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the Advantages of Cable-in-Conduit Forced-Flow
and Pool-Boiling Magnets**

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ASSESSMENT OF A MAGNET SYSTEM COMBINING THE ADVANTAGES OF CABLE-IN-CONDUIT FORCED-FLOW AND POOL- BOILING MAGNETS

ABSTRACT

ASSESSMENT OF A MAGNET SYSTEM COMBINING THE ADVANTAGES OF CABLE-IN-CONDUIT FORCED-FLOW AND POOL- BOILING MAGNETS

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This paper presents an idea for a magnet system that could be used to advantage in tokamaks and other fusion engineering devices. Higher performance designs, specifically newer tokamaks such as those for the International Tokamak Engineering Reactor (ITER) and Tokamak Physics Experiment (TPX) use Cable in Conduit Conductor (CICC) forced flow coils to advantage to meet field and current density requirements. Pool boiling magnets lack structural integrity to resist high magnetic forces since helium cooling areas must surround each conductor. Additionally the need for open cooling paths in pool boiling magnets precludes the effective use of solid film insulation within the coil bundle thus limiting their operating voltage. CICC magnets eliminate these disadvantages by using internal cooling. However, the CICC system introduces other disadvantages. Leakage is more likely and harder to repair than with pool boiling magnets. The single, heavy wall case of pool boiling magnets is replaced by kilometers of relatively thin wall conduit which must seal high pressure, cryogenic helium from the insulating vacuum space. Experience with The Magnet Fusion Test Facility (MFTF) and other facilities have shown leakage problems and the resultant quality control requirements of systems containing extensive helium piping to be very difficult. A second problem is that any leak can threaten the voltage standoff integrity of the magnet system. This is because a leak can result in low-pressure helium gas becoming trapped by limited conductance in the magnet bundle and low-pressure helium has poor dielectric strength. The system proposed here is basically a CICC system, with its inherent advantages, but bathed in higher pressure supercritical helium to eliminate the leak and voltage break-down problems. Schemes to simplify helium coolant plumbing with the proposed system are discussed. A brief historical review of related magnet systems is included. The advantages and disadvantages of using higher pressure, supercritical helium in combination with solid electrical insulation in a CICC system are discussed. Related electrical test data from some previous works are compiled and discussed.

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INTRODUCTION

A concept of encasing and bathing the coil bundle of cable in conduit magnets with supercritical helium is presented here. There are advantages to this design approach where magnet reliability is critical because the risk of leaks to the vacuum space can be substantially reduced. Reliability is very important for Tokamak magnets such as those in the present ITER and TPX designs. Tokamaks preclude easy removal of the TF (toroidal field) and lower PF (poloidal field) magnets because of interlocking, complex, welded structure and requirement for remote handling.

This paper covers the pros and cons of the helium flooded and vacuum operated CICC magnet systems.

OVERVIEW

Helium flooded magnets could substantially improve reliability compared to ones operating in a vacuum because the risk of leaks is greatly reduced. In the case of vacuum operation, the long lengths of relatively thin walled conduit and associated insulators and attachments must be vacuum tight. In the case of helium bathed magnets the vacuum to helium boundary is moved to a relatively thicker walled magnet case presenting much less area for potential leak paths.

Experience with MFTF at LLNL has shown that heavier walled magnet cases requiring multipass weld build-ups do not leak whereas tubing and fittings connections with single pass welds are leak prone. During MFTF construction approximately 100 leaks were found in tubing welds and thin walled nitrogen panels. MFTF has approximately 5000 tubing joints. No leaks were found in the welded magnet cases. This was expected since the successive passes of multipass weldments tend to cover over flaws in any one pass.

MFTF is similar to tokamak designs in that it is an extensive structure with relatively long flow paths. Consequently leak hunting is a difficult task. The long flow paths slow the more sensitive leak hunting techniques where helium, entering a leak, has to travel long distances to reach the detector. About nine man-years were required during MFTF construction to locate and repair leaks before operation could begin. Not all leaks were found. Extra vacuum pumping capacity was needed to maintain an acceptable insulating vacuum.

