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APPLICATION OF ROGOWSKI COIL IN FAST PULSED-CURRENT MEASUREMENTS OF CAPILLARY DISCHARGE

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The measurement of fast pulsed-current and observation of time variations of the current are important for diagnostics of high-current discharges. The most convenient method of measurement is the application of the Rogowski coil which can measure variable currents in a very wide range of frequency and current. We introduce the Rogowski coil in the measurements of current of the ablative capillary discharge. The discharge current is a very important characteristic of the process and its determination allows the estimation of the period of the discharge cycle and of the total inductance of the circuit. In our experiments, the discharge currents were of the order of magnitude of several kA, the discharge cycle periods were of the order of 300 ns and the total inductances were of the order of a few tens of nH.

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1. Introduction

The Rogowski coil is an air-cored toroidal coil, usually placed around a conductor with the aim to measure rates of change of current in the conductor. The variable magnetic field produced by the current induces a voltage in the coil which is proportional to the rate of change of the current. The direct output of the coil is given by $U_{\mathrm{out}} = M\mathrm{d}I/\mathrm{d}t$ where M is the mutual inductance of the coil and $\mathrm{d}I/\mathrm{d}t$

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is the rate of change of current in the conductor. The voltage can be integrated electronically so that the output from the integrator is a voltage that accurately reproduces the waveform of the current. The combination of a coil and an integrator provides the output which is independent of frequency, has an accurate phase response and can measure complex current waveforms and transients. The Rogowski coil current transducer can measure alternating currents in the frequency range from less than 0.1 Hz to about 1 GHz. The current measurement range is also very wide. from a few mA to over 1 MA. These transducers have an excellent transient response capability. They can be used for measurements on conductors of different forms and dimensions. Rogowski coil technology offers solutions for different current-measuring problems. Therefore, Rogowski coils have a very wide range of applications. In power applications, Rogowski coils are used to measure the current waveforms during the start-up of large electric motors. Also, Rogowski coils are used to monitor for sudden short-circuit testing providing information about generator time constants. Current transformers can be accurately calibrated on-site using Rogowski coil without their transport to a calibration laboratory. A rail gun is an electromagnetic method of launching a projectile requiring current of a few million amperes lasting for about a millisecond and Rogowski coils are ideal for studies of such pulsed power application. Rogowski coils have been found useful for measuring currents during welding processes. These and other applications are described in Refs. [1 – 3].

The Rogowski coil has many advantages over other methods of current measurement for the simplicity of its construction, and ease of measurement and calibration. Also, it is a non-contact method. One of the most important properties of a Rogowski coil measuring system is that it is linear. The output increases proportionally to the current up to the operating limit. There are no saturation effects and the mutual inductance is independent of the measured current. Because of linearity, Rogowski coils can be tested in the laboratory in advance using a simulated waveform at a lower current. Since there are no problems with non-linearity, we can be sure that it can be used at any level of current. Compactness and small weight allow easy transport and installation in any circumstances.

The possibility of measurements of large current and the observation of the manner in which the currents vary in time are of great diagnostic interest in high-current discharges. The most convenient method of measurement is based on the application of the Rogowski coil [4]. Capillary discharges, which operate at high currents, produce plasma which emits line radiation from highly ionised atoms. The measured plasma parameters match very well those of laser-produced plasmas. Discharges can be produced in many ways. For the application of plasma as a small source of light, one can use either gas-filled tubes or ablative capillaries [5 – 16].

Inductive measurements of the total current flowing through the discharge loop is possible using the Rogowski coil. There is no contact with the circuit in which the current is measured and this is a big advantage in the measurement of the total current flowing in the plasma, even in large systems such as tokamaks or theta pinch. [1, 6, 17 – 19].

2. Experiment

2.1. Ablative capillary discharge

The ablative capillary discharge has been described by Ellwi et al. [9]. Our experimental set up is shown in Fig. 1. The capillaries are made of polyvinylchloride or polyacetal, typically 20 to 50 mm in length, with hole diameters of 1 mm and smaller. Both discharge electrodes are of tungsten and have an axial bore. Capacitors of a total capacitance of 100 nF are connected directly to the capillary arrangement. A Rogowski loop is used to measure the rate of current change $\mathrm{d}I/\mathrm{d}t$. The total number of turns of the coil is 40 and the cross-sectional area is $1\,\mathrm{mm} \times 5\,\mathrm{mm}$. The signals from the coil (discharge current) and from the photomultiplier (photon spectra in the far UV region) were recorded with a fast Tektronix digital oscilloscope DAS 602 A (2 Gs/s, 500 MHz analogue bandwidth). Time observed photon spectra (Fig. 2) were obtained with a 1 m grazing-

