# STATUS OF RESONANT EXTRACTION FROM THE FERMILAB MAIN INJECTOR*

C.D. Moore♣, J. Firebaugh, P. Lucas, P. Prieto
FNAL, Batavia, IL

*Abstract*

One of the major advantages of the Fermilab Main Injector is that it will allow a vigorous program of fixed target physics to proceed independently from collider operations. Thus the commissioning goals for this new accelerator include a demonstration of resonant extraction. For purposes of this demonstration the extracted beam will be sent to the antiproton target station where the measured beam sizes will be used to help design beamlines for the 120 GeV fixed target programs. In order to achieve this goal an experiment has been performed to measure stopband parameters. An outline of the hardware and software to be used for extraction is described with an emphasis on upgrades to the system. Utilization of modern microprocessor technology and real-time software techniques will greatly simplify the regulation of extraction to obtain a smooth spill. The present state of extraction studies is given and the short term goals are explained.

## 1 INTRODUCTION

Extraction from the Main Injector takes place by bringing the beam into a half integer resonance thereby inducing the amplitude of betatron oscillations to increase until the particles are deflected by an electrostatic septum located at the MI32 region of the Main Injector [1]. The kick supplied by this electrostatic septum causes the particles to enter into the deflection region of two other electrostatic septa located at MI52. The kick supplied by these septa allows particles about to be extracted to move sufficiently far away from the circulating beam that a thicker magnetic septum may be used to eject the beam from the machine.

The extraction process begins by raising the normal horizontal machine tune from 26.42 toward 26.5. Because of tune spread, the number of particles with a tune in the half integer stop band can be controlled. There is enough octupole component from the main quadrupoles to provide the zero-th harmonic amplitude dependent tune shift needed for extraction although we have a set of independent zero-th harmonic octupoles to increase the efficiency of extraction. The stopband width is enlarged by a time varying set of 53rd harmonic quadrupoles, and the smoothness of the spill is modulated by moving the tune with a microprocessor system called QXR (Quad eXtraction Regulator). The extraction system design is based on the Tevatron beam extraction system [2].

## 2 EXTRACTION SYSTEM COMPONENTS

The different components of the extraction system are described.

### *2.1 Extraction Magnets*

There are 16 quadrupoles arranged into two orthogonal families (sine and cosine) with a strength of .255 kg-m/m per amp to give control of the 53rd harmonic.

There are 54 correction octupoles arranged to give a 0-th component octupole of strength 28 kg-m/m$^3$ per amp.

There are two .2Ω,1 mH air-core magnets used by the QXR system each with a strength of .092 kg-m/m per amp.

### *2.3 QXR Hardware*

The QXR air-core quadrupoles are driven by a current regulated power supply controlled by a VME-based microprocessor. Common mode and differential mode ripple current due to the dipole magnet power supplies is expected to be 20 mA at 360 Hz and 720 Hz. To attenuate ripple of these frequencies by 20 dB the magnets were designed around ceramic beam tubes, which permits the B field to have frequency components in the 3 kHz range. Background tasks running between extraction cycles (~ 2 seconds) are used for computations, communications and downloading parameters.

A MVME 2300 POWER PC CPU board residing in a VME-64 crate regulates the extraction process responding to accelerator timing events marking the beginning and end of flattop through a Fermilab designed interrupt handling board (VUCD). A 16 bit A/D digitizes the output of the 53 MHz resonant RF spill detector that measures the extracted beam. Circulating beam intensity is measured by a toroid in the machine, digitized and encoded onto a machine-wide communication system (MDAT). The processor responds to clock events through a board that decodes events. Communications between the processor and the current regulated power supply is done through a dedicated fiber optics link at 5760 Hz.

### *2.4 QXR Software*

A finite state machine (FSM) which changes states driven by clock events and software timers controls QXR

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♣ Email: cmoore@fnal.gov

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software. A 5760 Hz interrupt drives the FSM and is used to derive 2880 and 720 Hz timers which activate extraction and noise rejection regulation tasks which have highest priority. Background tasks running between extraction cycles ( ~ 2 seconds) are used for computations, communications and downloading parameters.

