Improvement of the Time Structure and Reproducibility of the Bevalac Spill*

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Abstract

The time structure of the Bevalac beam spill has been measured for spills with and without feedback. A new filter across the magnet has reduced spill ripple near 170 Hz. Low frequency (~a few Hz) spill structure has been improved by removing the scintillator used for feedback from the vacuum chamber, detecting instead radiation generated by collisions of beam particles with a wire chamber. Pulse-to-pulse variation of the circulating beam intensity has been reduced, and continuous tunability of the intensity introduced, by using a new feedback system. This system reduces the rf bucket height to spill beam until the proper intensity is reached.

I. INTRODUCTION

In order to serve the needs of both the nuclear physics and heavy ion medical therapy communities, it has become important to improve the time structure of the beam extracted from the Bevatron. Count-rate-limited nuclear physics detection systems would benefit from a reduction in the ratio of the maximum intensity to the average in a pulse. The UCSF-LBL heavy ion therapy program is beginning 3D conformal treatment, raster scanning tumors with the ion beam. Low frequency ($\leq$ 2 kHz) time structure in the extracted beam would result in spatial inhomogeneities in the dose delivered to the tumor. To investigate these problems, new measurements of spill time structure and its major cause, magnetic field ripple, have been made. These measurements will be presented in Section IIA. In Section IIB, we describe a new feedback detector which has decreased low frequency structure.

The Raster scanner treatment program also requires better control (to within a few percent) of the circulating beam intensity than has been possible, since the dose given is set to be a fixed percentage of the circulating beam intensity. Section III describes a feedback system which has been successful in decreasing the pulse-to-pulse variability of the circulating beam intensity to, in some cases, a few percent.

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II. TIME STRUCTURE OF THE EXTRACTED BEAM

A. *Bevatron Spill Time Structure*

Beam is extracted from the Bevatron either by using a single sextupole magnet to produce a third order resonance, or by ramping the magnetic field while keeping the particle energy constant. In the case of the resonant spill, the sextupole magnet current may be controlled by a feedback system, which measures the extracted intensity and changes the sextupole current accordingly to keep the intensity constant. Heavy ion therapy time structure requirements mandate the use of the feedback system.

Time structure in the beam spill derives from two sources: (1) ripple in the magnetic field of the synchrotron, and (2) delay in the feedback loop controlling feedback spills. Figure 1 shows the frequency spectrum of the single turn dB/dt pickup loop signal during the time when the main synchrotron field is held "constant" and the beam is extracted. Power to the (weak focusing) magnet is provided by a 12-phase half wave rectified motor-generator (MG). Ripple from this power source is seen at harmonics of the rectifiers' output frequency, which in the case of Fig. 1 is 59 Hz. Also present is low frequency structure at about 2-5 Hz. This has been shown to originate in the regulation loop on the generator. The field ripple shown in Fig. 1 is reduced from the natural ripple provided by the motor generator by two systems. The first is a set of LC filters with central frequencies of 170, 355, 658,

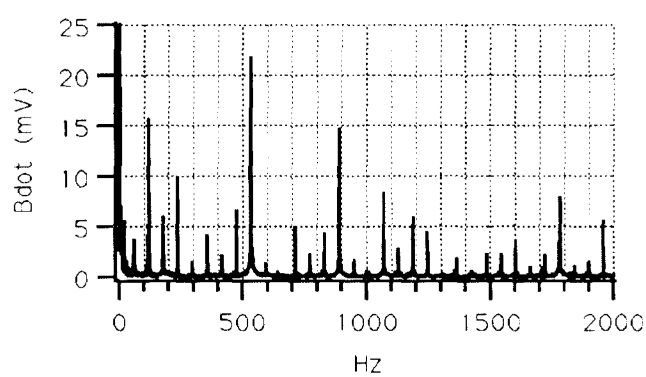

Figure 1. Frequency spectrum of dB/dt signal. B=2535 G.

1008, and 1345 Hz in parallel with each half of the magnet. The 170 Hz filters were added this year. They have attenuation of 16 and 18 dB at 170 Hz, and full width of 8.2 and 6.7 Hz respectively at the 3 dB points. The second, the "Ripple Reduction" feedback system, reads the dB/dt signal and adjusts pole face windings dynamically to compensate for changing field. This system has unity gain at 10 Hz and 10 kHz.

The frequency structure of the spill is shown in Fig. 2 for the case of a linear ramp for the sextupole current (no feedback). This spectrum is typical of what is seen, but pulse-to-pulse variation in individual spectral lines can be of the order of 50%. The MG harmonics can be seen, as well as line harmonics, but there are also lines at 100, 200, 500, and 1100 Hz. These are due to the fact that the the magnet ramp is digitally constructed using small 10 msec step functions. Thus these components will be relatively easy to eliminate. The largest ripple is in the 2-5 Hz region.

