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# Studies of Vircator Operation at FOI: Electrode Material Erosion Studies

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*The high-power microwave (HPM) pulse generation process in a narrowband source is studied in single-pulse reflex triode experiments and repetitive axial vircator experiments. Electrode erosion is identified as an important limiting phenomenon for efficient durable HPM generation. The stability of the pulse generation mechanism in a burst of ten pulses at 10 Hz in an axial vircator is examined. Different electrode material combinations display markedly different behaviors with respect to pulse amplitude, dominating frequency, pulse shape, and electrode erosion. Graphite emitters have proven to generate comparatively stable pulses, in a single burst and over several bursts. The vircator impedance during microwave emission is also more stable with graphite as emitter material than with velvet. These observations can be utilized to improve the operating performance of vircators and similar HPM sources.*

**KEYWORDS:** Electrode material erosion, High-power microwave, Vircator

## 1. Introduction

High-power microwave (HPM) devices may be used in systems for disrupting or destroying electronic equipment. To be practically useful on a typical mobile platform, an HPM device needs to be as compact and as efficient as possible. Radiation sources of the virtual cathode oscillator (vircator) type are simple and rugged but generally suffer from low efficiency.[5] Any improvement in the HPM pulse-generating process can be used to extend the range or reduce the size of the HPM device.

To achieve good effect in targets, it is desirable to generate several pulses with a high pulse repetition rate, but this increases the demand on average power from the pulsed-power supply and also results in considerable thermal stress on electrode materials in narrowband HPM sources. Electrode erosion decreases the lifetime of the radiation source and can also result in varying HPM pulse characteristics.

Electrode erosion in high-power electron beam devices is well known, especially for velvet emitters. For example, Zhang et al.[17] in 1991 showed scanning electron micrographs of molten and broken velvet fibers and compared breakdown delay times for different

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materials. Shiffler et al.[15] showed that carbon fiber cathodes coated with cesium iodide at 1-Hz repetitive operation have a lifetime superior to that of velvet cathodes but also that the CsI-coated fiber needs conditioning to achieve peak performance. More recently, Chen et al. tested several different cathode and anode materials in repetitive[7] and single-shot[6] reflex triode vircator geometry. They showed high peak power and long lifetime for cathodes with carbon fiber and etched aluminum emitters. The choice of anode material and geometry has also been shown to be important for the emission process at the cathode,[16] and it has been shown that a high geometric transparency is beneficial for high peak power.[6] Further aspects on anode and cathode materials, as well as additional references, can be found in the literature; see, e.g., the books by Barker et al.,[3] Barker and Schamiloglu,[4] and Benford et al.[5]

Studies performed at FOI address different aspects of the HPM pulse-generation process in a narrowband source. The pulsed radiation sources used in the experiments reported here are of the vircator type, specifically a reflex triode and an axial vircator. One reason for choosing a vircator as a radiation source is that it is relatively easy to alter the geometry and carry out parametric studies. This paper reports some experimental results pertaining to electrode erosion encountered in vircator experiments performed at FOI. In particular, results from electrode material erosion and microwave generation studies with bursts at a 10-Hz pulse repetition rate are presented.

## 2. Reflex Triode Single-Pulse HPM Generation

An initial study of HPM generation in vircators was conducted with a reflex triode. The objective was to perform a parametric study, including the influence of applied voltage, electrode distance, and electrode diameter on the generated radiation pulses. Results from this study have been reported elsewhere.[1,10,14]

The reflex triode used in the parametric study is shown schematically in Fig. 1. The anode was made of a woven stainless-steel mesh with nominal transparency 71% and 120-mm effective diameter fitted inside a brass torus. The cathode, a brass disk with 90-mm diameter, was placed concentrically above the anode and had an emitter surface consisting of either velvet cloth or metal nails.

The reflex triode was powered by a compact 400-J, 400-kV, single-shot Marx generator charged by a switching power supply with a programmable duty cycle to control the charging current.[2] The Marx generator and charger were housed inside a cylindrical volume with diameter 0.25 m and length 1.7 m. The Marx output current and voltage were measured along with the generated microwave pulse field strength.

In the parametric study performed with the reflex triode, the anode mesh showed evidence of electrode erosion being shifted in a direction away from the current feed (Fig. 2). This asymmetry is also seen in particle-in-cell simulations of the source and may be explained by a Lorentz force acting on the electron beam.[11] This means that the virtual cathode, formed below the anode in Fig. 1, will be displaced and excite oscillations in the resonant cavity at a location that is not exactly the mirror image of the cathode. Similar beam displacements may also occur in other configurations in which displacement of the electron beam can increase the inductance of the current loop, such as coaxial vircator geometries. In such cases, an optimal emitter position can be found with simulation.[12]

The electrode erosion observed after exposure to only a few dozen pulses in the reflex triode single-pulse experiments was seen as a local deformation and discoloring of the

