CHAPTER 1
INTRODUCTION

High energy physics, the study of matter at its most fundamental observed level, is divided into two general classes of research: theory and experiment. The drive of the theorist is to condense explanations of a broad class of phenomena to a simple model. The experimentalist must deal with existing technologies and abilities, seeking to observe exceedingly rare "events" in an attempt to reconcile our observations of nature with theory. These two work hand in hand, providing physicists with a progressively more coherent, cohesive and cogent understanding of the way nature works.

Experimental high energy physics accomplishes its task with particle accelerators, devices which raise the energies of particles such as protons and electrons, and in exotic cases, antiprotons, muons and other species, and collide them with other particles. (Accelerators also are used for other applications such as radiotherapy and coherent gamma ray production.) The objective is to create and observe events that occur at high energies, such as production of massive highly unstable particles (such as the top quark or the Higgs boson) or events that signal the effects of exceedingly weak processes (such as CP violation observed in B-meson systems).

Because these events are so weak, the number of events produced per unit time per unit cross section must be high in order to provide reasonable statistics for experimentalists. This is measured in terms of a quantity called the luminosity, a quantity depending on the frequency f with which bunches of particles interact, the number N of particles in each bunch and the transverse beam size σ. For round beams such as those at the Fermilab Tevatron,

$$L = \frac{f\, N^2}{4\pi\sigma^2}\ . \tag{1.1}$$

The current maximum luminosity achieved with a hadron collider, $L = 8.97 \cdot 10^{30}$ $\mathrm{cm}^2\ \mathrm{s}^{-1}$, was achieved at the Tevatron in April, 1993. Any effect that removes particles from the beam (reducing N) or increases the transverse size of the beam σ reduces the luminosity, or the efficiency of the accelerator in producing events of interest to high energy physicists.

Particle motion around an accelerator is approximately, but not completely, linear. Even without magnetic field and alignment errors (always present at the 10^{-4} level) the presence of sextupoles commonly used to correct the chromaticity also introduces nonlinear kicks. Nonlinearities, therefore, cannot be removed — they must be understood and corrected if their presence adversely affects accelerator performance and operations. The focus of this thesis is on effects, called resonances, driven by these nonlinearities — how their strengths can be measured, and how they might interact with modulations existing within the accelerator to affect the stability of particles in a storage ring or collider.

The study of the long-term stability of particles traveling around one of these devices is also a study of fundamental issues in classical dynamics, dating back to Poincaré's investigation of the long-term stability of the solar system in the late 19th century. Coincidentally, typical timescales are roughly the same order of magnitude for both systems: the solar system has existed in its present form for a few billion years (10^9 Earth orbits), and protons and antiprotons are stored in the Fermilab Tevatron for a few billion revolutions between beam dumps and refills. In order to prevent luminosity degradation in a collider over this time, the mechanisms responsible for growth of transverse particle oscillations about the central orbit over timescales up to billions of turns must be investigated. Such mechanisms fall into three categories — slow, medium and fast.

Fast amplitude growth is typically caused by severe distortions of the orbit, either by intense magnetic field errors (such as a reversed-polarity corrector or strong nonlinear fields) or by a major fault condition such as blockage of the beam pipe. Here the timescales for particle loss, either at the blockage or at the physical aperture, range from fractions of a turn to turns. Such losses are usually easy to diagnose with beam position and loss monitors, and it is of particular importance to guard against such losses in machines with superconducting magnets, where these losses could easily lead to a magnet quench.

Medium timescale amplitude growth occurs over timescales ranging from tens to thousands of revolutions. This growth is characteristically driven by distortions of the particle orbit, called resonances, created by nonlinear magnetic fields. Strong isolated resonances perturb the amplitudes of the orbit, possibly leading to loss at the physical aperture in tens to hundreds of turns. If many resonances are driven, nearby resonance structures in the phase space of particle motion can overlap, causing stochastic motion with timescales of up to thousands of turns (Schoch 1958). These sorts of mechanisms and structures have been investigated in the context of resonant trapping (Chao and Month 1974, Chao et. al. 1987b) and general nonlinear dynamics (Lichtenberg and Lieberman 1983) as applied to accelerators. Experience with such systems in real machines leads to constraints on the horizontal and vertical tunes at which operation is acceptable, reasonably far from loss-creating resonances.

Slow amplitude growth occurs over much much longer timescales, from 10^4 to 10^9 turns. These timescales are macroscopic, seconds to hours of actual accelerator operation, and are therefore normally very difficult to diagnose. Most mechanisms that drive slow growth depend strongly on the coupled multidimensional nature of the particle motion and weak sources of stochasticity or noise. Modulational (or thick-layer) diffusion, Arnold (or thin-layer) diffusion and amplitude growth driven by weak external noise all fall into this category (Lichtenberg and Lieberman 1983). Modulational diffusion (Vivaldi 1984, Chirikov et. al. 1985) is of particular interest in this dissertation because, as the name implies, it is driven by the modulation of a parameter of the dynamical system, in this case the accelerator tune.

Chapter 2 contains a review of fundamental concepts of accelerator physics that are relevant to remainder of this dissertation. A discrete Hamiltonian approach describing one-dimensional resonance islands is described in Chapter 3, including description of the primary tracking program used to simulate particles under the influence of a single nonlinear resonance. Chapter 4 extends this analysis to include both the effects of tune modulation and beta function modulation, comparing simulation and theory with excellent agreement. The tune modulation portion of Fermilab experiment E778 is described in Chapter 5, where particles trapped by nonlinear resonance islands were observed in a real accelerator and then detrapped in a controlled way with tune modulation. Chapter 6 returns to unperturbed resonance islands, extending the one-dimensional results of Chapter 3 to two transverse dimensions, and Chapter 7 investigates modulational diffusion, a multidimensional phenomena driven by tune modulation in two transverse dimensions.