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Investigation of an X-band magnetically insulated transmission line oscillator*

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An X-band magnetically insulated transmission line oscillator (MILO) is designed and investigated numerically and experimentally for the first time. The X-band MILO is optimized in detail with KARAT code. In simulation, the X-band MILO, driven by a 720 kV, 53 kA electron beam, comes to a nonlinear steady state in 4.0 ns. High-power microwaves (HPM) of TEM mode is generated with an average power of 4.1 GW, a frequency of 9.3 GHz, and power conversion efficiency of 10.8% in durations of 0–40 ns. The device is fabricated according to the simulation results. In experiments, when the voltage is 400 kV and the current is 50 kA, the radiated microwave power reaches about 110 MW and the dominating frequency is 9.7 GHz. Because the surfaces of the cathode end and the beam dump are destroyed, the diode voltage cannot increase continuously. However, when the diode voltage is 400 kV, the average power output is obtained to be 700 MW in simulation. The impedance of the device is clearly smaller than the simulation prediction. Moreover, the duration of the microwave pulse is obviously shorter than that of the current pulse. The experimental results are greatly different from the simulation predictions. The preliminary analyses show that the generations of the anode plasma, the cathode flare and the anode flare are the essential cause for the remarkable deviation of the experimental results from the simulation predictions.

Keywords: magnetically insulated transmission line oscillator (MILO), high-power microwaves (HPM), pulse shortening

PACC: 4252, 5265, 5270G, 5255E

1. Introduction

The magnetically insulated transmission line oscillator (MILO) is a relatively new type of coaxial crossed field microwave device designed specifically to generate microwave power at the gigawatt level. It requires no externally applied magnetic field to insulate the electron flow in the slow-wave structure (SWS). This self-insulating property, inherent in magnetically insulated lines, allows the device to handle an extremely large input beam power (tens of gigawatts) with ensuing that the electrical breakdown of the anode-cathode gap (AK gap) does not take place. It is a major hotspot in the field of high power microwave source research.[1−18] The field of high-power microwaves (HPM) has been developed rapidly in our country.[19−28] In our laboratory, an L-band MILO, which can generate a power of above 2.0 GW at a frequency of 1.76 GHz, about 20 ns pulse, has been investigated.[12,14] Furthermore, a C-band and an S-band MILO have also been investigated.[15,16]. The frequencies of the investigated MILO cover the L-, C-, and S-banded at present. In order to explore the operational feasibility of X-band MILO, an X-band MILO is designed and investigated numerically and experimentally for the first time in this paper.

The rest of the present paper is organized as follows. Section 2 presents the simulation results. Section 3 is devoted to the experimental results. Conclusions are given in Section 4.

2. Simulation results

The model of the investigated X band MILO is illustrated in Fig.1. It consists of a ten-cavity SWS, preceded by a one-cavity RF choke section. In or-

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der to enhance the power conversion efficiency, three extractor vanes are introduced into the device of the X-band MILO. The inner radii of the three extractor vanes are increased gradually, which is similar to the tapered MILO. The sharp taper provides a transition to the coaxial line and, additionally, facilitates the extraction of power from the energetic electron jet which flows from the diode end of the cylindrical cathode surface.[6]

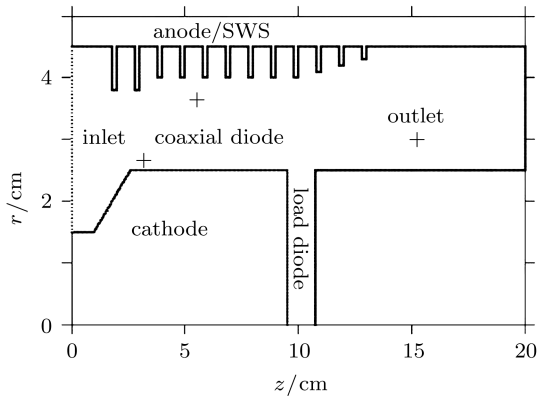


Fig.1. The model of the X band MILO.

The X-band MILO is optimized numerically with KARAT code. The optimized dimensions are as follows: (A) The cathode radius is 2.5 cm. (B) the RF choke vanes and the SWS vanes have inner radii of 3.8 cm and 4.0 cm respectively. The inner radius of three extractor vanes are 4.1 cm, 4.2 cm and 4.3 cm respectively. All vanes are 4.5 cm in outer radius, 0.2 cm in thickness, and 1.0 cm in period. (C) the outer radius of the beam dump are 2.5 cm.

The simulation begins with the injection of a dc transverse electromagnetic (TEM) wave at the inlet (Fig.1). The voltage associated with the TEM wave is a constant. The typical simulation results are shown as follows.

