Real time in-situ pulsed magnetic field coil deformation measurements with fiber Bragg sensors

M. Mainson, Julien Billette, Florence Lecouturier, Oliver Portugall, Rikken G.L.J.A., Emmanuel Marin

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M. Mainson, J. Billette, F. Lecouturier, O. Portugall, GLJA Rikken, LNCMP
E. Marin, Université St. Etienne.

1. Introduction.

Very high magnetic fields are one of the principal tools in the study of condensed matter. Generally speaking, the more intense the magnetic field, the more information that can be obtained from the system under study. At the current state of technology, the main limitation on the maximal field that can be generated in the laboratory with electro-magnets is the mechanical strength of the conductors and the reinforcement materials that allows the structure to withstand the Lorentz forces. To limit the heating of an electro-magnet due to the Joule effect, the current through the magnet can be pulsed. Typical pulse durations are between 1 and 100 ms. The increased design freedom for pulsed field coils allows to attain much higher field than with static field coils (82 T vs. 45T).

The mechanical stress induced by the Lorentz forces in pulsed coils is so high (typically 2.5 GPa for 80 T) that most metals will deform plastically, which will destroy the coil or at least severely degrade the coil lifetime. Modern finite element analysis allows to model the behaviour of pulsed coils with great precision in the elastic regime, but becomes unreliable in the plastic regime. Thus, accurate modelling of coil fatigue and predicting coil lifetime are not possible. It is therefore important to obtain real-time in-situ information on the mechanical deformation of pulsed field coils in order to understand coil behaviour in the plastic regime. Such understanding could allow to increase the maximum field attainable and to understand coil fatigue. As pulsed coils are in general compact structures, and the maximum deformation occurs near the centre of the coil, such measurements would require incorporating a very small strain sensor between the coil windings, without affecting the mechanical or electrical integrity. Additional requirements, inherent to pulsed coil operation are high speed, a large immunity to electromagnetic perturbations and operation at low temperatures (typically 77 K). The most suitable sensor type for this application, compatible with all the above requirements, are fiber Bragg strain sensors. [1].

Here we will describe a specially developed high speed fiber Bragg strain sensor system and its application for the study of mechanical deformation in pulsed magnetic field coils. Although optical sensors have been used in superconducting coils before [2], this is the first time that localized and time-resolved information is obtained on the deformation of pulsed coils during operation. Obviously, the system described here can find application in other high-speed, local deformation measurements on mechanical structures under difficult conditions.

2. Experimental.

A fiber Bragg Grating (FBG) consists of a single mode optical fiber whose core refractive index is spatially modulated [3]. Such a modulation affects the transmission of light through the fiber by reflecting the wavelength λ_B that corresponds to the Bragg resonance. As a result, a dip appears in the transmission spectrum as shown in figure 1, where λ_B is determined by the modulation periodicity Λ and the core effective refractive index n_e as follows:

$$\lambda_B = \mathbf{2n_e * \Lambda}$$

As a result, any variation of n_e or Λ induces a variation of λ_B. Such a variation can be due to a change in temperature(T), mechanical deformation ($\varepsilon = \Delta l/l$) or pressure (P) evolution, given in first order approximation by:

$$\frac{\Delta\lambda_B}{\lambda_B} = a\Delta T + b\varepsilon + c\Delta P$$

The principle of our readout system is to measure the transmission spectrum around the Bragg resonance with a fast multi-channel silicon CCD detector. The advantages of this method over the much simpler and potentially much faster readout of the Bragg resonance shift by a well chosen single wavelength readout are the insensitivity to intensity variations and the unequivocal determination of the Bragg resonance and thereby of the deformation. In order to have a good signal to noise ratio in the transmission measurement even with very short exposure times, we have chosen a superluminescent light emitting diode as light source [4]. For experimental convenience and maximum resolution and sensitivity, the central wavelength of our system was chosen at 980 nm.

