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# LINAC $H^-$-BEAM OPERATION AND USES AT FERMILAB

C. D. Curtis, G. M. Lee, C. W. Owen, C. W. Schmidt and W. M. Smart*†

## INTRODUCTION

In the spring of 1975, the decision was made to start preparations for negative hydrogen-ion injection into the Fermilab booster. The key to the success of this endeavor was the development of a reliable $H^-$ source of adequate intensity. Direct extraction sources giving $H^-$ beams over 100 mA had been produced by this time in Russia and reproduced in the U.S.A. at Brookhaven. Furthermore, the success of the multiturn-injection technique with use of thin stripping foils had been demonstrated at Argonne.[1] A surface-plasma source has been adopted for accelerator application at Fermilab and is described in a companion paper.[2] The goal of 50 mA at 750 keV with a pulse length of 60 μsec was achieved.

The usual motivation for $H^-$ injection into synchrotrons is to increase the intensity of the circulating proton beam by multiturn injection without increasing the phase-space area of the beam. In the Fermilab application, the high-intensity proton beam from the linac (up to 300 mA for single-turn booster injection) was already approaching the existing space charge limit of the booster. Although $H^-$ injection could not be expected to yield a dramatic increase in booster beam current immediately, other significant advantages were anticipated in $H^-$ operation. The lower beam current (~ 30 mA) would mean easier operation of the linac whose rf systems were not designed to accelerate beam current in the 200-300-mA range. The quality of the lower-current beam was expected to be better, with somewhat lower emittance and momentum spread. In addition, the different requirements of integrated beam intensity from the various linac beam users would be more readily satisfied with a programmed beam chopper. Another advantage became apparent in the lower loss of beam during capture in the booster, whose performance is discussed in another conference paper.[3]

A second preaccelerator and beam transport line were installed to facilitate switching between $H^-$ and $H^+$ operation. Installation was completed and $H^-$ beam first accelerated through the linac in October of 1977. The new injection girder for the booster was ready in February, 1978 and $H^-$ injection has been the primary operating mode since that time.

## THE 750-keV TRANSPORT LINE

Preparation for $H^-$ operation was carried out without interference with the ongoing high-energy physics program by excavating a second pit adjacent to the pit housing the operating Cockcroft-Walton accelerator. A second accelerator was installed in this pit with its $H^-$-beam direction at 45° to the $H^+$-beam direction as shown in Figure 1. An $H^-$ transport line was designed and installed to bring the $H^-$ beam through 45° and 90° bends into conjunction with the $H^+$ beam line just upstream of the last two triplets. These triplets, without field reversal, and the buncher are used in common for the positive and negative beams. The old $H^+$ line was lengthened by 16 inches to accommodate the 90° bend magnet.

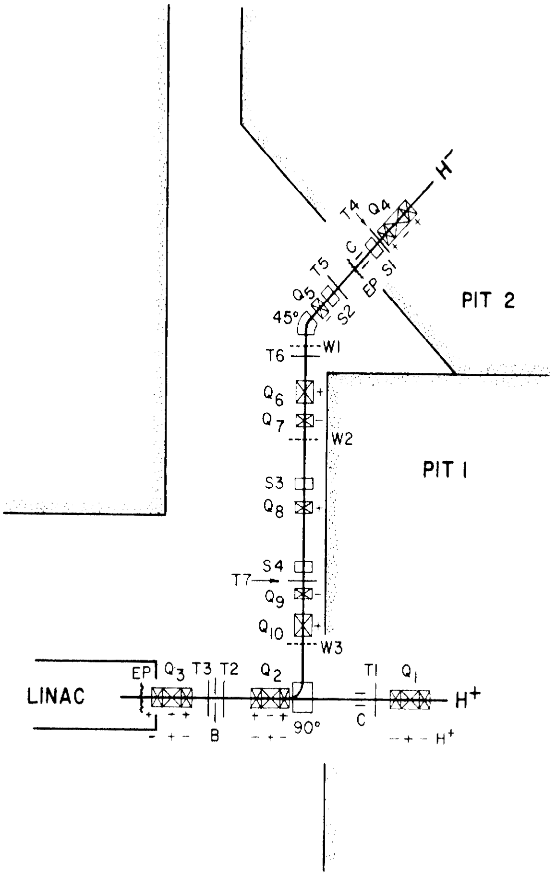

Fig. 1. Layout of 750-keV beam transport line. Quadrupole magnets (Q), steering magnets (S), buncher (B), beam chopper (C), beam-current toroids (T), emittance probes (EP), and multi-wire monitors (W). For the quads, + and - mean focusing and defocusing respectively in the horizontal plane.

