Cryogenic Aspects of a Demountable Toroidal Field Magnet

System for Tokamak Type Fusion Reactors

by

S. Y. Hsieh, J. Powell, J. Lehner

Department of Applied Science
Brookhaven National Laboratory
Upton, NY 11973

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Abstract

A new concept for superconducting Toroidal Field (TF) magnet construction is presented in this paper. It is termed the "Demountable Externally Anchored Low Stress" (DEALS) magnet system. In contrast to continuous wound conventional superconducting coils, each magnet coil is made from several straight coil segments to form a polygon which can be joined and disjoined to improve reactor maintenance accessibility or to replace failed coil segments if necessary. In this paper, we present a design example of a DEALS magnet system for a UWMAK II size reactor. The overall magnet system is described, followed by a detailed analysis of the major heat loads in order to assess the refrigeration requirements for the concept. Despite the increased heat loads caused by high current power leads (200,000 amps) and the coil warm reinforcement support system, our analysis shows that at most, only about one percent (~ 20 Mw) of the plant electrical output ($\sim 2,000$ Mw) is needed to operate the magnet cryogenic system. The advantages and the drawbacks of the DEALS magnet system are also discussed. The advantages include: capability to replace failed coils, increased accessibility to the blanket shield assembly, reduced reliability requirements for the magnet, much lower stress in conductor, easier application of improved high field brittle superconductors like Nb_3Sn , improved magnet safety features, etc. The drawbacks are the increased refrigeration requirements and the necessity of a movable coil support system. A comparison with a conventional magnet system is made. We conclude that the benefits of the DEALS approach far outweigh its penalties, and that the DEALS concept is the most practical, economical way to construct TF magnet systems for Tokamak reactors.

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1. Introduction

The toroidal field (TF) coils in a Tokamak fusion reactor have to be interlaced with the plasma chamber, OH and poloidal field coils, and the neutral beam, coolant and vacuum lines, etc., in a very complex arrangement. This makes the construction of the reactor cumbersome since the continuously wound TF coils have to be built on site first and the rest of the reactor components installed inside the coil assembly afterwards. This will create serious problems of space and accessibility and will require complicated installation procedures for that part of the reactor system inside the TF coil assembly. Figure 1 shows the complicated structures of the ORNL Tokamak EPR design.⁽¹⁾ In addition, the replacement of a failed TF coil after construction would be extremely difficult, if not impossible, which then requires that the TF coil system must be very reliable over its 30 year service lifetime. Replacing a failed TF coil in this type of reactor construction would involve removing and replacing a large number of highly radioactive, massive components with many major cuts and seals to be made. This means a very long plant down time, even if it were technically feasible, reduced plant availability and large capital losses. Figure 2 illustrates how TF coil reliability requirement depends on plant availability and replacement time. Conventional TF coils will have to be orders of magnitude more reliable than has been demonstrated to date if plant availability is to be above an acceptable limit of ~95%.

This paper presents an alternative TF coil concept which should avoid the above difficulties. This design concept is called the "Demountable Externally Anchored Low Stress" (DEALS) magnet system, and is intended to provide easier coil installation for reactor construction, as well as improved accessibility for reactor maintenance and repair. This magnet appears to be the most practical and economical method for Tokamak TF magnet systems. It may also be applied to other large

superconducting magnet systems. The penalty of the increased refrigeration due to coil supports and high current leads appears to be quite acceptable.

2. DEALS Magnet System

Each of the TF coils will be formed by several straight coil segments which could be readily joined (or disjoined) to form a polygon, in contrast to conventional wound coils, which would be either circular, oval, or D-shaped constant tension coils. In this design exercise, a rectangular shaped coil was chosen and sized to match overall dimensions of the UWMAK II constant tension D-shaped coil design, as shown in Figure 3.

