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SIMPLE EXPERIMENTAL METHODS TO CONTROL CHAOS IN A DOUBLE PLASMA MACHINE [1]

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We present two simple, effective and low-cost experimental methods to control chaos in **d**ouble **p**lasma (DP) machine plasma. By using a capacitor, we can substitute the low-frequency chaos (uncorrelated oscillations), which appears in the S-type negative differential resistance region of the static current-voltage ($I-V$) characteristic, by a nonlinear oscillation, the frequency of which is controlled by the external capacitance. By using an inductance we can suppress all higher harmonics of the natural nonlinear oscillations occurring in the N-type negative differential resistance region of the $I-V$ characteristic, obtaining purely sinusoidal oscillations, the frequency of which is determined by the external inductance.

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1 Introduction

The control of chaos is one of the most challenging problems of nonlinear physics [1, 2]. There is great interest in this field, especially in the view of controlled fusion projects. There are many theoretical approaches, but is not so easy to implement these to the experimental conditions. In practice we need simple, effective and, eventually, low-cost methods.

It is well known [3, 4] that, under certain experimental conditions (gas pressure, plasma density, electrons temperature), in the front of a positively biased electrode, immersed into plasma, a **c**omplex **s**pace **c**harge **c**onfiguration (CSCC) can appear, which is also sometimes called anode double layer. The static $I-V$ characteristic of the electrode shows at least two regions of negative differential resistance, one S-type and one N-type. The negative differential resistance S-type is related to the appearance and disappearance of a CSCC [3, 4], whereas the N-type negative differential resistance is related to the spatio-temporal dynamics of a CSCC [5, 6], or to the

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onset of a low-frequency instability [7]. Between these two regions uncorrelated low-frequency oscillations with a continuous spectrum can appear. Since the oscillations are uncorrelated, the plasma enters a chaotic state. To avoid this we have inserted a capacitor between the electrode and the ground. In this way the chaotic state is superseded by a regular oscillatory one. The frequency of the observed oscillations depends on the charging and discharging time constants of the capacitor.

In the N-type negative differential resistance region the plasma system performs strongly nonlinear oscillations, characterized by the presence of many higher harmonics in their spectrum. But, for many applications, harmonic oscillations are required, so we need to suppress the higher harmonics. This is possible by inserting an inductance into the external electronic circuit, in series with the electrode E and the power supply. The oscillation frequency depends on the inductance according to Thomson formula.

2 Experimental results

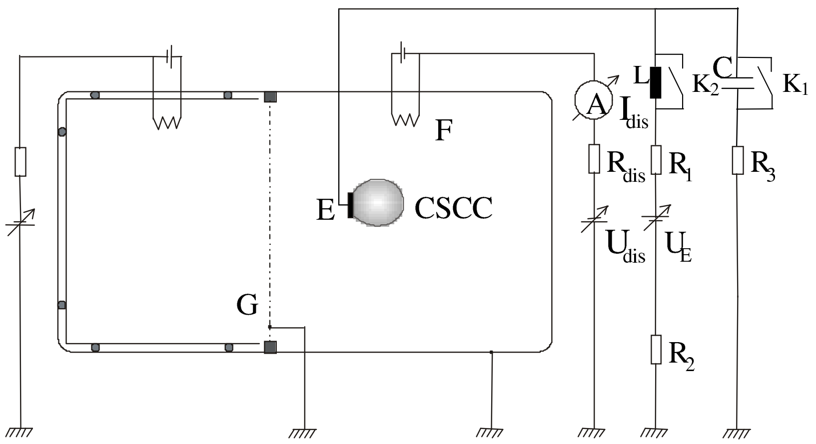

Fig. 1. Expreimental set-up of the Innsbruck DP-machine. G – grid, F – filament, $R_1 = 500\ \Omega$, $R_2 = 10\ \Omega$.

