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Parametric Study of the Reltron Oscillators

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ABSTRACT

In this paper, effect of the input DC electrical parameters, such as, pulse shape, cathode voltage and the post-acceleration voltage on the performance of reltron oscillator have been investigated. For this purpose, a typical reltron oscillator has been designed and simulated. The mode of excitation, resonant frequency and electric field patterns in the RF modulation cavity of the reltron structure has been studied through electromagnetic simulation. The RF output performance and effect of DC electric pulse shape is studied through 3D PIC simulation. To get a practical insight of the excitation signal effect on the performance of device operation, various pulse shapes with different rise, hold and fall time have been studied the pulse of hold time 70 ns and rise and fall time of 5 ns gives maximum stable RF power. Device parametric analysis for the different cathode and post-acceleration voltages has also been investigated. With a beam current of 750 A, cathode voltage of 200 kV and post-acceleration voltage of 800 kV, the device provides ~350 MW with ~46% efficiency.

Keywords: High power microwave (HPM); Klystron; reltron; Electron ware fare; Directed energy weapons

1. INTRODUCTION

In recent years, advancements in the microwave tube technology have made for expansion of the intelligent and compact high power microwave (HPM) sources. There is a need to develop a new generation of HPM devices, because conventional sources are not able to deal with the complex systems and advanced technologies. The existing HPM sources, such as, relativistic klystron, relativistic magnetron, relativistic BWO, vircator and MILO have been used for several strategic applications. However, these HPM devices are not suitable for many applications where one needs highly efficient, compact HPM source with long pulse and high repetition frequencies. Reltron is such a device which can overcome the limitations of these HPM sources to a large extent. Reltron is slow-wave microwave oscillator which has potential to serve for the directed energy weaponry and electronic warfare applications. Reltron is a variant of klystron, with changes here that:

(i) Of the bunching process in which the modulation cavity of reltron performs the double velocity modulation generating intense beam bunching
(ii) DC magnetic field is not required
(iii) The self-magnetic field generated inside the cavity is high enough for confining the electron beam.

Another attractive feature of reltron is that it can produce RF pulse width in excess of 1 μs duration with pulse energies up to 100 Joules, overtaking the other HPM sources that are restricted to pulse energies below 100 Joules and the pulse duration of about 100 cycles. Reltron can also be made frequency tunable of ±10% with respect to central frequency[1-5].

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The effect of various DC electrical input parameters on the reltron oscillator performance has not been reported. In this paper, an analytical model has been described to show that the desired resonating mode of the modulation cavity is π/2 mode, and subsequently, eigenmode simulation has been performed to characterise the modulation cavity while operating in this mode. Further, to explore the influence of various electrical input parameters, such as, pulse shape, cathode and post-acceleration voltages, the beam present, PIC simulation has been carried out.

2. ANALYSIS

The conceptual diagram of a high power reltron is as plotted in Fig. 1. It is made of an explosive emission electron emitter, RF interaction structure, post-acceleration gap, RF extractor and a collector. Explosive emission is used to emit the electrons from the velvet cathode surface which enters into the modulation cavity. This side coupled modulation cavity helps in double velocity modulation process to bunch the intense relativistic electron beam. The post-acceleration region is also connected with a high DC potential which is attached after the modulation cavity. This will enhance the beam power and lower down the energy spread. Rectangular waveguide is used to extract the RF output power[1,5].

In the first grid spacing of the RF interaction cavity electrons are modulated once, and then it enters into the second grid spacing and it again modulated in this region. When the induced gap voltage in the first grid spacing is sufficiently high, then the beam current much more than the space charge limiting current and virtual cathode formation takes place. Two processes occur after the virtual cathode is formed