A brief description of the DEALS conductor design, coil segment fabrication, coil assembly and coil support system is given in this paper. A more detailed description of the DEALS concept is given elsewhere.⁽³⁾

(A) Conductor design and coil segment fabrication

The following very desirable conductor design goals can be achieved with the DEALS magnet design concept:

- a. high current capability ($\geq 10^5$ amps);
- b. mechanical rigidity;
- c. cryostabilized (heat transfer coefficient $< 0.4 \text{ w/cm}^2$) and well cooled;
- d. simple, mass produced conductors and coil segments.

These requirements can be met with straight length flat plate type conductors of the type shown in Figure 4. Basically, the finished conductor is a long copper/SC plate with length ℓ , width w , and thickness t . Both ends of the conductor are machined to a thickness of $t/2$ for joining to other conductors during the coil assembly process. The cross section of this conductor in Figure 4 illustrates the simplicity of the design. The superconductor can be transposed braid or any other superconducting wire or tape. It is sandwiched between copper plates that are held

together by solder, a process similar to the construction used for the superconducting bubble chamber magnets. The cooling grooves are machined on both sides of the conductor plate as indicated in the same figure. The conductor for this design is 1.0 cm thick and 1.0 meter wide, and is fabricated in 20 and 30 meter lengths to form a 20 m x 30 m rectangular coil when assembled. The finished conductor plates are then stacked in a steel case which also serves as the liquid helium dewar (Figure 5). Insulating ceramic or organic composite plates are placed between the conductor plates during this assembly process. The photograph shows two cardboard models of 20 m and 30 m long coil segments. Each segment contains fifty conductor plates, with insulating plates between conductors and around the inside perimeter of the case. These fabricated coil segments are the basic units of the entire TF coil system, that is, all the coils are formed from these units. If any coil segment malfunctions, it can be replaced by a spare unit of corresponding length.

(B) Coil assembly

As mentioned above, each TF coil is formed from the basic coil segments, and there is no coil winding process on site. Instead, coil segments are joined together as shown in the center diagram of Figure 3. In this case the conductor ends are soldered together by inserted heater plates, which are later replaced by insulator plates to complete the turn-to-turn and coil-to-ground insulation. The finished coil is a 20 m x 30 m rectangular magnet as indicated schematically in Figure 3. It should be noted here that ceramic insulators can be used since the coil segments are straight lengths and no bending is required.

As a result of the end joining process, the conductor plates are all connected in series in a spiral form. The beginning and the end of the conductors in the rectangular multi-turn coil can then be connected to power leads or to neighboring TF coils. Each TF coil consists of 50 turns and there are 24 coils all together.

Table 1 shows some of the design parameters of a DEALS magnet system for a UWMAK II type fusion reactor.

The final step in the TF coil construction after the corner conductor joining process is to weld the corner cases and straight coil case sections together to form an integral helium dewar. Sleeve reinforcement is then welded around the corner region to strengthen its mechanical rigidity. It should be emphasized here that the soldering of the conductor plates is for electrical contact only. The welded corner case and the reinforcement sleeves provide the primary distributed rigid conductor support in the joint area. The actual coil and corner support depend on the coil support system which consists of 50 coil support pads of low thermal conductivity, and an external hydraulic support system which will be designed to automatically adjust the inplane and outplane loads to counteract the force loadings created by magnetic field and to compensate for the thermal expansion and contraction of the coil. One of the support pads is shown in Figure 6. Figure 7 shows how the load is transmitted from the coil case, via support pad, to an external room temperature hydraulic system which then transmits the magnetic loads to an external warm reinforcement support structure, such as a PCRV (Prestressed Concrete Reactor Vessel) similar to those used in some fission reactors. A preliminary stress analysis shows that average conductor stress is lower ($4 \times 10^7 \text{ N/m}^2$) and compressive in nature. Conventional wound coils have much higher stresses which are tensile in nature. The details of the stress analysis and coil support system is described in another paper.⁽³⁾

3. Major Heat Loads and Cryogenic Requirement

While the coil support system is analyzed separately elsewhere, the intent of this paper is to investigate whether the increased heat load created by high current leads and the external warm support system together with other heatloads for the system is reasonable. These heat input estimates are described below.

