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MAGNETS FOR RADIATION-RESISTANT ACCELERATORS

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The paper discusses the problem of radiation damage likely to be met with in particle accelerator installations and considers methods of protection based on the total exclusion of radiation sensitive materials. The use of mineral insulation for magnets is explored and a detailed description of a number of actual prototype magnets is included.

1. INTRODUCTION

Numerous studies have been made of the effect of highly ionizing radiation on materials and components required in the construction of high energy particle accelerators.[1] In general, radiation damage has been countered by determining the expected radiation dose in various regions of the installation, and selecting suitably resistant components and materials for the proposed application. This technique must be backed up by tests to failure of radiation sensitive components in similar environments; this enables predictions of service life to be made, and indicates where there is a need to develop simple replacement techniques. In order to specify the service life of a component with confidence, it is necessary to consider many and often synergistic environmental variables such as radiation quality, dose rate, oxidation, ozone attack, temperature and mechanical and electrical stress. This is a lengthy procedure and could be unacceptable in a project with timescale and cost limitations. An alternative is to provide adequate shielding for radiation-sensitive components.

A major problem, however, arises with the design of the magnets for the accelerator, for the beam lines and the target stations. Magnets are especially sensitive to damage since the coil, usually located and insulated with epoxy resin glass fibre composite, is normally close to the particle beam or experimental position. The purpose of this paper is to describe in detail the construction of prototype dipole and quadrupole magnets with mineral insulation, resulting in a fully radiation-hard component.

Mineral insulation performs much better following exposure to high levels of radiation dose than organic materials where the formation of gaseous byproducts results in loss of material, and ultimate polymer chain fragmentation.[2] The main problem with magnets made from mineral materials lies in the need to reconcile the intractable nature of such material with the many requirements expected from a magnet insulator, namely, provision of mechanical and electrical support for the copper windings under stress and, constraint of the windings to close dimensional tolerances under operating conditions. These requirements have dictated the need for the coil and coil support material to achieve a degree of integrity that is usually associated with the use of glass tape wrapping and vacuum impregnation with epoxy resin.

2. INORGANIC INSULATING MATERIALS

In order to discuss these materials it is convenient to characterize them under headings, namely, ceramics, glasses and refractory cements.[3]

2.1. *Ceramics*

The electrical properties of these materials, for example, porcelain, steatite, alumina, magnesia, quartz, have been well characterized, with the emphasis on high-temperature or high-frequency dielectric loss. Their electrical behaviour is more than adequate for the low-duty requirement of magnets. To make a conventional magnet from ceramics two techniques can be considered:

(i) The refractory powder is slipcast or press-formed around coils accurately prelocated into position by a suitable support jig and then fired to produce the required integrity.

(ii) Strips or blocks of ceramic are used to 'egg-crate' the copper coils during winding and the coil clamped to retain configuration.

The difficulty with the first technique is that the high firing temperatures needed to sinter the material exceed the melting point of copper. Further, the sintering process would result in gross dimensional changes probably leading to brittle fracture.

The second technique could be used to construct electromagnets, the main requirement being the highly sophisticated clamping necessary to prevent coil movement and provide insulation throughout the whole coil configuration. A further problem arises from using a hard and abrasive material with the soft copper of the coil, any slight movement of the ceramic in contact with the copper results in copper smearing which can lead to breakdown.

2.2. *Glasses*

Glasses are available which melt at much lower temperatures than the predominantly crystalline ceramic materials and which exhibit much better dimensional stability on cooling, but the problems described under ceramics apply also to the vitreous system at present. Some low temperature melting glasses and in particular glass-bonded mica can be moulded into complex shapes, using plastics fabrication techniques, to good dimensional tolerances. Though the pressures required for moulding are large and temperatures in excess of 350 °C must be used, these materials might afford a possible alternative to conventional plastic insulation materials. The mechanical and electrical properties of glass-bonded mica are good, although the performance of this material when subjected to ionizing radiation is not clear at present, but it is thought to be much superior to the organic plastics.

