

VACUUM STUDY OF ELECTROSTATIC DISCHARGE BASED RF PULSE GENERATOR

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Abstract: We investigated the effects of the package vacuum level on the performance of ^{63}Ni powered electrostatic discharge based RF pulse power generator. A vacuum packaged ^{63}Ni -powered self-reciprocating cantilever RF discharge system, designed to transmit at 306.5 MHz. The RF pulses were generated and transmitted over a very wide chamber pressure range from 8.7×10^{-7} mBar to 2×10^{-3} mBar. The output power, reciprocation period, and output frequency did not change over the vacuum pressure level range. To further understand the system, the emitted radioisotope current is also measured as a function of vacuum level, showing sharp increase in leakage at high pressures. The demonstration of power output at pressures in the milli-Torr range indicates that existing MEMS packages with log-term stable vacuum levels can be used with the self-reciprocating cantilever. With the high power density and long lifetime of the ^{63}Ni source, and wide vacuum operating regime, the RF power generator can revolutionize long term reliable sensor monitoring.

Keywords: Radioisotope, ^{63}Ni , power generation, vacuum

INTRODUCTION

An autonomous sensor system needs a miniature power source with a long in-use and shelf lifetime. For sensor networks working in harsh, inaccessible environments, battery replacement can be difficult or impossible, and expensive. While traditional power sources, such as chemical batteries, can only work up to several years without replacement, radioactive isotope power sources can work on time scale of the half-life which can be 100s of years. For example, ^{63}Ni power sources have a high energy density ($\sim 10^5 \text{kJ/m}^3$) and long half-life (100.2 years). ^{63}Ni emits β -particles with an average kinetic energy $E_{avg}=17.3\text{keV}$, and a penetration depth of less than $10\mu\text{m}$ in most solids. As a result, devices powered by ^{63}Ni thin-films can be deployed safely with millimeter or microscale shields. The emission of radioisotopes is mostly unaffected by the temperature. Hence, a sensor node using radioisotopes could operate from cryogenic to very high temperatures, enabling operation in harsh environments.

The power requirements for a typical low-power wireless sensor node are 1-10 nW for retaining the memory state, 0.1-1 mW for periodic sensing and processing, and 1-100 mW power for periodic wireless communication [1]. The power to retain memory states can be provided by betavoltaics as reported in [2] even with the low activity radioactive thin films presented here. However, the nanoWatt range power from the radioisotope film is insufficient for computation and transmission. MEMS radioisotope-powered piezoelectric power generators [3] can generate the output power needed for periodic sensing and processing using even small amounts of radioactivity. ^{63}Ni radioisotope actuated reciprocating piezoelectric [4] metal, and silicon cantilevers [5] [6] have been previously reported by our group to

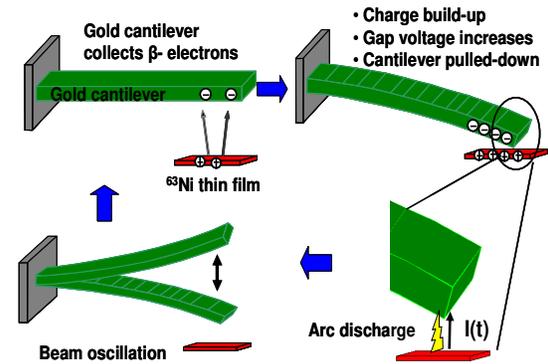


Figure 1. Schematic illustrating the radioisotope actuated reciprocation of metal cantilevers.

generate RF pulses in vacuum potentially for 100 years. However, realistically, the life time of device is only as long as its vacuum packaging retains vacuum. While it is important to have high quality vacuum packaging that would last for decades, it is equally important to make sure the device can function under a wide range of vacuum conditions, and tolerate as high a vacuum level as possible. In this paper, we studied the performance of the RF power generator at a wide range of vacuum conditions to establish the foundation for vacuum packaging to achieve long lifetime RF transmitters.

PRINCIPLE OF OPERATION

As illustrated in Figure 1, a gold cantilever ($5\text{cm} \times 6.5\text{mm} \times 300\mu\text{m}$) is placed $250\mu\text{m}$ above a ^{63}Ni radioactive thin film ($1\text{cm} \times 1\text{cm}$) with a 1.5 mCi activity. Positive charges are accumulated on an electrically isolated ^{63}Ni thin film due to the continuous emission of β -particles (electrons), which are collected on the gold cantilever. The accumulated charge increases with time, increasing the

