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Coaxial 30 kV Connectors for the RG220/U Cable
20 Years of Operational Experience

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For the fast pulsed magnet system of CERN's SPS and LEP particle accelerators, a special type of moulded coaxial high voltage cable connector is used in large quantities. These connectors are mounted on coaxial transmission lines, which connect pulse generators in buildings at ground level to the fast pulsed magnets situated in an underground tunnel. Well over 1500 such connectors have already been installed and many more will be needed for the construction of the LHC. This 14 TeV Large Hadron Collider, which has a circumference of 27 km, is now under construction at CERN. The paper summarizes the operational experience over the last 20 years and the design principles of the connector. It explains how the excellent reliability and the extremely low failure rate were achieved and outlines the causes of the rare replacements. The paper also discusses the ageing effects caused by radiation, as well as wear and tear during installation and manipulation. Finally it gives a report on our experience with coaxial connectors for cables of 30 kV/18 Ω, 60 kV/15 Ω, 60 kV/50 Ω, and 70 kV/42 Ω.

1. INTRODUCTION

By 1976 CERN had completed the construction of the 300 GeV proton accelerator located in a tunnel 40 to 60 meters below the surface. The accelerator is equipped with fast pulsed magnet systems to inject and extract the protons. The magnets are connected with high voltage transmission lines, to the pulse generators in surface buildings. They consist of up to 25 coaxial RG220/U cables in parallel and operate at 30 kV. The cable entrance boxes on the magnets as well as the pulse generators are filled with insulating fluid. The cable length varies between 60 and 120 meters.

Fig. 1 Cable connections in equipment building

In the event of servicing, failure or replacement of part of the equipment, it is essential that the high voltage cables can be removed easily and quickly without removing the insulating fluid. Each cable is therefore equipped at both ends with a high voltage cable plug which is inserted into a leaktight connector socket.

2. THE CABLE

The RG220/U cable consists of a solid inner copper conductor and a polyethylene insulation. For some applications an outer coating of semiconducting graphite is applied. A copper braid forms the return conductor. The braid is protected by a flame retardant sheath.

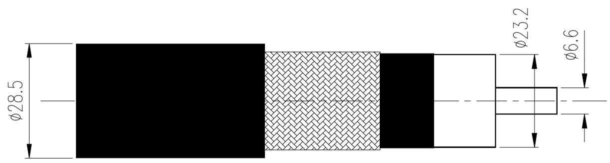

Fig. 2 RG 220/U cable

The coaxial 30 kV connectors on the market were not suitable, for mechanical and electrical reasons, for our requirements. We therefore decided to design a purpose-built high voltage connector.

3. DESIGN PRINCIPLES FOR THE CABLE CONNECTOR

The connector has to meet the following criteria:

* Safe design for fast pulses of 30 kV amplitude.
* Radiation resistant.
* Characteristic impedance close to 50 Ω.
* Leak-tight connector socket.
* Elastic interface between cable insulation and connector socket
* Grease must not be used between the cable connector and the socket.
* Cables must be mountable in confined areas with limited access.

Commercially available cable connectors use cylindrical insulators. This creates an air gap between the insulators of plug and socket, which leads to formation of corona when the connector is used for high frequency pulses. In addition, the formation of corona in this air gap is favoured in radioactive environment due to the higher concentration of ozone in the air.