Figures 2 and 3 display the results from particle-in-cell simulation of the X-band MILO. Figure 2 describes the time history of the RF power output at the outlet. The diagram shows that a nonlinear saturation occurs at about 4 ns, and an averaged RF power output is 4.1 GW in durations of 0–40 ns. Figure 3 gives the frequency spectrum associated with Fig.2. The dominant frequency is 9.3 GHz, which falls into X-band. The diagram also shows that the frequency spectrum is very pure. In this case, the applied voltage and current are 720 kV and 53 kA respectively, and the corresponding power conversion efficiency is calculated to be 10.8%. The simulation results show that the power output is highly sensitive to the load diode gap.

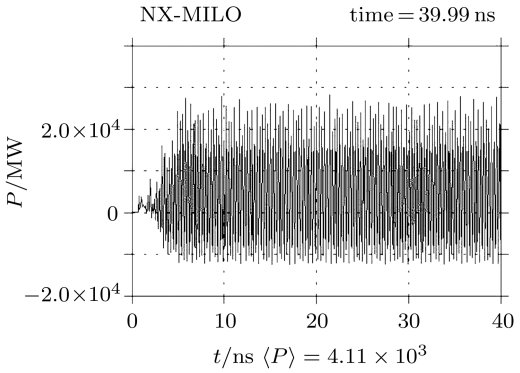


Fig.2. The RF power output vs time.

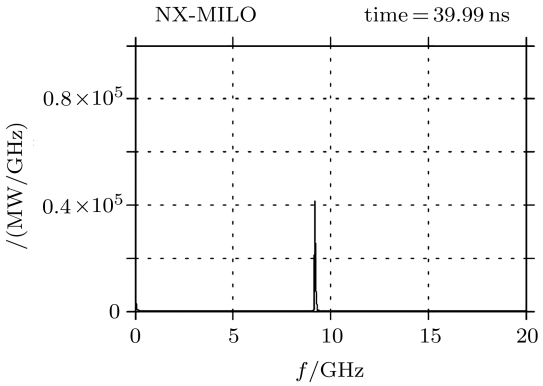


Fig.3. The RF output power spectrum.

3. Experimental results

The optimized configuration used in the experiment is shown in Fig.4. Note that the coaxial TEM wave is transformed into a TM_{01} mode by a mode converter in circular waveguide, which is then radiated from a cone-shaped horn antenna into air. In simulation, the microwave source and the mode converter are designed respectively. In experiment, the X-band MILO is driven by a self-built 800 kV, 10 Ω, 80 ns pulser: SPARK-01, a Marx-driven, coaxial-water-line machine in our laboratory. The entire apparatus is pumped down to a pressure of approximately 1.3×10^{-2} Pa. The radiated microwave is detected with the far-field measurement method.

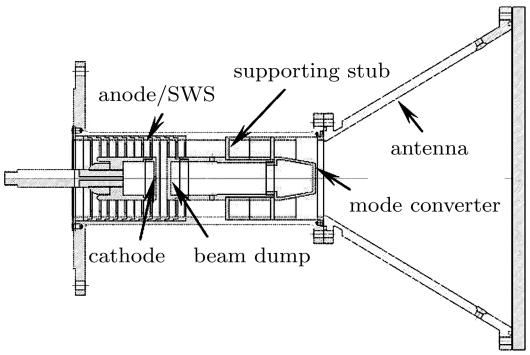


Fig.4. Sketch of the improved X band MILO.

Figure 5 shows the typical measured waveforms. Channel (CH) 1 shows the diode voltage waveform, and CH2 displays the relevant diode current waveform. CH3 exhibits the waveform of the radiated microwave, which is measured with far-field measurement method.[14,29] In the experiments, a measured horn is placed in the main lobe region. The signal which is measured by the horn is attenuated by fixed coaxial attenuators and demodulated by crystal-detector (model 2087-6001-00, manufactured by M/A-COM), and then transmitted by cable to the CH3 of the oscilloscope of TDS 3054B. In the experiments, the radiated frequency can be obtained by a standard heterodyne method, which mixes the signal from a horn located in far-field zones with another signal whose frequency is accurately known and close to the radiated frequency. CH4 shows the mixed signal, and CHM gives the relevant fast Fourier transform (FFT) of the mixed signal.

