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THIRD-ORDER RESONANCE COMPENSATION AT THE FNAL RECYCLER RING

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Abstract

The Recycler Ring (RR) at the Fermilab Accelerator Complex performs slip-stacking on 8 GeV protons, doubling the beam intensity delivered to the Main Injector (MI). At MI, the beam is accelerated to 120 GeV and delivered to the high energy neutrino experiments. Femilab's Proton Improvement Plan II (PIP-II) will require the Recycler to store 50% more beam. Simulations have shown that the space charge tune shift at this new intensity will lead to the excitation of multiple resonance lines. Specifically, this study looks at normal sextupole lines $3Q_x = 76$ and $Q_x + 2Q_y = 74$, plus skew sextupole lines $3Q_y = 73$ and $2Q_x + Q_y = 75$. Dedicated normal and skew sextupoles have been installed in order to compensate for these resonance lines. By measuring and calculating the Resonance Driving Terms (RDT), this study shows how each of the resonance lines can be compensated independently. Furthermore, this study shows and discusses initial investigations into compensating multiple lines simultaneously.

INTRODUCTION

The Fermilab accelerator complex under the current Proton Improvement Plan II (PIP-II) aims to reliably deliver a 1.2 MW proton beam to the DUNE (Deep Underground Neutrino Experiment) experiment. The addition of an 800-MeV superconducting linear accelerator along with improvements to the existing Main Injector (MI) and Recycler Ring (RR) will allow this facility to achieve such a goal [1].

The Recycler Ring at the Fermi National Accelerator Laboratory (Fermilab or FNAL) receives twelve batches of proton beam from the Booster. Once in the Recycler, a slip-stacking procedure is performed in order to double the bunch intensity and, consequently, beam is sent to the Main Injector. In the MI, beam is accelerated to 120 GeV and sent to either NuMI (Neutrinos at the Main Injector) or other experiments via Switchyard. The RR also sends beam to the muon campus after rebunching the proton buckets from 53 MHz to 2.5 MHz [2].

In order to achieve the PIP-II beam power objective, the Recycler will be required to store and accumulate 50% more beam than current operations. Simulations have shown that space charge tune shifts at such intensities will lead to the crossing of multiple betatron resonances, and consequently, this will lead to beam loss. Of particular interest are third order resonance lines which significantly reduce the dynamic aperture of the Recycler Ring [1].

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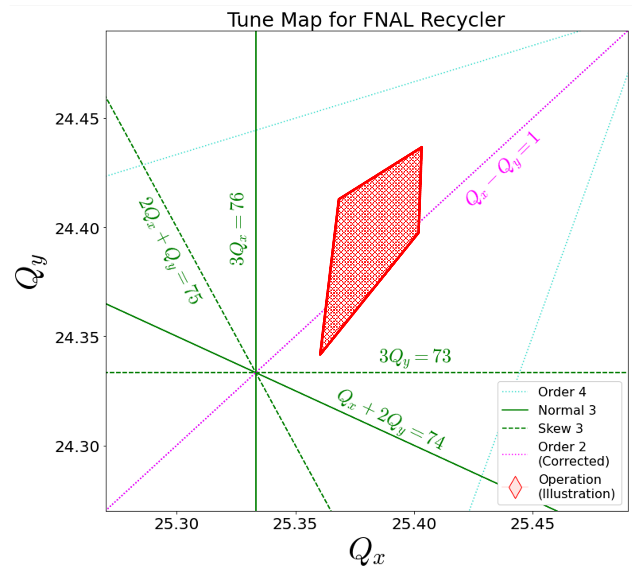

Figure 1: Tune map illustration of relevant resonance lines in present RR operation.

Figure 1 shows the tune map for the present RR operation, including an approximate tune footprint (filled diamond shape) for an approximate intensity of 5×10^{10} particles per bunch (ppb). As intensity is increased in the Recycler, the tune footprint area will increase to the point of intersecting the third order resonance lines. Resonance lines driven by normal sextupole components include $3Q_x = 76$ and $Q_x + 2Q_y = 74$. Skew sextupole lines include $3Q_y = 73$ and $2Q_x + Q_y = 75$. It is also worth pointing out that the coupling line $Q_x - Q_y = 1$ is already being corrected for with dedicated skew quadrupoles. The present work will describe how by measuring and controlling the resonance driving terms in the Recycler, we can use dedicated normal and skew sextupoles to compensate third order resonances.

