An Energy Feedback System for the MIT/Bates Linear Accelerator

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Abstract

We report the development and implementation of an energy feedback system for the MIT/Bates Linear Accelerator Center. General requirements of the system are described, as are the specific requirements, features, and components of the system unique to its implementation at the Bates laboratory. We demonstrate that with the system in operation, energy fluctuations correlated with the 60 Hz line voltage and with drifts of thermal origin are reduced by an order of magnitude.

1 Introduction and Motivation

Beam energy stability is of fundamental importance in any scattering experiment. Not only are the results of such experiments sensitive to fluctuations related...
in beam energy, but energy variations can significantly affect transmission through beam line elements that transport the beam to the experimental area. Instability can therefore result in beam losses, the subsequent creation of large backgrounds in the experimental detectors, and, especially if reliable extraction of observables depends critically on proper background subtraction, an increase in systematic uncertainties. In addition, beams are often injected into internal storage rings, where mismatch between the injected beam energy and the ring energy can again result in the significant losses and large backgrounds associated with beam scrape-off. It is also true that the energy of pulsed electron beams can be susceptible to slow drifts, and, especially if DC supply voltages and power are coupled to the AC line, to fluctuations at 60 Hz.

These issues are important at the MIT/Bates Linear Accelerator Center, where pulsed electron beams with energies of up to 1 GeV are generated for transport to two main experimental areas and for injection into the new South Hall Ring (SHR). In order to improve beam energy stability, we have recently designed and implemented a feedback system capable of adjusting the beam energy in response to both 60 Hz fluctuations and slow drifts. A beam position monitor (BPM) installed in a dispersive region of the beam line allows the energy of each pulse to be measured. The BPM signal, which is sensitive to changes in the amplitude or phase of any of the twelve klystrons that supply radio frequency power for the accelerator, is the system’s single “dial”. A phase shifter, the system’s single “knob,” is installed on one of the klystrons to allow small, rapid, computer controlled energy adjustments to effectively compensate for those changes.

This work was primarily motivated by a need to minimize beam energy variations on both short and long time scales for two experimental initiatives at MIT/Bates. First, the SAMPLE experiment requires a beam of exceptional stability to measure the parity violating spin-dependent cross section asymmetry of only a few parts per million in elastic electron scattering at backward angles from unpolarized hydrogen and deuterium targets[1]. During test runs, it was found that uncontrolled beam energy fluctuations led to scrape-off on a pair of energy limiting slits upstream of the SAMPLE apparatus. Sensitivity to the small parity violating observable was reduced by the background subsequently created in the detectors. Second, the maintenance of the beam’s energy and position within narrow limits is a prerequisite for the efficient operation of the SHR, a vital component of a new program of internal target experiments with the Bates Large Acceptance Spectrometer Toroid (BLAST).

The discussion is divided into four parts. In Section 2, we describe particular features of the accelerator and the beam at MIT/Bates that had significant impact on the design of the feedback system. We discuss in Section 3 the components of the feedback system and their functions in detail. In Section 4,
we present results that demonstrate the marked improvement in beam energy stability with the energy feedback system. Finally, in Section 5, we summarize our most significant results and conclusions.

2 Beam Structure and Beam Energy Instability

At Bates, beams of electrons are accelerated with longitudinal electric fields oscillating in a series of accelerating cavities at a radio frequency (RF) of 2856 MHz. RF power is delivered to the cavities through wave guides from up to twelve klystrons, and beams of different energies are prepared by adjusting the RF amplitude in each klystron. Electrons are injected at all RF phases, but those injected outside of a 120° phase window are immediately “chopped” or deflected into a metal beam stop by a transverse RF electric field. The remaining electrons are “bunched,” or compressed with a longitudinal RF electric field into a phase window of about 2°. The RF phases of all but one klystron are optimized with respect to a common reference signal so that the crest of the RF field in each accelerating cavity coincides with the 2° beam “bunches” as they pass through it. Klystron 6B, designated the “vernier”, is shifted away from its crest. The phase of the vernier can be adjusted, compensating for drifts in the RF phase or amplitude of the other klystrons.

