# 95 GHz Gyrotron with Ferroelectric Cathode

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Ferroelectric cathodes were reported as a feasible electron source for microwave tubes. However, due to the surface plasma emission characterizing this cathode, operation of millimeter wave tubes based on it remains questionable. Nevertheless, the interest in compact high power sources of millimeter waves and specifically 95 GHz is continually growing. In this experiment, a ferroelectric cathode is used as an electron source for a gyrotron with the output frequency extended up to 95 GHz. Power above a 5 kW peak and $\sim$0.5 $\mu$s pulses are reported; a duty cycle of 10% is estimated to be achievable.

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Ferroelectric cathodes were developed in the last few decades as a cold source of electrons as well as ions and plasma. Already in the initial reports of the electron emission from ferroelectric cathodes, the apparent possible applications were noted [1]: ''Electron beams with ever increasing density are required in accelerators, free-electron lasers, and electron tubes for radio frequency, microwave and x-ray generation....'' Many consequent reports explored the characteristics of the cathode, and scientific arguments regarding the exact emission mechanism were made. Review reports concluding hundreds of works regarding the ferroelectric cathodes are in Refs. [2–4]. Nowadays, it is well understood that the strong emission of the ferroelectric cathode is a plasma assisted effect and therefore inferior to the thermionic cathode for microwave tubes, due to the quality of the electron beam. Nevertheless, ferroelectric cathodes do have some advantages over thermionic cathodes, such as the possibility for higher current density and total current, immediate operation, low cost, and operation in modest vacuum conditions. Once the electron beam can be proven to be good enough, all these advantages can be harnessed in microwave tube devices.

Implementing the cathode in microwave tubes is evidently not so easy. Although electron emission was reported already in 1988, microwave radiation produced by a ferroelectric cathode driven tube was reported only a decade later. Since 1998, a few microwave tubes were reported upon with output radiation in the range of 3–10 GHz; these were based on a variety of interaction mechanisms [5–14]. Recently, a 23 GHz gyrotron with a ferroelectric cathode was reported [15]. Since the emission is based on surface plasma, obtaining a higher frequency remained uncertain. In this Letter, an experimental validation of a gyrotron with a ferroelectric cathode operating at 95 GHz is presented. This frequency was chosen as it is of practical interest for many applications. As is well known, there is an atmospheric band pass around this frequency where the propagation attenuation is relatively low. Applications in this frequency range are in wide band communication [16], security [17], imaging [18,19], radar [20–22], and other applications [23].

Gyrotrons [24–27] are a well known type of electron tube and are the dominant source of millimeter waves. Although it is a well established device, intensive research is still done to push further the performance of the gyrotron. Recent achievements are in the THz regime [28–30] and the picosecond regime [31]. Gyrotrons are usually operated with a magnetron injection gun based on a thermionic cathode [32–34]. Other types of cathodes were also investigated as electron sources for gyrotrons. Examples are field emission using arrays of silicon tips [35], explosive emission cathodes [36], and velvet cathodes [37]. A comparative study has been conducted of the different methods [38]. In this experimental work, the possibility to employ a ferroelectric electron gun in a high power millimeter wave source is explored. A ferroelectric electron gun was designed and built as an electron source of a 95 GHz gyrotron. Demonstrating such a gyrotron, operating at a power level of a few kW with considerable efficiency may promote applications that become practical in view of the unique characteristics of the cathode.

The experimental setup is illustrated in the following Figs. 1–5. The ferroelectric cathode used is shown in Fig. 1. It is made from a barium titinate ceramic disc ($\varepsilon_r > 3000$, 1.8 cm diameter) with metal electrodes on both sides. On the rear (nonemitting) side, there is a solid coated electrode, circular in shape with a 1.6 cm diameter. On the front (emitting) side, there is a glued ring shaped metal electrode, with a 1.5 cm diameter and $\sim$1 mm thickness. The ceramic is placed in a plastic case that is sealed with a grid on its front side, spaced 5 mm from the cathode front side.