FBG manufacture

As our fiber Bragg sensor is intended to be operated under harsh conditions like low temperatures (77°K) and high strains (up to 1 %), the fiber selection is critical. We have tested different fiber types and have chosen the pm980hp because it retains a good transmission under the conditions described above.
The periodic modulation of our FBG is obtained by means of an UV interference pattern, using Lloyd's mirror technique which is able to produce a sharp, deep FBG [5]. The fiber is loaded with H_2 in order to increase the photo-sensitivity [6] and was processed at the LTSI (Laboratoire Traitement du Signal et Instrumentation) by the CFOP team (Composant fibre optique et photo-sensibilité).
Figure 2 shows a typical transmission spectrum through our FBG in the unstrained and an axially strained state, the latter corresponding to a strain of 5600με +/-50με.
We have calibrated our FBS by gluing the fiber on a copper wire and applying a constant deformation to the wire by means of a commercial traction machine. At a deformation of 1 mm/min and with a sample length of 200 mm we observe the resonance shift shown in figure 3, which leads to a value for the parameter b in Eq. 2 of 0.82 at 77°k, close to typical values reported for this parameter [7].

Incorporation of FBG into coils

We have tested the fiber sensor system on small test coils, wound of rectangular copper-stainless steel wire [8] insulated with Kapton ribbons. The coil has typically 20 turns and 4 layers and produces a pulsed magnetic field of 40 T with a current of 20 kA. A typical magnetic field pulse is shown in figure 8 together with the Bragg strain measurement. First incorporation test show, as figure 5, that fiber jacket is deformed during shot. This deformation could introduce some difference between real and measured strain by sliding. In order to avoid this difference, fiber jacket is removed as figure 6 and the sensor is directly glued to the surrounding conductor with reinforced two component epoxy glue (Stycast ft850), which ensures good strain transmission from the windings to the fiber. The small diameter of the fiber allows it to fit in between the rounded corners of the conductors without being damaged (see figure 7), but for most of the tests, the fiber was simply wound on the outer winding layer.
Once the FBG is in position and the coil is completed, the rest of the fiber is protected by a jacket and connectors are put on each end. One is connected to the light source, and the other to the spectrometer. The coil is installed in a liquid nitrogen cryostat.

Data acquisition chain

The schematics of the data acquisition system are presented in figure 7. A transmission spectrum synchronised with the magnetic field pulse is recorded for each field shot (figure 8). The detector was a 2048 element silicon CCD array, coupled to 1200 lines/mm grating [Ocean Optics model h6], having a wavelength resolution of 0.08 nm which results in a strain resolution 100με for the FBG sensor. The detector's time property and the powerful light source allow a sampling rate FBG of 1 kHz. The magnetic field pulse is determined by a calibrated pick-up coil. A computer program determines λ_B for each spectrum.

3. Results

Three types of coil deformation were observed in our experiments. At low fields and currents, only elastic deformation of the windings due to the Lorentz force occurs, and after the shot, the Bragg resonance returns to its initial value. This is typical elastic deformation measurement during a shot is shown in figure X, and compared with finite element modelling of the coil. A good agreement is obtained, confirming the capability of the system for real time and in-situ deformation determination.
At high currents and magnetic fields, in addition to elastic deformation, plastic deformation can occur, and the coil heats up, causing thermal expansion. These two effects both result in a red-shift of the Bragg resonance after the shot, with respect to that before the shot. Allowing the coil to coil back down to 77 K (typically in 10 minutes) eliminates the thermal contribution to the observed deformation, and the remaining red-shift is entirely

due to plastic deformation. By monitoring the position of the Bragg resonance after the pulse, one can therefore determine both the plastic deformation and the local temperature just after the shot. Figure 8 shows a case for a field shot with elastic and thermal deformation.

Figure 9 shows for a series of field pulses of continuously increasing strength, the observed deformation long after the pulse (i.e. coil temperature back at 77 K) as a function of the field strength, together with the finite element modelling for plastic deformation. Clearly significant deviations are observed for strains above 0,1 % that remain to be explained, illustrating the limitations of finite element modelling in this regime.

4. Summary and conclusion

We have shown that a FBG can be incorporated as a strain sensor in pulsed magnetic field coils for real-time and in-situ coil deformation measurements, this is prove by the reliability between field and strain measurement. Moreover, good agreement is obtained with finite element modelling in the elastic regime, but clear deviations in the plastic regime are observed. These measurements can therefore allow to refine finite element modelling in this regime, which is essential for improving the maximum field and the coil lifetime. A further improvement under way is the realization of several Bragg gratings at different positions on one fiber with nearby but different resonance wavelengths that allow to simultaneously monitor deformations at different positions in a coil. The sensor system described here can of course also be used to determine mechanical deformation in other structures under similarly difficult conditions.

