Multi-frequency recirculating planar magnetrons

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The multi-frequency recirculating planar magnetron (MFRPM) is the first magnetron capable of simultaneous generation of significantly different output frequencies (1 and 2 GHz) in a single operating pulse. Design and simulation of a prototype MFRPM were followed by hardware fabrication and experimental verification using the Michigan Electron Long Beam Accelerator with a Ceramic insulator at $-300$ kV, $1-5$ kA, and 0.14–0.23 T axial magnetic field. Preliminary results demonstrated simultaneous generation of microwave pulses near 1 GHz and 2 GHz at powers up to 44 MW and 21 MW, respectively, with peak total efficiencies up to 9%. Published by AIP Publishing.

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wherein $f_2 = 2 \times f_1$, in a way that is analogous to peer-to-peer magnetron phase-locking. The SBO was designed using the two equations below with parameter constraints based on experimental hardware limitations

$$\frac{\cot \left( \frac{\omega h}{c} \right)}{\omega h} = \left( \frac{w}{L} \right) \sum_{n=-\infty}^{\infty} \sin^2 \left( \frac{\beta_n w}{2} \right) \coth \left( \frac{\gamma_n b}{\gamma_n h} \right), \quad (1)$$

$$V_{BH} = bB\beta_p c - \left( 1 - \sqrt{1 - \beta_p^2} \right) \frac{m c^2}{e}. \quad (2)$$

Eq. (1) is based on the existing theory for infinite, two-dimensional, planar cavity arrays. In Eq. (1), $h$ is the cavity depth, $w$ is the cavity width, $L$ is the circuit pitch, $b$ is the anode-cathode (AK) gap spacing, $\omega$ is the angular frequency, $c$ is the speed of light, $\beta_n = \beta_0 + 2\pi n/L$ and $\gamma_n = \sqrt{\beta_n^2 - \left( \omega/c \right)^2}$ for $n = 0, \pm 1, \pm 2, \ldots$, and $\beta_0$ is the propagation constant ($\beta_0 = 2\pi/\lambda_g$ for a guide wavelength $\lambda_g$).

Eq. (2) is the well-known Buneman-Hartree condition for magnetron beam-wave synchronism, which is a relativistic, single-particle treatment that relates the operating DC voltage, magnetic field, and AK gap spacing to achieve electron drift velocity synchronism (at the anode) with RF waves propagating at a given phase velocity on the slow-wave structure. In Eq. (2), $V_{BH}$ is the operating voltage for synchronism, $b$ is the AK gap spacing, $B$ is the magnetic field, and $\beta_p$ is the $c$-normalized RF phase velocity ($\beta_p = v_p/c = \omega/\beta_0 c$).

By using Eqs. (1) and (2), preliminary dimensions of the SBO could be determined subject to several constraints. As mentioned earlier, the desired operating mode for the SBO is the $\pi$-mode, which is the same as the LBO. The DC voltage for operation in the $\pi$-mode ($V_{BH}$) is fixed at the Michigan electron long beam accelerator with ceramic insulator (MELBA-C) operating voltage ($-300\text{kV}$). The maximum magnetic field $B$ in the AK gap is limited by the pulsed electromagnet specifications and both the choice and amount of anode material, but generally, the minimum necessary magnetic field for synchronism should not exceed 0.2 T. The cathodes used for the RPM have large surface areas and operate in an explosive emission, space-charge-limited regime, which makes it particularly difficult to achieve uniform electron emission. This may be exacerbated if the AK gap spacing is appreciably different for the SBO relative to the LBO, so each planar cavity array in the MFRPM has the same AK gap spacing $b$. Given the identical $b$ (and therefore identical beam velocity), the SBO must have the same RF phase velocity $\beta_p$ as the LBO. Since the frequency of interest for the SBO was chosen to be 2 GHz (an integer multiple of the LBO), $\omega$ is also constrained. For simplicity, the vane width and cavity width were the same in all candidate designs.

Further refinement of the cavity array dimensions used the 3D particle-in-cell code MAGIC to estimate the degree of beam loading on the frequency and adjust the planar cavity array dimensions to compensate. The final SBO design is composed of 8 resonant cavities having cavity depth $h = 3.18\text{cm}$, cavity width $w = 0.96\text{cm}$, and circuit pitch $L = 1.92\text{cm}$. The axial length of the SBO anode is the same as the LBO, which could potentially support axial mode formation, but is necessary in order to use the existing LBO and cylindrical recirculation bends from the RPM-12-A. The simple planar cavity array design suffers decreasing mode separation as the cavity number increases, so an 8 cavity design was chosen over a larger 12 cavity design to reduce the likelihood of mode competition.

Microwave power extraction is accomplished using the same approach used for the RPM-12-A. The centermost vane of each oscillator is connected to an antenna, which forms the inner conductor of a coaxial transmission line axially downstream from the magnetron. The coaxial transmission line is then transitioned to WR 650 and WR 340 waveguide for the LBO and SBO, respectively, using coax-to-waveguide mode converters. The waveguide outputs include the vacuum windows, directional couplers for microwave sampling, and Eccosorb-matched RF loads. It is important to note that the axial extraction assembly is a relatively straightforward implementation that could be applied within the limits of existing hardware and is not optimized for maximum power extraction. External quality factors for the LBO and SBO at their respective cold-tube $\pi$-mode frequencies are approximately 500.

