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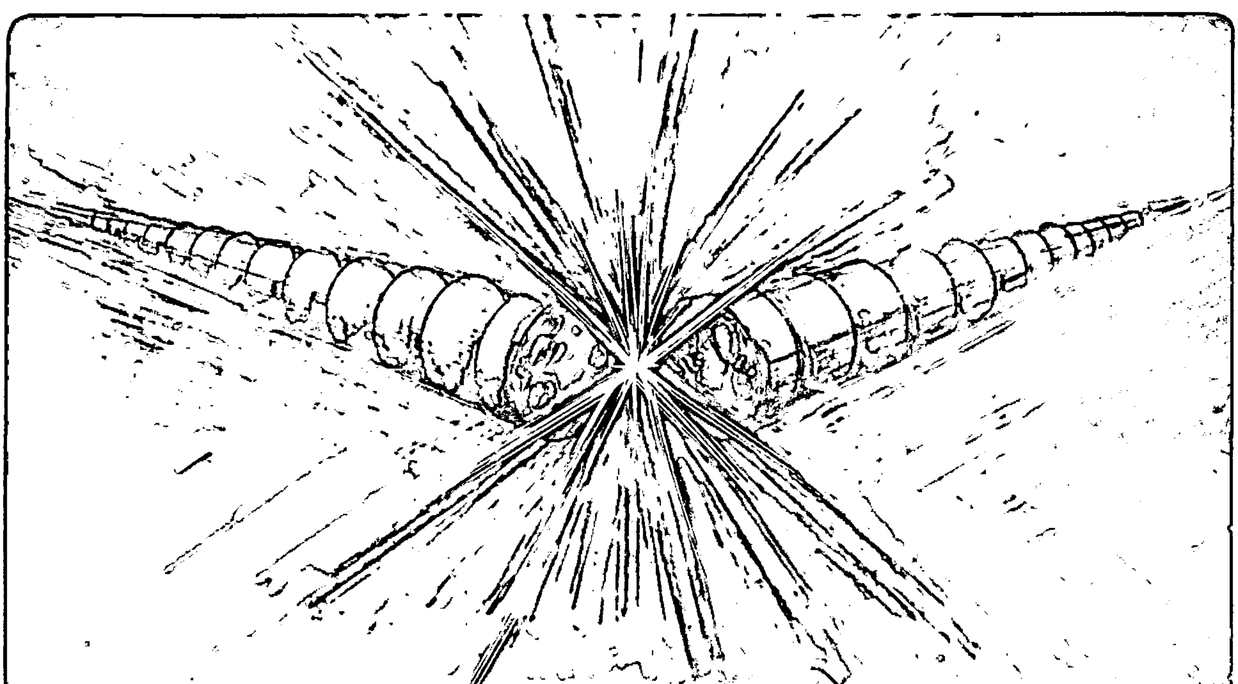

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DISCLAIMER

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I. Introduction

The electron cyclotron maser or gyrotron concept(1) has been developed to produce sources producing 200kW at 28 GHz continuously, and higher power outputs and frequencies in pulsed mode. These sources have been useful in electron cyclotron resonance heating (ECRH) in magnetically confined fusion devices. However, higher frequencies and higher power levels will be required in reactor-grade fusion plasmas, with likely requirements of 1.0 MW or more per source at 140 GHz.

Conventional gyrotrons use a cylindrical resonating cavity which interacts with a gyrating electron beam. The electron cyclotron frequency is made nearly equal to a cavity eigenmode frequency. The electron loses energy to the RF electric fields due to the cyclotron maser instability. The frequency produced is thus a function of the magnetic field in the cavity and the cavity dimensions. As the design frequency increases, the cavity must be made smaller, and thus power handling becomes more difficult. Conventional gyrotrons thus follow a trend of decreasing power for increasing frequency.