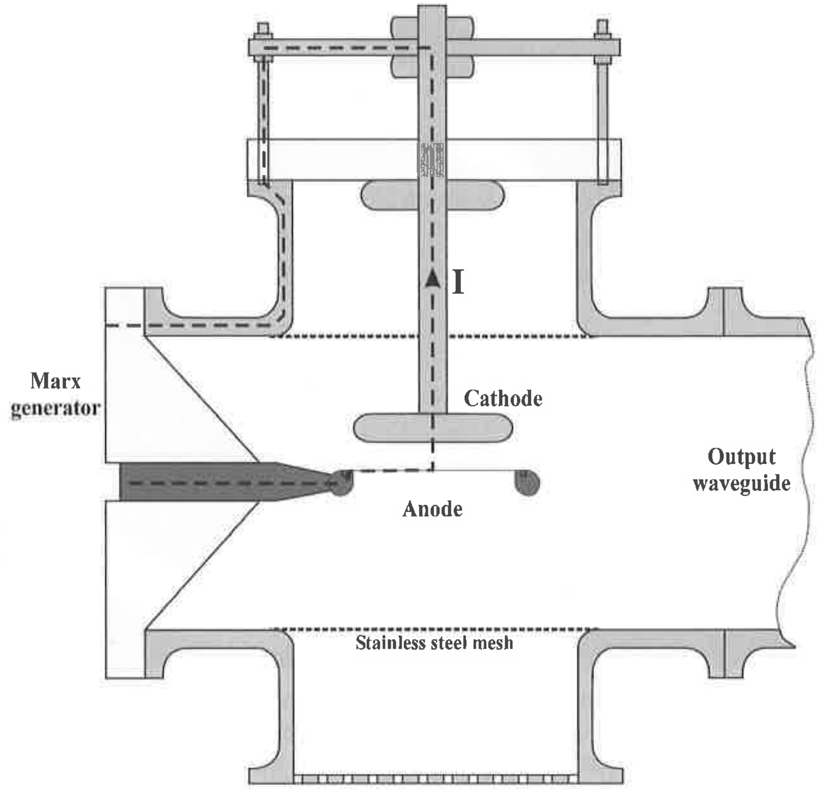



**Fig. 1.** Schematic drawing of the reflex triode geometry showing the current path (dashed line).

wires in the affected area of the anode mesh and as a discoloring and decomposition of the velvet emitter. These observations necessitated an investigation of electrode material durability for a large number of pulses at repetitive operation.

## 3. Axial Vircator Repetitive HPM Pulse Generation

A study of repetitive HPM pulse generation was conducted with an axial vircator and a 500-J, 500-kV, 25-stage Marx generator with a pulse repetition rate of 10 Hz (Refs. 7 and 13). The stability of the pulse-generation mechanism in bursts of 10 pulses at 10 Hz was examined. The axial symmetry precludes any beam displacement of the kind that was observed in the reflex triode.

The Marx generator and charger have a total length of 1.1 m and outer diameter of 0.3 m. In the experiments reported here, the Marx generator was charged to 400 kV, with a charged energy of 320 J. A capacitive voltage divider and a Rogowski current probe were situated at the Marx generator output.

The axial vircator housing consists of a standard 8 × 6 × 8 in. vacuum T-cross, with internal electrode and cavity configuration as seen in Figs. 3 and 4. The construction allows variation of the anode–cathode gap (AK-gap) distance, the resonance cavity depth, and the exchange of anode and cathode.

