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A ferroelectric electron gun in a free-electron maser experiment

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Abstract

An electron-gun based on a ferroelectric cathode is studied in a free-electron maser (FEM) experiment. In this gun, the electrons are separated from the cathode surface plasma, and are accelerated in two stages. The electron energy-spread is reduced sufficiently for an FEM operation in the microwave regime. A 14 keV, 1–2 A e-beam is obtained in a 0.1–2.1 μs pulse width. The pulse repetition frequency attains 3.1 MHz in ~50% duty-cycle. This gun is implemented in an FEM oscillator experiment operating around 3 GHz. The paper presents experimental results and discusses the applicability of ferroelectric guns in free-electron laser devices. © 2002 Elsevier Science B.V. All rights reserved.

1. Introduction

The electron gun is a key element in the design of any free-electron device [1]. Its performance and limitations determine the major characteristics of the entire device. Hence, new developments in cathodes and electron guns lead to advancements in the technologies of free-electron devices. This paper presents a novel gun based on a ferroelectric cathode and its implementation in a free-electron maser (FEM) experiment.

The electron emission from ferroelectric materials under spontaneous polarization reversal was observed first by Rosenman et al. [2] in 1984. The current density measured in the early experiments, $\sim 10^{-7}$ A/cm^2, classifies the corresponding emission mechanism as a "weak" effect. Much higher current densities reaching 100 A/cm^2, i.e. a "strong" ferroelectric electron emission effect, was observed in 1989 by Gundel et al. and subsequently studied by various research groups. These studies explored the emission mechanisms and the cathode properties (brightness, current density, perveance, energy-spread, pulse duration, lifetime, and material compositions). Ref. [3] is a comprehensive review on ferroelectric cathodes.

The main advantages of the ferroelectric cathode, as compared with the conventional thermionic cathode, are its (a) high current, (b) low cost and simple handling, (c) tolerated vacuum conditions, (d) cold operation, and (e) versatile shaping. On the other hand, the usage of ferroelectric cathodes for free-electron devices is problematic in other aspects. The ferroelectric strong electron emission evidently involves surface plasma effect [3]. Therefore, the emitted ions may interfere with the interaction, the electron energy-spread is relatively high, and voltage breakdowns tend to occur due to the gap-closures of the plasma. The pulse repetition frequency (PRF) of such cathode is limited by the plasma relaxation time. A severe limitation of the ferroelectric cathode is its short lifetime.

The first demonstration of microwave emission by a ferroelectric-based free-electron device is

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reported in Ref. [4]. A successive study [5] demonstrates the experimental feasibility of a cyclotron-resonance maser (CRM) based on a ferroelectric cathode. Due to its relatively large energy-spread acceptance, the gyrotron-CRM was the first device chosen for ferroelectric-cathode studies [6,7]. In the present study, an advanced ferroelectric electron gun is implemented in an FEM experiment. The paper presents the electron gun design and the FEM experiment, and discusses the applicability of ferroelectric cathodes in practical FEMs and other devices.

2. Ferroelectric electron gun

The ferroelectric electron-gun scheme is presented in Fig. 1. The electron gun is based on a ferroelectric cathode, made of a $10 \times 10 \times 1\,\mathrm{mm}^3$ lead-lanthanum-zirconium-titanate (PLZT) 12/65/35 ceramic plate. Two electrodes are positioned on the ferroelectric sample. The rear (non-emitting) electrode is made of a uniform $7 \times 7\,\mathrm{mm}^2$ silver-paint coating. The front (emitting) electrode consists of a $7 \times 7\,\mathrm{mm}^2$ stainless-steel grid, attached to the ceramic plate. The electron gun is activated by a positive trigger pulse (~ 1 kV) applied to the rear electrode, while the front electrode is grounded. This trigger pulse provides the electric field needed to create plasma on the cathode front surface, from which the electrons are extracted. The device operates in modest vacuum conditions of 10^{-4}–10^{-5} Torr.

