Study of the Operational Characteristics of Self-excited Push–Pull Vacuum Tube Oscillator for R.F. Ion Sources

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ABSTRACT—In the present work, we report the construction and analysis of a very simple radio-frequency (RF) generator suitable for use in ion sources. It is a self-excited push-pull RF oscillator constructed using 829B or GI30 twin beam-power tetrode valve. As RF oscillator is one of the most frequently skip part in the descriptions of RF ion sources in literatures, we conducted systematic study on the working of the oscillator to understand its operational characteristics. The oscillation conditions, stability in frequency and variation of RF output power with plate voltage are investigated to understand its operational characteristics. A modified form of photometric is employed to measure the RF output power of the oscillator. At 102 MHz and 900V plate voltage, the power delivered to the load is measured to be 79 watts which is 19 watts higher than the value reported earlier in literature for similar circuit configuration.

Keywords: RF Oscillator, Self-excited Push Pull Oscillator, Twin Beam Power Tetrode, Operating Conditions, Power Measurement, Photometric Method

INTRODUCTION

The use of RF voltage to create plasma in ion sources dates back to the late 1940s [1,2]. Ion sources have widespread applications in industrial plasmas [3], neutral-beam injection (NBI) systems for fusion devices [4], bio-medical sciences [5], particle accelerators [6], and mass-spectrometry [7]. In an RF driven ion source, the high frequency electric field accelerates free electrons to energies that are high enough to ionize atoms or molecules with which they collide. The density of the plasma thus created depends on the RF signal frequency and power, and plays crucial role in the performance of the ion source [8,9]. Numerous works have been reported in literature on the design and construction of RF ion sources [6,9]. However, these studies are mainly devoted to the extraction and different characteristics of plasma, and little attention has been paid towards RF oscillator.

Among the various design available, vacuum tube self-excited push-pull oscillator is one of the most commonly used RF signal generator in radio frequency (RF) driven plasma source. Even though there are now more efficient semi-conductor based RF power sources, vacuum tube oscillator, especially self-excited push-pull RF generator continues to occupy important place in the design and construction of RF ion sources due to its circuit simplicity, robustness, compactness and ease of maintenance. As electron tubes are high voltage devices and have operating conditions different from that of semiconductor devices, proper understanding of the performance of such device is important for their application in ion sources. Therefore, in the present work, we have constructed self-excited push-pull oscillator using twin beam-power tetrode for operation at around 100 MHz and study the different operational characteristics of the oscillator.

MATERIAL AND METHODS

Circuit Description

Schematic circuit diagram of an RF oscillator used in this study is shown in Fig. 1. The oscillator is based on the

http://doi.org/10.22232/stj.2016.04.01.09
design reported by Moak et al. [10]. The amplifying stage of the oscillator is a twin beam-power tetrode connected in push-pull arrangement with capacitive coupling to the control grid. The grid leak resistors $R_1$ and $R_2$ together with coupling capacitors $C_{g1}$ and $C_{g2}$ provide the necessary biasing to the grid. The LC frequency selector, also called RF coil or tank circuit, is made of copper tubing wound into two turns of coil. The parasitic or stray capacitance between the windings serves as the capacitive part of the LC tank circuit. The inductance and other parameter of the tank coil are calculated using a web-based calculator [11] employing current-sheet coil geometrical formula that is corrected for field non-uniformity and round wire [12,13].

In Fig. 1, $L_1$, $L_2$, C are the RF chokes and capacitor to prevent the dc source from RF signal interference. Resistor $R_1$ provides the necessary biasing voltage to the screen grid and it has to be of high wattage resistor not less than 20W. Low wattage below 15W results in excessive heating of the screen grid resistor, and thus changing the resistance value and operating point of the tube.