(A) Eddy current in copper

The configurational similarity between this coil conductor arrangement and conventional transformer core laminations results in much lower matrix AC losses due to the pulsed poloidal fields as compared to conventional wound coils with relatively much wider conductors. The alternatively stacked conductor and insulator plates in this coil design are made parallel to the direction of the pulsed field, in contrast to most superconducting coil designs where the wide surface of the conductor has to be wound perpendicular to the direction of the pulsed field. M. N. Wilson's⁽⁴⁾ formula for a conductor slab of thickness $2a$ parallel to the field pulse was used to estimate the losses.

$$Q = \frac{2(\Delta B)^2 a^2}{\pi^2 \rho t} \text{ (joules/m}^3\text{)} \quad (1)$$

where $a = 0.005$ m in the present conductor design; ΔB is chosen to be 0.5 Tesla; ρ is the resistivity and its average value is estimated to be 5×10^{-10} Ω -m as was used by ANL's EPR study;⁽⁵⁾ t is the rise time of 1 second. The burn cycle for a power reactor of UWMAK II type is expected to be on the order of 1000 seconds. This gives 2.88 kW (4°K) eddy current loss for a set of 24 DEALS coils. It should be noted that the computation does not include the shielding effect which could reduce the losses by another factor of 10, as suggested in ANL's EPR design.⁽⁵⁾

There are also eddy current losses in the coil case, but this term will not be considered in the present study. Knowing that the resistivity of stainless steel is several orders of magnitude higher than copper, the coil case's contribution to the losses should not cause any concern at this stage of study.

(B) Hysteresis in superconductor

This calculation was made on a thin sheet of superconductor of 1 mm thick and

1 meter wide, with the surface of the superconductor parallel to the pulsed field. The following formula from M. N. Wilson's work⁽⁴⁾ was used for this estimate.

$$Q/Q_o = \frac{\beta}{12} \text{ (joules/m}^3\text{) for } \beta < 2 \quad (2)$$

$$Q/Q_o = \left(\frac{1}{\beta} - \frac{4}{3\beta^2}\right) \text{ (joules/m}^3\text{) for } \beta \geq 2 \quad (3)$$

where $\beta = \frac{AB}{\mu_o J_c a}$, $Q_o = \frac{(AB)^2}{2\mu_o}$ and $2a$ is the thickness of the superconductor sheet.

These equations were plotted and the maximum of Q/Q_o was used to compute the hysteresis losses. This gives the total hysteresis loss of 2.16 kW (4°K) for the entire coil system.

(C) Power leads

The heat load through the gas-cooled leads is by far the largest loss in this design because of the high magnet current. According to the power lead analysis by General Electric Co., the loss is linearly proportional to the current carried and is 3.0×10^{-3} liter/hour/ampere/pair.⁽⁶⁾ Therefore, a set of twenty-four pairs of leads carrying 200,000 amps would require 14 MW of electrical power during operation to run a helium liquefier or refrigerator. In actual practice, coils can be grouped together and connected in series to reduce the number of power lead pairs required, if desired. Hence, 14 MW(e) would be the maximum room temperature power requirement for leads and this power requirement could readily be cut by a factor of 2 or 3. In addition, the value of 3×10^{-3} liter/hour/amp/pair is quite conservative as compared with the optimized power lead calculations of Hilal⁽⁷⁾ (100% Carnot efficiency). He projects an ideal power requirement of 300 W(e)/kA pair. With practical refrigerator efficiencies of ~25%, the input power required to overcome lead heat leaks would be only 5 MW(e).

(D) Coil case support pads

One of the coil case support pads is shown in Figure 6. Fifty such support pads per coil were chosen for this estimate. Both inplane and out-of-plane supports are assumed to be included in this number.

