TUTORIAL ON SUPERCONDUCTING ACCELERATOR MAGNETS*

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Abstract

A multimedia CD-ROM tutorial on the physics and engineering concepts of superconducting magnets for particle accelerators is being developed under a U.S. Dept. of Energy SBIR grant. The tutorial, scheduled for distribution this year, is intended for undergraduate junior or senior level science students, and portions will also be useful as resources for high school science classes. However, the unified presentation of the broad range of issues involved in the design of superconducting magnets for accelerators will also be of value to staff of research institutes and industrial concerns with an interest in applied superconductivity or magnet development. The source material is based on the worldwide R&D programs to develop superconducting accelerator magnets. A description of the content material and how it has been organized to be an effective educational presentation is discussed.

1. FOREWORD

In response to an SBIR solicitation to enhance the educational value of DOE funded technology, MJB Consulting was awarded Phase I and Phase II grants to develop a multimedia CD-ROM tutorial on Superconducting Accelerator Magnets. The material has been divided into five basic units, with the following themes: (1) Introduction to magnets and accelerators; (2) Superconductors for accelerator magnets; (3) Magnetic design methods for accelerator magnets; (4) Electrical, mechanical, and cryogenic considerations for the final magnet package; (5) Performance characteristics and measurement methods.

Technical and student reviews are in progress. Distribution for industrial users is planned for later this year; the educational version with a teacher guide is expected within six months of the initial release. The product will be available first as a CD-ROM set for the Windows platform; a Macintosh version is expected at a later date. Status information will be available from our web site [1].

2. SUBJECT AREAS

This tutorial material is organized in a structure that can be used as a complete course, as individual lessons to supplement physics and engineering courses, or as a reference that can be browsed. The content is organized so that a linear progression through the lessons provides a logical development of the material. However, all material is available at any time; it is possible to jump between topics as need for information dictates. The content of Units 1 and 2 is primarily concepts with minimal mathematics; Units 3, 4 and 5 present the detailed mathematical procedures related to the design and testing of magnets. The content for the five units includes the following topics:

Unit 1: Introduction to Magnets and Accelerators

- Introduction to particle physics and accelerator laboratories.
- Types of particle accelerators. Forces on charged particles in a magnetic field.
- Characteristics of dipole and quadrupole magnets for accelerators and how they act on particle beams.
- Function of principal parts of magnets; field line diagrams for normal and skew multipoles.
- Particle beam optics and the analogy between magnets and lenses; aberrations and errors in magnets and how they affect the beam.
- Introduction to superconductivity and the superconducting state. Types of superconducting materials suitable for accelerator magnet application.
- Types of magnet designs used for accelerator dipoles. Description and data for dipole magnets for RHIC, Tevatron, HERA, SSC, and LHC.
- Magnet construction and assembly procedures with videos of RHIC dipole construction at Northrop Grumman and SSC dipole construction at FNAL.
- Factors affecting the choice between superconducting and resistive magnets for accelerator applications.
- Magnet design issues, including structural, electrical insulation, coil cooling, environmental effects, superconductor development.
- Future superconducting magnet applications with overview of MagLev, MHD, SMES.

Unit 2: Superconductors for Accelerator Magnets

- Description of the manufacture of NbTi wire and cable.
- Short sample properties for NbTi materials, empirical formula for computing Jc at B and T, calculation of expected magnet performance with a given conductor.
- Manufacture and characteristics of Rutherford cable.
- Properties and present development status of superconducting materials for magnets (including HTS). Calculation of Jc of Nb_3Sn at B and T.
- An interactive program for computing some mechanical, electrical, and thermal properties of materials commonly used in accelerator magnet construction.

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Unit 3: Magnetic Design Methods for Accelerator Magnets

- Computing 2-D fields from current lines
- How fields are calculated with current shells.
- The effect of the iron yoke on the magnetic field. Iron saturation effects.
- Methods for optimizing the magnetic design using multiple shells and wedges. Calculating the optimum amount of superconductor. An interactive procedure is included for computing fields and multipoles in single layer dipole and quadrupole coils with an optional wedge and yoke.
- Methods used to calculate the magnetic fields produced by cos θ type coil ends. End spacers and their design.
- Discussion of available public domain and proprietary software for calculating magnetic fields in accelerator magnets.

