DOE/ER/10666--9

Report DOE/ER/10666-9

DE91 005718

Annual Report to the United States Department of Energy on Research Supported in Part Under Contract DE-AS05-80ER-10666

ADVANCED METHODS FOR THE COMPUTATION OF PARTICLE BEAM TRANSPORT AND THE COMPUTATION OF ELECTROMAGNETIC FIELDS AND BEAM-CAVITY INTERACTIONS

Alex J. Dragt Robert L. Gluckstern

Department of Physics and Astronomy University of Maryland College Park, Maryland 20742

November 1990

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ABSTRACT

The University of Maryland Dynamical Systems and Accelerator Theory Group carries out research in two broad areas: the computation of charged particle beam transport using Lie algebraic methods and advanced methods for the computation of electromagnetic fields and beam-cavity interactions. Important improvements in the state of the art are believed to be possible in both of these areas. In addition, applications of these methods are made to problems of current interest in accelerator physics including the theoretical performance of present and proposed high energy machines.

The Lie algebraic method of computing and analyzing beam transport handles both linear and nonlinear beam elements. Tests show this method to be superior to the earlier matrix or numerical integration methods. It has wide application to many areas including accelerator physics, intense particle beams, ion microprobes, high resolution electron microscopy, and light optics.

With regard to the area of electromagnetic fields and beam cavity interactions, work is carried out on the theory of beam breakup in single pulses. Work is also done on the analysis of the high frequency behavior of longitudinal and transverse coupling impedances, including the examination of methods which may be used to measure these impedances. Finally, work is performed on the electromagnetic analysis of coupled cavities and on the coupling of cavities to waveguides.

In addition to its research effort, the Dynamical Systems and Accelerator Theory Group is actively engaged in the education of students and post-doctoral research associates. To this end, it presents a regular graduate seminar course in accelerator physics, directs graduate students in M.S. and Ph.D. thesis research, and guides and fosters the research of post-doctoral research associates.

Substantial progress in research has been made during the past year. In addition, two students have received their Ph.D. degrees. A listing of students and post-doctoral research

associates trained by the Group over the past years and recent research accomplishments are summarized in the attached pages.

I. Educational Accomplishments

A. Students

One of the major goals of the Dynamical Systems and Accelerator Theory Group is the education of students. Listed below are past and present students associated with the program.

David Douglas, Ph.D. 1982.

Thesis: Lie Algebraic Methods for Particle Accelerator Theory.

Employment: Previously employed by the Lawrence Berkeley Laboratory.

Presently employed in Accelerator Theory at CEBAF.

Etienne Forest, Ph.D. 1984.

Thesis: Lie Algebraic Methods for Charged Particle Beams and Light Optics.

Employment: Accelerator Theory at Lawrence Berkeley Laboratory.

Janko Milutinovic, Ph.D. 1984.

Thesis work done in Elementary Particle Theory while simultaneously receiving training in Accelerator Theory.

Employment: Accelerator Theory at Brookhaven National Laboratory.

Liam Healy, Ph.D. 1986.

Thesis: Lie Algebraic Methods for Treating Lattice Parameter Errors in Particle Accelerators.

Employment: Previously at CERN. Presently employed at Naval Research Laboratory, and working in Celestial Mechanics.

Robert Ryne, Ph.D. 1987.

Thesis: Lie Algebraic Treatment of Space Charge.

Employment: Accelerator Theory at Lawrence Livermore National Laboratory.

Petra Schuett, Ph.D. 1989.

Worked one year (Fall 1987 through Spring 1988) at Maryland on Lie algebraic methods and Poisson solvers while simultaneously completing her Ph.D. thesis work done on Wake-Field Acceleration under Thomas Weiland at DESY.

Employment: Theoretische Elektrotechnik Group at the Darmstadt Technische Hochshule.

Govindan Rangarajan, Ph.D. 1990.

Thesis: Invariants for Symplectic Maps and Symplectic Completion of Symplectic Jets.

Employment: Accelerator Theory at Lawrence Berkeley Laboratory.

Rui Li, Ph.D. 1990.

Thesis: Analytic and Numerical Investigation of Longitudinal Coupling Impedances at High Frequency.

Employment: Accelerator Theory at CEBAF.

John Diamond, M.S. 1990.

Worked for two years (Fall 1988 through Spring 1990) as a pre-doctoral research assistant. He completed a calculation of the penetration of electric and magnetic fields through circular holes in a metallic wall of finite thickness. Received M.S. degree and now working with Adroit Systems.

Daniel Abell.

Performing pre-doctoral thesis research on the analytic properties of the transfer maps for the anharmonic oscillator and the pendulum.

William Detlefs.

Working on a Master's Thesis in Applied Mathematics. He is computing the frequency dependence of the longitudinal coupling impedance of a thin iris in a beam pipe.

