TUTORIAL ON SUPERCONDUCTING ACCELERATOR MAGNETS*

M. J. (PENNY) BALL, CARL L. GOODZEIT,
M J B Consulting, DeSoto, Texas, USA
and *RAINER B. MEINKE,*
Advanced Magnet Lab, Inc., Palm Bay, Florida, USA.

Abstract

The physics and engineering concepts involved in the design and development of superconducting magnets for particle accelerators are explained in a multimedia software application being distributed on CD-ROMs. The source material used in the development of this tutorial is based on the world wide research efforts that have been undertaken for magnets for high-energy accelerators such as the SSC, RHIC, and LHC programs. The material is organized into a lesson structure that is suitable for college physics and engineering courses. However, there is much supplementary material that is a valuable resource for professional users and magnet developers who need training or reference information. This paper describes aspects of the tutorial that are most relevant for designers and developers of superconducting magnets.

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1. OVERVIEW

In the fall of 1994, a project was begun to develop a CD-ROM tutorial on superconducting accelerator magnets. This work was funded under a U. S. Dept. of Energy (DOE) Small Business Innovative Research (SBIR) grant. The project is now nearing completion and the "Professional Edition" for institutional and industrial users is scheduled to be released in early 1998.

The scope of the material presented has been reported previously.[1,2] The content is organized into five units:

- Unit 1: Magnets and Accelerators (Introduction to accelerators, magnets, superconductivity)
- Unit 2: Superconductors for Magnets (Materials and manufacturing methods)
- Unit 3: Magnetic Design (Calculating magnetic field and harmonic content)
- Unit 4: Magnet Assembly (Mechanical, thermal and electrical design)
- Unit 5: Performance Testing and Measurement (Quenching, quench peformance, stress and strain)

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[1] M. Ball and C. Goodzeit, "Courseware on Superconducting Accelerator Magnets: An Interdiscplinary Application", Conference Proceedings of the Educational Institute for Superconductivity (EIS), June 13-14, 1996, Washington, D.C.

[2] M. Ball and C. Goodzeit, " Tutorial on Superconducting Accelerator Magnets", to be published by IEEE for Procedings of the 1997 Particle Accelerator Conference, Vancouver, B. C. May, 1997.

It is estimated that the complete tutorial contains the equivalent of about 25 hours of lecture and reference material. The topics in the five units can be categorized into the following 3 functional groups:

Category 1. Background material:

a. Introduction to particle physics
b. Introduction to accelerators
c. Future superconducting magnet applications
d. Superconductivity and magnets
e. Accelerator systems issues

Category 2. Reference material:

a. Mechanical, thermal and electrical properties of materials.
b. Parameters and construction features of magnets for existing or planned accelerators.
c. Mechanical and magnetic test data from actual magnet tests.

Category 3. Procedures in accelerator magnet design and construction:

a. Steps in manufacture and testing of superconducting wire and cable.
b. Cold mass and cryostat construction and assembly steps, with videos and diagrams.
c. Magnetic design procedures including an interactive routine that calculates the magnetic fields in dipole and quadrupole magnets.
d. Mechanical, thermal and electrical design procedures.
e. Mechanical and magnetic performance measurement techniques.

The background material would be useful for training new staff and for supplementary resources for college courses. The reference data and magnet design procedures would be of interest and value to magnet developers and designers. The next sections discuss the technical content in more detail.

2. REFERENCE MATERIAL

2.1. Material Properties Data

2.1.1 Superconducting Materials Data

Three types of superconducting materials (NbTi, Nb_3Sn, and HTS) are described and their properties are presented.

Critical current data for NbTi is based on a study made by G. Morgan of the measurements of the superconducting wire and cable used in the RHIC magnets at BNL[3]. Morgan's formula has been put into an interactive procedure that allows one to calculate critical current density as a function of temperature and applied field.
Other data that can be retrieved interactively are resistivity and specific heat of NbTi and NbTi/Cu composite mixture. This data is useful for calculation of quench propagation velocity in superconducting coils.

