TRANSFERS FROM HIGH POWER HADRON LINACS TO SYNCHROTRONS

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Abstract

The Fermilab Proton Driver is an example of a high power H- linear accelerator proposed as a new source of high brightness protons for the Main Injector synchrotron. Because of the elevated radioactive activation of accelerator components associated with beam losses during injection and acceleration, extra attention must be paid to RF manipulations wherein small losses were once deemed acceptable. Especially when injecting into existing synchrotrons from upgraded injectors, instabilities and beam loading make loss free manipulations especially problematic. This paper discusses some options for reducing the losses associated with common longitudinal beam manipulations.

INTRODUCTION

The advent of high power superconducting hadron linear accelerators has opened up the potential for activation of beamline components in very short periods of operation. As a result, it is imperative to take another look at injection requirements for the next stage of acceleration, which is often a synchrotron.

For example, many synchrotrons accelerate through their transition energy, wherein longitudinal focusing is lost and adiabatic beam dynamics no longer applied. In the presence of strong space-charge forces associated with the elevated beam currents enabled by these high power linacs, loss of particles out of the RF bucket quickly leads to beamline activation.

This paper will discuss the phase space size, longitudinal jitter, and coherent effects of interest in this scenario. This paper will concentrate on the example of the Fermilab Proton Driver [2] feeding the Main Injector.

PROTON DRIVER OVERVIEW

The Proton Driver Project calls for an 8 GeV H-minus linear accelerator that employs a series of acceleration technologies along its length. The upstream end of the linac utilizes a standard H-minus source coupled to a RFQ operating at 325 MHz. The H-minus bunches are then accelerated by a series of room temperature and superconducting spoke cavities [3] also operating at 325 MHz. At 400 MeV acceleration is switched to a 1300 MHz and superconducting elliptical multi-cell cavities [4]. From a kinetic energy of 1.2 GeV up to the final kinetic energy of 8.0 GeV cavities with unity geometrical betas are employed. The initial plan is to run low beam current (8.6 mA) and long pulse lengths (3 msec) in order to reduce the peak power and hence the number of klystrons. Ultimately triple current (26 mA) and shorter pulse lengths (1 msec) are planned, similar to the existing SNS [5] design.

ENERGY SPREAD REQUIREMENT

The Fermilab Main Injector [6] accelerates protons and antiprotons from a kinetic energy of 8 GeV to 150 GeV. It crosses through transition at a kinetic energy of 19.5 GeV. At low beam currents a 95% invariant longitudinal emittance of 0.7 eV-sec can be accelerated through transition without observable beam loss. But at higher beam currents the assumed maximum beam current required to insure 99.99% acceleration efficiency is 0.5 eV-sec.

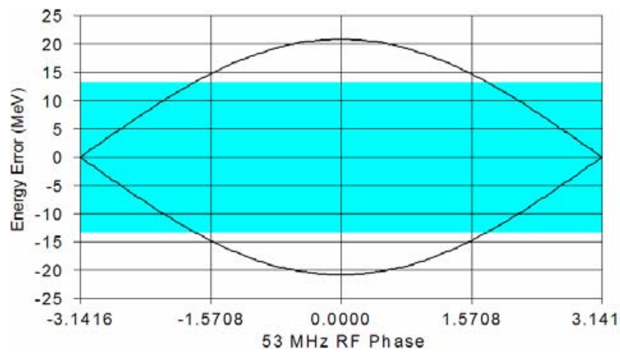

Figure 1: Phase space area of a 0.5 eV-sec RF bucket at injection in the Main Injector, along with the same area for a fully debunched beam (shaded area).

Given that the injection RF frequency in the Main Injector is 52.8114 MHz, there is no rational frequency relationship between the 325 MHz Proton Driver bunch frequency and the Main Injector RF buckets. Transfers might involve either adiabatic capture of a debunched charge distribution or direct population of an existing RF bucket by employing a fast chopper [5] at the upstream end of the linac. The must restrictive injection method from the point of view of Proton Driver beam dynamics is that of adiabatic capture.

A 0.5 eV-sec RF bucket at the injection kinetic energy of 8 GeV has a bucket half-height of approximately 21 MeV. But the same longitudinal phase space area for a fully debunched charge distribution has a half-height of roughly 14 MeV. These relative phase space areas are shown in figure 1.