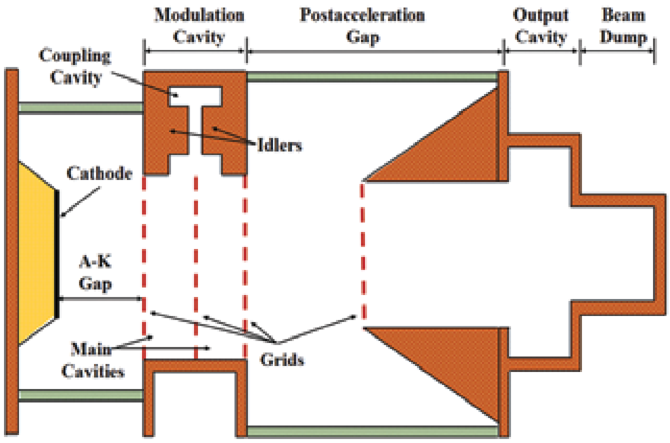

Figure 1. Schematic diagram of the reltron oscillator.

(i) It oscillates in between the first and second metal grids
(ii) Reflected electrons towards cathode are again returned back due to cathode potential.

A relationship between return current from the virtual cathode and the induced gap voltage is obtained using an equivalent circuit approach. An *RLC* circuit is used to represent the side coupled modulation cavity, than the resonant frequency is defined by $\omega = (LC)^{-1/2}$ and the quality factor is given as $Q = \omega RC = R/\omega L$. The total current (I_t) flowing in the cavity is defined as[5]:

$$I_t = I_R + I_L + I_C \tag{1}$$

where I_R, I_L, and I_C represents the individual currents flowing through the equivalent resistance (R) per unit length, capacitance (C) per unit length and inductance (L) per unit length of the RF circuit respectively. The above equation can:

$$I_t = \frac{V}{R} + \frac{1}{L}\int V dt + C\frac{dV}{dt} \tag{2}$$

The induced gap voltage V relation between the first and second grids can be calculated from[6]:

$$\frac{d^2V}{d\bar{t}^2} + \frac{1}{Q}\frac{dV}{d\bar{t}} + V = \frac{1}{Q}\phi_w \sin\bar{t} + I_s A\{\bar{t}\}\sin(\bar{t} - \varphi\{\bar{t}\} + \alpha) \tag{3}$$

Here, α is the phase shift, the terms $\varphi\{\bar{t}\}$ and $A\{\bar{t}\}$ represent the phase and amplitude , respectively, of the induced gap voltage, and ($\bar{t} = \omega t$) is the normalised time. Here, ϕ_w is steady state value and I_s is the return current.

Suppose the induced gap voltage of the RF interaction structure can be written as[6]:

$$V\{t\} = A\{\bar{t}\}\sin(\bar{t} - \varphi\{\bar{t}\}) \tag{4}$$

Then, the amplitude and its corresponding phase of the induced gap voltage can be written as[7]:

$$\frac{dA}{d\bar{t}} = \sin\varphi + (h\sin\alpha - 1)A \tag{5}$$

$$\frac{d\varphi}{d\bar{t}} = \frac{\cos\varphi}{A} + h\cos\alpha \tag{6}$$

Here, h is related to the intensity of the return current and the quality factor and which is given by $I_s Q$. The quality factor of the side coupled modulation cavity is assumed to be very high while the intensity is much lower than unity. This results made the value of h would be in the order of unity. Solving equations (5) and (6) provides a homogeneous solution as[5]:

$$h\sin\alpha > 1 \tag{7}$$

This condition is termed as oscillation condition of the reltron oscillator. The amplitude $A\{0\} = 1$ and the phase $\varphi\{0\} = \pi/2$ is kept as the initial condition to obtain this solution. By considering the nonlinear saturation condition, (5) and (6) are rewritten as[5]:

$$\frac{dA}{d\bar{t}} = \sin\varphi + [h(1-\kappa A^2)\sin\alpha - 1]A \tag{8}$$

$$\frac{d\varphi}{d\bar{t}} = \frac{\cos\varphi}{A} + h(1-\kappa A^2)\cos\alpha \tag{9}$$

