

# DEVELOPMENT OF A SUPERCONDUCTING DIPOLE WITH FAST-CYCLING MAGNETIC FIELDS

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## Abstract

Superconducting dipoles developed for the UNK project reached magnetic fields of up to 6.5 T, with ramp rates up to 0.8 T/s. Experimental data for magnet training and ramp rate dependence of the maximum current and dynamic losses, for magnets with two types of superconducting cable (zebra and oxide) are presented. Possible ways to reduce AC heating losses in dipoles with fast-cycling magnetic fields are presented. The results of analysis of heat generation and temperature conditions for such dipoles, using coils with improved conductors are presented.

## 1 INTRODUCTION

During the UNK project, superconducting (SC) dipoles were developed and produced in a pilot industrial batch of 25 magnets [1]. The operating field of the dipoles was 5.11 T, at 0.11 T/s ramp rate. Sizeable temperature and current margins allowed one to reach a magnetic field of up to 6.5 T, with field ramp rate of 0.8 T/s during magnet tests. Recently, a requirement for SC dipoles with fast-cycling magnetic fields appeared. The SIS-200 ring of GSI's planned Future Project [2] is presently based on the utilization of SC dipoles with ramp rates up to 1 T/s and field amplitudes up to 4 T. As is well known, increasing the ramp rate increases AC losses and thus operating costs. Improvements of the present UNK dipole design will be presented, to reduce these costs and extend the operating range of the dipoles to 6 T, with ramp rates of up to 4 T/s.

## 2 MAIN DIPOLE CHARACTERISTICS

The UNK dipole cross-section and its main parameters are shown in Fig. 1 and Table 1. The dipole coil consists of two layers, each with inter-turn spacers, to improve a field quality. The upper and lower coil halves are wound with continuous lengths of keystoneed 19 strands NbTi composite Rutherford cable. Conductor cooling is provided by liquid helium, in "herring bone" shaped cooling channels between turns. The width of the cable (without insulation) is 8.5 mm, the median thickness is 1.43 mm and the transposition pitch is 62 mm. The parameters of the SC wire are: diameter is 0.85 mm, 8910 6  $\mu$ m NbTi filaments, filament twist pitch is 10 $\pm$ 2 mm, Cu/NbTi ratio is 1.38:1. The coil is clamped in stainless steel collars, surrounded by an iron yoke, which is enclosed in a shell, forming the magnet cold mass. Two inter-turn spacers are placed in the end parts of the coil, for suppression of integral higher field harmonics and reduc-

tion of magnetic field enhancement in the magnet end. Thus, both field (in magnet straight section) and integral field (in magnet end) lower order harmonics are suppressed independently. The useful aperture (the region of the good field) is equal to 7/8 of the 40 mm coil inner radius. The dipoles trained from a starting quench current of about 5.7 kA to a plateau value of 6.7 kA (6.5 T) in 2-3 quenches.

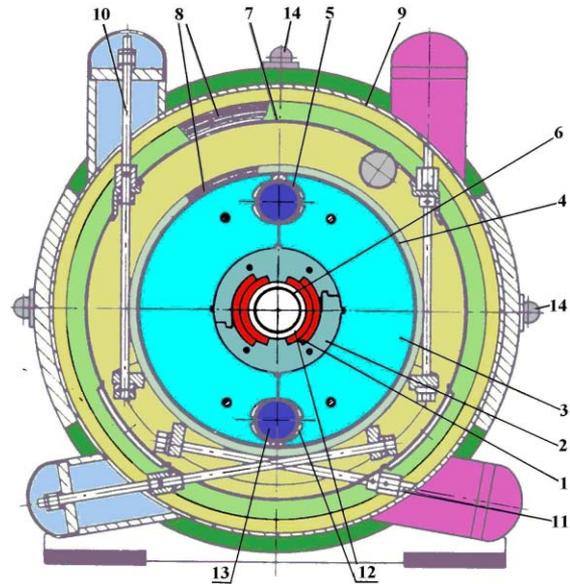


Fig. 1. Dipole cross-section: 1 – coil; 2 – collars; 3 – yoke; 4 – magnet outer shell; 5 – pipe of II phase He; 6 – beam tube; 7 – thermal shield; 8 – thermal insulation; 9 – vacuum vessel; 10, 11 vertical and horizontal supports; 12 – I phase He; 13 – II phase He; 14 - reference points.

