Nuclear Instruments and Methods in Physics Research A 358 (1995) 327–330

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Low-cost electron-gun pulser for table-top maser experiments

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Abstract

A simple 10 kV electron-gun pulser for small-scale maser experiments is presented. This low-cost pulser has operated successfully in various table-top cyclotron-resonance maser (CRM) and free-electron maser (FEM) experiments. It consists of a low-voltage capacitor bank, an SCR control circuit and a transformer bank (car ignition coils) connected directly to the e-gun. The pulser produces a current of 3 A at 10 kV voltage in a Gaussian like shape of 1 ms pulse width. The voltage sweep during the pulse provides a useful tool to locate resonances of CRM and FEM interactions. Analytical expressions for the pulser design and experimental measurements are presented.

1. Introduction

Cyclotron resonance masers (CRMs) [1] and free electron lasers (FELs) [2] are considered as relatively complicated and expensive devices, mainly because of the high-energy electron sources required for their operation. A major goal of the Tel Aviv University High-Power Microwave Laboratory is to develop low-voltage, low-cost integrated maser schemes [3] for practical applications. Several new low-voltage experimental masers have been developed in our laboratory during the last two years. These include the traveling-wave FEM [4], the periodic-waveguide CRM oscillator [5], the CRM in a non-dispersive waveguide [6], and the UHF ubitron-FEM oscillator [7].

The experimental CRM and FEM devices described in Refs. [5–7] have been operated successfully with an electron energy lower than 8 keV. The high-voltage pulses for these experiments have been produced by the low-cost pulser described in this paper. This 10 kV, 3 A pulser generates a ~1 ms pulse with Gaussian-like shape. The voltage sweep during the pulse provides a useful tool to identify the resonances of the examined maser.

A principle scheme of the pulser [8,9] is shown in Fig. 1. The low-voltage circuit consists of a capacitor bank C, an SCR switch, a diode D_C (which prevents a reverse recharging of the capacitor), and the primary winding of the transformer with w_1 turns. The high-voltage secondary winding (w_2 turns) is connected directly to the electron gun. An ordinary car ignition coil can be used as the transformer in this scheme. This simple pulser design is proposed for small university laboratories who seek a low-budget table-top FEL experiment for fundamental research and for student training. Analytical expressions for the pulser design and examples of its operation are presented in this paper.

2. Theory

The pulser shown in Fig. 1 can be implemented in practice with several transformers connected in parallel or in series, in order to increase the output current or voltage, respectively. A pulser scheme with two parallel transformers is shown in Fig. 2a. Its equivalent circuit shown in Fig. 2b includes the resistances R_1, R_2 and the inductances L_1, L_2 of the transformer primary and secondary windings, respectively. The electron gun response is approximated by a resistor R and a diode D in series. We also assume in this model a perfect magnetic coupling between the transformer windings, and ideal SCR and diodes D_C and D performance [8–10].

In this section we analyse the effect of the capacitance C and the number of parallel transformers m on the pulser characteristics: the initial capacitor voltage V_C, the pulse duration t_p, and maximum transformer magnetizing force F_m.

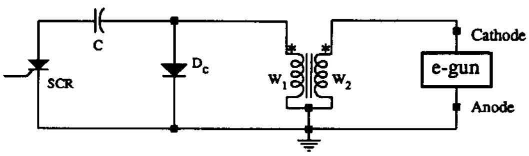

Fig. 1. A principle scheme of the pulser.

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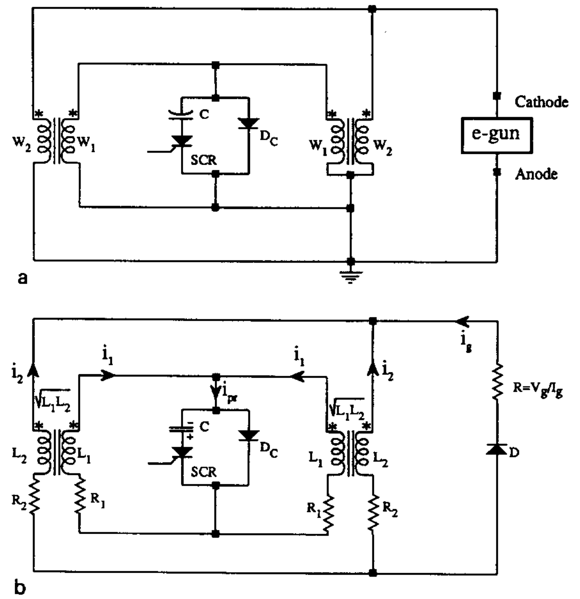

Fig. 2. A pulser with parallel transformers: (a) a principle scheme; (b) an equivalent circuit.