Units 4 and 5

The content material of the last two units is not yet in place. However, the following topics will be included:

Unit 4: Electrical, Mechanical, and Cryogenic Considerations for the Final Magnet Package

- Mechanical aspects of the cold mass design, such as Lorentz, thermal, and assembly loads.
- Design concepts and methods for collars and yokes.
- Data on mechanical properties of cold mass materials, including conductor stacks.
- Thermal design of magnets, with pool boiling and supercritical helium. Diffusion and cross flow cooling schemes for the cold mass.

Unit 5: Performance Characteristics and Measurement Methods

- Magnet quench and performance testing. Methods of locating quench origins. Training data from actual magnet tests.
- Quench protection methods for magnet strings and calculation of the maximum temperature from a quench.
- Magnetic performance measurements and techniques for dipoles and quadrupoles.
- Mechanical performance measurements, such as coil size, pre-stress, and end forces.

3. EDUCATIONAL APPROACH AND EXAMPLES

3.1 Educational approach

The guidelines for the technical level of this tutorial were that it should be suitable for a junior or senior level college course. Thus, we have attempted to keep the mathematical treatment of the material consistent with that objective. Most of the mathematical based presentations are in Unit 3, which deals with the magnetic design of the magnets. Here we have treated the material on a level that requires only the use of trigonometry and an understanding of the basics of differential and integral calculus. A useful reference for the development of this section was the 1989 paper by Mess and Schm∫ser [2].

To accommodate users with widely varying technical backgrounds, frequent use is made of “hot words” and “buttons” that can be clicked to give access to screens with more details, basic explanations, and background material. The tutorial thus also serves as a reference source that would be useful for those interested in superconductivity or magnet development because much technical data is available in these button accessible “sidetracks”.

3.2 Visuals

A major advantage of a multimedia presentation is the ability to include video clips and animation sequences, in addition to many photographs. Unit 1 includes a lesson that shows all steps in the production of a magnet, starting from the cable cleaning. This lesson has many video clips and is supplemented by animations that illustrate details. For example, Figure 1 shows part of the sequence that explains the steps in assembly and insulation of the superconducting coils into the cold mass. Unit 2 illustrates the steps in production of superconducting wire and cable with many animations.

These materials are intended to give students a good understanding of the complexity of making these large but extremely precise devices. This content will also be interesting for industrial staff, including technicians and engineers, so that they can appreciate where their particular specialty fits into the complete magnet construction process.

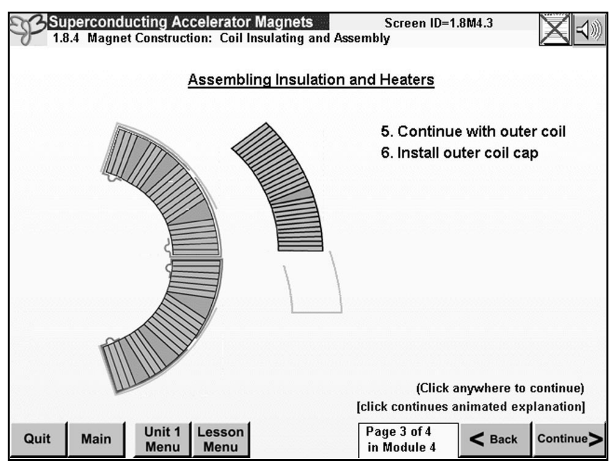

Figure 1

3.3 Exercises and Examples

The educational value of the tutorial is enhanced by the use of numerous exercises / examples: problems (with their solution available on a succeeding screen) or information about actual magnets. Some of these exercises are interactive, allowing the user to move symbols or input data values. Other exercises are to be solved off-line.

One interactive exercise in Unit 1 tests the student's understanding of the role of dipoles and quadrupoles in accelerators. The screen for this is shown in Figure 2. Diagrams are shown for dipole and quadrupole magnets, which must be placed in their correct positions on the diagram of two intersecting beams to produce the bending and focusing as shown.

