SUPERCONDUCTING SYNCHROTRON MAGNET PERFORMANCE IN A CLOSED CIRCUIT CRYOGENIC SYSTEM

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(presented by W. Heinz)

Abstract

In this paper technical criteria to design, build and operate synchrotron magnets are discussed. Some of the work performed at IEKP (Karlsruhe) is reported.

I. Summary

The parameters of pulsed superconducting synchrotron magnets are determined by the special requirements of superconducting and low temperature techniques, and by those of the users, especially by an effective ejection. The final choice of parameters is a balance between technical and technological possibilities, the economics and the requirements of the accelerator.

Some accelerator design criteria are proposed by the GESSS [1] committee, technical criteria to design, build and operate synchrotron magnets are discussed in this paper.

Dipole magnets, which are either under study, designed, or in a construction phase have central fields ranging between 4 - 5.5 T, useful aperture diameters of 6 - 8 cm and ultimately effective lengths of 5 - 7.5 m. The required field homogeneity in the useful magnet aperture should be better than one part in a thousand. The field pulse cycle time may vary between 8.5 to 20 s with a minimum field rise time of about 3 s.

To save valueable field volume and to improve evacuation, the magnet bore is cold. In order to energize the magnet in a reasonable time and extract the energy in a similar time, say 3 s, the magnet insulation must withstand a voltage to ground of about ± 3 kV. This voltage also determines the characteristics of the magnet protection system.

The helium vessel must be an integral part of the magnet. The amount of helium in the container should be as small as possible and should not exceed 10 liters per meter magnet length.

Each magnet must be electromagnetically decoupled from its neighbour. This is possible, if appropriate ferro magnetic shields are placed around the coils as close as possible. The iron shield should extend beyond the coil ends such, that the fringing field of one magnet does not link with the others. The magnet a.c. losses must be kept low. Using multifilament composite conductors and transposing the conductors (strands) into braids or cables, the losses due to flux sweep can be kept within tolerable limits. The laminated iron shell which is placed around the coil, in the helium vessel, contributes to the a.c. losses, but serves also as a coil support, enhances the central field and reduces stored field energy. The coils must be designed such that no field enhancement at the ends is encountered. All multipoles of even number and odd multipoles of the numbers 3, 5, 7, 9 and 11 should be eliminated. The coil structure must be able to withstand magnetomechanical stresses over the lifetime of an accelerator.

The design and construction of a test section that complies with the preceeding requirements has been started at IEKP Karlsruhe. A major part of this test section is a 400 Watt refrigeration plant, which enables magnets to operate continuously at 4.5°K. Various types of pulsed dipoles, either being studied, or partially built, will eventually be installed in a model magnet system. This system permits detailed study of the operation of several magnets simultaneously or individually. The chapters following summarize some of the work performed at IEKP (Karlsruhe), and present a study of the system operation.

II. Static and Dynamic Behaviour of Dipole Coils

II.1 Magneto- and Thermomechanical Behaviour

The overall coil current density chosen is 20 000 A cm^{-2}, which generates a field of 4.5 T in a useful aperture with a diameter of 6 cm. The coil has an inner diameter of 8 cm and an outer diameter of 14 cm. Although basic study is not terminated, the iron shell presently, has an inner diameter of 21 cm and is not saturated.

The coil form developed is a glass-fiber epoxy structure. The reasons for this choice are, unity relative permeability, good mechanical strength, and no eddy current losses. The thermal contraction of the coil form is matched to that of the conductor [2]. The vacuum tube may also be a glass-filament structure, which have H-film liners of negligable permeability to helium gas. Measured values of helium gas diffusing through such a structure are less than $7 \cdot 10^{-8}$ torr·lit·mm/sec·m^2·atm, at 300 K, which is the limit of the measurement accuracy of our apparatus. Calculations indicate, that the vacuum tube may also be made of nonmagnetic stainless-steel, if the pulse cycle time is in the range of 10 sec or longer 1).

The coil is subdivided into a number of blocks which limit the hot-spot-temperature, and **eliminate** the multipole components mentioned previously.

The Lorentz force acting radially outward on the largest coil block is 6×10^4 kp/m of length of magnet. To prevent conductor movement, each block is impregnated in a filled thermosetting, and is reinforced by non-magnetic stainless steel splitrings, placed axially at distance of 8 cm.