Here, $\kappa << 1$ i.e., nonlinear saturation coefficient less than unity. The return current damps the induced voltage when $h\sin\alpha < 1$, therefore, the oscillation in the RF interaction structure does not sustain. In the relativistic klystron this condition is used for the amplifier operation. The RF electric field amplitude increases exponentially when $h\sin\alpha > 1$. This leads to set up an oscillation in the cavity. The condition $h\sin\alpha = 0$ is the boundary between the amplifier and oscillator operation. At this condition the RF electric field starts saturating and the amplitude of saturation can be expressed as[12] :

$$A_s = \sqrt{\frac{h\sin\alpha - 1}{\kappa h\sin\alpha}} \tag{10}$$

When the reltron is operating in $\pi/2$ mode, the maximum amplitude of saturation can be found and therefore this mode is chosen as the resonating mode of the reltron oscillator. To endorse this behaviour a relationship between shift (α) and phase saturation amplitude (A_s) is depicted in Fig. 2 for κ = 0.002 and h = 1.5. It can be demonstrated from Fig. 2 that the maximum saturation amplitude is found at $\pi/2$ which approves the $\pi/2$ mode is the operating mode.

3. SIMULATION

To validate the oscillating mode conditions mentioned in section II and to observe the effect input DC parameters on the performance of reltron, the device is designed and simulated using particle-in-cell code CST Particle Studio. The input parameters such as voltage and current are applied through the

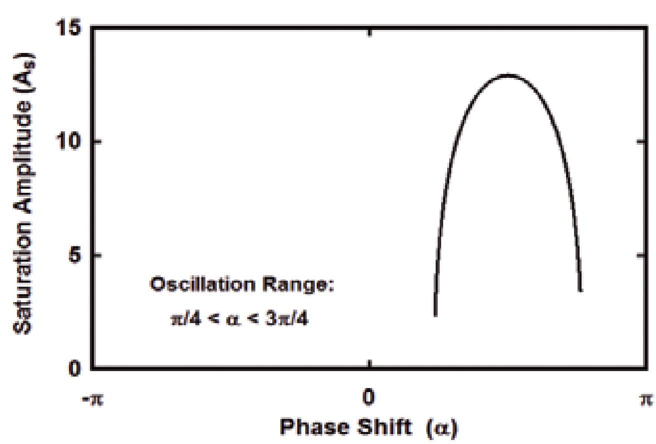

Figure 2. Variation of normalised saturation amplitude (A_s) with phase shift (α).

discrete ports while output is observed through a waveguide port. Explosive electron emission is chosen to carry out the PIC simulation. The electrical and design parameter used are listed in Table 1.

To demonstrate the desired resonating mode and the electric field pattern, the side coupled modulation cavity is simulated using eigenmode solver in electron beam absent condition. Since, the RF interaction struture is formed of three pillbox cavities, it oscillates at 0, $\pi/2$, and π resonating modes. The vector and contour plot of the $\pi/2$ resonating mode is depicted in Fig. 3 which shows that electric field appears in the radial cavity and the electric field in the axial cavities in opposite polarity. This is the condition when the maximum saturation amplitude can be obtained in the main cavities as mentioned in the previous section.

For performance evaluation of the reltron device beam present simulation is used. For this simulation, initially the excitation signal is taken as rectangular pulse of 80 ns pulse width with 1ns rise time. The electric field developed after the PIC simulation is plotted in Fig. 4. The frequency spectrum of reltron obtained through simulation is plotted in Fig. 5.

Table 1. Design parameters of reltron

Parameters	Values
Axial cavity radius	38.27 mm
Radial cavity radius	25.51 mm
Spacing between metal grids	18.70 mm
Spacing between anode-cathode	20.50 mm
Spacing of post-acceleration gap	53.30 mm
Frequency	2.75 GHz
Current	750 A
Total voltage	1000 kV