The electron gun arrangement is displayed in Fig. 2. A hollow subanode is placed $\sim$2 cm in front of the cathode grid, and an anode with a 6 mm aperture is placed 12 cm in front of the subanode. A focusing solenoid is used in the gun section to guide the electrons into the tube. The anode is grounded, and the cathode section is connected to a −42 kV potential. The cathode is ignited using a 3.5 kV

 

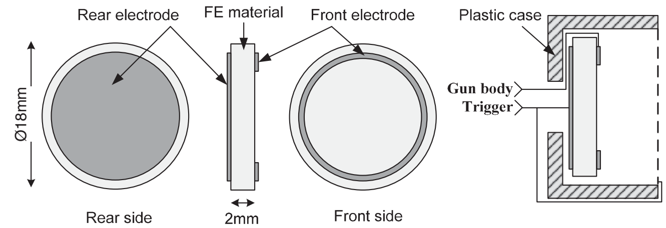


FIG. 1. The ferroelectric (FE) cathode arrangement.

pulse that is applied to the rear electrode and to the grid simultaneously, while the front electrode is kept at the cathode section potential. The subanode is connected to a 4 kV dc (relative to the cathode section), and the entire electron acceleration is completed at the grounded anode. The typical pulse duration is $\sim$500 ns.

The electron beam enters the resonator through an input taper (20.6 mm length) which serves as a mirror of the resonator (Fig. 3). A 24.4 mm long straight brass cylinder with a 7.07 mm diameter is used as the resonator, terminated with an output taper that widens to an aperture of 20 mm diameter. This taper serves also as a collector for the electron beam. At the end of the taper, there is a vacuum window. The resonator diameter is designed to fit a cylindrical TE02 mode at 95 GHz, and its length is designed for a single longitudinal half-wavelength. Wrapped around the resonator is a solenoid with longitudinal homogeneity of $\sim$0.5% which operates with $\sim$3.6 T pulses, fitting the first harmonic gyrotron operation. Two current measurements are carried out, at the collector and at the anode, by Rogowski coils. The system is pumped to $\sim 10^{-5}$ Torr with a turbo pump.

The phenomenon of ferroelectric emission is too "young" to be included in electron trajectory simulation codes. Nevertheless, a trajectory simulation from the cathode up to the resonator entrance was run (Fig. 4), knowing that the emission process itself is not adequately described, and therefore the simulation results are probably less accurate in comparison to thermionic emission simulations.

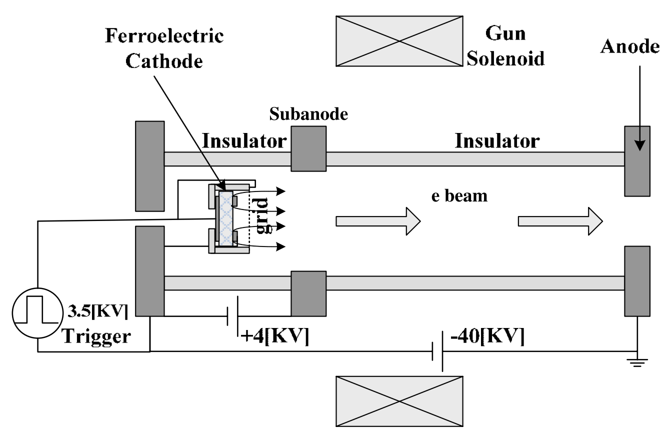


FIG. 2 (color online). The ferroelectric electron gun arrangement.

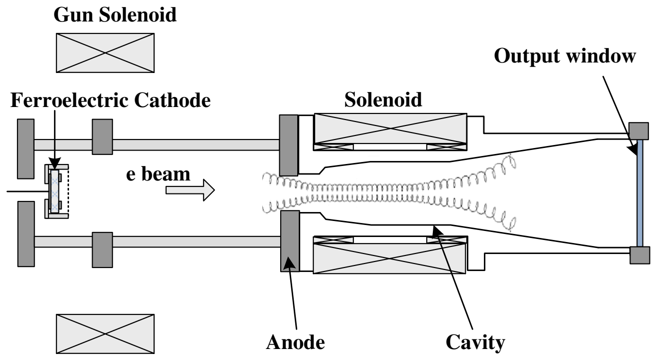


FIG. 3 (color online). The experimental setup of the ferroelectric cathode 95 GHz gyrotron.

The diagnostic setup is shown in Fig. 5. In front of the open cylindrical output of the waveguide, two rectangular horn antennas were located to receive the transmitted radiation pulses. The location of the first was fixed (it served as a reference channel), and the location of the second was varied during the experiment though held at a constant radius of 1.4 m, in order to obtain the transmitted pattern [39]. The receiving channel was based on WR10 standard components and included a 23 dBi Gain rectangular antenna, an attenuator, a 95 $\pm$ 1 GHz band pass filter (BPF), and a detector. This setup enables ensuring that the measured frequency was indeed 95 GHz, measuring the radiated power, and the radiated pattern.

