POSITIVE RESULTS WITH NEGATIVE HYDROGEN-ION INJECTION

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Initial trials of H^- injection into the Booster were carried out with very encouraging results during the coal-strike shutdown. A high point was the establishment of a new Booster intensity record of 3.46×10^{13} protons per Main-Ring cycle, a significant improvement over the previous record of 3.06×10^{13}. The new record was attained while injecting 15 turns of 24 mA H^- beam at 200 MeV from the Linac, corresponding to 8×10^{13} protons per Main-Ring cycle. The rapid success testifies both to the careful preparations by the Linac and Booster groups during the last two years and also to the essential simplicity of the method.

To appreciate the advantages of H^- injection, it is instructive to consider the limitations of previous injection methods. The original Fermilab design called for the injection into the Booster of four turns × 75 mA of protons from the Linac. Conventional injection into a circular accelerator requires the use of time-varying electromagnetic fields to move the particle orbits; otherwise the particles will hit the inflector electrodes on successive turns. The time-varying fields cause successive turns to be stacked side-by-side, thereby increasing the size of the injected beam. This illustrates the general restriction on beam density imposed by Liouville's theorem; it is impossible to increase the density of particles in phase space by means of conservative forces. In the case of the Booster, this so-called stacking in radial betatron space produces beams larger than the Booster can accept.

Since the acceptances of the Booster, the 8-GeV transport line, and the Main Ring are approximately matched, increasing the acceptance of the Booster would not solve the problem, but would merely transfer the losses downstream. Another drawback is that it is operationally difficult to set up and maintain the time-varying fields required for this method.

Use of one-turn injection into the Booster led to considerable improvement. This was made possible by a major change in the Linac mode of operation: the acceleration of very intense (up to 300 mA), short (4 μsec) beams of protons. The breakthrough was the realization that the Linac could provide very intense current for a short pulse. In time, record Booster and Main-Ring intensities, 3.06×10^{13} and 2.52×10^{13}, were achieved with very much simplified injection into the Booster. A single-turn kicker corrects the injection offset by deflecting the incoming beam onto the closed orbit, thereby avoiding large betatron oscillations that lead to beam growth.

The drawbacks of the single-turn mode of operation are that space-charge forces of the intense beam in the beam transport cause the beam qualities to degenerate and that control of the beam properties becomes more difficult as the current is raised. The Booster itself imposes additional limitations because of space-charge forces, particle instabilities, and barely adequate rf voltage. The net result is that Booster transmission declines from nearly 100% at very low current to about 60% with 5×10^{13} injected.

H^- injection circumvents the aforementioned limitations of the other injection methods. Relatively modest currents of 30 mA or less are used, for which the Linac can produce a long (50-100 μsec) pulse of very high quality and stability without subsequent deterioration due to space-charge forces. It is possible to inject many turns into the same phase space, avoiding the limitation of Liouville's theorem, because protons and H^- bend in opposite directions in magnetic fields and because a non-conservative process is used to change the H^- into protons. The trajectories of circulating protons and injected H^- are brought together by pulsed magnetic fields at injection; both protons and H^- then encounter a thin carbon stripping foil, where the H^- ions lose their two electrons and become protons, augmenting the circulating beam. After injection, the pulsed magnetic fields die away, moving the circulating beam off the foil. The multiple scattering and energy loss caused by the foil during the injection process are relatively small. The optimization of foil thickness, number of turns and magnitude of current for a given intensity must be determined empirically.

Although the primary motivation for the H^- project is added intensity for the high-energy physics program, there are other advantages. The addition of a second preaccelerator system and another injection method into the Booster provide redundancy, diminishing the probability of extended downtime because of failures of preaccelerator or injection apparatus. It should also be easier to vary the intensity with minimal retuning in response to varying requirements by changing the number of turns injected into the Booster.