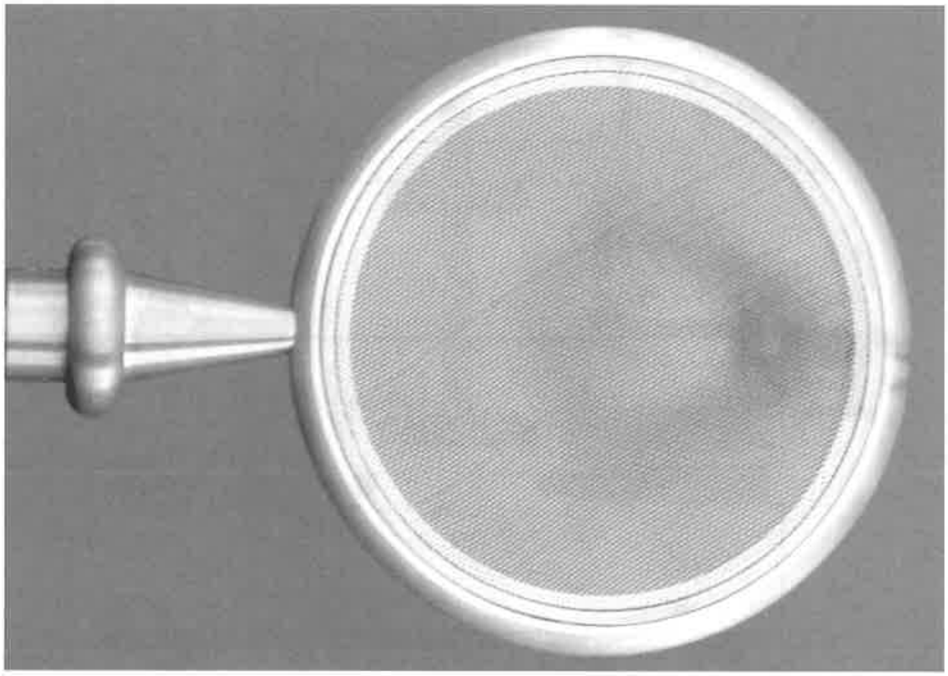


**Fig. 2.** Anode holder with anode mesh, displaying an erosion area displaced to the right, away from the current feed through the anode holder rod (photograph taken after a few dozen pulses). The image has been processed to enhance the discoloring.

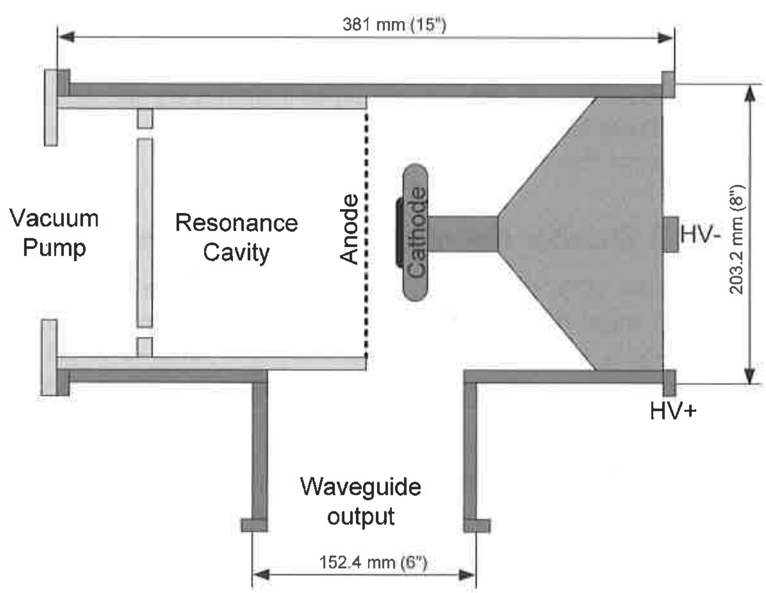



**Fig. 3.** Schematic drawing of the axial vircator geometry. Here microwaves are extracted only from the A-K gap into the waveguide.

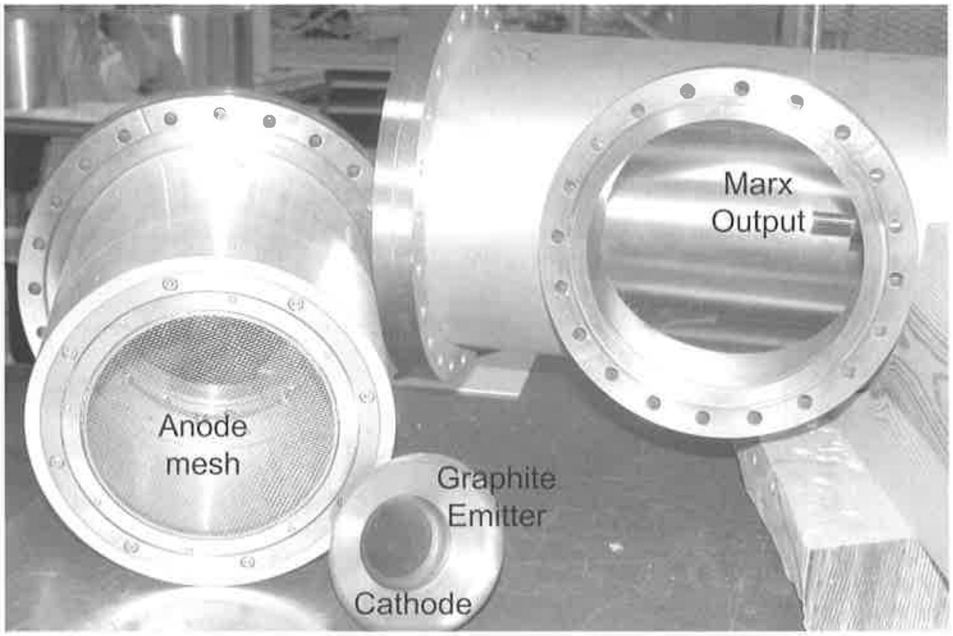



**Fig. 4.** Anode mesh holder, the cathode plate with attached graphite emitter, and the vacuum T-cross with the inner conductor from the Marx generator visible.

A 2-m-long waveguide is connected to the 6-in. output port of the vircator ending inside an anechoic chamber, where the radiated pulses are measured with four free-field B-dot probes. An optical signal is transmitted from the microwave registration to the current- and voltage-recording equipment, thus enabling relative timing of the microwave pulse and the voltage pulse. The end of the microwave pulse is taken as the instant when the average power of the signal has decreased to twice the power of the noise.