[3] G.H. Morgan "A New Critical Surface for RHIC NbTi", Brookhaven National Laboratory Memo 560-1 (RHIC-MD-2611) Jan. 6, 1997

Critical current density for Nb_3Sn as a function of temperature, field, and initial strain can also be computed interactively with a procedure that uses the Summers[4] formula.

We have not included detailed information on HTS material properties except for a general characterization of critical current density vs. field for material that may be of interest to magnet developers.
The status of the development of NbTi, NbTiTa, A-15, and HTS materials is presented in charts that were developed by P. Lee[5]. Figure 1 gives an example.

2.1.2 Magnet Construction Materials Data

Properties of materials used in superconducting magnets are required for design and performance calculations. During the course of the SSC project, a group at the SSC headed by A. Devred made a compilation of mechanical, thermal, and electrical properties for various materials [1][6]. A subset of this data has been included in an interactive form in the tutorial's Materials Science Library. In addition, another interactive table gives access to thermal contraction data over the temperature range 4.2K to 293K for a variety of materials including metals and alloys, plastics and composites, and molded coil samples[2][7].

Table 1 lists data from the Materials Science Library that is presently available in the tutorial and the input parameters that can be varied from typical default values.

Figure 2 shows the screen that is used to interactively retrieve the thermal contraction data. The example shows the table for the Plastics. Similar tables can be chosen for Metals and Coils. The values are displayed by clicking on the specific material name.

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4 L.T. Summers, J.C. McKinnell, S.L. Bray and J.W. Ekin, "Characterization of Multifilamentary Nb3Sn Superconducting Wires for Use in the 45-T Hybrid Magnet", IEEE Trans. Appl. Superconductivity, vol. 5, no. 2, 1764, June 1995

5 P. Lee, ASC-UW, http://www.cea.wisc.edu/~plee/homepage.shtml

6 Material properties functions from the Magnet Science Library have been put on-line by T. Ogitsu. See Http://supermag2.kek.jp/~programs/magexec.

7 "Thermal Contraction Measurements", BNL Technical Note:Magnet Division Note, 455-15, July 10, 1992.

Table 1 – Materials Science Library Contents

Material	Properties (Parameters)
Iron	Magnetic susceptibility (B) Specific heat (T) Thermal conductivity (T)
Copper	Poisson's ratio (T) Resistivity (RRR,T,B) Specific heat (T) Thermal conductivity (RRR,T,B) Thermal expansion coeff. (T) Young's modulus (T)
NbTi	Specific heat (T) Thermal conductivity (T) Critical current density (T,B)
NbTi/Cu composite	Enthalpy change (R_{CuS},T_0,T_1,B) Resistivity (R_{CuS},RRR,T,B) Specific heat (R_{CuS}, T,B) Thermal Conductivity (R_{CuS},RRR,T,B)
Nb_3Sn	Critical current density (T,B,e)
Kapton	Specific heat (T) Thermal conductivity (T)
Austenitic stainless steel	Resistivity (T) Thermal conductivity (T) Specific heat (T) Young's modulus (T)
RX 630	Description Table of properties
Ultem 2100	Thermal conductivity (T)

2.2. Parameters and construction features of some accelerator magnets

This section presents some parameters and construction features for some accelerator magnets that have been built or are currently in design. These include the following:

a. RHIC arc dipole
b. Tevatron dipole
c. SSC prototype dipole
d. HERA dipole
e. LHC dipole

We have attempted to include the following information about these magnets:
a. Principal parameters (operating conditions, length, weight, number used)
b. Description of components (Coils, Wire and cable, Yoke, Collars, Helium shell, Vacuum vessel, Support system)

A typical data page for one of these magnets is shown in Figures 3A and 3B.

2.3. Magnet mechanical and magnetic performance techniques and data.

The general techniques for magnetic field measurements in accelerator dipole and quadrupole magnets are presented, with typical data from major magnet designs. Methods and results for mechanical measurements (e.g., azimuthal coil stress and coil end forces during assembly, cool down, and operation) of SSC prototype dipole magnets are discussed. Procedures for locating the quench origin are described, and quench performance (training) data is presented for a number of typical magnets.