The H^- ions also provide flexibility for the Linac, which serves not only the high-energy physics program but also the Cancer Therapy Facility and, in the future, the Electron Cooling Ring. The varying beam requirements of these three programs can be served relatively easily by varying the pulse width on a time-sharing basis.

Although charge-exchange injection has been used for almost 20 years in low-current heavy-ion accelerators, application to high-energy physics awaited the development of a high-current H^- ion source. The pioneering work on such a source was carried out by G. I. Dimov at Novosibirsk. Subsequently, Th. Sluyters built a similar source at Brookhaven. The success of H^- injection into the ZGS at Argonne added to the confidence necessary to proceed with the Fermilab project. The source developed at Fermilab by C. Schmidt is a highly modified version of the Brookhaven source. This source is fundamental to the success of H^- injection.

A second Cockcroft-Walton preaccelerator system incorporating the new source was developed under the guidance of C. D. Curtis. The necessarily complex beam-transport system which matches the negative-ion beam to the Linac was designed and successfully commissioned by W. Smart. M. Shea and R. Goodwin developed a new microprocessor-based control system interfaced to the existing Linac control system. Electrical and mechanical engineering efforts were overseen by A. Donaldson and G. Lee, respectively.

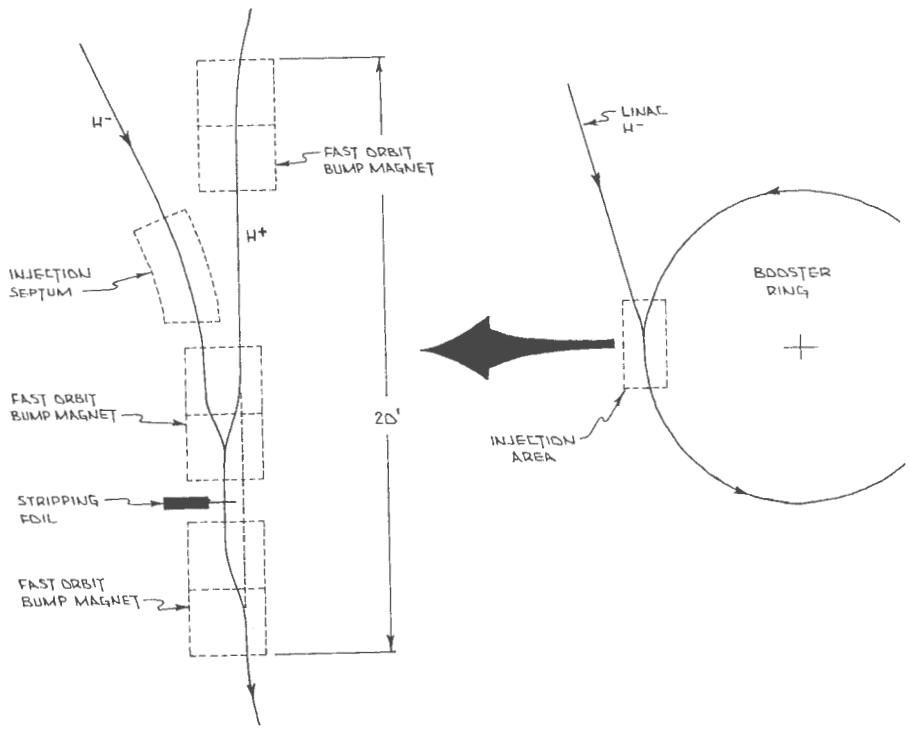
C. Owen carried out the modifications of the Linac itself. H^- beam was first accelerated through the Linac to 200 MeV last October 12. Since

then, currents as high as 42 mA have been reached, well above the design goal of 30 mA for 70 μsec (25 turns). This design goal corresponds to 1.7×10^{14} protons per Main-Ring cycle, about 2.5 times the capability with single-turn proton injection. How many of the available protons the Booster can successfully accelerate to full energy is a question of intense current interest.

