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Final Report of SBIR Phase II Project, DOE Grant DE-FG03-94ER81900: "A Multimedia Tutorial for Charged-Particle Beam Dynamics"

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Introduction

In September 1995 WhistleSoft, Inc., began developing a computer-based multimedia tutorial for charged-particle beam dynamics under Phase II of a Small Business Innovative Research grant from the U.S. Department of Energy. In Phase I of this project (see its Final Report) we had developed several prototype multimedia modules using an authoring system on NeXTStep computers. Such a platform was never our intended target, and when we began Phase II we decided to make the change immediately to develop our tutorial modules for the Windows and Macintosh microcomputer market.

We also decided, very early in Phase II, that it would be better to develop a series of tutorials for the project, now called *Accelerators and Beams*, and get them into the marketplace as they became individually available. (Our original proposal envisioned one grand tutorial on the whole subject.) This would provide some additional cash flow and would have the advantage of learning what the problems are in completing a project for the commercial market.

We originally designed the *Accelerators and Beams* tutorials for the academic market, and that is presently where most of our sales are. However, we have always had the idea in mind that we could later customize its separate modules for laboratory and/or industrial usage. This would extend the use of these modules to a non-traditional student audience, such as the technicians and operators employed at large accelerator facilities. We have therefore targeted a broad audience–from lower undergraduates and technicians up to graduate students and professionals in science and engineering. Much of our work so far, however, has been at an elementary level, i.e., accessible to end-users that have taken an algebra-based introductory physics course.

The tutorial modules comprising *Accelerators and Beams* integrate interactive On-Screen Laboratories™ with hypertext, line drawings, photographs, two- and three-dimensional animations, progressive disclosure on the screen (at the student's choice of pace), and video and sound. These multimedia techniques enhance the student's rate of learning and length of retention of the material. The modules run essentially equivalently on both Macintosh and Windows platforms.

This Report details our progress and accomplishments. It also gives a flavor of the look and feel of the presently available and upcoming modules.

Funding and Organizational Details

It soon became clear that development of publishable software was a more painstaking task than we previously realized. We soon concluded it was better to maintain a relatively small crew of programmers and authorers and stretch out the funding over four years (with two no-cost extensions) rather than to try to rush the process. This decision, we feel, has resulted in much better, more interactive software than we originally envisioned.

We did not come to this decision easily. The original principal investigator for this project, Richard K. Cooper, resigned from WhistleSoft in May 1996. One of the reasons for this was the rather unequal difference between roughing out content and actual creation of operative code and the frictions that that caused. Richard R. Silbar, president of WhistleSoft, took over as principal investigator and project manager at that time.

Personnel who have been most deeply concerned with the development of the *Accelerators and Beams* tutorials are, in addition to Cooper and Silbar, Drs. Andrew A. Browman (content expert), William C. Mead (content and authoring), and Robert A. Williams (programming). Others who have been involved in somewhat more peripheral roles include Charles Brownrigg, Kris Kern, Catherine Malloy, Patrick McGee and our student intern, Matthew Goldman.

We authored the tutorials discussed in this paper using Macromedia's Authorware software package. Graphical content was prepared using software such as Macromedia's Extreme 3D and FreeHand, Adobe's Photoshop and Premiere, and Hyperionics' HyperSnap.

One of the major operational steps in this project was the creation of a consistent *Style Guide* for our tutorials. This *Style Guide* defines the user interface, which we deliberately chose to resemble as much as possible a Web Browser, so as

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to minimize the learning curve for a typical end-user. The *Style Guide* also serves as a skeleton template for new (and future) technical tutorials that WhistleSoft may produce.

