets to leave the rest of the orbit unperturbed.

### Main Ring

The improvements in the main ring mentioned in Section II have increased the acceptance to $2.0\pi \times 2.5\pi$ mm-mr (8.9 GeV/c) making it feasible to stack 2 turns into the main ring. Because of the eventual operation of colliding beams, we choose to stack in momentum space. This project will be initiated this fall.

At present, there is an equal amount of rf power required for beam loading and dissipated in the main ring cavities. To accelerate $5 \times 10^{13}$ protons per pulse, twice as much rf power is needed for the beam. Our present rf system will be at its limit, therefore an additional power amplifier will be added to each of the 18 cavities.

A new main-ring abort system is being designed. The present abort system consists of bump magnets, an aluminum block (which serves as an aperture limit) and downstream collimators. The new system will use a full aperture single-turn extraction system plus a beam dump.

<u>Switchyard</u>

To be able to use the higher intensity, modifications are necessary in the extraction system and switchyard. The neutrino targets are limited to less than $2 \times 10^{13}$ protons per 2-millisecond pulse. Therefore, the extraction system will be modified to give many 2-millisecond pulses per main-ring flattop. The principal development will be the control of beam loss immediately following each pulse. In the switchyard, more quadrupoles will be added to control the beam profile in the septa to reduce beam loss. Collimators will also be added to localize high-radiation areas.

These improvements should provide $5 \times 10^{13}$ protons per main-ring cycle in a beam spill matching the experimental facilities requirements. The operation of the machine should also be more reliable.

## IV. Projects Associated with Colliding Beams

There are many projects in progress related to colliding beams at Fermilab; proton-antiproton and proton-proton. It has been possible during accelerator studies to store rf-bunched beam (100 milliamps) in the main ring at 200 GeV for 1 hour. The beam lifetime is consistent with beam gas scattering.

The present main ring vacuum is $10^{-7}$ torr. This is sufficient for an accelerator but limits a stored beam. Therefore, a program of cleaning, repairing small leaks, removing high-vapor pressure materials and baking of the vacuum chamber has begun. It is believed that a vacuum of $10^{-8}$ torr can be obtained giving a stored beam lifetime of many hours at 250 GeV.

All colliding-beam schemes require beam in the main ring in both directions. A project is underway to extract 10-GeV beam from the booster and inject it into the main ring in the opposite direction to the present beam (see Fig. 3a). The beam line is 600-m long. Three hundred and twenty meters will be new transport tunnel constructed with 4-foot diameter concrete pipe; the other 180 m of beam line will be in the main-ring tunnel. There will be quadrupoles approximately every 30 m.

The results of electron cooling from Novosibirsk[7] has stimulated other laboratories to pursue this exciting achievement. At Fermilab, a 200-MeV ring for electron cooling tests[6] is being constructed (see Figs. 3a and b). Part of the proton injection line from the linac already exists. It has been used for 200-MeV radiography experiments. The ring will be made up of 24 - 4-foot, 5-kGauss dipoles and 32 - 2-foot quadrupoles on a total circumference of 135 m. There will be one rf cavity for momentum stacking of beam. The vacuum will be $10^{-10}$ torr. To produce the electron beam in the long straight section (5 m), a modified SPEAR klystron electron gun will be used. The electron gun will be 28 Amps over 27 $cm^2$. To reduce power to less than 100 kW, an electron catcher similar to the gun will be used. The electron beam temperature in the center of mass of the protons and electrons is $T_\perp \cong 0.5$ eV and $T_\parallel << T_\perp$. The acceptance of the ring ($20\pi \times 40\pi$ mm-mrad at 200 MeV) corresponds to a proton beam with $T_\perp \cong 900$ eV and $T_\parallel \cong 700$ eV. The expected cooling rate for this system is 6 Hertz.