The new line utilizes five quadrupole magnets between the two bends to render the beam achromatic. The two bend magnets are in series on one power supply; with the achromatic design this minimizes the effect of power supply variations on beam centroid position and angle at the linac entrance. A trim coil, with a separate power supply, on the 90° bend magnet is used for the final bend angle adjustment. Steering coils (S1-S4 in Fig. 1) are used to center the beam in both transverse planes. Diagnostic equipment includes several beam-current toroids, a pair of emittance probes at each end and three multi-wire probes for size and position measurement of the beam. The wires can tolerate only very short beam pulses because of overheating, but a fast beam chopper can select any variable-length segment of the ion-source beam pulse. It may be of interest to note that the electrical sign on the wires is positive at 750 keV because of secondary electron emission while at 200 MeV the signal is negative and larger by a factor of approximately eight than the positive signal from a proton beam.

The achromatic line was designed with the aid of the computer program TRANSPORT modified to include space-charge effects.[4] The assumed beam emittance was 0.038 π and 0.13 π cm-mrad (normalized) in the horizontal and vertical planes respectively. No space-charge neutralization of the beam was assumed. The beam amplitudes along the 9.45-m transport line for both zero

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*Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.

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intensity and 50-mA beam is shown in Figure 2 for a particular design solution. This solution in terms of the location and strength of the quads is the one in use at the present, except for minor adjustments in quadrupole strengths found during empirical tuning.

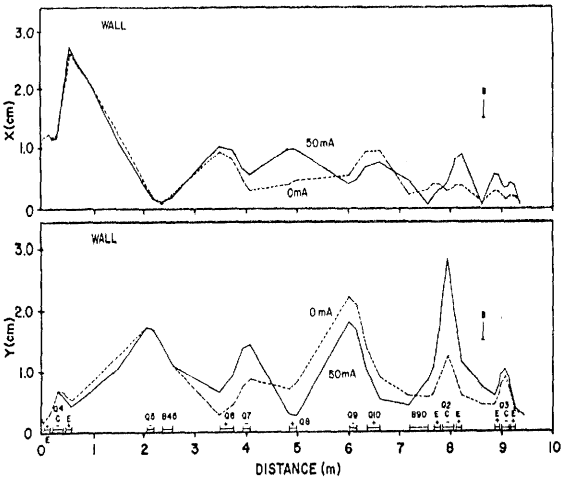

Fig. 2. Beam half width along the 750-keV transport line in the horizontal (X) and vertical (Y) planes for currents of 0 mA and 50 mA.

## LINAC FEATURES AND PERFORMANCE

Few changes in the linac systems were made in switching over to $H^-$ acceleration. Because of the large number (296) of quads in the linac and the desire to switch from $H^-$ to $H^+$ operation quickly, the polarities were left unchanged. In the absence of changes, the beam will no longer focus to the required narrow waist at the septum magnet, which switches the beam into the transport line leading to the booster synchrotron. The proper focus was restored, however, by adjustments in the relative strengths of the last four quads in the linac. Polarities were reversed in all quads and bending magnets in the 200-MeV diagnostic beam line and in the booster transport line.

For proton acceleration, the linac quads are tuned for high intensity (200-300 mA) operation and thus far remain at higher strengths (particularly in the low-energy end of the linac) than may be optimum for $H^-$ operation. The specific operating values of all quadrupole and steering magnet currents for $H^+$ and $H^-$ operation are stored in computer files and transmitted by computer to the power supplies at switchover time. Return to $H^+$ operation has been infrequent and brief, except for one period of about six weeks because of an $H^-$ orbit-bump-magnet failure in the booster.

During highest intensity $H^+$ operation, the normal rf-system feedback loop is assisted by a feed-forward pulse at beam time. For $H^-$ operation this assistance is removed. The transmission of the linac is typically 70-75% and the $H^-$ beam current from the linac most of the time has been 30-35 mA with a maximum over 40 mA. This current is a function of the ion-source history, remaining constant for most of the useful source life but falling to ~ 20 mA toward the end of a two-month period when ion-source cleaning restores the normal source performance. A slow variation in beam current with aging of the source is compensated for by a variation of the pulse length.

