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Analysis of tokamak plasma confinement modes using the fast Fourier transformation

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Abstract. The Fourier analysis is a satisfactory technique for detecting plasma confinement modes in tokamaks. The confinement mode of tokamak plasma was analysed using the fast Fourier transformation (FFT). For this purpose, we used the data of Mirnov coils that is one of the identifying tools in the IR-T1 tokamak, with and without external field (electric biasing), and then compared it with each other. After the Fourier analysis of Mirnov coil data, the diagram of power spectrum density was depicted in different angles of Mirnov coils in the 'presence of external field' as well as in the 'absence of external field'. The power spectrum density (PSD) interprets the manner of power distribution of a signal with frequency. In this article, the number of plasma modes and the safety factor q were obtained by using the mode number of $q = m/n$ (m is the mode number). The maximum MHD activity was obtained in 30–35 kHz frequency, using the density of the energy spectrum. In addition, the number of different modes across 0–35 ms time was compared with each other in the presence and absence of the external field.

Keywords. Tokamak; MHD power spectrum; fast Fourier transform.

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1. Introduction

The study of plasma behaviour as well as the MHD structure by tokamaks in plasma physics is interesting. Information such as the MHD activities, mode number, magnetic islands, and the instability of plasma can be found in it. Different diagnostics are used for studying plasma edge in tokamaks, and the Mirnov coils are one of the most prevalent diagnostics [1–10]. These coils (windings) have very simple design and the researcher can easily use it. They can record and register many of the applied programs in tokamaks in addition to the magnetic oscillations. The analysis of magnetic oscillations in Mirnov coils using the FFT method is an effective method to study the modes of tokamak plasma [11–20]. The 12-looped Mirnov coils (poloidally located at 30°) have been used in this article. After performing Fourier analysis on the information of Mirnov coils, the density of power spectrum was depicted in different angles in the presence and absence of the outer field, and then compared with each other. The number of plasma modes and the safety factor q were determined using the FFT method in the presence and absence of the outer field. The safety factor q plays a significant role in determining the stability of tokamak plasma and seems to be one of the important factor for transport theory [21–25]. In an axisymmetric equilibrium such as tokamak plasma each magnetic field line has a value of q. The field line follows a helical path as it goes around the torus on its associated magnetic surface. Knowledge of the q profile in a tokamak is fundamental for understanding the MHD properties of the plasma. The q might have been determined with magnetic measurement accuracy close to the plasma edge. Several methods such as the Farad revolving method and the ruby laser technology have been extended to determine q. The edge radial electric field is known to play an important role in the confinement of magnetized plasmas. Biasing experiments on tokamaks have been very successful in improving both the plasma energy and particle confinement parameters by setting up a radial electric field at the plasma edge. It is commonly accepted that improvement of both particle and energy confinement regimes can be induced in tokamaks by inserting electrically charged electrodes in the plasma edge region. The biased electrode drives a radial current between itself and the vacuum vessel and the resulting force generates sheared flows, which suppresses turbulence and related transport. Plasma turbulence is one of the main causes of anomalous transport in toroidal magnetic confinement devices. Edge charging experiments have been found to be important in modifying edge turbulence and transport, but the mechanism of charging penetration in edge fluctuations and its levels are different with respect to the operation of the devices. A velocity shear stabilization mechanism has been proposed to improve the plasma confinement. A clear correlation between the modifications of radial electric fields induced by bias and the reduction of turbulence has also been observed in several experiments. The control of the shear layer is therefore important to modify transport in tokamaks [26–33]. A study on time expansion of mode number, safety factor q in the presence and absence of the outer field as well as the maximum activity of MHD on the IR-T1 tokamak is presented in this article. IR-T1 tokamak is a small tokamak with large aspect ratio and circular cross-section (see table 1).

This article is organized as follows: The determination of the density of the power spectrum (PSD) using fast Fourier transformation is presented in §2, the number of tokamak plasma modes of IR-T1 tokamak and the safety factor q ($q = m/n$ (number of modes), in the presence and absence of biasing field are presented in §3. The summary and the conclusion is presented in §4. The electrode biasing system is presented in Appendix.

