Dynamics of mode competition in a gigawatt-class magnetically insulated line oscillator

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An axial mode competition is observed in a 1 GHz magnetically insulated line oscillator operating at gigawatt power level with a pulse duration of 130 ns. A fast-growing axial mode adjacent to desired π-mode starts up first and hops to the slow-growing and stable π mode. The dynamics of the mode competition is found to be strongly dependent on the time-varying axial velocity of the magnetically insulated electron beam. The experimental observation is verified by the particle-in-cell simulation using a time-frequency analysis. © 2007 American Institute of Physics.

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The magnetically insulated line oscillator (MILO) is a gigawatt-class high-power microwave tube which generates coherent radiation using an interaction of a magnetically insulated electron beam with an electromagnetic wave whose phase velocity is slowed down to the beam velocity by periodic cavities. The MILO is of a great attention due to its operation without an externally applied magnetic field for guiding a relativistic electron beam with a high current of tens of kiloamperes. This self-insulating property inhibits electrical breakdown of the anode-cathode gap, which enables the tube to handle extremely large input power of tens of gigawatts at a modest applied voltage of several hundred kilovolts. The principle of high-power microwave generation in the MILO was demonstrated in 1987. Experimental studies have been performed from the end of 1980s. Although the gigawatt-class output power has been achieved after continuous improvement, a severe power dip appears typically in the middle of the microwave output pulse, several hundred nanoseconds in duration. A pretty compelling explanation for pulse shortening caused by anode plasma formation is reported. However, the physical origin of the pulse shortening caused by such aspect as mode competition is not well understood yet in the MILO.

The interaction structure of the MILO is comprised of several cavities separated by periodically spaced disks. An oscillation starts when the average \( \mathbf{E} \times \mathbf{B} \) drift velocity of the magnetically insulated electron beam is synchronous to the phase velocity of the π mode of the periodic structure where the phase difference between adjacent disks is π. In this study, an experimental measurement of temporal and spatial behaviors of the field excited in each cavity is attempted to understand the cause of the pulse shortening. A mode competition between π mode and adjacent axial mode is observed experimentally and microwave pulse shows a dip during this process. The experimental measurement is compared with a numerical simulation using a particle-in-cell code, MAGIC. We elucidate the axial mode competition using a time-frequency analysis to understand the physical origin of the axial mode competition.

The experimental configuration of the MILO employed in this study is shown in Fig. 1. The Seoul National University’s Electron Beam Accelerator is capable of producing a pulse with a duration of 130 ns and a rise time of 20 ns in a single-shot mode. A capacitive voltage probe and an inductive current probe are installed at the front of the MILO and at output waveguide. The TM\(_{00}\) mode is chosen as an operating mode in this structure of six periodic cavities. Discrete axial modes of TM\(_{00}\) are shown in Fig. 2. The axial modes are characterized by a discrete set of phase variation in a period of cavities; \( k_s p = l \pi / N \), where \( k_s \) is axial wave number, \( p \) is period of cavities, \( N \) is the number of uniform cavities, and \( l \) is integer. Only \( l = 5, 6 \) corresponding to \( 5 \pi / 6 \) and π mode are supported in this scheme. The quality factors of other axial modes are negligibly small compared to those of \( l = 5, 6 \).

The MILO is designed so that the averaged axial drift velocity of electron is matched with phase velocity of the π mode of TM\(_{00}\) (Fig. 2). Since the kinetic energy of electron...
in MILO is depending on its radial position, the velocity of the radially distributed electron beam is expressed as a continuum such as the shaded area illustrated in Fig. 2.\textsuperscript{10,11} Then, the radially distributed electrons can simultaneously interact with the two axial modes of TM\textsubscript{00} mode.

A competition between these two axial modes is observed in experiment by a time-frequency analysis using data from rf B-dot probes in each cavity. When a voltage pulse of about 480 kV is applied, the rf power of about 1.5 GW peak is obtained experimentally, as shown in Fig. 3(a). A time-frequency analysis done for the microwave output signal as shown in Fig. 3(b) elucidates that this erratic behavior of microwave output power is caused by axial mode competition between \(l=5\) and \(l=6\) modes. The MILO initially starts in the \(l=5\) mode, but the desired \(l=6\) mode later dominates. The temporal and spatial behaviors of the field in each cavity, as shown in Fig. 3(c), also leads to the dynamics of mode competition.

Two-dimensional simulation using a particle-in-cell code, MAGIC, is employed to prove the dynamics of mode competition. For comparison with the experiment, the same input voltage pulse is used, as shown in Fig. 4(a). Similar to the experimental result, the \(l=5\) mode starts up first and the \(l=6\) mode finally suppresses the \(l=5\) mode as shown in Figs. 4(b) and 4(c). A severe power dip is seen after sudden fall of the \(l=5\) mode which is caused by the competition of axial modes.

In Fig. 5, the axial velocity stays near the interaction condition of the \(l=5\) mode during the first 50 ns after the voltage rise and the axial velocity goes down to the interaction condition of the \(l=6\) mode.

In this observation of axial mode competition in both experiment and numerical simulation, the \(l=5\) mode competes with the \(l=6\) mode and finally dies out. The \(l=6\) mode is eventually sustained stably during the rest of the voltage pulse. A fast-growing and well-established mode is subsequently suppressed by a later-starting mode. Similar dynamics of mode competition were also observed in the weakly tapered gyrotron backward-wave oscillator\textsuperscript{12} and in the pasotron.\textsuperscript{13}

Using a three-dimensional rf simulation code, MWS,\textsuperscript{14} the MILO cavity fill times \((Q_{1}/2\pi)\) are found to be 12.7 and 58.5 ns for the \(l=5\) and the \(l=6\) modes, respectively. The loaded quality factors, \(Q_{L}\), are estimated to be 79.4 at 0.97 GHz for the \(l=5\) mode and 332 at 0.99 GHz for the \(l=6\) mode. Also as seen from Fig. 5, the axial velocity of the magnetically insulated electron beam is synchronous to the phase velocity of the \(l=5\) mode during the first 50 ns. Here we can see the fast startup of the \(l=5\) mode both in experiment and simulation. Then in later time, the axial velocity of the magnetically insulated electron beam decreases meeting the interaction condition for the \(l=6\) mode. The temporal behavior of the axial velocity of the magnetically insulated electron beam explains the temporal behavior of the axial mode competition when the times of transitions are compared from Figs. 3–5. The dynamics of the magnetically insulated electron beam is well understood by the papers previously published.\textsuperscript{10} The average axial velocity of the beam is dependent on the average radial position of the beam between the cathode-anode gap.

In summary, an axial mode competition is observed in a 1 GHz magnetically insulated line oscillator (MILO) operating at gigawatt power levels with a pulse duration of 130 ns.
Using a time-frequency analysis of the measured microwave signal via rf B-dot probes, the dynamics show that a fast-growing axial mode adjacent to desired mode first starts up and hops to the slow-growing and stable mode. The physical origin of the axial mode competition is found to be a time-varying axial velocity of the magnetically insulated electron beam. This experimental observation is verified by particle-in-cell simulation using a time-frequency analysis. The severe dip in the middle of the microwave output pulse, i.e., pulse shortening, is a result of the axial mode competition.