![Circuit Diagram of RF Oscillator](image1)

Fig. 1: Circuit Diagram of RF Oscillator. Q = 829B/G130 Twin Beam-Power Tetrode; RF Coil: Tube Diameter = 0.6 cm, pitch = 1 cm, coil diameter = 7 cm; $R_1 = 20$ k$\Omega$, 20 W; $R_2 = R_4 = 6.8$ k$\Omega$, 1 W; $C_{g1} = C_{g2} = 1$ pF, 1 k$\Omega$; C = 50 $\mu$F, $L_1 = 586$ $\mu$H; $L_2 = 589.5$ $\mu$H.

DC power supply for the tube is obtained from a full-wave rectifier with centre-tapped 230V to 1kV step-up transformer and RC filtering circuit as shown in Fig. 2. Separate ac supply of proper voltage is employed to heat the filament. The applied plate voltage of the tube can be varied using a Variac (0-270 V) connected at the input of the step-up transformer.

The oscillator is naturally air cooled during operation and the frequency of the RF signal is directly measured with frequency counter FC 2400. Standard digital multimeters were used measured voltage and current.

**PHOTOMETRIC METHOD OF RF POWER MEASUREMENT**

To measure the RF output power, a modified form of photometric method is employed. The method is based on the ability of incandescent lamp to convert RF power into light that is then measured with a photometer [14,15]. The modification made in the present setup is the application of LDR as light sensor to improve the sensitivity and precision level of the measurement method. LDR is semiconductor device whose resistance decreases with the intensity of light incident on it. However, the dependence of LDR resistance on light intensity is not linear and varies as $bl^{-a}$ [16], where $L$ is the incident power per unit area, $a$ and $b$ being constants that depend on the material and shape of the resistor.

The experimental setup for RF power measurement is shown in Fig. 3. The setup consists of an ordinary 100 Watt, 230 V light bulb 'B' directly coupled to the RF tank coil using two parallel open wires of length 50 cm. Light emitted by the incandescent lamp is detected with a cadmium sulphide LDR (light-dependent resistor) photometer. For all measurements, LDR is kept at distance of 5 cm from the center of the bulb and $V_{LDR}$ is fixed at 7 V. To achieve impedance matching between the source and the load, the positions of the two output tapping points in the RF coil are adjusted till maximum LDR current reading is indicated by the ammeter. With 100 watt light bulb load, impedance matching is observed at 1/3$^\text{rd}$ of the coil center tapped point.

![Circuit Diagram of 1 kV DC Power Supply](image2)

Fig. 2: Circuit Diagram of 1 kV DC Power Supply. T = 100 VA Step-Up Transformer; D = IN 4007, 700 V (PIV); C = 330 $\mu$F, 450 V; R = 1.18 $\Omega$.

![Experimental Setup for RF Power Measurement](image3)

Fig. 3: Experimental Setup for RF Power Measurement
The LDR current reading at different light intensity is then calibrated using standard ac source of 50 Hz. In the calibration method, the transmitter is replaced by a variable standard ac source and the brightness of the bulb is adjusted to give LDR current reading equal to that recorded with RF power. After brightness adjustment is done, the value of ac power calculated from $P=VI$ is then just equal to the RF power absorbed by the filament.

All power measurements were conducted in a dark room to avoid interference from background light. Each measurement was repeated at least three times to check the consistency in our results and the maximum uncertainty in power measurement is calculated to be about 2%. Moreover, all measurements were conducted after the copper tank coil was first polished with sander paper to avoid the effect of tank coil oxidation.

RESULTS AND DISCUSSION

Operating Conditions

Fig. 1 shows the circuit diagram of RF oscillator using twin beam-power tetrode 829B. The oscillator is basically a push-pull Hartley oscillator employing grid-leak biasing method. It has the operating frequency of 102 MHz, which corresponds to the fundamental frequency as all the even harmonics are cancelled out in push-pull configuration. The oscillation frequency of the oscillator is primarily determined by the resonance frequency of the RF coil forming LC tank circuit and is given by

$$f = \frac{1}{2\pi\sqrt{LC}},$$  \hspace{1cm} (1)

At 102 MHz calculation using current-sheet coil geometrical formula [11] gives $L = 0.36 \ \mu$H and $C = 2.46 \ \mu$F, where $C$ is the stray capacitance of the coil. Therefore the self-resonance frequency of the tank coil according to Eq. (1) is 169 MHz. But this is far above the observed frequency of oscillation. To get oscillation at 102 MHz with $L = 0.36 \ \mu$H, the value of $C$ has to be 6.76 pF. The 4.3pF difference in capacitance is very close to the inter-electrode capacitance of the tube, which is 4.4 pF according to calculation from the tube data sheet [17]. This observation suggests that contribution from the inter-electrode capacitance should not be neglected while designing an RF coil to obtain operating frequency of desired value.