The experiments were performed in the DP-machine of the University of Innsbruck, schematically represented in Fig. 1. The DP-machine consists from a large cylindrical non-magnetic stainless steel tube (about 1 m longer and 0,6 m diameter), evacuated by a preliminary pump and a diffusion pump. A metallic grid separates the tube in two chambers: the source chamber (right hand of the tube in the Fig. 1) and the target chamber (left hand of the tube in Fig. 1). In each of the chambers the plasma is created by an electrical discharge between a hot filament (marked by F in Fig. 1) and the grounded tube as anode. Because of the small dimensions, the filament will collects just a negligible part of the ions, most of them diffusing in the middle of tube. The positive space charge will attract many electrons in this region. In this way, a high ionization degree plasma appears. To avoid the plasma loses, at the walls there is some magnetic traps, generally in form of permanent magnets with alternate polarity. In our experiments we used only the source chamber of the DP-machine of the University of Innsbruck. The plasma created in the source chamber was pulled away from thermal equilibrium by gradually increasing the voltage applied to a tantalum disk electrode E with 20 mm diameter. Fig. 2 shows the static $I - V$ characteristic obtained by gradually increasing and subsequently decreasing the potential on the electrode E, under the following experimental conditions: argon pressure p = 500 Pa, plasma density $n = 10^{16}$ m^{-3}.

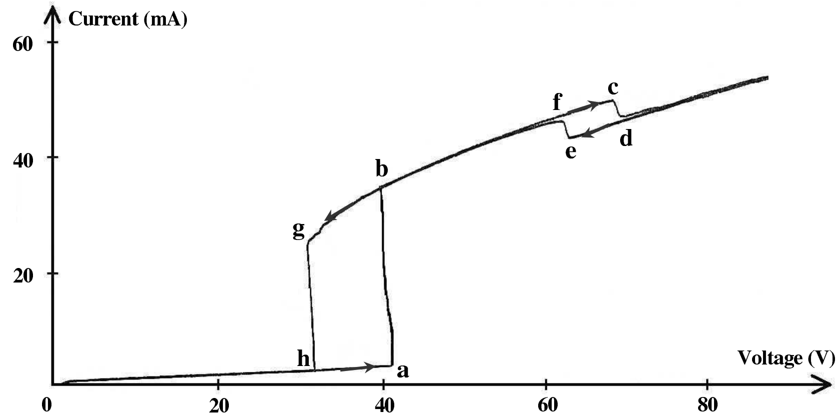

Fig. 2. Static I-V characteristic obtained in a DP-machine plasma.

When the voltage V is increased until the critical value, which corresponds to point **a** in the static characteristic (Fig. 2), the current I through the electrode jumps to a value corresponding to a new stable state (point **b** in the characteristic). After this jump, a quasi-spherical luminous CSCC, confined by an electrical **d**ouble **l**ayer (DL), appears in front of E. By increasing V between **b** and **c**, the CSCC remains in a relatively stable state. Fig. 3a and 3c show the current oscillations through the electrode and the **f**ast **F**ourier **t**ransform (FFT) of these, respectively, recorded in the neighbourhood of point **b**. We observe the occurrence of low-amplitude oscillations with a continuous low-frequency spectrum. To characterize these oscillations, we present the autocorrelation function (Fig. 3e) and the 3D Poincaré map through the reconstructed space (Fig. 3g), obtained by using the method of delays, proposed by Packard *et al.* [8], Ruelle [9] and Takens [10], extensively described in [11]. From these two figures we conclude that the oscillations are uncorrelated, giving rise to a low-dimensional chaotic state. By opening the switch K_1 (Fig. 1), we couple the capacitor C into the external circuit between the electrode E and the ground (see Fig. 1). In this way, oscillations appear in the external circuit [12], the period of which is determined by the charging and the discharging time constants of the capacitor. These are proportional to the capacitance C. The result is that the frequency of the oscillations is proportional to the inverse of the capacitance, experimentally proved in Fig. 4. Fig. 3b, 3d, 3f and 3h show the time series, the FFT, the autocorrelation function and the 3D Poincaré map through the reconstructed space, respectively, corresponding to these current oscillations.

