Current measurement by Faraday effect on GEPOPU

Correa N\textsuperscript{1}, Chuaqui H\textsuperscript{1}, Wyndham E\textsuperscript{1}, Veloso F\textsuperscript{2}, Valenzuela J\textsuperscript{1}, Favre M\textsuperscript{1} and Bhuyan H\textsuperscript{1}.

\textsuperscript{1}Departamento de Física, Pontifica Universidad Católica de Chile, Av. Vicuña Mackenna 4860, casilla 306, Santiago 22, Chile.
\textsuperscript{2}Present address: Departamento de plasmas termo nucleares, CCHEN, casilla 188-D, Santiago, Chile.

E-mail: nacorrea@puc.cl, hchuaqui@fis.puc.cl

Abstract. The design and calibration of an optical current sensor using BK7 glass is presented. The current sensor is based on the polarization rotation by Faraday effect. GEPOPU is a pulsed power generator, double transit time 120ns, 1.5 Ohm impedance, coaxial geometry, where Z pinch experiment are performed. The measurements were performed at the Optics and Plasma Physics Laboratory of Pontificia Universidad Católica de Chile. The verdet constant for two different optical materials was obtained using He-Ne laser. The values obtained are within the experimental error bars of measurements published in the literature (less than 15\% difference). Two different sensor geometries were tried. We present the preliminary results for one of the geometries. The values obtained for the current agree within the measurement error with those obtained by means of a Spice simulation of the generator. Signal traces obtained are completely noise free.

1. Introduction

The Faraday effect offers the potential for making devices that can measure electrical currents leaving the flow of the current unperturbed. This is due to the fact that the Faraday effect results from the interaction between the magnetic field that is produced by the current and a beam of light that passes through a material subjected to that field. When a linearly polarized beam propagates inside a dielectric material, its polarization is rotated under the influence of the parallel component of the magnetic field generated by the current $I$. The Faraday rotation $\Phi_F$ in the presence of a magnetic field $\vec{B}$, is given by the following relationship:

$$\Phi_F = \int_L \nu \vec{B} \cdot d\vec{l} \quad (1)$$

Where $\nu$, is the verdet constant of the dielectric material and $L$ is the interaction length. The total rotation angle will be given by the integration of the equation above, along the path of the laser, i.e., along a straight line. The length of the integration is equal to the length of our BK7 glass rod (Edmund Optics Hexagonal light pipe, uncoated), which is 125mm. With this consideration in mind, we can rewrite equation (1) for our geometry which gives:
\[ \Phi_F = \frac{\mu_0 I_\nu}{\pi} \left[ \ln(B + \sqrt{B^2 - x^2}) - \ln(R + \sqrt{R^2 - x^2}) \right] \] (2)

Where A and B are the respective ends of the rod \((AB = 125mm)\), \(R\) is the distance between the centre of the electrode and one end of the rod, \(x\) is the distance between the centre of the electrode and the centre of the glass bar.

### 1.1. The apparatus: GEPOPU

The apparatus used to carry out our current measurement was GEPOPU, a pulsed power generator situated in our laboratory which consists of different stages. The first one is a Marx capacitor bank, used to multiply the input charging voltage. The Marx bank has 8 capacitors charged by a DC high voltage power supply in parallel and discharged in series using a number of gaseous switches filled with nitrogen. The switch voltage is adjusted by varying the gas pressure at a fixed electrode separation. Triggering the switches causes the erection of the Marx, giving rise to an output voltage of \(8V_0\), where \(V_0\) is the voltage used to charge each capacitor. The design of this capacitor bank uses a plus-minus charge configuration reducing the number of switches by a factor of two. This configuration has a lower jitter and faster rise time of the output voltage, compared to a single polarity configuration. The entire marx generator is immersed in a tank filled with transformer oil, to prevent flashover.

The second stage of the generator, corresponds to a transmission line. In GEPOPU we have one line with two sections of matched impedance. The first part stores the energy being supplied by the Marx bank, which is transferred through a line spark gap to the transfer section. The duration of the current pulse is twice the transit time of the line, 120 ns. The line gap is filled with nitrogen. In order to improve the risetime of the current on the discharge camera (and last stage), a peaking gap separates the transfer section from the discharge chamber. For detailed information, see [1].

