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Free-electron maser driven by a two-stage ferroelectric electron gun

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A two-stage ferroelectric electron gun is employed in a free-electron maser (FEM) oscillator experiment. This gun produces a pulsed electron beam of a 5–15 keV energy, ~0.5 A current, and ~3% energy spread. The FEM output microwave pulse train is coupled out with a 66 W peak power. The microwave frequency is tunable in the range of 2.9–3.3 GHz by varying the electron beam energy. The interaction mechanism is identified by a comparison to the known FEM tuning relation. The energy spread of the two-stage ferroelectric electron gun satisfies the FEM acceptance parameter in the microwave regime.
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The discoveries of electron-emission phenomena from ferroelectrics have led to the development of ferroelectric cold cathodes with high current densities ($\sim 100\ \mathrm{A/cm^2}$).[1,2] As a plasma-assisted effect, the ''strong'' ferroelectric emission mode is characterized by a relatively large energy spread, and by the presence of ions near the cathode due to the plasma associated with the emission process.[3] These two features impede the applicability of ferroelectric cathodes in practical microwave tubes.

Ferroelectric cathodes are studied in experimental microwave tubes.[4–8] The two-stage ferroelectric electron gun[6–8] enables one to separate the electrons from the ions and to reduce the electron-beam energy spread. Its implementation in a cyclotron-resonance maser (operating in a gyrotron mode) yielded a 1.5 kW microwave power.[6] The relative contribution of the energy spread to the output signal line widening was found to be small.[8] However, the gyrotron mechanism is relatively tolerant to energy spread (thus, it was chosen for the first microwave-tube experiment with a ferroelectric cathode.)[4]

Free-electron masers (FEM's)[9] are essentially more sensitive to energy spread than gyrotrons. A preliminary FEM operation with a ferroelectric cathode yielded a relatively low microwave power.[10] In general, the frequency of the FEM radiation output should comply with the tuning condition,

$$\omega=(k_z+k_W)\nu_z\,, \tag{1}$$

where ω and k_z are the wave angular frequency and wave number, respectively, ν_z is the electron axial velocity, and k_W is the wiggler periodicity. The electron velocity is a dominant factor in the FEM tuning [Eq. (1)], thus, the electron energy spread may cause detuning and reduction of the FEM performance.[11]

This letter presents the two-stage ferroelectric electron-gun operation in an FEM experiment. The experimental setup is illustrated in Fig. 1. The device consists of three sections; the ferroelectric electron gun, the FEM interaction region, and the collector section. The electron gun includes two acceleration stages. The ferroelectric cathode is made of a $10\times10\times1\ \mathrm{mm^3}$ lead–lanthanum–zirconium–titanate 12/65/35 ceramic plate. Two electrodes are positioned on the ferroelectric plate. The rear (nonemitting) electrode is made of a uniform $7\times7\ \mathrm{mm^2}$ silver-paint coating. The front (emitting) electrode consists of a $7\times7\ \mathrm{mm^2}$ stainless-steel grid, attached to the ceramic plate. A ~1 kV trigger pulse is applied to the rear electrode in order to activate the plasma on the front surface. The same pulse is applied to the control grid, positioned 5 mm in front of the cathode as the first accelerating stage. The anode, in a distance of 6 cm, provides the second acceleration stage.

The two-stage electron-gun configuration suppresses the plasma expansion on the cathode surface; it separates the electrons from the ions, and reduces the electron energy spread to ~3% (~150 eV at 5 kV accelerating voltage). The energy spread was measured[10] by varying the voltage applied to a repelling electrode inserted before the collector. This gun operates in modest vacuum conditions of $10^{-4}-10^{-5}$ Torr. The current pulse width (typically 0.2 μs) is variable in the range 0.15–2 μs. The pulse repetition rate is tunable up to 3.1 MHz (duty cycle 0.5). The electron energy can be tuned up to 15 kV, and the typical beam current is ~0.5 A. The electron gun and its parametric measurements are described in more detail in Refs. 6–8 and 10. This two-stage gun con-

