GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 2/4/81

Project Title: Numerical Studies of Arnol'd Diffusion in the Beam - Beam Interaction of Intersecting Storage Rings

Project No: G-41-619

Project Director: Dr. Joseph Ford

Sponsor: U.S. Department of Energy

Agreement Period: From 11/1/80 Until 10/31/81 (Perf. & Rpts.)

Type Agreement: Contract No. DE-AS05-81ER40003

Amount: $52,000

Reports Required: Progress, Final

Sponsor Contact Person (s):

Technical Matters

Melvin Month
Office of Energy Research
Division of High Energy Nuclear Physics
Germantown, Maryland 20545

Contractual Matters
(thru OCA)

W.A. Mynatt
Chief
Contract Management Branch
Procurement & Contracts Branch
Department of Energy
Oak Ridge Operations
P.O. Box E
Oak Ridge, TN 37830

Defense Priority Rating: None

Assigned to: Physics (School/[illegible])

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 10/24/83

Project No. G-41-619 School/~~Lab~~ Physics

Includes Subproject No.(s) N/A

Project Director(s) Dr. J. Ford GTRI/~~GIT~~

Sponsor DOE, Oak Ridge, TN

Title: Numerical Studies of Arnol'd Diffusion in the Beam - Beam Interaction of Intersecting Storage Rings

Effective Completion Date: 10/31/81 (Performance) 10/31/81 (Reports)

Grant/Contract Closeout Actions Remaining:

- [x] None
- [ ] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other _____

Continues Project No. _____

Continued by Project No. G-41-621

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DOE Form IR-427
(1/79)

U.S. DEPARTMENT OF ENERGY

UNIVERSITY-TYPE CONTRACTOR AND GRANTEE RECOMMENDATIONS FOR DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

See Instructions on Reverse Side

1. DOE Report No. DOE/ER/40003-2

2. Contract No. DE-AS05-81ER40003

3. Title Numerical Studies of Arnol'd Diffusion in the Beam-Beam Interaction of Intersecting Storage Rings

4. Type of Document ("X" one)

- [X] a. Scientific and technical report
- [ ] b. Conference paper:
  - Title of conference _____
  - Date of conference _____
  - Exact location of conference _____
  - Sponsoring organization _____
- [ ] c. Other (Specify Thesis, Translations, etc.)

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Does this information product disclose any new equipment, process or material? [ ] Yes [X] No

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Are there any patent related objections to the release of this information product? If so, state these objections.

8. Submitted by — Name and Position (Please print or type)

Dr. Joseph Ford, Regents' Professor

Organization

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332

Signature

Date 10 August 1981

FOR DOE USE ONLY

9. Patent Clearance ("x" one)

- [ ] a. DOE patent clearance has been granted by responsible DOE patent group.
- [ ] b. Report has been sent to responsible DOE patent group for clearance.
- [ ] c. Patent clearance not required.

INSTRUCTIONS

Who uses this form: DOE contract administrators will designate the DOE contractors and grantees who are to use this form. Generally speaking, it will be used by educational institutions and other "not for profit" institutions. DOE national laboratories and other major contractors will generally use the longer Form DOE-426.

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Where to send: Send the document and the attached Form DOE-427 to the DOE contract administrator for transmittal to TIC unless the DOE contract administrator specifies otherwise.

Item instructions:

Item 1. The DOE report number will be constructed as follows and will consist of a prefix and a suffix. The prefix will consist of code DOE and seven characters for the applicable contract number (two alphabetic and five numeric). The suffix is a sequential number assigned by the contractor generating the report. Slashes and hyphens will be used as shown in the examples in the next column.

Reports issued in more than one binding or reissued as revisions or later editions will be identified by adding the additional suffixes to the basic number: e.g., Rev., Revision; Vol., Volume; Pt., Part; Add., Addendum; Ed., Edition.

Examples

If the contract number is DE-AC01-78ET01834.M002, the reports generated will be numbered:

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Item 2. Self-explanatory.

Item 3. Give title exactly as on the document itself.

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U.S. DEPARTMENT OF ENERGY

NOTICE OF ENERGY RD&D PROJECT

FORM DOE 538
(1/78)

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OMB NO. 38 R-0190

1. DESCRIPTIVE TITLE OF WORK

Numerical Studies of Arnol'd Diffusion in the Beam-Beam Interaction

2. PERFORMING ORGANIZATION CONTROL NUMBER

3. CONTRACT, GRANT OR PURCHASE ORDER NUMBER

DE-AS05-81ER10003

4. CONTRACTOR'S PRINCIPAL INVESTIGATOR/PROJECT MANAGER AND ADDRESS WHERE WORK IS PERFORMED

a. NAME *(Last, First, MI)* FORD, Joseph PHONE (404) 894-5255

b. BUSINESS ADDRESS: STREET School of Physics, Georgia Institute of Technology

CITY Atlanta STATE Georgia ZIP 30332

5. a. NAME OF PERFORMING ORGANIZATION

Georgia Institute of Technology *(Organization)* School of Physics (Department)

b. MAILING ADDRESS *(If Different From 4B)*

c. TYPE OF ORGANIZATION PERFORMING THE WORK (Enter applicable code from instructions). C U