According to a previous report,⁽⁸⁾ a support pad of epoxy fiberglass and stainless steel laminate, half a square meter in area and 10 cm thick, can be designed for a 2 watt heat leak from a 20°K heat station to the 4°K coil case region. Hence, the heat load per coil is 100 watt and the total load is 2.4 kW (4°K).

(E) Conductor joints

This coil construction method will definitely eliminate the tedious on-site coil winding process and the required winding machineries in the conventional design. However, the superconductor is no longer continuous and has to go through a resistive region at each conductor joint. In this design, there are 200 joints per coil and this may cause some concern about the Joule heating created at the joints. It turns out that the losses at the joints are insignificant provided that good electrical contact can be maintained. Since good electrical contact was set as our design goal in the support system⁽³⁾, the heat load can be estimated as follows:

Assume that the copper thickness between the superconductor at the joint is 2 mm thick. The resistance of a 2 mm thick resistive region with area 1.0 m x 1.0 m is given by

$$R = \rho \frac{L}{A} = 5 \times 10^{-10} \Omega\text{-m} \times \frac{0.002}{1 \times 1} = 10^{-12} \Omega . \quad (4)$$

The loss per joint is therefore,

$$I^2 R = (2 \times 10^5)^2 \times 10^{-12} = 4 \times 10^{-2} \text{ watt} . \quad (5)$$

And the loss per coil is

$$200 \times 4 \times 10^{-2} = 8 \text{ watt} \quad (6)$$

which results in 192 watts of total loss for a set of 24 coils. There are films of solder between the joint and between the superconducting braid (assuming 1.0 m wide continuous braid was used) and the copper stabilizer; however, their total thickness is less than a tenth of a millimeter and their contribution to the losses is negligible.

(F) Others

Calculation procedures for additional heat loads due to thermal radiation, instrumentation penetration, nuclear heating, etc., will not be discussed since their contribution is found to be insignificant compared with the major items described above. The nuclear heating in the UWMAK II design is 408 watts and we assume the same value for this design. The heat leak due to instrumentation penetrations is less than 200 watts. This is based on one-thousand 1 meter long No. 30 copper wires (per coil) connecting the room temperature and 4°K regions. Finally, the thermal radiation loss is estimated at ~250 watts. This number is based on the heat leaks from the 80°K radiation shield to the 4°K coil case as shown in Figure 6. The heat leaks from room temperature dewar to the 80°K radiation shield was not included. It should be pointed out here that the room temperature dewar and the radiation shield were designed to be permanent system components. The coil segment, shown in cross section in Figure 6 will be installed in or removed from this dewar complex through tracks and access space designed into the support structure.^(2,3) The support pads are detachable from the coil case. Details of the coil segment installation and removing processes are described elsewhere.⁽²⁾

Using a conversion factor of 326 W/W⁽⁹⁾, the above estimated heat loads require about 17 MW(e) of input refrigeration power. Therefore, 20 MW of room temperature refrigeration power should be more than adequate to handle the entire TF magnet

system. This is approximately one percent of the electrical output from a 2000 MW(e) reactor of the UWMAK II size. This preliminary analysis thus implies that the refrigeration load for the DEALS magnet system is well within the acceptable range. Furthermore, the above estimate is the maximum anticipated heat load. In an optimized design, the refrigeration requirement can be significantly lowered due to several factors:

a. One pair of 200,000 ampere power leads for each coil was used for the refrigeration requirement. If every three coils are connected together internally and shared the power leads, a factor of 3 of refrigeration power can be saved. In fact, due to the low coil inductance (0.3 henry per coil), the total inductance of a 3 coil set connected in series would have the same inductance of an ANL's second generation EPR coil (1.04 henry per coil), and should not hamper the energy removal capability. The use of thick ceramic insulators (~ 0.5 cm between turns and 2 cm between coil and ground greatly increases the voltage withstanding capability for faster energy removal.⁽²⁾

