ENERGY CORRECTION FOR HIGH POWER PROTON/H MINUS LINAC INJECTORS*

D. Raparia, Y. Y. Lee, J. Wei
BNL, Upton, NY 11973, U.S.A.

Abstract

High-energy proton / H minus energy (> GeV) linac injector suffers from energy jitter due to RF amplitude and phase stability. Especially in high power injectors this energy jitter results in beam losses more than 1 W/m that require for hand on maintenance. Depending upon the requirements for the next accelerator in the chain, this energy jitter may or may not require to be corrected. This paper will discuss the sources of this energy jitter, correction schemes with specific examples.

INTRODUCTION

For high power proton accelerators (Spallation Neutron Source (SNS) [1], European Spallation Source (ESS) [2], Proton Divers (PD) for super neutrino beam [3, 4], etc) face many challenges. The most important challenge is to keep the average losses less than 1W/m for hands on maintenance. The beam loss is caused by space charge effects, injection and extraction processes and longitudinal and transverse instabilities. To reduce space charge effects, one tries to reduce charge density in real space of the injected beam by various so called painting schemes. These painting schemes arranges injected ions into ring's transverse and longitudinal phase space to reduce the charge density in a given phase space. In some painting schemes transverse and longitudinal phase space are decoupled by injecting into the ring in dispersion free reason (for example SNS injection scheme [5]) while others schemes inject ion into dispersive reasons of the ring hence coupling transverse and longitudinal phase spaces (for example ESS injection scheme[6]) during the injection process. The transverse painting is important to avoid resonance crossing by minimizing space charge tune spread. The longitudinal painting is essential for controlling space charge and instabilities by Landau damping.

A successful longitudinal painting depends on two factors: (1) Uniform charge density in the longitudinal phase space which can be achieve by manipulating linac energy as in case of ESS or providing uniform energy spread from the linac as in case of SNS. (2) Reducing the longitudinal halo which can be minimized by stabilizing the linac energy and energy spread by controlling linac phase and energy jitter.

SOURCES OF THE ENERGY SPREAD AND ENERGY CENTROID JITTER

If the energy jitter from the linac is not controlled within the specification, it may result in beam leaking into extraction beam gap, beam escaping rf bucket and hitting the momentum aperture.

Energy jitter caused by systematic and random errors. Systematic errors include beam loading, beam transient, space charge, cavity errors, Lorentz detuning (in case of superconducting RF linac), and static rf cavity control uncertainties. Systematic errors can be mostly compensated by feed-forward.

Random errors include reference line temperature variation, linac injection mismatch, microphonics, dynamic RF cavity control uncertainties etc and can not be compensated by feed- forward.

The energy jitter directly depends on the number of rf control (N_{rf}) and can be estimated by

$$\frac{\delta E_k}{E_k} = \frac{1}{\sqrt{N_{rf}}}\left[\left(\frac{\delta V_c}{V_c}\right)^2 + \left(\tan\phi_s \Delta\varphi_s\right)^2\right]^{\frac{1}{2}}$$

Where N_{rf} is number of cavity / rf control module, E_k is the final energy, δE_k energy jitter, $\Delta E = V_c \cos\varphi_s$ energy gain per rf control module, Thus for same energy gain per rf control sand same level of rf control stability, the relative energy deviation at end of the linac can be less for a linac of higher energy.

In case of SNS: E_k ~ 1 GeV, φ_s ~ 20°, V_c ~ 10 MeV, $\delta V_c/V_c$ ~ 1%, $\Delta\varphi_s$ ~ 1°, N_{rf} ~ 100, gives $\delta E_k/E_k$ ~ 1.2E-3. In case of FNAL PD for one cavity per klystron (E_k ~ 8 GeV, N_{rf} ~ 800) $\delta E_k/E_k$ ~ 0.4 E-3 and for 8 cavity per klystron, $\delta E_k/E_k$ is about ~ 1.2E-3.