The experiment was operated in a pulsed mode. The solenoid was triggered first, its pulse duration was a few milliseconds, and, when the magnetic field reached 3.5 T, the electron gun was triggered with a much shorter pulse of $\sim$500 ns. Currents of $\sim$1 A were measured at the collector. During the current pulse, the resonator was excited and radiation readings were obtained at the detectors. A typical result can be seen in Fig. 6(a). Traces of the electron beam current at the collector and the radiation obtained at the receiving channel detector and the reference channel detector can be seen. Taking into account the overall channel losses (considering also the pattern gain that is shown further below), the generated power obtained according to both of the channels is $\sim$5 kW. The conversion efficiency is $\sim$12%. The experiment was repeated many times,

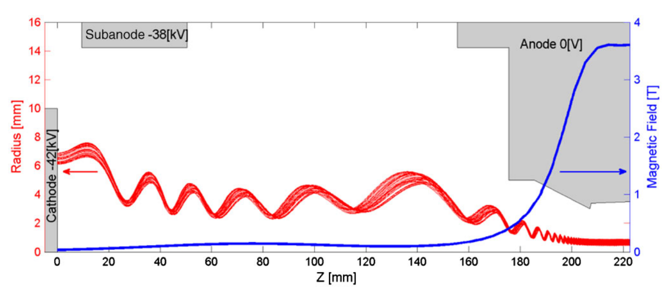


FIG. 4 (color online). Simulation of the electron beam trajectory.

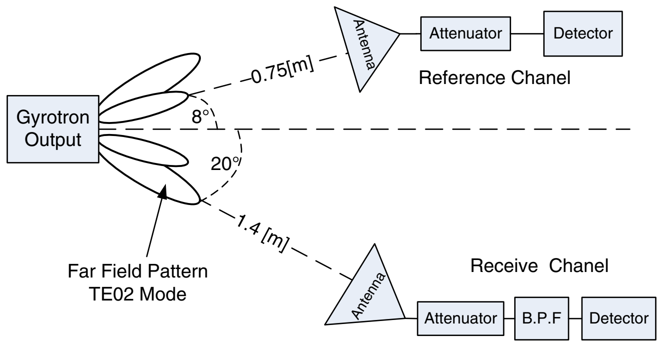


FIG. 5 (color online). The diagnostic setup.

and the repeatability of the results can be evaluated in Fig. 6(b), where an accumulation of many sequential pulses is seen. The small variations that are seen can be related to pulse-to pulse variations of the magnetic field.

In order to properly evaluate the radiated power in this setup, a description of the radiated pattern was needed. This task was done both theoretically and experimentally.

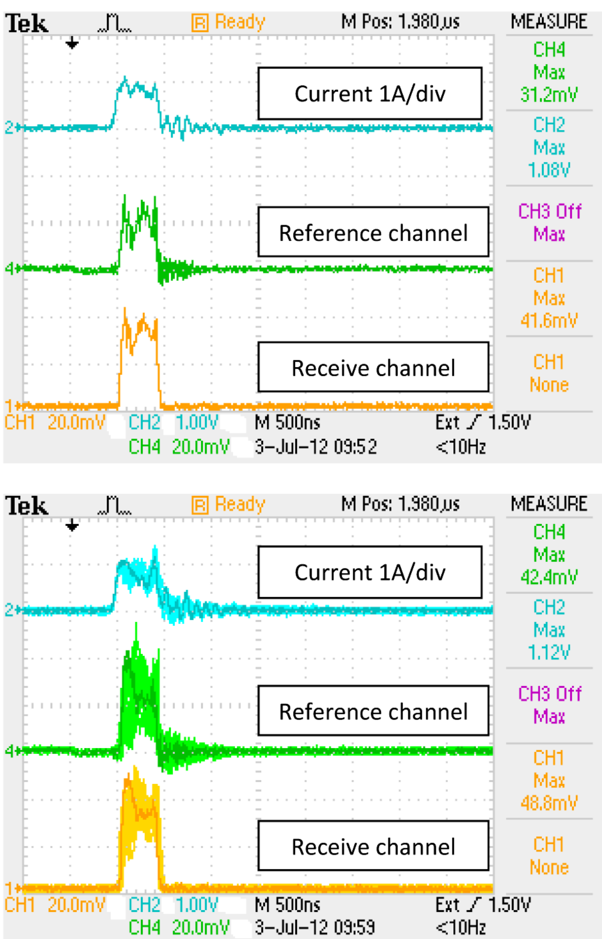


FIG. 6 (color online). Experimental results: the collector current and the detector's voltage readings in the two channels are seen. (a) A single typical pulse. (b) The accumulation of many subsequent pulses.

