INJECTION METHODS IN THE FERMI LAB BOOSTER

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Summary

At present there are two working injection methods; single-turn using a ferrite kicker magnet and multiturn using a pulsed set of 4 dipoles in one straight section. The operating characteristics of these methods are described. The expected implementation of H^- injection will involve the incorporation of devices for all three methods in one 6-m long straight section. The H^- scheme is described and the expected operating characteristics compared to the present methods.

Introduction

A booster synchrotron, cycling at 15 Hz, receives 200-MeV beam from a proton linac and delivers 8-GeV beam to the main-ring synchrotron. There are certain limitations which restrict the performance of the booster. These include, among other things, the intensity, transverse emittance and momentum spread of the linac beam as well as the transverse and longitudinal acceptance of the booster. Residual radioactivity resulting from loss of injected beam also places a premium on efficiency of capture and transmission of the linac beam.

The original booster design¹ provided for multiturn injection, however, a single-turn kicker was added during construction. The design acceptances were 90π mm-mrad, 45π mm-mrad, and 3.0 eV-sec for horizontal, vertical and longitudinal acceptances respectively. These values are adequate to accept into horizontal phase space four turns of linac beam with transverse emittances in both planes of 10π mm-mrad, and a momentum spread of $\Delta P/P$ of $\pm 0.9 \times 10^{-3}$. A design linac¹ beam of 75 mA having these properties would then give in excess of 5×10^{13} protons per main ring pulse, the design goal, for 13 booster batches. These properties for the linac beam were in practice achieved for 90% of the beam². On the other hand, the booster has achieved its design value for only the longitudinal acceptance, which necks down to this value at approximately 3 msec into the acceleration cycle. The operational acceptances are $\sim 25\pi$ and 16π mm-mrad^{3,4,5} in the horizontal and vertical planes respectively. The vertical emittance is limited by the extraction septum.

Three methods of injection are discussed in this paper. Single-turn and multiple-turn injection have been used. H^- injection with stripping is in the planning stage.

Multiturn Injection

After the early stage of booster operation with single-turn injection, multiturn operation was the rule³. Figure 1 shows the parallel displacement of the equilibrium orbit over to the wire septum of an electrostatic inflector by four orbit-bump dipole magnets. A pulsed septum magnet bends the incoming beam 8.3° before the final bend of 0.7° by the electrostatic inflector. The bump-magnet field was designed to decay at a rate of approximately one-half beam width per turn in order to stack beam in horizontal phase space. The original plan employed half-integral tune at injection. A more usual tune value in use is about 6.62.

Fig. 1. Multiturn Injection System

The small radial acceptance has made capture of beam for more than three turns very inefficient. Some beam intensities achieved from the booster and main ring together with overall booster transmission are shown in Table 1. Maximum main-ring beam does not always correspond to maximum booster beam. Much accelerator operation has used two-turn injection with linac beam current in the range of 80-150 mA. In addition to the dilution of phase space in the multiturn method, the beam is susceptible to loss vertically through coupling of the large radial amplitudes with vertical motion.

Single-Turn Injection

The same electrostatic inflector and septum magnet in Fig. 1 are used for single-turn injection and, in principle, no orbit-bump magnets are required. The incoming beam upon entering the booster is parallel to the closed orbit and displaced outward from it. Approximately one-quarter betatron wavelength downstream, in the next long straight action, a ferrite kicker removes the crossing angle at the central orbit. In practice, for much of the single-turn operation, a bump was placed in the closed orbit in the region of injection by four dc trim dipoles. This bump permitted careful alignment of the injection orbit and displacement of the orbit toward the inflector from which it returned to its normal position during acceleration. More recently the pulsed orbit-bump magnets are used to provide part of this orbit displacement so that the bump is more localized and the orbit moves faster back to its normal position.

Because of the greater booster transmission efficiency for single-turn over multiturn injection, a serious study of single-turn injection for higher linac beam current began in January 1976. It was possible at the time to operate at currents to 160 mA for short beam pulses. Momentum slewing because of insufficient rf power in the linac was compensated by the debuncher, which also reduced the increased momentum spread resulting from space charge. This immediately gave beam from the booster (and main ring) in excess of 80% of the intensity obtained by multiturn injection. In the months that followed, operation alternated between single-turn and two-turn injection while modifications to the column of the Crockcroft-Walton accelerator were in progress to increase further the linac beam current. Use of single-turn injection exclusively since last fall has given record 8-GeV and 400-GeV intensities (See Table I) of 2.3×10^{12} protons per booster cycle and 2.5×10^{13} protons per main ring cycle.