6. SUPPORTING ORGANIZATION

a. DOE PROGRAM DIVISION OR OFFICE *(Full Name)* Division of High Energy Physics

b. TECHNICAL MONITOR *(Last, First, MI)* Month, Melvin

c. ADDRESS *(If Different from DOE Hqs)*

d. ADMINISTRATIVE MONITOR *(Last, First, MI)*

7. PROJECT SCHEDULE (a) START DATE Nov. *(Month)* 1980 *(Year)* (b) EXPECTED COMPLETION DATE Nov. *(Month)* 1981 *(Year)*

8. a. FUNDING OPERATING AND CAPITAL EQUIPMENT OBLIGATION *(In Thousands of Dollars)*

FUNDING ORGANIZATION(S)		APPROXIMATE CUMULATIVE PRIOR FISCAL YEARS	CURRENT FY		
1. DOE		-0-	52,000		
2.					
3.					

b. DOE BUDGETING AND REPORTING CLASSIFICATION CODE

9. DIRECT SCIENTIFIC AND TECHNICAL MANPOWER

	PROFESSIONAL	GRAD. STUDENTS	OTHER	TOTAL
NUMBER	2			2
EQUIVALENT PERSONYEARS	1 1/3			1 1/3

DETACH HERE BEFORE SUBMITTING

10. SUMMARY OF WORK *(Limit to 200 words or less — include a description, objective, approach and a final product expected.)*

This research investigates Arnol'd diffusion as it occurs in high energy, intersecting storage rings due to the beam-beam interaction. Although Arnol'd diffusion is anticipated to be the ultimate limiting factor on beam stability and luminosity in heavy particle storage rings now under design or construction, almost nothing is known regarding the rate of Arnol'd diffusion as a function of beam parameters. The work underway seeks to extend earlier computations of Arnol'd diffusion to cover more realistic models of the beam-beam interaction in existing or proposed machines. The object of this research is to interpret and predict the associated beam-beam limit in storage ring machines.

11. PROGRESS SINCE LAST REPORT *(Limit to 100 words.)*

See accompanying pages

12. List publications in the last year that are available to the public which have resulted from the product. *(Please give a complete bibliographic citation. Use additional sheets if necessary.)*

See accompanying pages

13. GENERAL TECHNOLOGY CATEGORIES *(Enter applicable code or codes from instructions.)*

B1

14. PHASE OF RD&D *(Enter Project Percentages in Applicable Boxes)*

a. 100 Basic Research
b. Applied Research
c. Technology Development
d. Engineering Development
e. Demonstration

15. KEYWORDS: (Minimum of 5)

16. A. RESPONDENT'S NAME & ADDRESS

Professor Joseph Ford, School of Physics
Georgia Tech, Atlanta, Ga. 30332

B. PHONE NO. (404) 894-5255

C. DATE 10 August 1981

PROGRESS REPORT

DEPARTMENT OF ENERGY CONTRACT DE-AS05-81ER40003

FOR THE PERIOD NOVEMBER 1, 1980 - July 31, 1981

I. PERSONNEL

In addition to the Principal Investigator, Professor Joseph Ford, this research involved the Research Associate, Dr. Franco Vivaldi. Also involved were the informal consultants and collaborators, Professor B. V. Chirikov and colleagues (Novosibirsk, USSR) and Dr. J. L. Tennyson and colleagues (Berkeley, USA).

II. ACTIVITIES AND PAPERS

Dr. Franco Vivaldi attended DOE organized meetings at SLAC and Fermilab. He will spend the period August-October collaborating with Professor B. V. Chirikov and his colleagues at the Institute of Nuclear Physics in Novosibirsk, USSR. Professor Joseph Ford was an invited speaker at the "Workshop on Long-Time Predictions in Nonlinear Conservative Dynamical Systems," University of Texas, March 16-19, 1981, and at the "International Symposium on Synergetics," Schloss Elmau, Bavaria, April 27 - May 2, 1981. While in Europe, he also presented invited lectures at the Universities in Utrecht and Zurich (ETH).

