Energy Feedback System for the SSRL Injector Linac*

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Abstract

The energy feedback system for the SSRL Injector linac is presented. The feedback is implemented as a computer program in the SSRL Injector control system, and has been a valuable tool during the commissioning of the injector.

I. INTRODUCTION

The SSRL Injector microwave gun, linac, and booster were commissioned last year[1]. For efficient injection into the booster the linac beam energy must be stable to within about 1%. Unfortunately, fluctuations in the line voltage supplying the unregulated klystron modulators cause fluctuations in the linac beam energy, thus making the operation of the booster potentially very difficult. Without any corrections, the linac energy may drift by as much as one percent per minute or it may jump suddenly by one percent. Fortunately, the linac beam energy can be kept close to the desired value by using feedback on the low level controls of the klystrons feeding two of the linac sections. The energy of the linac is sampled at a beam position monitor[2] (BPM) downstream of the first magnet following the linac. The feedback loop is closed using a low-pass filter that noise from the BPM processing electronics. The feedback is implemented as a computer program (`energy_feedback`) written in `C` for the SSRL Injector control system[3], and is robust against various fault conditions, as a result of the many changes and adjustments suggested by the commissioning team who are mentioned in the acknowledgements.

II. LINAC BEAM ENERGY FLUCTUATIONS

The linac is described elsewhere[4]. Briefly, it is composed of three 10-ft 2856 MHz SLAC-type sections, each powered by a ~30 MW klystron pulsed for 2μs at 10 Hz. The energy gained by a particle travelling on the crest of the RF wave is

$$E_{\text{gain}}[\text{MeV}] = \sum_{i=1}^{3} 10\sqrt{P_i[\text{MW}]}\cos\phi_i \tag{1}$$

An attenuator and a phase shifter control the low level RF to the klystrons feeding sections 1 and 3. The modulators supplying the voltage to the klystron cathodes are not regulated. The voltage at which the pulse-forming network of the modulators charge varies with the line voltage supplied by the local utility. Typically the charging voltage is set at about 20 kV. A slight variation in klystron cathode voltage can cause a much greater variation in RF amplification since klystrons are very nonlinear devices.

III. BEAM ENERGY DETECTION

The energy of the particle is measured using the first Linac-to-Booster beamline (LTB) bending magnet as a spectrometer. Since $\gamma = E/mc^2 \approx 250$, the term energy will used interchangably with momentum. Magnet B1 of the LTB line bends the beam of the nominal energy E_0 horizontally by an angle of 41.57 degrees. A beam position monitor (BPM) is located downstream from the bending magnet. If the energy of the beam is increased by ΔE, then the beam position detected by the BPM will change by

$$\Delta x = \eta \frac{\Delta E}{E_0} \tag{2}$$

where η is the dispersion at the BPM position. Since there are no quadrupoles in between B1 and the BPM, the dispersion function can be calculated accurately to be 0.75 m.

IV. CLOSING THE LOOP

The variable RF attenuators upstream of the klystron RF drive input ports can be used to control the variations of the electron beam energy based on energy measurement of past pulses. For instance, if the high-voltage (HV) from the modulators start to drop a bit, then the attenuators can be adjusted to attenuate less. This prevents the klystron RF output power from dropping when the cathode HV drops. Although this is a nonlinear system, it is treated as linear to keep the feedback algorithm simple.

The amount of the attenuation can be set from the control system. Because of the nature of the attenuator[5], the attenuation is a highly nonlinear function of the programming voltage. (The attenuator operates by a DC current which is provided by a voltage programmable current driver.) The attenuation characteristics for linac section 1 was measured as a function of programming voltage. Using equation 1, one can calibrate the energy gain due to one linac section as a function of the attenuator setting. The voltage dependence on energy gain is plotted in figure 1 for the klystron of section 1. The data was taken with a maximum klystron RF power of 26.7 MW. Variations between klystrons will modify the vertical scale of the plot.

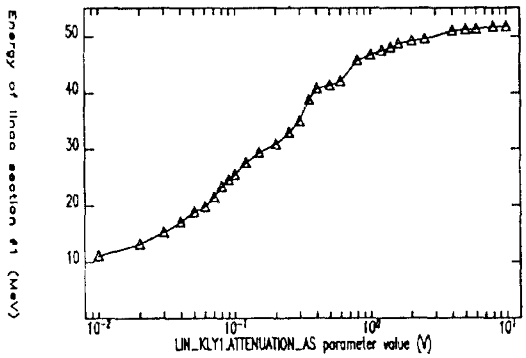

Figure 1
Calibration of attenuator of section 1

Since the electron beam enters the linac section 1 with an energy of ~2 MeV, there will be a small amount of bunch compression in the first few cells. Varying the RF power delivered to this section may upset the optimal RF phasing between the gun and section 1. Therefore the energy correction is split between section 1 and 3 by a ratio of 1 to 5. The klystron of section 2 is left untouched because it also controls the gun RF power.