A fast beam chopper in the 750-keV line is controlled by a logic system to provide time-shared beam pulses of different lengths to the different users. The electrostatic chopper provides, in addition to a stand-by pulse, adjustable pulse lengths typically of 45 μsec to the cancer therapy facility, 25 μsec to the booster for high-energy physics and ½ μsec to the electron-cooling ring experiment. A second chopper at 200 MeV further determines the fraction of the 25 μsec pulse which will be sent to the booster. The ion source and linac rf systems are operating continuously at a 15-Hz rate but displaced in time except when accelerated beam is requested.

Accelerator operators periodically check with wire scanners the variation in steering and momentum throughout the length of the 200-MeV beam pulse and endeavor to keep the positions at two successive wires within a few tenths of a millimeter and the momentum within a few parts in $10^4$. A debuncher reduces the momentum spread and stabilizes the mean momentum. Consequently the linac is not tuned to minimize momentum spread out of the linac but to optimize the effects of the debuncher. The present full $\Delta p/p$ from the linac is approximately 0.3%.

Beam emittances are measured at 750 keV after the first triplet and at the input to the linac with beam-destructive probes and at 200 MeV with three wire scanners. An example at 200 MeV is shown in Figure 3 for a 50-mA beam from the preaccelerator and 35 mA from the linac. The emittances at this beam-current level averaged over three runs taken on a later date at each of the emittance measuring locations are given in Table I.

TABLE I

| Location | $Q_4$ Exit | Linac Entrance | Linac Exit |
|---|---|---|---|
| beam current (mA) | 50.1 | 48.6 | 34.9 |
| $E_x$(cm-mrad) | $0.08\pi$ | $0.21\pi$ | $0.41\pi$ |
| $E_y$(cm-mrad) | $0.15\pi$ | $0.23\pi$ | $0.42\pi$ |

One will note the pronounced growth in emittance from Table I not only through the linac (a factor of approximately two), which is more or less typical for linacs, but also through the 750-keV transport line. One can say that distortions in the emittance of the beam from the source and column as well as field nonlinearities in the line contribute to this growth but studies which will explain the size of the effect have not yet been made. The need for substantial improvements in emittance has not existed.

In Figure 4 are plotted emittance values in the transverse planes at 200 MeV as a function of time during an early period of tests. The measurements are for beam currents greater than 25-mA and show some reduction in emittance with time as adjustments in a few quadrupole strengths in the 750-keV line were made.

Emittance as a function of beam current at 200 MeV is given in Figure 5. Measurements were spread over a period of several months and only the lowest range of values is plotted to show the trend of slow increase with increasing beam current. A plot of all measured values, including the earliest data, would show a large scatter of points extending upward from those points shown.

In conclusion, beam performance and reliability in both the linac and booster systems with $H^-$ operation is sufficiently good that work is now underway to convert the present standby $H^+$ preaccelerator to $H^-$ operation.

