GA–A22223

CONF-950905--40

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This is a preprint of a paper presented at the 16th IEEE/NPSS Symposium on Fusion Engineering, September 30–October 5, 1995, Champaign, Illinois, and to be printed in the *Proceedings.*

Work supported by
U.S. Department of Energy
Contract DE–AC03–89ER51114

GENERAL ATOMICS PROJECT 3466
DECEMBER 1995

GENERAL ATOMICS

Development of a New Error Field Correction Coil (C-coil) for DIII–D*

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ABSTRACT

The C-Coil recently installed on the DIII–D tokamak was developed to reduce the error fields created by imperfections in the location and geometry of the existing coils used to confine, heat, and shape the plasma. First results from C-coil experiments include stable operation in a 1.6 MA plasma with a density less than 1.0 x 10^{13} cm^{-3}, nearly a factor of three lower density than that achievable without the C-coil. The C-coil has also been used in magnetic braking of the plasma rotation and high energy particle confinement experiments.

The C-coil system consists of six individual saddle coils, each 60° wide toroidally, spanning the midplane of the vessel with a vertical height of 1.6 m. The coils are located at a major radius of 3.2 m, just outside of the toroidal field coils. The actual shape and geometry of each coil section varied somewhat from the nominal dimensions due to the large number of obstructions to the desired coil path around the already crowded tokamak. Each coil section consists of four turns of 750 MCM insulated copper cable banded with stainless steel straps within the web of a 3 in. x 3 in. stainless steel angle frame. The C-coil structure was designed to resist peak transient radial torces (up to 1800 Nm) exerted on the coil by the toroidal and poloidal fields. The coil frames were supported from existing poloidal field coil case brackets, coil studs, and various other structures on the tokamak.

INTRODUCTION

Progress in tokamak fusion energy research has led to routine operation in regimes in which the symmetry of the magnetic field is very important. Errors or asymmetries in the magnetic field can be caused by coil leads, eddy currents, small variations in coil fabrication, or slight mislocations of the large coil systems of the tokamak with respect to the magnetic center of the plasma. In some plasma discharges, magnetic field errors as low as one part in ten thousand are enough to significantly deteriorate plasma performance. These field errors can reduce the energy confinement, cause the growth of instabilities, lower the plasma rotation speed, produce asymmetries in the heat flux to the vessel walls, and lead to disruptions. For future devices with much larger power flux densities, disruptions and unexpectedly high heat fluxes could result in serious damage to the vessel walls. One of the most detrimental effects of error fields is "mode-locking," during which the error field interacts with small rotating magnetic islands and causes a cessation of rotation or "locking" to the stationary error field [1]. The amplitude of the mode then grows, leading to the loss of energy confinement and often a plasma disruption. Error field induced locked modes reduce the stable operating parameter space of the tokamak and inhibit the progress of the research program.

The recently installed C-coil ("correction coil") is used to apply a small radial magnetic field with the opposite phase of the error field, thus reducing the error field of the tokamak. The radial field is generated by flowing current through six separate saddle coils surrounding the tokamak, each 60° wide toroidally, spanning the midplane with a height of 1.6 m (Fig. 1).

Several experiments have been conducted using the C-coil to modify the inherent error field of the tokamak. It is used on a daily basis to help avoid plasma instabilities which limit the operating parameter space of the machine and allow, for example, stable operation at lower density than would have been possible without the coil. In addition, using a technique called "magnetic braking," the C-coil has been used to modify the rotation velocity profile of the plasma to help give insight to the physics of the very high energy confinement mode (VH–mode) [2].

DESIGN CRITERIA

The C-coil was designed to eliminate the error field at the location of the so-called m=2, n=1 mode [1] of a typical 3 MA plasma. Measurements of the error fields produced by the field-shaping coils indicated that the C-coil would be required to operate at 20 kA-turns to cance the 15 G error field. A design incorporating four turns of 750 MCM cable, pulsed to a maximum 5 kA, would satisfy these requirements.