Magnets wound with CICC conductor tend to increase the possibility of leaks compared to pool boiling magnets for the following reasons:

- a. The entire length of the relatively thin walled conduit winding constitutes potential leak sources.
- b. Most of the conduit is within the magnet bundle where it is inaccessible and not repairable.
- c. Numerous joints and taps are required for coolant flow and diagnostics.
- d. Numerous electrical insulators are required for the magnet coolant connections. Insulators inherently have a higher leak potential than welded metal joints.

Improved quality control (compared to MFTF) and extensive component testing would reduce the risk of leaks. Non destructive testing using acoustic emissions and other techniques are under study for the production of conduit.

The approach suggested by this paper circumvents the leak problem and associated quality control requirements by making leaks in the conduit, joints and insulators unimportant. This is done by moving the pressure boundary to the much thicker magnet cases.

Leaks present two problems. First they can destroy the insulating vacuum required to maintain cryogenic temperatures. Second they can degrade the vacuum resulting in relatively low voltage breakdowns through low pressure helium.

Present designs for both ITER and TPX magnets call for operation in a vacuum. The TPX design does include the capability, with some modifications, of helium flooding should unrepairable leaks occur in any of the 16 TF coils. One of the strong reasons for building TPX prior to the larger ITER machine is to determine workability and reliability of a large number of magnets of this design.

A COMPARISON OF CICC AND POOL BOILING MAGNETS

The proposed system combines some of the advantages of pool boiling and CICC magnets. Consequently it is helpful to understand the features of these magnet systems.

Pool boiling magnets are simpler in construction however they have some disadvantages that limit their use in high performance magnets. Coolant paths must be provided between each turn to permit helium coolant to contact the conductor. The resultant open areas reduce the strength of the winding. These open areas also preclude the effective use of solid electrical insulation between windings thus requiring the magnet to operate at lower voltages.

CICC magnets eliminate these disadvantages by flowing coolant inside a conduit containing conductor strands. Here the exterior of the conduit does not need to be cooled and it can be wrapped with solid electrical insulation and tightly packed into a strong magnet winding. However, coolant connections to the CICC magnet are more extensive and difficult and the leak potential is greatly increased as discussed above.

The proposed magnet system retains the CICC conductor with internal cooling so as to permit the use of solid insulation and a tightly packed, strong magnet winding. However, the leak potential of the CICC magnet is eliminated by pressurizing the area in the magnet winding external to the conduit and thus moving the pressure boundary to the magnet case as is the case with pool boiling magnets.

PERMISSIBLE LEAK SIZES FOR HELIUM FLOODED AND VACUUM OPERATED CICC

The proposed system makes leaks in the conduit, insulators etc unimportant because helium is intentionally present both inside and outside these components. The size of a permissible leak can be quite large since the only requirement is that it does not significantly divert coolant from the conductor. Typically a 1 mm diameter hole or less can easily meet this criteria. A leak this size can readily be detected by pressure decay or other means involving minimal testing and quality control.

Conversely, when sealing 5 K, 6 atmosphere helium from vacuum, as required when operating CICC in a vacuum, a leak that is not measurable at room temperature can degrade the insulating vacuum. An experience during the operation of FENIX demonstrates this. A leak in a helium coolant tube developed after several weeks of leak free operation resulting in loss of the insulating vacuum. After warming to room temperature for repairs, the leak could not be found by any normal leak hunting techniques. The problem was solved by replacing tubing sections in the suspected areas.

VOLTAGE AND INSULATION CONSIDERATIONS

The main concern of operating CICC magnets in helium as suggested here centers around voltage breakdown risks. A high vacuum is an excellent insulator whereas helium under some conditions has poor dielectric strength. TPX and other Tokamak designs require high voltages (several kV) for inductive ramping of the plasma current as well as fast current dumps required for coil protection.

