RESONANCE COMPENSATION STUDIES AT THE FNAL RECYCLER RING

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ABSTRACT

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Your acknowledgements here.

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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

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. 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 [4]. The work done for this thesis focuses on the Recycler Ring, so the machines upstream and downstream

The following chapter starts by giving a general description for the operation and physics of the Recycler Ring.

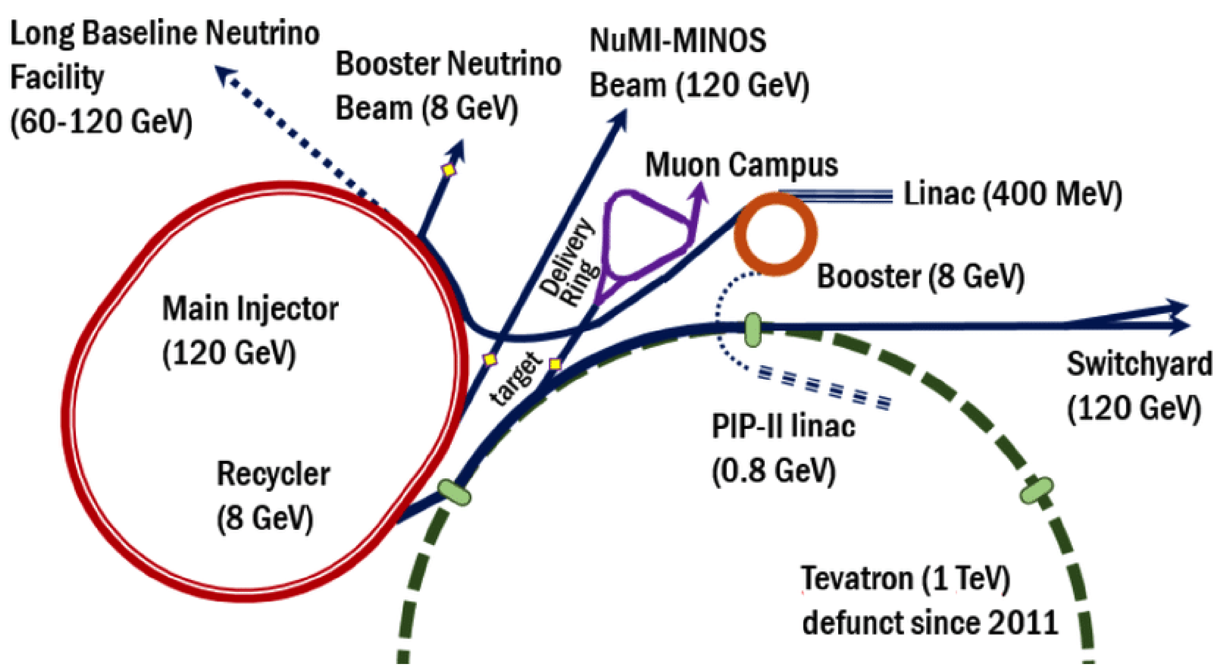

Figure 2.1 The past (Tevatron), present and future (PIP-II and LBNF) of the FNAL Accelerator Complex, taken from [3].

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

2.1 General Specifications

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

2.2 Tune Diagram and Resonances

2.3 High Intensity and Tune Footprint

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

BIBLIOGRAPHY

[1] Robert Ainsworth et al. "High intensity operation using proton stacking in the Fermilab Recycler to deliver 700 kW of 120 GeV proton beam". In: *Phys. Rev. Accel. Beams* 23 (12 Dec. 2020), p. 121002. DOI: 10.1103/PhysRevAccelBeams.23.121002. URL: https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.121002.

[2] R. Ainsworth et al. "High intensity space charge effects on slip stacked beam in the Fermilab Recycler". In: *Phys. Rev. Accel. Beams* 22 (2 Feb. 2019), p. 020404. DOI: 10.1103/PhysRevAccelBeams.22.020404. URL: https://link.aps.org/doi/10.1103/PhysRevAccelBeams.22.020404.

[3] Andrzej Wolski. *Beam Dynamics in High Energy Particle Accelerators*. 2nd. WORLD SCIENTIFIC, 2023. DOI: 10.1142/13333. eprint: https://www.worldscientific.com/doi/pdf/10.1142/13333. URL: https://www.worldscientific.com/doi/abs/10.1142/13333.

[4] M. Ball et al. *The PIP-II Conceptual Design Report*. Tech. rep. FERMILAB-TM-2649-AD-APC1516858. Fermilab, Mar. 2017. DOI: 10.2172/1346823. URL: https://www.osti.gov/biblio/1346823.

[5] Gerry Jackson. *The Fermilab recycler ring technical design report. Revision 1.2*. Tech. rep. FNAL-TM-1991ON: DE97051388; BR: KAHEP. Fermilab, Nov. 1996. DOI: 10.2172/16029. URL: https://www.osti.gov/biblio/16029.

[6] Sergei Nagaitsev. *Fermilab Antiproton source, Recycler ring and Main Injector*. Tech. rep. FERMILAB-FN-0957-AD. Fermilab, Mar. 2013. DOI: 10.2172/1127965. URL: https://www.osti.gov/biblio/1127965.

APPENDIX

YOUR APPENDIX