Introduction to Accelerator Dynamics

STEPHEN PEGGS
TODD SATOGATA

How does a particle accelerator work? The most direct and intuitive answer focuses on the dynamics of single particles as they travel through an accelerator. Particle accelerators are becoming ever more sophisticated and diverse, from the Large Hadron Collider (LHC) at CERN to multi-MW linear accelerators and small medical synchrotrons. This self-contained book presents a pedagogical account of the important field of accelerator physics, which has grown rapidly since its inception in the latter half of last century. Key topics covered include the physics of particle acceleration, collision and beam dynamics and the engineering considerations intrinsic to the effective construction and operation of particle accelerators. By drawing direct connections between accelerator technology and the parallel development of computational capability, this book offers an accessible introduction to this exciting field at a level appropriate for advanced undergraduate and graduate students, accelerator scientists and engineers.

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To
Rachel and Leah

Preface

This book addresses the single particle dynamics heart of the question; 'How does an accelerator work?', for readers who are accelerator users and operators, who are accelerator physicists or who are interested in real-world linear and nonlinear difference systems. The reader might be a synchrotron light source user, a collider experimentalist, a medical accelerator operator, an engineer in a beam instrumentation group or a controls professional in industry.

The level of the discussion is appropriate for graduate students, final-year undergraduates and practicing accelerator professionals. This is not an exhaustively complete reference handbook, at a high technical level. Rather, it is a pedagogical introduction to the subject, telling a self-contained and accurate story about a field of physics that was born and grew rapidly in the second half of the twentieth century, and which continues to mature by leaps and bounds in the twenty first. The treatment is rigorous enough to be accurate and useful, without letting unnecessary detail obscure the central theme. Deeper investigations of the 'back-stories' are left to other sources.

The central theme is that repetitive motion through an accelerator is a natural, convenient and well-motivated introduction to the generic linear and nonlinear behaviour of highly iterated difference systems. A circular accelerator – or even a linear accelerator – is one answer to another question: *'How do difference systems manifest themselves in the real world?'*

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1

Introduction

1.1 Differences or Differentials?

Computers have been used to model physical systems from their earliest days. The behaviour of these models is subtly but profoundly affected by the sequential and discrete nature of all digital computers, in which one step in an algorithm follows another, just as a charged particle follows one turn after another around a circular accelerator. Numerical tools – computers – make dynamical problems look like difference equations. Analytic tools – most pre-computer mathematics – make problems look like differential equations. The best choice of representation depends on the nature of the particular system being modelled, and on the questions that are to be answered.

Figure 1.1 illustrates a simple nonlinear system – a gravity pendulum with unit length – that is inherently continuous in time, and which is accurately represented by the differential equation

$$\theta'' = -g \sin(\theta) \tag{1.1}$$

where a prime indicates differentiation with respect to time, and g is the acceleration due to gravity. Numerically, this motion is simulated by breaking the motion into two steps that are iterated repeatedly. In the first step, the pendulum 'drifts' with a constant angular velocity θ' for a time Δt. In the second step, gravity is represented by a 'kick' impulse that instantaneously changes the angular velocity. This is written in pseudo-code as

$$\begin{aligned} &\text{until finished } \{ \\ &\qquad \theta = \theta + \theta' . \Delta t \\ &\qquad \theta' = \theta' - g \sin(\theta) . \Delta t \\ &\} \end{aligned} \tag{1.2}$$

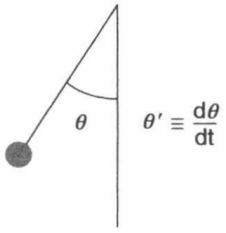

Figure 1.1 Phase space co-ordinates (θ, θ') for a unit length gravity pendulum.

Clearly, the differential and difference representations of a pendulum become identical as Δt approaches zero. Less clear is the potential for the numerical model to introduce artefacts into the simulated motion – behaviour that is not demonstrated by actual pendula.

Circular accelerators are inherently discrete in time, given the turn-by-turn nature of the progress of a test particle. It will be seen, in Chapter 4, that the *standard map* motion of Equation 1.2 (with g set equal to 1) also naturally describes the turn-by-turn longitudinal oscillations of a test particle, relative to an ideal particle at the centre of a bunch. Further, the standard map that naturally models many apparently independent nonlinear accelerator scenarios is a *standard* way to generate chaos, a phenomenon not demonstrated by gravity pendula.

Sometimes analytic solutions to differential equations are known. This is the case for the pendulum, a non-trivial nonlinear system (when large angles are considered) that was completely solved well before computers were invented. Analytic solutions to nonlinear *difference* systems are much rarer. Most traditional mathematical methods are implicitly continuous, and break down more or less completely when truly differential systems, like accelerators, are modelled.

Although computers and accelerators proliferated together, in the second half of the twentieth century, it took time to recognise the limitations of traditional continuous methods. For example, the difference map of Equation 1.2 can be forced into a differential representation by writing

$$\theta'' = -\sum_{n=1}^{\infty} \delta(t - n\Delta t)\ g\ \sin(\theta)\ .\ \Delta t \tag{1.3}$$

where the delta function $\delta()$ is non-zero every Δt units of time. The perceived advantage of this kind of representation of accelerators was that it enabled traditional Hamiltonian, Fourier and perturbation analysis tools to be used. It eventually became clear that traditional methods often break down more or less completely,

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