2.3. *Refractory Cements*

Refractory cements are used extensively in electrical applications such as the bedding of furnace windings, thermocouple wires and packaged heating elements. In general for these applications, mechanical stress requirements and electrical duty to be supported are low, but since these materials, and the ceramics and glasses also, give an electrical resistivity temperature coefficient which accords with the Hinrichson–Rash law $\ln R = a/T + b$, the resistivities obtained at high temperatures can be sufficiently poor to warrant concern. Therefore, in the published papers, resistivities are usually quoted for high temperatures that are not relevant to the construction of magnets. In the main, these refractory cements have embodied the High Aluminous Cement (HAC) material which is made from a calcined and ground mixture of limestone and bauxite or alumina. This material with or without various types of filler or aggregate is mixed with water and then slowly baked out to give a refractory insulator.

It is apparent that the most successful technique for the construction of heating elements, thermocouple sheaths and mineral-insulated cables makes use of preformed ceramic beads or compressed ceramic powder such as magnesium oxide. Magnets have already been designed and constructed using mineral-insulated cables now obtainable in square cross section.[4] The obvious problem with these materials, however, is the low conductor packing factor that follows from the use of the copper sheath round the insulator and conductor bar.

3. HYDRAULIC CEMENTS AND CONCRETE

It is considered that, of the materials discussed in the last section, the castable cements offer the most promising solution to magnet construction. A study of available literature shows that hydraulic cements and concretes can be prepared with good resistivity and mechanical integrity, although present data on their resistivity and other properties is extremely variable.[5] The reason for this inconsistency must lie in the ill-defined nature of the hydraulic cements themselves together with the variable composition and bulk properties of the aggregate. Hammond and Robson give a good account of this work with volume resistivities of greater than 10^{13} ohm cm for HAC and 10^{11} to 10^{12} ohm cm for Portland cements, both being dried at 105 °C and cooled in desiccated conditions.[6] They also demonstrate that surface resistivity, whilst of a similar high order to the volume resistivity when desiccated, falls rapidly when exposed to atmospheric moisture, the best results being obtained with the high-alumina cements.

The study of breakdown voltage indicates that voltages of 10 to 20 kV cm^{-1} could be obtained, the highest values again being obtained with HAC. These results indicate that after the first breakdown, subsequent ones occur at a voltage slightly lower than the initial breakdown but thereafter remain fairly constant. Other authorities give results which although not comparable through formulation variables and test procedures bear out the general conclusion outlined above.[7]

4. EXPERIMENTAL WORK AT RHEL

Work on the development of concrete insulation has been carried out at the Rutherford Laboratory under three general headings:

(i) Studies of the electrical and mechanical properties of cements and cement/aggregate systems.
(ii) Experiments to study the behaviour of bulk quantities of cement and cement/aggregate systems.
(iii) The design and construction of small model prototype electro-magnets with concrete insulation.

Specimens used for electrical tests were prepared in polystyrene boxes 10 cm × 15 cm × 7.5 cm and vibrated to compact the material. These are illustrated in Fig. 1. The electrodes incorporated were guard ring systems of 10 cm^2 area of copper

