PULSE COIL CONCEPTS FOR THE LCP FACILITY*

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SUMMARY

The pulse coils described in this paper are resistive copper magnets driven by time-varying currents. They are included in the Large Coil Test Facility (LCTF) portion of the Large Coil Program (LCP) to simulate the pulsed field environment of the toroidal coils in a tokamak reactor. Since TNS (a 150 sec, 5MA, igniting tokamak) and the Oak Ridge EPR (Experimental Power Reactor) are representative of the first tokamaks to require the technology developed in LCP, the reference designs for these machines, especially TNS, are used to derive the magnetic criteria for the pulse coils. This criteria includes the magnitude, distribution, and rate of change of pulsed fields in the toroidal coil windings.

Three pulse coil concepts are evaluated on the basis of magnetic criteria and factors such as versatility of design, ease of fabrication and cost of operation. The three concepts include (1) a pair of poloidal coils outside the LCTF torus, (2) a single poloidal coil threaded through the torus, and (3) a pair of vertical axis coil windings inside the bore of one or more of the toroidal test coils.

Derivation of Pulse Field Criteria

The TNS and Oak Ridge EPR reference designs were modeled assuming time dependent currents in the ohmic heating windings and plasma. It was soon concluded, after comparing the plasma histories (i.e., current vs time for all poloidal currents) and realizing that TNS may become the EPR or even the DEMO reactor, that TNS could serve as a credible example of the pulsed fields in any foreseeable reactor design. The magnetic criteria was then derived from TNS.

An examination of the plasma history for TNS indicated that pulsed fields in the toroidal coils should be calculated at time equals 0, 1, 2, and 10 seconds to determine extreme magnitudes and rates of change in a reactor environment. T = 0 seconds is the instant when the field magnitude is greatest, but the cause of the field is entirely the ohmic heating system. Since the TNS and other reactors could be designed to minimize the stray field from the OH coils in the region of the TF coil, it seems more relevant to simulate the pulse effects from the plasma and equilibrium coils.

By ignoring the OH current to find the pulsed fields in a "shielded" TNS toroidal field coil, it is evident that T = 2 seconds is the instant when the magnitude of pulse field is greatest. The criteria for the LCP facility, therefore, is to furnish a pulse coil system which produces a field in the LCP test coils with a magnitude and distribution similar to that of TNS at T = 2 seconds.

Since the pulse fields in TNS are produced by separate, transient currents in 30 ohmic heating coils, 20 equilibrium field coils and the plasma, the distribution of field in the TF coils, as well as the magnitude, shifts with time. Even assuming no effect from ohmic heating windings, the locations of the maximum fields in the TF coils vary, so it is impossible to duplicate the TNS environment in LCP with a single pulse coil regardless of its current cycle. It is possible, however, to devise a current cycle, which, when coupled with a particular field distribution will approximate the TNS environment.

To insure that LCP provides a pulsed field environment as severe as that which will be encountered in TNS, but at the same time minimizes the power supply requirement, the criteria for the pulse system for LCP is as follows:

1. A 2 sec ramp to the magnitude and approximate distribution of the pulsed field in TNS at T = 2 secs.
2. Hold at this current for 30 seconds.
3. Ramp down to zero current in 1 second.
4. Hold at zero current for 117 seconds.

Comparison of Pulse Coil Concepts

To provide a pulsed field environment for the LCP test coils that is consistent with the criteria derived from TNS, three different pulse coil concepts appear feasible. The first concept is a pair of poloidal coils outside the toroidal coils. The second concept is a single poloidal coil, analagous to the plasma current, threaded through the toroidal coils that provides a poloidal field around the entire torus. The third concept is a pair of vertical axis coils inside the bore of one or more test coils that produce a field localized to one toroidal coil.

In order to evaluate and compare these three concepts, certain parameters including the coil geometries, amp turns and current density, had to be estimated. A current density of 2250 amps/cm^2 was selected based on LN_2 cooling and a power supply vs copper cost tradeoff. The coil geometries were found by iterating single filament magnetic models several times to provide the best approximation to the desired field distribution. Using this information, the required amp turns for each coil, and the current density fixed the cross-sectional area for each coil. The coil models were adjusted to account for this finite cross section and after several more iterations, the final geometries shown in Figure 1 were derived.