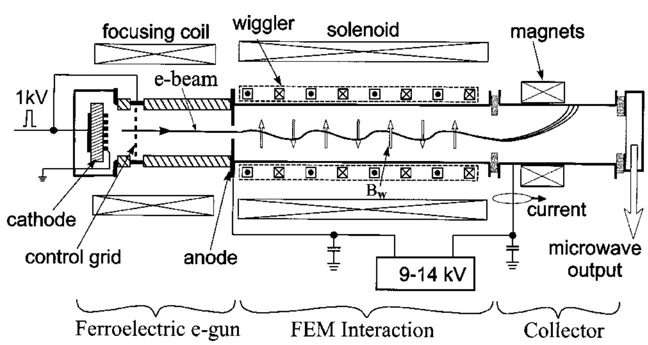

FIG. 1. The FEM experimental setup.

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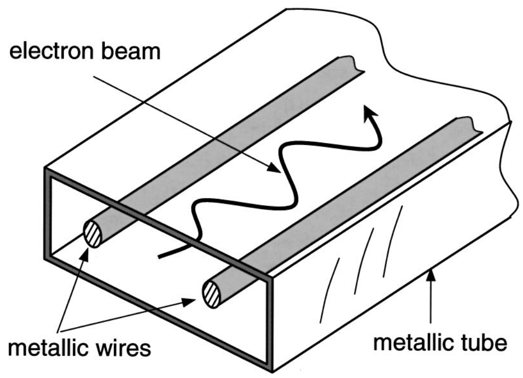

FIG. 2. The FEM interaction region.

figuration resembles, in some aspects (except the cathode type), the plasma gun presented in Ref. 12.

The electron beam is injected into the FEM interaction region (45 cm length). The microwave cavity consists of a standard rectangular waveguide ($0.9\times0.4\,\mathrm{inch}^2$) along which two metal wires are stretched as shown in Fig. 2. This structure supports a TEM wave without a cutoff frequency. Therefore, the FEM interaction can occur in relatively low voltages and low frequencies.[13] A solenoid applies an axial magnetic field (0.8 kG) to guide the electrons through the tube. A folded foil wiggler (22 periods, 2 cm each) provides an alternating magnetic field ($B_w\approx0.4\,\mathrm{kG}$) to undulate the electron beam. At the exit of the interaction region, the electron beam is dumped by permanent magnets to the collector walls. A Rogowsky coil measures the collected beam current.

The radiation output is coupled out from the oscillator cavity and fed to the microwave diagnostic setup shown in Fig. 3. After a 41 dB attenuation, the microwave signal is inserted into a microwave mixer detector (HP 5346A), where it is mixed with a local oscillator. An oscilloscope traces the microwave signal envelope, and a frequency–time–interval analyzer (HP 5372A) measures the intermediate frequency. The igniting trigger pulse and the corresponding electron current pulse are shown in Fig. 4. The microwave output pulses are shown in Fig. 5. The FEM was operated in this mode (at $\sim$1 Hz repetition rate) for many hours yielding stable results. A maximal microwave power of $\sim$66 W was measured, which corresponds to $>$1% electronic efficiency.

The frequency of the FEM microwave signals was measured as a function of the voltage in the range of 9–14 kV. The results are compared to the theoretical curve obtained from the FEM tuning condition (1), as shown in Fig. 6. In this analysis, the perpendicular and axial electron-beam ve-

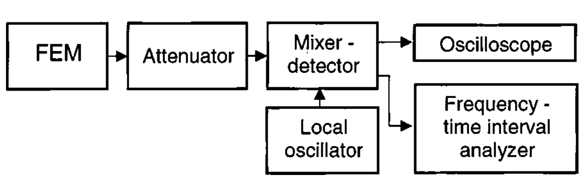

FIG. 3. The microwave diagnostic setup.