The Youngmodulus of the entire coil is about 10^6 kp/cm^2 (only 9 % of the coil volume is filled with pure epoxy), and thus the deflection of each block between reinforcement rings due to the Lorentz forces will be approximately 3 µm. The epoxy is loaded to about 60 % (by weight) with an inorganic filler. In addition the layers in each block are wrapped in glass-fiber tapes. The combination of inorganic reinforcements and glass-fiber tapes yield a higher thermal conductivity in each coil section 3) and a better matching of thermal contraction between impregnant and coil. The freed strain energy during cool down is not sufficient to generate major cracks in the epoxy which may lead to coil degradation and training. However two major disadvantages have to be overcome if e.g. loaded epoxies are used. The tensile strength of glass-fiber reinforced epoxies (7000 kp/cm^2 at 4.2 K) is reduced by a factor of 2.5 when inorganic filler is added to the mixture. The viscosity at impregnation temperature of the epoxy mixture is two to three orders of magnitude higher, when fillers are added.

The tensile strength reduction is partially compensated for (by about a factor of 1.6) if the filler is heat cleaned and chemically treated, and silicone complexes are added to the epoxy mixtures. A reduction of the viscosity at impregnation temperature is possible by using three component epoxy mixtures. By reducing the recommended amount of accelerator one can impregnate the coil at higher temperatures under vacuum. The starting viscosity of this mixture can be reduced to less than 2000cP, which is adequate for a uniform coil impregnation.

The maximum stress in a coil section (with 8 cm spacing between reinforcement rings) is 2.3×10^3 kp/cm^2. For a composite structure with Cu : Sc = 1.25 : 1, this corresponds at 4.5°K to 0.4 % strain. The copper (annealed OFHC copper used as a matrix) is slightly workhardend and it's resistivity at 1 % strain is increased to 1.16×10^{-10} Ohm·m(RRR = 150). However when the magnet is thermomechanically cycled 2), the tensile strength of copper is reduced about 30 % and the residual resistivity ratio is reduced to RRR = 135. Glass-filament epoxy structures are quite resistant to magnetomechanical cycling. The tensile strength after 10^6 cycles is reduced by a factor of 2.3 at 4.2 K 2).

II.2 Heating Effects due to Field and Current Sweeping

A.C. losses in superconducting pulsed magnets are reported extensively in the literature. Using composite conductors with 10 µm diameter filaments, the dipole a.c. losses (10 s cycle time) are about 11 Watt per meter magnet. The major contribution comes from hysteretic effects, eddy current effects and coupling effects between individual strands. Self field and auxiliary losses can be neglected 4). The dipole coil has an effective volume of 66.6×10^2 cm^3 and thus the average power density in the magnet is 1.65×10^{-3} W/cm^3, corresponding to a heat flux of 1.4×10^{-3} W/cm^2.

In order to consider temperature rise in an impregnated coil section a knowledge of the heat generated by the instantaneous a.c. losses is essential. The instantaneous power dissipation for a slab, having a volume of V = Ad is given for an ascending and descending field by 4):

$$P = V \cdot \frac{d}{4} \mu_0 \cdot J_c(B) \cdot \frac{dB}{dt} \qquad (1)$$

with d the slab dimension perpendicular to the field.

For constant $\dot{B}$ the instantaneous heat generated in the slab is proportional to the critical current density in the superconductor. During a sweep of the field between 0.45 T (field at an injection energy of 100 GeV) and 4.5 T maximum operating field, the critical current density in the superconductor change by an order of magnitude.

The heat generated in a coil package assuming symmetric boundary conditions, is carried away by thermal conduction through the coil and by heat transfer to the helium. The maximum temperature rise in the coil over the bulk helium temperature is to a first approximation *:

$$\Delta T = w_v \left| \frac{1}{2k} \left(\frac{a}{2}\right)^2 + \frac{a}{2h} \right| \qquad (2)$$

w_v is the instantaneous loss value per unit volume, k is the heat conduction through the coil matrix (conductor, glass-fiber-epoxy-filler), h is the heat transfer coefficient to the bath and a is the coil package width perpendicular to the coolant passages. The

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* Exact two dimensional calculation involve Fourier-series which are rapidly converging. The error in neglecting higher order terms in (eq. 2) is less than 15 %.

