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THE MULTITURN CHARGE EXCHANGE INJECTION SYSTEM FOR THE FERMILAB BOOSTER ACCELERATOR

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SUMMARY

Since March 1978 the Fermilab Booster has operated with H^- multiturn charge exchange injection. A record number of protons per Booster cycle has been injected and accelerated to 8 GeV. The details of the injection system are discussed as well as the Booster performance and the reliability of the method.

INTRODUCTION

The concept of Charge Exchange Injection (CEI) was discussed in a paper by Budker and Dimov in 1963.[1] The CEI method is based on the capture of protons by stripping electrons from H^0 atoms or H^- ions on the closed orbit of a cyclic accelerator. The injected beam is made to overlap with the closed orbit before charge exchange takes place. Due to the opposite curvature in a magnetic field of the injected and circulating beams, the CEI can be designed for injection of successive turns into the same transverse phase space. CEI can potentially improve the performance of an accelerator due to the increased "brightness" of the circulating beam with respect to the injected one. Liouville's theorem does not apply because charge exchange introduces an irreversible process in the beam path.

CEI has become a practical reality with the development of bright, high current H^- ion sources.[2]

CEI has been utilized in the Argonne ZGS and the ZGS Booster.[3] In 1976 the ZGS became the first High Energy Synchrotron to utilize CEI during normal operation.[4] CEI has been proposed for the Brookhaven AGS.[5]

Discussions for CEI in the Fermilab Booster started in 1973[6] and the first design efforts took place in 1975.[7] The Fermilab plans were outlined in 1976[8] and the injection methods into the Booster were reviewed in 1977.[9] The first operation with CEI in the Booster took place in March 1978.

CEI INTO THE FERMILAB BOOSTER

Previous to CEI the standard injection method into the Booster was single-turn proton injection. The record proton current from the Linac is 300 mA[9] resulting in a maximum possible number of protons for single-turn injection of 5.2×10^{12}. At the peak current, horizontal and vertical emittances are of the order of $16\pi \times 10^{-6}$ m.

The peak current obtained from the Linac during H^- operation is now 43 mA.[10] Seven turns of CEI at this current suffice to equal the maximum number of protons for single-turn H^+ injection. The horizontal and vertical emittances at the H^- record current are of the order of $8\pi \times 10^{-6}$ m.

The Booster is a rapid cycling (15 Hz) synchrotron, with an injection energy of 200 MeV from the Linac and an extraction energy of 8 GeV. The revolution time at injection is 2.78 μs. Thirteen Booster pulses are required to fill the Main Ring accelerator.

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The present limit of 60 μs on the length of the H^- pulse is due to the 15 Hz operation of the ion source.[2] With this limit the maximum number of protons available for CEI is 1.6×10^{13} in 22 turns. With ion source operation at lower rep. rates, injection could take place in a time window of 140 μs. Up to 50 turns of CEI could then possibly take place. For the peak H^- current this would correspond to a maximum of 3.8×10^{13} injected protons per Booster cycle. The incoherent space charge limit for a tune shift of 0.38 and a uniform charge distribution has been calculated to be 3.5×10^{12} protons.

THE INJECTION SYSTEM

Booster injection takes place in Long Straight #1. Figure 1 illustrates the H^- charge exchange injection system.

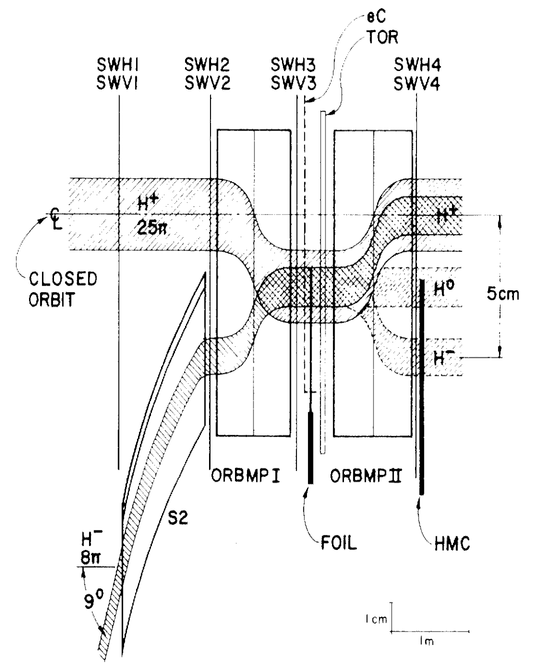

Fig. 1. The Fermilab Booster injection area for H^- multiturn charge exchange injection.