The transient currents i_1 and i_2 in the transformer primary and secondary windings, respectively, in Fig. 2b are described by the coupled equations

$$\left(R_1 + sL_1 + \frac{m}{Cs}\right) i_1(s) + s\sqrt{L_1 L_2}\, i_2(s) = V_C, \tag{1a}$$

$$s\sqrt{L_1 L_2}\, i_1(s) + \left(R_2 + mV_g/I_g + sL_2\right) i_2(s) = 0, \tag{1b}$$

where s is the time derivative Carson–Laplace operator. The number of transformers in parallel is denoted by m. The peak voltage and peak current of the electron gun are V_g and I_g, respectively.

The solution of Eqs. (1a) and (1b) yields a simple expression for the required initial capacitor voltage,

$$V_C = \frac{V_g}{\sqrt{L_2/L_1}} \left[1 + \frac{R_2 + R_1 L_2/L_1}{mV_g/I_g}\right]. \tag{2}$$

It follows from Eq. (2) that increasing the number of transformers in parallel m, results in a reduction in the required initial voltage V_C.

The analysis presented in this paper refers to the first transient interval of the pulser response. It lasts from the SCR ignition to the first zero of the electron-gun current, $t = t_p$, in which the magnetizing force attains its maximum. Hence, t_p is the pulse duration of the electron gun. Two dimensionless parameters are defined to characterize the pulser performance. The parameter n is related to the normalized capacitance in the pulser circuit by $n = CR_1(R_2 + mV_g/I_g)/(mL_2)$. The parameter k corresponds to the time-constant ratio of the high- and low-voltage loops as $k = 1 + L_1(R_2 + mV_g/I_g)/(L_2 R_1)$.

Two operating regimes, periodic and aperiodic, are defined according to the transient response of the pulser. The periodic operating regime is defined for n values in the range $n_{1cr} < n < n_{2cr}$, and the aperiodic regime is defined for n values outside this range, hence $n < n_{1cr}$, or $n > n_{2cr}$. The critical values of n for the transition between the periodic and aperiodic regimes are given, as in other schemes [11,12], by $n_{1cr} = (1 - \sqrt{1 - n_\omega^2})/n_\omega$, and $n_{2cr} = (1 + \sqrt{1 - n_\omega^2})/n_\omega$, where $n = n_\omega$ corresponds to the maximum free oscillation frequency in the periodic regime, and $n_\omega = 1/(2k - 1)$.

The pulse duration t_p and the maximum magnetizing force F_m are normalized as $t_{p*} = t_p/t_b$, and $F_{m*} = F_m/F_b$, where the corresponding base values are defined as $t_b = 3L_1/R_1$ and $F_b = w_1 V_C/R_1$.

In the periodic regime, the normalized pulse duration results in

$$t_{p*} = \frac{2kn}{3\alpha(k-1)} \arctan\frac{\alpha}{1+n} \tag{3a}$$

and the normalized maximum magnetizing force results in

$$F_{m*} = \sqrt{\frac{n}{k}} \exp\left(-\frac{1+n}{\alpha}\arctan\frac{\alpha}{1+n}\right), \tag{3b}$$

where the parameter α is defined in the periodic regime as $\alpha = (4kn - (1+n)^2)^{1/2}$.

In the aperiodic regime, the normalized pulse duration results in

$$t_{p*} = \frac{kn}{3\beta(k-1)} \ln\frac{1+n+\beta}{1+n-\beta} \tag{4a}$$

and the normalized maximum magnetizing force results in

$$F_{m*} = \frac{2n}{1+n-\beta}\left(\frac{1+n+\beta}{1+n-\beta}\right)^{-(1+n+\beta)/2\beta}, \tag{4b}$$

where the parameter β is defined in the aperiodic regime as $\beta = ((1+n)^2 - 4kn)^{1/2}$.