ERROR TOLERANCE

Because the vast majority of the length and cost of the Proton Driver is the unity geometrical beta section that starts at 1.2 GeV, and because so much of the upstream linac design was drawn from SNS parameters, it was decided to study the propagation of SNS emittances and jitter estimates starting at 1.2 GeV and propagating through the linac all the way to Main Injector injection.

Figures 2 and 3 show the evolution of the rms bunch length and rms energy spread down the length of the unity beta section of the Proton Driver. Figures 4 and 5 show the initial SNS level jitters at 1.2 GeV which maximize the phase and energy errors at the end of the linac.

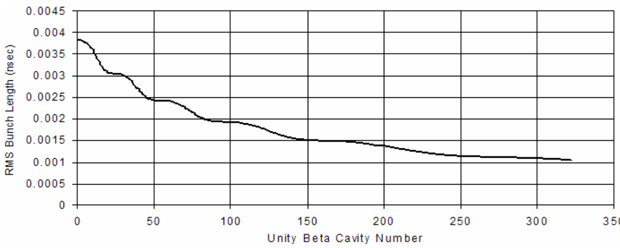

Figure 2: Calculated reduction in bunch length during acceleration from 1.2 to 8 GeV assuming SNS longitudinal emittance and no jitter errors.

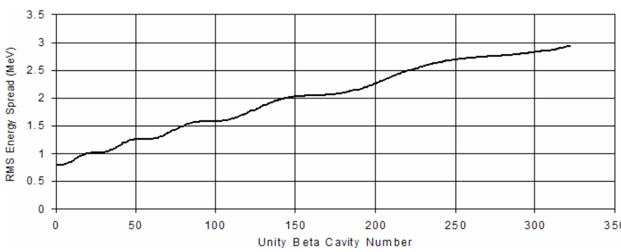

Figure 3: Calculated reduction in bunch length during acceleration from 1.2 to 8 GeV assuming SNS longitudinal emittance and no jitter errors.

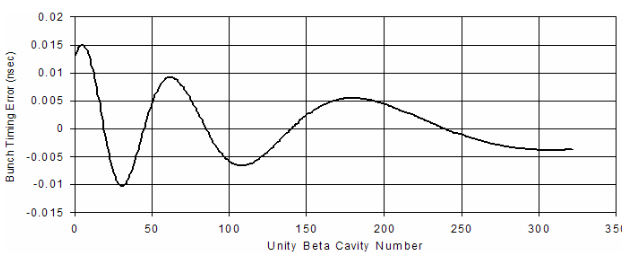

Figure 4: Propagation of SNS level phase and energy jitter from 1.2 to 8 GeV leading to maximal output phase error.

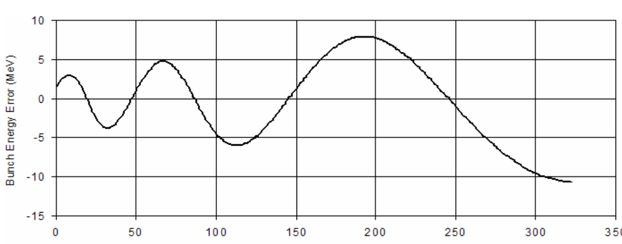

Figure 5: Propagation of SNS level phase and energy jitter from 1.2 to 8 GeV leading to maximal output energy error.

Averaging over all bunches, the 95% energy half width of the beam at the end of the Proton Driver is calculated to be approximately 19 MeV, which is larger than the allowable 0.5 eV-sec (see figure 6). Therefore it is necessary to apply correction schemes to reduce the energy spread. Possible correction methods are vector-sum compensation and the use of a debuncher cavity.

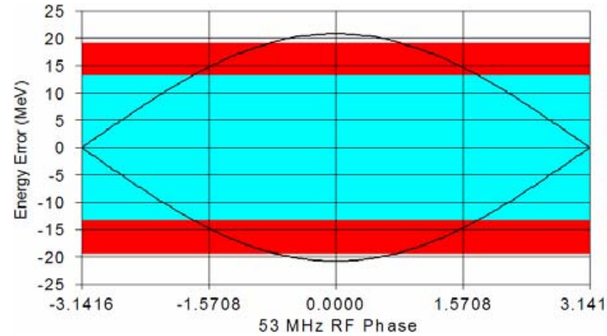

Figure 6: Beam energy width (total shaded area) out of the proton driver assuming SNS emittances and jitter levels.