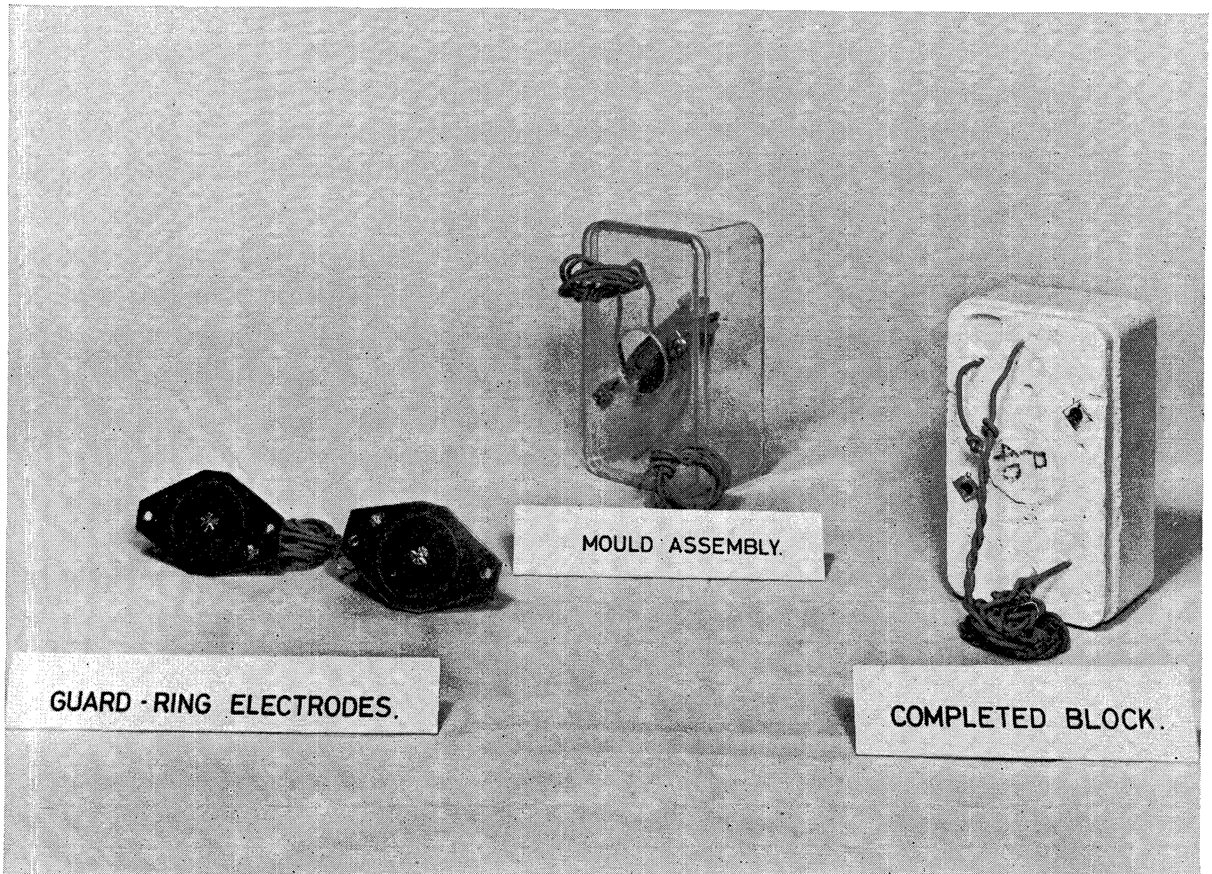

FIG. 1. Compacted specimens for resistivity tests.

on epoxy/glass laminate substrate, the electrode spacing being 1 cm. Specimens removed from the drying process must be isolated from atmospheric moisture either by sealing or storing in a dry enclosure such as a desiccator. Table I presents hinder impregnation of the closely packed coil turns. Most mixes so far investigated use aggregate smaller than 7 mesh sieve size. In the work discussed in this paper, choice of aggregate was restricted to silica or alumina materials.

TABLE I
Resistivity values (typical samples)

Cement type	Cement/ Aggregate ratio	Water/ Cement ratio	Resistivity ohm cm at 500 V.DC	Remarks
High Alumina (SECAR)	1/4	0.39	2×10^{13} 5×10^{9}	Desiccated Exposed to atmosphere
High Alumina (SECAR)	1/2	0.32	3×10^{13} 1×10^{9}	Desiccated Exposed to atmosphere
High Alumina (CIMENT FONDU)	1/4	0.50	1.3×10^{11}	Desiccated
White Portland (SNOWCRETE)	1/4	0.39	1.5×10^{13} 3×10^{9}	Desiccated Exposed to atmosphere
White Portland (SNOWCRETE)	1/4 (Different aggregate)	0.52	3×10^{13} 5×10^{8}	Desiccated Exposed to atmosphere
White Portland (SNOWCRETE)	1/2	0.33	5×10^{13} 1×10^{14}	Desiccated Desiccated
Ordinary Portland Cement	No aggregate	0.26	3×10^{13}	Desiccated

values of resistivity obtained from typical specimens. These data show that both White High Aluminous Cement (SECAR) and White Portland cement perform well electrically under dry conditions.

The aggregate systems were found to be generally similar in performance but some very good results have been obtained from systems not containing aggregate at all.

Concrete is characterized by high compressive strength but poor strength in tension. This characteristic is accommodated in designs for magnets by arranging for reinforcement to be applied in tension. One feature of concrete that has given concern is the shrinkage on cure. Aggregate additions will reduce the cure shrinkage but adversely affect the mechanical properties, for this reason it is very important to optimize the aggregate gradings for minimum shrinkage with best strength characteristics, at the same time avoiding the use of large particles which would

In addition to the laboratory studies of the properties of cement/aggregate systems it was considered necessary to investigate construction techniques with these materials. A programme of development work was, therefore, carried out to devise the best technique for making both dipole and quadrupole magnets. In the first instance a small model H magnet was made (Fig. 2). This consisted of twelve turns of 0.8 cm square conductor on a small split yoke approximately 22.0 cm × 12 cm × 8 cm, the whole being encased in alumina cement with external post-stressed bolts, stress being applied in one direction only. Interturn and other spacing requirements were achieved in this and all other magnets by the insertion of a number of strips of mineral material during the coil winding and location operations. During power tests, cracks were produced in a direction parallel to the externally-applied stress.

