UNLEASHING THE LIGHT AROUND THE ACCELERATORS

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Abstract

Optical fibres play today a vital role in communications, machine controls, instrumentation and safety systems. CERN will count at LHC commissioning over 25’000 installed fibre kilometres and more than 40’000 optical terminations. This paper describes the technology that will be used to provide the LHC complex with a sound optical fibre infrastructure via the surface and the underground. The optical fibre network must be extremely reliable and redundant loops shall exist to avoid single points of failure. Laser power used at the transmitter rarely exceeds 1 mW and optical connections must therefore have a high quality standard in order to keep optical reflections and attenuation within acceptable limits. The long distance surface optical fibres (in ducts) may suffer from mechanical stress and will therefore be permanently monitored via an autonomous monitoring system using optical time domain reflectometry. The optical fibres in the LHC tunnel will be subject to irradiation and will therefore darken, thus increasing their attenuation. This process will be closely monitored as well, in order to set off a replacement of these fibres in time.
1 INTRODUCTION

Optical fibres are in use at CERN at a relatively large scale, since the construction of the LEP accelerator. In these days optical fibre technology was expensive, which explains that few fibres were installed. The majority were ITU-651 graded-index 50/125 µm fibres. Single-mode fibres were still in their childhood, so only a small number of ITU-652 single-mode 9/125 µm fibres were installed.

Today optical fibres are used all over the world in many applications. Huge improvements have been achieved in quality, availability and important reductions in cost. Whilst the basic structure of optical fibre cables has not much progressed (jelly filled loose tube construction), very high fibre densities are nowadays possible with up to 1000 fibres in a cable.

LHC points 1, 5, 6, 7 and 8 are equipped with the above type of cables, specified by CERN with respect to fibre types, cable construction etc. Rather high fibre densities with up to 216 fibres on certain links have been installed in order to cope with the ever-increasing demand for optical fibres.

The optical fibres are mainly used for data communications (gigabit-Ethernet), telephony, machine reference signals, transmission of safety signaling etc.

Full redundant and reliable fibre networks will have to be installed for LHC. The LHC is a complex machine and unplanned machine down time will be costly. The LHC shall be realized according to INB\textsuperscript{1} rules and we must exclude single points of failure as far as possible.

LHC points 2, 32, 33 and 4 still have to be equipped with optical surface links. Underground machine and experimental areas will have to be serviced from the surface and the LHC tunnel will have to be equipped both for communications and beam instrumentation.

2 THE BLOWING TECHNOLOGY

Optical cables to the LHC surface points are installed in trenches in HDPE\textsuperscript{2} ducts along the 18 or 66 kV high voltage cables. Initially the cables were pulled with special machinery that had tensile force monitoring and control, to maintain pulling forces within 200 daN, in order not to damage the fibres.

Today optical cables are mostly blown into the ducts with specialized equipment. This is possible because optical cables are light. The advantages are:

- Long distances can be covered in one go (up to several km’s)
- The duct and the cable suffer less (ducts must be in a good condition)
- Gain in time and more economical

![Photo 1](image-url)

\textsuperscript{1} Inspection Nucléaire de Base
\textsuperscript{2} HDPE High Density Poly Ethylene
Serious problems with the HDPE ducts were encountered during the optical cable installations to LHC points 6 and 8. These ducts were laid some 15 years ago and had longitudinal cracks and breaks, which remain unexplained. Mechanical stress, due to ground movements may be a reason. Analysis of the tube material (both a temperature- and a spectrographic test) showed that the HDPE consistency was normal, but the outer sheath has oxidized.

Optical cables are blown into ducts with an air pressure of maximum 12 Bar at airflow of 10 m$^3$/min. It has become clear, that we cannot use such pressures with the old ducts.

The photo on the right, shows the tubes to P6 in the forest close to Maconnex. The blowing of cables became a real disaster. Finally, the whole track from “Ornex” to “Bois Chatton” had to be redone!

2.1 Blowing bare optical fibres

Several years ago, the British company BICC developed a technology called BloLite, to blow bare fibres into bundles of guiding tubes. The fibres were covered with a supplementary coating to increase the air-grip on the fibre. This technology had been developed to be able to increase flexibility and to reduce the initial cost of an installation. Also easy replacement of fibres was an issue.