Eric Salter.

First year graduate student. Presently working on an auxilliary program for MARYLIE that will produce floor coordinates for the elements of a beam line or accelerator. Also reviewing the analysis of longitudinal and transverse modes in wave guides and the effect of transitions in geometric parameters.

Velu Sinha.

Senior undergraduate student. Responsible for computer networking and general computational support.

Glen VanderWoude.

Second year undergraduate student and National Merit Scholar. Presently working on an auxilliary program for MARYLIE to compute various input particle distributions to be subsequently tracked by MARYLIE. Also responsible for production of MARYLIE manual and for general computational support.

B. Post-Doctoral Research Associates

Due to the shortage of personnel with doctoral training in accelerator physics, most post-doctoral research associates who join the Dynamical Systems and Accelerator Theory Group initially have little background in accelerator physics. Consequently, one of the major goals of the Group is also to provide training and research experience in accelerator physics at the post-doctoral level. Listed below are past and present post-doctoral research associates associated with the program.

Filippo Neri, Fall 1983 through Spring 1990.

Presently employed by Los Alamos National Laboratory.

Johannes van Zeijts, Fall 1987 to present.

Ivan Gjaja, Fall 1990 to present.

II. Research Accomplishments

Task A: Charged Particle Beam Transport

- 1. Brief summary of work accomplished
- a. Lie algebraic methods have been developed for the computation of moment transport directly from the transfer map without the need for ray tracing. Using these methods it has been shown there are generalized emittance invariants. In particular, there are three quantities that can be made out of quadratic moments that remain invariant even in the presence of (linear) horizontal, vertical, and synchrotron coupling. These quantities generalize the familiar mean-square emittance associated with linear one-dimensional motion to the fully coupled three-dimensional case. It has also been shown that one can construct an infinite number of invariants using third and higher-order moments. The quadratic moment invariants, and perhaps the higher-order moment invariants, should be useful in analyzing nonlinear aberration effects and nonlinear emittance growth. This work is described in a Physical Review Letter and two papers.
- b. Combined function quadrupoles (quadrupoles with normal and skew sextupole components and normal and skew octupole components) have been included in MARYLIE 3.0 as a standard library element. The production of this library element required extensive symbolic manipulation resulting in about 30 pages of FORTRAN code. This work has been written up, and is in routine use at Los Alamos and Argonne National Laboratories in connection with their neutral particle beam program.
- c. Combined function dipoles (dipoles with normal and skew quadrupole, normal and skew sextupole, and normal and skew octupole components) have been included in MARYLIE 3.0 as numerical GENMAP elements. This work has been written up, and is used extensively at Brookhaven National Laboratories and Grumman Aircraft in connection with the design of a compact light source.
- d. Solenoids, including fringe-field effects, have been included in MARYLIE 3.0 through third order as numerical GENMAP elements. This work has been written up.
- e. A special purpose symbol manipulation program for the analytic computation of Lie algebraic quantities and maps has been developed. This program, called SymboLie, is several orders of magnitude faster than general purpose symbolic manipulation programs. It will be used to attempt the analytic calculation of the third-order transfer map for the combined function dipole. It can also be used to compute analytically transfer maps to higher order.
- f. The transfer map associated with a reference plane rotation (Prot) has been computed to arbitrary order. This map is required to treat non-normal entry or exit dipoles to higher order.
- g. A special program, called TLie, has been developed for computing, concatenating and otherwise manipulating Lie algebraic transfer maps to arbitrary order. This program can be used for the numerical calculation of transfer maps, including all error and fringe-field effects, through arbitrary order. This program can also compute normal forms for transfer maps to arbitrary order.
- h. A group theoretic procedure has been discovered for characterizing in an invariant way the nonlinearities associated with a transfer map. This procedure makes it possible to

introduce an invariant scalar product and an associated norm in the vector space of Lie polynomials. This scalar product facilitates computation, and may also lead to a convient characterization of the nonlinearities of any given storage ring or beam transport line.

- i. A procedure has been obtained for factorizing any given transfer map (represented either as a Taylor series or in Lie-algebraic form) into a product of kick maps. The number of such kick maps required in any particular case has been found to be remarkably small. For example, the most general map in 6 variables through 11th order can be written as a product of 68 kicks. This procedure, and its implementation to high order, make extensive use of group theory and items g and h above. Transfer maps expressed in kick factorized form are ideal for long-term tracking studies. Preliminary studies have been made of the use of such methods for long-term tracking of the SSC. It appears that it will be possible both to speed up tracking calculations by two orders of magnitude compared to conventional tracking methods, and to treat far more realistic lattices.
- j. Analytic calculations have been made through third order for the transfer maps for steering magnets and mispowered dipoles. These analytic results have been compared numerically with the numerical results provided by TLIE. Perfect agreement has been found. Since the analytic calculations and the methods of TLIE are completely independent, this agreement checks the correctness of both procedures. It is expected that the analytically calculated maps will be incorporated into MARYLIE 3.1.
- k. An investigation has begun of the analytic properties of the transfer maps for the anharmonic oscillator and the pendulum. Since these maps can be obtained in terms of elliptic functions, it is expected that the complete singularity structure of both these maps and the associated normal form and normalizing maps can be found as a function of the two complex variables p and q. When this is accomplished, the theory of functions of several complex variables can in turn be used to determine the domain of convergence of the Taylor series expansions for all these maps.