A scheme to test proton-antiproton colliding beams has been designed using the small cooling ring. In the design 80-GeV protons are extracted from the main ring at 15 Hertz into the reverse injection line and targeted to produce 5.2 GeV antiprotons for injection into the booster. The booster decelerates the antiprotons to 200 MeV and injects them into the cooling ring. In the cooling ring, the antiprotons are momentum-stacked and cooled. About $10^9$ antiprotons can be collected in 3 hours. These antiprotons are then injected into the booster, accelerated to 8 GeV and injected into the main ring in the reverse direction. The protons are accelerated in the booster and injected in the normal direction in the main ring. At this point, both the protons and antiprotons are simultaneously accelerated to 250 GeV. A small beta (2.5 m) section is used in a main ring long straight section to enhance collisions. By extending the cooling ring to equal the booster circumference and adding more electron cooling

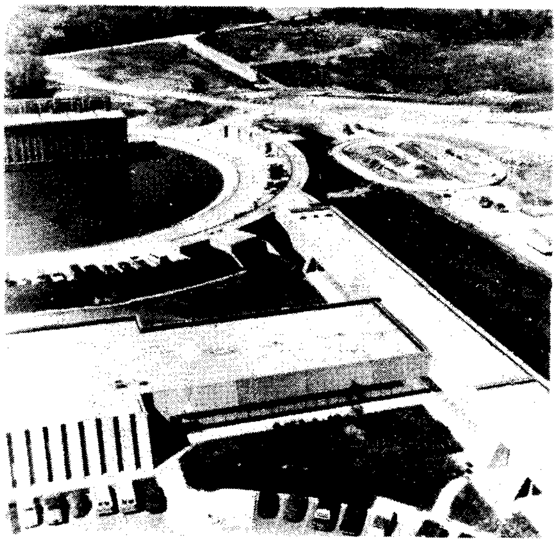

**Fig. 3a.** Picture taken from the hi-rise building looking at the linac, booster, new cooling ring and reverse injection line.

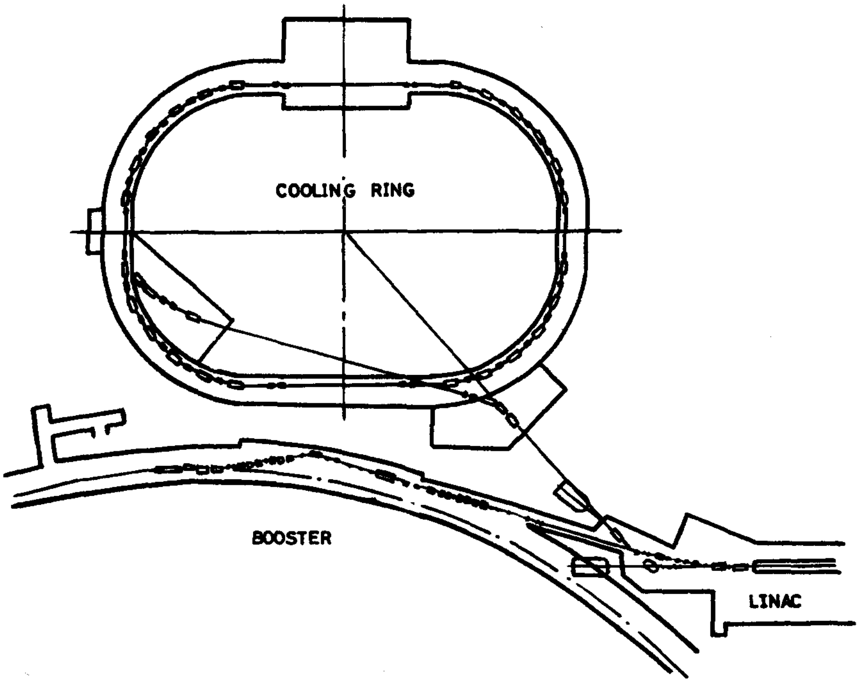


**Fig. 3b.** Plan view of linac, booster and new cooling ring.

regions, a luminosity of $10^{29}cm^{-2}sec^{-1}$ may be possible in the main ring for 250 GeV on 250 GeV.

Next year, construction will begin on a colliding-beam area in one of the main-ring straight sections. Depending on the design, the available space along the beams for experimental equipment is from 10-30 meters. The design of such an area should be finalized by Spring 1978 and construction completed by Spring 1979.

## V. Tevatron Project

The development of the Tevatron is being done by a gradual approach to the final project. The emphasis thus far has been to develop a good superconducting magnet (42.5 kGauss→1000 GeV). We now have such a magnet[/10/] (see Fig. 4).