By increasing the potential to the critical value corresponding to point **c** on the static characteristic (Fig. 2), the current through the electrode jumps to a value corresponding to an oscillatory

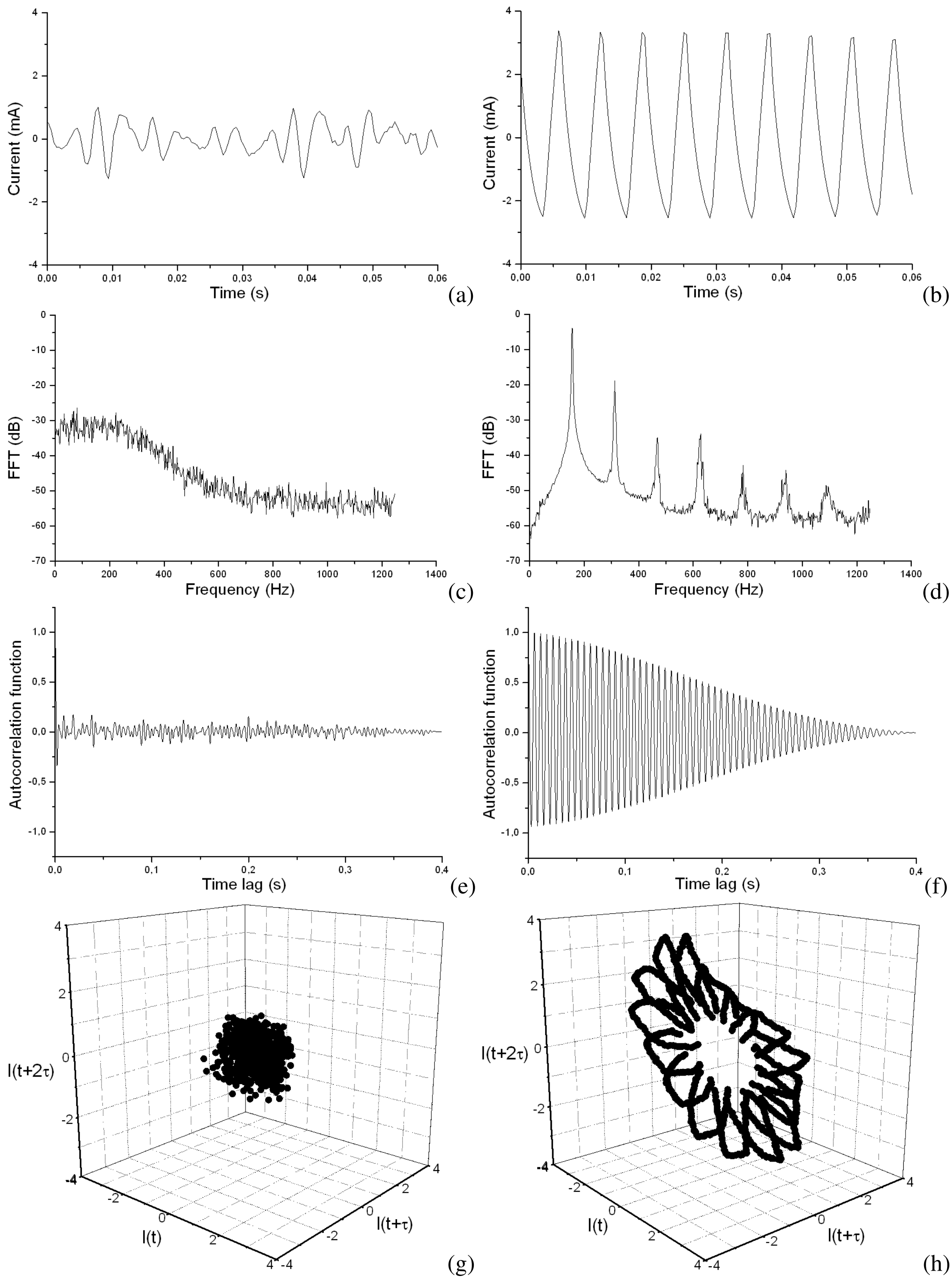

Fig. 3. The time series, the FFT, the autocorrelation function, and the 3D Poincaré map through the reconstructed space of the current oscillations, respectively, before (left column) and after (right column) the insertion of the capacitor (we find the delay time $\tau = 1.6$ ms).