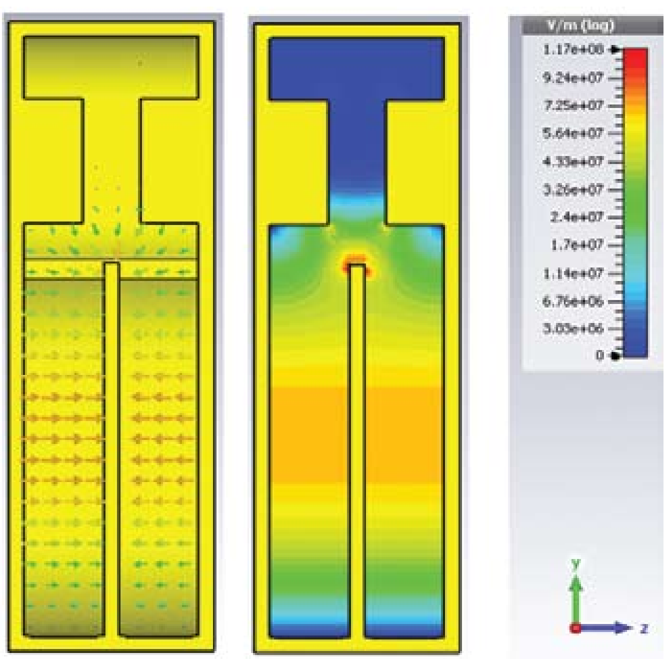

Figure 3. Electric field pattern in the side coupled modulation cavity in the $\pi/2$ mode resonating condition.

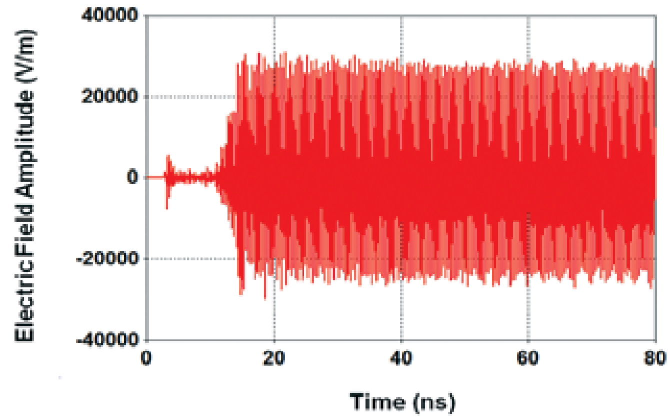

Figure 4. RF electric field obtained through the PIC simulation.

To validate design, we have taken the experimental reltron values of Miller[1], *et al.* and simulated the device with CST Particle Studio. With electrical parameters: cathode voltage = 100 kV, post-acceleration voltage = 750 kV, and beam current 750 A, the PIC simulation provided ~ 225 MW RF power with ~ 36 % efficiency[4], while Miller[1], *et al.* reported ~ 200 MW RF power with ~ 32 % efficiency. The PIC simulation results are in agreements with experimental values within ~ 5%.

A brief design and simulation of the reltron device is given by the authors in reference[4]. Figure 5, which indicates that the 2.75 GHz is the operating frequency of the device. The output power developed through the PIC simulation is plotted in Fig. 6, here the beam current is set at 750 A while the cathode and post-acceleration voltages are 200 kV and 800 kV, respectively. The peak RF output power developed is ~350 MW with ~46% efficiency.

To get a practical view point of the excitation signal on the performance of device operation, the excited pulse shape is varied by changing the rise, hold and fall time. The total time duration is 80 ns of which Fig. 7(a) is RF radiated power of rise and fall time 5 ns, hold time 70 ns, Fig. 7(b) is RF radiated of rise and fall time 10 ns, hold time 60 ns, Fig. 7(c) is RF radiated power of rise and fall time 15 ns, hold time 50 ns, Fig. 7(d) is RF radiated power of rise and fall time 20 ns, hold time 40 ns. In Figs. 7(a)-(c) the oscillation starts after 15 ns while in Fig. 7(b), it is at 22 ns. The RF powers are falling just after the hold time ends and fall time starts. This indicates that the RF radiated power depends on the shape of the excitation signal and the excited signal should have larger hold time.