2. Determination of the power spectrum density based on FFT

Power spectrum density (PSD) determines the energy changes of a Mirnov signal as a function of frequency.

Table 1. Main parameters of the IR-T1 tokamak.

Parameter	Value
Major radius	45 cm
Minor radius	12.5 cm
Toroidal field	<1.0 T
Plasma current	<40 kA
Discharge duration	<35 ms
Electron density	0.7–1.5 $\times 10^{13}$ cm^{-3}

In other words, it shows the maximum MHD activity [4]. The calculation of PSD is directly accomplished by the FFT technique presented in the MATLAB software. PSD is an accurate and very useful tool to identify the oscillating signal in the series of time data. In addition, it explains how the energy or the power of a signal is distributed by means of a signal [6]. Therefore, in view of the above discussion, the PSD was obtained by the FFT analysis based on the oscillations of Mirnov coils poloidally in the arbitrary angles of 90, 210 and 330° in the presence and absence of the outer field. For this purpose, the winding or the Mirnov coil was used (in poloidal mode) as in figure 1 and the PSD of Mirnov oscillations for 90, 210 and 330° in the IR-T1 tokamak are shown in figure 2.

It was observed that the diagram of power spectrum density has regular trend of amplitude reduction by frequency, and the maximum MHD activity is between 30 and 35 kHz. It shows that the outer field does not bring any change in the signals' frequency and only decreases its amplitude. In addition, it seems the maximum activity of MHD is obtained by considering the peaks.

3. Determination of the number of plasma modes and safety factor

The tokamak plasma can support different modes. The surface of plasma can have different forms that are called the rose petals (m). The Mirnov coils record the current time series resulting from the rotation of dipole plasma. The pole-based diagram of magnetic field oscillations can be depicted by analysing the fast Fourier transformation (FFT) on the data of Mirnov

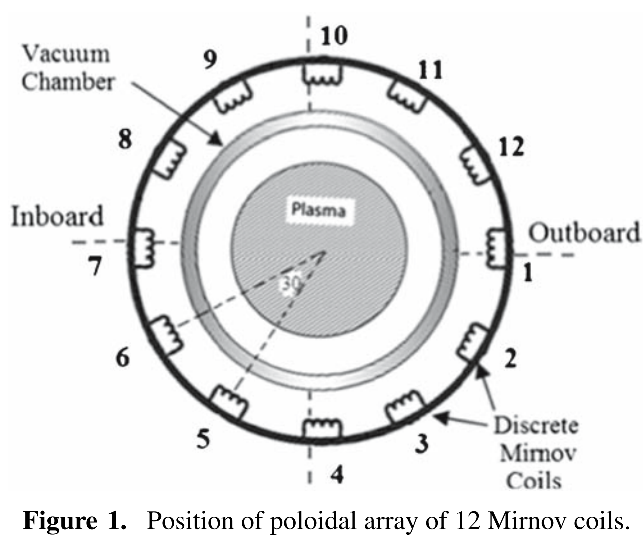

Figure 1. Position of poloidal array of 12 Mirnov coils.