The technology is well suited for the optical wiring of an office building, experiment or between buildings. However it cannot be justified on long distances and for outside plant installations. Blowing distances are limited, depending on the layout and situation, to a maximum of about 500 m.

Cascading techniques, if at all possible, are complicated and high fibre densities are not possible. The product is actually commercialized by Brandrex.

Ericsson copied more or less the BICC model. We installed a prototype of it in the SPS complex between the PCR and BA80 and blew a 6-fibre ribbon in a 5 mm tube over a distance of about 480 m. This was the absolute maximum distance we could achieve and the blowing exercise was complicated.

2.2 Guide tubes and mini optical cables

The system is based on individual guide tubes running through protective ducts and was invented by Draka Comteq NKF BV. In these guide tubes small, but "outside plant resistant" mini optical cables can be installed without any splice. It is a complete new solution for the laying of optical fibre access networks, which avoids the limitations of the above technologies and which introduces a great deal of flexibility for future upgrading.

Two types of guide tubes seem to have been standardized, a 7 mm tube and a 10 mm tube. The 7 mm tube can hold mini optical cables with up to 24 fibres; the 10 mm tube can hold mini optical cables with up to 72 fibres (the cable diameter is about 5 mm, which is extremely small for such a fibre count)$^3$.

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$^3$ These figures are from Draka Comteq NKF BV
The mini optical cables are similar to the jelly filled loose tube construction. The jelly avoids humidity penetration and acts also as a mechanical protective buffer. The cables can either be made with a stainless steel protection covered by a polyethylene sheath or be completely metal free. CERN prefers the metal free type for protection against electrical hazard.

The guide tubes can be blown with a Superjet\textsuperscript{4} at low air pressure (3 to 4 Bar). The Superjet is proven technology for the installation of optical cables and has been adapted to blow simultaneously up to 7 guide tubes. The guide tubes can be interconnected with simple, waterproof connection pieces. This technology seems to be the ideal solution for the upgrading of fragile ducts, as short sections can be installed and connected afterwards.

Once the guide tubes are in place, the mini optical cables can be blown in their turn using a Microjet. The Microjet is a small blowing unit (air pressure 10 bar), which can blow mini optical cables exceeding 1 km installation lengths. If necessary, several Microjets can be cascaded to achieve longer installation lengths with an uninterrupted cable.

The guide tube concept with the use of mini optical fibre cables allows parallel and serial upgradeability. Most often, when we plan new installations, we have not the faintest idea about final requirements. When we use for example a 25 mm duct, we can install 7x7 mm guide tubes and 24 fibres per guide tube, which gives us a total fibre count of 168, which is a good figure. Moreover we can fill the guide tubes with different fibre types, a cable on the contrary has a rigid structure; once it is in place you cannot change it.

3 INSTALLATIONS REQUIRED FOR LHC

LHC points have to be equipped with optical surface links. Underground machine and experimental areas will have to be serviced from the surface via the shafts and the LHC tunnel will have to be equipped both for communications, beam instrumentation and machine reference signals. Exact fibre counts will be worked out with the concerned parties and will be integrated in the final technical specifications.

3.1 LHC surface installations

All LHC surface points will require optical fibre connections to the PCR, to allow for redundant paths via the surface and the underground. Long distances are involved (up to 9 km) and we have therefore to plan carefully these installations, as they require heavy tools for the realization.

3.2 LHC surface to underground installations

The optical links coming from the PCR are terminated in the SR control rooms. From these room’s optical links to the underground service areas (US/UJ/UA) are required both for communications and machine reference signals. Also optical fibres for the beam instrumentation system have to be installed between the SR buildings and the pairs of beam position monitors in the LHC tunnel.

3.3 LHC tunnel installations for communications

Optical fibre links for communications and machine reference signals are required all around the LHC tunnel with partial stops at the alveoles. These links are part of the very important redundant optical fibre access network for LHC communications and machine control.

Initially it was foreseen to install the communications fibres in a 40 mm tube along the tunnel wall, together with the leaky feeder cable for radio communications. The tube would be equipped with a standard optical cable, allowing cable replacement in case of radiation damage\textsuperscript{5}. A second tube would be installed to allow replacement of the optical cable without interruptions.