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In order to circumvent this problem, the quasioptical electron cyclotron maser was proposed.[2,3] In this device, the closed resonator of the conventional gyrotron is replaced with an open, Fabry-Perot type resonator. The cavity modes are then the TEM-type modes of an optical laser. Electric fields in the cavity are thus of the form:

$$E_x^{nm} = E_0 \sin \frac{n\pi z}{L} \; e^{-(x^2 + y^2)/r_0^2} \; e^{-i\omega t} f(z) H_{nm}(x,y)$$

where $f(z)$ is a weak function of z, and $H_{nm}(x,y)$ are the Hermite polynomials. The lowest order mode (TEM_{00}) is thus a gaussian field distribution.

The advantage of this configuration is that the cavity size is not a function of frequency, since the length can be any half-integer number of wavelengths. Furthermore, the beam traverses across the cavity transverse to the direction of radiation output, and thus the RF window design is less complicated than in conventional tubes. The RF output, if obtained by diffraction coupling around one of the mirrors, could be in a TEM mode, which would allow for quasioptical transmission of the microwaves into the plasma in fusion devices.[4]

2. Experimental configuration

In order to test the quasioptical cyclotron maser concept, we have designed a 28 GHz proof-of-principle experiment. A schematic experiment is shown as Fig. 1. The experiment used a 10.0 kG field produced from a water-cooled copper Helmholtz pair. The magnet set has a nine-inch bore and allows a cylindrical vacuum tank to fit inside. The magnet configuration allows for the output RF to exit the field radially through the break between the Helmholtz pair. The resonator consists of two 2.9 inch diameter mirrors, which are approximately confocal with a separation distance of 15 cm. This gives a mode number (n) around 28.

The electron gun for this experiment consists of a magnetron injection gun manufactured by Varian. The gun injects an annular electron beam with a diameter of 6.0 mm at the resonator. The pitch ($V_\perp/V_\parallel$) of the electron beam is approximately 2.0. The gun runs at 80kV at currents up to 12.0 A.

A computer simulation has been written and run on the MFE Cray computer at Livermore to analyze the RF production efficiency of this device. The results indicate that efficiencies up to 25 percent could be realized with a cavity quality factor (Q) of 20,000. The code indicates optimum efficiency with peak electric fields on the order of 70kV cm^{-1}.

3. Experimental results

The diagnostics for the experiment consist of a calorimeter for power measurement along with a cavity wavemeter and diode crystal for frequency measurement. Diagnostics are also available to monitor electron beam current and voltage, along with background gas pressure and magnetic field.

Three different resonator configurations have been used, differing only in the output coupling configuration. In the first case, a WR-28 rectangular waveguide hole (0.140" x 0.280") in the output mirror was used to couple the RF output. While measured power was rather low (<250W), clearly spaced modes were identified, and the mode spacing (roughly 4% in frequency and magnetic field) agreed with the predictions for TEM excitation of the cavity. A second configuration was used consisting of a 0.69" circular hole on axis in the output mirror. The output was coupled into a 0.69" brass circular waveguide. Output power was higher for this case, on the order of 2kW. Also, a greater number of modes were seen, indicating higher order (TEM_{npq}, p, q = 0) modes. Cold tests using a reflected power bridge at 28 GHz revealed high Q modes of higher order.

As a means of coupling to the TEM_{00} mode, a coupling geometry consisting of annular slots at a radius of 0.75" in the output mirror was used. This resulted in as much as 10 kW output from the device. While this is less than the theoretical maximum power of ~125 kW, the discrepancy can likely be explained by loss mechanisms in the open resonator due to departure from the optics limit at this relatively low frequency. Presumably higher efficiencies, up to 25 percent, could be obtained with resonators with a higher Fresnel number ($a^2/\lambda D$), where losses due to diffraction would be lower.

4. Conclusions

We have shown that a quasioptical electron cyclotron maser can sustain oscillation and produce significant power output. Achieving ideal efficiency remains to be demonstrated, although this is more likely to occur with higher frequencies and with optimal coupling schemes. The experimental results lead the way to construction of high efficiency, high power cw masers at millimeter wavelengths. The design of a 1.0 MW, 100 GHz source for fusion reactor heating appears feasible, and is within the limits of current electron gun and magnet technology.

