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Design and Testing of a High Voltage Coil for the Kicker Magnets of CERN's Large Hadron Collider

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Abstract

The Large Hadron Collider (LHC), the world's largest proton and lead-ion accelerator, is currently under construction at CERN, Geneva, Switzerland. To extract the particle beams at the end of a physics run and in emergency situations 2 beam abort systems, built of 14 fast high-power kicker magnets each, are required. These magnets will operate at 35 kV and 30 kA with a pulse length of 90 µs and a rise time of 3 µs. A prototype magnet with a single turn high voltage coil has been built and tested. The magnet closely surrounds a ceramic vacuum tube. In order to insert this beam pipe into the magnet, the coil and the magnet have to be built in two halves which can easily be separated. The paper describes the design principles of the high voltage coil, the different options for the coil insulation material, as well as details concerning the adopted manufacturing process. The paper also discusses the extensive loss-factor measurements which have been carried out as part of the acceptance tests. Finally it reports on endurance tests of the coil when mounted inside the magnet yoke and working in pulsed mode.

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Design and Testing of a High Voltage Coil for the Kicker Magnets of CERN’s Large Hadron Collider

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The Large Hadron Collider (LHC), the world’s largest proton and lead-ion accelerator, is currently under construction at CERN, Geneva, Switzerland. It is located in an underground tunnel. To extract the particle beams at the end of a physics run and in emergency situations 2 beam abort systems, built of 14 fast high-power kicker magnets each, are required. These magnets will operate at 35 kV and 30 kA with a pulse length of 90 µs and a rise time of 3 µs. A prototype magnet with a single turn high voltage coil has been built and tested. The magnet closely surrounds a ceramic vacuum tube. In order to insert this beam pipe into the magnet, the coil and the magnet have to be built in two halves which can easily be separated. The paper describes the design principles of the high voltage coil, the different options for the coil insulation material, as well as details concerning the adopted manufacturing process. The paper also discusses the extensive loss-factor measurements which have been carried out as part of the acceptance tests. Finally it reports on endurance tests of the coil when mounted inside the magnet yoke and working in pulsed mode.

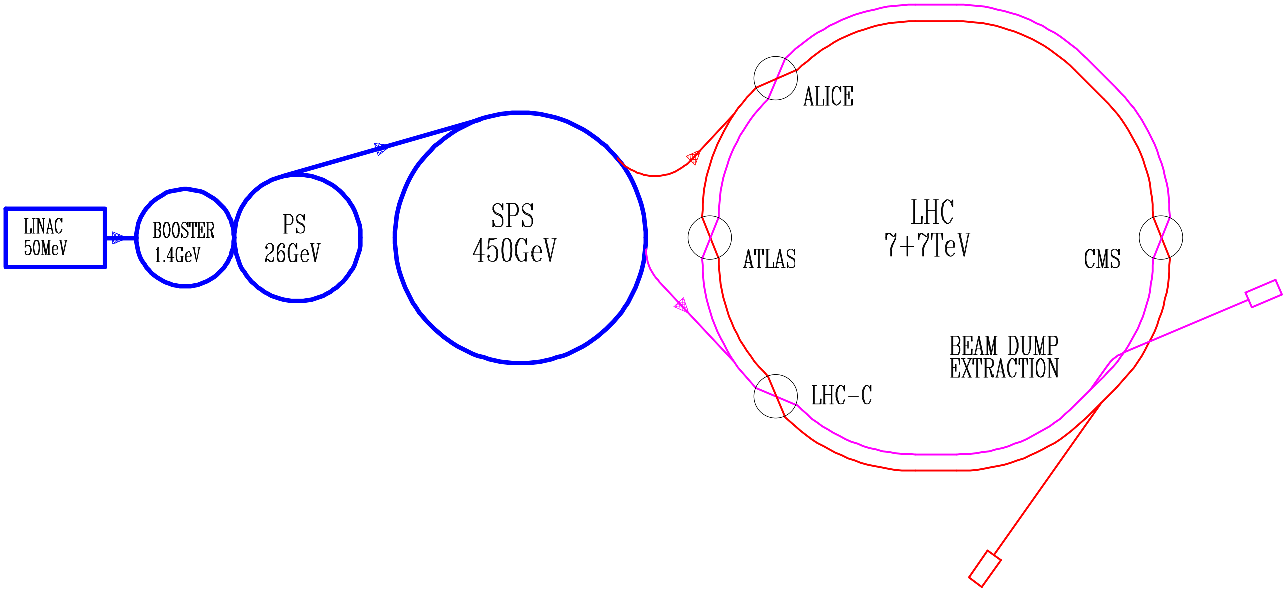


Fig. 1 Schematic layout of the CERN accelerator chain

1. INTRODUCTION

The maximum stored energy in each of the two LHC beams amounts to 334 MJ. Reliable and accurate beam dumping is of prime importance. Uncontrolled beam losses will cause damage or destruction of adjacent superconducting magnets and will induce unacceptable heat losses in the cryogenic cooling system. [1] Two dumping systems are required to remove the counter-rotating beams safely from the collider during setting up of the accelerator, at the end of a physics run, and in case of emergencies. They consist of two groups of 14 fast pulsed magnets, with a total length of 50 m.