The next step is to install one sector of these magnets in place in the main-ring tunnel (1/6 of the ring). A scheme developed by T. Collins of Fermilab will be used to run 100 GeV beam through 5 sectors of the conventional main ring and the sector of doubler magnets. The scheme uses a kicker magnet and 2 magnetic septa (one at each end of the sector). The kicker puts the beam on a new stable orbit going through the magnetic septa and the new sector. This is illustrated in Fig. 5. Bump magnets can be turned on adiabatically to smooth the orbit in the conventional machine. This test will be extremely valuable to understand operation of a superconducting accelerator. It is planned to bring this sector into operation next spring.

In the switchyard, we are converting the proton transport line to the neutrino target to superconducting magnets. Doubler magnets will be used where feasible. However, some new superconducting beam transport magnets will be required. This project will be completed in 1979.

The completion of the superconducting ring with limited rf and refrigeration is planned for the end of 1979.[/10/] Beginning in 1980, it will be possible to begin colliding-beam exercises. It is believed that 250-GeV protons in the main ring colliding with 1000-GeV protons in the doubler could yield a luminosity greater than $5 \times 10^{30}cm^{-2}sec^{-1}$. If antiproton cooling and accumulation is successful the expected luminosity for 1000-GeV protons on 1000-GeV antiprotons in the doubler should be greater than $10^{30}cm^{-2}sec^{-1}$.

To complete the Tevatron accelerator includes addition of more rf (i.e., 4 main-ring type cavities), doubling the refrigeration system (12 more 700-Watt helium refrigerators)[/7/] and installation of an ex-

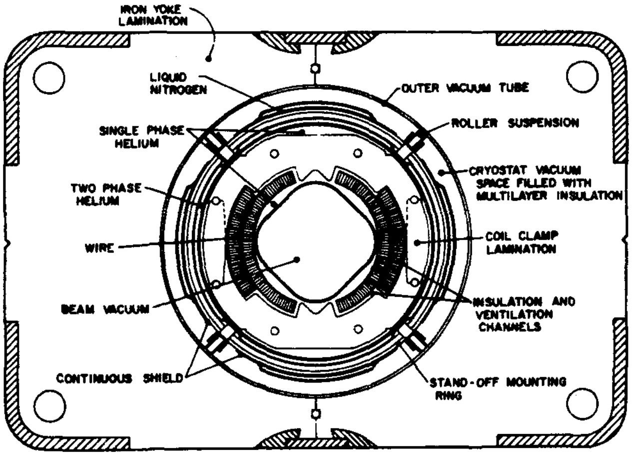


Fig. 4. Energy doubler/saver superconducting magnet.

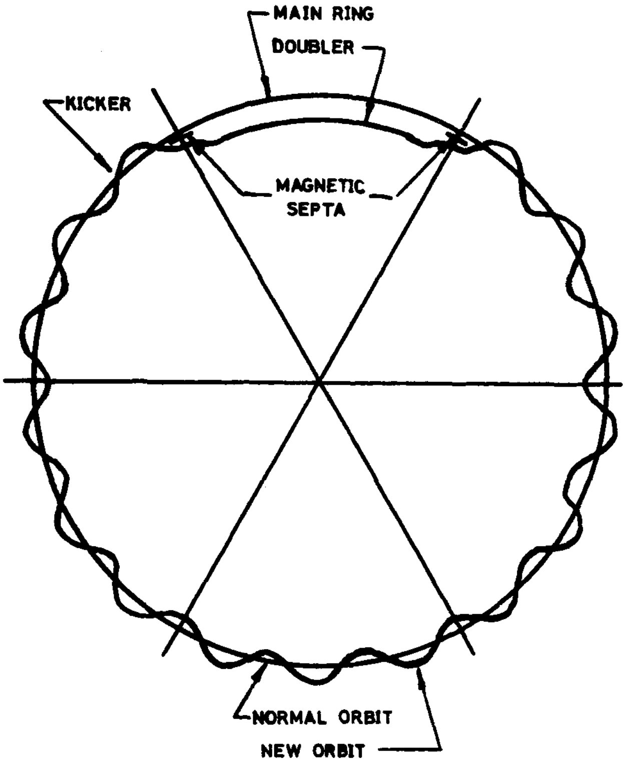


Fig. 5. Scheme to circulate beam through one sector of energy doubler/saver magnets.