It is useful to indicate here how our work in developing multimedia computer-based training (CBT) compares with the industry as a whole. Conventional wisdom says that to create one hour of CBT requires 250 or more man-hours of effort. This is the "best case situation" for high-level skill-oriented interactive courseware (K. C. Golas, Training Systems and Education Conference, Orlando FL, 1993). This means that producing CBT is expensive (estimate the man-hour cost as $100/hour). If the subject matter is specialized, such as it is in our case of accelerator physics, one must expect that private companies will *not* produce such software unless somehow supported with outside funding. With regard to our cost of production, it took some time for us to learn how to make our tutorials efficiently. By the end of the project, however, we came to doing things fairly well. For example, last summer we produced a six-hour CBT tutorial on Legendre Polynomials (not part of the Accelerators and Beams project) for a little over 600 man-hours of effort. This is about 2 ½ times better than the above-cited industry "best case" average.

This project has had the benefit of many useful suggestions from a large number (over 100) of user testers and reviewers of our prototype modules. Those reviewers include the judges in the *Computers in Physics* educational software contest as well as those selected by Physics Academic Software. Also, Prof. John S. Risley, editor of Physics Academic Software, provided continuing advice and criticism of our software modules over most of the project's duration.

Tutorial Content

If a student completes all the modules in the *Accelerators and Beams* project, the combined content would be roughly equivalent to a one-semester upper-undergraduate course at a university. It is not necessary, however, to do the entire course. A student (or non-student, for that matter) can pick and choose among the separately available modules, as desired or necessary. An important feature of our tutorials is the ability of the student to choose to work at his or her comfort level with respect to the mathematical detail. We indicate these levels–"Introductory," "Intermediate," and "Advanced"–by a color-coded background. An alternative labeling could just as well be "Technician," "Junior Engineer," and "Physicist." The presentation therefore ranges accordingly from one that is mostly descriptive with graphics to one, which is mathematical and abstract. The difficulty of the material obviously increases as one gets into the later modules, but one of our goals is to always have something accessible at the introductory level.

Our publisher, Physics Academic Software (see http://pcep.physics.ncsu.edu/pas), released our first module, *Vectors,* late in 1997. The *Forces* module began shipping in August 1998. *Motion in Electromagnetic Fields* became available in summer 1999 for purchase. A fourth module, *Dipole Magnets*, has been accepted for publication and will be available later in 1999. These four published modules have all won awards in the 1996, 1997 and 1998 *Computers in Physics* annual educational software contests.

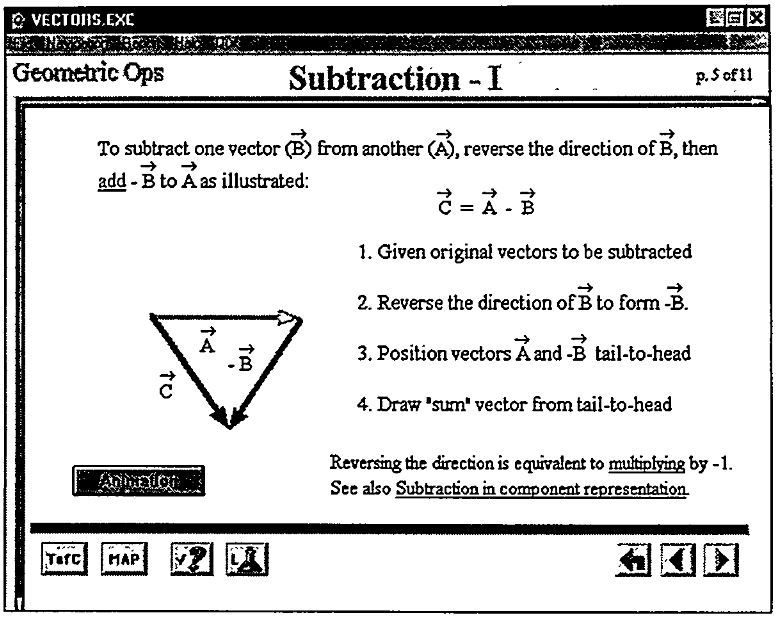
There are two other modules in preparation: *Quadrupole Magnets* and *Properties of Charged-Particle Beams.* We submitted the first of these to Physics Academic Software in June 1999, for peer-review prior to eventual acceptance by them for publication. The *Beams* tutorial is still in a rough, early state. It will be completed outside of SBIR funding.

