RESONANCE COMPENSATION STUDIES AT THE FNAL RECYCLER RING

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ABSTRACT

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LIST OF ABBREVIATIONS

MSU   Michigan State University

FNAL   Fermilab National Accelerator Laboratory

RR   Recycler Ring

MI   Main Injector

RDTs   Resonance Driving Terms

NuMI   Neutrinos at the Main Injector

PSB   CERN Proton Synchrotron Booster

CHAPTER 1

INTRODUCTION

The following thesis will explore the compensation of third-order resonances in the Fermilab Recycler Ring. Consequently, the structure of this work starts out by summarizing the dynamics of charged particles in a storage ring such as the RR. This first chapter starts out by summarizing single particle dynamics with the help of exponential Lie operators and moves forward to introduce a relevant concept of collective beam dynamics: the space charge tune shift. This theoretical overview gives segue into the second chapter of this thesis, where the Recycler Ring is introduced and described in detail. Motivation for the compensation of third order resonances is given in this chapter under the framework of current and future operation of the RR. With the basic physics concepts and the description of the machine put in place, the third chapter describes in full detail the scheme and experiments developed in order to compensate third order resonances at low intensities. Before moving to explore the Recycler Ring at high intensities, chapter four provides an interlude in order to show a series of experiments done at the CERN PS Booster. These experiments explore the use of advanced optimization algorithms in the aid of compensating multiple resonance lines simultaneously. Coming back to Fermilab, chapter five showcases the studies and experiments done at high intensities in the RR in order to understand the interplay between the compensation of resonance lines and space charge effects. Finally, chapter six brings down the curtain by providing some general conclusions and future work stemming from this thesis. For now, let this first chapter introduce some relevant concepts.

1.1 Basic Accelerator Elements

The most basic element of a particle accelerator can be thought of as a black box. This black box takes some single charged particle with initial transverse coordinates $\left(x_0, x_0', y_0, y_0'\right)$, as defined in a Frenet-Serret coordinate system, and maps them to some final coordinates $\left(x_f, x_f', y_f, y_f'\right)$. For simplicity, any longitudinal effect will not be taken into account for this analysis, but can be easily incorporated. By gathering the initial coordinates into a vector, i.e. $\vec{X}_0 = \left(x_0, x_0', y_0, y_0'\right)$, and doing

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the same for the final coordinates, i.e., $\vec{X}_f = \left(x_f, x'_f, y_f, y'_f \right)$, one can define the mapping $\mathcal{M}$ that relates both vectors, such that:

$$\vec{X}_f = \mathcal{M}\vec{X}_0. \tag{1.1}$$

For a charged particle inside some accelerator element that can be described using Hamiltonian dynamics, the mapping $\mathcal{M}$ can be understood in terms of Poisson brackets and exponential Lie operators [1–4].

Let $\vec{X} = (q_1, p_1, \ldots, q_n, p_n)$ be a 2n dimensional vector, made from n pairs of canonical coordinates (q_i, p_i) that make up the $2n$ dimensional phase space. And let two arbitrary functions $f\left(\vec{X}; s\right)$ and $g\left(\vec{X}; s\right)$ be functions of $\vec{X}$ and s, where s plays the role of the independent "time" coordinate. The Poisson brackets $[\bullet, \bullet]$ can be defined as:

$$[f, g] = \sum_{i=1}^{n} \frac{\partial f}{\partial q_i} \frac{\partial g}{\partial p_i} - \frac{\partial f}{\partial p_i} \frac{\partial g}{\partial q_i}. \tag{1.2}$$

Using this definition, one can explicitly write out the Poisson bracket definition for a 4 dimensional phase space described by state vector $\vec{X} = (x, x', y, y')$. This reads:

$$[f, g] = \frac{\partial f}{\partial x} \frac{\partial g}{\partial x'} - \frac{\partial f}{\partial x'} \frac{\partial g}{\partial x} + \frac{\partial f}{\partial y} \frac{\partial g}{\partial y'} - \frac{\partial f}{\partial y'} \frac{\partial g}{\partial y}. \tag{1.3}$$

The Lie operator $: f :$ acts on some function g and is the adjoint operator of the Poisson bracket operator. It's definition reads:

$$: f : g = [f, g]. \tag{1.4}$$

This specific $: \bullet :$ notation allows for a compact notation in order to define the exponential Lie operator. The exponential Lie operator of an arbitrary function f is defined as

$$e^{:f:} \bullet = \sum_{k=0}^{\infty} \frac{1}{k!} \left(: f : \right)^k \bullet. \tag{1.5}$$

CHAPTER 2

THE FNAL RECYCLER RING

The Fermilab Recycler Ring (RR) is one of the circular accelerators located in the Fermilab Accelerator Complex. It was originally designed to store and accumulate antiprotons that remained from a Tevatron event [5]. The recycling of antiprotons was deemed ineffective and was never operationally implemented [6]. Since 2011, the RR has been repurposed to act as a pre-injector to the Main Injector (MI) by storing and accumulating protons [7]. It is worth pointing out, that the MI and the RR share the same tunnel, which has a circumference of 3.319 km (2.062 mi).

