Brillouin optical fiber sensor for cryogenic thermometry

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ABSTRACT

Supraconductive installations are now commonly used in large facilities, such as power plants and particle accelerators. This requires a permanent temperature control at very low temperature, but cryogenic temperature measurements in the 1-77K range requires expensive calibrated temperature probes.

We report here the possibility to use stimulated Brillouin scattering in optical fibres for temperature sensing down to 1K. Such a technique offers the additional advantage to make possible distributed measurement, so that very large structures and systems can be controlled using a single fiber and a single analysing instrument. In addition only one by-pass for the fiber is required as input to the cryogenic vessel, that is definitely a key advantage for the design and the energy loss.

Brillouin scattering in optical fibers has never been investigated so far at temperature below 77K (nitrogen boiling point). This absence of interest probably results from the constant decrease of scattering efficiency that was observed while cooling the fiber down to 77K. Our measurements show the unexpected feature that scattering efficiency is significantly raised below 50K and is even much better than observed at room temperature.

The relevance and the feasibility of the technique is demonstrated in real scale on the supraconductive magnets for the future world largest particle accelerator, namely the large hadron collider (LHC) at CERN Laboratory in Geneva.

Keywords: optical fiber, cryogenic temperature, distributed sensor, Brillouin scattering.

1. INTRODUCTION

In the last twelve years, many papers dealing with Brillouin spectrum analysis for distributed strain or temperature sensing in optical fibres have been published. Different operational set-ups have been proposed so far, some of them being even commercially available. As far as temperature sensing is concerned, all these set-ups rely on the assumption of a linear dependence of the measured Brillouin frequency shift on the temperature. This assumption – though perfectly valid in the usual room temperature range – no longer holds in the domain discussed here.

Basically the Brillouin effect is a scattering of an incident lightwave by the acoustic phonons of a medium, the spectrum of the scattered light containing key information about the vibrational properties of the considered medium. Practically the centre of the Brillouin spectrum is directly proportional to the velocity of a vibration mode, while its linewidth is related to its characteristic damping time. In the quasi-unidimensional geometry of single-mode optical fibres [1], the Brillouin spectrum of the backscattered light is by far dominated by the resonance peak corresponding to the fundamental longitudinal acoustic mode.

As mentioned above, in a fairly wide temperature range (-25°C - 80°C) covering most of the usual applications, the Brillouin shift, that is the frequency difference between the incident and the scattered lightwaves, increases linearly, with a slope coefficient around 1.36 MHz/°C at 1319 nm [2]. Over the same temperature range the resonance linewidth steadily decreases.

As far as we know the low temperature domain has been much less studied by the fibre optics community. Nevertheless, there are some large cryogenic installations where distributed temperature monitoring, and thus the use of Brillouin effect in fibres, can be a valuable alternative. A particle accelerator, like the large hadron collider (LHC) under

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construction at CERN in Geneva, can be such a target installation where 1600 15m-long supraconducting magnets must be operated at a temperature of 1.8 K.

Solid state physicists have shown, partly by Brillouin spectroscopy on bulk samples, that glasses under 200 K, far from simply extrapolating their room temperature properties, exhibit new and interesting features [3, 4]. These give an invaluable insight into the physical, atomic-scale structure of the glass, and numerous theoretical works have been triggered by the results of such measurements. However to the best of our knowledge, nobody ever contemplated using silica in the form of optical fibres for temperature sensing purpose down to liquid helium temperature (4.2 K) or even below. In this paper we will present the Brillouin scattering properties of optical fibres as experimentally measured at ultra-low temperatures and discuss the possibilities for distributed cryogenic temperature sensing, accordingly. We then present a first example of real scale application.

2. TEMPERATURE CHANGE OF THE BRILLOUIN GAIN SPECTRUM

300 m of standard single-mode fibre have been installed over a circular copper plate (diameter 50 cm) and put into a large cryogenic vessel designed for long term experiments at liquid He temperatures. It was not clear in advance whether the fibre would mechanically overcome the extreme thermal cycle, so that we chose a radius of curvature as large as possible and we took care to avoid any strain along the fibre. It turned out that the attenuation loss at 4 K was only marginally higher than at room temperature. The copper plate was equipped with thermometers and heating resistances, and a standard regulation loop made possible a temperature stabilization within 0.2 K. Lowest temperatures down to 1.2 K were attained through partial evaporation of helium, at the expense of a poorer temperature uniformity.