The basic feedback algorithm steps are:

1. Measure the position of the beam x at the BPM following B1 relative to a set point x_{ref} selected by the operator.
2. Determine the absolute energy deviation from the set point:

$$\Delta E = E_0(x - x_{\text{ref}})/\eta \tag{3}$$

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3. Calculate the necessary attenuator change $\Delta V_{\rm att}$ for linac sections 1 and 3 using the calibration data in Figure 1:

$$\Delta V_{\rm att} = \frac{dV_{\rm att}}{dE} \Delta E \tag{4}$$

4. Change the attenuator settings in the database according to the above. The control system then sets the attenuator programming voltage to its new value.
5. Wait for the next beam position measurement and repeat.

For simplicity, the interpolation in step 3 is done by fitting straight line segments to the energy vs log of attenuator voltage curve.

Ideally a correction should be effected for every beam pulse, that is at a 10 Hz rate. However the hardware scans a different BPM along the LTB line at every beam pulse. In addition, the control system database, from which the BPM position data is gleaned, is updated approximately every 0.8 seconds, depending on the system CPU usage. Therefore the energy correction loop can be working at a maximum rate of 1.2 Hz.

V. STABILITY OF LOOP

The feedback system is susceptible to unstable oscillations if noise is not sufficiently filtered and if the gain (i.e. change in attenuator signal per sampling interval) is not correctly calculated.

The energy deviation signal includes noise from the BPM processing electronics which should be filtered out using a low-pass filter in a computer program. For convenience, the beam position difference

$$(x_{\rm diff})_k = (x_{\rm ref})_k - x_k = -\frac{\Delta E}{E_0}\eta \tag{5}$$

is the quantity that is filtered instead of the energy deviation. Here k means the $k^{\rm th}$ sample of a quantity. The latter value can be set interactively at an operator's console. The filter is of the form

$$(x_{\rm fil})_{k+1} = A(x_{\rm fil})_k + B(x_{\rm diff})_k \tag{6}$$

where the coefficients A and B are optimized for desired response time and minimum overshoot. The attenuator setting change $(\Delta V_{\rm att})_{k+1}$ is calculated so that the $(x_{\rm fil})_{k+1}/\eta$ portion of the energy deviation is corrected.

$$(\Delta V_{\rm att})_{k+1} = \frac{dV_{\rm att}}{dE}\frac{(x_{\rm fil})_{k+1}}{\eta} \tag{7}$$

Different running conditions such as klystron and modulator settings, and relative phase between linac sections may cause unintended changes in the feedback loop characteristics. The coefficients A and B can be readjusted easily to recover an optimal perfomance.

A low-pass filter allows the feedback system to track the energy well when a slow drift of the charging voltage of the modulators occurs with the high-frequency noise of the BPM electronics.

However, beam energy changes by 2% can suddenly occur because of line voltage changes. Because of the low-pass filter, the feedback loop may take as much as 10 seconds to bring the beam position back to its set point. The response of the feedback can be accelerated by temporarily switching to a faster low-pass filter (higher B value), which can be producing normally unused values in parallel all along. The faster low-pass filter simply assigns a larger weight to the current difference signal. When the beam position is close enough to the set point, the slower low-pass is reinstated.

The program determines automatically the threshold for the above filter-switching. A high-pass filter working in parallel is used to determine the RMS amplitude of the noise which the low-pass filter removes from the signal. The threshold is set to twice the noise level.

VI. FEEDBACK SYSTEM PERFORMANCE

Figure 2 shows the drift in beam position at the BPM during a five minute period. In order to test the feedback system a few parameters were recorded simultaneously for a period of 40 minutes. Figure 3 shows a voltage proportional to the charging voltage of the modulator. The sharp downward spikes in the Figure can be ignored; they are due to transients during the recharging of the modulator. That is, the envelope of the curve indicates the variation which should be compensated by the feedback. The beam position during the same period is plotted in figure 4. Note the steady value of the beam position during the high-voltage drift. The spikes on this plot are not spurious. They indicate how suddenly an energy change can occur, and how quickly the energy is corrected. The attenuator signal in Figure 5 basically reflects the error signal. The features of the plot correspond to the same features as the modulator charging voltage, the source of the error.

