Efficiency of HPM generation in air

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***Abstract*—The author estimates the efficiency of HPM generation produced in atmospheric air. The experimental work shows that 47 % of current flowing in the corona and spark channels is due to the high-speed electrons being responsible for HPM production.**

***Index Terms*— HPM generation, resonant cavity, efficiency, corona and spark channel discharges**

I. Introduction

THE Marx generator produces the voltage pulse of double exponential function if the resistance of the load, R_A is of high value in comparison to the characteristic impedance of the generator, R_G. In Fig. 1, R_A is 300 Ω and R_G is 18 Ω. R_G is given in Table I.

TABLE I

Characteristics of 9-stage Marx Generator

- Six capacitors per stage for the total of 54 capacitors
- 12 spark gaps per stage for the total of 120 spark gaps
- Each spark gap can be adjusted to a few microns
- Capacitance per stage is 15.6 nF
- Erected capacitance of the generator, C is 1.73 nF
- Ideal coaxial structure almost achieved
- Impedance of the generator, R_G is approximately 18 Ω.

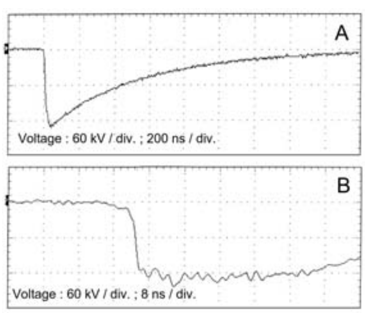

Fig. 1. Output voltage across 300 Ω load. Frame A gives the width of the pulse, and frame B the rise-time. The charging voltage is 14.7 kV/stage

If R_A is decreasing and approaching the value of R_G, it is necessary to consider the concept of the pulse-forming network in each stage of the generator.

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This concept offers the opportunity to obtain the square shaped pulse from the Marx generator [1,2].

II. Theoretical Formulation

The falling portion of the waveform shown in Fig. 1, Frame A can be described as:

$$V(t) = V_o \exp(-t/CR) \quad (1)$$

C is the erected capacitance of the generator and R is the total resistance in the circuit (= the impedance of the generator, R_G plus R_A of the load). When $V(t) = V_o/2$, then t becomes $T_{½}$:

$$T_{1/2} = 0.693\ RC \quad (2)$$

9-stage generator is used to generate HPM in atmospheric air with the experimental arrangement given in Fig. 2 and described in Ref. [3]. It appears that, the corona and spark channels are just short-circuiting the gap between the hot electrode, 2 and cold electrodes, 3. However, it is found that, the corona and spark channels are producing the HPM radiation by dissipating the energy supplied by the generator into radiation. The discharges are acting as the converter of the energy stored in the impulse into the HPM emissions. This effect can be manifested as the resistor, R_A in the current flow.

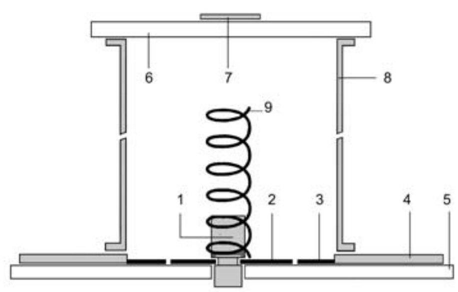

Figure 2; 1-HV output from the 9-stage Marx generator, 2–"hot" copper plate 3–"cold" copper ring, 4-ground flange of the generator, 5- and 6-plexiglass flanges, 7-partial reflector, 8-nipple, 9-helix. B-dot probe is placed above the partial reflector. The charging voltage is 17.5 kV/stage.

R_A can also be treated as the radiation resistance of the (equivalent) loop antenna in which the current, I_A arising from the fast runaway electrons is responsible for the HPM generation. The loop consists of plate 2, ring 3, discharges between 2 and 3 and the generator itself. See Fig. 2

The power, P_a radiated by such (equivalent) loop antenna is:

$$P_a = ½ R_A I_A^2 \quad (3)$$

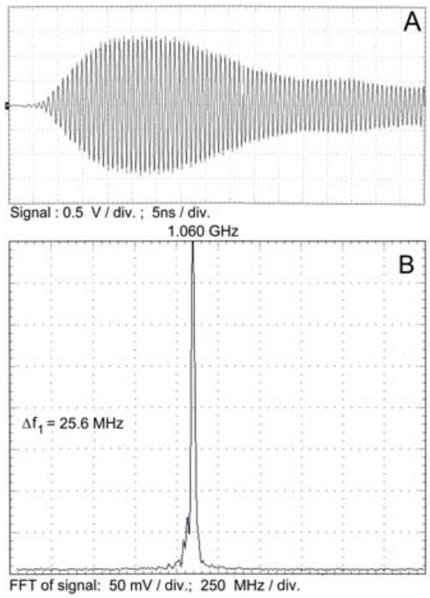

Figure 3. HPM signal is shown in Frames: A. Frame B is FFT of the signal.