RESONANCE COMPENSATION

Resonance Driving Terms

The Courant-Snyder variables $(\hat{x},\hat{p}_x,\hat{y},\hat{p}_y)$ or normalized phase space coordinates can be written to first order as:

$$\hat{u} = \sqrt{2J_u}\cos\left(\phi_u + \phi_{u_0}\right); \quad (1)$$

$$\hat{p}_u = -\sqrt{2J_u}\sin\left(\phi_u + \phi_{u_0}\right), \quad (2)$$

where u can stand either for the x or y coordinate, J_u and ϕ_u correspond to the action-angle variables and ϕ_{u_0} corresponds to the initial phase. It is worth pointing out that J_u is

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not constant due to non-linearities in the lattice. Therefore, the Normal Form formalism is introduced in order to find amplitude-independent coordinates I_u and ψ_u, such that the motion just depends on ψ_u, with some initial phase ψ_{u_0}. These are known as non-linear action-angle variables [3].

The resonance basis can be built by getting the quantity $h_u^{\pm} = \hat{u} \pm \hat{p_u}$ in terms of the number of turns N. Specifically, for h_x^- this reads:

$$h_x^-(N) = \sqrt{2I_x}e^{i\left(2\pi Q_x N+\psi_{x_0}\right)} - 2i \sum_{jklm} jf_{jklm} \left(2I_x\right)^{\frac{j+k-1}{2}} \left(2I_y\right)^{\frac{l+m}{2}} \cdot e^{i\left[(1-j+k)\left(2\pi Q_x N+\psi_{x_0}\right)+(m-l)\left(2\pi Q_y N+\psi_{y_0}\right)\right]}, \quad (3)$$

where Q_x and Q_y are the horizontal and vertical tune [3].

The generating function coefficients f_{jklm} can be related to the Hamiltonian resonance driving terms h_{jklm} through:

$$f_{jklm} = \frac{h_{jklm}}{1 - e^{2\pi i\left[(j-k)Q_x+(l-m)Q_y\right]}}, \quad (4)$$

where h_{jklm} are the generating coefficients of the one-turn map $\mathcal{M} = \exp\left[: h :\right]\mathcal{R}$. In this case, the matrix $\mathcal{R}$ is purely rotational, and the entire non-linear dynamics is encoded into the Hamiltonian kick, defined as:

$$h = \sum_{jklm} h_{jklm} \left(2J_x\right)^{\frac{j+k}{2}} \left(2J_y\right)^{\frac{l+m}{2}} e^{i\left[(j-k)\phi_x+(l-m)\phi_y\right]}. \quad (5)$$

Measurement of Resonance Driving Terms

The spectral decomposition of turn-by-turn by data for the resonance basis variable h_x^- reads:

$$h_x^-(N) = \sum_{j=1}^{\infty} A_j e^{i\left[2\pi\left(m_j Q_x N+n_j Q_y N\right)+\psi_j\right]}. \quad (6)$$

By comparing equations (3) and (6), an explicit relation can be drawn between the spectrum of h_x^- and its Normal Form expansion. This relation can be exploited in order to calculate the f_{jklm} coefficients, and consequently, the h_{jklm} driving terms from looking at the amplitude and phase of the spectral lines. Tables can be found in [3].

Experimentally, the elements in the resonance basis $h_u^{\pm}$ are built by looking at the Beam Position Monitor (BPM) data, which records the centroid position of the beam every turn. This measurement involves the data analysis of 208 (104 vertical, 104 horizontal) BPMs, located around the Recycler. The BPM system is triggered after the beam is pinged at a certain amplitude. Once the centroid data is saved, off-line analysis is used to estimate $\hat{p}_u$ at the position of every BPM. This is done with the help of previously calculated transfer matrices, where a reference BPM is used to estimate the momentum coordinate at other locations by interpolating the BPM data around that particular point.

