25-30 T WATER COOLED PULSE MAGNET CONCEPT FOR NEUTRON SCATTERING EXPERIMENT

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25-30 T Water Cooled Pulse Magnet Concept For Neutron Scattering Experiment

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Abstract-The Manuel Lujan Jr. Neutron Scattering Center, Los Alamos National Laboratory is in need of a high field, split-pair, pulse magnet that would provide a 25-30 T field in a 25 mm bore and 10 mm split gap for 2-4 ms at a repetition rate of 2 Hz. Single stack Bitter magnets of this type providing less than 20 T vertical field in the split gap have been constructed before. To produce higher fields, there is a need to use a multiple layer coil with internal reinforcement. The magnet should withstand up to $10^7$ cycles of loading and unloading. We have conducted a feasibility study that address these unique requirements.

I. INTRODUCTION

Since superconducting magnets are limited to fields less than 20 T, a 25-30 T split magnet has to be totally resistive or a hybrid (part resistive and part superconductive). If it is a dc magnet, the power and the cooling requirements would be extremely high (20-40 MW and 100-200 liters/sec). As a result a continuously cooled repetitive pulse magnet with a small duty factor (defined as average power + pulse power) would be the feasible economical solution.

Normal pulse magnets depend on their thermal heat capacity to absorb the pulse ohmic heating and warm up from usually 77 K to room temperature during the pulse time. Then they are cooled by liquid nitrogen over a long time (30 - 60 minutes) because of the slow thermal diffusion through the insulated winding. For faster cooling the winding has to be in contact with the coolant without an insulation barrier. It would also be advantageous to use a coolant with high heat transfer coefficient such as water.

A 25-30 T, 25 mm bore water cooled repetitive split pulse magnet with a small duty factor would have a 300-400 kW average power consumption compared to 40 MW for a dc magnet.

II. PULSE SHAPE AND ELECTRICAL CIRCUIT

The pulsed neutron source operates at repetition frequencies of 20 Hz, as shown in Fig. 1. It is desirable to operate the magnet in a synchronized way at the highest repetition rate (20 Hz). To accommodate the magnet cooling requirement, the magnet repetition frequency has to be much lower than the neutron source pulse frequency. We have selected 2 Hz operation frequency to reduce the power requirement by a factor of 10. Pulsed magnets driven by capacitor banks are resonant LC circuits and therefore develop a field that is semi-sinoidal in shape as shown in Fig. 1. The relation between the pulse width, $\Delta T$ and the circuit elements is approximately equal $\Delta T = \pi L / C$. Typical neutron pulse width is 25-100 $\mu$s. One desires the field to be fairly steady over this time, and therefore the magnet pulse width has to be ~ 1 ms. The limit on inductive voltages, conductor skin depth may require 2-4 ms magnet pulse width.

We have adapted the electrical circuit shown in Fig 2 [1]. The operation cycle starts as follows: 1- The capacitor is completely discharged and the charge and voltage changes to opposite polarity in 3 ms. The capacitor charge is reversed during the next 50 ms in the low loss inductor $L_i$. Then the capacitor voltage is brought back to its original voltage by charging it using the power source in about 300 ms time span. The capacitor voltage is held a short time before a new cycle starts.
III. PREVIOUS EXPERIENCE (BITTER MAGNETS)

Single stack, capacitor driven, water cooled Bitter magnets of this type providing up to 21 T vertical field in a non-split magnet and 16 T in a split magnet have been constructed and tested in Japan.[1,2] Because of the pulsed nature, the current in a single stack Bitter magnet flows only on the inner surface in a radial thickness equal to the skin depth which is about 3-6 mm for 1-4 ms half sine wave pulses. The rest of the disk provides mechanical support for the current carrying region.

Cooling holes (that can be another source for stress concentration in addition to the slit between overlapped discs) have to be located close to the energy dissipation region to remove the energy dissipated in the time between pulses (2 s in the Japanese design). The advantage of this concept is that it has low stored energy, since it is only a thin layer coil. The disadvantage is the large energy density needed to be removed which limits the repetition rate and the generation of higher fields. Another disadvantage is that the maximum stress is limited by the copper or copper alloy used in Bitter disks. The stress concentration and the temperature rise during the pulse limit the maximum field that can be obtained from that concept to 20-25 T in non-split coil and less than 20 T for a split magnet.