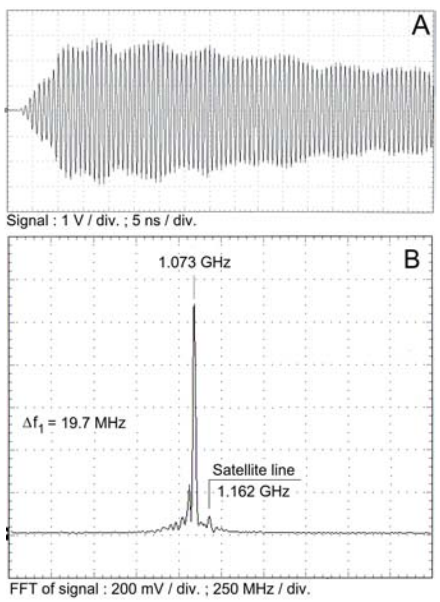

Figure 4. Caption is as in Fig. 3. The waveform has satellite line at 1.162 GHz. The frequency difference of 1.162 GHz-1.073 GHz= 89 MHz corresponds to the period of 11.2 ns.

P_a can be determined by measuring the radiation power leaving the resonant cavity via the area, S

$$P_r = ½ \int (E^2 / Z_0)\, dS \qquad (4)$$

E is the radiating electric field, Z_0 (=120π) the impedance of free space and dS is the element of the area. The power delivered by the generator is:

$$P = ½ V(t) I(t) = ½ [V(t)]^2 / (R_G + R_A) \qquad (5)$$

By equating Eq. 3 with Eq. 4, we can determine the percentage of current arising from the high-speed electrons.

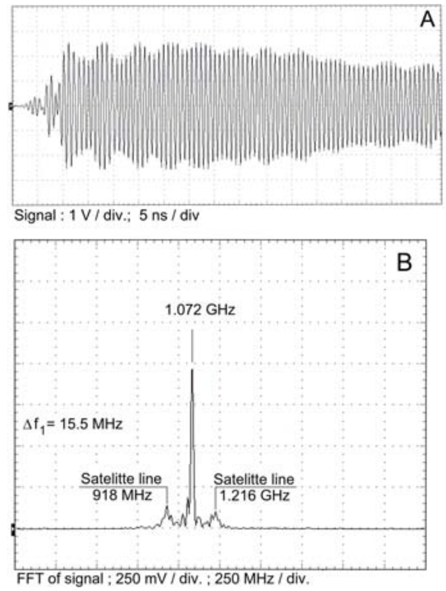

Figure 5. Caption is as in Fig. 3. There are two satellite lines at 918 MHz and 1.216 GHz. The frequency difference: 1.216 GHz-1.072 GHz= 144 MHz corresponds to the period of 6.9 ns. The frequency difference: 1.072 GHz-0.918 GHz= 154 MHz corresponds to the period of 6.5 ns.

The ratio, $\eta = P_r / P$ is the efficiency of HPM generation.

III. Experimental Results

With the conditions as in Ref. [3 and 4] the waveforms are recorded with the B-dot probe and 3 GHz oscilloscope and shown in Figs. 3 to 5. This oscilloscope has only sufficient numbers of sample points to show the details of the waveform, when the signal of the frequency of 1 GHz is viewed with the time scale of 5 ns / div. The waveforms in Figs 3 to 5 are recorded with 10 ns/ div. scale then the scale is expanded to 5 ns /div. We see that the satellite lines are present in Figs 4 and 5 and they are causing the “amplitude modulation” on 1.073 GHz (FFT) line in Fig. 4 and 1.072 GHz (FFT) line in Fig. 5. The frequency difference between the main line and the satellite line dictates the period of modulation that the satellite lines are performing on the main line. It was observed that the HPM emission with satellite lines yield larger output in comparison to that of Fig. 3.

Fig. 6 shows the waveforms when the data of Figs. 4 and 5 are recorded on 20 ns / div. time scale. In addition to the satellite lines, we have some indication of the low frequency lines at 172 MHz and 767 MHz. According to Ref. [4] the spectral bandwidth, Δf of the HPM line at 1.072 GHz is:

$$\Delta f \approx \Delta f_1 - \Delta f_2 \qquad (6)$$

Δf_1 is defined as the FWHM of 1.072 GHz (FFT) line given in Fig. 6. Δf_2 is the FWHM of the line that has only the single frequency at 1.072 GHz. The signal generator is used to generate the (reference) pulse and to get Δf_2. For a 150 wide pulse, the measured value of Δf_2 is 8.56 MHz.