3. MAGNET DESIGN PROCEDURES

3.1. Magnetic design procedures

This section presents the basics of calculating the magnetic fields in dipole and quadrupole magnets and illustrates how the main fields and harmonics are obtained for cases of dipole and quadrupole symmetry with and without the effect of an iron yoke. Its interactive program[8] is useful for those who would like to quickly compute the main field, allowed multipoles, and Lorentz forces in either a dipole or quadrupole magnet of the cos mθ type. This program considers a symmetrical single shell dipole or quadrupole with an optional wedge and an optional yoke; the basic dimensional parameters can be adjusted by either sliders or numerical entry, and the total current per quadrant is entered numerically. Figure 4a shows the input screen and Figure 4b shows the output screen for the computation of the field in a dipole magnet. This computation can also be applied to multi-layer magnets by means of superposition of the single layer results.

For those wishing to pursue magnetic calculations in further detail, we have included descriptions of the principal public domain and proprietary software packages available for this purpose (e.g. the Poisson group codes, OPERA and TOSCA).

3.2. Mechanical, electrical, and thermal design

Much magnet design technology that has evolved as a result of the SSC and RHIC programs has been incorporated into this unit. The design of a magnet is approached from the standpoint of assuming that it is a cold iron magnet with collared coils of the cosθ configuration. The following topics are presented:

a. Mechanical and thermal loads.

b. Materials selection options

c. Cold mass mechanical design methods

d. Cold mass thermal design methods using diffusion and cross flow cooling

e. Electrical insulation techniques

f. Cryostat design methods.

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[8] Program developed by Yuping Zhao and Rainer Meinke, based on their DESY calculations.

4. METHOD OF DISTRIBUTION AND UPDATES

The tutorial will be issued first as a "Professional Edition" on a set of CD-ROMs for Windows 95/NT or Macintosh. We expect to release it in two parts; the first part will consist of Units 1,2 and 3, and will be followed several months later by the second part with Units 4 and 5.

It is planned to offer an abridged and reorganized version of this material as a series of topics that would be suitable for course supplements in college level engineering and physics curricula.

Information on availability of the CD-ROM sets will be given on our web page[9].

5. 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[10]. 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.

In particular, some of the institutions who supplied material are:

Northrop Grumman; Railway Technical Research Institute of Japan;Lockheed Martin; Oxford Instruments; Fermi National Accelerator Laboratory; Brookhaven National Laboratory; Lawrence Berkeley National Laboratory; Applied Superconductivity Center - University of Wisconsin - Madison; Vector Fields, Ltd.; Texas Center for Superconductivity - University of Houston; Wah Chang.

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[9] Our web page is at http://web2.airmail.net/mjb1

[10] [A. Devred, et al., "Hawaiian Lectures on Magnets", Prepared for the 1994 US-CERN Joint Accelerator School, Maui, Hawaii, Nov. 3-9, 1994.