The ferroelectric gun consists of two acceleration stages. At the first stage, the electrons are extracted out of the ferroelectric surface plasma by the same trigger pulse applied on a stainless-steel grid electrode, placed 5 mm in front of the cathode. A high-voltage DC power-supply and a fast electronic switch (0–3 MHz PRF) produce the ~ 1 kV trigger pulses activating the cathode. The grid electrode is connected to the rear electrode. At the second stage, a DC accelerating voltage tunable in the range 5–15 kV is applied to the anode, distant 60 mm from the cathode. Teflon isolators maintain the vacuum and provide the gun outer structure. The cathode operates at room temperature, hence the use of Teflon as well as other simple means is enabled in this device.

A static magnetic field of 250 G is induced by external solenoid on the gun axis. This magnetic field limits the plasma expansion, prevents the natural spread of the electrons, and guides them on axis throughout the relatively long electron-gun section (60 mm) to a hole at the center of the anode, from which they leave the electron gun and enter into the electron tube. The electron beam passes through the tube, guided by an axial magnetic field induced by another solenoid. After the interaction region, the electrons enter into the collector section where they are kicked sideward by permanent magnets. The collector is electrically

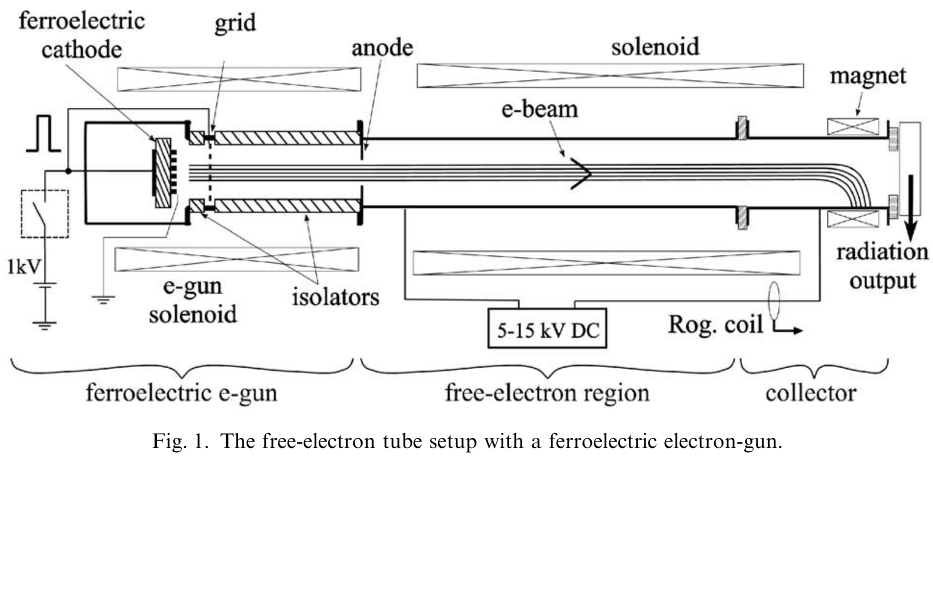

Fig. 1. The free-electron tube setup with a ferroelectric electron-gun.

isolated from the interaction region. A Rogovski coil measures the electron current in the collector.

The experimental system is operated in a semi-repetitive mode. TTL pulsers determine the synchronization between the electron gun and solenoid pulses. The magnetic field pulse duration is ~40 ms, repeated in a 1 Hz PRF. The ~1 kV trigger pulses supplied to the electron gun are driven by a solid-state switch (Behlke: HTS 80-PGSM) gated by TTL pulses. The electron-gun pulse duration is ~200 ns, hence, a macro-pulse consisting of many electron-gun micro-pulses is possible during the long solenoid pulse.