The Brillouin analyser instrument we used is based on the pump and probe method, the two lightwaves being created from one single laser source thanks to a $LiNbO_3$ electro-optic modulator. This set-up is fully described in a former publication [2]. It must be pointed out that it relies on the stimulated flavour of Brillouin scattering. Spontaneous Raman measurements, that can be a valid alternative at room temperatures, would be here totally ineffective as a result of the negligible triggering thermal noise at the Raman frequencies.

The typical values of the parameters of the Lorentzian Brillouin gain curve at room temperature for the specific fibre under consideration at 1319 nm are $\nu_B = 12.133$ *GHz* for the frequency shift and $\Delta\nu = 44$ *MHz* for the linewidth. In comparison with the gentle variation of these parameters over the ambiant temperature range, the results obtained at cryogenic temperatures show dramatic variations, as illustrated by the curves in Fig. 1. Neither the frequency shift nor the linewidth longer depend in a simple way on the temperature.

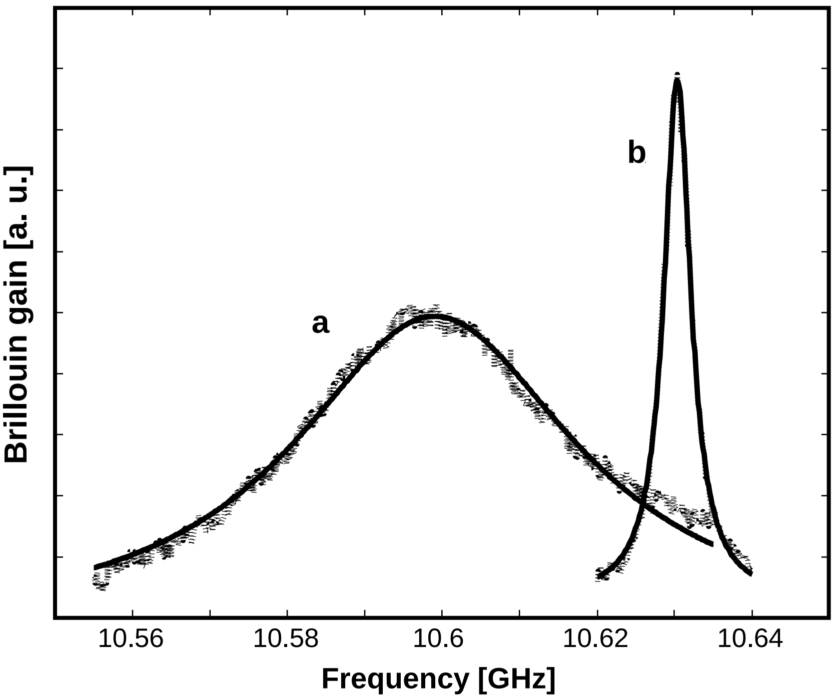

Fig.1 Typical Brillouin gain curves at 1319 nm for two cryogenic temperatures, showing the large observed changes of the resonance characteristics.

(a) T = 60 K, ν_B = 11.906 GHz, $\Delta\nu$ = 56 MHz

(b) T = 4.2 K, ν_B = 11.954 GHz, $\Delta\nu$ = 3 MHz

Fig.2 shows the relative variation of the central frequency ν_B of the Brillouin gain spectrum as a function of temperature T. The sound velocity V is simply related to the measured Brillouin frequency shift through $V = \frac{\lambda \nu_B}{2n}$, where λ is the vacuum wavelength of the incident lightwave and n the refractive index of the fibre [6]. The most striking features on this curve are a broad minimum around 50 K, a subsequent increase with decreasing temperature, and a maximum at 5 K followed by a new decrease. Our cryogenic installation did not allow us to follow the curve further down, but experiments in bulk glasses show that the sound velocity tends toward a constant value [4, 5].