VECTOR-SUM JITTER COMPENSATION

Given an appropriate error signal, it is possible to correct the output energy and phase errors of the linac by adjusting the phase of one or more RF cavities. Figures 7 and 8 show the amount of output time (phase) and energy change achieved by varying each cavity in the unity beta section of the Proton Driver. For one cavity at a time, a one degree change in phase was applied to an otherwise error free linac and the resultant time (phase) and energy change at the end of the linac were recorded. The shaded regions designate the groups of cavities that have the maximal effect on the linac output.

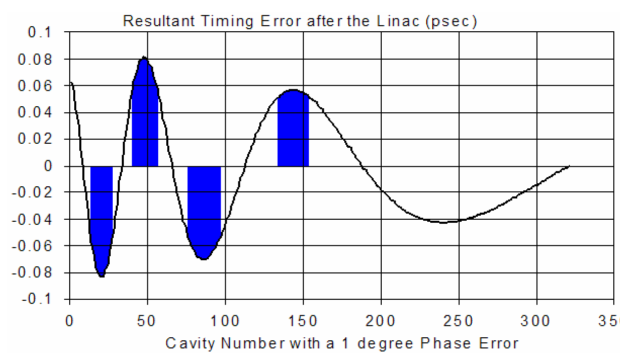

Figure 7: Timing (phase) correction per cavity upon a one degree change in the phase of that cavity.

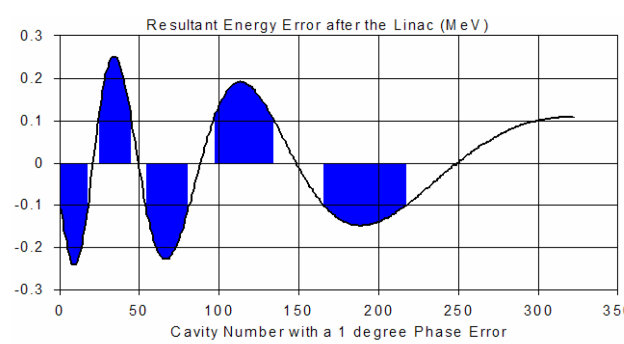

Figure 8: Energy correction per cavity upon a one degree change in the phase of that cavity.

Figure 9 shows the energy spread achievable when the jitter is fully compensated. The frequency distribution of the jitter and the bandwidth of correction achievable in high-Q cavities are an ongoing area of study.

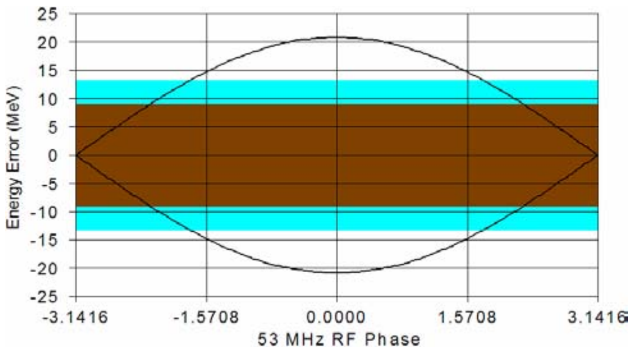

Figure 9: The dark (brown) shaded area is the output 95% energy spread of the Proton Driver when jitter is fully compensated. Note the no other correction is necessary.

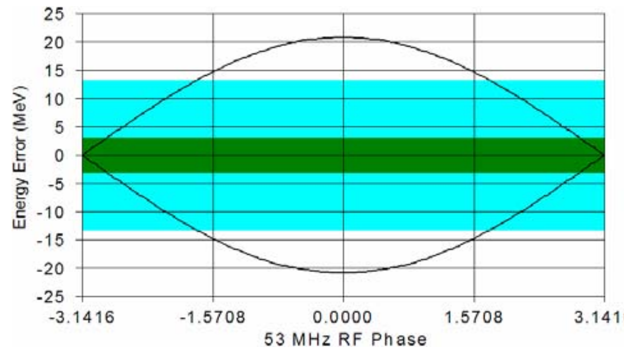

Figure 12: The dark (green) shaded area is the output 95% energy spread of the Proton Driver when only a debuncher cavity is used.