The RF transmitters deliver power only in short bursts followed by a substantial recovery period. A duty cycle, about 1% for the Bates facility, is therefore superimposed on the RF microstructure of the beam. Typically, the accelerator is configured for beam pulses of 3-25 µs in duration at a rate of 600 Hz. This time structure matches the frequency with which the beam polarization can be reversed at the Polarized Electron Source (PES). At the PES, electrons are photoemitted from a GaAs crystal illuminated by circularly polarized laser light with a helicity that can be chosen randomly at 600 Hz.

The beam pulses are synchronized with the laboratory’s 60 Hz AC line voltage, so that every pulse is associated with one of ten “time slots,” 1 ≤ n ≤ 10, each of which has a unique phase angle \( \frac{2n}{5} \pi \) with respect to the 60 Hz AC power cycle[2]. The first time slot is triggered by the positive-going zero crossing of the AC line voltage. Ideally, the properties of the beam would be independent of time slot. However, because DC power to the RF transmitters and the magnetic beam line elements is not perfectly isolated from the AC power, beam properties can fluctuate in ways that are highly correlated with the 60 Hz AC line, and therefore with time slot. For example, the strong dependence of beam energy on time slot is shown in Fig. 1. These data, obtained over a period of about 10 s with the energy feedback system disabled, show the beam’s fractional deviation \( \Delta \epsilon/\epsilon \) from the nominal beam energy for each time slot.
Fig. 1. Fractional energy change as a function of time slot over the range of the 60 Hz AC power cycle. Without feedback, beam energy varies by 0.3% over the power cycle, superimposed to set the vertical time scale.

The 60 Hz AC line voltage is superimposed to show the relative timing of each pulse and to set the vertical time scale. This figure demonstrates that beam energy variation in a single time slot can be at least an order of magnitude smaller than its variation over an entire power cycle. Overall variation can therefore be reduced significantly by a system capable of applying rapid time slot dependent energy corrections.

Beam energy is also subject to fluctuations at other frequencies, particularly slow drifts with characteristic times between 10 s and 1000 s. In Fig. 2, for example, the RF phase of the electric field in one of the klystrons with respect to the common RF reference is shown to correlate with temperature variations in the water that provides cooling to the transmitters and magnets. Uncompensated RF phase variations can lead to beam energy variations that, in turn, often result in unacceptable background levels.

Our feedback system is designed to compensate for both types of beam energy instability. Required of the system is the ability to

- monitor the beam energy $\epsilon_n$ in each time slot $n$, and accurately determine its average over a time interval $\Delta t$ which is small compared with the characteristic period of slow drifts;
- estimate, for each time slot, the difference $\Delta \epsilon_n$ between the beam energy $\epsilon_n$ and some ideal energy $\epsilon_0$;
- estimate and store, for each time slot, the phase shift $\Delta \phi_n \equiv -\Delta \epsilon_n \left( \frac{\partial \epsilon_n}{\partial \phi} \right)^{-1}$ required to minimize $|\Delta \epsilon_n|$;
- shift the phase of the energy correction klystron sufficiently in advance of each time slot so that the phase is stable before the beam is injected.
Fig. 2. Temperature variations in the laboratory cooling water, in °C, as a function of time. Also plotted is the RF phase of the electric field, in °, in one of the accelerating cavities.

Fig. 3. A plan view of the chicane, showing the BPM, the energy limiting slits, and the four dipole magnets EB1, EB2, EB3 and EB4. The central ray is represented as a dashed line.