Fig. 2 shows a typical ~2 A electron-current pulse of 0.3 μs duration measured in the collector (after passing a 60 cm long drift-tube), and its exciting HV trigger pulse. In order to measure the electron energy-spread at the end of the tube, the collector section was slightly modified. An isolated grid was inserted between the end of the tube and the collector. The grid was connected to a varying voltage, whereas the collector was connected to a 200 V higher voltage. The grid voltage was decreased until a full rejection of the electrons was achieved. Results of energy-spread measurements are shown in Fig. 3. Each point represents an average of 20 current measurements under the same voltage of the grid. The grid voltage was varied gradually from the tube voltage to zero. Consequently, the current was decreased from the full current to zero (i.e. fully rejected by the grid voltage). Fig. 3 shows also the derivative of the measured curve, which represents the energy distribution of the electron beam. Its full-width half-maximum (FWHM) corresponds to ~150 eV energy-spread. This measurement was conducted at 5 kV accelerating voltage, hence the energy-spread is ~3%.

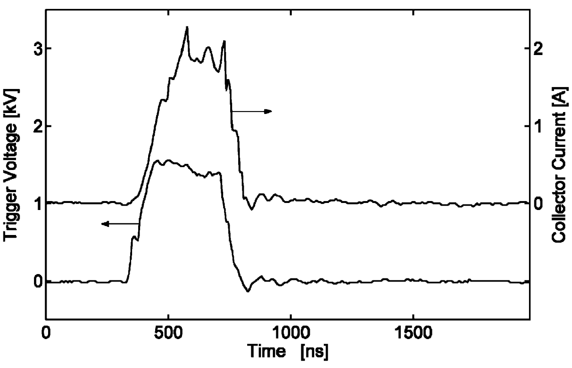

Fig. 2. The e-beam current (in the collector), and the exciting trigger voltage.

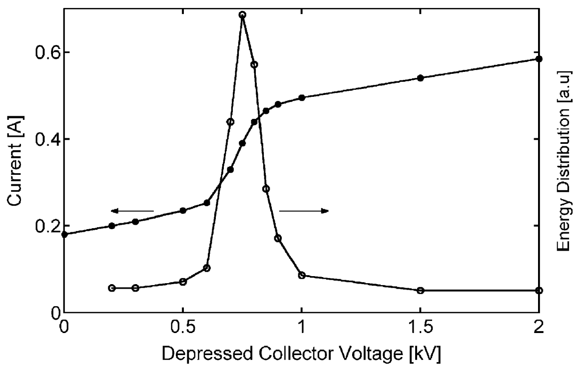

Fig. 3. Energy-spread measurements; the collector current vs. the repelling voltage (dots) and its derivative, the electron-energy distribution (circles).

For each magnetic-field pulse, a train (macro-pulse) of a few tens of pulses is applied on the electron gun at a repetition rate of ~1 MHz. (the device can operate in a two-time-scale mode). The ferroelectric gun has been operated with the same cathode in this mode for more than 150 h (i.e. $>10^7$ pulses) with no observable damage to the cathode or any deterioration of its performance.

3. FEM experiment

Following our gyrotron experiments [4–7] with a ferroelectric electron gun, it was implemented in an FEM experiment. This device is more sensitive than the gyrotron to energy-spread, thus the quality of the electron beam is more crucial.

The FEM scheme shown in Fig. 4 resembles the device presented in Ref. [8]. The tube consists of a rectangular waveguide with two metal wires stretched along with it. This transmission-line structure supports TEM waves and has a zero cutoff frequency. Therefore, this FEM can operate in relatively low frequencies and voltages. The electrons are undulated by a folded-foil wiggler (2 cm period), as in Ref. [9].

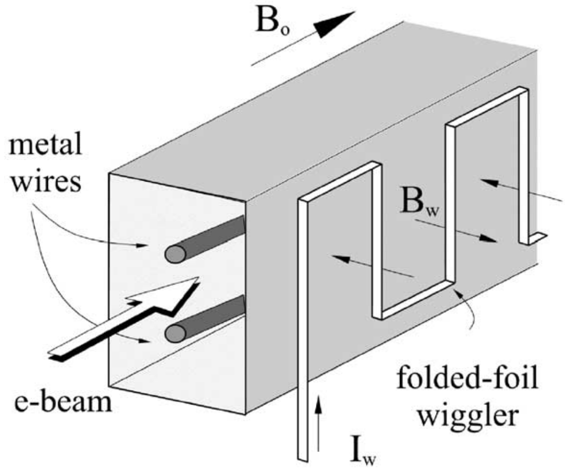

Fig. 4. The FEM scheme.

