LONGITUDINAL TRACKING STUDIES FOR THE AHF BOOSTER SYNCHROTRON*

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Abstract

The greenfield site option for the Advanced Hydrotest Facility (AHF) contains a 157-MeV H^- linac followed by two synchrotrons, a booster and a 50-GeV main ring. Several different lattice designs are under consideration for the main ring while two different booster designs are presently being studied. The first booster is a 4-GeV synchrotron operating at h=1 with a 5-Hz cycle. The second is a 9-GeV machine operating at h=2 with a 1-Hz cycle. Both designs are required to deliver ~3 x 10^{12} p/bunch. A longitudinal painting scheme was employed during injection to enhance beam quality and capture during the initial portion of the ramp. The longitudinal beam dynamics simulations were performed with the tracking code ESME. The purpose of these studies was to investigate parameter space and obtain estimates for the rf system requirements. This paper presents the results of these studies.

INTRODUCTION

The Advanced Hydrotest Facility as presently envisioned would allow for quantitative proton radiography of dynamic experiments in support of the stockpile stewardship program. The intensity and spatial resolution requirements dictate the charge per bunch and beam energy on target. With twelve axes for 3-D tomography and 1% intensity precision at the target, the 50-GeV Main Ring (MR) will be required to produce ~4.4 x 10^{13} protons per cycle (which includes losses and a safety factor). To fill ~22 rf buckets in the MR, a booster synchrotron will be required to provide ~3 x 10^{12} protons per bunch (ppb). Over the last two years, several MR and booster designs have been under consideration. One of the earlier booster designs was a 4-GeV synchrotron operating at h=1 with a 5 Hz cycle injecting into a MR of either conventional design that crosses transition or one with a negative momentum-compaction factor. The most recent booster design is a 9-GeV machine operating at h=2 with a 1 Hz cycle that would inject beam above transition in a conventional-style MR with a low γ_t.

BEAM DYNAMICS SIMULATIONS

The longitudinal, multi-particle beam dynamics simulations for these studies were performed with the program ESME [1]. In a typical run, 10^4 macroparticles were employed to represent ~4 x 10^{12} protons in a bunch. Space-charge impedance for a perfectly conducting wall was used and all low-level RF feedback was disabled. One handy feature of ESME is that the user can easily integrate additional subroutines into the code. This feature was used to produce several additional calculated quantities during the simulations.

Two new routines were added which calculated the bunching factor, σ_p/p, an estimate of the 95% longitudinal emittance and an estimate for the longitudinal microwave instability threshold using the Keil-Schnell criteria (using σ_p/p and a form factor of 1). Like the standard calculated quantities in ESME, these are calculated for each turn and stored in the history file for plotting or post-processing.

BOOSTER INJECTION

A 157-MeV H^- linac based upon the SNS design was used to provide the requisite beam for the booster. Following the linac are two rf tanks which serve a dual purpose. The first is to reduce the energy jitter of the beam out of the linac while the second is to vary the energy of the beam across a macropulse. This latter function will be combined in synchronous fashion with a beam chopper at the front-end of the linac and the booster rf system to provide a correlated, phase-energy painting scheme.

This longitudinal painting scheme produces a beam that is well matched to an existing rf bucket in the booster. The beam chopper is used to tailor the intensity of the beam through the macropulse and remove particles that would otherwise be outside of the rf bucket. By phase modulating the rf drive to the second post-linac rf tank, the energy of the beam injected into the booster can be varied over the rf bucket height. PARMILA beam dynamics simulations of the linac including the additional rf tanks were performed to create output distributions with 0 and ±1.15 MeV energy offsets. These distributions along with a simple $V_0\sin\phi$ representation of the energy gain in the second tank and the desired chopping pattern were then used to produce the input beam distribution. An example of the resulting longitudinal distribution following 150-turn injection into the 9-GeV booster is shown in Figure 1.