thermal conductivity of a coil consisting of composite conductors and epoxy is measured by Krafft 3) and is about 2×10^{-3} W/cm K, at 4.5 K when the coil is impregnated with pure epoxy, and 4.5×10^{-3} W/cm K, when filled epoxies are used. The heat transfer coefficient from the coil surface to the bath depends on the method of cooling. If pool boiling is selected, a maximum heat flux of 0.1 W/cm^2 is obtained at a temperature rise of 0.2 K. If two phase forced helium cooling is chosen, depending on the Reynolds number at the same temperature rise, a heat flux up to 0.6 to 0.8 W/cm^2 can be obtained. With no great difficulty helium velocities in the order of 0.2 ms^{-1} can be achieved through coolant passages having an hydraulic diameter of 0.5 mm, leading to the above heat flux. Allowing a maximum temperature rise of 0.2 K inside the coil over the bulk helium temperature (hot-spot), the median coil width of a = 1.2 cm (pool boiling and unfilled epoxy) and a = 1.8 cm (pool boiling and filled epoxy) can be permitted. The thermal diffusivity of a coil impregnated with filled epoxy is about 0.6 cm^{2}s^{-1} at 4.5 K.

Although it appears that the heat generated during ascending and descending magnetic fields can be transported to the bath without additional temperature rise, not enough data is presently available, to estimate instantaneous local heating effects at low fields in impregnated coil packages, which may lead to conductor degradation.

II.3 Field perturbations

The production of field multipoles within the useful magnet aperture depends on several factors. We summarize all the major sources of the field errors and put them into two **categories:** 5)

a. Asymmetric Coil Aberrations

1) Coil displacement errors:
Field errors due to the shifting of one coil half or a quarter of coil with respect to the others, field errors due to the shifting of one coil block with respect to anothers, and field errors due to the displacement of one conductor with respect to others. Dimensional changes of the conductor, and coil blocks can be included in this **category.**
2) Coil and iron shell displacement errors.
3) Errors which occur when the magnetic and geometric centers do not coincide.
4) Field perturbation due to current leads, conductor cross-overs.
5) Field errors due to short circuits in the coils. This effect is frequency dependant and must be avoided in pulsed magnets.

b. Symmetric Coil Aberration

1) Finite size effect of the conductor.
2) Elastic and inelastic conductor motion.
3) Eddy current and coupled loss effects.
4) Residual field effects.
5) Iron shell saturation effects.

All errors can be corrected by lumped quadrupoles, sextupoles, octupoles etc., provided they are about 2 to 3×10^{-3}. Field errors may occur by several aberrations simultaneously or by individual aberrations. For two required field homogeneities we have compiled the allowable aberration limits in table 1.

Table 1: Tolerance limits for a superconducting dipole magnet with a useful aperture of 6 cm diameter 5)

Permissible individual displacements in (mm)	Required field tolerance 2.5×10^{-3}	10^{-3}
Single conductor	$\geq$ 10	9
Single block	1.0	0.4
Coil half	0.25	0.1
Coil-iron shell displacement	0.25	0.1

Error calculation presented by Ries 6) and field measurements in a dipole coil relating coil tolerances to field errors are performed by Hartwig 7), do confirm the predictions of table 1. Elastic conductor motion must be kept small, primarily to avoid heating and degradation of the superconductor, rather than because of mechanical tolerances.

II.4 **Power Supply**

A 1000 GeV superconducting synchrotron magnet system has a stored energy in the range of 450 to 650 MJ 1). A superconducting synchrotron magnet power supply must include an energy storage system. For a system with a stored energy of 450 MJ, a current of I = 2000 A, a field rise time of 3.5 s, a voltage of 130 kV is to be expected over the entire synchrotron magnet system, therefore the power supply must be subdivided.

II.5 Protection and By-pass-Circuits

Protection and bypass circuits are required in a superconducting synchrotron to prevent the distruction of a superconducting magnet due to a quench. Quenches are caused by a number of reasons:

Power supply failure, power line failures, material fatigue, refrigeration and vacuum troubles, energy deposition in the coil due to the beam etc. If an energy of ~ 10^{-2} J is deposited in one cm^3 of magnet volume in one second 8), the heat cannot be removed fast enough to prevent a normal region from forming. This normal region will propagate causing the magnet to quench.

A typical superconducting dipole magnet will have 30 to 40 kg of conductor material per meter magnet length. The magnet stored energy is about 10^5 J per m. If such a magnet quenches, about 2.5 - 4 J/g will be deposited in the coil. This energy deposition will rise the coil temperature to about 70 K 2).

