Phase Locking of Relativistic Magnetrons

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Phase locking of relativistic magnetrons has been achieved at power levels of ~3 GW at 2.8 GHz, exceeding previous phase-locking power levels by 3 orders of magnitude. Two relativistic magnetrons interact directly through a short waveguide of length $l \sim n\lambda/2$ to allow locking. Power-density enhancement due to source coherence is directly measured in the radiation field. Phase locking occurs in ~5 ns and is reproducible. Extension to 10–100 GW appears feasible with arrays of oscillators.

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High-power microwave sources have been developed in recent years to power levels of 1–10 GW. Extension of these oscillator powers to higher levels may be inhibited by inherent limits to the electric field sustainable in resonant cavities and limits on cavity size. For example, mode competition will occur at large cavity volume since the number of modes scales as V/λ^3, where λ is the wavelength. In addition, the power-density limit set by the breakdown of air argues for distribution of power into an array of antennas. Therefore, for powers $\gg 10$ GW, groups of oscillators are a likely approach. In order to add a group of sources together, it is necessary to phase lock them together to achieve constructive interference. Locking produces an energy in the radiation field which scales as N the number of sources; power density scales as N^2. We report phase locking of two relativistic magnetrons at 3 GW total power; schemes for extension of the locking technique to larger numbers of oscillators are discussed.

Oscillator phase locking has been studied since World War II.[1-3] In these experiments the power of the driving master oscillator was much smaller than that of the driven oscillator. In the experiments reported here, the powers are of the same order. The important parameter is the injection ratio $\rho = (P_i/P_0)^{1/2} = E_i/E_0$ were P and E are the power and electric fields of the oscillators in question, and the subscripts are for the injecting and receiving oscillators. The equation which governs the phase difference between coupled oscillators is

$$\frac{d\phi}{dt} + \frac{|\rho|\omega_0}{Q_E}\sin\phi = \Delta\omega , \tag{1}$$

where ϕ is the phase difference between the two oscillators, ω_0 is the resonant frequency of each oscillator cavity, Q_E is the loaded cavity quality factor, and $\Delta\omega$ is the frequency difference between the oscillators ($\Delta\omega \ll \omega_0$). Phase locking occurs when $d\phi/dt = 0$, and the condition for locking is found to be[1,2] an allowable initial frequency difference

$$\Delta\omega = |\omega_i - \omega_0| \le \omega_0\rho/Q . \tag{2}$$

The time scale for locking to occur is given by

$$\tau \simeq Q/2\rho\omega_0 . \tag{3}$$

High-power oscillators have pulse durations of 10–100 ns; consequently, we desire short locking times and therefore large ρ. This facilitates locking of oscillators with larger frequency differences, allowing tolerance for oscillator differences in an array. Calculations using realistic pulse shapes and a time-dependent ρ show that the locking time scale should be a few nanoseconds.

Our experimental configuration is two relativistic magnetrons operating at ~1.5 GW each (Fig. 1). Relativistic magnetrons are reliable high-power oscillators; for a review, see Ref. 4. The magnetrons are fed from a split magnetically insulated transmission line and have very similar electrical and microwave operating properties. The connection between the two magnetrons is a short waveguide of length $L_c = V_p\tau_c$ where V_p is the phase velocity and τ_c is the transit time of the wave in the guide. Extraction is accomplished through three al-