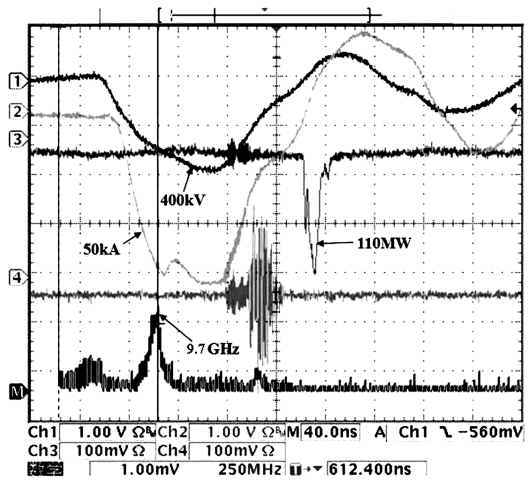


Fig.5. The typical measured waveforms.

In this case, the diode voltage is 400 kV, and the diode current is 50 kA. The radiated microwave power is 110 MW, and the dominating frequency is 9.7 GHz. Because the surfaces of the cathode end and the beam dump are destroyed as shown in Figs.6 and 7, the diode voltage cannot increases continuously. However, when the diode voltage is 400 kV, the average power output is 700 MW in simulation. In the experiments, the load diode gap changes continuously. However, the experimental results have not been improved. The experimental results are greatly different from the simulation predictions.

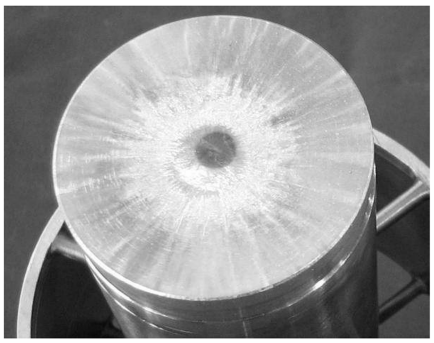


Fig.6. The destroyed molybdenum beam dump.

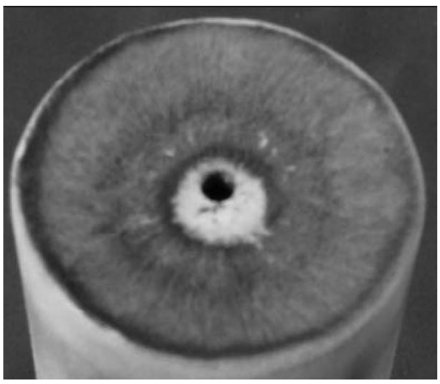


Fig.7. The destroyed cathode.

The impedance of the device is clearly smaller than the simulation prediction. The impedance is 13.6 Ω in simulation. However, it is only 8 Ω in experiment. Moreover, the duration of the microwave pulse is only 10 ns (full width at half maximum (FWHM)), but the duration of the current pulse is 80 ns. It is obvious that pulse shortening occurs in experiment. In simulation, when the diode voltage is 400 kV, the average current density is about 600 A/cm^2 in the load diode. The electron flow striking the beam dump generates dense anode plasma on the surface

of anode.[30−32] The formation of anode plasma initiates bipolar space-charge flow in the load diode. The bipolar space-charge flow results in the increase of the load current, which implies that the impedance of the device is diminished, and so the insulating magnetic field increases. It is obvious that the excess insulating magnetic field will weaken the beam-wave interaction and so result in the decrease of the power conversion efficiency and thus the power output. Finally, the beam-wave synchronous condition is entirely destroyed, and the MILO ceases operation, and so the pulse shortening is generated.

Figure 6 is the picture showing the molybdenum beam dump of the load diode after three pulse experiments have been performed. Figure 7 is the picture exhibiting the corresponding velvet cathode. In the process of the discharge of the explosive electron emission (EEE), a cathode flare (CF) appears on the cathode and an anode flare (AF) occurs on the anode. During the discharge, erosion occurs first on the cathode and later on the anode, after the appearance of CF and AF, respectively.[33] It is obvious that the CF and the AF destroy the velvet cathode and the molybdenum beam dump.

As mentioned above, the generation of the anode plasma severely perturbs the operation of the X-MILO, and the CF and the AF destroy the surfaces of the cathode and the anode of the load diode. They are the essential cause for the remarkable deviation of the experimental results from the simulation predictions.

4. Conclusions

An X-band magnetically insulated transmission line oscillator (MILO) is designed and investigated numerically and experimentally. In simulation, high-power microwaves of TEM mode is generated with an average power of 4.1 GW, a frequency of 9.7 GHz, and power conversion efficiency of 10.8%, when the voltage is 720 kV and the current is 53 kA. The device is fabricated according to the optimized configuration. In experiments, the measured microwave power is about 110 MW, and the dominating frequency is 9.7 GHz, when the device is driven by a 400 kV, 50 kA electron beam. However, when the diode voltage is 400 kV, the average power output is 700 MW in simulation. The experimental results are different considerably from the simulation predictions. The preliminary analyses show that the generations of the anode plasma, the CF and the AF are the essential cause for the distinct deviation of the experimental results from the simulation predictions.

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