The extraction process is divided into two independent regulation loops. The loop in figure 1 maintains constant the rate at which the beam leaves the machine by comparing the amount of circulating beam against a calculated reference. Its loop bandwidth ranges from DC to 30 Hz (nominally). The regulation process utilizes a feedback loop operating in real time at 720 Hz during extraction; however the error signal is also stored during the spill and processed between spill cycles.

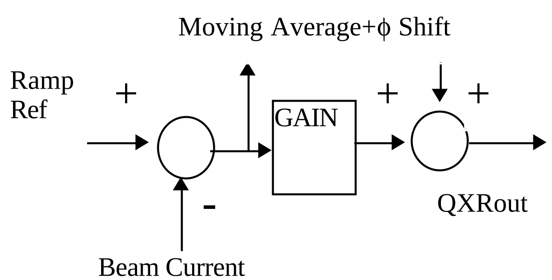


Figure 1: Representation of QXR beam extraction fast feedback and feedforward regulation components.

Error signals, which repeat from cycle-to-cycle, are averaged and weighted, then applied to the next cycle during spill. The averaged data is added to the present QXR output with a phase advance correction, compensating for unwanted signals that repeat from cycle to cycle and have a fixed phase.

Frequencies present in the spill between 30 Hz and kHz are bucked out using a separate regulation loop based on an adaptive noise compensation scheme. Sixty Hz and its harmonics comprise the majority of the unwanted frequencies modulating the spill. Therefore an adaptive rejection loop shown in figure 2 was designed to primarily attenuate these frequencies.

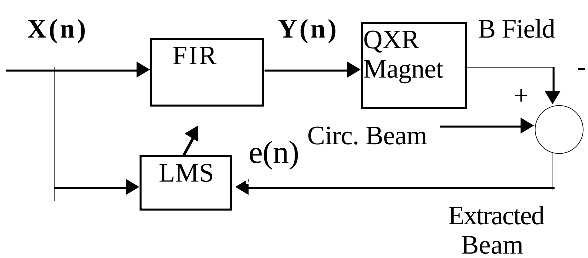


Figure 2: X(n) represents 60 Hz and its harmonics generated by a line locked software generator. It is used by the Least Mean Squares and FIR filter sections as reference signals. Y(n) drives the air core magnets that attenuate the unwanted line frequencies in the extracted beam.

The finite impulse response filter (FIR) is defined by

$$y_n = \sum_{l=0}^{L-1} w_l(n) x_{n-l} \qquad (1)$$

and the filter coefficients are computed during the adaptation process by the Least Mean Squares (LMS) algorithm using the method of steepest decent.

$$w(n+1)=w(n)+2\mu x(n)e$$

The coefficient μ is a convergence factor. Since extraction and spill smoothing are non-stationary processes, an adaptive approach to noise attenuation may prove to be more robust than the approach taken in the TeV QXR.

## 2.5 Electrostatic Septa

There is one 10-foot long electrostatic septum with 2 mil diameter tungsten-rhenium wires at location MI-32 and two 10-foot septa with 4 mil wires at location MI-52. At 80 kV/cm they each will give a 68-microradian kick to a 120 GeV/c beam.