The first comparison to be made between the three pulse coil concepts regards the field distribution each produces in the toroidal field coils. Figure 2 illustrates the contrast between these distributions and the distribution of the TNS system at T = 2 seconds. It is apparent that none of the concepts duplicate the desired TNS conditions. The third design, i.e., a pair of vertical axis coils in the bore of a TF coil, provides the best match of the tangential field component and as good a match as any of the concepts for the perpendicular field component.

A second area of comparison between the three pulse coil concepts regards the versatility of the design concerning such factors as the ability to pulse the LCP test coils selectively, modify the field distribution, and remove or replace the test coils easily.

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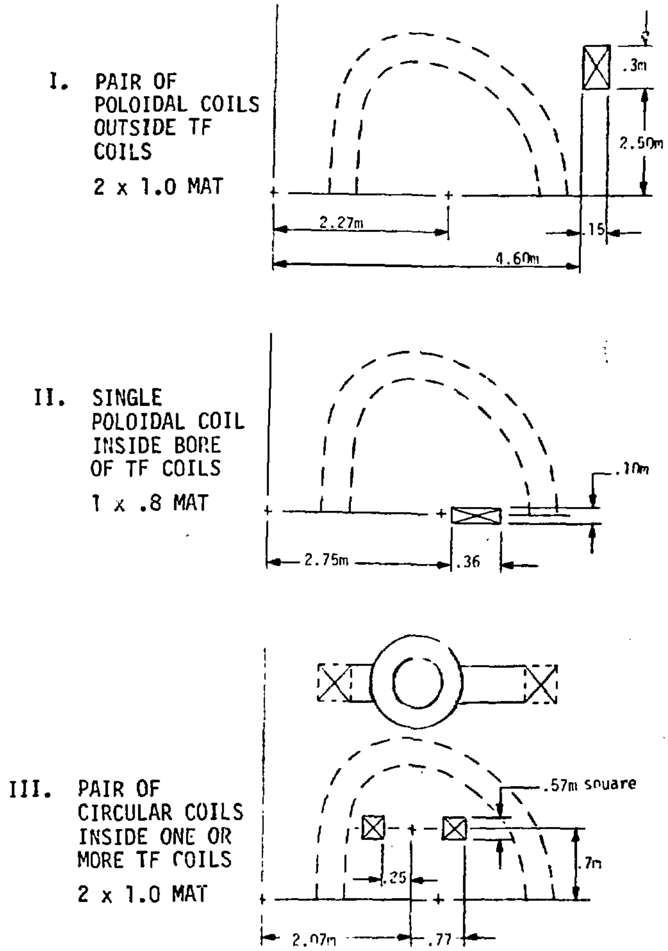

Figure 1
PULSE COIL CONCEPT GEOMETRIES

The first concept, the pair of coils outside the toroidal coils, is fairly versatile. Although it cannot pulse a single test coil, it does allow some field modification by operating in the cusp mode. Also, this concept presents no significant obstacle to removal or replacement of the test coils, and could double as part of the torque ring structure.

The second concept, the single poloidal coil, has very limited versatility. There is no way to pulse the test coils selectively and since it is a single winding, its field distribution at a given current cannot be adjusted without altering its geometry. In addition, removing or replacing any of the test coils would require the pulse coil to be dismantled.

The third concept, the pair of vertical axis coils in the bore of one or more test coils, seems to offer the greatest versatility. Any combination of test coils could be pulsed depending on the number of pulse coil systems installed. The field distribution could be modified by operating in the cusp mode, as in the first concept, or by pulsing only the top or bottom winding. Finally, when removing or installing toroidal coils, this system would present the least difficulty due to its comparatively small size.