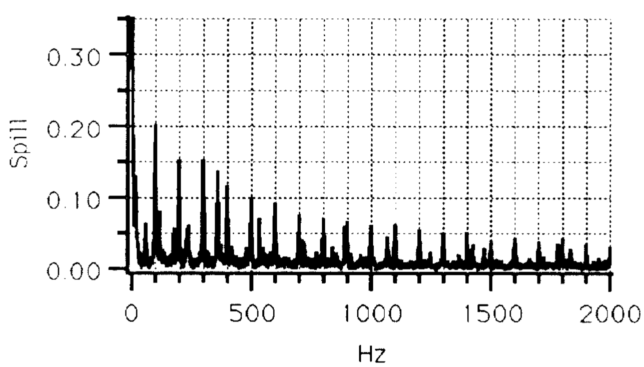

Figure 2. Frequency spectrum of extracted beam, normalized to 0 Hz component. No Feedback. B=2535 G. Ne^{+10} at $4x10^8$ particles per 1 second spill.

Figure 3 is a typical spectrum for a feedback spill. Again, pulse-to-pulse variation is significant, but the frequencies of the major spectral components do not change. It is evident from the scale that the feedback system effectively removes most low frequency ripple. What remains are a few MG lines at frequencies without filters, a power line component at 360 Hz, and 2-5 Hz structure, which is reduced by the feedback, but on occasion is still significant. There is also a broad peak of amplitude 0.35 times the DC level of the spill at about 5 kHz, not shown in Fig. 3. This is due to the fact that particles require about 100 μs from the time they are destabilized to the time they reach the feedback detector. During this delay time, enough beam will spill so that when beam is detected, the feedback system will turn the extraction off until the average extracted intensity is again equal to the reference value set. Thus the extraction sextupole is turned off and on at a frequency between 3 and 10 kHz, depending on machine and feedback conditions. If the loop gain of the system is decreased, not as much beam will spill during the delay time. The height of the 5 kHz peaks will decrease, and their frequency will increase. Thus reducing field ripple, which would permit a decrease in loop gain, is one path to reducing the 5 kHz ripple. The 5 kHz peaks are the largest ripple in the feedback spill, but do not affect raster scanning therapy because of their frequency.

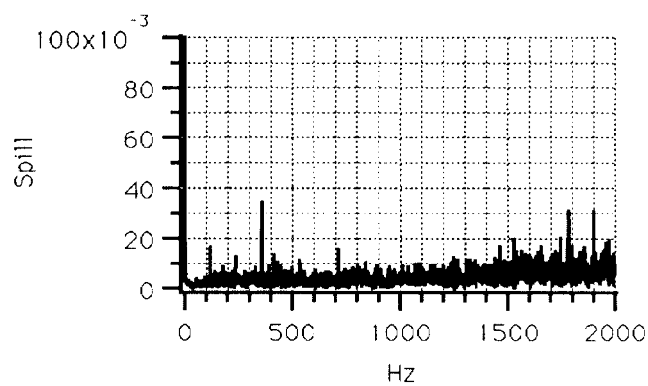

Figure 3. Frequency spectrum of extracted beam with feedback active. B=2535 G. Ne^{+10} at $3x10^8$ particles per 1 second spill. Values normalized to 0 Hz component.

B. Improvements in the Extraction Feedback Detector

The extraction feedback system measures the intensity of the extracted beam vs. time, and subtracts from it the requested (reference) level. The extraction sextupole current is then changed, in proportion to this difference, in order to make the extracted intensity equal to the reference. The feedback detector consisted, until recently, of a scintillator and photomultiplier tube. The scintillator was located in the path of the extracted beam, and for high intensity beams (e.g.,≥about 10^9 particles per one second spill for Ne^{+9} at 585 MeV/nucleon). the scintillator browned in a matter of 4-5 hours. The browning was spatially inhomogeneous. Since the beam sweeps across the scintillator during extraction, this browning essentially caused a time-dependent change in the calibration of the feedback detector during the spill. When the beam swept across a brown part of the scintillator, the detector output would decrease, causing the feedback system to increase the sextupole current, and thus the spill rate. This resulted in a variation of order 30-50% in the extracted intensity vs. time.