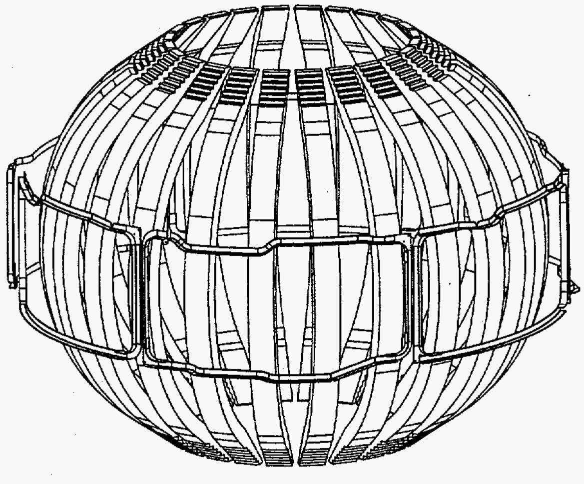

Fig. 1. C-coil structure installed on DIII–D.

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*Work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

Many often conflicting criteria influenced the engineering design of the C-coil [3]. The first issue resolved was the toroidal location of the coil sections. Only a limited number of locations could provide the clearance to fit the vertical legs, while providing nominal error field correction capability. The final design located the centers of the six coil sections at toroidal angles 19°, 79°, 139°, 199°, 259°, and 319°. One of the most prominent design requirements was the need to install the coil around the existing machine with a minimum impact on existing systems, which required the cross sectional shape of the coil to be small. The structural design had to provide for many small deviations from the basic geometry in order to clear all of the obstructions in the coil path. Alternatively, the obstructing object sometimes had to be modified to allow the C-coil to fit. Each of the six coil structures was built in multiple sections to allow installation in the congested space near the tokamak. This also provides the capability for partial removal of a coil section to enable temporary access to equipment trapped by the coil and the ability to modify a coil structure in the future to implement new installations.

The coil support structure had to be made of low permeability materials to minimize the forces and prevent the creation of additional uncontrolled magnetic error fields near the tokamak. High radial forces transmitted to the coil conductors from the toroidal and poloidal fields had to be reacted to maintain the stresses and deflections within acceptable limits. Electrically, the C-coil had to be isolated to 5 kV and electrical closed loops in the structure had to be avoided to prevent excessive eddy currents. The electrical resistance and inductance of each of the six saddle loop circuits had to be designed for acceptably low ohmic heating during pulses and had to be compatible with the voltage and current capabilities of available power supplies.

DESIGN CONCEPTS

The C-coil design process was unlike that of the existing toroidal and poloidal field coils since they were designed, built, and installed as an integral part of the tokamak, whereas the C-coil was installed *in situ.* The high radial forces required continuous or at least frequent support of the coil conductors. One early design concept called for the installation of four air cooled 750 MCM cables into round metallic conduits to provide continuous support. Forming the conduits to the numerous bends and turns was determined to be too difficult, however, and the problem was exacerbated by the minimum 4.5 in. diameter conduit required per the National Electrical Code. Feeding the 1.5 in. diameter cables through conduit was also found to be extremely difficult, even in short sections.

Square extruded copper conductors with a hollow core for liquid cooling, as used in the existing poloidal field coils, were also considered in an attempt to decrease the cross section of the coils. At best, the cross section would have been reduced to 6.1 cm (2.4 in.) square, not a substantial reduction from the baseline design utilizing a 3 in. x 3 in. stainless steel angle. Fabrication of the solid conductor coils would have required a substantially greater effort and would have been extremely time consuming, considering all the bends and turns. In addition, standard coil fabricating methods would have been used including pre-impregnated fiberglass and polyimide insulation wrapping of the individual conductors for turn-to-turn isolation and vacuum epoxy impregnation.

Many concepts were also considered for structurally supporting air cooled insulated cables on an open frame structure. Considerations were given to aluminum and stainless steel angles, crosses, I-beams, and channels. Aluminum was ruled out because of excessive deflection under load (low Young's Modulus) and low strength after welding. Four turns of insulated cable, installed in a stainless steel angle, 3 x 3 x 0.25 in., was found to have the best combination of compact size, strength, and stiffness, along with a relatively easy method to install the cable within the web of the angle as shown in Fig. 2.