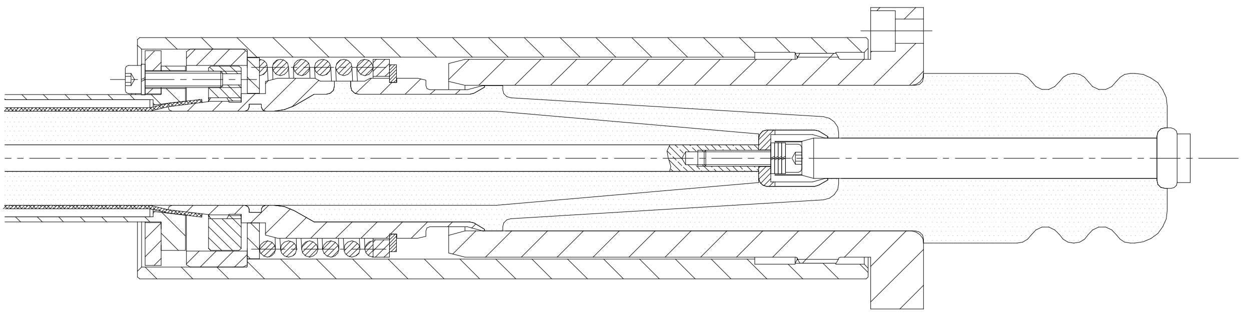

Fig. 3   RG 220/U cable connector assembly

The CERN design is based on a conical construction using an deformable, conical insulator which is moulded onto the machined cable (Fig. 3). The cable plug is pushed with a spring into the connector socket. The soft connector insulation adapts perfectly to the shape of the socket. In this way the surface between the connector insulation and the socket insulation is kept free of air.
Grease must not be used between connector and socket, it becomes hard in radioactive environments, this can cause mechanical damage to the connector during manipulation. Special attention has to be paid to the interface between the polyethylene insulation of the cable and the moulded conical insulation. It is difficult to mould material to polyethylene.

4. MACHINING OF THE CABLE

The best way to avoid air inclusions between the cable insulation and the moulded insulation is to machine the polyethylene with a good surface finish.

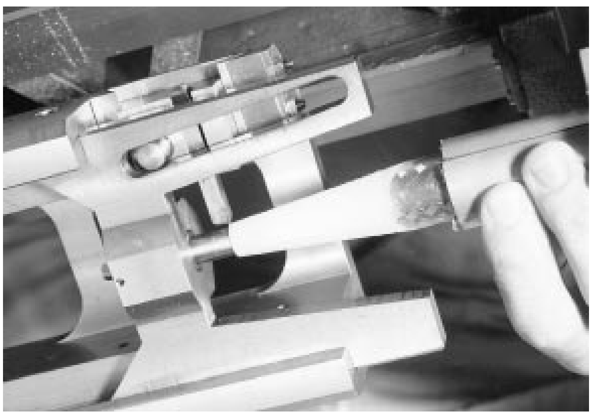

Fig 4   Tool to machine RG220/U cable

A special machining tool has been developed, it is mounted on a small and easily transportable lathe. This procedure allows the use of a cutting tool, similar to the ones used on standard lathes, which revolves around the cable (Fig. 4). This principle allows adapting the diameter, as well as the geometry of the surface to be machined, to individual requirements. To avoid eccentricity the cable is firmly fixed in the centre of the machining tool. This is particularly important for the flexible RG220/U cable. Several other types of cable (Fig. 5), (Fig. 8), (Fig. 9) have been machined with similar tools.

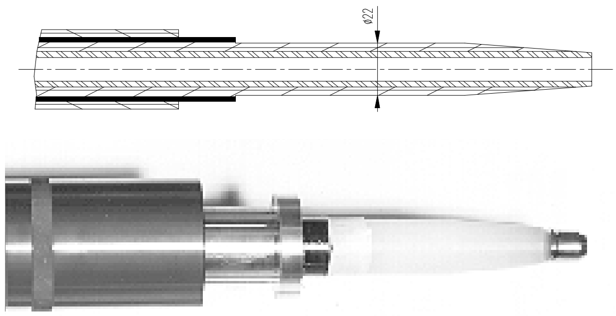

Fig. 5   Cable end of type 35 kV/18 Ω

5. MOULDING

The insulation which is moulded onto the machined cable insulation has to fulfil several requirements :

- The dielectric constant must be larger in comparison to the one of polyethylene. This compensates the impedance reduction due to the different ratio of diameters in the socket as compared to the one in the cable.
- The material must remain elastic over many years, even in radioactive environment and
- Easily mouldable on polyethylen.