ENERGY CENTROID JITTER CORRECTION

The correction of energy centriod can be accomplished by fast feed-back or passive energy correction cavity. Fast

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#raparia@bnl.gov

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feed-back time should be shorter than the corrector cavity characteristic time and the ratio of the fast feed-back time to the linac pulse length should be lower the acceptable loss fractions. For example, Fermilab proton diver linac (8 GeV) proposed fast feed back solution as follows: in high energy beam transport (HEBT) line, there will be a copper cavity will be located after the arc in the HEBT with 1-2 MHz bandwidth. The idea is to measure average energy offset in the arc and then correct in the copper cavity located down stream of the arc. The residual cavity to cavity phase and amplitude jitter is much faster then the system response time and must be acceptable for ring injection [7]

Assuming that during the response time of fast feed-back energy is not corrected and eventually .these particles will fall out of ring rf bucket and lost. If response time for fast feed-back is ~10 μs and linac pulse length is ~ 1 m, and assume 10% beam pulse lie out side of the energy acceptance of the ring, than beam loss fraction is 0.001, which may not be acceptable for MW beam power. Passive energy correction scheme involve a corrector cavity operating at the linac frequency at distance L form the linac and phase lock to the linac. The particle with design energy (synchronous) sees the -90 degrees (zero voltage) hence does not change the energy. The particle having more energy than the design energy arrives earlier than the synchronous particle and sees the negative voltage hence lose the excess energy. The particle having less energy than the synchronous particle arrives later than the synchronous and sees the positive voltage and gain the required energy. The energy gain (loss) depends on the time difference (phase difference) between the off energy particles and the synchronous particle and the cavity voltage. There are limits to this correction scheme, first if the phase slip is more than 90 degrees then the particle does not gain (lose) the correct amount of energy. Secondly if the phase slip is less than the phase jitter than aging off energy particle does not gain (loss) the correct amount of energy. Ideally we want maximum phase difference of less than 60 degrees.

The phase slip a for the distance L is given by

$$\Delta\phi_{slip} \approx \frac{\omega_{rf} L}{\beta c} \frac{1}{\gamma(\gamma+1)} \frac{\delta E_k}{E_k} \qquad (1)$$

Where β and γ are the relativistic parameters for beam, c is the speed of light, ω_{rf} is rf frequency of the linac and δE_k is the energy error. The condition to achieve successful energy correction is given by

$$\delta\varphi_{jitter} << \frac{\omega_{rf} L}{\beta c} \frac{1}{\gamma(\gamma+1)} \frac{\delta E_k}{E_k} < \frac{\pi}{2} \qquad (2)$$

The distance L need to realize passive energy correction is a strong function of beam energy

$$LV_{ec} \approx \frac{\beta c \gamma(\gamma^2 - 1) m_0 c^2}{\omega_{rf}} \qquad (3)$$

where V_{ec} is required voltage of the corrector cavity. In case of SNS; β=0.875, γ=2.1, f_{rf}=805 MHz, V_{ec}=3 MV and L=115m, In case of FNAL PD: β=0.99448, γ=9.5, f_{rf}=1.3 GHz, V_{ec}=20 MV and L=1460m.

Figure 1 shows the product of length L meters and corrector cavity voltage V in MV as function of beam energy in GeV. Note the log scale on y-axis.

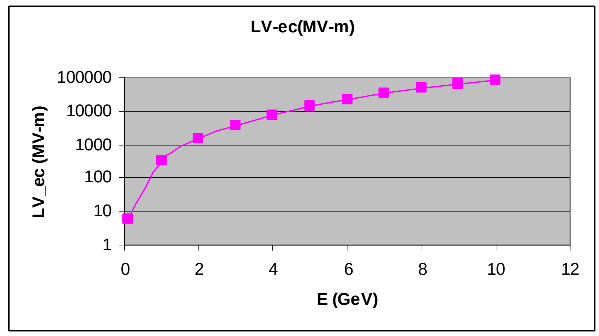

Figure 1: Product of L in meters and corrector cavity voltage in MV as function of energy.