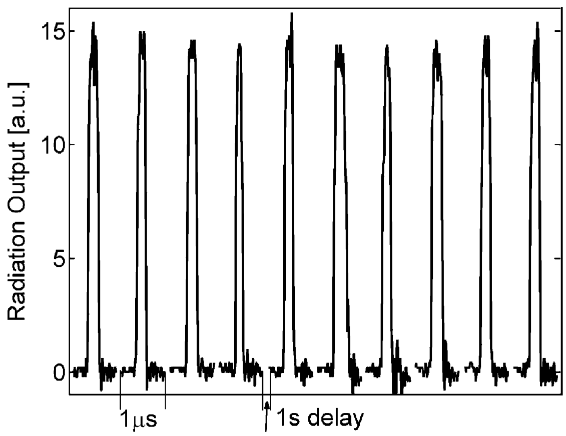

Fig. 5. The FEM radiation output.

The peripheral setup is similar to the gyrotron experiment [6]. A heterodyne mixer followed by a frequency-time-interval analyzer (HP 5372A) measures the microwave signal frequency. A calibrated detector measures the output power. The FEM is operated repetitively in a ~1 Hz PRF. A typical FEM output is shown in Fig. 5. The microwave pulse duration is ~0.2 μs, every 1 s. The microwave output power coupled via free-space antennas is ~16 W peak. The FEM interaction occurs with a 12.6 keV, 0.5 A e-beam. The measured frequency of the output signal is 3.2 GHz. The FEM is operated in this mode continuously for several hours. The experimental parameters and results are listed in Table 1.

Table 1
Experimental parameters

Electron-gun parameters	
Ferroelectric material	PLZT (12/65/35)
Cathode area	$7 \times 7\,mm^2$
Gun length	60 mm
Trigger voltage	0.8–1.5 kV
Anode voltage	5–14 kV
e-beam current	1–2 A
Pulse width	0.15–2 μs
Energy spread	~150 eV
Maximal PRF	3.1 MHz
Vacuum preasure	$<10^{-4}$ Torr
Cathode lifetime	$>10^7$ pulses
FEM parameters	
Undulator (folded-foil) periodicity	2 cm
Undulator magnetic field	1 kG
Cavity (interaction) length	70 cm
Microwave frequency	3.2 GHz
Microwave power	16 W

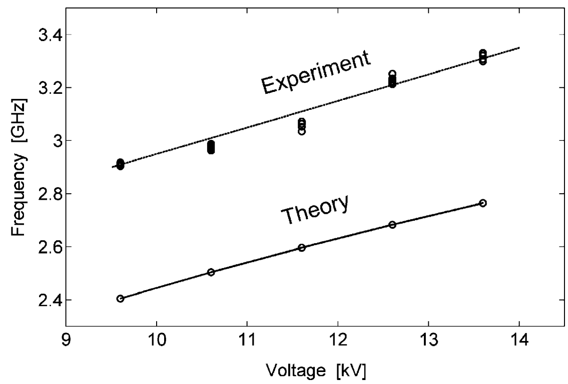

Fig. 6. Frequency measurements vs. accelerating voltage (experiment and theory).

The verification of the FEM interaction (rather than a CRM interaction) is based on several considerations. Frequency measurements of the FEM output signal were taken with slight variations in the accelerating voltage. The experimental tuning results shown in Fig. 6 indicate a positive linear dependence of the operating frequency on the accelerating voltage. This positive dependence, typical to FEM oscillations with a backward wave, is opposite to the negative frequency–voltage dependence in a backward-wave CRM. Furthermore, a CRM interaction with a TEM mode in the speed of light requires an extremely large perpendicular velocity as demonstrated in Ref. [10]. The final consideration that excludes the possibility of a CRM interaction is that the CRM tuning condition is simply not satisfied in the present experimental parameters.