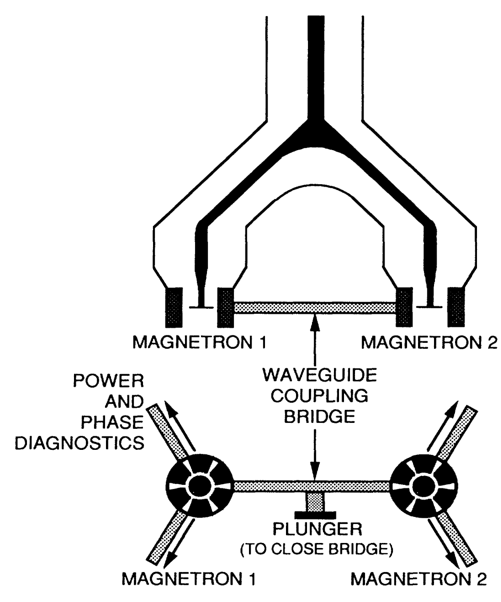

FIG. 1. Identical magnetrons energized by the same pulsed-power driver and coupled by connecting waveguide bridge. Microwaves extracted from each magnetron are analyzed with power and phase diagnostics.

ternate vanes of the six vanes on each magnetron.[5] One output vane feeds the connector and the other two are used for power, frequency, and phase diagnostics. In these experiments $\rho^2 \approx \frac{1}{3}$ (Ref. 5). The waveguide has an H-plane tee in the center with a sliding plug which can block communication between the two magnetrons.

Power is provided from a Marx-waterline system operating at 1 MV, 2.8 Ω, 120 ns. Adjustment of a shunt resistor at the junction of the output switch and the vacuum transmission line gives a voltage pulse that is trapezoidal and flat for 60 ns. Microwave pulse duration is ~30 ns. We use a washer cathode to enhance power output.[6] The magnetrons have been operated in the π and 2π modes at 2.8 and 3.8 GHz, respectively. Power is measured by power samplers and directional couplers connected to the output waveguides. Frequencies are measured by mixing a local oscillator with a fraction of the rf signal from the power samplers and observing the difference frequencies.

To determine relative phase between the magnetrons, we use Anaren model 2A0756 phase discriminators. Two outputs are produced; one is proportional to the sine of the phase difference and the other to the cosine of the phase difference. Phase angle is deduced from the arctangent of the signal ratio. The system was calibrated under cw operation and validated by measuring the phase difference between adjacent vanes.[7] The angular resolution of this phase measurement technique was determined to be $\pm 10°$.

With favorable anode-cathode alignment and other prerequisites for stable operation, locking occurs after ~5 ns. The phase relation of the two magnetrons is constant during the pulse, and reproducible from shot to shot (Fig. 2). Locking ceases because the power pulse ceases. Since the phase difference takes up the same angle on repeated shots, this is an example of phase locking not frequency locking. This is a very practical requirement to place on coherent oscillators because phase adjustments in the feed of an array would not be possible on a shot-to-shot basis.

The condition analogous to Eq. (2) for phase locking with finite connector length is[8]

$$|\Delta\omega| \leq 2\omega_0\rho\,|\cos\omega\tau_c|/Q\,. \tag{4}$$

Note that for small $\cos\omega\tau_c$, corresponding to $n\pi/2$ (n odd) phase difference of the connector, phase locking cannot occur. The locked phase difference between the oscillators occurs in two modes: zero-phase difference and π-phase difference, depending on the connector length.[8] In our experiment $\tau = 5.4\lambda$ and 8.5λ in the π and 2π modes, respectively. In both cases ~180° phase difference is observed.

A complementary demonstration of phase locking that relies solely on power measurements is the constructive interference of the radiated microwave fields from multiple sources. This was done by radiating from two antennas onto power-density diagnostics in the far field. One waveguide from each magnetron was connected to its own horn antenna in a screen box lined with microwave absorbing foam. On the centerline opposite and facing the two horns was one open-ended waveguide. This guide communicated through a waveguide coupler and attenuators to a crystal detector. We canceled out the 180° phase difference by using different waveguide lengths to the two antennas. We tabulated the received power for three conditions: antenna No. 1 covered with absorber, antenna No. 2 covered with absorber, and both antennas open. This way we could turn a magnetron "off" without interfering with its operation. If the radiated fields added incoherently, i.e., the magnetrons were not phase locked, we would have expected to measure 35 kW/cm^2 with both antennas open (based on the mea-