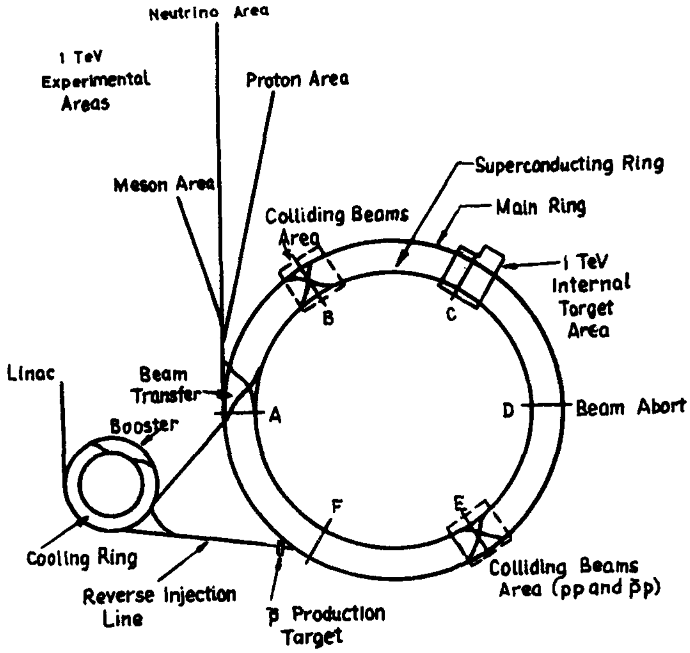


Fig. 6. Schematic plan of the Fermilab TeV program.

traction system. The extraction system is planned to be similar to the present main ring system with the same capabilities. We may try 1/3 integer resonant extraction instead of the present 1/2 integer. The advantage of 1/3 is a smaller magnetic aperture requirement, the disadvantage is more sensitivity to instabilities and multipulse operation. This is scheduled for completion the end of 1980.

During 1980, the Neutrino Area will be converted for 1000-GeV operation. This will include hardening the Neutrino shield and construction of a separate line for muon physics. After that, the Proton Area will be upgraded for 1000 GeV and then the Meson Area. The principal upgrade is the replacement of conventional magnets with superconducting magnets.

The initial operation of the fixed-target program is planned to have a 1-minute cycle time, 20 seconds for acceleration, 20 seconds of flattop and 20 seconds for the ramp to come down. The average intensity would be $10^{12}$ protons/second (total $6 \times 10^{13}$/pulse). It is imagined that the physics program might be 1/2 fixed-target physics and 1/2 colliding beams. The Tevatron is illustrated in Fig. 6.

With the discoveries of weak neutral currents,[15] and charm,[16] gauge theories now enjoy a certain credibility. They predict[17] new heavy particles, for example, intermediate vector bosons, and promise very exciting physics from the Tevatron.

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## Д И С К У С С И Я

А.А.Коломенский: В своем докладе Вы не упомянули о проекте POPAE. Что вы можете сказать о Ваших планах относительно встречных протон-электронных пучков?

F.R.Huson: There have been studies at Fermilab on a possibility for electron ring to have proton-electron colliding beams. I am sure that one day something can happen in that direction. However at the moment priority has been given to the tests of electron cooling in the small cooling ring.

А.А.Наумов: Решался ли вопрос о влиянии потерь частиц на сверхпроводящие магниты в аспекте долгосрочных эффектов и нагрева ?

F.R.Huson: Yes, we have made a preliminary study of beam losses on the superconducting magnets. We believe that we can take up to $5 \cdot 10^{13}$ in the present doubler design. What we have to do is to put collimators after the septum for extraction and abort systems. We find that the most difficult thing is the single turn extraction, because of no time for cooling. We believe that we can solve this problem.

А.А.Наумов: Я хотел бы отметить, что проект чрезвычайно интересен и многообразен, также хотелось бы пожелать больших успехов в его реализации и, прежде всего, в реализации электронного охлаждения, которое сулит получение встречных протон-антипротонных пучков.