A number of different electrode materials have been tested, including velvet and graphite emitters as well as anodes made of stainless-steel mesh, parallel stainless-steel wires, and parallel molybdenum wires.[8,9] In the experiments reported here the AK gap was 12 mm.

The velvet and polished graphite emitters both have a diameter of 55 mm and are mounted on 100-mm-diameter flat brass disks with rounded edges. The stainless-steel mesh anode is an AISI 316 woven mesh with 0.22-mm wire diameter and 1.6-mm wire separation distance. The molybdenum wire has a diameter of 0.25 mm and is mounted through holes drilled in a brass ring, which gives a wire separation of about 3 mm. Hence, the geometric transparency of the stainless-steel mesh anode is about 77%, and the geometric transparency of the molybdenum wire anode is more than 90%.

In the experiments reported here, the orientation of the molybdenum wire anode was with the wires at right angles to the extraction direction of the output waveguide, i.e., at right angles to the plane of Fig. 3.

As illustrated for three electrode material combinations in Figs. 5–7, the repeatability of the voltage and current pulse shapes in a burst of 10 pulses is high, but there are significant differences for the electrode material combinations.

With a velvet emitter, the current starts to increase almost immediately after the voltage is applied and reaches its maximum about 50 ns before the voltage maximum, whereas

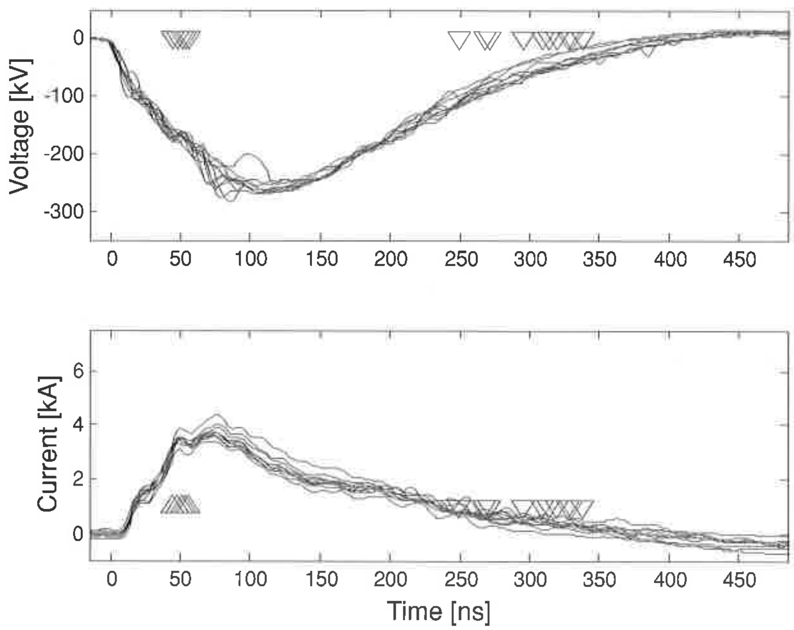



**Fig. 5.** Voltage and current pulses for a 10-pulse burst with stainless-steel mesh anode and velvet emitter. Triangles mark start and end times for the microwave pulse.

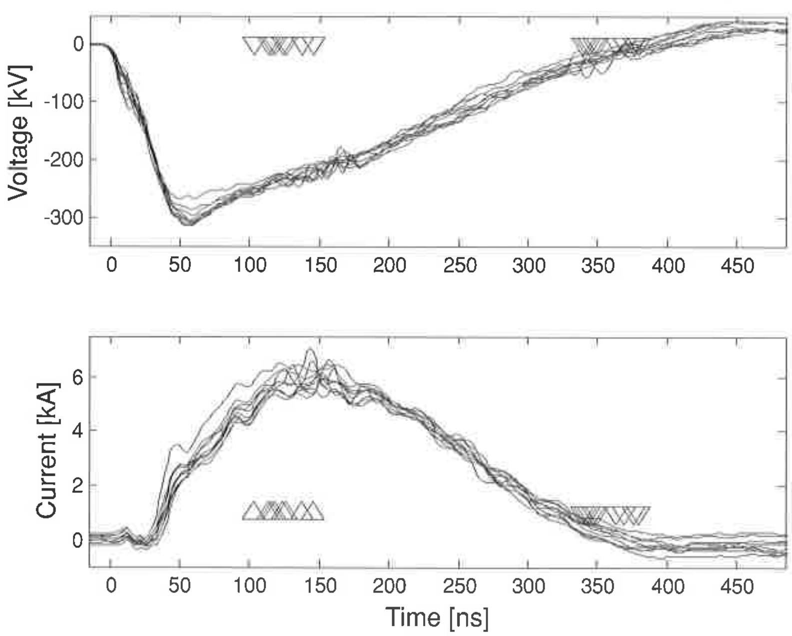



**Fig. 6.** Voltage and current pulses for a 10-pulse burst with stainless-steel mesh anode and graphite emitter. The triangles mark start and end times for the microwave pulse.