Figures

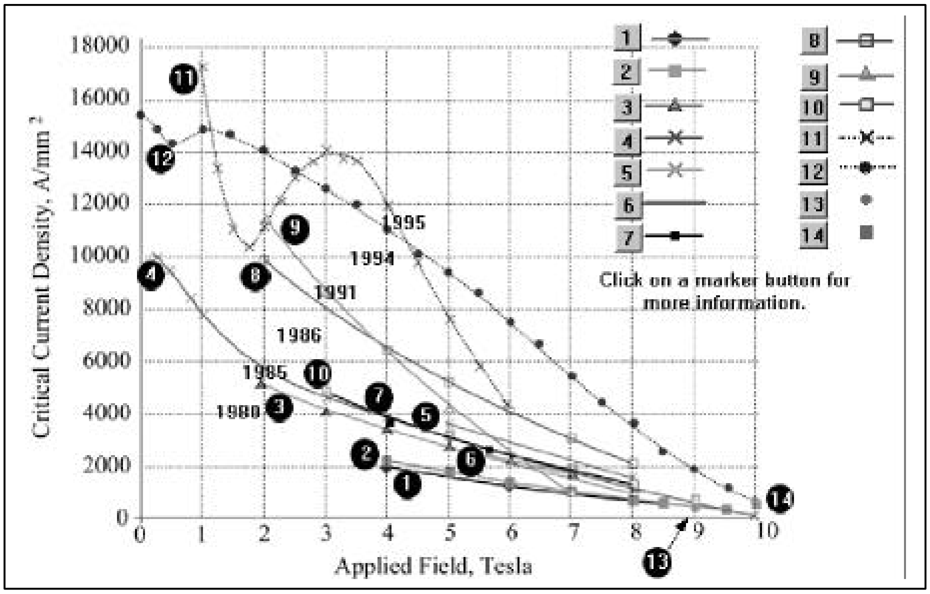

Figure 2. Thermal contraction data access from interactive table

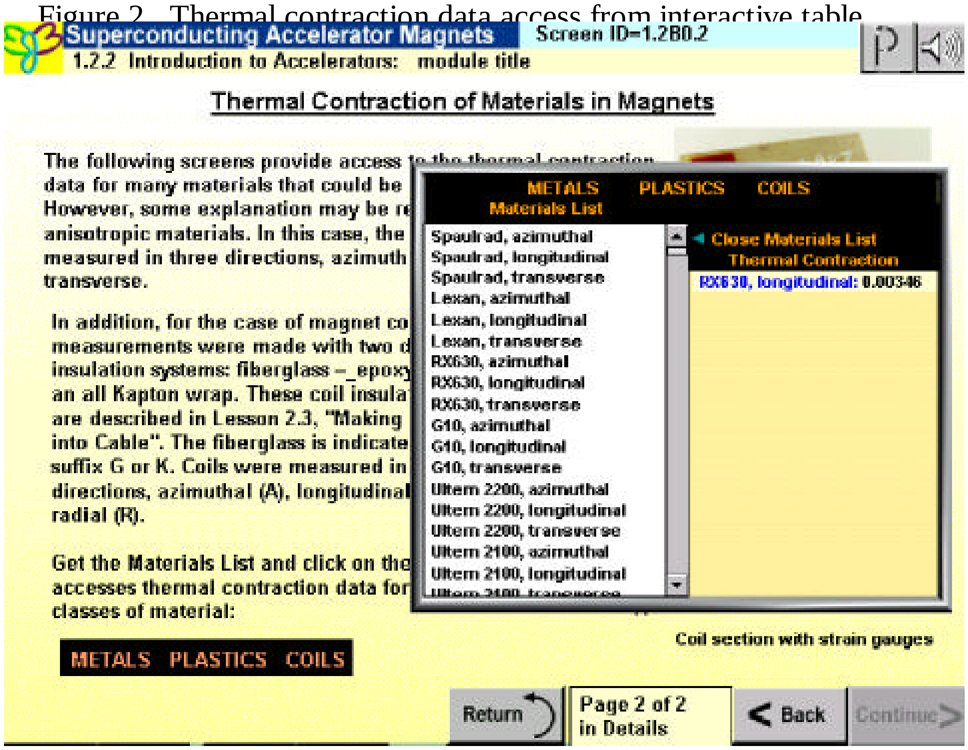

Figure 3A – Details about components are available by clicking on an item.

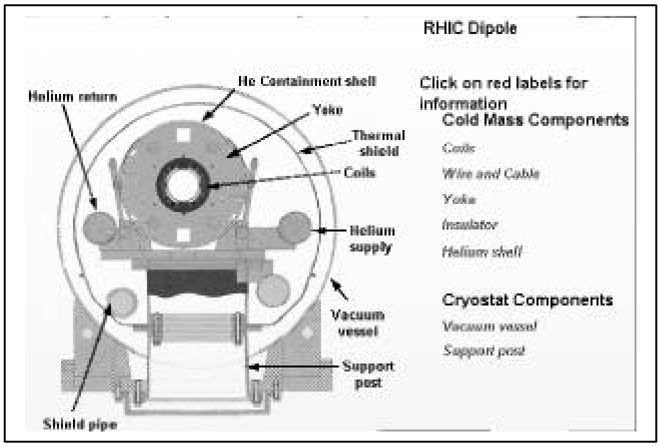

Figure 3B - Typical screen showing wire and cable parameters.