The resistance of the insulation on this model was similar to that previously obtained from

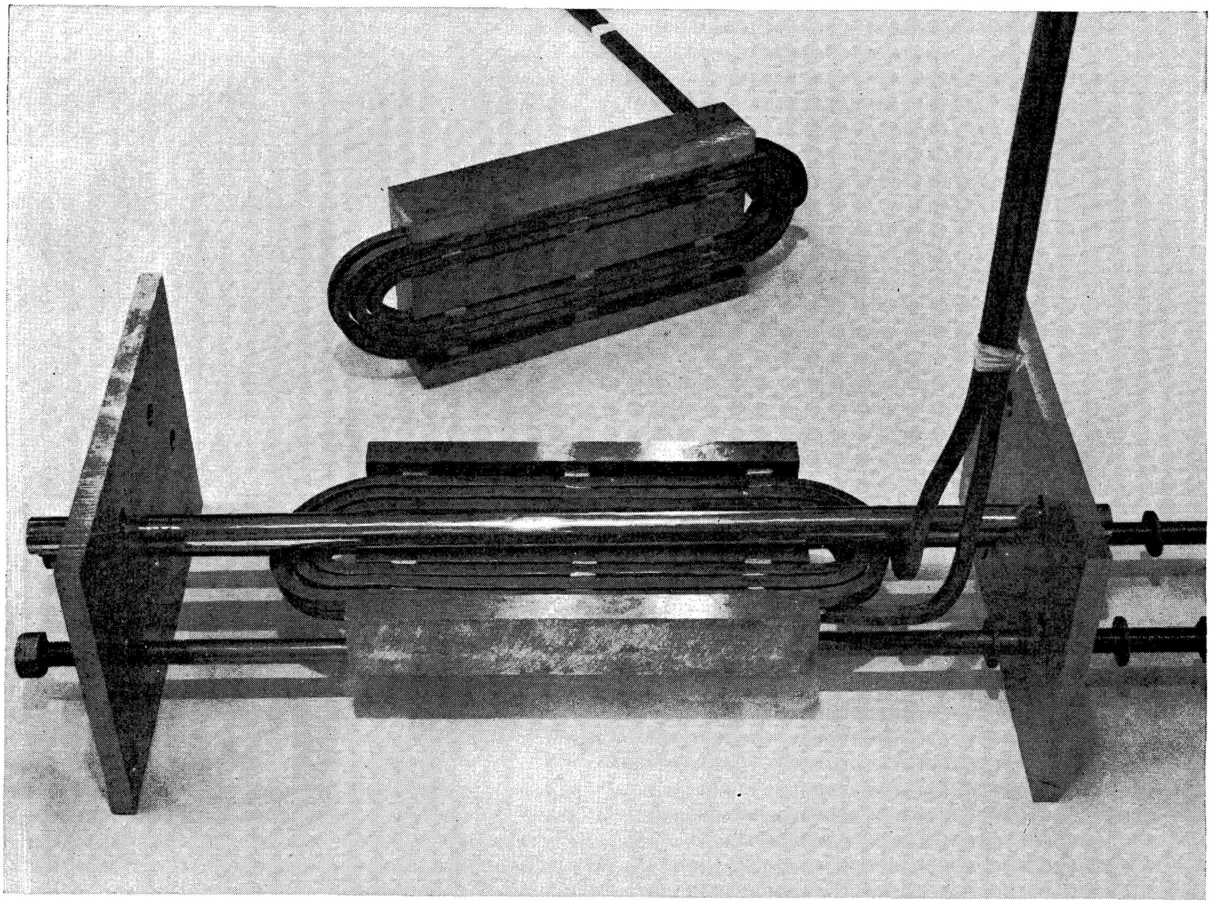

FIG. 2. Model H magnet.

laboratory test samples exposed to normal atmospheric conditions.

