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Abstract

As part of the upgrading of the CERN antiproton source facility, the target station and injection line are being rebuilt. The beam transport magnets immediately downstream of the target are expected to receive a lifetime radiation dose in the range 10^8 to 10^9 Gy. It was decided that these magnets, two quadrupoles and two dipoles, were to be made entirely of inorganic materials. They are to be powered by existing pulse power supplies which have 25 kJ capacitor banks operating at 4 kV. Two solutions have been adopted. For the quadrupole magnets, each pole has eight turns which are insulated by air and supported by ceramic pieces. The peak current is 4 kA. In the case of the dipole magnets, it was decided to use a single turn carrying a peak current of 70 kA together with a 18:1 turns-ratio matching transformer. The coil insulation is a combination of air and pieces made from a newly available hydrated calcium aluminate cement.

Introduction

Magnets in particle accelerators and beam transfer lines are exposed to ionizing radiation and suffer damage in varying degrees depending on the dose to which they are subjected. Usually, by taking care to minimize beam losses and choosing adequate quality materials, the damage can be limited and magnet failure does not occur. For high beam intensities it is not always possible to keep beam losses sufficiently low, or intense radiation levels may arise when a beam is intentionally allowed to strike a target. Magnet failure will occur unless special measures are taken in their construction.

Magnet excitation coils are often made by wrapping the conductor bars with woven glass fiber apes and vacuum impregnating the winding with an epoxy esin which is then cured to produce a magnet coil in a single block without voids. This technique can produce coils that survive radiation doses in the range 10^7 to 10^8 Gy. When higher doses have been anticipated, the use of epoxy resins has been abandoned in favour of inorganic materials. Examples of this approach include the use of coaxial cable filled with magnesium oxide powder as insulator [1] or setting the conductors in a high-alumina cement [2]. Magnets built in this way are more suitable for low-voltage direct-current operation. Another approach [3] used metallized ceramic insulators. The complete coil assembly was brazed together in a hydrogen furnace and proved to be a very difficult operation.

ACOL Requirements

A project (named the Antiproton Collector, or ACOL [4]) has been under construction at CERN to enhance the accumulation rate of antiprotons ($\bar{p}$) which are used subsequently for p-$\bar{p}$ collisions in the Super Proton Synchrotron. The 26 GeV/c proton beam from the Proton Synchrotron is focused onto a target, and the resulting antiprotons taken by means of a large acceptance beam-line to the new collector ring. The intensity of the proton beam at the target is expected to reach a value of 2×10^{13} protons per pulse. The pulse has a length of 0.6 μs and a repetition period of 2.4 s. It was estimated that the first few magnets downstream of the target would receive radiation dose between 10^8 and 10^9 Gy over a period of ten years. The magnets most affected are the first two quadrupoles and the following two dipoles.

In order to reduce the cost of electrical power in operating the transfer line it was decided to use pulsed magnets wherever possible (the duty cycle can be reduced to 1% or less) and the reason for this decision was reinforced by the availability of suitable power supplies on the CERN site. The use of these power supplies imposes design restrictions on the magnets. The peak operating voltages and currents must not exceed 4 kV and 4 kA respectively, and the load stored energy is restricted to 25 kJ. These parameters require that the load inductances are kept below 4 mH. The dipole magnet has therefore to be made in two 1.5 m long units. The magnet coil insulating system should be entirely inorganic, it should support the pulsed electromagnetic forces and be able to hold a peak operating voltage of 4 kV.

Quadrupole magnets with some of these requirements had been constructed and successfully operated for the past two years. Their excitation windings consisted of 4 turns in a single layer mounted on each magnet pole using aluminium oxide ceramic mounting pieces and relying on 4 mm of air for insulation. The stored energy for these magnets was 3 kJ. It was decided to employ the same concept for the new quadrupole magnets. However, for the two dipole magnets it was considered that it would be better to match the magnet to the power supply through a step-down transformer and construct the magnet winding in one turn using heavy copper bars, thereby enabling a simpler mechanical design for the coils as well as a lower operating voltage for the magnets. The transformers have sufficient radiation shielding so that suitable organic insulating materials could be used in their construction.

The current waveform for both the quadrupole and dipole magnets is a single, moderately damped sinewave with a duration of approximately 25 ms.