Table 1. The main parameters of the dipole.

|                                      |                |
|--------------------------------------|----------------|
| Magnetic field, T                    | 5.11           |
| Operating current, kA                | 5.25           |
| Critical current at 4.25 K, kA       | 6.5            |
| UNK trapezoid field cycle, T         | 0.67-5.11-0.67 |
| UNK trapezoid time cycle, s          | 40-38-40       |
| Averaged AC losses per cycle, W      | 6              |
| Cryogenic system load at 4.4/80 K, W | 5/25           |
| Stored energy, kJ                    | 570            |
| Inductance, mH                       | 45             |
| Bore diameter, mm                    | 68             |
| Coil length, mm                      | 5800           |
| Iron length, mm                      | 5600           |
| Magnetic length, mm                  | 5664           |
| Magnet weight, kg                    | 6000           |

Two types of the cable were used for study of AC losses. The first had 9 wires coated with Sn+5%Ag alloy

(zebra) and the other 10 wires with a natural oxide coating. The second had all wires with a natural oxide coating (oxide). The typical critical current versus ramp rate dependence for magnets with these two conductors is presented in Fig. 2.

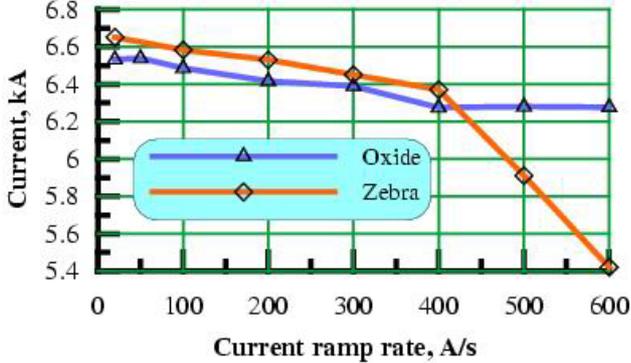


Fig. 2. Critical current versus ramp rate for two types of conductor coatings.

One can see that the oxide coating performs better than the zebra, above 400 A/s. The typical behaviour of AC losses during the UNK cycle for these dipoles versus ramp rate has an almost linear dependence (Fig. 3). These two figures (2&3) show the advantage of the oxide cable over the zebra cable. The reason is that the oxide cable has a transverse resistance nearly an order of magnitude greater than that of the zebra cable. Thus, inter-strand eddy currents and consequently AC losses in the oxide cable are reduced.

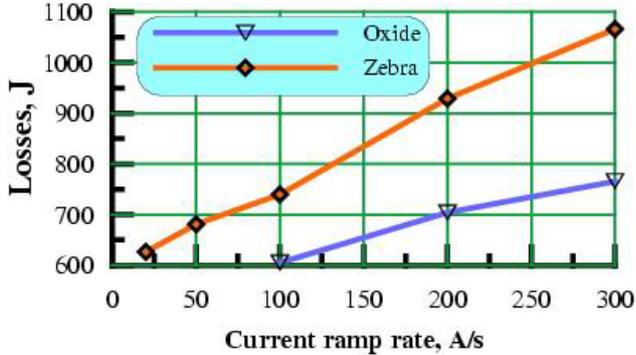


Fig. 3. AC losses versus ramp rate for two types of dipoles.

### 3 REDUCTION OF AC LOSSES

Heat generation in the coil and iron of the UNK magnet are in the approximate ratio of 3:1 during the UNK cycle. The losses in the iron yoke consist of hysteresis losses and eddy current losses. The selection of iron with a small coercivity and a large resistance, as well as with thin iron sheets with a special high resistance coating allows one to lessen the total losses in the yoke.

The losses arising in the current carrying elements of the coil give the main contribution to the heat load of the magnet. They consist of three constituents [3]:

1. *Hysteresis losses in the SC wire.* The power loss has a linear dependence on filament diameter  $d_f$  and  $dB/dt$  for  $B > 0.1$  T:

$$P_h = \frac{2}{3\pi} J_c d_f \dot{B} \left[ 1 + \left( \frac{J}{J_c} \right)^2 \right], \quad (1)$$

where  $J_c = J_c(B, T)$  is the critical current. Therefore, decreasing the diameter of the SC filaments from 6 to 4  $\mu\text{m}$  should give a loss reduction factor of 1.5 for  $P_h$ .

2. *Matrix losses in the SC wire.* This loss has a quadratic dependence on both twist pitch  $l_p$  and  $dB/dt$ :

$$P_c = \frac{l_p^2 \dot{B}^2}{4\pi^2 \rho_e}, \quad (2)$$

where  $\rho_e = \rho_e(B)$  is the specific effective resistance of the Cu matrix. Experimental results confirm that the decrease of  $l_p$  from 10 to 4 mm gives a decrease of the matrix losses by the factor 6.25. Another way of decreasing losses is to use either CuNi or CuMn resistive barriers, which surround clusters of NbTi filaments [4]. This method requires the development and production of new SC wire, which will be more expensive in comparison with existing UNK superconductor.

