MEASUREMENT OF TEVATRON EXTRACTION PARAMETERS AND COMPARISON OF MODEL TO MEASUREMENTS

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Abstract

An accurate model of the half integer resonance extraction process in the Tevatron requires a knowledge of the extraction parameters such as the strengths of the 39th harmonic quadrupole and 0th harmonic octupole. This paper describes a series of experiments that determine the extraction parameters. Results of target wire scans, which measure the profile of the extracted beam, are then compared to the Tevatron model.

1 INTRODUCTION

During the 1996/1997 Fixed Target Run at Fermilab the Tevatron goal was to resonantly extract 2.5×10^{13} protons per pulse using fast spill pulses lasting several milliseconds and a slow spill period lasting 20 seconds. Extracting this beam intensity without quenching the superconducting magnets requires a precise knowledge of the extraction process to minimize particle losses. This paper describes measurements made to improve the accuracy of a model of Tevatron resonant extraction and shows comparisons of these measurements to the model calculation. The accurate extraction model led to a reduction of beam losses and an increased extracted intensity.

2 EXTRACTION PARAMETERS

Half integer resonant extraction in the Tevatron is implemented using two 39th harmonic quadrupole circuits (sine and cosine components) and a 0th harmonic octupole circuit [1]. Ignoring the effects of momentum spread and vertical motion, the horizontal phase space topology during the half integer extraction process is determined by the tune defect, $\delta_x = 0.5 - \nu_x$, the sine and cosine components of the 39th harmonic quadrupole,

$$Q_{39\mathrm{s}} = \frac{1}{2B\rho}\oint ds\beta_x B'_y \sin(2\psi_x)ds \qquad (1)$$

$$Q_{39\mathrm{c}} = \frac{1}{2B\rho}\oint ds\beta_x B'_y \cos(2\psi_x)ds \qquad (2)$$

and the zeroth harmonic octupole,

$$O_0 = \frac{3}{8B\rho}\oint ds\beta_x^2 \frac{B'''_y}{6}ds. \qquad (3)$$

The tune (ν_x), beta function (β_x), and phase advance (ψ_x) refer to the linear lattice values with the extraction devices deactivated ($Q_{39\mathrm{s}} = Q_{39\mathrm{c}} = O_0 = 0$). The integrals in Equations 1–3 are determined by the excitation level (B'_y and B'''_y) of the extraction circuits: the 39th harmonic quadrupoles and the 0th harmonic octupoles.

When $Q_{39\mathrm{s}} = Q_{39\mathrm{c}} = O_0 = 0$, the particle trajectories in the normalized phase space are circles centered on the origin. The excitation of the extraction circuits disturbs the phase space into that shown in Fig. 1 with the two circular separatrices given by

$$(x \mp \sqrt{\frac{Q_{39}}{O_o}}\sin\frac{\xi_0}{2})^2 + (y \pm \sqrt{\frac{Q_{39}}{O_o}}\cos\frac{\xi_0}{2})^2 = \frac{2\pi\delta}{O_0} \qquad (4)$$

where $y = \alpha x + \beta x'$, $Q_{39} = \sqrt{Q_{39\mathrm{s}}^2 + Q_{39\mathrm{c}}^2}$, and $\tan\xi_0 = Q_{39\mathrm{s}}/Q_{39\mathrm{c}}$. The region of overlap of the two circles is the stable region and the resonantly extracted particles stream out along the circles. Once the particles stream sufficiently far they are kicked transversely by passing through the field region of an electrostatic septum resulting in their separation from the circulating beam. One half turn later the separated particles are extracted with a Lambertson magnet and delivered to experiments.

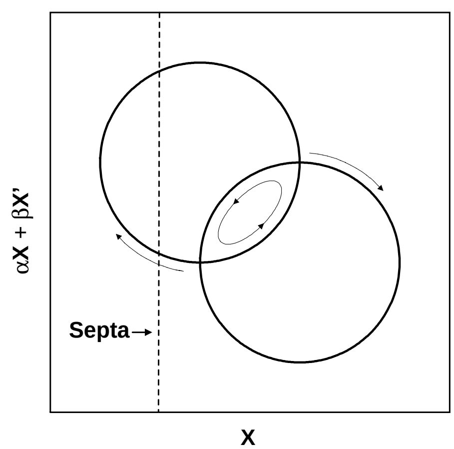

Figure 1: Sketch of separatrices in normalized horizontal phase space during resonant extraction. The arrows show the direction of motion in phase space.

3 TEVATRON MODEL

In developing a model of the extraction process we started with a design lattice of the Tevatron with the correction circuits set to reproduce the measured tunes and chromaticities. We then included effects we believed important for an accurate model: the tunes, the 39th harmonic quadrupole, the 0th harmonic octupole, the extraction septa position, the chromaticity, and the beam momentum spread. There

* Operated by University Research Association for the United States Department of Energy

are several parameters which were not considered in this model but are not believed to have a large effect. These include vertical motion, transverse coupling, the 39th and 78th harmonic octupole component, and higher order magnetic multipoles in the dipole magnets. No attempt was made to understand the effects of coupling however the coupling resonance in the Tevatron was compensated with two families of skew quadrupoles.