b. The AC losses in copper matrix and the hysteresis losses in superconductor are somewhat overestimated, since solid plate or sheet were used in both calculations. The spaces in the copper matrix occupied by the superconductor and the machined cooling grooves were not considered in the analysis. Similarly, the benefit of the filamentary nature of the superconducting braid was not included in the hysteresis loss calculation. Therefore, both losses are too high. In addition, further reductions can be achieved by shielding.⁽⁵⁾

c. The heat load due to the support pads was estimated using the best available data⁽⁸⁾ and the values should be reasonably correct. Thicker support pads could reduce these heat leaks, however. The remaining heat loads were conservatively estimated but are relatively small and will not significantly affect the final total heat leak even if they can be reduced.

We therefore concluded that the refrigeration load for the DEALS magnet system is low enough that the benefits of the DEALS system will not be significantly compromised by refrigeration considerations.

4. Discussion

The bolted magnet is not new. Many conventional copper magnets were constructed with bolted joints. For example, the Doublet II TF magnet⁽¹⁰⁾ is actually a set of rectangular copper coils bolted together in a spiral form. However, the application of this idea to superconducting coil winding is a fundamental departure from the conventional way of making superconducting magnets. It is therefore necessary to justify the DEALS approach for Tokamak fusion reactor TF coils. One must assure that:

- . There are no fundamental technical obstacles.
- . The benefits of this design outweigh the penalties.

The major differences between DEALS coil and conventional coil designs are the deviation from continuous winding and, in the case of the D-shaped coils, constant tension. According to our analyses⁽²⁾ there are no fundamental problems in these two areas. First, the coil can be adequately supported^(2,3) to give relatively low stress in the coil, in fact, well below the stress levels in conventional coil designs. Second, the conductor joints can be soldered and sufficiently supported to assure good electrical contact and mechanical rigidity. There do not appear to be any other fundamental questions associated with the DEALS magnet design concept.

It is generally required that complex machines be demountable and serviceable, unless the unit is cheap enough to be discarded if malfunctions occur. Fusion reactors will certainly not fall in this latter category. A major advantage of the DEALS magnet concept is its demountability, in contrast to the continuous winding

conventional coils. Actually, the DEALS magnet concept offers additional benefits besides demountability. These include:

- . Because failed magnet segments can be readily replaced, the reliability and quality assurance requirements on superconducting magnets do not have to be as stringent.

- . The identical conductors and the magnet coil segments can be fabricated, mass produced and tested at a central factory using present techniques and then shipped to reactor sites. Field assembly work for a DEALS magnet will be much less for conventional superconducting magnets.

- . Stress in the DEALS conductor is much less than for conventional superconducting magnets, as a result of the distributed external support reinforcement.

- . Reinforcement can be a PCRV (Prestressed Concrete Reactor Vessel) or other warm structure, instead of more expensive cold reinforcement.

- . The straight length conductor geometry and the low stress in the conductor allows the use of brittle high field superconductors such as Nb_3Sn , etc. For the same reason, straight length ceramic plate can also be used for electrical insulations, thus improving the radiation durability as compared with organic insulators.

- . Conductors can be shaped and placed to minimize pulsed field losses.

- . Low coil inductance (less than 1 henry) minimizes energy extraction time in quench or accident situations.

- . Finally, in comparison to the conventional TF magnet system, the cost reductions from the simpler coil fabrication and assembly process should be substantial. Also, the much shorter repair time for replacing a failed coil segment could save a considerable amount of money due to decreased reactor down time.

Benefits and advantages other than those suggested above can be derived from the DEALS design concept such as MAXAMAK and MULTIMAK.⁽¹¹⁾ For example, the

rectangular magnet can be made taller while retaining its width to gain more accessibility for blanket and chamber maintenance, while the overall size of a conventional coil would have to increase much more to achieve the same goal. Similarly, with the DEALS concept, the TF coil assembly height could be increased so that several plasma chambers could share the same TF coil system. This would significantly increase reactor output without increasing its diameter. Finally, all the outside vertical coil segments or all the top horizontal coil segments could be disconnected and removed to gain the maximum accessible space for reactor repair and maintenance. These advantages are explored in detail in another paper.⁽¹¹⁾

However, there are a few penalties of the DEALS concept:

- . The increased heat load caused by high current power leads and coil support pads.