Vectors

This module, which is roughly like a mathematical appendix to our more accelerator-oriented modules, was our "test vehicle" in which we worked out many of the user interface issues that constitute our *Style Guide*, which now serves as a template for creating a new module. The content of *Vectors* is divided into five sections:

1. Fundamentals and Definitions
2. Historical Vignettes
3. Examples of Vectors Use in Physics
4. Vector Operations in the Geometrical Representation
5. Vector Operations in the Component Representation

A representative page from Section 4 looks like this:



Note the Animation button, which goes through the steps of how the vector **C** = **B** - **A** is constructed. The buttons at the lower left take the student to a Table of Contents, a Concept Map (from which one can also navigate), a set of multiple-choice self-test Questions, and an On-Screen Laboratory.™ In this laboratory the student is presented two randomly chosen vectors, **A** and **B**. He or she must then, by dragging, stretching and rotating arrows on the screen representing them, form the difference, **C** = **B** - **A**. For the corresponding page on vector subtraction in Section 5 (Components), its Laboratory invokes an integrated built-in calculator for working out the components of **C** = **B** - **A** from the given **A** and **B** components.

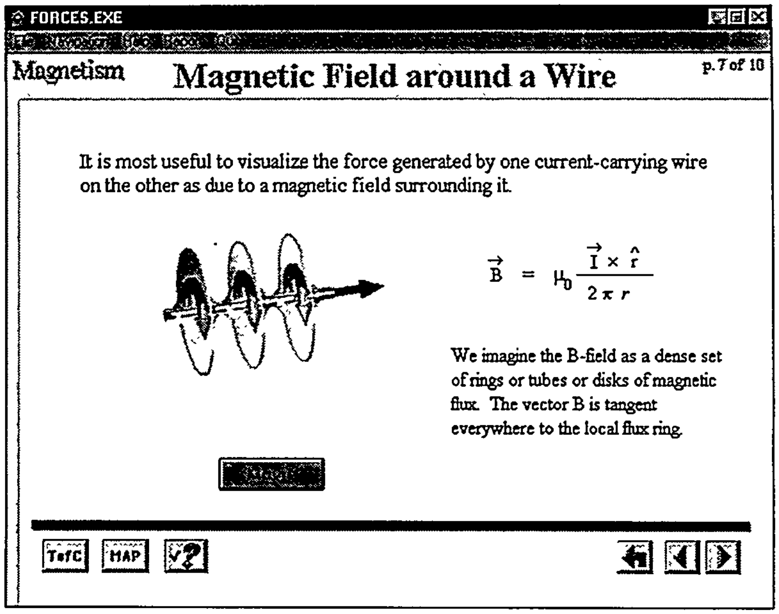
To summarize and to indicate the size of the *Vectors* module, it has 51 Content Pages, 20 self-test Question Pages, 57 Answer Pages, and 14 On-Screen Laboratories.™ This tutorial has ISBN numbers 1-56396-719-7 (Windows) and 1-56396-722-7 (Macintosh).

Forces

In this module we review the concepts of forces and motion, with special emphasis on electromagnetism. (This is the fundamental force of importance for accelerator physics.) The sub-topics covered in this module are:

1. Fundamental Quantities
2. History; and a Tour of the Four Fundamental Forces
3. Forces and Motion
4. Electrostatic Forces
5. Electromagnetic Forces

An important feature of this module is the use of three-dimensional animations, since electromagnetic forces are often hard to visualize in two dimensions. Our animations often involve "moving camera" points of view. Here is a page from Section 5 showing the movie of how the magnetic field builds up as electric charges start moving through the section of wire conductor.



In *Forces* we used sound, but only sparingly. Buttons click when pressed and there are short sound effects associated with actions on the screen, but there are no narrative sound files. This was partly inspired by a desire to keep this module small enough to be deliverable on floppy diskettes rather than CD-ROMS.