Scotchcast® 815, an unfilled solvent free epoxy resin of the 3M company, was chosen for this purpose. It has good adhesion to metals and plastic, high flexibility and low viscosity.
To reduce the risk of air inclusions, the moulding has to be carried out under vacuum. The resin is first outgassed then mixed with the hardener and outgassed again for 20 minutes in a glass container. The moulds are filled slowly in a vertical position at a pressure of 12 Torr. The resin enters into the mould at the lowest possible point and fills it completely. Additional resin has to fill the connection tubes to compensate for the shrinkage of the resin during the curing cycle. After completion of the filling, air pressure is re-established and the resin is cured for 15 hours at 40 °C.

6. MATERIAL CHARACTERISTICS

The main material data of Polyethylene/Lupolen and Scotchcast® 815 are given below.

6.1 Polyethylene/Lupolen

Specific weight	0.94 g/cm^3
Dielectric constant at 1 kHz	2.3
Dielectric strength	>150 kV/mm
Tensile strength	15.3 MPa
Elongation	600 - 650 %
Hardness Shore A	32 - 55

There are many different types of polyethylene. We use the type Lupolen 1812D/1812 DSK.

6.2 Scotchcast® 815

Specific weight	1.14 g/cm^3
Dielectric constant at 50 Hz	5.7
Dielectric strength	24 kV/mm
Tensile strength	1 MPa
Elongation	33 %
Hardness Shore A	55

7. RADIATION RESISTANCE

7.1 Radiation dose in the accelerator tunnel

The integrated radiation dose measured in the vicinity of the installed cable connectors was as follows:

From year /year	dose rate
1976/1990	1.0×10^5 Gray
1991/1993	1.0×10^5 Gray
1976/1996	5.5×10^5 Gray

7.2 Polyethylene

Polyethylene can be used in areas where radiation dose rates do not exceed 10^6 Gray. It is commonly used at $<5 \times 10^5$ Gray. The change of elongation is the most significant sign of ageing; depending on the type of polyethylene, it drops by a factor of 5 for dose rates of $>1 \times 10^6$ Gray [1].

7.3 Scotchcast® 815

Scotchcast® 815, consists mainly of epoxy urethan resin. It has excellent radiation properties and remains flexible even with high radiation doses of up to 1×10^6 Gray. At this radiation level the modulus of elasticity varies by only 1 to 4 %. At 5×10^6 Gray the modulus of elasticity drops to 30% and the ultimate flexible strength to 13% of their initial values [1].

The hardness of the moulded resin varies with the curing cycle. The values of a freshly moulded connector are between 68 and 70. These values do not vary much with the total radiation dose. With a dose of 5.5×10^5 Gray values from 62 to 70 are measured. (All values in Shore A).

8. PRICIPAL CAUSES OF CONNECTOR REPLACEMENT

No failures due to high voltage breakdown have been observed during the 20 years of service. In some very rare instances corona formation in between the connector socket and the moulded insulation of the cable socket has been observed (Fig. 6).

Fig. 6 Connector with traces of corona

Mechanical damage while connecting or disconnecting is the principal cause of replacements. In certain areas, the cables are installed in positions of difficult access, where the cable is bent with a small radius close to the connector. This can lead to mechanical damage of the insulation whilst inserting the connector.
Another reason for replacement is damage to the silver-coated central conductor clamp. This finger contact is fragile due to its central position and its limited flexibility.

9. APPLICATION OF THIS DESIGN CONCEPT TO CONNECTORS FOR OTHER CABLES

9.1 Type 35 kV/18 Ω

This cable is equipped with a solid outer Aluminium conductor of 2.8 mm thickness and therefore particularly difficult to install. It meets the new fire resistance regulations for flame and fire propagation [2] as well as the stringent requirements of electro-magnetic compatibility EMC. However, the design principle of the coaxial connector is identical to the one discussed above. This cable is used for the fast pulsed magnet system of the LEP accelerator. It will be re-deployed for the kicker magnets of the Large Hadron Collider (LHC) now under construction (Fig. 7).
The long flat-top duration (90µs) and the high current (3 kA/per cable) need particular attention.