The beam optical design of the injection line requires the following parameters for the first two quadrupole and dipole magnets:

Table 1 - Magnet types

		QDE6010	QF06020	BHZ6030
Magnet length	(m)	0.90	0.90	1.65
Field	(T)			1.00
Gradient	(T/m)	8.59	7.72	
Horizontal aperture	(mm)	172	114	400
Vertical aperture	(mm)	114	88	88

The $\bar{p}$-beam passes through these magnets in air, no vacuum chamber is required.

Construction Materials

Magnet Yokes

The yokes were constructed from 0.65 mm thick transformer steel laminations. These were supplied with an inorganic insulating coating created by varnishing and baking the steel sheet. The varnish contains phosphoric acid. The stacks of laminations were constrained between mild steel end plates which were 40 mm thick for the quadrupole magnets and 20 mm for the dipoles.

Coils

The copper conductor for the quadrupole coils was in the form of tubing with an outer diameter of 10 mm and an inner cooling hole 5 mm in diameter. For the dipoles, solid copper bars 20 mm thick and 82 mm high were used.

Coil Spacing and Supporting Pieces

The electrical insulation of the coils from the steel of the yokes is provided by having a sufficiently large air gap. This has been found to be adequate even in the presence of ionizing radiation. For the pulsed magnets, the voltage across the coil is at its lowest value during the period the proton beam pulse is on the target.

However, the coils must be supported and clamped. The most suitable insulators are made from inorganic ceramics such as porcelain or, where greater strength is needed, high-temperature fired alumina. Sintered ceramics are expensive and difficult to machine. Grinding these materials is necessary if good mechanical tolerances are required.

An alternative material, which would seem to have good radiation-resistant and mechanical properties, has recently become available. It is a hydrated, macro-defect free calcium aluminate cement referred to as NIMS [6] (new inorganic materials). The raw material is made from very finely ground "high alumina" cement with 7% water soluble polymer. Before setting, it can be moulded or extruded but not cast or poured. The finished product can be machined with normal hardened tools. Some difficulty was experienced when trying to make bushings from solid rod but this was overcome by starting with extruded tube. Exposure to γ-radiation has shown that the bending strength falls from an initial value of 150 MPa to 50 MPa after an exposure of 3×10^6 Gy. Further exposure up to 9×10^6 Gy produced no further change in the bending strength.

Organic Materials

We were not completely successful in excluding all organic materials. Some have been used in non-critical roles and others as a matter of expediency because of the need to have operating magnets even if their life-time turns out to be shorter than we would like. However, we have been careful in our choice. The following organic materials have been used.

Kinel 5504 is the proprietary name for a polyimide resin, reinforced with chopped glass fibers. Vetronit is glass tape impregnated with epoxy resin, while Kapton is polyimide film. The resistance of these materials to radiation can be found in the compilations of Schönbacher and Stolarz-Izycka [7].

Pulsed Quadrupole Magnets

In order to meet the restrictions imposed by the power supplies, the quadrupole apertures were matched to the beam envelope, though not to the extent of making the poles asymmetric. The stored energy for both types was nearly the same because although a higher gradient is required for the QD type, it has smaller bore radius and a narrower pole width. The coil slots, however, were made identical in the two magnets. Since the yoke lengths differed by only 6 mm, the same coil design could be used for both. The magnet programs PE2D and TOSCA were used for the detailed designs, with the 12-pole component due to the pole-ends being compensated in the pole profiles [5]. It was assumed that the 40 mm-thick solid steel end-plates would not contribute to the magnetic lengths due to the short pulse length. Later measurements showed this to be only partly true.

In order to ensure that there would be no lamination chatter, insulated through-bolts were used on each pole. The coils comprised 8 turns which were supported along the magnet length by spaced ceramic pieces which themselves were held in place by wedges, made from Kinel. These pieces are in turn pulled up by means of bolts passing through the return yokes. The use of Kinel was justified by the fact that the wedges play no electrical role in the construction of the magnet. The laminations were shaped at the rear of the coil slot to accept the ceramic supports and force them against the laminations under the action of the wedge (Fig. 1).