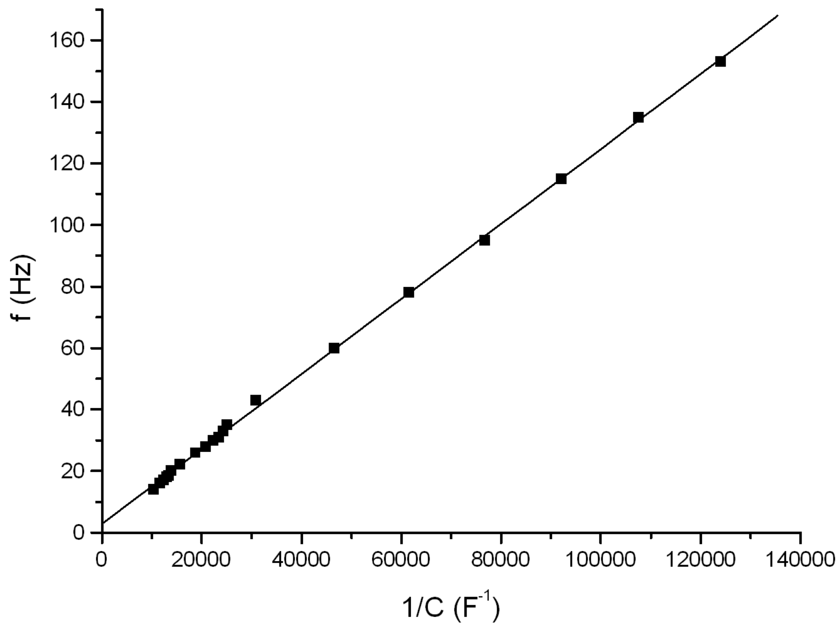

Fig. 4. The linear dependence between the oscillation frequency and the inverse of the capacitance.

state of the plasma system. This means that point **c** is a Hopf bifurcation point [13]. The current oscillations are presented in Fig. 5a, and the corresponding FFT in Fig. 5c. We observe the existence of many higher harmonics, thus the oscillations are strongly nonlinear. Fig. 5e and 5g show the autocorrelation function and the 3D Poincaré map through the reconstructed space, respectively. By opening the switch K_2 (Fig. 1) we introduce the inductance L into the external circuit in series with the electrode E and the power supply. The proper choice of L can lead to the transformation of nonlinear oscillations into harmonic ones. Figs. 5b, 5d, 5f and 5h show the current oscillations, the FFT, the autocorrelation function and the 3D Poincaré map through the reconstructed space, respectively, for the case when the inductance is inserted. We observe the disappearance of all higher harmonics from the spectrum, with the oscillations assuming a sinusoidal shape. The 3D Poincaré map through the reconstructed space has a perfect circular shape, which is characteristic for harmonic oscillations. The square of the oscillation frequency depends on the inverse of the inductance, according to the Thomson formula (Fig. 6).

3 Discussion

The $I - V$ characteristic of the plasma shows two regions of negative differential resistance, one of S-type and one of N-type. After the first jump of the current (**a** $\rightarrow$ **b** in Fig. 2) a CSCC is formed in front of the electrode E (Fig. 1) as a luminous quasispherical object, confined by an electrical DL. Because of the strong nonlinearity of this structure, the noise, which is permanently present in the system, can induce some uncorrelated oscillations of the current, corresponding