If one assumes a more severe case, where the energy from a number of magnets, say 30, is deposited into one magnet, the coil temperature may rise to maximum 350 K. This is acceptable from standpoint of heating, but the voltage generated during such a quench over the whole magnet will exceed the limiting ± 3 kV, given above. The synchrotron should be divided into groups of 15 to 20 magnets with a protection circuit across each group.

Figure 1 illustrates the current, voltage and temperature variation with time during a quench of a single 1 m long model magnet not electrically interconnected to other magnets in the system. If a single magnet in a system quenches, no protection circuit is necessary. The Karlsruhe magnet system will have a protection system, when more than one magnet is electrically connected in series.

II.6 Coil Performance in Prototype Dipoles

Dipole coils built and tested so far at Karlsruhe have a cross-sectional shape of intersecting ellipses with no iron shell. The coil ends were bend up and down at angles of 30°, 45° and 90°. A copper model having an effective length of about 1 m and an elliptical coil aperture of 12.9×8 cm^2 (useful aperture 9×6 cm^2) was operated for several days on the Karlsruhe refrigerator circuit (Fig. 2). The full capacity of the refrigerator (400 W at 4.5 K) was utilized to cool the magnet during continuous d.c. and pulse operation. The coilform (glass-epoxy-structural material) was supported at two points 84 cm apart. When a uniform load of 400 kp was applied over the coil length, the maximum coil deflection measured was 0.3 mm! This coil deflection is thus more than the tolerance limit given in table 1. The coils in future magnet will have to be supported rigidly at various points within the iron shell. Mechanical tolerances achieved in each double pancake (0.57 cm thick) varied statistically between 0.2 and 0.7 mm. The displacement errors between coil halves were about 0.1 mm. Using auxiliary coils the field homogeneity of 2×10^{-3} was achieved. Without correcting coils the field perturbation was about 7×10^{-3}.

Employing better manufacturing techniques, coil packages were wound with single strand composite conductors. These pancakes exhibited tolerances in the order of 0.04 mm. The coil packages are about 50 cm long and about 0.6 cm thick with coil ends bend 90°. The packages were impregnated individually in an epoxy-aromatic-amine mixture with no filler. When individual packages were energized, training effects and degradation were observed only after the first cool down. Subsequent operations and cool downs did not exhibit training, even when the coils generated a field of 3 T.

A superconducting dipole magnet, 50 cm long, consisting of 2 x 7 double pancakes (0.4 mm diameter, single strand) was tested and produced so far a field of 3 T at a current of 40 A. The coil overall current density was 22×10^3 A/cm^2. The dipole exhibited training effects only during the first 10 quenches.

III. Magnet-Cooling and Operation

III.1 The Karlsruhe Magnet-Refrigeration System

The Karlsruhe magnet system consists of the following major components:

1-5 superconducting magnets in separate cryostats; 2000 A magnet power supplies; magnet protection circuits; a 400 W (4.5°K) refrigerator; rigid and flexible cold gas transfer lines; refrigeration control and auxiliary parts; a helium gas recovery system.

Figure 3 illustrates schematically the major components of the magnet cooling circuit.

Normal operating characteristics of the refrigeration system are shown in table 2. The magnets are connected to the refrigerator by about 40 m of coaxial transfer lines.. During normal operation, the estimated pressure drop in the high pressure lines will not exceed 2 atm; the return line pressure drop is about 0.2 atm.

Table 2 shows that 25 watts of refrigeration is required for each pair of 2000 A current leads from liquid helium to room temperature. This is due to the fact that 4 m^3/hr STP of helium gas must pass through each pair of leads to cool them down. This gas does not pass through the refrigerator heat exchanger, and as a result, the refrigerator sees this as an equivalent liquefaction of 5.5 l/hour. A liquefaction of 5.5 l/hour requires about 22 W of refrigeration capacity. The remaining refrigeration required removes the heat leaking down the leads.

Finally we discuss the method used to recover a quenched magnet:

Important quench time constants are as follows:

- **i) The quench propagation time constant is 0.01 s - 0.1 s**
- **ii) The time required to deposit the magnet field energy as heat in the coils is: 0.7 s - 1.5 s.**
- **iii) The time constant of the heat removal from the coil to the helium bath is: 10 s - 20 s.**

a) The individual magnet cryostats are designed for 5 atm internal pressure. At 4 atm the relief valve will open allowing the gas to be recovered in a 100 m^3 gas bag. In most cases the pressure build up in the cryostat is lower than 1 atm; little or no gas will pass through the relief valve.

b) As the quench proceeds, the excess cold helium gas, which has been boiled off will pass through transfer lines into the heat exchanger. The cold gas transmits most of its refrigeration to the incomming high pressure gas and to the heat exchanger itself.

c) The helium gas boiled off by the quench is recovered warm, after it leaves the refrigerator cold box.

d) The refrigeration is stored in the heat exchanger and can be used to speed up the recovery of the quenched magnet.