3. *Cable losses.* The loss is caused by inter-strand eddy currents in the cable and depends on the transposition length of the wire  $L$ , the ratio of thickness/width of the cable  $\alpha$ , and effective crossing  $\rho_\perp$  and adjacent  $\rho_\parallel$  resistances between wires in the cable:

$$P_C = \frac{L^2}{16} \left( \frac{8}{15} \frac{\alpha^2 \dot{B}_\perp^2}{\rho_\perp} + \frac{1}{3} \frac{\dot{B}_\perp^2}{\rho_\parallel} + \frac{1}{4} \frac{\dot{B}_\parallel^2}{\alpha^2 \rho_\parallel} \right), \quad (3)$$

where  $B_\perp$  and  $B_\parallel$  are the perpendicular and parallel components of the field. The first term in eq. 3 gives the main contribution to  $P_C$ , due to coefficient  $\alpha^2$  in the numerator. Moreover, usually  $B_\perp > B_\parallel$  in the coil. The reduction of the first term can be achieved by either increasing the effective resistance  $\rho_\perp$  or by insertion of a spacer (core) into the cable, in order to increase  $\rho_\perp$ . Unfortunately, parameter  $L$ , which can also decrease the cable losses, is limited by the manufacturing method and the transposition angle of strands cannot be less than  $72^\circ$  [5].

Thus, we have the possibility of reducing the total losses in the coil by decreasing the filament diameter and twist pitch in the wires, as well as to suppress the inter-strand losses, as already mentioned. However, there is a lower limit to the reduction of the filament diameter, due to the proximity effect [6]. As one reduces the filament diameter (keeping the filament spacing to filament diameter constant), the effective filament diameter starts to increase, as the filament spacing decreases and adjacent filaments become proximity coupled. Both filament diameter and twist pitch reduction can be achieved in existing SC wires for UNK dipoles. Estimates show the lower limit values should be  $d_f = 4 \mu\text{m}$  and  $l_p = 4$  mm, which determine new cable dimensions, in which  $\alpha \cong 8.5$ .

### 4 EFFICIENCY OF DIPOLE

The maximum field  $B_{\text{max}}$  in the central cross section of the magnet is found in the last turn of the first layer of the coil (counting anticlockwise from the medium plane) and exceeds the central field by 9.6%. The maximum power loss arises during uninterrupted triangular cycles and a

steady state temperature condition is reached after several (4-5) cycles. A trapezoid cycle (ascent-plateau-descent-plateau) improves the efficiency of the magnet because the coil is cooled during a plateau.

Further calculations were made taking into account expected properties of the improved current carrying element with above-mentioned  $df$ ,  $lp$  values and minimized cable losses. It is assumed that the temperature of liquid helium is constant along a length of the magnet.

Fig. 4 shows the temperature behavior in the last turn of the inner layer versus time for triangular (solid) and trapezoidal (dotted) cycles for parameters  $B = 6$  T,  $dB/dt = 4$  T/s. The duration of the plateau is chosen as the minimum time necessary to allow the turn time to cool below the critical temperature. The thin lines show the critical temperature, which is determined by the magnetic field and properties of the superconductor. The heavy lines show the changes of the real temperature in the coil.

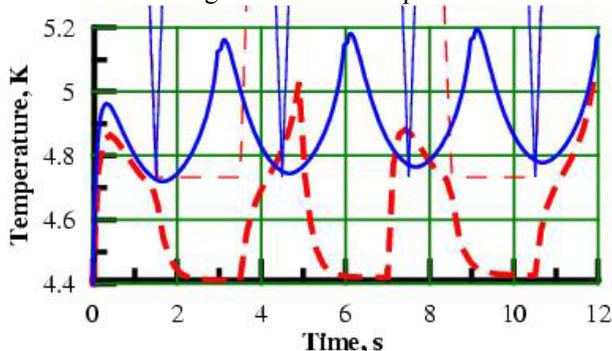


Fig. 4. Temperature dependence in the last turn of the coil versus time for the triangle (solid) and trapezoid (dotted) cycles.

Fig. 5 shows the dependence of the maximum achievable field ramp rate versus field amplitude for the triangular and trapezoidal cycles. It is necessary to have about a 2 s plateau for the trapezoidal cycle at 6 T and 1 s at 5 T, to raise  $dB/dt$  up to 4 T/s.

