

OPERATION OF THE TEVATRON EXTRACTION SYSTEM

L. Chapman, D.A. Finley, M. Harrison, W. Merz, H. Pfeffer
*Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, IL 60510

Summary

The Fermilab Tevatron is currently in the middle of its second running period for fixed target physics. Steady operation has been established at 800 GeV with 1×10^{13} protons being extracted. Beam spill over the 20 - 23 second flattop is regulated by a closed loop feedback and a feed forward learning system controlled by a microprocessor.¹ Eight power supplies have their waveforms programmed by the microprocessor in an attempt to reduce the modulation on the beam spill. In addition the microprocessor can insert a pause in the slow spill and cause the extraction of a high intensity (3×10^{12}) fast (1-2 milliseconds long) pulse.

A description of the extraction system as well as analysis of the spill modulation encountered during commissioning are presented in this paper. Current status of the spill structure is also discussed.

Introduction

Extraction from the Tevatron takes place by bringing the beam into a half integer resonance that causes the amplitude of the betatron oscillations to grow in a controlled manner. These oscillations continue to grow, until the particles are deflected by an electrostatic septum. The kick supplied by the electrostatic septum allows particles about to be extracted to move sufficiently far away from the circulating beam so that a thicker magnetic septum may be used to steer the beam out of the ring.²

The extraction process is begun by raising the normal horizontal machine tune, $Q = 19.42$, toward 19.5. Because of tune spread the number of particles with a tune in the half integer stop band can be controlled. Particles may be extracted over a period of time either by moving their tunes into the stop band or by increasing the stop band width to encompass the tune of the particles.³ The latter was chosen in this case. The stop band width is controlled by programming a set of 39th harmonic quadrupoles. However, this is a linear resonance and in the limiting case of no tune spread the beam is either all stable or all unstable. The method by which phase space is separated into stable and unstable regions is accomplished by introducing an octupole component.⁴ The tune of a particle now becomes a function of the betatron amplitude. Small amplitude particles are stable while large amplitude particles stream out along the separatrix until they encounter the extraction septum. The scenario for extraction is:

1. Raise machine tune (zeroth harmonic) to near the $1/2$ integer resonance; $Q=19.48$
2. Turn on 39th harmonic quadrupole, (both sine and cosine terms).
3. Turn on a zeroth harmonic and 39th harmonic octupole.
4. Turn on slow (low frequency response) 39th harmonic quadrupoles with feedback control. This element actually starts beam extracting.
5. Turn on fast (higher frequency response) 39th harmonic quadrupole with feedback for bucking spill modulation.

The remainder of this paper discusses the implementation and operation of items 4 and 5 listed above.

Spill Regulation System

The system that regulates the rate at which beam is extracted consists of two functionally separated elements. Both elements are under the control of a central microprocessor which is linked to the main accelerator control system. The two elements each consist of a set of four power supplies and magnets located around the ring. They are connected to the microprocessor and receive their waveforms through a dedicated serial data link. Although all eight quadrupoles affect the amplitude of the 39th harmonic term and consequently the stopband width, a split is made in functionality by restricting groups of four to operate over distinct bandwidths. A low frequency set has a dc to 3 Hz response. A higher frequency set has an ac response out to about 3 kHz. This separated function supplies nearly independent control over the spill rate and spill modulation. In addition this provides a convenient way of maintaining extraction while studying spill modulation with the high frequency system turned off. It is also possible to use the high frequency system as a noise system to drive beam and measure the response.