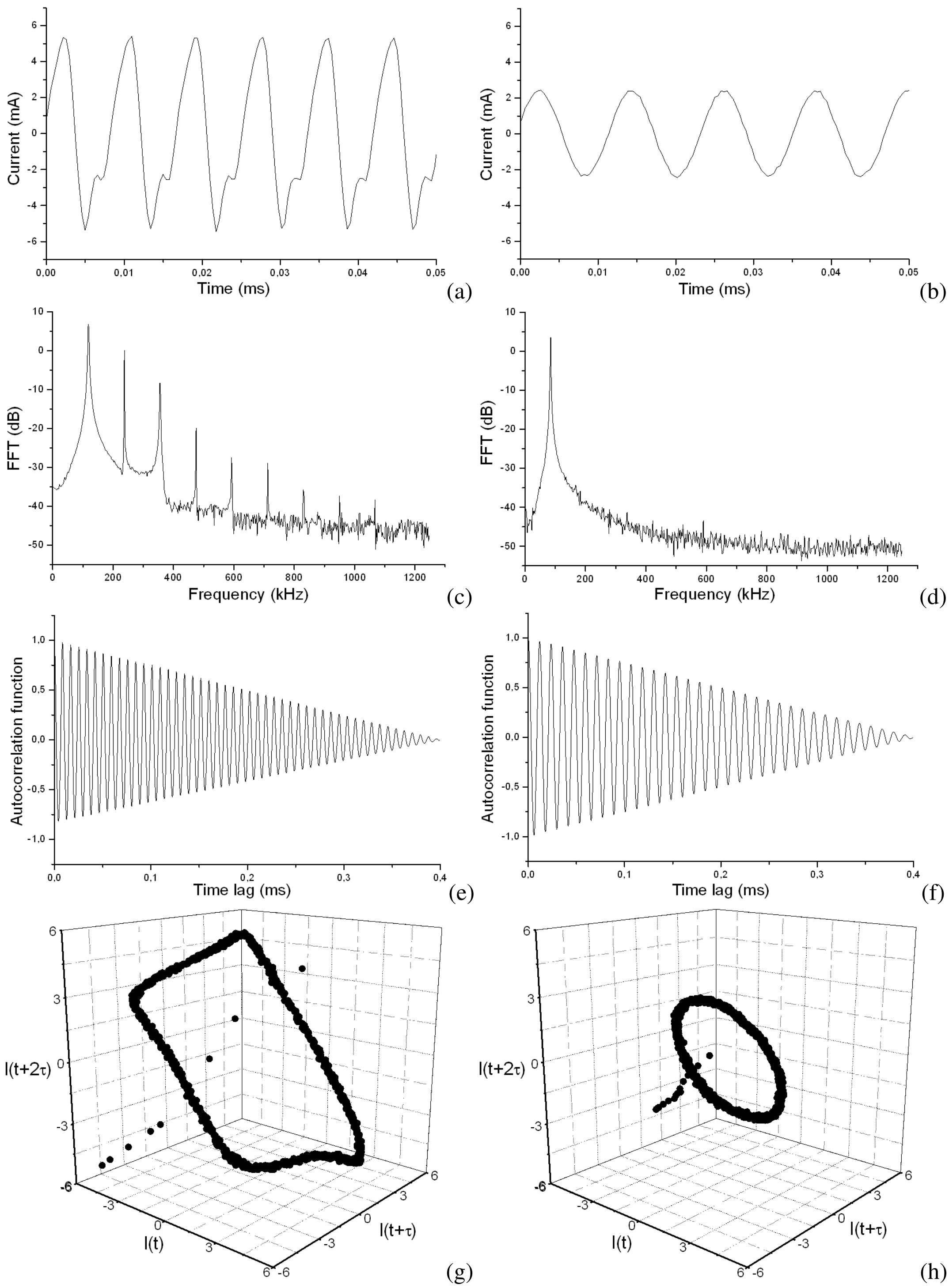

Fig. 5. The time series, the FFT, the autocorrelation function, and the 3D Poincaré map through the reconstructed space of the current oscillations, respectively, before (left column) and after (right column) the connection of the coil (we find the delay time $\tau = 2.4\ \mu$s).