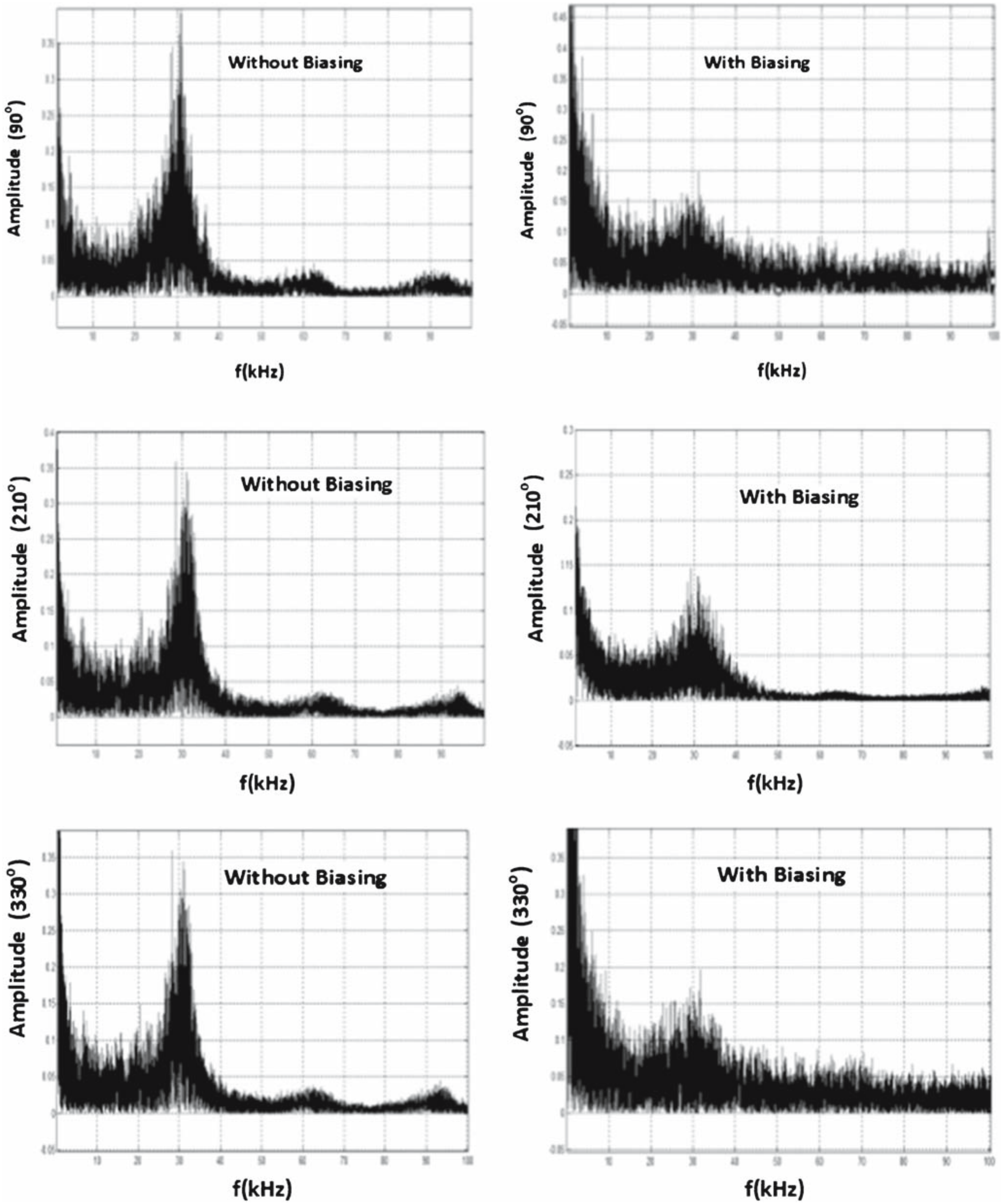

Figure 2. Power spectrum density of Mirnov oscillations for 90, 210 and 330° in the IR-T1 tokamak.

coils. In a pole-based diagram, the surface of plasma can be shown in different time intervals. The *m* mode numbers are determined in each time interval. In these diagrams, we indicate the surface of plasma in four time intervals with and without the outer field (see figure 3).