The low frequency elements are servoed to a Tevatron beam intensity signal which is not sensitive to the RF structure. The signal is sampled during the spill and compared to an ideal signal by the microprocessor. The resultant error is used to modify the power supply output. The error is saved, smoothed and time shifted so it may be used on the next extraction cycle. In this manner repetitive errors are "learned" out. The power supply waveform becomes the accumulated errors over many cycles plus the small error occurring on the current cycle. This feed forward technique reduces lag error on a limited bandwidth system by giving essentially unlimited gain to repetitive errors (smoothing tends to reduce the gain). The time shifting can be adjusted to optimize corrections according to the beam response. This is more important in the higher frequency bucking system, where the major phase shift is caused by the delayed response of the beam to changes in the power supplies. The response time of the beam to a step change in 39th harmonic term was measured and is of the order of 1 to 2 milliseconds corresponding to 50 to 100 turns. The implication is an upper frequency limit of several hundred Hz where real time feedback, using an intensity signal, can be effective in reducing spill modulation.

The bucking system is implemented in the same fashion as the low frequency system. It uses as its principle servo signal an extracted beam intensity monitor (an RF cavity tuned to 53 MHz driven by the beam). The amplitude modulation on this signal is filtered to provide a dc to 3 kHz bandwidth signal for one control input and a .1 Hz - 30 Hz bandwidth signal for another control input. The dc component left in the higher BW signal allows a spill duty factor calculation by the microprocessor.

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The higher frequency signal is used as a feed forward correction on subsequent extraction cycles after removing the dc component and undergoing smoothing and time shifting. Since this stored signal contains information about all previous cycles what remains are modulation components that are locked in phase with the accelerator cycle. These include power supply ripple frequencies. Gain at these frequencies can be large and phase shift compensated due to the "learning" algorithm.

The lower bandwidth signal is used for real time feedback. The bandwidth was chosen to match the low frequency components in the spill. The real time feedback is necessary because of the presence of frequency components that are not locked in phase with the accelerator cycle and are not capable of being "learned" out. The microprocessor output for the bucking supplies is the sum of real time and learned signals. All gains, time shifts, smoothing and learning algorithms values are adjustable through the main accelerator control system.

Slow Spill

To maintain a constant rate of extraction the beam must be moved smoothly through the resonance. The spill rate is given by;

$$\frac{dN}{dt} = \frac{dN}{dN} \times \frac{dQ}{dt}$$

The term dQ/dt is composed of two parts; \dot{Q}_0 , the desired tune shift required for a given extraction rate and, \dot{Q}_n the unwanted tune modulation from any other source. Figure 1 is a picture of the extracted beam spill monitor.

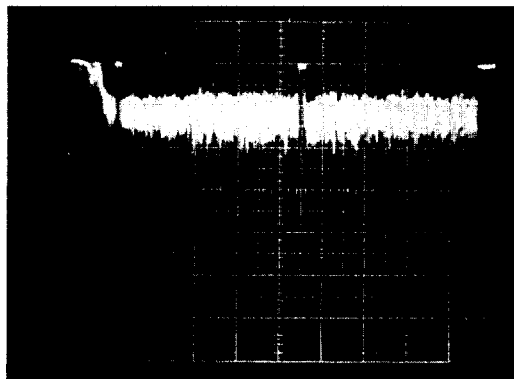


Figure 1 Extracted Beam Spill Signal
22 Second Spill (>2 Sec/)

2.5x10¹⁰ protons/second with 2 pauses for fast spill

Commissioning of the low frequency part of the system was relatively straight forward and consisted of minor debugging and parameter optimization. The real effort has been to reduce the higher frequency modulation on the spill. The initial tactic in attacking the problem was to identify sources of each frequency component and correct them. A low frequency spectrum analyzer proved invaluable in this process. Three major categories of problems were eventually identified in the commissioning; 1) power supply ripple and regulation, 2) RF associated phenomena, and 3) mechanical vibrations of the accelerator quadrupole magnets.