Figs. 3a and 3b show the dependence of t_{p*} and F_{m*} on the parameter n for different values of k as results from Eqs. (3) and (4). It follows from the Figs. 3a and 3b that, for a constant k, the pulse duration and the maximum magnetizing force depend monotonically on the dimensionless parameter n, and consequently, on the capacitance C.

In order to find the effect of varying the number of parallel transformers in the pulser, we obtain $\mathrm{d}n/\mathrm{d}m = -CR_1R_2/(L_2 m^2) < 0$, and $\mathrm{d}k/\mathrm{d}m = L_1 V_g/(I_g L_2 R_1) > 0$. Hence, an addition of a parallel transformer to the pulser circuit results in a decrease in the n parameter, and in an increase in the k parameter. Consequently, according to the analysis above and Fig. 3, both t_p and F_m decrease if m increases.

3. Practical implementation

The pulser scheme described in this paper has been constructed in several versions. It operates successfully in various maser experiments, including a traveling-wave FEM [4], a periodic-waveguide CRM [5], a CRM in a

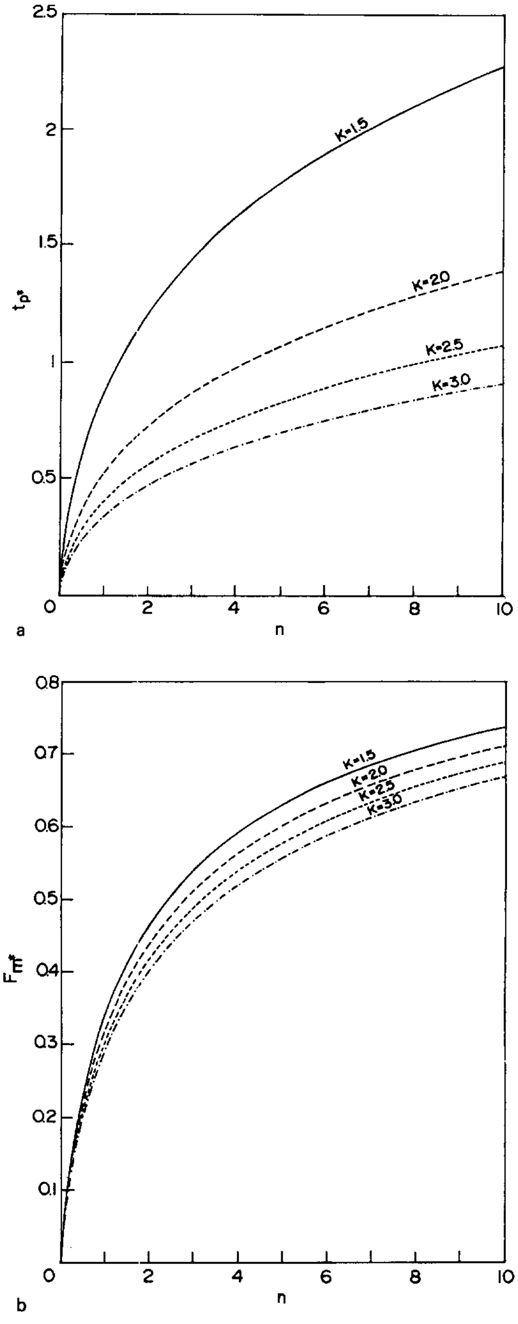

Fig. 3. The effect of the pulser normalized parameters n and k: (a) the normalized pulse duration t_{p*}. (b) The transformer maximum magnetizing force F_{m*}.