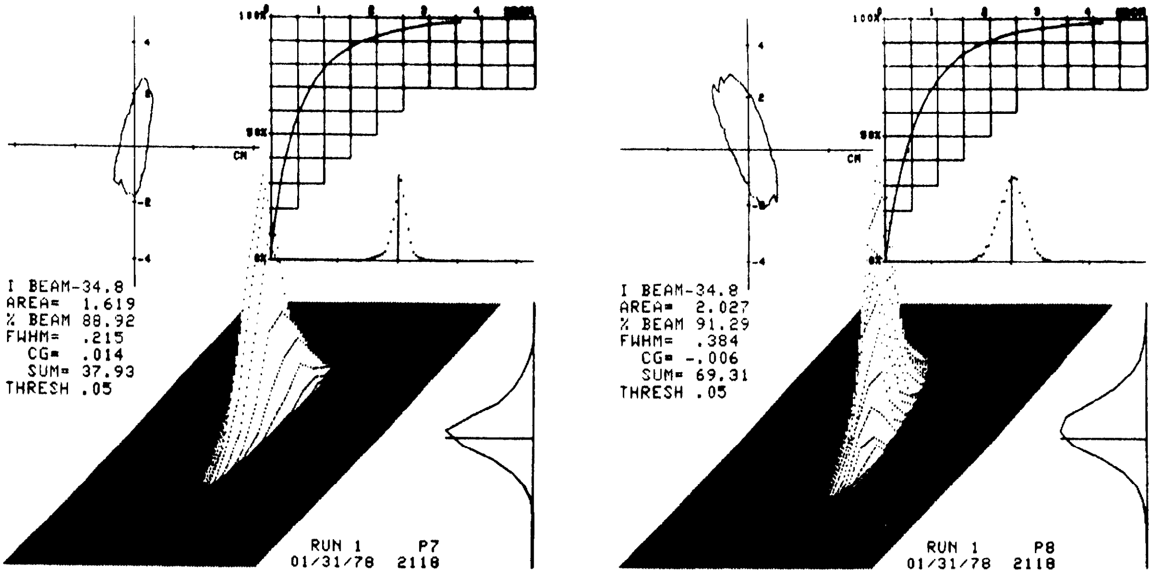

Fig. 3. Emittance plots at 200-MeV in the horizontal (P7) and vertical (P8) planes.

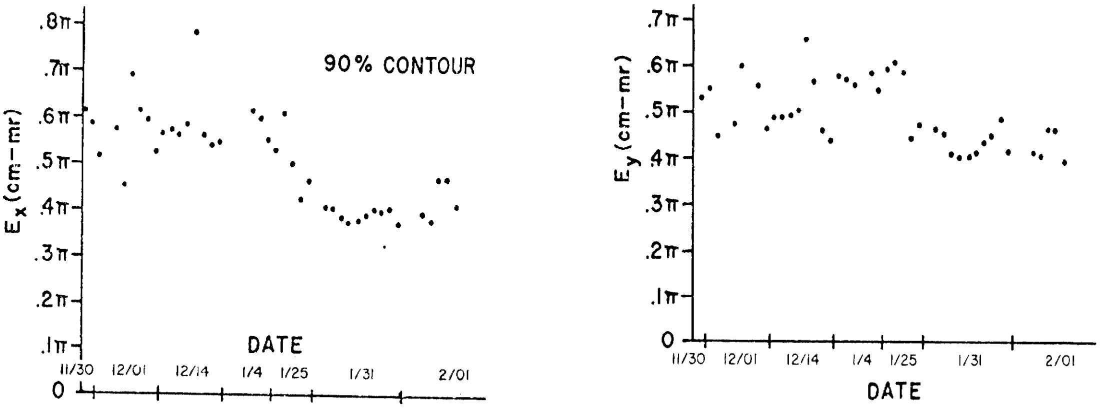

Fig. 4. Progression of 200-MeV normalized emittance values with adjustments in the 750-keV line for the horizontal (X) and vertical (Y) planes.

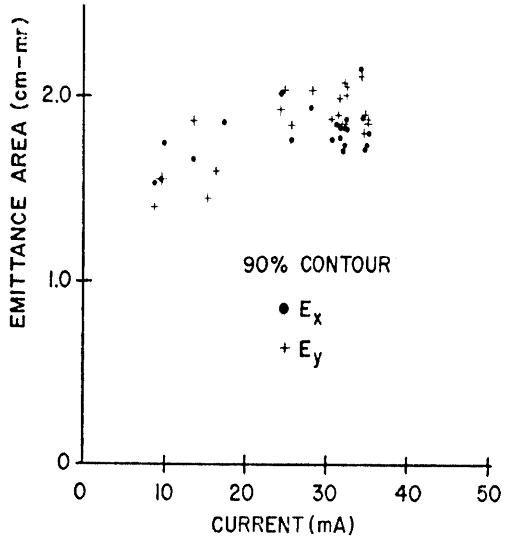

Fig. 5. Emittance vs. beam current at 200-MeV in the horizontal (X) and vertical (Y) planes.

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## REFERENCES

1. C. W. Potts, "Negative Hydrogen-Ion Injection into the Zero Gradient Synchrotron", IEEE Trans. Nucl. Sci., NS-24, 1385(1977).

2. C. W. Schmidt and C. D. Curtis, "A 50-mA Negative Hydrogen-Ion Source", proceedings of this conference.

3. C. Hojvat, et al., "The Multiturn Charge Exchange Injection System for the Fermilab Booster Accelerator", proceedings of this conference.

4. F. J. Sacherer and T. R. Sherwood, "The Effect of Space Charge in Beam Transport Lines", IEEE Trans. Nucl. Sci., NS-18, 1066(1971).