ANALYSIS

A. Structural Requirements

Forces on the C-coil resulting from the toroidal and poloidal fields of the tokamak were analyzed. When current flows in the C-coil, the toroidal field causes a radial force on the vertical legs and the poloidal field causes a radial force on the horizontal legs of a magnitude given by

$$F/l = I_c \times B \quad ,$$

where F/l is the linearly distributed force (Newtons per meter), I_c is the current in the C-coil (ampere-turns), and B is the magnetic field (Tesla). The largest force is on the horizontal legs of the C-coil and results from the sum of poloidal fields created by the E-coil, nearby F-coils, and the plasma current. The steady state value is never expected to exceed 4450 N/m (300 lb/ft), but plasma disruptions can produce transient forces up to 8000 N/m (540 lb/ft) for a few dozen

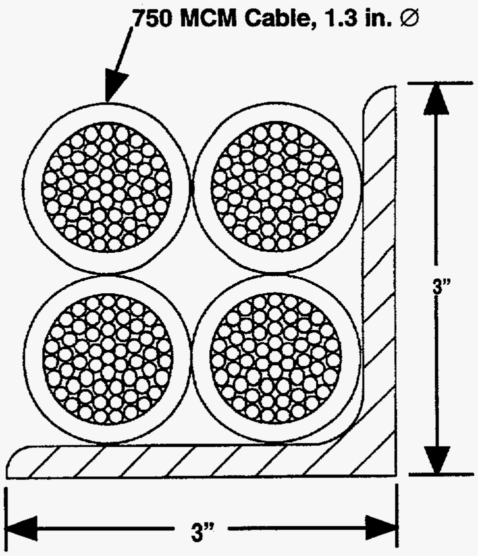

Fig. 2. C-coil cross section.

milliseconds. The horizontal legs of the C-coil also provide a convenient and unavoidable "step" or platform for personnel working on the tokamak. With this in mind the structure was also designed to easily support the localized vertical force of a persons weight.

B. Stress Analysis

Initially, hand calculations were performed to determine the scope of the stresses and deflections on the coil structures. As the design concept was finalized, a static structural analysis utilizing COSMOS finite element software was performed to verify the design. The maximum stress in the horizontal legs of the structure was found to be 173 MPa (25 Ksi) and the maximum stress in the vertical legs was 138 MPa (20 Ksi), well below the 207 MPa (30 Ksi) allowable stress for welded stainless steel structures. In practice the stresses are expected to be lower due to the compliance in all of the connections in the system. The maximum deflection was calculated at 3.0 mm (0.12 in.), which was also considered acceptable. Also of concern were stresses created in the toroidal field coil cross-over joint resulting from reacting the 12.5 kN (2800 lb) strut load. A maximum shear stress of 0.4 MPa (70 psi) in the cross over joint epoxy was calculated, well below the 14 MPa (2000 psi) allowable fatigue stress [4].

C. Thermal Analysis

The C-coil was conservatively designed utilizing 750 MCM cable to limit the surface temperature to 54°C (129°F) under worst case conditions. This is considered to be the discomfort threshold for personnel contact and is well below the cable rated capacity of 90°C. Also of concern was excessive heating of the numerous polyurethane tubes, fibers, and cables in contact with the C-coil. Worst case heating results from repetitively flowing 5 kA in the C-coil for 5 s followed by 12 minutes of passive radiative and convective cooling. The heat transfer rate was assumed to be reduced by 20% because the four cables are tightly bundled together and shielded on two sides by the stainless steel angle, reducing the area available for cooling. In practice, the surface temperature of the coil has never exceeded 43°C (110°F), as the duty cycle on the coil has never been high enough to reach the design limits.

ELECTRICAL DESIGN ISSUES

The coil design is intended to accommodate (i.e., correct the error fields of) a high current, short pulse plasma (3 MA for 5 s) or a low current, long pulse plasma (1 MA for 60 s). For the 3 MA plasma, a C-coil current of up to 20 kA-turns is required (5 kA in four turns). The size of the conductor was determined by careful consideration of the thermal, electrical and physical parameters. The 750 MCM cable chosen was 5000 V, MV-90 rated and utilized cross linked polyethylene (XLP) insulation. This type of cable is much stiffer (and therefore more difficult to work with) than the EPR rubber jacketed cable typically used at DIII–D, but the smaller diameter allowed it to fit perfectly into the web of the stainless steel angle. The standard configuration for error field correction is to connect two of the six sections in series. In this case, the resistance and inductance for two four-turn sections connected in series, including the cabling between the C-coil and the power supply, is estimated to be R=10 mΩ and L=100 μh, respectively. The necessary voltage to maintain 5 kA in the coil is 50 V, well within the capability of the power supplies. Three power supplies, each capable of 125 V, 5 kA operation, are connected to the three diametrically opposed pairs of C-coil sections.