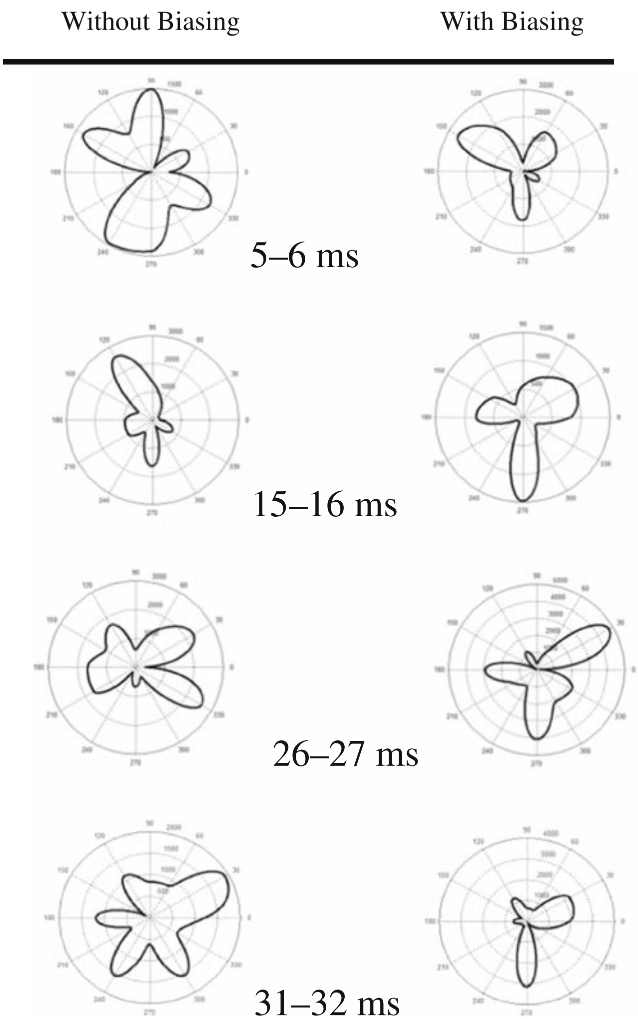

Figure 3. Polar diagram of the Mirnov oscillations for different time intervals with and without bias.

The first time interval 5–6 ms indicates that the mode number in the presence of the outer field (biasing) is $m = 4$ and without the outer field is $m = 5$, the second time interval is 15–16 ms, indicating that the mode number in the presence of the outer field is $m = 3$ and without the outer field is $m = 4$, the third time interval is 26–27 ms, indicating that the mode number in the presence of the outer field is $m = 5$ and without the outer field is $m = 5$, the fourth time interval is 31–32 ms, indicating that the mode number in the presence of the outer field is $m = 4$ and without the outer field is $m = 5$. According to the above discussion, we determined the safety coefficient q from mode numbers ($q = m/n$) during the time interval of 0–35 ms because this time interval is the discharging time duration in the IR-T1 tokamak. The toroidal mode number n is equal to 1 ($n = 1$) in the IR-T1 tokamak (large aspect ratio tokamak). The dotted diagram of q safety factor using