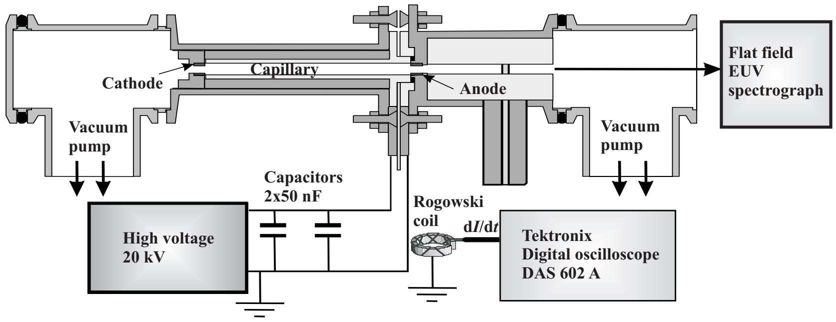

Fig. 1. Experimental set-up.

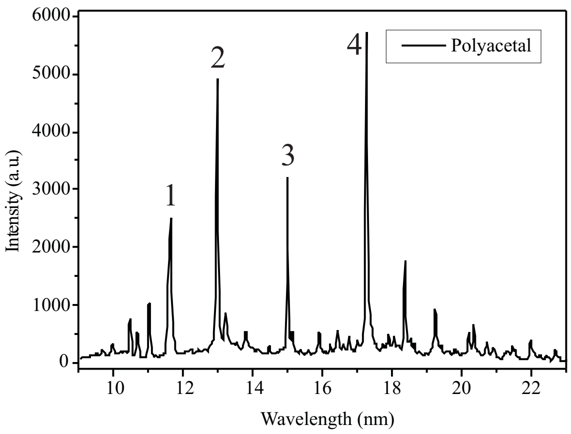

Fig. 2. Observed discharge spectrum with polyacetal capillary. The lines are: (1) 11.6350-11.6421 nm *O VI $1s^2 2p$-$1s^2 5d$, (2) 12.9785-12.9871* nm *O VI $1s^2 2p$-$1s^2 4d$, 3 15.0089-15.0125* nm *O VI $1s^2 2s$-$1s^2 3p$, 4 17.2935-17.3079* nm *O VI $1s^2 2p$-$1s^2 3d$ (two wavelenghts are quoted because the resolution does not allow identification).*

incidence spectrometer combined with a NE 111a plastic scintillator (exit slit of 200 μm) linked by fibre optics to the photomultiplier (Hamamatsu R 2496, rise time of 0.7 ns).

3. *Discharge current*

A Rogowski coil technique is the application of known Ampere's law, which provides the relationship between the current flowing and the magnetic field around it. The frequencies of waveforms in the present measurements were in the range of 1 MHz, corresponding to wavelength of electromagnetic waves of 300 m. Since the size of the measuring system is much smaller, the quasy-static approximation could be used. The total flux linkage by the coil can be written as an integral,

$$\phi = N \oint_l \int_A \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{l} \mathrm{d}A \,, \tag{1}$$

where d$\boldsymbol{l}$ is a line element along the loop, $\boldsymbol{B}$ is the magnetic field, A is the cross-sectional area of the coil and N is the total number of turns of the Rogowski coil (see Fig. 3).

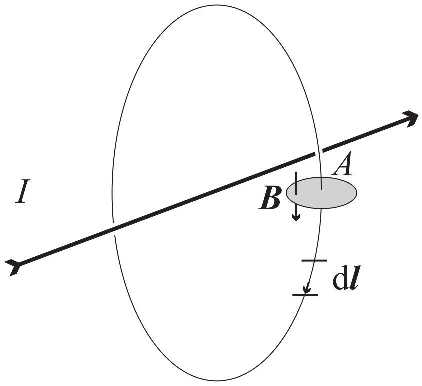

Fig. 3. Principle of operation of Rogowski coil. I is the total current encircled by l. A is the cross-sectional area of the coil. $\boldsymbol{B}$ is the magnetic field. d$\boldsymbol{l}$ *is the line element along the loop.*

Ampere's law

$$\oint_l \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{l} = \mu_0 I \,, \tag{2}$$

has been used for the evaluation of the integral, where I is the total current encircled by l and μ_0 is the magnetic permeability of free space. Thus

$$\phi = N A \mu_0 I \,, \tag{3}$$

and

$$U_{\mathrm{Rog}} = -\frac{\mathrm{d}\phi}{\mathrm{d}t} = -NA\mu_0 \frac{\mathrm{d}I}{\mathrm{d}t}\,. \tag{4}$$

Rogowski coil can be used to provide experimental demonstration of Ampere's law because the voltage output from the coil is independent of the way the coil is placed round the conductor. We have to provide that the ends of the coil are brought together. It is essential that we have a response caused only by current which flows through the loop. External sources fields and currents do not have effects.