The presently available transverse acceptances of the Booster are $25\pi \times 10^{-6}$ m horizontally and $16\pi \times 10^{-6}$ m vertically. Although the design apertures of 90π and $40\pi \times 10^{-6}$m respectively have never been achieved, all injection apertures of 47 mm H x 56.6 mm V were designed to accommodate them.

The diagnostic equipment consists of four sets of horizontal and vertical wire scanners SWH and SWV, and a current transformer TOR. HMC and eC are electrodes to monitor the number of unstripped H^- ions and stripped electrons, respectively.

The 200 MeV beam transport line is located at 9° with respect to the long straight axis. The injected beam is bent by 9° in S2, emerging parallel to the closed orbit. The first pulsed orbit bump magnet ORBMPI is used to superimpose the trajectories of any circulating beam and the injected H^- beam. The mixed beam of protons and H^- ions traverses a stripping foil,

FOIL. The two electrons are removed from most of the H^- ions and a beam mainly composed of protons emerges from the downstream side of the foil. The protons are repositioned on the closed orbit by the second pulsed orbit bump magnet ORBMPII. The pair of pulsed magnets ORBMP form a local orbit displacement at Long Straight #1.

As the circulating beam must also traverse the stripping medium many times during and for some time after injection, multiple scattering results in the growth of the emittance of the circulating beam. Thus, after injection is completed, the ORBMP fields decay in 30 μs (10 turns), moving the circulating beam off the stripping foil.

STRIPPING FOILS

The studies undertaken for the selection of the type of stripping foils, the method of preparation, and the handler device, are discussed elsewhere.[11] Carbon foils of 200 $\mu g cm^{-2}$ thickness were selected as a good compromise between stripping efficiency, multiple scattering and cost. An accumulated number of protons in excess of 2×10^{19} has been injected through a single foil with no beam-induced damage.

For the maximum of 50 turns of CEI, H^- emittances, and 200 $\mu g cm^{-2}$ thick foils, the transverse emittance blow-up is expected to be less than 15%. The emittance blowup due to multiple scattering has not been measured experimentally during CEI operation. Transverse mismatch between the injected beam and the machine lattice hides the effect of the foil.

In longitudinal phase space the energy loss expressed in terms of $\Delta p/p$ is 2.2×10^{-6} per foil passage. Energy loss seems to be the dominant mechanism for beam losses if the circulating beam is purposely kept on the foil after injection.

OPERATION

Commissioning of H^- CEI began on February 24, 1978, and on March 10th it became the normal injection method for high energy physics operation.

Normal tuning proceeds by setting the amplitude of the ORBMP pulse, thus fixing the distance between the injected beam and the closed orbit. The injection position and angle bumps for the Booster ring are then tuned to minimize the betatron oscillations as observed in a transverse beam pickup.

The eC signal is shown in Figure 2 together with the current pulse in the ORBMP magnets. The timing of the magnets is such that the circulating beam starts to move away from the foil as soon as the last turn is injected. The eC signal is composed of two parts: i) the electrons stripped from the injected beam give rise to a flat contribution over the injection time; ii) secondary emission of electrons from the foil by the circulating beam increases in a staircase fashion as the intensity increases turn after turn and lasts beyond injection until all circulating beam has cleared the foil.

Figure 3 shows the position of the beam during injection as obtained with the single wire scanner SWH3; an absolute gain amplifier makes the H^- and H^+ signals both positive. Each trace corresponds to a successive turn with injection starting at the bottom. The large signal corresponds to the injected H^-. The H^+ signal can be seen moving from a position overlapping the incident beam towards the inside of the machine into the unperturbed closed orbit.

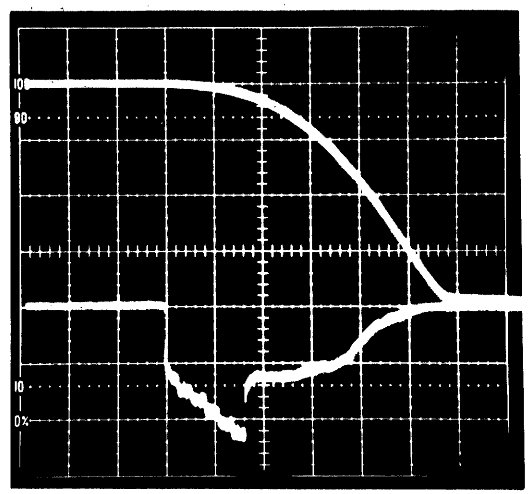

Fig. 2. Top trace: ORBMP current pulse waveform. Bottom trace: eC signal for six turn injection. Sweep 10 μs/division.