4 GEV BOOSTER

The 4-GeV Booster is a symmetric, 9-sided lattice with a γ_t of 8.9 and circumference of 261 m. It is designed to operated at h=1 with a repetition rate of 5 Hz. The rf frequency spans the range of 0.592 to 1.128 MHz. The MR requirements for this machine dictate a 95% longitudinal emittance of ~2 eV-s. To accommodate this size beam and a non-zero dP_s/dt during injection, the rf voltage and synchronous phase were initially set to 8.0 kV and 2 degrees, respectively. Using the correlated phase-energy painting scheme, injection occurs over 150 turns

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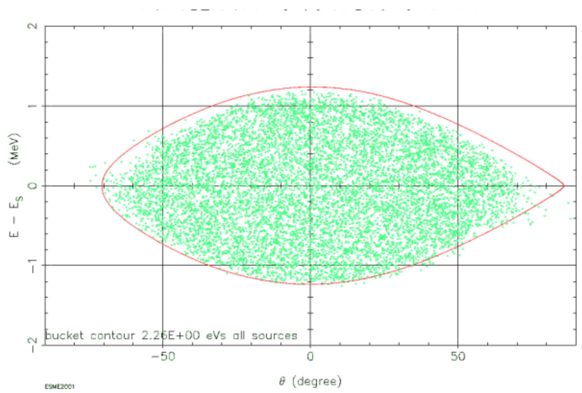

Figure 1: Longitudinal distribution of beam in 9 GeV booster following injection using correlated phase-energy painting scheme.

or 253 µs. The beam energy is swept repeatedly over ±1.15 MeV and the phase width chopped to within ±150 degrees. To inject 4 x 10^{12} ppb will require a peak (average) beam current from the linac of 5.0 (2.5) mA.

The magnet program is designed to provide the net energy gain in 121 ms. The asymmetry between rising and falling portions of the ramp was chosen to reduce the maximum rf voltage required during acceleration, while keeping the voltage across each main dipole magnet below the maximum available from the programmable power supply. The ramp begins with dP_s/dt constant at 373 MeV/c/s for the first 260 µs. This is immediately followed by a parabolic increase in P_s up through the first 10 ms. During this time the rf bucket area is increased slowly to help limit particle loss. All beam loss occurs during the first few milliseconds. The majority of acceleration occurs during the long linear ramp to ~97% of the final momentum. During the linear ramp, which ends at 113.5 ms into the cycle, the rf voltage and phase are held constant. During the last 7.5 ms of the cycle, dP_s/dt is reduced linearly to zero. The rf voltage is maintained at the maximum value while the synchronous phase diminishes to further reduce the phase-width of the beam for easier extraction.

Curves for P_s and dP_s/dt are shown in Figure 2. Over the cycle V_{rf} reaches a maximum of 64 kV while ϕ_s remains below 32 degrees as shown in Figure 3. The 95% emittance is nearly constant over the cycle at ~2.1 eV-s. The threshold for microwave instability was estimated to be a minimum of ~180 Ω at the end of the cycle. Beam capture and transmission is very good with over 99% of the injected particles reaching extraction.

9 GEV BOOSTER

The 9-GeV Booster is a 16-sided design with a γ_t of 13.87 and circumference of 480 m. It is expected to operate at h=2 and a repetition rate of 1 Hz, although an h=1 option is also being considered. The rf frequency

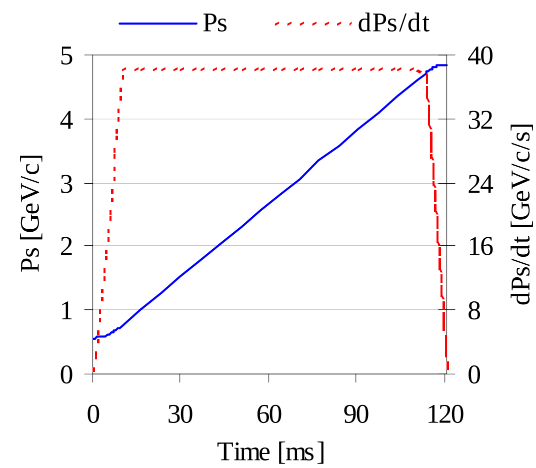

Figure 2: Synchronous momentum (P_s) and dP_s/dt vs. time for the 4 GeV booster.

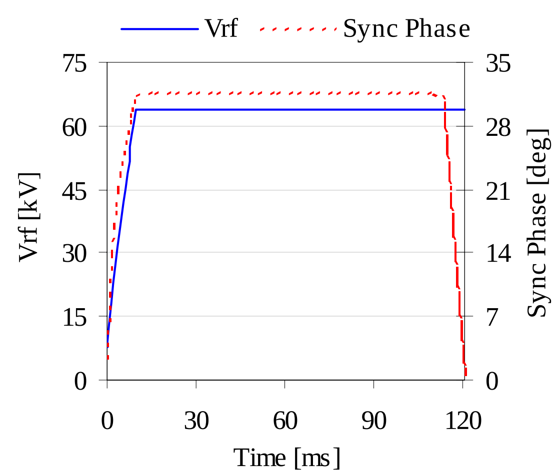

Figure 3: RF Voltage and Synchronous phase (ϕ_s) vs. time for the 4 GeV booster.

