PARTICLE ACCELERATOR DESIGN : COMPUTER PROGRAMS

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Foreword

The art of high-energy particle accelerator design has evolved greatly since the period around 1930 when the Cockcroft–Walton and Van de Graaff generators, the linear resonance-accelerator, and the cyclotron were developed for the study of nuclear reactions. Major steps in the evolution of cyclic particle accelerators include the discovery of phase stability and the use of alternating-gradient focusing, with the result that current devices are as large as 2 km in diameter and are capable of producing particles with an energy of several hundred GeV. Included in these developments are stored beams of sufficient intensity and quality that elementary-particle reactions can be productively studied at the intersection of two oppositely directed beams, thus making available a tremendously greater center-of-mass energy than would be realized from the particles of a single beam impinging onto a stationary target.

The present state of accelerator technology requires that the design of the instrument and facilities be optimized. For beyond considerations of reliability and versatility, one must respect that the construction and operation expenditures are substantial, the lead times for setting up the larger facilities amount to several years, and many experimental teams will depend on the scheduled availability of a particular accelerator facility. The experimental devices external to the accelerator and the beam-transport lines thereto involve concepts and components similar to those that are associated with the accelerator itself and must be planned with comparable care.

The progress of the accelerator art understandably has necessitated an increased understanding of the physical phenomena that govern accelerator performance and an increased sophistication in the quantitative evaluation of these phenomena. Back-of-envelope calculations, rule-of-thumb designs, and cut-and-try developments thus no longer are adequate approaches to many accelerator questions. Although model work in some cases can be useful—for example in checking and in providing manufacturing experience relating to a provisional final design—this frequently is an impractical or time-consuming route to the resolution of design problems.

It is current practice for the accelerator designer to rely heavily on extensive calculations for many features of his design, and these calculations, in order to be specific, typically are completed only after considerable numerical work. It thus has been fortunate that, beginning perhaps in the mid-1950's, accelerator designers were able to benefit from the concurrent development of automatic stored-program digital computers.

Automatic digital computation of course is of great assistance to the accelerator theorist both for investigating new concepts and in proceeding with a specific design. The most common and basic problems to which digital computations have been applied in accelerator design are, however, those of the types treated in this book—namely boundary-value (or eigenvalue) problems for static or dynamic electromagnetic fields and the single-particle dynamics of particles moving in a prescribed field. Flexible and efficient programs have been developed over the past several years, especially in accelerator and plasma-physics laboratories, and are now available to the accelerator designer for the numerical solution of such problems. Clearly these programs also have application in other fields of physical science and technology where similar (or mathematically identical) problems arise, and they indeed have been so used.

The basis on which certain of the computational programs have been constructed and the means for employing them most efficiently may have been aided in some cases by sophisticated theoretical numerical analysis and, in others, may have been guided chiefly by experience. A definitive treatment of such questions is not attempted in this book, which instead is intended primarily to outline in an explicit way (in some cases aided by flow charts) the characteristics of certain working programs that are available and to describe the options available in their use. Texts and monographs, symposia proceedings, and review articles are available concerning accelerator technology and the field of plasma physics, but a correspondingly explicit description of computational techniques applicable to these fields unfortunately has been essentially restricted to isolated reports concerning individual programs. We therefore are indebted to Mr. Colonias for undertaking the collection and exposition of the material contained in the present work, of which a substantial part has been developed through his own effort and that of his immediate associates. It may be hoped that this material not only will be informative for the physical scientist or engineer who will have applications for the programs discussed, but that also the numerical analyst may recognize areas where a fuller understanding or new approaches can be developed.