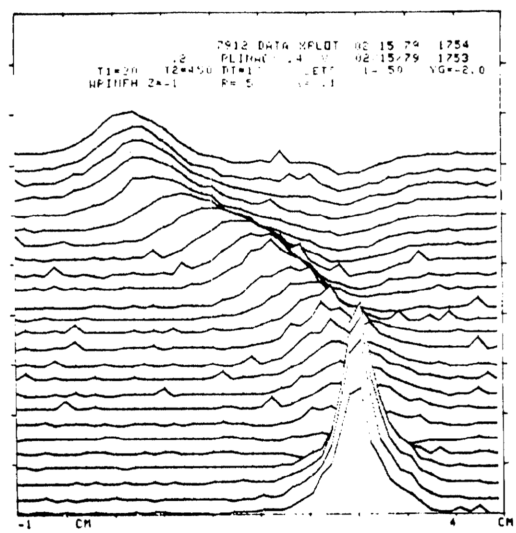

Fig. 3. Horizontal position of the beam at wire SWH3. Each trace corresponds to a successive turn. Injection starts at the bottom trace.

Figure 4 shows the circulating beam current at injection during operation with 6 turn injection. Small injection losses can be observed. The bulk of the Booster losses occur over the first milliseconds of the acceleration cycle.

No significant difference has been observed between the 8 GeV beam sizes with CEI and single-turn H^+ injection.

To compare H^- CEI with previous operation of the Booster, Figure 5 shows a compilation of Booster transmissions versus number of injected protons per Main Ring cycle (13 Booster pulses). Only the best recorded transmissions at a given intensity are shown. CEI seems to yield transmissions of the order of 10% higher for extracted intensities between 2 to 3×10^{13} protons. It is difficult to say whether this improvement is due solely to CEI or to the general evolution of the accelerator. At higher intensities the situation is different, as Booster intensity records have been set with CEI beyond extrapolations of previous Booster transmissions. The first intensity record with CEI was obtained March 4, 1978, less than a month after

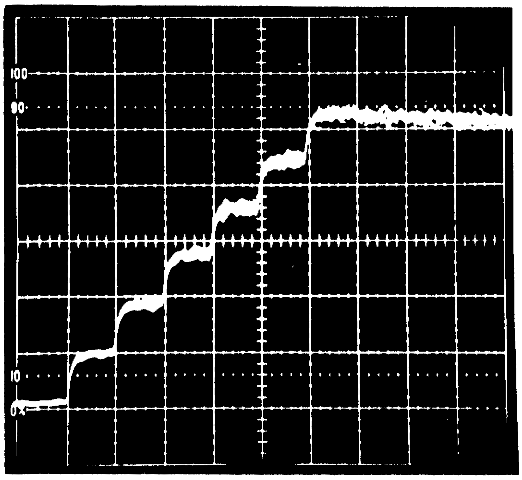

Fig. 4. Circulating beam current during injection for 6 turn CEI. Sweep 1 turn/division.

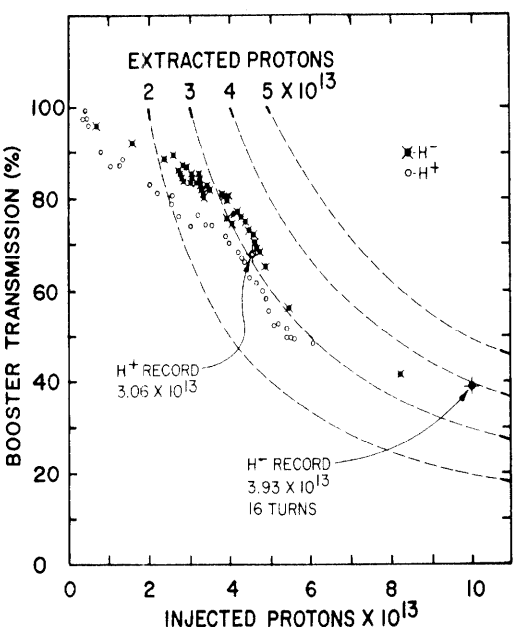

Fig. 5. Fermilab Booster transmission versus injected number of protons per Main Ring cycle (13 Booster cycles).

commissioning the system, with 3.46 x 10^{13} protons per Main Ring cycle. The present intensity record of 3.93 x 10^{13} 8-GeV protons was obtained in September 1978, with 16 turns of CEI for a total of 10^{14} protons injected per Main Ring cycle. This record represents an increase of nearly 30% over the last single-turn H^+ record. With H^- CEI into the Booster, the Main Ring has obtained a new intensity record of 2.7 x 10^{13}.

In conclusion, H^- multiturn charge exchange injection has been implemented in the Fermilab Booster accelerator resulting in record accelerated intensities. The stripping foils, the mechanically most delicate part of the system have proven to be very reliable and have not resulted in any downtime during operation. The new system allows the operation of the Booster at regions of injected charge not available before.

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