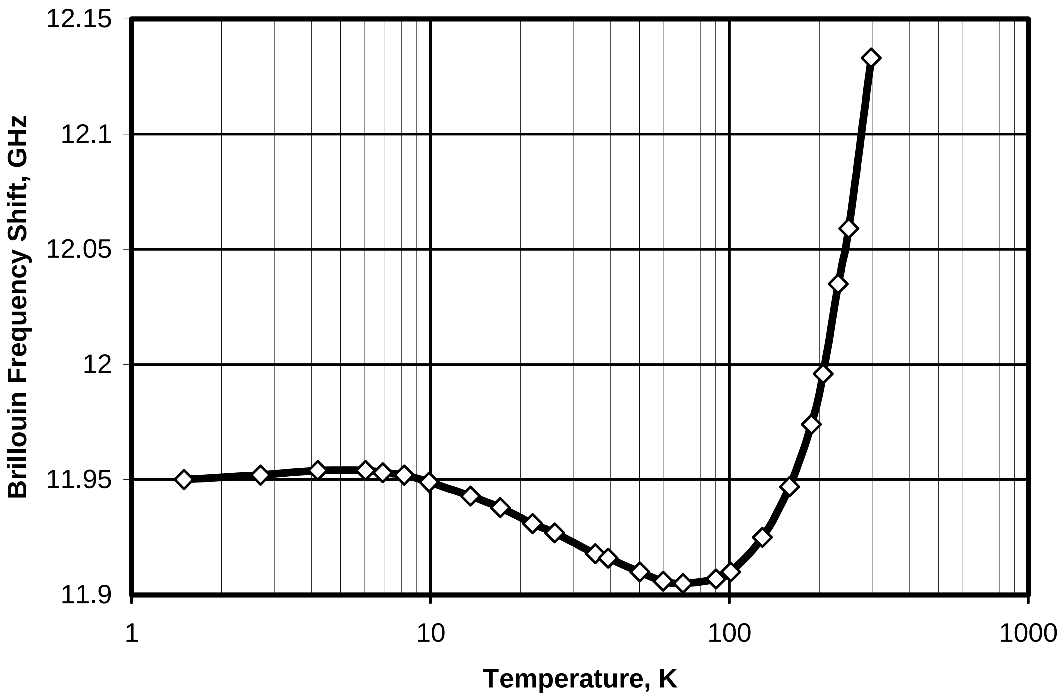

Fig.2 Variation of the central frequency of the Brillouin gain spectrum in a single-mode fiber, from very low to ambient temperatures. The acoustic velocity changes proportionally.

The observed behavior of the acoustic velocity in the 1-6 K range matches very well the prediction of a model based on tunneling processes. The decrease of acoustic velocity with temperature between 7 and 70 K is also well explained by the consequences of thermally activated relaxation processes. But as a paradox the steady increase of the acoustic velocity above 70 K up to ambient temperatures and beyond is still unexplained.

In Fig. 3 the linewidth $\Delta\nu$ of the Brillouin gain spectrum is shown, that is directly proportional to the phonon absorption (inversely proportional to the phonon lifetime). A second value derived from the measurements, the ratio $Q^{-1} = \frac{\Delta\nu}{\nu_B}$ has an important physical meaning. It gives the so-called internal friction, directly proportional to the phonons absorption. We notice in Fig. 3 a strong peak around 130 K and a monotonical decrease down to a few K. Here again, the limited temperature coverage prevents us from observing the expected behaviour at still lower temperatures, namely a plateau down to 0.1 K and a subsequent logarithmic decrease.