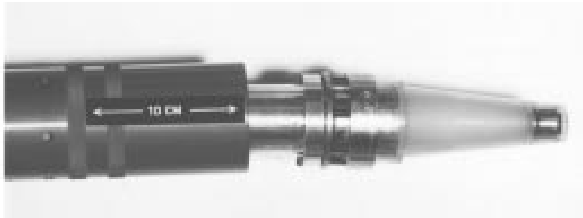

Fig. 7   Connector for cable type 35 kV/18Ω

9.2 Type 70 kV/42 Ω

The machining of this large diameter cable was particularly difficult, due to the stiffness and the large manufacturing tolerances. Some cables had up to 5 mm of ovalness of the insulation and 2 mm of eccentricity of the central conductor. The cable had to be machined over a length of 160 mm (Fig 8). The cable is used to interconnect the power switches to the pulse forming networks. As it is important to keep this connection as short as possible, the cable is bent to a U-shape with a total length of less than 2 meters and 0.7 m bending radius. This resulted in axial movement of the inner conductor. The cables were therefore first bent to their final configuration and then machined and moulded. The machining was carried out with a similar tool as the one used for the RG220/U cable. The bent cable is attached to a mechanical support and such permanently held in U-shape. In spite of the difficult procedure, we never observed any failure of these cables.

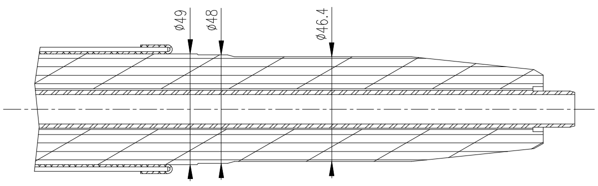

Fig. 8   Cable end of type 70 kV/42 Ω

9.3 Type 60 kV/15 Ω

The same design principle was used for this cable. It was not possible to machine the cable in the same way as 50 Ω cables, due to the different ratio of the diameters of the inner conductor to the outer conductor. However, the design of the cable connector is almost identical to the RG220/U type. This cable connector has been in service from 1975 onwards. It was mainly used for the prototypes and for the development work of the high voltage power switches and the pulse forming networks.

9.4 Type 60 kV/50 Ω

This cable has a solid inner copper conductor of 10.4 mm diameter and an outer diameter of 47 mm. It has a semiconducting layer on both sides of the polyethylene insulation. It is machined over a length of 150 mm (Fig. 9). The cable is used in length of 6 meters to interconnect the power switches to the pulse forming networks. Due to the semiconducting layer and its short length it is not leak-tight (as the 70 kV/42 Ω cable). To avoid the formation of air-inclusions during moulding, a O-ring seal is placed in a groove on the outside of the central conductor.

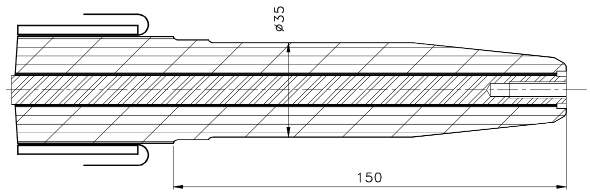

Fig. 9   Cable end of type 60 kV/50 Ω

9. CONCLUSIONS

The RG220/U cable connector has been used very successfully for 20 years under difficult conditions. Its design principle can be applied to a wide variety of other cable types and voltages. The principle of the tool for machining the cable can, as well, be adapted to many different cable types. The main manufacturing difficulty is the execution of the finger contacts to tight tolerances. These contacts must be handled with care and checked individually before assembly.

The radiation resistance of Scotchcast® 815 is better compared to polyethylene and does therefore not limit the use of this connector design.

Finally, the design was successfully adapted to mass production and the price can be compared favourably with a commercial 30 kV connector.

For the Large Hadron Collider two large injection and two extraction systems are under construction requiring more than 800 coaxial high voltage connectors. In view of our very positive experience and the excellent long term behaviour, we conclude that the design of these connectors is also perfectly adapted for the new projects.

Acknowledgements:

The design of these connectors where originated by the late H. Kuhn. We acknowledge especially the contribution of H. Tröhler and R. Chappuis who optimised the tooling and the moulding procedure.

References:

1) Compilation of radiation damage test data. Part II Thermosetting and thermoplastic resins. CERN 79 - 08 Health and Safety Division.
2) IEC 332-3 Category CF Flame and fire propagation for cables.