Next it was decided to build a small H magnet suitable for use in an accelerator beam line (Fig. 3), based on the existing Daresbury Nuclear Physics Laboratory H5 magnet which has a moderate field of 11.5 kG at a power rating of 15 kW.

The magnet has 80 turns of 6 mm × 6 mm conductor with a water connection to every 8 turns. Its design did not involve any alteration to the coil geometry, except that a minimum spacing of 1.0 mm is desirable between adjacent conductors. This is necessary to ensure penetration of the mortar of cement and fine aggregate mix. At each end of the yoke where the coils project, a temporary casting provided a mould for the mortar and a means for pre-stressing both the steel-work holding the coil ends and also the stainless steel flight tube through the magnet gap.

The mortar was introduced into the top of the casing at each end of the magnet while on a vibrating table and small holes were provided in the centre of the yoke top to allow trapped air to escape. The magnet was completed and performed satisfactorily on test. Table II gives the performance data.

A second H5 magnet, shown in Fig. 4, was designed to overcome some of the shortcoming of the first prototype. This magnet was designed to be filled with concrete pumped in under pressure in order to ensure that the concrete would be permanently under compressive stress in all directions even when raised to a temperature of 100 °C, thus preventing hair-line cracks forming in

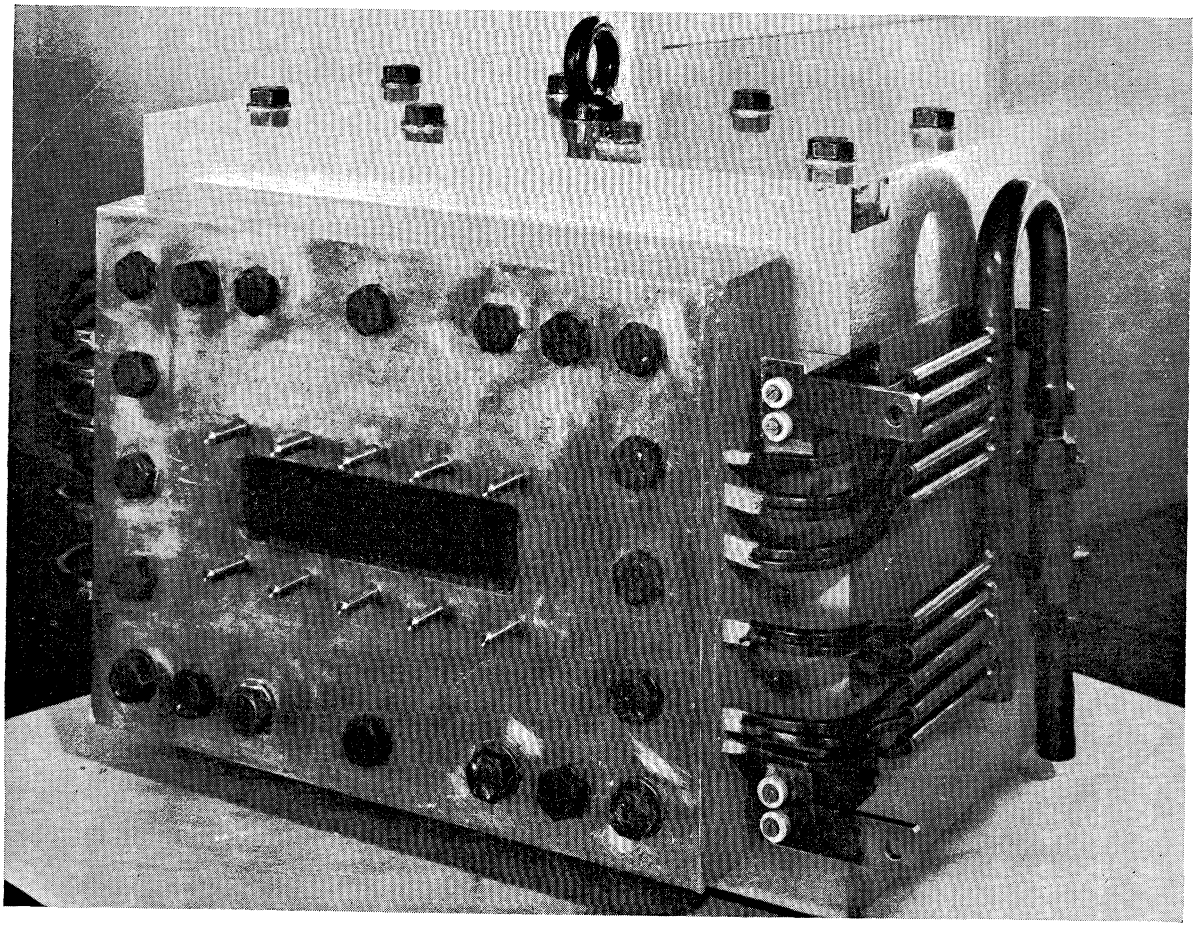

FIG. 3. H5-type magnet (first prototype).