Voltage break down in Helium

Helium dielectric strengths vary greatly. The lowest strengths reported⁵ are for tracking voltages (along solid surfaces) with warm helium present. Values as low as 2 kV/cm have been measured.¹ Conversely helium appears to be an excellent insulator at cryogenic temperatures without tracking solids present. Typical values of 200 kV/cm are reported.^{2,3,4,5,6,7}

Although magnet systems operate at cryogenic temperatures where helium dielectric strength is good, high temperatures (typically 150K) can be reached during a magnet quench. The proposed system would operate at several atmosphere pressure to improve dielectric strength and these pressures could be relied upon with proper cryogenic system design. A number of studies^{2,3} show a near linear improvement of breakdown voltage with increasing density (associated with higher pressures) thus substantial improvements over the lower value of 2 kV/cm can be expected resulting in reasonable dielectric strengths for system design. It is further expected that tracking voltages can be substantially increased by use of proper configurations at the so called triple point (the junction of electrode, dielectric and gas). Tracking break down testing is done with the voltage gradient along to solid surface.

Solid sheet insulation across the gradient or at a large angle to the gradient should improve conditions.

Voltage Break down in a Vacuum

The dielectric strength of a good vacuum is extreme high. Figure 1 is the Paschen curve for helium showing high dielectric strengths in a vacuum. The concern with operation of a magnet system in a vacuum is that should a leak occur, low pressure helium from the leak could be trapped by diffusion limitations of the potted magnet bundle resulting in conditions near the Paschen curve minimum. Helium pressure is unpredictable since both the size of the leak and diffusion constant of the magnet bundle are unpredictable. Using typical values for:

- a. helium leak rates in existing systems
- b. diffusion constants for potted coils with expected cracks or imperfections
- c. breakdown path lengths

it can be shown that breakdown voltages of 200V or less can occur.

In either helium or vacuum operation we should assume some cracks will exist between layers of insulating film either initially or after thermal and mechanical stress cycling. By using multiple layers of thin film insulation (such as Kapton or Mylar) it would appear open paths or cracks along the voltage gradients could be eliminated. That is cracks between the film layers are at near right angles to the voltage gradient. A test program is recommended to study how effective such layers are in real geometry's such as tubing tees and CICC joints under conditions of high vacuum, poor vacuums, and higher pressure helium.

Using only film insulation without potting or other fillers has the advantage of permitting slippage between film layers caused by thermal movement. Westinghouse had problems with fillers tending to tear the film insulation and they solved the problem by using only Kapton film in their LCP coil. One can speculate that stresses in a potted insulating system can cause cracking through the film layers resulting in undesirable open paths at right angles to the conductor and along the voltage gradient.

DESIGN OF A HELIUM FLOODED TF COIL

An example of a helium flooded TF coil is shown in figures 2,3,4. Here the coil is pancake wound with parallel flow paths entering each pancake on the outside diameter of the magnet. Another advantage of the flooded case magnet is shown here. It is the possible elimination of coolant connections and insulators at the conductor. In figure 3 the return helium also floods the case via a common plenum and individual pancake passes through notches cut in the conduit. Substantial savings in costs, required room, and complexity can be realized by thus eliminating numerous fittings, connections and insulators.

HISTORICAL INFORMATION

Information concerning advantages and disadvantages of different magnet systems can be obtained from existing magnets. A very brief review highlighting relevant information follows:

Detector Magnets

About a dozen superconducting detector magnets have been built high energy physic accelerators. All of these magnets operate in vacuum and have had little or no problem with leaks or voltage breakdown over the years. This experience tends to support use of vacuum operated coils. However, none use CICC conductor. Typical construction of detector magnets utilize an aluminum bobbin or cylinder. The conductor, usually aluminum stabilized and not containing coolant paths, is insulated and wound on the inside of the bobbin either as a wet lay-up with epoxy or layed-up then vacuum impregnated. Design is such that cool down results in greater contraction by the bobbin resulting in a tightening bond between the bobbin and conductor to insure good thermal contact. The bobbin is then cooled by helium flowing in paths on the outside of the bobbin.