The design of the coil support structure provided for 5 kV isolation from all other structures of the tokamak. At the corner joints, NEMA G-10 fiberglass-epoxy composite insulating material, adhesive backed polyimide tape (Kapton) [5], and flexible 0.06 in. thick polyetherimide sheet material (Ultem) [6] were used to achieve the required insulation. Each turnbuckle connection on the structure was insulated utilizing 0.25 in. thick G-10 washers press fit on filament wound epoxy-fiberglass bushing material, Dixon CJ [7]. The Dixon CJ bushing material was required for its high radial load capacity (35 Ksi) and 300 V/mil electrical isolation.

FABRICATION AND INSTALLATION

Each of the six stainless steel angle coil support frames was first rolled to conform to a toroidal radius of 3.2 m, after which the custom bends, turns, and transitions to avoid obstacles were added. A combination of rolled bends, fabricated (welded) bends, and mitered butt weld joints were used in fabrication of the structure. Rolled bends were used for radii greater than 15 in., fabricated bends were used for bend radii as low as 6 in., the minimum bend radius of the 750 MCM cable, and mitered joints were typically used for gradual transitions in the structure. Typically, an outside vendor formed and tack welded the coil sections. The structures were then fit to the machine, modified as necessary, and final welded. Many of the bends and turns can be seen upon close examination of Fig. 1 and a typical bend as installed on the machine is shown in Fig. 3. Temporary support platforms, clamps, and overhead rigging supported the structure as the support struts were positioned. Bolted flange joints utilizing G-10 insulators were installed in the center of each of the upper and lower horizontal legs, providing two electrical breaks to avoid closed loops. The vertical legs were bolted to the upper and lower horizontal legs utilizing a three inch long overlap joint with four 1/2 in. diameter flat head screws.

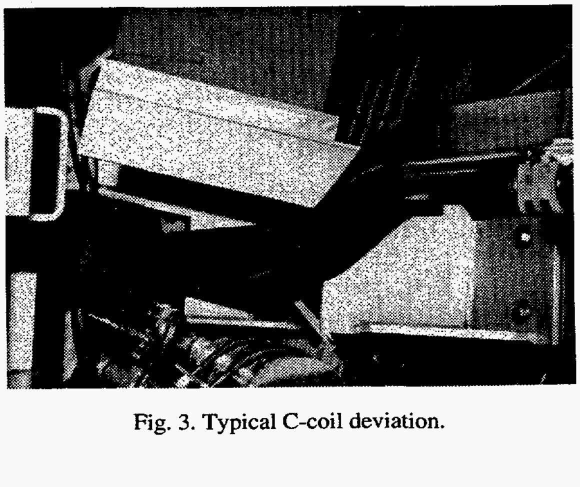

Fig. 3. Typical C-coil deviation.

"Corner joints" were installed on two diagonal corners, the lower joint provided a turn to turn transition point and a location to connect the leads, and the upper joint provided a bolted joint to disassemble each of the tour conductor turns, if necessary. The compact corner joint design utilizes two 1/2 in. dia. studs and various G-10 spacers to make four or six connections. The studs were made of Armco A-286 [8] high strength stainless steel and were isolated from the structure and the cable lugs with the same high strength bushing material as used in the support strut installation. This design requires two insulation failures to ground a coil conductor to the structure. The corner joints were designed to provide 5 kV isolation between conductors and structure but only needed to provide 10–12 V isolation from turn to turn. The isolation between the support frame, the coil conductors, and other structures of the tokamak was tested with several 5 kV hi-pots during various phases of construction. Belleville washers, preloaded to 44.5 kN (10,000 lb), were installed on the studs to compensate for thermal expansion and creep in the G-10 insulators. An exploded view of an upper corner joint is illustrated in Fig. 4.