The thermal diffusion length at room temperature is very small compared to typical value of 3 (3-6 mm). As a result all heat generated during the pulse will be absorbed by the heat capacity of the current carrying region resulting in a temperature jump, \( \Delta T \) that is related to the central field \( B_{so} \) in a long solenoid, as shown in Fig. 3. The temperature rise is independent of the pulse width or material resistivity given the assumptions discussed above. This illustrates the difficulty in getting fields higher than 25 T in non-split coil as the temperature rise would exceed 120 C. Shorter solenoids would experience a larger temperature rise than the ideal long solenoid.

VI. MULTI-LAYER PULSE MAGNETS

The use of a mechanically de-coupled multi-layer winding reinforced with high modulus structural materials can remove some of the difficulties associated with single stack Bitter coils in generating fields of 25-30 T. The winding has to be made out of a conductor that its width is smaller than the skin depth to minimize the eddy current losses. The advantages of this concept are: 1- the current carrying region is spread over many layers compared to only one skin depth region in one layer magnet, thus reducing the power density and temperature rise. 2- the non-current carrying portion of the disks is replaced by higher modulus material to reduce the stresses in the current carrying region.

Generation of higher fields would require internal reinforcement to limit the stresses below the fatigue limit of known conductors and reinforcement materials. Such conductor/internal reinforcement arrangement would increase the stored energy and the ohmic heating power requirement (though the power density is reduced). There is a need to optimize the trade off between the increase in the inductive power due to the introduction of the reinforcements and the decrease in stresses and power density. The success of such system would require a confirmation of the fatigue properties of conductor and reinforcement materials.

A. Eddy Current Losses

In multi-layer windings, the eddy current losses will be higher than in a single layer magnet unless the winding radial thickness, \( w \) is less than the skin depth, \( \delta \). To illustrate this, we address the eddy current heating as function of number of layers in a long coil with no mid-plane split. The winding radial thickness, the turn current and total number of turns is kept constant. The ohmic heating power for a 30 T, 50 mm bore, 3 ms half sine-wave pulse width magnet is calculating using simple analytical formula. Fig. 4 shows that there is a need to reduce the layer radial thickness (width) below the skin depth in order to cut the shielding currents and reduce the ohmic power.

![Fig. 3 Temperature rise, \( \Delta T \) following a pulse as function of the central field \( B_o \) for a long solenoid. Note that the temperature rise is independent of the resistivity \( \rho \) or the pulse width \( \Delta t \).](image)

![Fig. 4 Power loss vs. number of layers in a 30 T pulse magnet. Shielding and transport currents are shown for a two layer winding. The skin depth should be larger than the conductor width, \( w \) to reduce the eddy currents.](image)
B. Material Characterization

Materials characterization of three conductor materials and one reinforcement material has been conducted up to 10^7 cycles (the desired life time of the magnet) to supplement the existing data base. The conductors tested were two variations of CuAg materials (0.7 mm thick sheet and 5 mm X 8 mm rectangular wire) and BeCu alloy sheet material (0.4 mm thick). The characterization of the conductors includes 293 K static tensile tests, 293 K fatigue tests, and 393 K fatigue tests. BeNi has been chosen as reinforcement for its excellent corrosion resistance and fatigue life (900 MPOA for up to 10^7 cycles). All the tests conducted agree with literature and manufacturer values. Fig. 5 shows the results for the conductor test results. The conclusion is that the conductor should be designed for a fatigue values less than 400 MPa and the reinforcement for less than 800 MPa.

C. Conceptual Design

In trying to go beyond the Japanese experience, we chose the maximum field of 25-30 T, and it soon become clear, as explained above, that we need a geometry that allows the current density to spread radially (with internal reinforcement between layers) larger than the skin depth which is the limit in the single Bitter stack concept. A poly-helix design with internal reinforcement has been selected as a preferred geometry. The helices are one layer winding reinforced by high modulus material and are cooled by high velocity water (8-10 m/s) on the inner surface. The poly helices can be made out of; 1- Bitter stacks, 2-wire wound helices, and 3- machine wound helices.