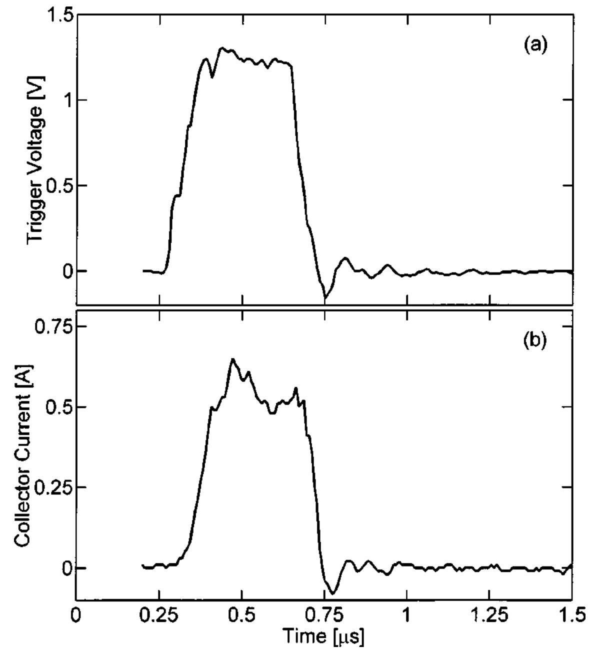

FIG. 4. The cathode trigger voltage (a), and the corresponding collector current (b).

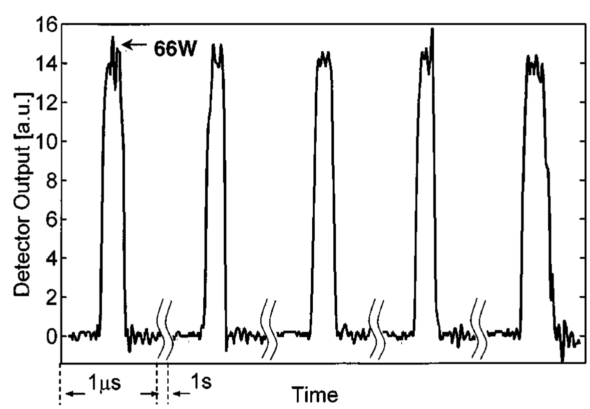

FIG. 5. The detected FEM output microwave signal.

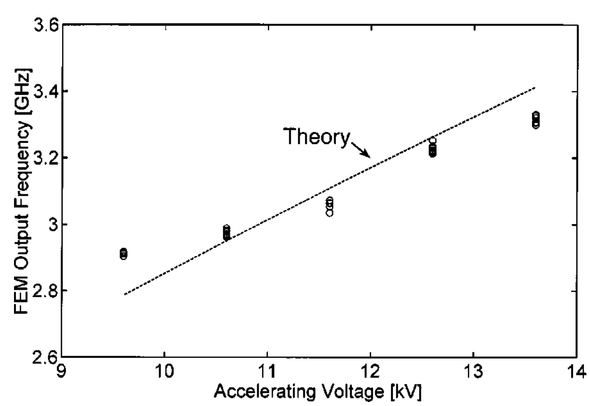

FIG. 6. The output signal frequency vs the electron accelerating voltage (circles), in a comparison to the FEM theoretical tuning condition (dashed curve).

locity components were calculated by an electron-trajectory simulation, using the actual accelerating voltage and wiggler magnetic fields (note that the theoretical curve in Fig. 6 is not a straight line). The agreement between the experimental measurements and the theoretical results confirm the FEM interaction mechanism in this experiment (the cyclotron-resonance interaction[14] is not feasible in these operating conditions).

The FEM sensitivity to the electron-beam energy spread is characterized[11] by the spread acceptance parameter $\overline{\theta}_{th}^{ac}$ (i.e., the electron spread reducing the FEM power gain to half of its zero-spread value). The $\sim$150 eV energy spread obtained by this two-stage ferroelectric electron gun is well within the FEM acceptance range in the present experimental condition. Furthermore, it satisfies the FEM acceptance requirement up to $\sim$30 GHz. Hence, in view of the ferroelectric-cathode advantages; the high current density, reasonable energy spread in two-stage configuration, low cost, and simple operation, this cathode could be considered as a candidate for pulsed high-power FEM devices.

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