The cathode is the MCC-2v, which uses $3.61\text{cm}^2$ velvet squares as the electron emitters attached using conducting silver epoxy adhesive to both sides of each of the 5 bars forming the structure, and provides a 2.6 cm AK gap. A MCC is geometrically similar to the transparent cathode in that it provides a source of both electric and magnetic priming, but it also serves to increase the coupling between each of the SWSs. Emission from non-velvet surfaces is reduced using Glyptal insulating enamel to maintain a magnetron impedance near the MELBA-C design specification of 100–150 $\Omega$. The axial magnetic field is produced using two...
electromagnet coils in a pseudo-Helmholtz configuration centered on the MFRPM anode. The time delay between triggering the electromagnets and MELBA-C is chosen to allow diffusion of the magnetic field into the structure with a peak occurring in the center of each SWS. Axial magnetic fields ranged from 0.14 to 0.23 T. Operating pressures are $10^{-7}$–$10^{-6}$ Torr. The microwave signal sampled from each directional coupler is split using a 3 dB power divider, with one signal recorded directly using a fast Tektronix 7404 oscilloscope (10 Gsamples/s), and the other signal fed to calibrated Agilent 8472B low-barrier Schottky diodes for power measurement captured using a Tektronix 3054 oscilloscope. Attenuation of all components (directional couplers, cables, splitters, and attenuators) is determined at the design frequencies of the two oscillators. Operating voltage is determined using a CuSO$_4$ voltage divider, and current is determined using time-integrated Rogowski coil signals, each captured using the Tektronix oscilloscope.

Results for 123 shots were obtained. Currents and voltages at peak microwave power were 1.7–5.3 kA and 170–288 kV, respectively, with magnetron impedances from 44 to 155 $\Omega$. Fig. 2 presents data illustrating typical behavior of the MFRPM prototype. The LBO begins oscillating first, which is consistent with expectations from the standpoint of the analytic solutions to Eq. (1). The derivation of Eq. (1) involves solutions for the fringing RF fields from the cavities whose magnitudes scale as $\sinh(\gamma_n x) \approx \sinh(\pi x/L)$ for the $n$-mode in the AK gap, where $x$ is the distance from the cathode surface; this suggests that the electric field magnitude decays with $x/L$. Since $L$ is twice as large for the LBO than the SBO, the fringing L-band fields are considerably stronger and the Brillouin electron hub can reasonably be expected to excite LBO startup earlier than the SBO for equal hub height, which is the case here given the AK gap is the same. A time-frequency analysis (TFA) of both the LBO and SBO signals reveals an intriguing feature, namely the 2 and 4 GHz harmonic content of the LBO signal. The LBO 2 GHz harmonic is not always the same frequency as the SBO fundamental, so the origin of the harmonic is not necessarily due to the SBO.31 Characterizing the power content and the origin of these harmonics will be the focus of future work.

Fig. 3 shows the peak output power for both oscillators vs. magnetic field. Best operation was observed at the maximum field that could be produced by the electromagnets, with peak LBO and SBO powers as high as 44 MW and 21 MW, respectively, with peak total efficiencies (based on the peak of the sum of the power traces for both oscillators) up to 9%. Here, total efficiency is defined as the ratio of peak output power to the product of voltage and current to the cathode. The high external Q of the oscillators strongly implies that improvements in the extraction coupling and load characteristics would lead to improved powers and efficiencies.32 Given that the solution to Eq. (2) for an operating voltage of 300 kV and a 2.6 cm AK gap is a magnetic field of 0.16 T, the high magnetic fields for best operation are

FIG. 2. Sample experimental MELBA-C shot no. 13616. (a) Shot plot illustrating voltage, current, and detected RF powers for both oscillators. Peak LBO (SBO) powers were 24 MW (15 MW) at 0.98 GHz (2.0 GHz). (b) Time-frequency analysis for the LBO. (c) Time-frequency analysis for the SBO.

FIG. 3. Experimental powers for both oscillators vs. magnetic field.
somewhat surprising. A possible explanation may be the early formation of cathode plasma, effectively shrinking the AK gap and therefore requiring a higher magnetic field to maintain beam-wave synchronism.\textsuperscript{6}

These results validate the concept of the multi-frequency recirculating planar magnetron prototype as a means of simultaneously generating microwaves at two different frequencies using two slow-wave structures. Using a combination of analytic theory and particle-in-cell simulations, a set of simple planar cavity arrays produced 16 ± 8 MW and 8 ± 5 MW at approximately 1 GHz and 2 GHz, respectively, over the broad range of magnetic fields tested, with peak powers of 44 MW and 21 MW at the oscillators’ respective design frequencies. Future work will focus on characterizing the operation of the prototype, including the L-band oscillator harmonics.

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