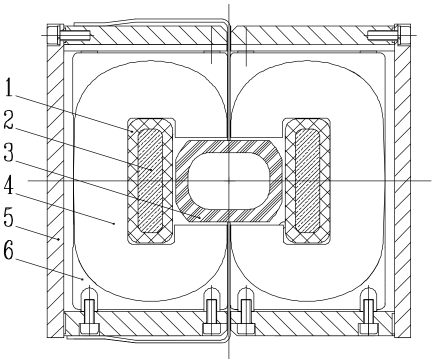
The high voltage coil of the beam dumping system has to meet several difficult criteria and is one of the key elements of the system.

The operating voltage of the magnet depends on the energy of the proton beam and varies between 2 kV and 35 kV. It rises within 50 ns and decays in 3 µs. The current pulse has 30 kA amplitude, a rise time of 3 µs and a flat top duration of 90 µs. The magnets work at low repetition rate (a few pulses per day) and must have a lifetime of about 10^5 pulses.

2. KICKER MAGNET DESCRIPTION

The magnet (Fig. 2) consists of a steel yoke composed of 2 tape-wound steel cores of 50 µm thin Si-steel, into which an opening is cut. A ceramic vacuum chamber is placed in the centre of the magnet. The cores are moulded in epoxy to provide mechanical stability. Two times 20 cores of 50 mm width are assembled, to form a magnet of 1 m length. The magnet is powered by a one-turn excitation coil.

In order to insert the ceramic chamber, with its two large vacuum flanges at both ends, the magnet and its excitation coil can be opened horizontally.



1 Insulation high voltage coil
2 Conductor high voltage coil
3 Ceramic beam pipe
4 Magnet core
5 Mechanical frame
6 Epoxy reinforcement

Fig. 2 Cross-section of kicker magnet

3. DESIGN OF HIGH VOLTAGE COIL

3.1 Description

The one-turn excitation coil (Fig. 3) consists of two solid high purity copper conductors of 51x12 mm cross-section, connected with cross-over rods. One conductor is L-shaped, and the other one is straight. The minimum insulation thickness is 5 mm. The coil terminates in a coaxial high voltage socket, to which the transmission line from the pulse generator is connected.

In order to fix the earth potential to the surface of the insulation a high resistive carbon paint is applied.

The straight conductor is equipped at both ends with moulded sockets and stress rings (Fig. 4).

The L-shaped conductor comprises at one end the high voltage input connector and at the other end moulded sockets with stress rings. The bend of the conductor is designed with the maximum possible radius in order to facilitate the wrapping with insulation tape. Along the concave surface of the bend, the thickness of the conductor has been reduced from 12 mm to 7 mm to compensate for build-up of additional insulation thickness.

The insulated cross-over rods of circular cross-section provide the opening facility of the coil to insert the ceramic chamber and to assure the electrical contact to the opposite straight conductor.