Because of the extreme stiffness of the conductor cabling, a combination of clamps, hydraulic cable benders, and a portable five-ton hydraulic press specially developed for this operation were utilized in forcing the group of four cables to follow the many tight bends and turns of the support structure. On tighter bends, the cables frequently had to be formed one at a time, as the hydraulic press could not overcome the stiffness of the cables. On occasion, the cable group was found to be stiffer than the stainless steel angle structure, causing the structure to deform to the cable. Band-It [9] stainless steel band clamps, 1/2 in. wide, were installed on six inch centers to hold the cable in the web of the angle and to minimize the tensile loads in the cable resulting from the radial forces. Occasionally the bands, capable of withstanding a tensile load of 6675 N (1500 lb), would snap from the forces involved in forming the cable. Small fiberglass angle pieces were installed under the band clamps to avoid cutting the cable insulating jackets. Fig. 5 shows the portable hydraulic press in use and the installation of the band clamps with insulating fiberglass angles.

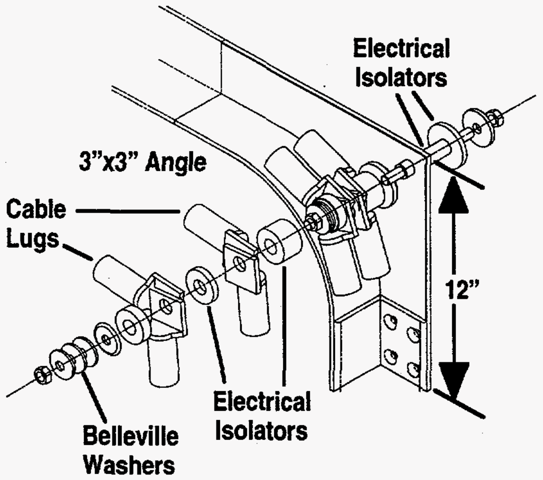

Fig. 4. Exploded view of an upper corner joint assembly.

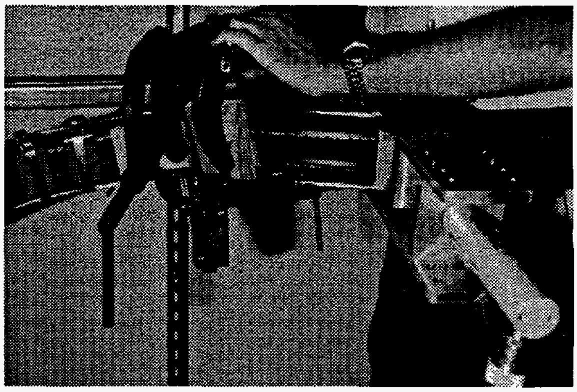

Fig. 5. Installation of 750 MCM cables with c-clamps and the portable hydraulic press.

The installation of the C-coil structure was aided by the fact that, unlike the existing toroidal and poloidal field coils on the machine, small deviations from the basic geometry were expected and acceptable. Typical deviations of 4–5 cm were not considered significant and larger deviations, up to 22 cm radially and in elevation, were reviewed on a case by case basis. Hydraulic levels and tape measures provided more than adequate precision, laser sighting equipment was not necessary. The as-built C-coil geometry was incorporated in the feedback control algorithm to compensate for all of the deviations from the basic geometry.

STRUCTURAL SUPPORTS

Early design concepts for attaching the C-coil to the tokamak called for "standard" mounting brackets, with a few exceptions for special cases. These brackets, in a flat plate, channel, or angle configuration, were to attach to existing brackets on the poloidal field coil box beams. After careful study of the tokamak and the path of the C-coil, the conclusion was that half of the brackets would have to be custom made at a prohibitive cost; thus a better design was needed. Alinabal [10] commercial aluminum turnbuckles (struts) with aluminum spherical rod ends were found to be an extremely flexible and inexpensive method for attaching the coil structures to the tokamak. Although each location was unique, a typical installation would have five strut pairs on both the upper and lower horizontal legs of each coil section, one pair on either end, and the remaining three pairs evenly spaced on 32 in. centers across the legs as shown in Fig. 6. Each pair was installed in a 3-bar linkage configuration. The maximum load calculated for the struts installed in this configuration was 12.5 kN (2800 lb), well below the 30 kN (6720 lb.) critical buckling load. Stability in the structure is provided by the vertical legs of the coils and by the offset in the mounting locations of the support struts. These one inch diameter struts, developed for the automotive racing industry, were available "off the shelf" in a wide range of lengths and rod end diameters. Each strut assembly was able to provide two inches of adjustment, which was found useful in adjusting (steering) the coil structures to the desired final positions. The spherical rod ends also provided angular compliance for the differential movement between the stationary poloidal field coil cases and the toroidal field coils,