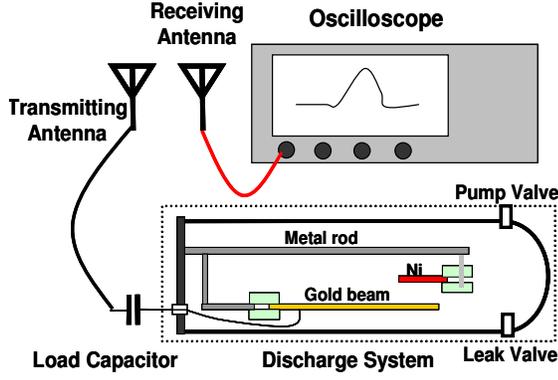


Figure 2. Schematic illustrating the testing setup for the discharge system with 47pF load capacitor connected.

electrostatic force pulls the cantilever towards the radioisotope thin-film emitter. When the gap between

the cantilever and radioactive source is small enough, electrostatic discharge occurs through the gap. As the electrostatic force is eliminated, the spring force pulls the beam and leads to a beam mechanical oscillation. The cantilever motion and discharge process repeats itself every few minutes, and in the device implemented in this study, the reciprocation period was minutes.

As the cantilever approaches the source, the electrostatic discharge induced current results in a current pulse with very short time duration of less than 1ns. The electrical energy stored in the capacitor, integrated over the reciprocation period, is released in a very short greatly amplifying the power from the radioactive source. Even though the radioisotope emitted power is ~70 nanowatts, from a regulatory safe amount of ^{63}Ni , hundreds of microwatts of transmitted power is generated. Since the half-life of ^{63}Ni is 100 years, this RF transmitter can work autonomously for several decades, or even a century.

When electrostatic discharge occurs, it is accompanied by two phenomena: the injection of discharge current and the radiation of electromagnetic pulses generated due to abrupt current change [7][8]. The discharge current can be derived from the equivalent arc resistance, reported by Rompe and Weizel [7]. Assuming the channel conductivity is proportional to the dissipated ohmic energy, the arc resistance can be shown to be

$$R(t) = \frac{d}{\sqrt{2a \int_0^t i(\xi)^2 d\xi}} \quad (1)$$

where R is the arc resistance, d is the arc length, a is empirical constant, and, i is the current. Assuming the discharge current is a single shot impulse current, the current maximum amplitude can be expressed as

$$I_{max} = \frac{C_0 V_s a (V_s/l)^2}{3\sqrt{3}} \quad (2)$$

where C_0 is gap capacitance before discharge, V_s is the spark voltage, and l is the spark gap length. The nominal discharge period can be written as

$$\tau = \frac{3\sqrt{3}}{a(V_s/l)^2} \quad (3)$$

As shown in Equation (2) and (3), the maximum current is proportional to the discharge voltage, gap capacitance, and the square of the gap breakdown field, while the nominal period is solely determined by the breakdown field.

The current pulse generates a magnetic field in the far-field zone which can be derived as

$$H(t) \approx \frac{\rho}{R} \frac{l}{2\pi} \frac{1}{cR} \frac{\partial i(t - R/c)}{\partial t} \quad (4)$$

where R is the distance from the discharge point to the observation point (ρ, ϕ, z), and c is the speed of light. The electromagnetic wave transmits wirelessly with its frequency determined by the discharge period. This pulse developed from this current pulse if wide-bandwidth single pulse, and is difficult to control. However, the wide-bandwidth discharge current pulse can be coupled into and modulated by various passive LC components to generate desired RF signal output (Figure 2), in the form of a load capacitor at the discharge cantilever. The output RF signal of the system is determined by the total parasitic and load capacitance.

To characterize the discharge system as a function of vacuum, a 47pF load capacitor connected to the system and an antenna to transmit the signal, which is detected wirelessly with another antenna and recorded with a real time oscilloscope. The chamber is first pumped down to 8.7×10^{-7} mBar, and then the pressure is slowly increased with a leak valve while taking measurements. The vacuum pressure levels rises with a rate of from

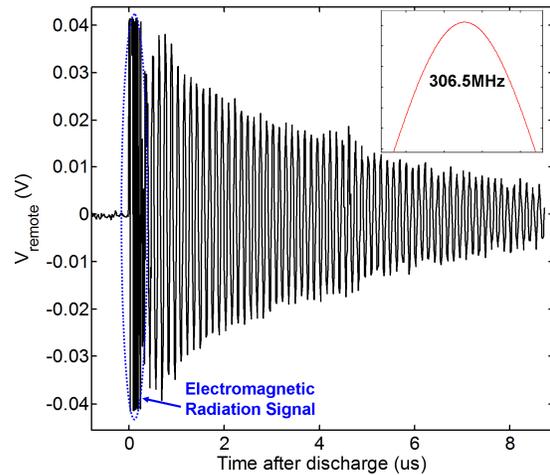


Figure 3. Experimental RF signal output of the discharge system with short electromagnetic radiation signal and pulse current induced LC signal at 306.5MHz