Table 2: Normal heat loads as various magnet systems operate at 4.5°K on the refrigerator

	1 Magnet	**3 Magnets**	**5 Magnets**
	5 sec. cycle, room temperature leads (2000 A)	**10 sec. cycle, room temperature leads (2000 A)**	**17 sec. cycle, superconducting leads connecting the magnets in series**
Primary transfer line	50	50	50
Secondary transfer lines	10	30	50
Magnet cryostat	5	15	25
Room temperature leads	25	75	25
A.C. losses in the magnet	30	40	40
Total heat load	120	210	190

If a single 1 m long magnet quenches in the system about 5 kg of helium (40 liters at 1 atm), can be boiled off. Cryostats which hold less than 5 kg of helium, will boil off the helium contained there in. The rest of the field energy remains as heat in the coils.

The Karlsruhe refrigerator heat exchanger is capable of handling a quench of at least 300 kJ without opening any of its relief valves. The refrigeration system is capable of automatically cooling down, operating and recovering the quenches of a number of superconducting magnets. The operation up to eight one meter long magnets seems feasible. This will permit us to model reasonably well the conditions which will exist in an actual superconducting synchrotron.

References

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7) G. Hartwig; KFK-Report Nr. 1472 (1971)

8) H. Brechna, W. Maurer; KFK-Report 1468 (1971) and KFK-Report 1469 (1971)

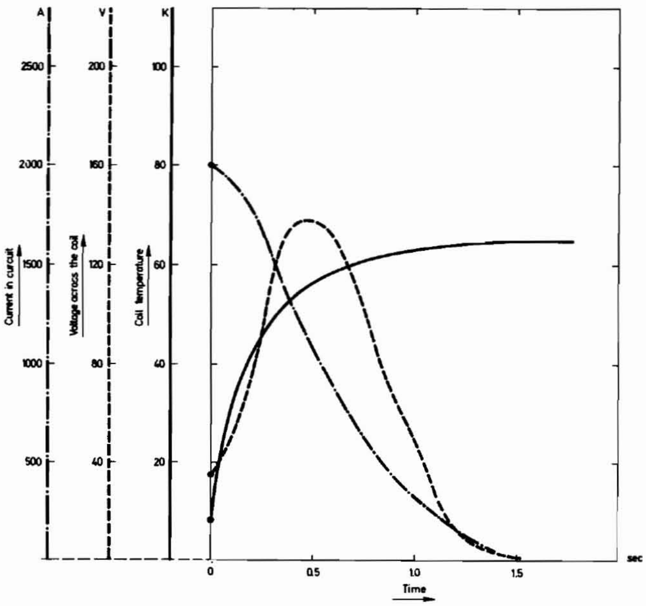

Fig. 1: Quench characteristics of a 4.5 T, 8 cm aperture diameter, 1 m long superconducting dipole.

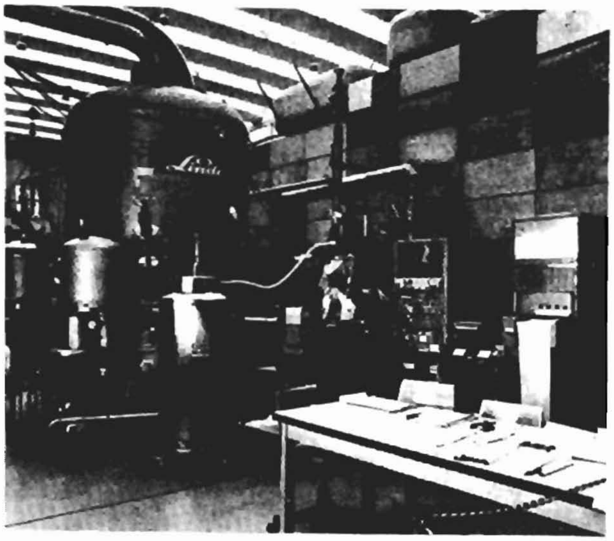

Fig. 2: 1 m cryogenic dipole and the Karlsruhe 400 W (4.5°K) refrigerator plant.