3 Instrumentation and Operation

There are three main components of the energy feedback system. First, energy is monitored with a BPM installed between the two dipole pairs of a magnetic chicane located downstream of the accelerator and shown schematically in plan view in Fig. 3. The chicane disperses the beam horizontally in the region between the dipole pairs. By definition, the trajectory of electrons with the “central” energy passes equidistant from a pair of moveable, heavy metal, water cooled slits, positioned to the left and right of the center of the beam line. Electrons of higher energy and higher rigidity follow shorter trajectories than electrons of the central energy and therefore pass through the chicane to beam left. In contrast, lower energy electrons follow longer trajectories that pass through the chicane to beam right. Typically, the slits are positioned symmetrically with a separation of 33 mm, limiting the beam energy spread in the chicane to ±0.5%[3].
The BPM, located 1.5 m downstream of the slit, is a non-resonant RF cavity perpendicular to the beam with a diode at each end. The RF pulse structure of the beam induces oscillation in both diodes, with a relative RF phase proportional to the beam’s displacement from the center of the cavity. Due to the correlation of 33 mm/% between horizontal beam position and energy, the phase is also proportional to the beam energy’s relative deviation from the central energy. The error signal, a voltage proportional to this phase, is produced by the BPM’s output stage, and is integrated over the duration of each pulse and digitized in a 16 bit ADC. The intrinsic position resolution of this BPM is of order 50 µm, with typical output voltages, before amplification, of about 3 mV/mm displacement.

The second component of the feedback system is a remotely controlled ferrite core phase shifter with a 12 bit digital interface[4]. This digital phase shifter (DPS) is installed on the vernier klystron. Changes in the RF phase stabilize in about 1 ms and can be made in increments as small as 3 mr.

The third component is a computer controlled interface between the error signal and the phase shifter. The interface performs three functions. Two of the three functions, data acquisition and energy correction, are controlled by a low level microcode executing CAMAC read and write instructions in synchronization with the 600 Hz pulse rate. Data analysis, a third function of the interface, is performed asynchronously by a separate program. The flow of information between the components of the energy feedback system is indicated schematically by the diagram in Fig. 4.

Before enabling the feedback system, the accelerator is prepared according to a standard procedure. First, the ten digital bit patterns that encode the phase shift for each time slot are initialized to the middle of their full range, which is limited in software to 45°. Next, all klystrons are phased with respect to the common RF reference. To first order, the beam energy is then independent of small drifts in phase from the RF crest. The phase of the vernier klystron is then manually shifted away from its crest by about 22°, half of the system’s full range. In this configuration, beam energy is quite sensitive to automatic adjustments by the feedback system of the vernier’s RF phase.

Occasionally, the beam operators adjust one or more of three software parameters in order to optimize the performance of the system. One of these parameters is the ideal energy \( \epsilon_0 \), toward which the feedback system is programmed to drive the actual beam energy. This ideal energy is chosen to optimize the experimental running conditions, and must be within 0.5% of the central energy. Otherwise, the beam will collide with the energy limiting slits. The operators can also select the number of beam pulses to be sampled before a new set of phase shifts is determined. This affects the speed with which the system corrects the energy, and the statistical precision of the corrections. A
Fig. 4. An overview of the energy feedback system. A BPM signal is digitized in a CAMAC ADC and read after each beam burst. A time slot scaler (TMS), incremented at 600Hz and cleared on the positive-going zero crossing of the 60 Hz power cycle, identifies the time slot of every event in the data stream. A low-level microcode controls data acquisition from CAMAC, data shipment to a high-level analyzer, and the download of bit patterns to the digital phase shifter (DPS). The analyzer computes the appropriate phase shift and bit pattern for each time slot.

The third parameter specifies the sign and magnitude of the phase shifts with respect to beam energy deviations. The value of this parameter, used to control overshoot and undershoot, has normally been obtained from an experimental measurement of $\frac{\partial \epsilon}{\partial \phi}$ and has been found to be near 0.0043%/mr (0.075%/degree). However, its optimum value has been shown to vary by at most 10% for widely varying beam tunes and is now rarely remeasured. Following these preparations, energy feedback is enabled.

At 1.6 ms prior to each pulse, the CAMAC system extracts a digital bit pattern corresponding to the phase shift for the next time slot from one of ten locations in a LeCroy 8206A CAMAC memory module (MM1) and transfers the pattern to a TTL output register (DSP PR-612) connected to the phase shifter’s digital interface. Within 1 ms, the phase shift of the vernier klystron is stable. After each pulse, the CAMAC system reads the digitized BPM error signal along with a label identifying the current time slot. The digitized data are packaged and distributed to the analysis program at 7.5 Hz.