The *Forces* module is larger than *Vectors*, having 78 Content Pages, 39 Question Pages, 52 Answer Pages, and 3 On-Screen Laboratories.™ This tutorial has ISBN numbers 1-56396-797-9 (Windows) and 1-56396-798-7 (Macintosh).

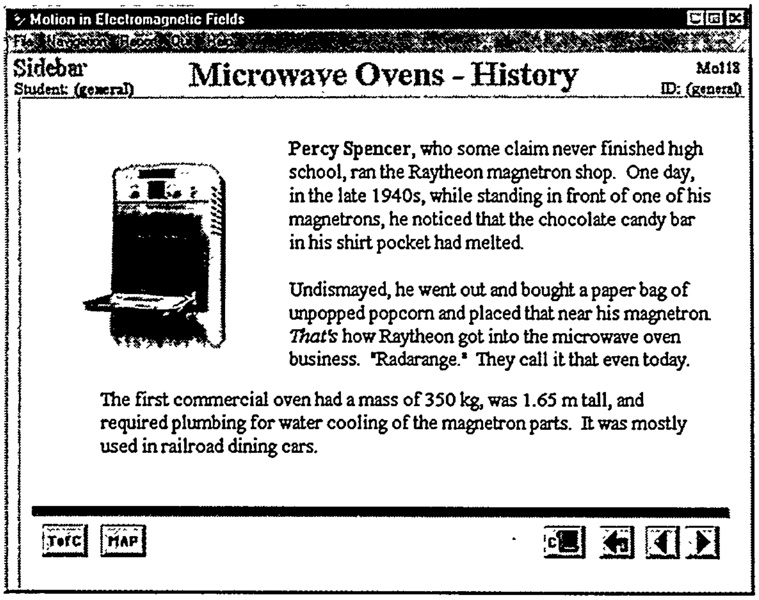
Motion In Electromagnetic Fields

The *Motion in Electromagnetic Fields* module also covers five subtopics:

1. Circular Motion in Uniform Magnetic Fields
2. Magnetic Rigidity; Spectrometers
3. Wien Filter
4. Cyclotron
5. Magnetron

Section 4 on cyclotrons uses three-dimensional "exploded" drawings, animations, and video clips of a modern medical cyclotron. There are also some intermediate level pages that go into the relativistic limitations on the classical cyclotron and ways physicists have learned to work around those limitations.

The magnetron, Section 5, is a complicated crossed-field device, but we were able to get the idea of its operation across in surprisingly elementary terms. Some of the simulations in this section integrate the differential equation of motion for the electrons in the crossed fields, drawing the complicated electron orbits "in real time." Intermediate-level pages cover the derivation of the equation of motion and its numerical solution. Here is a page giving an amusing historical sidelight on microwave ovens (which are powered, of course, by magnetrons).



We like including such historical vignettes in our tutorials, and feedback from our student testers indicates that they do also.

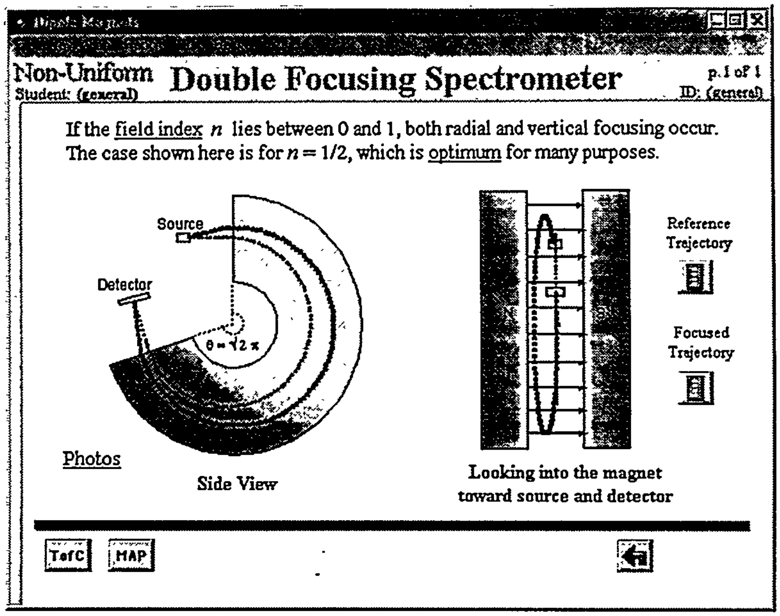
The *Motion* module has 63 Content Pages, 17 Question Pages, 23 Answer Pages, and 6 On-Screen Laboratories.™ Motion will be distributed on a hybrid CD-ROM.