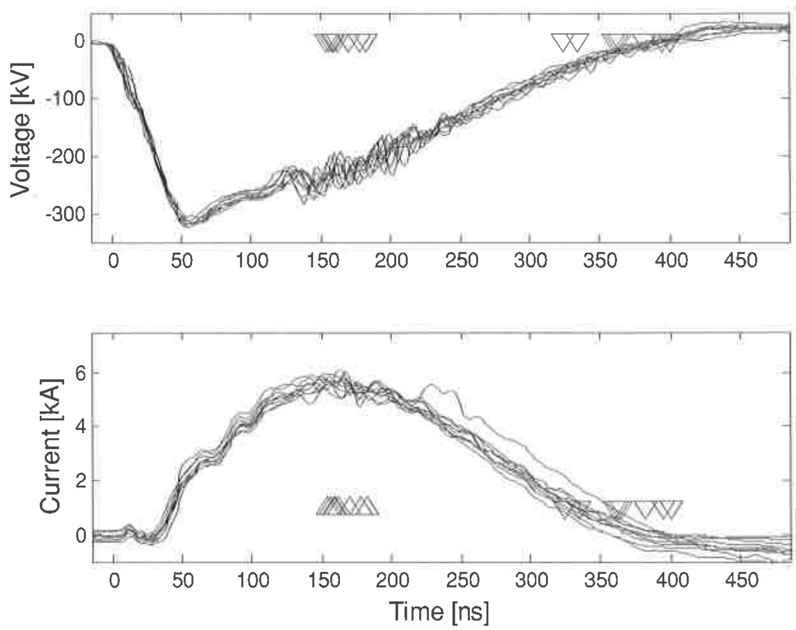



**Fig. 7.** Voltage and current pulses for a 10-pulse burst with molybdenum wire anode and graphite emitter. The triangles mark start and end times for the microwave pulse.

the graphite emitter experiments exhibit a delay of about 30 ns from the voltage increase until the current starts to rise and the current maximum is reached about 100 ns after peak voltage. The voltage rise is much slower and the start of microwave radiation is significantly earlier with a velvet emitter than with a graphite emitter.

Figure 8 shows the impedance of the radiation source, calculated from the voltage and current measurements for the three electrode material combinations. It is seen that the impedance behaves irregularly when a velvet emitter is used, whereas it is very similar for the 10 pulses in a burst when using a graphite emitter. Furthermore, with a graphite emitter the impedance is almost stable at about 30–35 Ω during most of the microwave generation interval. With a velvet emitter, the impedance initially decreases to a minimum of about 50 Ω and increases during the microwave emission to more than 100 Ω.

There are minor differences between the two impedance curve sets with a graphite emitter and different anodes, but the overall behaviors are similar. The initial impedance decrease is slower with a molybdenum wire anode, which is reflected in a delayed onset of microwave radiation by about 40–50 ns.

Comparing the peak magnetic field strengths and the pulse widths for the 10 pulses in a burst, as in Fig. 9, it is seen that both quantities vary between the individual pulses in a burst and between different electrode material combinations. A more thorough comparison is obtained by averaging over a series of 20 consecutive bursts. The results are shown in Figs. 10–12 for the three electrode material combinations. To the left in each figure the variation of the averages of peak field strength, pulse length, and dominating frequency taken over the 10 pulses in a burst is displayed. To the right in each figure the averages of the same quantities are taken for each pulse in the burst sequence over the series of bursts. Error bounds given are one standard deviation.