2. Publications and Reports

- 1. L. Healy and A. Dragt, Concatenation of Lie Algebraic Maps, Springer-Verlag Lecture Notes in Physics, 352 (1989).
- 2. A. Dragt et al., Theory of Emittance Invariants, Springer-Verlag Lecture Notes in Physics, 343 (1989).
- 3. G. Rangarajan et al., Generalized Emittance Invariants, Proceedings of the 1989 IEEE Particle Accelerator Conference (1989).
- 4. A. Dragt and C. Mottershead, Optimization of Multipole Octupole Strengths for Correction of Telescope Aberrations, University of Maryland and Los Alamos National Laboratory Technical Report (1989).
- 5. G. Rangarajan et al., Solvable Map Representation of a Nonlinear Symplectic Map, to appear in Particle Accelerators (1990).
- 6. A. Dragt et al., Numerical Third-Order Transfer Map for Combined-Function Diple, to be submitted to Nuclear Instruments and Methods (1990).
- 7. J. van Zeijts et al., Analytic Third-Order Transfer Map for Combined-Function Quadrupole, to be submitted to Nuclear Instruments and Methods (1990).
- 8. A. Dragt, Numerical Third-Order Transfer Map for Solenoid, to appear in Nuclear Instruments and Methods (1990).
- 9. F. Neri and G. Rangarajan, Kinematic Moment Invariants for Linear Hamiltonian Systems, Phys. Rev. Let. 10 (1990).
- 10. J. van Zeijts and F. Neri, Concatenating Lie Algebraic Exponentials, University of Maryland Technical Report (1990).
- 11. A. Dragt et al., Lie Algebraic Treatment of Moments and Moment Invariants, University of Maryland Technical Report (1990).
- 12. J. van Zeijts and F. Neri, Prot to High Order, University of Maryland Technical Report (1989).
- 13. G. Rangarajan and K.C.D. Chan, Transverse Resistive Wall Effects on the Dynamics of a Bunched Electron Beam, Phys. Rev. A. <u>39</u> (1989).
- 14. G. Rangarajan and K.C.D. Chan, Transient State of a Bunched Electron Beam Subject to Resistive-Wall Instability, Phys. Rev. A. 41 (1990).
- 15. G. Rangarajan and K.C.D. Chan, Transient Resistive-Wall Effects of a Bunched Electron Beam in a Wiggler, to appear in Particle Accelerators (1990).
- 16. R. Ryne and A. Dragt, Magnetic Optics Calculations for Cylindrically Symmetric Beams with Space Charge, to appear in Particle Accelerators (1990).
- 17. A. Dragt et al., Comment on Round-Off Errors and on One-Turn Taylor Maps, to appear in Proceedings of the Capri Conference on Nonlinear Problems in Accelerator Design, World Scientific (1990).

18. L. Healy, A. Dragt, and I. Gjaja, Computation of Error Effects in Hamiltonian Systems Using Lie Algebraic Methods, preprint in preparation (1990).

Task B: Computation of Electromagnetic Fields and Beam-Cavity Interactions

- 1. Brief summary of work accomplished
- a. Work has continued on beam breakup, in collaboration with Filippo Neri and, more recently, Johannes van Zeijts. The analysis of beam breakup with coupling between cavities has been completed. In it universal curves have been obtained for all values of the coupling constant ranging from those corresponding to the cumulative beam breakup limit at one extreme (dispersion band width less than Q-1 for each mode) to the other extreme of regenerative beam breakup where only one mode in the dispersion band is excited at a time (Q-1 for each mode is less than the spacing between modes). The new results are for the case where Q-1 is intermediate between the mode spacing and the band width.