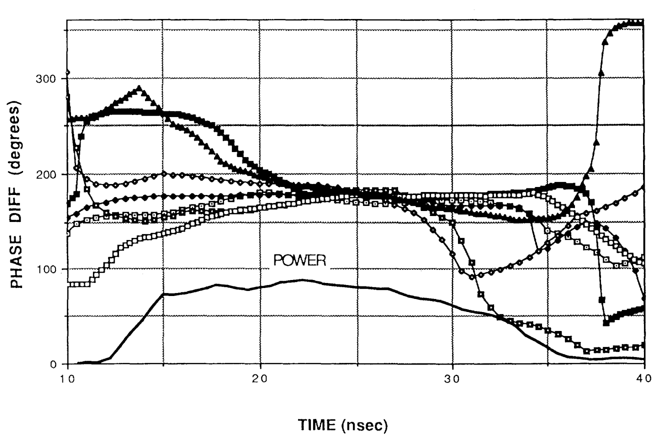

FIG. 2. Phase difference between magnetrons for seven consecutive shots. Detected microwave power history is shown. Total power is 2.8 GW at 2.8 GHz in π-mode operation.

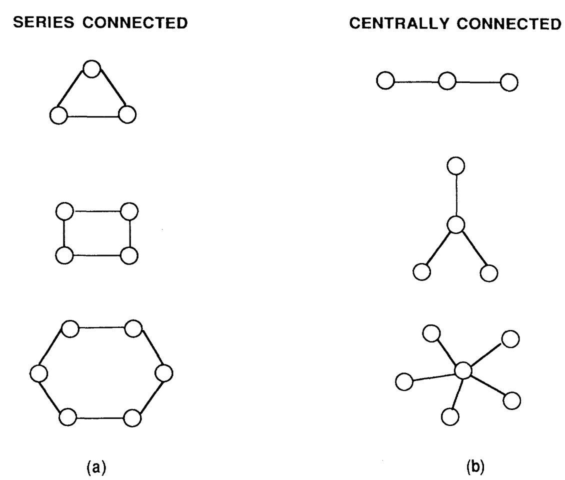

FIG. 3. Multiple-oscillator configurations for phase locking. (a) Series-connected, and (b) centrally connected geometries.

surements of the individual radiation fields). If the fields added coherently, we would have expected to measure 68 kW/cm^2. We did, in fact, measure 64 kW/cm^2, demonstrating that the magnetrons were indeed phase locked.

Having demonstrated phase locking at a power level of 3 GW, 3 orders of magnitude higher than previous magnetron work,[3] we are currently investigating geometry effects for groups of oscillators in the configurations. Series-connected oscillators, such as that shown in Fig. 3(a), are connected to their nearest neighbors. Each oscillator arrives at its final phase through a process of mutual interaction with the other oscillators. In the centrally connected geometry in Fig. 3(b), each outer oscillator is connected to a central oscillator and to no other; consequently, the final phase arises by interaction between the central oscillator and the satellite oscillators. This is essentially a system of two oscillator units and a direct extension of our experiment. Calculations show that phase locking occurs much more rapidly in the centrally connected geometry. There is a limitation on the connector length to avoid chaos. For the present magnetron design, this is $L_c \lesssim 14\lambda$ (Ref. 9). Arrays can easily be built within this constraint. Experiments are underway to investigate magnetron array phase locking.

In conclusion, phase control of high-power magnetrons has been demonstrated in a strongly coupled regime with $\rho \sim \frac{1}{3}$. Array design does not seem to be fundamentally limited by requirements on the connector length. Theory of strongly coupled oscillators agrees well with the data and prescribes coupler length in multiples of $\lambda/2$. Multiple-oscillator arrays appear to be a feasible route to high-power densities with total powers in the domain 10–100 GW. Calculations show rapid locking ($\sim$5 ns) of centrally connected geometries.

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