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Simulation investigation of X-band MILO*

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Abstract: An X-band magnetically insulated transmission line oscillator (MILO) is configured and investigated numerically with KARAT code. The design thought is introduced, and the typical simulation results are illustrated and analyzed. In simulation, when the voltage is 520 kV, and the current is 64 kA, the high-power microwave (HPM) of TEM mode is generated with a power of 2.18 GW, a frequency of 9.3 GHz, and a power conversion efficiency of 6.5%.

Key words: MILO; HPM; Beam dump; PIC method

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The magnetically insulated 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) without ensuing electrical breakdown of the anode-cathode gap(AK gap). It is a major hotspot in the field of high power microwave source research[1-6]. In the related leading laboratories of the world, such as Air Force Weapons Laboratory(USA), Sandia National Laboratory(USA), Culham Laboratory(U. K.), Institute of Electromagnetic Researches (Ukraine), etc., intensive researches on the MILO have been carried out.

The frequency of the investigated MILO is focused on the L-band and the C-band at present[1-6]. The X-band MILO is rarely investigated[7]. An X-band MILO is configured and investigated numerically with KARAT code.

1 Basic principle

The configuration of the MILO is illustrated in Fig. 1. The configuration is cylindrically symmetric about the z-axis. It consists of a seven-cavity SWS, preceded by a one-cavity rf choke section. The last vane of the SWS is also part of the extractor, referred as the extractor vane. The inner radius of the extractor vane is slightly larger than those of other SWS vanes, providing a good match of the gap electric field to that of the output coaxial transmission line (CTL)[2]. The load region is composed of both the right end and the end surfaces of the cathode, the beam dump disk and the inner conductor of the output CTL. The electron beam emission region is confined by placing velvet on the cathode running from the upstream side of the second choke vane to the right end of the cathode and the end surface of the cathode. The velvet is used as the emitting surface and is pasted on the cathode with glue.

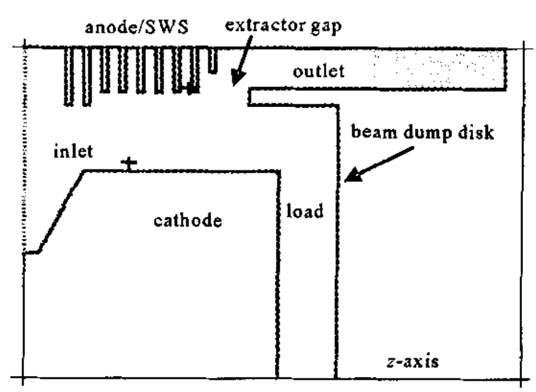

Fig. 1 Configuration of the MILO

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The basic principle of the MILO, using Fig. 1 for reference, will be described as follows. A high-voltage pulse is introduced from the left and propagates to the right in Fig. 1. Electrons are emitted from the velvet. The electrons of the load current are emitted from both the side and the end surface of the cathode extended into the beam dump region. The load current generates the dc magnetic field in the SWS section, which prevents the electrons from reaching the anode. This self-insulating property inhibits electrical breakdown of the AK gap. At the same time, this dc magnetic field plays a key role in the synchronism between the drifting electrons and a certain electromagnetic wave, whose characteristics are determined by the SWS, transferring energy from the electron beam to the electromagnetic wave. The growing electromagnetic wave induces an rf voltage across the extractor gap which produces a TEM wave in the coaxial section around the beam dump[2]. The TEM wave propagates down the section of the coaxial waveguide.

2 Design

It is well known that the frequency of the MILO is determined by the period and depth of the SWS. By reducing the period and the depth of SWS, an X-band MILO is configured and investigated numerically with KARAT code.

For more efficient operation and more compact structure, a new-type beam dump has been introduced into this X-band MILO in simulation[8]. The new-type beam dump has two advantages. On the one hand, the axial distance from the downstream end of the cathode to the beam dump disk can be adjusted continuously by axially moving of the beam dump disk. The axial distance affects the load current, and hence the dc magnetic field in the SWS. If the axial distance is very large, the insulating of this dc magnetic field will be insufficient and the electrons in the SWS would just flow out to the vanes, possibly initiating an electric arc. If the axial distance is not large enough, the insulating will be very strong, pulling the electron flow away from the inner radius of the SWS. At the same time, improper dc magnetic field will affect the synchronism between the electron beam and the electromagnetic wave. All these will reduce the energy of the electron beam coupling into the electromagnetic wave and result in the decrease of the power conversion efficiency and thus the output power. In the conventional MILO[1-4] (see Fig. 2[1]), however, it is difficult to adjust the dc magnetic field because no part of it can be moved easily. Therefore, this improved device is able to operate at the optimal state by easily adjusting the axial distance, which leads to the increase of the power conversion efficiency and thus the radiation power. On the other hand, the device is more compact than the conventional MILO. As mentioned above, in the X-band MILO, the electrons of the load current are emitted from both the side and the end surface of the cathode extended into the beam dump region. According to simulation, the end surface of the cathode provides more than half of the total load current. However, in the conventional MILO, the electrons of the load current are emitted only from the side of the cathode extended into the beam dump region. Therefore, in order to generate the same load current, the length of the cathode extended into the beam dump region will be obviously shorter in the case of the X-band MILO. At the same time, the shortened cathode is also favorable to the control of the symmetry of the emission of the electron beam and results in optimal operation of the device.