### 2. Experimental Section

Two experimental setups were used in this research.

The first one, was used to perform measurements of the verdet constant for two different materials: BK7 glass and acrylic, by means of the application of an AC current. The power supply used was a transformer 220V-10V, whose current was limited by the use of two resistances in series. The first one, \(R_1\) composed of four ceramic resistors of 3.3\(\Omega\) each in parallel and \(R_2\) in series with this combination, 0.1\(\Omega\). The voltage across \(R_2\) is proportional to the applied current. The value of the current was changed by means of the values of \(R_1\).

A linear polarizer is used to adjust the laser polarization to 45\(^\circ\), to obtain the maximum signal difference between both polarization states. The bar of material was placed in the interior of the coil, the laser beam passes through it. The entire experimental setup used to measure the verdet constant is shown in figure 1.
The second experiment, was used to perform the current measurement at the GEPOPU generator under short-circuit. A brewster angle polarizer was used to produce a linearly polarized beam, before the analyzer a λ/2 was used to adjust the photodiode (FDS100-Thorlabs) signals to achieve equal values. The PBS is the analyzer to provide both polarization states. Two lenses are used to feed the laser signals to a fibre optics, each of them going to a fast photodiode. The material used to measure the current, in this case a BK7 glass bar is situated on a groove on the solid brass short circuit.

3. Results and Discussion

The verdet constant of the two different materials obtained, gives us a difference of less than 15%, compared to the values found in the literature[2],[3].

\[ \nu_{BK7} = 2.1501 \pm 0.0036 \left( ^\circ Tcm \right) \quad \nu_{acrylic} = 1.4863 \pm 0.0081 \left( ^\circ Tcm \right) \]  

With these values, we proceed to measure the current using the setup in figure 2, using BK7 glass bar. The signals obtained using BK7 glass for both polarization states is shown in the graph below, together with the trace of the rogowski coil, the traditional method to measure the current in this type of generator.
Figure 3. The top trace is the integrated rogowski coil, while the lower oscilloscope traces are the parallel and perpendicular polarizations.

It is apparent that the traces shown on figure 3 have similar forms, the difference in starting time between the rogowski coil signal (grey trace) and the optical signals is due to different lengths of cable.

The graph shown in figure 4 corresponds to the current obtained by the application of the Faraday rotation formula (2). The difference between both signals is mainly due to the calibration factor. The apparent current prepulse on the photodiode signals at $\sim 25\text{ns}$ on the left trace and $\sim 125\text{ns}$ on the right trace, is due to electrical noise generated by the Marx bank.

On the next traces we can see that our results agree with the simulations, the traces have similar form and rise times (figure 5). In the image, the perpendicular trace has not been plotted.
Figure 4. Traces of current obtained by the application of the Faraday rotation formula. In the lower graph, the difference between both signals is due to the calibration factor.

Figure 5. Normalized traces of current obtained from an optical signal (top), simulation (centre) and rogowski coil (bottom).

4. Conclusion
A non-invasive way to perform current measurement has been presented. A method of characterization of different materials has been developed which gives an error of less than 15%.
The traces obtained using Faraday rotation show a good response in time and have similar shape to those obtained by simulation or by a rogowski coil. Work is in progress to achieve a consistent photodiodo calibration and the development of a new geometry, which considers a closed optical path around the current, in order to avoid errors due to asymmetry of the current distribution.

Acknowledgments
The present work has been funded by Proyecto PUENTE N° 9/2010, VRAID, and Departamento de Física, Pontificia Universidad Católica de Chile.

References
[1] M. Favre, “Pulse Technology”, Proc. Symposium on Small Plasma Physics Experiments (ICTP, Trieste, Italy) 1989, p. 170.
[2] E. Munin et al., J. Phys. D: Appl. Phys. 1992, 25 1653.
[3] Eul Ha Hwang and Byoung Yoon Kim, Meas. Sci. Technol. 2006, 17 2015.