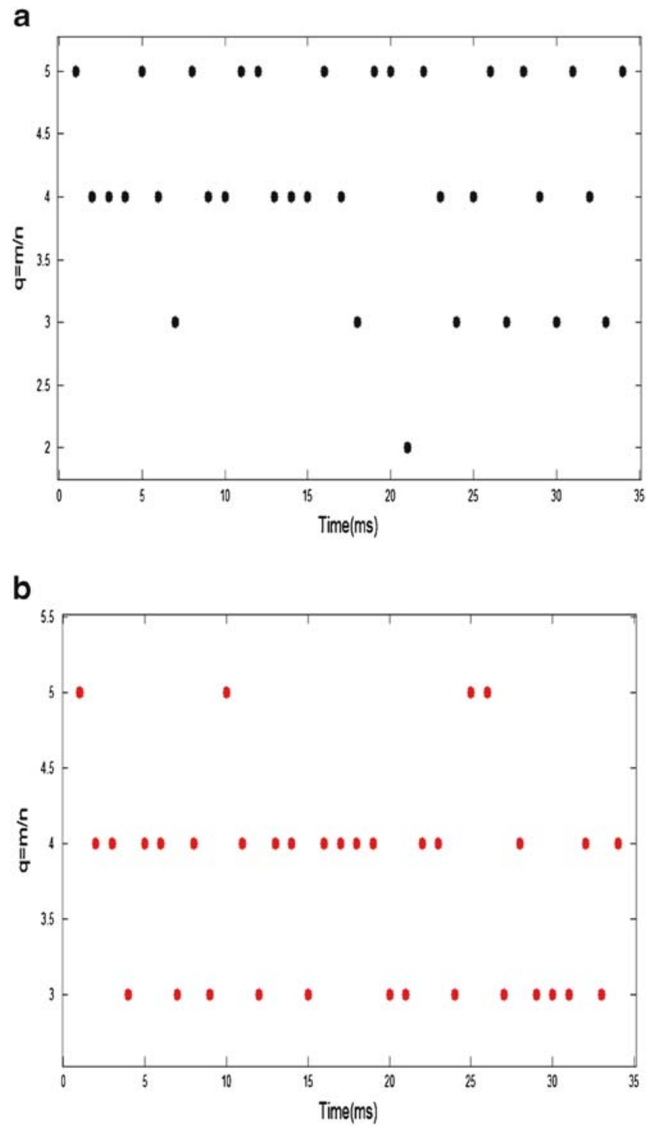

Figure 4. The dotted diagram of q safety factor using the mode numbers (**a**) without and (**b**) with bias.

the mode numbers with and without bias seen in figure 4 and table 2 gives the mode numbers with and without the outer field.

4. Summary and conclusion

The edge radial electric field is known to play an important role in the confinement of magnetized plasmas. Biasing experiments on tokamaks have been very successful in improving both the plasma energy and particle confinement parameters such as q by setting up a radial electric field at the plasma edge. It is commonly accepted that improvement of both particle and energy confinement regimes can be induced in tokamaks by electrically charging the electrodes inserted in

Table 2. The number of plasma modes in the presence and absence of the outer field.

	Mode number 2 between 0 and 35 ms	Mode number 3 between 0 and 35 ms	Mode number 4 between 0 and 35 ms	Mode number 5 between 0 and 35 ms	Modes average
With bias	0	13	17	4	3.73
Without bias	1	6	14	13	4.14

the plasma edge region. The biased electrode drives a radial current between itself and the vacuum vessel and the resulting force originates sheared flows, which have a suppressing effect on turbulence and related transport. Plasma turbulence is one of the main causes of anomalous transport in toroidal magnetic confinement devices. Edge charging experiments have been found to be important in modifying edge turbulence and transport, but the mechanism of charging penetration in edge fluctuations and its levels are different with respect to the operation of the device. A velocity shear stabilization mechanism has been proposed to be responsible for an improvement in plasma confinement. A clear correlation between the modifications of radial electric fields induced by bias and the reduction of turbulence has also been observed in several experiments. The control of the shear layer is therefore an important tool to modify transport in tokamaks. The confinement mode of the tokamak plasma was analysed using the FFT with and without biasing. The results can be summarized as follows:

(1) In this article, the maximum MHD activity was obtained using the FFT technique and the density of power spectrum in 30–35 kHz frequency. It was observed that as per the results, the outer field (bias) does not cause any change in the frequency of signals and only causes the decrease of their amplitude.
(2) In the studies carried out on the plasma mode using the pole-based diagrams, the Mirnov oscillations were observed with and without the outer field and it is seen that the modes were decreased in the presence of the outer field during the desired times and the whole times; it can be said that the limiter bias plays an important role in the stability of IR-T1 tokamak.
(3) The values of safety factor obtained by the mode numbers are $2 \leq q \leq 5$ that was observed by comparing the safety coefficient in the presence of outer field (biasing) and in the absence of outer field. The mode numbers in the presence of outer field is less in comparison with the mode without it, during similar time intervals, indicating more stability of plasma.

Appendix

Design, construction and experimental set-up of the electrode biasing system

IR-T1 tokamak is a low beta, large aspect ratio, and circular cross-section tokamak (see table 1), which has two stainless steel grounded fully poloidal limiters with a radius of 12.5 cm. In the experiments described, the position of the biased electrode has been varied between 11.5 and 12.5 cm, and the bias is applied between the electrode and the grounded vessel. The electrode consists of a stainless steel circular head, 2 mm in radial direction (width) and 2 cm in poloidal direction (diameter). It is inserted approximately 1 cm past the fixed poloidal