Dipole Magnets

This module on bending magnets (which also have focusing properties) covers the following topics:

1. Uniform bending magnets
2. Non-uniform bends
3. Fringe fields
4. The Kerst-Serber equation.

The fourth section, unlike the first three, is at an intermediate level, requiring some calculus and knowledge of Maxwell's equations. By the time the student has finished this module, he or she will understand the operation of the double-focusing spectrometer, even the peculiar bend angle of $\pi\sqrt{2}$ radians. The page on the double-focusing spectrometer uses a 2D animation, with the motion of the charged particle moving through the spectrometer being shown simultaneously in side and head-on views:

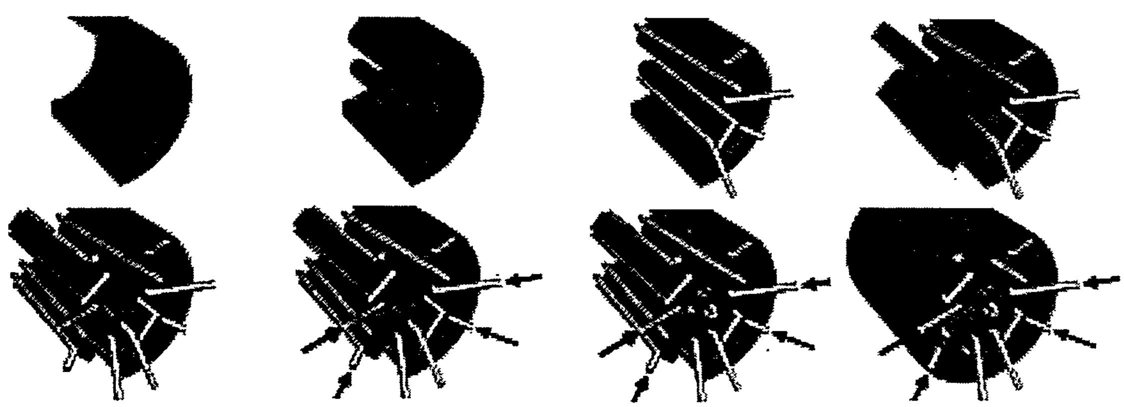


First, note that the color of the background bars has changed from blue to beige. This indicates a topic at an intermediate level. (Topics at an advanced level–of which we have very few (so far)–have rose-colored background bars.) The screen snap shown here is what the student sees after having first pressed the Reference Trajectory movie icon, then the Focused Trajectory icon. The particle paths are traced out from source to target in less than a second. This, like all of our animations, can be repeated as often as the student wishes.