For each time slot $n$, the analyzer computes an average error $\Delta \epsilon_n$ and a phase shift $\Delta \phi_n$ from a total accumulation of about 1000 beam pulses (100 in each time slot). These new phase shifts are encoded as digital bit patterns and downloaded to the CAMAC system. However, because the analyzer operates asynchronously, a download of the bit patterns directly into the memory module MM1 can interrupt the 600 Hz access of the microcode to its contents. To prevent this, the new bit patterns are written asynchronously into ten locations of a separate memory module MM2. When all ten patterns have been loaded, an additional flag is set to indicate a Data Ready condition. Prior to
Fig. 5. Fractional energy change as a function of time slot over the range of the 60 Hz AC power cycle. The lower (upper) panel shows the behavior of the beam with the energy feedback system disabled (enabled). The 60 Hz AC line voltage is superimposed to set the time scale.

the first beam pulse in a ten time slot sequence, the Data Ready condition triggers the transfer to MM1 of the new bit patterns in MM2. The transfer is controlled by the microcode, requires 400 µs, and is completed 1 ms before the next memory access. Although the system’s frequency response would normally be limited to about 1 Hz by the time required to acquire a statistically significant sample, it effectively compensates for 60 Hz fluctuations by simultaneously implementing an independent feedback loop for each of the ten time slots.

Separate analog signals, corresponding to the highest and lowest of the ten digital phase shift values for a given sample cycle, are piped from the CAMAC acquisition hardware to the main accelerator control room and monitored as a function of time. Should slow but constant energy drifts cause the feedback algorithm to approach either its high or low software limit, the beam can be rephased, and the digital bit patterns can be reset for all time slots to the center of the feedback system’s software range.

4 Energy Feedback Performance

Two figures demonstrate the ability of the system to meet its design goals. The first, Fig. 5, shows the behavior of the beam on a time scale of a few seconds as a function of time slot, both with and without the energy feedback
Fig. 6. Fractional energy change as a function of time for a single time slot, with and without the energy feedback system.

system. In each of the two panels the data are averaged over an interval of about 10 s. With feedback disabled, beam energy fluctuates over the range of the AC power cycle by 0.3% (lower panel). With feedback enabled and, in this example, adjusted for an ideal energy 0.4% above the central energy, fluctuations are controlled at the level of about 0.02% (lower panel). Moreover, RMS fluctuations per time slot are reduced by a factor of 2. The second, Fig. 6, shows the effect of the system over long periods of time for an individual time slot. With feedback disabled, the characteristic magnitude of slow beam energy drifts is about 0.2% of the central energy. However, the feedback system, enabled in this case for a set point equal to the central energy, effectively eliminates these drifts.

5 Summary and Conclusion

Although 60 Hz AC line voltage fluctuations and slow, temperature dependent changes in accelerator hardware can induce energy instabilities, we have developed a reliable feedback system at the MIT/Bates Linear Accelerator which can compensate for these changes. Before the installation of this system, 60 Hz line voltage fluctuations induced energy fluctuations of up to 0.4%, and slow phase variations of thermal origin induced energy fluctuations of up to 0.2%. With the energy feedback system enabled, beam energy is measured on a pulse by pulse basis while rapid changes are made in the RF phase in one of the accelerating cavities, controlling energy fluctuations at the level of 0.02%.

Two important sources of energy instability have been effectively eliminated, resulting in a beam with an energy spread that is limited only by the width
of the energy distribution within a 3-25 µs beam pulse. This system provides improved beam stability, a decrease in background due to beam scrape-off during transport, and a simplification in the operation of the accelerator. The energy feedback system developed here has proven to be so successful that its use is now a routine part of the standard operating procedure for the MIT/Bates Linear Accelerator.

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References

[1] B.A. Mueller et al., Phys. Rev. Lett. 78, 3824 (1997).

[2] K. Kumar, Ph.D. thesis, Syracuse University, 1990, unpublished.

[3] All energy deviations quoted in this article are with respect to the BPM in the chicane. An independent Energy Compression System, located downstream of the chicane, narrows the beam energy distribution by an additional order of magnitude.

[4] Model No. 1C011-009, manufactured by the Microwave Applications Group