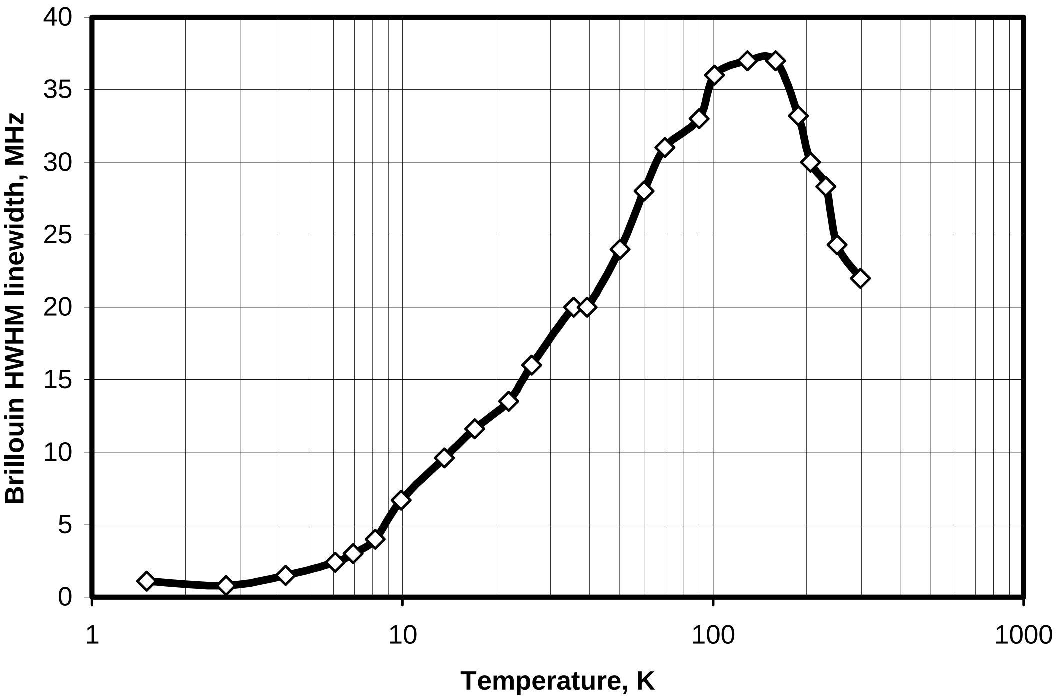

Fig.3 Half width at half maximum of the Brillouin gain spectrum as a function of temperature. The minimum is at about 2.5 K and the value of the HWHM linewidth is 0.8 MHz at this temperature.

3. REAL SIZE MONITORING USING DISTRIBUTED MEASUREMENTS

Tests of distributed measurements were performed in real conditions by installing a fibre in a future magnet of the Large Hadron Collider at CERN, as shown in Fig.4. The fibre was placed over the surface of the inner vessel containing the liquid helium, so that a direct monitoring of the actual temperature of the superconducting elements is achieved. Five coils of fibres are equally spaced along the cylinder-shaped magnet to improve the spatial accuracy of the

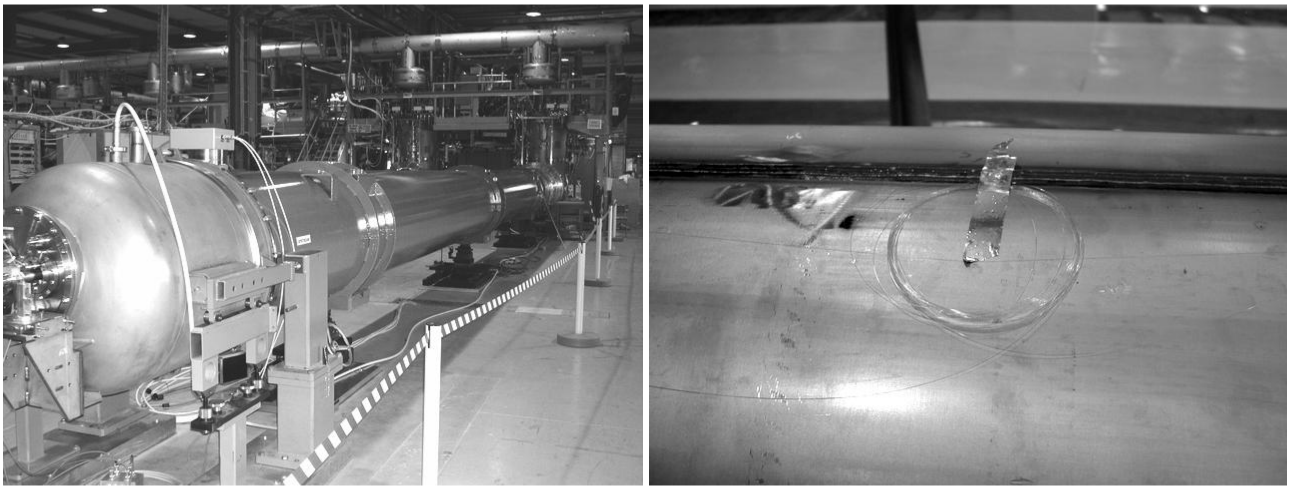

Fig.4 Magnet of the future CERN large hadron collider (left) and installed fiber for probing temperature on the wall of the liquid helium inner vessel (right).

measurement. Fig. 5 shows (curves a to d) distributed measurements performed at successive times during the early stages of the vessel filling with liquid helium. Each step corresponds to one of the 20 m fibre coils. The temperature gradient along the vessel can be easily observed, the filling inlet being placed at the right side of the structure. It should be pointed out that the coldest temperature observed during this measurement is not below 50 K at this early stage of cooling down. The anomalous change of Brillouin shift is clearly highlighted on the final measurement (curve e) at a uniform temperature of 2 K and is observed as an upshifted Brillouin distribution.