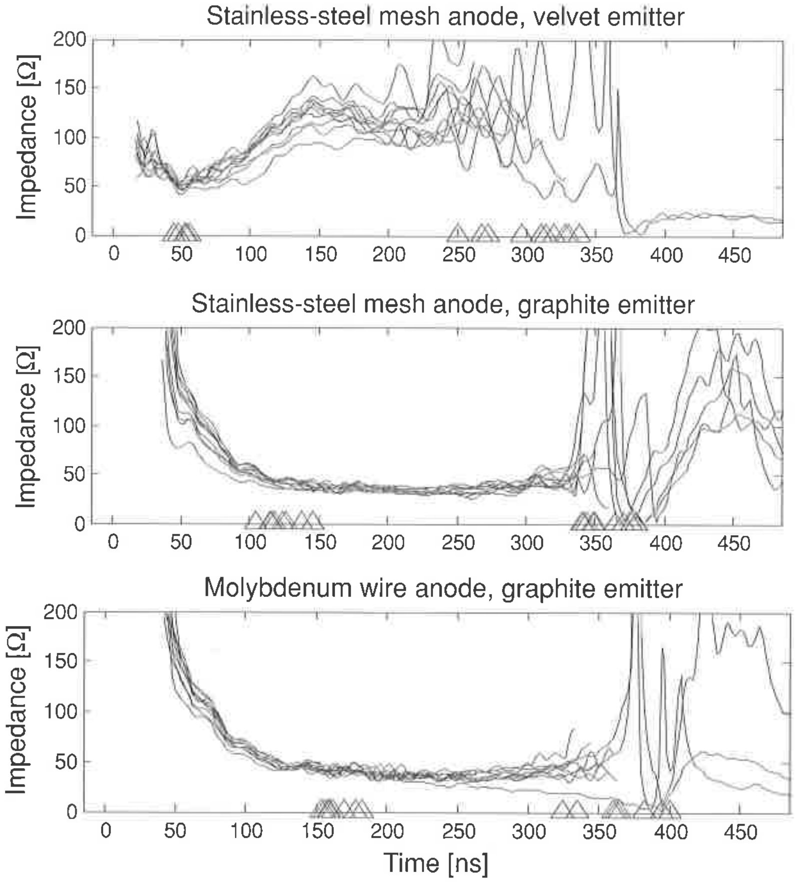



**Fig. 8.** Radiation source impedance for the three electrode material combinations.

In the first 10 bursts in each series the erected Marx voltage is 340 kV, whereas the last 10 bursts are obtained with an erected Marx voltage of 405 kV. The increased Marx output voltage in the middle of each series is clearly manifested only in the field strength for the graphite emitter and molybdenum wire anode combination. This is not seen in the two cases with a stainless-steel mesh anode. The statistical variation of field strength, pulse length, and frequency also seems to be smaller with a molybdenum wire anode.

For both velvet and graphite emitters in combination with a stainless-steel mesh anode, the field strength and pulse length tend to decrease toward the last four pulses in a burst, and the statistical variation of all the quantities increases for the last pulses in a burst. Neither of these tendencies is observed in the case with the molybdenum wire anode and graphite emitter. This may indicate that the microwave generation is more stable with the molybdenum wire anode.

The highest peak fields and pulse lengths are obtained for the first pulses in a burst with a velvet emitter, but this does not necessarily imply that velvet provides the highest microwave pulse energy or efficiency.

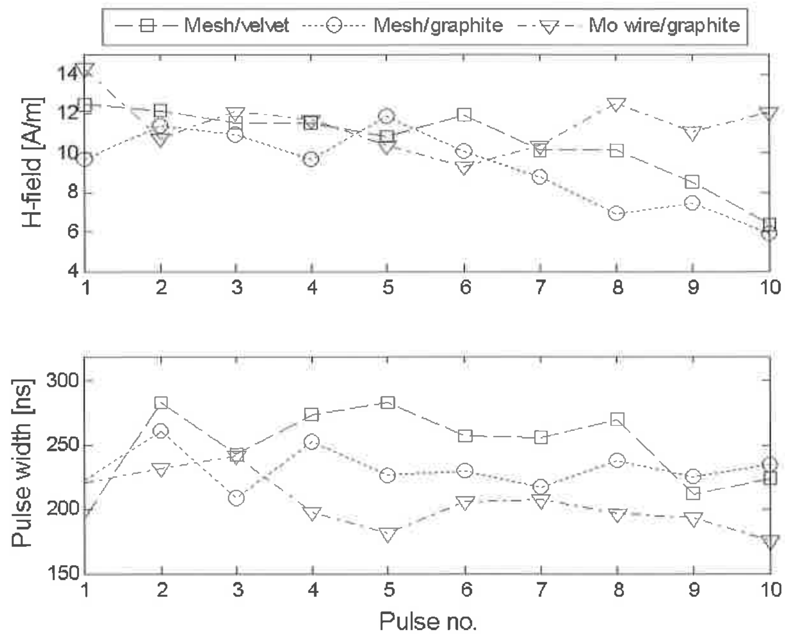



**Fig. 9.** Maximum H-field and pulse width for the 10 microwave pulses in one burst for the different anode/cathode configurations.

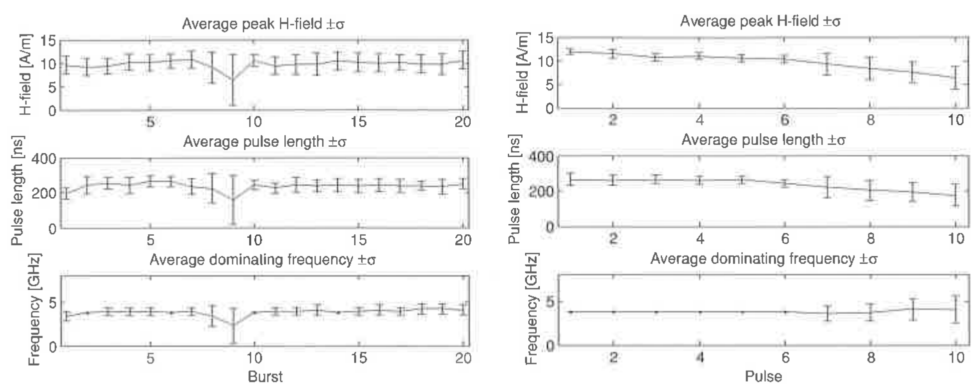



**Fig. 10.** Average peak H-field, pulse length, and frequency. Averages are taken over the 10 pulses in each burst for a series of 20 bursts (left) and over the 20 bursts for each pulse in the burst sequence (right). Velvet emitter and stainless-steel mesh anode.