A simple scheme allowed easy identification of the origin of power supply ripple. By injecting ripple into power supplies it was possible to get a quantitative measure of a power supply's contribution to spill modulation. This was done with all major power supplies

and identified two sources which were easily corrected by improving regulation and filtering. There still remain line frequency components at 60, 120, 180 and 360 Hz and higher. Since the accelerator repetition rate is line locked, the ripple is repetitive on a cycle to cycle basis and can be corrected for by the bucking learning system. This system is capable of reducing the amplitude of these components by up to 12 db. The amount of reduction is frequency dependent with the lowest frequency having the greatest reduction. Improvement in the 360 Hz ripple is only about 4 db. Above 360 Hz the learning algorithm has little effect. Additional reduction in the 360 Hz and other higher frequency line components was accomplished by adjusting other Tevatron parameters. In particular a marked improvement in these and other high frequency (<3 kHz) components was achieved by setting the machine chromaticity to a positive value. It had been noted that both the amplitude and phase of these spill modulations varied in a nearly linear way during the course of the 20 second flattop. By raising the chromaticity and increasing the tune spread the amplitude variation during the spill diminished and the phase shift was also lessened. Interestingly, it was found that this effect was frequency dependent with higher frequencies showing the most phase shift. We verified that the phase shift was not a result of the driving source by using the bucking system to cause tune modulation. Below 120 Hz the phase shift in the beam modulation was small while at frequencies of 360 Hz and above the phase shift is in excess of 180°. It is likely that this phase shift is what reduces the effectiveness of the learning algorithm at higher frequencies.

Several other modifications to power supplies were made to reduce common mode ripple. These include active ground systems on floating high order correction power supplies and improved bypass/shunt control on the main Tevatron power supplies that turn off at flattop. The former was a source of 180 Hz and the latter of 360 Hz ripple.

Two spill modulation components have their origins in the rf system. One frequency, which was flattop energy dependent, was the result of a beat frequency between two oscillators in the low level rf system. By switching to a single fixed frequency oscillator during extraction the problem was negated. The second and more difficult problem is spill modulation at the synchrotron frequency. For the Tevatron this is around 35 Hz at 800 GeV. Since the modulation has no repeatable phase relationship with the accelerator repetition rate, learning over many cycles is not effective. At the present time only real time feedback from the spill signal is used. Incoherent synchrotron oscillation allow a tune distribution which can be controlled somewhat by adjusting the chromaticity. It becomes easier to extract smoothly if the tune distribution is relatively uniform. However coherent synchrotron oscillations strongly modulate both the tune and beam position at the extraction septa. Consequently the spill has this structure. In addition, coherent oscillation within a bucket causes preferential extraction of that bucket. Bunch spreaders in both the Tevatron and Main Ring attempt to cause a more uniform population within a bucket by shaking the RF phase for a short period of time. This clearly improves the bucket to bucket structure of the extracted beam. Correcting for "super buckets" in spill is well out of the range of the servo system's capabilities.

During initial turn on of Tevatron extraction two of the major frequency components in the spill were 4.62 Hz and 19.8 Hz. These frequencies were found to be coming from mechanical vibrations.

The 4.62 Hz vibration has its origin in the helium liquefier (CHL) plant's 4000 horsepower 277 rpm synchronous (26 pole) motors. The pilings for the motor pads are sunk into bedrock a few hundred meters from the accelerator enclosure. Vibrations transmitted through the ground to the tunnel floor are sufficient to shake the comparatively light quadrupole structures in the ring. The amplitude (maximum of ~20 microns) of the vibration attenuates with distance from CHL. Because the vibrations are line locked it is possible to choose an accelerator repetition rate such that the phase of the vibrations repeat on a cycle to cycle basis. The learning algorithm is able to entirely cancel the effect if the cycle time is an integer multiple of 13/15 (the cycle time being settable in 1/15 second increments).

During measurements of the quadrupole vibration it was also found that the 19.8 Hz component in the spill also had mechanical origin. Roughing pumps at 48 locations around the ring had been placed on quadrupoles. The 1200 rpm induction motor was the source of the problem. Because induction motors have a slip frequency with respect to the line it was not possible to "learn" out the frequency component. The pumps consequently had to be remounted on a new support stand. This does not entirely cure the problem as the quadrupole support structure has a resonant frequency with a fairly high Q at 15 - 25 Hz. The remaining 19.8 Hz spill structure and its second harmonic are frequently the largest spill component. The horizontal beam damper system has helped to reduce this effect. The damper system improved both by about 10 db by presumably reducing the coherent beam motion. Figure 2 is a frequency spectrum of the extracted beam intensity monitor.