ENERGY CORRECTION FOR SNS LINAC

As a direct consequence of cavity rf phase and amplitude control uncertainties, the beam energy and phase jitters are induced. Figure 2 show histograms of beam centroid energy and phase jitters at the end of the linac for ±1° and ±1% rf phase and amplitude uncertainties (upper plots) and for ±0.5° and ±0.5% rf phase and amplitude uncertainties. These are the results of 1000 linac runs using the Ltrace code. When the LLRF control uncertainties increase by factor of two, the centroid energy and phase jitter almost doubles. [8]

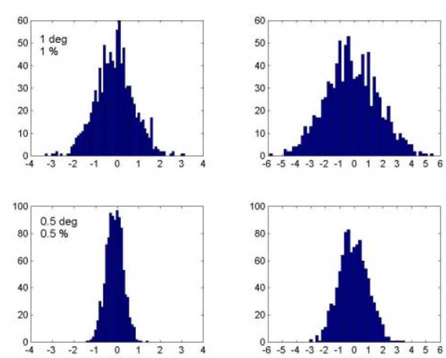

Figure 2: Histograms of beam centroid energy and phase jitters at the end of linac for ±1° and ±1% rf phase and amplitude control (upper plots) and for ±0.5° and ±0.5% rf phase and amplitude control.

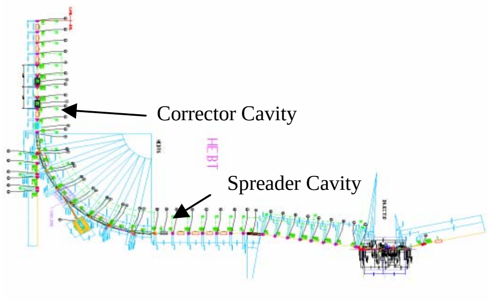

Figure 3: HEBT transport line and the location of corrector and spreader cavities.

Energy error is corrected with the energy corrector cavity (ECC) located some distance (115 m) downstream of the last tank. Figure.3 shows the locations of the corrector and spreader cavities. Using energy dependent phase slip, energy error is corrected by a RF cavity of suitable amplitude and phase. The limit of correction is from the phase error (~ 4 degrees) at the last tank.

Figure 4 shows the beam centroid energy jitters at the end of the linac (left column) and after the ECC (right column) for the two sets of rf control uncertainties. As is shown, beam centroid energy jitter after the ECC degrades from ±0.2MeV to ±0.4MeV. The probability that residual beam energy jitter is less than 0.2 MeV is 99% for phase and amplitude errors of ±0.5° / ±0.5% and 90% for phase and amplitude error of ±1.0° / ±1.0%. Clearly residual energy jitter is caused by phase jitter.

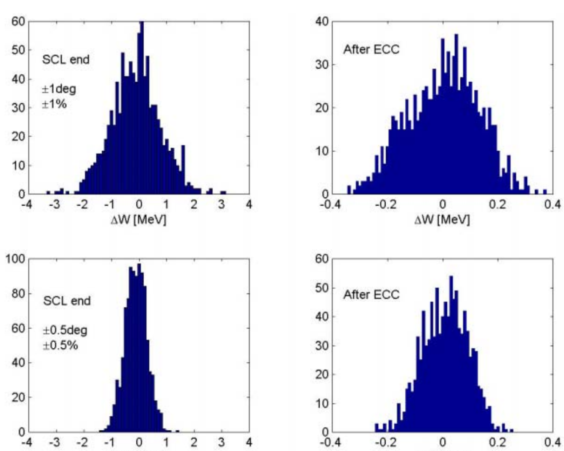

Figure 4: Histograms of beam centroid energy at the end of the linac and after the ECC for the two sets of rf control.

Figure 5 shows the beam envelops through the linac and HEBT for mismatch beam into the linac. One should note that energy corrector cavity not only correct the beam energy but also reduces the energy spread, which help reducing the energy tail after the energy spreader cavity.

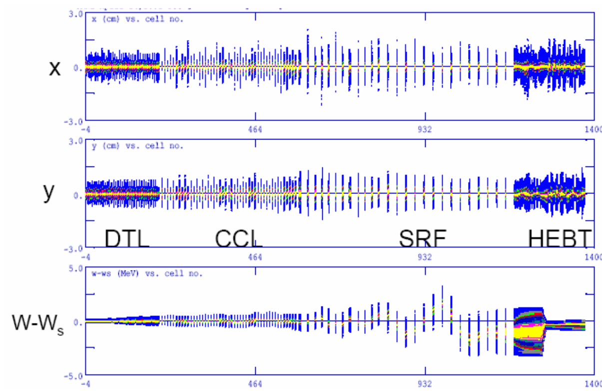

Figure 5: Beam envelopes through the SNS linac and HEBT.

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