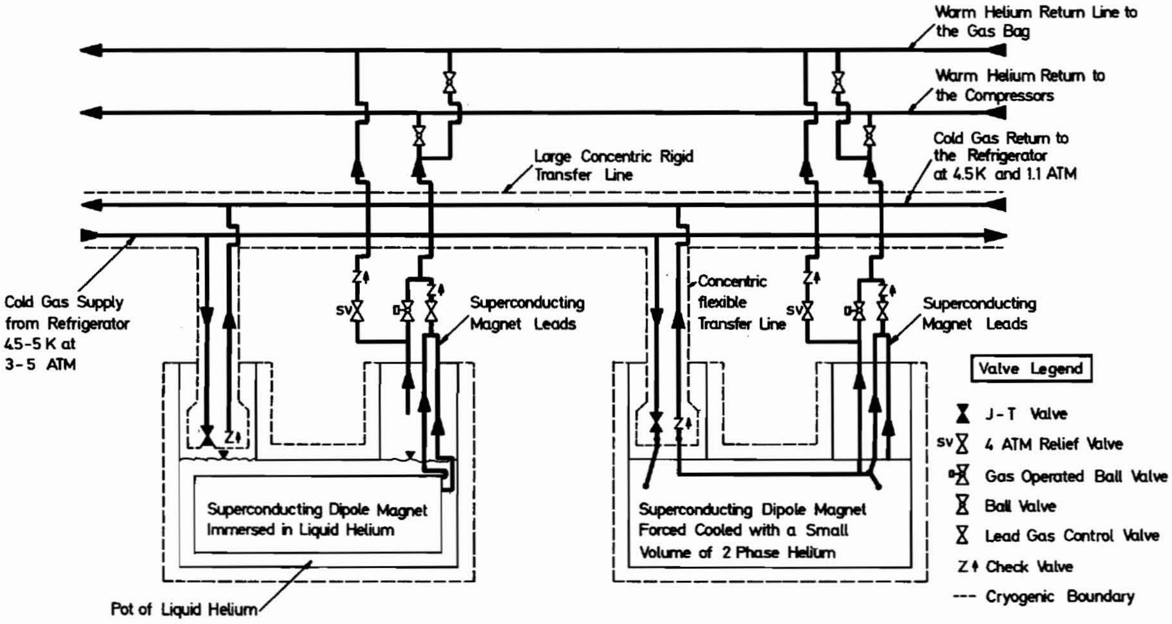

Fig. 3: Karlsruhe superconducting magnet cooling scheme

DISCUSSION

P.F. SMITH: What type of conductor or cable was used to wind your superconducting dipole model?

W. HEINZ: The tested dipole has a two-component single-strand conductor of 0.4 mm diam. with 130 filaments each of 23 μm diam. It is a forerunner of the dipole I described that will have 1 m long coils wound of cables carrying 2000 A.

G. BRIANTI: What is the field precision achieved with winding tolerances of 0.04 mm?

W. HEINZ: Field mapping is not yet completed but in a similar dipole with mechanical winding tolerances of 0.2 mm, a field homogeneity of 2×10^{-3} was achieved in 80% of the coil aperture.

R. WIDERØE: What material was used as a filler for the epoxy?

H. BRECHNA: Fillers used are alumina and quartz with a grain size of 10 μm or less. The ratio of epoxy to filler is up to 60% by weight.

G.K. GREEN: The point of coil protection in case of quenching which you mentioned is very important but why did you select a voltage so high as ± 3 kV?

W. HEINZ: It is a figure that we are confident we can achieve. For a magnet system with stored energy of 450 MJ, a peak current of 2000 A and a 3 s rise, a voltage of 150 kV is to be expected.

G.K. GREEN: I believe that the power supply should be further subdivided to give lower voltage, hopefully less than ± 1 kV.

W. HEINZ: We think that 3 kV is a reasonable compromise, taking into account the costs of a further subdivision of the power supply and the costs of better insulation.

J.P. BLEWETT: Could you explain how the conductor blocks and cooling channels are arranged in the dipole?

W. HEINZ: In the tested dipole, there are 2 x 7 horizontally arranged double pancakes, each 6 mm thick. Cooling channels are located between each of these double pancakes which are 1 mm wide. The space for these channels is provided by spacers and adequate steps in the glass-fiber coil structure. The coil I described with the cos θ current distribution is a race-track construction, approximated by 3 blocks per quadrant. The design and arrangement of the cooling channels is not yet frozen.