The reader will note that options available in some of the programs described here include the use of cathode-ray (CRT) display and the possibility of interactive computation. Such features can make a computer facility become a particularly powerful tool for a physical scientist or engineer, who, through use of these options, can obtain promptly a clear appreciation of the results of a computation and, based on these results, instruct the computer how to proceed. Although by no means a substitute for thought, the computer thus becomes a very effective tool in providing orientation with respect to a new problem (sometimes revealing the possibility of qualitatively unanticipated results), as well as furnishing accurate numerical results relative to any specific case. In this spirit the program SYNCH, described in Chapter V, permits one to "construct" an accelerator from specified magnetic elements, instruct the computer to optimize certain parameters (if desired) in accord with specified criteria, and to examine visually the orbit or beam-envelope characteristics that would result. The programs described in this book, and certainly others that will be developed in the future, thus may be regarded as illustrating an important trend to which Dr. Kowarski referred in the following words during the September 22nd evening meeting of the 1971 International Conference on High-Energy Accelerators:

> ...Now we are at the beginning of a new kind of extension by machine: the computer comes to supplement the theoretician's brain. We cannot foresee what this...kind of creativity in physics will bring, but we may expect that, just as Ernest Lawrence's contribution was decisive to the development of the nuclear machines, the name of John von Neumann will be remembered in connection with the origins of computational physics.

L. JACKSON LASLETT

Berkeley, 1972

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Preface

Rapid progress in numerical methods, coupled with the development of advanced computer systems with large memories and nanosecond speeds, have made possible the formulation of the sophisticated computer programs that have become indispensable in the modern nuclear laboratory. However, the magnitude and complexity of the problems involved and the existence of an enormous amount of literature make it very difficult for one to obtain an understanding of the capabilities and limitations of a particular program; dozens of articles written by specialists must be read. Even then, the user may find himself unable to utilize one or the other program because of insufficient operational detail. Thus, he embarks upon the formidable task of writing "another program," adding another series of papers in the already existing large number of duplicate programs.

The aim of this book is to give a concise account of some of the most important computer programs applicable to accelerator design, assemble these programs under one cover, and present the research worker with information by which he may determine a program's effectiveness.

The arrangement of the book and the selection of the programs have been the result of the personal experience and professional career of the author for over fifteen years in the digital computing field, the last six of which have been spent in charge of computer applications for accelerator design at Lawrence Berkeley Laboratory.

The programs reflect what the author feels to be necessary for a generalized discussion and include mathematical development of programs, operating procedures, program organization, and application techniques. The book is concerned primarily with the description of these programs rather than with a comprehensive and exhaustive treatment of theoretical details. Most programs are followed by illustrative examples indicating the manner by which the program is used, and each chapter includes a number of suggested references keyed to the programs. At strategic points comparison tables are given, which describe the vital statistics of each program, such as computer language used, core size, time for solution, availability, etc.

In assembling this book I have delved liberally into the theoretical material published by accelerator scientists and engineers. I have also tried to be meticulous in acknowledging the sources of all material covered; any omissions are purely accidental.

My discussion of the programs is in the nature of sampling—rather than reviewing—with a definite bias toward topics with which I have been personally involved.

The book is divided into three parts. Part A covers computer programs relating to the calculation of two-dimensional magnetic and electric fields, as well as progress made in the area of three-dimensional calculations. Part B covers programs relating to the calculation of orbits of particles in a magnetic and/or electric field. Here, we deal with programs capable of analyzing various properties of cyclotrons, various problems relating to transverse orbit motion in synchrotron design, as well as with programs relative to the design of beam transport systems. Part C covers some representative programs useful in the design of linear accelerator-type cavities.

Acknowledgments

No book is ever written without the author having received a considerable amount of generous assistance from others. I wish to thank Dr. Elon Close for assisting me in preparing the introductions to this book and for his participation with Drs. Arthur Paul, Steven Sackett, and Paul Concus in undertaking the tedious task of reading and criticizing the content of the book from the point of view of the specialist in the field.

I am particularly indebted to my friend and colleague, Bruce Burkart, whose untiring efforts in criticizing, correcting, and supporting this book made its publication possible.

The editorial help of Mary Wildensten and the typing of the completed manuscript by Virginia Franks is also gratefully acknowledged.