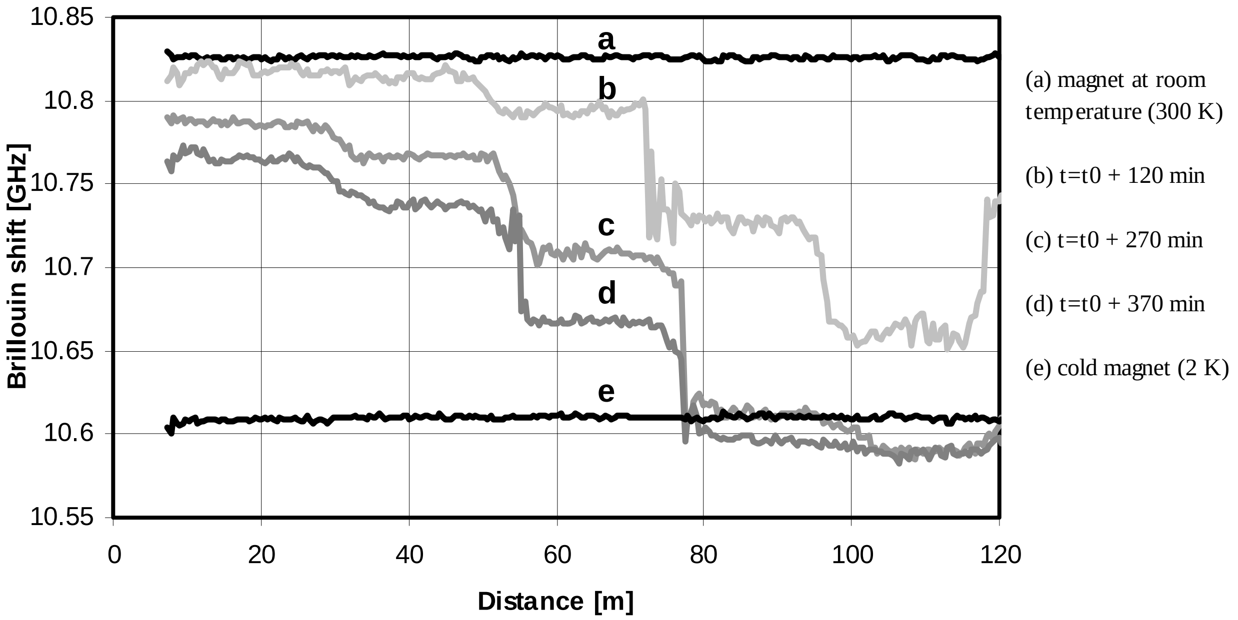

Fig. 5 Brillouin shift spatial distribution during the cooling of a supraconducting magnet to be installed in the future large hadron collider.

This example shows that Brillouin temperature sensing can be used in cryogenics, since the fibres keep all their guiding and low attenuation properties and stimulated Brillouin scattering remains efficient. Nevertheless, in comparison with the usual applications, two new problems arise, that are clearly visible in Fig. 2. The first is the ambiguity in the determination of the temperature from the measured acoustic velocity, distinct temperatures corresponding to identical velocities. The difficulty can be certainly removed by using also the linewidth information of Fig. 3, that does not need to be determined precisely for this purpose.
The second problem is the quasi-zero slope in the most interesting region between 1.5 and 5 K, due to the extremum around 5 K. Resorting to the linewidth is here of little interest, since its variation is also weak. Actually the problem is not as severe as expected at first glance, since the linewidth narrowing, quite evident in Fig. 1, results in a more precise determination of the centre of the Brillouin gain spectrum. A rough estimation shows that an accuracy of the order of 0.1 K can be achieved in the 1-10 K range. But the 10-fold decrease in the linewidth requires consequently longer pump pulses, otherwise the spectrum of the pulses would totally screen the intrinsic Brillouin spectrum. This results in a lower spatial resolution, that has to be compensated by a special fibre installation, such as the fibre loops depicted above.

The principle of using optical fibre as sensors for cryogenic temperatures has been demonstrated, together with the capability to measure temperatures down to 1 K in a real installation. Such a sensing technique offers decisive advantages over classical sensors for the control of superconducting installations, since the fibre makes possible distributed and long-range measurements and the control of the entire installation, accordingly. In addition the thermal capacity of the fibre is low and reduces massively the thermal bridges to the ambient environment when compared to classical sensors. Finally the calibration is greatly simplified, the fibre being calibrated in a single procedure.

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