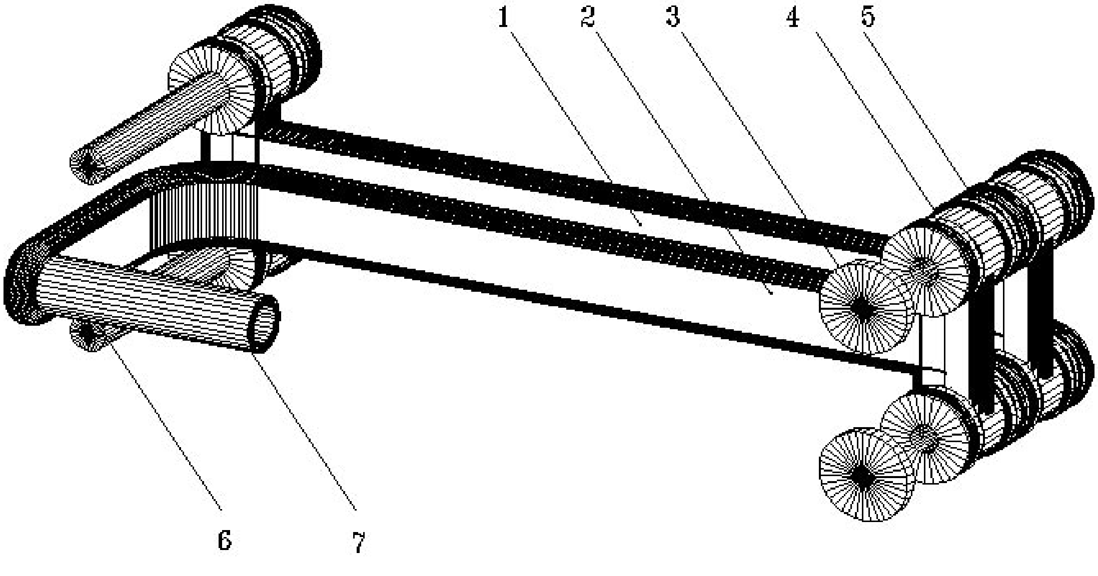
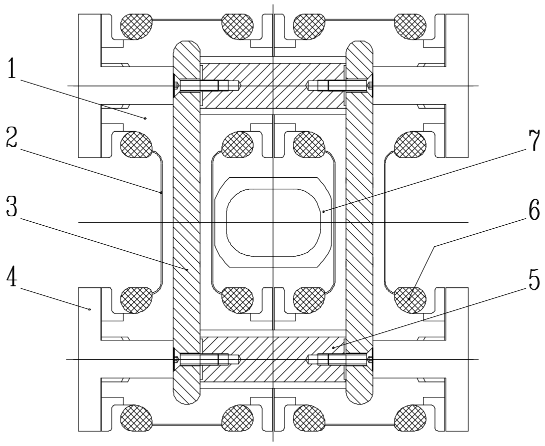


Fig. 3 High voltage coil

1 Straight conductor of high voltage coil
2 L-shaped conductor of high voltage coil
3 Removable plug
4 Cross over socket
5 Short cross-over rod (not visible)
6 Long cross-over rod, connection to earth potential
7 High voltage connector

These rods are mounted into the moulded sockets and fixed with screws. The access holes to the screwheads are closed by removable plugs.

The design of these sockets had to allow for sufficient distances to avoid flash-over to earth potential, and to permit a satisfactory solution to ending the high resistive coating without considerably increasing the electrical fringe field. Vacuum moulds were used to mould the cross-over sockets. Stress rings, made of dolomite filled epoxy, coated with resistive carbon paint, were used to finish off the ends of the carbon painting. They were bonded with highly conductive epoxy to the body of the coil, ensuring excellent electrical contact between the carbon paint on the rings and the conductive layer on the coil and sockets.



1 Insulation high voltage coil
2 Carbon coating
3 Conductor high voltage coil
4 Removable plugs
5 Cross-over rods
6 Stress ring
7 Ceramic vacuum chamber

Fig. 4 Cross-section of the coil end with cross-over rods and stress rings

The method used for moulding the insulator socket of the high voltage connector on the end of the L-shaped conductor, was similar to that used for the cross-over sockets. The cylindrical entrance conductor was made of CuCrZr copper-alloy (0.4% Cr, 0.1% Zr), which has greatly improved hardness, but, compared to high purity (OFHC) copper, almost equivalent electrical conductivity.

3.2 Preparation of the conductors prior to wrapping

In order to assure the best possible adhesion of the tape to the copper surface, the following cleaning procedure was applied:

Rough degreasing with industrial solvent followed by degreasing with hot (60ºC) alkaline solvent. Washing in demineralized water and neutralization with sulphuric and chromium acid type Sulfamico®. Rinsing in demineralized water and drying with methanol. This treatment removes the oxide layer on the surface of the copper. A layer of varnish (Isola 793®) is applied. This procedure was chosen rather than fine grain sandblasting, where the result depends to a great extent on the workmanship. Due to the softness of the copper, there was also a risk of modifying the shape of the conductor and finding minute sand particles stuck in the surface.

3.3 Insulation material

The coil insulation is made of isostatically hot-pressed resin-rich glass-mica tape. The insulation tape is a class F, Samicatherm® [2] tape with modified characteristics according to the requirements of Ansaldo [3], (Type Ansaldo #4675). This tape has a lower resin content, but has improved mechanical properties. It is specifically used for insulation of stator bars of electric machines with voltages up to 12 kV.