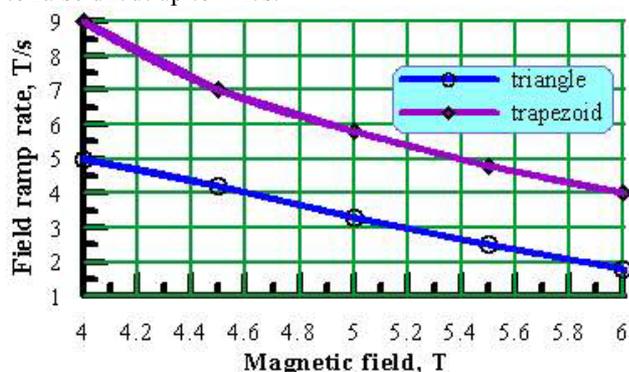


Fig. 5. Maximum achievable field ramp rate versus amplitude of magnetic induction for triangular and trapezoidal cycles.

Fig. 6 presents the loss surface per cycle in the coil  $W = W(B, dB/dt)$  for a 1-meter length of the magnet. These calculations were made taking into account the real distribution of the field  $B$ , its components  $B_{\perp}$  and  $B_{\parallel}$  and the critical current  $J_C$  over the volume of the coil. One can see that the total losses have a linear dependence versus  $dB/dt$  and a logarithmic dependence versus field  $B$ . The

maximum  $W$  is equal to 85 J/m for  $B = 6$  T and  $dB/dt = 4$  T/s.

Table 2 gives calculated values of power loss, per meter magnet length, for some reference points  $B$  and  $dB/dt$ .

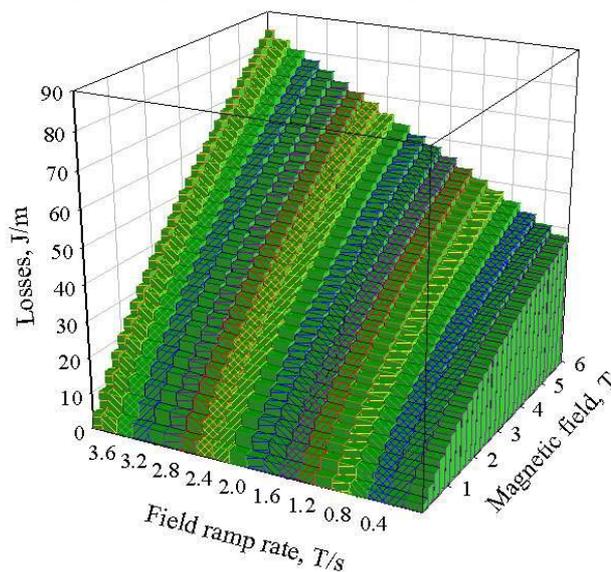


Fig. 6. Losses as a function of field and field ramp rate.

Table 2. Specific power loss (W/m), before and after upgrade of the conductor, for some reference values of  $B$  and  $dB/dt$ .

|                        | UNK        |           | Upgrade  |           |          |
|------------------------|------------|-----------|----------|-----------|----------|
| Field, T               | 6          | 6         | 6        | 4         | 4        |
| $dB/dt$ , T/s          | 4          | 4         | 1        | 4         | 1        |
| Hysteresis             | 25         | 17        | 6        | 17        | 4        |
| Matrix                 | 80         | 13        | 1        | 13        | 1        |
| Cable                  | 60         | 6         | 1        | 6         | 1        |
| <b>Total in coil</b>   | <b>165</b> | <b>36</b> | <b>8</b> | <b>36</b> | <b>6</b> |
| Hysteresis yoke        | 10         | 3         | 1        | 1         | 0        |
| Eddy yoke              | 20         | 0         | 0        | 0         | 0        |
| <b>Total in yoke</b>   | <b>30</b>  | <b>3</b>  | <b>1</b> | <b>1</b>  | <b>0</b> |
| <b>Total in magnet</b> | <b>195</b> | <b>39</b> | <b>9</b> | <b>37</b> | <b>6</b> |

## 5 CONCLUSION

A study of the possibility of using the UNK dipole with an upgraded conductor at higher ramp rates than originally envisioned gives positive results. The design of the dipole should allow one to raise the central magnetic field above 6 T and to operate at field ramp rates up to 4 T/s. At the same time, the level of the losses can be reduced, to decrease operating costs.

## 6 REFERENCES

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