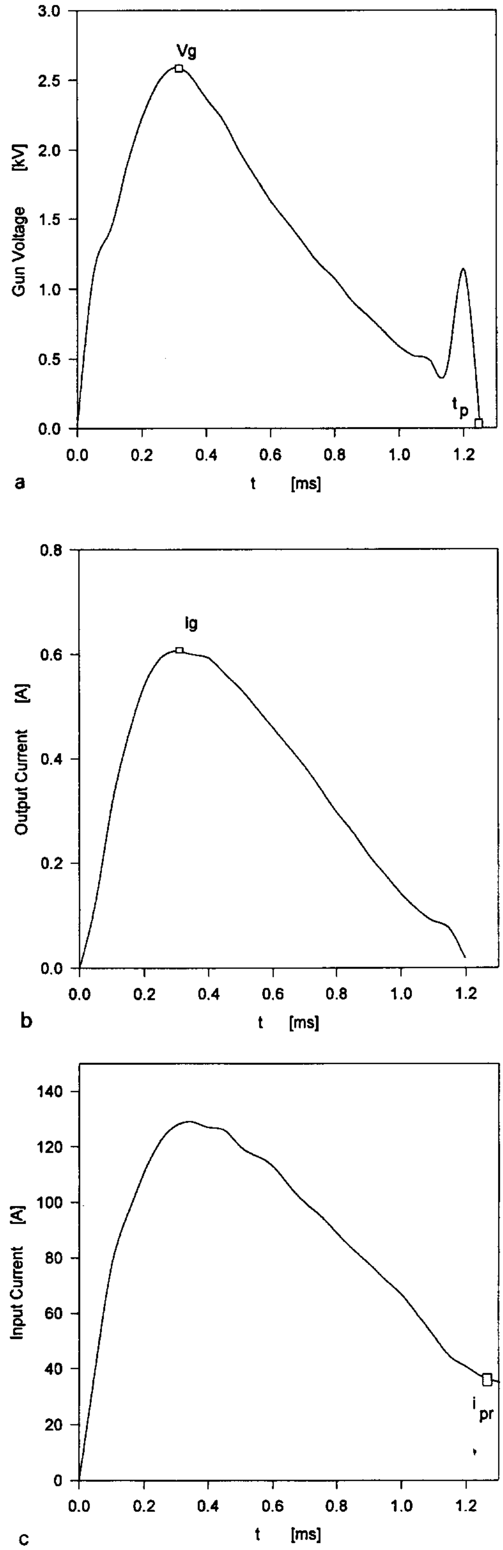

Fig. 4. Typical measurements of a thermionic electron gun pulse: (a) the electron-gun voltage; (b) the electron-gun cathode current; (c) the primary current of the transformer bank.

non-dispersive waveguide, and the FEM experiment in the UHF regime. The pulsers are operated in the range V_g = 2–10 kV, I_g = 0.2–3.0 A and $t_p \sim 1$ ms. As transformers, we use ordinary car ignition coils (Diamand LB-88, with $R_1 = 2.8\ \Omega$, $R_2 = 11,150\ \Omega$, $L_1 = 0.003$ H, and $L_2 = 44.6$ H). The number of parallel transformers m varies in our experiments from 1 to 3. The capacitances of the capacitor bank is variable in order to enable operation in both the periodic and the aperiodic regimes. The initial voltage of the capacitor bank is controlled in the experiment. The cathode current $i_g(t)$ is measured by a Rogovski coil and detected with the e-gun voltage $u_g(t)$ and the primary current of the transformer bank ($i_{pr} = mi_1$) by an oscilloscope. Typical traces are shown for example in Figs. 4a–4c. The remanent primary current at the end of the pulse, $i_{pr}(t_p)/m$, is proportional to F_m, and is used to evaluate a variation in the maximum magnetizing force F_m.

The effects of the number of parallel transformers m and the capacitance C on the parameters V_C, t_p and F_m has been studied experimentally and compared with the above analysis. The difference between the theoretical and the experimental results is demonstrated in an example in which $V_g = 2.6$ kV, $I_g = 0.62$ A, $C = 350\ \mu$F, and $m = 3$. The experimental results, shown in Figs. 4a–4c, yield in these conditions $V_C = 130$ V and $t_p = 1.24$ ms. The theoretical analysis presented in the previous section results in this case in $V_C = 110$ V and $t_p = 0.94$ ms. Hence, the analytical expressions presented in this paper provide a useful estimate for the pulser performance. These can be used as a simple tool for a preliminary design of pulsers for small-scale nonrelativistic FEM and CRM experiments.

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