Although detector magnets represent successful operation of magnets in vacuum there are differences between them and CICC magnets as can be seen from the above description. In detector designs helium plumbing can be made more substantial and accessible and have fewer connections and insulators. Helium is separated from conductor voltage by the aluminum bobbin. If helium does leak it goes directly to the open vacuum space where it can be

readily detected. It cannot be trapped in the presents of conductor voltage as is the case in CICC magnets. Still voltage break down is a concern in detector magnets. Typically operating voltages are limited to a few hundred volts. Leads are well insulated in G-10 tubes and insulators in helium lines are limited to two or three required to support vapor cooled leads. One exception is the proposed GEM detector magnet for SSC. Its design is similar to that described above except the conductor does carry a helium flow path to aid in heat distribution from joints and possible flaws in the conductor to bobbin epoxy joint.

T-15 Tokamak

T-15 is a 2.4 m tokamak located in Moscow. It utilizes superconducting TF magnets (PF magnets are resistive) operating at 4.5K. Conductor is not CICC but uses helium flow paths within a copper stabilized NiSn solid conductor. The conductor operates in a vacuum. Initially operating voltage (dump voltage) was 500 V with a center tap resulting in 250 V to ground. Initial testing resulted in some voltage break downs due to helium leakage, possible helium trapping within the solid insulation and imperfect solid insulation. The problem was solved by reducing dump voltage to 250 V (125 V to ground) and improving solid insulation.

Westinghouse Coil for LCP

The Westinghouse coil was built for testing at the Large Coil Test Facility (LCP) at ORNL. It is a CICC, NiSn magnet operating in a vacuum. It proved successful and had no leak or voltage break down problems during testing. Westinghouse did enclose the magnet in a case such that it could be pressurized with helium if leaks had occurred. Their concern was that troublesome leaks might have occurred that were too small to detect during room temperature testing. Extensive leak testing was done during construction.

Some voltage break down problems did occur during construction. A glass wrap insulation damaged Kapton film wraps. The solution was to use only Kapton film insulation. Epoxy potting was not used to permit thermal movement between the Kapton film and the conductor.

SUMMARY

On balance the decision of operating CICC magnets in a vacuum or supercritical helium environment is an engineering judgment call. Current Tokamak designs lean toward magnets operating in a vacuum. It is the author's judgment that operation of the TF coils in supercritical helium is the better choice based on his experience with MFTF and other systems. If the vacuum option is chosen, the design should include the capability being modified for helium flooding should unrepairable leaks occur. TPX follows this design concept. Thus the TPX project will provide invaluable information for future reactor size Tokamaks such as ITER regarding magnet reliability and design.

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Fig. 1 PASCHEN CURVE FOR HELIUM

Fig. 2 HELIUM INLET ARRANGEMENT FOR FLOODED TF COIL

Fig. 3 HELIUM OUTLET PLENUM FOR FLOODED TF COIL

Fig. 4 HELIUM OUTLET (OR INLET) PLENUM WITH VOLTAGE
STAND-OFFS

Fig. 1 PASCHEN CURVE FOR HELIUM

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Fig. 4 HELIUM OUTLET (OR INLET) PLENUM WITH VOLTAGE
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PASCHEN CURVE FOR HELIUM

Fig. 5

TENTATIVE SECOND CHOICE FOR TF COIL SHE FLOW ARRANGEMENT

- CAN BE USED IF COIL IS NOT POTTED OR AREA BETWEEN CASE AND CONDUIT IS LEAKY

VOLTAGE STANDOFFS FOR TF COIL PLENUMS

Fig. 7

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