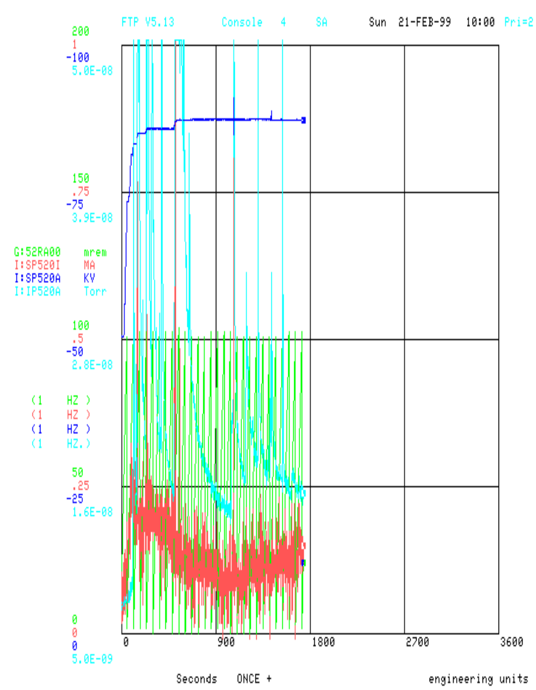


Figure 3. Conditioning the MI-52 septa

Figure 3 shows the start of conditioning the septa in order to prepare them for use. The graph shows the first half hour during which the voltage was raised to 88 kV. The lower traces show the effect of sparking on the vacuum and the current drawn from the supply.

## 2.6 Magnetic Septum

There are three 10-foot magnetic Lambertson magnets also located in the MI-52 region of the Main Injector which serve to guide the beam onto the external beam line.

# 3 EXTRACTION MEASUREMENTS

The phase and strength of the intrinsic 1/2 integer stopband were measured by ramping the two orthogonal families of harmonic quads to cause resonance. Operationally this was done by raising the main tune to 26.485 and then raising and lowering the current in the circuits until beam loss was observed. The value of the current in the two families necessary to cancel the intrinsic stopband was deduced from the measurements and this value of the current was the starting value for the ramps built in for extraction.

# 4 STATUS

The current status of extraction is shown in Figure 4 where we are resonantly losing the beam from the machine without trying to use the extraction septa. The cosine family of the 53rd harmonic quadrupoles was ramped up from the value experimentally measured in section 3. QXR was turned on after some beam had been extracted (lost) by the cosine ramp.

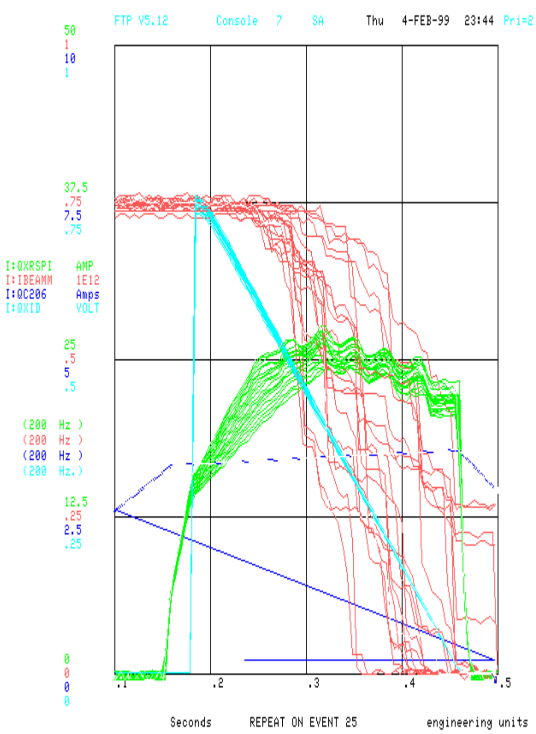


Figure 4. Resonantly Extracted (Lost) Beam

Figure 4 shows beam being resonantly being extracted (lost) from the machine. The solid curve on the bottom is the current in the 53$^{rd}$ harmonic ramp, the somewhat irregular lines starting halfway across the plot depict the beam left in the machine after extraction has started and the wavy lines in the middle show the current in QXR attempting to smooth out the spill.

The Main Injector went down due to a vacuum failure before QXR was tuned up and the electrostatic septa could be used to send beam to the PBAR production target. After the present shutdown we will attempt to send 2E13 resonantly extracted with smoother spill to the PBAR production dump.

# 5 REFERENCES

[1] The Fermilab Main Injector Technical Design Handbook
[2] L. Chapman, D. Finley, M. Harrison, and W. Merz "Tevatron Extraction Microcomputer", IEEE Transactions on Nuclear Science, Vol. NS-32, No 5, October 1985.