4. Discussion

The ferroelectric electron-gun presented in this paper is designed to minimize the electron energy-spread related to the ferroelectric plasma emission, and to overcome breakdowns caused by the plasma expansion and subsequent gap shortening. Due to the two-accelerating-stage design, several useful features are achieved. The electron extraction is made by a low voltage and therefore the damage to the cathode is minimized. The positive first stage extracts electrons from the plasma and turns it to positive plasma. Hence, the positive grid-electrode rejects the remained plasma, repels it back to the cathode, and improves the regeneration of the cathode surface. Once the electrons have passed the first electrode, they are subjected to the second-stage voltage, and are accelerated without the interference of the ions locked in the first stage. Therefore, a full separation of the electrons from the ions is obtained. The first electrode serves also as a buffer between the second-stage high-voltage and the plasma, preventing a gap-closure and breakdowns.

The ferroelectric-gun presented above differs from the common scheme in which the cathode trigger-voltage serves also as the accelerating voltage for the electrons. The voltage is unstable there because of the plasma creation, and the electron energy-spread is too large to be used in microwave tubes. Therefore, the common scheme is not adequate for microwave electron tubes. In the present two-stage ferroelectric electron-gun, the accelerating voltage separated from the triggering voltage is much more stable, and therefore is acceptable for microwave free-electron devices [11].

This first operation of an FEM with a ferroelectric electron-gun shows the principle feasibility of this scheme. It overcomes several limitations attributed to ferroelectric cathodes (namely, gap-closure breakdown, lifetime, poor energy-spread, and limited PRF operation), and is significant also because of its simplicity and its extreme low cost. These enable a variety of FEM experiments in small laboratories, and a range of novel applications for low-cost high-power FEMs. The high-current ferroelectric electron-gun may lead to the development of high-power FEMs and other free-electron devices. The versatility and simplicity of the cathode geometrical shaping may enable novel implementations of multi-beam CRM and FEM arrays [12], and new FEM features such as spatial angular-steering of the output radiation beam [13].

References

[1] V.L. Granatstein, R.K. Parker, C.M. Armstrong, Proc. IEEE. 87 (1999) 702, and references therein.
[2] G. Rosenman, V.A. Okhapkin, Yu.L. Chepelev, V.Ya. Shur, Sov. Phys.-JETP Lett. 39 (1984) 477.
[3] G. Rosenman, D. Shur, Ya. E. Krasik, A. Dunaevsky, J. Appl. Phys. 88 (2000) 6109, and references therein.
[4] R. Drori, D. Shur, E. Jerby, G. Rosenman, R. Advani, R.J. Temkin, Radiation bursts from a ferroelectric-cathode based tube, IEEE, IR and MM Waves Conference Digest, Wintergreen, Virginia, 20–25 July, 1997, pp. 67–68.
[5] R. Drori, M. Einat, D. Shur, E. Jerby, G. Rosenman, R. Advani, R.J. Temkin, C. Pralong, Appl. Phys. Lett. 74 (1999) 335.
[6] M. Einat, E. Jerby, G. Rosenman, Appl. Phys. Lett., accepted for publication.
[7] M. Einat, E. Jerby, G. Rosenman, IEEE-MTT, accepted for publication .
[8] R. Drori, E. Jerby, Phys. Rev. E. 59 (1999) 3588.
[9] M. Einat, E. Jerby, A. Shahadi, Nucl. Instr. and Meth. A 375 (1996) 21.
[10] E. Jerby, A. Shahadi, R. Drori, M. Korol, M. Einat, M. Sheinin, V. Dikhtiar, V. Grinberg, M. Bensal, T. Harhel, Y. Baron, A. Fruchtman, V.L. Granatstein, G. Bekefi, IEEE Trans. Plasma Sci. 24 (1996) 816.
[11] M. Einat, Ph.D. Thesis, in preparation.
[12] E. Jerby, A. Kesar, M. Korol, L. Lei, V. Dikhtyar, IEEE Trans. Plasma Sci. 27 (1999) 445.
[13] E. Jerby, Phys. Rev. A 41 (1990) 3804.