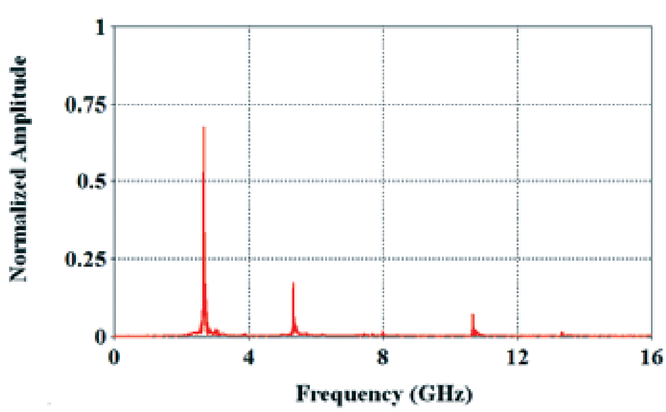

Figure 5. Frequency spectrum of the typically selected device.

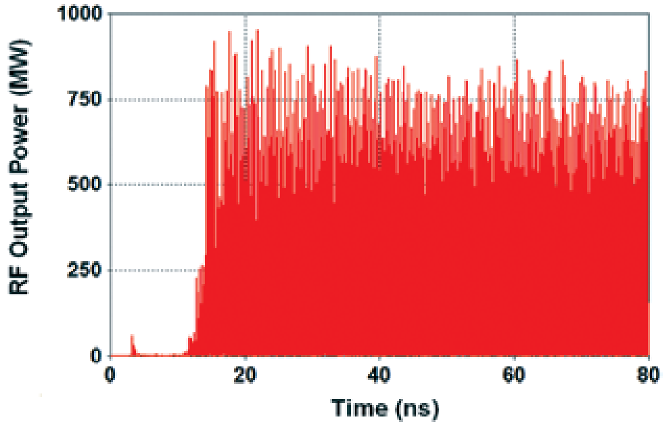

Figure 6. Developed RF power at the outport port.

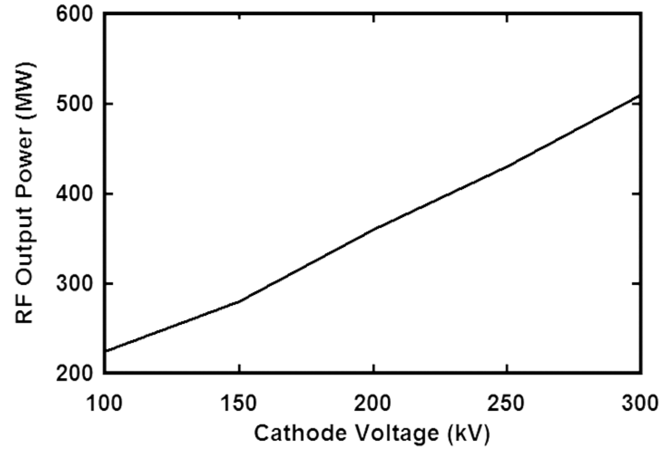

Figure 8. Variation of RF output power w.r.t cathode voltage.

The performance of the reltron on the cathode voltage is depicted in Fig. 8, which indicates that the RF output power in the cavity is significantly improved up to a threshold limit as the cathode voltage is increasing. This is due to the electrons emitting from the cathode surface with higher accelerating potential. With a beam current of 750 A, cathode voltage of 300 kV and post-acceleration voltage of 800 kV, the device provides ~510 MW with ~62% efficiency. The performance of the reltron also varies with the post-acceleration potential and is as shown in Fig. 9. At higher post-acceleration potential, the bunched electrons move with higher velocity, approaching towards the velocity of the light. This phenomenon enhances the RF output developed at the extraction cavity. These DC potentials are important factors for improving the performance of the device.

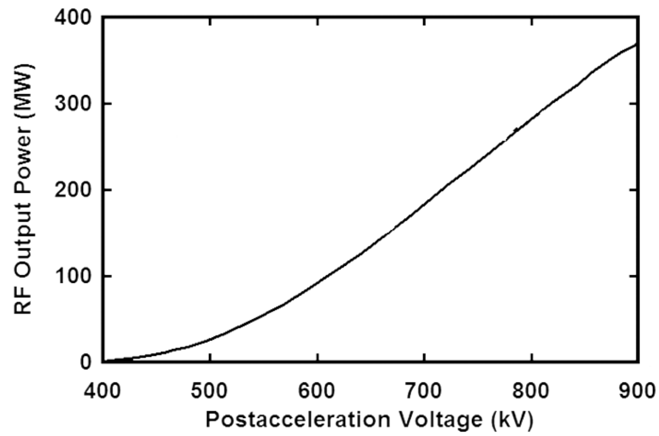

Figure 9. Variation of RF output power w.r.t post-acceleration voltage.