The following papers have appeared or will appear:

1. J. Ford, "Ergodicity for Economists," in New Quantitative Techniques for Economic Analysis, Edited by G. P. Szego (Academic Press, Inc., New York, 1981).
2. J. M. Greene, R. S. MacKay, F. Vivaldi, and M. J. Feigenbaum, "Universal Behavior in Families of Area-Preserving Maps," accepted for publication in Physica D.
3. F. Vivaldi and J. Ford, "Symmetries in 1.5 Degree of Freedom Hamiltonian Systems," J. Math. Phys. (to be submitted).
4. B. V. Chirikov, J. Ford, F. M. Izrailev, and D. L. Shepelyansky, "Modulational Diffusion in Nonlinear Oscillator Systems," to appear in Proc. IX Intl. Conf. on Nonlinear Oscillations, Kiev, 1981.

III. BRIEF DESCRIPTION OF THE RESEARCH

In high energy particle accelerators, a weak instability--Arnol'd or modulational diffusion-- arises in the colliding particle beams whenever the stochastic particle motion orthogonal to a stochastic layer is transformed into motion (diffusion) along it. The original orthogonal motion, whose detailed features ultimately determine the diffusion rate, can be locally modelled by relatively simple two degree of freedom systems that can be studied in detail. Our initial efforts have been focused on such two degree of freedom systems with

the aim of developing techniques for determining the stochastic threshold and the location and shape of stochastic components through the analysis of periodic orbits and their bifurcations. In collaboration with Greene, MacKay, and Feigenbaum, we have obtained results regarding stochastic components which have a universal character and which are, therefore, applicable to any beam-beam model. Some of these techniques have been further developed and applied by us to a class of systems driven by a periodic force yielding results of particular interest for modulational diffusion in beam-beam interactions. Specifically, in the case of a modulated system, we have derived a general analytical estimate for the layer width. As our first effort to observe modulational diffusion, we followed the earlier work of Chirikov and Izrailev which studied a monodimensional, modulated system coupled to one additional dynamical variable. We thereby not only observed modulational diffusion we also improved the previously given semi-analytical estimates and we obtained a set of critical values for one system parameter (detune) at which the diffusion rate dramatically increases.

In our most recent research, we have turned to multi-dimensional models. Specifically, we have considered coupled, nonlinear oscillator systems similar to those studied earlier by Chirikov. For these systems, the diffusion arising from the modulation of the driving frequency and of the coupling coefficient has been separately investigated. Semi-analytical expressions for the diffusion rate have been obtained for each type of modulation.

Annual Progress Rpt. for G-41-619/Final
Last data item for this project - no Final Rpt
continued by G-41-609

system parameters broadens the already existing stochastic layers due to "self-modulation". Modulational diffusion is therefore, in general, much more rapid than Arnol'd diffusion. As a consequence, modulational diffusion is potentially the most dangerous weak instability in the beam-beam interaction as has been recently recognized.[14] In the next section, we discuss our recent studies of modulational diffusion.

II. PROGRESS REPORT ON PREVIOUS AWARD: DE-AS05-81ER40003

A weak instability— Arnol'd or modulational— arises whenever the stochastic motion orthogonal to a stochastic layer is transformed into motion (diffusion) along it. The original orthogonal motion, whose detailed features ultimately determine the diffusion rate, can be locally modelled by relatively simple two degree of freedom systems that can be studied in detail. Our initial efforts have been focused on such two degree of freedom systems with the aim of developing techniques for determining the stochastic threshold and the location and shape of stochastic components through the analysis of periodic orbits and their bifurcations. In collaboration with Greene, MacKay, and Feigenbaum[15], we have obtained results regarding stochastic components which have a universal[15] character and which are, therefore, applicable to any beam-beam model. Some of these techniques have been further developed and applied (by us) to a class of systems driven by a periodic force yielding[16] results of particular interest for modulational diffusion in beam-beam interactions. Specifically, in the case of a modulated system, we have

derived a general analytical estimate for the layer width. As our first effort to observe modulational diffusion, we followed Chirikov and Izrailev[13] in studying a monodimensional, modulated system coupled to one additional dynamical variable. We thereby not only observed modulational diffusion we also improved the previously given semi-analytical estimates and we obtained a set of critical values for one system parameter (detune) at which the diffusion rate dramatically increases.

In our most recent research, we have turned to multi-dimensional models. Specifically, we have considered coupled, nonlinear oscillator systems similar to those described in Ref. 3 and 4. For these systems, the diffusion arising from the modulation of the driving frequency and of the coupling coefficient has been separately investigated. Semi-analytical expressions for the diffusion rate have been obtained[17] for each type of modulation.

Publications completed during the present Contract period are listed as Ref. 15, 16, and 17.

III. PROPOSED RESEARCH

The principal direction of our future research lies with continuing our systematic numerical and analytical investigations of the effects of weak instabilities— Arnol'd and modulational diffusion-- arising in the beam-beam interaction. Specifically, we intend to develop analytical and