Measured linac emittance typically has increased with increasing beam current but slowly enough that

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the brightness increases. This behavior favors high-current single-turn injection. Linac currents up to 300 mA in a pulse length of 4 μ sec have been achieved. See Fig. 2 for an accumulation of operating emittance values over a period of time for three variations of the accelerating column.

Fig. 2. Linac emittance as a function of current for a variety of operating conditions.

Figure 3 shows an accumulated record of operating booster transmission as a function of beam current for single-turn injection. Note the linear upper boundary of the booster transmission.

H⁻ Injection

Increase in phase-space density by stripping the two electrons from H⁻ beam injected for many turns on the same orbit, long suggested, has been demonstrated nicely at Argonne^{6,7}. The injection process as envisioned at Fermilab is shown in Fig. 4. The same long straight section will be used for either H⁺ or H⁻ injection by using some of the same magnets in both cases. A third pair of orbit-bump magnets will change places with the electrostatic inflector for H⁻ injection as shown. The orbit is held fixed during injection and is returned to its normal position during the first few turns after injection. An example of the numbers involved to reach the design goal, 5×10^{13} protons per cycle out of the main ring, is as follows. If we assume 80% transmission of the main ring, 50% transmission of the booster and 90% stripping efficiency, a linac beam of 30 mA will require about 21 turns or a linac pulse length of about 58 μ sec. For this stripping efficiency, a foil of the Argonne variety (mostly carbon) has a thickness of about 300 μ g/cm². It will produce a trivial energy loss of 1 keV/turn and produce an rms scattering angle of less than 1/2 mrad for those protons longest on the foil. If we assume a linac emittance of 107 mm-mrad, the growth in emittance for a matched beam due only to multiple scattering is approximately 6% and 22% in the horizontal and vertical planes respectively⁸.

A few foils prepared at Argonne have been tested in the 200-MeV circulating beam of the booster⁹. The thinner foils tend to confirm the lifetime of $\sim 10^{16}$ protons achieved at Argonne. A multiple-foil holder and changer is required.

Fig. 3. Booster efficiency measured as the ratio of 8-GeV beam to 200-MeV beam out of the linac for single-turn injection. The solid curve represents the approximate maximum transmission attainable.

Fig. 4. H⁻ injection system.

Comparison and Conclusions

Single-turn injection proves a practical competitive scheme for sufficiently high linac-beam intensity. It has yielded ~25% more beam intensity at 400 GeV than has multiturn injection. In addition, the efficiency of single-turn injection is much higher and leads to less residual radioactivity. Linac beam currents greater than 250 mA have rarely been used because of little gain in booster intensity at these levels but more importantly because of increased booster beam size which the main ring cannot accept. These facts as well as the linear fall off of booster transmission with increasing current and other data suggest space charge limited performance within the available booster acceptance. A recent experiment which detailed the beam loss over a large time interval during the acceleration cycle, for which the maximum energy was 4 GeV, also points toward this conclusion.

In view of the possible approach to the space-charge limit from incoherent tune shift, it is difficult to predict great improvement in performance with H⁻ injection, without further improvement in the booster's

TABLE I
OPERATIONAL INTENSITY RECORDS

Injection Method	No. of Turns	Linac Current (mA)	Booster/Linac Efficiency (%)	Max. Booster Intensity (10^{12})	Date	Max. Main Ring Intensity (10^{13}) 13 Booster Batches	Date
Orbit Bump	4	85	29	1.71	6-10-75	1.75	6-10-75
	3	115	36	2.12	12-8-75	1.73	12-8-75
	2	150	37	1.93	1-20-76	2.02	1-20-76
Single-Turn Kicker	1	265*	50	2.33	12-11-76	2.48	12-12-76
H ⁻ Stripping	≥20	30					

*Maximum current is 300 mA for 4-μsec pulse

transverse acceptance. The smaller momentum spread and emittance expected in the injected H⁻ beam, however, should prove some advantage.

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