TABLE II
Magnet performance data H5 (first prototype)

Field intensity	= 11,400 G (14,800 G maximum)
Area of field	= 32 × 20 cm
Height of gap	= 5 cm
Cross section of flight tube	= 20 × 5 cm
Length of flight tube	= 50 cm
Normal energizing current	= 375 A (600 A maximum)
Power dissipation of windings	= 15 kW (48 kW maximum)
Cooling water flow	= 1300 lh^{-1}
Total weight	= 600 kg

the concrete and initiating a breakdown when subjected to a high-voltage test.

The procedure for filling this magnet was rehearsed on a number of perspex tubes filled with steel and copper sections to represent the cross-sectional areas to be filled. Filling was carried out on a vibrating table.

Concrete can achieve resistivities adequate for insulation of magnet coils. This is conditional on complete dryout and the maintenance of sealed or desiccated conditions and it is questionable whether these conditions can be always guaranteed. Accordingly, the technique of lining the yoke with thin sheets of high-resistivity ceramic material was adopted.

The second H5 prototype on test gave the following results:

Insulation test between conductors 400 MΩ
Conductors to earth 400 MΩ

It was also flash tested satisfactorily at 2 kV for

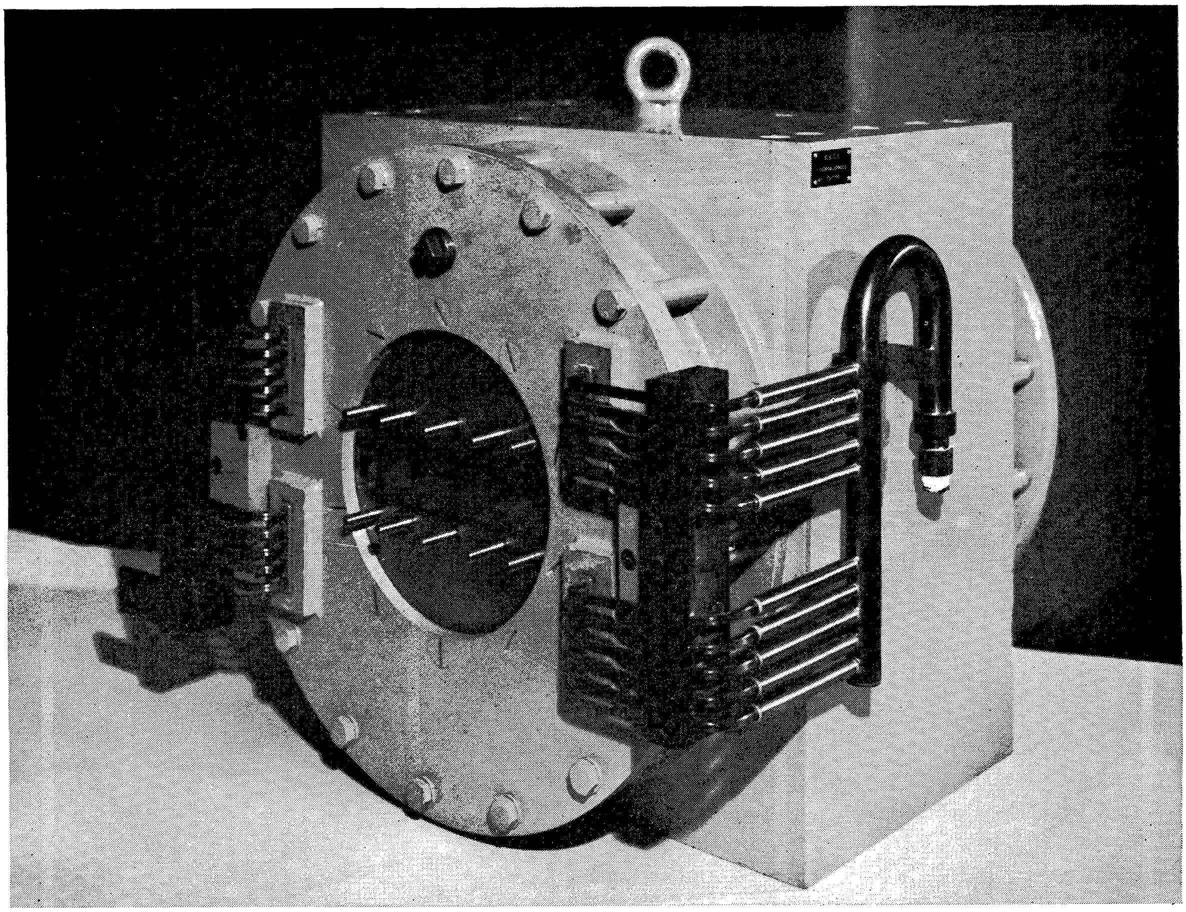

FIG. 4. H5 magnet filled with concrete (second prototype).

1 minute. This magnet has been installed and is operating in a beam line at the Daresbury Nuclear Physics Laboratory.

Figure 5 shows a quadrupole magnet prepared using similar techniques and installed in an electron accelerator beam line.

The prototypes so far considered have been designed specifically for use in beam lines. A conceptual design for an accelerator magnet for a multihundred GeV installation based on the use of concrete as insulator has been prepared by the authors.[8] Figure 6 shows the layout of this design in which the concrete provides support for both coil pack and laminated yoke.

5. RADIATION RESISTANCE OF CONCRETE

The radiation resistance of concrete is considerably higher than that of organic materials as is shown in a recent review of studies of its behaviour in reactor environments.[9] Whilst there are no detailed studies on the effect of long term accelerator radiation on the mechanical properties of concrete, there are no records of failure of concrete in the biological shield of atomic reactors that can be ascribed to radiation. Evidence from the exposure of samples, and tests on concrete shields exposed to high levels of neutron and γ-radiation, indicates that standard quality concrete preserves its mechanical strength under nuclear radiation.[10]

6. CONCLUSION

It has been demonstrated by the production of prototypes that magnets can be successfully constructed using radiation hard materials.[11,12] It follows that if these techniques can be applied in the