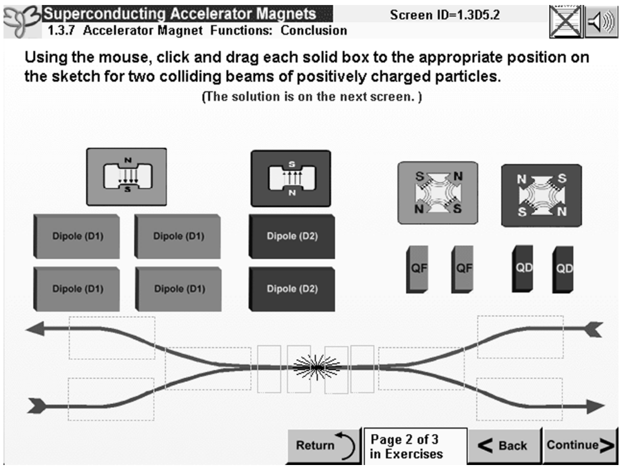

Figure 2

Unit 1 also contains labeled cross section diagrams of the RHIC dipole assembly and cold mass. When the label for a part is clicked, a pop-up box with an explanation of the function of that part is displayed. This interactive example is demonstrated on our web page [1].

Illustrative examples are used to complete the understanding of key issues and provide useful reference points. For example, in Unit 2 formulas are presented for the relationship between critical current, field, and temperature in NbTi superconductor. Then their use is illustrated by the following examples:

Problem: The critical current of the superconducting wire used in the RHIC magnets is 264 A in a field of 5 T and at 4.2 K. If the maximum field on the superconductor in the magnet is 5.3 T and the associated maximum temperature is 4.5 K, what would be the expected critical current of the wire under these conditions?

Problem: Calculate the critical current for Nb_3Sn with a net strain of -0.001 at the point where the peak field is 13.1 T and the conductor temperature is 4.35 K.

Figure 3 shows an example from Unit 3, which is used to illustrate principles of magnetic field calculation.

Also in Unit 3, a detailed example is used to illustrate the process of optimizing the superconductor in a magnetic design. Stepping through this example provides the user with a basic understanding of the principles involved in achieving a magnetic design.

Problem: Develop the magnetic design for a 50 mm diameter aperture dipole magnet using a NbTi conductor, with an iron yoke, that will produce a central field of 9 T at a maximum operating temperature of 2.0 K. Assume that the maximum field in the conductor is 5% greater than the central field. A reasonable assumption to keep the amount of superconductor to a minimum is to assume that the operating margin is 15%.

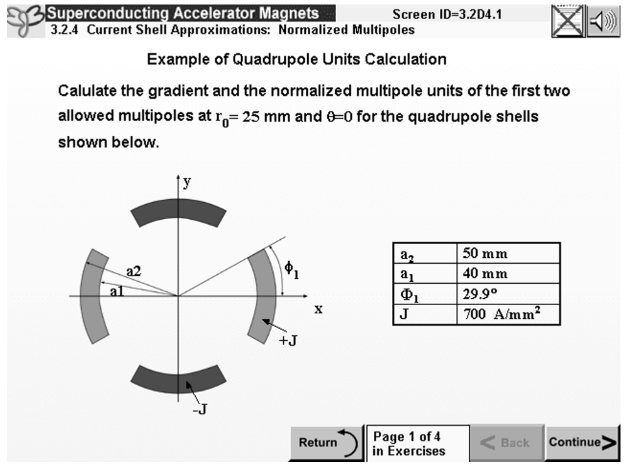

Figure 3

4. SOURCE MATERIAL AND ACKNOWLEDGEMENTS

The initial inspiration for the tutorial was the lecture material developed by Arnaud Devred for the Superconducting Super Collider (SSC) magnet program. Presentations from CERN Accelerator Schools have been important sources also. Magnet developers and superconductor scientists at laboratories and industrial firms, both U.S. and international, have supplied valuable data that has enabled completion of the technical content.

The following institutions have also supplied material: Northrop Grumman; Lockheed Martin; Oxford Instruments; Fermi National Accelerator Laboratory; Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Applied Superconductivity Center-University of Wisconsin-Madison, Texas Center for Superconductivity- University of Houston.

REFERENCES

[1] The URL for the web page is: http://web2.airmail.net/mjb1

[2] K.-H. Mess and P. Schmüser: 'Superconducting Accelerator Magnets', CERN 89-04, CERN Accelerator School – Superconductivity in Particle Accelerators, Proceedings, CERN, Geneva 1989, p 87.