C. Hojvat is in charge of the work at the Booster end. The design was initiated by R. Johnson when he was group leader and continued under C. Ankenbrandt. The first step was to replace three dipoles in the 200-MeV line, which were strong enough to cause premature field stripping of the H^- ions. Schemes to reverse the dipoles and quadrupoles in the 200-MeV line were also worked out.

The injection apparatus in the Booster itself has been completely replaced with components for both H^- and single-turn proton injection, all mounted on a box girder. The layout is shown in the figure on the next page. The Fermilab Magnet Facility has aided in the construction of the pulsed magnets needed for the two injection methods. K. Bourkland developed the necessary pulsed power supplies. D. Cosgrove was responsible for the mechanical design of the girder, aided by T. Schmitz. D. Maxwell and J. Wildenradt spearheaded the mechanical assembly and installation and provided expertise with vacuum techniques.

The most delicate component is the stripper itself, a carbon foil 2-in. × 1.4-in. in area. Thicknesses of 100, 200, and 300 $\mu g/cm^2$ are being tried. The foils are mounted in a C-shaped frame; the beam moves across the free

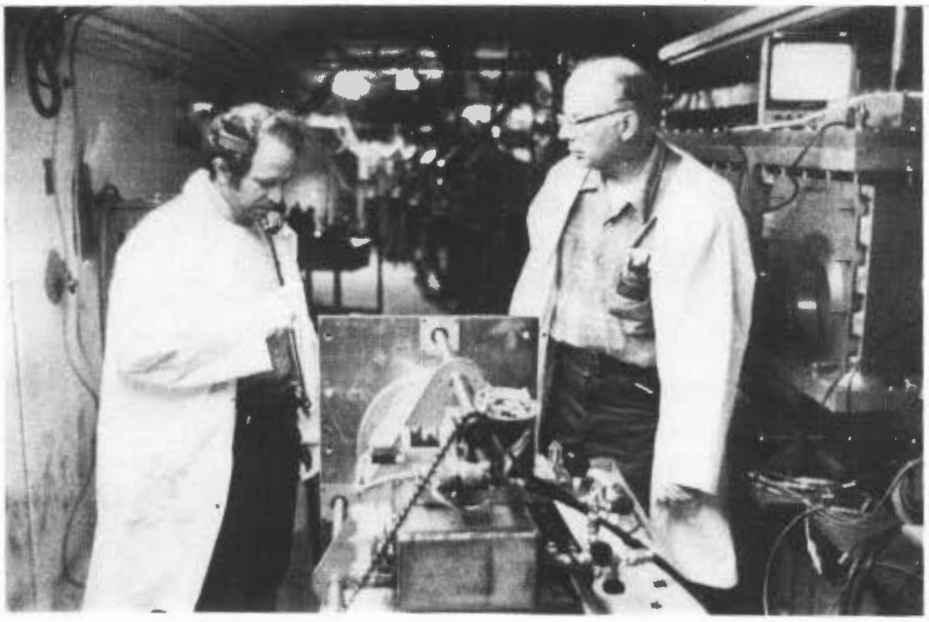


Schematic layout of H^- injection into the Booster.

edge after injection. Foil lifetimes greater than 120 hours have been obtained in beam-exposure tests. A simple conveyor-belt device for remotely changing foils has been incorporated in the design.

The application of negative-ion injection to Fermilab was originally suggested by L. Teng, who has supported and helped the work at all stages.

Many other people have also contributed to the success of this project. Their contributions are gratefully acknowledged.



Carlos Hojvat (left) and David Cosgrove (right) in the Booster tunnel working on the new injection girder.

(Photograph by Fermilab Photo Unit)

Sparking across the terminals of a 150-kV high voltage switch. The switch and dummy load are employed in the testing of the power supply for the electron cooling ring high voltage. The switch and load were designed and fabricated by A. R. Donaldson and M. R. Palmer.

(Photograph by Fermilab Photo Unit)