In several experimental series an area in the middle of the anode was eventually completely eroded after a number of bursts. Cathodes also exhibited erosion and were often sputtered with material from the eroded anode.[9]

The anodes used in the three experimental series considered here are seen in Fig. 13 after exposure to 20 bursts with 10 pulses at 10-Hz pulse repetition frequency. Both anodes

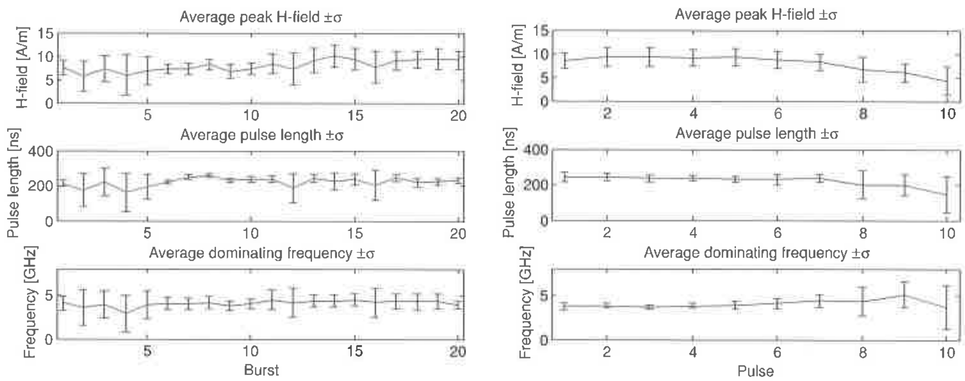



**Fig. 11.** Same as Fig. 10, with graphite emitter and stainless-steel mesh anode.

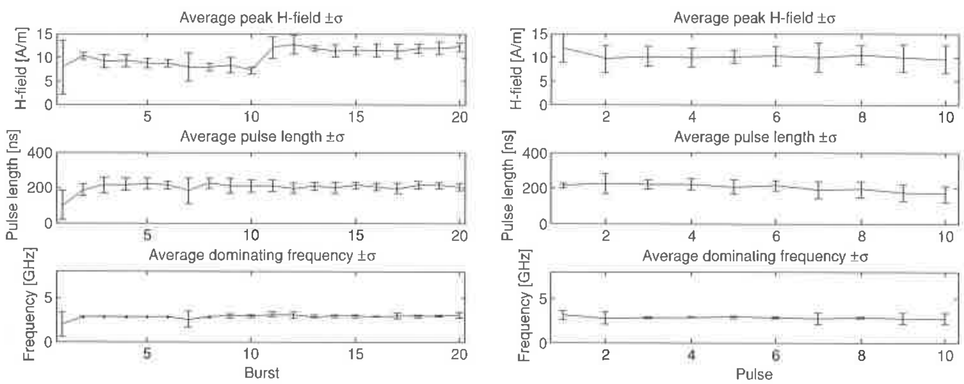
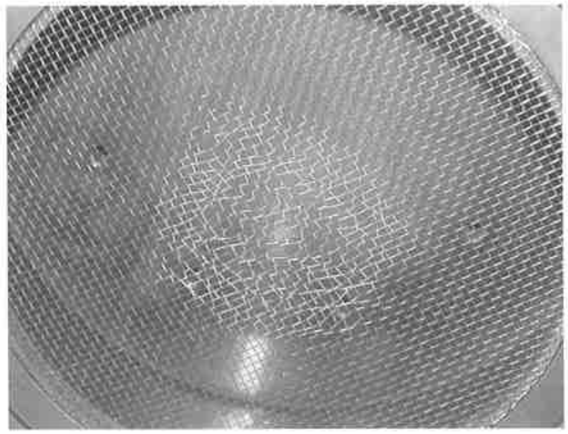



**Fig. 12.** Same as Fig. 10, with graphite emitter and molybdenum wire anode.

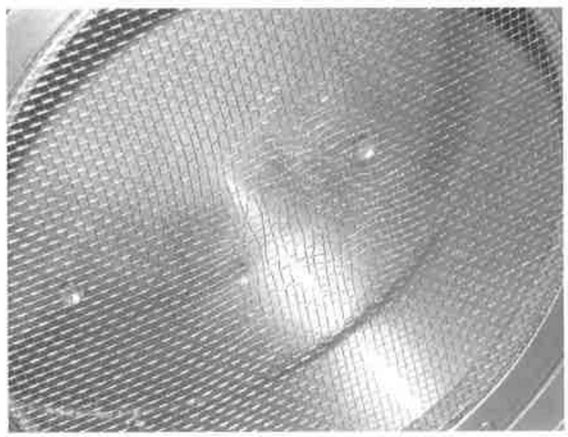
made of stainless-steel mesh exhibit deformation and surface discoloring. However, the molybdenum wire anode shows weaker signs of being affected.