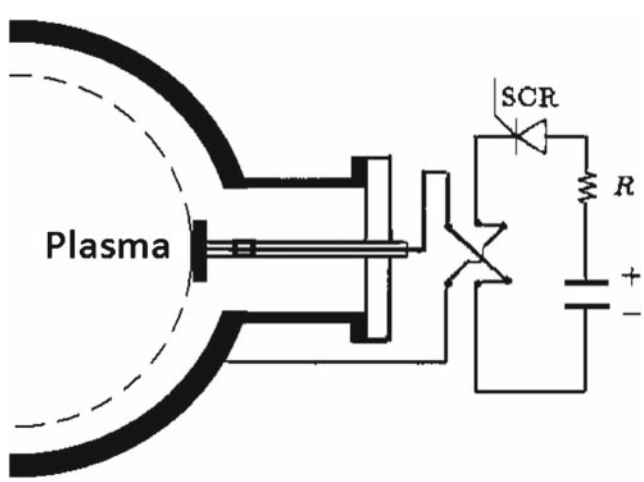

Figure 5. Schematic drawing of the electrode biasing system in IR-T1 tokamak.

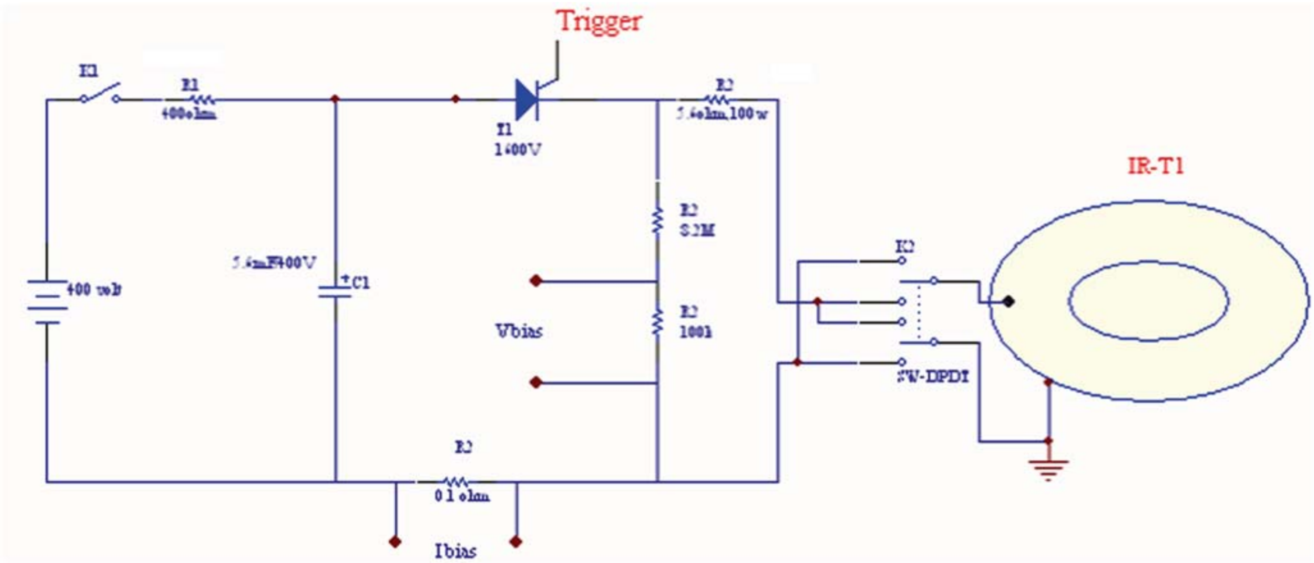

Figure 6. Electric circuit of the electrode biasing system used in IR-T1 tokamak.

limiter into the plasma through the low field side of the tokamak as shown in figure 5. Also the electric circuit of the electrode biasing system used in IR-T1 tokamak is shown in figure 6. A capacitor bank biases the electrode positive or negative with respect to the grounded wall. The applied electrode voltage V_{bias} is in the range -400 to $+400$ V, and the bias current I_{bias} is in the range -40 to $+40$ A. Biasing experiments were performed in a regime with ohmic heating.

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