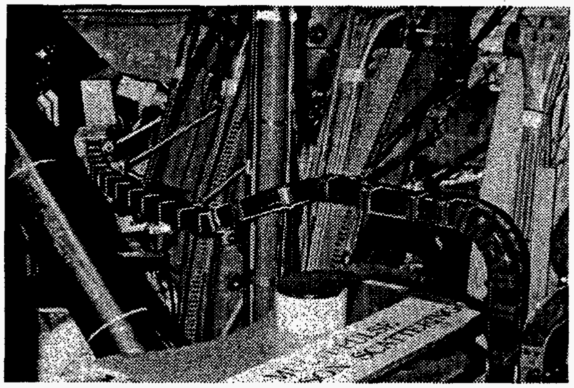

Fig. 6. C-coil installation at 109°–169°.

now linked through the C-coil. (The toroidal field coils can translate up to 0.25 in. toroidally during a shot.) In addition to the poloidal field coil box beams, beamline flange bolts, an obsolete limiter mounting structure, and toroidal field coil clamping studs were utilized to support the coil. Fig. 6 illustrates the completed installation of the coil at 109°–169°, one of the easier sections to install.

EXPERIMENTAL RESULTS

The C-coil is now in routine use during plasma operations on DIII–D as a tool to help avoid plasma instabilities like locked modes. The currents in the C-coil sections are optimized for maximum error field correction during plasma discharges by a digital real-time feedback control system. The algorithm used to calculate the required C-coil currents is based on minimization of the lowest order error field mode components, using the poloidal and toroidal field coil currents along with previous measurements of their contributions to the error field as input parameters.

Experiments have also been done in which the phase and amplitude of the C-coil field are systematically scanned to find optimal values which increase the stable operating parameter space of the tokamak [11]. Fig. 7 shows the results of an experiment in which the C-coil was used to achieve stable operation at densities a factor of three lower than would have been possible without error field correction. This capability is important for experiments studying plasma heating effects, which are more pronounced at low density.

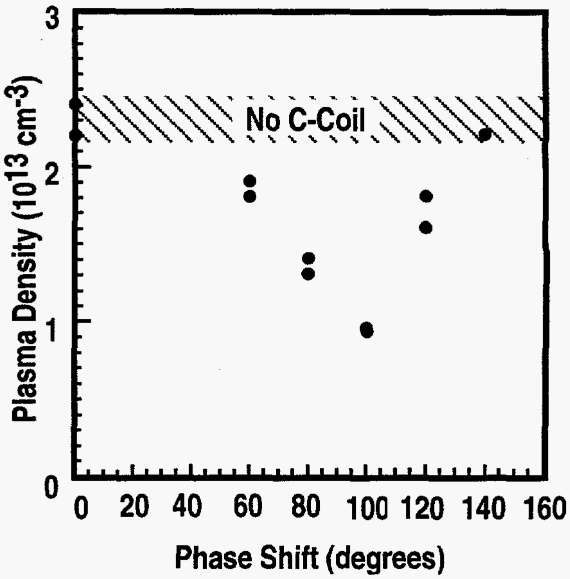

Fig. 7. Threshold density for the onset of locked modes as a function of the phase of the C-coil correction field for optimal C-coil current.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the large group of people who contributed to the completion of this project, including J. Cometa, R. Gibson, and J. Upham for design work, C. Baxi, T. Hodapp, R. La Haye, P. Petrach, K. Redler, E. Reis, T. Taylor for technical assistance, and G. Cox, G. Vavrunek, R. Williams, and the Chula Vista Electric Crew who so skillfully installed the system.

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