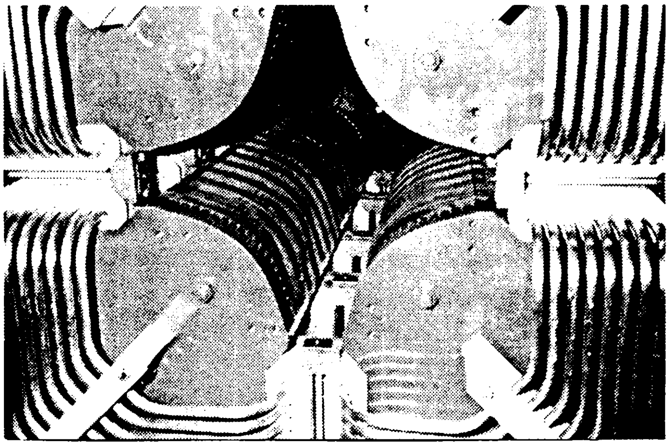

Fig. 1 - Pulsed quadrupole magnet showing coil clamps

The coil tails are supported off the yoke-ends by standard commercial porcelain insulators (Fig. 2). Inside the coils slot, the conductors are separated by 5 mm with a minimum clearance to the yoke of 15 mm.

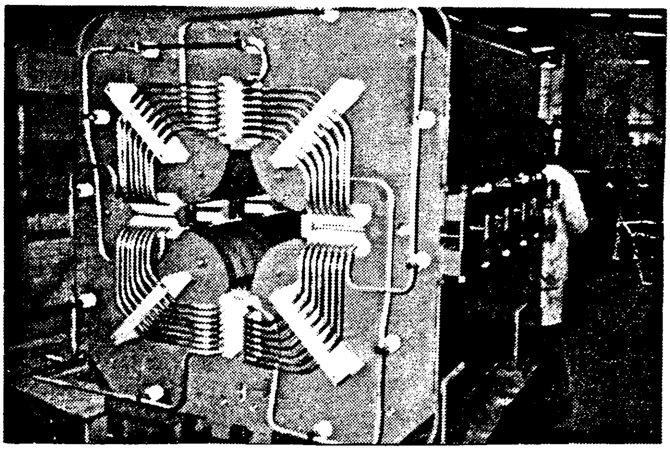

Fig. 2 - Quadrupole magnet showing coil tail mounting

In order to reduce costs, the conductor grooves in the coil-slot ceramics were specified to be sufficiently deep to allow for variation in conductor diameter and straightness, as well as the shrinkage which occurs during firing, so as to avoid the need for a final grinding to size. Some distortion also occurred during firing and as a result most of the holes formed by the ceramic pairs were over-size, sometimes by as much as a millimeter. Packing had been anticipated, however, and woven glass cloth was chosen as the medium. This was apparently successful, since, when fully assembled, the conductors were firmly held in position. Unfortunately, the impulsive forces on conductors carrying 4 kA in fields of up to 1 T are considerable, so that after being tested for about 50,000 pulses much of the glass cloth packing had been crushed and was finding its way out of the coil supports. It was clear that eventually the conductors would be free to move, would work-harden and possibly fracture.

The coils were, therefore, dismantled and tests performed to see whether the ceramics could be made to fit the conductors by first grinding the mating faces and then drilling out the holes to size. This was not successful due to excessive wear of the bit. As an interim measure, the ceramics were replaced by similar pieces made from vetronit. The holes were made 0.1 mm larger than the nominal conductor size, and the two pieces pressed round the conductors with the aid of clamps. Small screws were used to keep the two halves of the vetronit pieces together once the clamps were removed. In some cases excessive curvature of the conductors had first to be removed by means of a steel press tool.

The four quadrants of the magnet are located on their mating faces by means of captive steel dowels. It was noted that sparking had occurred between some of the dowels and the laminations due to the omission of the Kapton insulation. This was corrected when the coils were replaced on their poles and the whole reassembled. The coils were very rigid and easily withstood the 10 kV d.c. flash test. The magnets were each tested for over 300,000 pulses at 3.2 kV and 3.8 kA at a repetition period of 2.4 s. The temperature of the yoke rose over a period of several hours, eventually reaching 50°C. There was a slight vibration of some of the coil tails, but no discernable movement of the coil supports. The magnets were installed and have been pulsed more than 10^6 times, but in the absence of radiation. There has been no observable change in their condition during this time, and it is felt that, as far as the mechanical construction is concerned, they should operate for several years without failure.