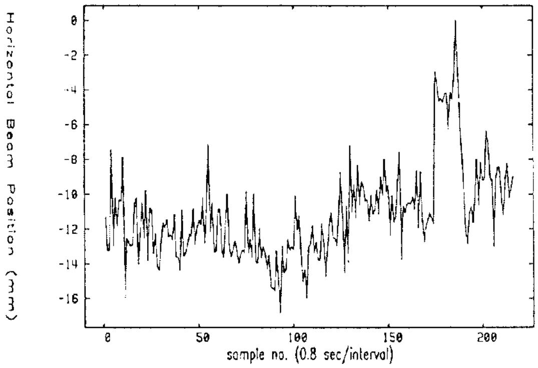

Figure 2
Beam position drift without feedabck

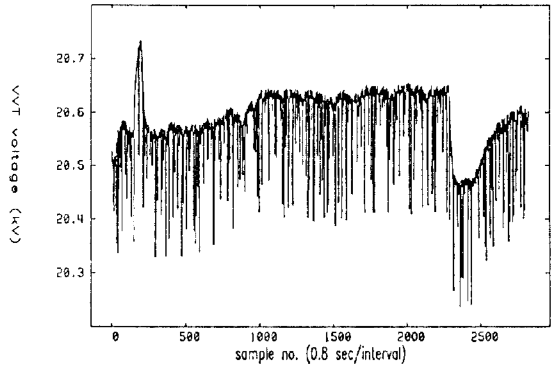

Figure 3
Charging voltage of modulator

VII. FAULT CONDITIONS

The computer program that implements the feedback must be able to distinguish between various error conditions, and hold the loop until some conditions are met. For instance, the sum signal of the BPM strips are continually monitored for possible absence of beam. If the feedback loop was not put on hold, the program would assume that the beam is centered exactly in

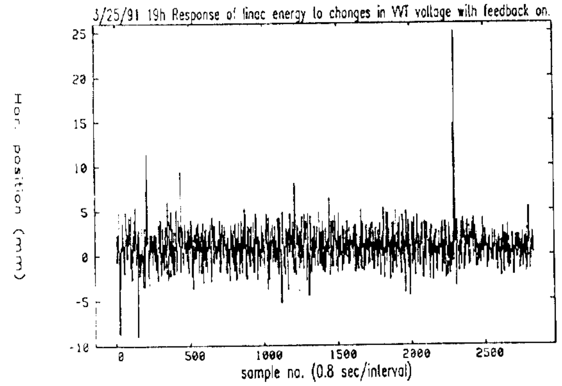

Figure 4
Beam position during feedback

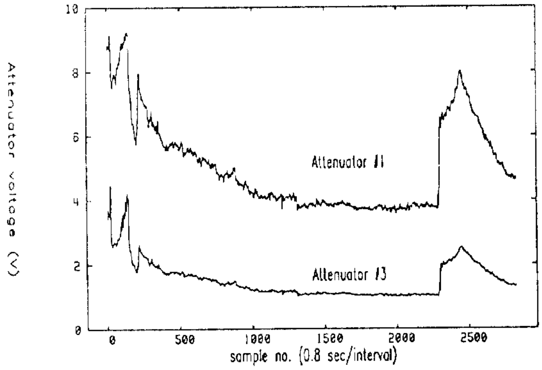

Figure 5
Attenuator signal during feedback

the BPM. If the set point was not 0 mm, then the attenuator settings would become unstable and reach their limits.

An occasional glitch in the BPM processing equipment causes the BPM database value to be exactly 0mm or exactly ±25 mm (database software limits defined for BPM's) for a single sample. These values are ignored by the feedback, and the program waits a sampling interval before reading the next beam position. When the reading persists for two consecutive samples, then either the beam is lost or the beam energy jumped out of the range of the BPM. The former case was mentioned in the previous paragraph. For the latter case the feedback system considers the beam to be exactly at the limit and switches on the fast feedback.

When the most "active" attenuator (linac section 3) reaches its limits, that is, it cannot provide more power to a drooping klystron, the other attenuator continues working until it too reaches its limit. At this point, the line voltage determines the operating energy of the linac, thus forcing a reduction of the LTB beamline magnet strengths and the booster injection energy.

Occasionally, due to personnel protection system faults, the RF powering the microwave gun and linac sections is turned off. Recovering the previous beam energy and the small energy spread (.1%) takes a few minutes of waiting after the RF is turned back on. The transient effect and the temporarily large energy spread (which can be viewed on a removable phosphorescent screen following the BPM) can be traced to the nature of the microwave gun. The feedback system is capable of turning itself back on as soon as the BPM detects a sufficient amount of beam. It is interesting to watch the beam on the phosphorescent screen as the beam energy is quickly returned to its original value while the energy spread is still stabilizing.

VIII. POSSIBLE IMPROVEMENTS

At large beam offsets the BPMs become nonlinear. The dependence can be derived analytically[6]. If the individual BPM button signal strengths were available to the control system, it would be a simple matter to include the correct beam position in the computer program.

The attenuators of section 1 and 3 could be calibrated automatically as an option when the feedback program is invoked. Assuming that the klystron voltage remains stable during the procedure, the attenuator could be swept through a range of values while the BPM detects the beam position within its limits. The data points could be stored as a fitted function which the feedback algorithm could call. This scheme would have the advantage that it would removes possible daily variations of klystron properties and other imponderables.

IX. CONCLUSION

A linac beam energy feedback system was found to be necessary for injection into the SSRL booster during periods of line voltage fluctuations. The system was implemented by writing a computer program for the control system. The feedback performance for a 40 minute period was described.

X. ACKNOWLEDGEMENTS

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XI. REFERENCES

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