\textsuperscript{4} High precision machine, developed by Plumettaz/CH in collaboration with Dutch PTT and NKF BV. http://www.plumettaz.ch/en/cjsj/optical_fibre.html
\textsuperscript{5} The optical fibres will suffer from radiation during LHC operation. Radiation measurements on optical fibres have been done in TCC2. The results are being published and available via the RADWG.
When the guide tube technology was presented to the LHC tunnel installation working group, it was proposed that the second tube were abandoned in favor of the flexibility of the guide tube technology and thus generate substantial cost savings.

Moreover, the guide tube technology has the advantage that not many spare fibres need to be installed as they can easily be added at any time. Not only is the initial investment much lower, but also many spare fibres will not be unnecessarily irradiated as they are simply not there.

3.4 LHC tunnel installations for beam position monitoring

Optical fibres for the beam position monitoring system will have to be installed between each pair of Beam Position Monitors and the corresponding instrumentation in the SR building. Actually it is foreseen to equip each pair of BPM’s with 6 single-mode fibres.

About 35 positions more or less equally spread at each side of a machine octant, will have to be connected. We have proposed to install 25 mm flexible ducts, which would be pre-equipped with seven 7 mm guide tubes. Each 350 m sector can in this way be serviced from the flexible duct, with an outlet each 50 m. Tube sectors can be interconnected with standard connection pieces as well as guide tubes. Five of such ducts would thus be needed for each half octant. The same system can also be used for the transfer lines.

The pre-equipped tubes can be installed during the control cabling installation phase before the installation of the QRL and Cryostats. Only once a machine sector has been installed, the mini optical fibre cables can be blown in order not to be damaged during the heavy installation works.

The fibres must be blown in one go from the SR to the BPM (longest distance about 3500 m) and cascading techniques using an extra Microjet at the bottom of the shaft will be needed. The advantage lays in the fact that no intermediate splicing is necessary and that the mini fibre cables can easily be replaced at any time, without needing access behind the machine equipment.

3.5 LHC experimental areas

The LHC experimental areas are not yet considered in this paper, but the same technology can be used.

4 OPTICAL FIBRE TYPES

Optical glass fibre production can still today be considered as a wonder of modern technology. A preform of ultra pure silica is produced, usually by chemical vapour deposition technology and by adding concentrations of dopants (germanium oxide) to obtain the required refractive index profile across the diameter. The preform is heated in a furnace and the fibre is drawn to its final size of 125 µm and covered with layers of flexible coatings to its final size of 250 µm.

At CERN we use mainly two optical fibre types.

- Graded index multimode fibres (ITU G-651; 50/125 µm) and

In the LEP accelerator special temperature compensated single-mode optical fibres were used for the complex radio reference frequency phase shift compensation. These fibres have a temperature coefficient of better than 14x that of normal single-mode fibres. The basic fibre is the same, but the coatings are different with a negative temperature coefficient. Instead of the fibre becoming longer with temperature increase, it becomes mainly thicker explaining the better longitudinal temperature behaviour and so phase behaviour for high frequencies. These fibres will be re-used for the 400 MHz radio frequency reference to P4.

Optical transmission can be considered in 3 optical transmission windows (850 nm, 1310 nm and 1550 nm). In these windows the attenuation is low and the chromatic dispersion well defined. We use mainly the 850 nm and the 1310 nm window.
5 OPTICAL CONNECTORS

The heart of an optical network is the optical connector. Not only must the connector be perfectly aligned and mated with other connectors in order to assure low losses in the order of some tenths of a dB, but they must also have an acceptable reflection coefficient, to avoid perturbations on the laser source. Optical connectors are always male connectors, which are fixed together via an optical adapter.

Laser sources are extremely sensitive to nearby reflections, whilst the output power only ranges from about 0 to –10 dBm (0 dBm = 1 mW). The dynamic range of very good systems can reach 30 dB, but for average systems and systems with LED sources we must count with not more than 10 dB.

The attenuation of a connector is determined by its quality. Normally we count for power budget calculations 0.5 dB loss per connector even though this figure is to high with respect to today’s values. For the return loss we count a minimum of –35 dB.