Preliminary test results and literature survey on the effect of stress concentration on fatigue life show a drop by a factor of two or more in stress values due to stress concentrations. Therefore it appears that poly-helix winding made out of Bitter stacks would be a risky option in terms of fatigue life due to stress concentration in a 25-30 T magnet except the most outer one where the hoop stresses are usually small. As a result, we started looking into ways of making the windings out of one layer helices made out of CuAg or CuBe insulated wires. We have preferred the wire wound helices over the machine wound helices for two reasons; 1- the wire has a corner so we would have more turn to turn insulation compared to sharp corners for machined helices out of a cylinder, 2- the wires are more available.

The insulated wire wound helices would be impregnated and machined on the inner surface to expose the conductor for cooling. Then each helix would be cut at the mid-plane to provide the winding for the upper and lower half of the magnet. Each half would have four layers connected in series and both halves will be connected in series on the outside of their non-metallic housing. The reinforcement would be either carbon fiber or BeNi. Both have large modulus and long fatigue life at stress level at least twice the design stress. The BeNi is available in sheets that can be wrapped around the winding with insulation in between to eliminate eddy current circulation during the pulse. The current connection between one helix and another will be in the form of a 1 mm thick CuBe end plate that has a slit similar to a resistive magnet plate. This end plate would carry the current uniformly radially from one layer to another.

Fig. 6 shows a schematic of one quadrant of a 25 mm bore 25-30 T 4 helices conceptual design that consist of 4 mechanically independent units. The first three are made out of CuAg winding reinforced by BeNi sheets. The last one is made out of copper or Glidcop(CuAl) Bitter plates. The split for each region is selected to minimize the axial force on the first three regions and maximize it on the outer Bitter stack region. The outer Bitter stack have very low hoop and radial stresses and can be supported easily from the top by tie rods that is connected to a bottom end plate. There is also the possibility of supporting the inner three layers from the top due to the small axial force on each as shown in Fig. 6. Table 1 list the dimensions, the current density and the axial force in each region for a 30 T design.

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A 25 T, 2.5 ms, 11.15 kV, 95.8 kA pulse option (that is similar to the one shown in Fig. 6 and listed in Table I) but has a larger split gap in each region by 12 mm) would permit more view of the sample and reduces the axial loads for easier axial support. The inductance and the capacitance of this system are 0.084 mH and 7.4 mF.

D. Numerical Simulation of Magnetic Field and Thermal Diffusion during the pulse.

We have conducted a complete numerical simulation for both the current and field diffusion in addition to using simple analytical expressions. The NHMFL computer code protect was used for this analysis. The first layer or the inner helix (4 mm wide) was divided into 8 radial layers each 0.5 mm wide. These 8 layers are electrically in parallel and in thermal contact with each other. The 8 layers representing the inner helix are in series with the other three helices. The inner surface of the conductor is cooled with water (h = 2.0 x 10^5 W/m^2 K). A half sine wave current source is applied for a 3 ms to investigate the current and temperature pattern inside the inner helix. The results came in very good support to our simple analytical model in terms of predicting the average temperature inside the conductor. Fig. 7 shows the current density in each radial section of the conductor. Fig. 8 shows the temperature distribution vs. time and the temperature distribution at the end of the pulse along with the simple analytical model results.

![Current density pattern in layer #1](image)

**Fig. 7** J in kA/mm^2 in each radial section of the first helix conductor. Conductor is divided into 8 parallel layers. The sum of the currents in the 8 layers is equal to total current.

![Numerical vs. analytical model for temperature distribution](image)

**Fig. 8a** The temperature distribution at the peak and the end of the pulse along with the simple analytical model results.

![Temperature pattern in Layer #1](image)

**Fig. 8b** The temperature distribution vs. time showing the temperature rise during the 3 ms pulse and the 500 ms cooling time.

V. CONCLUSION

The material characterization testing and the numerical and analytical evaluation of a 30 T, 30 mm bore split pulse magnet leads to the following conclusions: 1-Single stack Bitter coils can only support fields up to 20 T. Fields higher than that requires poly-helix design that consist of winding reinforced with high modulus support. 2-Water cooling is more efficient and much cheaper than liquid nitrogen cooling. 3-CuBe and CuAg are good materials for winding as both of them show good fatigue life. BeNi is a good material for reinforcement because of its resistance to corrosion and its excellent fatigue properties. 4 - It is possible to design a large split gap 25 T magnet that meets the fatigue constraints over the 10-7 cycle life time or 30 T with a smaller split gap.

VI. REFERENCES