The relative ease of fabrication is a third basis for comparison of the pulse coil concepts. Factors such as the quantity of materials that are needed, especially copper, the type of structure and the tolerances that are necessary, and the amount of field work vs shop work required are important to this evaluation.

The pair of poloidal coils outside the torus would require approximately 25,000 Kg (28 tons) of copper and a large quantity of non-magnetic structural material. The structure must not only support the weight of the copper, but also the magnetic loads imposed by all six test coils interacting with the pulse coils. This concept would require a good deal of field construction since installing the system as a single unit would be nearly impossible.

The single poloidal coil threaded through the bore of the test coils would require only 6000 Kg (6-1/2 tons) of copper, but a much more complex structure is needed compared to that of the first concept. This is because a single coil would be loaded with nearly the same magnetic forces as both coils of the first concept combined, and would have less space available for supports. Another problem would be installing the pulse system with the toroidal coils in place or vice-versa. Readily breakable field joints would pose a difficult design problem for a multi-return coil, and unwinding and rewinding the coil in place for each test coil change would be even more difficult since the test facility is housed inside of a close-fitting vacuum vessel and the winding torque would have to be supplied by a mechanism in the torus.

The pair of vertical axis pulse coils in the bore of one or more test coils brings the amount of copper needed down to 3000 Kg (3-1/3 tons) and would require less supporting material than the other concepts since the external magnetic loads would be due almost entirely to a single test coil. In addition, both coil windings could be wound on a common bobbin in the shop and installed as a single unit with a minimum of field work.

Operating parameters form the final basis for comparison of the pulse coil concepts. Included here are requirements such as steady state and transient power, cooldown and in-use LN_2 refrigeration, and helium boil off due to eddy currents induced in components at 4K.

Table 1 summarizes the operating parameters for each conept, for the pulse cycle, geometry and current density discussed earlier. This listing illustrates a clear advantage of the third concept in every category.

It should be noted here, however, that only one pair of coils is assumed for the third concept, so only one test coil is pulsed. If there was a requirement for pulsing all six test coils simultaneously, then six pairs of pulse coils would be necessary. All of the parameters would then be multiplied by a factor of 6 and the third concept would become less attractive. However, since there is presently no requirement to pulse all six test coils at once, there is no reason to pay for the extra costs incurred by doing so (as with the first two concepts). In addition, if any of the toroidal coils cannot withstand the pulse field, the ability to pulse selectively becomes necessary to avoid impacting the test plan.

Based on the foregoing comparisons, a pair of coils in the bore of a test coil is the most suitable concept for LCP. As indicated, this concept is advantageous because it (1) provides the best match to the desired field distribution, (2) has a versatile configuration that can be built in the shop as a unit, and (3) requires the least power and refrigeration.