Fast Spill

An experimental requirement for short duration, high intensity pulses of beam exists. Support for this mode is provided through the same microprocessor and data transmission link as is used in the slow spill control. Clock events are generated which signal a fast pulse is to occur. The microprocessor decodes the event and interrupts its slow spill operation to generate the fast beam pulse. The general scenario for creating a fast pulse is; 1) halt slow spill by decrementing the output of all 8 power supplies that operate on slow spill, 2) pause for a length of time to allow steering magnets to reach new levels, 3) output a waveform to two pulser power supplies that extract the beam, 4) pause to allow steering magnet changes and loss monitors to recover, 5) gracefully re-establish slow spill.

Typical operation has been with up to 3×10^{12} protons extracted over two milliseconds during a 250 millisecond pause in slow spill. Up to four pulses have been extracted during a 20 second slow spill. The pulse width is variable up to about 12 milliseconds and the intensity of each pulse is regulated by microprocessor "learning". Recently during tests up to 1×10^{13} protons were extracted in a single pulse. This is an increase in spill rate of nearly 5 orders of magnitude over the slow spill rate. Special care has been taken to reduce beam loss during extraction, including collimators located at the appropriate places in the ring, in order to prevent quenches of the superconducting magnets.

Conclusions

The increase in spill length made possible by a superconducting accelerator places an added burden on all accelerator systems if a reasonable duty factor is to be maintained. Tight specification on all power

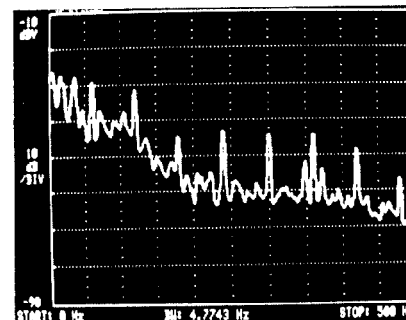
supplies greatly reduced the demands on the bucking system. With the reduction in line frequency modulations in the spill a somewhat unexpected new source was uncovered. A strong low frequency unsynchronized modulation has proved to be the largest component currently in the spill. Nevertheless operation with spill lengths of 22 seconds (at a 65 second repetition rate) and duty factors of 90% (3 kHz bandwidth) are routine. Typical slow spill rates vary between 5×10^{10} protons/second to 5×10^{11} protons/second. The microprocessor system is presently capable of supporting up to a 35 second spill.

The bucking system has a bandwidth of about 400 Hz for repetitive errors. The real time feedback for the bucking system is presently limited at approximately 30 Hz. The limitation was imposed to allow raising the gain sufficiently high to combat the 19.8 Hz spill modulation. Since the bucker holds the amplitude of the modulation constant, the percent modulation is reduced at higher spill rates.

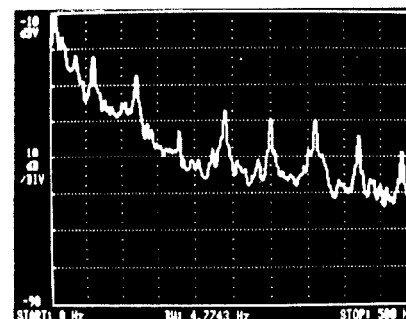
Finally it should be noted that most of the work on understanding spill modulation would have been enormously more difficult without the ability to separate each source in the frequency domain. The low frequency spectrum analyzer allowed treating each frequency as a separate phenomena rather than as the jumble it appears to be when viewed in the time domain.

References

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3. Edwards, D., Physics of High Energy Particle Accelerators (BNL/SUNY Summer School 1983), AIP Conference Proceedings No 127, p 42-50
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a) Bucking System ON



b) Bucking System OFF

Figure 2 Beam Spill Frequency Spectrum
(Averaged over 20 second spill)