The values of $R_g$ and $C_g$ in the grid leak network determine the control grid bias voltage and hence the operating point of the tube. The amount of bias voltage depends on the amplitude, frequency of the signal and grid leak time constant [18]. In high power RF oscillator, the RC time constant has to be kept at low value relative to the cycle time of the signal [19]. In our case, the grid leak time constant is 6.8 ns which is about one-half cycle of the operating frequency. When the value of grid leak resistor is changed from 6.8 kΩ to 22 kΩ, the observed frequency decreased by about 47 MHz. The decrease in frequency is due to occurrence of intermittent oscillation caused by large value of $R_g$. At high value of $R_g$, and hence RC time, the bias voltage developed is too large that oscillation stops, and restarts after the capacitor has discharged through $R_g$ till proper grid biasing voltage is reached again [17]. Intermittent oscillation has frequency lower than the operating frequency.

Frequency and power stability are other important characteristics to consider in the operation of the oscillator. In the present oscillator, the operating frequency is found to decrease by about 1% as a result of loading, as well as tank coil oxidation. Tank coil oxidation is the formation of copper oxide layer on the surface of the RF coil. It increases the effective dielectric constant between the coil windings constituting the capacitive part of the tank circuit. Since the tank circuit determines the frequency of oscillation, any variation in the conditions of the external circuit will be coupled back into the frequency determining portion of the oscillator. These variations result in the above observed frequency instability. Tank coil oxidation is also found to reduce the output power by about 10%. This is due to the higher electrical resistance of copper oxide layer leading to lower Q value of the coil. The efficiency of the oscillator including power supply unit is also measured and found to be 37%.

RF OUTPUT POWER

LDR has spectral response almost similar to human eye and the low temperature coefficient. According to our measurement, the change in LDR current per degree Celsius is only about 0.02 mA. But incandescent light bulb wasted most part of the input energy in the form of heat and only less than 5% is converted into visible light. Therefore, RF power converted into heat will not be detected by LDR. However, the calibration method eliminates all the needs to consider the undetected part of the RF power dissipated in the filament except light.

Fig. 4 shows the plot of RF output power at different plate voltages using 829B and its equivalent, GI30. It can be seen that both tubes have almost the same performance within their respective operating conditions. As the plate
voltage increases the RF output power also increases accordingly and no saturation is seen within the range of measurement. However, the variation of output power with plate voltage is not linear and can be best described by a quadratic function. The nature of the power can be attributed to the characteristic of LDR response towards the intensity of light. The RF power directly indicated by the present measurement technique is 79 ± 2% watts at 900V. This is much higher than the value reported by Moak et al. [10], which is 60 watts for the same circuit configuration and plate voltage. However, the method or device used by Moak for power measurement was not shown in the report. Even then, we can say from our result that the modified technique is more sensitive than their, which could only be attributed to the introduction on LDR detector.

**CONCLUSION**

In the present work, a self-excited push pull RF oscillator is constructed using 829B vacuum tube. The oscillator has operating frequency of 102 MHz and is quite stable with respect to loading, tank coil oxidation and changes of vacuum tubes of equivalent types. However, copper oxide layer formation on RF coil surface could result in a decrease of RF output power as much as 10%. The variation of RF output power with plate voltage is non-linear characteristic of LDR response. The RF power measured using our modified technique is about 79 watts that is 19 watts higher than the value reported earlier in literature for similar circuit configuration. The difference is attributed to the increase in sensitivity due to the introduction of LDR detector in the modified techniques.

**REFERENCES**