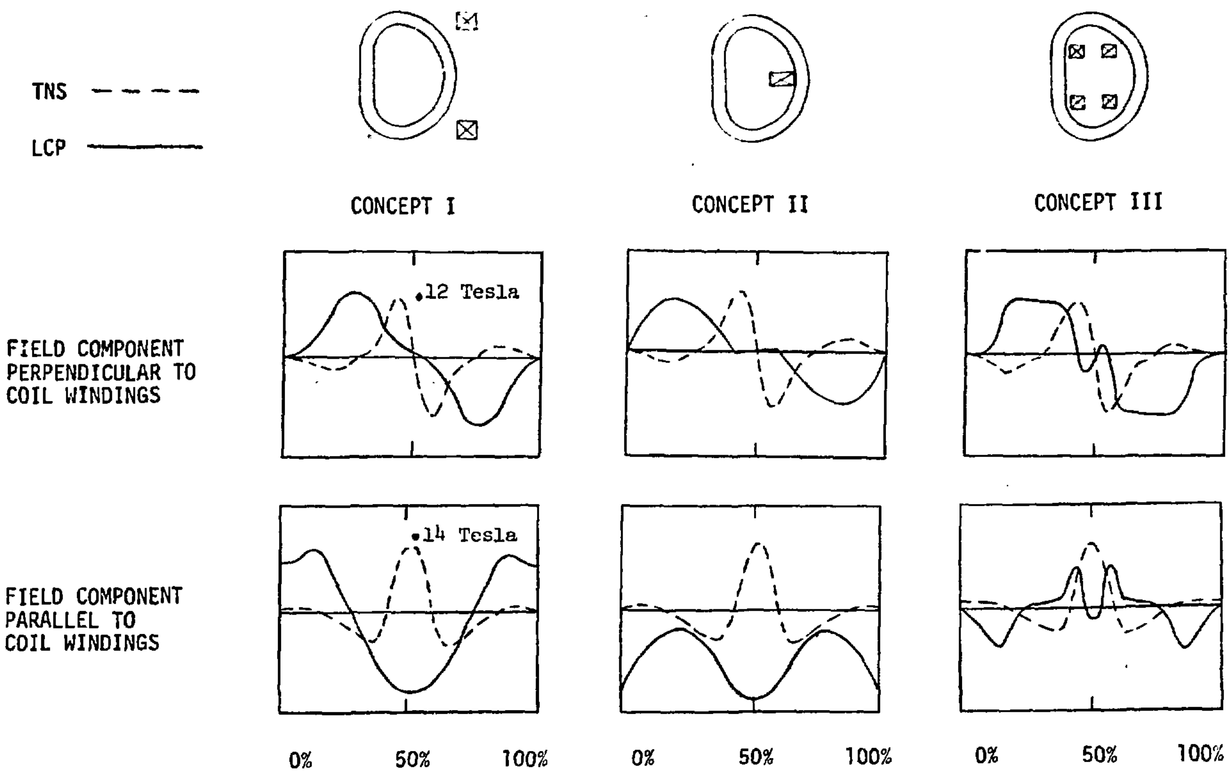

FIGURE 2
PULSE FIELD DISTRIBUTION AROUND TF COIL PERIMETER

TABLE 1
ESTIMATED OPERATING PARAMETERS

	I	II	III*
Current @ Peak Field, (MAT)	2 x 1.	.8	2 x 1.
Average Length per turn (cm)	3000	1850	340
Cross-section of Copper (cm^2)	2 x 445	360	2 x 445
Resistance/turns^2 ($\mu\Omega$)	1.33/2	1.02	.14/2
Inductance/turns^2 (μH)	2 x 28.5	18.6	2 x 1.0
Stored Energy, $LI^2/2$ (MJ)	2 x 14.3	6.0	2 x .5
Maximum Resistive Power (MW)	2 x 1.33	.65	2 x .14
LN_2 Vaporized (Liters/pulse)	2 x 332	164	2 x 15
Circulation to maintain 80K (Liters/pulse)	2 x 8000	4000	2 x 365
Cooldown Ref. (C_u only, 300-80K) (MW)	2822	693	295
Eddy Current Power @4K (W)	325	56	5
Maximum Inductive Power (MW)	2 x 14.25	9.30	2 x .54
Maximum Total Power (MW)	2 x 15.60	9.86	2 x .60
Average Total Power (MW)	2 x .54	.26	2 x .03

*Numbers are for 1 set of coils

Preliminary Pulse Coil Design

Following the selection of the pulse coil concept, a more detailed design was undertaken. The effort was directed toward enhancing the versatility, simplifying the fabrication and reducing the cost of operation.

The resulting pulse coil design and its location in the test stand is shown in Figure 3. Three pulse coils and three support segments are provided so three different test coil designs can be pulsed before rearranging the system. To facilitate rearrangement, each pulse coil is contained in a module which occupies a 60° arc so the support segments and pulse coil modules are interchangeable. While this triples the cost of coil fabrication over a single coil unit, it makes the facility much more versatile.