Pulsed Dipole Magnets

These magnets (Fig. 3) bend negatively-charged particles with a momentum of 3.5 GeV/c through an angle of 7°. The remnant of the primary 26 GeV/c proton beam and other high-energy particles also enter these magnets which are therefore constructed with the gap open on one side to allow these particles to leave the magnet without striking any part of it.

The yoke was built by stacking laminations, which had been cut using a laser beam, between 20 mm thick mild-steel end-plates. The compressed stack is held together with four angle plates which are welded along the corners of the block and then securely welded to the end plates. It was found necessary to follow the supplier's instruction and use Argon arc welding to avoid spluttering because of the presence of the insulating layers on the laminations.

The limitations imposed by the available power supplies required that the coil would need 18 turns. The construction of a multiturn coil with sufficient mechanical strength, using only inorganic insulating materials, would be both difficult and, because only two units were needed, expensive. It was therefore decided to construct a coil with a single turn by brazing together solid 20 mm thick copper bars and to connect the magnet to the power supply through a 18:1 turns-ratio step-down transformer.

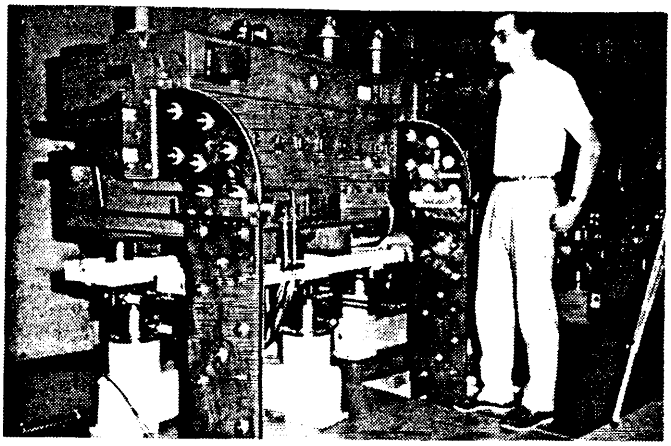

Fig. 3 - Radiation-hard pulsed dipole magnets on beam-line

The transformer, which is located in a trench several meters from the beam-line, is better shielded from the radiation and can be built using inorganic insulating materials which still must be chosen to be radiation-resistant but which will be exposed to a much lower dose than the magnets. There is also the advantage that the maximum voltage between coil and yoke is reduced to 200 V.

The coil consists, then, of a single bar along the back of the magnet gap with a 2 mm air gap at top and bottom and two bars, each of half gap height, located above and below the gap on the open side of the magnet. A terminal end is made in the form of a parallel-strip bus-bar, 30 cm wide, ending in flanges to which a similar strip-line, connected to the transformer, can be bolted (Fig. 4).

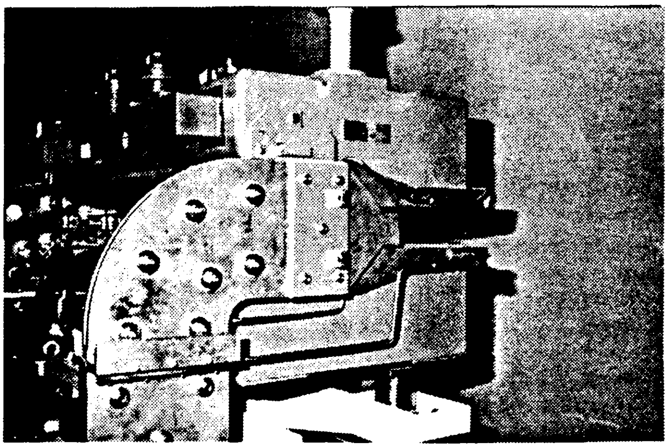

Fig. 4 - Strip-line connection for dipole magnet

The yoke and coil were prepared for fixing the coil in the following manner. When stacking the yoke, eight rectangular holes (16 mm × 16 mm), equally spaced along the yoke, were formed, centred on the median plane (Fig. 5). Corresponding to the positions of these holes, copper studs, were brazed to the inner conductor bars so that tie-bolts could be introduced through the yoke and pull the coil up against the end of the gap, insulation being provided by 2 mm thick sheets of NIMS. The system is designed to prevent relative motion of the coil to the yoke. Only the two central tie-bolts were positively located at the coil which was then free to expand longitudinally. The two coil bars places along the open face of the magnet were each held by six clamps and insulated with NIMS pads (Fig. 6). The heat dissipation in a coil was calculated to be 2 kW and water-cooling has been provided by soldering pierced copper bars to the central bar. It is these bars, in fact, which bear up against the insulation at the back of the gap.