Because of their importance to resonant extraction our model also included the effects of lattice errors (such as the octupole component in the main dipoles) which contribute to the integrals in Equations 1–3. The model included the lattice errors by adding an offset to each of the three extraction circuits: the sine and cosine 39th harmonic quadrupole and the 0th harmonic octupole. The idea is to set the values of $Q_{39\mathrm{s}}$, $Q_{39\mathrm{c}}$, and O_0 in the model equal the those in the Tevatron when lattices errors are present. The offsets were determined from beam measurements described in the next sections.

3.1 *Tune and 39th Harmonic Quadrupole*

To determine the amount of residual 39th harmonic in the Tevatron the horizontal tune was measured as a function of the strength of 39th harmonic sine and cosine quadrupole circuits denoted T:Q39S and T:Q39C. Figure 2 shows the measured tunes when T:Q39S is varied. The data were fit to the analytically expected form

$$\nu_x = 0.5 - \sqrt{\delta_o^2 - Q'(I_{39\mathrm{s}} - I_{39\mathrm{s}0})^2} \qquad (5)$$

where $I_{39\mathrm{s}0}$, $Q^{'}$, and δ_o are determined from the data. $I_{39\mathrm{s}0}$ is the T:Q39S current that produces a 39th harmonic quadrupole component canceling that produced by the error fields. We find $I_{39\mathrm{s}0} = 1.3$ Amps. A similar measurement was done with T:Q39C and with a fit we find $I_{39\mathrm{c}0} = -1.35$ Amps. In the model these fit values, $I_{39\mathrm{s}0}$ and $I_{39\mathrm{c}0}$, are subtracted from to the amounts intentionally added by the 39th harmonic quadrupole circuits. With these offsets included the tune versus strength of T:Q39S was calculated using the model and the results are shown in Fig. 2.

3.2 *0th Harmonic Octupole*

The bunched beam tune spectrum consists of a central tune line and several synchrotron sidebands. The width of the central line depends on the 0th harmonic octupoles and higher order multipoles. The width of the central tune line was measured [2] as a function of the 0th harmonic octupole circuit denoted T:OZF and the data is shown in Fig. 3. These data were fitted to the form

$$\Delta\nu = \sqrt{k^2(I - I_{\mathrm{off}})^2 + (\Delta f)^2} \qquad (6)$$

where k, I_{off}, and Δf are determined from the data. The slope of the fitted curve, k, in the region with large current agrees well with the slope expected with a 20π mm-mrad horizontal emittance beam and the octupole circuit used. The value of I_{off} could be affected by the presence of higher order multipoles. However these higher order multipoles probably have similar effects on the extraction process as they do on the tune spread so we believe that Equation 6 should be an accurate description for the extraction model.

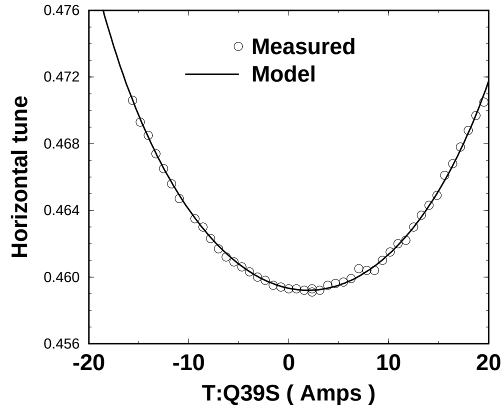

Figure 2: Measurement of horizontal tune versus setting of 39th harmonic quadrupole circuit T:Q39S. The circles are the measured tunes the solid line is the model calculation with an extra -1.3 Amps added to the T:Q39S circuit.

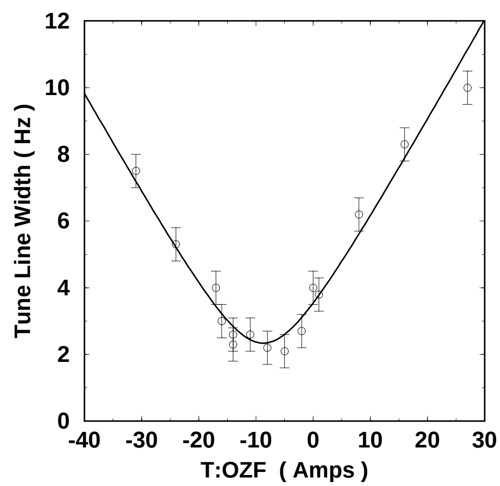

Figure 3: Measurement of horizontal tune width versus setting of the 0th harmonic octupole circuit T:OZF. The circles are the measured values and the solid line is a phenomenological fit described in the text.

