Available online at www.sciencedirect.com
ScienceDirect
Fusion Engineering and Design 81 (2006) 2381–2388
Fusion Engineering and Design
www.elsevier.com/locate/fusengdes

Superconducting magnet and conductor research activities in the US fusion program

P.C. Michael[a,*], J.H. Schultz[a], T.A. Antaya[a], R. Ballinger[a], L. Chiesa[a], J. Feng[a], C.-Y. Gung[a], D. Harris[a], J.-H. Kim[a], P. Lee[b], N. Martovetsky[c], J.V. Minervini[a], A. Radovinsky[a], M. Salvetti[a], M. Takayasu[a], P. Titus[a]

[a] MIT-Plasma Science and Fusion Center, 185 Albany St., Cambridge, MA 02139, USA
[b] Applied Superconductivity Center, University of Wisconsin-Madison, Madison, WI 53706, USA
[c] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Abstract

Fusion research in the United States is sponsored by the Department of Energy's Office of Fusion Energy Sciences (OFES). The OFES sponsors a wide range of programs to advance fusion science, fusion technology, and basic plasma science. Most experimental devices in the US fusion program are constructed using conventional technologies; however, a small portion of the fusion research program is directed towards large scale commercial power generation, which typically relies on superconductor technology to facilitate steady-state operation with high fusion power gain, *Q*. The superconductor portion of the US fusion research program is limited to a small number of laboratories including the Plasma Science and Fusion Center at MIT, Lawrence Livermore National Laboratory (LLNL), and the Applied Superconductivity Center at University of Wisconsin, Madison. Although Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL) are primarily sponsored by the US's High Energy Physics program, both have made significant contributions to advance the superconductor technology needed for the US fusion program. This paper summarizes recent superconductor activities in the US fusion program.

Keywords: Superconductor; Superconducting magnet; Fusion technology

1. Introduction

The largest proposed United States activity in magnetic confinement fusion is the International Thermonuclear Experimental Reactor (ITER). The United States has proposed to supply four of the seven modules (six in the assembly plus one spare) needed for the ITER Central Solenoid (CS). The ITER CS is a 840 tonnes system, requiring 138 tonnes of Nb_3Sn superconductor strand. The CS has a peak flux density of 13 T, a peak current of 45 kA and stores 6 GJ of magnetic energy. The CS will provide up to 277 Wb of magnetic flux to inductively drive 15 MA of plasma current in ITER. Key issues for the CS design have

---

* Corresponding author. Tel.: +1 617 253 3186;
fax: +1 617 253 0807.
E-mail address: michael@psfc.mit.edu (P.C. Michael).

0920-3796/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.fusengdes.2006.07.023

been identified as: prediction of Nb_3Sn superconductor cable performance in the presence of large transverse Lorentz loads, and verification of the structural integrity of the CS magnets during cyclic operation. The United States development effort for ITER has focused on these two issues.

Lawrence Berkley National Laboratory (LBNL), the Plasma Science and Fusion Center at M.I.T. (MIT-PSFC), Lawrence Livermore National Laboratory (LLNL), and the Advanced Magnet Laboratory (AML) recently produced and tested a magnet system capable of focusing intense beams of heavy ions for inertial confinement fusion. The prototype focusing magnet developed for the heavy ion fusion (HIF) program consisted of a superconducting quadrupole doublet integrated inside of a low heat-leak cryostat.

MIT-PSFC and Columbia University designed, built, and recently produced the first plasmas of the levitated dipole experiment (LDX). LDX is one of the OFES's innovative confinement concepts plasma science experiments. LDX is the largest levitated dipole experiment in the world. The core of the LDX machine comprises three superconductor coils. Each coil employs a significantly different superconductor technology, which is best suited to that coil's function in the device.

2. Superconductor technology for ITER

The International Thermonuclear Experimental Reactor (ITER) program is an international magnetic confinement fusion (MCF) project involving The People's Republic of China, the European Union, India, Japan, the Republic of Korea, the Russian Federation, and the United States of America [1]. ITER is a burning-plasma, engineering test reactor based on the tokomak configuration. It is designed to generate inductively driven plasmas producing 500 MW of fusion energy for durations of up to 500 s with a Q of about 10. The overall objective of ITER is to demonstrate the technological feasibility of fusion energy for commercial power production.

The conductors for the ITER magnet systems employ a cable-in-conduit (CIC) configuration. Conductors for the ITER CS contain approximately 1000 superconductor and copper strands that are combined into a multiple stage cable and encased in a structural metal jacket, which also serves as the pressure boundary for the cable's supercritical helium coolant. Subdivision of the conductor into large numbers of superconductor strands significantly increases its wetted perimeter, resulting in a marked increase in conductor stability.

Two large CIC superconducting "model" coils were built and tested during the engineering design activities (EDA) phase of the ITER program, which ran from 1993 through 2001. One coil was intended to simulate the operation conditions expected of the ITER CS [2], while the second coil was intended to simulate the operation conditions expected of the ITER toroidal field (TF) coils [3]. The US provided the 74 tonnes support structure and a 47 tonnes, 10 layer inner module for the CS Model Coil, and participated strongly in both the CS and TF Model Coil test programs. Although both magnet systems fulfilled all of their technical objectives, the measured conductor performance for each coil was significantly below the behavior predicted prior to the start of testing.

2.1. Superconductor strand and cable investigations

Most investigators attribute the discrepancy in observed conductor performance to a combination of high transverse electromagnetic loading of the CIC combined with its relatively low transverse stiffness [4]. As the cable in a CIC conductor deforms under electromagnetic loading, it typically compresses towards one side of the conduit. Transverse loads are concentrated at points where the strands cross over one another in the cable pattern. At the same time, the unsupported strand lengths between these cross-over points bend under the influence of the Lorentz force loading. To help distinguish the consequences from these two effects, an experimental program was implemented at the MIT-PSFC and at the Applied Superconductivity Center (ASC) to: examine the effect of pure bending on strand performance, observe filament cracking as a function of bending strain and strand type, and to evaluate cable performance at several transverse loads.

2.1.1. Strand investigations

Two test configurations were developed at MIT-PSFC to investigate the effect of bending on the criti-