We tested several single-mode connectors and selected the E-2000/APC connector for LHC. This connector has an angled polished end face, which has the advantage of a high return loss figure of better than –55dB. The connector has moreover a dust and laser protection cap. This connector has imposed itself on the market and is widely used amongst the telecom operators.

The graph below shows the repeatability of insertion loss for the E-2000 connector.

![Figure 2](image)

In the multimode applications we continue to use the ST connector. This connector is widely distributed and has a good specification. There is however a tendency to go for push/pull connectors.

Basically any connector can be used. When sole users want to terminate fibres their end with another connector, then that is possible without any problem.
6 OPTICAL FIBRE MONITORING

The optical fibres in the ducts in surface trenches may be subject to mechanical stress and the fibres in the LHC machine will be subject to radiation. They should therefore be closely monitored in order to raise an alarm, as soon as the attenuation and/or reflection exceed preset threshold levels.

Extensive radiation measurements have been done in the TCC2 radiation test area and we continue to do these measurements with different types of optical fibres and optical cables.

The radiation environment in TCC2 is supposed to reflect the type of radiation, which we can expect in the LHC accelerator, but for similar integrated doses we have a much shorter time scale due to the high radiation levels in TCC2.

Single-mode fibres resist better to radiation than multimode fibres. The multimode fibres have dopants, which disintegrate with radiation and darken the silica thus increasing the attenuation values. Single-mode fibres have hardly any dopants and do resist much better in a radiation environment. We have noted however that bare fibre behaves different (less sensitive) from fibres surrounded by other materials. More detailed investigation is necessary and results will be published as soon as the data is available. The figure below shows the measurement results over a period of 6 months and a total integrated dose of 500 Gy.

![Figure 3](image)

From the above results we can easily deduct that we should refrain from using multimode fibres in the LHC tunnel. In agreement with the Communications Infrastructure Working Group (CIWG), we have decided to use only single-mode fibres in the tunnel. Multimode fibres can however be used around the LHC detectors in the experimental areas, as distances are usually short here.

For the monitoring of CERN’s main optical trunks and tunnel fibres, we purchased an optical fibre monitoring system from Acterna. This system has been installed in the optical laboratory in building 104. The system has 24 optical ports, which is largely sufficient for the whole CERN complex, as each port can test optical links with a total length of 200 km. Such distances are not considered at CERN.
The system is based on a Remote Test Unit (RTU) with a powerful optical time domain reflectometer, which operates at a wavelength of 1550 nm in order to be able to detect eventual micro bending (the longer the wavelength, the better). Micro bending might occur when fibres are under mechanical stress (for example in the surface ducts). We dedicate basically 1 fibre per trunk cable to the monitoring system. By testing 1 fibre, we test 80 % of the cable statistically seen.

It is also possible to multiplex the test signal and the operational signal on the same fibre. In this case wavelength division multiplexing technology has to be applied, which makes the system very costly. We decided to test only one single fibre, as most fibre transmission systems have their own surveillance and monitoring.

The ports 1 to 8 will be used for the corresponding 8 octants of LHC and the surface links from the PCR to these octants. Four other ports will be used for main optical trunks, leaving 12 spare ports for possible future use.

The figure below shows the basic operation. A fibre is tested during a preset time, set by the operator of the system. The optical switch then switches to the next port number programmed by the operator. Once the preset sequence has been terminated it starts all over again, 24 hours a day.

Remote Test Unit

A fibre is tested during a certain time and the measured OTDR trace results are averaged and then compared to an initial reference measurement. If the measurement results do not correspond to the reference measurement (minus a programmable offset), the system will raise an alarm.

The system management operates under Windows98 and all parts of the system are connected to the CERN network.
The management system supports SNMP (Simple Network Management Protocol), which is supported by most supervision systems. In this way the optical fibre monitoring can be connected in due time to the overall CERN network management system.

The figure below shows the measurement method as described above.

![Figure 5]

7 CONCLUDING REMARKS

This paper, even though already pretty exhaustive, has only highlighted some crucial parts of our work. I tried to give an as good as possible view on what we are doing and hope that I have succeeded in creating some curiosity in our field.

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