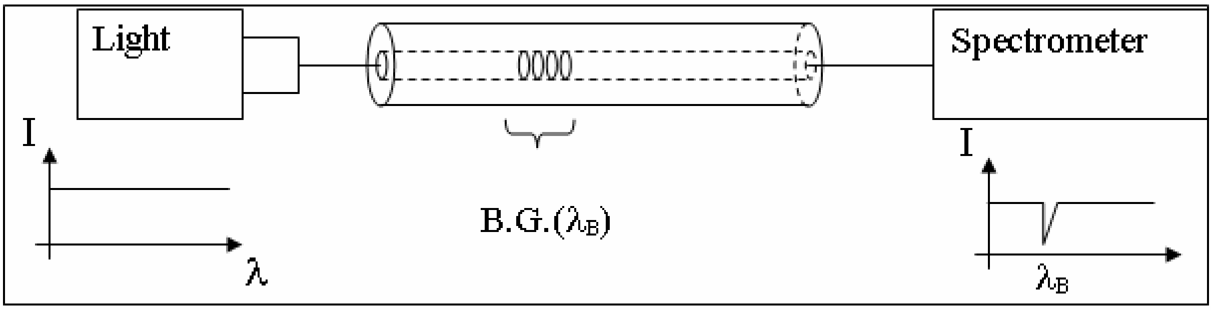

Figure 1 - Fiber Bragg gratting effect

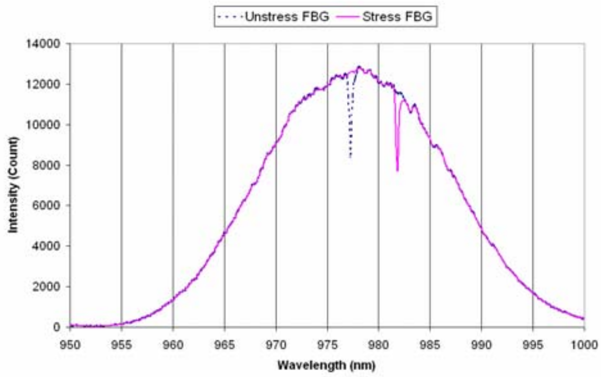

Figure 2 - Typical transmission spectrum through our FBG in the unstrained and an axially strained state