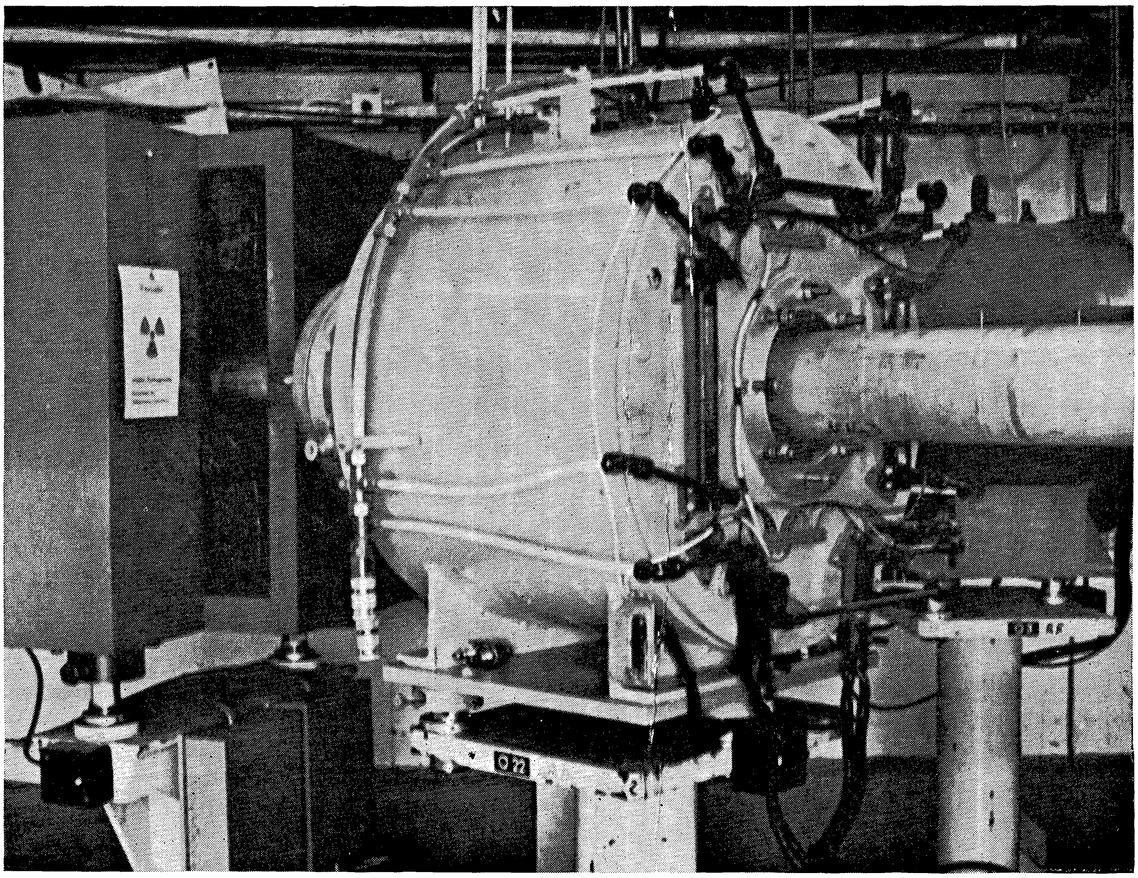

FIG. 5. Quadrupole magnet (photograph courtesy of Lintott Engineering).

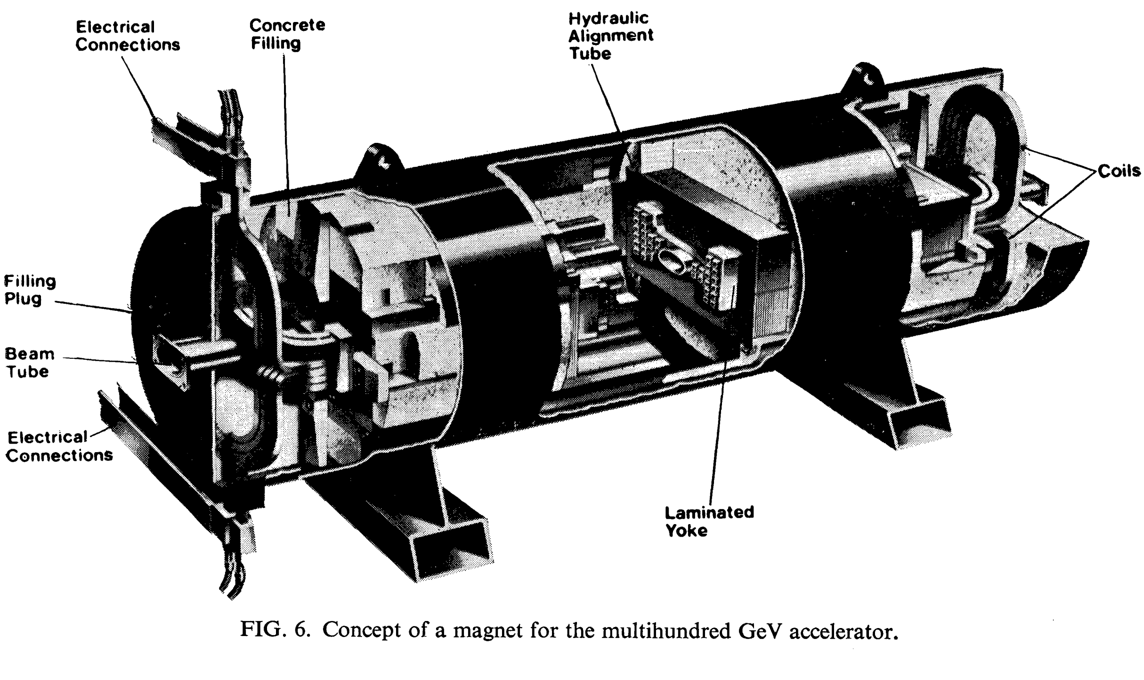

FIG. 6. Concept of a magnet for the multihundred GeV accelerator.

construction of synchrotron magnets and other beam handling magnets, such installations can be made completely radiation 'hard' thus obviating the need for expensive replacement contingencies. It becomes less important from damage considerations, to achieve high particle beam extraction efficiencies and further, one can also consider the possibility of internal targetting methods, hitherto not possible in such high energy accelerators. These factors together constitute a valuable contribution to the operational flexibility of such an installation.

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