3 Typical results by simulation

In simulation, the high-power microwave of TEM mode is generated with a power of 2.18 GW, a frequency of 9.3 GHz, and a power conversion efficiency of 6.5%, when the voltage is 520 kV, and the current is 64 kA.

Fig. 3 and Fig. 4 are the results from particle-in-cell simulation of the X-band MILO. Fig. 3 plots the time history of the rf output power at the midpoint of the outlet. The diagram shows that a nonlinear saturation occurs at about 4 ns, and the averaged rf output power is 2.18 GW. Fig. 4 gives the frequency spectrum

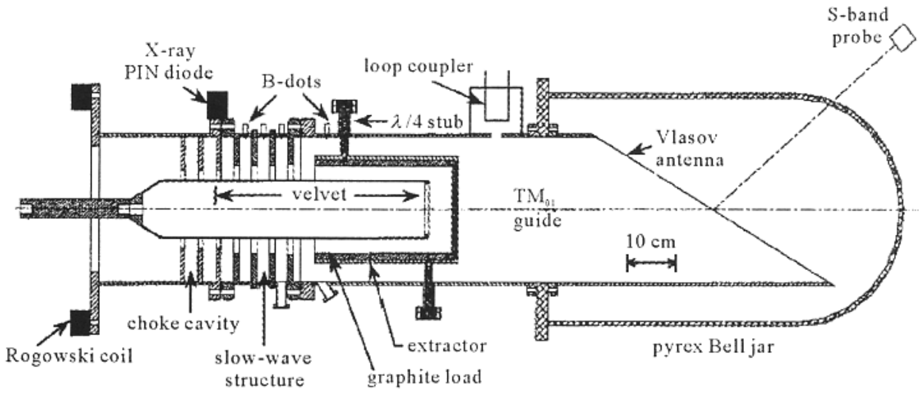

Fig. 2 Sketch of the conventional MILO

associated with Fig. 3. The dominant frequency is 9.3 GHz, which falls into X-band. The diagram shows also that the frequency spectrum is very pure. In this case, the applied voltage and current are 520 kV and 64 kA respectively, and the corresponding power conversion efficiency is calculated to be 6.5%.

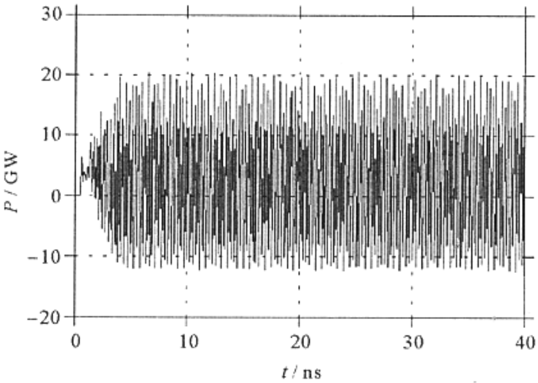

Fig. 3 Output power *vs* time at $z=15.0$ cm

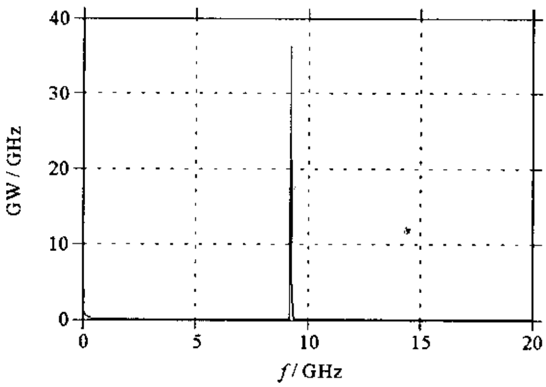

Fig. 4 Fourier spectrum of the signal

Fig. 5 is a plot of the energy flow versus z. The diagram shows the input power is 33 GW at inlet, and the energy flow is modulated in the SWS region, transferring energy from the electron beam to the electromagnetic wave. The growing electromagnetic wave induces an rf voltage across the extractor gap which produces a TEM wave in the coaxial section around the beam dump. Fig. 6 gives the distribution of electrons in the phase space. The diagram indicates that the electron beam is well bunched in the SWS region and most electrons have lost their energy, which proves that the beam energy has been converted into the microwave energy effectively.