Main characteristics of the insulation tape:

Thickness	0.215 mm
Weight	330 ± 25 g/m^2
Mica content	145 ± 6 g/m^2
Glass content	34 ± 3 g/m^2
Dracon content	22 ± 4 g/m^2
max. pull strength	100 N/cm width
Stroke cure time of the resin at 130°C	630 s
Dielectric strength (23°C)	≥ 35 kV/mm

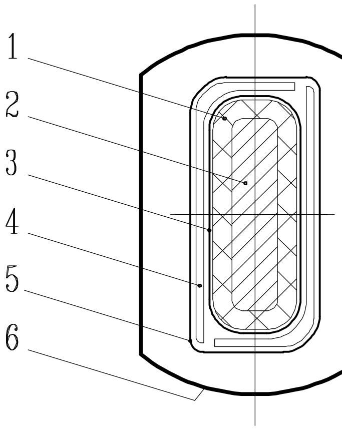
3.4 Radiation resistance

During the service-life, all components of these kicker magnets will be exposed to an integrated radiation dose of at least 10^6 Gy. As the radiation behaviour of this type of insulation was unknown, samples were irradiated at a dose rate of 220 kGy/h and were submitted to flexural tests, IEC Standard 544 and ISO 178. The test results were satisfactory and are equivalent to a Radiation Index (RI) of 7.6.

3.5 Conductor wrapping

The Samica tape is heated with hot air during the winding process, which makes it become slightly sticky. It then adheres better and with fewer air inclusions, to the previous layer of tape. To protect the fragile mica insulation on the surface against mechanical damage during handling and magnet assembly, a last layer of dry glass tape is applied.
Once the component has been prepared in this way, it is then wrapped in sacrifice layers of tedlar tape.

To ensure tight mechanical tolerances and smooth surface finish, two L-shaped steel profiles are put around the insulated conductor and held in place with another layer of tedlar tape. The sacrifice layers serve as a leak tight barrier between the insulation and the hot liquid, during hot-pressing, it facilitates demoulding.



1 Insulation high voltage coil
2 Conductor high voltage coil
3 Sacrifice (tedlar) tape
4 L-shaped profile
5 Sacrifice (tedlar) tape
6 Pressure vessel filled with bitumen

Fig. 3 Schematic view of hot-pressing

3.6 Hot-pressing

The isostatic hot-pressing technique is based on the idea of wrapping the conductors with tape which contains somewhat less resin, but contrary to classical hot-pressing, all resin remains inside the insulation. It consists of a vacuum vessel into which the wrapped conductor is inserted. A rough vacuum is established and the remaining air evacuated. Then the vessel is filled with hot liquid and pressure is applied. The vessel is then heated and the resin in the tape liquefies. The dry glass tape is completely impregnated with the resin which is seeping out of the mica tape. The outside pressure causes the L-shaped profiles to move until they touch each other, thus limiting the compression of the insulation tape and ensuring the required mechanical tolerances. Generally tolerances in the range of +0.1 mm and -0.3 mm are obtained. Normally insulation thickness varies between 2 mm and 3 mm. After several tests it was found that this technique can also be used for an insulation thickness of up to 6 mm.

3.7 Conductive coating

The resistivity of the conductive coating, which is applied to the surface of the coil, varies between 150 Ω/□ and 300 Ω/□, depending to a large extent on its thickness. As the coating consists mainly of carbon particles, it is best applied with a spay-gun. This resistive coating is connected to the earth potential by metal clamps.

3.8 Alternative options concerning insulation material and techniques

In order to keep the magnet as small as possible and to ensure homogeneity of the magnetic field, it was decided to allow a maximum insulation thickness of 5 mm.
Epoxy impregnated glass tape, which is usually employed for coil insulation, was not suitable as its dielectric strength is too low. Typical values for equivalent glass tape with comparable conductor geometry are 10 kV for 3 mm insulation thickness.

VPI Insulation:

Previous experiences with glass-mica insulated high voltage coils showed excellent insulation quality with the vacuum pressure impregnation technique (VPI). However, the mould which surrounds the coil must be vacuum leak-tight and is very expensive. In addition, very precise workmanship is required for the application of the dry insulation. The method is only cost-effective for large numbers of insulated conductors and VPI is difficult to use if the insulation thickness is more than 3 mm. The different layers of tape are tightly wrapped around the conductor, ensuring the maximum possible amount of mica in the insulation. Epoxy resin cannot penetrate through mica flakes and must seep through the different layers of tape whilst at the same time evacuating the air. Results depend as well on the traction force of the tape during wrapping. If a slight gap remains between the wrapped coil and the impregnation mould, the resin tends to pass through this channel and does not penetrate sufficiently into the layers of mica insulation. Very slow filling, over several hours, and continuous evacuation of any remaining air, allows high quality insulation.