In Ref. 4 it is shown that the coherence effect is responsible for the “pulse shortening” phenomenon. Following the analysis

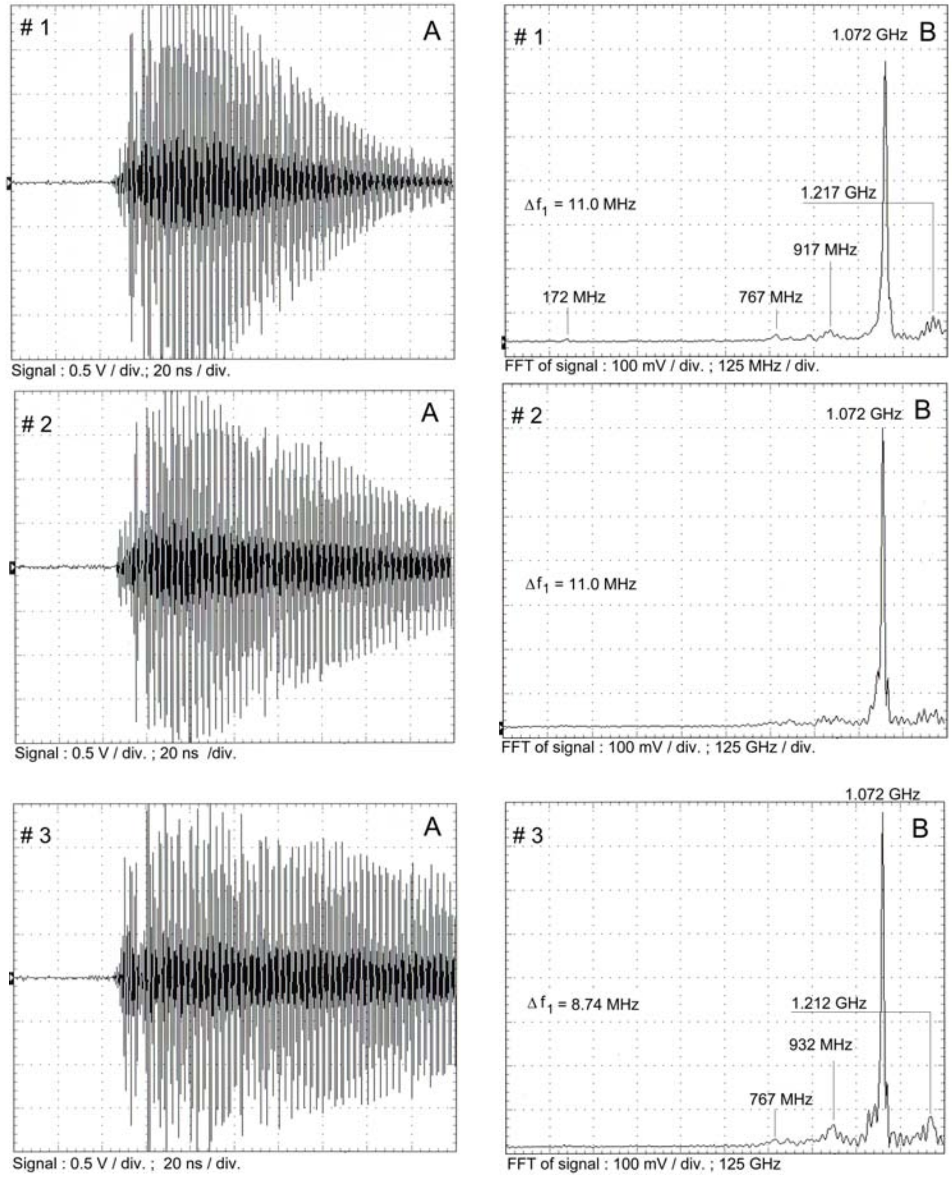

Fig. 6. Three shots are presented to indicate variations from shot to shot. HPM waveform is given in Frame A and FFT of the waveform in Frame B.

For frequency of 1.07 GHz, the amplitude of the signal from the B-dot probe of 1 Volt corresponds to the electric field of approximately 3 kV/cm.

given in Ref. [4] it was established that the coherence is not relevant factor in governing the shape of the waveform shown in Fig. 6. This fact justifies the use of Eq. 1

By observing the envelope of the HPM signals shown in Fig 6, $T_{1/2}$ (defined by Eq. 2) is obtained. In shot #1 $T_{1/2}$ is 70 ns, in shot # 2 $T_{1/2}$ is 110 ns and in shot # 3 $T_{1/2}$ is estimated to be in the range of 200 ns. From Eq. 2, we get that R_A is 40 Ω in the shot #1, 74 Ω in shot #2 and 149 Ω in shot #3.

Let us consider shot # 2. For R_A being of large value (i.e., $R_A >> R_G$), V≈ 9*17.5 kV=157.5 kV. With R_A =74 Ω and R_G =18 Ω we get from Eq. 5 that P is 134 MW and I= 1.7 kA.

Fig. 4 gives that, E ≈ 4 div.*0.5 V/ div. *3 [(kV/cm)/V]=6 kV/cm. This is because the signal from the probe of 1 Volt corresponds to the electric field of approximately 3 kV/cm. Using Eq. 4 with the area, S of 175 cm^2, P_r is 8.35 MW. This makes the efficiency of HPM generation: $\eta = P_r / P$ to be 6.2 % in the first 30 ns. With this value of P_r from Eq. 3, I_a is 646 A. This makes that 47 % of the current supplied to the generator belongs to the high speed electrons being present in 1 to 2 mm gap and subjected to high MV/cm electric fields.

IV. REFERENCES

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Biography: (not available)