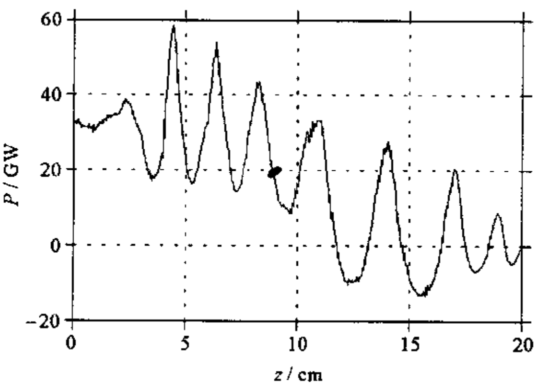

Fig. 5 Energy flow *vs* z

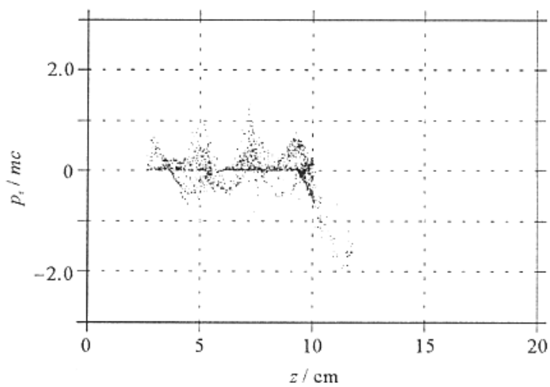

Fig. 6 Particles in the phase space

Fig. 7 shows E-fields versus time at the midpoint of the outlet and indicates that $E_r \neq 0$, $E_z \approx 0$, $E_t = 0$. Fig. 8 gives B-fields versus time at the midpoint of the outlet and shows that $B_t \neq 0$, $B_r = B_z = 0$. Fig. 7 and Fig. 8 indicates that the mode of radiated microwaves is TEM mode. The TEM wave propagates down the section of coaxial waveguide.

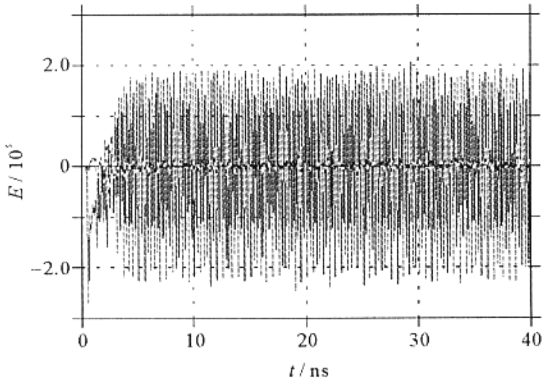

Fig. 7 *E*-fields *vs* time at output window at $z=15.0$ cm, $r=3.00$ cm

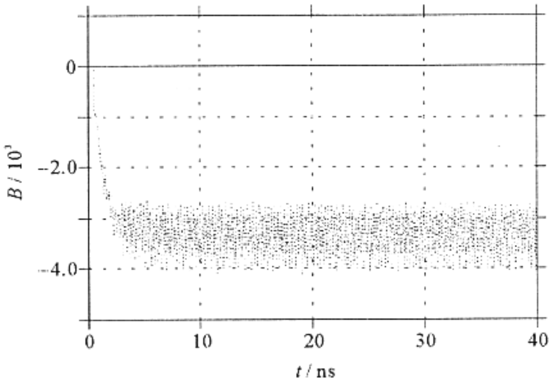

Fig. 8 *B*-fields *vs* time at output window at $z=15.0$ cm, $r=3.00$ cm

4 Conclusion

An X-band magnetically insulated transmission line oscillator is configured and investigated numerically with KARAT code. In simulation, when the voltage is 520 kV, and the current is 64 kA, the high-power microwave of TEM mode is generated with a power of 2.18 GW, a frequency of 9.3 GHz, and a power conversion efficiency of 6.5%.

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X 波段磁绝缘线振荡器的模拟研究

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摘 要： 设计了一个具有新型收集极的 X 波段磁绝缘线振荡器，并利用 KARAT 程序对其进行了深入的数值模拟研究。对设计思想进行了介绍，并对典型模拟结果进行了图示和分析。当工作电压为 520 kV，电流为 64 kA 时，模拟中获得了 2.18 GW 的微波输出功率，频率为 9.3 GHz，功率转换效率为 6.5%，辐射微波的主模式为 TEM 模。

关键词： 磁绝缘线振荡器； 高功率微波； 收集极； PIC 方法