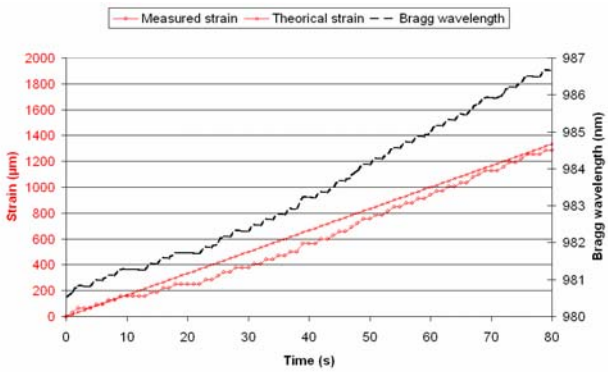

Figure 3 - Bragg resonance shift

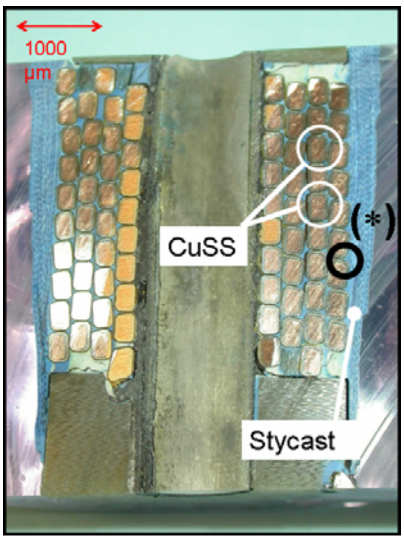

Figure 4 - Test coil section

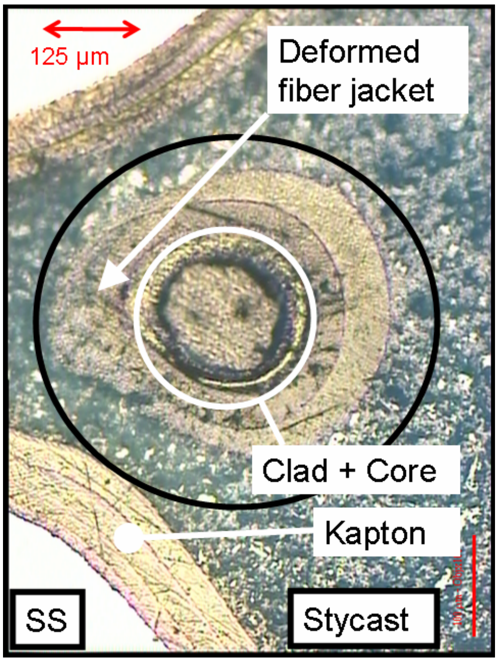

Figure 5 - Implemented fiber behaviour

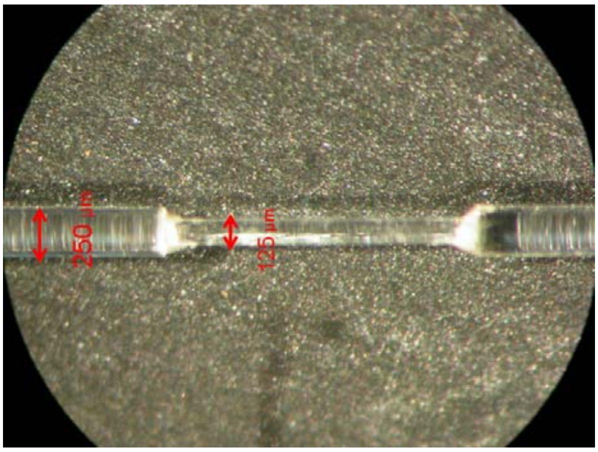

Figure 6 - Stripped fiber

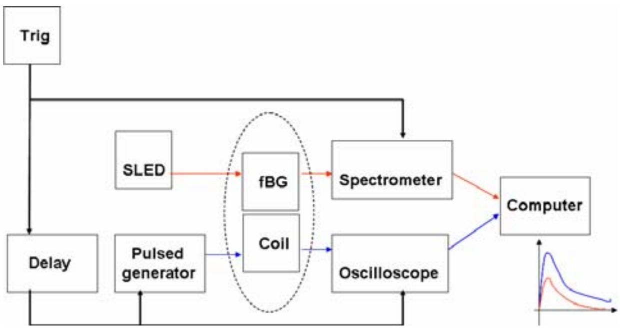

Figure 7 - Schematics data acquisition chain

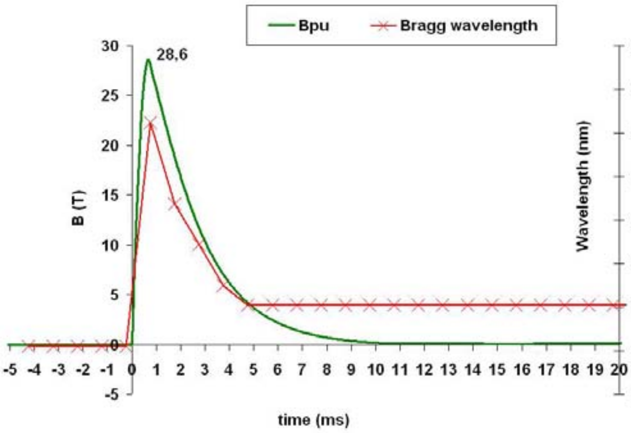

Figure 8 - Field and Bragg wavelength shift

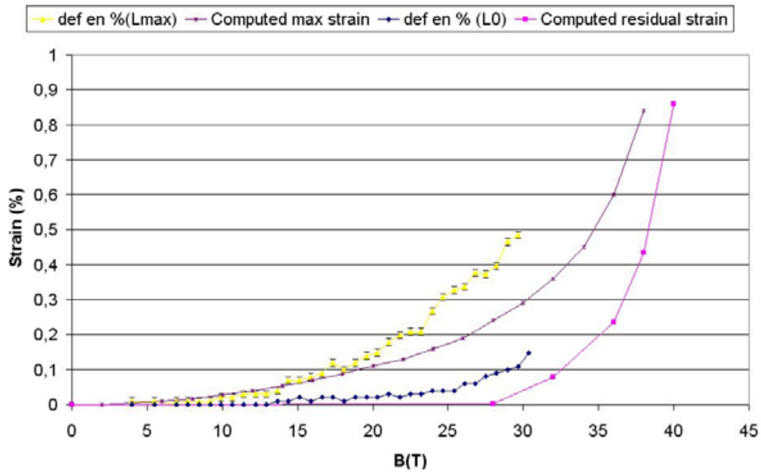

Figure 9 - Fem vs Measurement

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