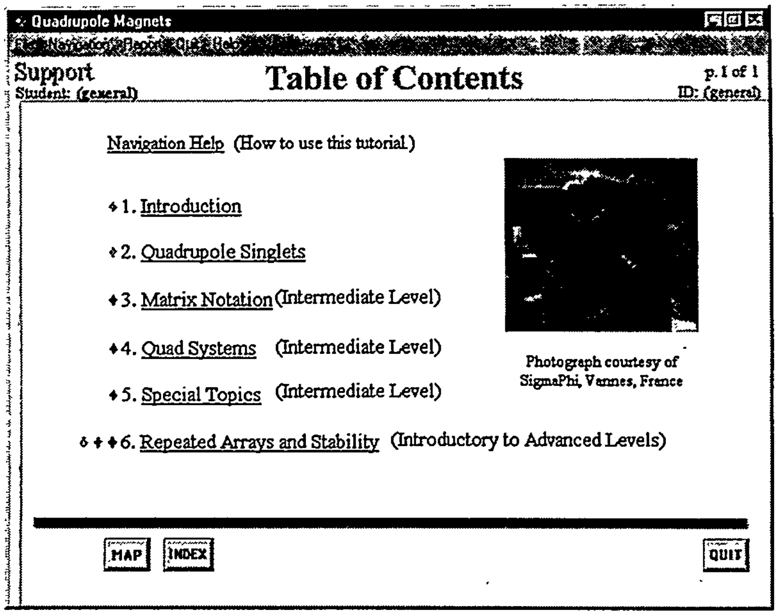
Dipole Magnets consists of 43 Content Pages, 20 Question Pages, 29 Answer Pages, and 3 Laboratory Pages.

Quadrupoles

The next module in the Accelerators and Beams series is entitled *Quadrupole Magnets*. These are the magnetic elements most used for focusing charged-particle beams. The following picture is a montage of 3D drawings showing how one builds up and activates a quadrupole magnet.



In the tutorial itself these 3D renderings form a series of eight pages, together with commentary about what the pieces are and how they operate. The *Quadrupoles* module also covers aspects of higher-multipole magnets. Its Table of Contents page looks like



Quadrupole Magnets consists, at this point, of 103 Content Pages, 41 Question Pages, 65 Answer Pages, and 12 Laboratory Pages. These numbers may change depending on the comments received from the Physics Academic Software reviewers.

Properties of Charged-Particle Beams

The final module in this series, *Properties of Particle Beams*, is work in progress. It goes into the definition of beam size, phase space, beam envelopes, and space charge effects. It has the most advanced materials of the modules that we have built so far. One feature about the *Beams* module is that here we have made extensive use of sound for narrations accompanying the content pages. We have also implemented it with jump-outs to (and returns from) a Glossary of beam dynamics terms.

The Table of Contents for *Beams* is, provisionally,

1. Overview
2. Definitions
3. Beam Size Variations
4. Lenses
5. Envelope Equations (Intermediate Level)
6. Space Charge Effects (Advanced Level)

Lessons Learned

We began this project as scientists knowing something about beam optics and accelerators but rather little about multimedia techniques. At first we felt somewhat cramped by the small amount of "real estate" on the screen. We were basically trying to write a textbook to be read on a screen, which we soon learned was not such a great idea. It took us some time to realize that the computer should be used for the things that the computer does better than other media. In the process, however, we were also pleasantly surprised to find that we could find ways of presenting in simple terms what we thought were complicated concepts.

In this regard, we feel that the two-and three-dimensional animations we have learned to make are especially useful for computer-based training in a technical subject like accelerator physics. That was not one of the things we anticipated when we began this project.

Publications and Talks

The major publications (and products) arising from this project are, of course, the software tutorials themselves. In addition to those, however, we have given a number of invited papers, contributed papers and posters at various conferences on our work. These include:

1. R. R. Silbar, "A Self-Paced Tutorial in Hypertext on Vectors," invited paper at the Winter Meeting of the Am. Assoc. of Physics Teachers, Phoenix AZ, Jan. 1997 (AAPT Announcer, **26**, 54, Dec. 1996).
2. R. R. Silbar, "A Multimedia Tutorial for Charged-Particle Dynamics," Particle Accelerator Conf. '97, Vancouver BC, May 1997.
3. R. R. Silbar, "A Multimedia Tutorial for Charged-Particle Dynamics," Summer Meeting of the Am. Assoc. of Physics Teachers, Denver CO, Aug. 1997 (AAPT Announcer, **27**, 83, July. 1997)
4. R. R. Silbar, "*Accelerators and Beams*: A Multimedia Tutorial," in *Appl. Of Accelerators in Research and Industry*, ed. by J. L. Duggan and I. L. Morgan, AIP Conf. Proc. **392**, 1231, 1997.
5. R. R. Silbar, W. C. Mead, and R. A. Williams, "*Forces*: A Self-Paced Multimedia Tutorial," invited paper at the Winter Meeting of the Am. Assoc. of Physics Teachers, New Orleans LA, Jan. 1998 (AAPT Announcer, **27**, 83, Dec. 1997).
6. R. R. Silbar, A. A. Browman, and W. C. Mead, "The Qualitative Magnetron," Winter Meeting of the Am. Assoc. of Physics Teachers, New Orleans LA, Jan. 1998 (AAPT Announcer, **27**, 93, Dec. 1997).
7. R. R. Silbar, A. A. Browman, W. C. Mead and R. A. Williams, "The Qualitative Magnetron: Self-Paced Computer-Based Training Accessible to Technicians," Workshop on Accelerator Operations '98, Vancouver BC, May 1998.
8. R. R. Silbar, A. A. Browman, W. C. Mead and R. A. Williams, "A Computer-Based Tutorial on Double-Focusing Spectrometers," Div. Of Nucl. Phys. Meeting, Santa Fe NM, Oct. 1998 (BAPS **43**, 1554, 1998).
9. W. C. Mead, A. A. Browman, and R. R. Silbar, "The Qualitative Magnetron: Part of a Computer-Based Tutorial," Div. Of Nucl. Phys. Meeting, Santa Fe NM, Oct. 1998 (BAPS **43**, 1555, 1998)
10. R. R. Silbar, "Computer-Based Training for Particle Accelerator Personnel," in *Appl. Of Accelerators in Research and Industry*, ed. by J. L. Duggan and I. L. Morgan, AIP Conf. Proc. **475**, 1104, 1999.
11. R. R. Silbar, A. A. Browman, W. C. Mead, and R. A. Williams, "*Accelerators and Beams*: Multimedia Computer-Based Training in Accelerator Physics," in *Appl. Of Accelerators in Research and Industry*, ed. by J. L. Duggan and I. L. Morgan, AIP Conf. Proc. **475**, 1114, 1999.
12. R. R. Silbar, A. A. Browman, W. C. Mead, and R. A. Williams, "*Motion in Electromagnetic Fields* and *Dipole Magnets* Tutorials," invited paper at the Winter Meeting of the Am. Assoc. of Physics Teachers, Anaheim CA, Jan. 1999 (AAPT Announcer, **28**, 92, Dec. 1998).
13. R. R. Silbar, A. A. Browman, W. C. Mead and R. A. Williams, "A Computer-Based Tutorial on Double-Focusing Spectrometers," Winter Meeting of the Am. Assoc. of Physics Teachers, Anaheim CA, Jan. 1999 (AAPT Announcer, **28**, 104, Dec. 1998).
14. R. R. Silbar, A. A. Browman, W. C. Mead and R. A. Williams, "Dipole Magnets: A Computer-Based Multimedia Tutorial," Particle Accelerator Conf. '99, (presented by R. J. Macek), New York NY, April 1999.
15. R. R. Silbar, "Multimedia Computer-Based Training in Accelerator Physics," First Int. Conf. On Mathematics and Science Education Technology (*M/SET 99*), San Antonio TX, March 1999 (p. 2 of Conf. Proc., Assoc. for Adv. Of Computing in Education, ISBN 1-880094-34-7).
16. R. R. Silbar, W. C. Mead, and R. A. Williams, "Animations in Physics Educational Software," World Conf. On Educational Multimedia, Hypermedia, and Telecommunications (*Ed-Media 99*), Seattle WA, June 1999 (p. 466 of Conf. Proc., Assoc. for Adv. Of Computing in Education, ISBN 1-880094-35-5).
17. R. R. Silbar, A. A. Browman, W. C. Mead, and R. A. Williams, "Computer-Based Tutorials for Accelerator Physics: One Company's Approach," World Conf. On Educational Multimedia, Hypermedia, and Telecommunications (*Ed-Media 99*), Seattle WA, June 1999.