This situation was corrected by installing, outside the beam pipe, a system consisting of a photomultiplier tube, with a scintillator connected by a short light pipe. The system detects fragments scattered mainly from an upstream wire chamber, as well as gamma rays produced by the fragments. Thus the system is referred to as the Beam Fragment Detector. The light pipe allows the PM tube to reside within a metal pipe, for magnetic shielding, while the scintillator remains outside of the pipe for full exposure to fragments. In this configuration browning is negligible, and the simplicity, high amplification, and fast response of the PM tube are retained. The system response is linear with beam intensity, and is not sensitive to changes in beam position. A further practical advantage is that the whole system is outside of the vacuum, thus making maintenance and changes simple. The system has been used satisfactorily for 1.5 years.

Problems and limits of the system derive from the fact that since the scintillator is not in the beam, it detects 2 to 3 orders of magnitude fewer "particles" than a scintillator in the beam. Thus it is sensitive to "noise" consisting of fragments sprayed from beam scraping in the extraction channel. Normally this scraping does not occur. The low signal amplitude also means that the system cannot be used at low spill rates (e.g.,$\leq 1.6 \times 10^8$ particles/s for He^{+2} at 660 MeV). The signal level could be increased by various means, including enlarging the scintillator, but for these low intensity cases the old system with the scintillator in the beam works well. Finally, the system only samples 1 particle for every 10^2 or 10^3 beam particles, so the accuracy of its statistics on the extracted beam is imperfect. Thus we see broadband "shot noise" in the spectrum of the detector signal. For the desired accuracy, bandwidth, and intensities presently desired (1% accuracy below 2 kHz, and intensities $\geq 10^8$ particles per 1 second spill) this is not a problem.

III. FEEDBACK CONTROL OF THE CIRCULATING BEAM INTENSITY

The circulating beam intensity in the Bevatron varies from pulse to pulse by up to 50%, due to variations in the injector output. Moreover, the intensity is controlled by attenuators, and therefore is not easily continuously tunable. A new feedback system has been tested which has been successful in reducing the pulse-to-pulse variation to less than 7%, and which allows continuous tunability. The feedback detector is the "Beam Induction Electrode", or BIE,-- two parallel plates through which the beam passes, which measure the total circulating charge. Because the signal is so small, it is beat against the accelerating rf, which has the same frequency as the beam buckets, in a superheterodyne detector, and the amplitude of the signal at the difference frequency is measured. The feedback system compares this to a requested reference level, and decreases the rf amplitude, dumping beam, if the actual intensity exceeds the reference. A similar system was used at the Bevatron several years ago [1] to spill beam onto an internal target. Results are shown in Fig. 4. Each dot on this graph shows the intensity of one pulse of the synchrotron. Intensities above 1×10^9 are from pulses for which the feedback system was off. As can be seen from the figure, the intensity can be changed continuously over about a factor of 10. Within this range the pulse-to-pulse variation is $\leq 7\%$. The system has been used successfully over periods of hours to hold the intensity constant within this accuracy, and often to within a few percent.

Problems with the feedback system stem from the fact that the output of the superheterodyne detector is sensitive to the input waveform phase and shape, as well as to the amplitude of the signal. As the system dumps particles, the pulse shape and the phase of the beam with respect to the rf change, giving a false reading of the intensity. The error is often the same, pulse to pulse, over long periods of time, allowing for the success reported above. But it changes with machine and beam parameters. Thus it is impossible at present to predict in advance the exact value of the reference that will produce a given intensity. On occasion we have also seen long term(~60% in 0.5 hour) drift in the intensity. The pulse-to-

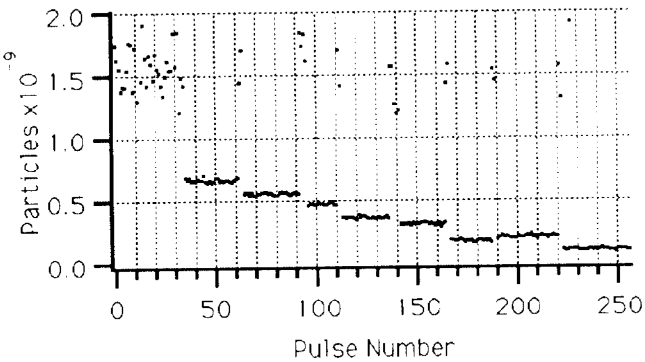

Figure 4. Intensity value from the BIE vs. Pulse Number, for B=2535 G, He^{+2}.

pulse variation in the error accounts for the 7% accuracy limit we have observed. Efforts are underway to design a new detector which would accurately measure circulating charge. We are confident, given the success with the present system, that such a detector would enable accurate intensity control.

IV. REFERENCES

[1] Fred H. G. Lothrop, Rev. Sci. Instr., vol 37, No. 3, pp. 358-361, March 1966.