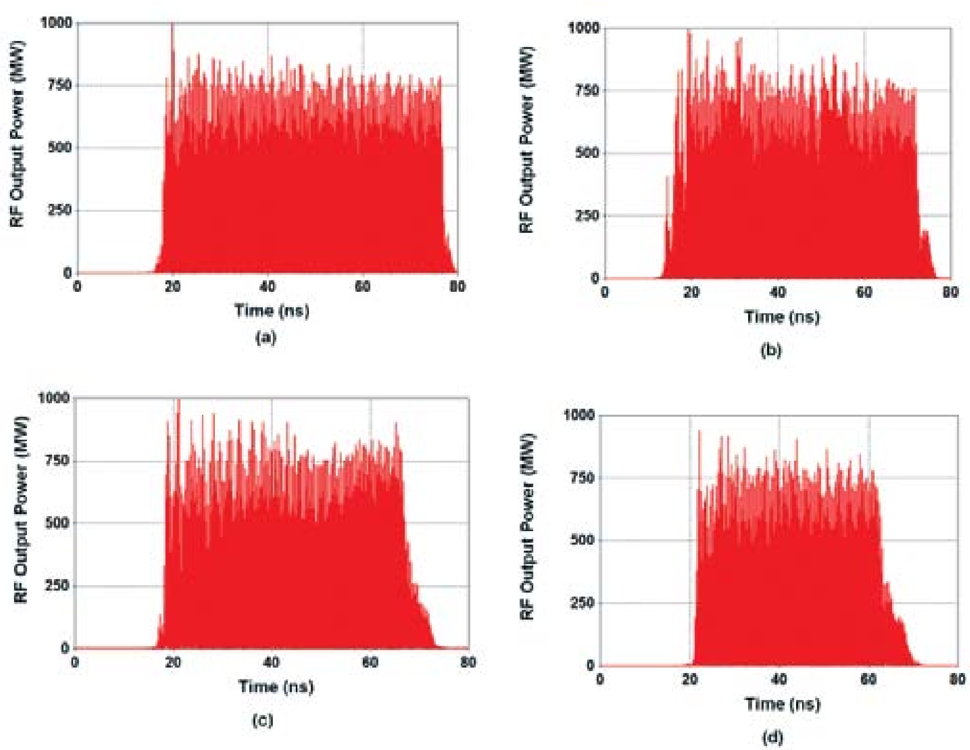

Figure 7. RF output power for (a) rise and fall time 5 ns, hold time 70 ns (b) rise and fall time 10 ns, hold time 60 ns. (c) rise and fall time 15 ns, hold time 50 ns (d) rise and fall time 20 ns, hold time 40 ns.

4. CONCLUSIONS

Oscillation conditions of the reltron device are demonstrated. It is shown that at the π/2 phase mode in the modulation cavity, produces maximum saturation amplitude for κ = 0.002 and h = 1.5. The electromagnetic simulation predicted that in case of π/2 mode of operation, the RF fields in main cavities of the side coupled modulation cavity system are in phase while RF field is absent in the coupling cavity. The results show that with the rise or fall of the pulse, the output power varies accordingly and the pulse of hold time 70 ns and rise and fall time of 5 ns gives maximum stable RF power. With a beam current of 750 A, cathode voltage of 200 kV and post-acceleration voltage of 800 kV, the device provides ~350 MW with ~46% efficiency. At higher cathode and post-acceleration voltages the RF output power increases up to a threshold limit which increases the performance of the reltron tube.

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In this paper, he has performed, analytical and interpretation part.