The operating cost is highly dependent on the type of cooling supplied to the coils. The original design called for forced flow liquid nitrogen, but this resulted in a high nitrogen refrigeration load. To reduce this load and thus lower the operating cost, a forced flow water-cooled design was considered as an alternative. A comparison of these two systems indicates that the fabrication costs and refrigeration load would be substantially reduced using water as a coolant. Because the water is at room temperature, however, the coils must be shielded since only surfaces with temperatures of 80K or lower are allowed to radiate to the test coil. This 80K temperature limit is derived from a consideration in LCP to simulate even the thermal loads that will occur in a tokamak reactor. The final choice of coolant was based on considerations of LN_2 demand, its concomitant connected piping capacity, and complex design requirements vs the relatively inexpensive water coolant with its straightforward design approach and thermal shield. When preliminary calculations showed the relative ease with which insulation could be placed to isolate the pulse coils thermally, water was selected as the base reference design coolant.

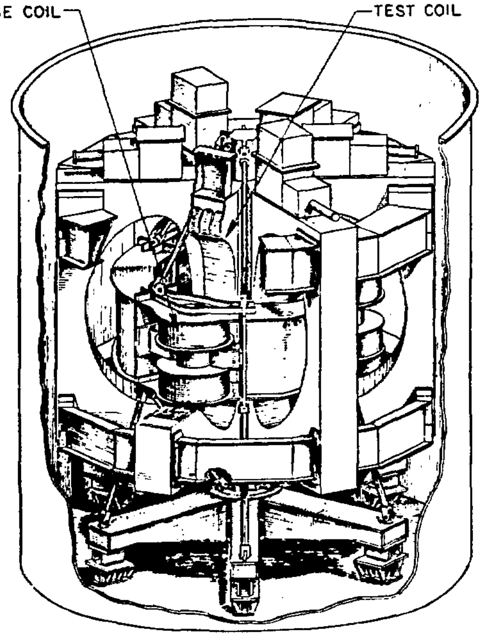

Figure 3
OVERALL VIEW OF LARGE COIL TEST FACILITY
SHOWING LOCATION OF PULSE COILS AND TEST COIL

Preliminary structural sizing has been performed to arrive at a welded plate construction for the coil module. In addition, a conceptual plan for the coil windings, coolant headers, and forced cooled power leads has been devised. This design is illustrated in Figure 4.

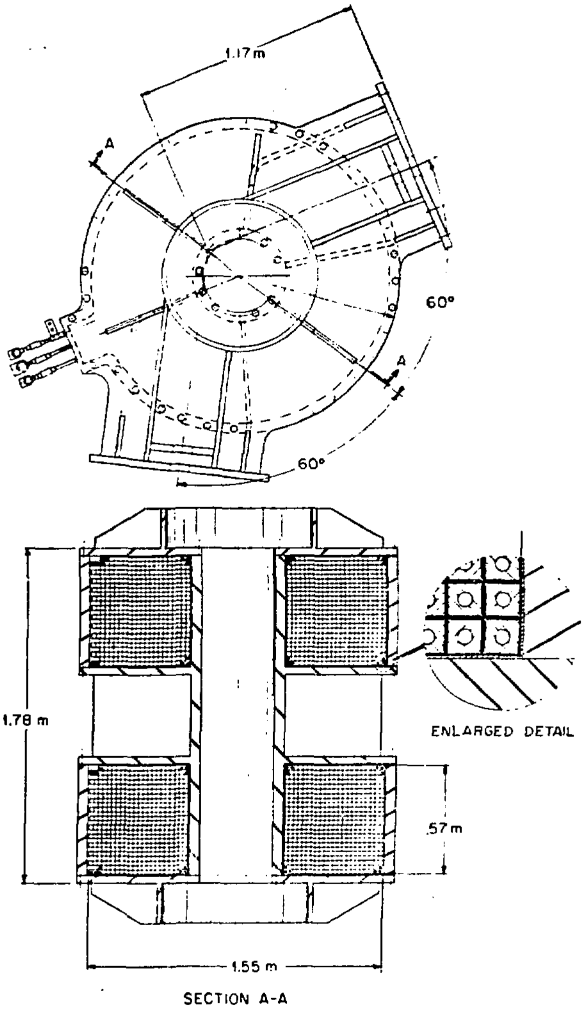

Figure 4
PULSE COIL MODULE
PRELIMINARY DESIGN