The spectral information of the resonance basis $h_u^{\pm}$ can be calculated using the SUSSIX software [4]. SUSSIX uses a NAFF (Numerical Analysis of the Fundamental Frequencies) algorithm in order to get an enhanced tune resolution. Figure 2 shows a typical h_x^- spectrum for horizontal BPM data. For this particular case, the horizontal spectral line $L_{-2,0}$ will allow for the calculation of the h_{3000} driving term. Table 1 summarizes the spectral lines that correspond to each resonance line and RDT relevant to this work.

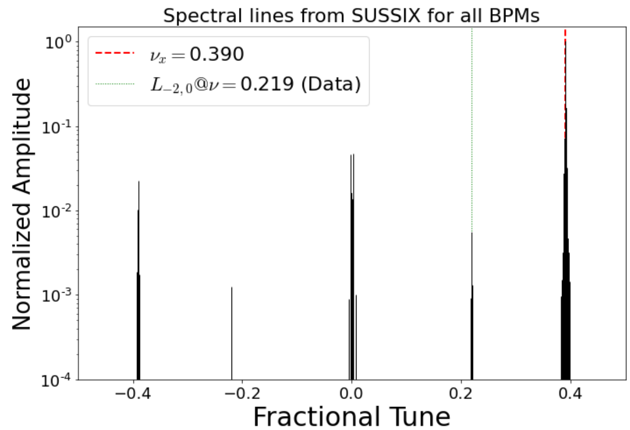

Figure 2: Normalized spectral lines after using SUSSIX for $3Q_x = 76$ compensation.

Table 1: Corresponding RDTs and spectral lines for each resonance line

Res. Line	RDT	Hor. Spect.	Vert. Spect.
$3Q_x = 76$	h_{3000}	(-2,0)	-
$Q_x + 2Q_y = 74$	h_{1020}	(0,-2)	(-1,-1)
$3Q_y = 73$	h_{0030}	-	(0,-2)
$2Q_x + Q_y = 75$	h_{2010}	(-1,-1)	(-2,0)

Compensation of Third-Order Resonances

In order to minimize the resonance driving terms for each resonance line, two pairs of normal sextupoles and two pairs of skew sextupoles have been installed in the Recycler Ring. The location of these dedicated elements was previously optimized in order to reduce chromatic effects [1].

For $3Q_x = 76$ and $Q_x + 2Q_y = 74$, the compensation scheme starts by scanning the four individual normal sextupoles, and extracting the corresponding RDT, either h_{3000} or h_{1020}. The RDTs' real and imaginary part are plotted against sextupole current. The slopes of these linear plots can be used to build the M matrix which will couple the RDT to the sextupole currents. By inverting this matrix, the compensation currents I_i that cancel out the bare machine driving term $h_{jklm}^{(bare)}$ can be calculated. In particular, for $3Q_x$ compensation, this system reads:

$$\begin{pmatrix} I_{sc220} \\ I_{sc222} \\ I_{sc319} \\ I_{sc321} \end{pmatrix} = M^{-1} \begin{pmatrix} -|h_{3000}^{(bare)}| \cos \psi_{3000}^{(bare)} \\ -|h_{3000}^{(bare)}| \sin \psi_{3000}^{(bare)} \\ 0 \\ 0 \end{pmatrix}. \quad (7)$$

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For the other two skew lines, a similar procedure can be carried out. The skew sextupoles' currents are scanned and the corresponding RDT is extracted from the BPM data. The RDT can be separated into its real and imaginary part, as can be shown in Fig. 3 for the $3Q_y$ and its corresponding h_{0030} driving term. After extracting the linear correlation in these plots, a similar linear system to that of equation (7) can be solved to get compensation currents for the skew sextupoles.

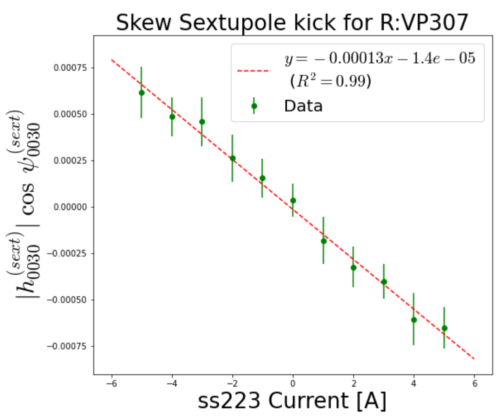

Figure 3: Real part of RDT against skew sextupole 223 current for a particular BPM

EXPERIMENTAL VERIFICATION

Transmission Scans

In order to verify the calculated compensation currents work, the transmission through the resonance line was studied. By setting the tune ramps to cross the corresponding resonance, the fractional transmission can be calculated from beam intensity data. The sextupole currents can be scanned in a grid as shown in Fig.4. It can also be seen that maximum transmission happens within 10% of the calculated operation point.