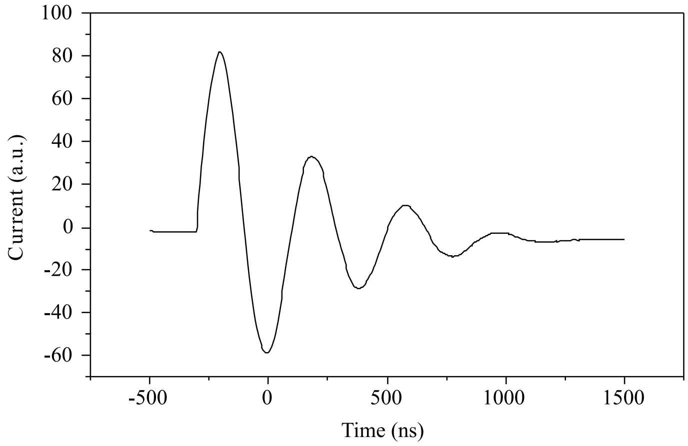

Fig. 4. A typical capillary discharge current signal (given in arbitrary units) recorded in the measurement with the Rogowski coil, using a polyacetal capillary 30 mm *long with a 0.8* mm *diameter hole, high voltage of 8* kV *and two capacitors of the total capacitance of 100* nF*.*

The period of the discharge cycle depends on the capillary length and damping corresponding to a total inductance. We can consider the capillary discharge as an electric oscillating circuit (Fig. 4). For calibration, we first strongly reduce the damping, usually by using a short, large-bore capillary. In that case we have the smallest inductance of circuit. Then the discharge current is given by:

$$I(t) = I_0 \mathrm{e}^{-\delta t} \sin \omega t\,, \tag{5}$$

with

$$\delta = \frac{R}{2L}\,, \tag{6}$$

and

$$\omega = \frac{2\pi}{T} = \sqrt{\frac{1}{LV - \delta^2}}\,. \tag{7}$$

From this follows

$$I_0 = U_0 \sqrt{\frac{C}{L}}\,, \tag{8}$$

where L is the inductance, C is the capacitance, R is the resistance, U_0 is the initial voltage and T is the period of the capillary discharge cycle. The period T can be obtained from the integrated $\mathrm{d}I/\mathrm{d}t$ signal. Next, we find the logarithmic decrement of damping Λ, inductance L and resistance R:

$$\Lambda = \ln \frac{|I(t)|}{|I(t+T/2)|} = \ln \frac{|I(T/4)|}{|I(3T/4)|} = \frac{RT}{4L}\,, \tag{9}$$

$$L = \frac{T^2}{4C(\pi^2 + \Lambda^2)}\,, \tag{10}$$

and

$$R = \frac{4L}{T}\Lambda\,. \tag{11}$$

This completes the expressions needed for the analysis of results of the measurements.

4. *Results and discussion*

Measurements current of the capillary discharge using a Rogowski coil was performed several times under different working conditions. The discharge current depends on the initial conditions (high voltage, pressure etc.), capillary material, length of capillary and other factors. The main results were obtained using capillaries made of polyacetal (CH_2O)n with a length of 30 mm and a bore of 0.8 mm. Some measurements were made using five capacitors (each of 20 nF) of a total capacity of 100 nF, connected directly to the capillary star-like arrangement, and some with two 50 nF capacitors (see Fig. 1). The discharge was initiated by raising the voltage up to 8 kV and the maximum current was about 18 kA, calculated using Eqs. (5) – (8) and recorded signal data. The accuracy of the measurements of the current was limited by the inaccuracy of the determination of the mutual inductance and of the oscilloscope display (the accuracy of measurement of the maximum current was about 10%). However, the waveform of the discharge current was used for the determination of two other characteristics of the process: the period of the discharge cycle and the total inductance of the circuit. These results are of much better accuracy.

The results obtained with five 20 nF capacitors are shown in Table 1. The period of the discharge cycle T was about 280 ns, which corresponds to a total inductance of 20 nH.