Next, I would like to thank the many individuals, institutions, publishers, and organizations who have generously permitted the use of illustrations. In particular, I thank the University of California, Lawrence Berkeley Laboratory, and the Atomic Energy Commission for supporting my efforts in making this publication possible.

Finally, I thank my wife Becky and my children John-John and Elisabeth for their patience and understanding.

Part A PROGRAMS FOR MAGNETIC AND ELECTRIC FIELDS

1. Introduction

Part A of this book deals with programs that calculate static magnetic and electric fields for particle accelerators. The calculation of such fields for essentially arbitrary geometries with various current and charge distributions has been of prime interest for many years, and much effort has been expended on the solution of such problems as they arise from applications of electromagnetic theory. Furthermore, the development of particle accelerators has created a need for easily available solutions to sets of problems, any one of which is of enough complexity to require an expenditure of considerable time and effort to arrive at a usable solution. The desire for usable engineering-type solutions is intense in this field, since it is the electric and magnetic field intensities that determine the motion of the particles for which these accelerators and their associated transport and experimental systems are designed.

Although in general, a solution for any particular problem can be arrived at by what we shall call classical methods (some of which are briefly mentioned below), only since the availability of the modern high-speed digital computer and numerical algorithms has it become possible to furnish solutions easily and economically to a wide class of problems. With such solutions available, it then becomes possible to do numerical design parameter studies before equipment is built.

Interest in the dynamics of charged particles in electric and magnetic fields is not limited to particle accelerators; other applications include cosmic rays, electron microscopes, field spectrometers, and the common television cathode-ray tube. Nor is interest in magnetic and electric field calculations of a limited nature restricted to only those in the accelerator field even though these programs have been developed principally by people associated with particle accelerators. While these programs may be considered simply as numerical algorithms for obtaining solutions to Maxwell's equations, they have inherent in them certain peculiarities and limitations.

In the sections that follow, we give a brief review of typical problems solved and the methods of solution. Following this, we describe some of the programs themselves. No attempt is made to be complete or exhaustive, our goal being to furnish a reasonable background for the programs which will be introduced to the reader. It is only by actually using such programs that one can begin to understand and master them. It is hoped, however, that the material presented will provide the reader with a sufficient view of what the programs do and how they are similar or different.

a. Statement of the Problem to Be Solved

We assume that there is a region in which the source of the electromagnetic field is a distribution of electric charge and current, and we further assume that the fields are static. We then wish to find solutions to Maxwell's equations, which can be written as

$$\nabla \times \mathbf{E} = 0, \qquad \nabla \times \mathbf{H} = \mathbf{J}, \tag{1.1}$$

where **E**, **H**, and **J** are, respectively, the electric field intensity, magnetic field intensity, and current density. Our region, or universe, can be all space; or in the cases with boundary conditions, part of the total space; or in the cases with symmetry, part of the total region of interest. There may be different materials within the universe.

Associated with the intensities, **E** and **H**, are the electric displacement **D** and magnetic induction **B**. These quantities are related in that $\mathbf{D} = \mathbf{D}(\mathbf{E})$ and $\mathbf{B} = \mathbf{B}(\mathbf{H})$ are functions of the intensities. We also know that $\mathbf{J} = \mathbf{J}(\mathbf{E})$ for the current density. We shall restrict ourselves to the simple functional relations

$$\mathbf{D} = \varepsilon\mathbf{E}, \; \mathbf{B} = \mu\mathbf{H}, \; \mathbf{J} = \sigma\mathbf{E}, \tag{1.2}$$

where ε and μ are the inductive capacities of the material present and σ is the conductivity of the material. Equations (1.1) and (1.2) then furnish five relations between the quantities **E**, **D**, **H**, **B**, and **J**.

Although ε and μ may be tensors and **E** and **D** may have different directions, in practice this occurs so rarely that only one of the programs, JASON, allows such to be the case. In the other programs ε and μ are assumed to be scalar