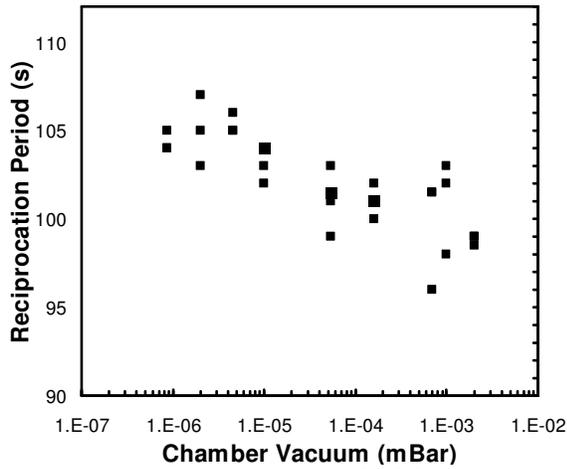


Figure 4. Reciprocation period of the system at different vacuum levels. Multiple data points are recorded at each vacuum level.

10^{-5} mBar/hour to 10^{-2} mBar/hour controlled by the leak valve.

EXPERIMENTAL RESULTS

The RF signal detected wirelessly at 8.7×10^{-7} mBar is shown in Figure 3, with $10 \mu\text{s}$ duration and frequency of 306.5 MHz. The reciprocation period of the system is 104 seconds. A signal component with much higher frequency is also detected at the beginning, which is the electromagnetic radiation signal corresponding to the original current pulse. As the vacuum level slowly increases inside the discharge chamber, the discharge time and output wireless RF signal is recorded and analyzed. As shown in Figure 4, the discharge time stays almost constant at 104 seconds from 8.7×10^{-7} mBar to 2×10^{-3} mBar. The frequency of the output RF signal also remains constant at 306.5 MHz (Figure 5). At pressure level of 2.2×10^{-3} mBar, the system abruptly stops reciprocating.

To understand the independence of discharge signal with vacuum level, the discharge process can be divided into the cantilever pull-down process, and

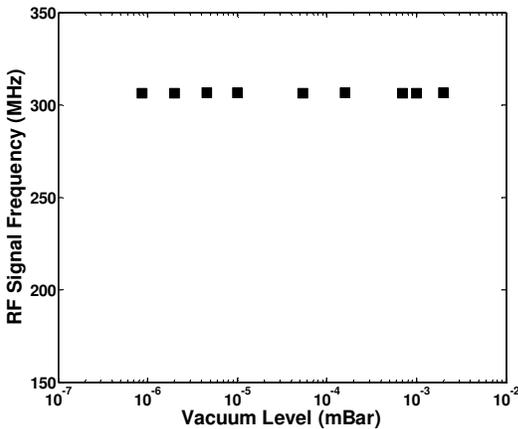


Figure 5. Frequency of the RF signal at different vacuum levels.

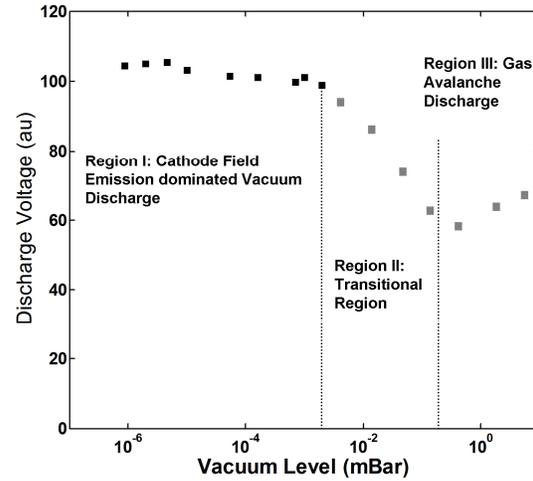


Figure 6. Schematic illustrating the discharge mechanisms of the vacuum breakdown at different vacuum levels [9].

the electrostatic discharge process. With vacuum level higher than 10^{-3} mBar, there are not enough gas molecules in the gap to be ionized. The reciprocation time, which is determined the cantilever stiffness, gap size, and the net radioisotope current, stay the same as long as sufficient voltage can be built across the capacitor. In the electrostatic discharge process, at high vacuum, due to the lack of gas molecules across the gap, the discharge is dominated by cathode surface field emission [9], which is independent of the pressure. However, as the pressure increases to above 2×10^{-3} mBar, the gas avalanche discharge becomes dominant [10], which increases the average leakage current across the gap (Figure 6). At sufficiently high leakage current, the self-reciprocation ceases due to insufficient voltage built-up across the gap to pull the cantilever.