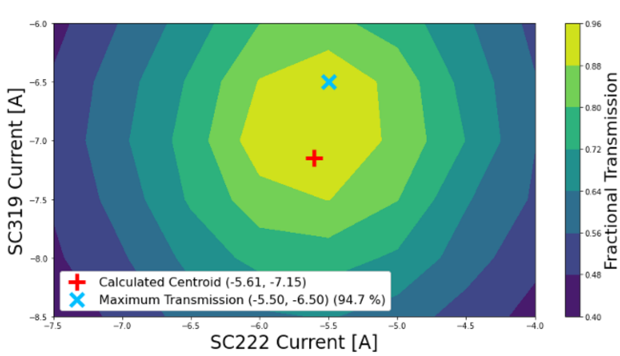

Figure 4: Particle transmission through the $3Q_x$ close to calculated compensation.

Tune Map Scan

Another useful tool to visualize resonance compensation is to build a tune map scan. In order to build these plots, dedicated quadrupoles that control the tune of the Recycler are ramped to map out the tune area of interest. The beam loss rate is measured and interpolated throughout this area. Figure 5 shows the bare machine scan with no compensation. The beam loss bands can be correlated to the resonance lines as illustrated in Fig.1. Figure 6 shows a scan when calculated currents are input into the normal and skew sextupoles for compensation of $3Q_x$ and $3Q_y$. The beam loss reduction can be seen at the location of these lines. Effectively, the strengths of these third-order lines are being decreased by 2 orders of magnitude, making them comparable to fourth and fifth order lines.

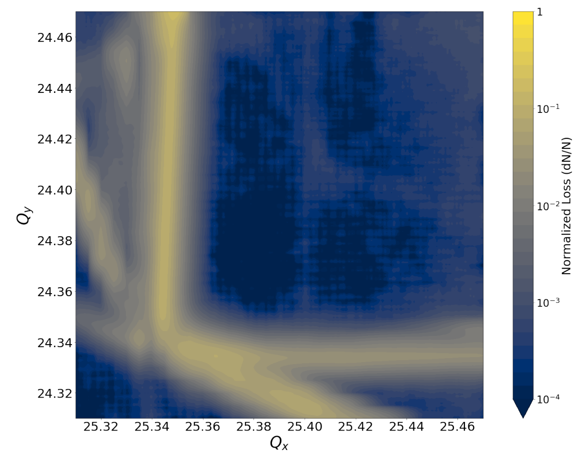

Figure 5: Tune map scan for bare machine (no compensation sextupoles turned on).

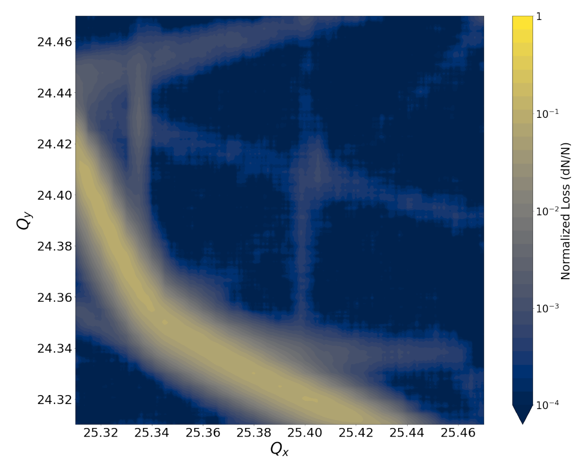

Figure 6: Tune map scan with $3Q_x$ and $3Q_y$ compensation.

CONCLUSIONS

By measuring and controlling the resonance driving terms in the Recycler Ring, the compensation of individual and multiple third-order resonance lines has been demonstrated in the FNAL Recycler Ring. Results show further studies need to be done as to how compensating one or multiple resonance lines may affect other lines by making them stronger.

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