3.3 *Extraction Septa Position*

An important parameter in accurately calculating the step size is the position of the electrostatic septa with respect to the center of the beam. To determine the septa position accurately we used survey information and verified the position using beam measurements. From survey data the upstream end of the electrostatic septa was determined to be 14.7 mm to the radial inside and aligned at an angle of 160 μrad with respect to the closed orbit. In an experiment where the beam position was measured while a low intensity beam was slowly moved into the electrostatic septa until the beam was extinguished it was determined that the electrostatic septa was 0.4 mm closer to the beam than indicated by the survey data. The survey information and beam measurements are consistent when the uncertainty of the measurement and the accuracy of the beam position monitors are considered. We chose to use the survey data in our model.

3.4 Model Calculations

With the above measurement of the relevant extraction parameters the phase space of the beam during resonant extraction can be calculated at any location in the Tevatron. Figure 4 shows the calculated horizontal phase space (from particle tracking) just after the electrostatic septa. The particles were launched in horizontal phase space at points near the separatrix and with a momentum spread of $\sigma_p/p = 0.00017$ corresponding to a measured bunch length of $\sigma_\tau = 2$ ns. The disconnected segment in the upper left corner of the plot is the beam that has been kicked 62 μrad by passing through the septum. The width of the extracted beam is the step size (about 8 mm) and angle at which the beam is incident on the septa wires is 160 μrad.

While resonantly extracting in the Tevatron the electrostatic septa are aligned remotely to reduce the losses downstream of the septa. The loss minimum occurs when the particles hitting the septa are incident parallel to the septa wires. Thus the 160 μrad angle of incidence calculated by the model is consistent with the surveyed 160 μrad angle of the aligned septa.

To further test the accuracy of the Tevatron model a set of target scans was made near the extraction septa and extraction Lambertsons. By moving a wire horizontally into the extracted portion of the beam and measuring the losses on a downstream loss monitor as a function of target wire position we get a profile of the beam intensity as a function of position. Figure 5 is a comparison of one of these measurements with model calculations at a target location just downstream of the septa and shows good agreement between the model and measurements. The beam on the left is the extracted beam which is separated from the circulating beam by about 1.5 mm at the location of the wire target.

The knowledge gained from the modeling process described in this paper contributed to increasing the intensity of extracted beam. For instance the step size was increased from several millimeters in the early part of the fixed target run to the 8 mm shown in Fig. 4. The increased step size resulted in lower losses from the septa wires since a smaller percentage of beam hits and interacts with the septa wires. The calculated phase space at the entrance to the extraction Lambertsons resulted in a realignment of the Lambertsons which reduced the losses downstream of the Lambertson and again resulted in higher intensity extracted beam.

In conclusion, a model of the Tevatron extraction process was developed starting with basic theory and using a set of measurements to refine the accuracy of the model. Comparisons of the model agreed well with the other independent measurements such as target wire scans. The understanding gained from this process led to improvements in the operation of the Tevatron during fixed target operations.

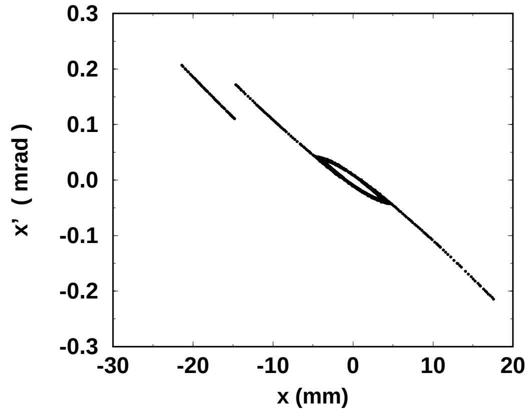

Figure 4: Horizontal phase space at the extraction septa as determined from tracking particles near the separatrices.

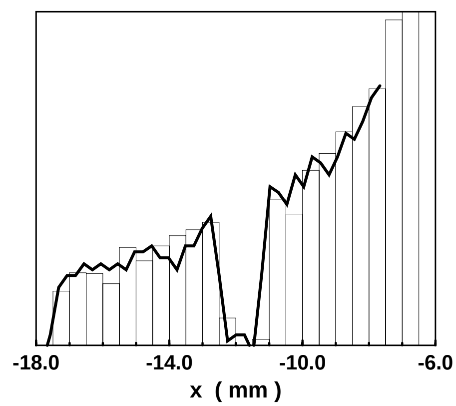

Figure 5: Measured (solid line) and modeled (histogram) profile of extracted beam and tail of circulating beam at the wire target scanner downstream of the electrostatic septa. The vertical scale is loss rate for the measurement and number of particles in the model.

4 ACKNOWLEDGMENTS

We would like to thank Bruce Hanna for getting the wire target scanners working, Leo Michelotti for helping us understand the theory of resonant extraction.

5 REFERENCES

[1] M. Harrison, "Resonant Extraction at the Tevatron", *AIP Conference Proceedings* 184, pp. 2009–2032, (1989).

[2] J. Marriner, M. Martens, "Measurement of the Tune Spread in the Tevatron vs Octupole Strength", EXP-199, Fermilab Internal Publication. (1996).