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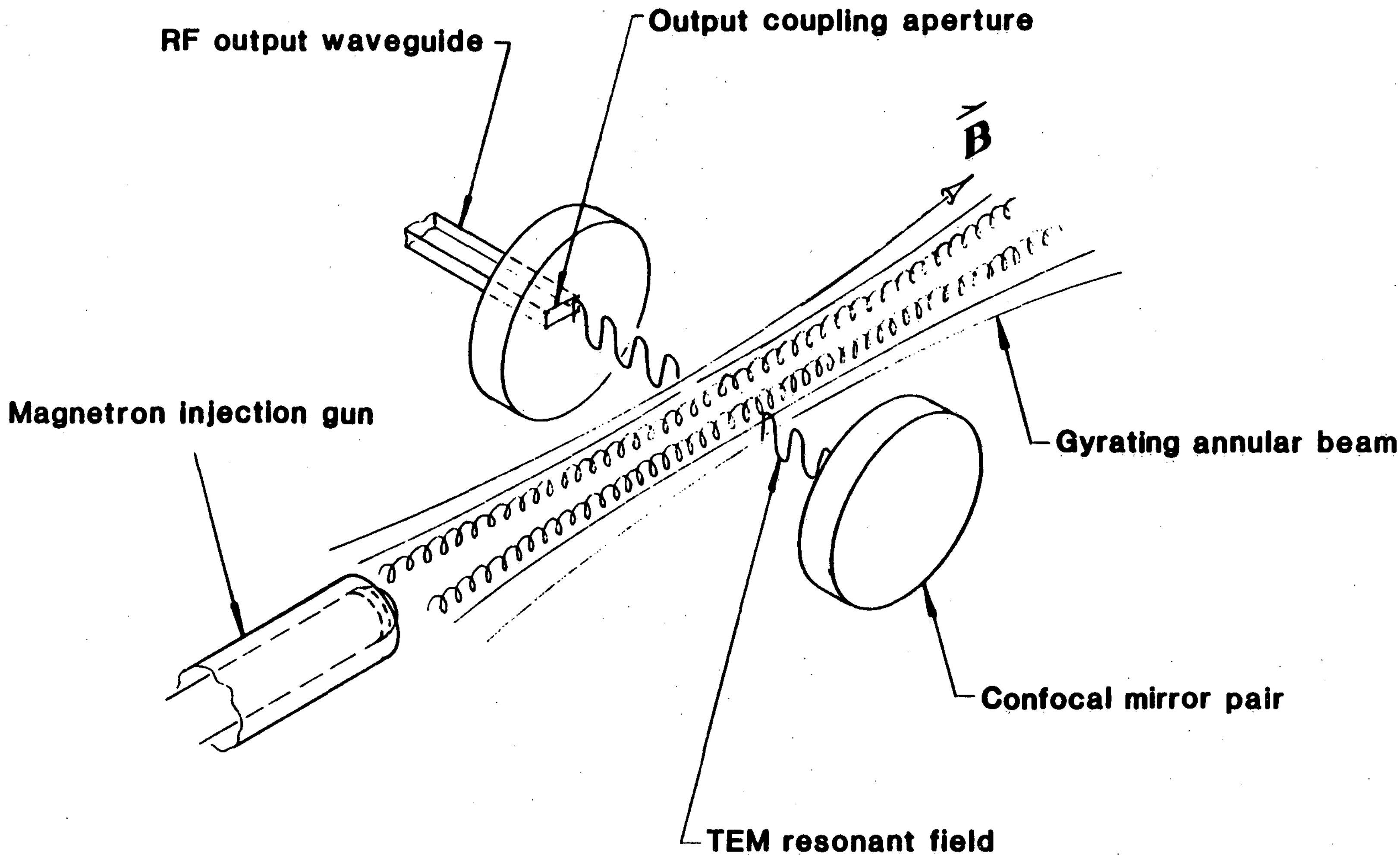

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Fig. 1. Schematic of Quasioptical Maser Experiment.

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