The MI/RR complex is fed protons by the Proton Source, which by itself consists of the Pre-Accelerator, the Linear Accelerator (Linac), and the Booster. The Pre-Accelerator systems provide H^- ions to the Linac, where they are accelerated to an energy of 400 MeV. After this, the beam is injected into the Booster, which is a rapid-cycling synchrotron operating at a 15 Hz repetition rate. During this injection process, the H^- beam passes through a carbon stripping foil, and it incorporates to the circulating proton beam. The Booster ramps the energy up from 400 MeV to 8 GeV. This 8 GeV proton beam can either go to the Booster Neutrino Experiments or get injected into the Recycler Ring. Once in RR the beam has two possible destinations: 1) high energy neutrino experiments through MI or 2) Muon Campus. For the latter, proton beam gets rebunched from 53 MHz to 2.5 MHz and transported to Muon Campus. For high energy neutrino experiments, the proton beam gets slip-stacked, hence doubling the intensity that gets injected into Main Injector. Once in MI, the beam is accelerated to 120 GeV and sent to the NuMI (Neutrinos at the Main Injector) beam facility [6–8]. A description of the accelerator complex is shown in figure 2.1, including the experimental beamlines which feed neutrino, muon and fixed target experiments.

The work done for this thesis focuses on the Recycler Ring. The following chapter starts by giving a general description for the operation and physics of the Recycler Ring. The next sections introduce and motivate the compensation of third order resonances for high intensity operation.
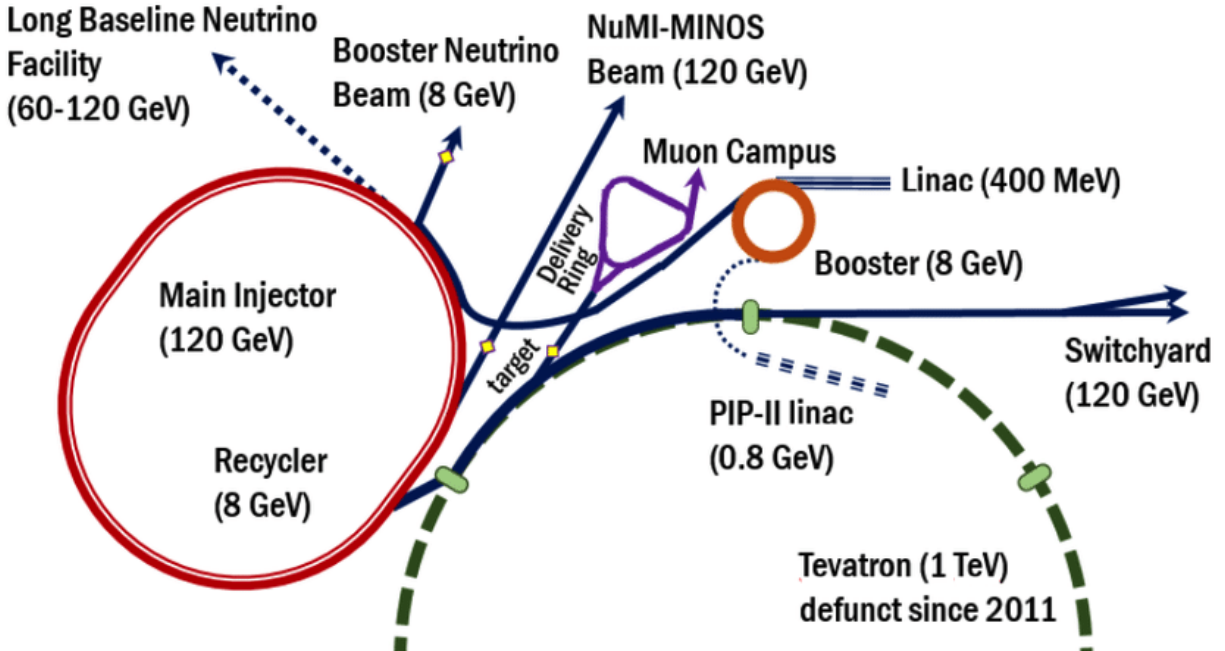
Figure 2.1 The past (Tevatron), present and future (PIP-II and LBNF) of the FNAL Accelerator Complex, taken from [3].

2.1 General Specifications

The RR is a permanent magnet storage ring operating at a fixed momentum of 8.835 Gev/c. [9] [10]

2.2 Tune Diagram and Resonances

2.3 High Intensity and Tune Footprint

Table 2.1 Typical Recycler Ring properties for beam sent to NuMI

Parameter	Value	Unit
Circumference	3319	m
Momentum	8.835	GeV/c
RF Frequency	52.8	MHz
RF Voltage	80	kV
Harmonic Number	588	
Synchrotron Tune	0.0028	
Slip Factor	-8.6×10^{-3}	
Superperiodicity	2	
Horizontal Tune	25.43	
Vertical Tune	24.445	
Horizontal Chromaticity	-6	
Vertical Chromaticity	-7	
95% Normalized Emittance	15	π mm mrad
95% Longitudinal Emittance	0.08	eV s
Intensity	$5 \times 10^{10}, 8 \times 10^{10}$ (PIP-II)	ppb
MI Ramp Time	1.333, 1.133, 1.067	s
Booster Frequency	15, 20 (PIP-II)	Hz

CHAPTER 3

COMPENSATION OF THIRD-ORDER RESONANCES AT LOW INTENSITIES

3.1   Global RDTs and Lattice Model

3.2   Measurement of Third Order RDTs

3.3   Compensation of RDTs

3.4   Optimization of Compensation Currents

3.5   Experimental Verification of Compensation

3.5.1   Dynamic Loss Map

3.5.2   Static Tune Scans

CHAPTER 4

RESONANCE COMPENSATION STUDIES AT THE CERN PS BOOSTER

4.1   General specifications

4.2   Tune Diagram and Operation

4.3   Optimization Algorithms for Resonance Compensation

4.4   Experimental Verification of Compensation

CHAPTER 5

HIGH INTENSITY STUDIES

5.1   Global RDTs and Intensity-Dependent Effects

5.2   Space Charge Tune Shift

5.3   Measurement of Tune Shift

5.4   Static Tune Scans at Different Intensities

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

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APPENDIX

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