RHIC Superconducting Wire and Cable Properties

Wire Parameters	
NbTi composition (% Ti)	47.0
Critical current (A)*	264
Jc (non-Cu) (A/mm^2)*	2600
Copper-to-superconductor ratio	2.25
Filament diameter (µ)	6 µm
Strand diameter (mm)	.648
No. of filaments	3510
Strand twist pitch (per m)	75
Copper residual resistance ratio.	38

Cable Parameters	
Critical current (A)*	7524
Number of strands	30
Cable width (bare) (mm)	9.73
Cable mid thickness (bare) (mm)	1.166
Keystone angle (deg)	1.20
Cable twist pitch (per m)	74±5
Residual resistance ratio, R296/RIO	38

* Measured at 4.2K and 5T.

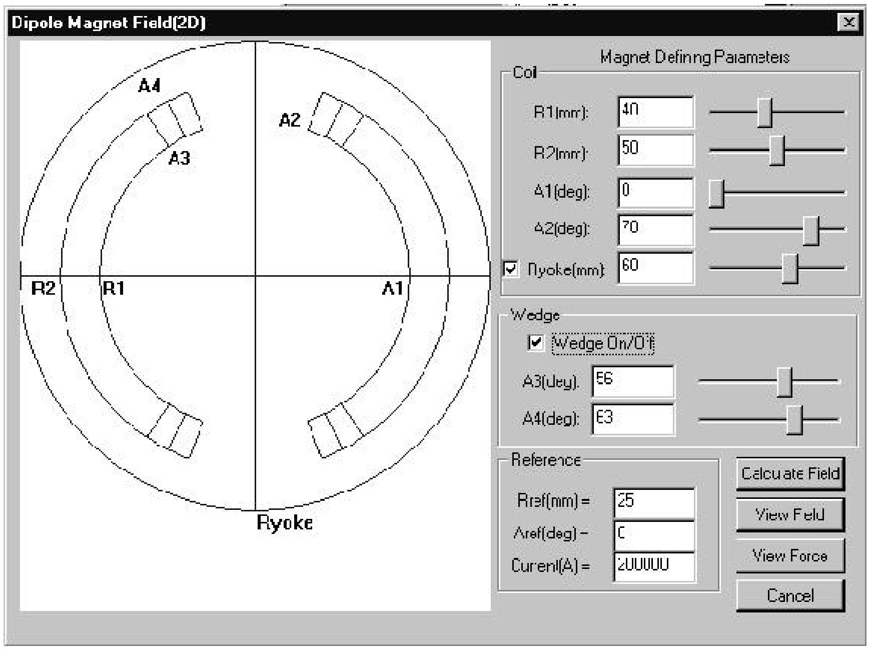

Figure 4a
Screen showing parameters for dipole field calculations. Data can be entered numerically or by moving sliders.

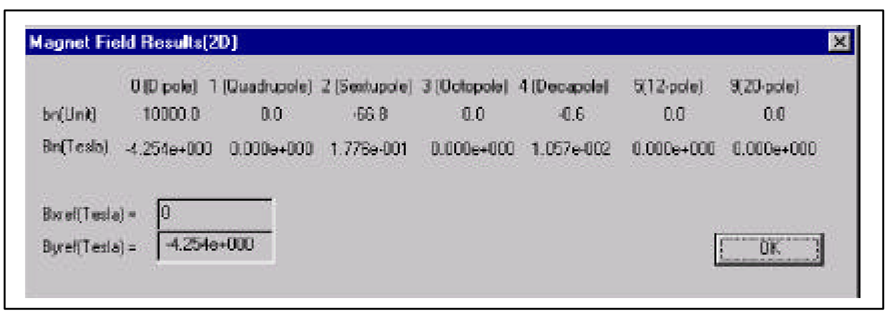

Figure 4b. Output screen from magnetic field computation.