covers the range of 0.644 to 1.244 MHz. The main ring fed by this booster also requires a 95% longitudinal emittance of ~2 eV-s. To accommodate this beam, an rf bucket is established with the voltage and synchronous phase at 2.3 kV and 2 degrees, respectively. Using the correlated phase-energy painting scheme, injection occurs over 150 turns or 466 µs. The beam energy is swept repeatedly over ±1.2 MeV and the phase width chopped to within ±73 degrees. To inject 4 x 10^{12} ppb will require a peak (average) beam current from the linac of 5.5 (2.3) mA.

The magnet program is designed to provide the net energy gain in 600 ms. An asymmetric ramp is used that begins with dP_s/dt at 283 MeV/c/s. P_s increases in a cubic fashion for the first 10 ms. During this time the rf bucket area is kept approximately constant to help limit the rf voltage. The cubic ramp was chosen over a parabolic to help maintain a slightly better bunching factor early in the cycle. All beam loss occurs within the first 10 ms. The majority of acceleration occurs during the long linear ramp to ~96% of the final momentum. During the linear ramp, which ends at 550 ms into the cycle, the rf voltage and phase are held constant. During the last 50 ms of the cycle, dP_s/dt is reduced linearly to zero. The rf voltage is maintained at the maximum value while the synchronous phase decreases to further reduce the phase-width of the beam for easier extraction and increase $\Delta p/p$ to raise the threshold for microwave instability.

Curves for P_s and dP_s/dt are shown in Figure 4. Over the cycle V_{rf} reaches a maximum of 61 kV while ϕ_s remains below 26 degrees as shown in Figure 5. The 95% emittance is nearly constant over the cycle at ~1.9 eV-s. The threshold for microwave instability was estimated to be a minimum of ~22 Ω at the end of the cycle. Beam capture and transmission is very good with ~99% of the injected particles reaching extraction.

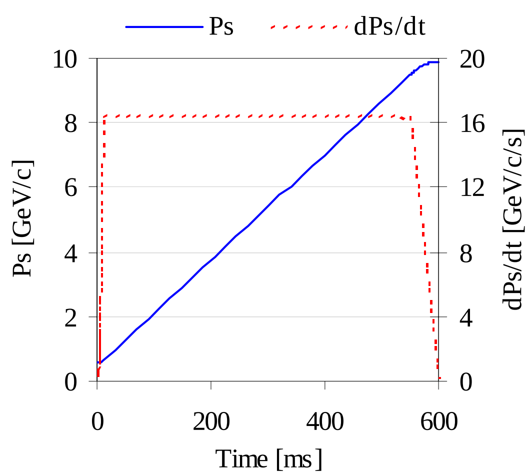

Figure 4: Synchronous momentum (P_s) and dP_s/dt vs. time for the 9 GeV booster.

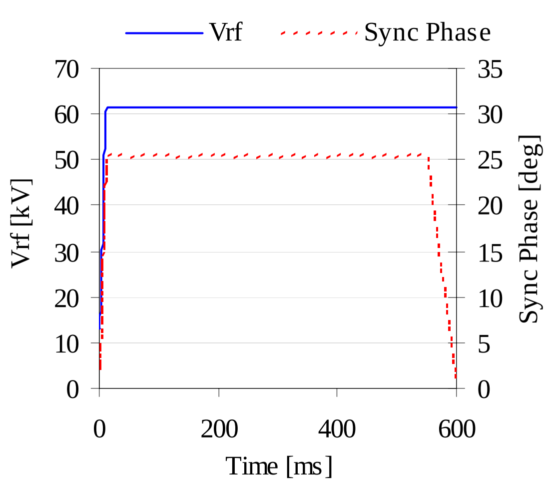

Figure 5: RF Voltage and Synchronous phase (ϕ_s) vs. time for the 9 GeV booster.

SUMMARY

The multiparticle tracking code ESME has been used to develop and study the acceleration process in two different booster synchrotron designs for AHF. A correlated phase-energy injection scheme was used during multi-turn injection to maintain beam quality and reduce losses. The results from the studies show both booster designs exhibit low losses, maintain beam quality and require only modest amounts of rf voltage.

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REFERENCES

[1] http://www-ap.fnal.gov/ESME/