- . The requirement of a carefully designed massive coil support system which not only supports the coil during magnet operation but also has to be retractable to provide access space for removing and inserting coil segments.

Actually, these two penalties are probably not as significant as they might seem, since the conventional TF coil systems are tending to bear the same burden. For example, in ANL's second generation EPR design,⁽¹²⁾ the coil inductance is reduced to 1.04 henry (19.5 henry originally) by using fewer conductor turns and an increased operating current of 60,000 amperes, which will suffer a similar heat leak penalty to DEALS. A second example is the MIT's collisional Tokamak design⁽¹³⁾ which generates high maximum magnetic fields (15 Tesla) and is relatively compact in size compared to the UWMAK II fusion reactor. However, the D-shaped coil system is designed to be enclosed in a massive cold steel support structure somewhat similar to the DEALS magnet PCRV support reinforcement. In practice, the DEALS support structure can accommodate the thermal shrinkage of the coil via the hydraulic

system while the rigid cold steel support structure in the MIT design may still face the differential thermal contraction problem between different metals. It appears that the coil support structure, cold or warm, will be a required feature in any TF magnet coil designs when the peak field goes beyond 10 Tesla.

Based on our analyses, we conclude that the DEALS magnet design concept appears to be the most practical and economical way for Tokamak reactor TF coil construction. Further study and experimental investigation should be carried out so that more detailed comparisons with conventional magnet designs can be made.

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Figure 1

Figure 2

Figure 3

CROSS-SECTION THRU CONDUCTOR

NOT TO SCALE

Figure 4

Figure 5

NOT TO SCALE

Figure 6

Figure 7

Table 1

No. of Coils	24
Coil Size	20m x 30m
Coil Cross-Section (including 4-side insulation, each 2 cm thick)	0.785m x 1.04m
No. of Turns Per Coil	50
Conductor Sizes (SC and Copper)	(1) 0.01m x 1m x 30m (2) 0.01m x 1m x 20m
SC Sizes*(NbTi)	(1) 0.001m x 1m x 30m (2) 0.001m x 1m x 20m
Insulator Sizes **	(1) 0.005m x 1m x 30m (2) 0.005m x 1m x 20m
Peak Field at Conductor (@5.75m)	8.35 Tesla
Field at Plasma Center (@13.0m)	3.69 Tesla
Operating Current	2×10^5 amps
Amp-Turns Per Coil	10^7
Total Amp-Turns	2.4×10^8
Average Current Density Over Conductor	$2000\text{A}/\text{cm}^2$
Average Current Density Over Coil	$1300\text{A}/\text{cm}^2$
Required Heat Transfer Rate When All Current Flows in Copper Stabilizer	$\sim 0.2 \text{ watt}/\text{cm}^2$
Inductance Per Coil	~ 0.33 henry
Total Inductance	~ 7.9 henry
Stored Energy Per Coil	6.6×10^9 joules
Total Stored Energy	1.58×10^{11} joules
Average Pulsed Field Rate Over TF Coil	0.5 Tesla/sec.
Rise Time (or down-time)	1 second
Plasma Burn Time	1000 seconds
Estimated Heat Leaks (Eddy current, power lead, coil case supports, etc.)-Rm. temp. power requirement	16.62 Mw
Estimated Refrigeration Requirement-Rm. temp. power requirement	20 Mw
Total Conductor Length Per Coil	4800 m
Total Conductor Volume Per Coil	48 m^3

*SC cross-section calculated for highest field of 8.35 Tesla

**Approximate dimensions