Recent attention has been focussed on single bunch beam breakup² where the tail of a single bunch is deflected by the wakefield from the head of the bunch as the beam traverses a set of identical cavities. This phenomenon can be suppressed by BNS damping where the tail of the bunch has its energy artifically reduced compared to the head while it traverses the cavities. We have developed a universal formulation of the effect of BNS damping on single bunch beam breakup³ and are currently comparing this formulation with numerical simulations. In addition we have been investigating the phenomenon of "autophasing", a suggestion of Balakin to suppress single bunch beam breakup completely by correctly shaping the dependence of energy on longitudinal position within the bunch.

b. The work on the calculation of longitudinal coupling impedance is continuing in collaboration with Rui Li. We recently obtained a general result for the high frequency (ω) behavior of the impedance for a large number (N) of pill boxes⁴. This analysis yields the correct result for a periodic structure if N $\rightarrow \infty$ for large but finite ω , and the $\omega^{1/2}$ result if $\omega \rightarrow \infty$ for large but finite N. A new result is the N^{1/2} $\omega^{-1/2}$ dependence for large ω rather than the N $\omega^{-1/2}$ result obtained if impedances are added. Numerical simulations are now being performed which corroborate this important reduction. In addition, progress has been made in understanding the oscillations of the impedance with frequency at high frequency.

Another aspect of this work is the analysis of the transmission coefficient for a pulse on a wire passing through a cavity and beam pipe⁵. This technique, which is the basis for measurement of coupling impedance, is shown to produce results which are extremely close to those corresponding to the coupling impedance of the cavity.

- c. Work has also been recently completed on the computation of the penetration of electric and magnetic fields through circular holes in a wall of finite thickness. A variational formulation is used for both the interior (detuning) and exterior (external radiation) polarizability and susceptibility. A carefully chosen trial function with many adjustable parameters allows one to obtain numerical values for these parameters for arbitrary thickness/radius ratio accurate to about 10 p.p.m.
- d. Work has recently started on the calculation of the coupling impedance of an iris in a beam pipe. Numerical work is almost complete on the behavior of the longitudinal coupling impedance for a thin iris as a function of frequency. The work is of interest because of the need for collimators in future linear colliders to obtain small beams and high luminosities.

e. Work is also being carried on in collaboration with S. Krinsky and L.H. Yu of BNL on the effect of wiggler errors on FEL gain.

2. Publications and Reports

- 1. Beam Breakup with Coupling Between Cavities, with F. Neri, Particle Accelerator <u>25</u>, 11 (1989).
- 2. Single Bunch Beam Breakup, with F. Neri, Proceedings of the Particle Accelerator Conference, Chicago, IL, March 1989, p. 812.
- 3. Suppression of Single Bunch Beam Breakup by BNS Damping, with F. Neri and J. van Zeiits, presented at the Linac Conference, Albuquerque, NM, September 1990.
- 4. High Frequency Dependence of the Coupling Impedance for a Large Number of Obstacles, Proceedings of the Particle Accelerator Conference, Chicago, IL, March 1989, p. 1157.
- 5. Analysis of Coaxial Wire Measurement of Longitudinal Coupling Impedance, with R. Li, Proceedings of the 14th International Conference on High Energy Accelerators, KEK, Japan, August 1989, p. 861; Particle Accelerators 29, 159 (1990).
- 6. Penetration of Fields Through a Circular Hole in a Wall of Finite Thickness, with J.A. Diamond, accepted for publication in IEEE Transactions on Microwave Theory and Techniques.
- 7. High Frequency Behavior of the Longitudinal Impedance for a Cavity of General Shape, Phys. Rev. D, 39, 2773 (1989).
- 8. Longitudinal Impedance of a Periodic Structure at High Frequency, Phys. Rev. D, <u>39</u>, 2780 (1989).
- 9. Electric Polarizability and Magnetic Susceptibility of Small Holes in a Thin Screen, with R. Li and R.K. Cooper, IEEE Transactions in Microwave Theory and Techniques, Vol. 38, No. 2, 186 (1990); see also Vol. 38, No. 10, 1529 (1990).
- 10. Calculation of Universal Scaling Function for Free Electron Laser Gain, with L.H. Yu and S. Krinsky, Phys. Rev. Letters 64, 3011 (1990).
- 11. Wakefields in a Dielectric Waveguide, LANL Report AT-6:ATN-90-1 (1990).
- 12. Analysis of Slotted Cylindrical Shell for Use as a Compact Wiggler, LANL Report AT-6:ATN-90-2 (1990).
- 13. Wiggler Fields and Orbital Motion for a Slotted Cylindrical Shell, LANL Report AT-6:ATN-90-6 (1990).
- 14. Completness of the Cavity Kernel Used in Calculating Longitudinal Coupling Impedance, CERN Report SL/90-99 (AP), August 1990.
- 15. Compensation of Single Bunch Beam Breakup in a Chain of Long Periodic Linac Cavities, CERN Report, to be published (1990).
- 16. Longitudinal Coupling Impedance of an Iris in a Beam Pipe, CERN Report, to be published (1990).

17. Analysis of a Possible Beam Position Monitor for the Next Linear Collider, LANL Report, AT-6:ATN-90-13 (1990).

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