A numerical calculation was programed using CST code, and the results are presented in Fig. 7, together with the results of two sets of measurements. The measurements were performed while the angle of the antenna in the receiving channel was gradually moved along a constant radius of 1.4 m. The readings were normalized to the reference channel, which was stable. The normalization was done to eliminate the influence of small variations that may occur among subsequent pulses. Each point in the graph represents an average of 5 measurements in the same location. This experiment was repeated twice. As can be seen, the measured pattern indeed represents the expected pattern for a TE02 mode radiating out of the output cylinder. From this graph, the gain pattern is obtained for calculating the radiated power.

The repetition rate of the device is limited to $\sim$0.1 Hz by the charging time of the power supplies and the rise in temperature of the solenoid. This parameter can be enhanced by implementing a proper cooling system and improved power supplies.

In order to demonstrate the cathode's ability to emit high repetition rate pulses [8,40], the setup was modified to include several micropulses of the cathode within each single macropulse of the solenoid (Fig. 8). Several pulses at a $\sim$0.7 MHz repetition rate and $\sim$25% duty cycle are presented. The average power during this period is therefore above 1 kW. This result shows that fast recovery of the cathode is possible, but the nature of its operation is in a repetitive pulse mode and not a long continuous pulse mode as in a thermionic cathode.

Finally, it should be noted that this tube has unique practical parameters stemming from the nature of the cathode. The cathode itself cost about \$1 (compare this with the $\sim$\$10 000 cost of a thermionic cathode for the magnetron injection gun usually used in gyrotrons). It is a cold cathode allowing the use of simple low cost materials. Modest vacuum is needed. The shelf lifetime even in air is unlimited, and no preparation or "standby" mode is needed before operation. The tube can be left at air

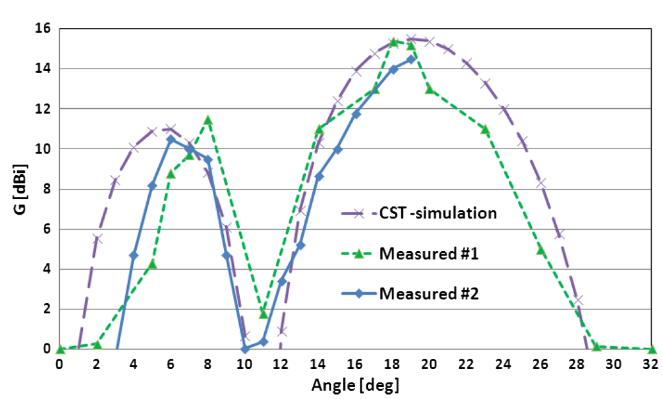


FIG. 7 (color online). Measurement and theoretical evaluation of the radiated pattern.

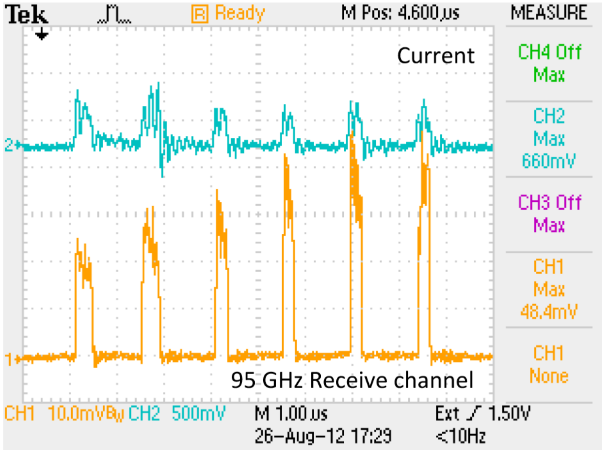


FIG. 8 (color online). Operation at ~0.7 MHz repetition rate, ~25% duty cycle, and above 1 kW average power during a macropulse of the solenoid.

pressure when not in use. No periodical refreshment of the cathode is needed. Once the operation of a ferroelectric cathode in a 95 GHz gyrotron is proven feasible, for certain applications where these characteristics are important, it becomes the superior candidate for use in gyrotrons specifically, as well as in other electron tubes.

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