

RESONANCE COMPENSATION STUDIES AT THE FNAL RECYCLER RING

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ABSTRACT

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS	vi
CHAPTER 1: SINGLE PARTICLE DYNAMICS	1
1.1: Basic Accelerator Elements	1
1.2: Normal Form	1
1.3: Resonances in Circular Accelerators	1
1.4: Resonance Driving Terms	1
CHAPTER 2: THE FNAL RECYCLER RING	2
2.1: General Specifications	3
2.2: Tune Diagram and Resonances	3
2.3: High Intensity and Tune Footprint	3
CHAPTER 3: COMPENSATION OF THIRD-ORDER RESONANCES AT LOW INTENSITIES	5
3.1: Global RDTs and Lattice Model	5
3.2: Measurement of Third Order RDTs	5
3.3: Compensation of RDTs	5
3.4: Optimization of Compensation Currents	5
3.5: Experimental Verification of Compensation	5
CHAPTER 4: RESONANCE COMPENSATION STUDIES AT THE CERN PS BOOSTER	6
4.1: General specifications	6
4.2: Tune Diagram and Operation	6
4.3: Optimization Algorithms for Resonance Compensation	6
4.4: Experimental Verification of Compensation	6
CHAPTER 5: HIGH INTENSITY STUDIES	7
5.1: Global RDTs and Intensity-Dependent Effects	7
5.2: Space Charge Tune Shift	7
5.3: Measurement of Tune Shift	7
5.4: Static Tune Scans at Different Intensities	7
CHAPTER 6: CONCLUSIONS AND FUTURE WORK	8
BIBLIOGRAPHY	9
APPENDIX YOUR APPENDIX	10

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

CHAPTER 1

SINGLE PARTICLE DYNAMICS

The most basic element of a particle accelerator can be thought of as a black box. This black box takes some initial transverse coordinates x_0, x'_0, y_0, y'_0 , as defined in a Frenet-Serret coordinate system, and maps them to some final coordinates x_f, x'_f, y_f, y'_f . For simplicity, any longitudinal effect will not be taken into account for this analysis [1] [2] [3] [4].

1.1 Basic Accelerator Elements

1.2 Normal Form

1.3 Resonances in Circular Accelerators

1.4 Resonance Driving Terms

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 [1]. 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 [1, 6, 7]. A description of the accelerator complex is shown in figure 2.1, including the experimental beamlines which feed neutrino, muon and fixed target experiments [6].

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.

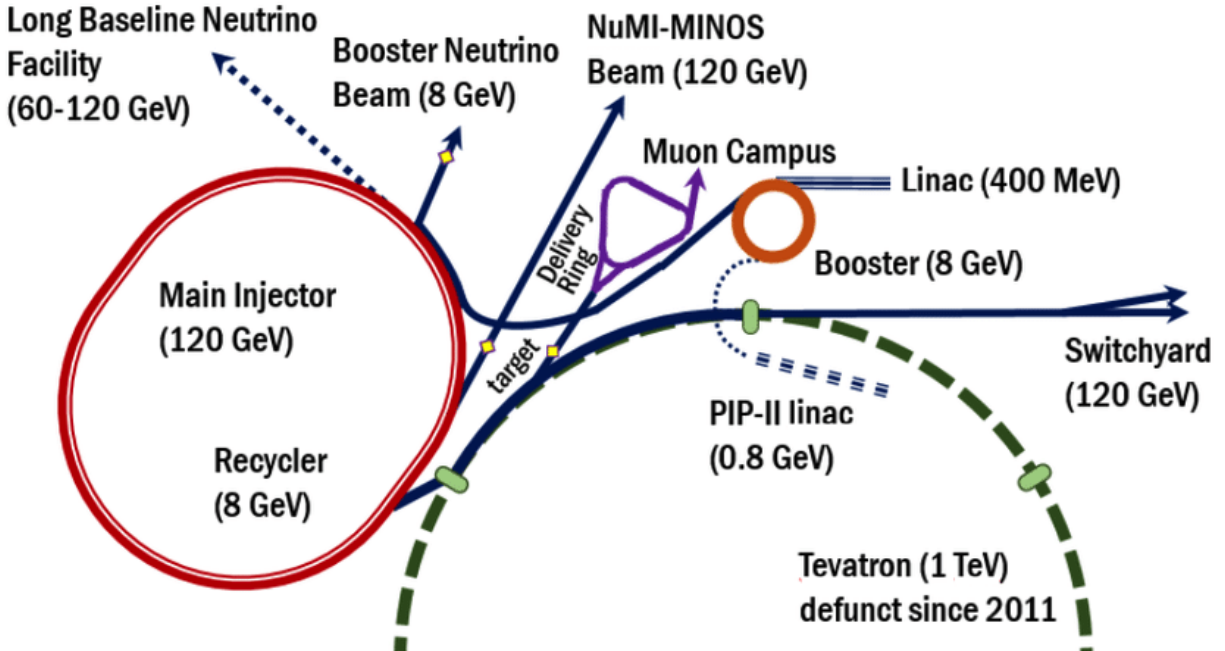


Figure 2.1 The past (Tevatron), present and future (PIP-II and LBNF) of the FNAL Accelerator Complex, taken from [3].

2.1 General Specifications

The RR is a permanent magnet storage ring operating at a fixed momentum of 8.835 GeV/c. [4]

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	5×10^{10} , 8×10^{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
YOUR APPENDIX