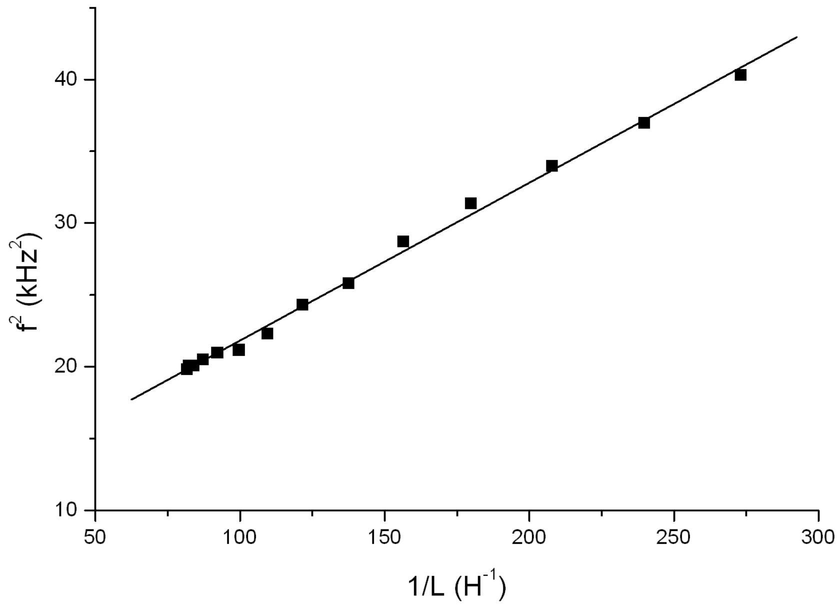

Fig. 6. The linear dependence between the square of the oscillation frequency and the inverse of the inductance (according to the Thomson formula).

to jumps of the structure between various unstable states, characterized by different electrical conductivities. For plasma applications this chaotic state is not desirable. If we can control the noise level in the system, we can minimize its amplitude and obtain a fairly stable state. But usually it is very difficult to control the noise level experimentally. A second alternative is to substitute these chaotic dynamics by a periodically one and to control these dynamics by controlling the frequency of the oscillations. This is the method, which we use. The periodically state is obtained by inserting a capacitor into the external electrical circuit (Fig. 1). The physical mechanism of these oscillations is described in [12]. The charging and the discharging time constants of the capacitor determine the frequency of the oscillations (Fig. 4). In this way we can control the dynamics of the CSCC by modifying the capacitance C. By using a suitable electronic filter, we can eliminate the effect of this periodical component from the recorded experimental signal.

In point **c** of the $I - V$ characteristic (Fig. 2) the plasma system undergoes a supercritical Hopf bifurcation. The resulting oscillatory behaviour corresponds to the transition of the DL into a propagating state, during which new DLs are successively regenerated and decaying [5,6]. The frequency of these oscillations is determined both by the values of external circuit elements and by the characteristics of the plasma (including the DL). The existence of many higher harmonics in the spectrum (Fig. 5c) proves the strong nonlinearity of the oscillations. These higher harmonics can be very advantageous in some applications, as e.g. high frequency generators. But in most of the applications it is preferable to generate harmonic (sinusoidal) oscillations. According to the Thomson formula, we can obtain harmonic oscillations by modifying the capacitance or the inductance either of plasma, or of the external electrical circuit elements (capacitors and coils). Our choice was to insert an inductance into the external electrical circuit and to find a suitable value of the inductance in such a way that the obtained current oscillations will be harmonic (Fig. 5b). In this case we obtain a resonance between the power source of oscillations (the dc power supply) and the oscillatory circuit (plasma together with the external electrical circuit elements).

4 Conclusion

We propose two simple, effective and low-cost methods to control the chaos in DP machine plasma. The first method permits the substitution of a chaotic state (uncorrelated low-frequency oscillations) by a periodically one, the frequency of which can be easily controlled. The second method eliminates all higher harmonics of a strongly nonlinear oscillation obtaining a harmonic (sinusoidal) one. For the both methods we need only passive circuit elements, namely capacitors and inductances.

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