DEBUNCHER CAVITY COMPENSATION

By placing a 1300 MHz RF cavity with a peak energy gain of 50 MV, it is possible to reduce the energy spread of the beam by rotating energy spread into time (phase) spread. The problem with this concept is that energy centroids larger than the original jitter levels are possible if the phase offsets of bunches are large enough. Figures 10 and 11 show that this adverse effect is not possible with SNS levels of jitter, even without vector-sum use.

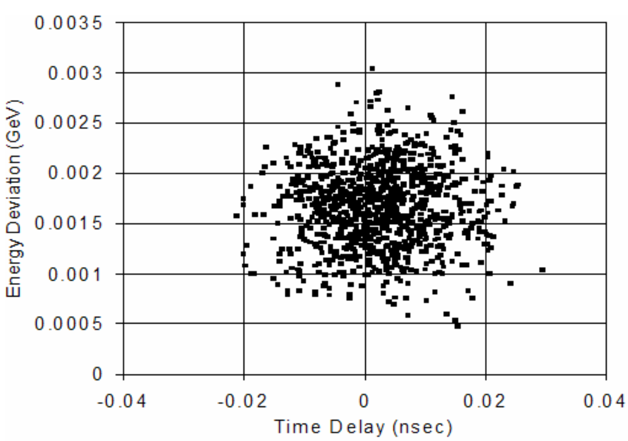

Figure 10: Phase space distribution after the debuncher cavity given the linac output phase error in Figure 4.

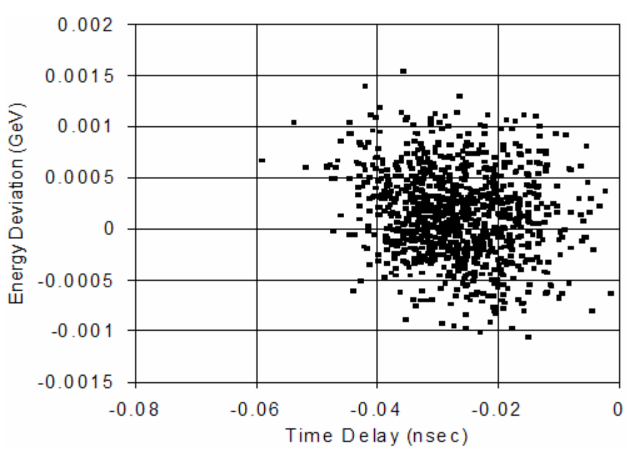

Figure 11: Phase Space distribution after the debuncher cavity given the linac output energy error in Figure 5.

MICROWAVE INSTABILITY

Despite the best intentions of the above compensation techniques, it is possible that the beam will not survive intact in the Main Injector due to an estimated Z/n of 5.5 Ohms. The frequency relationship between the linac and synchrotron cause a fully modulated beam with a fundamental frequency near the cut-off frequency of the Main Injector vacuum chamber, causing intense wake fields. Preliminary simulations have been started.

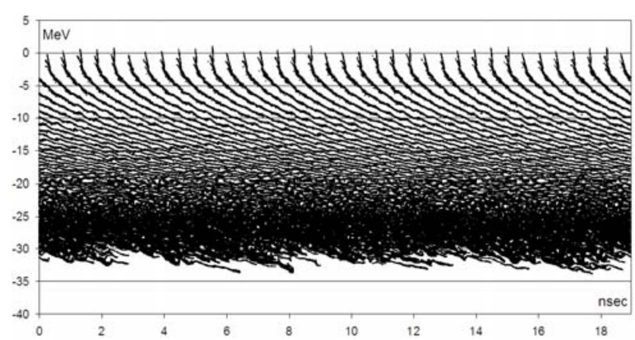

Figure 13: Preliminary calculation of energy spread growth in the Main Injector over the 270 turns of injection.

REFERENCES

[1] This work was performed under a contract from the Fermi National Accelerator Laboratory.

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[5] "Preliminary Design Report - Superconducting Radio Frequency Linac for the Spallation Neutron Source", SNS-SRF-99-101 (December 20, 1999).

[6] Fermilab Main Injector Technical Design Handbook; S.Mishra, "High Luminosity Operation of the Fermilab Accelerator Complex", Proc. 2003 U.S. Part. Accel. Conf. (2003).