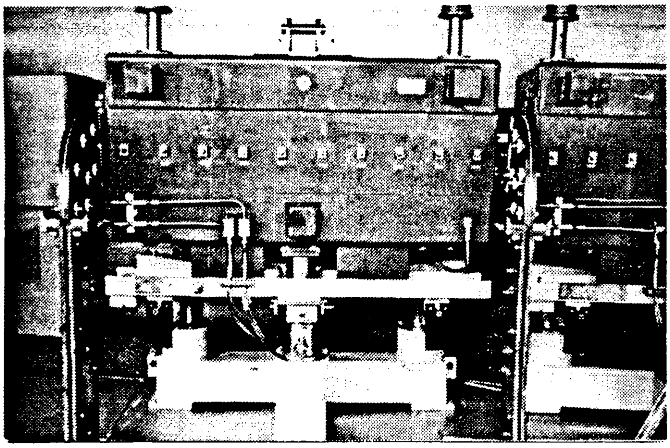

Fig. 5 - Magnet rear showing the bolts for holding coil

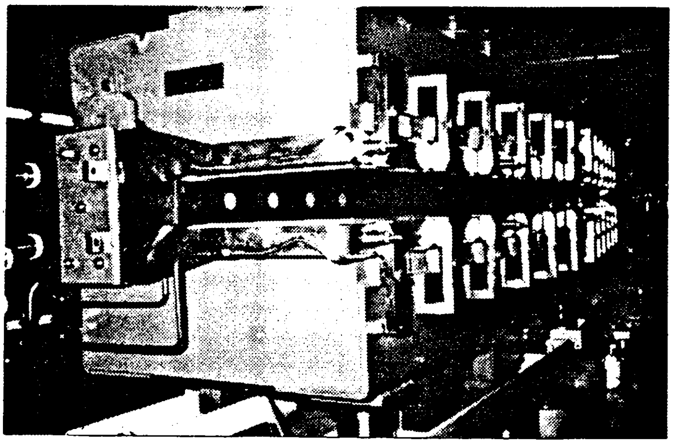

Fig. 6 - Clamping system along open side of magnet gap

The first unit was successfully tested with 10^5 pulses at full excitation but the second failed almost immediately. On inspection it was found that a short-circuit had developed because two of the tie-bolts were touching the yoke. Further investigation showed that this was due to a manufacturing fault which was rectified. On reassembling the magnets it was found that there was still an earth fault, this time due to a small piece of machining swarf that had fallen into one of the tie-rod holes. Since there are number of regions where there are small, relatively inaccessible, airgaps providing insulation, it is clear that the magnets must be assembled carefully under clean conditions. In order to prevent any further faults of this nature the tie-bolts have been wrapped with Kapton film. After we succeeded in blowing out the offending piece of metal with compressed air, both units were successfully tested to 3×10^9 pulses. These tests were in the absence of radiation. The magnets have been installed and run without any apparent problems with the proton beam on the target, but only for a few hundred pulses so far.

Discussion

These magnets are really prototypes, however, we had to meet the ACOL project deadline for their installation. We will therefore be watching their operational performance with great interest. The use of the NIMS material is a novelty which we hope will be successful as it adds a new inexpensive option to the materials available for this type of magnet construction. As far as the quadrupoles are concerned, it is expected that the insulation properties of the substitute coil supports will last for at least two years of target operation. During that time it is planned to build spare quadrupoles with inorganic coil supports. Because NIMS is easily machined and would be used in bulk form, tests will be undertaken to see whether it is suitable in other respects for this purpose. We are a little concerned about its use from the point of view of its apparent tendency to crack under point-loading. The alternative would be to recover the aluminium oxide pieces already made, probably by a combination of grinding and the use of a larger diameter conductor.

It should be pointed out that the magnet designs were influenced by the fact that we wanted to use existing power supplies which were available at little cost to the project. For example, the mass and heat dissipation for the dipole magnet transformer could have been considerably reduced if the charging voltage for the power supply capacitor bank had been somewhat higher.

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