Hot-pressing:

Hot-pressing with tapes, where the resin content varies between 100 g/m^2 and 180 g/m^2 has also been considered. The project specific tooling is less demanding. A relatively complicated hot-press is nevertheless required. It has been used previously on similar high voltage coils. [4] It was difficult to adapted the pressure and the temperature to the thickness of the insulation. The relatively large amount of resin ensures a complete soak of the whole insulation. The excess resin flows out during the hot-pressing and the insulation thickness varies considerably from one coil to the next.

Small variations in temperature and/or pressure lead to dry spots.
Above all, the L-shaped geometry of the conductor, is not suitable for a normal hot-press. It would have made this process very complicated.

Isostatic hot-pressing:

As result, a combination of resin-rich tape and isostatic hot-pressing, which requires a minimum of tooling, was the best compromise for this type of coil insulation.

4. ELECTRICAL TESTS

4.1 Loss factor (tan δ) measurements

The test voltage for this magnet coil has been set to 26 kV r.m.s. 50 Hz. The quality of the conductor insulation is determined by the tan δ, loss factor, measurements. In the absence of an international standard, the French (EDF) Standard [5] was closely followed. The parameters were: voltage range from 0 kV to 26 kV r.m.s. 50 Hz with 2 kV intervals and total variation of tan δ $< 20*10^{-3}$ with $< 4*10^{-3}$ variation per interval. All insulated conductors met these requirements.

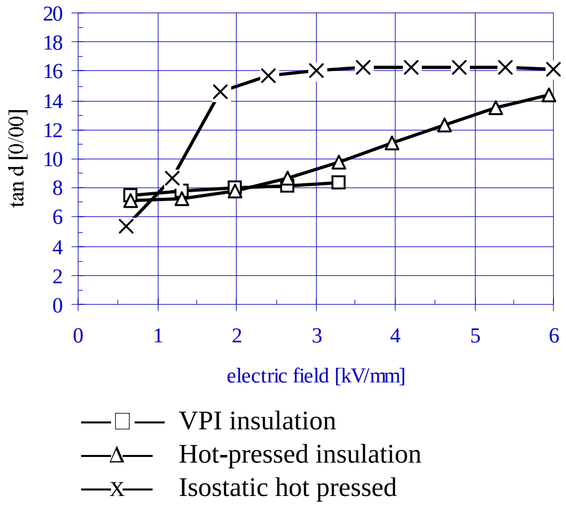


Fig. 5 tan δ loss factor measurements

It might be of interest to compare the loss factor for different types of insulation methods. In Fig. 5, tan δ is shown as a function of the electrical field in the insulation for three different procedures. The VPI system, with epoxy impregnated glass-mica materials, has a low and constant tan δ due to the homogenous impregnation under vacuum. The -Δ- curve for hot-pressing is characteristic for resin-rich glass-mica type. The isostatic hot-pressing, curve -x- , is most suited to series production of generator bars with a maximum of 3 mm insulation thickness. As it would be very costly to vary the parameters of the processing plant for a small quantity of special conductors, the high voltage coil was produced in a standard manufacturing cycle of generator bars with relatively thin insulation. The evacuation period for the air was insufficient for the insulation thickness of 5 mm. This resulted in a higher tan δ compared with the other processes. Nevertheless, the voltage holding was tested from 40 kV to 50 kV r.m.s. 50 Hz for 100 hours without failure. Isostatic hot-pressing is cost effective for any quantity of conductors, providing the geometry remains simple.

4.2 Long term tests

A long term (30'000 pulses) pulse test was carried out at 30 kV, with a pulse length of 90 µs and a repetition rate of 3 pulses per minute. This is equivalent to 10 years of operation. The coil was mounted in the magnet yoke, no failure occurred on any insulating part. The tests revealed that great care has to be taken in the design of the electrical contacts of the cross-over rods as well as the high voltage connector. The high current of 30 kA, the fast pulse rise time of 3 µs, and the pulse length in the range of about 2 ms require high contact pressure and silver coating. For the copper conductor material CuCrZr copper is preferable.

5. CONCLUSIONS

The design of the high voltage coil for the LHC beam dumping system is influenced by several factors.
Most important is the consideration that this coil is one of the key components of the safety system of the new Large Hadron Collider. In case of failure anywhere in the accelerator complex, the beam dumping system must operate totally reliable and function under all circumstances.
Furthermore, a cost-efficient system, which does not need servicing and which functions without failure for at least 10 years, was required.
Radiation resistance of the insulating material and its long term behaviour had to be taken into account.

The excellent results of the high voltage tests have demonstrated that very reliable excitation coils can be built by using the isostatic hot pressing method.

References:
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