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Abstract - The design, construction and testing of a superconducting pulse coil with high field ramp rates are described. The pulse operation has been done by a condenser discharge with a clamp circuit. The coil was charged up to 4 T at a pulsing rate of 200 T/s by applying the maximum terminal voltage of 8 kV. The a.c. loss per pulse was 0.2% of the stored energy. These results demonstrate the feasibility of superconducting poloidal coils for medium size tokamaks.

The Reacting Plasma Project (R-Project) of the Institute of Plasma Physics, Nagoya University is developing a D-T burning, medium size tokamak /1/. Conceptual design studies have clarified the need for poloidal field (PF) coils with a pulsing rate of about 100 T/s. In a totally superconducting version of this tokamak, the design of the PF coils presents formidable problems: The required pulse rate of 100 T/s is roughly ten times higher than that of large scale tokamaks such as NET, ETR, FER and INTOR. Since 1981, the R & D team has been engaged in the design, construction and test of small-scale model coils /2,3,4/. The objective is to identify the critical elements of the design and the technology required. In a first model coil, RPC-I, we obtained a pulse rate of 150 T/s, but suffered breakdown of layer to layer insulation /3/. The second model coil, RPC-II, has been constructed with a reinforced insulation. The design criteria and test results of this RPC-II are presented.

I - CABLED CONDUCTOR

The construction of the superconducting cable is illustrated in Fig. 1. The main requirement was low a.c. losses at high pulsing rates, which forced us to start from a rather thin basic strand. The specifications are given in Table 1. The various levels are twisted in opposite direction. The first level consists of three basic
strands and has a twist pitch of 17 mm. It was compacted by drawing through a die resulting in 3-4% reduction of the cross sectional area. The second level consists of six subcables and a CuNi-clad copper wire of 0.65 mm diameter and has a pitch of 31 mm. It was compacted by drawing through a 1.78 mm die. The final cable consists of 21 subcables twisted around an insulated SUS strip (0.75 mm x 20 mm) at a twisting pitch of 180 mm. During final cabling, the conductor was compacted by using a Turk's head machine to ensure mechanical rigidity. The finished cable is 4.1 mm thick and 23.3 mm wide. About 500 m of cable were produced. Its current-carrying capacity at 4.2 K is 10 kA in a field of 6 T.

II - MODEL PULSE COIL RPC-II

Table 2 lists the basic parameters of the pulse coil. The coil was wound on a G-11 former and forms a solenoid of 22 layers. After completion of the winding, many layers of wet bands of epoxy fiberglass were added and cured in situ to support the hoop stress. Special care was needed to overcome the problems of high voltage and cryogenic stability. The coil must withstand a terminal voltage of about 10 kV. In order to meet this requirement, we have adopted the winding configuration shown in Fig. 2. The narrow sides of the rectangular cable were covered with an adhesive fiberglass tape. Furthermore single turns were separated from one another by G-10 plates (Fig. 2a). The layer to layer insulation was ensured by five Kapton sheets of 0.25 mm total thickness. These sheets were put between two 0.8 mm thick G-10 spacers to provide cooling channels in the vertical direction (Fig. 2b). About 45% of the surface of the cable are exposed to liquid helium. The cryogenic stability of the coils is mainly determined by the ratio of vapour to liquid of helium in the winding during the pulse operation of the coil. The measurements of a.c. losses of a short sample have been made in a pulsat field /2,5/ and the loss time constants at a field Bm=4.0 T are given in Table 3. From the data of the final cable, we can calculate the ratio of vapour to liquid at high field region of the coil as 25%. This is smaller than the critical value, 30%, at which the heat transfer characteristics begin to deteriorate.

III - EXPERIMENTAL ARRANGEMENT AND TEST RESULTS

Figure 3 shows the cross section of the pulse coil assembled in a stainless steel cryostat. Special GFRP casing encloses the coil in order to allow calorimetric measurements of the a.c. losses. Refilling of the liquid helium from the outside of the casing can be made by opening a plug. A capacitor bank of a maximum energy of 600 kJ (12 mF, 10 kV) serves as power supply.

The coil is charged up to a present current in 18.7 ms following a sinusoidal wave shape and discharged to zero with the help of a clamp circuit with a time constant of about 50 ms. An example of the wave form is given in Fig. 4. The a.c. losses per pulse are measured calorimetrically with a gas flow meter and have been plotted in Fig. 5 as a function of the peak field Bm. Note that Bm is proportional to the pulsing rate dB/dt, since the field rise time is fixed. The loss per pulse Q(J) versus Bm(T) seems to follow a relation,

\[ Q = 43 B_m^{1.7} \]

A parallel experiment on the a.c. losses of a short sample was done: A sample coil wound from 1.5 m of the final cable was set in the bore of the pulse magnet and the losses were measured by a standard electric method. These values together with a calculation of the field distribution in the RPC-II coil were used to estimate the total loss of the coil. The result is shown by the full line in Fig. 5, which seems to confirm the observed losses, eq.(1).

In the first model coil RPC-I, the breakdown of layer to layer insulation occurred at a coil terminal voltage of 7.6 kV. In order to confirm the improved coil structure of RPC-II, the same voltage was chosen as the maximum operation point. Figure 6 shows the load line of the coil RPC-II. As indicated by the closed circle, the maximum peak field was 3.74 T with a peak current of 4.24 kA and the coil terminal
voltage of 7.62 kV. After five pulse operations with a repetition period of 15 min., the coil has suffered no change in pulsing characteristics. In Fig. 6, the critical current \( I_c \) and the quenching current in pulse fields \( I_q / 2 \) were estimated from the experiments on a 2nd level subcable. The cold-end recovery current in static fields, \( I_r \), observed on the final cable is also shown.

IV - CONCLUSION

A small-scale superconducting coil wound from a low loss cabled conductor has been tested. So far the coil was charged up to a field of 3.74 T at a coil terminal voltage of 7.62 kV. Since the waveform of the rising field was sinusoidal with a rise-time of 18.7 ms, the average and the maximum of the pulse rates were 200 T/s and 314 T/s, respectively. The a.c. loss in this pulse operation was 0.23 % of the energy stored in the coil. In the next phase, we intend to test the coil in a mode of the ohmic heating coil of a tokamak machine where the field versus time has a nearly trapezoidal wave form.

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REFERENCES

Adhesive fiberglass tape (0.18mm t)

Adhesive Kapton tape (0.05mm t)
Adhesive fiberglass tape (0.18mm t)

Five Kapton sheets (0.25mm t)

between turns and between layers insulation, cf. text

Waveform of the coil current

Loss per pulse $Q(J)$ versus $B_m(T)$

Load line of the coil and limiting currents of the cable