EMITTED CURRENT VERSUS VACUUM

To experimentally verify the vacuum discharge theory mentioned in the last section, a high

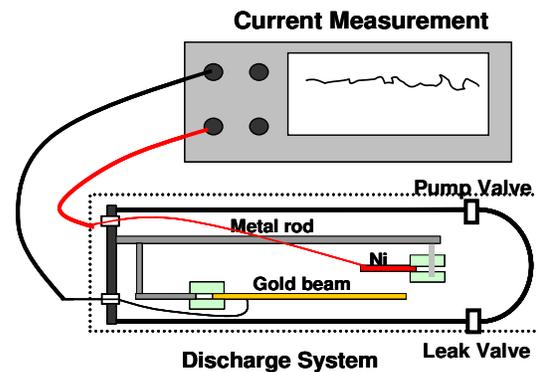


Figure 7. Schematic illustrating the testing setup for the emitted current measurement with a high impedance current meter

impedance current meter (Keithley 2400) is connected across the gap to measure the radiated emitted current as a function of vacuum (Figure 7).

With a net 1.5mCi activity for the film used, the current emitted from the source is 8.8pA. Gas atoms in the gap can be ionized creating electron-ion pairs. Generally the ions and electrons recombine. In addition, the primary electrons generate a number of secondary electrons that can ionize gas atoms, and also recombine them. When measured across a zero bias capacitor, the ion recombination leads to increased current across the capacitor. The current measurement (Figure 9) confirms the reciprocation period pressure dependence (Figure 6). The emitted current stays constant below 1×10^{-4} mBar. From 1×10^{-4} mBar to 2×10^{-3} mBar, the current has a weak pressure dependence described by $I(p) = I_0 - A \times \log(p/p_0)$, where I_0 is -8.725 pA, p_0 is 1×10^{-4} mBar, and A equals to 1.275×10^{-12} . Above the threshold pressure of $\gg 2 \times 10^{-2}$ mBar, a rapid rise in current is detected.

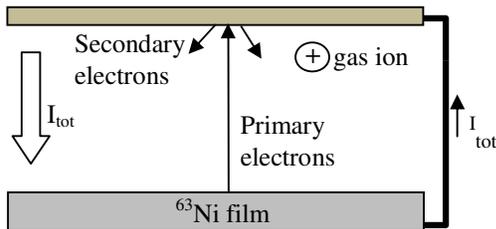


Figure 8. Higher gas pressure leads to increased ion production.

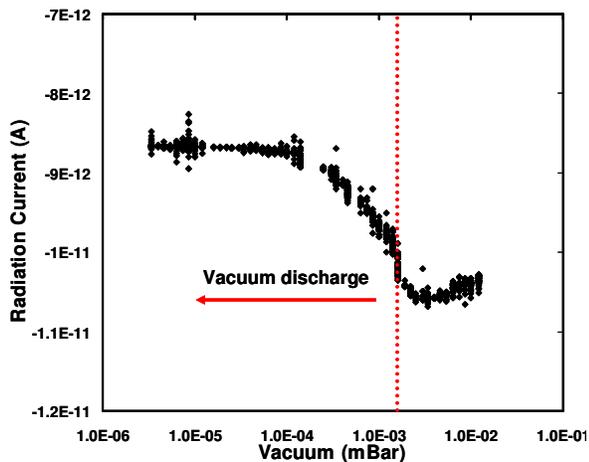


Figure 9. Experimental measurement of ^{63}Ni emitted current at under different vacuum condition with a 1.5mCi source

CONCLUSIONS

In this paper, we studied the performance of ^{63}Ni powered electrostatic discharge based RF pulse power generator under different vacuum conditions. The system is found to work at a pressure as high as 2×10^{-3} mBar without loss of performance. The radioisotope current is investigated with respect to

vacuum level in the chamber, which confirms the existence the vacuum discharge at pressure below 2×10^{-3} mBar. The demonstration of RF pulse power generation at pressures in the milli-Torr range shows that existing MEMS packages with log-term stable vacuum levels can be used with microfabricated the self-reciprocating cantilever. We can achieve an integrated discharge system in less than 1cc volume. Since the half life of ^{63}Ni is 100 years, the integrated transponder can work autonomously for decades, which can revolutionize long term reliable sensing and monitoring. Such devices can be buried deep inside structural constructs such as steel and concrete, where changing batteries, and harvesting vibrational or EM energy is not reliable.

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