For a comparison, we made measurements with a similar experimental setup, using two capacitors of a total capacity of 100 nF. The same capillary made of polyacetal (length of 30 mm and diameter of 0.8 mm) was used because the period of the discharge cycle depends on the capillary length. The high voltage was also

8 kV and the current was about 13 kA. Equation 10 gives us the period of the discharge cycle T of about 400 ns and a corresponding total inductance L of 40 nH (Table 2).

TABLE 1. The period of the discharge cycle T, logarithmic decrement of damping Λ and the total inductance L of the circuit determined for ablative capillary discharge with polyacetal capillary (length of 30 mm *and hole diameter of 0.8* mm*), high voltage of 8* kV *and 5 capacitors of the total capacitance of 100* nF*. Current is given in arbitrary units.*

$I(T/4)$	$I(3T/4)$	T	Λ	L
(arbitrary units)		(ns)	–	(nH)
24.36	21.00	272	1.16	18.70
24.93	18.92	276	1.32	19.15
24.98	20.16	280	1.24	19.77
24.84	20.12	284	1.23	20.34
24.90	20.84	288	1.15	21.01
25.30	20.26	280	1.25	19.76

TABLE 2. The period of the discharge cycle T, logarithmic decrement of damping Λ and the total inductance L of the circuit determined for the ablative capillary discharge with polyacetal capillary (length of 30 mm *and hole diameter of 0.8* mm*), high voltage of 8* kV *and 2 capacitors of the total capacitance of 100* nF*. Current is given in arbitrary units.*

$I(T/4)$	$I(3T/4)$	T	Λ	L
(arbitrary units)		(ns)	–	(nH)
212.72	137.60	392	1.55	38.18
82.20	58.72	390	1.40	38.09
85.52	55.52	400	1.54	39.78
86.24	63.82	392	1.35	38.57
91.52	58.96	396	1.55	38.96

We showed that a number of capacitors, even though they have the same total capacitance, can significantly change the period of the discharge cycle and the corresponding total inductance. In experiments where a low inductance is essential we have to optimise working conditions.

In comparison with other similar processes [5, 8, 9-16, 20] we found that our results showed very good agreement and are in the same range. This means that the discharge currents were of an order of magnitude of kilo amperes, discharge cycle periods were of the order of magnitude of 100 ns and total inductances were of the order of magnitude of nH. In some experiments authors used polyacetal as the capillary material and comparison of main parameters is in Table 3.

TABLE 3. Comparison of some experiments with capillaries made of polyacetal.

Ref.	Authors	Experiment	Discharge cycle periods Discharge currents Total inductances
[10]	Boboc et al.	Intensity enhancement of the C^{5+} Balmer radiation excited by capillary discharge pumping	350 ns 40 – 80 kA –
[11]	Bobrova et al.	MHD simulations of plasma dynamics in pinch discharges in in capillary plasmas	440 ns 30 – 40 kA –
[12], [21]	Steden and Kunze	Observation of gain at 18.22 nm in the carbon plasma of a capillary discharge	240 ns 10 – 12 kA 15 nH
This article	Pleslić and Andreić	Calibration of Rogowski coil in fast pulsed current measurements	280 – 400 ns 13 – 18 kA 20 – 40 nH

5. *Conclusion*

Current monitoring by a calibrated Rogowski coil is a very good method for monitoring a discharge current pulse. The discharge current is an important parameter that depends on high voltage, capillary material, length of capillary and other factors. We used them also for the determination of another two characteristics of the process: the period of the discharge cycle and the total inductance of the circuit. Calculations showed that discharge currents were of the order of magnitude of kA (10-20 kA in our investigation with polyacetal as capillary material and a high voltage of 8 kV) and that the total inductance of the circuit varied from 20 nH to 40 nH.

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PRIMJENA ROGOWSKIJEVE ZAVOJNICE U MJERENJIMA BRZIH STRUJNIH IMPULSA U KAPILARNOM IZBOJU

Mjerenje brzih strujnih impulsa i promatranje promjena struje s vremenom važni su za dijagnostiku u visoko-strujnim izbojima. Najprikladnija metoda mjerenja je primjena Rogowskijeve zavojnice, kojom se mogu mjeriti promjenjive struje u vrlo širokom frekventnom intervalu. U ovom radu opisujemo mjerenja struje ablativnog kapilarnog izboja pomoću takve zavojnice. Izbojna je struja vrlo važan parametar za karakterizaciju procesa i njeno nam mjerenje omogućuje određivanje perioda izbojnog ciklusa i ukupne induktancije kruga. U ovim su mjerenjima izbojne struje bile reda veličine više kA, periodi izbojnih ciklusa oko 300 ns a ukupne induktancije su bile reda veličine nekoliko desetaka nH.