The emitters are shown in Fig. 14 after use in 20 bursts each. The velvet shows evidence of burning of the fiber tips, whereas the graphite has small dents irregularly spaced over the surface. Both the velvet emitter and the graphite emitter used together with a stainless-steel mesh anode are stained with material from the anode mesh. Small metal particles are also spread over the emitter. The same irregular metal coating is seen on the cavity walls, and sometimes small fragments of mesh wire with melted ends are found on the cavity floor after a series of bursts.

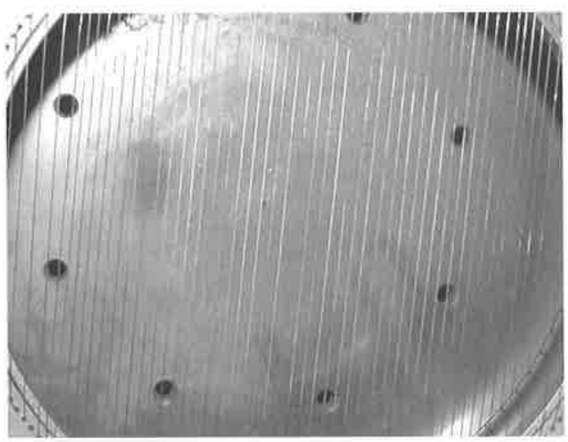
The least affected emitter is the graphite emitter that was used with the molybdenum wire anode. There is some staining and dents, but considerably fewer than for the graphite emitter used with the stainless-steel mesh anode. The staining and deposited particles on the graphite surface appear to be more evenly distributed when used together with the molybdenum wire anode. Unfortunately, the last image in Fig. 14 is slightly out of focus, but discolored areas can be seen.



(a)



(b)

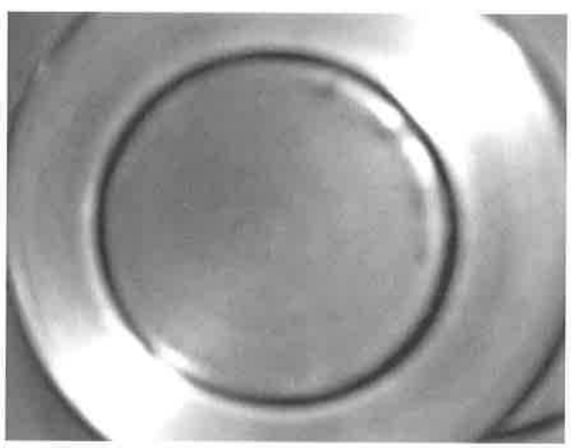


(c)

**Fig. 13.** Anodes after 20 bursts of 10 pulses at 10 Hz for velvet/steel mesh (a), graphite/steel mesh (b), and graphite/molybdenum wire (c) combinations.

(a)

(b)



(c)

**Fig. 14.** Cathode emitters after 20 bursts of 10 pulses at 10 Hz for velvet/steel mesh (a), graphite/steel mesh (b), and graphite/molybdenum wire (c) combinations.

## 4. Conclusion

Studies of the microwave generation and endurance of electrode materials for different combinations of anode and cathode materials may be utilized to improve the operating performance of vircators and similar HPM sources. Both single-pulse experiments and repetitive HPM pulse generation show that electrode erosion is a significant factor limiting the durability of an HPM source.

Repetitive operation does put a lot of stress on the electrode materials in a vircator. Different electrode materials display markedly different behaviors with respect to microwave field strength, pulse length, dominating frequency, and electrode erosion.

The impedance of the vircator during the microwave emission phase is seen to depend on the choice of anode and emitter materials, something that enables rough impedance control in a vircator, of chosen geometry and dimensions, by the selection of electrode materials. Graphite emitters seem to give a stable vircator impedance during the microwave emission as well as a more stable microwave pulse generation during repetitive operation than velvet emitters.

In experiments with the stainless-steel mesh anode, the time for onset of microwave radiation shows less variation with a velvet emitter than with a graphite emitter. However, in experiments with a graphite emitter, the molybdenum wire anode experiments exhibit less variation in the time for onset of microwave radiation than those with a stainless-steel mesh anode.

Although the velvet emitter has advantages, such as early onset of microwave generation and high peak power, it suffers significant erosion, taken over several series of bursts. Graphite emitters are seen to be more durable than velvet but exhibit significantly more anode erosion with a stainless-steel mesh anode than with a molybdenum wire anode. A graphite emitter together with a molybdenum wire anode appears to generate comparatively stable pulse shapes, within a single burst as well as over several bursts.

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